

¹ Generically Orthogonal Decompositions of
² Collision Events and Measurement
³ Combinations in Standard Model $VH(b\bar{b})$
⁴ Searches with the ATLAS Detector

⁵ A DISSERTATION PRESENTED
⁶ BY
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¹³ IN THE SUBJECT OF
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20 **Generically Orthogonal Decompositions of Collision Events**
21 **and Measurement Combinations in Standard Model $VH(b\bar{b})$**
22 **Searches with the ATLAS Detector**

23 **ABSTRACT**

24 This thesis describes variations on the two lepton channel of the Run-2 search for the SM Higgs
25 boson produced in association with a vector boson using different variable sets for multivariate anal-
26 ysis (MVA) training. The three variable sets in question are the set of variables from the fiducial anal-
27 ysis, a set based on the Lorentz Invariants (LI) concept, and a set based on a combination of masses
28 and decay angles derived using the RestFrames (RF) package. Aside from the variable sets used for
29 MVA training and discriminant distributions, the analysis is otherwise identical to the fiducial an-
30 lysis. Both the LI and RF sets perform competitively on the basis of significances, with the RF set
31 showing a $\sim 3.5\%$ improvement in expected fits to Asimov and data, though neither set boosts ob-
32 served significance. Both sets also reduce the observed error on $\hat{\mu}$, with the LI set reducing the error
33 due to systematics by 7.5% and the RF set doing so by 16%.

34 The issue of combining multiple results from different channels and datasets is also examined
35 through the combination of the fiducial Run 1 and Run 2 ATLAS $VH(b\bar{b})$ results, which results in
36 an observed signal strength of $0.90^{+0.18}_{-0.18}(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$ and an observed (expected) significance
37 of 3.6 (4.0) standard deviations, the first ever evidence of this process.

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¹³¹ THIS THESIS WOULD NOT HAVE BEEN POSSIBLE without large amounts of espresso.

吾生也有涯，而知也无涯。以有涯隨无涯，殆已；
已而為知者，殆而已矣。

Zhuangzi, Book 3

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133

Introduction

134 SINCE THE DISCOVERY of a Standard Model (SM) like Higgs boson at the LHC in 2012[1][2], one
135 of the main outstanding physics goals of the LHC has been to observe the primary SM Higgs decay
136 mode, $H \rightarrow b\bar{b}$, with efforts primarily targeted at searching for Higgs bosons produced in associ-
137 ation with a leptonically decaying vector (W or Z , denoted generically as V) boson. This primary

¹³⁸ Higgs decay mode also offers the best opportunity to observe direct Higgs coupling to quarks. As
¹³⁹ the integrated luminosity of data collected at the LHC increases, $H \rightarrow b\bar{b}$ searches will increasingly
¹⁴⁰ become limited by the ability to constrain systematic uncertainties, with the latest result from AT-
¹⁴¹ LAS at $\sqrt{s} = 13$ TeV using 36.1 fb^{-1} of pp collision data already approaching this regime, having a
¹⁴² $VH(b\bar{b})$ signal strength of $1.20^{+0.24}_{-0.23}(\text{stat.})^{+0.34}_{-0.28}(\text{syst.})$ at $m_H = 125$ GeV [3].

¹⁴³ While this effort will likely require a combination of several different methods at various differ-
¹⁴⁴ ent stages in the analysis chain, one possible avenue forward is to revise the multivariate anlaysis
¹⁴⁵ (MVA) discriminant input variables used, as various schemes offer the promise of reducing system-
¹⁴⁶ atic uncertainties through more efficient use of both actual and simulated collision data. This thesis
¹⁴⁷ discusses two such alternate MVA schemes, the RestFrames (RF) and Lorentz Invarants (LI) vari-
¹⁴⁸ ables, in the context of the 2-lepton channel of the Run 2 analysis in [3] and [4], henceforth referred
¹⁴⁹ to as the “fiducial analysis,” before a brief discussion of combinations across channels and datasets.

¹⁵⁰ Electroweak symmetry breaking, Standard Model Higgs production and decay, and event level
¹⁵¹ variables are treated in Chapter 1. The Large Hadron Collider and ATLAS detector are the subject
¹⁵² of Chapter 2. Data and simulation samples used are described in Chapter 3. Signal and background
¹⁵³ modeling with accompanying systematis are defined in Chapter 4. Object and event reconstruction
¹⁵⁴ definitions and event selection requirements are outlined in Chapter 5. The multivariate analysis, in-
¹⁵⁵ cluding a description of the LI and RF variable sets and a summary of performance in the absence of
¹⁵⁶ systematic uncertainties, is described in Section 6. The statistical fit model and systematic uncertain-
¹⁵⁷ ties are described in Section 7, and the fit results may be found in Chapter 8. Combining channels
¹⁵⁸ and datasets at different \sqrt{s} values is discussed in the context of the Run 1 + Run 2 SM $VH(b\bar{b})$

¹⁵⁹ combination in Chapter 9. Finally, conclusions and closing thoughts are presented in Chapter 10.

¹⁶⁰ Editorial notes:

¹⁶¹ 1. pdf will be *probability* distribution function

¹⁶² 2. PDF will be *parton* distribution function

¹⁶³ 3. Unless otherwise stated, ATLAS and LHC/CERN images are from public available material
¹⁶⁴ from experiment webpages. Copyright terms may be found here <https://atlas.cern/>
¹⁶⁵ **copyright**.

*The relationship between theorists and experimentalists
is like that between a truffle farmer and his pig*

Howard Georgi

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The Standard Model Higgs and Collider

168

Event Variables

169 MUCH HAS BEEN SAID about the so-called Standard Model (SM) of particle physics, so only the
170 bare essentials of electroweak symmetry breaking and Higgs production relevant to SM $VH(b\bar{b})$ will

¹⁷¹ be addressed here. This discussion follows [5] Chapter 11 in both content and notation. We then

¹⁷² move onto the treatment of kinematic variables in collider events, including the two novel schemes

¹⁷³ considered in this thesis, the Lorentz Invariants (LI) and RestFrames (RF) concepts.

¹⁷⁴ I.I THE STANDARD MODEL HIGGS BOSON

¹⁷⁵ The generic scalar Lagrangian potential (the kinetic term will be addressed later) for a scalar in the

¹⁷⁶ SM is:

$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (I.1)$$

¹⁷⁷ where Φ is a complex scalar doublet field under $SU(2)$ from which the physical Higgs emerges after

¹⁷⁸ symmetry breaking. Its four degrees of freedom are typically decomposed as follows:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ \phi^0 + i\alpha^0 \end{pmatrix} \quad (I.2)$$

¹⁷⁹ ϕ^+ is the complex charged component of the Higgs doublet, and ϕ^0 and α^0 are the CP-even and

¹⁸⁰ CP-odd neutral components, respectively.

¹⁸¹ If the sign of $m^2 \Phi^\dagger \Phi$ is negative, Φ acquires a *vacuum expectation value* or VEV:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \sqrt{\frac{2m^2}{\lambda}} \end{pmatrix} \quad (I.3)$$

¹⁸² with this value typically denoted $v = \sqrt{2m^2/\lambda} = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV (with the coupling

¹⁸³ of the 4-Fermi effective theory of weak interactions measured through experiments involving muon
¹⁸⁴ decay), and ϕ^0 is rewritten as $\phi^0 = H + v$.

¹⁸⁵ This non-zero VEV induces spontaneous symmetry breaking in the SM's gauge (local) symme-
¹⁸⁶ try group of $SU(3)_C \times SU(2)_L \times U(1)_Y$ since the VEV does not respect the $SU(2)_L \times U(1)_Y$
¹⁸⁷ symmetry of the Lagrangian (i.e. $\langle \Phi \rangle$ is not invariant under a gauge transformation of this group).

¹⁸⁸ Three of the four generators of this subgroup are spontaneously broken, which implies the existence
¹⁸⁹ of three massless Goldstone bosons, which are in turn “eaten” by linear combinations of the W^a
¹⁹⁰ (with coupling strength g) and B (with coupling strength g') bosons to form the longitudinal polar-
¹⁹¹ izations of the familiar W^\pm and Z bosons, with the last generator giving rise to the usual, unbroken
¹⁹² $U(1)_{EM}$ symmetry and its massless photon, A , as well as the scalar Higgs boson H . To see this, one
¹⁹³ starts with the full Higgs SM Lagrangian (kinetic minus potential only)

$$\mathcal{L}_{Higgs} = (D_\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi), \quad D_\mu \Phi = (\partial_\mu + ig\sigma^a W_\mu^a + ig' Y B_\mu / 2) \Phi \quad (1.4)$$

¹⁹⁴ One simply plugs in the reparametrized Φ with $\phi^0 = H + v$, collects the terms involving v together
¹⁹⁵ with the appropriate W and B kinetic terms to extract:

$$M_W^2 = \frac{g^2 v^2}{4}, \quad M_Z^2 = \frac{(g'^2 + g^2) v^2}{4} \quad (1.5)$$

¹⁹⁶ This is left as an exercise for the reader; this exercise also makes manifest that the Higgs couples with
¹⁹⁷ the W^\pm and Z with strength quadratic in the gauge boson masses. Since the Higgs field also respects

¹⁹⁸ the $SU(3)_C$ color symmetry, the eight gluons are also left massless, and the H is left interacting with
¹⁹⁹ photons and gluons primarily through heavy quark loops (i.e. no tree-level interactions).

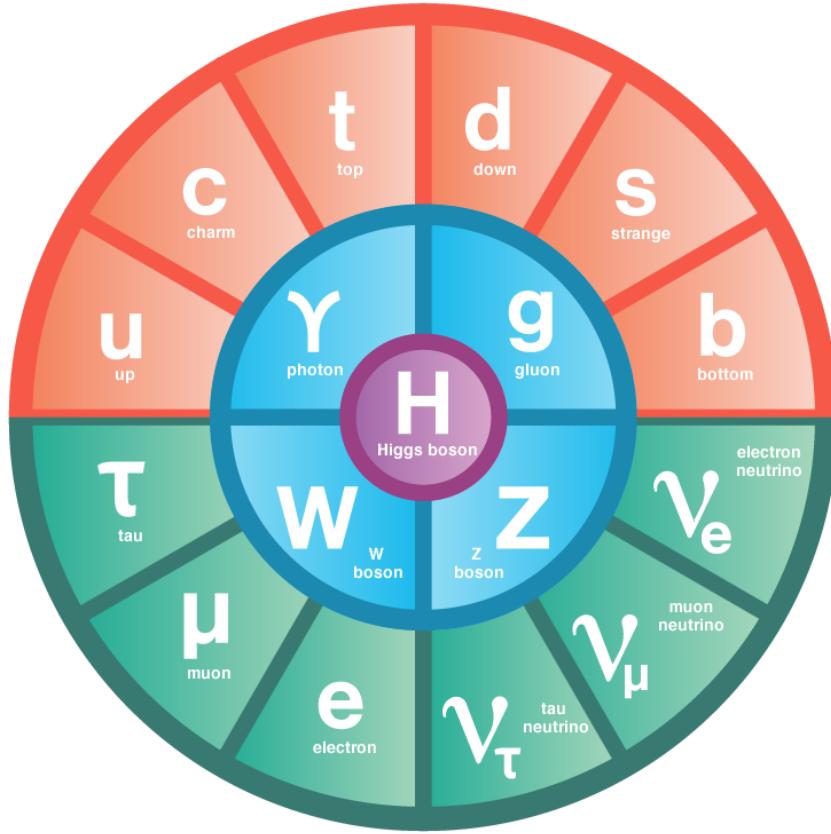


Figure 1.1: The fundamental particles of the Standard Model. IC: [6]

²⁰⁰ The Higgs is often introduced to the public at large as the mechanism through which fundamen-
²⁰¹ tal fermions (enumerated in Figure 1.1) acquire mass—this is through the Yukawa interactions of the
²⁰² Higgs:

$$\mathcal{L}_{Yukawa} = -\hat{h}_{d_{ij}} \bar{q}_{L_i} \Phi d_{R_j} - \hat{h}_{u_{ij}} \bar{q}_{L_i} \tilde{\Phi} u_{R_j} - \hat{h}_{l_{ij}} \bar{l}_{L_i} \Phi e_{R_j} + h.c. \quad (1.6)$$

²⁰³ where $\tilde{\Phi} = i\sigma_2 \Phi^*$, q_L (l_L) and u_R , d_R (e_R) are the quark (lepton) left-handed doublets and right

204 handed singlets of the weak $SU(2)_L$ group, with each term parametrized by a 3×3 matrix in family
205 space (also known as the fermion generations). The neutrinos have been purposely omitted since
206 the mechanism that generates their mass is as of yet unknown, though these Yukawa interactions
207 could have a non-zero contribution to neutrino masses. Once the Higgs VEV value is known and
208 the Yukawa interaction matrices $\hat{b}_{f_i j}$ (with $i, j \in \{1, 2, 3\}$) are diagonalized, the fermion masses
209 can simply be written as $m_{f_i} = b_{f_i} v / \sqrt{2}$. The SM has no motivation for any of these mass values,
210 instead leaving them as empirically determined free parameters.

211 Note that from \mathcal{L}_{Yukawa} , it is easy to see that the Higgs couplings with fermions scale linearly with
212 fermion mass. Higgs self-couplings and beyond the standard model (BSM) Higgs scenarios are be-
213 yond the scope of this thesis.

214 I.2 HIGGS BOSON PRODUCTION AND DECAY AT THE LARGE HADRON COLLIDER

215 The leading order Feynman diagrams for the four dominant modes of Higgs production at the LHC
216 are shown in Figure 1.2, each described briefly in turn. The dominant process, accounting for some
217 87% of Higgs production at the nominal LHC center of mass energy of 14 TeV, is gluon-gluon fu-
218 sion (ggF), shown at top left in Figure 1.2. At high center of mass energies, most of a proton's mo-
219 mentum is predominantly carried by gluons (as opposed to the constituent valence quarks associ-
220 ated with the hadron's identity). This, along with the difficulties associated with high luminosity
221 antiproton beam production, is why the LHC was designed as a proton-proton collider instead of
222 a proton-antiproton collider (like the Tevatron or SppS). As mentioned above, the Higgs does not
223 couple directly to gluons but must instead be produced through the fermion loop shown in the fig-

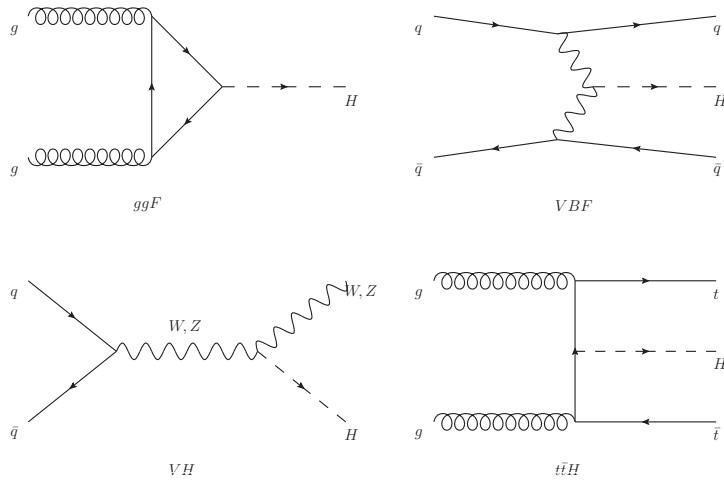


Figure 1.2: Dominant Higgs production modes.

ure. The heaviest fundamental fermion by far is the top quark, with $m_t = 173$ GeV, so top loops dominate this process. While not particularly relevant for this thesis, about 14% of events in the lepton channel of the $H \rightarrow b\bar{b}$ analysis are ggF initiated.

The next most prevalent process is vector boson fusion (VBF), where vector bosons (W or Z , denoted generically as V) from quarks in the colliding protons “fuse” to form a Higgs. These quarks typically form jets in the forward region, which provide a unique signature for this process. This process is not relevant for this thesis.

The third leading process is “Higgsstrahlung” or Higgs production in association with a vector boson, often simply VH production. In this process, a quark-antiquark pair in the colliding protons forms an energetic vector boson, which then radiates a Higgs (this is similar to photon emission of accelerating electrons, called “Bremsstrahlung,” hence the name). Some fraction of the time (about 21% of the time for WH and 6.7% of the time for ZH), the energetic V will decay leptonically (i.e.

236 into a decay involving an electron or a muon), which provides a unique and triggerable signature
 237 for this process. Another 20% of the time for ZH production, the Z will decay to neutrinos, which
 238 are not absorbed by detectors and show up as missing transverse energy (\vec{E}_T^{miss}), another triggerable
 239 signature. This ability to trigger on leptons and \vec{E}_T^{miss} and the requirement that this leptonic signa-
 240 ture be consistent with a V allow one to significantly reduce the impact of multijet background (a
 241 very common generic processes at the LHC) on analysis. Hence, this is the process of primary impor-
 242 tance to this thesis.

243 The final important Higgs production process is $t\bar{t}H$ production, the box diagram in the lower
 244 right of Figure 1.2. Again, the top pair provides a useful signature for analysis. This, like VBF, is also
 245 not considered in this thesis.

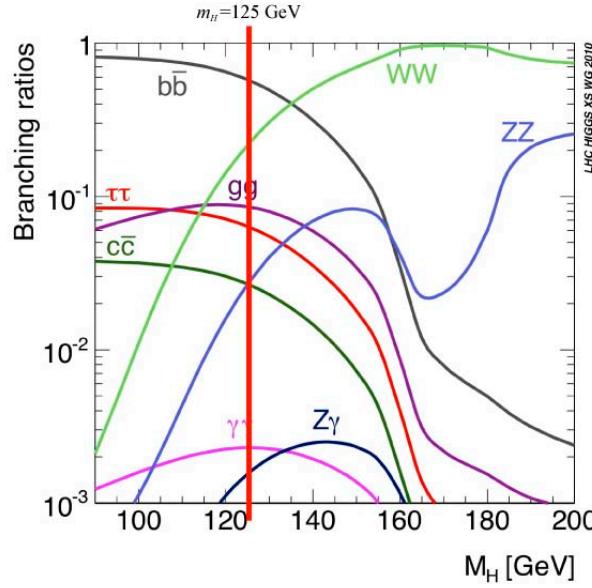


Figure 1.3: Higgs decay mode branching fractions as a function of its mass; a line has been drawn at the observed Higgs mass of 125 GeV.

Once the Higgs has been produced, it can decay in a number of ways, as shown in Figure 1.3. By far the most dominant decay mode of the Higgs is to $b\bar{b}$ with a branching fraction of 58%. This b -quark pair then hadronizes into two b -jets (for a more thorough discussion of jets and b -jets in particular, see Section 5.5). However, many processes at the LHC create pairs of b -jets with invariant masses consistent with the Higgs and have much higher production rates ($t\bar{t}$ production at the LHC is in the neighborhood of hundreds of pb, compared to Higgs cross sections of a few pb), so a clear process signature is necessary to study $H \rightarrow b\bar{b}$ production at the LHC. This is why the bulk of search efforts have focused on VH production. A summary of Higgs production cross sections and simple extrapolations to raw numbers of Higgs bosons produced for VH for leptonically decaying V is shown in Table 1.1

\sqrt{s} (TeV)	ZH	WH	ggF	total σ	$N_{V \rightarrow \ell^+ \nu} H$
7	$0.34^{+4\%}_{-4\%}$	$0.58^{+3\%}_{-3\%}$	$15.3^{+10\%}_{-10\%}$	17.5	$4.7 \text{ fb}^{-1} \rightarrow 589$
8	$0.42^{+5\%}_{-5\%}$	$0.70^{+3\%}_{-3\%}$	$19.5^{+10\%}_{-11\%}$	22.3	$20.3 \text{ fb}^{-1} \rightarrow 3100$
13	$0.88^{+5\%}_{-5\%}$	$1.37^{+2\%}_{-2\%}$	$44.1^{+11\%}_{-11\%}$	50.6	$36.1 \text{ fb}^{-1} \rightarrow 11100$
14	$0.99^{+5\%}_{-5\%}$	$1.51^{+2\%}_{-2\%}$	$49.7^{+11\%}_{-11\%}$	57.1	$1000 \text{ fb}^{-1} \rightarrow 343000$

Table 1.1: Cross sections (in pb) for processes important to the SM VH ($b\bar{b}$) analysis and the total Higgs cross section as a function of center of mass energy. Also given are the total number of Higgs bosons produced for given luminosities through both WH and ZH processes. Uncertainties are theoretical.

1.3 COLLIDER EVENTS AND EVENT LEVEL VARIABLES

Collision data in experiments like ATLAS is structured using what is known as the *event data model*. In this model, one collision corresponds to one event. Since each bunch crossing contains more than one proton, there can be more than one collision per event and more than one hard scatter per col-

260 lision. For each collision, tracks in an experiment's inner detector are used to identify the most ener-
 261 getic collision, which is taken to be the event. The raw data, the various tracks, energy deposits, and
 262 hits in the detector, undergo reconstruction (described at length in Chapter 5) both through auto-
 263 mated, experiment-wide, standardized production and through analysis-specific level selections, cor-
 264 rections, and calibrations. The result of this considerable effort is a collection of labeled 4-vectors,
 265 representing the final state objects. This is shown in Figure 1.4.

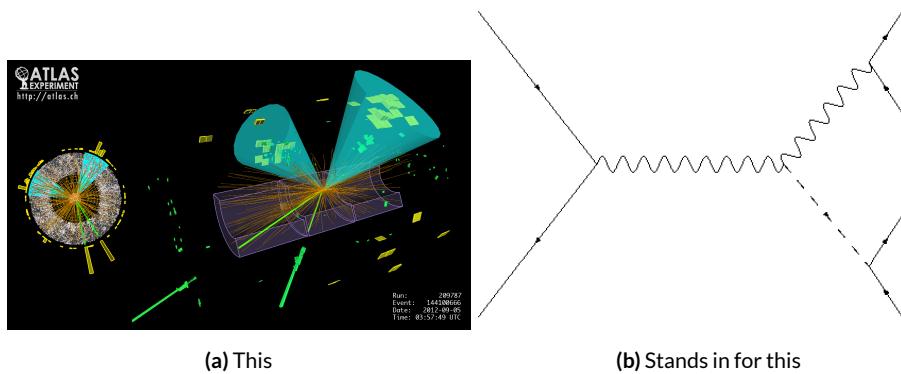


Figure 1.4: Reconstruction in a nutshell

266 In the process that is the focus of this thesis, every event ultimately is condensed into a lepton pair
 267 (two electrons or two muons), two or three jets*, all 4-vectors, and a \vec{E}_T^{miss} vector in the transverse
 268 plane. Further selection then takes place to winnow down events into interesting regions of phase
 269 space hopefully more rich in signal-like events. Once events are selected in a search like the one in
 270 this thesis, one then analyzes the data to test its consistency with some background only hypothesis
 271 to produce the usual statistical results. This can be done in various ways, with principal approaches

*Sometimes more, though this is a small fraction of events, and the wisdom of this choice may be questioned

272 being: a simple counting experiment (often referred to as the “cut and count” approach), a func-
273 tional fit for excesses over a falling background spectrum (the so-called “bump hunt” used in anal-
274 yses like the $H \rightarrow \gamma\gamma$ discovery channel), or the use of discriminant distributions as PDF’s in a
275 likelihood fit (the approach of this analysis). These distributions can be simple counts (i.e. single bin
276 distributions) in analysis regions, quantities of interest (the distribution of the invariant mass of the
277 two b -jets in selected events with the greatest transverse momenta, m_{bb} , is used as a validation), or a
278 multivariate analysis (MVA) discriminant.

279 **I.4 CHARACTERIZATION WITH EVENT-LEVEL VARIABLES**

280 Traditionally, particle physicists have favored the approach of using distributions of physical vari-
281 ables since it is easier to develop physical intuition for what these distributions should look like
282 during validation, so it is no surprise that as many LHC analyses have transitioned to using MVA
283 techniques that these variables form the basis of many very robust physics results. These variables
284 do quite well summarize many of the main physics features of an event for the signal topology, cer-
285 tainly much better than feeding all 18–22 4-vector components directly into a machine learning algo-
286 rithm. In $ZH \rightarrow \ell\ell b\bar{b}$ events, for example, one wishes to characterize the ZH system by using the
287 lepton pair as a stand-in for the Z and the b -jet pair as a stand-in for the H , and composite variables
288 like m_{bb} and $m_{\ell\ell}$ can be used to check whether events are consistent with these objects. There are
289 also variables like \vec{p}_T^V that characterize the momentum scale of the event, angles like $\Delta R(b_1, b_2)$ and
290 $\Delta\phi(V, H)$ that can be further used to characterize the overall “shape” of these events, and variables
291 like \vec{E}_T^{miss} that can discriminate against backgrounds like $t\bar{t}$ that do not have a closed topology.

292 Nevertheless, the intuition based approach, with incremental addition of variables as they prove
293 useful in the lifetime of an analysis's iterations, does beg the question of whether there is a more sys-
294 tematic way to treat this information. There are clearly patterns to which variables are useful: these
295 correspond to important information about the hypothesized physics objects and their relation-
296 ships, and there have been many attempts to systematize the way these variables are found. Such
297 systematic, top-down approaches often promise to increase performance in two ways. The first is by
298 having higher descriptive power, often through some sophisticated treatment of the missing trans-
299 verse energy in an event, \vec{E}_T^{miss} . \vec{E}_T^{miss} is just a single quantity, and if there is just one invisible object
300 in a desired event topology, using \vec{E}_T^{miss} on its own often provides sufficient sensitivity. In more com-
301 plicated topologies with multiple invisible particles in the final state, for example in many supersym-
302 metry searches, a more careful treatment of the missing energy is often necessary.

303 The second means of improvement is through using a more orthogonal basis of description,
304 which allows one to more efficiently use data and simulation samples. A more orthogonal basis im-
305 plies that variables contain less overlapping information with each other and so allow for a more
306 efficient exploration of parameter space. This means one can gain higher sensitivity from equivalent
307 datasets using a more orthogonal basis. To see why this might be the case, take an MVA discrimi-
308 nant for $ZH \rightarrow \ell\ell b\bar{b}$ formed using only the classic variables $\Delta R(b_1, b_2)$ and p_T^V . In the $ZH \rightarrow$
309 $\ell\ell b\bar{b}$ topology, the transverse mass of the Z and H (and hence the lepton pair and jet pair) are equiv-
310 alent. This means that at higher p_T^V the p_T of b -jets will also be higher, which in turn implies that
311 they will have a smaller angle of separation and hence a smaller $\Delta R(b_1, b_2)$. This correlation is not
312 unity—each variable still does have information the other does not—but is still very high. Hence,

313 when training an MVA, which in principle knows nothing about these variables other than some
314 set limits, an undue number of training events will be wasted converging upon relations that could
315 be known *a priori*, and while this might be easy to hard code in for a two variable toy example, the
316 dimensionality of any real discriminant makes this prohibitive. An MVA that uses data (both ac-
317 tual and simulated) more efficiently will also tend to be have lower variance, offering a potential av-
318 enue for reduction in the error on quantities of interest due to systematic uncertainties. Details of
319 how this plays out in a likelihood fit will be deferred to the discussion of the fit model used in the
320 $VH(b\bar{b})$ search in Chapter 7.

321 Many of these novel schemes are designed to explicitly address the first issue of invisibles in the
322 final state in channels where it is of paramount importance while having the second issue as some-
323 thing of a fringe benefit. However, as the amount of data taken at the LHC grows, analyses will in-
324 creasingly become systematics limited, so an exploration to the veracity of the second claim has great
325 potential for the high luminosity era of the LHC. The $ZH \rightarrow \ell\ell b\bar{b}$ process offers a great setting for
326 investigating this issue on its own since its closed topology largely mitigates any improvement from
327 more sophisticated treatments of \vec{E}_T^{miss} . We introduce two of these more top-down approaches to
328 event-level variables below: the “Lorentz Invariant” (LI) [7] and “RestFrames inspired” (RF) [8]
329 variable schemes. A broad overview of the concepts behind these schemes will be given here, with a
330 more in-depth discussion of their implementation deferred until Chapter 6.

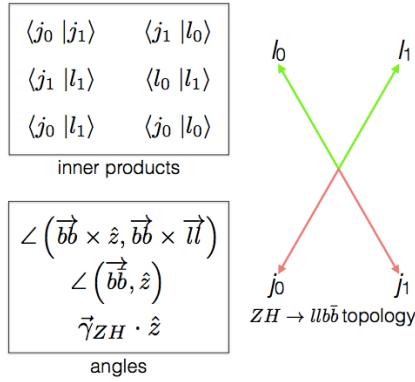


Figure 1.5: Summary of LI variables in the $ZH \rightarrow \ell\ell b\bar{b}$ topology.

³³¹ **I.5 LORENTZ INVARIANTS**

³³² The LI variables, first put forth by S. Hagebeck and others [7], are based upon the concept that
³³³ once the 4-vectors of an event are determined, all of the information in an event are encoded into
³³⁴ their inner products (Lorentz invariant quantities, hence the name) and the angles between them.
³³⁵ This makes for 16 quantities in all: the ten inner products of the 4-vectors, the three Euler angles,
³³⁶ and the three parameters specifying the boost of the ZH system. The masses of the four final state
³³⁷ objects are not considered very useful and so can be removed to leave six meaningful inner products
³³⁸ (the ${}_4C_2$ combinations[†] between distinct final state 4-vectors). Since these inner products can have
³³⁹ an ill-defined physical interpretation and in order to help MVA training, each inner product is scaled

[†] ${}_nC_r = \frac{n!}{r!(n-r)!}$, read “ n choose r ” and known as the binomial coefficient, is the number of unique possible ways to choose combinations of r objects from a total set of n without regard to ordering within combinations.

³⁴⁰ by:

$$x \rightarrow \frac{x}{x + c} \quad (1.7)$$

³⁴¹ where c is the mean of the distribution in the signal MC distribution. These inner products are de-
³⁴² noted $x_i y_j$, where x and y are either j (for jet) or l (for lepton) and the indices are either o (i) for
³⁴³ the leading (subleading) object by p_T in the event.

³⁴⁴ The number of useful angles can be reduced by recognizing some symmetries inherent in the fi-
³⁴⁵ nal state. The symmetry around the beam axis eliminates one angle. Furthermore, the boost of the
³⁴⁶ VH system is primarily in the beam direction (z) direction, marginalizing the utility of the trans-
³⁴⁷ verse boost angles. This leaves the boost in the z direction, denoted `gamma_ZHz`, and two angles
³⁴⁸ chosen to be the angle between the $b\bar{b}$ system and the beam (`angle_bb_z`) and the angle between
³⁴⁹ $(\vec{b}_1 + \vec{b}_2) \times \hat{z}$ and $(\vec{b}_1 + \vec{b}_2) \times (\vec{l}_1 + \vec{l}_2)$ (`angle_bbz_bbll`).

³⁵⁰ These variables do contain a lot of information similar to the usual set: there are mass equivalents
³⁵¹ ($j_0 \leftrightarrow m_{bb}$, and $l_0 \leftrightarrow m_{\ell\ell}$) and angles. Instead of individual final state object scales, there
³⁵² are the four jet/lepton inner products, though this correspondence (and indeed any physical inter-
³⁵³ pretation) is far from clear. An important advantage of the LI variable set is that all of the variables
³⁵⁴ are in it are orthogonal in the signal case by construction. A drawback of this framework in a com-
³⁵⁵ pletely closed final state is that there is no way to treat E_T^{miss} in a Lorentz invariant way.

³⁵⁶ There is also no prescription for any additional jets in the event beyond the two b -tagged jets.
³⁵⁷ They are simply ignored in these variable calculations since the fiducial analysis requirement of ex-

358 actly two b -tagged jets eliminates any combinatoric ambiguity, and additional, untagged jets are as-
359 sumed (not entirely rigorously) to be unrelated to the signal-like hard scatter.

360 **1.6 RESTFRAMES VARIABLES**

361 The RestFrames variables [8], calculated using the software package of the same name, is based upon
362 the idea that the most natural frame in which to analyze objects of the signal decay tree is in their in-
 dividual production (rest) frames. The signal decay tree for $ZH \rightarrow \ell\ell b\bar{b}$ is show in Figure 1.6. Gen-

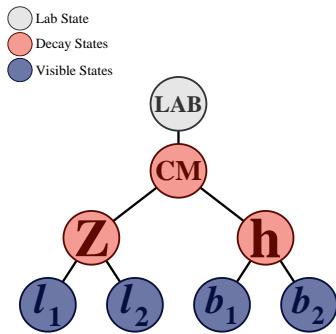


Figure 1.6: The $ZH \rightarrow \ell\ell b\bar{b}$ decay tree.

363
364 erally, one does not typically have enough information to determine exactly each of the intermediate
365 rest frames or the boosts between the frames, but in a completely closed final state like $ZH \rightarrow \ell\ell b\bar{b}$,
366 this can be done in the usual way by adding the 4-vectors of the final state objects and solving the
367 usual equations from special relativity (RestFrames does this automatically for each event).

368 Each frame has associated with it the boost from its immediate parent and a mass scale; that mass
369 (in this case the correspondence between RF mass variables and standard mass variables is exact) and
370 the angles between the Euclidean three vector associated with boost and the axis of the decay prod-
371 ucts provide useful variables. In general, the polar angle (typically given as a cosine) is considered

372 more useful than the azimuthal angle (typically just a $\Delta\phi$), though this is dependent on the candi-
 373 date decay tree. The Z frame, for example, has M_Z , which is just the usual $m_{\ell\ell}$, $\cos Z$, the cosine of
 374 the polar angle between the lepton momentum axis in their production frame and the boost from
 375 the ZH center of mass (CM) frame, and the angle dphiCMZ .

376 In addition to the masses and angles attached to individual object rest frames, energy scales associ-
 377 ated with the CM frame can be used to contextualize other event level quantities. In particular, one
 378 can use the mass of the CM frame as a natural scale to evaluate the momentum of the CM frame,
 379 and the p_T of the CM frame as a natural scale for the event's E_T^{miss} , yielding the variables:

$$R_{p_T} = \frac{p_{T,\text{CM}}}{p_{T,\text{CM}} + M_{\text{CM}}}, \quad R_{p_z} = \frac{p_{z,\text{CM}}}{p_{z,\text{CM}} + M_{\text{CM}}}, \quad R_{\text{met}} = \frac{E_T^{\text{miss}}}{E_T^{\text{miss}} + p_{T,\text{CM}}} \quad (\text{I.8})$$

380 denoted R_{p_T} , R_{p_z} , and R_{met} . These can be thought of as behaving like significance based variables
 381 in particle physics, like METHT or impact parameter significances, or event level defined versions
 382 of the scalings applied to the LI inner products. These are used instead of the final state object scales
 383 and standard E_T^{miss} of the standard variable set.

384 Unlike the LI variables, the physical interpretation of RF variables is very clear. Everything has
 385 physical units, and these are variables one might have introduced in the usual process of develop-
 386 ing an MVA with the traditional mindset. The solution to the issue of additional jets in an event is
 387 not immediately clear. In order to keep the two non-standard MVA's on as equal footing as possi-
 388 ble, the approach of simply ignoring additional jets is taken in this thesis. Nevertheless, it would be
 389 easy enough to redefine the H intermediate frame to have, for example, the two b -tagged jets and the

390 highest p_T untagged jet for any subset of events. This flexibility is not a feature of the Lorentz Invari-
 391 ants framework. Of course, `RestFrames` cannot tell you what approach to take, but it is capable of
 392 handling more flexible topologies once optimization studies have been completed.

393 **I.7 EXTENSIONS TO THE I AND O LEPTON CHANNELS**

394 Both the LI and RF variable concepts are readily extendable to the i-lepton channel. In this topol-
 395 ogy, one of the leptons in the $ZH \rightarrow \ell\ell b\bar{b}$ diagram is replaced by a neutrino, the lone invisible
 396 particle in this final state. We can assume that the neutrino has zero mass and transverse momentum
 397 equal to the \vec{E}_T^{miss} in the event, leaving one undetermined degree of freedom, the longitudinal mo-
 398 mentum of the neutrino, p_z^ν .

399 The LI concept was in fact initially formulated to improve sensitivity in the i-lepton channel,
 400 with the same orthogonality of variables described in the 2-lepton case being the main draw. The
 401 LI approach to estimating the neutrino longitudinal momentum is outlined in [7], which we repro-
 402 duce here. We first guess the neutrino energy in its rest frame and then boost to the lab frame:

$$\langle E_\nu \rangle = \frac{1}{4} m_{WH} \implies \langle p_z^\nu \rangle = \beta \gamma \langle E_\nu \rangle = \frac{p_z^{WH}}{m_{WH}} \langle E_\nu \rangle = \frac{1}{4} p_z^{WH} \quad (\text{I.9})$$

403 Finally, assuming energy and momentum in aggregate are equally shared among final state con-
 404 stituents, we arrive at

$$\langle p_z^\nu \rangle = \frac{1}{4} \times \frac{4}{3} (p_z^l + p_z^{j0} + p_z^{j1}) \quad (\text{I.10})$$

405 The RF approach for the i-lepton case amounts to replacing the $Z \rightarrow \ell\ell$ in I.6 with $W \rightarrow \ell\nu$.

406 As alluded to in the 2-lepton discussion, when there is missing information in the final state from
 407 invisible particles and/or combinatoric ambiguities, recursive jigsaw reconstruction (RJR) offers a
 408 standard toolkit for deriving estimated boosts between rest frames by analytically minimizing on
 409 unknown quantities. While in more exotic final states with multiple invisible particles and com-
 410 binatoric ambiguities the choice of jigsaw rule can be subjective, the case of W is well-studied and
 411 outlined in detail in Section V.A. of [8]. It reproduces the usual transverse mass of the W in place of
 412 MZ in the 2-lepton case. Not surprisingly, the underlying calculation is also much the same as the LI
 413 case (where rest frames and boost were explicitly invoked); again, information is the same, only its
 414 decomposition is different.

415 The 0-lepton channel would appear to present some difficulty as two neutrinos in the final state
 416 introduce extra degrees of freedom, but both concepts may be extended by treating the invisibly
 417 decaying Z as a single invisible particle and requiring the Z to be on-shell, as shown schematically in
 418 Figure 1.7. Both of these requirements may be folded into the 1-lepton framework to produce similar
 sets of variables.

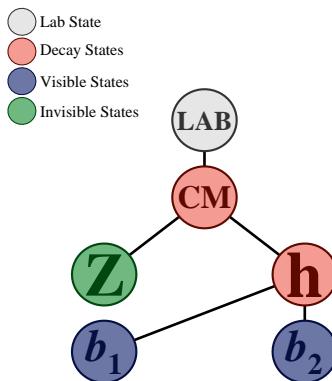


Figure 1.7: The $ZH \rightarrow \nu\nu b\bar{b}$ decay tree.

419

Variable	Name	0-lepton	1-lepton	2-lepton
\vec{p}_T^V	pTV		✓	✓
$\vec{E}_{\text{T}}^{\text{miss}}$	MET	✓	✓	✓
$\vec{p}_T^{\text{jet}1}$	pTB1	✓	✓	✓
$\vec{p}_T^{\text{jet}2}$	pTB2	✓	✓	✓
$\text{MV}_{2\text{C10}}(\text{jet}_1)^*$	$\text{MV}_{2\text{C10B1}}$	✓	✓	✓
$\text{MV}_{2\text{C10}}(\text{jet}_2)^*$	$\text{MV}_{2\text{C10B2}}$	✓	✓	✓
m_{jj}	mBB	✓	✓	✓
$\Delta R(\text{jet}_1, \text{jet}_2)$	dRBB	✓	✓	✓
$ \Delta\eta(\text{jet}_1, \text{jet}_2) $	dEtaBB	✓		
$\Delta\phi(V, H)$	dPhiVBB	✓	✓	✓
$\Delta\eta(V, H)$	dEtaVBB			✓
$M_{\text{eff}}(M_{\text{eff}3})$	HT	✓		
$\min(\Delta\phi(\ell, \text{jet}))$	dPhiLBmin		✓	
m_{T}^W	mTW		✓	
m_{ll}	mLL			✓
$\Delta Y(W, H)$	dYWH		✓	
m_{top}	mTop		✓	
Only in 3 Jet Events				
\vec{p}_T^{jet3}	pTJ3	✓	✓	✓
$\text{MV}_{2\text{C10}}(\text{jet}_3)^*$	$\text{MV}_{2\text{C10B3}}$	✓	✓	✓
m_{jjj}	mBBJ	✓	✓	✓

Table 1.2: Variables used to train the multivariate discriminant. Starred variables (b -tag scores) are not included in current versions of the standard discriminants, but have traditionally been included and most likely will be reintroduced as soon as their accompanying systematics are available.

⁴²⁰ While the precise variables that would be included in 0- and 1-lepton LI and RF MVA discrimi-
⁴²¹ nants is beyond the scope of this thesis, looking at Table 9.1, we can see the dimensionality and in-
⁴²² puts of the discriminants of the fiducial analysis. The correspondence for LI/RF variables and stan-
⁴²³ dard variables extends nicely to the other lepton channels. The reduction in multiplicity of variables
⁴²⁴ owing the lower number of degrees of freedom provided by treating the Z as a single invisible par-
⁴²⁵ ticle in the 0-lepton channel would likely not be an issue, as one would just be able to use a greater
⁴²⁶ fraction of available variables in the MVA discriminant.

Noli turbare circulos meos

Archimedes

2

427

428 The Large Hadron Collider and the ATLAS

Detector

429

430 THE CERN ACCELERATOR COMPLEX AND ITS EXPERIMENTS stand as a testament to human in-
431 genuity and its commitment to the pursuit of fundamental knowledge. In this chapter, we give a

⁴³² cursory overview of the CERN accelerator complex, including the Large Hadron Collider (LHC),
⁴³³ before moving on to a more detailed review of the ATLAS detector.

⁴³⁴ **2.1 THE CERN ACCELERATOR COMPLEX**

⁴³⁵ The journey of protons from hydrogen canister to high energy collisions through the CERN ac-
⁴³⁶ celerator complex, illustrated in Figure 2.1, is also one through the history of CERN’s accelerator
⁴³⁷ program. After being ionized in an electric field, protons are first accelerated in a linear accelera-
⁴³⁸ tor, LINAC 2*, to a kinetic energy of 50 MeV. From there, they are fed into the Proton Synchotron
⁴³⁹ Booster†, which further accelerates them to 1.4 GeV and, as its name implies, feeds them to the 628
⁴⁴⁰ m Proton Synchotron (PS, 1959[10]) and up to 25 GeV. The penultimate stage is the 7 km Super
⁴⁴¹ Proton Synchotron (SPS, 1976; responsible for the discovery of the W and Z bosons and the 1983
⁴⁴² Nobel Prize [11]), which accelerates the protons to a kinetic energy of 450 GeV. Finally, these 450
⁴⁴³ GeV protons are injected into the LHC[12], a proton-proton collider housed in the 27 km circumfer-
⁴⁴⁴ ence tunnel that housed the Large Electron Positron Collider (LEP) before its operations ceased in
⁴⁴⁵ 2000.

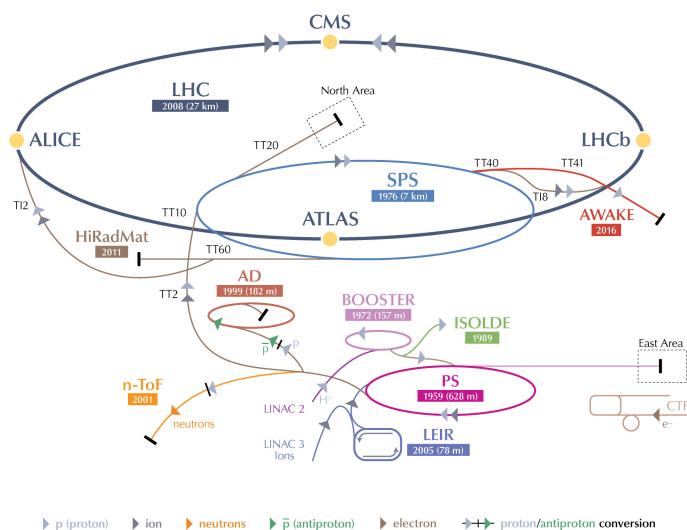
⁴⁴⁶ **2.2 THE LARGE HADRON COLLIDER**

⁴⁴⁷ The LHC was designed to function primarily as a proton-proton collider with a center of mass en-
⁴⁴⁸ ergy $\sqrt{s} = 14$ TeV and an instantaneous luminosity of $1 \times 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$, though it is also capable

*1978’s LINAC 2 is the successor to 1959’s LINAC 1; it will be replaced in 2020 by LINAC 4; LINAC 3 is responsible for ion production.

†Protons can be directly from a LINAC into the PS, but the higher injection energy allows for approximately 100 times more protons to be used at once[9], 1972.

CERN's Accelerator Complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine Dvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

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Figure 2.1: The CERN Accelerator Complex [13]

⁴⁴⁹ of producing heavy ion (Pb-Pb) collisions, which it does for approximately one month in a typical
⁴⁵⁰ year of physics collisions. Owing to an accident at the beginning of the LHC's initial run, the acceler-
⁴⁵¹ ator has operated at center of mass energies of 7, 8, and now 13 TeV.

⁴⁵² One of the major cost-saving features of the he LHC is that, unlike the defunct Superconducting
⁴⁵³ Supercollider (SSC), its construction did not call for a purpose built tunnel, with the LHC instead
⁴⁵⁴ being housed in the old LEP tunnel. LEP, however, like the Tevatron, was a particle-antiparticle
⁴⁵⁵ collider, which meant that both beams could circulate within the same beam pipe, so the LEP tun-
⁴⁵⁶ nel was never built to house two separate storage rings and magnet systems (as the SSC would have
⁴⁵⁷ had). To accomplish the technically challenging task of housing two storage rings and sets of mag-
⁴⁵⁸ nets in one system, the LHC magnets feature a "twin bore" design. The magnets themselves make
⁴⁵⁹ use of superconducting NbTi cables and are cooled using superfluid helium to a temperature of 2
⁴⁶⁰ K, which allows for operational field strengths in excess of 8 T. A stable design is achieved by having
⁴⁶¹ the magnets share a common cold mass (a 27.5 ton iron yoke for each dipole kept at 1.9 K in which
⁴⁶² the magnets and beam pipes are embedded) and cryostat and by arranging the superconductor wind-
⁴⁶³ ings so that the magnetic fluxes of the two systems rotate in opposite directions. This results in an
⁴⁶⁴ extremely complicated magnetic structure. The design layout of an LHC dipole magnet is shown
⁴⁶⁵ in Figure 2.2. These dipole magnets are responsible for bending the LHC's proton beams, and their
⁴⁶⁶ strength is the principal limiting factor in the center of mass energy achievable at a circular collider.

⁴⁶⁷ The ideal version of a proton beam in the LHC consists of infinitely small bunches of protons
⁴⁶⁸ of equal momentum equally spaced in the LHC ring (itself not a perfect circle). In reality, the pro-
⁴⁶⁹ tons in the beam deviate from each of these assumptions, with dispersion in both physical space

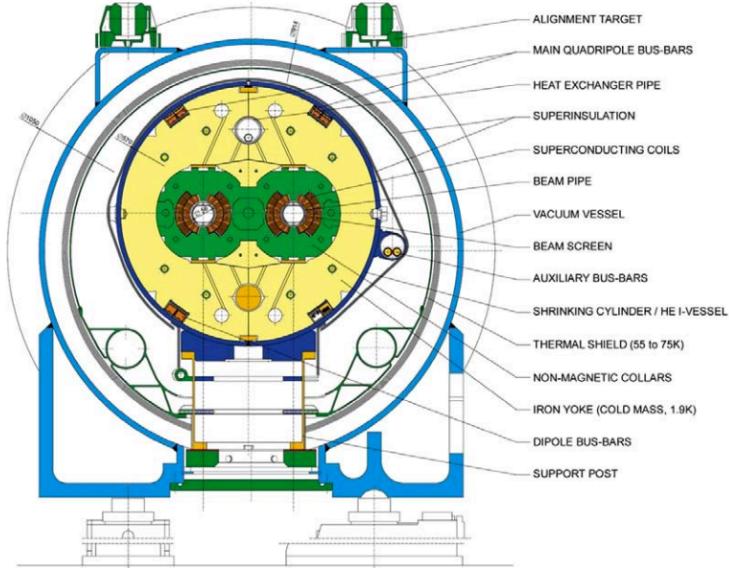
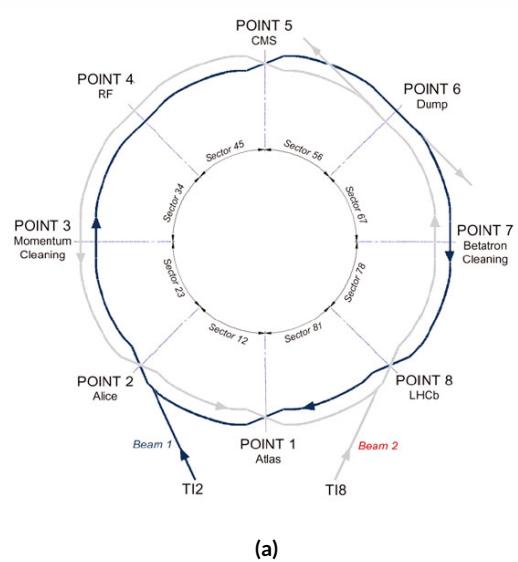


Figure 2.2: Schematic drawing of an LHC dipole magnet and cryogenics system.

and momentum space. In general, charged particles in an accelerator ring will demonstrate pseudo-harmonic “betatron” oscillations about the ideal orbit, the amplitude of which gives a characteristic of the beam’s size. In order to get high energy protons to actually collide, different magnets are used to focus the beam and help nudge deviating particles back into more ideal behavior. There are quadrupole magnet assemblies in the short straight sections to accomplish this, as well as quadrupole, octupole, and sextupole magnets interspersed throughout the length of the LHC ring for beam stabilization and other higher order corrections. The interior of the LHC beam pipe operates at a nominal pressure of $\sim 10^{-7}$ Pa, famously more rarefied than outer space.

The LHC ring itself is between 45 m and 170 m below ground and has a 1.4% incline towards Lac Léman with eight arcs and eight straight sections. In the middle of each of the eight straight sections,

480 there are potential interaction points (each colloquially referred to by its number as “Point N ”),
481 with each point housing either accelerator infrastructure or an experiment. A schematic of the con-
482 tents of each component, as well as a more detailed view of the infrastructure in the LHC ring, can
483 be found in Figure 2.4.



(a)

Figure 2.3: Schematic and detailed views of the LHC ring. IC: [14], [15]

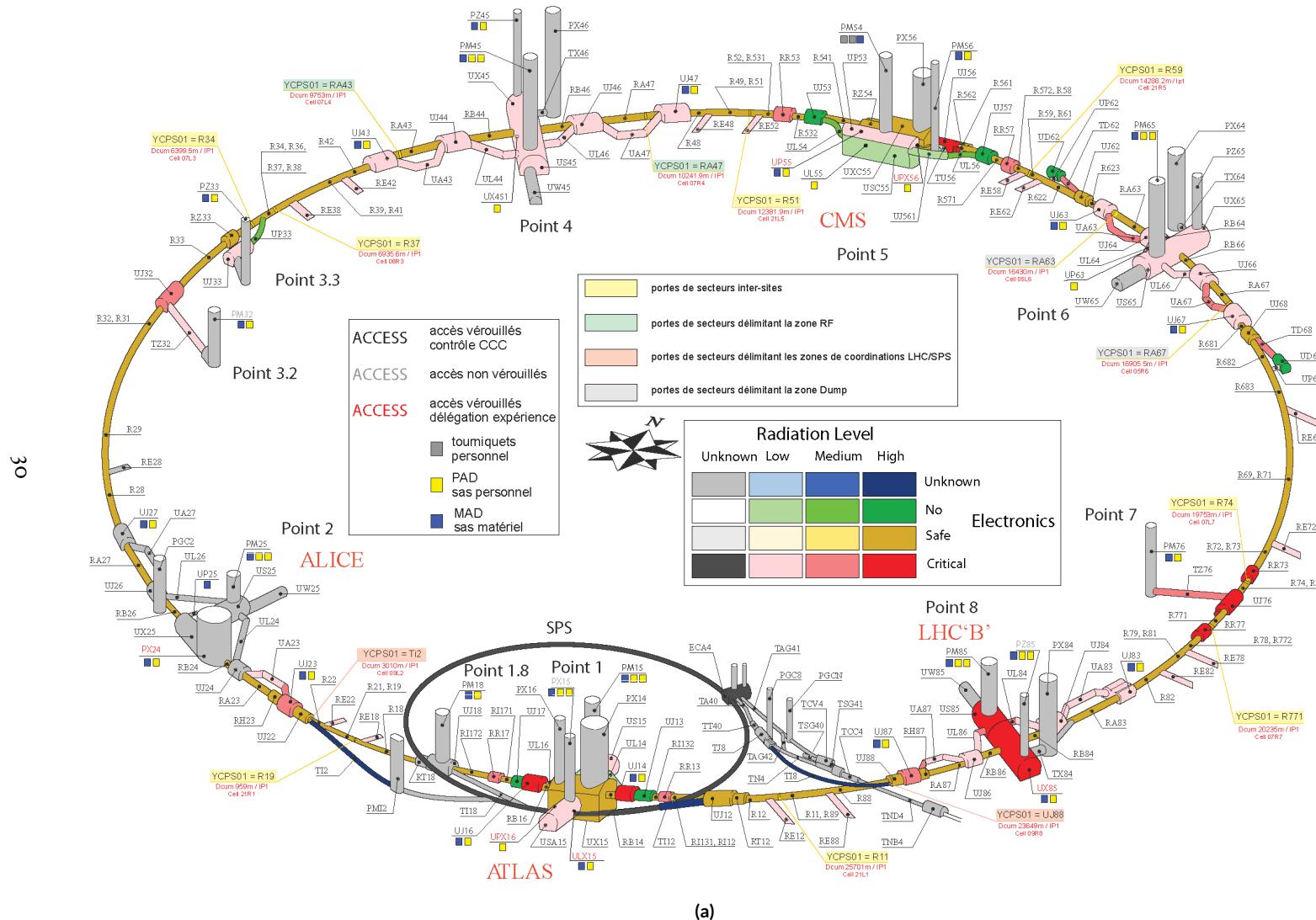


Figure 2.4: Schematic and detailed views of the LHC ring. IC:[14], [15]

484 Points 1, 2, 5, and 8 house the LHC’s experiments, ATLAS (*A Toroidal LHC ApparatuS*, one
485 of the two general purpose detectors, discussed in detail below), ALICE (A Large Ion Collider Ex-
486 periment, a dedicated heavy ion experiment), CMS (Compact Muon Solenoid, the other general
487 purpose detector), and LHCb (LHC beauty, a *B* physics experiment), respectively. Point 3 houses a
488 series of collimators that scatter and absorb particles in the beam with a large momentum deviation
489 (which will have different orbital radii) from other particles in the beam (“momentum cleaning”),
490 while Point 7 has a similar setup to remove particles with large betatron amplitudes (“betatron clean-
491 ing”). Both of these dedicated cleaning assemblies are in addition to the magnetic focusing assem-
492 blies discussed above and address the same issues. Point 4 contains the LHC’s RF (radio frequency;
493 400 MHz) acceleration system, responsible for taking protons from their injection energy of 450
494 GeV to their collision energy of 3.5, 4, 6.5, or 7 TeV. Point 6 is where the energetic ionizing radiation
495 of circulating beams can be safely taken out of the collider into a block of absorbing material, either
496 at the end of a data-taking run or in the event of an emergency (in the event of irregular behavior,
497 it is essential to do this as quickly as possible to minimize damage to the accelerator and to experi-
498 ments); this is known as a “beam dump.”

499 **2.3 ATLAS AT A GLANCE**

500 **2.3.1 COORDINATES AND DISTANCES IN THE ATLAS DETECTOR**

501 *A Toroidal LHC ApparatuS* is one of the two (the other being CMS) general purpose, high lumi-
502 nosity detectors at the LHC, located at Interaction Point 1, as described above. With a length of 44

503 m and a height of 25 m, it is the detector with largest physical dimensions at the LHC.[‡]. While pri-
 504 marily a high luminosity proton-proton collision detector, ATLAS does collect heavy ion collision
 505 data, typically for one month during a year of typical operation.

506 The ATLAS coordinate system is shown in Figure 2.5. It is a right-handed coordinate system cen-
 507 tered at the nominal collision point, with the x axis pointing towards the center of the LHC ring,
 508 the z axis pointing up, and the y axis completing the right-handed coordinate system.

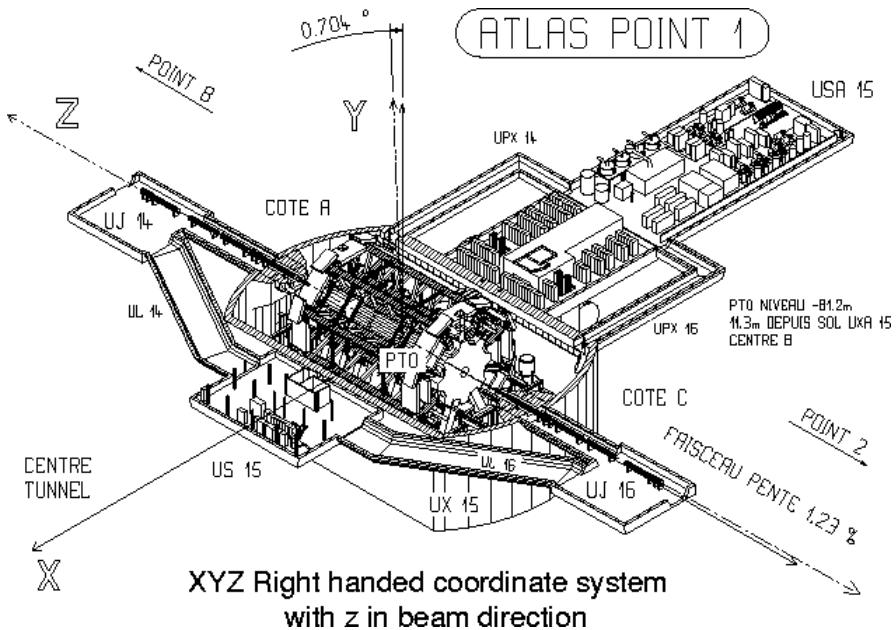


Figure 2.5: The ATLAS coordinate system. "A" side is the airport, and "C" side is "Charlie's," a pub in Saint-Genis, France.

509 While the Cartesian coordinates are useful for specifying the locations of things like detector com-
 510 ponents and activated calorimeter cells, cylindrical polar coordinates with the same origin, z axis, and
 511 handedness are often more suitable, with a point in 3-space expressed as (r, ϕ, η) . r is the perpen-

[‡]This is the only reason CMS can call itself “compact.”

512 dicular distance from the beam axis. This differs from the usual spherical ρ , the distance of a point
 513 from the origin, because the ATLAS detector is cylindrical[§], and so detector components are more
 514 easily located using r instead of ρ . In some contexts, the latter is used, though this is (or should be)
 515 made clear. ϕ is the usual (right-handed) azimuthal angle around the beam axis, with o at the $+x$
 516 axis.

517 In a lepton collider where total momentum is conserved, a useful coordinate is the relativistic
 518 rapidity of a particle:

$$y = \frac{1}{2} \ln \left[\frac{E + p_z}{E - p_z} \right] \quad (2.1)$$

519 with E and p_z as the energy and longitudinal momentum of the particle, respectively. The rapidity
 520 is the relativistic analog of a rotation angle; boosts can be added in a manner similar to rotations[¶],
 521 and differences in rapidity are invariant under boosts. In a hadronic collider, where the participants
 522 in the hard scatter are partons inside of the proton of unknown momentum fraction, longitudinal
 523 momentum is not conserved. Nevertheless, since the incident momentum is entirely longitudinal,
 524 momentum is still conserved in the transverse plane, so quantities like transverse momentum \vec{p}_T
 525 or energy (E_T)^{||} are often very useful in analysis. However, in the massless limit^{**}, we can take $E =$

[§]“toroidal;” the hole is the beam pipe

[¶]Generally, one need only insert the appropriate factor of i , the square root of -1 ; this introduces differences in sign and changes all of the trigonometric functions associated with rotations into hyperbolic trigonometric functions.

^{||}Energy is not a vector quantity, but one can take the scalar or vectorial sum of vectors formed from energy deposits with their location as the direction and energy value as magnitude. In practice, primitives are almost always assumed to be massless, so transverse energy and momentum may loosely be thought of as equivalent, with $E_T = |\vec{p}_T| = p_T$

^{**}not a terrible one for most particles depositing energy in the calorimeter; pions have masses of ~ 130 MeV, and typical energies of calorimeter objects are $\sim 10^3$ GeV, making for a boost of roughly 100.

526 $\sqrt{p_T^2 + p_z^2}$. Hence, with θ taken as the zenith angle and o corresponding to the $+z$ direction, for a
 527 massless particle, $p_z = E \cos \theta$. Using the usual half angle formula $\cos \theta = (1 - \tan^2 \theta) / (1 + \tan^2 \theta)$

528

$$\gamma = \frac{1}{2} \ln \left[\frac{1 + \cos \theta}{1 - \cos \theta} \right] = \frac{1}{2} \ln \left[\frac{(1 + \tan^2(\theta/2)) + (1 - \tan^2(\theta/2))}{(1 + \tan^2(\theta/2)) - (1 - \tan^2(\theta/2))} \right] = -\ln \left(\tan \frac{\theta}{2} \right) \quad (2.2)$$

529 This last expression, denoted η , is known as the pseudorapidity and is used instead of the polar
 530 angle as a coordinate in hadron colliders. Moreover, pion production (the most common hadronic
 531 process) is constant as a function of η in $p\bar{p}$ collisions.

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right) \quad (2.3)$$

532 Lower values of $|\eta|$ ($\lesssim 1.3$) correspond to more central areas of the detector known as the “barrel,”
 533 with the typical layout here being concentric, cylindrical layers. Larger values of $|\eta|$ (to ~ 2.5 for
 534 some systems and up to as much as $\sim 4.5 - 5$ for others) are known as the “end caps,” where ma-
 535 terial is typically arranged as disks of equal radius centered on the beam pipe stacked to ever greater
 536 values of $|z|$. This terminology will be useful when discussing the various subsystems of the ATLAS
 537 detector. Since decay products from a collision propagate radially (in the calorimeter portions of
 538 the detector with no magnetic field), the radial coordinate is not so important for composite physics
 539 objects like electrons or jets, which are typically expressed as momentum 4-vectors. Hence, η and ϕ
 540 are often the only useful spatial coordinates. Distances between objects are often expressed not as a

541 difference in solid angle, but as a distance, ΔR , in the $\eta - \phi$ plane, where

$$\Delta R_{12} = (\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2 \quad (2.4)$$

542 Two important concepts when discussing particles traveling through matter (e.g. particle detec-

543 tors) are radiation lengths and (nuclear) interaction lengths, which characterize typical lengths for

544 the energy loss of energetic particles traveling through materials. In general, the energy loss is mod-

545 eled as an exponential

$$E = E_0 e^{-l/L} \quad (2.5)$$

546 where E_0 is the initial energy, and L is a characteristic length. These lengths depend both on the in-

547 cident particle and the material through which they pass. In the case of uniform, composite mate-

548 rials, the length may be found by calculating the reciprocal of the sum of mass fraction weighted

549 reciprocal characteristic lengths of the components. This formula works quite well for modeling the

550 very regular behavior of electromagnetic showers (energetic photons convert into electron/positron

551 pairs, which emit photons...). In this case, L is denoted X_0 ; this is the radiation length. Hadronic

552 showers are far more complicated, with shower multiplicity and makeup being much more vari-

553 able^{††}. Nevertheless, a characteristic length can be tabulated for a standard particle type, typically

554 pions, and is called the nuclear interaction length.

^{††}Different initial hadrons will shower very differently, and hadronic showers will have phenomena like neutral pions converting to photons (which then shower electromagnetically), making them much trickier to deal with.

555 2.3.2 GENERAL LAYOUT OF ATLAS

556 The ATLAS detector and its main components are shown in Figure 2.6. ATLAS is designed as a
557 largely hermetic detector, offering full coverage in ϕ and coverage in $|\eta|$ up to 4.7. The multiple sub-
558 systems allow for good characterization of the decay products from collisions in the LHC. The in-
559 nermost system is the inner detector (ID); composed primarily of silicon pixels and strips immersed
560 in a magnetic field, it is designed to reconstruct the curved trajectories of charged particles produced
561 in collisions while taking up as little material as possible.

562 Surrounding the ID is the liquid argon based electromagnetic calorimeter (ECAL), which is de-
563 signed to capture all of the energy of the electromagnetic showers produced by electrons and pho-
564 tons coming from particle collisions. The ECAL is in turn encapsulated by a scintillating tile and
565 liquid argon based hadronic calorimeter (HCAL) that captures any remaining energy from the jets
566 produced by hadronizing quarks and gluons.

567 The outermost layer of ATLAS is the muon spectrometer (MS), which has its own magnetic field
568 produced by toroidal magnets. Muons are highly penetrating particles that escape the calorimeters
569 with most of their initial momentum, so the MS and its magnets are designed to curve these charged
570 particles and measure their trajectories to measure their outgoing momenta. Each of these detector
571 systems has several principal subsystems and performance characteristics, which will be described in
572 turn below.

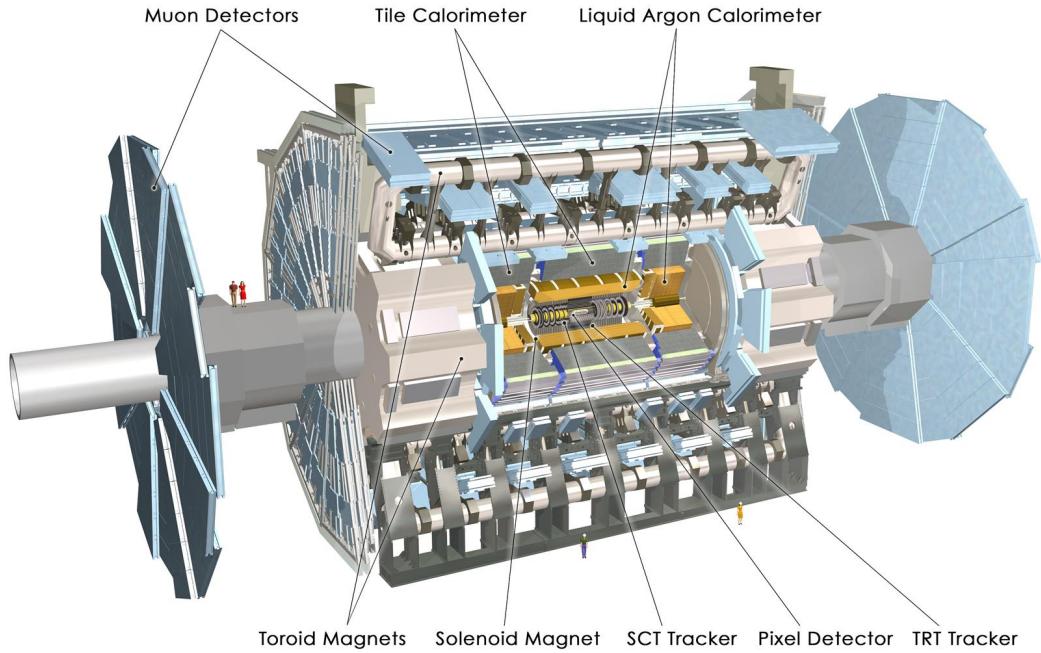


Figure 2.6: The ATLAS detector with principal subsystems shown.

573 2.4 THE INNER DETECTOR

574 ATLAS's inner detector (ID) is surrounded by a 2 T superconducting solenoid that is cryogenically
 575 cooled to a temperature of 4.5 K. The ID uses two silicon detector subsystems (the Pixel and Semi-
 576 Conductor (strip) Tracker (SCT)) to track the curved trajectories of charged particles emanating
 577 from particle collisions and a Transition Radiation Tracker (TRT) composed of gas straw detectors
 578 with filaments for e/π discrimination, as shown in Figure 2.7. The ID offers full coverage in ϕ and
 579 extends to an $|\eta|$ of 2.5.

580 Since the components of the ID do not provide an energy measurement, it is desirable for a track-
 581 ing system to have as small a material budget as possible so that more accurate energy measurements

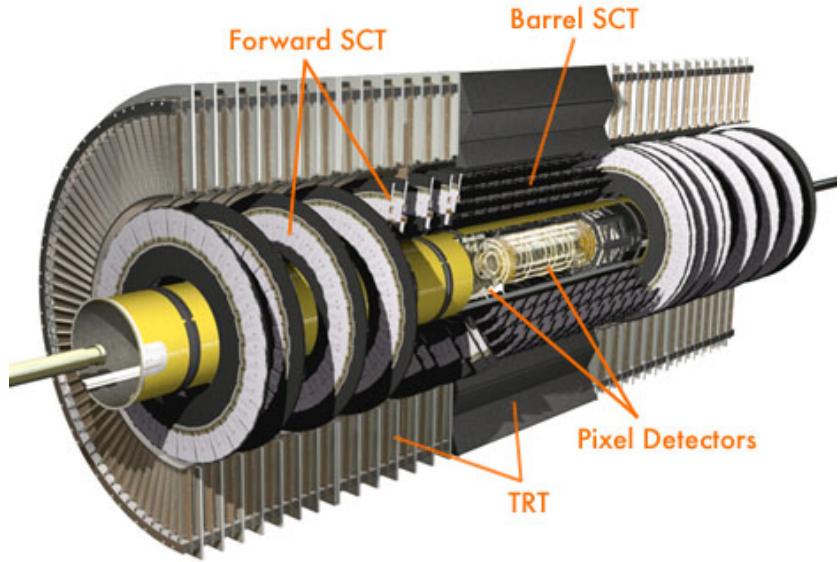


Figure 2.7: The ATLAS inner detector. IC: [16]

582 may be done in the calorimeters. Generally, there are two radiation lengths in the inner detector (the
 583 precise figure varies with η); the full material budget, with the layout of the individual layers in each
 584 subsystem, can be seen in Figure 2.8.

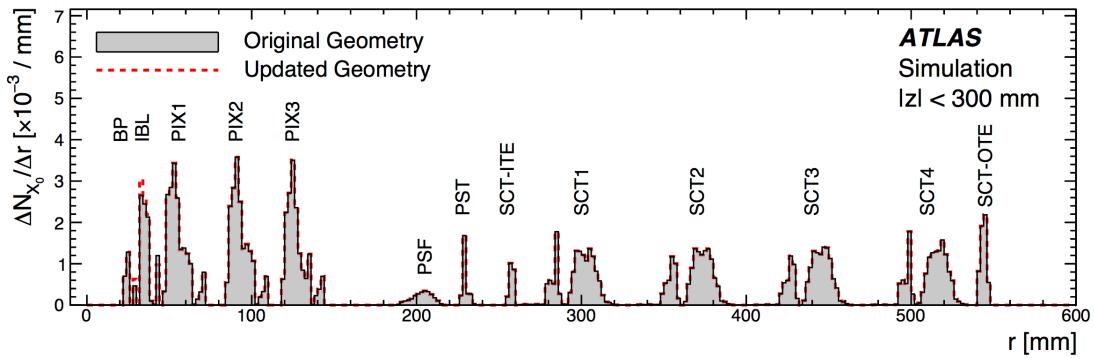


Figure 2.8: The ID material budget. IC: [17]

585 2.4.I THE PIXEL DETECTOR

586 The innermost part of ATLAS is the Pixel Detector, which, as the name suggests, is comprised of
587 four layers of silicon pixels in the barrel at 32, 51, 89, and 123 mm from the beam pipe, and three lay-
588 ers in the end caps at 495, 580, and 650 mm from the beam pipe, with over 80 million channels total.

589 The innermost layer of pixels, the insertable *B* layer (IBL) was installed during the 2013–14 LHC
590 shutdown. The pixels are cooled to a temperature of $\sim -5^\circ\text{C}$, with N_2 gas and operate at 150–600
591 V. The pixels themselves come in two sizes $50 \times 400(600) \times 250 \mu\text{m}$, with the larger pixels in the
592 outer layers. They provide nominal resolution of $10(115) \mu\text{m}$ resolution in $r - \phi$ direction.

593 In order to improve total coverage in the detector and prevent any gaps, pixels are not installed
594 flush with each other. Pixels in the barrel are tilted at about 20° , with an overlap in $r - \phi$, as shown
595 in Figure 2.9. The disks of the ID end caps are rotated with respect to each other by 3.75° .

596 2.4.2 THE SILICON MICROSTRIP DETECTOR (SCT)

597 The layout of the SCT is similar to that of the Pixel detector, except that, for cost considerations, the
598 SCT uses silicon strips. These strips are also cooled to $\sim -5^\circ\text{C}$ with N_2 gas and operate from 150–
599 350 V. Strip dimensions are $80 \times 6000 \times 285 \mu\text{m}$, and provide nominal $17(580) \mu\text{m}$ resolution in
600 $r - \phi(z)$. Barrel strips feature an 11° tilt and come in four layers at 299, 371, 443, and 514 mm. There
601 are nine end cap disks on each side at z values varying from 934–2720 mm.

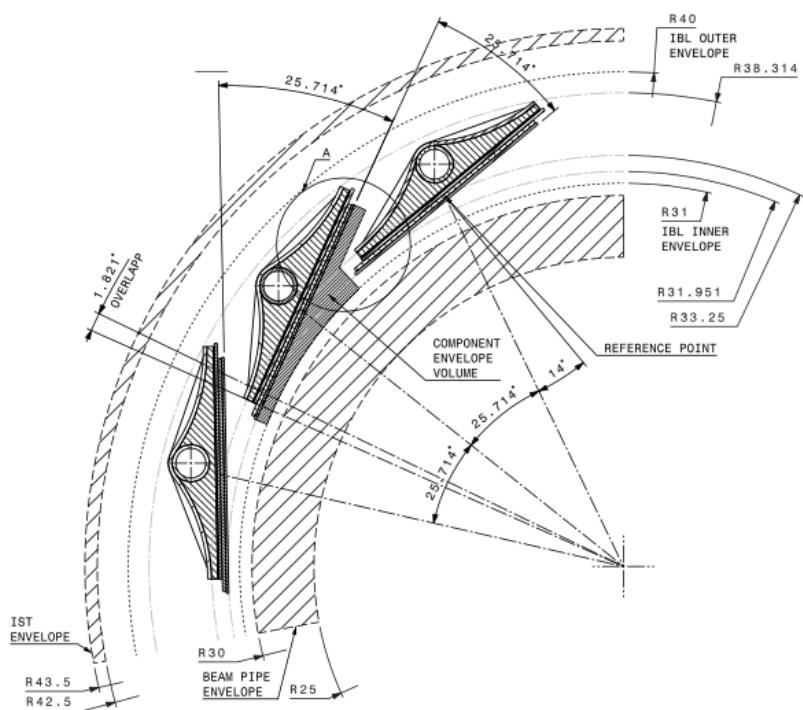


Figure 2.9: Arrangement of pixels in the barrel. IC: [18]

602 2.4.3 TRANSITION RADIATION TRACKER (TRT)

603 The final and outermost subsystem in the ID is the Transition Radiation Tracker (TRT). It provides
604 coverage for $|\eta|$ up to 2.0 and is composed of straw detectors with a 4 mm diameter that run the
605 length of the detector module. The straws provide $130 \mu\text{m}$ resolution, are filled with a Xe-CO₂-O₂
606 (70-27-3) gas combination, and operate at -1500 V. The filaments and foil lining inside the straws
607 induce X-ray emission in electrons and pions passing through the TRT as they move from a dielec-
608 tric to a gas; this “transition radiation” is the source of the TRT’s name. Since the energy deposited
609 due to transition radiation is proportional to the relativistic boost γ , for constant momentum, this
610 is inversely proportional to mass. Thus, electrons will have $\sim 130/0.5 = 260\times$ more transition
611 radiation than pions, in principle enabling excellent electron/pion discrimination. The TRT will be
612 replaced by silicon strips in the Phase II upgrade.

613 2.5 THE ATLAS CALORIMETERS

614 ATLAS has four main calorimeter systems: the liquid argon based Electromagnetic Calorimeter
615 (ECAL), the Hadronic End Cap (HEC), the Forward Calorimeters (FCAL), and the scintillating
616 tile based hadronic Tile Calorimeter in the barrel. Their layout and material budget in interaction
617 lengths can be seen in Figure 2.II.

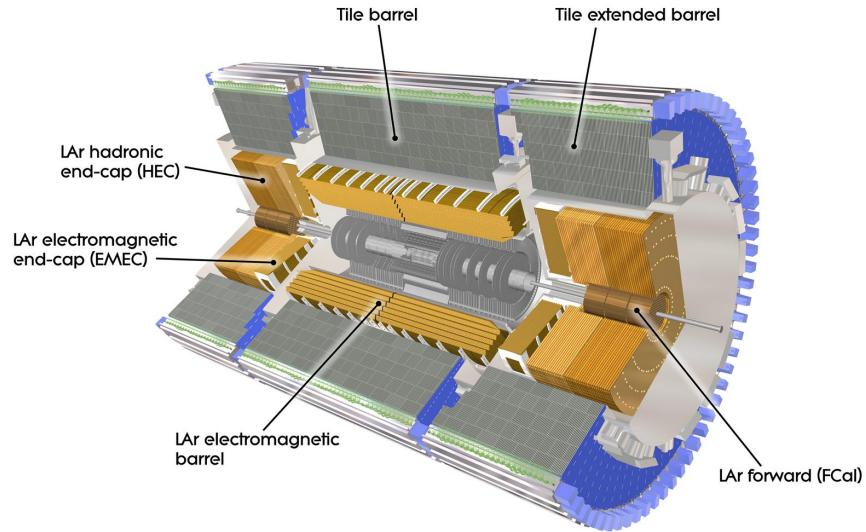


Figure 2.10: The ATLAS calorimeters.

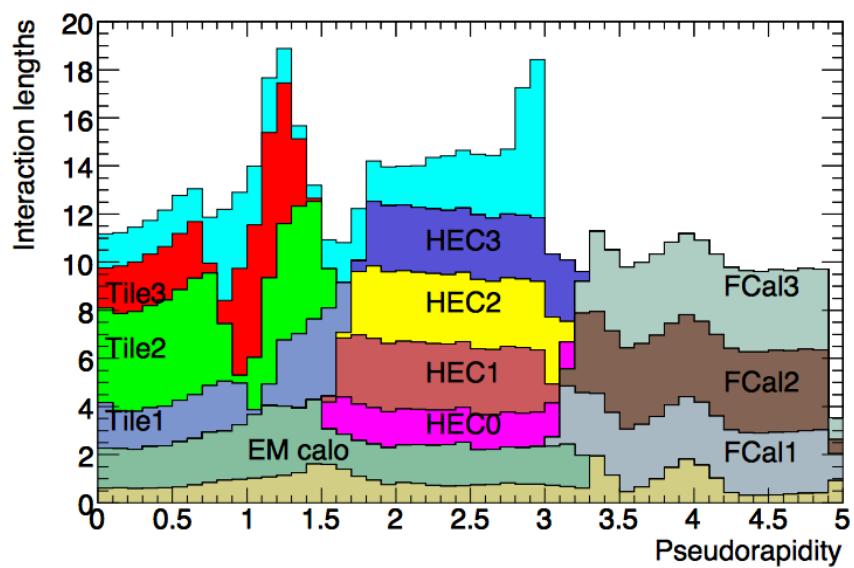


Figure 2.11: Material depth of the ATLAS calorimeters. IC: [16]

618 2.5.1 CALORIMETER RESOLUTION

619 Before diving into the specifics of each of the ATLAS calorimeters, we review some aspects of calorime-
620 ter energy resolution performance. A calorimeter’s relative energy resolution (a ratio) can be broken
621 up into three orthogonal components, as shown in Equation 2.6.

