

1 A search for sparticles in zero lepton final states

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3 Submitted in partial fulfillment of the

4 requirements for the degree of

5 Doctor of Philosophy

6 in the Graduate School of Arts and Sciences

7 COLUMBIA UNIVERSITY

8 2016

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ABSTRACT

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A search for sparticles in zero lepton final states

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Russell W. Smith

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16 center, but the abstract itself should be written as a regular paragraph on the page,
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Acknowledgements

Dedication

Introduction

67 Particle physics is a remarkably successful field of scientific inquiry. The ability to
 68 precisely predict the properties of a exceedingly wide range of physical phenomena,
 69 such as the description of the cosmic microwave background [1, 2], the understanding
 70 of the anomalous magnetic dipole moment of the electron [3, 4], and the measurement
 71 of the number of weakly-interacting neutrino flavors [5] is truly amazing.

72 The theory that has allowed this range of predictions is the *Standard Model*
 73 of particle physics (SM). The Standard Model combines the electroweak theory of
 74 Glashow, Weinberg, and Salam [6–8] with the theory of the strong interactions, as
 75 first envisioned by Gell-Mann and Zweig [9, 10]. This quantum field theory (QFT)
 76 contains a number of particles, whose interactions describe phenomena up to the TeV
 77 scale. These particles are manifestations of the fields of the Standard Model, after
 78 application of the Higgs Mechanism. The particle content of the SM consists only of
 79 six quarks, six leptons, four gauge bosons, and a scalar Higgs boson.

80 The Standard Model has some theoretical and experimental deficiencies. The SM
 81 contains 26 free parameters ¹. We would like to understand these free parameters
 82 in terms of a more fundamental theory.

83 The major theoretical concern of the Standard Model, as it pertains to this thesis,
 84 is the *hierarchy problem*[11–15]. The light mass of the Higgs boson (125 GeV) should be
 85 quadratically dependent on the scale of UV physics, due to the quantum corrections

¹This is the Standard Model corrected to include neutrino masses. These parameters are the fermion masses (6 leptons, 6 quarks), CKM and PMNS mixing angles (8 angles, 2 CP-violating phases), W/Z/Higgs masses (3), the Higgs field expectation value, and the couplings of the strong, weak, and electromagnetic forces (3 α_{force}).

86 from high-energy physics processes. The most perplexing experimental issue is the
87 existence of *dark matter*, as demonstrated by galactic rotation curves [16–22]. This
88 data has shown that there exists additional matter which has not yet been seen
89 interacting with the particles of the Standard Model. There is no particle in the SM
90 which can act as a candidate for dark matter.

91 Both of these major issues, as well as numerous others, can be solved by the
92 introduction of *supersymmetry* (SUSY) [15, 23–35]. In supersymmetric theories, each
93 SM particles has a so-called *superpartner*, or sparticle partner, differing from given SM
94 particle by 1/2 in spin. These theories solve the hierarchy problem, since the quantum
95 corrections induced from the superpartners exactly cancel those induced by the SM
96 particles. In addition, these theories are usually constructed assuming *R*–parity,
97 which can be thought of as the “charge” of supersymmetry, with SM particles having
98 $R = 1$ and sparticles having $R = -1$. In collider experiments, since the incoming
99 SM particles have total $R = 1$, the resulting sparticles are produced in pairs. This
100 produces a rich phenomenology, which is characterized by significant hadronic activity
101 and large missing transverse energy (E_T^{miss}), which provide significant discrimination
102 against SM backgrounds [36].

103 Despite the power of searches for supersymmetry where E_T^{miss} is a primary
104 discriminating variable, there has been significant interest in the use of other variables
105 to discriminate against SM backgrounds. These include searches employing variables
106 such as α_T , $M_{T,2}$, and the razor variables (M_R, R^2) [37–47]. In this thesis, we
107 will present the first search for supersymmetry using the novel Recursive Jigsaw
108 Reconstruction (RJR) technique. RJR can be considered the conceptual successor
109 of the razor variables. We impose a particular final state “decay tree” on an events,
110 which roughly corresponds to a simplified Feynmann diagram in decays containing
111 weakly-interacting particles. We account for the missing degrees of freedom associated
112 with weakly-interacting particles by a series of simplifying assumptions, which allow

113 us to calculate our variables of interest at each step in the decay tree. This allows
114 an unprecedented understanding of the internal structure of the decay and additional
115 variables to reject Standard Model backgrounds.