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C \quad (2.6)$$

622 S is the photoelectron statistics or stochastic term and represents the coefficient to the usual count-
623 ing term (assuming Gaussian statistics); N is a noise term, which is constant per channel (and hence
624 comes in as $1/E$ in the relative energy resolution); and C is a constant “calibration” term, which re-
625 flects how well one intrinsically understands a detector (i.e. mismodelling introduces an irreducible
626 component to the energy resolution). If any detector were perfectly modeled/understood, it’s C
627 term would be zero. $N \sim 0.1 - 0.5$ GeV for a typical calorimeter regardless of type, so S and C
628 are typically quoted.

629 A typical stochastic term scales as $S \sim \text{few\%} \sqrt{d_{\text{active}} [\text{mm}] / f_{\text{samp}}}$, where f_{samp} is the sampling
630 fraction or the ratio of a calorimeter by mass is composed of an active material (i.e. one that regis-
631 ters energy deposits). The tile calorimeter, for example, has a sampling fraction of about 1/36. There
632 are several reasons that this fraction is so low. First, many active volumes have insufficient stopping
633 power; one wants to capture as much energy as possible from electromagnetic and hadronic showers
634 inside the calorimeter, and this simply is not possible for most active media (one notable exception

635 to this is the CMS crystal-based calorimeter; ATLAS is a more conservative design), so well-behaved
636 absorbers like lead or iron are necessary to ensure all the energy is contained within a calorimeter.
637 Another factor is cost; things like liquid argon are expensive. Finally, most active media are unsuit-
638 able for structural support, so sturdy absorbing materials help relieve engineering constraints.

639 **2.5.2 THE ELECTROMAGNETIC CALORIMETER (ECAL)**

640 The ECAL has liquid argon (LAr) as an active material and lead as an absorber. The ECAL barrel
641 extends to $|\eta|$ of 1.475, with three layers at 1150, 1250, and 2050 mm, and its end cap, comprised of
642 two wheels, covers $1.375 < |\eta| < 2.5$, (3.2) for the inner (outer) wheel, with 3 (2) layers out to
643 3100 mm. There is a 1.1 (0.5) cm thick layer of LAr pre-sampler up to $|\eta|$ of 1.8 in the barrel (end cap)
644 of the ECAL, which is designed to aid in correcting for electron and photon energy loss in the ID.

645 The LAr and lead absorber are arranged in alternating, beveled, sawtooth layers in what is known
646 as an “accordion” geometry, shown in Figure 2.12, which shows the layout of a barrel module in the
647 ECAL. The absorber thickness is 1.53 (1.13) mm for $|\eta|$ less (more) than 0.8 to ensure a constant sam-
648 pling fraction. This arrangement helps provide greater coverage in ϕ .

649 The ECAL overall typically covers 2–4 interaction lengths or about 20–40 radiation lengths. Its
650 performance corresponds to resolution coefficients $S = 0.1 \text{ GeV}^{-1/2}$ and $C = 0.002$ with a 450
651 ns drift time. In order to optimize the material budget and overall detector construction, the ECAL
652 barrel infrastructure is integrated with that of the ID’s solenoid. The granularity of the ECAL barrel
653 middle layer, $\Delta\eta \times \Delta\phi$ cells of size 0.025×0.025 , are used to define the granularity of calorimeter
654 cluster reconstruction in ATLAS.

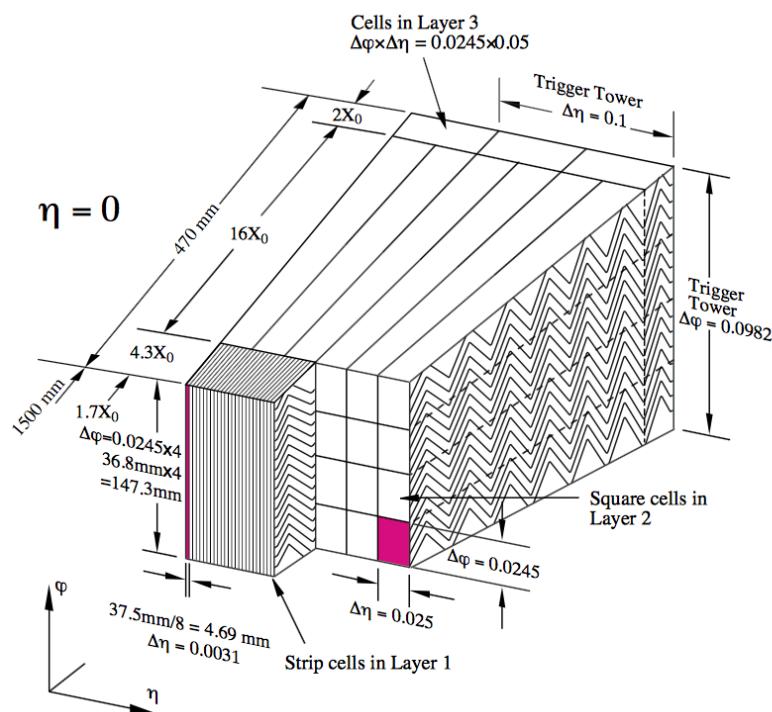


Figure 2.12: The accordion geometry of the LAr electromagnetic calorimeters is prominently shown in this illustration of an ECAL barrel module. IC: [16]

655 2.5.3 HADRONIC END CAPS (HEC)

656 The HEC covers an $|\eta|$ range of 1.5 to 3.2. Like the ECAL end caps, the HEC consists of two identi-
657 cal wheels out to a distance from the beam axis of 2030 mm; its layout is shown in Figure 2.13. The
658 HEC also has LAr as the active material, but instead has flat copper plates as absorbers for sampling
659 fraction of 4.4% and 2.2% in the first and second wheels, respectively. Its granularity in $\eta - \phi$ is
660 0.1×0.1 for $|\eta|$ up to 2.5 and 0.2×0.2 in the more forward regions.

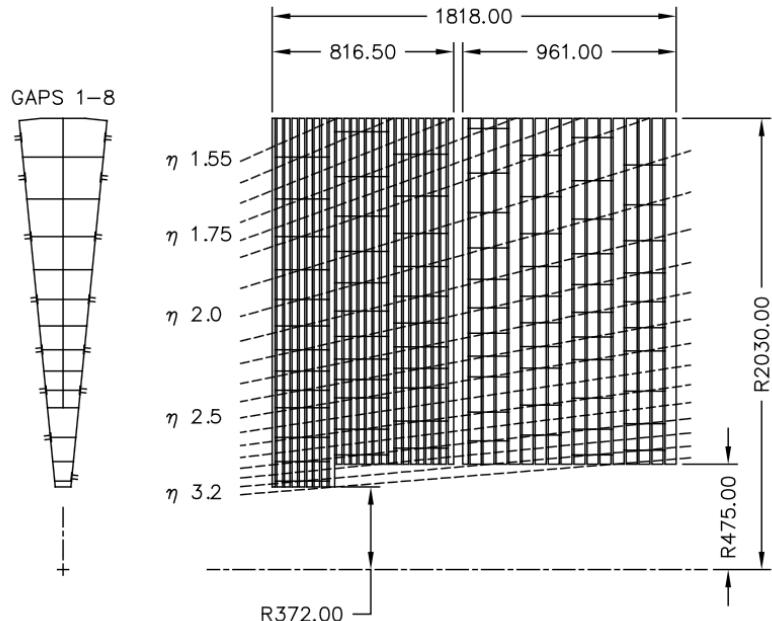


Figure 2.13: The layout of the HEC in $r - \phi$ and $r - z$; dimensions are in millimeters. IC: [16]

661 2.5.4 THE FORWARD CALORIMETER (FCAL)

662 The FCAL covers an $|\eta|$ range from 3.1 to 4.9, again using LAr as the active material in gaps between
663 rods and tubes in a copper-tungsten matrix, as shown in Figure 2.14. These system has characteris-
664 tic performance corresponding to stochastic term of $S \approx 1 \text{ GeV}^{-1/2}$. There are three modules in
665 the FCAL: one electromagnetic and two hadronic, with the latter two featuring a higher tungsten
666 content for a larger absorption length.

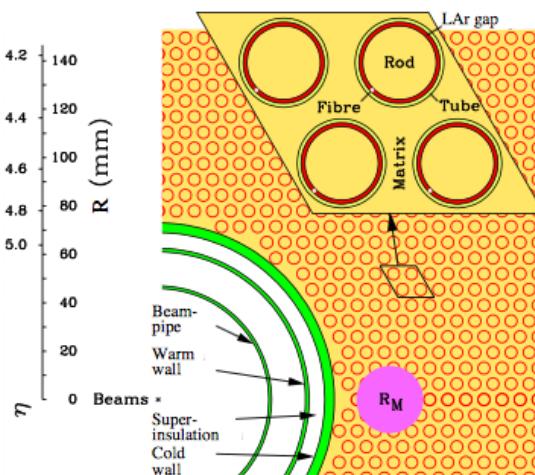


Figure 2.14: The material layout for a typical section of the FCAL in the transverse plane. IC: [16]

667 2.5.5 THE HADRONIC TILE CALORIMETER

668 The tile calorimeter, covering an $|\eta|$ of up to 1.7 is made up of 64 modules in the barrel (each cover-
669 ing $\Delta\phi$ of $360/64 = 5.625^\circ$), each with a layout as in Figure 2.15. It is designed to be self-supporting
670 for structural reasons, and so is the only calorimeter without LAr as a an active medium, with a stag-
671 gered matrix of active scintillating polystyrene and supporting steel. It operates at 1800 V with a 400

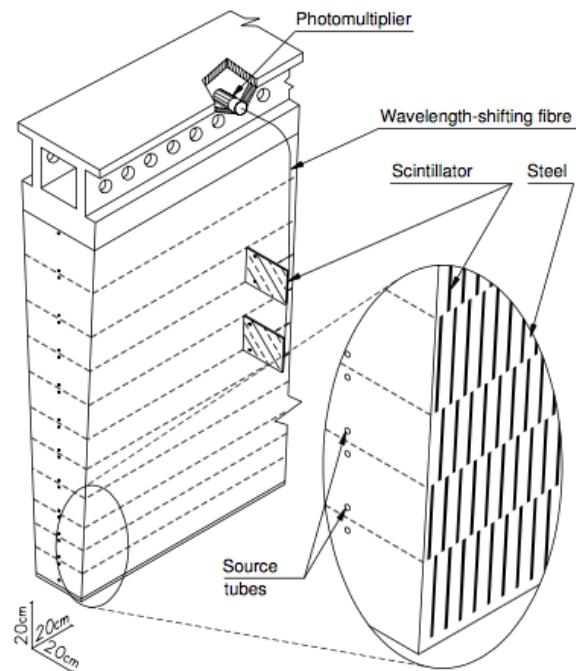


Figure 2.15: The material layout for a typical section of the hadronic tile calorimeter. IC: [16]

672 ns dead time and has a thickness corresponding to 10–20 interaction lengths (2.28–4.25 m). Its cells
673 have a $\Delta\eta \times \Delta\phi$ granularity of 0.1×0.1 in the first two layers and 0.2×0.1 in the last layer. Its
674 performance corresponds to $S = 0.5 \text{ GeV}^{-1/2}$ and $C = 0.05$ (0.03 after calibration).

675 2.6 THE MUON SPECTROMETER

676 Since the energy of muons is not captured within the calorimeters, the stations of the ATLAS MS
677 surround the entire detector and provide tracks of outgoing muons that can be matched to tracks in
678 the ID. The ATLAS toroids, which provide field strengths of up to 2.5 (3.5) T in the barrel (end cap)
679 with typical strengths of 0.5–1.0 T, bend the muons, which allows for a muon momentum measure-
680 ment since the muon mass is known. The relative momentum resolution of a tracker (assuming, as
681 in ATLAS, that bending primarily happens in the ϕ direction) may be expressed as

$$\frac{\sigma_{p_T}}{p_T} = c_0 \oplus c_1 \cdot p_T \quad (2.7)$$

682 The c_0 term represents a degradation in resolution due to multiple scattering, and is typically 0.5–
683 2% [19]. The c_1 term describes the phenomenon of, holding magnetic field constant, higher momen-
684 tum muons curving less. This term has typical values of $10^{-3} - 10^{-4} \text{ GeV}^{-1}$. At very high p_T val-
685 ues, this is of particular concern since a very small curvature can result in charge misidentification.

686 A cross-sectional view (in $r-z$) of the muon spectrometer with station names, detector types, and
687 layouts is shown in Figure 2.16. There are three layers of muon detectors in both the barrel (at 5 000,
688 7 500, and 10 000 mm) and end cap (at 7 000 (11 000), 13 500, and 21 000 mm), with the innermost

689 end cap layer split in two due to the end cap toroid. This corresponds to an $|\eta|$ range up to 2.4 for
 both precision and trigger coverage, and up to 2.7 for precision detection only.^{†‡}

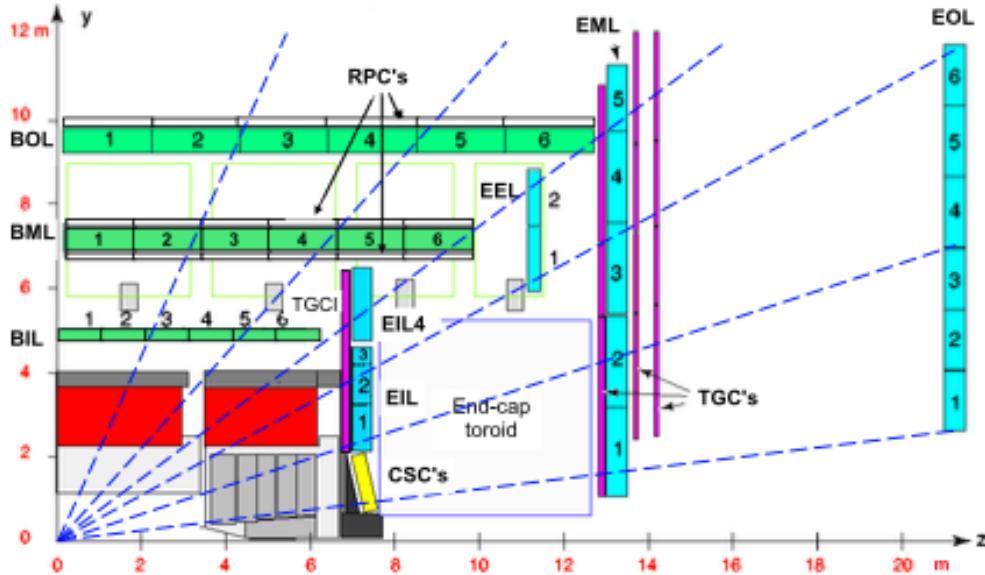


Figure 2.16: The ATLAS muon spectrometer. Naming of the MDT stations obeys the following convention [BE] (barrel or end cap) [IEMO] (inner, inner extended (end cap only), middle, or outer layer) [1-6] (increasing in z (r) for the barrel (end cap)), so EI1 is the station in the inner most end cap layer closest to the beam pipe. IC: [16]

690
 691 The MS can reconstruct muons with transverse momenta from 5 GeV up to 3 TeV (with 10% res-
 692 olution at 1 TeV (3% at 100 GeV)). Detectors in the MS fall into two broad headings, precision detec-
 693 tors and trigger detectors, both described below. Nominal performance of the current detector types
 694 in the MS is summarized in Figure 2.17, a table taken from [16]. It should be noted that $|\eta|$ ranges
 695 quoted below, where applicable, do not include the range 0-0.1, where this a gap in the MS to allow
 696 for cabling and other services to the ATLAS detector; for a discussion of compensatory measures in

^{†‡}This will change with the New Small Wheel Phase I Upgrade. cf. Appendix A

⁶⁹⁷ muon reconstruction, see Chapter 5.

Type	Function	Chamber resolution (RMS) in			Measurements/track		Number of	
		z/R	ϕ	time	barrel	end-cap	chambers	channels
MDT	tracking	35 μm (z)	—	—	20	20	1088 (1150)	339k (354k)
CSC	tracking	40 μm (R)	5 mm	7 ns	—	4	32	30.7k
RPC	trigger	10 mm (z)	10 mm	1.5 ns	6	—	544 (606)	359k (373k)
TGC	trigger	2–6 mm (R)	3–7 mm	4 ns	—	9	3588	318k

Figure 2.17: ATLAS MS detector performance. IC: [16]

⁶⁹⁸ 2.6.1 PRECISION DETECTORS

⁶⁹⁹ The ATLAS MS has two types of precision detectors: Monitored Drift Tubes (MDT's) and Cathode Strip Chambers (CSC's). An MDT is a tube with a 3 cm diameter with length depending on
⁷⁰⁰ the station in which the tube is located. The tube is filled with an Ar/CO₂ gas mixture and has a
⁷⁰¹ tungsten-rhenium wire at its center that is kept at 3 000 V when operational. The MDT's provide 35
⁷⁰² μm resolution (per chamber) in their cross-sectional dimension (there is no sensitivity along the axis
⁷⁰³ of the wire). Resolution of this magnitude requires very precise knowledge of the location of the
⁷⁰⁴ wires within the MDT's; this is generally true for detectors in the MS (trigger as well as precision);
⁷⁰⁵ to this end, stations of the MS are aligned using an optical laser system. For a detailed description
⁷⁰⁶ of how misalignment can affect performance, see Appendix A for a detailed discussion of misalign-
⁷⁰⁷ ment's simulated effects on the performance of the proposed Micromegas trigger processor in the
⁷⁰⁸ New Small Wheel (NSW) of the Phase I upgrade. Their 700 ns dead time, however, precludes their
⁷⁰⁹ use as trigger detectors and also in the region of the small wheel (innermost endcap) closest to the
⁷¹⁰ beam pipe ($|\eta|$ from 2.0 to 2.7), where rates are highest.

712 In this region, the precision detectors are the CSC's, which have a much lower dead time of ~ 40
713 ns. These are multiwire proportional chambers with cathode planes that have orthogonal sets of
714 strips, allowing for a measurement in both principal directions. CSC detector sizes also vary by sta-
715 tion, coming in both small and large chambers. The CSC strip pitch is 5.31 (5.56) mm for the large
716 (small) chambers, with position determined from the induced charge distribution in the strips. This
717 corresponds to a nominal resolution of 60 (5 000) μm per plane in the bending (non-bending) direc-
718 tion. These are slated to be replaced by Micromegas detectors in the NSW.

719 **2.6.2 TRIGGER DETECTORS**

720 Trigger detectors have a fundamentally different role than the precision detectors, instead needing to
721 deliver “good enough” approximate values of muon track positions and p_T values. The MS has two
722 types of trigger detectors: Resistive Plate Chambers (RPC’s) in the barrel and Thin Gap Chambers
723 (TGC’s) in the end caps. They collectively cover an $|\eta|$ range to 2.4, and their arrangement is shown
724 in Figure 2.18.

725 The RPC’s are parallel plate detectors with a dead time of 5 ns and a thickness of 2 mm, kept at
726 a potential of 9 800 V; they are deployed in three layers. RPC’s, too, feature strips with orthogonal
727 arrangements on the top and bottom planes, with a strip pitch of 23–35 mm.

728 The TGC’s are multiwire proportional chambers with a dead time of 25 ns. Also, featuring or-
729 thogonal strips, the TGC’s also provide a ϕ measurement to compensate for the lack of MDT sensi-
730 tivity in this direction. There are four layers of TGC’s in the end cap. TGC’s will be supplanted by
731 sTGC’s (small thin gap chambers) in the NSW.

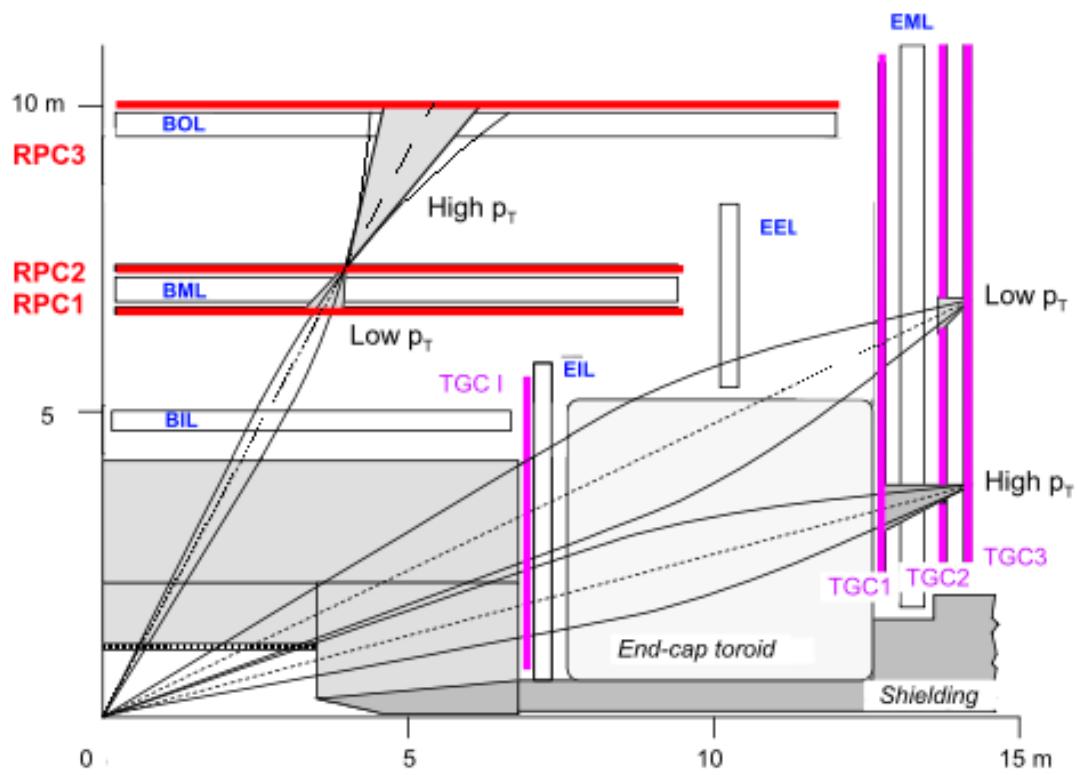


Figure 2.18: ATLAS MS trigger detector arrangement. IC: [16]

⁷³² For more details on how detector level trigger objects work in the ATLAS MS, see Appendix A
⁷³³ for details on the Micromegas trigger processor algorithm.

What do you read, my lord?

Words, words, words.

Hamlet, 2:2

3

734

735

Data and Simulated Samples

736 THE DATA AND Monte Carlo simulation (MC) samples used in this thesis are the same as in the fidu-
737 cial analysis. The data corresponds to 36.1 fb^{-1} of pp collision data collected in 2015+16 at the AT-
738 LAS detector at $\sqrt{s} = 13 \text{ TeV}$. Details of the Run 1 analysis referenced in Chapter 9, may be found
739 in [20]. Only events recorded with all systems in ATLAS in good working order and passing certain

740 quality requirements, according to a Good Run List (GRL), are analyzed.

741 Details about MC samples may be found in [21], and signal and background modeling are dis-
742 cussed in the next. The $ZH \rightarrow \ell\ell b\bar{b}$ process is considered for both multivariate analysis (MVA)
743 optimization and the final statistical analysis, while $WH \rightarrow \ell\nu b\bar{b}$ and $ZH \rightarrow \nu\nu b\bar{b}$ production
744 are included in the final statistical analysis only. Signal MC samples were generated separately for qq
745 and gg initiated VH processes. $qqVH$ samples were generated with Powheg MiNLO + Pythia8
746 [22, 23] with the AZNLO [24] tune set and NNPDF3.0 PDF [25], with alternate samples gener-
747 ated using MadGraph5_AMC@NLO [26] for the hard scatter generation and Pythia8 for the
748 hardronization, parton shower (PS), underlying event (UE), and multiple parton interactions (MPI).
749 Nominal $ggZH$ samples were generated using Powheg for the matrix element (ME) and Pythia8
750 for the parton shower (PS), underlying event (UE), and multiple parton interactions (MPI), again
751 applying the AZNLO tune and NNPDF3.0 PDF set. [27]

752 The background processes considered in these studies are $Z+jets$, $t\bar{t}$, and diboson production for
753 both MVA optimization and the final statistical analysis with single top production and $W+jets$
754 only considered in the final statistical analysis. $V+jets$ samples are generated using Sherpa 2.2.1 [28]
755 for both the ME and PS. These samples are generated in different groups, according to the identity
756 of the V , the max (H_T, p_T^V) of events, with further subdivisions according to the flavor of the two
757 leading jets in an event, b , c , or l , for a total of six categories. $t\bar{t}$ samples are generated using Powheg
758 with the NNPDF3.0 PDF set interfaced with Pythia8 using the NNPDF2.3 PDF's and the Al4
759 tune [29]. Single top samples use Powheg with the CT10 PDF's interfaced with Pythia6 using
760 the CTEQ6L1 PDF's [30, 31]. Diboson samples are generated with Sherpa 2.2.1 interfaced with the

⁷⁶¹ NNPDF_{3.0} NNLO PDF set normalized to NLO cross sections [[32](#)].

*There are certain calculations one simply doesn't do in
public.*

Alan Blaer

4

762

763

Signal and Background Modeling

764 THIS CHAPTER summarizes the modeling of the dominant signal and background processes in
765 this analysis, including corrections and systematic uncertainties (systematic uncertainty, also called
766 nuisance parameter (NP), titles are set in **this** font) related to each process. Further details on the
767 specifics of these topics, including in-depth studies for the derivation and definitions of some of the

768 quantities cited, may be found in [21]. We start with a general discussion of modeling and associated
769 major categories of uncertainties before addressing each of the physics processes.

770 **4.1 EVENT GENERATION IN A NUTSHELL**

771 Before diving into the specifics of modeling and systematic uncertainties associated with each ma-
772 jor set of physics processes considered in this analysis, we review at a schematic level* the problem
773 of simulation event generation. Once a physics processes of interest has been determined, how one
774 simulates an ensemble of particle collisions to model the process in question. This is illustrated in
775 Figure 4.1. Note that the scope of this problem does not include how these generated collision prod-
776 ucts propagate through one's detector. This problem is left for Chapter 5.

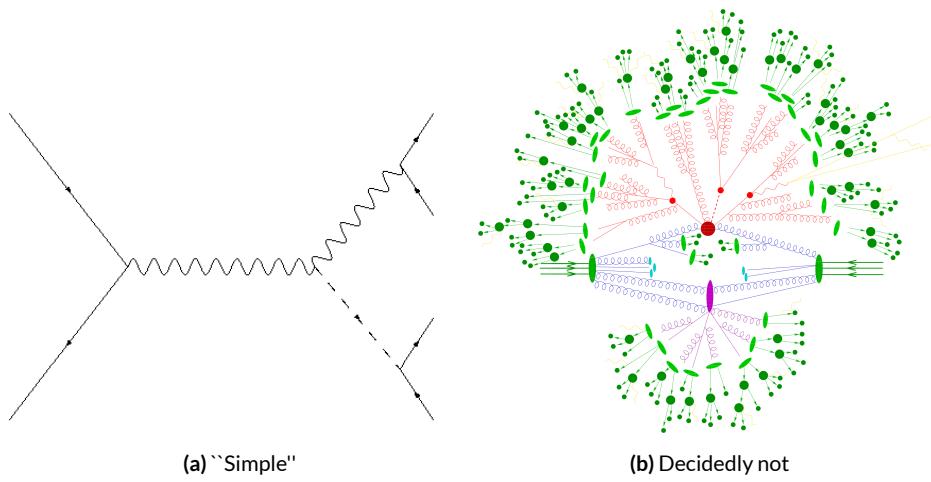


Figure 4.1: The problem here is how to get from (a) to (b).

777 The primary source of complication in event generation comes from dealing with hadronic ob-

*i.e. this will not be a technically rigorous discussion. For a more thorough treatment, the reader is di-
rected to the usual references.

jects both in the initial state (the lefthand side of Figure 4.1 (a); the LHC is a hadron collider) and the final state (this analysis searches for Higgs decays to b -jets, the lower righthand side of Figure 4.1).
Common to all hadronic objects, by definition, are the many considerations that go into calculations in quantum chromodynamics (QCD). In calculating the hard scatter process itself, one must make a variety of choices, such as the parton distribution function (PDF) set to use and to what order in perturbation theory to do the calculation (common choices are leading order (LO), (next to) next to leading order ((N)NLO), and (next to) next to leading log (NNLL)) [33]. Similar considerations often need to be made for the electroweak parts of an event. These considerations and others in event generation (broadly called event generator “tuning”) will be discussed in more detail below.

The initial state includes not only the hard scatter partons that generate the physics process of interest, but also the rest of the partons in the colliding protons, known as the underlying event (UE). Moreover, the hard scatter partons may not be the only interacting partons in an event, further complicating matters; this phenomenon is known as multiple parton interactions (MPI). Specific to the final state are the kinematic distributions of the final state objects—what their energies and angular distributions will be—in addition to the overall cross section of the process that is measurable by the detector (acceptance effects). Furthermore, one has to model hadronization, the process by which any free (colored) partons in an event transform into colorless hadrons.

Typically, it takes several steps and tools to accomplish this. The hard scatter itself is often modelled with a dedicated event generator like PowHEG [22] or MADGRAPH [26], with events generated then interfaced with a tool like PYTHIA [23] for the PS, UE, and MPI, though there are exceptions (SHERPA [34], for example, can do both the hard scatter and hadronization/ for some pro-

799 cesses).

800 4.2 DESCRIPTION OF MODELING UNCERTAINTY CATEGORIES

801 Each of the steps in event generation described above has associated uncertainties. Some uncertain-
802 ties are inherent in the calculations themselves. The choice of which order in perturbation theory
803 to do a calculation, for example, comes with it an implicitly defined level of precision[†]. Extrapolat-
804 ing from one energy/momentum scale to another also introduces uncertainty. Furthermore, there
805 is no *a priori* correct choice to make at each step in event generation, so each choice (the choice of
806 generator, PDF set, parton shower calculator, all of their configurable parameters, etc.) implies an
807 additional layer of uncertainty.

808 In order to quantify these choices, each source of systematic uncertainty is treated separately and
809 given a unique name. To make this more concrete, take the specific example of the uncertainty asso-
810 ciated with the $H \rightarrow b\bar{b}$ branching ratio of 58%, called `ATLAS_BR_bb`, which encapsulates a num-
811 ber of effects (higher order terms, the mass of the b quark, and choice of α_S). The quoted (in prin-
812 ciple asymmetric) uncertainty on the Higgs BR is not itself a direct input into the analysis model.
813 Instead, the effect of varying the branching ratio up and down by one standard deviation is propa-
814 gated to simulated collision events and recorded (i.e. the analysis is run with the Higgs branching
815 ratio at $\pm 1\sigma$, and the results are recorded alongside the nominal result). The nominal and “up” and
816 “down” variations are then typically taken to define a normally distributed, freely floating param-

[†]though this is less well-defined in QCD calculations than for electroweak calculations since they don’t converge

817 eter in the statistical fit model. Since these parameters associated with systematic uncertainties are
818 not typically considered interesting quantities, they are often referred to as “nuisance parameters”
819 (NP’s). The terms “systematic,” “systematic uncertainty,” and “nuisance parameter” are often used
820 interchangeably.

821 The specifics of exactly how the effects of variations are saved and propagated to the full fit model
822 are deferred to Chapter 7. The discussion here is confined to how systematic uncertainties for signal
823 and background modeling and their accompanying variations are defined. Modeling systematics are
824 derived separately for each physics process (simulation sample). Sometimes, all of the variation for
825 a given process is encapsulated in a single systematic, but oftentimes the variations from multiple
826 considerations are distinct enough to be treated separately. Furthermore, each of these separate sys-
827 tematics for a given sample/process may be treated in a number of ways (e.g. 0-lepton events may
828 be treated differently from 2-lepton events). An additional subtlety is that a continuous parameter
829 like a branching ratio lends itself quite naturally to defining Gaussian $\pm 1\sigma$ variations, while for dis-
830 crete variations, like choice of PDF set for parton showers, how to proceed is less obvious. This is
831 addressed on a case-by-case basis, as described below.

832 Before enumerating each of the principal physics processes and their systematics, we begin by
833 describing considerations and choices that must be addressed for every physics process in order to
834 make the discussion of individual samples and systematics both clearer and less repetitive.

835 4.2.1 PHYSICS CONSIDERATIONS

836 In general, evaluating the uncertainties arising from the many choices in event generation entails
837 producing alternate samples of events, which practically means tuning parameters in the various soft-
838 ware packages and/or using alternate packages/libraries to make new samples. Once these samples
839 have been created, they are compared at truth-level (particle level) using a package called Rivet [35]
840 instead of using the full ATLAS detector reconstruction for computational considerations. Given
841 the nature of the problem and the tools, there are generally three main categories of physics issues,
842 each described below.

843 UNDERLYING EVENT AND PARTON SHOWER

844 The modeling of the underlying event (UE) and parton shower (PS) are usually handled by the same
845 package and so are usually treated together. The typical nominal choice in the fiducial analysis is
846 PYTHIA8. One approach to modeling these uncertainties is simply to see what happens when a
847 different model is used and then compare this alternate set of events to the nominal set, taking the
848 difference as the (implicitly one standard deviation) scale of variation. Another approach is to vary
849 some parameter within a given model, for example, using different tunes in the A14 set for PYTHIA8
850 with their accompanying variations, to characterize the scale of variation.

851 A natural question is how to treat these two approaches on the same footing. When examining
852 a set of potential variations related to the same process or effect, oftentimes the largest single varia-
853 tion in a set is picked as defining the scale for the systematic uncertainty. Another approach is to use

854 the average over a set of variations.[‡] The ATLAS_UEPS_VH_hbb systematic, for example, uses the
855 Pythia8 + A14 tunes approach to determine the scale of UE variation and compares Pythia8 with
856 Herwig7 to characterize the PS variation. Each of the A14 tunes comes with an up and down varia-
857 tion, and the difference between each of these variations and a nominal setup may be expressed as a
858 ratio, R , of total events.

859 As is often done when a physical argument can be made for combining related, but ultimately
860 orthogonal categories/measurements/uncertainties/systematics, the combined UE+PS systematic is
861 taken to be the sum in quadrature of these two effects:

$$\sum_{tunes} \max_{tune} (|R_{up} - R_{down}|) \oplus \sigma_{PS} \quad (4.1)$$

862 QCD SCALE

863 The term “QCD scale” in the context of modeling uncertainties refers to the choice of renormal-
864 ization (μ_R) and factorization (μ_F) scales used in QCD calculations. These are typically treated to-
865 gether. Usually, some multiplicative scale factor, f , is chosen, and each scale is varied in concert with
866 the other scale by 1, f , and $1/f$ (nine total combinations), sometimes with a cap on how large the
867 combined variation can be (so ignoring the (f, f) and $(1/f, 1/f)$ cases). Just as in the UE+PS, the
868 largest variation is usually taken as the systematic uncertainty.

869 Another important choice in the context of renormalization, to deal with infinities inherent in

[‡]Generally, the maximum is used if it is much larger than other variations, and the average is used if scales are comparable. In general, the historical preference is to be conservative.

870 quantum field theory calculations with loops, is the choice of regularization (to keep track of the
871 infinities) and subtraction schemes (to eliminate them). A common combination is dimensional reg-
872 ularization (deforming the four dimensional integral to $4 - \varepsilon$ dimensions and then taking $\varepsilon \rightarrow 0$)
873 with $\overline{\text{MS}}$ (“MS-bar” (MS for “minimal subtraction”) subtracts off only the infinities plus some com-
874 mon factors that always appear in dimensional regularization). For more details, see, for example,
875 [33]. While each scheme is internally consistent, each can yield different answers at a given order of
876 calculation (and different subtraction schemes may be used for calculations at different orders).

877 PARTON DISTRIBUTION FUNCTIONS AND α_s

878 Finally, separate uncertainties are often made for the choice of parton distribution function (PDF)
879 set and associated choice of strong coupling for $\text{QCD}(\alpha_s)$. Much as in the previous two cases, one
880 can vary the parameter α_s and study what samples of simulation events made using different PDF
881 sets relative some nominal setup look like. Similarly, one can take the maximum, average, or sum in
882 quadrature of different variations to characterize a systematic uncertainty.

883 4.2.2 MODELING SYSTEMATIC TYPES

884 With the concept of what type of effect is taken as a single systematic uncertainty and how its varia-
885 tions are generally evaluated, it is now time to turn to the issue of what exactly is being varied.

886 ACCEPTANCE/NORMALIZATION

887 The most basic type of modeling uncertainty is a normalization uncertainty, often called an accep-
888 tance uncertainty. This simply denotes the uncertainty on the number of predicted events for a
889 given process in a given region of phase space (usually delineated by the number of leptons in the
890 final state and sometimes also by the number of and jets the p_T^V [§] of an event) and is usually expressed
891 as a percent.

892 As an example, the uncertainty on the theoretical prediction of the $H \rightarrow b\bar{b}$ branching ratio,
893 denoted ATLAS_BR_bb (it is an ATLAS-wide systematic), is expressed as a normalization system-
894 atic with a value of 1.7%, affecting all VH processes. Now imagine we have an event in a VH sample
895 with weight 1.0. The nominal histograms for this region gets filled with this event's relevant informa-
896 tion with weight 1.0, while the ATLAS_BR_bb__1up (__1do) histograms get filled with weight 1.017
897 (0.983).

898 SHAPE SYSTEMATICS

899 In addition to normalization systematics expressed as single numbers attached to different processes
900 in different regions, there are also the so-called “shape systematics” and “shape corrections,” heuristi-
901 cally differences in distributions that exist in distributions even after correcting for normalizations,
902 which gives distributions a different “shape” even if their integrals are the same (c.f. Figure 4.3).

[§]This is the transverse mass of the lepton pair for 2-lepton events, the vectorial sum of the single lepton and \vec{E}_T^{miss} for 1-lepton events, and the \vec{E}_T^{miss} for 0-lepton events.

903 These have the schematic form

$$w_{event} = A_{region} \times f_{region}(event) \quad (4.2)$$

904 where w_{event} is the simulated event's weight, A_{region} is the overall normalization (in principle includ-
905 ing any systematics), and $f_{region}(event)$ is some function of event-level variables, usually a single vari-
906 able, like p_T^V or m_{bb} . The purpose of these systematics is to take into account (in the case of a system-
907 atic) or correct (in the case of a correction applied to the event weight) the non-trivial dependence
908 of a normalization on one of these quantities. Some of these are taken from histograms while others
909 are parametric functions (in this analysis, usually linear ones).

910 An example of the former case is the quantity δ_{EW} , the difference between the nominal $qqVH$
911 cross section and the differential cross section as a function of p_T^V at next to leading order (NLO). As
a correction, this term is simply used as a correction factor $k_{EW}^{NLO} = (1 + \delta_{EW})$.

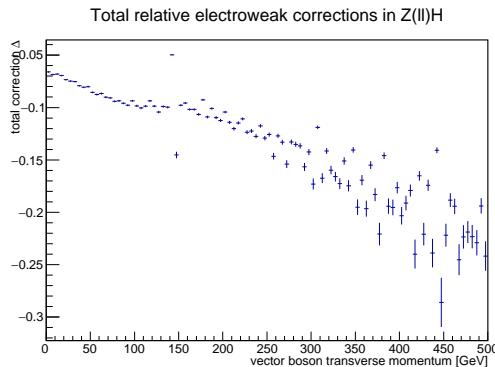


Figure 4.2: The δ_{EW} correction term for 2-lepton $qqZH$.

912

913 An example of the latter case is the systematic associated with the m_{bb} dependence of the the

914 $t\bar{t}$ normalization for 2 jet, $p_T^V \in [75, 150]$ GeV, 2 lepton events. In this case, a variety of effects are
 915 studied (ME, PS, UE), as shown in Figure 4.3. The top half of the plot is the m_{bb} plot for this re-
 916 gion, with the black bars representing the nominal spectrum and spectra generated with different
 917 ME, PS, and UE choices. The ratio plot in the bottom half of the figure shows the scale of varia-
 918 tion normalized to bin content. From this ratio plot, it is clear that the choice of ME (pink points)
 919 was seen to have the largest effect on normalization. The linear fit in the plot reasonably envelopes
 920 this maximum variation was done, and so is taken as the systematic variation. Hence, in this case,
 921 $f_{region}(event)$ is a linear function of m_{bb} , with positive (negative) slope for the up (down) variation.

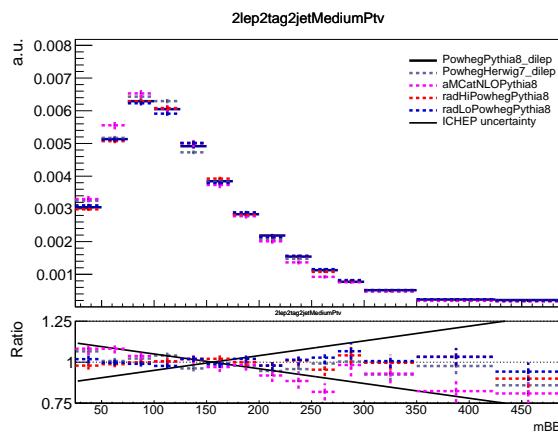


Figure 4.3: The derivation of the 2-lepton $t\bar{t} m_{bb}$ shape systematic.

922 DIVIDING MODELING UNCERTAINTIES: ACCEPTANCE RATIOS

923 In addition to uncertainties on absolute normalizations (both inclusive and region specific), mod-
 924 eling uncertainties are sometimes introduced for the ratio of normalizations between different re-
 925 gions. While these can be simple ratios, evaluating a systematic's effect between regions means eval-

926 uating nominal and alternate choices between regions, so the so-called “double ratio” is often taken
 927 as the scale of variation (plus one). The ATLAS_UEPS_VH_hbb systematic mentioned above, for ex-
 928 ample, has associated with it, ATLAS_UEPS_VH_hbb_32JR. This systematic is evaluated by dividing
 929 the 3 jet to 2 jet ratio in the nominal setup by the same ratio in an alternate setup. These ratios gener-
 930 ically look like:

$$\frac{\text{Acceptance}[\text{Category}_A(\text{nominalMC})]}{\text{Acceptance}[\text{Category}_B(\text{nominalMC})]} \Big/ \frac{\text{Acceptance}[\text{Category}_A(\text{alternativeMC})]}{\text{Acceptance}[\text{Category}_B(\text{alternativeMC})]} \quad (4.3)$$

931 Double ratio systematics are often included in addition to single systematics when a single system-
 932 atic could potentially overestimate the total variation due to a single effect. In the above example,
 933 the choice of UE+PS in signal events may cause different overall variation in 2 jet events as compared
 934 to events with 3 or more jets due to QCD considerations. However, extrapolating between jet mul-
 935 tiplicities can be a non-trivial exercise entirely regardless of the choice of generator for UE+PS (cf.
 936 the discussion of the Stewart-Tackman approach 4.2.2 below), so to include this variation in a single
 937 systematic would lead to overly conservative systematic uncertainties. Hence, using previous knowl-
 938 edge of this separate variation between jet multiplicity regions, one can define a double ratio system-
 939 atic for a more accurate fit model.

940 The three main categories are ratios between different flavor regions, ratios between different lep-
 941 ton channels[¶], and ratios between regions with different numbers of jets, n_{jet} . The first category is
 942 only relevant for $V+jets$ systematics and will be treated in that process’s dedicated section below. As

[¶]e.g. $Z+$ heavy flavor jets (at least one b -jet in the event; often denoted “hf” normalizations in 0- and 2-lepton events

943 this thesis is primarily concerned with the 2-lepton channel, the second category will not be treated
 944 in detail, though the treatment is much the same as other ratio systematics.^{||} In order to discuss the
 945 n_{jet} ratios in systematics (e.g. the ratios in the double ratio example), we must first describe how ex-
 946 clusive n_{jet} cross section calculations are done.

947 THEORETICAL ASIDE: STEWART-TACKMANN A way to calculate uncertainties on processes in re-
 948 gions with different numbers of jets was developed by Stewart and Tackmann and is implicitly used
 949 for most n_{jet} ratio systematics [36]. The problem is how to calculate the cross section and associated
 950 uncertainty for a process with exclusively N jets in the final state. Generically:

$$\sigma_{\geq N} = \sigma_N + \sigma_{\geq N+1} \quad (4.4)$$

951 The physical interpretation of one parton to one jet is an idealized case. In order to demarcate
 952 between jets, one has some quantity that is used as a cutoff in an integral that defines the border be-
 953 tween jet regions.

$$\sigma_{\geq N} = \int_0^{p_{cut}} \frac{d\sigma_N}{dp} + \int_{p_{cut}} \frac{d\sigma_{\geq N+1}}{dp} \quad (4.5)$$

954 Since these cutoffs (not necessarily constant, etc.) can make calculations more complicated, inclu-
 955 sive cross sections tend to be easier to calculate. Hence, it is usually much easier to evaluate the two
 956 inclusive cross sections and find the uncertainties on these by varying α_S in the usual way (cf. Sec-

^{||}Such ratios allow for information in one channel to help constrain other channels, particularly for hard to model processes like $Z+\text{hf}$. This helps to reduce final overall uncertainties in combined fits. For a discussion of the interplay of nuisance parameters in combined fits, cf. Chapter 9.

⁹⁵⁷ tion 4.2.1). One then assumes the inclusive uncertainties are uncorrelated, for a covariance matrix for
⁹⁵⁸ $\{\sigma_{\geq N}, \sigma_N, \sigma_{\geq N+1}\}$ of (with Δ_x^2 as the variance associated with x):

$$\Sigma = \begin{pmatrix} \Delta_{\geq N}^2 & \Delta_{\geq N}^2 & 0 \\ \Delta_{\geq N}^2 & \Delta_{\geq N}^2 + \Delta_{\geq N+1}^2 & -\Delta_{\geq N+1}^2 \\ 0 & -\Delta_{\geq N+1}^2 & \Delta_{\geq N+1}^2 \end{pmatrix} \quad (4.6)$$

⁹⁵⁹ These calculations contain Sudakov double logs of $\ln^2(p/Q)$, where Q corresponds to the scale
⁹⁶⁰ of the hard scatter process (m_H), and p_{cut} is usually something like a p_T cutoff. When integrating
⁹⁶¹ over all of the phase space, these terms can come to dominate calculations when $p \gg Q$. The $N+1$
⁹⁶² term in the covariance matrix is an uncertainty associated with the cutoff, but the Sudakov double
⁹⁶³ logs will dominate any higher order terms. Stewart and Tackmann give the following reasoning:

⁹⁶⁴ “In the limit $\alpha_S^2 \approx 1$, the fixed-order perturbative expansion breaks down and the logarithmic
⁹⁶⁵ terms must be resummed to all orders in α_S to obtain a meaningful result. For typical experimental
⁹⁶⁶ values of p_{cut} fixed-order perturbation theory can still be considered, but the logarithms cause large
⁹⁶⁷ corrections at each order and dominate the series. This means varying the scale in α_S in Eq. (9) di-
⁹⁶⁸ rectly tracks the size of the large logarithms and therefore allows one to get some estimate of the size
⁹⁶⁹ of missing higher-order terms caused by p_{cut} , that correspond to Δ_{cut} . Therefore, we can approxi-
⁹⁷⁰ mate $\Delta_{cut} = \Delta_{\geq 1}$, where $\Delta_{\geq 1}$ is obtained from the scale variation for $\sigma_{\geq 1}$.”

⁹⁷¹ The above considerations are important for this analysis since phase space is separated into 2 and
⁹⁷² ≥ 3 jet regions, and the uncertainties for these regions are anti-correlated.

973 4.3 PROCESS SPECIFIC SYSTEMATIC SUMMARIES

974 Brief descriptions of modeling systematics, including recapitulations of nominal sample generation,
 975 are given in the following sections. The general approach here is to copy the relevant summary tables
 976 and describe any major deviations from the general procedures described in the previous section.
 977 The dominant backgrounds for the 2-lepton channel are $Z+hf$ and $t\bar{t}$, accounting for well over 90%
 978 of all background events. Diboson samples are the next-leading background and are an important
 979 validation sample; others are included for completeness. A summary of all the modeling systematics
 in this analysis are given in Table 4.1.

Process	Systematics
Signal	$H \rightarrow bb$ decay, QCD scale, PDF+ α_s scale, UE+PS (acc, p_T^V , m_{bb} , 3/2 jet ratio)
$Z+jets$	Acc, flavor composition, $p_T^V+m_{bb}$ shape
$t\bar{t}$	Acc, $p_T^V+m_{bb}$ shape
Diboson	Overall acc, UE+PS (acc, p_T^V , m_{bb} , 3/2 jet ratio), QCD scale (acc $(2, 3$ jet, jet veto), p_T^V , m_{bb})
Single top	Acc, $p_T^V+m_{bb}$ shape

Table 4.1: Summary of modeling systematic uncertainties, with background samples listed in order of importance.

980

981 4.3.1 SIGNAL PROCESSES

982 Nominal signal $qqVH$ samples are generated using PowHEG with the MINLO (multiscale improved
 983 NLO) [37] procedure applied interfaced with PYTHIA8 using the AZNLO tune [24] and NNPDF3.0
 984 PDF set [25]. For the 2-lepton case, gluon fusion initiated Higgs production is also considered (ac-
 985 counting for $\sim 14\%$ of the total cross section in this channel), with samples generated with PowHEG

⁹⁸⁶ interfaced with PYTHIA8 using the AZNLO tune. The NNPDF2.3 set [38] is used for both the ME
⁹⁸⁷ and UE+PS.

⁹⁸⁸ Alternate samples $qqVH$ samples are generated using MADGRAPH5_aMC@NLO [39] for the
⁹⁸⁹ ME and PYTHIA8 for the UE+PS, hadronization and MPI. The NNPDF2.3_5f FFN PDF sets and
⁹⁹⁰ the Al4 tune [40]; the latter has variations included. PowHEG+MinLO+HERWIG7 were samples
⁹⁹¹ were also used for systematics.

⁹⁹² The signal systematics categories are $H \rightarrow bb$ decay cross section, QCD scale, PDF+ α_s scale, and
⁹⁹³ UE+PS. Additionally, there is the NLOEWK correction described above. The correction scale factor
⁹⁹⁴ is derived using the HAWK MC software. To encapsulate NNLOEW effects the maximum of 1%,
⁹⁹⁵ the square of the correction factor, and the photon induced cross section is used as a systematic.

⁹⁹⁶ Table 4.2, reproduced from [21], summarizes the signal cross section systematics, which are ap-
⁹⁹⁷ plied uniformly across the analysis channels (as applicable).

Sys Name	source	Norm. effect	applied to
ATLAS_BR_bb	$H \rightarrow bb$ dec. unc. (HO effects, m_b , α_s)	1.7%	all VH
ATLAS_QCDscale_VH	QCD scale uncertainty	0.7%	$qq \rightarrow VH$
ATLAS_QCDscale_ggZH	QCD scale uncertainty	27%	$gg \rightarrow ZH$
ATLAS_pdf_Higgs_VH	PDF+ α_s uncertainty	1.9% 1.6%	$qq \rightarrow WH$ $qq \rightarrow ZH$
ATLAS_pdf_Higgs_ggZH	PDF+ α_s uncertainty	5.0%	$gg \rightarrow ZH$

Table 4.2: Summary of all systematic uncertainties on the VH cross section including their value, source and the corresponding nuisance parameter name.

⁹⁹⁸ The remaining signal systematics are analysis channel specific and are summarized in Table 4.3.
⁹⁹⁹ The methodologies match those described in Section 4.2. The UE+PS systematics were derived us-
¹⁰⁰⁰ ing the alternate samples mentioned above; QCD scale uncertainties were derived by varying scales

1001 by 1/3 and 3; and PDF uncertainties were derived by comparing the nominal set with the PDF4-
 1002 LHC15_30 PDF set [41].

NP name	oL		iL		zL	
	2j	3j	2j	3j	2j	$\geq 3j$
ATLAS_UEPS_VH_hbb	10.0%	10.0%	12.1%	12.1%	13.9%	13.9%
ATLAS_UEPS_VH_hbb_32JR	–	13.0%	–	12.9%	–	13.4%
ATLAS_UEPS_VH_hbb_VPT	shape only		shape+norm			
ATLAS_UEPS_VH_hbb_MBB	shape only					
QCDscale_VH_ANA_hbb_J2	6.9%	–	8.8%	–	3.3%	–
QCDscale_VH_ANA_hbb_J3	-7%	+5%	-8.6%	+6.8%	-3.2%	+3.9%
QCDscale_VH_ANA_hbb_JVeto	–	-2.5%	–	3.8%	–	–
QCDscale_VH_ANA_hbb_VPT	shape only		shape+norm			
QCDscale_VH_ANA_hbb_MBB	shape only					
pdf_HIGGS_VH_ANA_hbb	1.1%	1.1%	1.3%	1.3%	0.5%	0.5%
pdf_VH_ANA_hbb_VPT	shape only		shape+norm			
pdf_VH_ANA_hbb_MBB	shape only					

Table 4.3: Summary of all systematic uncertainties on the VH acceptance and shapes originating from altering the PDF and α_S uncertainties, including their corresponding nuisance parameter name.

1003 4.3.2 $V+$ JETS

1004 Nominal $V+$ jets samples are generated using SHERPA 2.2.1@NLO** [42] for both the ME and PS,
 1005 interfaced with the NNPDF’s and using a five quark flavor scheme, and alternative samples are de-
 1006 rived using MADGRAPH5 interfaced with PYTHIA8. In order to increase statistics in important re-
 1007 gions of phase space, these samples were separated into kinematic slices based on p_T^V and into bins of
 1008 jet flavor. The kinematic slices were in the quantity $\max(H_T, P_T^V)$ and had the intervals [0–70, 70–
 1009 140, 140–280, 280–500, 500–1000, > 1000] GeV. The jet flavor slices were made using flavor vetoes
 1010 and filters:

**SHERPA 2.1 is used for some variations not available in SHERPA 2.2.1.

- BFilter: at least 1 b-hadron with $|\eta| < 4, p_T > 0$ GeV
- CFilterBVeto: at least 1 c-hadron with $|\eta| < 3, p_T > 4$ GeV; veto events which pass the BFilter
- CVetoBVeto: veto events which pass the BFilter and/or the CFilterBVeto

These in turn are related to the main flavor regions used in the analysis, based on the flavor of the two leading jets in an event (based on p_T). These five flavors (with up, down, and strange collectively known as “light”) yield six different flavor combinations: bb, bc, bl (these first three collectively known as “heavy flavor” or $V+hf$), cc, cl, ll (or just “light” or l). Ratio systematics are often made with respect to the acceptance in the bb region.

$V+jet$ systematics are derived in several steps. The first is to use double ratios of acceptances between analysis regions and nominal versus alternative MC’s (so $(\text{Region1-nominal}/\text{Region2-nominal}) / (\text{Region1-alternate}/\text{Region2-alternate})$). The main region comparisons are 2 jet versus 3 jet ($3+jet$ for 2-lepton) and then 0-lepton versus 2-lepton (1-lepton) for $Z+hf$ ($W+hf^{\dagger\dagger}$). The final uncertainty contains the sum in quadrature of four effects:

1. Variation of 0.5 and 2 of QCD scales in the SHERPA sample
2. Sum in quadrature of half the variation from different resummation and CKKW merging scales ^{††}
3. Maximal variation between nominal setup and SHERPA 2.2.1 with the MMHT2014nnlo68cl and CT14nnlo PDF sets
4. Difference between the SHERPA and MADGRAPH₅ sets

^{††}The $W+hf$ CR versus the SR is also considered for $W+hf$

^{‡‡}cf. [43], Section 2 for a summary of the CKKW method for different parton multiplicities used in SHERPA

1031 Summaries of the Z +jets uncertainties are provided here; the reader is referred to [21] for the
 1032 W +jets systematics, as these events are virtually non-existent in the 2-lepton case with which this
 1033 thesis is almost exclusively concerned. In Table 4.4, from [21] are the normalization systematics.

Process	Name	prior in region					
		2jet			(\geq)3jets		
		$_{\text{2L: lo}}$	$_{\text{2L: hi}}$	$_{\text{oL}}$	$_{\text{2L: lo}}$	$_{\text{2L hi}}$	$_{\text{oL}}$
$Z+l$	SysZclNorm	18%					
$Z+cl$	SysZlNorm	23%					
$Z+hf$	norm_Zbb	Floating Normalization					
$Z+hf$	SysZbbNorm_L2_J3	-	-	-	30%	30%	-
$Z+hf$	SysZbbNorm_J3	-	-	-	-	-	17%
$Z+hf$	SysZbbNorm_0L	-	-	7%	-	-	7%
$Z+hf$	SysZbbPTV	effect on each region obtained from shape rw					

Table 4.4: Effect of modeling systematics on Z +jets normalization in the 2lepton regions. For systematic uncertainties implemented with a prior the effect of $1-\sigma$ variation is reported. The uncertainties labelled as Zbb act on the entire $Z+hf$ background. Region labels ``lo'' and ``hi'' refer to event p_T^V .

1034 The flavor composition ratio systematics are in Table 4.5, also from [21].
 1035 Finally, the p_T^V and m_{bb} shape systematics are derived using control regions in data. The func-

1036 tional form for the p_T^V systematic is $\pm 0.2 \log 10(p_T^V/50\text{GeV})$, and that of the m_{bb} systematic is $\pm 0.0005 \times$
 1037 $(m_{jj} - 100\text{ GeV})$.

1038 4.3.3 TOP-PAIR PRODUCTION

1039 Nominal $t\bar{t}$ samples are produced with POWHEG at NLO for the ME calculation using the NNPDF3.0
 1040 PDF set interfaced with PYTHIA8.210 using the A14 tune and the NNPDF2.3 PDF set at LO. The

These use the same selections as the signal regions except for b -tags (0, 1, and 2 tags are studied), with the added requirement in 2tag regions that m_{bb} not be in the range of 110–140GeV.

Category	Nuisance Parameter Name	Prior	Applied to
$Z+bc/Z+bb$	SysZbcZbbRatio	40%	$Z+bc$ events (0-Lepton)
		40%	$Z+bc$ events (2-Lepton 2jet)
		30%	$Z+bc$ events (2-Lepton ≥ 3 jet)
$Z+bl/Z+bb$	SysZblZbbRatio	25%	$Z+bl$ events (0-Lepton)
		28%	$Z+bl$ events (2-Lepton 2jet)
		20%	$Z+bl$ events (2-Lepton ≥ 3 jet)
$Z+cc/Z+bb$	SysZccZbbRatio	15%	$Z+cc$ events (0-Lepton)
		16%	$Z+cc$ events (2-Lepton 2jet)
		13%	$Z+cc$ events (2-Lepton ≥ 3 jet)

Table 4.5: The priors on the relative acceptance variations for $Z+hf$. The first column details the flavor components across which the acceptance variation is being considered, the second column lists the names of the corresponding nuisance parameter in the Profile Likelihood Fit, the third contains the value of the prior and the fourth column the processes and categories to which this nuisance parameter is applied.

parameters `hdamp` (nominal value $1.5m_{top}$, a resummation damping factor for ME/PS matching that can heuristically thought of as tuning high p_T radiation) in PowHEG and `pThard` (nominal value 0) and `pTdef` (nominal value 2) in PyTHIA (both control merging with PowHEG) are varied to evaluate certain systematics. Alternative $t\bar{t}$ samples use PowHEG+HERWIG7, MADGRAPH5_aMC-@NLO+PyTHIA8.2, and the nominal setup with varied tunes and parameter values. Uncertainties are taken to cover the largest difference between the nominal and any of these alternate configurations.

The overall $t\bar{t}$ normalization is a floating normalization, and further systematics attached to the ratio of acceptances between regions (3-to-2 jet, SR-to-WhfCR, and 1-to-0 lepton) are defined using double ratios; these are summarized in Tables 4.6 and 4.7, taken from [21].

Shape systematics for p_T^V and m_{bb} are linear and taken to cover the largest difference reasonably. The use of a top $e - \mu$ control region helps constrain this.

	0-lepton		1-lepton			
Systematic	2j	3j	WCR 2j	SR 2j	WCR 3j	SR 3j
norm_ttbar	floating normalization					
SysttbarNorm_L0	8%	8%	-	-	-	-
SysttbarNorm_J2	9%	-	9%	9%	-	-
SysttbarNorm_DWhfCR_L1	-	-	25%	-	25%	-

Table 4.6: Effect of modeling systematics on $t\bar{t}$ normalization in the 0 and 1-lepton analysis region.

	2jet		≥ 3 jets	
	lo	hi	lo	hi
norm_ttbar_J2_L2	floating normalization	-	-	-
norm_ttbar_J3_L2	-	-	floating normalization	-
SystTbarPTV_L2_L2	effect on each region obtained from shape rw			

Table 4.7: Effect of modeling systematics on $t\bar{t}$ normalization in the 2lepton regions. The SystTbarPTV_L2_L2 systematic is implemented as a shape systematic over the full $VpT > 75$ GeV range, and as a result has different acceptance effects in the low and high VpT regions. Systematics are treated the same in both signal and control regions, and “lo” and “hi” refer to the p_T^V split in events.

1052 well, as described above in 4.2.2. These are summarized in Table 4.8, again taken from [21].

Analysis region	Uncertainty	Value	Source	NP
o,1 lepton	p_T^V shape	shape	fit through largest deviation (aMC@NLO + PYTHIA8)	TTbarPTV
2 lepton	p_T^V shape	norm	fit through largest + shape	deviation (aMC@NLO + PYTHIA8)
TTbarPTV_L2				
o,1 lepton	$m_{b\bar{b}}$ shape	shape	fit through largest only	deviation (aMC@NLO + PYTHIA8)
TTbarMBB				
2 lepton	$m_{b\bar{b}}$ shape	shape	fit through largest only	deviation (aMC@NLO + PYTHIA8)
TTbarMBB_L2				

Table 4.8: Summary of all shape uncertainties for the $t\bar{t}$ process with short descriptions and the name of the corresponding nuisance parameters.

1053 4.3.4 DIBOSON PRODUCTION

1054 Three diboson production processes (collectively denoted VV) are important for these analyses: ZZ ,

1055 WZ , and WW . Nominal samples are created using SHERPA 2.2.1 using the NNPDF3.0 PDF set. Al-

1056 ternative samples use Powheg+Pythia8 and Powheg+Herwig++. The methodology here is

1057 similar to that of the $t\bar{t}$ systematics, with both overall acceptance and lepton channel specific uncer-

1058 tainties, with the exception that UE+PS and QCD scale are treated separately (PDF+ α_S was found

1059 to be negligible). p_T^V shape systematics are described using linear fits, while $m_{b\bar{b}}$ shape systematics

1060 are described using hyperbolic tangents (third degree polynomials) in the 2 jet (3 jet) regions. Once

1061 again, summary tables from [21] are reproduced here.

Sys Name	source	Norm. effect	applied to
SysWWNorm	overall cross section uncertainty	25%	WW in all regions
SysWZNorm	overall cross section uncertainty	26%	WZ in all regions
SysZZNorm	overall cross section uncertainty	20%	ZZ in all regions

Table 4.9: Summary of all systematic uncertainties on the diboson cross section including their value, source and the corresponding nuisance parameter name.

NP name	oL: $ZZ \rightarrow \nu\bar{\nu} b\bar{b}$		1L: $WZ \rightarrow \ell\nu b\bar{b}$		2L: $ZZ \rightarrow \ell^+ \ell^- b\bar{b}$	
	2j	3j	2j	3j	2j	$\geq 3j$
SysVZ_UEPS_Acc	5.6%	5.6%	3.9%	3.9%	5.8%	5.8%
SysVZ_UEPS_32JR	-	7.3%	-	10.8%	-	3.1%
SysVZ_UEPS_VPT	shape+norm			shape only		shape+norm
SysVZ_UEPS_MBB	shape only					
SysVZ_QCDscale_J2	10.3%	-	12.7%	-	11.9%	-
SysVZ_QCDscale_J3	-15.2%	+17.4%	-17.7%	+21.2%	-16.4%	+10.1%
SysVZ_QCDscale_JVeto	-	+18.2%	-	+19.0%	-	-
SysVZ_QCDscale_VPT	shape+norm			shape only		shape+norm
SysVZ_QCDscale_MBB	shape only					

Table 4.10: Summary of the systematic uncertainties on the VH acceptance in each analysis region and on the p_T^V and $m_{b\bar{b}}$ shapes originating from altering the QCD scale, including their nuisance parameter name.

4.3.5 SINGLE TOP PRODUCTION

Single top sample are generated separately for the different production channels (s , t , and Wt) using POWHEG with the CT10 NLO PDF's interfaced with PYTHIA6 using the PERUGIA2012 PS tune and the corresponding CTEQ6L1 LO PDF's and PHOTOS (TAUOLA) for QED final state (τ) decay.

Production	Uncertainty	Value	Source	Nuisance Parameter
s -channel	overall normalization	4.6%	sum in quadrature of μ_R , μ_F , α_S and PDF uncertainties	<code>sstopNorm</code>
t -channel	overall normalization	4.4%	sum in quadrature of μ_R , μ_F , α_S and PDF uncertainties	<code>sstopNorm</code> correlated with 2 jet and 3 jet case
t -channel	2 jet region acceptance of deviations in alternative generators	17%	sum in quadrature	<code>sstopAcc</code> correlated with overall and 3 jet case
t -channel	3 jet region acceptance	20%	sum in quadrature of deviations in alternative generators	<code>sstopAcc</code> correlated with overall and 2 jet case
Wt channel	overall normalization	6.2%	sum in quadrature of μ_R , μ_F , α_S and PDF uncertainties	<code>sstopWtNorm</code> correlated with 2 jet and 3 jet case
Wt channel	2 jet region normalization	35%	sum in quadrature of deviations in alternative generators	<code>sstopWtAcc</code> correlated with overall and 3 jet case
Wt channel	3 jet region normalization	41%	sum in quadrature of deviations in alternative generators	<code>sstopWtAcc</code> correlated with overall and 2 jet case
t -channel	p_T^V shape	shape	fit through largest deviation (POWHEG+ HERWIG++) $\pm 0.001 \times p_T^V \mp 0.17 + 1$	<code>SstopPTV</code>
t -channel	$m_{b\bar{b}}$ shape	shape	fit through largest deviation (POWHEG+ PYTHIA6 radHi-radLo) $\pm 0.0008 \times m_{b\bar{b}} \mp 0.12 + 1$	<code>SstopMBB</code>
Wt channel	p_T^V shape	shape	fit through largest deviation (POWHEG+ PYTHIA6 with diagram subtraction) $\pm 0.003 \times p_T^V \mp 0.69 + 1$	<code>SstopWtPTV</code>
Wt channel	$m_{b\bar{b}}$ shape	shape	fit through largest deviation (POWHEG+ PYTHIA6 with diagram subtraction) $\pm 0.0036 \times m_{b\bar{b}} \mp 0.52 + 1$ $(m_{b\bar{b}} < 275 \text{ GeV}) \mp 0.47 + 1$ $(m_{b\bar{b}} \geq 275 \text{ GeV})$	<code>SstopWtMBB</code>

Table 4.11: Summary of all uncertainties for the single top process with short descriptions and the name of the corresponding nuisance parameters, updated for the winter baseline analysis.

子路曰：衛君待子而為政，子將奚？

子曰：必也正名乎！

Confucius, *The Analects*

5

1067

1068

Object and Event Reconstruction and

1069

Selection

1070 IN BREAKING WITH THE STANDARD CONVENTION both object definitions and their associated

1071 experimental systematic uncertainties will be defined in this chapter: the hope is that the proximity

1072 of these descriptions will allow them to elucidate each other. Summary tables are almost exclusively
1073 taken from [44] or [4]. This analysis, like most analyses in ATLAS, use central object definitions
1074 from collaboration combined performance (CP) groups^{*} using standard analysis tools and recom-
1075 mendations from these groups for the various objects and their accompanying systematic uncertain-
1076 ties.

1077 Before proceeding to the objects used in this analysis, we begin with a few remarks on uncertain-
1078 ties associated with object reconstruction. Event-level variables and selections are discussed more in
1079 depth in Chapters 1 and 6. As described in Section 4.2, systematics quantify the uncertainty asso-
1080 ciated with certain effects, and are generally treated in an analysis by saving histograms of discrimi-
1081 nating distributions corresponding to the nominal analysis except with the systematic in question
1082 varied by plus and minus one standard deviation each (one histogram each). While for modeling
1083 systematics this only corresponds to different event weights, for experimental systematics like those
1084 described in this chapter (with the exception of flavor tagging and certain trigger systematics), this is
1085 done by varying the parameter in question and re-running reconstruction with the systematic varied
1086 before recomputing all event level quantities and then saving discriminant values in their appropri-
1087 ate distributions. This is, in general, a much more computationally intensive process in the analysis,
1088 which is why an entire software framework, the `CxAODFramework`, was created for this analysis (see
1089 Section 3 of [44] for more details).

*Teams of physicists within ATLAS dedicated to studying different aspects of reconstruction general to very many analyses. An example is the ATLAS Muon CP group, whose duties include providing definitions for how muons are reconstructed in ATLAS, different quality requirements and thresholds, and muon related systematic uncertainties, as well as software packages to make these definitions and guidelines easier to implement.

¹⁰⁹⁰ 5.1 TRIGGERS

¹⁰⁹¹ Tables of the triggers used with the 2015 and 2016 datasets are given in Tables 5.1 and 5.2.

o lep	1 lep	2 lep
HLT_xe70	HLT_xe70 HLT_e24_lhmedium_L1EM20VH OR HLT_e60_lhmedium OR HLT_e120_lhloose	HLT_mu20_iloose_L1MU15 OR HLT_mu40 HLT_e24_lhmedium_L1EM20VH OR HLT_e60_lhmedium OR HLT_e120_lhloose

Table 5.1: Summary table of triggers used in 2015 Data.

¹⁰⁹² The o-lepton channel uses a \vec{E}_T^{miss} trigger, while the 2-lepton channel uses single lepton triggers,
¹⁰⁹³ with the 1-lepton analysis using both. Since the o- and 1-lepton channels are largely beyond the scope
¹⁰⁹⁴ of this thesis, the discussion here will be limited to the single lepton triggers; the interested reader is
¹⁰⁹⁵ directed towards [44] and its cited sources for an in-depth discussion of the use of the \vec{E}_T^{miss} trigger.

¹⁰⁹⁶ The efficiency of triggers is in general different on simulated datasets than in actual data collected
¹⁰⁹⁷ in ATLAS, so a scale factor to correct for this difference in efficiency must be applied to simulation
¹⁰⁹⁸ events. This scale factor is given by the muon CP group for muons for both the 1- and 2-lepton cases
¹⁰⁹⁹ and from the electron CP group for the 1-lepton case. For the two electron case, this was calculated
¹¹⁰⁰ by the analysis team as (details in [44]):

$$\frac{1 - (1 - \epsilon_{\text{MC}}^{e1} \times \text{SF}^{e1}) \times (1 - \epsilon_{\text{MC}}^{e2} \times \text{SF}^{e2})}{1 - (1 - \epsilon_{\text{MC}}^{e1}) \times (1 - \epsilon_{\text{MC}}^{e2})} \quad (5.1)$$

¹¹⁰¹ There are also systematic uncertainties associated with these trigger efficiencies. The single elec-
¹¹⁰² tron trigger efficiency systematic uncertainty is encapsulated in a single systematic, `EL_EFF_Trigger_-`

period	o lep	1 lep	2 lep
A	HLT_xe90_mht_L1XE50	HLT_xe90_mht_-L1XE50, HLT_e26_-lhtight_nod0_-ivarloose OR HLT_-e60_lhmedium_nod0 OR HLT_e60_medium OR HLT_e140_-lhloose_nod0	HLT_mu24_-ilosse(data), HLT_-mu24_ilosse_-L1MU15(MC) OR HLT_mu40, HLT_e26_-lhtight_nod0_-ivarloose OR HLT_-e60_lhmedium_nod0 OR HLT_e60_medium OR HLT_e140_-lhloose_nod0
B-D ₃	HLT_xe90_mht_L1XE50	HLT_xe90_mht_-L1XE50, HLT_e26_-lhtight_nod0_-ivarloose OR HLT_-e60_lhmedium_nod0 OR HLT_e60_medium OR HLT_e140_-lhloose_nod0	HLT_mu24_ivarmedium OR HLT_mu50, HLT_-e26_lhtight_nod0_-ivarloose OR HLT_-e60_lhmedium_nod0 OR HLT_e60_medium OR HLT_e140_-lhloose_nod0
D ₄ -E ₃	HLT_xe110_mht_-L1XE50	HLT_xe110_mht_-L1XE50, HLT_e26_-lhtight_nod0_-ivarloose OR HLT_-e60_lhmedium_nod0 OR HLT_e60_medium OR HLT_e140_-lhloose_nod0	HLT_mu24_ivarmedium OR HLT_mu50, HLT_-e26_lhtight_nod0_-ivarloose OR HLT_-e60_lhmedium_nod0 OR HLT_e60_medium OR HLT_e140_-lhloose_nod0
$\geq F_1$	HLT_xe110_mht_-L1XE50	HLT_xe110_mht_-L1XE50, HLT_e26_-lhtight_nod0_-ivarloose OR HLT_-e60_lhmedium_nod0 OR HLT_e60_medium OR HLT_e140_-lhloose_nod0	HLT_mu26_ivarmedium OR HLT_mu50, HLT_-e26_lhtight_nod0_-ivarloose OR HLT_-e60_lhmedium_nod0 OR HLT_e60_medium OR HLT_e140_-lhloose_nod0

Table 5.2: Summary table of triggers used in 2016 Data.

1103 **Total_1NPCOR_PLUS_UNCOR**, while the single muon trigger efficiency has two components, one
1104 each for the sample statistics, **MUON_EFF_TrigStatUncertainty**, and systematic uncertainties
1105 **MUON_EFF_TrigSystUncertainty** associated with that efficiency’s measurement.

1106 While the momentum associated with the lowest un-prescaled single lepton triggers changes de-
1107 pending on data-taking conditions (the numbers associated with the triggers in the tables can be
1108 thought of as nominal p_T values for trigger level objects), the lowest typical value is ~ 25 GeV. In
1109 order to maintain this triggering capability on low p_T muons in the higher luminosity environment
1110 of the Run 3 LHC and beyond, trigger-capable detectors will be installed in upgraded New Small
1111 Wheels (NSW) of the ATLAS muon detector during the Phase I upgrade. Detailed studies in sim-
1112 ulation of the trigger algorithm performance under nominal and misaligned conditions for the Mi-
1113 cromegas detectors to be installed in the NSW may be found in Appendix A.

1114

5.2 ELECTRONS

1115 Electrons in ATLAS are reconstructed using a combination of the ATLAS electromagnetic calorime-
1116 ter (ECAL) and inner detector (ID). Reconstruction begins by searching for so-called “seed clusters”
1117 in the ECAL. The ECAL is divided into a 200×256 tower grid in the $\eta - \phi$ plane, with each tower
1118 having a size of 0.025 square in η and ϕ , corresponding to the granularity of the ECAL in its middle
1119 layer, with all energy in a tower summed longitudinally. A “sliding window” of 3×5 cells in the
1120 $\eta - \phi$ plane is then used to identify EM clusters associated with electrons based on criteria detailed
1121 in [45]. This comparatively simple algorithm (in contrast to jet reconstruction detailed below) is
1122 effective since electromagnetic showers have a well defined behavior and shape.

1123 Once seed clusters have been formed, they are associated with tracks in the inner detector. Com-
 1124 bined cluster-tracks pairs form electron candidates. In order for a electron candidate to be consid-
 1125 ered a suitable electron for analysis, it must pass certain quality requirements, based on a cut on the
 1126 value of a likelihood-based (LH) discriminant (cf. [46] for details). This discriminant is given by:

$$d_{\mathcal{L}} = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B}, \quad \mathcal{L}_S(\vec{x}) = \prod_{i=1}^n P_{s,i}(x_i) \quad (5.2)$$

1127 where the s and S (b and B) subscripts refer to distributions in fiducial signal (background) distri-
 1128 butions in bins of $|\eta|$ and E_T . The $P(x_i)$ are probability distributions functions (pdf)'s for input
 1129 variables. Several sets of input variables exist for increasingly stringent quality requirements on elec-
 1130 trons; this analysis uses Loose LH electrons as the base for electron selection, with the input vari-
 1131 ables relating to leakage into the hadronic calorimeter (HCAL), shower and energy deposits in each
 1132 of the ECAL layers, track quality requirements, TRT hits, and track-cluster matching. This analysis
 1133 adds a LooseTrackOnly isolation requirement (the p_T sum of tracks within a certain $\eta - \phi$ distance
 1134 of the candidate track must be below a certain value), impact parameter significance cuts, and an ex-
 1135 plicit B-layer hit requirement. The ZH -signal electrons must further pass a 27 GeV p_T cut ($1.05 \times$
 1136 $p_T^{trigger}$). These requirements are summarized in Table 5.3.

e Selection	p_T	η	ID	d_0^{sig}	$ \Delta z_0^{BL} \sin \theta $	Isolation
$VH - loose$	>7 GeV	$ \eta < 2.47$	LH Loose + B-layer cut	< 5	< 0.5 mm	LooseTrackOnly
$ZH - signal$	>27 GeV	$ \eta < 2.47$	LH Loose + B-layer cut	< 5	< 0.5 mm	LooseTrackOnly
$WH - signal$	>27 GeV	$ \eta < 2.47$	LH Tight	< 5	< 0.5 mm	FixedCutHighPtCaloOnly

Table 5.3: Electron selection requirements.

1137 5.2.1 ELECTRON SYSTEMATICS

1138 The electron CP group has tabulated standard systematic uncertainties to be associated with the use
1139 of reconstructed electrons in ATLAS analyses in two main categories. The first category is related
1140 to efficiency corrections and is broken into three components: identification (`EL_EFF_ID_Total-`
1141 `CorrUncertainty`), reconstruction (`EL_EFF_Reco_TotalCorrUncertainty`), and isolation
1142 (`EL_EFF_Iso_TotalCorrUncertainty`). The second category deals with electron energy scale
1143 (roughly, the uncertainty in taking the energy deposits in an EM cluster and turning them into an
1144 electron energy) and energy resolution (the width associated with this). This is in practice a very
1145 complicated procedure, with over 60 systematics associated, but this analysis is not at all sensitive
1146 to these effects and so a simplified model of two systematics, `EG_RESOLUTION_ALL` and `EG_SCALE-`
1147 `_ALL`, is used.

1148 5.3 MUONS

1149 This analysis uses the standard CP muon collection in an event, though these muons in ATLAS are
1150 constructed in a variety of ways; for full details see [47] and [48]. Most muons are constructed us-
1151 ing tracks in the chambers of the muon spectrometer (MS), with a variety of algorithms available.
1152 MS tracks are sufficient to reconstruct a muon (a fit on these tracks can be used to point back to an
1153 interaction point for vertex matching, for example) and, in the $|\eta| \in (2.5, 2.7)$ interval where there
1154 is no tracking, these standalone (SA) muons are the default. The most common and robust form
1155 of muon reconstruction combines tracks in the MS with tracks in the ID (more precisely, a global

refit with hits from both subsystems is typically done) to form combined (CB) muons. CB and SA
 muons automatically pass the loose reconstruction requirements for the Loose muons used in this
 analysis. Additionally, since there is a gap in the $|\eta| < 0.1$ range in the MS to make room for cabling
 and other detector services, there are two further muon types used in this range: the segment tagged
 (ST) muons that match ID tracks to segments in the MDT or CSC chambers and the calorimeter
 tagged (CT) muons that match ID tracks to calorimeter clusters consistent with minimum ionizing
 particles (which muons in ATLAS generally are).

Further quality requirements are imposed on Loose muons for the different muon categories
 used in this analysis. Isolation requirements similar to the electrons in corresponding categories are
 imposed, and impact parameter requirements are also imposed. The ZH signal muons also have a
 p_T cut at 27 GeV and a requirement that the muon fall within the $|\eta|$ range of the ID.

μ Selection	p_T	η	ID	d_0^{sig}	$ \Delta z_0^{\text{BL}} \sin \theta $	Isolation
$VH - \text{loose}$	$> 7 \text{ GeV}$	$ \eta < 2.7$	Loose quality	< 3	$< 0.5 \text{ mm}$	LooseTrackOnly
$ZH - \text{signal}$	$> 27 \text{ GeV}$	$ \eta < 2.5$	Loose quality	< 3	$< 0.5 \text{ mm}$	LooseTrackOnly
$WH - \text{signal}$	$> 25 \text{ GeV}$	$ \eta < 2.5$	Medium quality	< 3	$< 0.5 \text{ mm}$	FixedCutHighPtTrackOnly

Table 5.4: Muon selection requirements.

5.3.1 MUON SYSTEMATICS

Similar to the treatment of systematic uncertainties associated with the electrons, muons have CP de-
 fined systematics. The muon momentum scale and resolution systematics are divided into three cat-
 egories associated one for uncertainties related to ID tracks (`MUONS_ID`), one for MS tracks (`MUONS-
 _MS`), one for the overall scale (`MUONS_SCALE`), and two for charge dependent momentum scales

1172 (`MUON_SAGITTA_RHO` and `MUON_SAGITTA_RESBIAS`). The remaining systematics have a STAT and
1173 SYS component corresponding to the sample statistics and systematic uncertainties for their individ-
1174 ual components. Efficiency scale factors use different standard candles in different p_T ranges (J/ψ 's
1175 (Z 's) below (above) 15 GeV), and so these systematics are broken up into two categories (`MUON_EFF-`
1176 `_STAT` and `MUON_EFF_SYS`; `MUON_EFF_STAT_LOWPT` and `MUON_EFF_SYS_LOWPT`). There are also
1177 isolation systematics (`MUON_ISO_STAT`, `MUON_ISO_SYS`) and track to vertex association systematics
1178 (`MUON_TTVA_STAT`, `MUON_TTVA_SYS`).

1179 **5.4 MISSING TRANSVERSE ENERGY**

1180 High precision performance of \vec{E}_T^{miss} is not so crucial to the 2-lepton analysis (though it is very im-
1181 portant to the other channels), so the interested reader is referred to [49]. \vec{E}_T^{miss} in ATLAS is the neg-
1182 ative vectoral sum of physics objects (in this analysis just jets and leptons, though in principle also
1183 including τ 's and γ 's) and a so-called track based soft term (TST). The TST is comprised of valid
1184 ID tracks not associated with any physics objects in an event. These tracks must be associated to an
1185 event's primary vertex, have a $p_T > 0.4$ GeV, and pass other quality requirements.

1186 The \vec{E}_T^{miss} systematic uncertainties relevant to this analysis are related to track based energy scale
1187 and resolutions in both the soft term and in the jets and are: `MET_SoftTrk_ResoPara`, `MET_Soft-`
1188 `Trk_ResoPerp`, `MET_SoftTrk_ScaleDown`, `MET_SoftTrk_ScaleUp`, `MET_JetTrk_Scale-`
1189 `Down`, and `MET_JetTrk_ScaleUp`.

1190 5.5 JETS

1191 Unlike leptons, all analyses considered in this thesis are sensitive to factors regarding jet reconstruc-
1192 tion and associated systematic uncertainties. A general discussion of jets precedes jet reconstruction
1193 in ATLAS and associated systematics relevant to this thesis.

1194 5.5.1 JET ALGORITHMS

1195 The hadronic nature of jets makes jet reconstruction a lot more complicated than electron or photon
1196 reconstruction, where a regular shower shape and track matching (or lack thereof in the case of the
1197 chargeless photon) provide a fairly straightforward and robust approach. The interested reader is
1198 referred to [50] for an excellent survey, from which this discussion is greatly abbreviated.

1199 Looking at an event like the one in Figure 5.1, unambiguous individual jets are particularly easy to
1200 identify, more or less popping out of the $\eta - \phi$ plane plot, but this is not always the case.

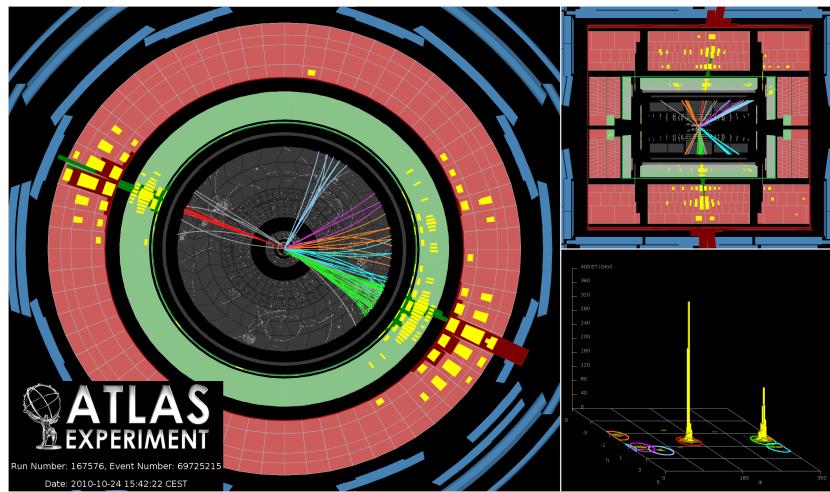


Figure 5.1: A clean ATLAS dijet event.

1201 Two general methods of turning particles/calorimeter towers into jets exist: cone-based and se-
 1202 quential recombination. The general theme of the former is to find a hard (energetic) particle and
 1203 draw a circle around it in the $\eta - \phi$ plane in an intelligent manner, while the theme of the latter
 1204 is to find some metric of distance between particles and then to cluster pairs based on this distance
 1205 into jets in an intelligent way. Cone-based algorithms are simple (and therefore generally quite fast)
 1206 but generally lack some properties of the sequentially recombined jets (though there are notable ex-
 1207 ceptions like SISCone). Cone algorithm reconstructed jets are important for trigger level objects in
 1208 ATLAS, though since no jet triggers are used in this analysis, they will not be discussed any further
 1209 here.

1210 The general drawback of cone-based algorithms is that they are not infrared and collinear (IRC)
 1211 safe. That is, neither the emission of a soft (IR) quark or gluon during hadronization nor the collinear
 1212 splitting of hard particles during hadronization should not change the final jet collection in an event.
 1213 These are fairly common edge cases and can lead to certain pathologies in QCD calculations. In-
 1214frared and collinear safety are diagrammed schematically in Figures 5.2 (a) and (b), taken from [50].

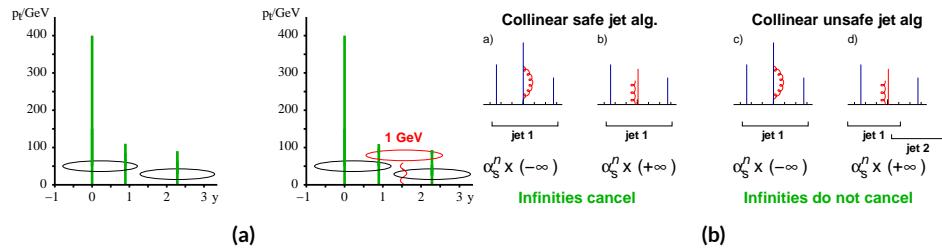


Figure 5.2: Infrared (a) and collinear (b) safety.

1215 Sequential recombination algorithms are generally safe from these effects, as these edge cases are
 1216 very “close” to each other by construction. A sequential recombination algorithm proceeds as fol-

1217 lows

- 1218 1. Evaluate the set of distances d_{ij} (for pairs of objects) and d_{iB} (the “beam distance” for each
1219 individual object)

$$d_{ij} = \min \left(p_{Ti}^{2p}, p_{Tj}^{2p} \right) \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = p_{Ti}^{2p} \quad (5.3)$$

- 1220 2. Find the minimum distance

- 1221 3. If the minimum distance is:

- 1222 • A d_{ij} : cluster these objects together, and go to step 1
- 1223 • A d_{iB} : call the i^{th} object a jet, remove it from the set of objects to be clustered, and go to
1224 step 1

- 1225 4. Repeat until all objects are clustered into jets

1226 The choices one must make in sequential recombination are the size parameter R , akin to a cone
1227 radius in cone-based algorithms, and the momentum power p . Common choices and their trade-offs
1228 are:

- 1229 • + η : the k_t algorithm; favors the softer particles in an event, so the cluster sequence gives a history
1230 of hadronization, but jet shapes are irregular (i.e. not circular in the $\eta - \phi$ plane)
- 1231 • o: the Cambridge-Aachen algorithm: a pure distance metric; less substructure but jets tend to
1232 be more circular
- 1233 • - η : the anti- k_t algorithm: clustering begins with hardest particles in an event; regular, localized
1234 jet shapes, but virtually no substructure in clustering history

1235 Jet reconstruction using all three algorithms on the same event, as well as SISCone, are shown in
1236 Figure 5.3.

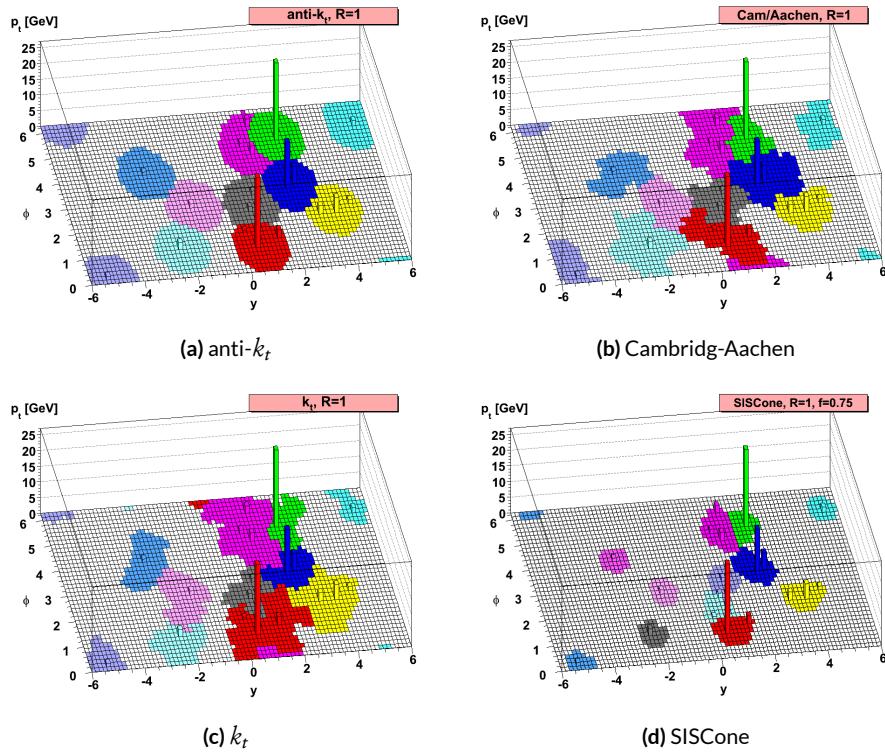


Figure 5.3: Different jet algorithms used on the same event. IC:[50]

1237 All three algorithms have uses for different applications in ATLAS, with anti- k_t $R = 0.4$ jets
1238 being the default jet collection.[†] These are the jets used in this analysis.

1239 If the choice of jet algorithm seems a little arbitrary, it is. There is no one-size-fits-all jet collection
1240 perfect for every application, and analyzers have to make these choices for themselves. One interest-
1241 ing choice is the jet size parameter, R . A large R jet will contain more of the radiation coming from a
1242 final state object, but its large size makes it susceptible to contamination from the underlying event
1243 and pileup (as well as other analysis objects if R is sufficiently large or objects sufficiently boosted),
1244 with small R jets having the opposite features. $R = 0.4$ is a fairly middle-of-the-road choice. A natu-
1245 ral question to ask is whether there needs to be just one jet collection in an analysis. Might there not
1246 be more information to be gained from looking at more jet sizes or clusterings? Preliminary studies
1247 point to this answer being yes and are addressed in Appendix B.

1248 5.5.2 STANDARD ATLAS HBB JETS

1249 There are a few considerations that arise with jets in physical detectors. The first is what type of ob-
1250 ject to use as the stand in for “particles” since ATLAS measures energy deposits, not pions. The ap-
1251 proach ATLAS has settled upon are calorimeter topological clusters (or CaloTopoClusters for short)
1252 [S1]. Unlike the sliding window algorithm used for electron clusters, CaloTopoClusters use a noise
1253 significance based approach in the “4-2-o” algorithm. Each cell in the electromagnetic and hadronic
1254 calorimeters (ECAL and HCAL, respectively) has associated with it a characteristic noise level (N in
1255 Equation 2.6), with this noise level in each channel, it is possible to construct a “significance” for the

[†]The other collections find their primary uses in jet substructure techniques. For an example, cf. the discussion of jet trimming in Appendix B.

registered energy deposit in a given channel for a given event by dividing the measured value by its characteristic noise. Groups of cells having a significance of 4 are taken as the centers of clusters in the $\eta - \phi$ plane. The second layer in a cluster includes all neighboring cells to the central layer with significance of at least 2, and the final layer includes all the nearest neighbors to the second layer.
 This is described in Figure 5.4 from [52].

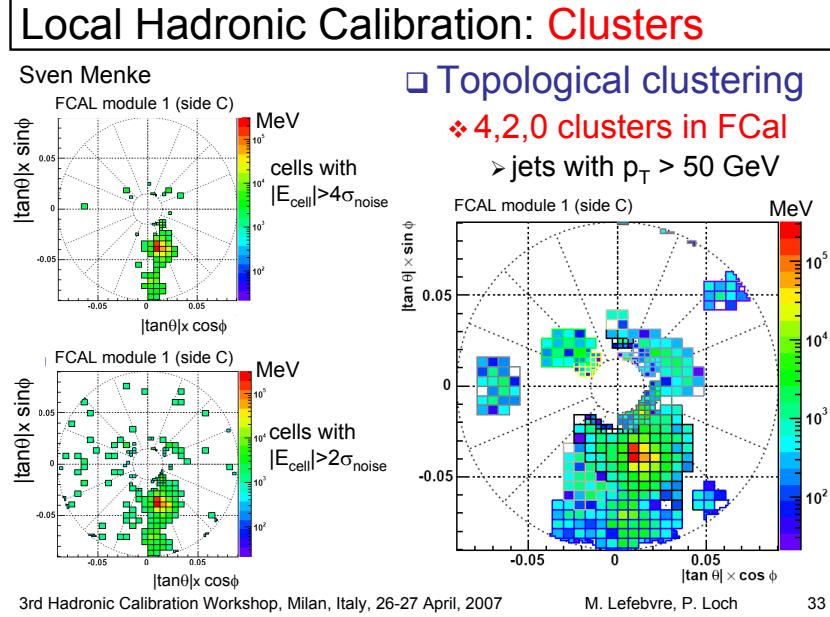


Figure 5.4: A description of the 4-2-0 clustering algorithm.

Once CaloTopoClusters have been formed and clustered into jets, they are calibrated using the electromagnetic (EM) scale (the scale for clusters coming from EM showers). Further details may be found in [53].

Jets in this analysis fall into two categories, “signal” and “forward” jets, and are required to pass certain quality requirements, described in Table 5.5. All jets must pass a series of jet cleaning require-

ments using calorimeter level variables to eliminate jets coming from problematic calorimeter cells
 and certain backgrounds. Some signal jet candidates also make use of a Jet Vertex Tagger (JVT) that
 uses primary vertex and jet and track p_T information to decide whether certain soft jets are likely to
 have come from the the primary (hard scatter) vertex in an event or are to be considered pileup. Fur-
 ther details on JVT may be found in [54]. Jets are further corrected using standard CP tools and a
 dedicated PtReco correction, all outlined in Section 7.3 of [44].

Jet Category	Selection Requirements
Forward Jets	jet cleaning $p_T > 30 \text{ GeV}$ $2.5 \leq \eta < 4.5$
Signal Jets	$p_T > 20 \text{ GeV}$ and $ \eta < 2.5$ jet cleaning $\text{JVT} \geq 0.59$ if ($p_T < 60 \text{ GeV}$ and $ \eta < 2.4$)

Table 5.5: AntiKt4EMTopoJets selection requirements. The jet cleaning is applied via the JetCleaningTool, that removes events in regions corresponding to hot calorimeter cells.

Overlap removal in this analysis is done according to the following precedence, taken from [44]
 with further steps only taken into account if an object survives previous steps:
 • tau-electron: If $\Delta R(\tau, e) < 0.2$, the τ lepton is removed.
 • tau-muon: If $\Delta R(\tau, \mu) < 0.2$, the τ lepton is removed, with the exception that if the τ lepton
 has $p_T > 50 \text{ GeV}$ and the muon is not a combined muon, then the τ lepton is not removed.
 • electron-muon: If a combined muon shares an ID track with an electron, the electron is re-
 moved.
 If a calo-tagged muon shares an ID track with an electron, the muon is removed.

- electron-jet: If $\Delta R(\text{jet}, e) < 0.2$ the jet is removed.
- For any surviving jets, if $\Delta R(\text{jet}, e) < \min(0.4, 0.04 + 10 \text{ GeV}/p_T^e)$, the electron is removed.
- muon-jet If $\Delta R(\text{jet}, \mu) < 0.2$ or the muon ID track is ghost associated to the jet, then the jet is removed if the jet has less than three associated tracks with $p_T > 500 \text{ MeV}$ ($\text{NumTrkPt} < 3$) or both of the following conditions are met: the p_T ratio of the muon and jet is larger than 0.5 ($p_T^\mu/p_T^{\text{jet}} > 0.5$) and the ratio of the muon p_T to the sum of p_T of tracks with $p_T > 500 \text{ MeV}$ associated to the jet is larger than 0.7 ($p_T^{\text{muon}}/\text{SumPtTrkPt} > 0.7$).
- For any surviving jets, if $\Delta R(\text{jet}, \mu) < \min(0.4, 0.04 + 10 \text{ GeV}/p_T^\mu)$, the muon is removed.
- tau-jet: If $\Delta R(\tau, \text{jet}) < 0.2$, the jet is removed.
 - electron-fat jet: If $\Delta R(e, \text{fat jet}) < 1.2$, the fat jet is removed.
- Jets are corrected using a muon-in-jet correction and then a kinematic fitter (Appendix D of [4]) for the 2-lepton case (PtReco correction for the 0- and 1- lepton case). The muon-in-jet correction is designed for b -jets. Since the decay of a b -quark to a c -quark and finally to a light quark (these are the multiple vertices for which JetFitter in Section 5.6.1 searches) involves two weak decays, there are two W -bosons involved in the decay. Some of these will decay semileptonically, and, while electron and τ energy will be captured by the calorimeters, semileptonic μ 's will only be registered in the MS, which occurs in some 44% of all decays from a theoretical standpoint, which amounts to about 12% in practice (due to track isolation requirements for the leptons). This value is about 1–2% for electrons, which deposit their energy in the calorimeter and so require no correction; any jet with a valid lepton associated to it is deemed semileptonic (all others are called hadronic). Any jet with muons associated with it has the closest muon's 4-vector (in the $\eta - \phi$ plane) added to it.

1301 The PtReco correction is a scale factor on the muon-in-jet corrected jet's 4-vector based on the
 1302 jet's p_T and whether the jet is hadronic or semileptonic. This correction factor is based on particle
 1303 level studies done on a TruthWZ sample. As the o- and i-lepton cases are not the focus of this thesis,
 1304 the interested reader is directed to Section 7.3 of [44].

1305 The kinematic fitter used in 2-lepton events with two or three jets takes as its input 12 fit parame-
 1306 ters,

- 1307 • energies of 2 electron or p_T of 2 muons
- 1308 • energies of 2 b -jets
- 1309 • η, ϕ of 2 leptons and 2 jets
- 1310 • p_X and p_Y of $\ell\ell b\bar{b}$ system.
- 1311 • $m_{\ell\ell}$

1312 and 3 constraints for the variation of these parameters,

- 1313 • parameters : Gaussian (b -jet energy : Transfer Functions (TF); these are denoted L , with an
 1314 L_{truth} as a prior) (the ϕ parameters)
- 1315 • p_X and p_Y of $\ell\ell b\bar{b}$ system : zero with a width of 9 GeV obtained from ZH signal MC.
- 1316 • m_{ll} : Breit-Wigner (BW) distribution of Z boson (final term, leptons denoted Ω)

1317 which leads to test statistic from the usual likelihood formalism to be minimized in each event:

$$\begin{aligned}
 -2 \ln \mathcal{L} = & \sum_{i=j} \left(\frac{(\phi_i^n - \phi_i^0)^2}{\sigma_\phi^2} \right) + \left(\frac{(\Omega_l^n - \Omega_l^0)^2}{\sigma_\Omega^2} \right) - 2 \ln(L^j) - 2 \ln(L_{truth}^j) \\
 & + \sum_{i=x,y} \frac{(\sum p_i^n - \sum P_i)^2}{\sigma_{\sum p_i}^2} + 2 \ln((m_{\ell\ell} - M_X^2)^2 + M_X^2 \Gamma^2)
 \end{aligned} \tag{5.4}$$

1318 5.5.3 JET SYSTEMATICS

1319 As with the electron systematics, jet energy scale (JES) and resolution (JER) are the two principal
1320 considerations for systematic uncertainties, with even more standard. JER, as with the electron en-
1321 ergy resolution, is a single systematic uncertainty, `JET_JER_SINGLE_NP`. There is also a single JVT
1322 efficiency `JET_JvtEfficiency` systematic uncertainty. There are 88 nominal JES systematics, and
1323 this analysis is sufficiently sensitive to these variations that a single systematic is grossly insufficient.
1324 Nevertheless, some simplification is possible, with the 75 of these nuisance parameters (mostly statis-
1325 tical uncertainties related to the Z +jet and γ +jet calibrations) being reduced to 8, and several explic-
1326 itly named nuisance parameter. These remaining named NP's are: 3 NP's related to the η intercali-
1327 bration used to extrapolate standard calibrations to other jet η regions, 4 NP's related to the flavor
1328 composition of principle background samples (W/Z +jets, top, and diboson), 4 pileup systematics, a
1329 single NP for the b -jet energy scale, a high p_T jet energy scale systematic, and one for jets that punch
1330 through the HCAL to leave energy deposits in the MS. These are listed explicitly in Table 5.7.

1331 5.6 FLAVOR TAGGING

1332 Given that the final state in this analysis involves pairs of jets originating from b -quarks, deploying
1333 effective flavor tagging algorithms is imperative. While flavor tagging in general can be used to isolate
1334 any flavor (b , c , or light (u , d , s , or gluon-initiated jets)), this analysis exclusively looks for b -jets, so
1335 this disucssion will focus on b 's. At truth-level in sumlation, this is fairly straightforward: one need
1336 only look at the particles contained within a jet and seeing if any include a b -quark (sometimes a B

₁₃₃₇ hadron) in the decay chain.

₁₃₃₈ **5.6.1 DIRECT TAGGING**

₁₃₃₉ One of the most distinctive features of b -jets is the presence of secondary vertices, as illustrated in Fig-
₁₃₄₀ ure 5.5. While most partons created in particle collisions will hadronize promptly, b -quarks will first
₁₃₄₁ hadronize into B -hadrons, which have lifetimes of about a picosecond. This small but finite lifetime
₁₃₄₂ means that these particles will travel about half a millimeter or so before decaying into a jet in much
₁₃₄₃ the usual way, and the tracks from this decay will point back to this displaced, secondary vertex.

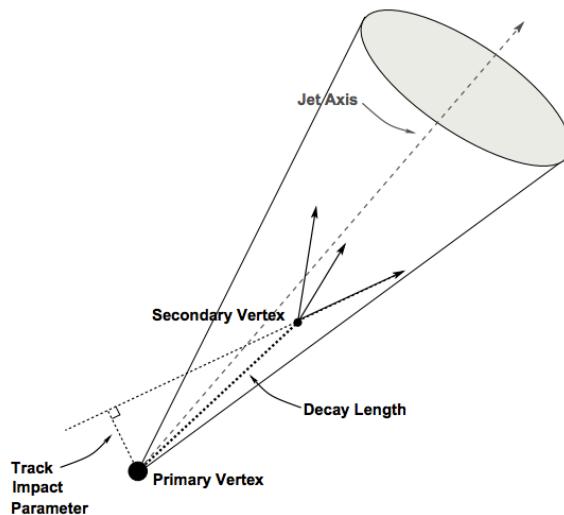


Figure 5.5: An illustration of a secondary vertex in a b -jet. Image credit: [55]

₁₃₄₄ There are various secondary vertex algorithms used as inputs to the nominal b -tagging algorithm
₁₃₄₅ [56], with three main types of algorithms used as inputs

- ₁₃₄₆ 1. Track impact parameter based algorithms: I₂PD (signed transverse only; more pileup ro-
₁₃₄₇ bust), I₃PD (signed transverse and longitudinal)

- 1348 2. Inclusive secondary vertex reconstruction: SV1 (start with two track vertex pairs and con-
 1349 struct a secondary vertex)
- 1350 3. Multiple vertex reconstruction (decay chain): JetFitter ($PV \rightarrow b \rightarrow c$ decay chain using Kalman
 1351 filter)
- 1352 All of these are combined into a boosted decision tree (BDT) and trained on five million $t\bar{t}$ events
 1353 with an 90%/10% light/ c jet background to form the MV2c10 algorithm, with 10 referring to the per-
 1354 centage of charm events in the training background. The 10% charm ratio was found to be a good
 1355 balance between increased charm rejection capability (as opposed to MV2c00, which has no charm
 1356 in the background training samples) and loss in light jet rejection (compared to MV2c20, which has
 1357 20% charm events in background training samples).

1358 ANALYSIS SPECIFIC CONCERNS AND SYSTEMATIC UNCERTAINTIES In addition to specifying
 1359 the tagging algorithm, the working point efficiency must be specified. As with selection algorithms
 1360 in general, there is a trade off between efficiency/recall (identifying all the b -jets, minimizing type
 1361 II error) and purity/precision (making sure all jets positively identified are in fact b -jets, minimiz-
 1362 ing type I error). Nominal efficiency working points have been calibrated by the flavor tagging CP
 1363 group and are outlined in Table 5.6.

name	MV2c10 weight cut	b -tag eff, [%]	c RR	light RR
FixedCutBEff_60	0.9349	60.03	34.54	1538.78
FixedCutBEff_70	0.8244	69.97	12.17	381.32
FixedCutBEff_77	0.6459	76.97	6.21	134.34
FixedCutBEff_85	0.1758	84.95	3.10	33.53

Table 5.6: b -tagging working points available for MV2c10 for AntiKt4EMTopoJets. RR is the rejection rate (the inverse of efficiency).

1364 These values are aggregate figures, as both the jet's p_T and η are inputs to the MV2c10 discrim-
1365 inant. The working point chosen for this analysis is the 70% `FixedCutBEff_70` working point,
1366 with "fixed cut" referring to the fact that this particular usage of the MV2c10 BDT value is a simple
1367 cut value.

1368 Just as with the trigger and lepton identification efficiencies, flavor tagging efficiencies differ from
1369 their nominal values somewhat depending on what simulation or data sample is being used. To
1370 account for this difference, just as in the other cases, scale factors are applied to simulation event
1371 weights. It is through these event weights, as with the modeling systematics, that the flavor tagging
1372 systematic uncertainties are applied. Given that there are 24 input variables to MV2c10 and that
1373 flavor tagging is in general a very difficult problem, it is not surprising that, as with the JES, there
1374 are very many systematic uncertainties associated with flavor tagging. However, as with JES, the
1375 CP group has compacted the full systematic set into a reduced set of 13 systematic uncertainties: 3
1376 each associated with c and light jets, 5 for b -jets (with the naming convention `FT_EFF_Eigen_-`
1377 ($B|C|Light$) N), one for the extrapolation of scale factors to different jet p_T regimes (`FT_EFF_-`
1378 `Eigen_extrapolation`), and one for the charm to bottom extrapolation (`FT_EFF_Eigen_-`
1379 `extrapolation_from_charm`) [57]. This schematic is a middle-of-the-road "Medium" set of sys-
1380 tematics.

1381 5.6.2 TRUTH TAGGING

1382 Since imposing a 2 b -tag requirement overwhelmingly rejects events dominated by c - and light jets,
1383 statistics in such MC samples are very low. In order to circumvent this problem and restore full MC

1384 statistics, the tag rate function, or “truth-tagging” procedure (in contrast to the standard or “direct
1385 tagging” procedure) is applied, in which all events are kept but given a weight that preserves the over-
1386 all shape and normalization of underlying distributions. Intuitively, this is done by giving events with
1387 real b -jets in MC a much higher weight than events having only c - or light jets. Truth-tagging is ap-
1388 plied to all samples when conducting MVA training in order to maximize statistics and reduce the
1389 risk of overtraining. Truth-tagging is also used for data-MC comparison plots in 2-tag regions and
1390 for $V + cc$, $V + c\ell$, $V + \ell$, and WW samples used in the final likelihood fit. A detailed description of
1391 the truth-tagging process is provided below.

1392 Each jet in a given event has associated with it a b -tagging efficiency, denoted ε , that is a function
1393 of its p_T , η , and real flavor (b , c , or light) from truth-level information in MC. Intuitively, this effi-
1394 ciency can be thought of as the likelihood that a given jet will be b -tagged. Hence, b -jets have a much
1395 higher b -tagging efficiency than c -jets, which in turn have a higher b -tagging efficiency than light jets.
1396 We define a truth-tag weight for a given combination of tagged and untagged jets as the product of
1397 the efficiencies of the tagged jets times the product of the complement of the efficiencies of the un-
1398 tagged jets. For example, for an event with three jets, labeled 1, 2, and 3, if jets 1 and 2 are tagged, and
1399 jet 3 is untagged, the truth-tag weight associated with this combination is

$$\varepsilon_1 \varepsilon_2 (1 - \varepsilon_3) \quad (5.5)$$

1400 In order to obtain a truth-tag weight for an event, one takes the sum of the weights for each pos-
1401 sible tag combination. The current analysis requires that all events have exactly two b -tagged jets, so

1402 the truth-tag weight is the sum of all the weights of all possible pairs of tagged jets (events with fewer
 1403 than two jets are discarded). Going back to the three jet example, one has the possible combinations:
 1404 jets 1+2 as tagged and jet 3 as untagged; jets 1+3 as tagged and jet 2 as untagged; and finally jets 2+3 as
 1405 tagged and jet 1 as untagged, which yields a total event weight of

$$w_{tot} = \varepsilon_1 \varepsilon_2 (1 - \varepsilon_3) + \varepsilon_1 \varepsilon_3 (1 - \varepsilon_2) + \varepsilon_2 \varepsilon_3 (1 - \varepsilon_1) \quad (5.6)$$

1406 For some applications (e.g. in order to use variables like pTB1, the p_T of the harder b -tagged jet in
 1407 an event, in MVA training), it is necessary to choose a combination of jets in an event as “tagged.”
 1408 This combination is chosen randomly, with the probability for a given combination to be chosen
 1409 being proportional to its truth-tag weight. In the three jet example, the probability of tagging jets
 1410 1+2 is:

$$\frac{\varepsilon_1 \varepsilon_2 (1 - \varepsilon_3)}{w_{tot}} = \frac{\varepsilon_1 \varepsilon_2 (1 - \varepsilon_3)}{\varepsilon_1 \varepsilon_2 (1 - \varepsilon_3) + \varepsilon_1 \varepsilon_3 (1 - \varepsilon_2) + \varepsilon_2 \varepsilon_3 (1 - \varepsilon_1)} \quad (5.7)$$

1411 Though not used in the current analysis, functionality exists for generic truth-tagging require-
 1412 ments (i.e. an arbitrary number of tags on an arbitrary number of jets) through the logical combina-
 1413 toric extension and for so-called “pseudo-continuous tagging,” where a b -tag score is generated for
 1414 each jet in a given event. Since a random combination of jets is set by hand to pass the b -tagging cuts
 1415 regardless of its b -tag score, a new score must be generated if this information is to be used in further
 1416 analysis. Under current settings, jets that are tagged are assigned a random b -tag score that is sampled
 1417 from the MV2c10 cumulative distribution above the 70% efficiency working point cut. All other

¹⁴¹⁸ jets in the event are assigned a random b -tag score below the 70% working point cut. Since these dis-
¹⁴¹⁹ tributions are discrete, the scores are not truly continuous (cf. example distributions in Figure 5.6), hence the “pseudo-continuous” nomenclature.

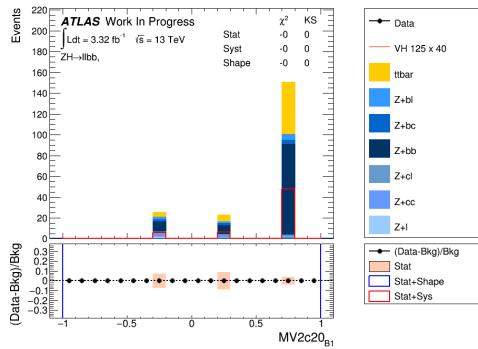


Figure 5.6: An example of a pseudo-continuous b -tagging distribution

¹⁴²⁰

¹⁴²¹ A number of closure tests were performed on both the nominal and several systematics cases. In
¹⁴²² the plots that follow, truth (solid) and direct (dashed) tagging distributions for m_{bb} and $\Delta R(b_1, b_2)$
¹⁴²³ in different p_T^V regimes for 2 lepton, 2 jet events. Agreement between the truth and direct tagging
¹⁴²⁴ cases is generally very good, an example of which can be seen in Figure 5.7 for a signal qqZllH125
¹⁴²⁵ sample, and the overall benefit of truth-tagging can be somewhat dramatically seen in the corre-
¹⁴²⁶ sponding plots $Z + \ell$ samples in Figure 5.8. At high p_T^V ($p_T^V > 200$ GeV), however, in events with two
¹⁴²⁷ real b -jets, there is a much greater likelihood that the b -jets will merge into a single jet, which render
¹⁴²⁸ the naïve assumption that jets remain discrete invalid. While this does not appear to be a problem in
¹⁴²⁹ most samples (cf. $t\bar{t}$ in Figure 5.9), there is a mismodelling effect at low m_{bb} and low $\Delta R(b_1, b_2)$ at
¹⁴³⁰ $p_T^V > 200$ GeV for $W/Z + bb$ samples where truth-tagging overestimates the number of events in
¹⁴³¹ this merged regime, as can be seen in Figure 5.10

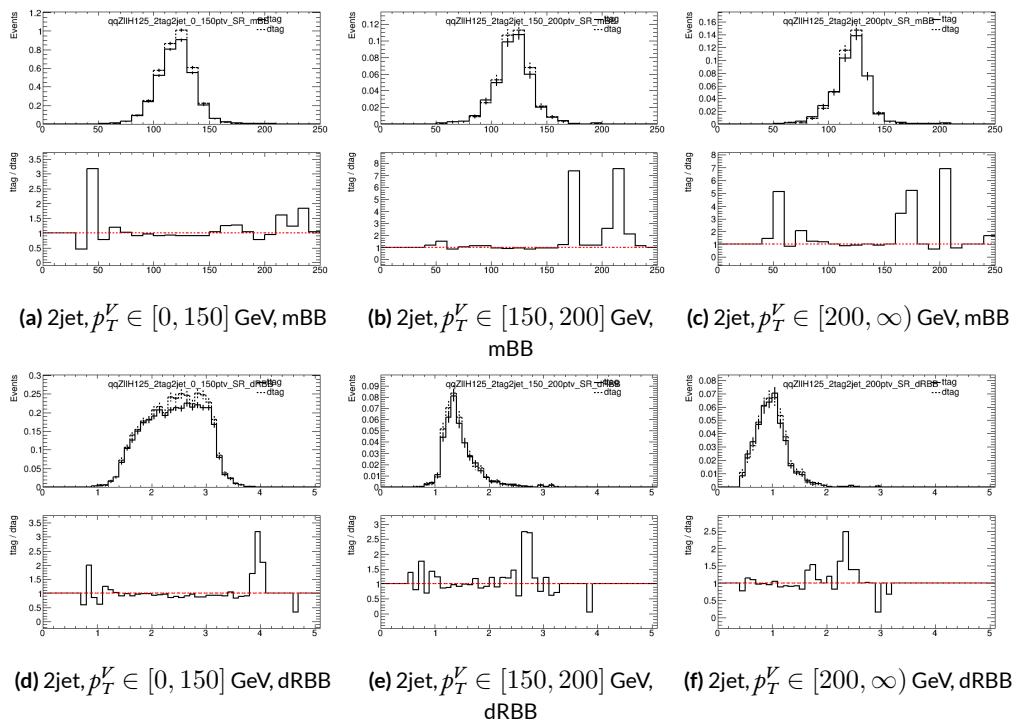


Figure 5.7: Truth-tagging closure tests for 2 lepton, 2 jet qqZIIH125 samples in three different p_T^V regions.

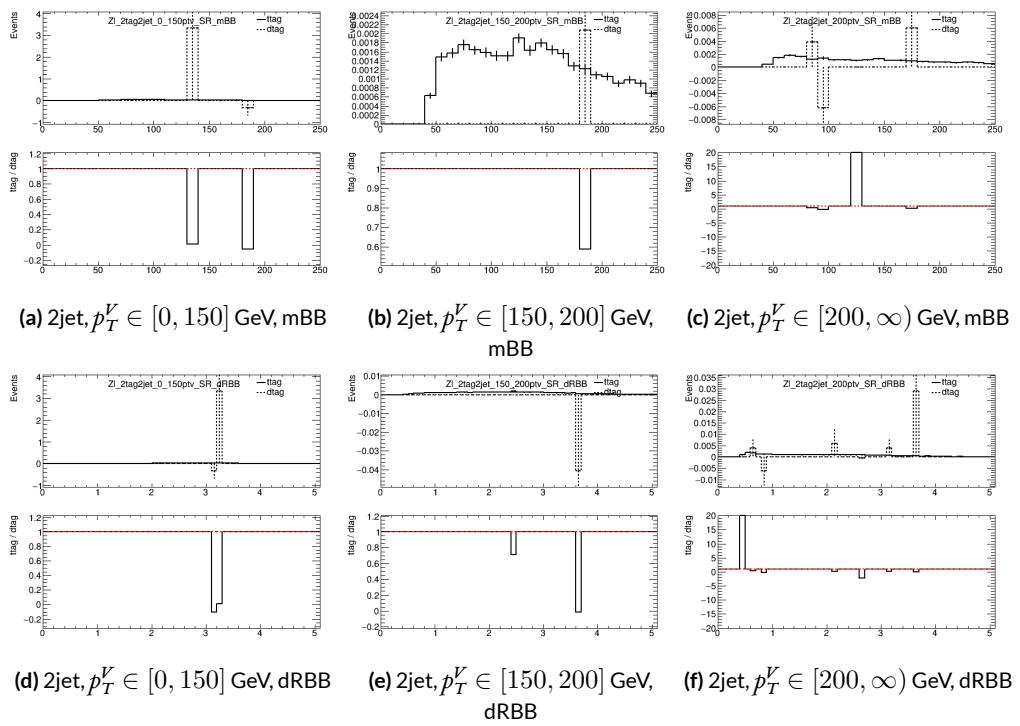


Figure 5.8: Truth-tagging closure tests for 2 lepton, 2 jet $Z + \ell$ samples in three different p_T^V regions.

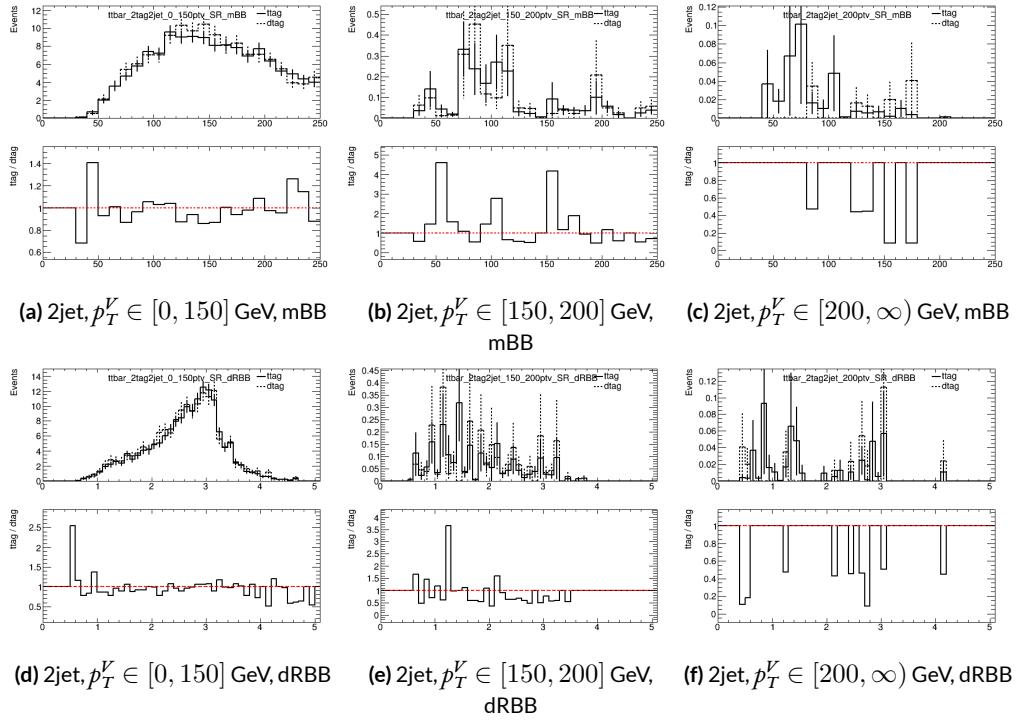


Figure 5.9: Truth-tagging closure tests for 2 lepton, 2 jet $t\bar{t}$ samples in three different p_T^V regions.

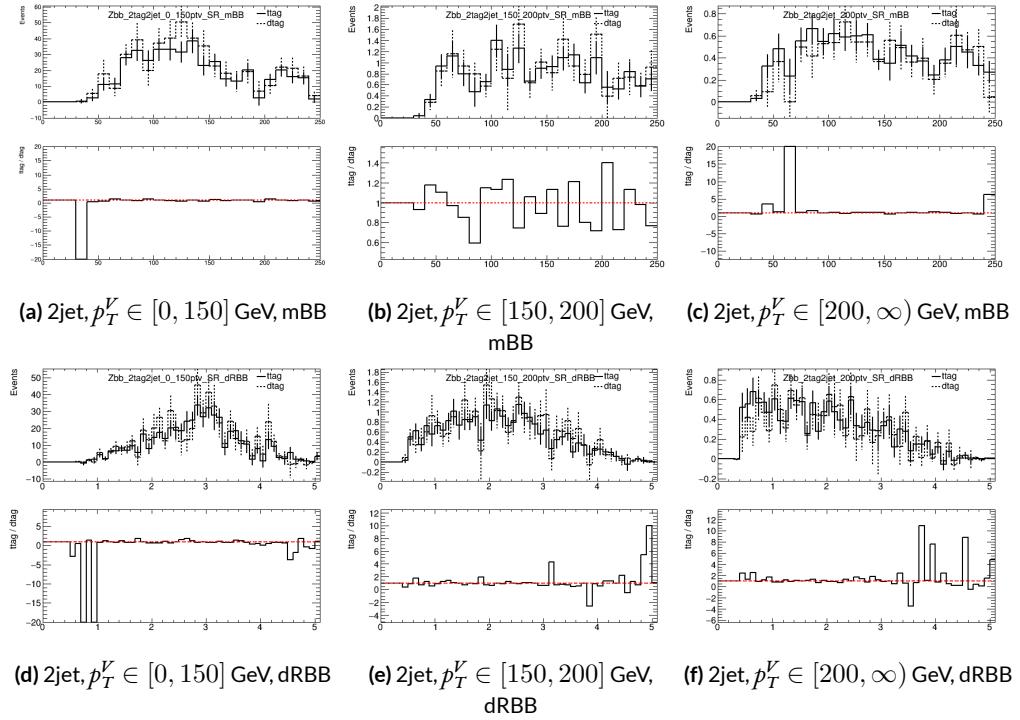


Figure 5.10: Truth-tagging closure tests for 2 lepton, 2 jet $Z + bb$ samples in three different p_T^V regions.

1432 5.7 MISCELLANIA AND SYSTEMATICS SUMMARY

1433 A summary of all experimental systematics, taken from [4], may be found below. In addition to the
1434 systematics discussed above, there are also two further systematics, on the total integrated luminosity
1435 and on the event reweighting factor used to account for pileup, both included in Table 5.7.

1436 5.8 EVENT SELECTION AND ANALYSIS REGIONS

1437 With object and event reconstruction described, it is now time to address which events are actually
1438 selected for use in analysis. This analysis focuses specifically on the 2-lepton channel of the fiducial
1439 analysis, with the event selection and analysis region definitions being identical. Common to all
1440 lepton channels in the fiducial analysis is the set of requirements on the jets in a given event. There
1441 must be at least two central jets and exactly two signal jets that have been “*b*-tagged” according to the
1442 MV2c10 algorithm [56], with at least one of these *b*-jets having $p_T > 45$ GeV. For MVA training and
1443 certain background samples, a process known as “truth-tagging” is applied instead of the standard
1444 *b*-tagging to boost sample statistics and stabilize training/fits (cf. [4] Section 4.2 for details). After
1445 event selection, the *muon-in-jet* and *PtReco* corrections, described in [44] 6.3.3-4, are applied to the
1446 *b*-jets.

1447 In addition to the common selections, there are 2-lepton specific selections. All events are re-
1448 quired to pass an un-prescaled single lepton trigger, a full list of which may be found in Tables 5 and
1449 6 of [44] with the requirement that one of the two selected leptons in the event must have fired the
1450 trigger. There must be 2 VH-loose leptons, and at least one of these must be a ZH-signal lepton (cf.

Systematic uncertainty	Short description	Reference
Luminosity	uncertainty on total integrated luminosity	Section 11.1 in Ref. [44]
Pileup Reweighting	uncertainty on pileup reweighting	Section 11.1 in Ref. [44]
	Electrons	
EL_EFF_Trigger_Total_1NPCOR_PLUS_UNCOR	trigger efficiency uncertainty	Section 11.2.2. in Ref. [44]
EL_EFF_Reco_Total_1NPCOR_PLUS_UNCOR	reconstruction efficiency uncertainty	Section 11.3.1. in Ref. [44]
EL_EFF_ID_Total_1NPCOR_PLUS_UNCOR	ID efficiency uncertainty	Section 11.3.1. in Ref. [44]
EL_EFF_Iso_Total_1NPCOR_PLUS_UNCOR	isolation efficiency uncertainty	Section 11.3.1. in Ref. [44]
EG_SCALE_ALL	energy scale uncertainty	Section 11.3.2. in Ref. [44]
EG_RESOLUTION_ALL	energy resolution uncertainty	Section 11.3.2. in Ref. [44]
	Muons	
MUON_EFF_TrigStatUncertainty	trigger efficiency uncertainty	Section 11.2.2. in Ref. [44]
MUON_EFF_TrigSystUncertainty	reconstruction and ID efficiency uncertainty for muons with $p_T > 15$ GeV	Section 11.4.1. in Ref. [44]
MUON_EFF_STAT	reconstruction and ID efficiency uncertainty for muons with $p_T < 15$ GeV	Section 11.4.1. in Ref. [44]
MUON_EFF_SYS	isolation efficiency uncertainty	Section 11.4.1. in [44]
MUON_EFF_STAT_LOWPT	track-to-vertex association efficiency uncertainty	Section 11.4.1. in Ref. [44]
MUON_EFF_SYST_LOWPT	momentum resolution uncertainty from inner detector	Section 11.4.2. in Ref. [44]
MUON_ISO_STAT	momentum resolution uncertainty from muon system	Section 11.4.2. in Ref. [44]
MUON_ISO_SYS	momentum scale uncertainty	Section 11.4.2. in Ref. [44]
MUON_TTVA_STAT	charge dependent momentum scale uncertainty	Section 11.4.2 in Ref. [44]
MUON_TTVA_SYS		
MUON_ID		
MUON_MS		
MUON_SCALE		
MUON_SAGITTA_RHO		
MUON_SAGITTA_RESBIAS		
	Jets	
JET_21NP_JET_EffectiveNP_1	energy scale uncertainty from the in situ analyses splits into 8 components	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EffectiveNP_2	energy scale uncertainty from the in situ analyses splits into 8 components	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EffectiveNP_3	energy scale uncertainty from the in situ analyses splits into 8 components	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EffectiveNP_4	energy scale uncertainty from the in situ analyses splits into 8 components	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EffectiveNP_5	energy scale uncertainty from the in situ analyses splits into 8 components	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EffectiveNP_6	energy scale uncertainty from the in situ analyses splits into 8 components	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EffectiveNP_7	energy scale uncertainty from the in situ analyses splits into 8 components	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EffectiveNP_8restTerm	energy scale uncertainty from the in situ analyses splits into 8 components	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EtaIntercalibration_Modeling	energy scale uncertainty on eta-intercalibration (modeling)	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EtaIntercalibration_TotalStat	energy scale uncertainty on eta-intercalibrations (statistics/method)	Section 11.5.1. in Ref. [44]
JET_21NP_JET_EtaIntercalibration_NonClosure	energy scale uncertainty on eta-intercalibrations (non-closure)	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Pileup_OffsetMu	energy scale uncertainty on pile-up (mu dependent)	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Pileup_OffsetNPV	energy scale uncertainty on pile-up (NPV dependent)	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Pileup_PtTerm	energy scale uncertainty on pile-up (pt term)	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Pileup_RhoTopology	energy scale uncertainty on pile-up (density ρ)	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Flavor_Composition_Zjets	energy scale uncertainty on $Z+jets$ sample's flavour composition	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Flavor_Composition_Wjets	energy scale uncertainty on $W+jets$ sample's flavour composition	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Flavor_Composition_top	energy scale uncertainty on top sample's flavour composition	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Flavor_Composition	energy scale uncertainty on VV and VH sample's flavour composition	Section 11.5.1. in Ref. [44]
JET_21NP_JET_Flavor_Response	energy scale uncertainty on samples' flavour response	Section 11.5.1. in Ref. [44]
JET_21NP_JET_BJES_Response	energy scale uncertainty on b-jets	Section 11.5.1. in Ref. [44]
JET_21NP_JET_PunchThrough_MC15	energy scale uncertainty for punch-through jets	Section 11.5.1. in Ref. [44]
JET_21NP_JET_SingleParticle_HighPt	energy scale uncertainty from the behaviour of high- p_T jets	Section 11.5.1. in Ref. [44]
JET_JER_SINGLE_NP	energy resolution uncertainty	Section 11.5.1. in Ref. [44]
JET_JvtEfficiency	JVT efficiency uncertainty	Section 11.5.1. in Ref. [44]
FT_EFF_Eigen_B	b -tagging efficiency uncertainties (“BTAG_MEDIUM”): 3 components for b jets, 3 for c jets and 5 for light jets	Section 11.7. in Ref. [44]
FT_EFF_Eigen_C		
FT_EFF_Eigen_L		
FT_EFF_Eigen_extrapolation	b -tagging efficiency uncertainty on the extrapolation to high- p_T jets	Section 11.7. in Ref. [44]
FT_EFF_Eigen_extrapolation_from_charm	b -tagging efficiency uncertainty on tau jets	Section 11.7. in Ref. [44]
	MET	
METTrigStat	trigger efficiency uncertainty	Section 11.2.1. in Ref. [44]
METTrigTop/Z	track-based soft term related longitudinal resolution uncertainty	Section 11.6. in Ref. [44]
MET_SoftTrk_ResoPara	track-based soft term related transverse resolution uncertainty	Section 11.6. in Ref. [44]
MET_SoftTrk_ResoPerp	track-based soft term related longitudinal scale uncertainty	Section 11.6. in Ref. [44]
MET_SoftTrk_Scale	track MET scale uncertainty due to tracks in jets	Section 11.6. in Ref. [44]

Table 5.7: Summary of the experimental systematic uncertainties considered. Details on the individual systematic uncertainties can be found in the given Sections of Ref. [44].

1451 Tables 5.3 and 5.4 for definitions). This lepton pair must have an invariant mass between 81 and 101
 1452 GeV. In addition to the jet corrections described above, a kinematic fitter is applied to the leptons
 1453 and two leading corrected jets in an event with three or fewer jets[‡] to take advantage of the fact that
 1454 the 2-lepton final state is closed (cf. [20]); these objects are only used for MVA training/fit inputs.

1455 In order to increase analysis sensitivity, the analysis is split into orthogonal regions based on the
 1456 number of jets and the transverse momentum of the Z candidate (the vectoral sum of the lepton
 1457 pair; this p_T is denoted p_T^V): 2 and ≥ 3 jets; p_T^V in $[75, 150), [150, \infty)$ GeV. In addition to the signal
 1458 regions where the leptons are required to be the same flavor (e or μ), there are top $e - \mu$ control
 1459 regions used to constrain the top backgrounds.

1460 All of these requirements are summarized in 5.8.

Category	Requirement
Trigger	un-prescaled, single lepton
Jets	≥ 2 central jets; 2 b -tagged signal jets, harder jet with $p_T > 45$ GeV
Leptons	2 VH-loose leptons (≥ 1 ZH-signal lepton); same (opp) flavor for SR (CR)
$m_{\ell\ell}$	$m_{\ell\ell} \in (81, 101)$ GeV
p_T^V regions (GeV)	$[75, 150), [150, \infty)$

Table 5.8: Event selection requirements

1461 It should be noted that the use of ≥ 3 jet events is a 2-lepton specific selection. These regions are
 1462 exclusive 3 jet regions in the 0- and 1-lepton channels, but the fiducial 2-lepton analysis was found to
 1463 see a $\sim 4\%$ gain in sensitivity in studies by including ≥ 4 jet events [4].

[‡]The gain from using the kinematic fitter is found to be smeared out in events with higher jet multiplicities.

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偏に風の前の塵に同じ。

Heike monogatari

6

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1465

Multivariate Analysis Configuration

1466 IN ORDER TO fully leverage the descriptive power of the 13 TeV dataset, this analysis makes use of a
1467 multivariate (MVA) discriminant. Where traditionally event counts or single discriminating vari-
1468 ables per region of phase space have been fed to fits, MVA discriminants seek to integrate additional
1469 information not captured in the conventional phase space cuts plus dijet invariant mass distribu-

1470 tions. Formulating the MVA discriminant is an exercise in supervised learning to construct a binary
1471 classifier, where one uses labeled “signal” and “background” MC events to optimize the parameters
1472 of a statistical model—in this case a boosted decision tree (BDT) with some set of physically moti-
1473 vated variables (or “factors”). The interested reader is directed to the standard references on machine
1474 learning for further details. Sample and variable selection, including variables derived using the the
1475 RestFrames and Lorentz Invariants concepts introduced in Sections 1.5–1.7, are discussed in Section
1476 6.1; MVA training is treated in Section 6.2; and the data statistics only (no systematics) performance
1477 of the three MVA discriminants is explored in Section 6.3.

1478 6.1 TRAINING SAMPLES AND VARIABLE SELECTION

1479 A subset of samples described in Chapter 3 is used for multivariate analysis training, with $qqZH \rightarrow$
1480 $\ell\ell b\bar{b}$ and $ggZH \rightarrow \ell\ell b\bar{b}$ used as signal samples and $Z+jets$, $t\bar{t}$, and VV used as background samples.
1481 Truth-tagging (Section 5.6.2) is used on all samples in MVA training to improve training statistics
1482 and stability. All figures quoted in this section scale distributions to a luminosity of 36.1 fb^{-1} .

1483 6.1.1 STANDARD VARIABLES

1484 The standard set of variables taken as a baseline is the same as used in the fiducial analysis. The vari-
1485 ables fall into several main categories: energy/momenta scales of composite objects (m_{bb} , m_{bbj} ,
1486 p_T^V , $m_{\ell\ell}$), angles ($\Delta R(b_1, b_2)$, $\Delta\phi(V, H)$, $\Delta\eta(V, H)$), transverse momenta of the jets in the event
1487 ($p_T^{b_1}$, $p_T^{b_2}$, $p_T^{j_3}$), and E_T^{miss} . Input distributions for these variables in all the 2 (≥ 3 jet) analysis signal
1488 regions may be found in Figure 6.1 (6.2). The “kf” at the end of variable names denotes that these

are derived using 4-vectors that are the result of the kinematic fitter. The distributions in the figure

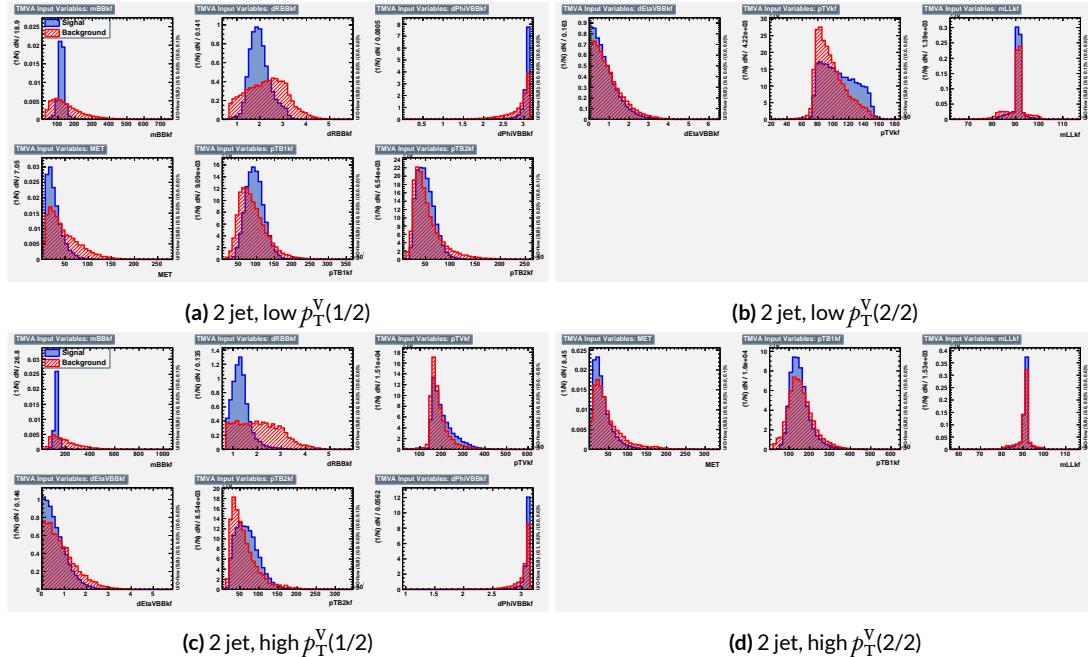


Figure 6.1: Input variables in 2 jet signal regions for the standard variable set. Signal distributions are in red, and background distributions are in blue.

1489

1490 are used as inputs for one of the two k-folded final discriminants, and the order of the distributions
 1491 is the hyperparameter optimized order for feeding into the BDT; what precisely this means will be
 1492 discussed in following sections. While variables in the analysis regions are generally similar, there are
 1493 some notable exceptions. p_T^V and the correlated $\Delta R(b_1, b_2)$ have different shapes, by construction
 1494 for the former and by correlation for the latter, at low and high p_T^V . * The ≥ 3 jet regions also have
 1495 variables that are not applicable to the 2 jet regions; the inclusion of m_{BBJ} (the invariant mass of the
 1496 two b -jets and leading untagged jet) in particular is of note and suggests a potential avenue forward

*Recall that higher p_T^V means, in a balanced final state like $ZH \rightarrow \ell\ell b\bar{b}$, the b -jet pair will have higher p_T and hence be more collimated (lower $\Delta R(b_1, b_2)$); this is not necessarily the case for background events, as the distributions show.

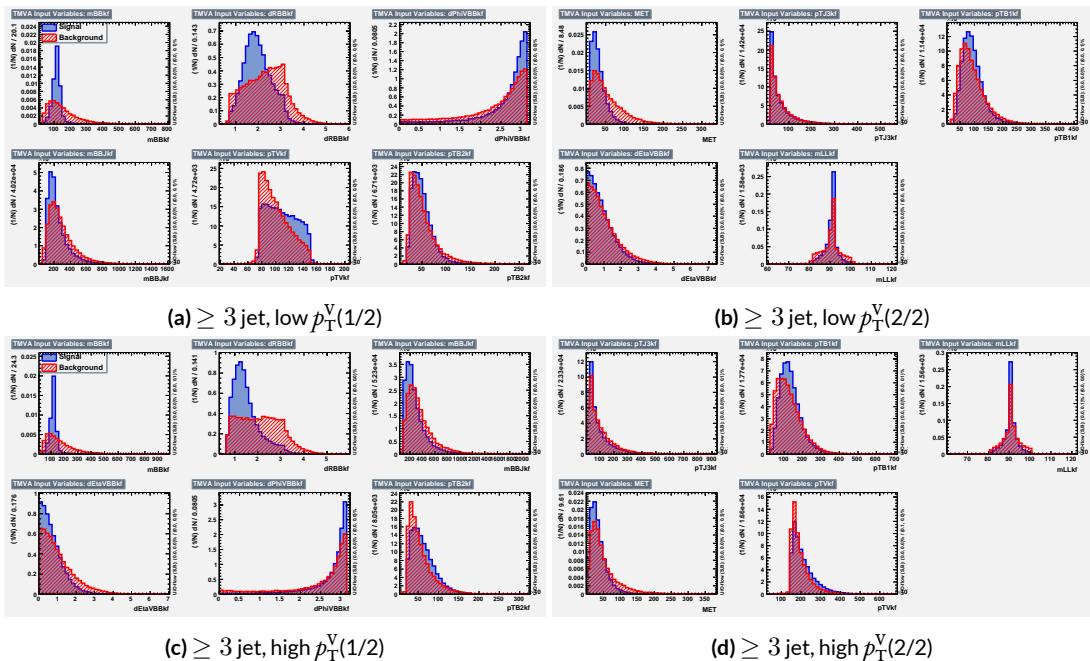


Figure 6.2: Input variables in ≥ 3 jet signal regions for the standard variable set. Signal distributions are in red, and background distributions are in blue.

¹⁴⁹⁷ for refinements of the non-standard variables.

1498 Looking at the correlation matrices for the standard variables in Figure 6.3, it is easy to see that

there are large number of non-trivial correlations

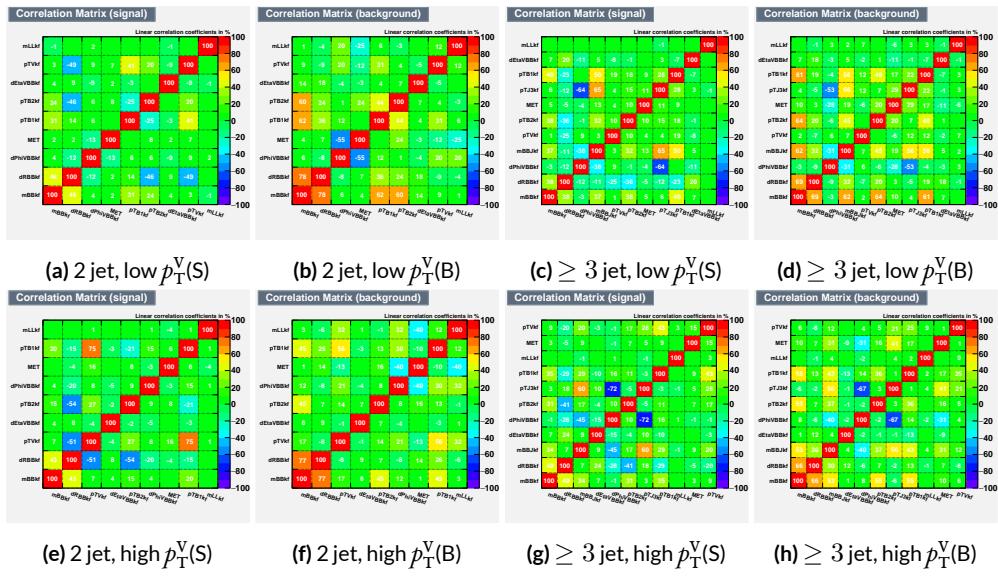


Figure 6.3: Signal and background variable correlations for the standard variable set.

1499

1500 6.1.2 LORENTZ INVARIANTS

1501 In choosing the set of variables used for a set of Lorentz Invariants based discriminants, we decided
 1502 to use S. Hagebeck's set from [7] and related studies. Distributions of these variables in the same
 arrangement as with the standard variables may be seen in Figures 6.4 and 6.5. One thing to note

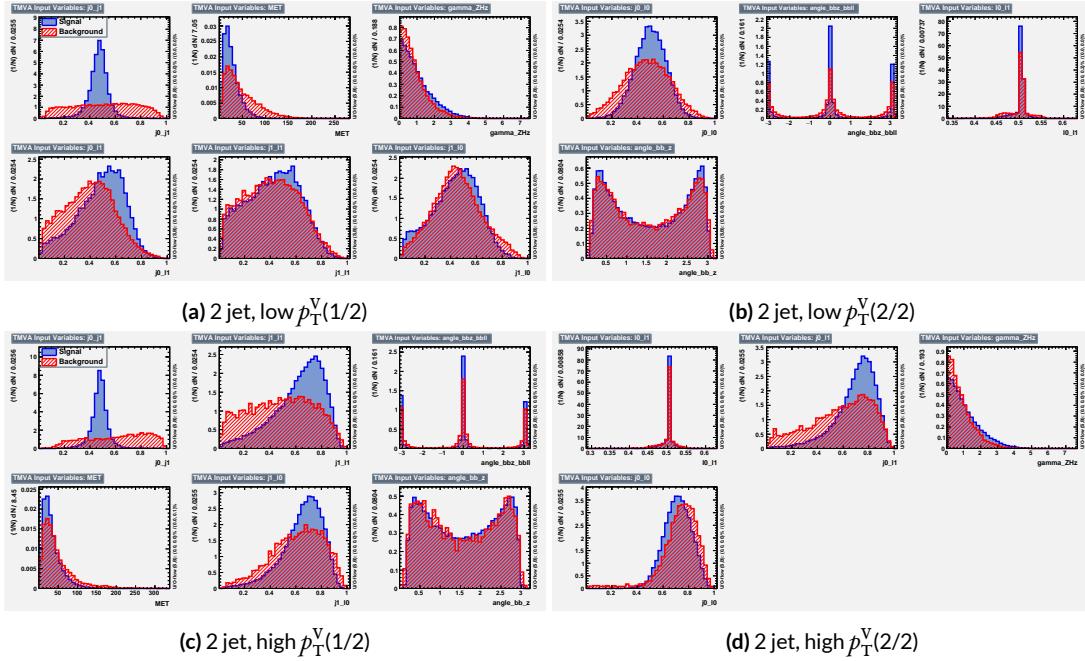


Figure 6.4: Input variables in 2 jet signal regions for the LI variable set. Signal distributions are in red, and background distributions are in blue.

1503

1504 about the variable set chosen here is that \vec{E}_T^{miss} has been added to the standard LI set. Since the LI
 1505 construction assumes that this quantity is zero, there is no obvious way to include it. Nevertheless,
 1506 as the correlation matrices for the LI variables show in Figure 6.6, there is actually very little correla-
 1507 tion between \vec{E}_T^{miss} and the other variables (with this being slightly less the case for the background
 1508 correlations, as to be expected since $t\bar{t}$, a principal background, is \vec{E}_T^{miss} -rich). Hence, if including

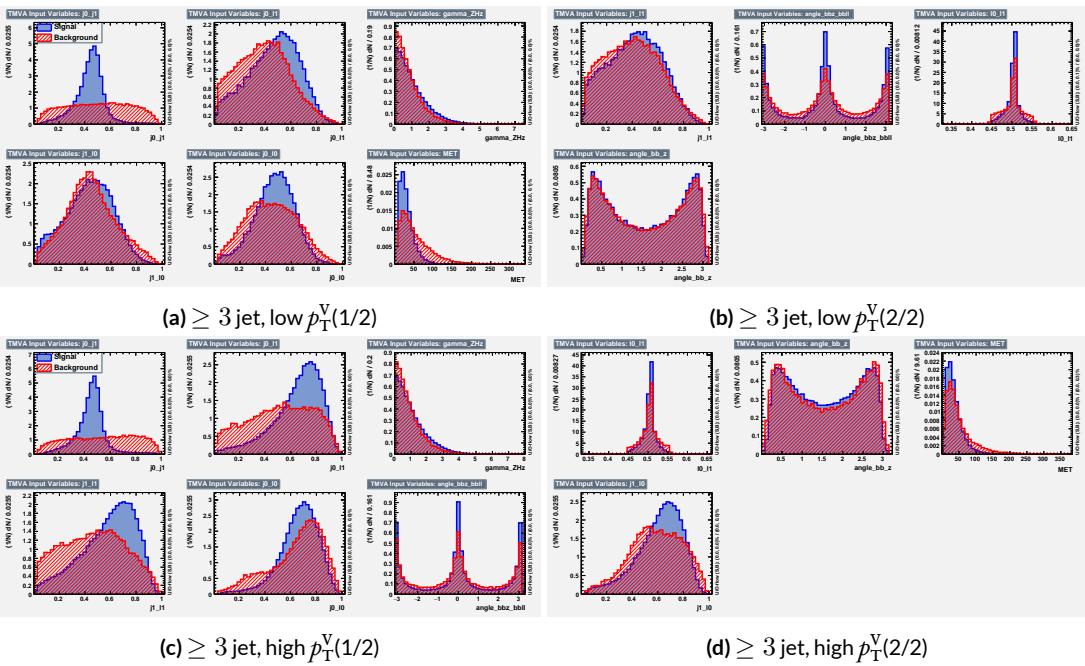


Figure 6.5: Input variables in ≥ 3 jet signal regions for the LI variable set. Signal distributions are in red, and background distributions are in blue.

1509 \vec{E}_T^{miss} violates the spirit somewhat of the LI variables, it does not break terribly much with the aim of having a more orthogonal set.

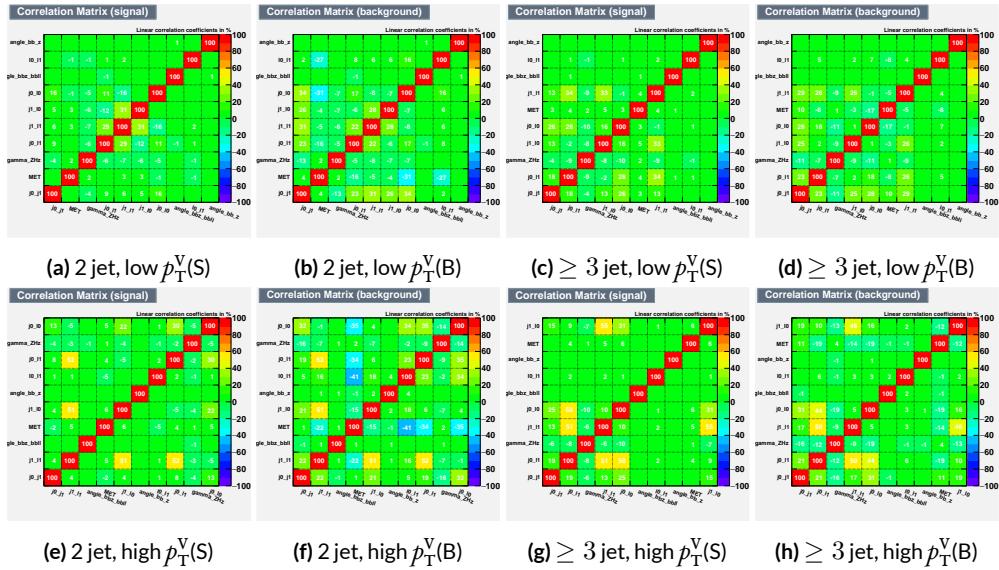


Figure 6.6: Signal and background variable correlations for the LI variable set.

1511 6.1.3 RESTFRAMES VARIABLES

1512 There is no precedent for using the RestFrames variables in the $ZH \rightarrow \ell\ell b\bar{b}$ analysis, so a subset
1513 of possible RF variables had to be selected as the basis of a discriminant. The masses and cosines of
1514 boost angles from parent frames for the CM, Z , and H frames gives six variables, and it was decided
1515 that it would be good to match the LI in terms of variable number and treatment (i.e. no special
1516 treatment of the third jet), which leaves four more variables. In addition to the cosines, there are
1517 also the $\Delta\phi$ angles. Furthermore, there are the event-by-event scaled momentum ratios, both lon-
1518 gitudinal and transverse. There is also both a $\Delta\phi$ and an CM-scaled ratio for the \vec{E}_T^{miss} . All of these
1519 variables were included in a ranking using slightly different training settings as the main hyperpa-
1520 rameter optimization variable ranking described below. The goal of this study was not to develop a
1521 discriminant, as the number of variables is too high, but rather to see which ones are generally use-
1522 ful. Table 6.1 shows the results of this study. Percent gains (losses) at each step by adding the variable
1523 with biggest gain (smallest loss) are shown in green (red). The final row shows an aggregate rank-
1524 ing, calculated simply by adding up a variables ranks in all bins and ordering the variables smallest
1525 to greatest. This simple aggregation does not take into account which regions are potentially more
1526 sensitive and so where taken simply to give an idea of how variables generally performed. With this
1527 in mind, the RF variables were chosen to be the masses M_{CM} , M_H , and M_Z , the angles $\cos CM$, \cosh ,
1528 $\cos Z$, $\cos \phi CMH$, and the ratios R_{pt} , R_{pz} , and R_{met} . Their distributions may be seen in Figures 6.7
1529 and 6.8.

1530 Correlations for the chosen RF variables are shown in Figure 6.9. These correlations are much

Region	Variable Chain
2jet pTVbin1	Rpt (65.8%), Rpz (29.0%), cosZ (11.4%), MZ (-1.75%), dphiCMH (7.26%), cosCM (3.95%), cosH (0.142%), MCM (2.18%), dphiCMZ (-2.3%), dphiCMMet (-0.236%), dphiLABCM (0.404%), Rmet (-4.04%)
3jet pTVbin1	Rpt (50.8%), Rpz (15.6%), MZ (14.8%), cosZ (3.08%), MCM (3.79%), dphiCMH (3.24%), cosH (0.755%), dphiCMMet (1.04%), Rmet (-1.03%), cosCM (5.31%), dphiCMZ (-1.27%), dphiLABCM (-2.88%), pTJ3 (-1.27%)
2jet pTVbin2	Rpt (52.0%), Rpz (13.8%), cosZ (16.9%), cosH (6.49%), MCM (1.71%), cosCM (6.21%), Rmet (4.25%), dphiCMMet (-1.53%), dphiLABCM (-0.757%), dphiCMH (0.213%), MZ (-0.788%), dphiCMZ (-2.39%)
3jet pTVbin2	Rpt (31.5%), Rpz (21.6%), cosH (8.97%), cosZ (1.42%), cosCM (11.3%), dphiCMZ (-2.84%), MCM (8.17%), dphiCMH (-0.841%), dphiLABCM (-0.00318%), dphiCMMet (-2.6%), pTJ3 (-3.21%), MZ (-1.8%), Rmet (-6.29%)
Aggregate	Rpt (o,o,o,o), Rpz (i,i,i,i), cosZ (2,3,2,3), cosH (6,6,3,2), MCM (7,4,4,6), MZ (3,2,10,11), dphiCMH (4,5,9,7), cosCM (5,9,5,4), dphiCMMet (9,7,7,9), dphiCMZ (8,10,11,5), Rmet (11,8,6,12), dphiLABCM (10,11,8,8)

Table 6.1: Full RF variable ranking study summary. Green (red) percentages represent gains (losses) in a validation significance at each step.

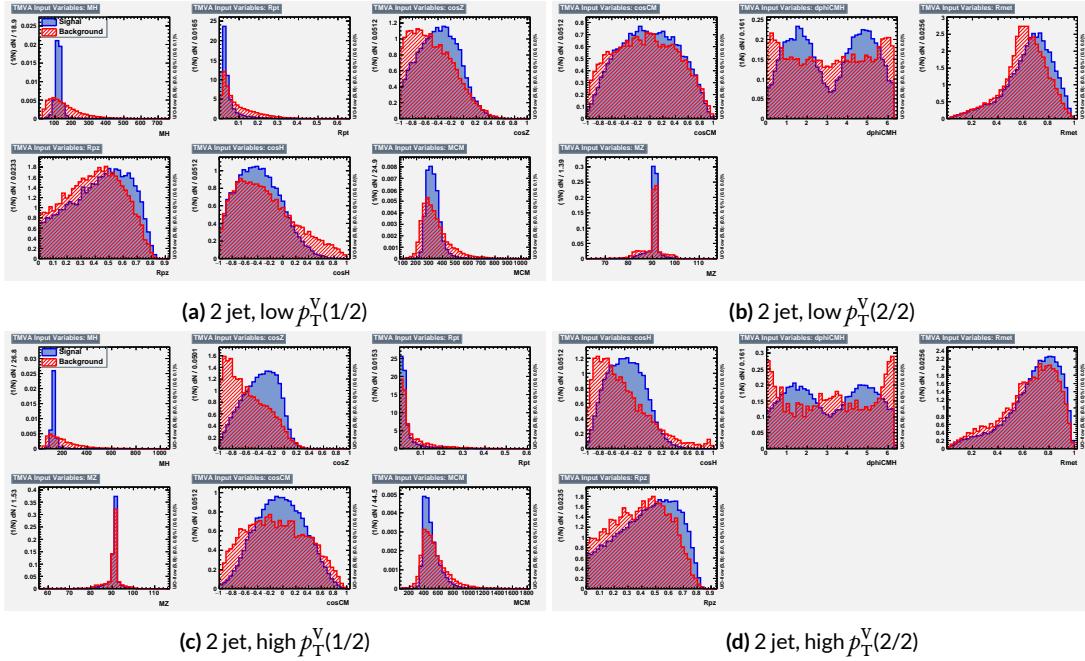


Figure 6.7: Input variables in 2 jet signal regions for the RF variable set. Signal distributions are in red, and background distributions are in blue.

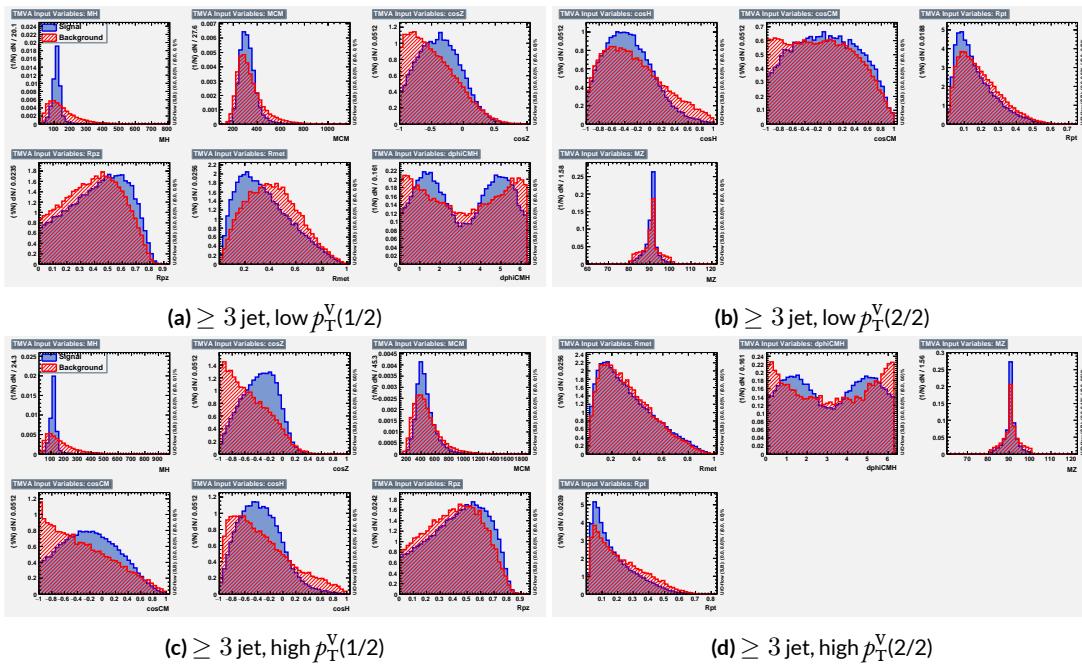


Figure 6.8: Input variables in ≥ 3 jet signal regions for the RF variable set. Signal distributions are in red, and background distributions are in blue.