116 This thesis describes a search for the superpartners of the gluon and quarks, the
117 gluino and squarks, in final states with zero leptons, with 13.3 fb^{-1} of data using
118 the ATLAS detector. We organize the thesis as follows. The theoretical foundations
119 of the Standard Model and supersymmetry are described in Chapters 2 and 3. The
120 Large Hadron Collider and the ATLAS detector are presented in Chapters 4 and 5.
121 The reconstruction of physics objects is presented in Chapter 6. Chapter 7 provides
122 a detailed description of Recursive Jigsaw Reconstruction and a description of the
123 variables used for the particular search presented in this thesis. Chapter 8 presents
124 the details of the analysis, including details of the dataset, object reconstruction,
125 and selections used. In Chapter 9, the final results are presented; since there is no
126 evidence for a supersymmetric signal in the analysis, we present the final exclusion
127 curves in simplified supersymmetric models.

*The Standard Model*130 **2.1 Overview**

131 The Standard Model (SM) is another name for a theory of the internal symmetry
 132 group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ and its associated set of parameters. The SM is the
 133 culmination of years of work in both theoretical and experimental particle physics. In
 134 this thesis, we take the view that theorists construct a model with the field content and
 135 symmetries as inputs, and write down the most general Lagrangian consistent with
 136 those symmetries. Assuming this model is compatible with nature (in particular, the
 137 predictions of the model are consistent with previous experiments), experimentalists
 138 are responsible for testing the parameters by measurements.

139 Additional theoretical background is in ?? . The philosophy and notations are
 140 inspired by [48, 49].

141 **2.2 Field Content**

The Standard Model field content is

$$\begin{aligned} \text{Fermions} &: Q_L(3, 2)_{+1/3}, U_R(3, 1)_{+4/3}, D_R(3, 1)_{-2/3}, L_L(1, 2)_{-1}, E_R(1, 1)_{-2} \\ \text{Scalar (Higgs)} &: \phi(1, 2)_{+1} \\ \text{Vector Fields} &: G^\mu(8, 1)_0, W^\mu(1, 3)_0, B^\mu(1, 1)_0 \end{aligned} \tag{2.1}$$

142 where the $(A, B)_Y$ notation represents the irreducible representation under $SU(3)$
 143 and $SU(2)$, with Y being the electroweak hypercharge. Each of these fermion fields

144 has an additional index, representing the three generation of fermions.

145 We observed that Q_L, U_R , and D_R are triplets under $SU(3)_C$; these are the *quark*
146 fields. The *color* group, $SU(3)_C$ is mediated by the *gluon* field $G^\mu(8, 1)_0$, which has
147 8 degrees of freedom. The fermion fields $L_L(1, 2)_{-1}$ and $E_R(1, 1)_{-2}$ are singlets under
148 $SU(3)_C$; we call them the *lepton* fields.

149 Next, we note the “left-handed” (“right-handed”) fermion fields, denoted by $L(R)$
150 subscript, The left-handed fields form doublets under $SU(2)_L$. These are mediated
151 by the three degrees of freedom of the “W” fields $W^\mu(1, 3)_0$. These fields only act
152 on the left-handed particles of the Standard Model. This is the reflection of the
153 “chirality” of the Standard Model The left-handed and right-handed particles are
154 treated differently by the electroweak forces. The right-handed fields, U_R, D_R , and
155 E_R , are singlets under $SU(2)_L$.

156 The $U(1)_Y$ symmetry is associated to the $B^\mu(1, 1)_0$ boson with one degree of
157 freedom. The charge Y is known as the electroweak hypercharge.