1531 lower than for the standard case but still slightly higher than for the LI case. Notably, many strong
 1532 correlations that exist for signal events do not exist in background events and vice versa, so what is
 1533 lost in orthogonality may very well be recuperated in greater separation[†]. Given the generally better
 1534 performance of the RF sets, as we shall see in following sections and chapters, this slight tradeoff is
 1535 likely an aesthetic one, with the main benefits of a more orthogonal basis likely realized at this level
 1536 of correlation.

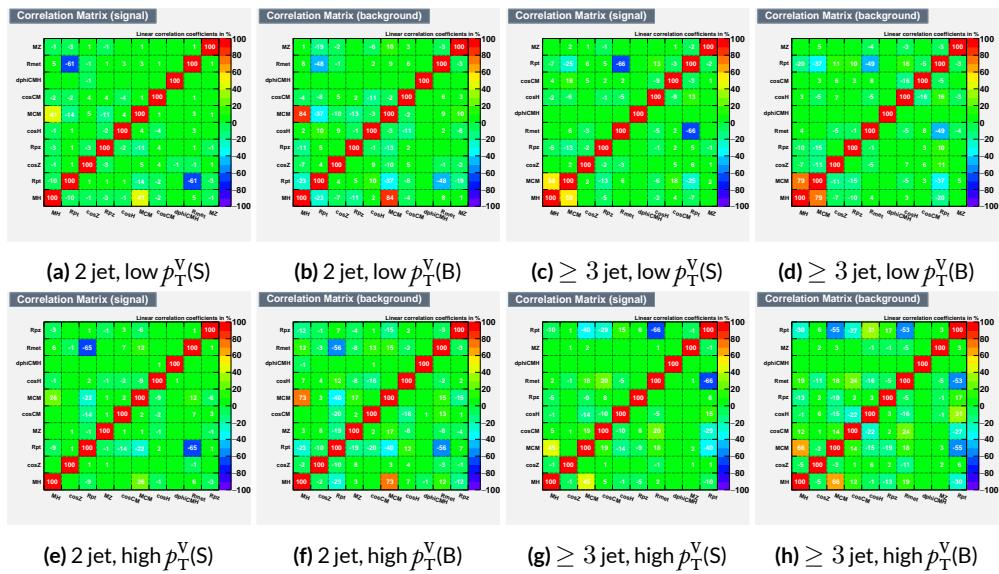


Figure 6.9: Signal and background variable correlations for the RF variable set.

1537 A summary of the variables used in the three cases is given in 6.2.

[†]It is very hard to say for certain whether this is the case for MVA discriminants, and such dedicated studies might make worthwhile future studies.

Variable Set	Variables
Standard	mBB, mLL, (mBBJ), pTV, pTB1, pTB2, (pTJ3), dRBB, dPhiVBB, dEtaVBB, MET 9(11) vars
Lorentz Invariants	j0_j1, j0_l1, l0_l1, j1_l1, j0_l0, j1_l0, gamma_ZHz, angle_bbz_bbll angle_bb_z, MET 10 vars
RestFrames	MH, MCM, MZ, cosH, cosCM, cosZ, Rpz, Rpt, dphiCMH, Rmet 10 vars

Table 6.2: Variables used in MVA training. Variables in parentheses are only used in the ≥ 3 jet regions.

1538 6.2 MVA TRAINING

1539 With variables chosen, the MVA discriminants must be trained and optimized. MVA training and
 1540 hyperparameter optimization (in this case, just the order in which variables are fed into the MVA) is
 1541 conducted using the “holdout” method. In this scheme, events are divided into three equal portions
 1542 (in this case using `EventNumber%3`), with the first third (the “training” set) being used for the initial
 1543 training, the second third (the “validation” set) being used for hyperparameter optimization, and
 1544 the final third (the “testing” set) used to evaluate the performance of the final discriminants in each
 1545 analysis region.

1546 The MVA discriminant used is a boosted decision tree (BDT). Training is done in TMVA using
 1547 the training settings of the fiducial analysis [4][‡]. For the purposes of hyperparameterization and test-
 1548 ing, transformation D with $z_s = z_b = 10$ is applied to the BDT distributions, and the cumulative
 1549 sum of the significance $S/\sqrt{S + B}$ in each bin is calculated for each pair of distributions.

1550 Transformation D is a histogram transformation, developed during the Run 1 SM $VH(b\bar{b})$ search,

[‡]Namely, !H:!V:BoostType=AdaBoost:AdaBoostBeta=0.15:SeparationType=GiniIndex:-PruneMethod=NoPruning:NTrees=200:MaxDepth=4:nCuts=100:nEventsMin=5%

1551 designed to reduce the number of bins in final BDT distributions and thereby mitigate the effect of
 1552 statistical fluctuations in data while also maintaining sensitivity. Such an arbitrary transformation
 1553 may be expressed as:

$$Z(I[k, l]) = Z(z_s, n_s(I[k, l]), N_s, z_b, n_b(I[k, l]), N_b) \quad (6.1)$$

1554 where

- 1555 • $I[k, l]$ is an interval of the histograms, containing the bins between bin k and bin l ;
- 1556 • N_s is the total number of signal events in the histogram;
- 1557 • N_b is the total number of background events in the histogram;
- 1558 • $n_s(I[k, l])$ is the total number of signal events in the interval $I[k, l]$;
- 1559 • $n_b(I[k, l])$ is the total number of background events in the interval $I[k, l]$;
- 1560 • z_s and z_b are parameters used to tune the algorithm.

1561 Transformation D uses:

$$Z = z_s \frac{n_s}{N_s} + z_b \frac{n_b}{N_b} \quad (6.2)$$

1562 Rebinning occurs as follow:

- 1563 1. Begin with the highest valued bin in the original pair of distributions. Call this the “last” bin
1564 and use it as l , and have k be this bin as well.
- 1565 2. Calculate $Z(I[k, l])$
- 1566 3. If $Z \leq 1$, set $k \rightarrow k - 1$ and return to step 2. If not, rebin bins $k-l$ into a single bin and name
1567 $k - 1$ the new “last” bin l .
- 1568 4. Continue until all bins have been iterated through; if $Z \leq 1$ for any remaining n of the
1569 lowest-valued bins (as is often the case), simply rebin these as a single bin.

1570 Variable ranking is done iteratively (greedily) in each analysis region. In each set, the validation
 1571 significance of a BDT using an initial subset of variables is calculated ($dRBB$ and mBB for the stan-
 1572 dard set; $j_0_j_1$ for the LI set; and MH for the RF set). Each of the remaining unranked variables
 1573 are then added separately, one at a time, to the BDT. The variable yielding the highest validation
 1574 significance is then added to the set list of ranked variables and removed from the list of unranked
 1575 variables. This process is repeated until no variables remain. These rankings are shown in Figures
 1576 **6.10–6.12.** Rankings tend to be fairly stable.

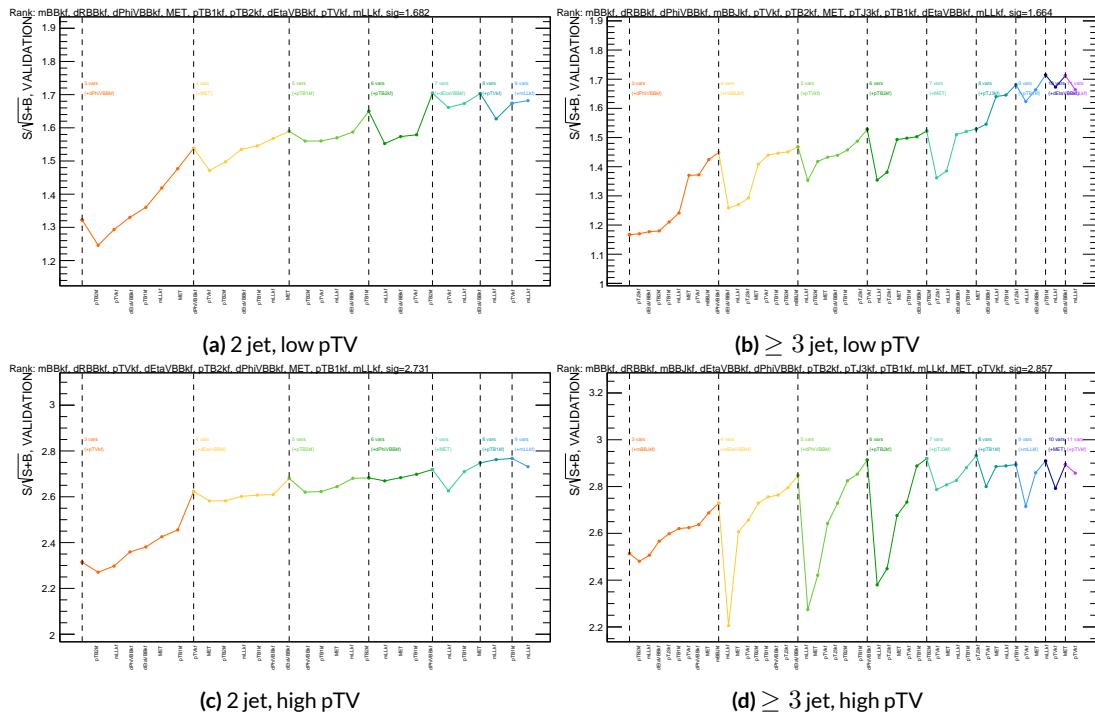


Figure 6.10: Rankings for the standard variable set.

1577 Once variables have been ranked, the BDT may be used both to evaluate performance in a simpli-
 1578 fied analysis scenario in the absence of systematic uncertainties (described below in Section 6.3) and

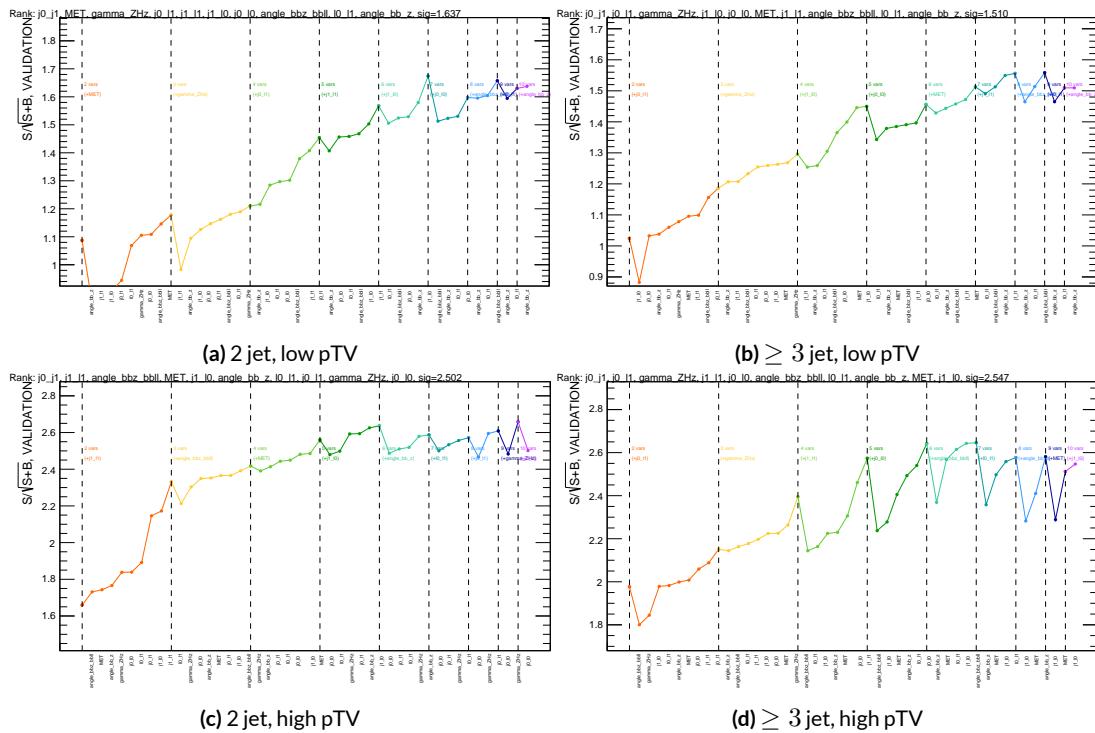


Figure 6.11: Rankings for the L1 variable set.

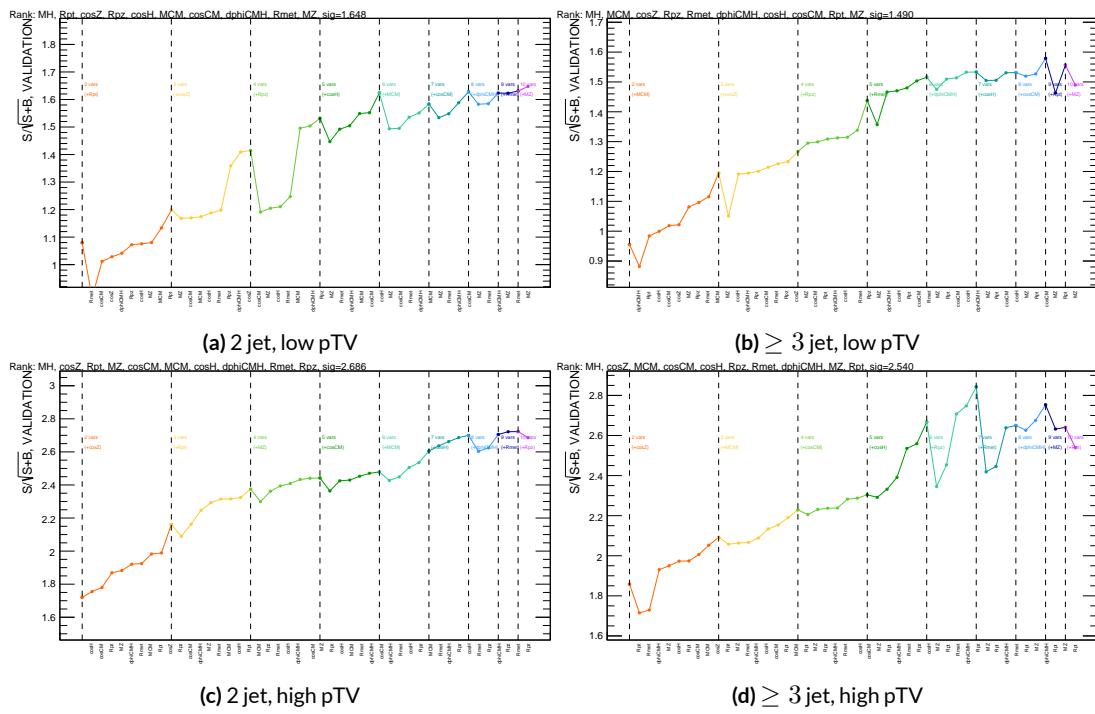


Figure 6.12: Rankings for the RF variable set.

1579 to create xml files for the production of fit inputs for an analysis including systematics. Following
1580 the approach taken in the fiducial analysis, BDT discriminants using two “k-folds” are produced to
1581 prevent overtraining, since the samples used for training are the same as those used to produce in-
1582 puts for the full profile likelihood fit. In this scheme, a BDT trained on events with an even (odd)
1583 `EventNumber` are used to evaluate events with an odd (even) `EventNumber`.

1584 6.3 STATISTICS ONLY BDT PERFORMANCE

1585 As described above, cumulative significances can be extracted from pairs of signal and background
1586 BDT output distributions in a given region. In order to evaluate performance of variable sets in the
1587 absence of systematic uncertainties, such pairs can be constructed by evaluating BDT score on the
1588 testing set of events using the optimal variable rankings in each region. We show two versions of
1589 each testing distribution for each variable set in each signal region in Figures 6.13–6.15. The training
1590 distribution is always shown as points. The plots with block histograms with numbers of bins that
1591 match (do not match) the training distribution do not (do) have transformation D applied. Trans-
1592 formation D histograms are included to show the distributions actually used for significance evalu-
1593 ation, while the untransformed histograms are included to illustrate that the level of overtraining is
1594 not too terrible[§]. For better comparison of the distributions, all histograms have been scaled to have
1595 the same normalization.

1596 As can be seen in the summary of cumulative significances for each of these analysis regions and
1597 variable sets in Figure 6.16, the performance of each of the variable sets is quite similar. The standard

[§]The raw distributions include a K-S test statistic for signal (background) distributions.

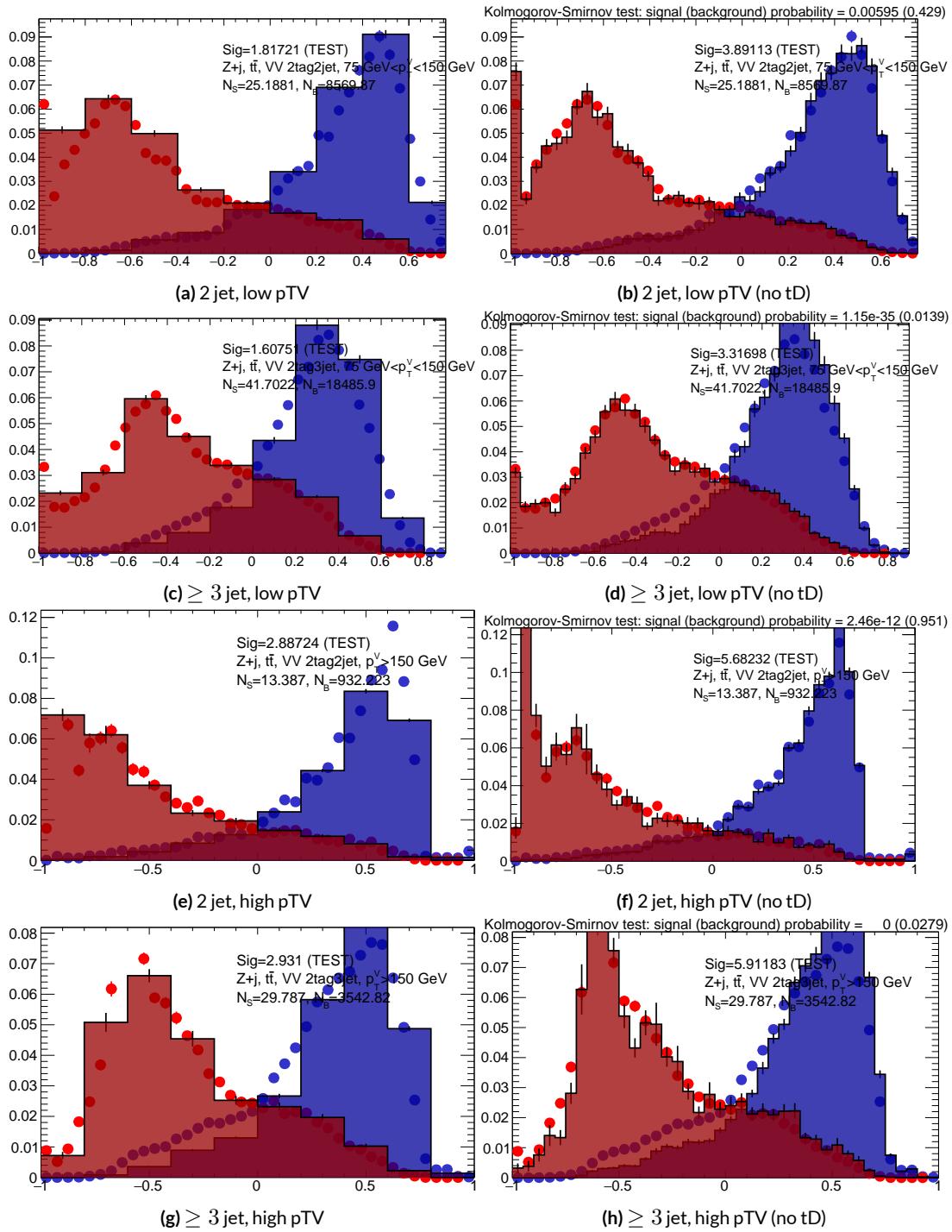


Figure 6.13: Training (points) and testing (block histogram) MVA distributions used for stat only testing for the standard variable set.

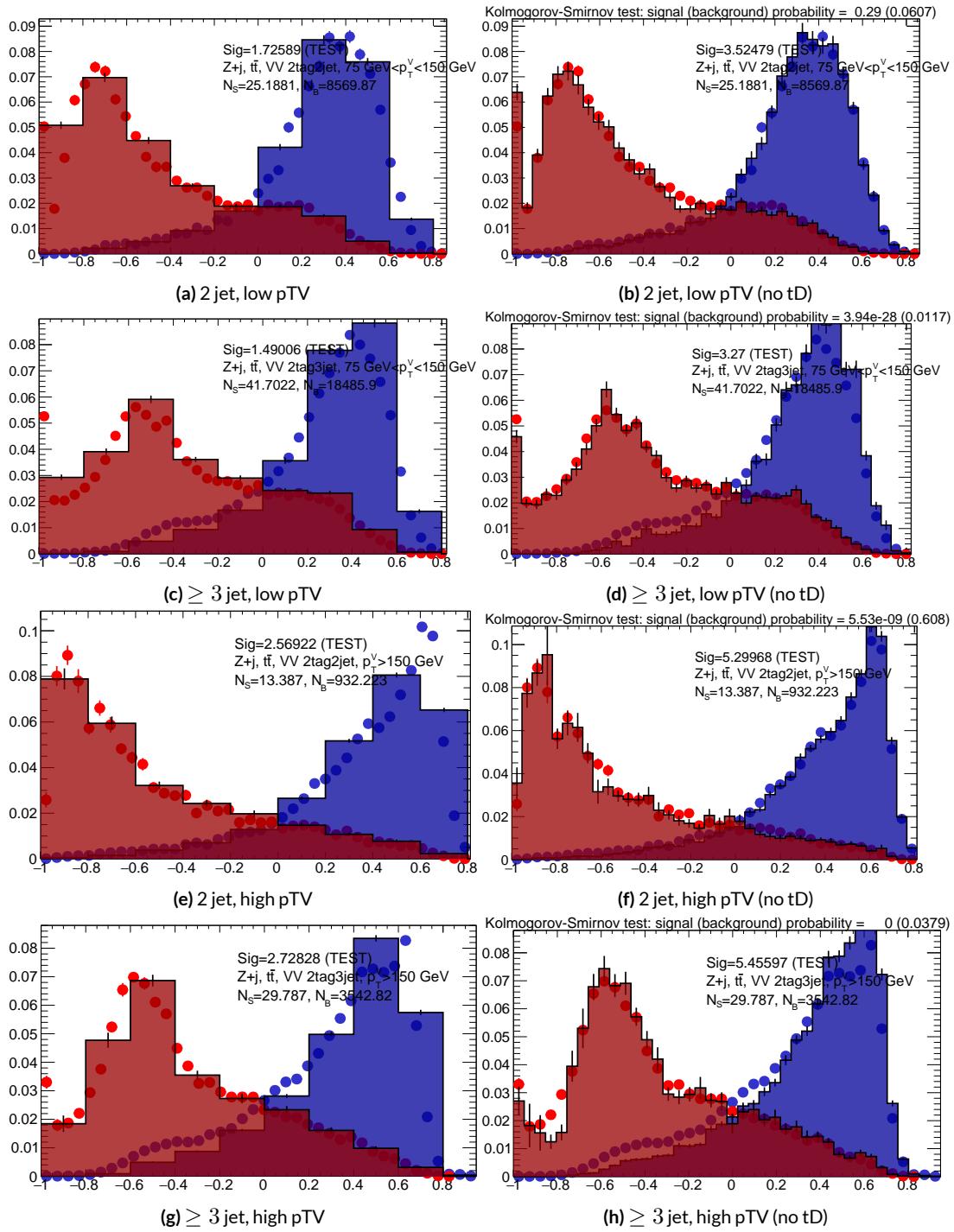


Figure 6.14: Training (points) and testing (block histogram) MVA distributions used for stat only testing for the LI variable set.

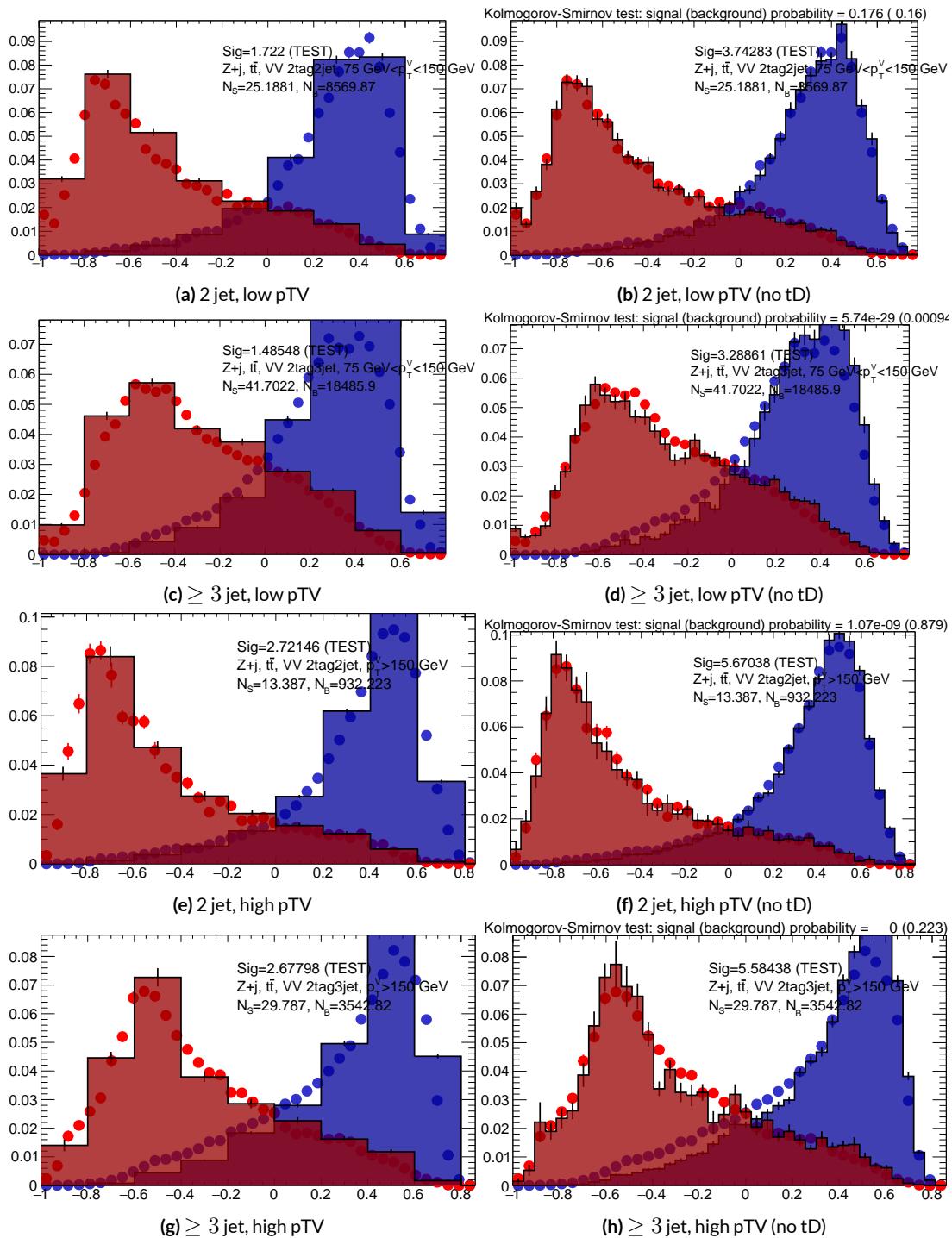


Figure 6.15: Training (points) and testing (block histogram) MVA distributions used for stat only testing for the RF variable set.

1598 set performs best, with the LI (RF) set having a cumulative significance that is 7.9% (6.9%) lower.
 1599 This suggests that the LI and RF variables, in the $ZH \rightarrow \ell\ell b\bar{b}$ closed final state, have no more in-
 1600 trinsic descriptive power than the standard set. That these figures are all relatively high (~ 4.5) is
 1601 due largely to the absence of systematics and possibly in part due to the fact that many of the most
 1602 significant bins occur at high values of the BDT output, which, as can be seen in any of the testing
 distributions, contain a small fraction of background events. An interesting feature to note in Fig-

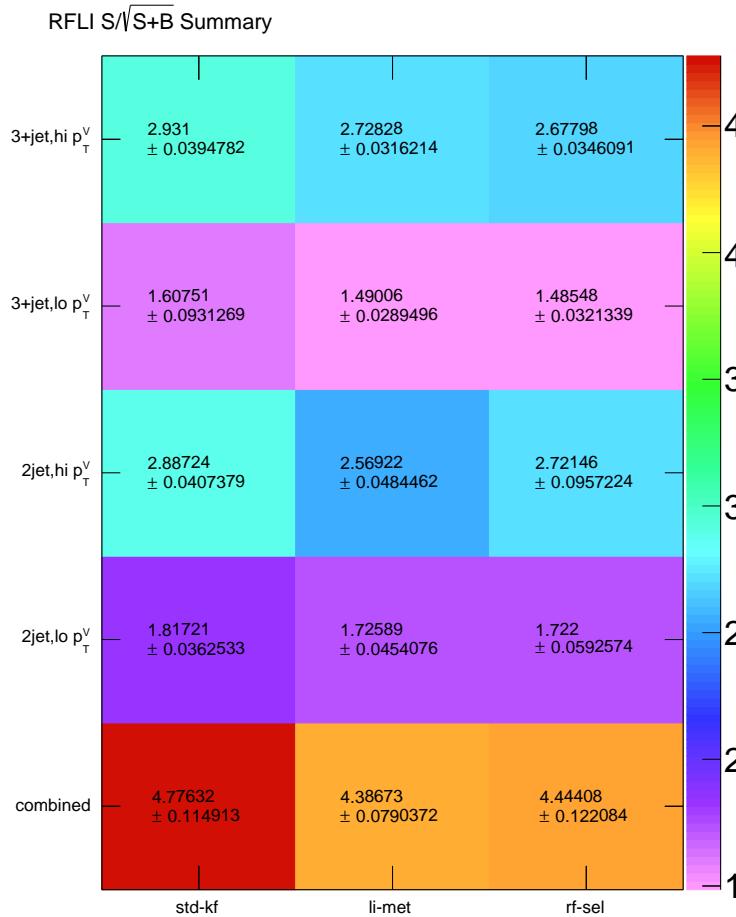


Figure 6.16: Results of testing significances sorted by analysis region and variable set.

1603

₁₆₀₄ ure 6.16 is that while the standard set does perform better in all regions, the gap is larger in the ≥ 3
₁₆₀₅ jet regions, suggesting that further optimization in the ≥ 3 jet case could be useful. Moreover, as
₁₆₀₆ discussed at the end of Chapter 5, the choice of ≥ 3 jet and not exclusive 3 jet regions is a 2-lepton
₁₆₀₇ specific choice and may not be justified for the non-standard variable sets.

Multivac picked you as most representative this year.

Not the smartest, or the strongest, or the luckiest, but

just the most representative. Now we don't question

Multivac, do we?

Isaac Asimov, "Franchise"

1608

7

1609

Statistical Fit Model and Validation

1610 THE ULTIMATE GOAL of an analysis like the search for SM $VH(b\bar{b})$ decay is to say with as much
1611 justified precision as possible with the ATLAS collision data whether or not the SM-like Higgs ob-
1612 served in other decay modes also decays to b -quarks and, if so, whether this rate is consistent with
1613 the SM prediction. In the limit of perfect modeling of both background processes and detector/reconstruction,

₁₆₁₄ the only free parameter is this production rate, referred to typically as a “signal strength,” denoted μ ,
₁₆₁₅ with $\mu = 1$ corresponding to the SM prediction and $\mu = 0$ corresponding to the SM with no
₁₆₁₆ Higgs.

₁₆₁₇ To get a better sense of what this might look like, take a look at the example discriminant distri-
₁₆₁₈ bution in Figure 7.1. The black points are data (with statistical error bars), and the colored block
₁₆₁₉ histograms have size corresponding to the number of predicted events for each process in each bin of
₁₆₂₀ the final BDT. In the limit of perfect understanding, a fit would correspond to a constant scale fac-
₁₆₂₁ tor on the red, signal histogram, where one would choose a best fit μ value, denoted $\hat{\mu}$, that would
₁₆₂₂ minimize the sum in quadrature of differences between the number of observed data events and
₁₆₂₃ $\mu s_i + b_i$, where s_i and b_i are the predicted number of signal and background events in each bin.

₁₆₂₄ The only source of uncertainty would be due to data statistics, so for an infinitely large dataset with
₁₆₂₅ perfect understanding, μ could be fitted to arbitrary precision. This, of course, is not the case since
₁₆₂₆ there is a finite amount of data and very many sources of systematic uncertainty, discussed in pre-
₁₆₂₇ vious chapters. This chapter will first describe how systematic uncertainties are integrated into the
₁₆₂₈ statistical fit of this analysis before describing two sets of cross checks on both a validation VZ fit and
₁₆₂₉ on the fit for the VH fit of interest.

₁₆₃₀ 7.1 THE FIT MODEL

₁₆₃₁ In order to derive the strength of the signal process $ZH \rightarrow \ell\ell b\bar{b}$ and other quantities of interest
₁₆₃₂ while taking into account systematic uncertainties or nuisance parameters (NP’s, collectively de-
₁₆₃₃ noted θ), a binned likelihood function is constructed as the product over bins of Poisson distribu-

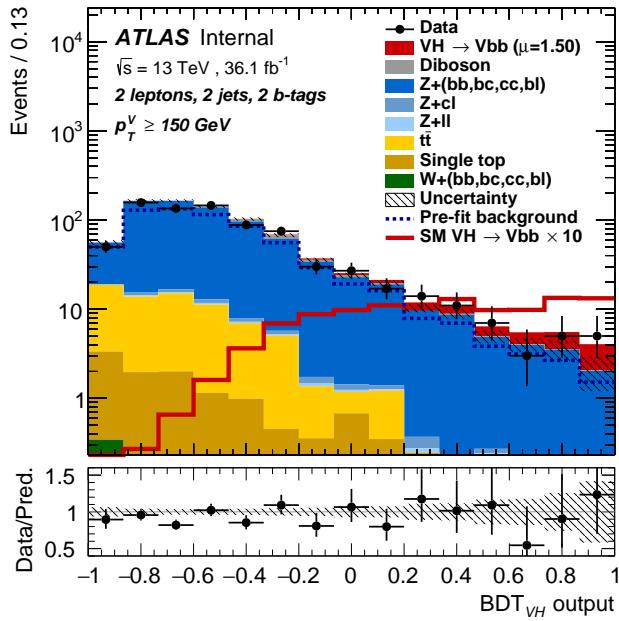


Figure 7.1: An example postfit distribution. The reason this looks different from postfit distributions later in this chapter is that this is a log plot.

1634 tions:

$$\mathcal{L}(\mu, \theta) = \text{Pois}(n | \mu S + B) \left[\prod_{i \in \text{bins}} \frac{\mu s_i + b_i}{\mu S + B} \right] \prod_{j \in \text{NP's}} \mathcal{N}_{\theta_j}(\theta_j, \sigma_j^2 | 0, 1) \quad (7.1)$$

1635 where n is the total number of events observed, s_i and b_i are the number of expected signal and back-

1636 ground events in each bin, and S and B are the total expected signal and background events. The

1637 signal and background expectations generally are functions of the NP's θ . NP's related to the nor-

1638 malization of signal and background processes fall into two categories. The first set is left to float

1639 freely like μ while the second set are parametrized as log-normally distributed to prevent negative

1640 predicted values. All other NP's are parametrized with Gaussian priors. This results in a "penalty"

1641 on the NLL discussed below of $(\hat{\alpha} - \mu_\alpha)^2 / \sigma_\alpha^2$, for NP α , normally parametrized with mean μ_α

1642 (corresponding to the nominal prediction) and variance σ_α^2 (derived as discussed in Chapters 4 and

1643 5) for an MLE of $\hat{\alpha}$.

1644 One can maximize^{*} the likelihood in Equation 7.1 for a fixed value of μ to derive estimators for
1645 the NP's θ ; values of θ so derived are denoted $\hat{\theta}_\mu$ to emphasize that these are likelihood maximizing
1646 for a given μ . The profile likelihood technique finds the likelihood function's maximum by compar-
1647 ing the values of the likelihood over all possible values of μ using these "profiles" and picking the
1648 one with the greatest $\mathcal{L}(\mu, \hat{\theta}_\mu)$ value; these values of μ and θ are denoted $\hat{\mu}$ and $\hat{\theta}$. The profile like-
1649 lihood can further be used to construct a test statistic[†]

$$q_\mu = -2 \left(\log \mathcal{L}(\mu, \hat{\theta}_\mu) - \log \mathcal{L}(\hat{\mu}, \hat{\theta}) \right) \quad (7.2)$$

1650 This statistic can be used to derive the usual significance (p value), by setting $\mu = 0$ to find the com-
1651 patibility with the background-only hypothesis [58]. If there is insufficient evidence for the signal
1652 hypothesis, the CL_s method can be used to set limits [59].

1653 In order to both validate the fit model and study the behavior of fits independent of a given dataset,
1654 a so-called "Asimov"[‡] dataset can be constructed for a given fit model; this dataset has each bin equal
1655 to its expectation value for assumed values of the NP's and a given μ value (in this case, $\mu = 1$, the
1656 SM prediction).

^{*}Maximization is mathematically identical to finding the minimum of the negative logarithm of the likelihood, which is numerically an easier problem.

[†]The factor of -2 is added so that this statistic gives, in the asymptotic limit of large N , a χ^2 distribution.

[‡]A reference to the short story quoted at the beginning of this chapter in which a computer picks a single voter to stand in for the views of the entire American electorate.

1657 7.2 FIT INPUTS

1658 Inputs to the binned likelihood are distributions of the BDT outputs described in Chapter 6 for the
1659 signal regions and of m_{bb} for the top $e - \mu$ control regions. These regions split events according
1660 to their p_T^V and number of jets. All events are required to have two b -tagged jets, as well as pass the
1661 other event selection requirements summarized in Table 5.8; the only difference between the signal
1662 and control region selections is that the same flavor requirement (i.e. leptons both be electrons or
1663 muons) is flipped so that events in the control region have exactly one electron and one muon. The
1664 BDT outputs are binned using transformation D, while the m_{bb} distributions have 50 GeV bins,
1665 with the exception of the 2 jet, high p_T^V region, where a single bin is used due to low statistics.

1666 Input distributions in MC are further divided according to their physics process. The signal pro-
1667 cesses are divided based on both the identity of associated V and the number of leptons in the final
1668 state; $ZH \rightarrow \ell\ell b\bar{b}$ events are further separated into distributions for qq and gg initiated processes.
1669 $V+jets$ events are split according to V identity and into the jet flavor bins described in Chapter 3.
1670 Due to the effectiveness of the 2 b -tag requirement suppressing the presence of both c and l jets,
1671 truth-tagging is used to boost MC statistics in the cc , cl , and ll distributions.[§] For top backgrounds,
1672 single top production is split according to production mode (s , t , and Wt), with $t\bar{t}$ as single category.
1673 Diboson background distributions are also split according to the identity of the V 's (ZZ , WZ , and
1674 WW). Fit input segmentation is summarized in Table 7.1.

1675 [§]Since WW is not an important contribution to the already small total diboson background, no truth-
tagging was applied here, in contrast to the fiducial analysis.

Category	Bins
# of Jets	2, 3+
p_T^V Regions (GeV)	$[75, 150], [150, \infty)$
Sample	data, signal $[(W, qqZ, ggZ)] \times n_{lep}$, $V+jets [(W, Z)] \times (bb, bc, bl, cc, cl, ll), t\bar{t}$, diboson (ZZ, WW, WZ) , single top (s, t, Wt)

Table 7.1: Fit input segmentation.

1675 7.3 SYSTEMATIC UNCERTAINTIES REVIEW

1676 Tables 7.2 and 7.3 summarize modeling (Chapter 4) and experimental (Chapter 5) systematic uncer-
 1677 tainties considered in this analysis, respectively. In addition to these, simulation statistics uncertain-
 1678 ties (“MC stat errors”) are also included in the fit model. There is one distribution per systematic
 1679 (one each for up and down) per sample per region. The $\pm 1\sigma$ variation for a systematic is calculated
 1680 as the difference in the integrals between the nominal and up/down varied distributions.

Process	Systematics
Signal	$H \rightarrow bb$ decay, QCD scale, PDF+ α_S scale, UE+PS (acc, p_T^V , m_{bb} , 3/2 jet ratio)
$Z+jets$	Acc, flavor composition, $p_T^V+m_{bb}$ shape
$t\bar{t}$	Acc, $p_T^V+m_{bb}$ shape
Single top	Acc, $p_T^V+m_{bb}$ shape
Diboson	Overall acc, UE+PS (acc, p_T^V , m_{bb} , 3/2 jet ratio), QCD scale (acc (2, 3 jet, jet veto), p_T^V , m_{bb})

Table 7.2: Summary of modeling systematic uncertainties.

1681 The systematics distributions undergo processes known as “smoothing” and “pruning” before
 1682 being combined into the final likelihood used in minimization.
 1683 The difference between systematics varied distributions and nominal distributions approaches

Process	Systematics
Jets	21 NP scheme for JES, JER as single NP
E_T^{miss}	trigger efficiency, track-based soft terms, scale uncertainty due to jet tracks
Flavor Tagging	Eigen parameter scheme (CDI File: 2016-20_7-13TeV-MC15-CDI-2017-06-07_v2)
Electrons	trigger eff, reco/ID eff, isolation eff, energy scale/resolution
Muons	trigger eff, reco/ID eff, isolation eff, track to vertex association, momentum resolution/scale
Event	total luminosity, pileup reweighting

Table 7.3: Summary of experimental systematic uncertainties.

1684 some stable value in the limit of large simulation statistics, but if the fluctuations due to simulation
 1685 statistics in a distribution are large compared to the actual physical effect (whether this is because
 1686 the actual effect is small or if the actual distribution is derived from a small number of simulation
 1687 events), then systematic uncertainty will be overestimated by, in effect, counting the MC stat error
 1688 multiple times. Smoothing is designed to mitigate these effects by merging adjacent bins in some
 1689 input distributions. Smoothing happens in two steps (the full details of smoothing algorithms may
 1690 be found in [4] and in the `WSMaker` code):

- 1691 1. Merge bins iteratively where bin differences are smallest in input distributions until no local
 1692 extrema remain (obviously, a single peak or valley is allowed to remain)
- 1693 2. Sequentially merge bins (highest to lowest, like transformation D) until the statistical uncer-
 1694 tainty in a given bin is smaller than 5% of merged bin content

1695 Not all systematic uncertainties defined are included in the final fit. Systematics are subject to
 1696 “pruning” (individually in each region/sample: there are two histograms per systematic (up/down)
 1697 per region per sample, so pruning just consists of removing the histograms from the set of distribu-
 1698 tions included in the likelihood) if they are do not have a significant impact, defined as follows:

- Normalization/acceptance systematics are pruned away if either:
 - The variation is less than 0.5%
 - Both up and down variations have the same sign

- Shape systematics pruned away if either:
 - Not one single bin has a deviation over 0.5% after the overall normalization is removed
 - If only the up or the down variation is non-zero

- Shape+Normalization systematics are pruned away if the associated sample is less than 2% of the total background and either:
 - If the predicted signal is < 2% of the total background in all bins and the shape and normalization error are each < 0.5% of the total background
 - If instead at least one bin has a signal contribution > 2% of the total background, and only in each of these bins, the shape and normalization error are each < 2% of the signal yield

7.4 THE VZ VALIDATION FIT

One of the primary validation cross-checks for the fiducial analysis was a *VZ* fit—that is, conducting the entire analysis but looking for $Z \rightarrow b\bar{b}$ decays instead of the Higgs. The idea here is that the Z is very well understood and so “rediscovering” Z decay to b 's is taken as a benchmark of analysis reliability since the complexity of the fit model precludes the use of orthogonal control regions for validation as is done in other analyses (generally, if there is a good control region, one prefers to use it

1718 to constrain backgrounds and improve the fit model). To do this, a new MVA discriminant is made
 1719 by keeping all hyperparameter configurations the same (e.g. variable ranking) but using diboson
 1720 samples as signal. For the 2-lepton case, this means using $ZZ \rightarrow \ell\ell b\bar{b}$ as the signal sample. This
 1721 new MVA is used to make the inputs described in Section 7.2, and the fit is then run as for the VH
 1722 fit (again, with ZZ as signal). VH samples are considered background in these diboson fits.

1723 The VZ fit sensitivities for the standard, LI, and RF fits are summarized in Table 7.4. The ex-
 1724 pected significances are all fairly comparable and about what was the case in the fiducial analysis.
 1725 The observed significance for the standard set matches fairly well with the expected value on data,
 1726 but the LI and RF observed significances are quite a bit lower.

	Standard	LI	RF
Expected (Asimov)	3.83	3.67	3.72
Expected (data)	3.00	2.95	3.11
Observed (data)	3.17	1.80	2.09

Table 7.4: Expected (for both data and Asimov) and observed $VZ \rightarrow \ell\ell b\bar{b}$ sensitivities for the standard, LI, and RF variable sets.

1727 These values, however, are consistent with the observed signal strength values, which can be seen
 1728 in Figure 7.2 (b), with both the LI and RF fits showing a deficit of signal events with respect to the
 1729 SM expectation, though not by much more than one standard deviation (a possible explanation is
 1730 explored in the following section). Just as in the VH fits, errors arising systematic uncertainties are
 1731 lower in the fits to the observed dataset. That the effect is not noticeable in Asimov fits is not too
 1732 surprising, since this analysis (and these variable configurations in particular), is not optimized for
 1733 VZ .

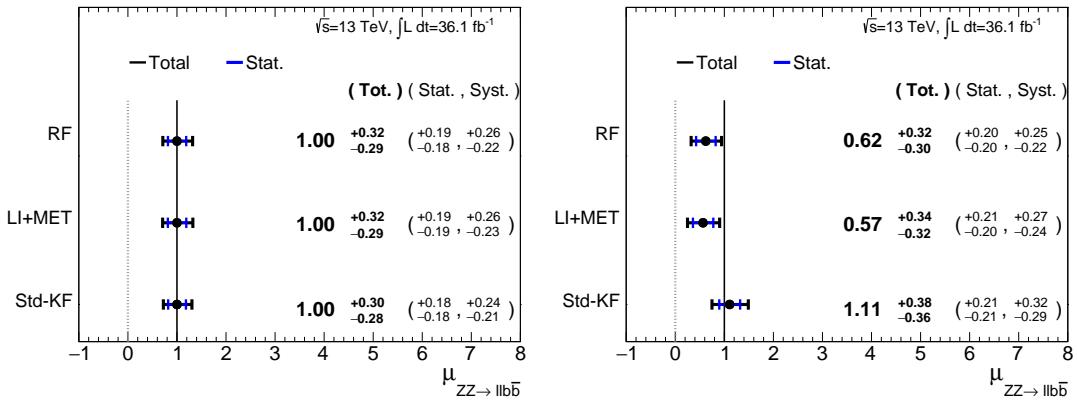


Figure 7.2: μ summary plots for the standard, LI, and RF variable sets. The Asimov case (with $\mu = 1$ by construction) is in (a), and $\hat{\mu}$ best fit values and error summary are in (b).

1734 7.4.I 2 AND ≥ 3 JET FITS

1735 While the treatment of simply ignoring any additional jets in the event seems adequate for the VH
 1736 analysis (discussed below), the potential shortcoming of this treatment appears in the VZ analysis
 1737 when the 2 and ≥ 3 jet cases are fit separately⁴, as can be seen in Figure 7.3. Compared to the stan-
 1738 dard fit, the LI and RF fits have lower $\hat{\mu}_{\geq 3 \text{ jet}}$ values, consistent with the interpretation that the ad-
 1739 ditional information from the third jet in the ≥ 3 jet regions for the standard case is important for
 1740 characterizing events in these regions for VZ fits.

1741 A natural question to ask is why this would be an issue for the VZ but not the VH case. One
 1742 potential answer is that at high transverse boosts, there is a greater probability for final state
 1743 radiation in the hadronically decaying Z , so there are more events where the third jet should be in-
 1744 cluded in the calculation of variables like $m_{b\bar{b}}$ or for angles involving the $b\bar{b}$ system (e.g. $\cos\theta$ in the
 1745 RF case). While the absolute scale at which the low and high p_T^V regions are separated remains the

⁴standalone fits, with half the regions each, not 2 POI fits

same does not change from the VH to the VZ analysis, 150 GeV, the implicit cutoff on the transverse boost of the hadronically decaying boson does. For the Higgs, with a mass of 125 GeV, the p_T^V cutoff corresponds to $\gamma \sim 1.56 - 6.74$, but for the Z , with a mass of 91 GeV, this is $\gamma \sim 1.93 - 9.21$, about 23–37% higher.

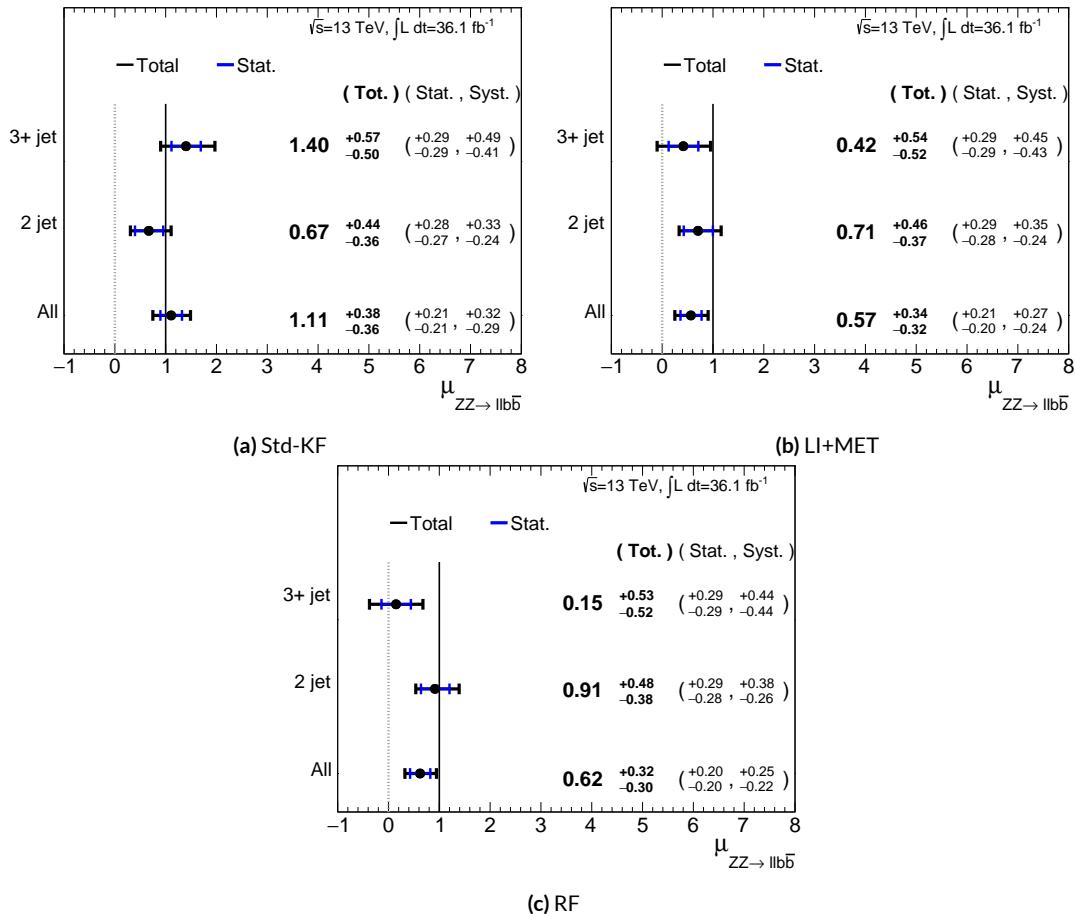


Figure 7.3: $\hat{\mu}$ summary plots with standalone fits for the different n_{jet} regions for the standard, LI, and RF variable sets.

If either the LI or RF schemes were to be used in a mainstream analysis, these validation fits suggest that the third jet ought to be included in variable schemes (e.g. by adding the third jet to the

1752 Higgs in the high p_T^V case). On the issue of whether or not ≥ 4 jet events should be included, the RF
1753 set shows very little sensitivity to this change (a 2 jet and 3 jet only fit moves $\hat{\mu}$ to 0.64, while doing so
1754 for the LI set moves it to 0.40), so this, like the addition of the third jet into the variable sets, would
1755 have to be addressed individually. Nevertheless, this optimization is beyond the scope of this thesis,
1756 which aims to preserve as much of the fiducial analysis as possible for as straightforward a compari-
1757 son as possible.

1758 For completeness, we include the full set of fit validation results for the VZ fit, explaining them in
1759 turn.

1760 7.5 NUISANCE PARAMETER PULLS

1761 The first set of plots statistical fit experts will want to look at are the “pulls” and “pull comparisons.”
1762 In these plots, the best fit (nominal) values and one standard deviation error bars are shown for ob-
1763 served (Asimov) pull plots, with the green and yellow bands corresponding to $\pm 1, 2\sigma$, respectively.
1764 These plots are divided by NP category for readability. [¶] In pull comparisons, these pulls are over-
1765 layed and color-coded. Pull comparisons here have the following color code: black is the standard
1766 variable set, red is the LI set, and blue is the RF set.

1767 A well-behaved fit has pulls close to nominal values (“closeness” should be interpreted in the
1768 context of pull value divided by pull error). As can be seen in Figures 7.4–7.8, the fits for the three
1769 different variable sets are fairly similar from a NP pull perspective, though the $Z+jets$ m_{bb} and p_T^V

¶Over 100 non-MC stat NP’s survive pruning in these 2-lepton only Run 2 fits; well over 500 survive in the Run 1+Run 2 combined fit.

1770 NP's and the jet energy resolution NP are heavily pulled (a handful of poorly behaved pulls is not
 1771 uncommon, though typically warrants further investigation). As a general note, these pull plots cal-
 1772 culate pulls using a simultaneous HESSE matrix inversion, which is fine for relatively small fits, but
 1773 the more reliable MINOS result, which calculates the impact of each NP on its own, should be cross-
 1774 checked for significant pulls**. The ranking plots below do this.

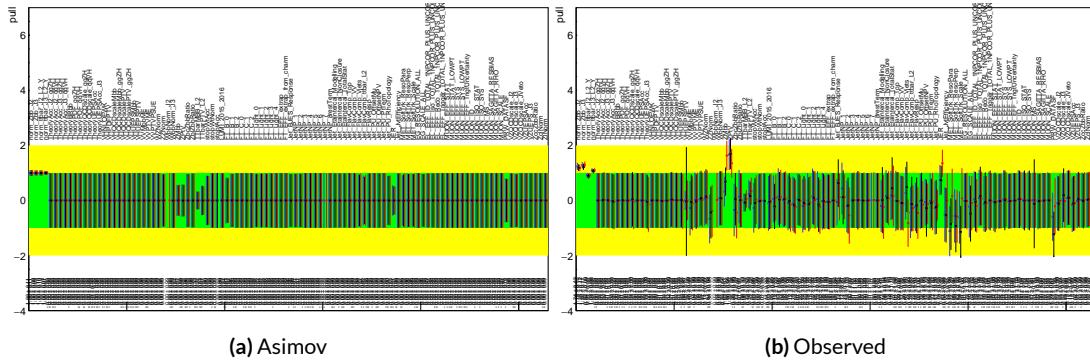


Figure 7.4: Pull comparison for all NP's but MC stats.

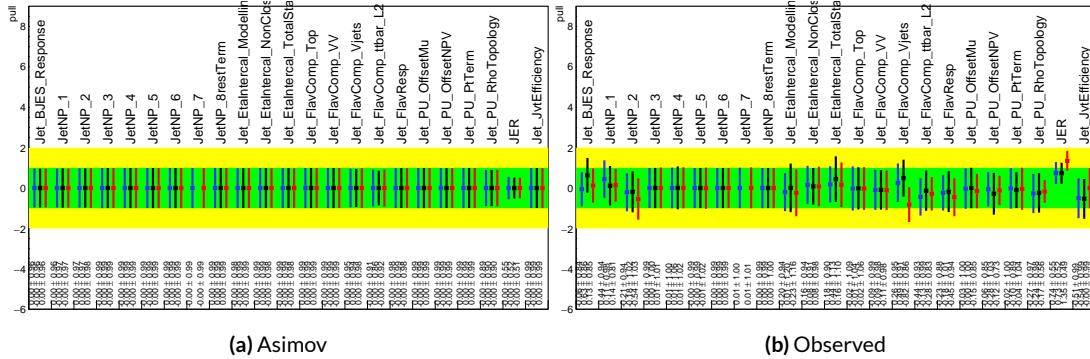


Figure 7.5: Pull comparison for jet NP's.

1775 Nuisance parameter correlation matrices (for correlations with magnitude at least 0.25) for all
 1776 three variable set fits can be found in Figures 7.10–7.12. These are useful for seeing which NP's move

**This becomes more of an issue for very large fits, like the full Run 1 + Run 2 combined fits in Chapter 9.

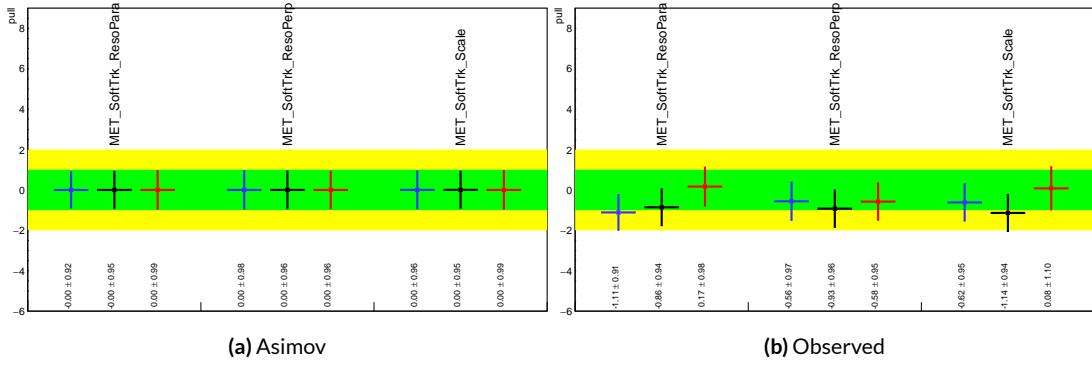


Figure 7.6: Pull comparison for MET NP's.

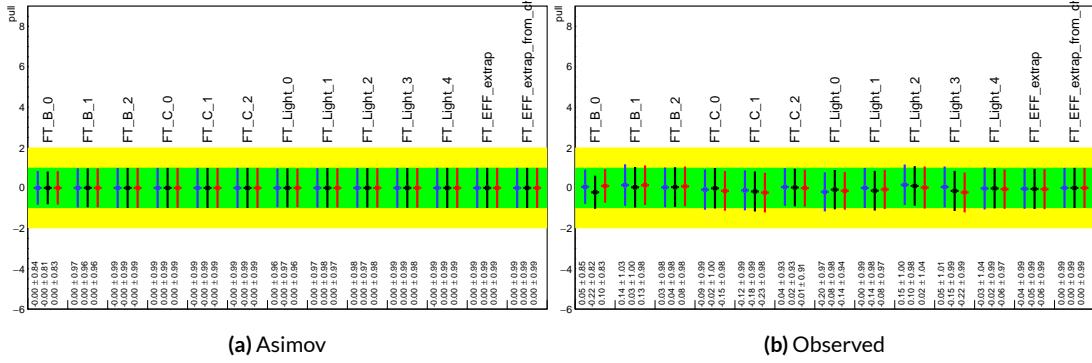


Figure 7.7: Pull comparison for Flavour Tagging NP's.

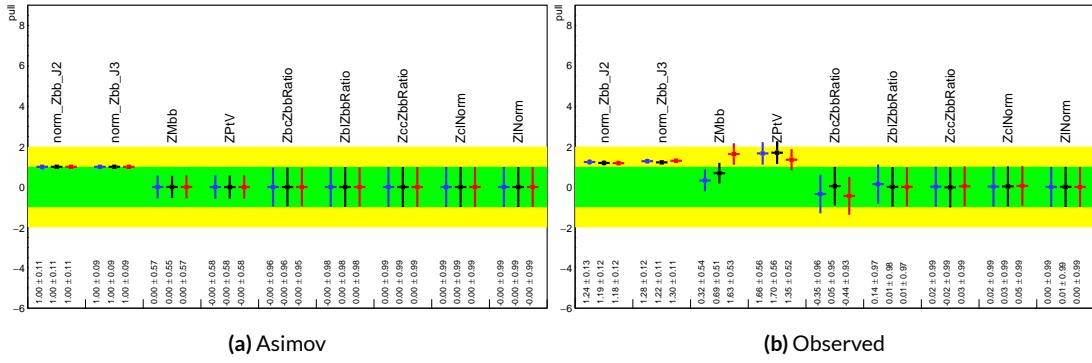


Figure 7.8: Pull comparison for Z +jets NP's.

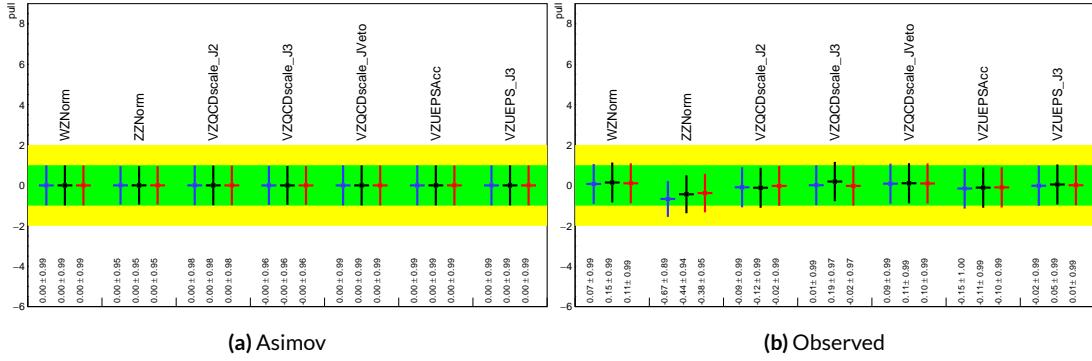


Figure 7.9: Pull comparison for signal process modeling NP's.

1777 together (if there is no physical argument for them to do so, this is a potential indicator that further

1778 investigation is warranted).

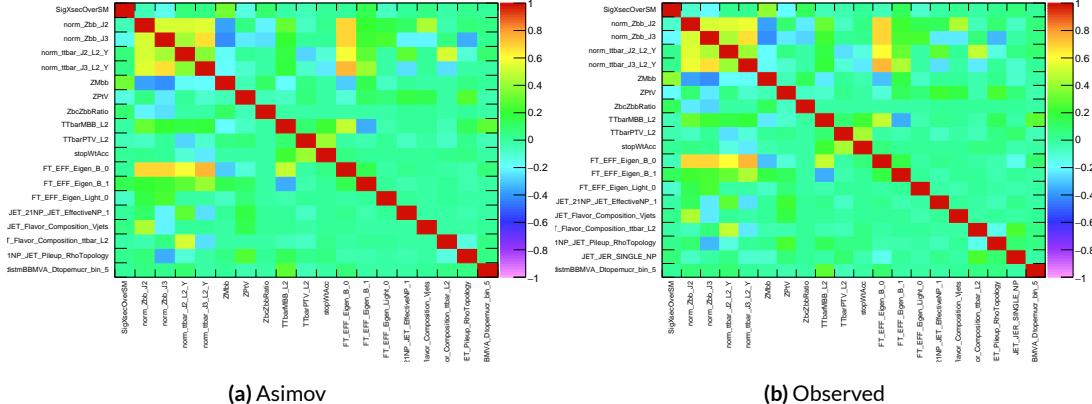


Figure 7.10: NP correlations for standard variable fits.

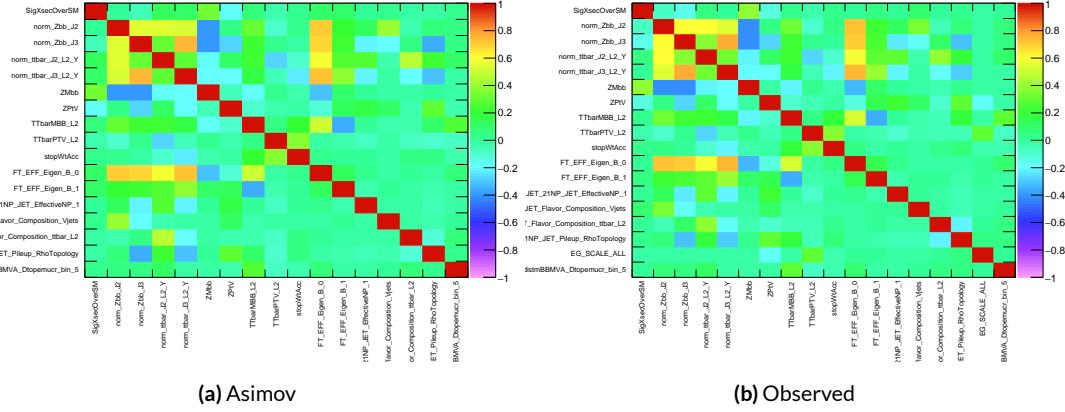


Figure 7.11: NP correlations for LI variable fits.

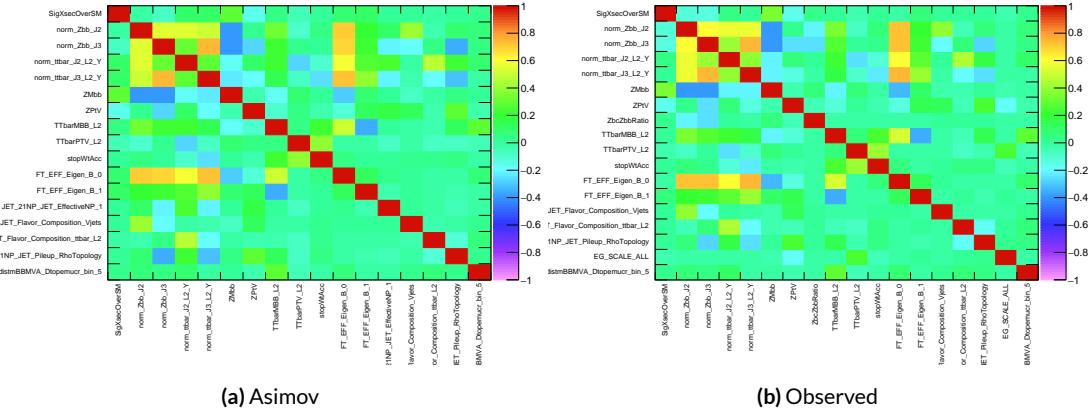


Figure 7.12: NP correlations for RF variable fits.

1779 7.5.1 NUISANCE PARAMETER RANKING PLOTS AND BREAKDOWNS

1780 The next set of fit results that is used to diagnose the quality of a fit is the impact of different nui-
 1781 sance parameters on the total error on μ , both individually and as categories. Figure 7.13 shows the
 1782 top 25 nuisance parameters ranked by their postfit impact on $\hat{\mu}$; these plots use the aforementioned,
 1783 more reliable MINOS approach. This set of rankings is fairly similar, with $Z+jets$ systematics being
 1784 particularly prominent. The advantage of seeing individual nuisance parameter rankings, as op-
 1785 posed to impacts of categories in aggregate, is that particularly pathological NP's are easier to see;
 1786 in particular, jet energy resolution and $Z+jets p_T^V$ systematic from the pull comparison plots show
 up with high rankings. Yellow bands are pre-fit impact on μ .

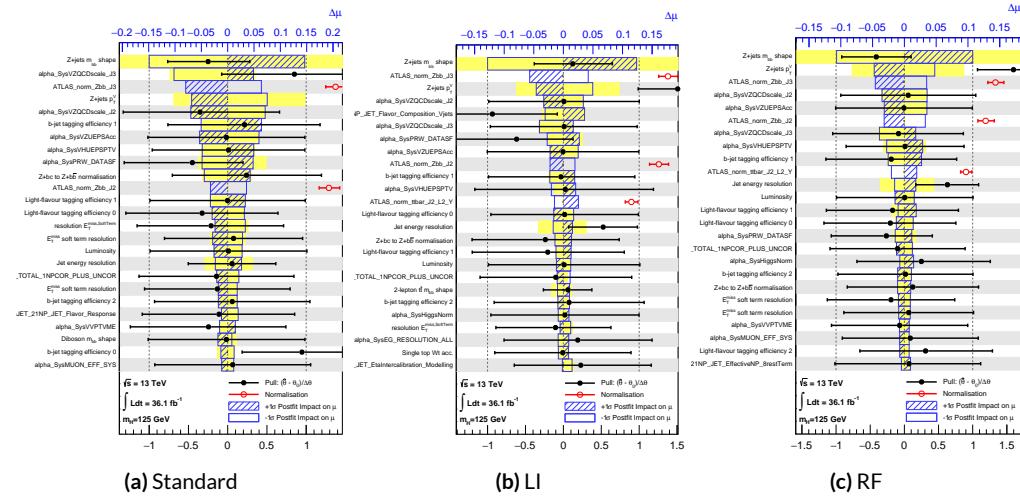


Figure 7.13: Plots for the top 25 nuisance parameters according to their postfit impact on $\hat{\mu}$ for the standard (a), LI (b), and RF (c) variable sets.

1787

1788 This is consistent with the picture of NP's taken in aggregate categories in Tables 7.5 and 7.6,
 1789 known as “breakdowns,” with $Z+jets$ in particular featuring prominently. Of particular interest

¹⁷⁹⁰ is also the lower impact of MC stats in the observed fit.

	Std-KF	LI+MET	RF
Total	+0.305 / -0.277	+0.324 / -0.292	+0.319 / -0.288
DataStat	+0.183 / -0.179	+0.190 / -0.186	+0.188 / -0.184
FullSyst	+0.244 / -0.212	+0.262 / -0.226	+0.258 / -0.221
Floating normalizations	+0.092 / -0.084	+0.098 / -0.079	+0.094 / -0.076
All normalizations	+0.093 / -0.084	+0.098 / -0.079	+0.094 / -0.076
All but normalizations	+0.214 / -0.179	+0.229 / -0.188	+0.224 / -0.182
Jets, MET	+0.052 / -0.043	+0.041 / -0.034	+0.047 / -0.037
Jets	+0.034 / -0.029	+0.033 / -0.028	+0.032 / -0.026
MET	+0.035 / -0.027	+0.015 / -0.012	+0.020 / -0.016
BTag	+0.064 / -0.051	+0.063 / -0.031	+0.059 / -0.032
BTag b	+0.053 / -0.041	+0.061 / -0.028	+0.055 / -0.025
BTag c	+0.011 / -0.010	+0.006 / -0.005	+0.007 / -0.006
BTag light	+0.030 / -0.027	+0.016 / -0.013	+0.022 / -0.019
Leptons	+0.021 / -0.012	+0.022 / -0.014	+0.023 / -0.014
Luminosity	+0.039 / -0.022	+0.039 / -0.022	+0.040 / -0.022
Diboson	+0.049 / -0.028	+0.047 / -0.026	+0.047 / -0.026
Model Zjets	+0.106 / -0.105	+0.113 / -0.110	+0.102 / -0.099
Zjets flt. norm.	+0.039 / -0.053	+0.024 / -0.029	+0.021 / -0.031
Model Wjets	+0.000 / -0.000	+0.000 / -0.000	+0.000 / -0.000
Wjets flt. norm.	+0.000 / -0.000	+0.000 / -0.000	+0.000 / -0.000
Model ttbar	+0.015 / -0.013	+0.032 / -0.017	+0.030 / -0.016
Model Single Top	+0.004 / -0.003	+0.009 / -0.008	+0.005 / -0.004
Model Multi Jet	+0.000 / -0.000	+0.000 / -0.000	+0.000 / -0.000
Signal Systematics	+0.003 / -0.003	+0.003 / -0.003	+0.003 / -0.003
MC stat	+0.097 / -0.094	+0.108 / -0.103	+0.107 / -0.104

Table 7.5: Summary of impact of various nuisance parameter categories on the error on μ for Asimov fits for the standard, LI, and RF variable sets.

	Std-KF	LI+MET	RF
$\hat{\mu}$	1.1079	0.5651	0.6218
Total	+0.381 / -0.360	+0.339 / -0.316	+0.322 / -0.299
DataStat	+0.214 / -0.211	+0.210 / -0.205	+0.201 / -0.197
FullSyst	+0.315 / -0.292	+0.267 / -0.241	+0.252 / -0.225
Floating normalizations	+0.120 / -0.122	+0.095 / -0.089	+0.082 / -0.079
All normalizations	+0.121 / -0.123	+0.095 / -0.090	+0.082 / -0.079
All but normalizations	+0.279 / -0.254	+0.228 / -0.200	+0.213 / -0.184
Jets, MET	+0.076 / -0.065	+0.045 / -0.043	+0.038 / -0.033
Jets	+0.047 / -0.040	+0.044 / -0.041	+0.027 / -0.024
MET	+0.055 / -0.046	+0.015 / -0.015	+0.012 / -0.010
BTag	+0.083 / -0.079	+0.041 / -0.031	+0.041 / -0.035
BTag b	+0.063 / -0.059	+0.032 / -0.022	+0.031 / -0.026
BTag c	+0.018 / -0.017	+0.008 / -0.007	+0.010 / -0.009
BTag light	+0.051 / -0.046	+0.024 / -0.021	+0.025 / -0.022
Leptons	+0.022 / -0.011	+0.015 / -0.008	+0.019 / -0.008
Luminosity	+0.044 / -0.022	+0.026 / -0.006	+0.027 / -0.008
Diboson	+0.049 / -0.026	+0.025 / -0.013	+0.027 / -0.017
Model Zjets	+0.156 / -0.162	+0.133 / -0.133	+0.115 / -0.117
Zjets flt. norm.	+0.061 / -0.089	+0.041 / -0.064	+0.028 / -0.056
Model Wjets	+0.000 / -0.001	+0.000 / -0.001	+0.000 / -0.001
Wjets flt. norm.	+0.000 / -0.001	+0.000 / -0.001	+0.000 / -0.001
Model ttbar	+0.015 / -0.024	+0.018 / -0.005	+0.017 / -0.009
Model Single Top	+0.005 / -0.003	+0.010 / -0.008	+0.007 / -0.004
Model Multi Jet	+0.000 / -0.001	+0.000 / -0.001	+0.000 / -0.001
Signal Systematics	+0.005 / -0.004	+0.009 / -0.006	+0.005 / -0.006
MC stat	+0.140 / -0.143	+0.132 / -0.131	+0.128 / -0.129

Table 7.6: Summary of impact of various nuisance parameter categories on the error on $\hat{\mu}$ for observed fits for the standard, LI, and RF variable sets.

1791 7.6 POSTFIT DISTRIBUTIONS

1792 Finally, postfit distributions for the MVA discriminant (m_{bb}) distribution in the signal (top $e - \mu$
1793 control) region for the standard, Lorentz Invariant, and RestFrames variable sets are shown. It is
1794 generally considered good practice to check the actual postfit distributions of discriminating quan-
1795 tities used to make sure there is good agreement. ^{††} It should be noted that agreement is not always
1796 great when “eyeballing” a distribution, as fits are messy and $V+hf$ modeling is notoriously hard.
1797 This is particularly true in the VZ fit since normalizations for $Z+hf$ in particular are derived using
1798 VH optimized sidebands. This is also why a lot of these plots are presented as log plots (which hide
1799 disagreement better; the general argument goes that one has the ratio plots on the bottom and log
1800 plots allow one to see rare backgrounds in plots).

^{††}Sometimes distributions of input variables (MC histograms scaled by their postfit normalizations) are also used.

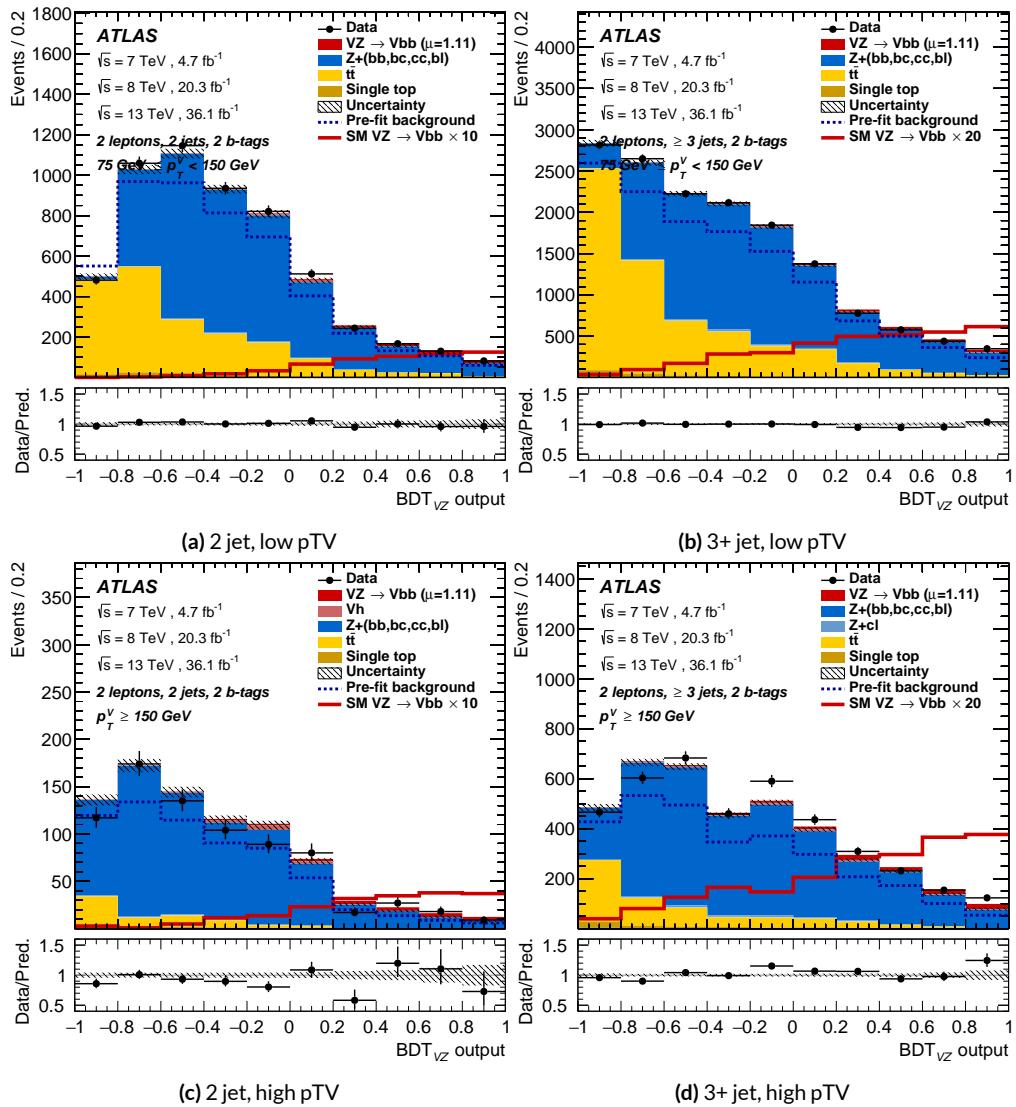


Figure 7.14: Postfit BDT_{VZ} plots in the signal region for the standard variable set.

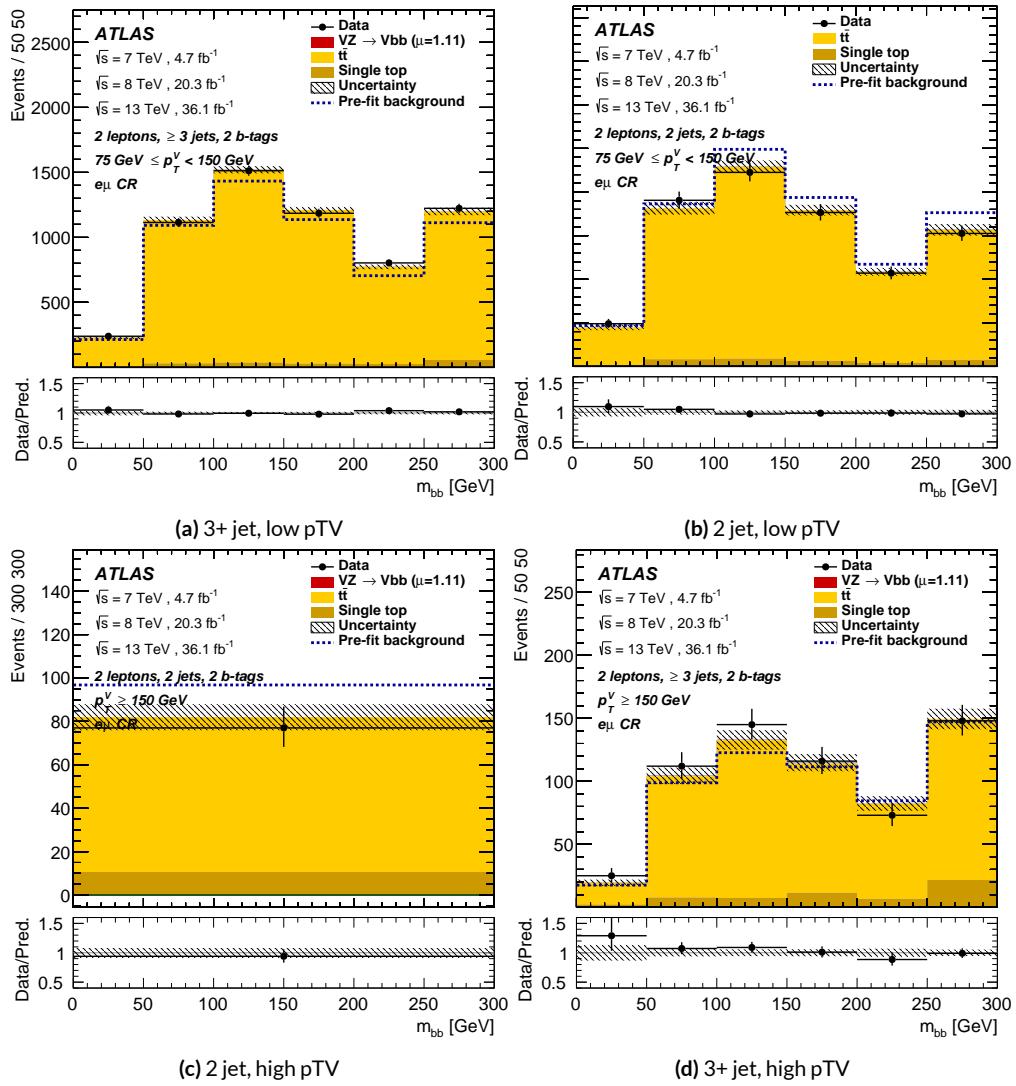


Figure 7.15: Postfit m_{bb} plots in the top $e - \mu$ CR for the standard variable set.

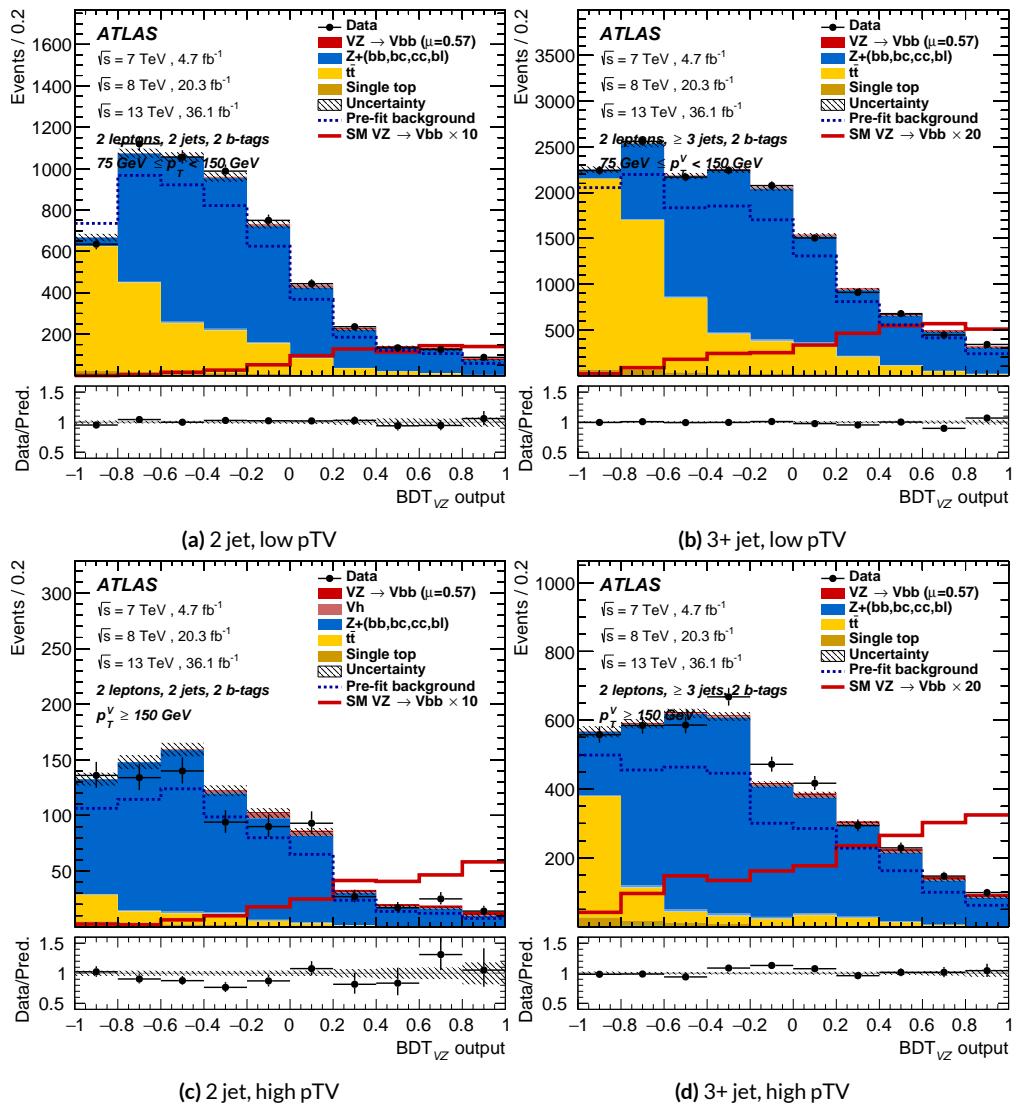


Figure 7.16: Postfit BDT_{VZ} plots in the signal region for the LI variable set.

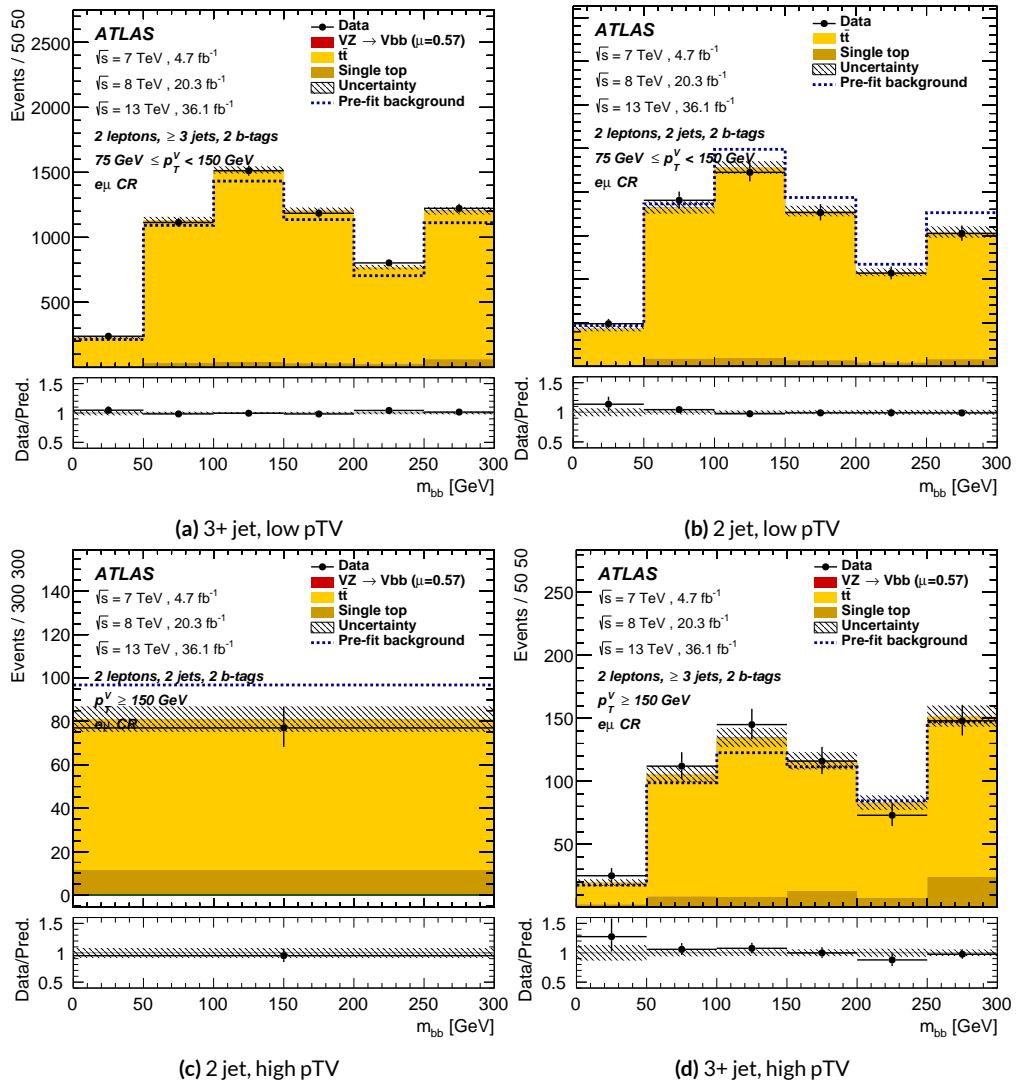


Figure 7.17: Postfit m_{bb} plots in the top $e - \mu$ CR for the LI variable set.

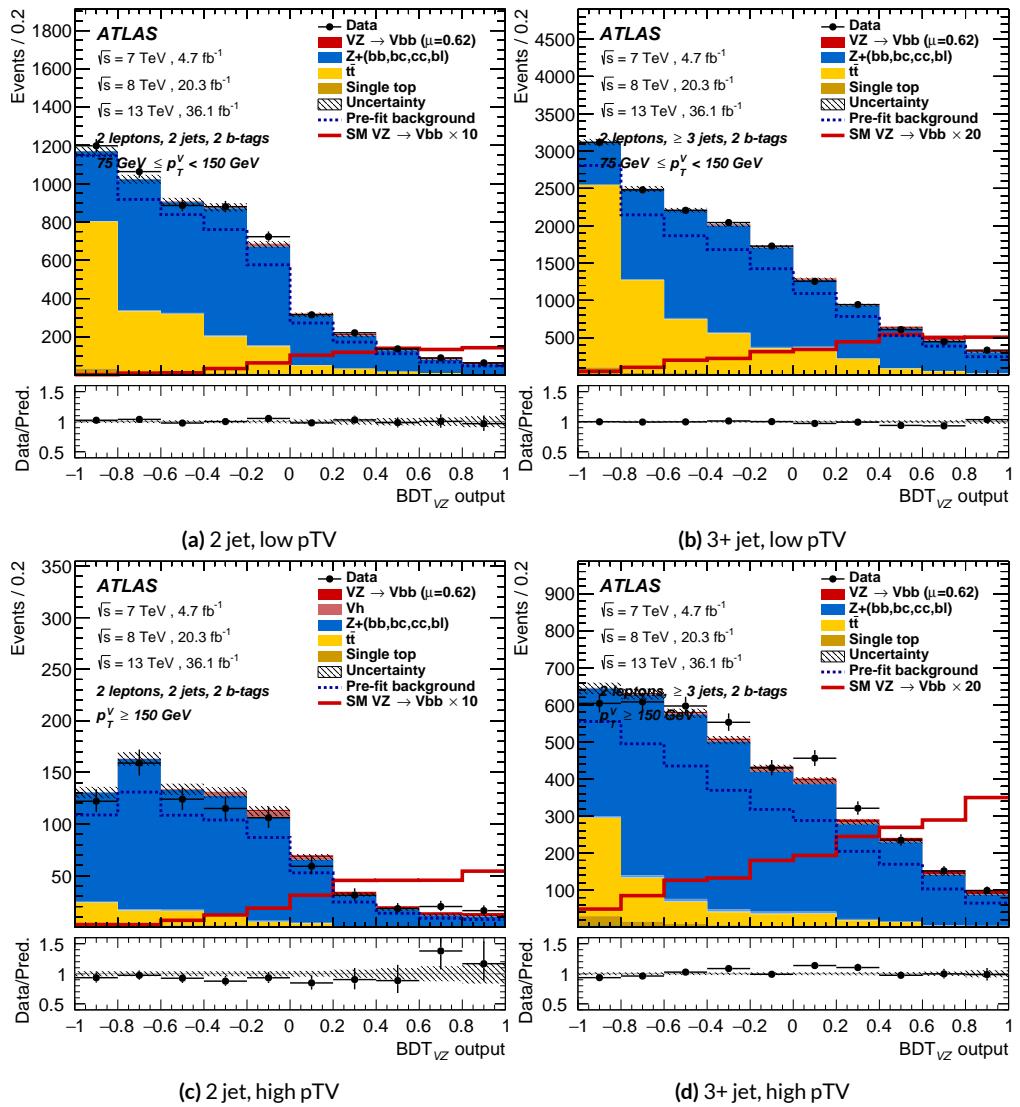


Figure 7.18: Postfit BDT_{VZ} plots in the signal region for the RF variable set.

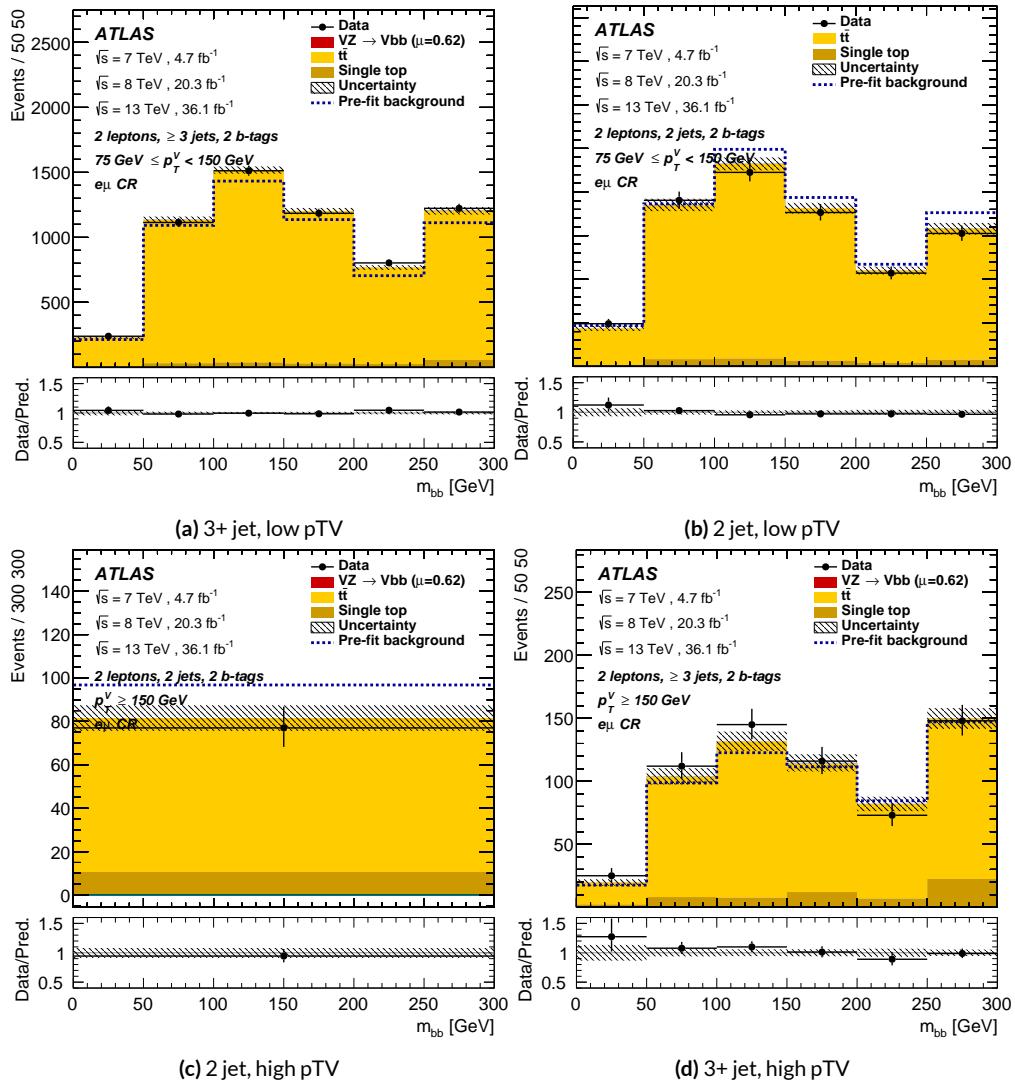


Figure 7.19: Postfit m_{bb} plots in the top $e - \mu$ CR for the RF variable set.

1801 7.7 VH FIT MODEL VALIDATION

1802 We now move onto the fit validation distributions and numbers for the VH fit of interest.

1803 7.7.1 NUISANCE PARAMETER PULLS

As can be seen in Figures 7.20–7.24, the fits for the three different variable sets are fairly similar from a NP pull perspective. Again, black is the standard variable set, red is the LI set, and blue is the RF set. The possible exception is the signal UE+PS p_T^V systematic, which looks very different for all three cases (underconstrained for the standard, but overconstrained for the novel variable cases), though this difference goes away in the ranking plot, meaning this is almost certainly an unphysical artifice of the faster HESSE inversion used to produce the pull comparison plots.

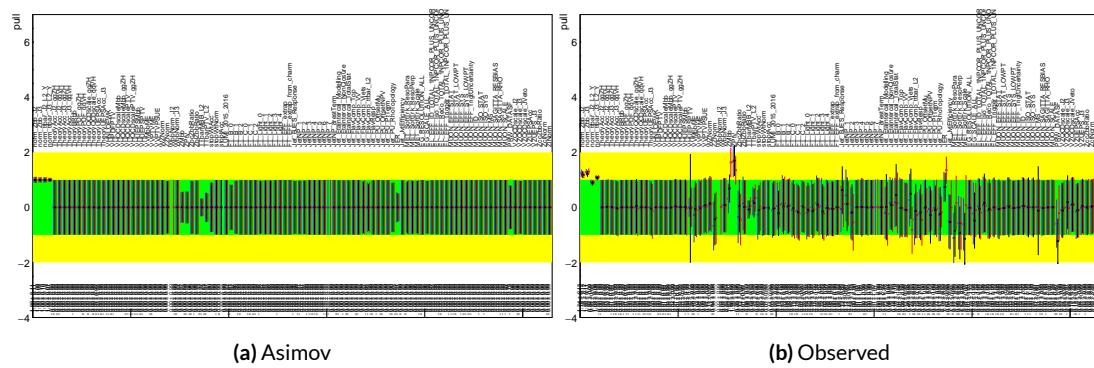


Figure 7.20: Pull comparison for all NP's but MC stats.

1810 Nuisance parameter correlation matrices (for correlations with magnitude at least 0.25) for all
1811 three variable set fits can be found in Figures 7.26–7.28.

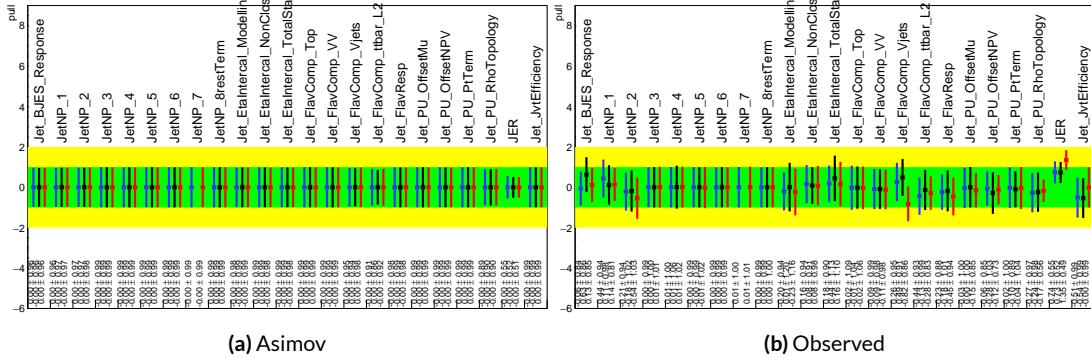


Figure 7.21: Pull comparison for jet NP's.

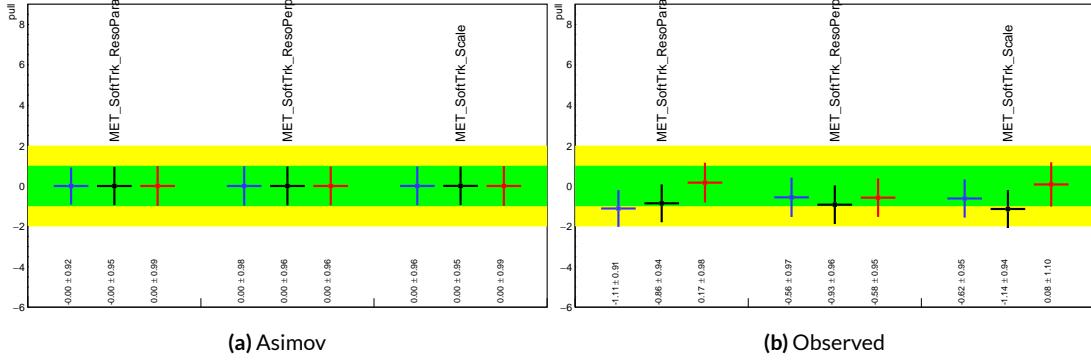


Figure 7.22: Pull comparison for MET NP's.

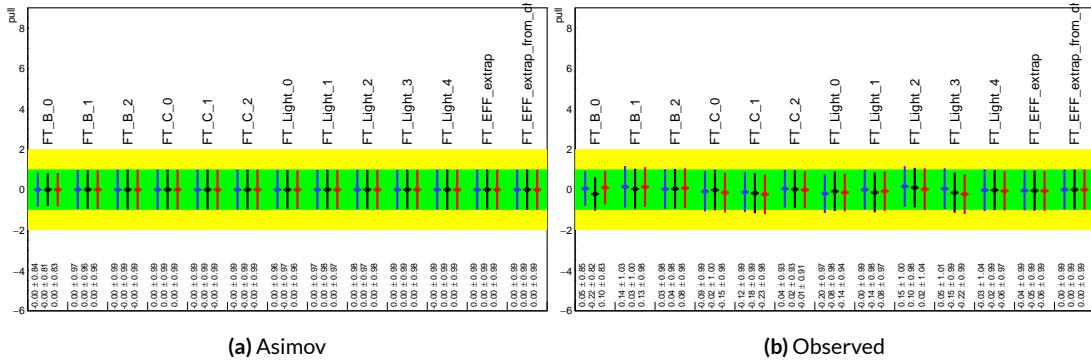


Figure 7.23: Pull comparison for Flavour Tagging NP's.

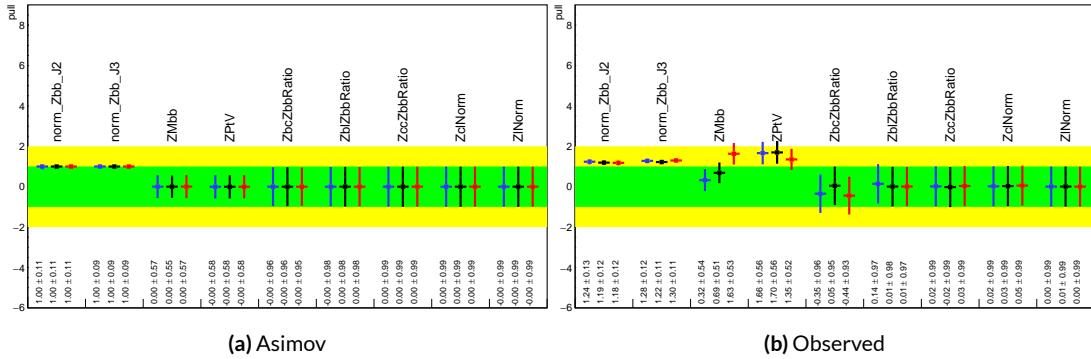


Figure 7.24: Pull comparison for $Z + \text{jets}$ NP's.

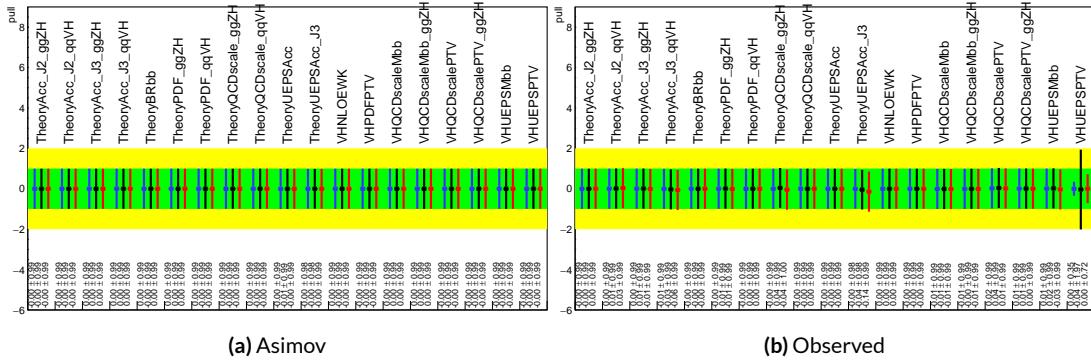


Figure 7.25: Pull comparison for signal process modeling NP's.

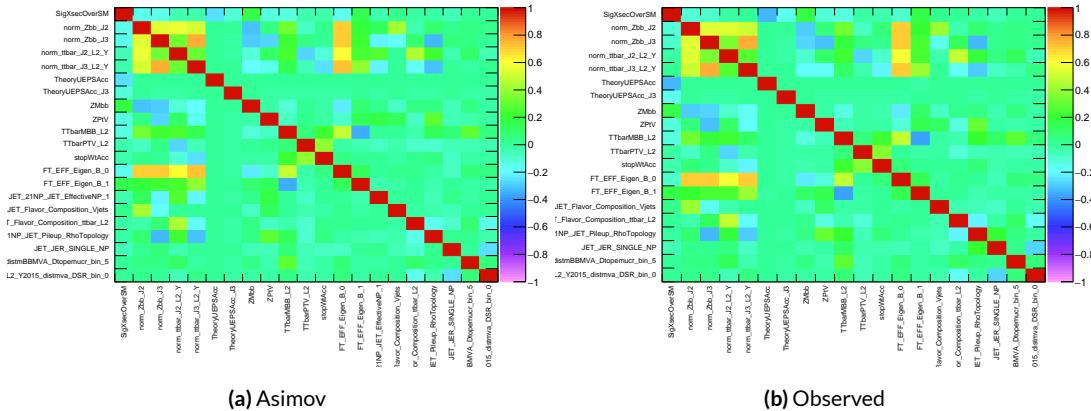


Figure 7.26: NP correlations for standard variable fits.

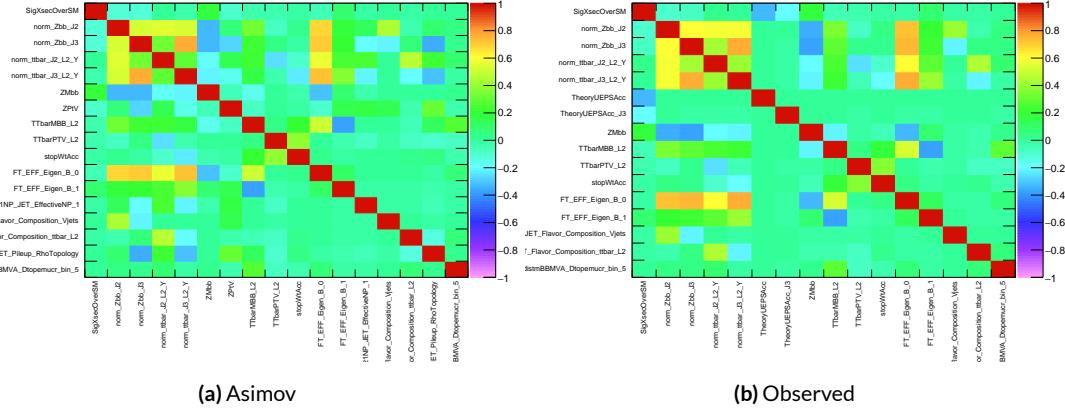


Figure 7.27: NP correlations for LI variable fits.

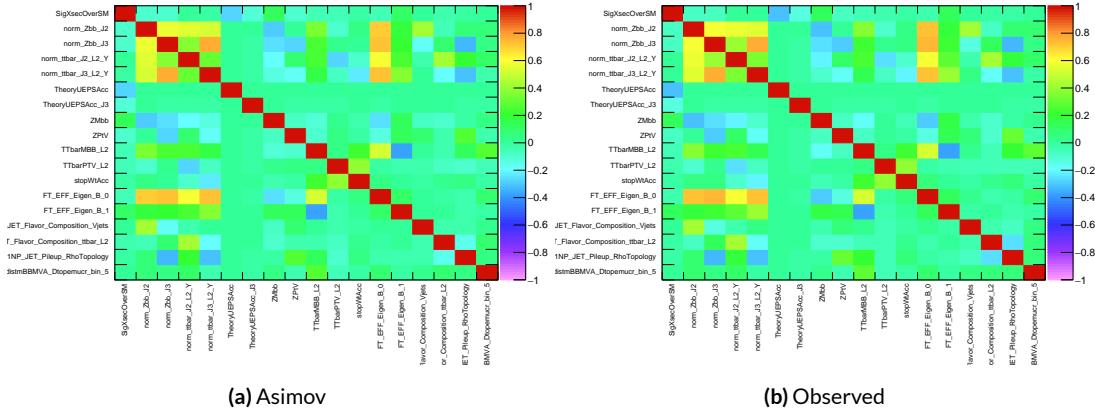


Figure 7.28: NP correlations for RF variable fits.

1812 7.7.2 FULL BREAKDOWN OF ERRORS

1813 A postfit ranking of nuisance parameters according to their impact on $\hat{\mu}$ for the different variable
 1814 sets may be found in Figure 7.29, with rankings being fairly similar. In particular, the signal UE+PS
 1815 p_T^V systematic is top-ranked for all three variable sets and also looks very similar, unlike in the pull
 1816 comparison plot, reiterating the importance of evaluating individually the impact of highly ranked
 1817 NP's. The $Z+jets p_T^V$ is highly pulled in all three cases, though this is less severe for the non-standard
 1818 set (it is off the scale for the standard variable ranking). The RF discriminant mitigates the effect of
 1819 poorly modeled jet energy resolution better than the other sets.

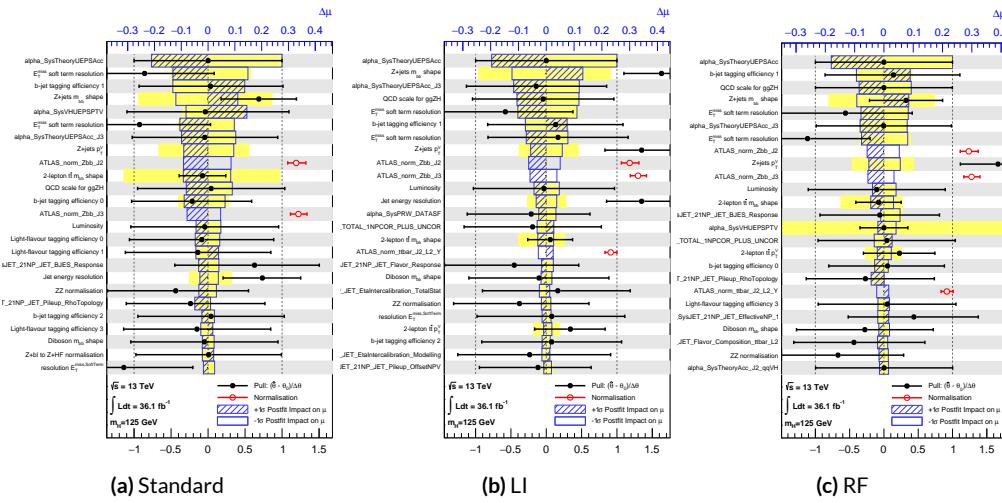


Figure 7.29: Plots for the top 25 nuisance parameters according to their postfit impact on $\hat{\mu}$ for the standard (a), LI (b), and RF (c) variable sets.

1820 The Asimov (Table 7.7) and observed (Table 7.8) breakdowns both consistently suggest that the
 1821 LI variable set does a better job of constraining systematic uncertainties than the standard set and
 1822 that the RF set does better still. It is also not surprising that the gain is more substantial in the ob-

¹⁸²³ served fit than in the Asimov fits, as in the latter there are the “penalty” terms from pulls in addition
¹⁸²⁴ to the overall broadening in the likelihood.

	Std-KF	LI+MET	RF
Total	+0.608 / -0.511	+0.632 / -0.539	+0.600 / -0.494
DataStat	+0.420 / -0.401	+0.453 / -0.434	+0.424 / -0.404
FullSyst	+0.440 / -0.318	+0.441 / -0.319	+0.425 / -0.284
Floating normalizations	+0.122 / -0.125	+0.110 / -0.111	+0.093 / -0.089
All normalizations	+0.128 / -0.129	+0.112 / -0.112	+0.099 / -0.092
All but normalizations	+0.403 / -0.274	+0.387 / -0.250	+0.382 / -0.227
Jets, MET	+0.180 / -0.097	+0.146 / -0.079	+0.122 / -0.083
Jets	+0.051 / -0.030	+0.044 / -0.035	+0.025 / -0.042
MET	+0.173 / -0.091	+0.140 / -0.074	+0.117 / -0.063
BTag	+0.138 / -0.136	+0.069 / -0.071	+0.076 / -0.078
BTag b	+0.125 / -0.125	+0.067 / -0.070	+0.073 / -0.075
BTag c	+0.018 / -0.016	+0.004 / -0.004	+0.005 / -0.005
BTag light	+0.057 / -0.051	+0.020 / -0.014	+0.009 / -0.018
Leptons	+0.013 / -0.012	+0.029 / -0.026	+0.012 / -0.023
Luminosity	+0.052 / -0.020	+0.050 / -0.016	+0.050 / -0.019
Diboson	+0.043 / -0.039	+0.035 / -0.031	+0.038 / -0.029
Model Zjets	+0.119 / -0.117	+0.124 / -0.127	+0.095 / -0.086
Zjets flt. norm.	+0.080 / -0.106	+0.052 / -0.092	+0.026 / -0.072
Model Wjets	+0.001 / -0.001	+0.001 / -0.001	+0.000 / -0.001
Wjets flt. norm.	+0.000 / -0.000	+0.000 / -0.000	+0.000 / -0.000
Model ttbar	+0.076 / -0.080	+0.025 / -0.035	+0.025 / -0.040
Model Single Top	+0.015 / -0.015	+0.002 / -0.004	+0.021 / -0.007
Model Multi Jet	+0.000 / -0.000	+0.000 / -0.000	+0.000 / -0.000
Signal Systematics	+0.262 / -0.087	+0.272 / -0.082	+0.290 / -0.088
MC stat	+0.149 / -0.136	+0.168 / -0.154	+0.153 / -0.136

Table 7.7: Expected error breakdowns for the standard, LI, and RF variable sets

	Std-KF	LI+MET	RF
$\hat{\mu}$	1.7458	1.6467	1.5019
Total	+0.811 / -0.662	+0.778 / -0.641	+0.731 / -0.612
DataStat	+0.502 / -0.484	+0.507 / -0.489	+0.500 / -0.481
FullSyst	+0.637 / -0.451	+0.591 / -0.415	+0.533 / -0.378
Floating normalizations	+0.153 / -0.143	+0.128 / -0.118	+0.110 / -0.109
All normalizations	+0.158 / -0.147	+0.130 / -0.119	+0.112 / -0.110
All but normalizations	+0.599 / -0.402	+0.544 / -0.354	+0.486 / -0.318
Jets, MET	+0.218 / -0.145	+0.198 / -0.113	+0.167 / -0.106
Jets	+0.071 / -0.059	+0.065 / -0.047	+0.036 / -0.051
MET	+0.209 / -0.130	+0.190 / -0.102	+0.152 / -0.077
BTAG	+0.162 / -0.166	+0.093 / -0.070	+0.115 / -0.099
BTAG b	+0.142 / -0.147	+0.090 / -0.066	+0.110 / -0.094
BTAG c	+0.022 / -0.021	+0.006 / -0.006	+0.007 / -0.007
BTAG light	+0.074 / -0.072	+0.025 / -0.022	+0.031 / -0.029
Leptons	+0.039 / -0.029	+0.035 / -0.031	+0.034 / -0.030
Luminosity	+0.079 / -0.039	+0.073 / -0.034	+0.069 / -0.032
Diboson	+0.047 / -0.043	+0.031 / -0.028	+0.029 / -0.028
Model Zjets	+0.164 / -0.152	+0.141 / -0.143	+0.101 / -0.105
Zjets flt. norm.	+0.070 / -0.109	+0.041 / -0.086	+0.033 / -0.083
Model Wjets	+0.001 / -0.001	+0.001 / -0.000	+0.001 / -0.001
Wjets flt. norm.	+0.000 / -0.000	+0.000 / -0.000	+0.000 / -0.000
Model ttbar	+0.067 / -0.102	+0.029 / -0.040	+0.040 / -0.048
Model Single Top	+0.015 / -0.020	+0.001 / -0.005	+0.004 / -0.006
Model Multi Jet	+0.000 / -0.000	+0.000 / -0.000	+0.000 / -0.000
Signal Systematics	+0.434 / -0.183	+0.418 / -0.190	+0.364 / -0.152
MC stat	+0.226 / -0.201	+0.221 / -0.200	+0.212 / -0.189

Table 7.8: Observed signal strengths, and error breakdowns for the standard, LI, and RF variable sets

1825 7.7.3 POSTFIT DISTRIBUTIONS AND S/B PLOTS

1826 Postfit distributions for the MVA discriminant (m_{bb}) distribution in the signal (top $e - \mu$ control)
1827 region for the standard, Lorentz Invariant, and RestFrames variable sets are found in Figures 7.30–
1828 7.35. Here, as in the VZ fit, agreement is reasonable. In a combined fit with all three channels, $Z+hf$
1829 normalizations in particular would be correlated across the 0- and 2-lepton channels, which might
1830 help to better constrain this mismodeling (and perhaps as a result some of the $Z+jets$ systematics as
1831 well).

1832 One final type of plot presented as a result is the binned $\log_{10} (S/B)$ in signal regions distribu-
1833 tions may be found in Figure 7.36. For these plots, one fills a histogram with the $\log_{10} (S/B)$ ratio in
1834 each postfit distribution bin weighted by the total number of events. In this case, a log plot is help-
1835 ful because the highest bins would be invisible on a linear plot. These distributions are allegedly use-
1836 ful for seeing where most of one's sensitivity lies. Practically, it is problematic if the pull (from the
1837 null hypothesis) is higher at lower S/B values, which may indicate a poorly optimized discriminant.

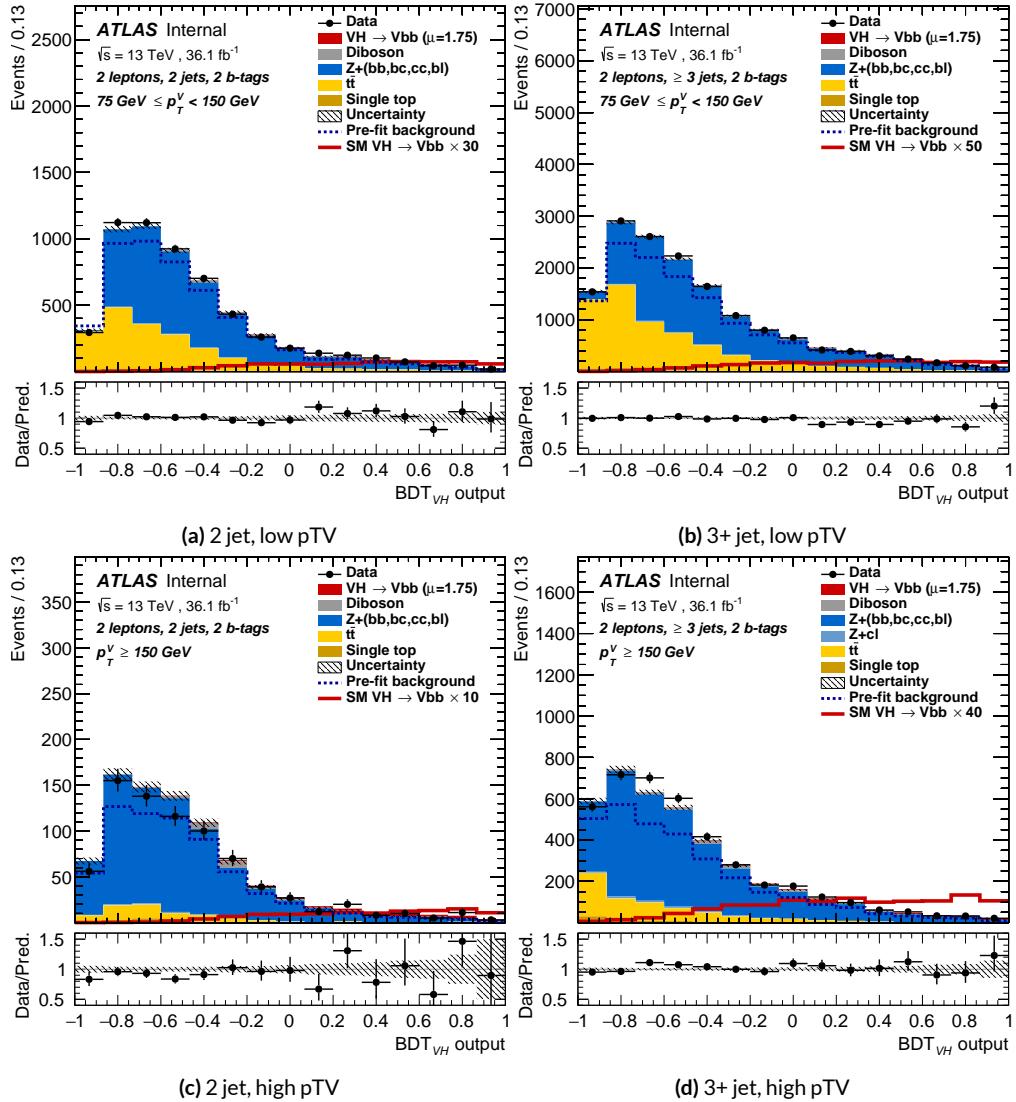


Figure 7.30: Postfit BDT_{VH} plots in the signal region for the standard variable set.

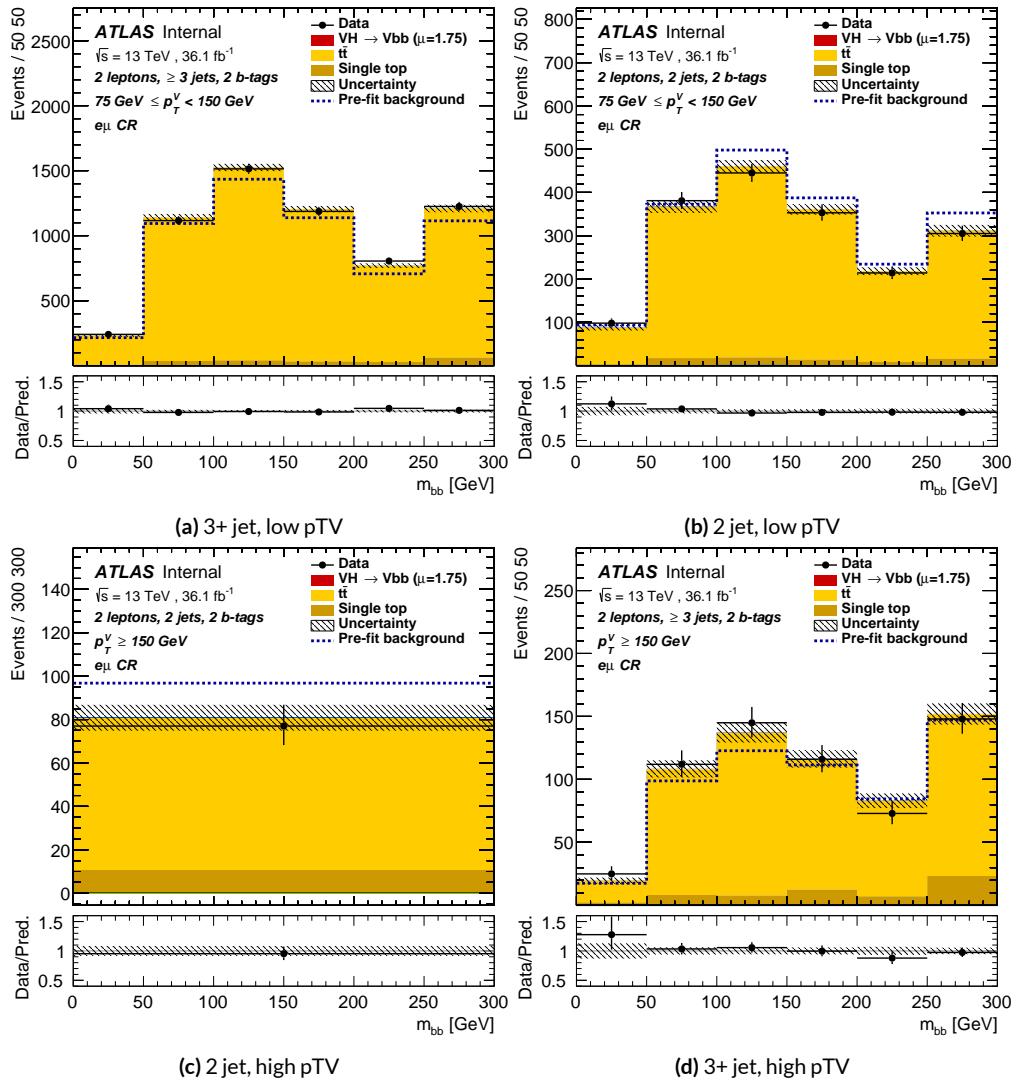


Figure 7.31: Postfit m_{bb} plots in the top $e - \mu$ CR for the standard variable set.

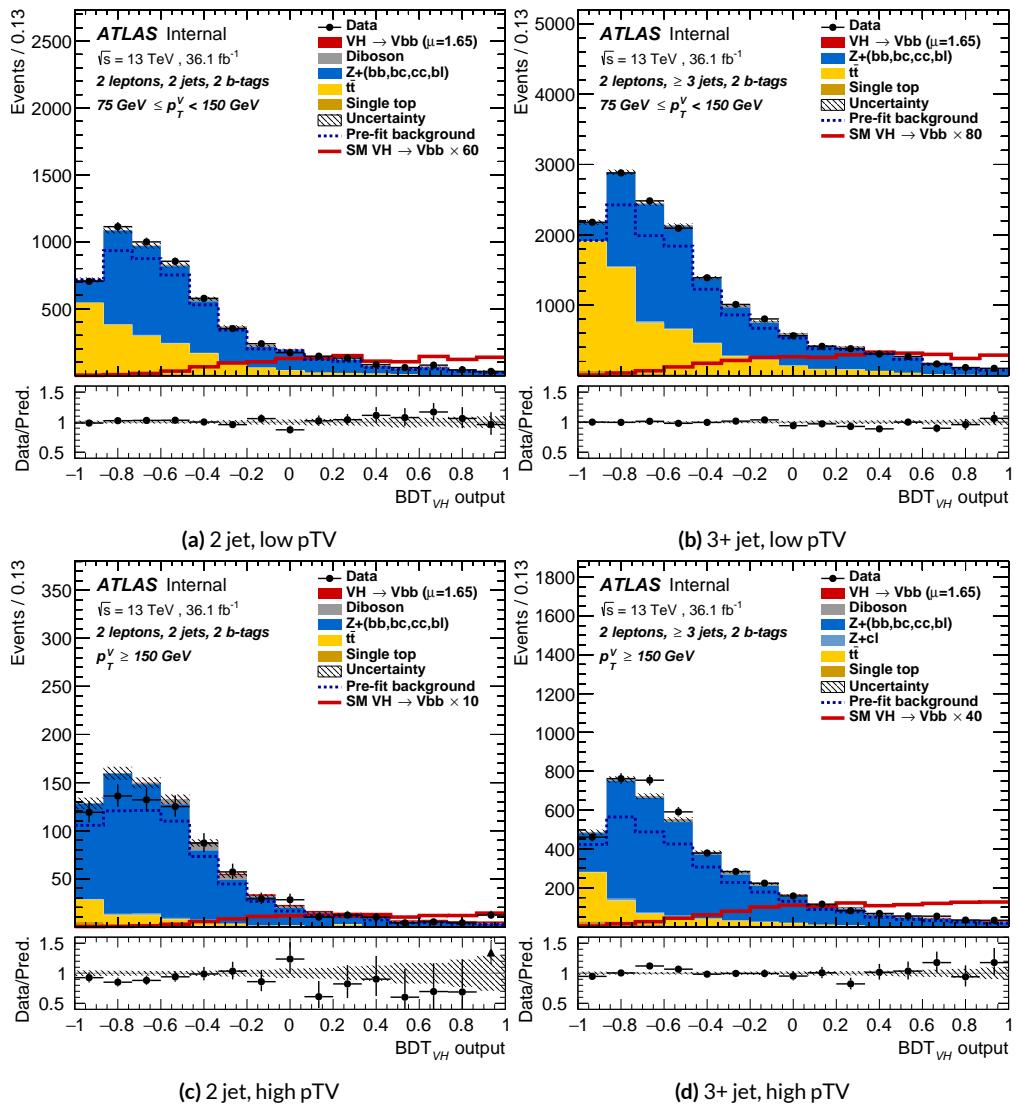


Figure 7.32: Postfit BDT_{VH} plots in the signal region for the LI variable set.

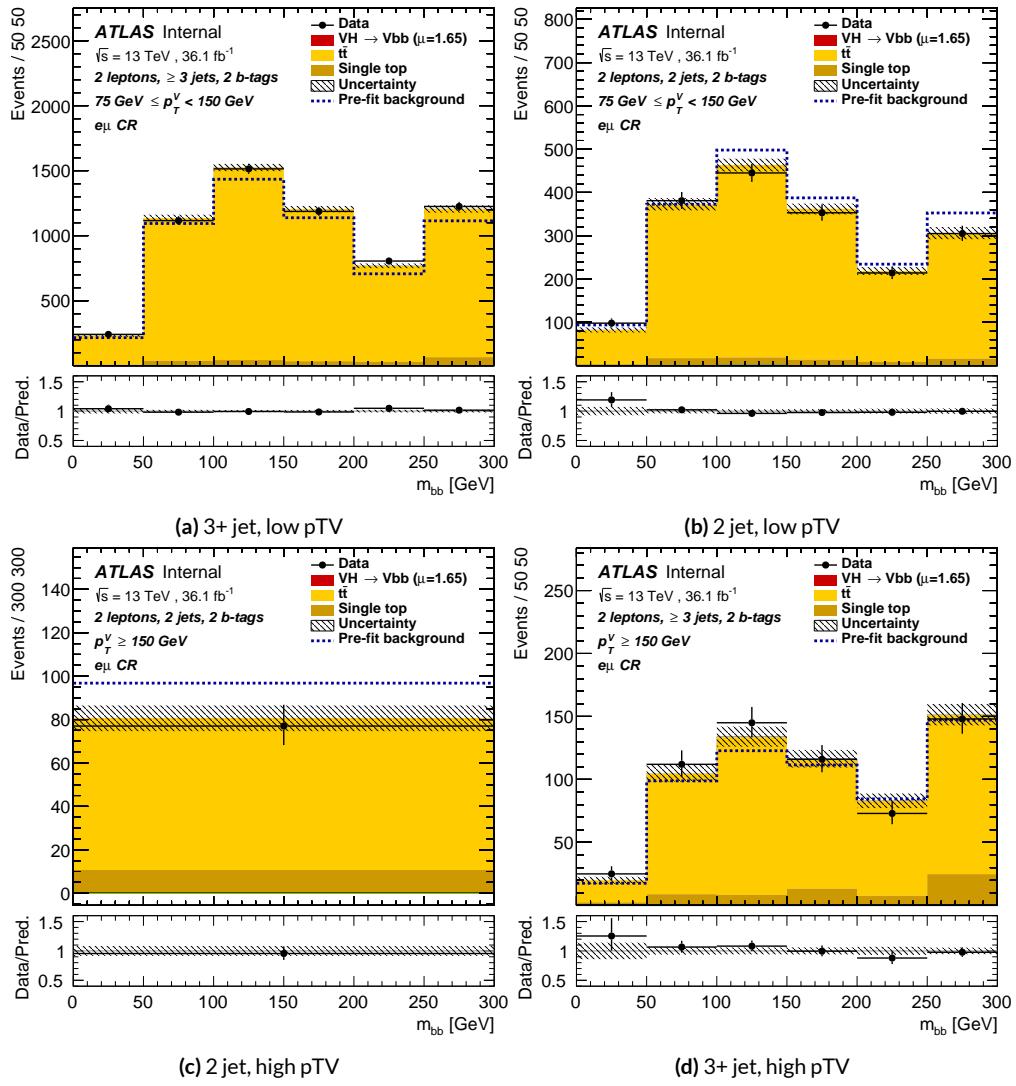


Figure 7.33: Postfit m_{bb} plots in the top $e - \mu$ CR for the LI variable set.

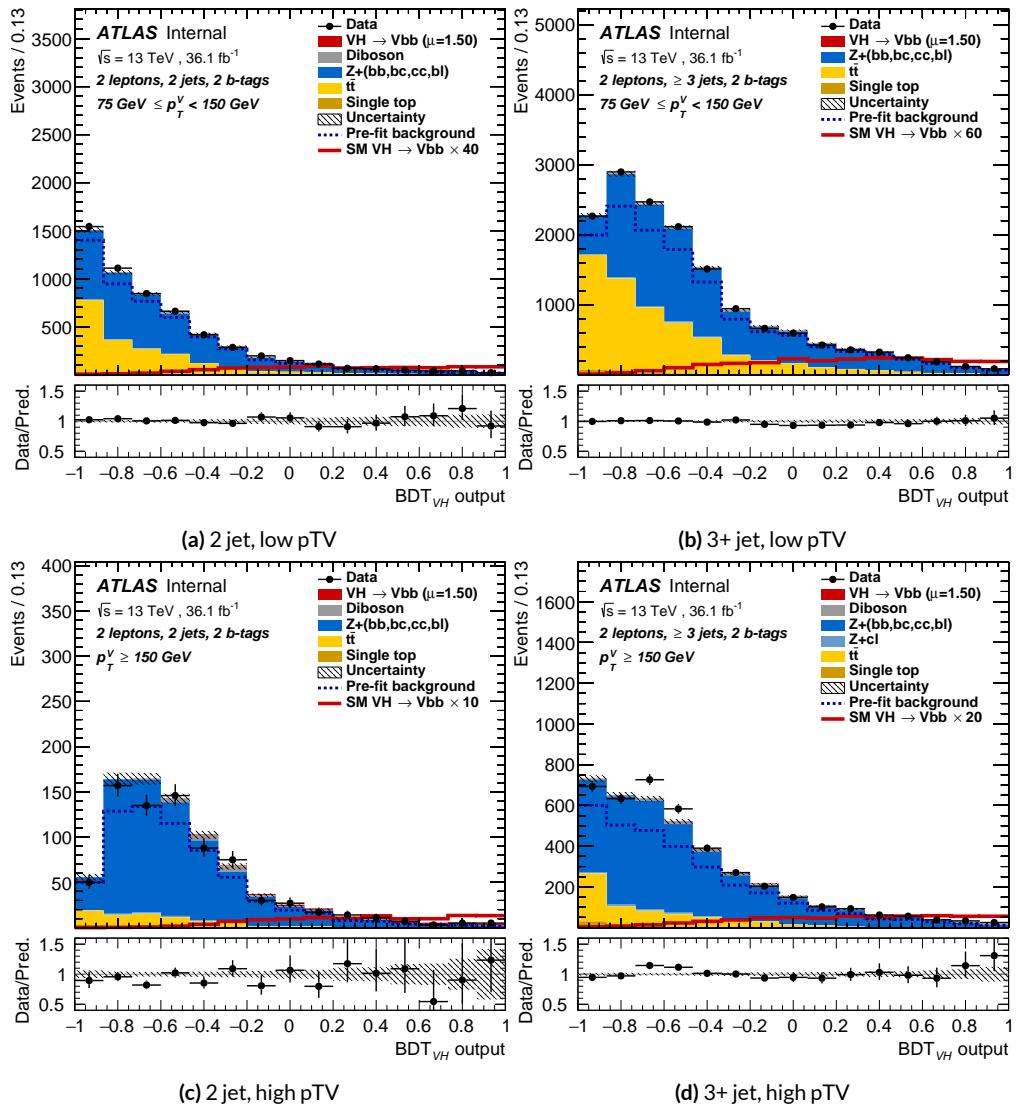


Figure 7.34: Postfit BDT_{VH} plots in the signal region for the RF variable set.

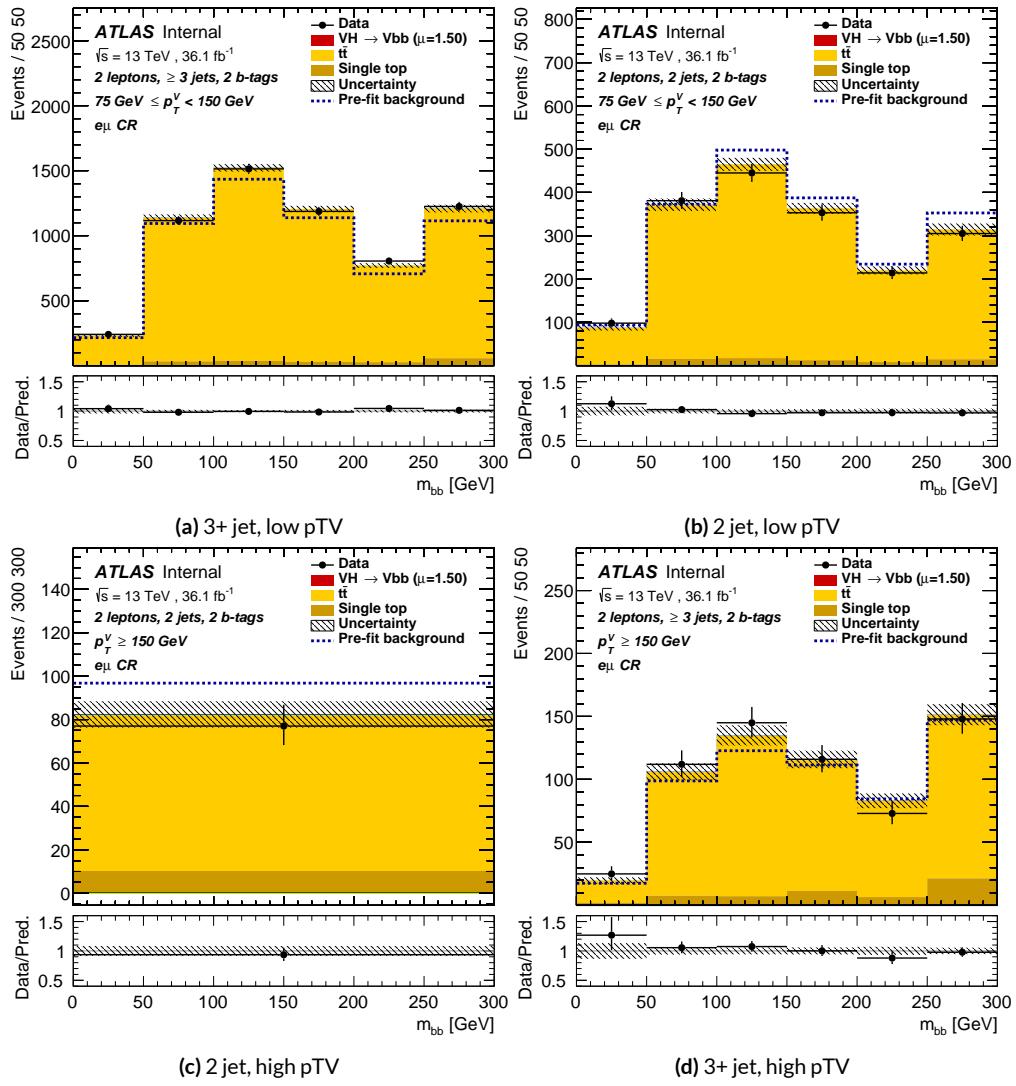


Figure 7.35: Postfit m_{bb} plots in the top $e - \mu$ CR for the RF variable set.

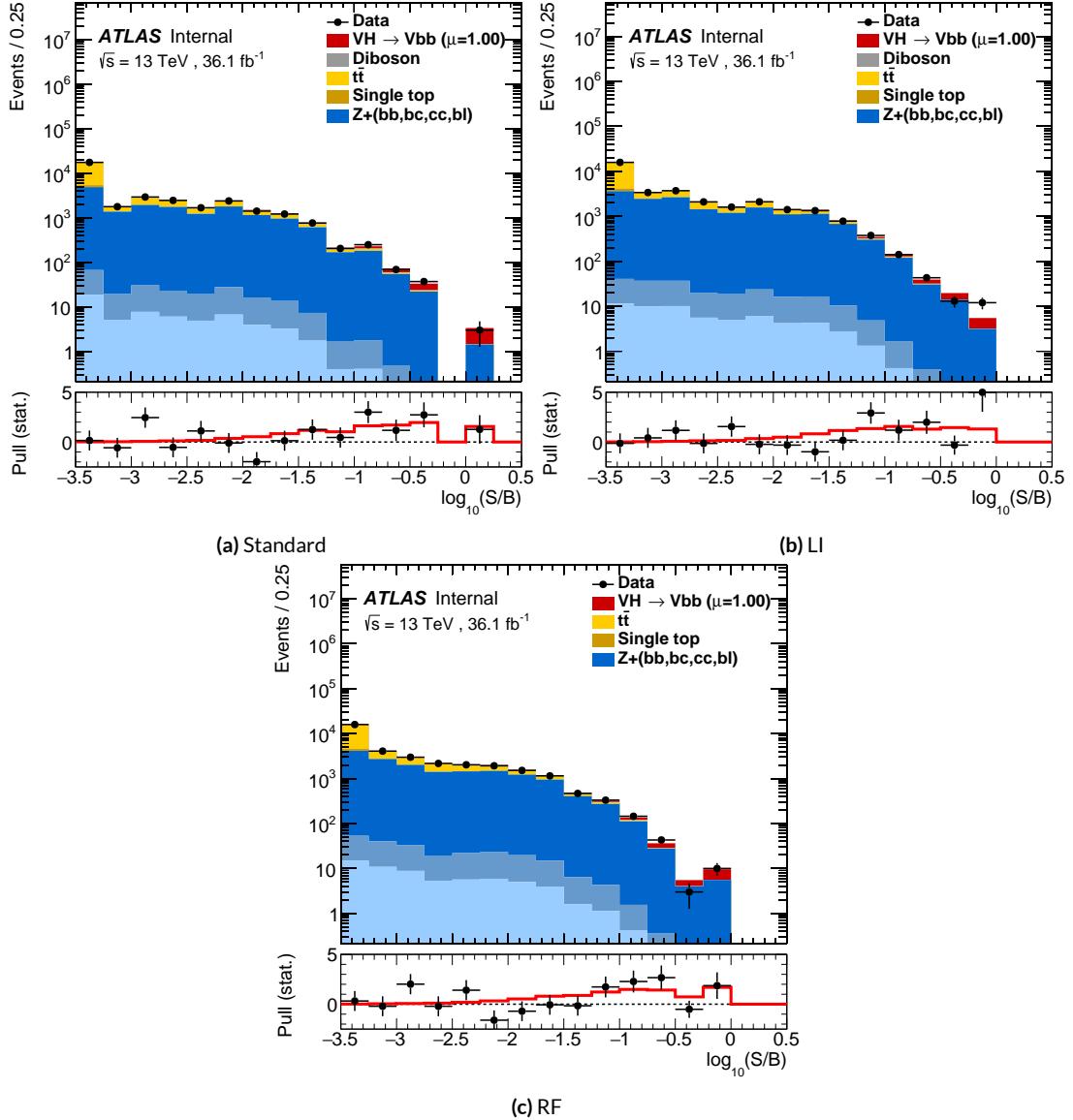


Figure 7.36: Binned S/B plots for the standard (a), LI (b), and RF (c) variable sets. Signal is weighted to $\mu = 1$ for comparison to the SM prediction.

*Kein Operationsplan reicht mit einiger Sicherheit
über das erste Zusammentreffen mit der feindlichen
Hauptmacht hinaus.*

Helmuth von Moltke

1838

8

1839

Fit Results

1840 THE RESULTS IN THIS CHAPTER were first reported in [60] and describe how the three different
1841 fit models detailed and validated Chapter 7, corresponding to the standard, RF, and LI variable sets
1842 described in Chapter 6 perform on actual VH fits. In particular sensitivities, nuisance parameter
1843 impacts, and signal strengths on expected fits to Asimov datasets and both expected and observed

1844 fits on the actual 36.1 fb^{-1} dataset are compared.

1845 Expected and observed sensitivities for the different variable sets may be found in Table 8.1. The
1846 RF fits feature the highest expected sensitivities, outperforming the standard set by 3.5% and 3.4%
1847 for fits to Asimov and observed datasets, respectively. The LI variable has a lower significance than
1848 both for expected fits to both Asimov and data with a 6.7% (1.7%) significance than the standard set
1849 for the Asimov (observed) dataset. While the fit using standard variables does have a higher observed
1850 significance than both the LI and RF fits, by 2.8% and 8.6%, respectively, these numbers should be
1851 viewed in the context of the best fit $\hat{\mu}$ values, discussed below. That is, the standard set may yield the
1852 highest sensitivity for this particular dataset, but this is not necessarily (and likely is not) the case for
1853 any given dataset.

	Standard	LI	RF
Expected (Asimov)	2.06	1.92	2.13
Expected (data)	1.76	1.73	1.80
Observed (data)	2.87	2.79	2.62

Table 8.1: Expected (for both data and Asimov) and observed significances for the standard, LI, and RF variable sets.

1854 A summary of fitted signal strengths and errors for both the Asimov (a) and observed (b) datasets
1855 are shown in Figure 8.1.* A summary of error breakdowns is given in Tables 8.2 (Asimov) and 8.3
1856 (observed) for total error, data statistics contributions, total systematic error contributions, and cat-
1857 egories for which the total impact is ≥ 0.1 for the standard fit. As is to be expected for both the
1858 Asimov and observed dataset fits, the contribution to the total error on μ arising from data statistics

*For reference, the standalone 2-lepton fit from the fiducial analysis is $2.11^{+0.50}_{-0.48}(\text{stat.})^{+0.64}_{-0.47}(\text{syst.})$

¹⁸⁵⁹ is nearly identical, since each set of fits uses the same selections and data.[†]

	Std-KF	LI+MET	RF
Total	+0.608 / -0.511	+0.632 / -0.539	+0.600 / -0.494
DataStat	+0.420 / -0.401	+0.453 / -0.434	+0.424 / -0.404
FullSyst	+0.440 / -0.318	+0.441 / -0.319	+0.425 / -0.284
Signal Systematics	+0.262 / -0.087	+0.272 / -0.082	+0.290 / -0.088
MET	+0.173 / -0.091	+0.140 / -0.074	+0.117 / -0.063
Flavor Tagging	+0.138 / -0.136	+0.069 / -0.071	+0.076 / -0.078
Model Zjets	+0.119 / -0.117	+0.124 / -0.127	+0.095 / -0.086

Table 8.2: Summary of error impacts on total μ error for principal categories in the Asimov standard, LI, and RF fits.

	Std-KF	LI+MET	RF
Total	+0.811 / -0.662	+0.778 / -0.641	+0.731 / -0.612
DataStat	+0.502 / -0.484	+0.507 / -0.489	+0.500 / -0.481
FullSyst	+0.637 / -0.451	+0.591 / -0.415	+0.533 / -0.378
Signal Systematics	+0.434 / -0.183	+0.418 / -0.190	+0.364 / -0.152
MET	+0.209 / -0.130	+0.190 / -0.102	+0.152 / -0.077
Flavor Tagging	+0.162 / -0.166	+0.093 / -0.070	+0.115 / -0.099
Model Zjets	+0.164 / -0.152	+0.141 / -0.143	+0.101 / -0.105

Table 8.3: Summary of error impacts on total $\hat{\mu}$ error for principal categories in the observed standard, LI, and RF fits.

¹⁸⁶⁰ The contribution from systematic uncertainties, however, does vary considerably across the vari-
¹⁸⁶¹ able sets. The Asimov fits are a best case scenario in the sense that, by construction, all NP's are equal
¹⁸⁶² to their predicted values (and so no "penalty" is paid for pulls on Gaussian NP's). The systematics er-
¹⁸⁶³ ror from the LI fit is slightly higher (subpercent) than that from the standard fit, and 4.6% higher er-
¹⁸⁶⁴ ror overall due to differences in data stats. The RF Asimov fit, however, has a 6.5% lower total error

[†]Though not exactly identical. Since the BDT's are different for the different variable sets, the binning (as determined by transformation D) and bin contents in each set are generally different, leading to slightly different data statistics errors.

1865 from systematics than the standard Asimov fit (and a 2.2% lower error overall). Moreover, for both
 1866 the LI and RF sets, errors are markedly smaller for the MET and Flavor Tagging categories, with the
 1867 RF fit also featuring a smaller errors on Z +jets modeling; the only notable exception to this trend in
 1868 Asimov fits are the signal systematics.

1869 These trends are more pronounced in the observed fits. As can be seen in Table 8.3, both the LI
 1870 and RF fits have smaller errors from systematic uncertainties, both overall and in all principal cate-
 1871 gories, with the LI and RF fits having 7.5% (3.7%) and 16% (8.8%) lower systematics (total) error on
 1872 $\hat{\mu}$, respectively.

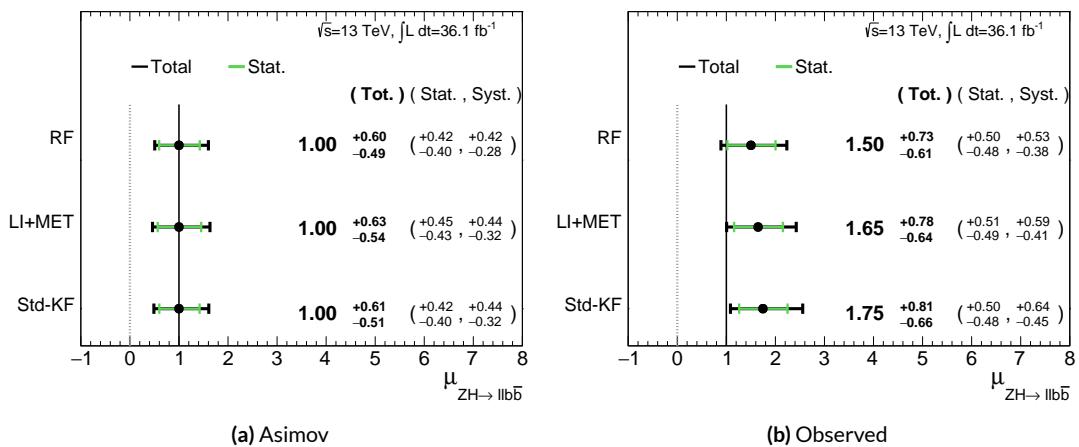


Figure 8.1: μ summary plots for the standard, LI, and RF variable sets. The Asimov case (with $\mu = 1$ by construction) is in (a), and $\hat{\mu}$ best fit values and error summary are in (b).

1873 Studying the performance of the Lorentz Invariant and RestFrames variable sets at both a data
 1874 statistics only context and with the full fit model in the $ZH \rightarrow \ell\ell b\bar{b}$ channel of the $VH(b\bar{b})$ anal-
 1875 ysis suggests that these variables may offer a potential method for better constraining systematic un-
 1876 certainties in $VH(b\bar{b})$ searches as more orthogonal bases in describing the information in collision

1877 events.

1878 The marginally worse performance of the LI and RF variables (7.9% and 6.9%, respectively) with
1879 respect to the standard variable at a stats only level illustrates that neither variable set has greater
1880 intrinsic descriptive power in the absence of systematics in this closed final state. Hence, any gains
1881 from either of these variable sets in a full fit come from improved treatment of systematic uncertain-
1882 ties.

1883 With full systematics, the LI variable set narrows the sensitivity gap somewhat, with lower signif-
1884 icances by 6.7% (1.7%) on expected fits to Asimov (data) and by 2.8% on observed significances. The
1885 RF variable set outperforms the standard set in expected fits with 3.5% (3.4%) higher significance
1886 on Asimov (data), but has an 8.6% lower observed significance, though the observed significances
1887 should be viewed in the context of observed $\hat{\mu}$ values.

1888 Moreover, the LI and RF variable sets generally perform better in the context of the error on μ .
1889 The LI fit is comparable to the standard set on Asimov data and has a 7.5% lower total systematics er-
1890 ror on $\hat{\mu}$ on observed data, while the RF fit is lower in both cases, with systematics error being 6.5%
1891 (16%) lower on Asimov (observed) data.

1892 These figures of merit suggest that both the LI and RF variables are more orthogonal than the
1893 standard variable set used in the fiducial analysis. Moreover, the RF variable set does seem to con-
1894 sistently perform better than the LI set. Furthermore, both variable sets have straightforward exten-
1895 sions to the other lepton channels in the $VH(b\bar{b})$ analysis. The magnitude of any gain from the
1896 more sophisticated treatment of E_T^{miss} in these extensions is beyond the scope of these studies, but
1897 the performance in this closed final state do suggest that there is some value to be had in these non-

¹⁸⁹⁸ standard descriptions independent of these considerations.

*If I have seen further, it is by standing on ye shoulders of
giants.*

Isaac Newton

9

1899

1900

Measurement Combinations

1901 WHILE THE DISCUSSION thus far has focused on improvements looking towards future in just the
1902 $ZH \rightarrow \ell\ell b\bar{b}$ channel, any actual result for SM $VH(b\bar{b})$ combines all channels and all available
1903 datasets. Using additional channels at a given center of mass energy is straightforward since the fit
1904 model is designed with this combination in mind. This will be described in the context of the 36.1

1905 fb^{-1} 13 TeV result in Section 9.1.

1906 Combining dataset results (known as “workspaces”) from different center of mass energies is not
1907 so simple an exercise since both the underlying physics (and its associated modeling) and the treat-
1908 ment of key experimental considerations, like flavor tagging, and their associated systematics change
1909 from dataset to dataset. A combined fit model must take these considerations into account, and the
1910 formulation of the fit model combining the Run 1 ($\sqrt{s} = 7 \text{ TeV}$ with 4.7 fb^{-1} of data, and $\sqrt{s} = 8$
1911 TeV with 20.3 fb^{-1} of data) and Run 2 ($\sqrt{s} = 13 \text{ TeV}$ with 36.1 fb^{-1}) SM $VH(b\bar{b})$ results is the topic
1912 of Section 9.2. Its results, as reported in [3], are given in 9.3.

1913 9.1 LEPTON CHANNEL COMBINATIONS

1914 Preparation of results for the o- and i-lepton channels is functionally very similar to above discus-
1915 sions in Chapters 4, 5, 6, and 7. From a modeling standpoint, each channel comes in with different
1916 dominating background processes and dedicated simulation, described at length in [21], though
1917 there is a lot of overlap. In particular, $t\bar{t}$, , and diboson production is important for all three chan-
1918 nels. The only important process not discussed here is contribution from multijet background,
1919 which is a small but important background in the i-lepton case.

1920 With respect to object definitions, no new objects are defined in the o- and i-lepton analyses,
1921 though the treatment of \vec{E}_T^{miss} is of greater concern in these channels, as \vec{E}_T^{miss} is a part of the signal
1922 final states in these channels. Triggers and event selection requirements are optimized by channel. A
1923 full list of requirements is given in Table 9.1 from [4].

1924 The mechanics of MVA training and implementation is very much the same across analysis chan-

Common Selections	
Jets	≥ 2 central jets
b -jets	2 b -tagged signal jets
Leading jet p_T	> 45 GeV
$ \Delta R(\text{jet1}, \text{jet2}) $ (cut-based only)	$\leq 1.8 (p_T^V < 200 \text{ GeV}), \leq 1.2 (p_T^V > 200 \text{ GeV})$
o Lepton	
Trigger	HLT_xe70, xe90_mht, and xe110_mht
Leptons	o VH-loose lepton
\vec{E}_T^{miss}	> 150 GeV
S_T	> 120 (2 jets), > 150 GeV (3 jets)
$ \min \Delta\phi(\vec{E}_T^{\text{miss}}, \text{jet}) $	$> 20^\circ$ (2jet), $> 30^\circ$ (3jet)
$ \Delta\phi(\vec{E}_T^{\text{miss}}, b) $	$> 120^\circ$
$ \Delta\phi(\text{jet1}, \text{jet2}) $	$< 140^\circ$
$ \Delta\phi(\vec{E}_T^{\text{miss}}, E_{T, \text{trk}}^{\text{miss}}) $	$< 90^\circ$
p_T^V regions (BDT)	> 150 GeV
p_T^V regions (cut-based)	$[150, 200]$ GeV, $[200, \infty]$ GeV
1 Lepton	
Trigger	e channel: un-prescaled single electron Tables 5 and 6 of Ref. [44]
Leptons	μ channel: see o-lepton triggers 1 WH-signal lepton
\vec{E}_T^{miss}	> 1 VH-loose lepton veto
m_{top}	> 30 GeV (e channel)
m_T^W (cut-based only)	< 225 GeV or $m_{bb} > 75$ GeV
p_T^V regions (BDT)	< 120 GeV
p_T^V regions (cut-based)	> 150 GeV $[150, 200]$ GeV, $[200, \infty]$ GeV
2 Lepton	
Trigger	un-prescaled single lepton Tables 5 and 6 of Ref. [44]
Leptons	2 VH-loose leptons (≥ 1 ZH-signal lepton)
$m_{\ell\ell}$	Same flavor, opposite-charge for $\mu\mu$ $81 < m_{\ell\ell} < 101$ GeV
\vec{E}_T^{miss} significance (cut-based)	$\vec{E}_T^{\text{miss}}/\sqrt{H_T} < 3.5\sqrt{\text{GeV}}$
p_T^V regions (BDT)	$[75, 150], [150, \infty]$ GeV
p_T^V regions (cut-based)	$[75, 150], [150, 200], [200, \infty]$ GeV

Table 9.1: Summary of the signal event selection in the 0-, 1- and 2-lepton analyses.
186

1925 nels, with the major difference being the selection of input variables to the BDT discriminants. For
1926 a discussion of how the different final states affect variable selection see the discussion in Section 1.7
1927 and in particular Table for the input variables used in the final analysis.

1928 As previously mentioned, the fit model is flexible enough to seamlessly integrate combined results
1929 for the three separate lepton channels for a given dataset. Most nuisance parameters are treated as
1930 common across all fit regions. Some regions will have greater bearing on certain nuisance parameters—
1931 2-lepton regions, virtually free of W +jets events, will have virtually no effect on W +jets modeling
1932 systematics, for example. One notable exception are NP's with `_L[012]` suffixes, which are pre-
1933 dominantly the double ratio systematics discussed in Section 4.2.2 and function similar to the 2 vs.
1934 greater than 3 jet event double ratio systematics.

1935 Adding different channels has great potential to constrain certain systematic uncertainties. Look-
1936 ing at the breakdown of systematic uncertainties in 2-lepton fits in Table 7.8, for example, multijet
1937 and W +jets NP's contribute virtually no uncertainty, while \vec{E}_T^{miss} and Z +jets have very high impacts
1938 on the uncertainty on $\hat{\mu}$. 1-lepton events will bring up the multijet and W +jets uncertainties (and
1939 justify their inclusion in the combined fit model; their inclusion in the 2-lepton fit is for portabil-
1940 ity and a sanity check). Since the 2-lepton final state is by construction \vec{E}_T^{miss} free, it is not surpris-
1941 ing that uncertainty due to \vec{E}_T^{miss} is high. Single channel standalone fits are never final results in this
1942 analysis, so the result relies on the other channels to better and more accurately constrain this uncer-
1943 tainty since these other final states do have \vec{E}_T^{miss} in their final states and are the channels for which
1944 the \vec{E}_T^{miss} treatment in the analysis has been optimized. Furthermore, something like Z +hf modeling
1945 is difficult to do given how constrained the analysis signal region is. Combining the information in

¹⁹⁴⁶ the o- and 2-lepton results (and introducing double ratio NP's to recognize that these channels do
¹⁹⁴⁷ have important differences) also helps to constrain this difficult systematic uncertainty.

¹⁹⁴⁸ Once the fit inputs in each channel have been prepared and validated, a combined workspace can
¹⁹⁴⁹ be directly constructed using the combined fit model. Significances are given in Table 9.2, and $\hat{\mu}$
¹⁹⁵⁰ summaries for 2 and 3 POI fits are given in Figure 9.1. This combined workspace with observed sig-
¹⁹⁵¹ nificant strength of $1.20^{+0.24}_{-0.23}$ (stat.) $^{+0.34}_{-0.28}$ (syst.) is the Run 2 input for the Run 1 + Run 2 combination
¹⁹⁵² discussed below.

Channel	Exp. sig. (Asimov)	Exp. sig. (data)	Obs. sig.
o-lepton (SR)	1.99	1.73	0.53
1-lepton (SR+CR)	1.81	1.81	2.30
2-lepton (SR+CR)	1.95	1.86	3.55
o,1,2-lepton (SR+CR)	3.19	3.03	3.54

Table 9.2: Observed significance from an unconditional fit to the data corresponding to 36.1 fb^{-1} and expected significances from a fit to an Asimov dataset and from a fit to the data. Expected significances from individual regions are estimated separately.

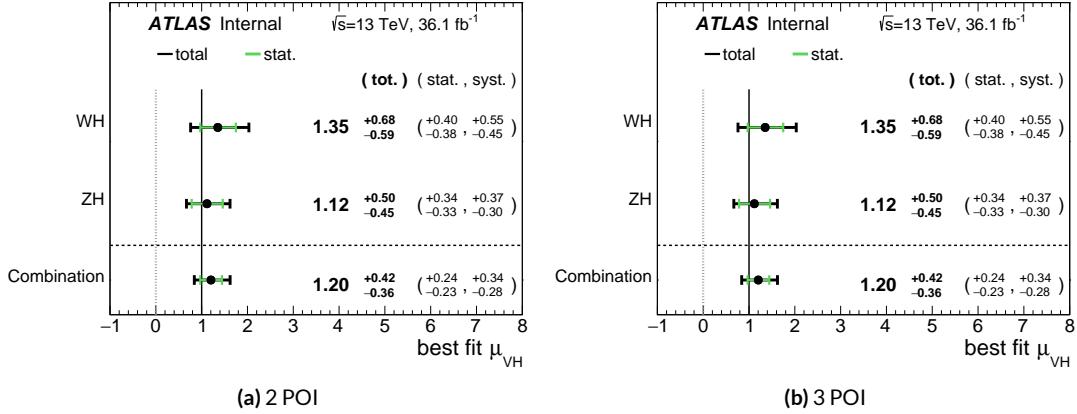


Figure 9.1: Run 2 signal strength summary plots for 2 (WH/ZH, (a)) and 3 (0, 1, and 2 lepton, (b)) POI fits.

1953 9.2 THE COMBINED FIT MODEL

1954 It is clear the signal strength parameter of interest should be fully correlated among the different
1955 datasets. Some signal modeling systematics were left unchanged from Run 1 through Run 2 and/or
1956 were designed to be explicitly correlated. Beyond these two special cases, it is not immediately clear
1957 what level of correlation should be imposed. The general methodology for settling upon a correla-
1958 tion scheme is as follows:

- 1959 1. Identify which NP categories have significant impacts on μ
- 1960 2. Of these NP's, identify which have one-to-one correspondences or established correlation
1961 schemes among \sqrt{s} values
- 1962 3. Test whether correlation has a sizable impact on expected fit quantities

1963 The only two sizable experimental NP categories are jet energy scale (JES) and flavor tagging sys-
1964 tematics. Correlation schemes of varying degrees of completeness exist for these categories, so ex-
1965 plicit NP correlations can be tested for these two categories. As these studies were conducted before
1966 unblinding, "sizable impact" was judged by comparing fit results (sensitivities, pull comparisons,
1967 and breakdowns) on combined workspaces using the unblinded and public $\mu = 0.51$ result for
1968 Run 1 and Asimov data for the Run 2 result. These are treated in Sections 9.2.1 and 9.2.2. Modeling
1969 systematics require a slightly different treatment, and are explored in 9.2.3.

1970 As noted in Chapter 7 when looking at pull comparison plots for combined workspaces, the error
1971 bars in these plots are calculated using a simultaneous HESSE matrix inversion, which can fail to give
1972 sensible values for high dimensional models (the combined workspaces have well over 500 NP's).
1973 This is not true of the nuisance parameter ranking plots, which use a MINOS based approach to test

¹⁹⁷⁴ the effect of each NP individually. This is much slower but much more rigorous, which is why only
¹⁹⁷⁵ ranking plots appear outside of supporting material and pull comparisons are considered “diagnos-
¹⁹⁷⁶ tic” plots.

¹⁹⁷⁷ 9.2.1 JET ENERGY SCALE SYSTEMATICS

¹⁹⁷⁸ Fortunately for the case of jet energy scale systematics, the JetEtMiss group provides two recom-
¹⁹⁷⁹ mended “strong” and “weak” correlation schemes between Run 1 and Run 2. These were used as
¹⁹⁸⁰ a point of departure for the JES combination correlation scheme. However, the JES NP’s in both
¹⁹⁸¹ the Run 1 and Run 2 workspaces are a reduced set of NP’s, with some 56 (75) NP’s reduced to 6 (8)
¹⁹⁸² for Run 1 (2). In order to restore the full set of JES NP’s, the effective NP’s in each workspace are un-
¹⁹⁸³ folded using maps detailing the linear combinations of unfolded NP’s that form the effective NP’s.

¹⁹⁸⁴ The linear combinations used to unfold the effective JES NP’s were calculated as follows:

$$NP_{i,eff} = \frac{\sum_j A_{ij} |NP_{j,unf}| NP_{j,unf}}{\sqrt{\sum_j A_{ij}^2 |NP_{j,unf}|^2}} \quad (9.1)$$

¹⁹⁸⁵ where *eff* and *unf* are for effective and unfolded NP’s, respectively, the A_{ij} ’s are scalar coefficients
¹⁹⁸⁶ taken from raw maps, and $|NP_{j,unf}|$ are the amplitudes of the unfolded NP’s. The raw A_{ij} and scaled
¹⁹⁸⁷ maps for Run 1 and Run 2 may be found in Figure 9.2

¹⁹⁸⁸ Unfolding was found to have very little effect on both expected sensitivities and errors, as can be
¹⁹⁸⁹ seen in Tables 9.3–9.6.

¹⁹⁹⁰ It was also found that fit sensitivities and breakdowns were similarly indifferent to the use of ei-

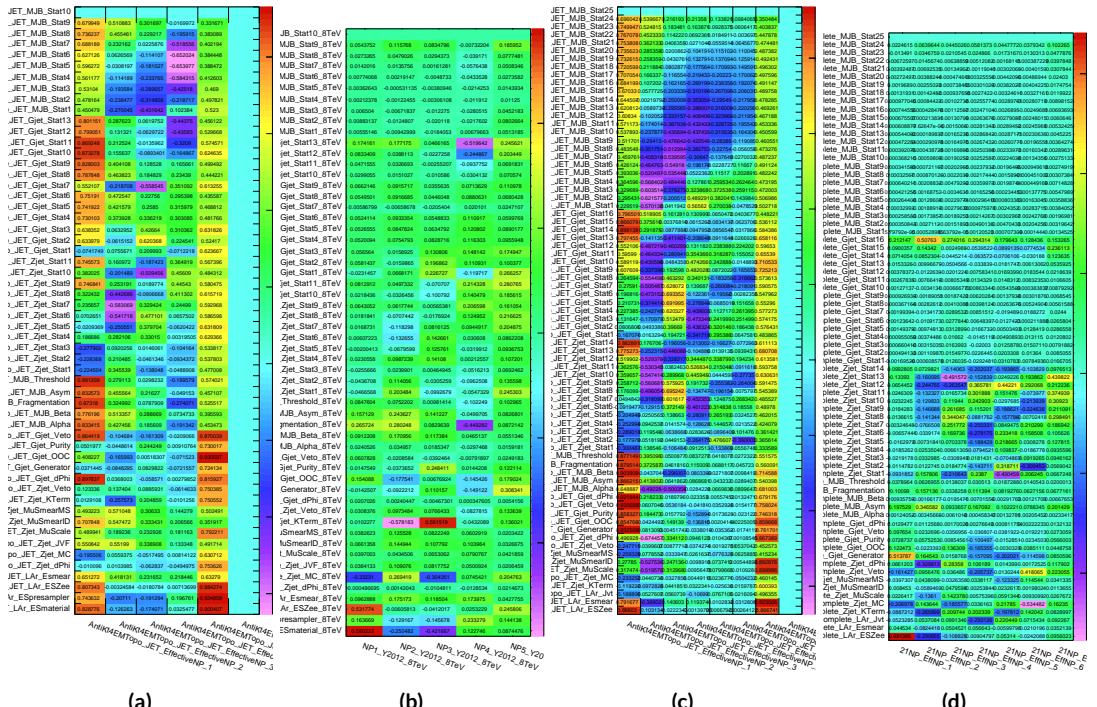


Figure 9.2: The raw and scaled coefficients for unfolding Run 1 (a and b) and Run 2 (c and d), respectively

	R ₁ Unf	R ₁ Eff	R ₂ Unf	R ₂ Eff	Comb Unf	Comb Eff
Exp. Sig.	2.604	2.606	3.014	3.014	4.005	3.998
Obs. Sig.	1.369	1.374	3.53	3.53	3.581	3.571
Exp. Limit	0.76 ^{+0.30} _{-0.21}	0.76 ^{+0.30} _{-0.21}	0.73 ^{+0.29} _{-0.21}	0.73 ^{+0.29} _{-0.21}	0.51 ^{+0.20} _{-0.14}	0.51 ^{+0.20} _{-0.14}
Obs. Limit	1.21	1.21	1.94	1.94	1.36	1.37

Table 9.3: Expected and observed sensitivities for Run 1, Run 2, and combined workspaces with effective and unfolded JES NP's.

	R ₁ Unfold	R ₁ Eff
$ \Delta\hat{\mu} $		0.0018
$\hat{\mu}$	0.5064	0.5082
Total	+0.400 / -0.373	+0.401 / -0.373
DataStat	+0.312 / -0.301	+0.312 / -0.301
FullSyst	+0.250 / -0.220	+0.251 / -0.220
Jets	+0.060 / -0.051	+0.060 / -0.052
BTag	+0.094 / -0.079	+0.095 / -0.079

Table 9.4: Error on signal strength breakdowns for Run 1 workspaces with effective and unfolded JES NP's.

	R ₂ Unfold	R ₂ Eff
$ \Delta\hat{\mu} $		0.0
$\hat{\mu}$	1.2051	1.2052
Total	+0.421 / -0.366	+0.421 / -0.366
DataStat	+0.239 / -0.234	+0.239 / -0.234
FullSyst	+0.346 / -0.282	+0.346 / -0.282
Jets	+0.066 / -0.047	+0.066 / -0.047
BTag	+0.119 / -0.106	+0.119 / -0.106

Table 9.5: Error on signal strength breakdowns for Run 2 workspaces with effective and unfolded JES NP's.

	Comb Unfold	Comb Eff
$ \Delta\hat{\mu} $		0.0006
$\hat{\mu}$	0.8992	0.8985
Total	+0.278 / -0.261	+0.278 / -0.261
DataStat	+0.185 / -0.181	+0.185 / -0.181
FullSyst	+0.208 / -0.187	+0.208 / -0.188
Jets	+0.040 / -0.044	+0.041 / -0.036
BTag	+0.076 / -0.076	+0.077 / -0.076

Table 9.6: Error on signal strength breakdowns for combined workspaces with effective and unfolded JES NP's.

¹⁹⁹¹ ther the strong or weak JES correlation schemes, as shown in Tables 9.7 and 9.8.

	JES Weak Unfold	JES Weak Eff	JES Strong Unfold	JES Strong Eff
Exp. Sig.	3.57	3.57	3.59	3.59
Exp. Limit	$0.493^{+0.193}_{-0.138}$	$0.494^{+0.193}_{-0.138}$	$0.493^{+0.193}_{-0.138}$	$0.493^{+0.193}_{-0.138}$

Table 9.7: Expected sensitivities for both effective and unfolded combined workspaces using the strong and weak JES correlation schemes.

	Comb Unfold	Comb Eff	Strong Unfold	Strong Eff
$\Delta\hat{\mu}$	0.0009		0.0025	
Total	+0.269 -0.254	+0.27 -0.255	+0.27 -0.255	+0.27 -0.255
DataStat	+0.181 -0.177	+0.181 -0.177	+0.181 -0.177	+0.181 -0.178
FullSyst	+0.199 -0.183	+0.2 -0.183	+0.2 -0.183	+0.201 -0.183
Jets	+0.0387 -0.032	+0.041 -0.0337	+0.0425 -0.0329	+0.0432 -0.0338
BTag	+0.0975 -0.0933	+0.098 -0.0936	+0.0979 -0.0935	+0.098 -0.0936

Table 9.8: Error on signal strength breakdowns for both effective and unfolded combined workspaces using the strong and weak JES correlation schemes.

¹⁹⁹² Comparisons of top ranked nuisance parameters in Figures 9.3–9.5 and for the complete JES pull

¹⁹⁹³ comparisons in Figures 9.6–9.9 also show very little difference with respect to correlation scheme

¹⁹⁹⁴ (except obviously for the number of JES NP’s). Constrained pulls in pull comparisons should once

¹⁹⁹⁵ again be taken as a shortcoming of HESSE and not the fit model.

¹⁹⁹⁶ As a result of these studies, the weak JES correlation scheme with uncorrelated effective JES NP’s

¹⁹⁹⁷ (i.e. just the b -jet energy scale NP) has been chosen as the treatment of JES in the Run 1 + Run 2

¹⁹⁹⁸ combined fit.

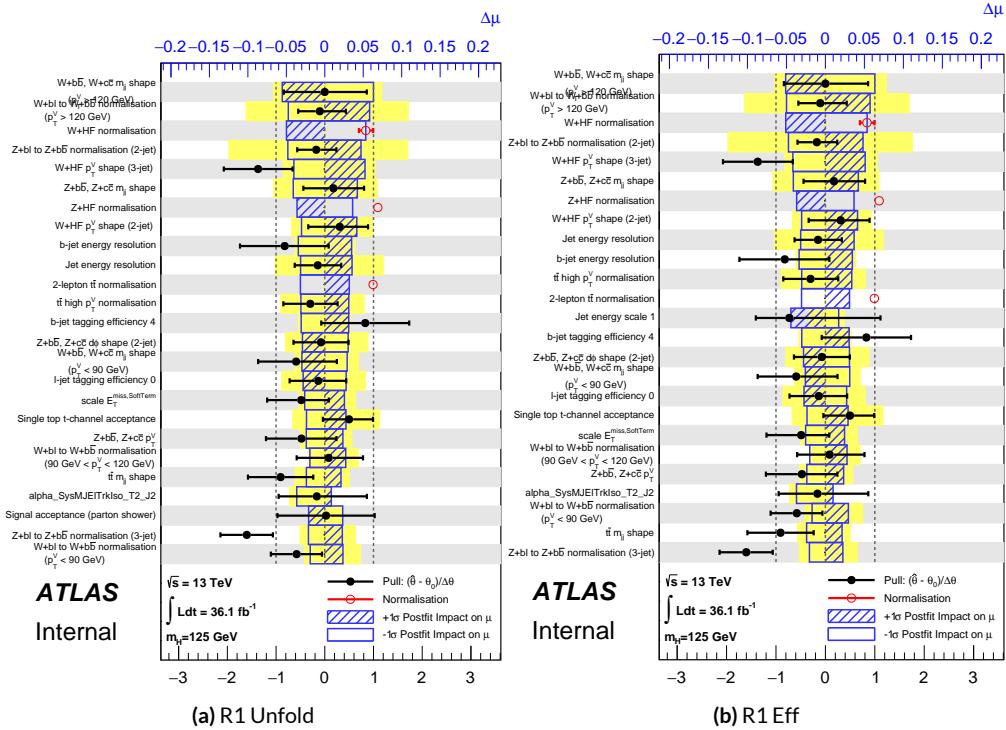


Figure 9.3: Ranks for the effective and unfolded JES NP Run1 combined workspaces.

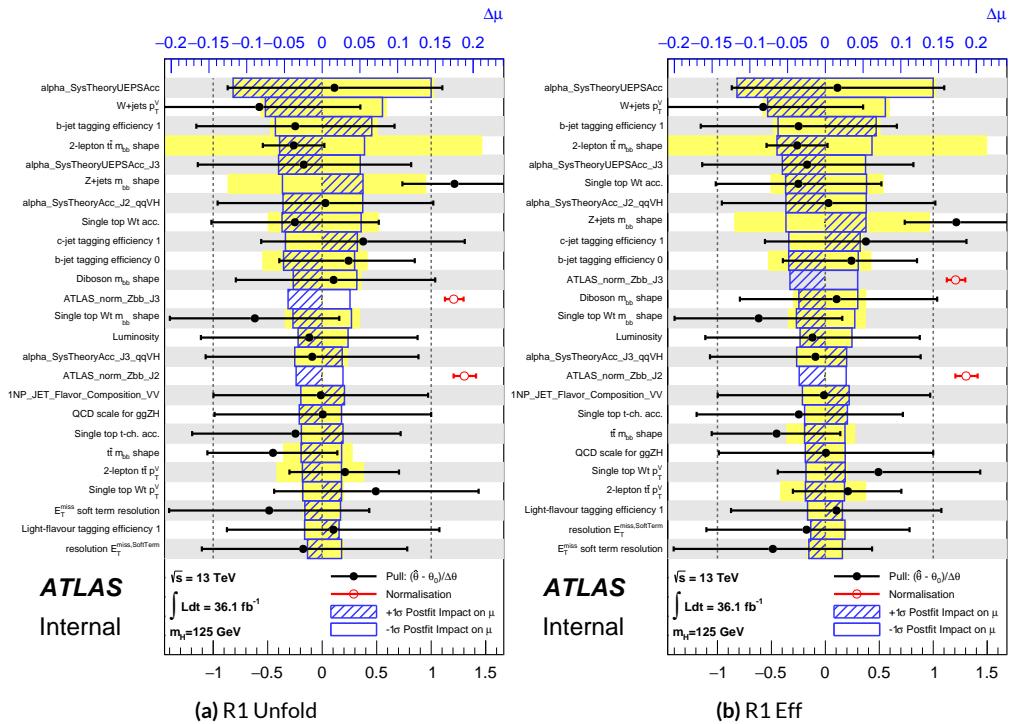


Figure 9.4: Ranks for the effective and unfolded JES NP Run2 combined workspaces.

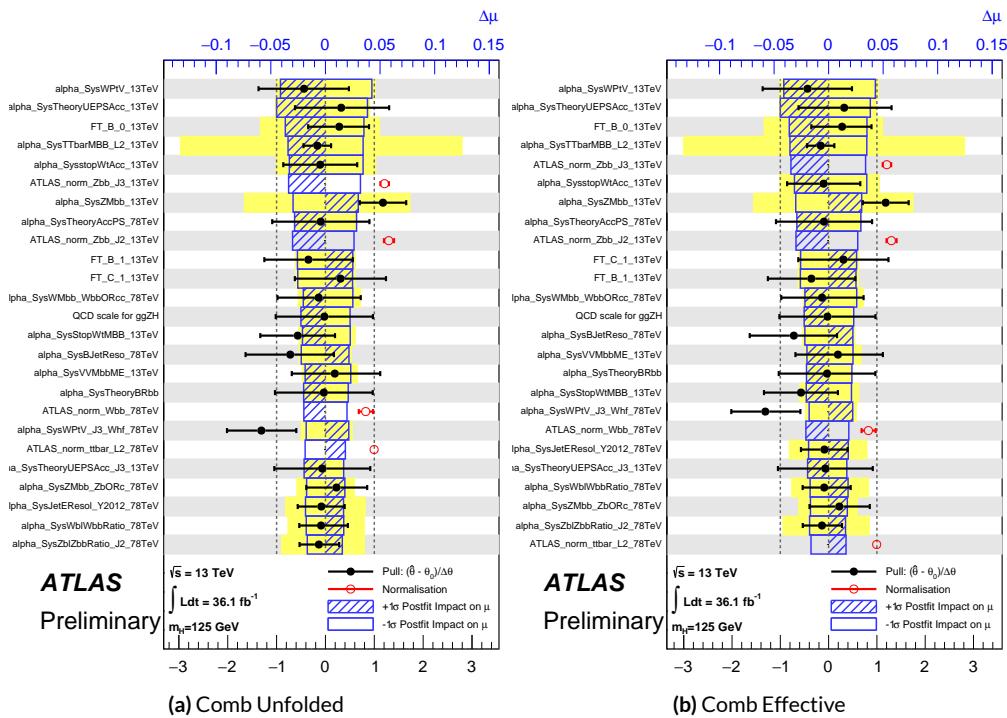


Figure 9.5: Ranks for the effective and unfolded JES NP Run1+Run2 combined workspaces.

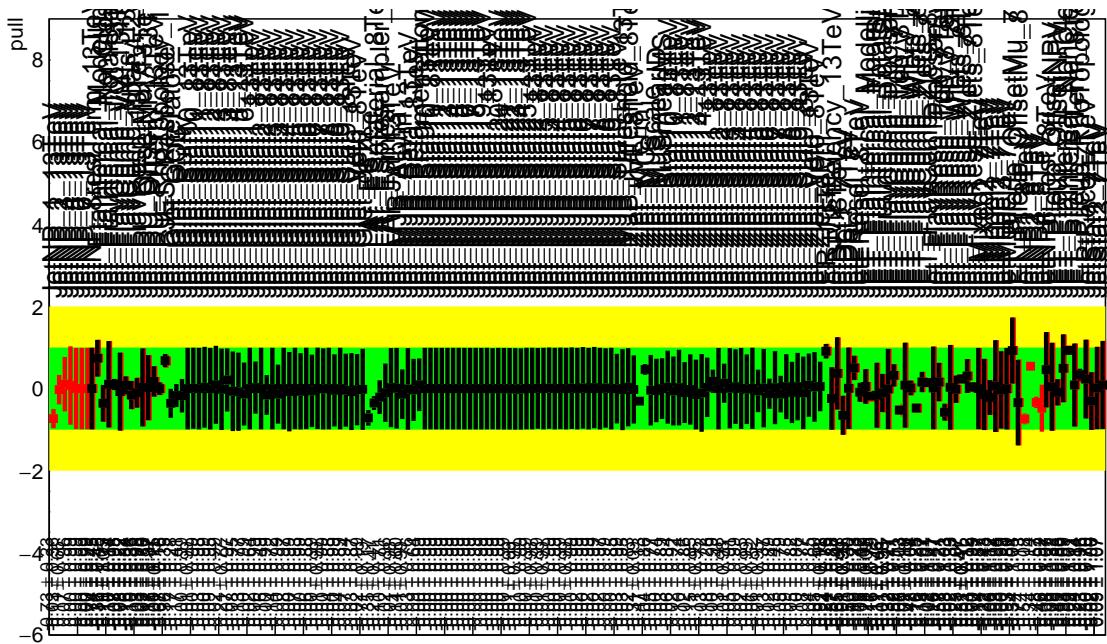


Figure 9.6: Pull Comparisons: jesu---Jet Comb Unfold, Comb Eff, Strong Unfold, Strong Eff

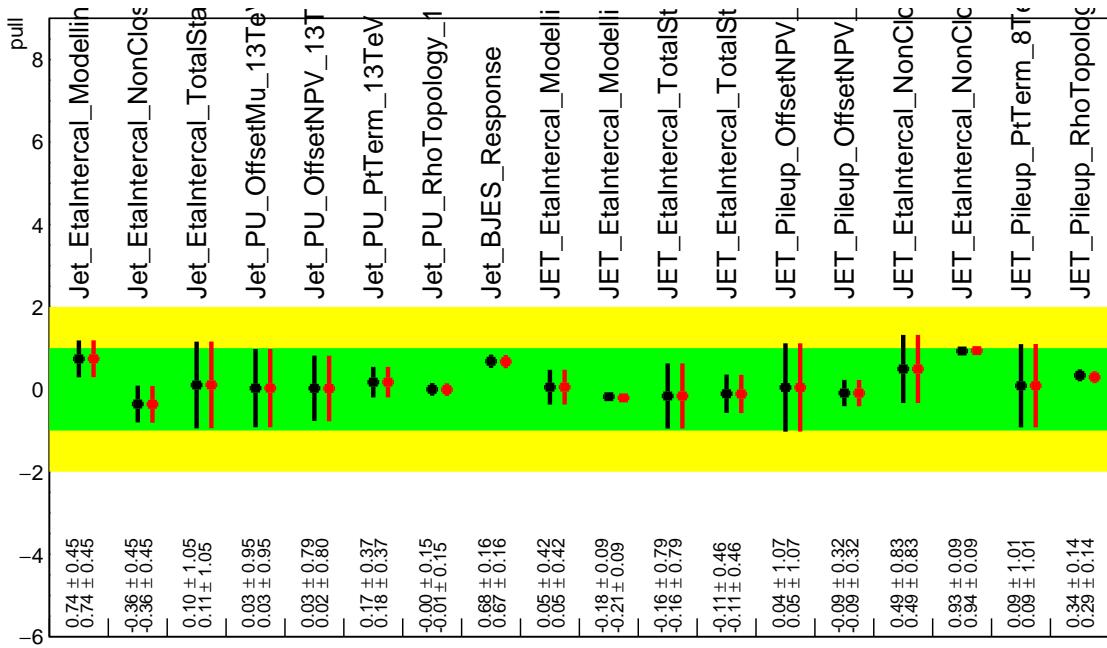


Figure 9.7: Pull Comparisons: jesu---JetMatched Comb Unfold, Comb Eff, Strong Unfold, Strong Eff

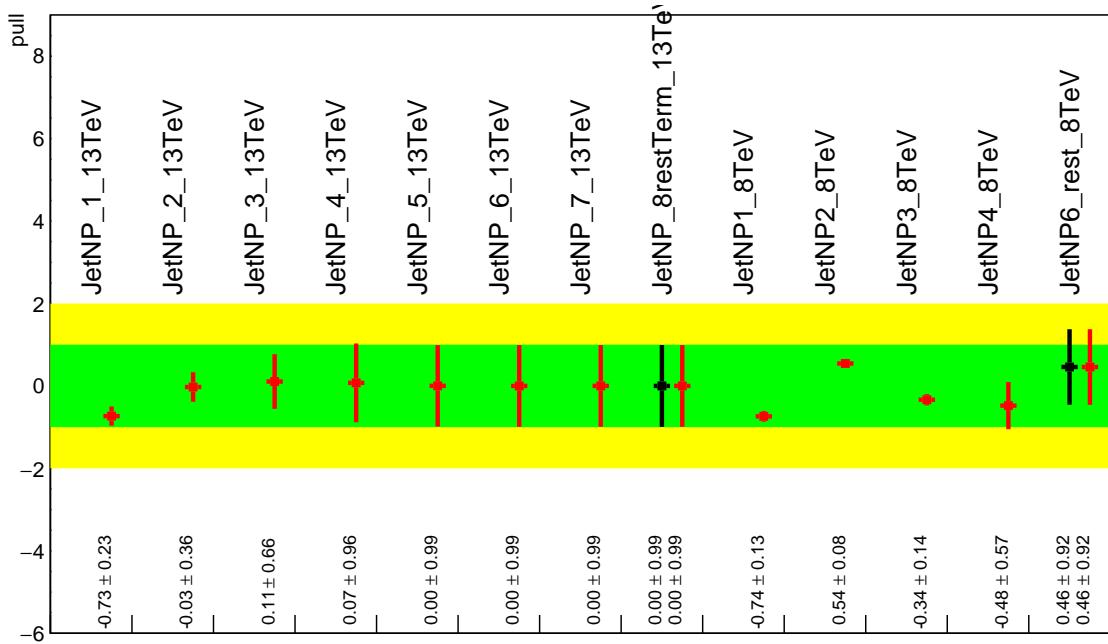


Figure 9.8: Pull Comparisons: jesu---JetEff Comb Unfold, **Comb Eff**, Strong Unfold, **Strong Eff**

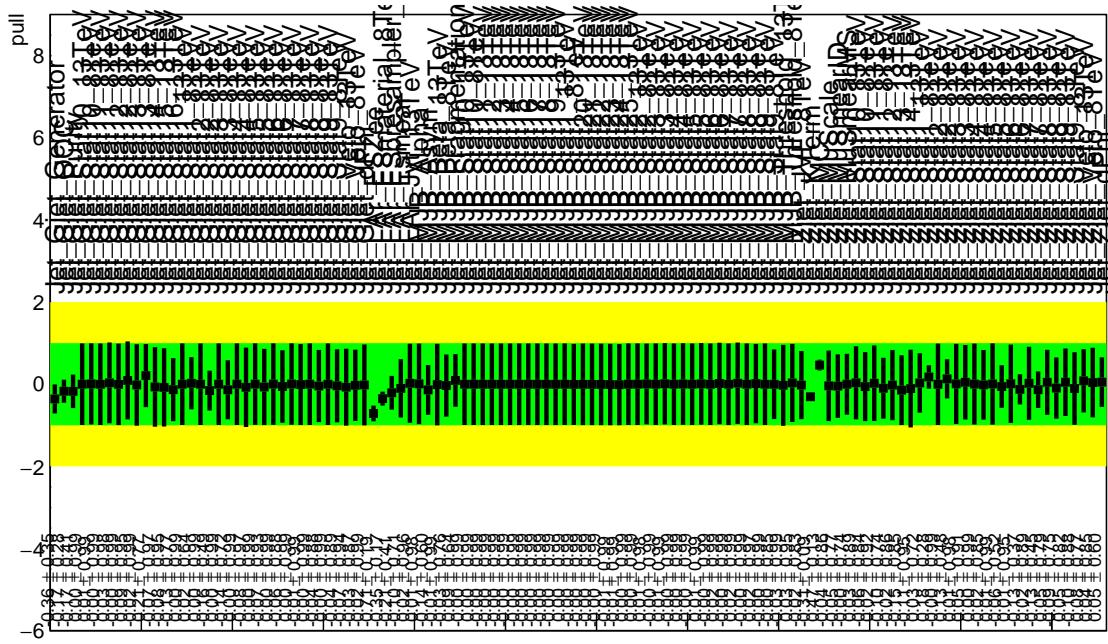


Figure 9.9: Pull Comparisons: jesu---JetUnfold Comb Unfold, **Comb Eff**, Strong Unfold, **Strong Eff**

1999 9.2.2 FLAVOR TAGGING

2000 Unfortunately, the ATLAS Flavor Tagging group did not provide any recommendations for corre-
2001 lating Run 1 and Run 2 NP's, though given the high ranking of these NP's in the Run 2, result, per-
2002 forming at least some studies was deemed crucial. Nevertheless, great improvements and changes to
2003 the treatment of flavor tagging between Run 1 and Run 2 does weaken the argument for any strong
2004 flavor tagging correlation scheme.

2005 Given that c -tagging changed significantly between Run 1 and Run 2 and that light tagging NP's
2006 are very lowly ranked, these sets of NP's are left uncorrelated. Moreover, the change in the physical
2007 meaning of the effective b -tagging NP's means a full correlation of such NP's (insomuch as they exist
2008 in each result) is one of limited utility. Hence, it was decided to leave flavor tagging NP's uncorre-
2009 lated. However, since the meaning of the leading b -tagging NP's is approximately constant across
2010 years and since Run 2 b -tagging NP's are very highly ranked in both the Run 2 only and combined
2011 fits, tests correlating these NP's were conducted, the results of which can be seen below. It should be
2012 noted that the leading B NP at 8 TeV, SysBTagB0Effic_Y2012_8TeV, has an opposite effect on $t\bar{t}$
2013 normalization than the 7 and 13 TeV NP's, and so must be flipped using a similar strategy as for JES
2014 unfolding. Initial studies of flavor tagging correlations did not flip this NP, and so results for this
2015 scheme (labeled "Bo 8TeV Not Flipped") have also been included for comparison.

2016 It is clear from these results that correlating the leading effective Eigen NP associated with b 's can
2017 have a noticeable effect on final fit results and that the 8 TeV Bo NP is the most important compo-
2018 nent of a combined Bo NP. It is also not so surprising that the 8 TeV result should drive the com-

	Comb Eff	BTag Bo	Bo 8TeV Not Flipped
Exp. Sig.	3.998	4.127	3.921
Obs. Sig.	3.571	3.859	3.418
Exp. Limit	0.51 ^{+0.2} _{-0.143}	0.5 ^{+0.196} _{-0.14}	0.517 ^{+0.202} _{-0.144}
Obs. Limit	1.37	1.41	1.35

Table 9.9: Expected and observed sensitivities for a combination featuring the weak JES scheme, combination with the weak JES scheme + leading b NP's correlated, and the b correlation with the 8 TeV NP with sign unflipped.

	Comb Eff	BTag Bo	Bo 8TeV Not Flipped
$ \Delta\hat{\mu} $	—	0.0446	0.0268
$\hat{\mu}$	0.8985	0.9431	0.8717
Total	+0.278 / -0.261	+0.275 / -0.256	+0.282 / -0.263
DataStat	+0.185 / -0.181	+0.180 / -0.177	+0.189 / -0.186
FullSyst	+0.208 / -0.188	+0.207 / -0.186	+0.209 / -0.186
BTag	+0.077 / -0.076	+0.071 / -0.068	+0.079 / -0.075
BTag b	+0.062 / -0.059	+0.055 / -0.049	+0.064 / -0.060

Table 9.10: Breakdowns of the impact of different NP sets on total error on $\hat{m}\hat{\mu}$ for a combination featuring the weak JES scheme and a combination with the weak JES scheme + leading b NP's correlated.

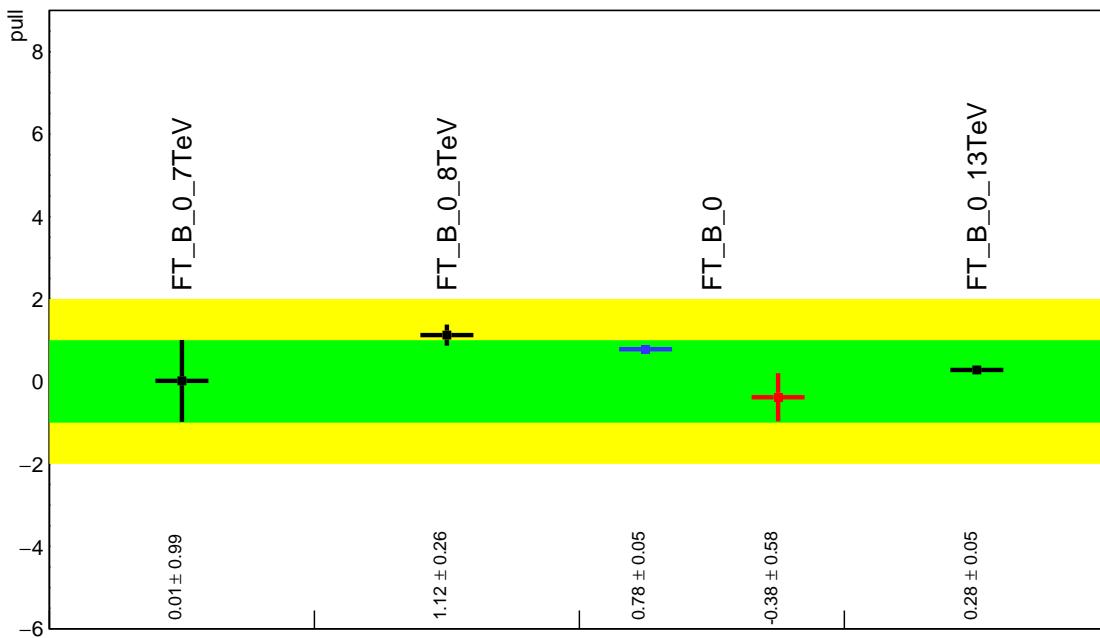


Figure 9.10: Pull Comparisons: btag-b---BTagB0 Comb Eff, **BTag BO**

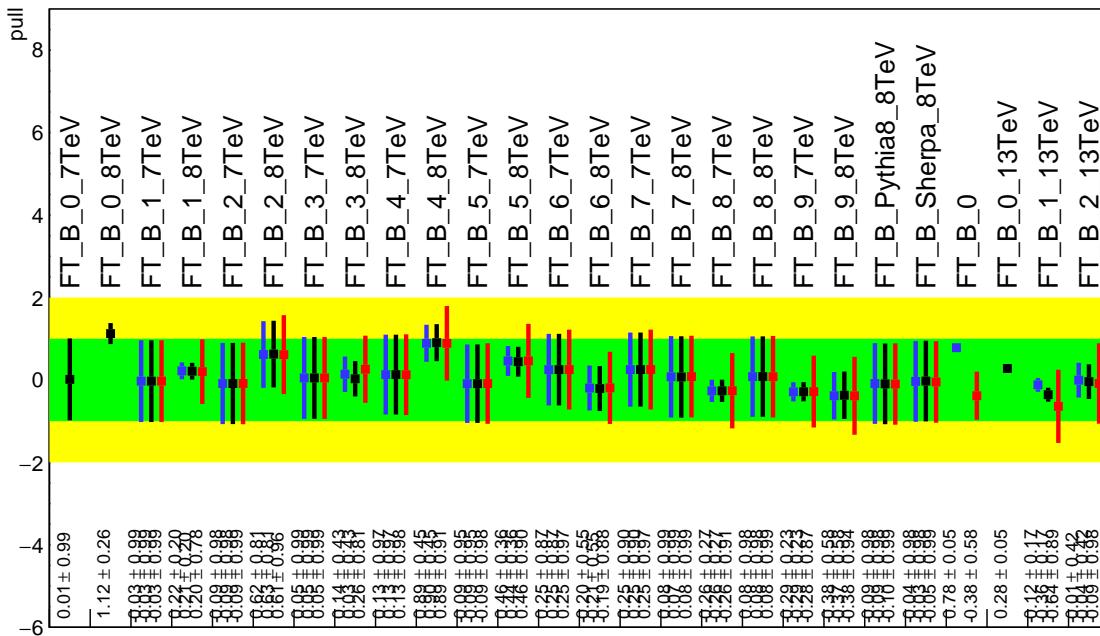


Figure 9.11: Pull Comparisons: btag-b---BTagB Comb Eff, **BTag BO**

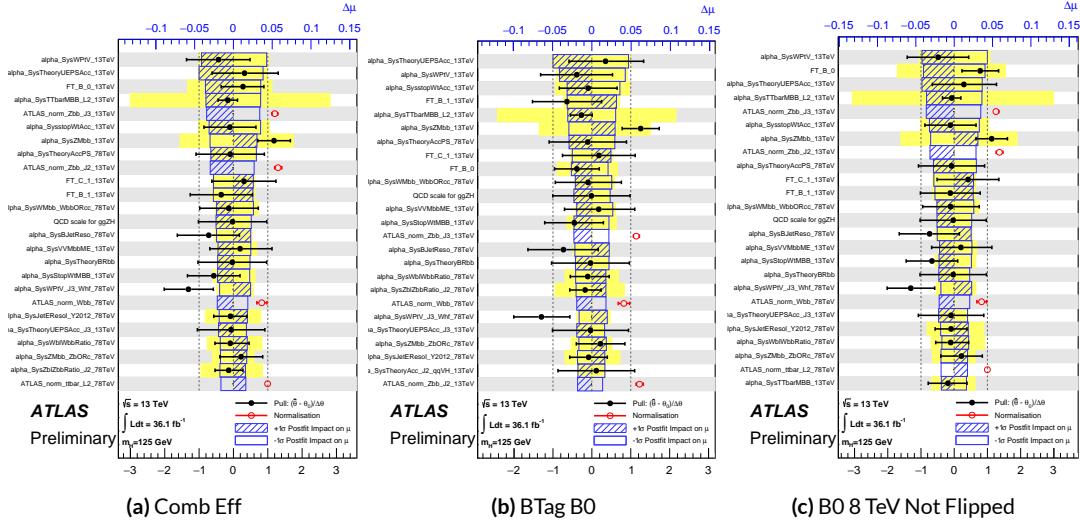


Figure 9.12: NP rankings for a combination featuring the weak JES scheme and a combination with the weak JES scheme + leading b NP's correlated.

2019 bined nuisance parameter since it is the only result to make use of both pseudocontinuous tagging-
 2020 based and 1 b -tag regions into the final fit, implicitly yielding much more information about b 's. The
 2021 13 TeV fit has neither of these regions. What is less clear is whether there are sufficient grounds for
 2022 implementing this correlation (i.e. does the correspondence of these NP's across years warrant a full
 2023 correlation). While there are no current plans to do so, this matter warrants careful scrutiny if Run 1
 2024 is to be combined with future results.

2025 9.2.3 MODELING SYSTEMATICS

2026 Another principal systematic category is modeling uncertainties. The effect of correlating groups
 2027 of systematics was estimated using the same strategy employed by the ATLAS/CMS SM VH ($b\bar{b}$)
 2028 combination for Run 1. This extrapolation can be used to estimate the impact of correlations on
 2029 the estimated signal strength, the total error on the signal strength, and the χ^2 of the result. The

2030 impact of such correlations is no more than a few percent effect, as the following tables demonstrate,
 2031 beginning with the category with the greatest shift, W+jets modeling, in Table 9.11.

	$ \Delta\mu $	σ	$ \Delta\sigma $	χ^2
$\rho=-1$	0.0024	0.2448	0.011 (4.3%)	0.95
$\rho=-0.6$	0.0015	0.2493	0.00654 (2.55%)	0.9804
$\rho=-0.3$	0.0008	0.2526	0.00325 (1.27%)	1.0045
$\rho=0$	—	0.2558	—	1.0298
$\rho=0.3$	0.0008	0.259	0.0032 (1.25%)	1.0564
$\rho=0.6$	0.0017	0.2622	0.00636 (2.49%)	1.0844
$\rho=1$	0.0029	0.2664	0.0105 (4.11%)	1.1242

Table 9.11: Run 1 + Run 2 W+jets modeling correlation projections

2032 9.2.4 FINAL CORRELATION SCHEME

2033 The final Run 1 + Run 2 correlation scheme is shown in Table 9.12. As detailed above, neither JES
 2034 nor modeling systematics had any demonstrable effect on combined fit results. Hence, only signal
 2035 NP's and the b -jet energy scale are correlated (the weak JES scheme without unfolding). While the
 2036 effect of flavor tagging correlations is less clear, the result physical arguments for correlation are less
 2037 strong; the size of effect was discovered rather late in the analysis process; and no nuisance parameter
 2038 unfolding maps exist for flavor tagging as they do for JES, so it was decided to leave these uncorre-
 2039 lated as well.

7 TeV NP	8 TeV NP	13 TeV NP
	ATLAS_BR_bb	SysTheoryBRbb
	SysTheoryQCDscale_ggZH	SysTheoryQCDscale_ggZH
	SysTheoryQCDscale_qqVH	SysTheoryQCDscale_qqVH
—	SysTheoryPDF_ggZH_8TeV	SysTheoryPDF_ggZH
—	SysTheoryPDF_qqVH_8TeV	SysTheoryPDF_qqVH
—	SysTheoryVHPt_8TeV	SysVHNLOEWK
SysJetFlavB_7TeV	SysJetFlavB_8TeV	SysJET_21NP_JET_BJES_Response

Table 9.12: A summary of correlated nuisance parameters among the 7, 8, and 13 TeV datasets.

2040 9.3 COMBINED FIT RESULTS

2041 9.3.1 COMBINED FIT MODEL VALIDATION

2042 Before moving onto the final results, we present the rest of the validations for the Run 1 + Run 2
 2043 combined fits, beginning with impacts of ranked individual nuisance parameters in Figure 9.13 and
 2044 for all nuisance parameter categories in Table 9.13. Both of these sets of results point to the most im-
 2045 portant nuisance parameters being signal systematics, b -tagging, and V +jets modeling systematics,
 2046 with Run 2 NP's generally being higher ranked. That some NP's are strongly pulled is not unusual
 2047 as the fit model has so many NP's; V +jets modeling in particular has been historically difficult.

2048 In addition to looking at the behaviors of nuisance parameters to gauge fit model performance
 2049 and stability, fits are conducted using multiple parameters of interest. Typical divisions are Run 1
 2050 vs. Run 2, lepton channels, and WH vs ZH . As mentioned in Chapter 7, the profile likelihood test
 2051 statistic given in Equation 7.2 is, in the limit of large sample statistics, a χ^2 distribution with degrees
 2052 of freedom equal to the number of parameters of interest plus number of nuisance parameters.
 2053 Thus, changing the number of interest parameters and leaving the rest of the fit model unchanged

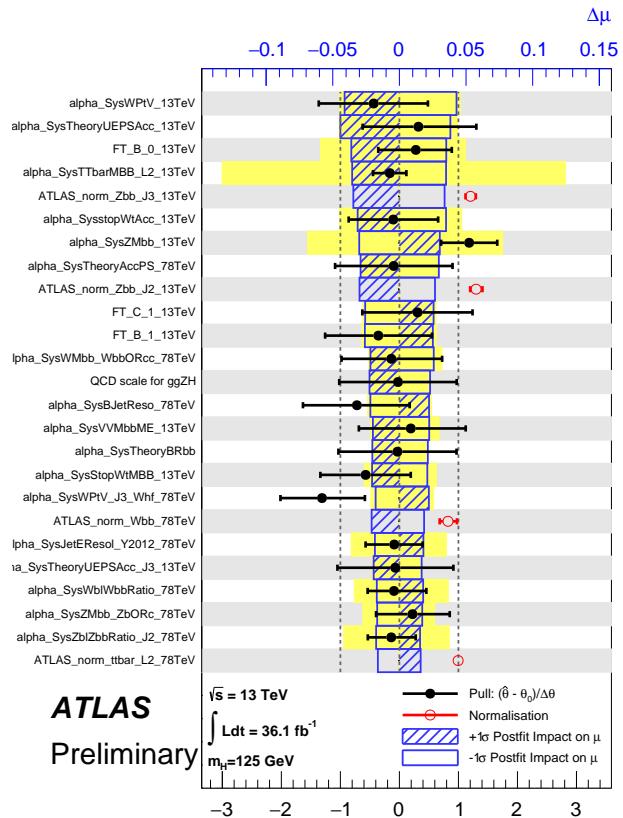


Figure 9.13: Ranked nuisance parameters for the Run1+Run2 combination.

Total	+0.278 / -0.261
DataStat	+0.185 / -0.181
FullSyst	+0.208 / -0.188
Floating normalizations	+0.055 / -0.056
All normalizations	+0.068 / -0.069
All but normalizations	+0.192 / -0.172
Jets, MET	+0.046 / -0.040
Jets	+0.041 / -0.036
MET	+0.023 / -0.018
BTag	+0.077 / -0.076
BTag b	+0.062 / -0.059
BTag c	+0.033 / -0.032
BTag light	+0.028 / -0.028
Leptons	+0.008 / -0.008
Luminosity	+0.026 / -0.014
Diboson	+0.030 / -0.027
Model Zjets	+0.049 / -0.050
Zjets flt. norm.	+0.032 / -0.040
Model Wjets	+0.082 / -0.083
Wjets flt. norm.	+0.031 / -0.027
Model ttbar	+0.047 / -0.046
ttbar flt. norm.	+0.025 / -0.026
Model Single Top	+0.047 / -0.045
Model Multi Jet	+0.027 / -0.038
Signal Systematics	+0.098 / -0.052
MC stat	+0.080 / -0.084

Table 9.13: Summary of the impact of different nuisance parameter categories on the total error on $\hat{\mu}$ for the combined Run1+Run2 fit.

2054 means that the difference between the nominal fit and a fit with more parameters of interest ought
 2055 to also be distributed as a χ^2 distribution with degrees of freedom equivalent to the number of extra
 2056 parameters of interest. This difference can then be interpreted as a compatibility between the two
 2057 results using the standard tables for this distribution, giving another gauge of fit performance. These
 2058 are shown in Table 9.14.

Fit	Compatibility
Leptons (3 POI)	1.49%
WH/ZH (2 POI)	34.2%
Run 1/Run 2 (2 POI)	20.8%
Run 1/Run 2 \times Leptons (6 POI)	7.10%
Run 1/Run 2 \times WH/ZH (4 POI)	34.6%

Table 9.14: Summary of multiple POI compatibilities. The well-known Run 1 7 TeV 0-lepton deficit is responsible for the low compatibility with the 6 and 3 POI fits.

2059 The low compatibilities associated with treating the lepton channels as separate parameters of
 2060 interest are a symptom of the low signal strengths associated with the Run 1 0-lepton channel, in par-
 2061 ticular the 7 TeV result. Given the relatively small amount of data associated with the 7 TeV result,
 2062 this should not be a cause for alarm. Signal strength summary plots for the fits treating Run 1 and
 2063 Run 2 separately are shown in Figures 9.14-9.16, where the effect of the Run 1 parameters can be seen
 2064 graphically.

2065 9.3.2 FINAL RESULTS

2066 The combined results yields an observed (expected) significance of 3.57 (4.00) and an observed (ex-
 2067 pected) limit of 1.37 ($0.510^{+0.200}_{-0.143}$), with a signal strength of $\hat{\mu} = 0.898^{+0.278}_{-0.261}$.

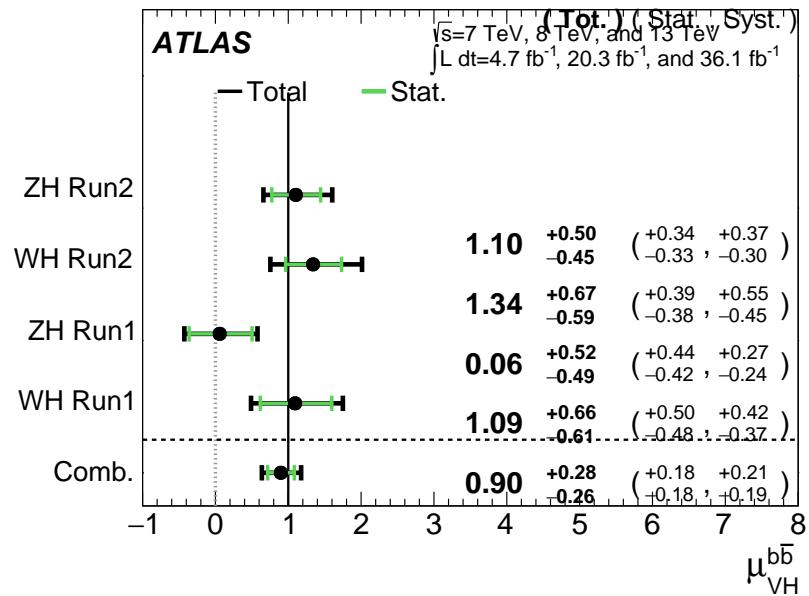


Figure 9.14: $\hat{\mu}$ summary plot for a four parameter of interest fit.

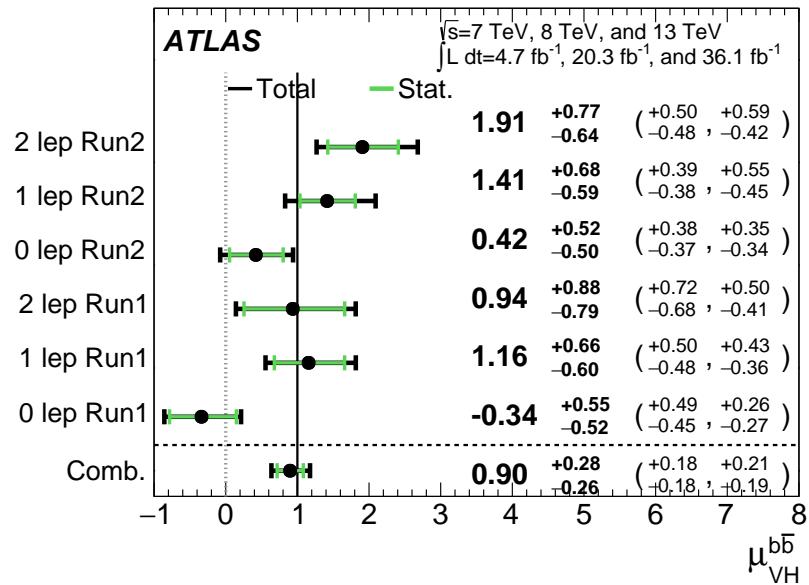


Figure 9.15: $\hat{\mu}$ summary plot for a six parameter of interest fit.

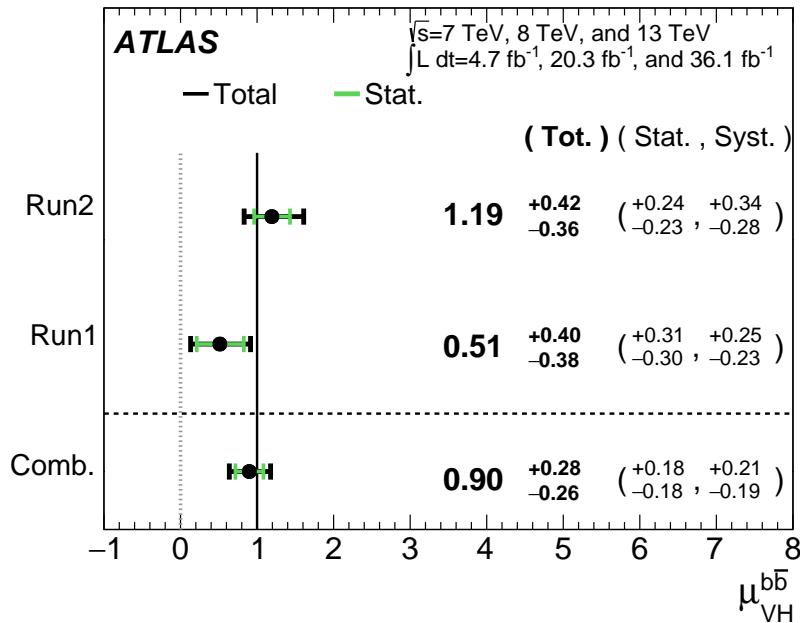


Figure 9.16: $\hat{\mu}$ summary plot for a two parameter of interest (Run 1 and Run 2) values.

2068 The two and three parameter of interest fit signal strength summary plots, as well as a summary
 2069 of the historical values of the 7, 8, and 13 TeV results may be found in Figures 9.17-9.19. The main
 2070 results for Run 1, Run 2, and the combination may be found in Table 9.15. These results were collec-
 2071 tively noted as the first ever experimental evidence for SM $VH(b\bar{b})$ in [3].

Dataset	$\hat{\mu}$	Total Error in $\hat{\mu}$	Obs. (Exp.) Significance
Run 1	0.51	+0.40 / -0.37	1.4 (2.6)
Run 2	1.20	+0.42 / -0.36	3.54 (3.03)
Combined	0.90	+0.28 / -0.26	3.57 (4.00)

Table 9.15: A summary of main results for the Run 1, Run 2, and combined fits.

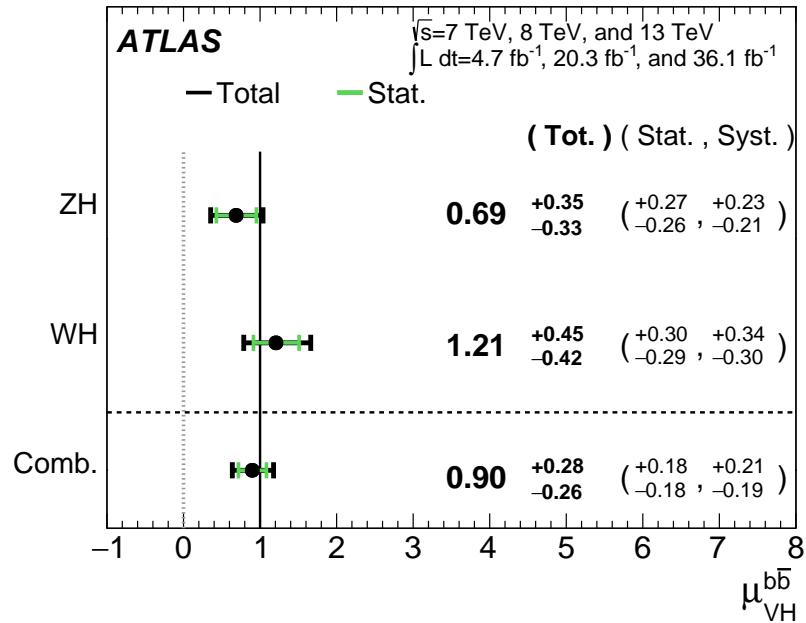


Figure 9.17: $\hat{\mu}$ summary plot for a two parameter of interest fit.

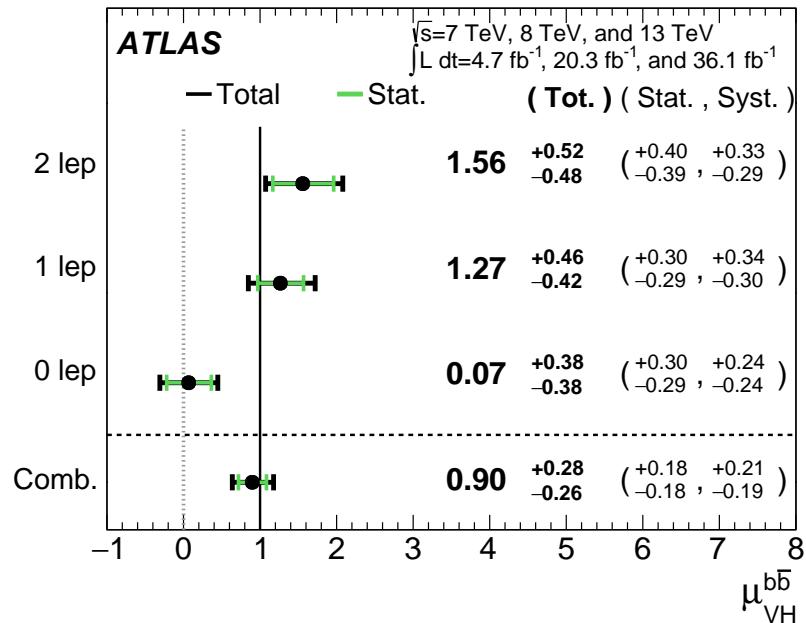


Figure 9.18: $\hat{\mu}$ summary plot for a three parameter of interest fit.

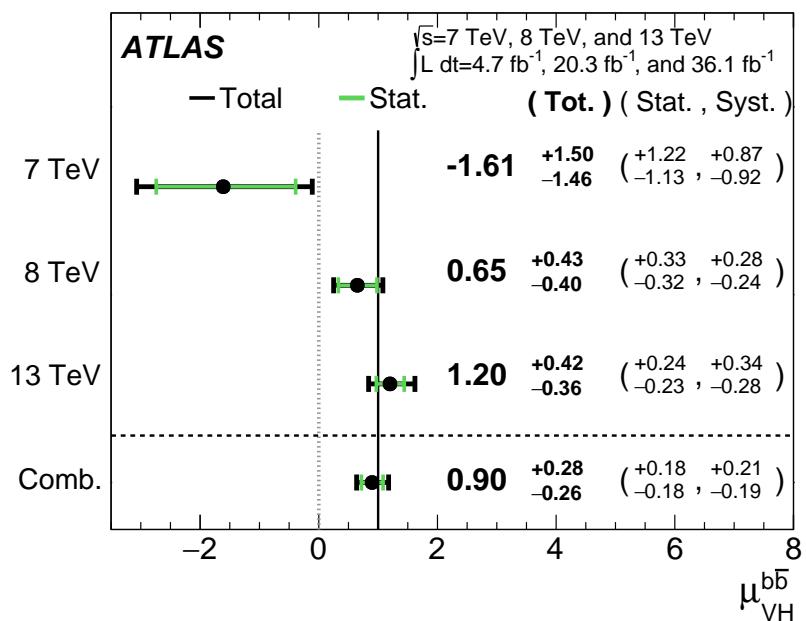


Figure 9.19: $\hat{\mu}$ summary plot for different \sqrt{s} values.

Vanitas vanitatum, omnis vanitas

Ecclesiastes 1:2

10

2072

2073

Closing Thoughts

2074 SINCE BOTH THE LHC and ATLAS are performing very well, it is only a matter of time before the
2075 evidence for SM $VH(b\bar{b})$ passes the 5 Gaussian standard deviation threshold necessary for discovery.
2076 Official discovery may come less than a year after reports of first evidence and may not even require
2077 a combination with the Run 1 result, depending on the latter two years of ATLAS Run 2 data (2017

2078 and 2018).

2079 It is entirely natural to ask, then, how essential the techniques and results described in this thesis
2080 will prove to be moving forward. Neither the LI/RF multivariate techniques nor combination with
2081 Run 1 datasets and their accompanying low signal strength values are necessary for discovery, and
2082 the latter may not even be essential to timely^{*} discovery of SM $VH(b\bar{b})$. Nevertheless, both sets of
2083 results hold great potential as key parts of a concerted ensemble of efforts towards precision Higgs
2084 physics.

2085 With the perhaps final major center of mass energy increase at the energy frontier ever complete,
2086 analyses must rely on increased integrated luminosity. Hence, it is becoming increasingly likely that
2087 any new fundamental physics at colliders will require the use of results of systematics limited analy-
2088 ses. This is the regime where the techniques described in this thesis will be most useful.

2089 As the LHC and its experiments undergo successive stages of upgrades and operate in evermore
2090 extreme environments, the statistical fit models used to describe LHC data will continue to evolve in
2091 complexity and diverge from their predecessors. The techniques described in Chapter 9 will become
2092 increasingly more vital to producing the best physics results possible. The improvement in precision
2093 from $\hat{\mu}_{VH} = 1.20^{+0.24}_{-0.23}(\text{stat.})^{+0.34}_{-0.28}(\text{syst.})$ to $\hat{\mu}_{VH} = 0.90^{+0.18}_{-0.18}(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$ is just the begin-
2094 ning.

2095 The best methods for reduction of systematic uncertainties will naturally depend in part on the
2096 state of the art for both fundamental physics process and detector modeling, but techniques that
2097 can reduce systematic uncertainties independent of fit model, dataset, and physics process provide

*i.e. before or coincident with CMS

2098 a promising avenue forward. The improvements in systematic uncertainties using the Lorentz In-
 2099 variant and RestFrames variable techniques in the $ZH \rightarrow \ell\ell b\bar{b}$ analysis, summarized in Table 10.1,
 2100 show that a smarter and more orthogonal decomposition of information in a collision event pro-
 2101 vides benefits independent of any clever treatment of \vec{E}_T^{miss} (which both schemes also provide). Both
 2102 techniques are readily extendable to other analysis channels, with the RestFrames concept demon-
 2103 strating stronger performance and greater flexibility to nearly completely generic final states.

	Standard	LI	RF
$\hat{\mu}$	$1.75^{+0.50, 0.64}_{-0.48, 0.45})$	$1.65^{+0.51, 0.59}_{-0.49, 0.41}$	$1.50^{+0.50, 0.53}_{-0.48, 0.36}$
Asi. $\Delta err(\mu)$	—	< 1%, +4.6%	-6.5%, -2.2%
Obs. $\Delta err(\hat{\mu})$	—	-7.5%, -3.7%	-16%, -8.8%
Stat only sig.	4.78	4.39 (-7.9%)	4.44 (-6.9%)
Exp. (Asi.) sig.	2.06	1.92 (-6.7%)	2.13 (+3.5%)
Exp. (data) sig.	1.76	1.73 (-1.7%)	1.80 (+3.4%)
Obs. (data) sig.	2.87	2.79 (-2.8%)	2.62 (-8.6%)

Table 10.1: Summary of performance figures for the standard, LI, and RF variable sets. Uncertainties on $\hat{\mu}$ are quoted stat., syst. In the case of the latter two, % differences are given where relevant. Differences in errors on μ are on full systematics and total error, respectively.

2104 Critical work remains to be done refining and extending the treatment of both the LI and RF
 2105 techniques in $VH(b\bar{b})$ analyses and their fit models, and completely independent techniques, like
 2106 the use of multiple event interpretations addressed in Appendix B promise further improvements
 2107 still.

2108 No one can say for certain what the future of the energy frontier of experimental particle physics
 2109 may hold, but more nuanced treatments of the information in collision events born of meaningful
 2110 physical insight are sure to light the way.

If it's stupid but it works, it isn't stupid.

Conventional Wisdom

A

2111

2112 Micromegas Trigger Processor Simulation

2113 IN ORDER TO PRESERVE key physics functionality by maintaining the ability to trigger on low p_T

2114 muons, the Phase I Upgrade to ATLAS includes a New Small Wheel (NSW) that will supply muon

2115 track segments to the Level 1 trigger. These NSW trigger segments will combine segments from the

2116 sTGC and Micromegas (MM) trigger processors (TP). This note will focus in particular on the al-

2117 gorithm for the MMTP, described in detail with initial studies in [61]. The goal of this note is to de-
2118 scribe the MMTP algorithm performance under a variety of algorithm settings with both nominal
2119 and misaligned chamber positions, as well as addressing a number of performance issues.

2120 This note is organized as follows: the algorithm and its outputs are briefly described in Section
2121 A.1; Monte Carlo samples used are in Section B.1; nominal algorithm performance and certain quan-
2122 tities of interest are described in Section A.3; algorithm performance under misalignment, misalign-
2123 ment corrections, and corrected performance are shown in Section A.9; and conclusions are pre-
2124 sented in Section A.24.

2125 A.1 ALGORITHM OVERVIEW

2126 The MMTP algorithm is shown schematically in Figure A.1, taken from [61], where a more detailed
2127 description may be found. The algorithm begins by reading in hits, which are converted to slopes.
2128 These slopes are calculated under the assumption that the hit originates from the IP; slopes calcu-
2129 lated under this assumption are denoted by a superscript g for global in order to distinguish them
2130 from local slopes calculated using only hits in the wedge. In the algorithm simulation, events are
2131 screened at truth level to make sure they pass certain requirements. The track's truth-level coor-
2132 dinates must place it with the wedge since some generated tracks do not reach the wedge. These
2133 hits are stored in a buffer two bunch crossings (BCs) in time deep that separates the wedge into so-
2134 called "slope-roads." If any given slope-road has sufficient hits to pass what is known as a coinci-
2135 dence threshold, a fit proceeds. A coincidence threshold is a requirement for an event expressed as
2136 $aX+bUV$, which means that an slope-road must have at least a hits in horizontal (X) planes and at

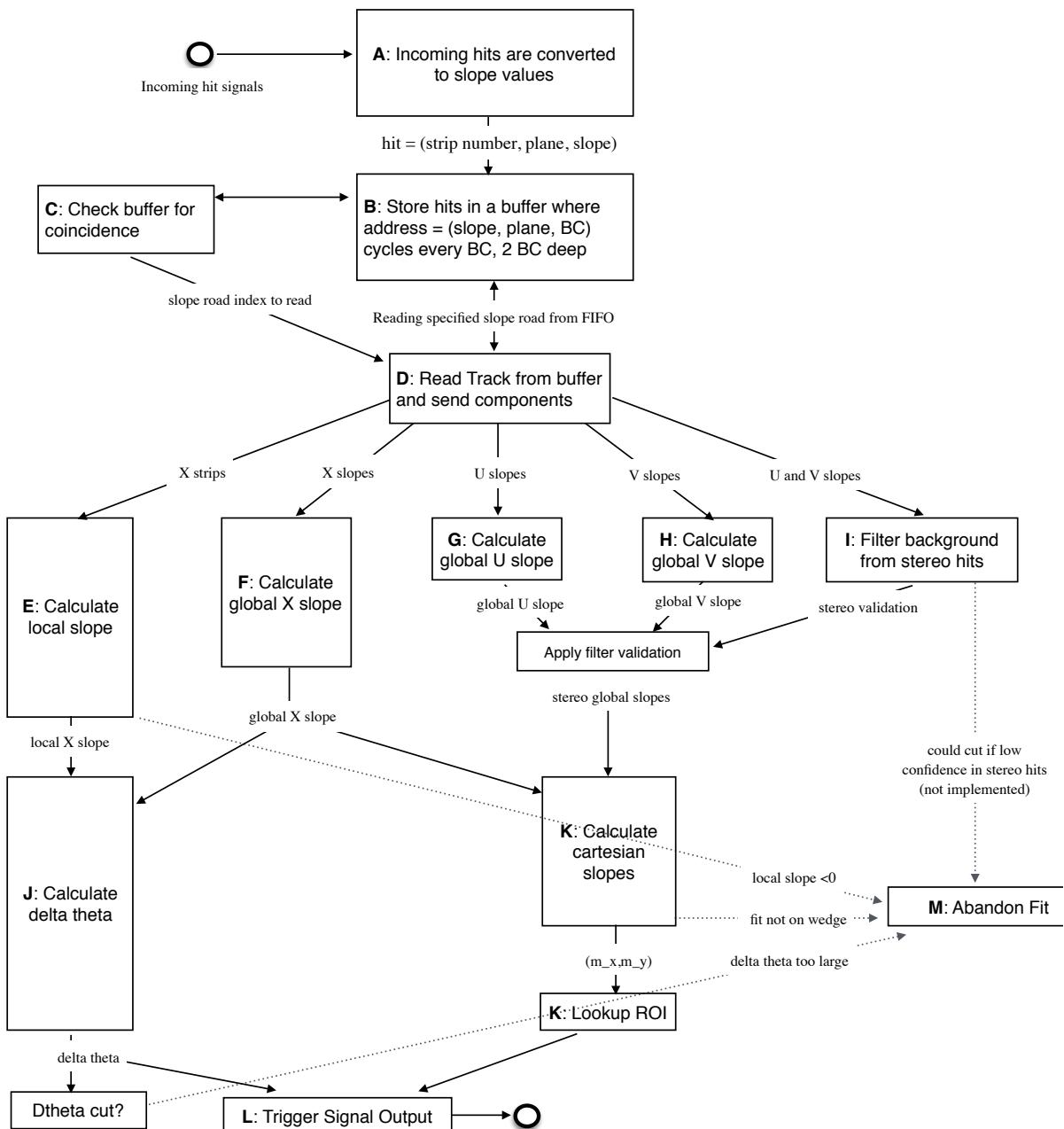


Figure A.1: A flow chart describing the algorithm steps, taken from [61].

2137 least b hits in stereo (U or V (corresponding to positive and negative stereo rotations)) planes. For
 2138 coincidence thresholds with a $2X$ hit requirement there is the extra requirement that, in the case of
 2139 only $2X$ hits, one be on each quadruplet in order to ensure an adequate lever arm for the $\Delta\theta$ calcu-
 2140 lation. Note that less stringent (lower hit) coincidence thresholds are inclusive; i.e. a slope-road pass-
 2141 ing a $4X+4UV$ cut automatically passes $2X+1UV$. The coincidence threshold, size of the slope-roads
 2142 (denoted b), and the number of slope-roads into which each horizontal and stereo hits get written
 2143 centered upon their nominal value are configurable parameters of the algorithm.

2144 An individual hit's slope is calculated as shown in Equation A.1, where y_{base} is the local y coordi-
 2145 nate (orthogonal to the beamline and direction of the horizontal strips) of a station's base, w_{str} is the
 2146 strip pitch, n_{str} is the hit's strip number, and z_{plane} is the location of the hit's plane along the beam-
 2147 line.

$$M_{hit} = \frac{y}{z} = \frac{y_{base}}{z_{plane}} + \frac{w_{str}}{z_{plane}} \times n_{str} \quad (\text{A.1})$$

2148 In the fit, individual hit slopes in a slope-road are used to calculate global slopes associated with each
 2149 plane type, which are averages (e.g. M_X^{ℓ} for the average slope of horizontal planes). These in turn are
 2150 used to calculate the three composite slopes: slopes associated with the horizontal (m_x) and vertical
 2151 coordinates (m_y) and the local slope of hits in the horizontal planes (M_X^l), all of which are shown in
 2152 Equation A.4. Note that the expression for M_X^l differs but is equivalent to the expression given in
 2153 [61]. This is due to a procedural change in the algorithm. The local X slope is expressed in [61] as:

$$M_X^{local} = A_k \sum_i y_i z_i - B_k \sum_i y_i, \quad B_k = \frac{1}{n} \sum_i z_i A_k = \bar{z} A_k \quad (\text{A.2})$$

2154 Procedurally, this entails doing the sums over y_i and $y_i z_i$, multiplying the sums by A_k , B_k , and then
 2155 subtracting both of these numbers, $\mathcal{O}(10^3)$, to get local slopes, $\mathcal{O}(10^{-1})$, while requiring preci-
 2156 sion on these numbers on the order of $\mathcal{O}(10^{-3})$. This requires precision in the sums $\mathcal{O}(10^{-7})$,
 2157 and with 32 bit fixed point numbers, there are deviations with respect to the floating point calcula-
 2158 tions at the level of $\mathcal{O}(10^{-5})$, which is enough to introduce a significant bias in the $\Delta\theta$ calculation.

2159 In order to prevent these errors, we do the subtraction first

$$M_X^{local} = A_k \sum_i y_i z_i - B_k \sum_i y_i = A_k \sum_i (y_i z_i - y_i \bar{z}) = B_k \sum_i y_i \left(\frac{z_i}{\bar{z}} - 1 \right) \quad (\text{A.3})$$

2160 Thus, we change the order of operations and store $1/\bar{z}$ instead of A_k in addition to B_k . We also
 2161 change the units of y_i and z_i in the calculation by dividing the millimeter lengths by 8192.* With
 2162 these changes, a 32 bit fixed point based algorithm has essentially identical performance to that of an
 2163 algorithm based on the usual C++ 32 floating point numbers. Future work includes converting the
 2164 32 bit fixed point arithmetic to 16 bit where possible in the algorithm. While introducing 16 bit num-
 2165 bers uniformly might seem preferable, since simple 16-bit operations in the firmware can be done in
 2166 a single clock tick, and a larger number of bits increases the algorithm latency, some numbers in the
 2167 algorithm will require a larger number of bits, in particular in the local slope calculation, which is
 2168 the single calculation in the algorithm requiring the largest numeric range.

2169 In Equation A.4, θ_{st} is the stereo angle of 1.5 degrees; the sums are over relevant planes; \bar{z} is the
 2170 average position in z of the horizontal planes; and y_i and z_i in the local slope expression refer to the y

*Chosen since it is a perfect power of 2 and of order the length scale of z in millimeters

2171 and z coordinates of hits in X planes.

$$m_x = \frac{1}{2} \cot \theta_{st} (\mathcal{M}_U^g - \mathcal{M}_V^g), \quad m_y = \mathcal{M}_X^g, \quad \mathcal{M}_X^l = \frac{\bar{z}}{\sum_i z_i^2 - 1/n (\sum_i z_i)^2} \sum_i y_i \left(\frac{z_i}{\bar{z}} - 1 \right) \quad (\text{A.4})$$

2172 From these composite slopes, the familiar expressions for the fit quantities θ (the zenith), ϕ (the az-
2173 imuth[†]), and $\Delta\theta$ (the difference in θ between the direction of the segment extrapolated back to the
2174 interaction point and its direction when entering the detector region; the following is an approxima-
2175 tion) may be calculated, as noted in [61]:

$$\theta = \arctan \left(\sqrt{m_x^2 + m_y^2} \right), \quad \phi = \arctan \left(\frac{m_x}{m_y} \right), \quad \Delta\theta = \frac{\mathcal{M}_X^l - \mathcal{M}_X^g}{1 + \mathcal{M}_X^l \mathcal{M}_X^g} \quad (\text{A.5})$$

2176 Looking at Equations A.4 and A.5, the dependence of fit quantities on input hit information be-
2177 comes clear. $\Delta\theta$ relies exclusively on information from the horizontal (X) planes. Both θ and ϕ rely
2178 on both horizontal and stereo slope information. However, the sum in quadrature of m_x and m_y in
2179 the arctangent for θ means that θ is less sensitive to errors in stereo hit information than ϕ . Given
2180 that θ_{st} is small, $\cot \theta_{st}$ is large (~ 38), so m_x multiplies small differences in \mathcal{M}_U and \mathcal{M}_V , where m_y
2181 is simply an average over slopes. This means that while errors in horizontal hit information will af-
2182 fect all three fit quantities, comparable errors in stereo hits will have a proportionately larger effect
2183 on θ and particularly on ϕ . The $\Delta\theta$ cut after step J in Figure A.1 has been implemented, requiring
2184 all fits to have $|\Delta\theta| < 16$ mrad. This requirement ensures good quality fits but also slightly reduces

[†]Defined with respect to the center (y) axis and *not* the axis of the strips (x) as is sometimes typical, so a hit along the center of the wedge has $\phi = 0$

2185 algorithm efficiency.

2186 **A.2 MONTE CARLO SAMPLES**

2187 The Monte Carlo (MC) samples used for these studies were generated in Athena release 20.1.0.2 us-
2188 ing simulation layout ATLAS-R2-2015-01-01-00 with muon GeoModel override version MuonSpectrometer-
2189 R.07.00-NSW and modifications to have two modules per multiplet and xxuvuvxx geometry with a
2190 stereo angle of 1.5 degrees. Muons of a single p_T were generated around the nominal IP with a smear-
2191 ing of 50 mm along the beam line and 0.015 mm orthogonal to it; these muons were pointed toward
2192 a single, large sector of the NSW. Each event consists of one muon fired towards the single NSW
2193 wedge separated by effectively infinite time from other events.

2194 **A.3 NOMINAL PERFORMANCE**

2195 In order to evaluate algorithm performance, a number of quantities are evaluated, including the fit
2196 quantities θ , ϕ , and $\Delta\theta$ as well as algorithm efficiency. Unless otherwise stated, that algorithm is
2197 run with a 4X+4UV coincidence threshold, slope-road size of 0.0009, an X tolerance of two slope-
2198 roads (i.e. hits in horizontal planes are written into the two slope-roads closest to the hits' value),
2199 a UV tolerance of four slope-roads[†], and a charge threshold requirement on hits of 1 (measured in
2200 units of electron charge) for a sample of 30 000 events with a muon p_T of 100 GeV. Samples were
2201 also generated for p_T values of 10 GeV, 20 GeV, 30 GeV, 50 GeV, and 200 GeV, which were used in

2202 [†]The larger tolerance on stereo hits takes into account the particulars of the m_x calculation mentioned in
Section A.1.

2202 some of the following studies.

2203 **A.4 FIT QUANTITIES**

2204 In order to evaluate the performance of the algorithm’s fit quantities θ , ϕ , and $\Delta\theta$, fit values are com-
2205 pared to truth-level MC values. The residual of the three fit quantities, $\theta_{fit} - \theta_{tru}$, $\phi_{fit} - \phi_{tru}$, and
2206 $\Delta\theta_{fit} - \Delta\theta_{tru}$, are recorded for every fitted track. The distributions of these quantities, in particular
2207 their biases and standard deviations, are then used to evaluate performance. In most cases, follow-
2208 ing [61], the mean and standard deviation of a 3σ Gaussian fit are quoted, as they capture the main
2209 features of the algorithm and generally behave like the raw mean and rms. Nevertheless, discussion
2210 of the raw quantities will be included when their behavior deviates markedly from that of the 3σ fit
2211 quantities.

2212 The truth-level quantities used in residual distribution are taken from information in the MC.

2213 These come directly from the MC for θ , ϕ , and $\Delta\theta$. These quantities, along with the geometry of
2214 the (large) wedge, are then in turn used to calculate truth-level values for any intermediate quantities
2215 used in the algorithm. $m_{x,tru}$, for instance, is given by $\tan \theta_{tru} \sin \phi_{tru}$.

2216 Residual distributions for fit quantities under the previously described default settings of the al-
2217 gorithm are shown in Figure A.2. Both the $\theta_{fit} - \theta_{tru}$ and $\Delta\theta_{fit} - \Delta\theta_{tru}$ distributions feature a
2218 mostly Gaussian shape with more pronounced tails. The mean bias for these distributions is negligi-
2219 ble at under one tenth of a milliradian, and the fitted (raw) rms values are 0.349 (0.614) mrad for θ
2220 and 1.03 (2.55) mrad for $\Delta\theta$. The case of the $\phi_{fit} - \phi_{tru}$ distribution is less straightforward, with both
2221 the shape and bias arising from the xxuvuvxx geometry and relatively large extent of one of the two

2222 η -stations, as explained in Appendix B of [62]. The fitted (raw) rms for the ϕ distribution is 8.67
 2223 (16.6) mrad.

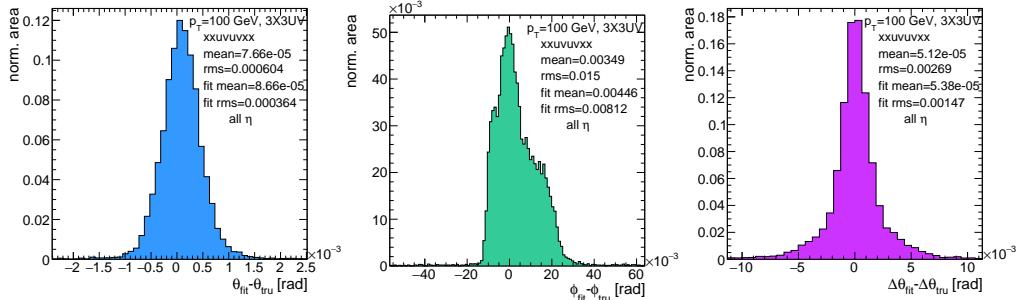


Figure A.2: Nominal residual plots; $\theta, \phi, \Delta\theta$ for $p_T = 100 \text{ GeV}$ muons

2224 Both increasing muon p_T and increasing muon η for a fixed p_T imply increasing muon energy. As
 2225 muons become more energetic, two effects compete in affecting the quality of fit. On the one hand,
 2226 higher energy muons are deflected less by the ATLAS magnetic field, which should tend to improve
 2227 the quality of the fit, since the fitted θ (upon which $\Delta\theta$ also relies) and ϕ values are calculated under
 2228 the infinite momentum muon (straight track) assumption. However, as muon energy increases, the
 2229 likelihood that the muon will create additional secondaries increases, which creates extra hits that
 2230 degrade the quality of the fit. While the geometry of the multiplet is such that there is very good res-
 2231 olution in the direction orthogonal to the horizontal strip direction, the shallow stereo angle of 1.5
 2232 degrees means that early hits caused by secondaries can have an outsize impact on m_x . $\Delta\theta$, which
 2233 does not rely upon stereo information should feel the effect of secondaries the least and benefit from
 2234 straighter tracks the most and hence benefit from higher muon energies; ϕ , relying upon stereo in-
 2235 formation the most, would be most susceptible to secondaries and benefit the least from straighter

2236 tracks and hence least likely to benefit from higher muon energy; θ relies upon both horizontal and
 2237 vertical slope information, though small errors are less likely to seriously affect the calculation, so the
 2238 two effects are most likely to be in conflict for this fit quantity.

2239 The interplay of these effects on the residual standard deviations can be seen in their dependen-
 2240 cies on η (Figure A.3; note that the final point in each of these plots is the rms of the distribution
 2241 overall η) and p_T (Figure A.4). For $p_T = 100$ GeV muons, $\Delta\theta$ performance increases with η (en-
 2242 ergy), and ϕ performance decreases, as expected;[§] for θ , the two effects appear to compete, with per-
 2243 formance first increasing with η until the effects of secondaries begins to dominate. Integrated over
 2244 all η , the effects are less clearly delineated. Both $\Delta\theta$ and θ performance increases with increasing p_T ,
 2245 suggesting straighter tracks with increasing energy are the dominant effect for these quantities, while
 2246 ϕ performance appears to improve and then deteriorate (the slight improvement at high p_T is due to
 2247 the addition of the $\Delta\theta$ cut into the algorithm, which filters out very poor quality fits).

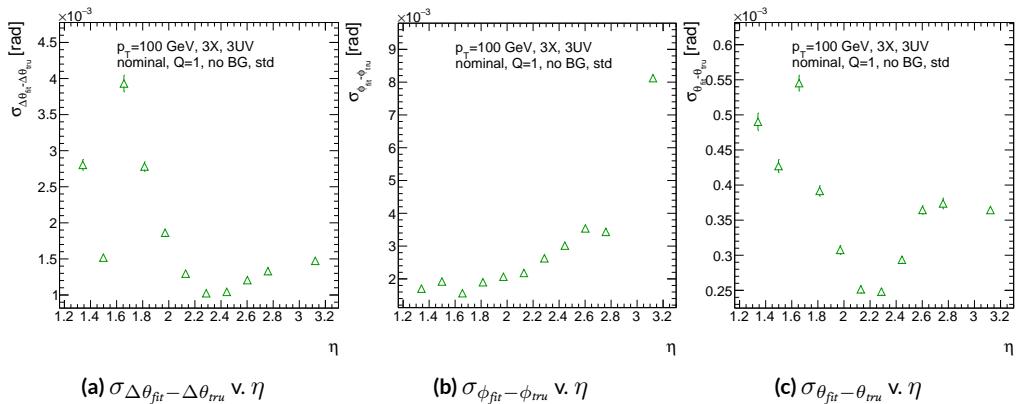


Figure A.3: The rms distributions of $\Delta\theta$, ϕ , and θ as a function of η for $p_T = 100$ GeV; the final point in each plot is the rms obtained from a fit to the full distribution including all η bins.

[§]The much worse overall performance for ϕ is due to the η dependent bias and other effects

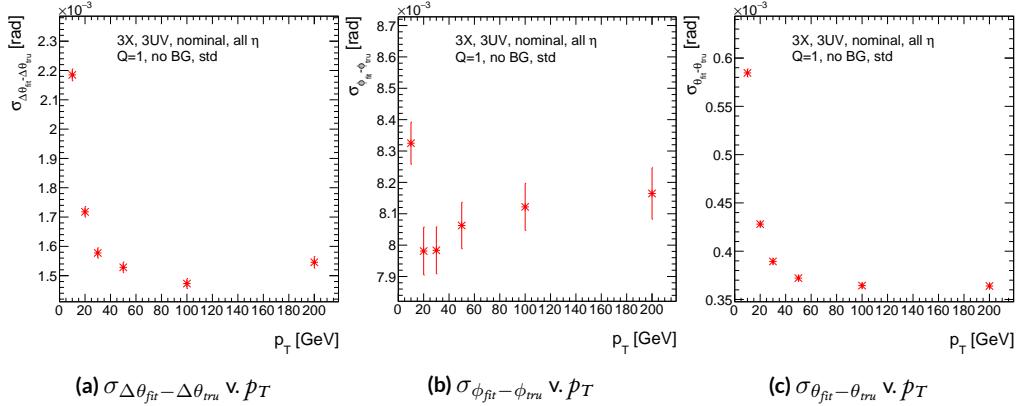


Figure A.4: The rms distributions of $\Delta\theta$, ϕ , and θ as a function of p_T .

2248 The rms of the three benchmark quantities as a function of algorithm set (i.e. slope-road) coinci-
 2249 dence threshold are shown in Figure A.5 using Gaussian fits and in Figure A.6 for the raw quantities.
 2250 The fitted σ 's for θ and ϕ are fairly stable across coincidence threshold. $\Delta\theta$, on the other hand, per-
 2251 forms better particularly for the most stringent coincidence threshold; this is a result of the fact that
 2252 additional information for more hits greatly improves the quality of the local slope fit calculation.
 2253 The raw rms is a different story. Naïvely, one would expect the performance to get better with more
 2254 stringent coincidence threshold, but this is not the case in Figure A.6. As the coincidence thresh-
 2255 old gets more stringent, fewer and fewer tracks are allowed to be fit. When moving from 2X hits to
 2256 3X hits, the tracks that get vetoed populate the tails of the distribution outside the 3σ fit range but
 2257 are not in the very extremes of the distribution. While tracks with 2X hits are of lower quality than
 2258 those with 3 and 4 X hits, tracks with the very worst fit values pass even the most stringent coinci-
 2259 dence threshold requirements (e.g. as a result of many hits arising from a shower of secondaries).
 2260 This is best illustrated when comparing the 2X+1UV $\Delta\theta$ residual distribution with the 4X+4UV

distribution in Figure A.7. As both the overlayed normalized curves and ratio distribution show,
 while the most central regions are fairly similar, the $\omega X + 1$ UV distribution is much more prominent
 in the tails but not the extreme tails, which means that, though the overall $\omega X + 1$ UV raw rms goes
 down, the overall quality of algorithm fits is worse.

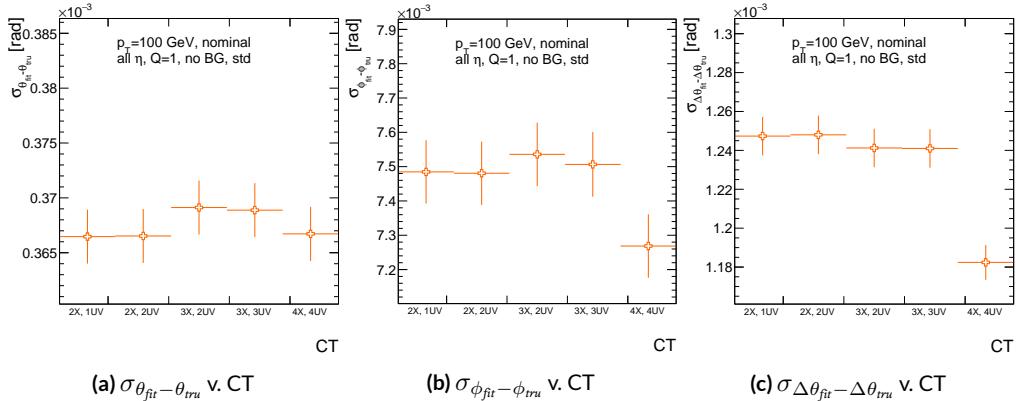


Figure A.5: The fitted rms of residual distributions for θ , ϕ , and $\Delta\theta$ as a function of coincidence threshold for $p_T = 100$ GeV.

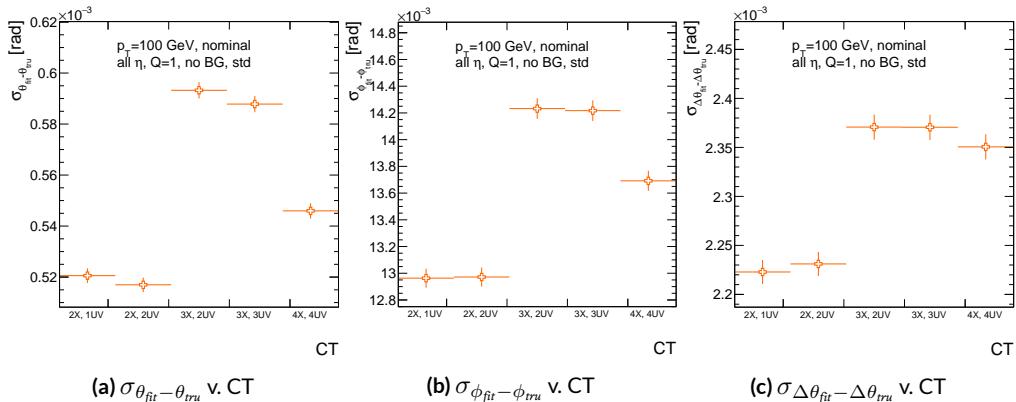


Figure A.6: The raw rms of residual distributions for θ , ϕ , and $\Delta\theta$ as a function of coincidence threshold for $p_T = 100$ GeV.

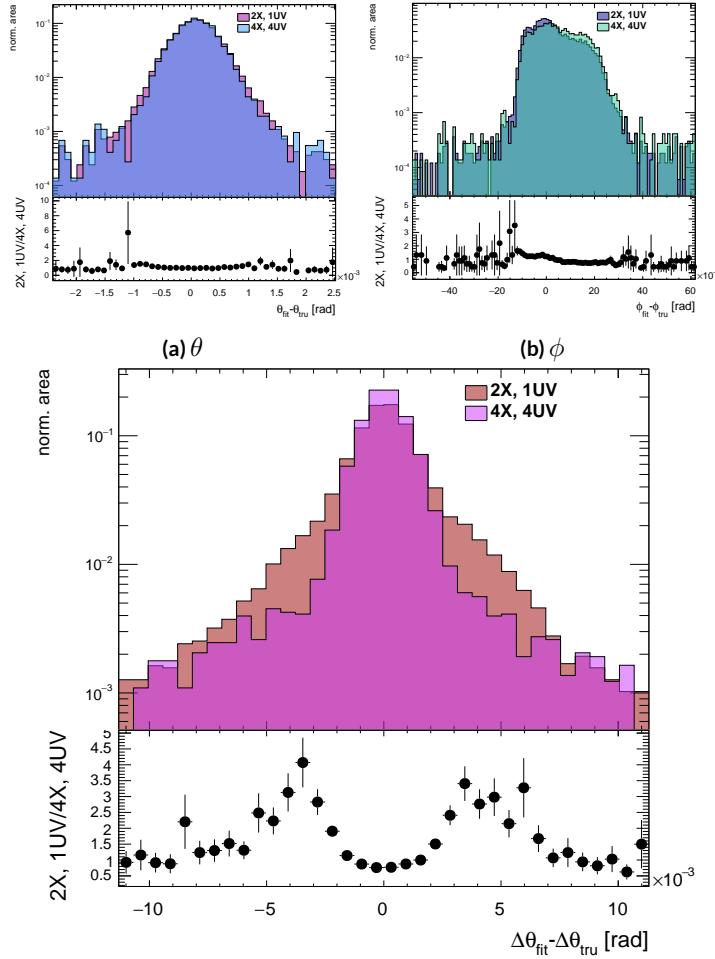


Figure A.7: Nominal $\Delta\theta$ residual distribution for $p_T = 100$ GeV muons with coincidence thresholds 2X+1UV and 4X+4UV normalized to the same area and plotted together (top) as well as the ratio of the 2X+1UV distribution and the 4X+4UV per bin.

2265 A.5 EFFICIENCIES

2266 Two general efficiencies have been formulated to study the performance of the MMTP algorithm.

2267 The first, denoted ε_{alg} , is the fraction of tracks that pass some (slope-road) coincidence threshold

2268 configuration that are successfully fit. An event that passes a slope-road coincidence but does not fit

2269 fails because some of the hits included are of sufficiently poor quality to throw off the fit. This effi-

2270 ciency answers the question of how often the algorithm performs fits when technically possible, giv-

2271 ing a measure of overall algorithm performance for a given configuration. For example, $\varepsilon = 95\%$ for

2272 $3X+2UV$ means that 95% of tracks that produce at least $3X$ hits and $2UV$ hits in at least one slope-

2273 road will be successfully fitted 95% of the time. The performance of this efficiency as a function of

2274 coincidence threshold, η (with the final point once again being the efficiency integrated over all η),

2275 and p_T is shown in Figure A.8. ε_{alg} is fairly constant in η and decreases with increased p_T , which can

2276 be attributed to the increased likelihood of secondaries introducing lower quality hits that cause the

2277 fit to fail.

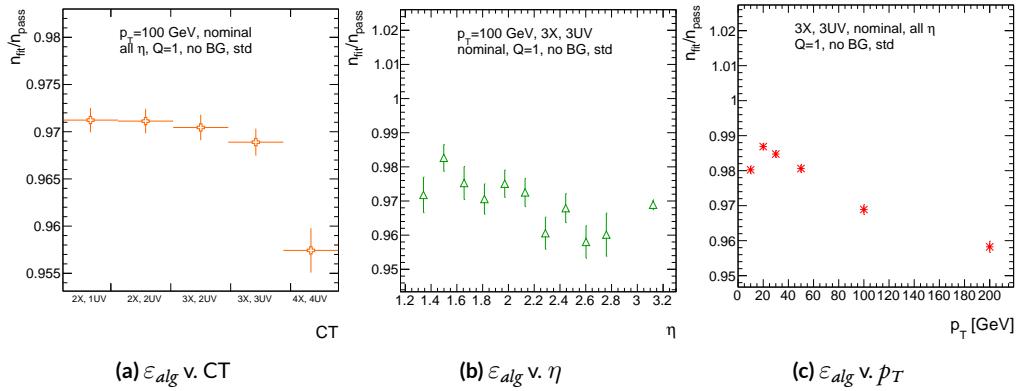


Figure A.8: ε_{alg} and as a function of coincidence threshold, η (final point is ε_{alg} integrated over all η), and p_T .

2278 The second efficiency type, denoted ε_{fit} , is the fraction of tracks that enter the wedge whose fits
 2279 (if any) satisfy a given coincidence threshold. This efficiency can be used to help establish an optimal
 2280 coincidence threshold setting in the algorithm, balancing the improved overall fit quality of higher
 2281 thresholds with the greater number of fits for lower thresholds. Hence, an ε_{fit} of 95% at 3X+2UV
 2282 means that 95% of tracks entering the wedge are fit and that these fits include at least 3X and 2UV
 2283 hits. ε_{fit} as a function of coincidence threshold is shown in Figure A.9 (a), which shows that the ma-
 2284 jority of fits having at most 3X+3UV hits. That there is a marked drop to 4X+4UV is not surpris-
 2285 ing, as there is a substantial population outside the 4X+4UV bin in Figure A.10. The behavior of
 2286 ε_{fit} with η in Figure A.9 (b) (with the final point once again being the efficiency integrated over all
 2287 η) is much more varied, with geometric effects of detector acceptance coming into play. The per-
 2288 formance of ε_{fit} as a function of p_T , shown in Figure A.9 (c), is similar to that of ε_{alg} coincidence
 2289 threshold, again consistent with the effects of secondaries at higher energies.

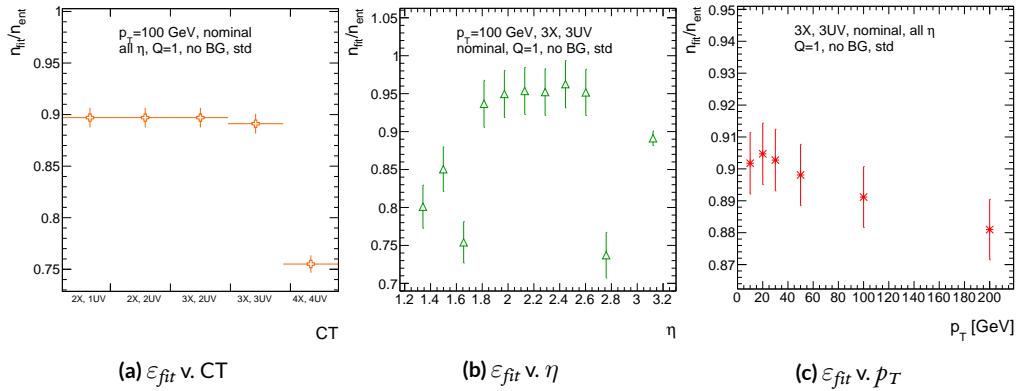


Figure A.9: ε_{fit} and as a function of coincidence threshold, η (final point is ε_{fit} integrated over all η), and p_T .

2290 In order to better understand efficiency behavior with coincidence threshold, the distribution of

2291 highest slope-road coincidence thresholds in events is shown in Figure A.10, with the o,o bin con-
 2292 taining events that did not meet requirements for the minimum $2X+1UV$ coincidence threshold for
 2293 a fit to occur. That the efficiency is lower at higher coincidence threshold suggests that most of the
 2294 fits that fail have high hit multiplicity (i.e. a similar number fails in each of the coincidence thresh-
 2295 old bins in Figure A.8 (a)), which is consistent with the interpretation that the primary source of fit
 2296 failures is bad hits originating from secondaries created by higher energy muons.

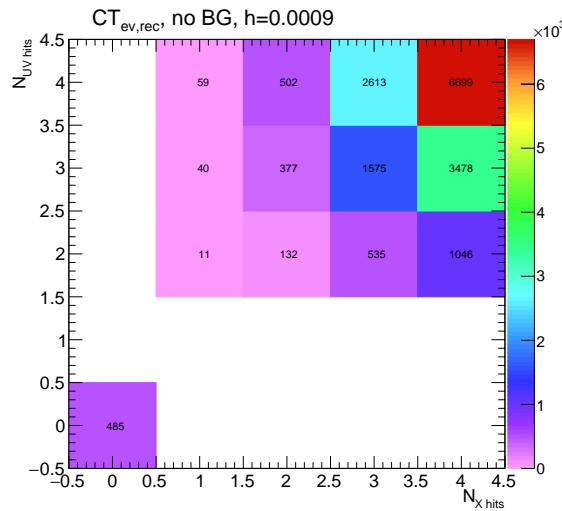


Figure A.10: The distribution of highest slope-road coincidence thresholds in events; the 0,0 bin is the number of events passing selection requirements that fail to form the minimum $2X+1UV$ coincidence threshold necessary for a fit.

2297 A.6 INCOHERENT BACKGROUND

2298 The default slope-road size and tolerances associated with horizontal and stereo hits used in the
2299 above studies were configured to optimize algorithm performance, similar to studies in [61]. In or-
2300 der to evaluate algorithm performance under conditions with more limited resources, as might be
2301 expected at run-time, additional studies were conducted with the slope-road size and hit tolerances
2302 set equivalent to the sensitive area of a single VMM chip[¶] both with and without generation of inco-
2303 herent background.

2304 Incoherent background is generated based on the assumption that the intensity only varies as a
2305 function of the distance from a point to the beamline, r . The number of hits per unit area per unit
2306 time as a function of r is given in Equation A.6 and taken from [61].

$$I = I_0 (r/r_0)^{-2.125} \quad (\text{A.6})$$

2307 where $r_0 = 1000$ mm and $I_0 = 0.141$ kHz/mm²

2308 Background generation happens per event as follows:

- 2309 1. Determine the total number of hits to be generated in this event according to a Poisson distri-
2310 bution
- 2311 2. Assign a time to hits uniformly in $[t_{\text{start}} - t_{\text{VMM}}, t_{\text{end}}]$ where start and end are for the event
2312 clock and t_{VMM} is the VMM chip deadtime (100 ns)
- 2313 3. Assign a plane to hits uniformly
- 2314 4. Assign a ϕ value to hits uniformly

[¶]One VMM is assumed to cover 64 MM strips at 0.445 mm each.

2315 5. Assign an r to hits according to Equation A.6

2316 6. Calculate hit information according to these values.

2317 The expectation value for the Poisson distribution is determined by integrating Equation A.6

2318 over the surface area of the wedge to get the total hit rate for the wedge, Γ , and then multiplying this

2319 by the length of the time window over which hits may be generated. With $H = 982$ mm, $b_1 =$

2320 3665 mm, and $\theta_w = 33\pi/180$, we find^{||}:

$$\Gamma = 2I_0 r_0^{2.125} \int_0^{\theta_w/2} d\phi \int_{H \sec \phi}^{(H+b_1) \sec \phi} r dr r^{-2.125} = 98.6657 \text{ MHz} \quad (\text{A.7})$$

2321 In this case, we have taken the nominal values of the MM sector geometry for H (wedge base), b_1

2322 (the wedge height), and θ_w (the wedge opening angle).

2323 The effects of incoherent background and larger slope road size are summarized in Figure A.11 for

2324 efficiencies and in Figure A.13 and Table A.1 for residual of fit quantities.

2325 Figure A.11 show the effect of both wider slope-roads and the introduction of background on ef-

2326 ficiencies. The introduction of wider slope-roads increases the chance that an early errant hit (either

2327 from secondaries/ionization or background) will be introduced into the fit, and the presence of in-

2328 coherent background greatly increases the number of such errant hits. Both wider slope-roads and

2329 background drive down the number of fits (numerator) in both efficiencies, and background can

2330 artificially inflate the denominator of ε_{alg} , a reco-level, slope-road coincidence threshold. The shape

2331 of the ε_{fit} versus coincidence threshold distributions remains fairly constant with each complicat-

^{||}Using Mathematica and the extra factor of r from the volume element

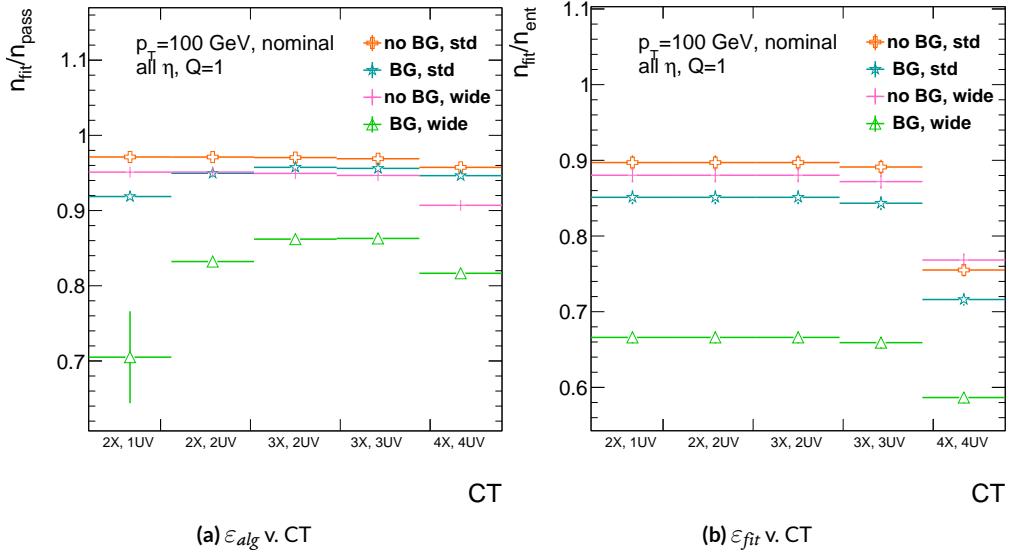


Figure A.11: The algorithm and total efficiencies as a function of coincidence threshold for different background settings and slope-road sizes (standard and wide (one slope road as 1 VMM chip)).

ing factor (standard, wider slope-roads, background, both wider slope-roads and background), suggesting many muons will simply not be fit with any number of hits; ε_{fit} does not take into account the coincidence threshold of tracks that are not fit, so the effect appears uniform across coincidence threshold. The effects seen for ε_{alg} , which are not uniform across coincidence threshold can be better understood when examining the distribution of event highest coincidence thresholds, shown for wide slope-roads both without and with background in Figure A.12. Take, for example the 2X+1UV case. The 2X+1UV bin in particular has a marked increase when background is introduced. No new good tracks are introduced between the no background and background cases, so the increase is entirely due to bad, background hits; hence, these events do not (and should not) fit, causing the particularly pronounced drop in this bin between these two cases in Figure A.11.

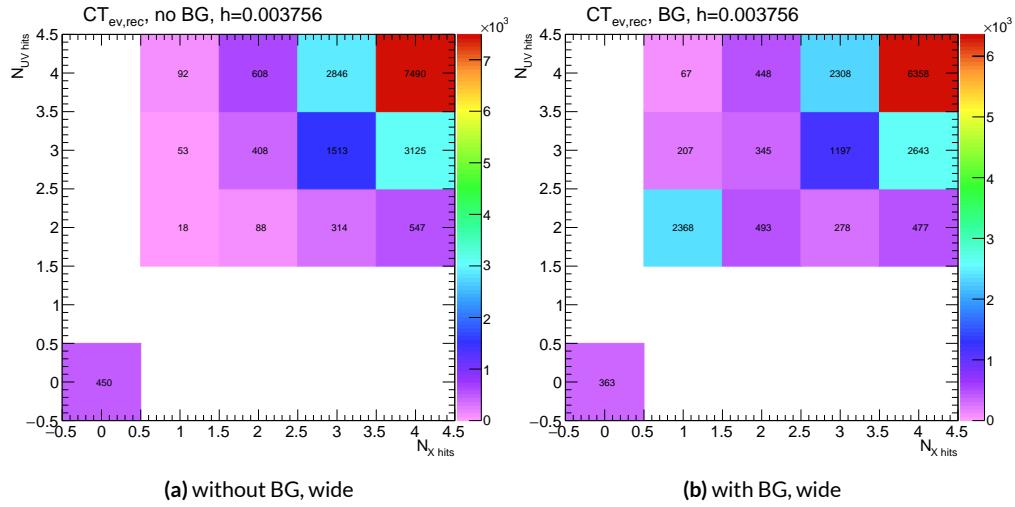


Figure A.12: The distribution of highest slope-road coincidence thresholds in events for the algorithm with wide slope-roads (width of 1 VMM) both without (a) and with (b) incoherent background; the 0,0 bin is the number of events passing selection requirements that fail to form the minimum $2X+1UV$ coincidence threshold necessary for a fit.

The effect of increasing slope-road size and incoherent background on fit quantity residual rms values as a function of p_T is shown in Figure A.13. As the figure shows, the fitted rms values are fairly robust against increased slope-road size and background. This does not hold for all of the raw rms values, however, as shown in Table A.1. Just as with the efficiencies, the introduction of background has a larger effect than that of increased slope-road size, which does not seem to have an overly large impact on any of the fit quantities on its own. While $\Delta\theta$ remains robust to both increased slope-road size and background (likely due to the $\Delta\theta$ cut of 16 mrad built into the algorithm), θ shows some degradation in performance, and the ϕ residual raw rms shows a very large increase upon the introduction of background. Nevertheless, the contrasting behavior of the fitted and raw rms values suggests that tracks that drive up the raw rms values already had very poor fit quality even before the introduction of background, so the impact on fit quantities should remain fairly limited.

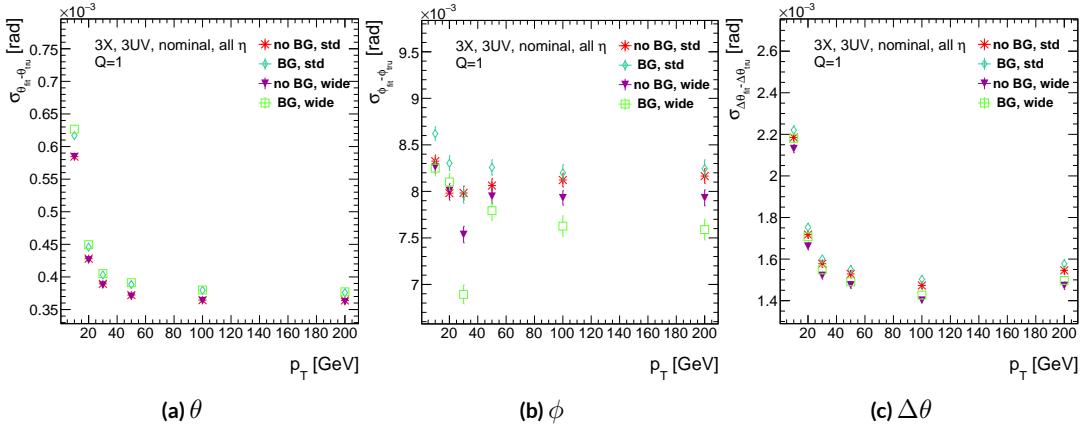


Figure A.13: The three fit quantity residual rms values as a function of p_T for different background settings and slope-road sizes (standard and wide (one slope road as 1 VMM chip)).

	No BG, std	No BG, wide	BG, std	BG, wide
θ	0.364 (0.604)	0.363 (0.542)	0.379 (0.886)	0.380 (1.07)
ϕ	8.12 (15.0)	7.93 (13.2)	8.20 (24.6)	7.63 (24.8)
$\Delta\theta$	1.47 (2.69)	1.40 (2.66)	1.50 (2.89)	1.43 (2.90)

Table A.1: The fitted (absolute) σ of fit quantity residuals in mrad under different algorithm settings.

2353 As Table A.1 shows, rms values appear to be robust to an increase in slope-road size. Neverthe-
2354 less, though the fitted σ residual values are also fairly robust to the introduction of background, the
2355 raw rms values are not. While the raw $\Delta\theta$ rms stays stable, both θ and ϕ suffer noticeable degra-
2356 dation, which suggests that the introduction of background has a detrimental effect on horizontal
2357 slope residual (i.e. on stereo strips in particular). This level of degradation is likely acceptable for θ ,
2358 though further steps may need to be taken to address ϕ .

2359 A.7 BCID

2360 A fitted track's BCID is determined by the most common BCID associated with its hits. Concerns
2361 were raised that this might cause incorrect BCID association for fitted tracks. In order to address
2362 this, the rate of successful BCID association for fitted tracks was recorded. Figure A.14 shows the
2363 dependence of this success rate as a function of p_T and coincidence threshold in the different back-
2364 ground and resource conditions used in the previous section. The successful BCID identification
2365 rate is always over 99.5%, demonstrating that this issue is not a concern with the state-of-the-art de-
2366 tector simulation.

2367 A.8 CHARGE THRESHOLD

2368 The MMTP uses the first hits registered passing a charge threshold requirement given in units of
2369 electron charge. In principle, it would be beneficial to be able to use any hits that are registered re-
2370 gardless of deposited charge, but in the high rate environment envisioned for the NSW, this require-
2371 ment might need to be raised. Nominal algorithm settings have this charge threshold requirement

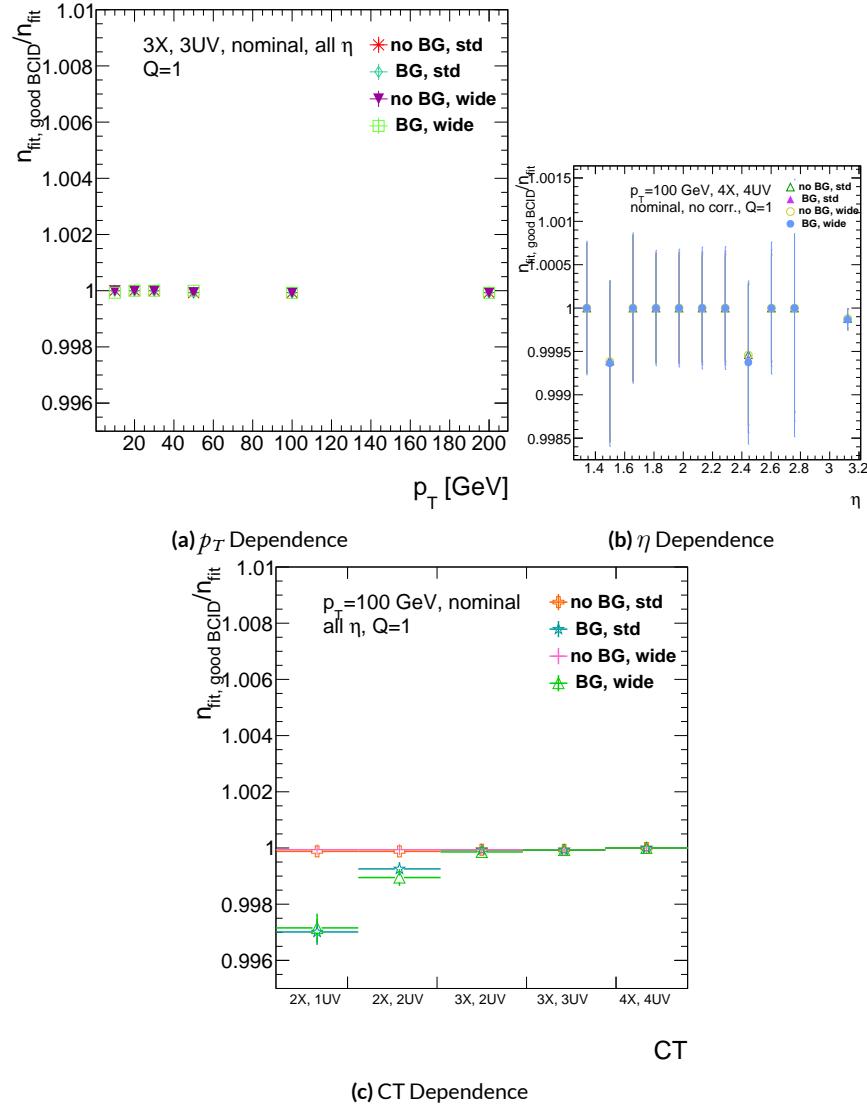


Figure A.14: The rate of good BCID association based majority hit BCID as a function of p_T and coincidence threshold.

2372 set to 1, and studies were conducted on algorithm performance for charge threshold values of 0, 1,
 2373 and 2. Efficiencies as a function of coincidence threshold for different charge thresholds are shown
 2374 in Figure A.15. Increasing the charge threshold lowers both efficiencies, particularly at high coinci-
 2375 dence threshold, which suggests that energetic muons with secondaries create both very many hits
 2376 and hits with higher charge. While the shapes of the fit quantity distributions as a function of p_T in
 2377 Figure A.16 are fairly constant across charge threshold, performance is not. θ and $\Delta\theta$ show some im-
 2378 provement with higher charge threshold, particularly at low p_T , suggesting that resolution improves
 2379 in the vertical direction, but ϕ shows degradation at higher charge threshold, which is a symptom
 2380 of more highly charged particles experiencing greater bending in the ATLAS magnetic field in the ϕ
 2381 direction.

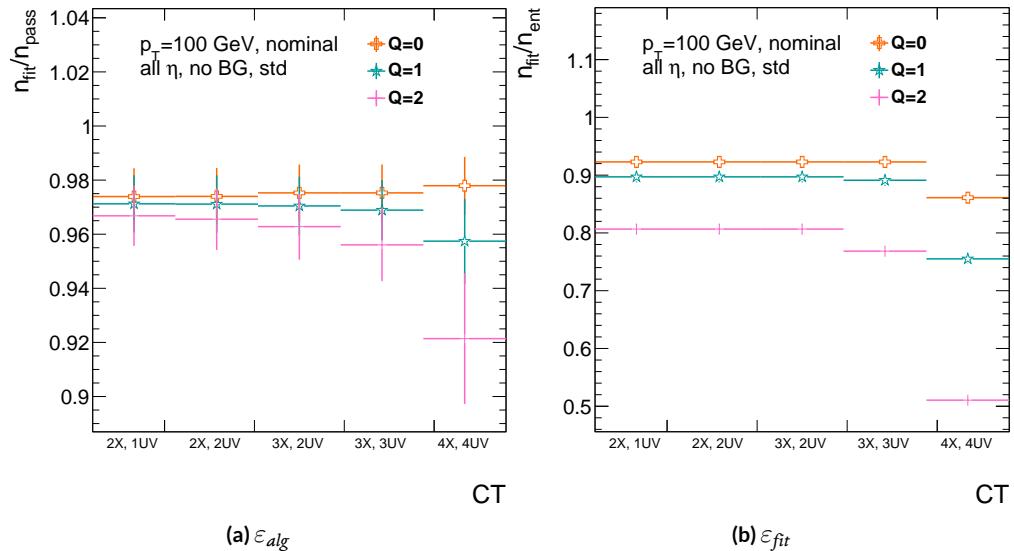


Figure A.15: The efficiencies as a function of coincidence threshold for charge thresholds of 0, 1, and 2.

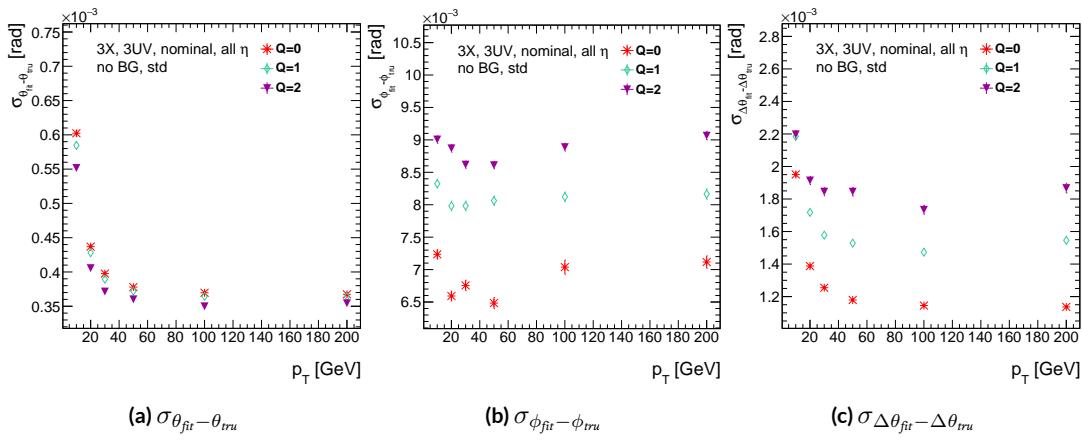


Figure A.16: The fit quantity residual rms values as a function of p_T for charge thresholds of 0, 1, and 2.

2382 A.9 MISALIGNMENTS AND CORRECTIONS

2383 The performance of the trigger algorithm under misalignment has been studied for each of the six
2384 alignment quantities (three translations and three rotations all along the principal axes) described
2385 in [?] and [?], whose convention we will follow here. For the simulated wedge studied here the
2386 local coordinates described in [?] are taken to be centered at the center of the base of the wedge^{**},
2387 the local t axis corresponds to the axis of the beam line, the local z axis corresponds to the direction
2388 orthogonal to both the beam line and the horizontal strips, and the local s axis completes the right-
2389 handed coordinate system. The rotation angles α , β , and γ correspond to rotations around the local
2390 t , z , and s axes, respectively. Note that the local s , z , and $-t$, axes correspond to the usual global x , y ,
2391 and z axes. Misalignments were studied in twenty evenly spaced increments from nominal positions
2392 to misalignments of 1.5 mrad for the rotations (-1.5 mrad to +1.5 mrad for the γ case), and of 5 mm
2393 (a roughly corresponding linear shift) for the translations. In all cases, the front quadruplet is mis-
2394 aligned while the rear quadruplet remains in its nominal position. While only the front quadruplet
2395 of a single wedge is misaligned, the framework for misalignment presented below could be used to
2396 study generic local and global misalignments. The six misalignments are schematically represented
2397 in Figure A.17.

2398 Chamber misalignments manifest themselves as altered strips in algorithm input. In order to sim-
2399 ulate the effects of misalignment, the change in the local y coordinate—the distance from the bot-

240 **Not, as is sometimes the case, the centroid position for simplicity's sake, as the agreed upon geometry
of the detector changed several times while studies were in progress; any transformation in a centroid-origin
coordinate system can of course be formed by a combination of the six transformations examined.

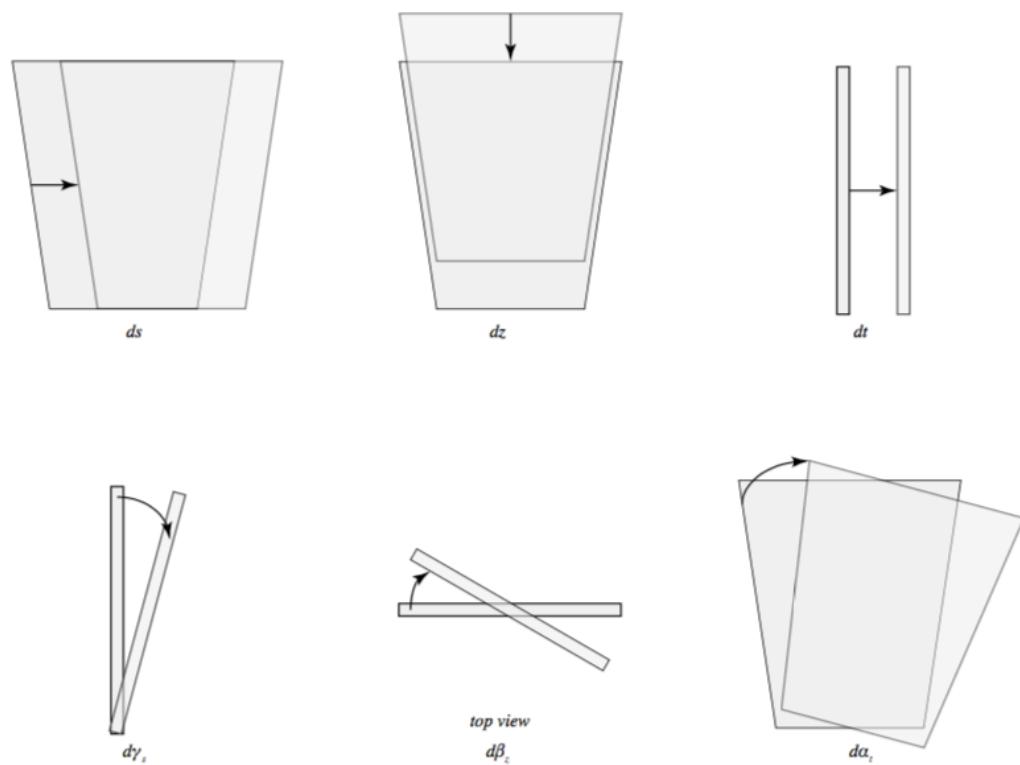


Figure A.17: The different misalignment cases as defined in the AMDB manual.

2400 tom wedge center in the direction perpendicular to both the beamline and the strip direction—is
 2401 calculated for a track coming straight from the interaction point defined by the truth-level θ and ϕ
 2402 angles for generic misalignment. This displacement in y is then added to input hit information and
 2403 the algorithm is then run normally.

2404 To understand how this displacement is calculated, some notation first needs to be described.

Table A.2: A summary of notation used in this section: note that non-AMDB notation is used in this section.

Symbol	Definition
s_x, s_y, s_z, \vec{s}	Position of the muon hit in ATLAS global coordinates; the infinite momentum muon track
\hat{n}	Vector normal to the plane; taken to be \hat{z} (the beamline) in the nominal case
$\vec{\mathcal{O}}_{IP}^{g,l}$	Position of the interaction point in ATLAS global (g) or wedge local (l) coordinates
$\vec{\mathcal{O}}_{base}^{g,l}$	Position of the plane base in ATLAS global (g) or wedge local (l) coordinates; $(0, y_{base}, z_{pl})$ ($(0, 0, 0)$) for the nominal case in global (local) coordinates
$\vec{\zeta}$	$\vec{s} - \vec{\mathcal{O}}_{base}$
primed quant.	quantities after misalignment

2405 Generically speaking, a hit is the intersection of a line (the muon track) with a plane (the individual plane in the multiplet). We assume the muon moves in a straight line defined by the origin and
 2406 the truth-level θ_{pos} and ϕ_{pos} (i.e. the infinite momentum limit) and that the MM plane is rigid and
 2407 defined by a point, which we take to be the center of the bottom edge of the plane, and a normal
 2408 vector, which we take to be the z axis in the nominal case.

2410 The coordinate axes x, y, z axes used here correspond to the usual AMDB $s, z, -t$ axes. Since the
 2411 direction does not really matter when studying misalignment or corrections thereof, the major dif-

²⁴¹² ference is the choice of origin.

²⁴¹³ The muon track we denote^{††} \vec{s} , the bottom point of the plane $\vec{\mathcal{O}}_{base}$, and the normal vector \hat{n} .

²⁴¹⁴ The muon track will always be given as (the wedge gets moved, not the muon):

$$\vec{s} = \mathcal{O}_{IP} + k\hat{s} \quad (\text{A.8})$$

$$\hat{s} = \sin \theta_{pos} \sin \phi_{pos} \hat{x} + \sin \theta_{pos} \cos \phi_{pos} \hat{y} + \cos \theta_{pos} \hat{z} \quad (\text{A.9})$$

$$\vec{s} = k\hat{s} = \frac{z_{pl}}{\cos \theta_{pos}} \hat{s} = z_{pl} (\tan \theta \sin \phi \hat{x} + \tan \theta \cos \phi \hat{y} + 1) \quad (\text{A.10})$$

²⁴¹⁵ where $k \in \mathbb{R}$, along with the unit vector \hat{s} , defines the point where the track intersects the wedge.

²⁴¹⁶ Rotations are done before translations, according to the order prescribed in the AMDB guide for

²⁴¹⁷ chamber alignment, so the axes the principal axes of the plane are rotated according to the following

²⁴¹⁸ matrix (where s , c , and t are the obvious trigonometric substitutions)

$$\begin{aligned} & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{pmatrix} \begin{pmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{pmatrix} \begin{pmatrix} c\alpha & -s\alpha & 0 \\ s\alpha & c\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\gamma & -s\gamma \\ 0 & s\gamma & c\gamma \end{pmatrix} \begin{pmatrix} c\alpha c\beta & -s\alpha c\beta & s\beta \\ s\alpha & c\alpha & 0 \\ -c\alpha s\beta & s\alpha s\beta & c\beta \end{pmatrix} \\ & = \boxed{\begin{pmatrix} c\alpha c\beta & -s\alpha c\beta & s\beta \\ s\alpha c\gamma + c\alpha s\beta s\gamma & c\alpha c\gamma - s\alpha s\beta s\gamma & -c\beta s\gamma \\ s\alpha s\gamma - c\alpha s\beta c\gamma & c\alpha s\gamma + s\alpha s\beta c\gamma & c\beta c\gamma \end{pmatrix}} = \mathcal{A} \end{aligned} \quad (\text{A.11})$$

^{††}Recall ϕ_{pos} is defined with respect to the y axis instead of the x axis, as might otherwise be typical.

2419 The thing that matters is what the new strip hit is—i.e. what the new y value is since this, along
 2420 with a plane number, is all that is fed into the algorithm. To find this, we must solve for the new
 2421 point of intersection with the rotated plane and then apply the effects of translations. The path con-
 2422 necting the base of the wedge with the intersection of the muon track will always be orthogonal to
 2423 the normal vector of the plane. Our quantities after misalignment, denoted by primed quantities,
 2424 will look like

$$\mathcal{O}_{base} \rightarrow \mathcal{O}_{base} + ds\hat{x} + dz\hat{y} + dt\hat{z} = \mathcal{O}'_{base}, \quad \hat{n} \rightarrow A\hat{n} = A\hat{z} = \hat{z}', \quad \vec{s} \rightarrow k'\hat{s} + \mathcal{O}_{IP} = \vec{s}' \quad (\text{A.12})$$

2425 so, moving to explicit, global coordinates in the last line so we can do the computation (relying on
 2426 the fact that any vector in the wedge, namely $\vec{\zeta}' = \vec{s}' - \mathcal{O}'$ the local coordinates of the interaction
 2427 point, is necessarily orthogonal to \hat{n}):

$$0 = \hat{n} \cdot (\vec{\mathcal{O}}_{base} - \vec{s}') \rightarrow 0 = A\hat{z}' \cdot (\vec{\mathcal{O}}'_{base} - (k'\hat{s} + \vec{\mathcal{O}}_{IP})) \quad (\text{A.13})$$

$$\rightarrow k' = \frac{s\beta\vec{\mathcal{O}}'_{base-IP,x} - c\beta s\gamma\vec{\mathcal{O}}'_{base-IP,y} + c\beta c\gamma\vec{\mathcal{O}}'_{base-IP,z}}{\hat{s} \cdot \hat{z}'} \quad (\text{A.14})$$

$$= \frac{s\beta ds - c\beta s\gamma(y_{base} + dz) + c\beta c\gamma(z_{pl} + dt)}{s\beta s\theta s\phi - c\beta s\gamma s\theta c\phi + c\beta c\gamma c\theta} \quad (\text{A.15})$$

2428 To find our new y coordinate, we need to evaluate $s'_y = \hat{y}' \cdot k'\vec{s}'$ to find the final correction of:

$$\Delta y = \vec{\zeta}' \cdot \hat{y}' - \vec{\zeta} \cdot \hat{y} = (k'\hat{s} - \vec{\mathcal{O}}'_{base}) \cdot \hat{y}' - (s_y - y_{base}) \quad (\text{A.16})$$

²⁴²⁹ The correction will be plane dependent since (denoting the stereo angle ω):

$$\hat{y}_x = \hat{y} \rightarrow \hat{y}'_x = -s\alpha c\beta \hat{x} + (c\alpha c\gamma - s\alpha s\beta s\gamma) \hat{y} + (c\alpha s\gamma + s\alpha s\beta c\gamma) \hat{z} \quad (\text{A.17})$$

²⁴³⁰ and

$$\begin{aligned} \hat{y}_{U,V} = & \pm s\omega \hat{x}' + c\omega \hat{y}'_{U,V} = [\pm c\alpha c\beta s\omega - s\alpha c\beta c\omega] \hat{x} + [\pm (s\alpha c\gamma + c\alpha s\beta s\gamma) s\omega \\ & + (c\alpha c\gamma - s\alpha s\beta s\gamma) c\omega] \hat{y} + [\pm (s\alpha s\gamma - c\alpha s\beta c\gamma) s\omega + (c\alpha s\gamma + s\alpha s\beta c\gamma) c\omega] \hat{z} \end{aligned} \quad (\text{A.18})$$

²⁴³¹ A.10 INDIVIDUAL CASES

²⁴³² Currently we only study the cases where one misalignment parameter is not zero. We examine these
²⁴³³ in detail below, calculating the most pertinent quantities in the misalignment calculation, k'/k and
²⁴³⁴ the new horizontal and stereo y axes. Before setting out, we simplify the expressions for the trans-
²⁴³⁵ formed \hat{y}' 's, removing any terms with the product of two sines of misalignment angles, which will be
²⁴³⁶ zero.^{††}

$$\hat{y}'_x = -s\alpha c\beta \hat{x} + c\alpha c\gamma \hat{y} + c\alpha s\gamma \hat{z} \quad (\text{A.19})$$

²⁴³⁷

$$\hat{y}'_{U,V} = [\pm c\alpha c\beta s\omega - s\alpha c\beta c\omega] \hat{x} + [\pm s\alpha c\gamma s\omega + c\alpha c\gamma c\omega] \hat{y} + [\mp c\alpha s\beta c\gamma s\omega + c\alpha s\gamma c\omega] \hat{z} \quad (\text{A.20})$$

^{††}If only one misalignment parameter is non-zero, then two or more sines will contain at least one term will contain $\sin 0 = 0$.

²⁴³⁸ If the translations are zero,

$$k' = \frac{-c\beta s\gamma y_{base} + c\beta c\gamma z_{pl}}{s\beta s\theta s\phi - c\beta s\gamma s\theta c\phi + c\beta c\gamma c\theta}, \quad k'/k = \frac{-c\beta s\gamma y_{base}/z_{pl} + c\beta c\gamma}{s\beta t\theta s\phi - c\beta s\gamma t\theta c\phi + c\beta c\gamma} \quad (\text{A.21})$$

²⁴³⁹ A.II $ds \neq 0$

²⁴⁴⁰ $k'/k = 1$ (the point of intersection does not move closer or further from the IP), and only the stereo
²⁴⁴¹ planes are affected. Note that only relevant term in Equation A.16, for the stereo strip \hat{y} for $\vec{\mathcal{O}}'_{base} =$
²⁴⁴² $ds\hat{x}$ is:

$$\pm \sin \omega ds \approx \pm 0.0261 ds \quad (\text{A.22})$$

²⁴⁴³ meaning that a displacement in x of 17 mm, more than three times the range of misalignments studied,
²⁴⁴⁴ would be necessary for a shift in the stereo planes corresponding to one strip width.

²⁴⁴⁵ A.12 $dz \neq 0$

²⁴⁴⁶ $k'/k = 1$ (the point of intersection does not move closer or further from the IP). This case is the
²⁴⁴⁷ trivial one (cf. Equation A.16 with $\vec{\mathcal{O}}'_{base} = dz\hat{y}$). y just gets moved in the opposite direction as the
²⁴⁴⁸ wedge. Correction is an additive constant.

²⁴⁴⁹ A.13 $dt \neq 0$

²⁴⁵⁰ $k'/k = (z_{pl} + dt) / z_{pl}$. y gets modified by a simple scale factor. Correct by storing changing definitions
²⁴⁵¹ of plane positions in algorithm to match the misaligned values.

²⁴⁵² A.14 $\alpha \neq 0$

²⁴⁵³ $k'/k = 1$ and

$$\hat{y}'_x = -s\alpha\hat{x} + c\alpha\hat{y} \quad (\text{A.23})$$

$$\hat{y}'_{U,V} = [\pm c\alpha s\omega - s\alpha c\omega] \hat{x} + [\pm s\alpha s\omega + c\omega] \hat{y} \quad (\text{A.24})$$

²⁴⁵⁴ A.15 $\beta \neq 0$

²⁴⁵⁵ We have $k'/k = (1 + \tan \beta \tan \theta \sin \phi)^{-1}$, and

$$\hat{y}'_x = \hat{y} \quad (\text{A.25})$$

$$\hat{y}'_{U,V} = \hat{y} \pm (c\beta\hat{x} - s\beta\hat{z}) s\omega \quad (\text{A.26})$$

²⁴⁵⁶ A.16 $\gamma \neq 0$

$$k'/k = \frac{1 - \tan \gamma \frac{y_{base}}{z_{pl}}}{1 - \tan \gamma \tan \theta \cos \phi} \quad (\text{A.27})$$

$$\hat{y}'_x = c\gamma\hat{y} + s\gamma\hat{z} \quad (\text{A.28})$$

$$\hat{y}'_{U,V} = \pm s\omega\hat{x} + c\omega\hat{y} - s\gamma c\omega\hat{z} \quad (\text{A.29})$$

²⁴⁵⁷ In order to evaluate algorithm performance under misalignment and corrections for misalign-

²⁴⁵⁸ ment, the absolute means and relative resolutions of the fit quantities θ , ϕ , and $\Delta\theta$ are measured as

2459 a function of misalignment. In the following, results will only be shown for which the effects of mis-
2460 alignment are significant. “Significant,” for misalignments of 1 mm (0.3 mrad) for translations (ro-
2461 tations) means more than a 5% degradation in rms and/or bias shifts in θ , ϕ , and $\Delta\theta$ of 0.01 mrad, 1
2462 mrad, and 0.1 mrad, respectively.

2463 While corrections are typically done on a case-by-base basis, they fall under two general cate-
2464 gories, analytic and simulation based. Analytic corrections rely upon specific knowledge of the mis-
2465 alignment, with each case being handled separately; as such, the additional resources required, both
2466 extra constants and operations, if any, vary accordingly. Simulation based corrections are all done in
2467 the same manner. The algorithm is run over a training MC sample (same setup but with $p_T = 200$
2468 GeV instead of the normal 100 GeV sample so as not to overtrain the corrections), and the mean bi-
2469 ases for θ , ϕ , and $\Delta\theta$ are saved for different, equally spaced regions in the $\eta - \phi$ plane over the wedge
2470 based on the fitted θ and ϕ values. Currently, these values are saved for 10 η and 10 ϕ bins (100 η, ϕ
2471 bins total), with the number of bins in each direction being a configurable parameter. When the al-
2472 gorithm runs with simulation based correction, this table of constant corrections is saved in a LUT
2473 before runtime, and corrections are added to final fit quantities based on the (uncorrected) θ and
2474 ϕ fit values. With the settings mentioned, this is 300 extra constants ($10\eta\text{-bins} \times 10\phi\text{-bins} \times 3$ fit
2475 quantities) and two extra operations (a lookup and addition for each quantity done in parallel). The
2476 simulation correction can, in principle, also be applied to the algorithm in nominal conditions with
2477 non-trivial improvements, as detailed below in Section A.17. Depending on the misalignment case in
2478 question, different approaches work better. A summary of correction methods, including resources
2479 necessary for the individual analytic cases, is shown in Table A.3.

	Δ_s	Δz	Δt	γ_s	β_z	α_t
Analytic Resources	yes+ 11c/2op	yes+ oc/oop	yes+ oc/oop	yes 56c/1op	no —	yes 400c/2n _X op, 32c/12n _X op
Simulation	yes+	no	no	no	yes+	yes+

Table A.3: A summary of corrections with additional constants/operations (written as $n_{const}c/n_{ops}op$; n_X is the number of X hits in a fit) necessary for analytic corrections. Yes means a correction exists but might not entirely remove misalignment effects, while yes+ means a quality of correction is only limited by knowledge of misalignment and memory

2480 A.17 SIMULATION CORRECTION OF THE ALGORITHM UNDER NOMINAL CONDITIONS

2481 In addition to using simulation based correction to counter the effects of several classes of misalign-
2482 ment, the correction can be applied at to the algorithm under nominal conditions. The main effect
2483 of this correction is to mitigate the effects of the bias in stereo strips. As such, the correction has a
2484 larger effect on quantities that rely on the aggregate slope m_y , as can be seen in in Figure A.18, im-
2485 proving $\sigma_{\theta_{fit} - \theta_{true}}$ resolution by about 25%, and reducing $\sigma_{\phi_{fit} - \phi_{true}}$ by over 50% and restoring a largely
2486 Gaussian shape. The slight, apparent degradation in $\Delta\theta$ is due to a more mild version of the effect
2487 seen in Figure A.7.

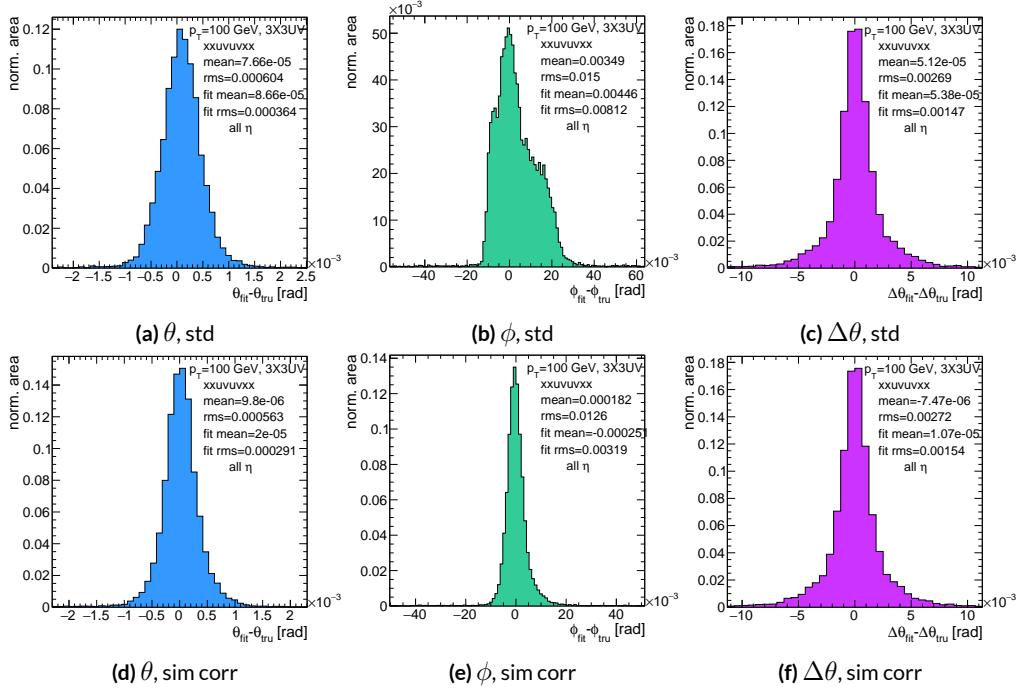


Figure A.18: Nominal residual plots for both uncorrected and simulation corrected cases; $\theta, \phi, \Delta\theta$ for $p_T = 100$ GeV muons

2488 As can be seen in Figure A.19, the simulation based correction also removes the η dependence to
 2489 fit quantity resolution distributions, as expected. One consequence of this is that simulation-based
 2490 corrections applied to the misalignment cases below will restore performance to the “sim” and not
 2491 the “std” distributions of Figure A.18. Hence, when making comparisons between simulation cor-
 2492 rected curves and the nominal performance point, simulation-corrected distributions of benchmark
 quantities versus misalignment will often look generally better.

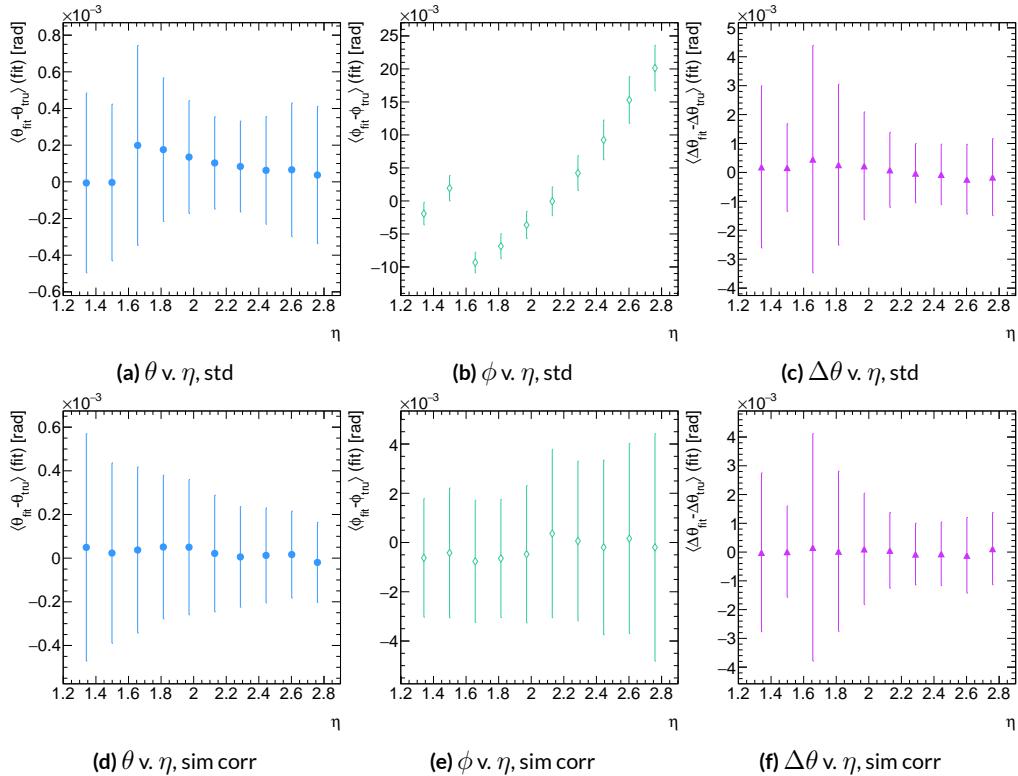


Figure A.19: Nominal residual plots as a function of η with points as means and error bars as rms values in each η bin for the angles $\theta, \phi, \Delta\theta$ for $p_T = 100$ GeV muons in the uncorrected and simulation corrected cases.

2493

2494 That the improvements from a simulation-based correction improve performance of the algo-

2495 rithm in nominal conditions most for the quantities that depend most on stereo information (ϕ and
 2496 θ) and remove the η dependence of fit quantity resolutions suggests that there could, in principle, be
 2497 analytic corrections that could be applied to the nominal algorithm. One possible solution is to in-
 2498 troduce an additional set of constants, having the y_{base} depend on the strip number, similar to the γ_s
 2499 correction for z_{plane} described in Section A.21, which would add a lookup per hit and $8 \times n_{bins,y}$ extra
 2500 constants that would be optimized as the γ_s correction was.

$$M_{hit} = \frac{\gamma}{z} = \frac{y_{base}}{z_{plane}} (n_{str}) + \frac{w_{str}}{z_{plane}} n_{str} \quad (\text{A.30})$$

2501 The simulation correction residual rms values suggest a limit on the quality of such correction
 2502 and could perhaps be implemented generically on their own regardless of misalignment for rms val-
 2503 ues on fit quantities of 0.291 mrad for θ , 3.19 mrad for ϕ , and 1.54 for $\Delta\theta$, which represent a 20%
 2504 improvement for θ , a 62% improvement for ϕ , and a slight degradation in $\Delta\theta$ of 4.7%, again owing
 2505 to an effect similar to the one in A.7.

2506 A.18 TRANSLATION MISALIGNMENTS ALONG THE HORIZONTAL STRIP DIRECTION (Δs)

2507 A translation in s (i.e. along the direction of a horizontal strip) only affects the stereo strips, and,
2508 since the stereo angle is small, a very large misalignment is necessary for effects to be noticeable (a
2509 misalignment of roughly 17 mm corresponds to one strip's misalignment in the stereo planes). The
2510 only quantity to show any meaningful deviation with misalignments with translations in s is the ϕ
2511 residual bias (a change of 0.4 mrad at $\Delta s = 1$ mm), as can be seen in the uncorrected curve of Figure
2512 A.20.

2513 A translation in s induces a constant shift in the calculated horizontal slope, m_x in Equation A.4.
2514 This constant shift should only depend on which stereo planes included in a fit are misaligned and
2515 how misaligned they are. Hence, the correction to m_x , for a sum over misaligned stereo planes i ,
2516 with their individual misalignments in s and plane positions in z is:

$$\Delta m_x = \frac{1}{N_{\text{stereo}}} \sum_{i, \text{misal stereo}} \frac{\Delta s_i}{z_{i, \text{plane}}} \quad (\text{A.31})$$

2517 Given prior knowledge of misalignment, these corrections to m_x can be performed ahead of time
2518 and saved in a lookup table (LUT), similar to the LUT used for constants in the X local slope (M_x^l)
2519 calculation. The added overhead of this analytic correction is hence eleven constants in memory, a
2520 lookup, and one addition. The correction perfectly corrects the effects of misalignment, as can be
2521 seen in Figure A.20. The simulation based correction described above can also be used to correct
2522 for Δs misalignments, with the results of that correction also shown in Figure A.20. The apparent

2523 discrepancy between the simulated and analytic correction is a natural consequence of the fact that
 2524 the simulation correction, as previously mentioned, restores the ϕ residual distribution to an overall
 2525 more Gaussian shape.

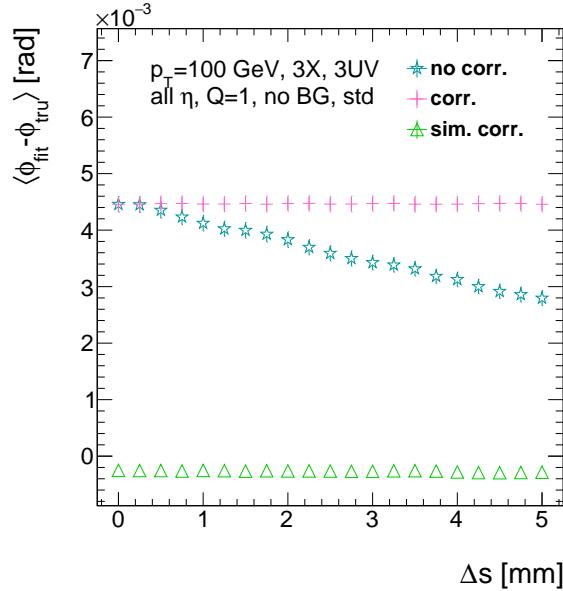


Figure A.20: The mean of the ϕ residual as a function of misalignment for the uncorrected case and the analytic and simulation correction cases.

2526 A.19 TRANSLATION MISALIGNMENTS ORTHOGONAL TO THE BEAMLINE AND HORIZON-
2527 TAL STRIP DIRECTION (Δz)

2528 A translation in AMDB z , the direction orthogonal to both the beamline and the horizontal strip
2529 direction, corresponds to a translation in the y of Equation A.1, affecting all slope calculations. This
2530 has a large impact on the θ residual bias and both the bias and rms of $\Delta\theta$ residual, as can be seen in
2531 Figures A.21 (a)–(c). The marked degradation and non-linear behavior in performance at very high
2532 levels of misalignments is a result of low statistics; there are fewer fits at high level of misalignments
2533 since for $\Delta z \gtrsim 3$ mm, most fits will fail the $\Delta\theta$ cut. The θ bias shifts by about 0.075 mrad at $\Delta z =$
2534 1 mm, and $\Delta\theta$ shifts by about 5 mrad for the same level of misalignment. While the fitted rms of the
2535 $\Delta\theta$ residual remains fairly stable for $\Delta z < 1$ mm or so, between $\Delta z = 2$ mm and $\Delta z = 3$ mm, the
2536 rms increases by 15% before the $\Delta\theta$ cut issue mentioned above intervenes.

2537 Fortunately, these misalignments are straightforward to correct with knowledge of the misalign-
2538 ment. The only modification necessary for this correction is to change the definitions of y_{base} in
2539 Equation A.1 for the individual hit slope addressing. This is done before runtime and adds no over-
2540 head to the algorithm, and the correction quality is only limited by knowledge of the misalignment.
2541 The results of this correction are also shown in Figures A.21 (a)–(c) and restore nominal perfor-
2542 mance.

Since $\Delta\theta = \frac{M_x^l - M_x^e}{1 + M_x^l M_x^e}$ and $M_x^l = B_k \sum y_i (z/\bar{z} - 1)$, a shift Δy translates (with typical slope values of ~ 0.3) to $5B_k (z_1 + z_2)/\bar{z}$ (with B_k in units of inverse mm); set equal to 16 mrad ($\Delta\theta$ is centered at zero), this corresponds to $\Delta y = 2.7$ mm

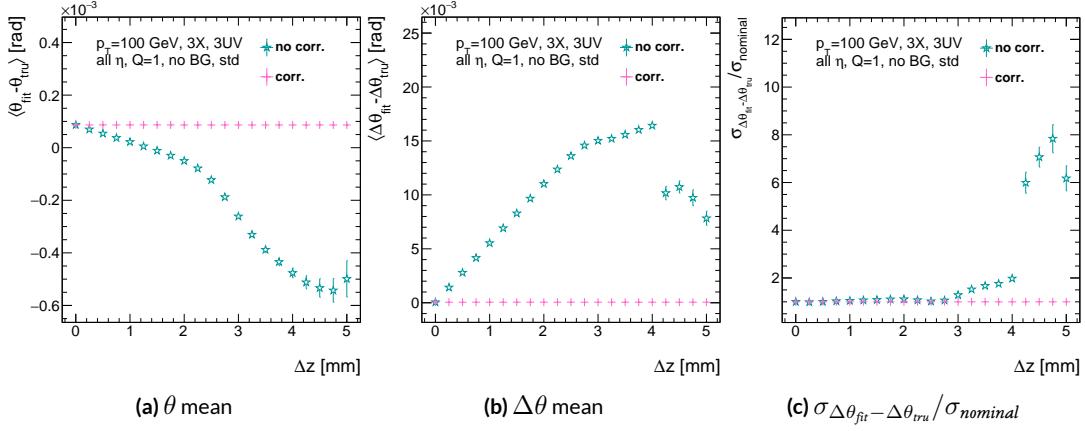


Figure A.21: The affected quantities of Δz misalignments: θ bias, $\Delta\theta$ bias, and $\sigma_{\Delta\theta_{\text{fit}} - \Delta\theta_{\text{tru}}} / \sigma_{\text{nominal}}$ for both the misaligned and corrected cases.

2543 A.20 TRANSLATION MISALIGNMENTS PARALLEL TO THE BEAMLINE (Δt)

2544 The effects of misalignment due to translations in t are very similar to those due to translations in
 2545 z without the complication of the $\Delta\theta$ cut, affecting the z instead of the y coordinate that enters
 2546 into hit slope calculations. Again, θ bias, $\Delta\theta$ bias, and $\sigma_{\Delta\theta_{fit}-\Delta\theta_{true}}$ are the primarily affected quan-
 2547 tities. For $\Delta t = 1$ mm, θ bias shifts by about 0.02 mrad, $\Delta\theta$ bias shifts by just under 2 mrad, and
 2548 $\sigma_{\Delta\theta_{fit}-\Delta\theta_{true}}$ degrades by about 20%. The correction for this misalignment once again costs no over-
 2549 head and consists of changing stored constants in the algorithm, in this case the positions along the
 2550 beamline of the misaligned planes, with results similarly limited by knowledge of the misalignment.

2551 The slight improvement with correction to $\Delta\theta$ rms is due to the real effect of a larger lever arm.

2552 Both the misaligned and corrected distributions of affected quantities of interest are shown in Fig-
 ure A.22.

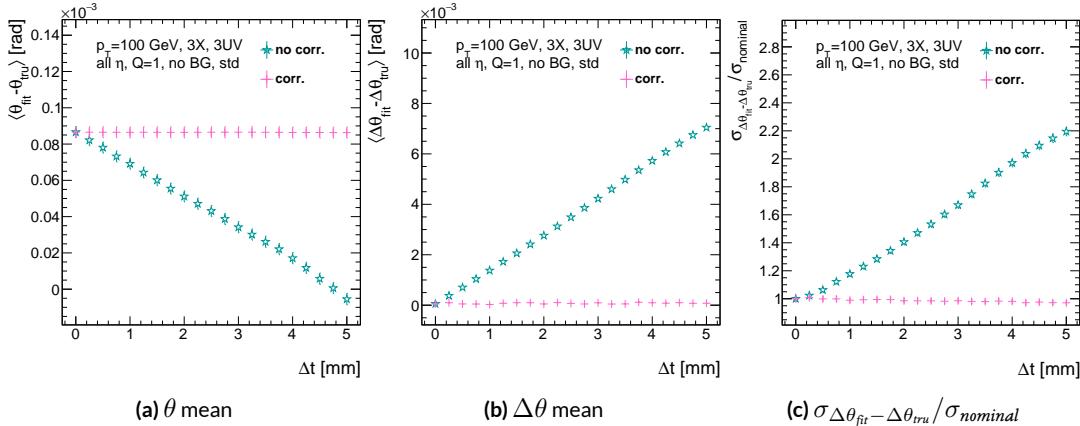


Figure A.22: The affected quantities of Δt misalignments: θ bias, $\Delta\theta$ bias, and $\sigma_{\Delta\theta_{fit}-\Delta\theta_{true}} / \sigma_{nominal}$ for both the misaligned and corrected cases.

2554 A.21 CHAMBER TILTS TOWARDS AND AWAY FROM THE IP (γ_s ROTATION)

2555 Chamber misalignment due to rotations around the s axis act effectively like a translation in t that
2556 depends on strip number. These rotations tilt misaligned chambers away from (towards) the IP for
2557 positive (negative) values of γ_s . Since, unlike for the other two rotation cases that will be studied,
2558 positive and negative rotation values are not symmetric, this misalignment is studied for both posi-
2559 tive and negative γ_s values. The divergent effect at the tails is a result of a large population of fits not
2560 having fit quantities within the cores, and so not appearing in the fit rms. Once again, affected quan-
2561 tities of interest θ bias, $\Delta\theta$ bias, and $\sigma_{\Delta\theta_{fit}-\Delta\theta_{tru}}$. The effects of misalignment can be seen in Figures
2562 A.23 (a)–(c). The relationship between biases and γ_s is roughly linear with $\Delta\gamma_s = 0.3$ mrad (the an-
2563 gular scale corresponding to linear shifts of ~ 1 mm) corresponding to 0.005 mrad (0.12 mrad) for θ
2564 ($\Delta\theta$). For $\sigma_{\Delta\theta_{fit}-\Delta\theta_{tru}}$, degradation is not symmetric. For negative (positive) γ_s , with the quadruplet
2565 tilted towards (away from) the IP, slope-roads are artificially expanded (shrunk), decreasing (increas-
2566 ing) the granularity of the trigger, explaining the asymmetry in Figure A.23 (c), with the degradation
2567 being a 10% (25%) effect for γ_s of $+(-)0.3$ mrad.

2568 Corrections are less simple in this case. In principle, corrections of the same accuracy of the trans-
2569 lations could be calculated per strip, but the overhead of one correction per strip (many thousands
2570 of constants) is prohibitive. Instead, each plane was divided into eight equal segments with a t value
2571 (z in the slope calculation) assigned to strips in each region to correct for the misalignment. This
2572 amounts to 56 extra constants and a 2D instead of a 1D LUT for z positions while the algorithm
2573 runs. The corrected distributions can also be seen in Figures A.23 (a)–(c). The corrections, while not

as effective as for the simple translation cases, are still very effective with the quoted misalignment values for bias shifts down to 0.001 mrad (0.25 mrad) for θ ($\Delta\theta$) and no more than a 2% degradation in $\sigma_{\Delta\theta_{fit}-\Delta\theta_{true}}$ for $|\gamma_s| = 0.3$ mrad.

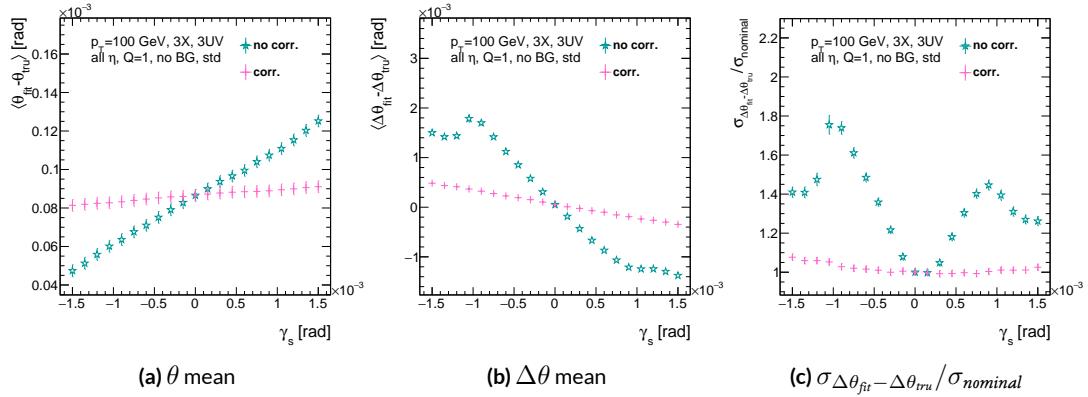


Figure A.23: The noticeable effects of rotations in the s axis and the behavior of these quantities (θ and $\Delta\theta$ bias shifts and $\sigma_{\Delta\theta_{fit}-\Delta\theta_{true}}/\sigma_{nominal}$) with and without misalignment correction.

2577 A.22 ROTATION MISALIGNMENTS AROUND THE WEDGE VERTICAL AXIS (β_z)

2578 While misalignments coming from rotations around the z axis (the direction orthogonal to both
 2579 the beamline and the horizontal strip direction) foreshorten the strips as seen from the IP and add
 2580 a deviation in t , the long lever arm largely washes out any effects of this misalignment. Only the
 2581 $\sigma_{\Delta\theta_{fit}-\Delta\theta_{tru}}$ is noticeably affected, though only at severe misalignments, with only about a 1% degra-
 2582 dation in performance at $\beta_z = 0.3$ mrad (corresponding to a linear shift of ~ 1 mm). A simulation
 2583 based correction works well to cancel out the effects of this misalignment, and the $\sigma_{\Delta\theta_{fit}-\Delta\theta_{tru}}$ as a
 2584 function of misalignment with and without corrections are shown in Figure A.24. The apparent
 2585 2% effect in the simulation corrected curve is a result of a more mild version of the effect shown in
 2586 Figure A.7.

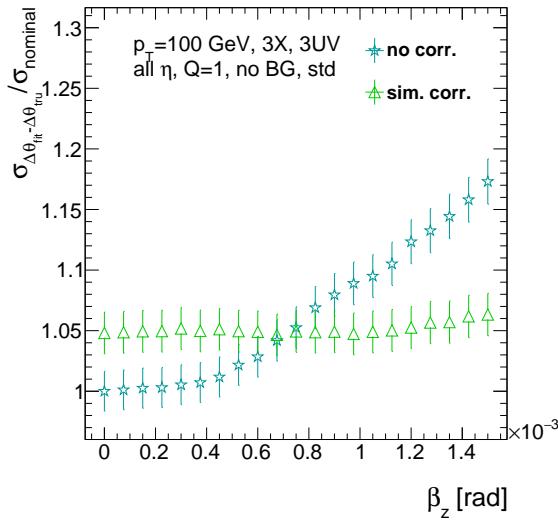


Figure A.24: The effects of rotations in the z axis on $\sigma_{\Delta\theta_{fit}-\Delta\theta_{tru}} / \sigma_{nominal}$ a function of β_z both with and without misalignment corrections.

2587 A.23 ROTATION MISALIGNMENTS AROUND THE AXIS PARALLEL TO THE BEAMLINE (α_t)

2588 Misalignments arising from rotations around the t axis (parallel to the beamline at the center of
2589 the base of the wedge) are essentially rotations in the ϕ direction. The quantities of interest most
2590 affected are the ϕ bias and $\sigma_{\Delta\theta_{fit}-\Delta\theta_{tru}}$, as shown in Figures A.25 (a) and (b), respectively, and cor-
2591 respond to a shift in ϕ bias of 0.2 mrad and a 10% degradation in $\sigma_{\Delta\theta_{fit}-\Delta\theta_{tru}}$ for $\alpha_t = 0.3$ mrad
2592 (corresponding to a linear shift of ~ 1 mm). The raw instead of fitted mean ϕ biases is used in Fig-
2593 ure A.25 (a) to better illustrate the effect of misalignment.

2594 Since the effect of misalignment is dependent on horizontal (along the strip direction, \hat{s}) in addi-
2595 tion to vertical information, corrections cannot be applied before a fit takes place. The ϕ bias shift is
2596 uniform over the entire wedge, so a constant additive correction to ϕ based on the level of misalign-
2597 ment can be applied to all fits depending on how many misaligned stereo planes enter in the fit. $\Delta\theta$
2598 is less straightforward, but corrections to the y and z information used in the local slope calculation
2599 in Equation A.4 can be applied once θ_{fit} and ϕ_{fit} are known. These corrections are calculated ahead
2600 of time in bins of uniform η and ϕ as with the simulation corrections using the same framework
2601 as the misalignment calculation. The results of both types of correction can be seen in Figure A.22.
2602 The apparent discrepancy between the simulation and analytic corrections in the ϕ bias happens for
2603 the same reason as in the Δs misalignment correction cases, as simulation correction restores a more
2604 Gaussian shape to the ϕ residual distribution opposed to the uncorrected nominal case, as discussed
2605 in Section A.17.

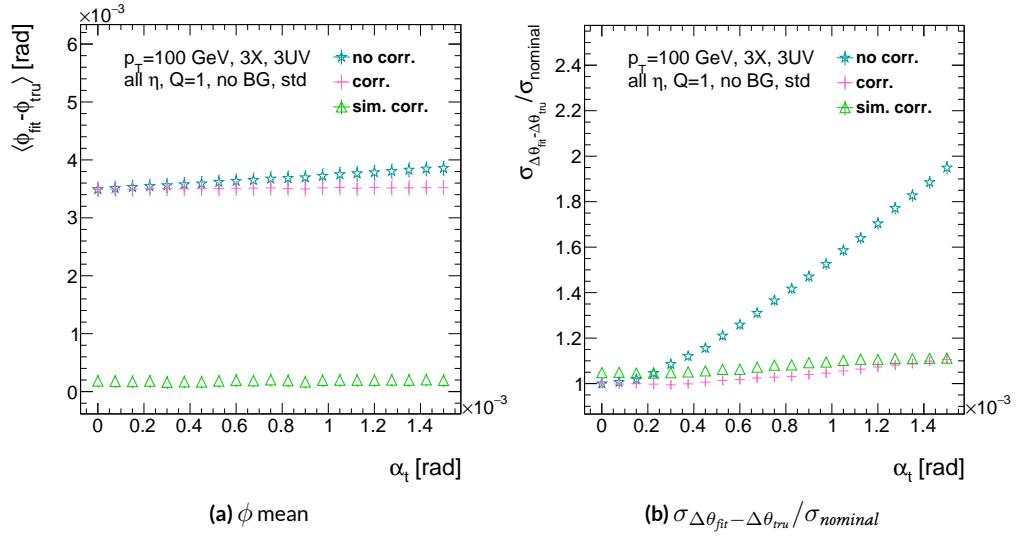


Figure A.25: The effects of rotation misalignments around the t axis for ϕ bias and $\sigma_{\Delta\theta_{\text{fit}} - \Delta\theta_{\text{true}}} / \sigma_{\text{nominal}}$ as a function of misalignment. The uncorrected and both the analytic and simulation correction cases are shown.

2606 A.24 CONCLUSION

2607 The algorithm for Micromegas detectors in the NSW Trigger Processor performs well in a variety of
2608 conditions and has proven robust to a number of effects to deliver measurements on muon tracks
2609 of the three angles θ , ϕ , $\Delta\theta$. Under nominal conditions, the rms values for the residuals of these
2610 quantities are 0.364 mrad for θ , 8.12 mrad for ϕ , and 1.47 mrad for $\Delta\theta$. Algorithm performance was
2611 found to be largely independent of the charge threshold setting, and a hit majority BCID associa-
2612 tion was found to provide proper timing information over 99.7% even in the most relaxed settings
2613 (2X+1UV coincidence threshold requirement+wide slope-road+background). The introduction of
2614 wide slope-roads to better mimic potentially limited algorithm resources at run time and the intro-
2615 duction of incoherent background was found to have a manageable effect on fit quantity residual
2616 rms values and on total algorithm efficiency for sufficiently stringent coincidence threshold. The ef-
2617 ffects of the three translation and three rotation misalignments specified by AMDB convention were
2618 studied, and correction methods for each of the six cases was developed. Simulation-based correc-
2619 tions were found to improve nominal algorithm performance to residual rms value of 0.291 mrad for
2620 θ , 3.19 mrad for ϕ , and 1.54 for $\Delta\theta$, which represent improvements of 20%, 62%, and -4.7%, respec-
2621 tively. Misalignment corrections were found to restore nominal performance for all but the rotation
2622 around the s axis, and a summary of tolerances may be found in Table A.4.

	No Correction	Correction
Δs	4 mm (ϕ bias)	> 5 mm
Δz	0.25 mm ($\Delta\theta$)	> 5 mm
Δt	0.25 mm ($\Delta\theta$)	> 5 mm
γ_s	0.15 mrad ($\Delta\theta$ bias)	0.75 mrad
β_z	0.9 mrad ($\Delta\theta$ rms)	> 1.5 mrad
α_t	0.375 mrad ($\Delta\theta$ rms)	> 1.5 mrad

Table A.4: A summary of levels of misalignment corresponding to a 10% degradation in any residual rms or, for biases shifts of 0.01 mrad for θ , 1 mrad for ϕ , and 0.25 mrad for $\Delta\theta$ for both the uncorrected and corrected cases; > 5 mm and > 1.5 mrad mean that such a degradation does not occur for the range of misalignment studied. Most affected quantity in parentheses.

Tod-Not-Brot

Old German Proverb

2623

B

2624

Telescoping Jets

2625 ANOTHER APPROACH TO IMPROVING $ZH \rightarrow \ell\ell b\bar{b}$ is the use of telescoping jets [63], which har-
2626 nesses the power of multiple event interpretations. The use of multiple event interpretations was
2627 originally developed with non-deterministic jet algorithms like the Q-jets (“quantum” jets) algo-
2628 rithm [64]. When a traditional or “classical” algorithm, such as the Cambridge-Aachen[65] and

2629 anti- k_t [66] algorithms, is applied to an event, it produces one set of jets for that event, i.e. a single
2630 interpretation of that event. With multiple event interpretations, each event is instead given an en-
2631 semble of interpretations. In the case of Q-jets, this ensemble is created through a non-deterministic
2632 clustering process for an anti- k_t jet algorithm. With telescoping jets, multiple jet cone radii (the char-
2633 acteristic size parameter, R) around a set of points in the pseudorapidity-azimuth ($\eta - \phi$) plane are
2634 used to generate a series of jet collections. Instead of an event passing or not-passing a given set of
2635 cuts, a fraction (called the cut-weight, z) of interpretations will pass these cuts. This cut-weight al-
2636 lows for enhanced background suppression and increased significance of observed quantities for a
2637 given data set, as detailed in Ref. [67]. The telescoping jets algorithm provides the benefits of mul-
2638 tiple event interpretations without the significant computational overhead of a non-deterministic
2639 algorithm like the Q-jets algorithm, and its multiple cone sizes are particularly suited to studying
2640 processes like associated production, which suffers from a pronounced low tail in the dijet invariant
2641 mass distribution due to final state radiation (FSR) “leaking” outside the relatively narrow jets used
2642 for object reconstruction.

2643 B.I MONTE CARLO SIMULATION

2644 The MC simulated samples used in this study are the same as in Ref. [?]. The signal sample used
2645 is generated in PYTHIA8 [68] with the CTEQ6L1 parton distributions functions (PDFs) and AU2
2646 tune[69, 70, 71] for the ZH process with $m_H = 125$ GeV (henceforth, $ZH125$). The primary back-
2647 ground processes examined in this study were Z +jets with massive b and c quarks. These samples
2648 are generated with version 1.4.1 of the SHERPA generator [72].

2649 B.2 JET RECONSTRUCTION AND CALIBRATION

2650 In order to construct telescoping jets, jet axes must first be found around which to “telescope.” In
2651 the reconstructed-level analysis, the anti- k_t algorithm with $R = 0.4$ is used to reconstruct jets from
2652 topological clusters in the calorimeters. The four vectors of these anti- k_t algorithm with $R = 0.4$ jets
2653 are calibrated to match truth information obtained from simulation and validated in data. To take
2654 into account the effect of pile-up interactions, jet energies are corrected using a jet-area based tech-
2655 nique [73], and each jet with $p_T < 50$ GeV and $|\eta| < 2.4$ is subject to a requirement that at least 50%
2656 of the scalar sum of the p_T of tracks matched to this jet be composed of tracks also associated with
2657 the primary vertex. Jet energies are also calibrated using p_T and η -dependent correction factors [74].
2658 Furthermore, at least two jets must have $|\eta| < 2.5$ in order to be b -tagged. The MV1 algorithm [75]
2659 [? ? ?] is used for b -tagging. Once jets are reconstructed and b -tag weights have been calculated, the
2660 two hardest, b -tagged jets are used as the telescoping jet axes. Additional details can be found in Ref.
2661 [76].

2662 After the telescoping jet axes have been established, telescoping jets are constructed using topo-
2663 logical clusters in the calorimeters at a variety of jet cone sizes. Including the original anti- k_t jets
2664 used for the $R = 0.4$ case, twelve total sets of jets of cone sizes ranging from $R = 0.4\text{--}1.5$ are
2665 constructed, with each successive size having a radius 0.1 larger than the preceding set. For each jet
2666 axis, telescoping jets consist of any topological cluster lying within R of the axis. In the event of over-
2667 lap, clusters are assigned to the closer jet axis. If a given cluster is equidistant from the two jet axes,
2668 the cluster is assigned to whichever jet axis is associated with the anti- k_t jet with higher p_T . Calibra-

2669 tion for the telescoping jets is conducted using corrections for anti- k_t calorimeter topological cluster
2670 jets; the $R = 0.4$ corrections are used for telescoping $R = 0.5$, and the $R = 0.6$ corrections are
2671 used for telescoping $R \geq 0.6$ (cf. Sec. B.4). The telescoping cone jets ($R \geq 0.5$) at reconstructed
2672 level are trimmed using Cambridge-Aachen jets with $R = 0.3$ and $f_{cut} = 0.05$ with respect to the
2673 untrimmed jet p_T [77]. Since these jets are trimmed, the active area correction is not applied. In the
2674 event a Z candidate electron falls within R of the axis of a telescoping jet, its 4-momentum is sub-
2675 tracted from that of the jet vectorially.

2676 A similar process is used to construct telescoping jets in the truth-level analysis below. Instead of
2677 the two hardest b -tagged anti- k_t with $R = 0.4$ jets reconstructed with calorimeter topological clus-
2678 ters, the two hardest truth b -jets in an event are used. Instead of making a cut on b -tagging weight
2679 to b -tag, truth jets are examined to see whether a b -hadron with $p_T > 5$ GeV is contained within
2680 $\Delta R < 0.4$ of the jet axis; the presence of a b -hadron is used to b -tag truth-level jets. These two jets
2681 again provide the jets for the $R = 0.4$ case and the axes around which telescoping takes place. Stable
2682 truth particles, not including muons and neutrinos, are used in place of calorimeter topological clus-
2683 ters. Z candidate electron-telescoping jet overlap removal is performed at truth level, too. Missing E_T
2684 is calculated using the vector sum of the four momenta of stable truth-level neutrinos. Since there
2685 are no pileup particles stored at truth level, truth-level telescoping jets are not trimmed.

2686 B.3 EVENT RECONSTRUCTION AND SELECTION

2687 Events are selected on the basis of a combination of leptonic, jet, and missing E_T requirements,
2688 which are outlined in Table B.1. Leptons are categorized by three sets of increasingly stringent qual-

2689 ity requirements, which include lower limits on E_T , upper limits on $|\eta|$, impact-parameter require-
2690 ments, and track-based isolation criteria. The requirements differ for electrons [78] and muons
2691 [79]. Events are selected with a combination of single lepton, dielectron, and dimuon requirements.
2692 Each event must contain at least one lepton passing medium requirements and at least one other
2693 lepton passing loose requirements. These leptons are used to create a dilepton invariant mass cut to
2694 ensure the presence of a Z boson and suppress multijet backgrounds.

2695 Event selection requirements are also imposed on the anti- k_t with $R = 0.4$ jets. There must be at
2696 least two b -tagged jets in a given event. The p_T of the harder b -tagged jet must be at least 45 GeV, and
2697 the second b -tagged jet must have p_T of at least 20 GeV. There are further topological cuts on the
2698 separation of the two jets $\Delta R(b, \bar{b})$, the distance between the two jets in the (η, ϕ) plane, according
2699 to the transverse momentum of the Z boson, p_T^Z . These are shown in Table B.2.

2700 The truth-level analysis has the same missing E_T , jet p_T , m_{ll} , and additional topological selection
2701 criteria, but the use of truth-level information simplifies the other requirements. Instead of lepton
2702 quality requirements, Z boson candidate leptons' statuses and MC record barcodes are checked to
2703 ensure the leptons are stable.

2704 In the jet calibration validation, the reconstructed level analysis lepton and m_{ll} requirements are
2705 imposed, but neither the missing E_T nor the jet selection requirements are applied so as not to bias
2706 the validation.

Requirement	Reconstructed	Truth	Validation
Leptons	1 med. + 1 loose	2 produced by Z boson	1 med. + 1 loose
b -jet	2 b -tags	2 b -jets	—
p_T jet 1 (jet 2)		$> 45 \text{ GeV} (> 20) \text{ GeV}$	—
Missing E_T		$E_T^{\text{miss}} < 60 \text{ GeV}$	—
Z boson		$83 < m_{ll} < 99 \text{ GeV}$	

Table B.1: A summary of basic event selection requirements. Truth-level b -tagging is done with truth-level information.

$p_T^Z [\text{GeV}]$	$\Delta R(b, b)$
0–90	0.7–3.4
90–120	0.7–3.0
120–160	0.7–2.3
160–200	0.7–1.8
> 200	< 1.4

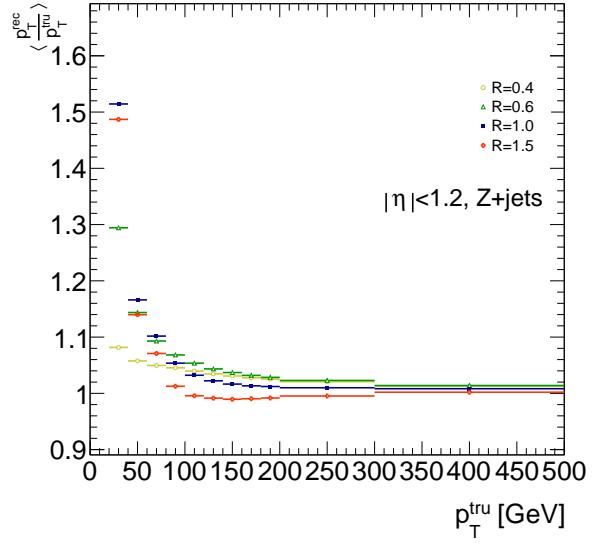
Table B.2: Topological requirements of the event selection.

2707 B.4 VALIDATION OF JET CALIBRATION

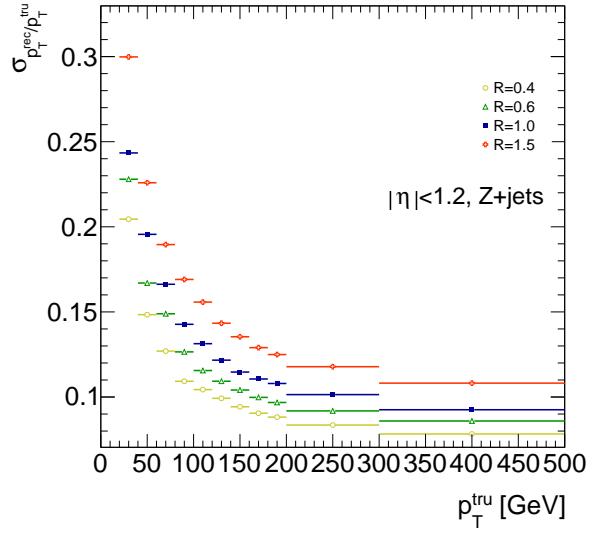
2708 In order to validate the jet energy scale and resolution of jets constructed with this telescoping-jets
 2709 algorithm, values of $p_T^{\text{rec}}/p_T^{\text{tru}}$ are studied for each value of R for the Z +jets MC sample. In a given
 2710 event, all jets, not just the two hardest b -tagged jets, are telescoped. These jets are constructed in the
 2711 same way as in the reconstructed and truth-level analyses; reconstructed-level jets are made from
 2712 calorimeter topological clusters within R of the anti- k_t with $R = 0.4$ jet axes and then trimmed,
 2713 and truth-level jets are made from stable truth particles within R of the anti- k_t with $R = 0.4$ jet
 2714 axes. The reconstructed and truth-level telescoping jet ensembles are matched according to the sep-
 2715 aration in the (η, ϕ) plane of their corresponding anti- k_t with $R = 0.4$ jets used as seeds. Only jets

2716 with $|\eta| < 1.2$ are examined here, and the results of studies on the $ZH125$, ZZ , and $t\bar{t}$ samples, as
 2717 well as over other $|\eta|$ ranges, are outlined in [63]. Any reconstructed jets not within $\Delta R = 0.3$ of a
 2718 truth jet are discarded. In the event that multiple reconstructed jets are the same distance away from
 2719 a given truth jet, the reconstructed jet with the highest p_T gets matched. Matching is retained for all
 2720 R values (i.e. telescoping seeds are matched, and telescoping jets are assumed to match if the anti- k_t
 2721 jets from which their seeds are derived match).

2722 Once anti- k_t with $R = 0.4$ reconstructed and truth jets are matched, response functions are cre-
 2723 ated by generating a series of distributions of p_T^{rec}/p_T^{tru} in 20 GeV bins of p_T^{tru} from 20–200 GeV, one
 2724 bin for 200–300 GeV, and one bin for 300–500 GeV for each R , with bins chosen for purposes of
 2725 statistics. Ensembles with $p_T^{tru} < 20$ GeV are ignored since no calibration exists for jets with trans-
 2726 verse momentum below this value. The values of $\langle p_T^{rec}/p_T^{tru} \rangle$ in each p_T^{tru} bin are calculated by doing
 2727 a two sigma gaussian fit on the distribution of p_T^{rec}/p_T^{tru} in that bin and taking the mean of that fit,
 2728 and the error on the mean is taken from the error of this parameter in the fit. The resolutions are the
 2729 values of the square root of the variance on this fit. As the total response distributions in Figure B.1
 2730 show, performance is best for low R values and high values of p_T^{tru} . Figure B.1 shows the $R = 0.4$
 2731 (anti k_t) case to show a baseline for performance, $R = 0.6$ to show the deviations with “correct”
 2732 calibrations, and $R = 1.0, 1.5$ to show how big those deviations get with larger R jets. The resolu-
 2733 tions, $\sigma_{p_T^{rec}/p_T^{tru}}$, as a function of p_T^{tru} are shown in Figure B.1(b). For $p_T^{tru} > 60$ GeV, response is fairly
 2734 consistent over various R values. Resolution, as might naively be expected, is worse for increasingly
 2735 larger values of R . For $p_T^{tru} < 60$ GeV, resolution degrades, and response degrades in particular for
 2736 increasing R ; this is likely a result from residual pileup effects.



(a)



(b)

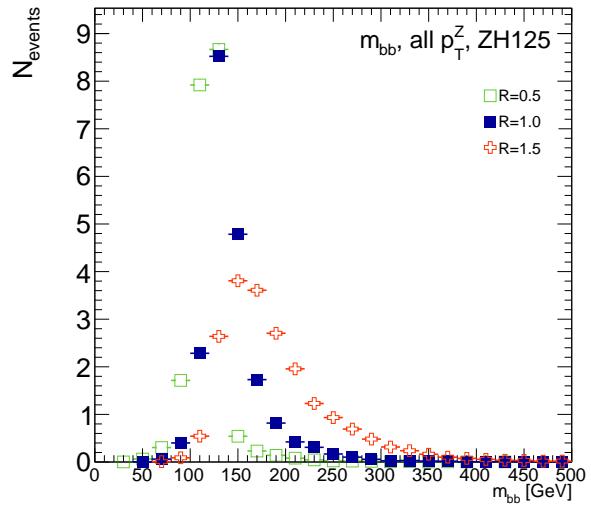
Figure B.1: The mean and resolution of p_T^{rec}/p_T^{tru} for the background $Z+jets$ sample for $|\eta| < 1.2$ and for $R = 0.4, 0.6, 1.0$, and 1.5 in 20 GeV bins of p_T^{tru} for 20-200 GeV, one bin for 200-300 GeV, and one bin for 300-500 GeV, with bins chosen for purposes of statistics.

2737 B.5 TRUTH-LEVEL ANALYSIS

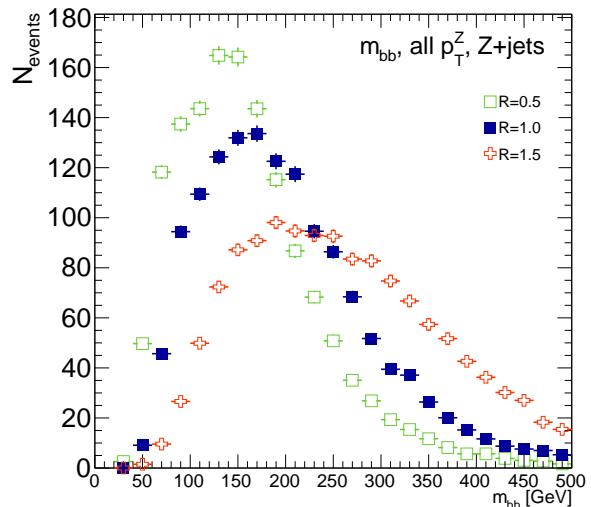
2738 To understand the limits and sources of any potential improvements, a truth-level analysis was con-
2739 ducted on MC samples with a ZH_{125} signal sample and a $Z+jets$ background sample. Distributions
2740 for the dijet invariant mass, m_{bb} , were made for each telescoping radius. Both signal and background
2741 samples develop more pronounced tails in the high m_{bb} region as R increases, as shown in Figure
2742 B.2. N_{events} is normalized to expected values in data.

2743 One way to take advantage of this information is to make a cut on m_{bb} for two different radii.
2744 This is graphically depicted in Figure B.3 for the optimized combination of $m_{bb,R=0.9}$ (telescoping
2745 cone jets constructed as outlined in Sec. B.2) vs. $m_{bb,R=0.4}$ (anti- k_t jets). At truth-level, the majority
2746 of events in the signal ZH_{125} sample are concentrated in relatively narrow region of parameter space,
2747 where this is certainly not the case for the more diffuse $Z+jets$ background sample.

2748 Another way to take advantage of multiple event interpretations is to make use of an event's cut-
2749 weight, denoted z and defined as the fraction of interpretations in a given event that pass a certain set
2750 of cuts (in this note, a cut on m_{bb}). The distribution of cut-weights for a sample of events is denoted
2751 $\rho(z)$. To enhance the significance of a cut-based analysis, events can be weighted by the cut-weight
2752 or any function $t(z)$ of the cut-weight. Weighting events by $t(z)$ modifies the usual $S/\delta B$ formula
2753 used to calculate significances. In this note, δB is based on Poissonian statistics and is taken as $0.5 +$
2754 $\sqrt{0.25 + N_B}$, where N_B is the number of background events.

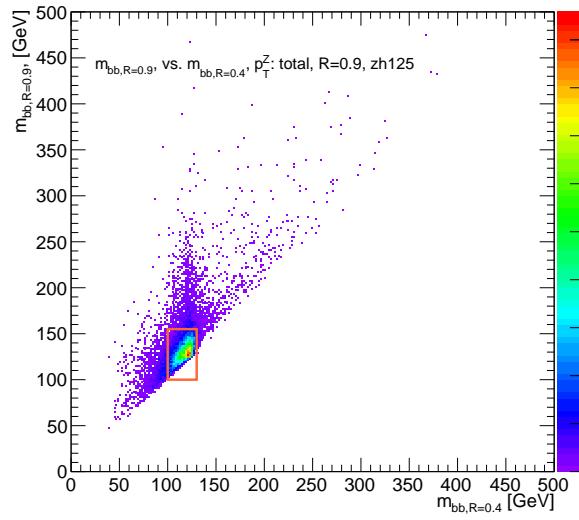


(a)

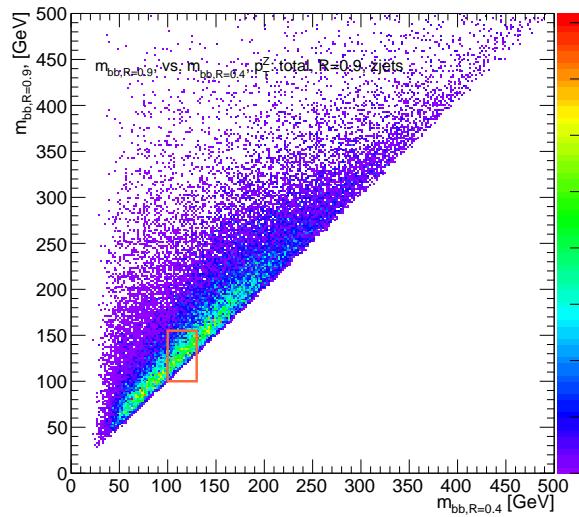


(b)

Figure B.2: The m_{bb} distribution for the telescoping jets with $R = 0.5, 1.0$, and 1.5 truth-level jets is shown for the signal and background samples in (a) and (b), respectively.



(a)



(b)

Figure B.3: The 2D distribution of $m_{bb,R=0.9}$ vs. $m_{bb,R=0.4}$ is shown for signal and background truth-level samples in (a) and (b), respectively. The region chosen for the double m_{bb} cut is outlined in orange.

2755 B.6 ERRORS ON TELESCOPING SIGNIFICANCES

2756 Significances of measurements are quoted in units of expected background fluctuations, schemati-
2757 cally, $S/\delta B$. For counting experiments with high numbers of events, we can use Gaussian statistics
2758 and express this as S/\sqrt{B} , which we here denote as \mathcal{S} . However, with lower statistics, it becomes
2759 more appropriate to use Poissonian statistics, and

$$\mathcal{S}_{gaus} = \frac{S}{\sqrt{B}} \rightarrow \mathcal{S}_{pois} = \frac{S}{0.5 + \sqrt{0.25 + B}} \quad (\text{B.1})$$

2760 where $0.5 + \sqrt{0.25 + B}$ is the characteristic upward fluctuation expected in a Poissonian data set
2761 using the Pearson chi-square test[80].

2762 B.7 COUNTING

2763 The significance is given as above, where $S = N_S$ and $B = N_B$. That is, the signal and background
2764 are just the number of events in signal and background that pass some cuts. The error for the Guas-
2765 sian case is the standard:

$$\Delta \mathcal{S}_{gaus} = \frac{1}{\sqrt{B}} \Delta S \oplus \frac{S}{2B^{3/2}} \Delta B \quad (\text{B.2})$$

2766 The error for the Poissonian case is:

$$\Delta \mathcal{S}_{pois} = \frac{1}{0.5 + \sqrt{0.25 + B}} \Delta S \oplus \frac{S}{2(0.5 + \sqrt{0.25 + B})^2 \sqrt{0.25 + B}} \Delta B \quad (\text{B.3})$$

²⁷⁶⁷ where \oplus denotes addition in quadrature, and $\Delta S(B)$ is the error on signal (background).

²⁷⁶⁸ B.8 MULTIPLE EVENT INTERPRETATIONS

²⁷⁶⁹ Using multiple event interpretations changes the formulae used in with simple counting. That is, S

²⁷⁷⁰ is not necessarily merely N_S , the number of events passing some signal cuts, and similarly for B and

²⁷⁷¹ N_B . Using an event weighting by some function of the cut-weight, z , denoted $t(z)$, $S = N_S \langle t \rangle_{\rho_S}$

²⁷⁷² and $B = N_B \langle t^2 \rangle_{\rho_B}$. So

$$\mathcal{S}_{t,gaus} = \frac{N_S \langle t \rangle_{\rho_S}}{\sqrt{N_B \langle t^2 \rangle_{\rho_B}}} \rightarrow \mathcal{S}_{t,pois} = \frac{N_S \int_0^1 dz t(z) \rho_S(z)}{0.5 + \sqrt{0.25 + N_B \int_0^1 dz t^2(z) \rho_B(z)}} \quad (\text{B.4})$$

For histograms, everything is done bin-wise. The notation used below is as follows: ρ_i is the value of $\rho(z)$ at bin i (where the bins run from 0 to n_{tel} , where n_{tel} is the total number of telescoping radii). $t_i = t_i(\rho_{S,i}, \rho_{B,i}, i/n_{tel})$ is the value of $t(z)$ at bin i , which can depend, in principle, on $\rho_{S,i}$, $\rho_{B,i}$, and i/n_{tel} (the last of which is z in bin i). Explicitly,

$$N = \sum_{i=0}^{n_{tel}} \rho_i, \quad \int_0^1 dz t(z) \rho_S(z) = \sum_{i=0}^{n_{tel}} t_i \rho_{S,i}, \quad \int_0^1 dz t^2(z) \rho_B(z) = \sum_{i=0}^{n_{tel}} t_i^2 \rho_{B,i}$$

²⁷⁷³ For the calculations that follow, let $\xi = \sum_{i=0}^{n_{tel}} t_i \rho_{S,i}$, $\psi = 0.5 + \sqrt{0.25 + N_B \sum_{i=0}^{n_{tel}} t_i^2 \rho_{B,i}}$,

²⁷⁷⁴ $\partial_S = \frac{\partial}{\partial \rho_{S,i}}$ (and similarly for B), so $\mathcal{S}_t = N_S \xi / \psi$

²⁷⁷⁵ Some partial derivatives:

$$\begin{aligned}\partial_S N_S &= 1, & \partial_{B,i} N_B &= 1 \\ \partial_S \xi &= t_i + (\partial_S t_i) \rho_{S,i}, & \partial_B \xi &= (\partial_B t_i) \rho_{B,i} \\ \partial_S \psi &= \frac{N_B t_i (\partial_S t_i) \rho_{B,i}}{\sqrt{0.25 + N_B \sum_{i=0}^{n_{tel}} t_i^2 \rho_{B,i}}}, & \partial_B \psi &= \frac{\sum_{i=0}^{n_{tel}} t_i^2 \rho_{B,i} + N_B (t_i^2 + 2t_i (\partial_B t_i) \rho_{B,i})}{2\sqrt{0.25 + N_B \sum_{i=0}^{n_{tel}} t_i^2 \rho_{B,i}}} \\ \partial_S \mathcal{S}_t &= \frac{\xi}{\psi} + \frac{N_S}{\psi} \partial_S \xi - \frac{N_S \xi}{\psi^2} \partial_S \psi, & \partial_B \mathcal{S}_t &= N_S \left(\frac{1}{\psi} \partial_B \xi - \frac{\xi}{\psi^2} \partial_B \psi \right)\end{aligned}$$

²⁷⁷⁶ Thus,

$$\Delta \mathcal{S}_{t,i} = \left[\frac{\xi}{\psi} + \frac{N_S}{\psi} \partial_S \xi - \frac{N_S \xi}{\psi^2} \partial_S \psi \right] \Delta \rho_{S,i} \oplus N_S \left[\frac{1}{\psi} \partial_B \xi - \frac{\xi}{\psi^2} \partial_B \psi \right] \Delta \rho_{B,i} \quad (\text{B.5})$$

²⁷⁷⁷ and the total error is given by the sum in quadrature over all bins i of $\Delta \mathcal{S}_{t,i}$.

²⁷⁷⁸ B.9 $t(z) = z$

²⁷⁷⁹ With $t(z) = z$, $t_i = i/n_{tel}$, so $\partial_S t_i = \partial_B t_i = 0$. So:

$$\begin{aligned}\partial_S \psi &= \partial_B \xi = 0 \\ \partial_S \xi &= \frac{i}{n_{tel}} \\ \partial_B \psi &= \frac{\sum_i i^2 \rho_{B,i} + N_B t^2}{n_{tel} \sqrt{n_{tel}^2 + N_B \sum_i i^2 \rho_{B,i}}}\end{aligned}$$

²⁷⁸⁰ so $\Delta\mathcal{S}_{z,i}$ reduces to

$$\Delta\mathcal{S}_{t,i} = \left[\frac{\xi + N_S t_i}{\psi} \right] \Delta\rho_{S,i} \oplus \left[\frac{N_S \xi}{\psi^2} \partial_B \psi \right] \Delta\rho_{B,i} \quad (\text{B.6})$$

²⁷⁸¹ B.10 $t(z) = \rho_S(z) / \rho_B(z)$

²⁷⁸² With the likelihood optimized* $t^*(z) = \rho_S(z) / \rho_B(z)$, $t_i = \rho_{S,i} / \rho_{B,i}$, so $\partial_S t_i = 1 / \rho_{B,i}$ and $\partial_B t_i =$

²⁷⁸³ $-\rho_{S,i} / \rho_{B,i}^2$. So:

$$\begin{aligned} \partial_S \xi &= 2 \frac{\rho_{S,i}}{\rho_{B,i}} = 2t_i \\ \partial_B \xi &= -\frac{\rho_{S,i}}{\rho_{B,i}} = -t_i \\ \partial_S \psi &= \frac{N_B t_i}{\sqrt{0.25 + N_B \sum_i \rho_{S,i}^2 / \rho_{B,i}}} \\ \partial_B \psi &= \frac{\sum_i \rho_{S,i}^2 / \rho_{B,i} - N_B (\rho_{S,i} / \rho_{B,i})^2}{\sqrt{1 + 4N_B \sum_i \rho_{S,i}^2 / \rho_{B,i}}} \end{aligned}$$

²⁷⁸⁴ simplifying somewhat the terms in the per bin error in Equation B.6.

²⁷⁸⁵ The new significance figure using multiple event interpretations becomes, with ρ_S and ρ_B denot-
²⁷⁸⁶ ing the cut-weight distributions in signal and background, respectively

$$\frac{S}{\delta B} = \frac{N_S \langle t \rangle_{\rho_S}}{0.5 + \sqrt{0.25 + N_B \langle t^2 \rangle_{\rho_B}}} \quad (\text{B.7})$$

*for the Gaussian statistics case

²⁷⁸⁷ Of particular interest is the likelihood optimized $t(z)$,[†] $t^*(z) = \rho_S(z)/\rho_B(z)$. m_{bb} windows are
²⁷⁸⁸ chosen separately for each scheme studied to maximize total significances and are summarized in
²⁷⁸⁹ Table B.3.

$$\left(\frac{S}{\delta B}\right)_z = \frac{N_S \epsilon_S}{0.5 + \sqrt{0.25 + N_B (\epsilon_B^2 + \sigma_B^2)}} \quad (B.8)$$

²⁷⁹⁰

$$\left(\frac{S}{\delta B}\right)_{t^*(z)} = \frac{N_S \int_0^1 dz \frac{\rho_S^2(z)}{\rho_B(z)}}{0.5 + \sqrt{0.25 + N_B \int_0^1 dz \frac{\rho_S^2(z)}{\rho_B(z)}}} \quad (B.9)$$

²⁷⁹¹ where $\epsilon_{S,B}$ are the means of $\rho_{S,B}(z)$ and σ_B^2 is the variance of $\rho_B(z)$. Further details can be found in
²⁷⁹² Refs. [63, 67] and Appendix B.6.

Analysis Type	$S/\delta B$ Type	Optimal m_{bb} Window
Reconstructed	$anti-k_t R = 0.4$ $t(z) = z$ $t(z) = \rho_S(z)/\rho_B(z)$ $anti-k_t R = 0.4$, telescoping $R = 0.6$	$90-140$ GeV $110-155$ GeV $110-155$ GeV $95-140$ GeV ($R = 0.4$), $105-160$ GeV ($R = 0.6$)
Truth	$anti-k_t R = 0.4$ $t(z) = z$ $t(z) = \rho_S(z)/\rho_B(z)$ $anti-k_t R = 0.4$, telescoping $R = 0.9$	$100-130$ GeV $115-140$ GeV $120-135$ GeV $100-130$ GeV ($R = 0.4$), $100-155$ GeV ($R = 0.9$)

Table B.3: m_{bb} windows studied. These windows were chosen to optimize significances over all p_T^Z .

²⁷⁹³ The truth-level distributions $\rho_S(z)$, $\rho_B(z)$, and $\rho_S(z)/\rho_B(z)$ are shown for the m_{bb} window
²⁷⁹⁴ that optimizes $(S/\delta B)_{t^*(z)}$ in Figure B.4, and significance improvements as a function of p_T^Z are
²⁷⁹⁵ summarized in Figure B.5. Uncertainties in Figures B.5 and B.9 are statistical uncertainties. JES sys-

[†]Derived under the assumption of Gaussian statistics in Ref [67]

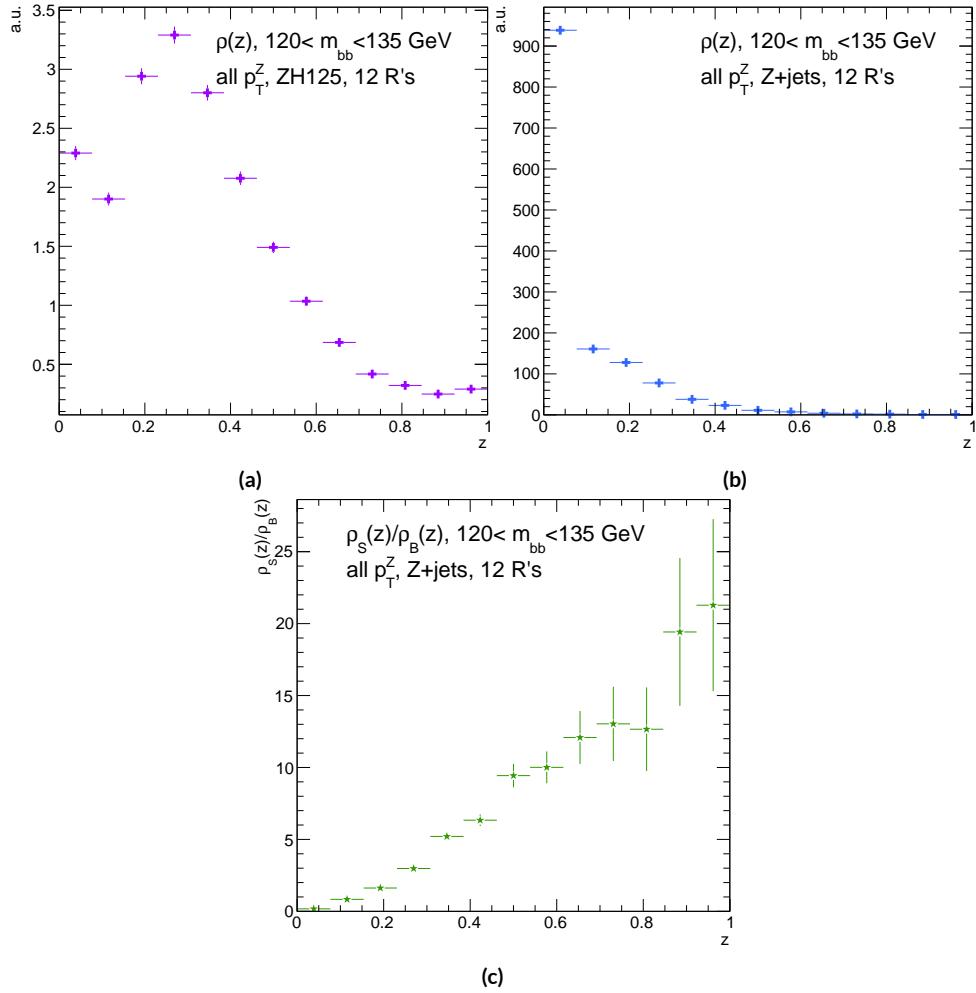


Figure B.4: Truth-level $\rho(z)$ distributions for the m_{bb} window optimizing $(S/\delta B)_{r^*(z)}$. $\rho_S(z)$ for the signal $ZH125$ sample is shown in (a), and $\rho_B(z)$ for the background $Z+jets$ sample is shown in (b). The distribution of $\rho_S(z)/\rho_B(z)$ for these samples is shown in (c).

2796 tematics will need to be evaluated for different R 's, as modeling uncertainties is an outstanding is-
 2797 sue, but these systematics will likely be strongly correlated for the different R 's and are not antici-
 2798 pated to be a very large contribution to total uncertainties. While the two dimensional m_{bb} cut and
 2799 $t(z) = z$ schemes only showed marginal improvement at truth level at 2.87%[‡] and 1.45%, respec-
 2800 tively, the likelihood optimized $t^*(z)$ showed a more substantial 40.7% improvement overall, with
 2801 a steady increase in improvement with increasing p_T^Z . Figure B.5 (d) summarizes the improvements
 2802 with respect to p_T^Z for the $t^*(z)$ event weight for five, seven, and twelve telescoping radii (interpreta-
 2803 tions) per event. Improvements increase with a greater number of interpretations and are more pro-
 2804 nounced at higher p_T^Z for this scheme. The optimal $120 < m_{bb} < 135$ GeV window for $t^*(z)$ case
 2805 is among the smallest studied. The benefits of this window's narrowness are suggested in Figure B.4.
 2806 While the background cut-weight distribution, $\rho_B(z)$ in Figure B.4 (b) behaves as one might with
 2807 a marked peak at $z = 0$, the signal $\rho_S(z)$ distribution peaks at a relatively modest $z = 0.3$, which
 2808 indicates that much of the gain at truth level comes from background rejection. This is possible at
 2809 truth level since there is both truth-level information available and no smearing and since ρ_S/ρ_B is
 2810 the relevant quantity (as shown in Figure B.4 (c)).

[‡]The limited improvement is provably due to the simplified treatment of the 2D case; better performance with a more sophisticated treatment has been observed in Ref. [81].

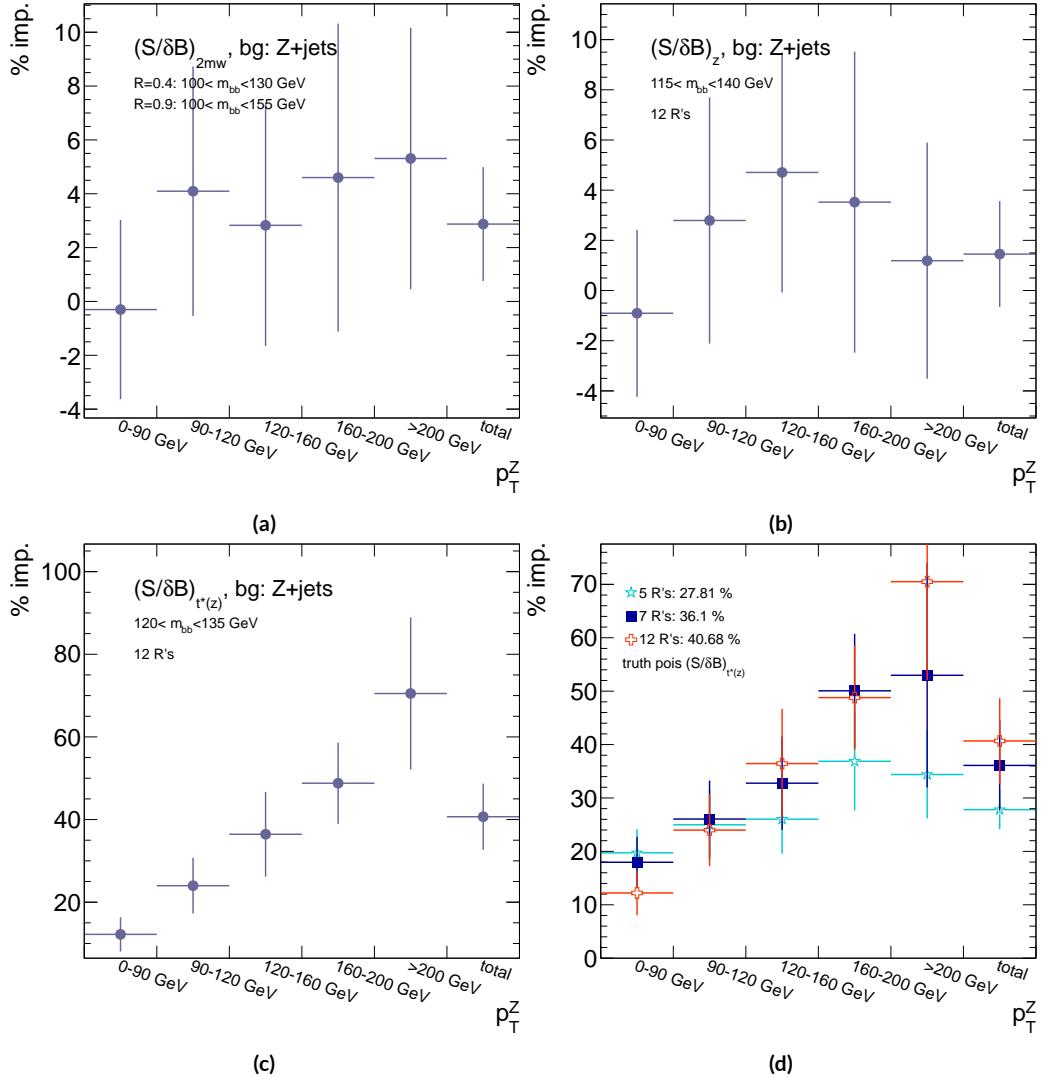


Figure B.5: A summary of the improvements for different truth-level telescoping jet cuts and weights is shown in bins of p_T^Z . The final bin is the total improvement over all p_T^Z . Shown are improvements for the 2D m_{bb} cut (a), $t(z) = z$ (b), $t(z) = t^*(z)$ with 12 radii (c), and $t(z) = t^*(z)$ for various radii (d).

2811 B.II RECONSTRUCTED-LEVEL ANALYSIS

2812 At reconstructed level, the same overall effect of introducing a high tail in m_{bb} distributions with
2813 increasing R is evident in comparing Figures B.2 and B.6. The optimal m_{bb} windows, however, grow
2814 larger, due to the lack of truth-level information.

2815 Total significance gains at reconstructed level for the two dimensional m_{bb} cut and the $t(z) = z$
2816 case are similar, at 2.87% and 1.45%, respectively. The optimal two-dimensional m_{bb} cut at recon-
2817 structed level is $95 < m_{bb,R=0.4} < 140 \text{ GeV}$, $105 < m_{bb,R=0.6} < 160 \text{ GeV}$. Just as at truth level,
2818 the $R = 0.4$ m_{bb} cut is comparable to the optimal single $R = 0.4$ m_{bb} cut, and the second m_{bb} cut is
2819 at similar values (cf. Table B.3 and Figures B.3 and B.7). However, the optimal second telescoping ra-
2820 dius is markedly smaller at $R = 0.6$ versus the optimal truth-level second radius of $R = 0.9$, which
2821 suggests that effects like pileup at reconstructed level obscure correlations between the $R = 0.4$
2822 interpretations and limit the usefulness of larger R interpretations in this particular scheme. The
2823 $t(z) = z$ case has a wider optimal window and yields about half the improvement it does at truth
2824 level.

2825 The optimal m_{bb} window for the $t^*(z)$ case is also markedly wider at reconstructed level, at $110 <$
2826 $m_{bb} < 155 \text{ GeV}$ in comparison to the truth-level optimal $120 < m_{bb} < 135 \text{ GeV}$. The $\rho(z)$ dis-
2827 tributions for the signal $ZH125$ and background $Z+\text{jets}$ as well as the $\rho_S(z) / \rho_B(z)$ in this window
2828 are shown in Figure B.8. Compared with the truth-level distributions in Figure B.4, both the sig-
2829 nal and background optimal $\rho(z)$ distributions have higher values at higher z . The peak in $\rho_S(z)$ at
2830 $z = 1$ suggests that at reconstructed level, maximizing the number of more “signal-like” events is

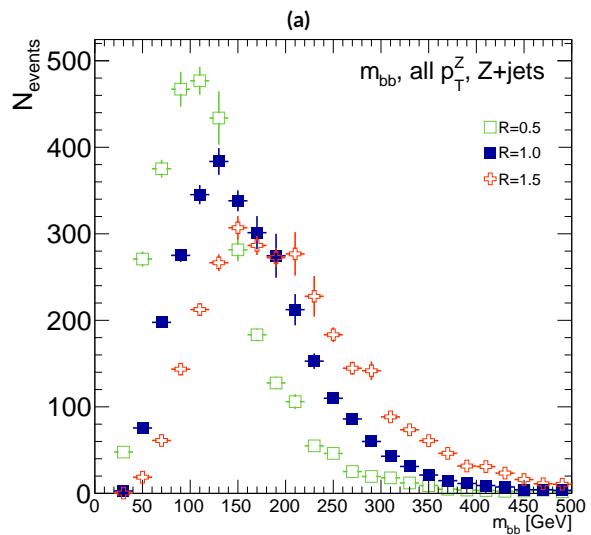
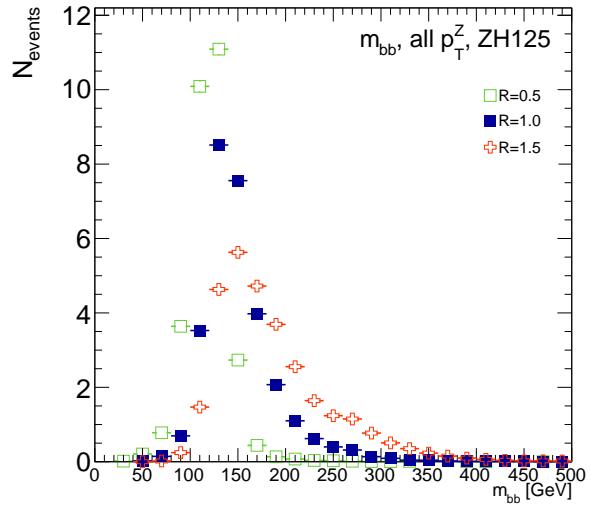


Figure B.6: The m_{bb} distribution for the telescoping jets with $R = 0.5$, $R = 1.0$, and $R = 1.5$ reconstructed-level jets is shown for the signal and background samples in (a) and (b), respectively.

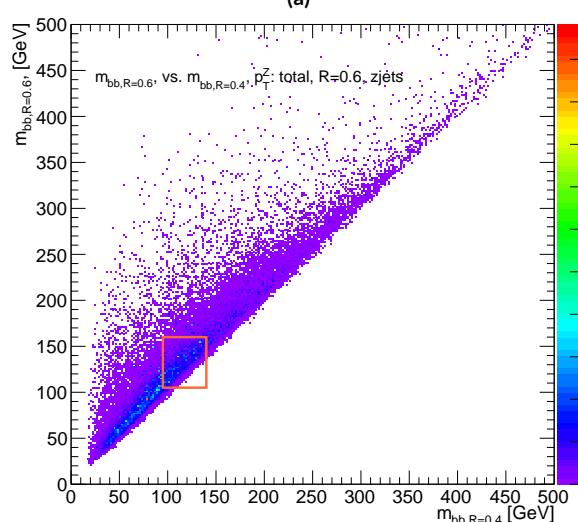
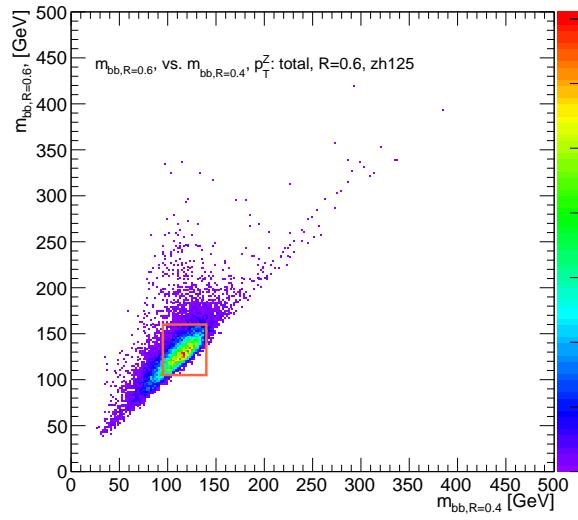


Figure B.7: The 2D distribution of $m_{bb,R=0.8}$ vs. $m_{bb,R=0.4}$ is shown for signal and background reconstructed-level samples in (a) and (b), respectively. The region chosen for the double m_{bb} cut is outlined in orange.

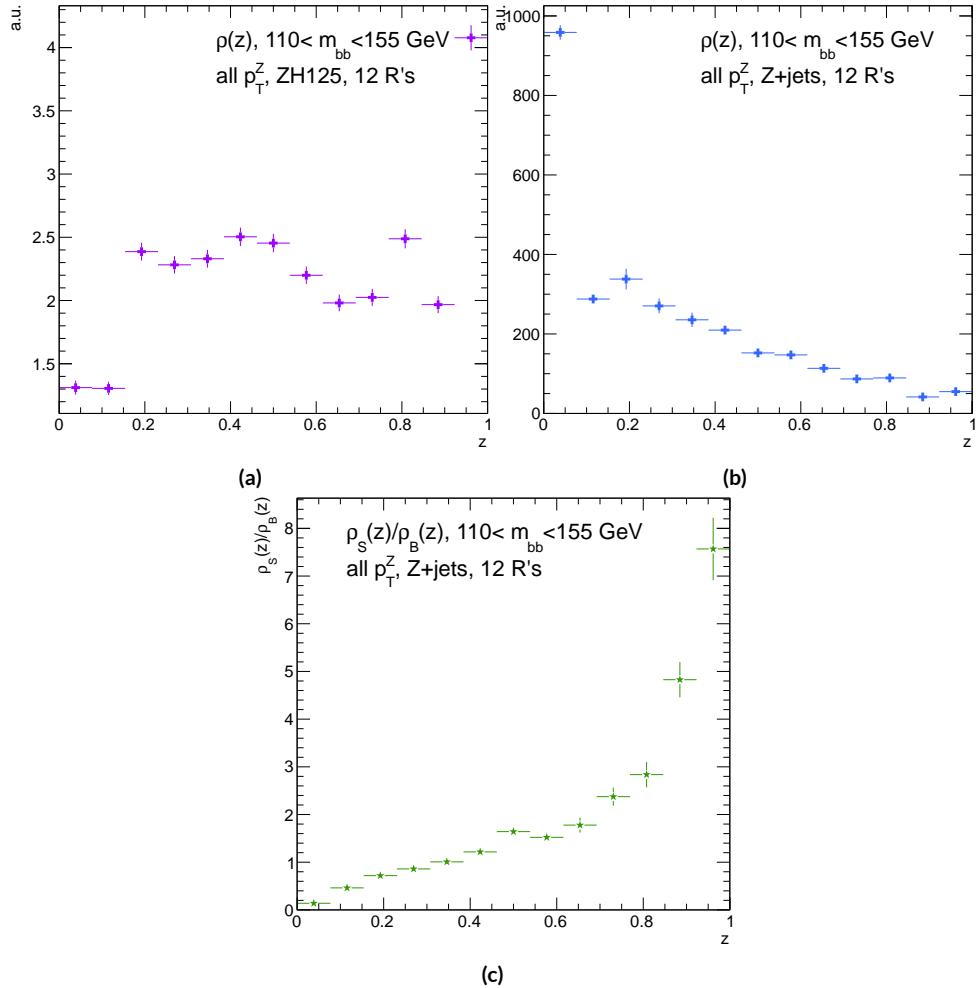


Figure B.8: Reconstructed-level $\rho(z)$ distributions for the m_{bb} window optimizing $(S/\delta B)_{t^*(z)} \cdot \rho_S(z)$ for the signal $ZH125$ sample is shown in (a), and $\rho_B(z)$ for the background $Z+jets$ sample is shown in (b). The distribution of $\rho_S(z)/\rho_B(z)$ for these samples is shown in (c).

2831 the key to optimizing significances, as opposed to the optimal, background suppressing $\rho(z)$ distri-
 2832 butions at truth level. The use of a greater number of interpretations per event (telescoping radii)
 2833 does appear to result in overall greater improvement as at truth level, as twelve radii performed bet-
 2834 ter than five, but this is less clear at reconstructed level, as shown in Figure B.9 (d). The improve-
 2835 ment at reconstructed level using an event weight of $t^*(z)$ is 20.5%, just over half the improvement
 2836 at truth level but still quite significant. Summaries of improvements as a function of p_T^Z for all three
 2837 cases studied and for the $t^*(z)$ case for different numbers of telescoping radii are shown in Figure
 2838 B.9.

Type	0–90	90–120	120–160	160–200	> 200	total
akt4 _{rec}	0.47492	0.28214	0.28339	0.25748	0.37337	0.76887
akt4 _{tru}	0.57414	0.30655	0.37309	0.35042	0.53569	0.98619
$2 m_{bb,rec}$	0.48903	0.2858	0.28812	0.25972	0.38297	0.78611
$2 m_{bb,tru}$	0.5724	0.3191	0.38364	0.36655	0.56414	1.0145
z_{rec}	0.50698	0.27962	0.29937	0.25688	0.36846	0.79158
z_{tru}	0.56894	0.31511	0.39065	0.36277	0.54206	1.0005
$t^*(z)_{rec}$	0.55085	0.29931	0.33367	0.30107	0.51321	0.92649
$t^*(z)_{tru}$	0.64425	0.38008	0.50904	0.5214	0.91337	1.3873

Table B.4: A summary of significances for different weighting schemes and cuts and for reconstructed and truth jets for a luminosity of 20.3 fb^{-1} . akt4 refers to the standard cut-based analysis using anti- k_t with $R = 0.4$ jets. Column titles are p_T^Z regions in GeV.

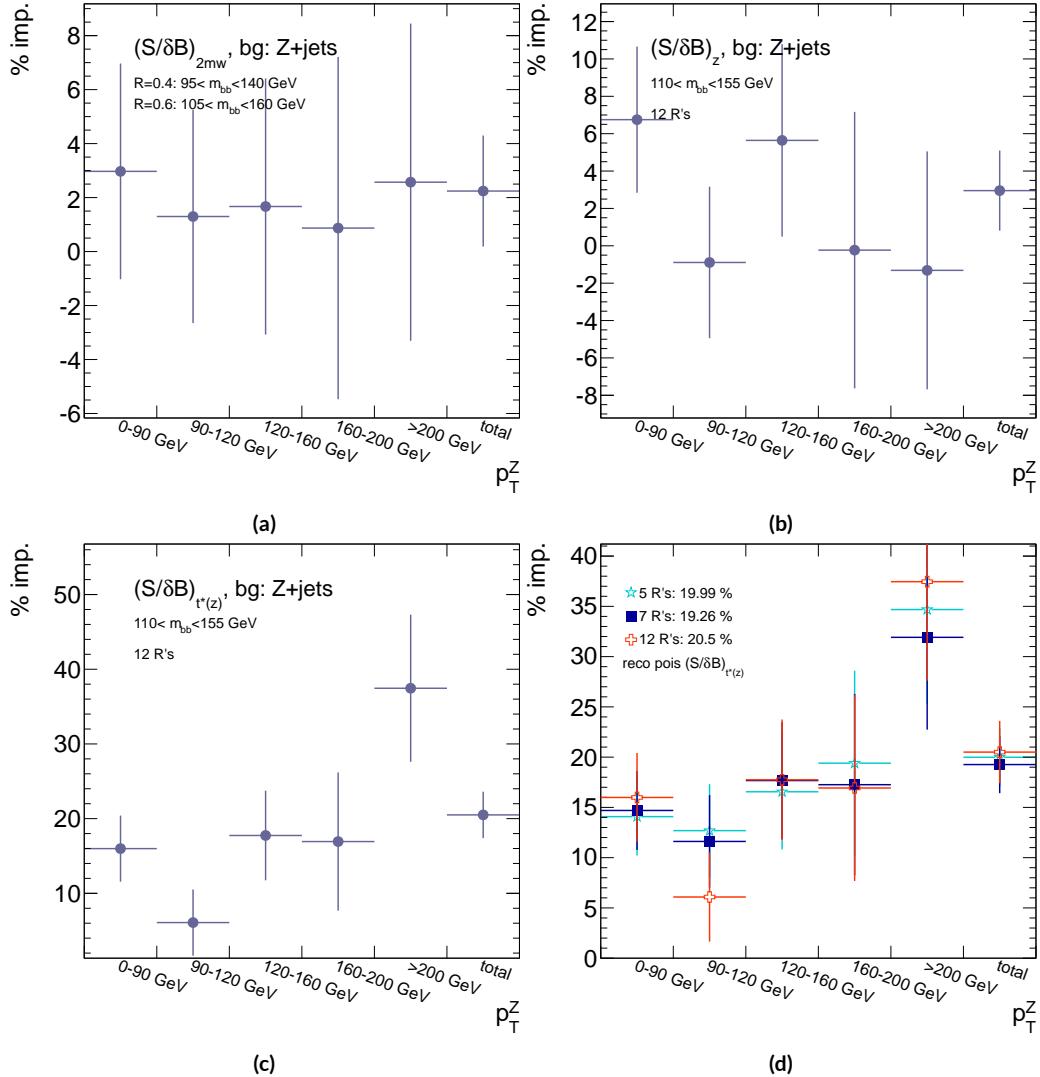


Figure B.9: A summary of the improvements for different reconstructed-level telescoping jet cuts and weights is shown in bins of p_T^Z . The final bin is the total improvement over all p_T^Z . Shown are improvements for the 2D m_{bb} cut (a), $t(z) = z$ (b), $t(z) = t^*(z)$ with 12 radii (c), and $t(z) = t^*(z)$ for various radii (d).

2839 B.12 CONCLUSIONS AND PROSPECTS

2840 The use of telescoping jets to provide multiple event interpretations shows promise as an avenue to
2841 increase significances in the $H \rightarrow b\bar{b}$ search in ATLAS and make an observation in the systematics-
2842 limited environment of early Run 2. A preliminary study using the telescoping jets algorithm with
2843 12 telescoping radii to build 12 event interpretations on 2012 Monte Carlo based on the full, cut-
2844 based Run 1 analysis yielded a 20.5% improvement in $S/\delta B$ over using anti- k_t with $R = 0.4$ alone
2845 at reconstructed level using a likelihood maximized event weighting to study the $ZH \rightarrow llb\bar{b}$ pro-
2846 cess. The jets used in this note at reconstructed level were trimmed in order to guarantee reasonable
2847 resolution in the large- R interpretations. The algorithm, in particular, showed discriminating power
2848 at high p_T^Z , so better performance can be expected in Run 2 with a higher \sqrt{s} and higher numbers of
2849 events with large p_T^Z . Additionally, the many simplifying assumptions regarding jet calibration and
2850 the relatively basic use of information[§] from multiple invariant masses in this note suggest that even
2851 further improvements than those quoted are possible. While this note did not explore the corre-
2852 lations between multiple event interpretations and the variables used in the BDT of the latest multi-
2853 variate version of the $H \rightarrow b\bar{b}$ analysis[20], new phenomenological studies suggest that such corre-
2854 lations are not strong[81]. The corresponding reconstructed-level study, using a BDT, is left for future
2855 work. Also left for future work are better understanding the effects of jet trimming and which inter-
2856 pretations are the most useful.

[§]For examples of more sophisticated treatments compared to the treatment in this note, see Ref [81].

Ah, peut on être heureux?

Quand on forme des autres voeux?

J. P. Rameau, Forêts Paisibles

2857

C

2858

Progress in Particle Physics and Existential

2859

Threats to the American World Order

2860 INTERNATIONAL COLLABORATIONS with thousands of scientists like those at CERN's (the Euro-

2861 pean Organisation for Nuclear Research) 27 km circumference Large Hadron Collider (LHC) are

2862 fast becoming the norm in many fields of science, making the past seven decades of discovery in par-
2863 ticle physics seem a natural part of history's long march of progress. Seemingly arcane terms like dark
2864 matter and the Higgs boson (the infamous "God particle") even pop up in blockbuster movies and
2865 primetime television. All of this, however, would have been impossible without the fascist and then
2866 communist existential threats to the American world order throughout the 20th century.

2867 The Manhattan Project and its atomic arsenal were a direct response to the threat of global fas-
2868 cism in World War II. They both secured the United States' position as a world power at the end of
2869 the war and laid the foundations for many particle physics developments for the following three
2870 decades. High ranking American officials were well aware that this would have been impossible
2871 without the contributions of particle physicists. Some of these physicists, like Enrico Fermi and
2872 Arthur Compton, were already Nobel laureates and luminaries in the field. Others, like Richard
2873 Feynman and Owen Chamberlain, would go on to make their marks in the decades following the
2874 war. Though a few of these physicists, most notably Edward Teller, would continue their work on
2875 nuclear weapons, most of these physicists would return to basic science research as the nation turned
2876 towards the uneasy peace time of the Cold War.

2877 Particle physicists' service and connections made during the war would serve them well in the
2878 decades to come as the military-controlled Manhattan Project transitioned to the civilian-led Atomic
2879 Energy Commission (AEC). The AEC was founded in 1946 to oversee the nuclear arsenal, the devel-
2880 opment of atomic power, and related fundamental research in the United States. Many of those on
2881 AEC board were former Manhattan Project particle physicists, including Glenn Seaborg, the AEC
2882 chairman from 1961-1971. Congressional oversight for AEC funding consisted of a single committee,

2883 the Joint Committee on Atomic Energy (JCAE), whose deliberations often took place behind closed
2884 doors owing to the AEC's sensitive national security mission. Elementary particle physics research
2885 was clearly central to the AEC mission at its founding, as nuclear fission was the bleeding edge of par-
2886 ticle physics at the beginning of World War II and represented the culmination of decades of highly
2887 specialized research that had no immediately obvious practical application. Furthermore, particle ac-
2888 celerator technology, the main workhorse then as now for basic science research in particle physics
2889 and the most expensive item on any particle physicist's wish list, had been crucial to many of these
2890 discoveries. The anticipation of future windfalls as momentous as the power of the atom and the ex-
2891 emplary performance of particle physicists during the war ensured that experimental particle physics
2892 and particle accelerators would remain the crown jewel of AEC research throughout the organiza-
2893 tion's existence.

2894 The AEC's sizable budget (thanks to its crucial mission of securing the nation's nuclear arsenal)
2895 and lavish support were the biggest contributing factors to the development of particle physics in
2896 the mid 20th century through its funding of accelerator facilities. Particle accelerators use powerful
2897 electromagnetic fields to take beams of subatomic particles, usually protons or electrons, as close to
2898 the speed of light as possible before colliding them into either fixed targets or other beams to pro-
2899 duce high energy collisions. Physicists use these collisions to test models of the universe that predict
2900 behavior in these extreme regimes. Without more energetic collisions, progress becomes function-
2901 ally impossible. While the first such accelerator was smaller than the average human hand, studying
2902 more complete models of the universe called for more energetic collisions and hence bigger, more
2903 powerful, and more expensive accelerators.

2904 Soon, these experiments became too big and expensive for individual universities to operate on
2905 their own. Progress in American particle physics became entirely dependent on the AEC, and hence
2906 on the continued threat of nuclear annihilation. National laboratories, all under AEC stewardship,
2907 became regional centers of research for particle physicists. By the late 1960's, Brookhaven National
2908 Laboratory, Lawrence Berkeley National Laboratory, and the Stanford Linear Accelerator Center
2909 hosted the majority of cutting edge accelerator facilities in the country alongside a dwindling num-
2910 ber of single university accelerators. By the decade's end Cornell hosted the only such university op-
2911 erated facility. The competitive rivalry among these different institutions fostered American success
2912 and dominance in experimental particle physics through the 1970's. The culmination of AEC pa-
2913 tronage was the National Accelerator Laboratory (now Fermilab), which began operations in 1967.
2914 Fermilab's construction was not a foregone conclusion given the economically challenging backdrop
2915 of the Vietnam War, but an emphasis on cost effective plans for both the laboratory and accelerator
2916 backed by the full support of the AEC secured Fermilab's funding. Fermilab would ultimately be-
2917 come home to the Tevatron, the final particle accelerator in the United States to claim the title of the
2918 world's most powerful.

2919 Particle physics only became more dependent on the existence of a Soviet threat with the end of
2920 the AEC. Due to budgetary pressures, the AEC was abolished in 1975, and its duties were eventually
2921 reorganized into the Department of Energy (DOE). Under DOE administration, proposed parti-
2922 cle physics experiments now had to compete against research projects from the entire range of fields
2923 germane to American energy instead of only other nuclear and particle physics projects. Moreover,
2924 DOE leadership had far fewer officials with track records of supporting particle physics research

2925 projects above all others. Nevertheless, there remained one last, great effort to promote collider
2926 physics in the United States, the Superconducting Supercollider (SSC). The SSC was an incredibly
2927 ambitious design: a 50 mile ring under the Waxahachie desert with superconducting magnets to ac-
2928 celerate protons and antiprotons to energies more than three times higher than the LHC's current
2929 world record. The project was conceived during the Reagan administration and billed as a megapro-
2930 ject to reassert American dominance as the president took a more aggressive approach to the Soviet
2931 threat. Unfortunately, the project was perhaps too ambitious and suffered from management prob-
2932 lems. It is not surprising, then, that the end of the Cold War spelled the end of the SSC. With no
2933 external threat to American global dominance, there was little impetus to continue funding such an
2934 expensive and over-budget project. There has not been a single initiative since for the United States
2935 to recapture its once commanding lead over efforts in Western Europe.

2936 Western Europe was the only other serious center of 20th century particle physics, and successes
2937 there also depended upon five decades of existential threat to the United States, though in a less di-
2938 rect fashion. Most obviously, American institutions and physicists have been essential to the devel-
2939 opment of European particle physics, just as European physicists were crucial to the success of the
2940 Manhattan Project. Seven of the ten Cold War era CERN Directors General were either educated
2941 or did research at American universities, and every major particle physics discovery since the end of
2942 World War II has relied on both American and European talent and infrastructure. Furthermore,
2943 the European approach to experimental particle physics, epitomized by CERN, emphasized consen-
2944 sus and cooperation and was emblematic of larger geopolitical currents on the European continent
2945 in the latter half of the 20th century. Such a culture and its success would have been impossible with-

2946 out the same threats that facilitated American success in particle physics. While limited resources of
2947 member states were no doubt contributing factors in CERN's genesis, the collaborative culture of
2948 CERN and other pan-European organizations was a reaction to centuries of competition for conti-
2949 nental dominance. After the total destruction of the world wars, enough was enough. The relatively
2950 peaceful prosperity on the Western side of the Iron Curtain made European cooperation possible,
2951 while the threat at Western Europe's doorstep only heightened the urgency of pan-European desires.
2952 Hence, the symbolic importance of European unity during the Cold War is hard to underestimate, and
2953 CERN-facilitated European cooperation made it a forerunner to organizations like the European
2954 Union and a model to the world. Every major achievement in particle physics after 1940 therefore
2955 relies on facilities and institutions on both sides of the Atlantic that would never have been formed
2956 without the back to back threats of global fascism and Soviet Communism.

2957 With the cancellation of the SSC in 1993 and the closing of Fermilab's Tevatron in 2011, CERN
2958 and its LHC remain the lone laboratory and experiment at the energy frontier. The United States
2959 is now a mere "observer state" at CERN: American talent and funding are essential to CERN and
2960 its mission, but the United States does not have a seat on CERN's governing council. It remains
2961 to be seen whether a legacy of over six decades of international cooperation will provide sufficient
2962 motivation for particle physics to continue at CERN after the LHC without guarantee of any dis-
2963 covery at the next experiment. Current nuclear threats, while attention grabbing, are far from exis-
2964 tential and unlikely to reignite any initiative for distinctly American science megaprojects. The only
2965 other prospect for a future collider at the energy frontier is China, whose nationalistic desire for su-
2966 perpower status may prove a sufficiently powerful and lasting motivator for the next generation of

²⁹⁶⁷ collider.

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