158 To better understand the phenomenology of the Standard Model, let us investigate
159 each of the *sectors* of the Standard Model separately.

160 Electroweak sector

The electroweak sector refers to the $SU(2)_L \otimes U(1)_Y$ portion of the Standard Model gauge group. Following our philosophy of writing all gauge-invariant and renormalizable terms, the electroweak Lagrangian can be written as

$$\mathcal{L} = W_a^{\mu\nu} W_{\mu\nu}^a + B^{\mu\nu} B_{\mu\nu} + (D^\mu \phi)^\dagger D_\mu \phi - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2. \quad (2.2)$$

where $W_a^{\mu\nu}$ are the three ($a = 1, 2, 3$) gauge bosons associated to the $SU(2)_L$ gauge group, $B^{\mu\nu}$ is the one gauge boson of the $U(1)_Y$ gauge group, and ϕ is the complex Higgs multiplet. The covariant derivative D^μ is given by

$$D^\mu = \partial^\mu + \frac{ig}{2} W_a^\mu \sigma_a + \frac{ig'}{2} B^\mu \quad (2.3)$$

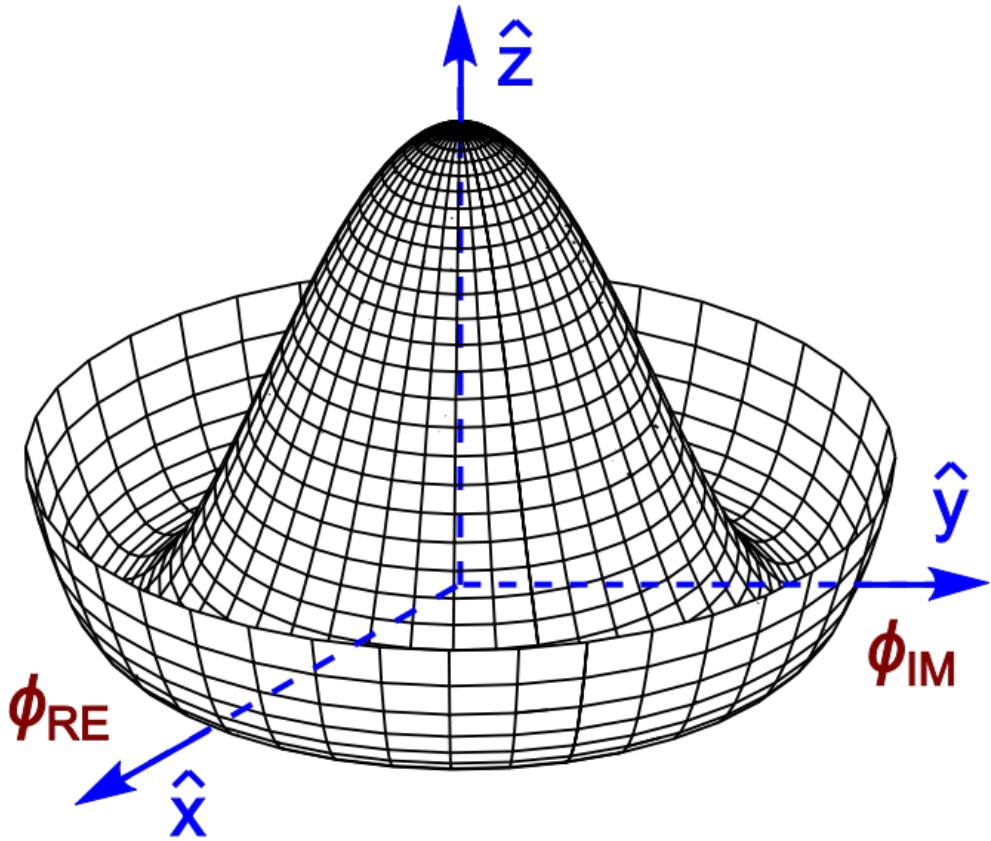


Figure 2.1: Sombrero potential

where $i\sigma_a$ are the Pauli matrices times the imaginary constant, which are the generators for $SU(2)_L$, and g and g' are the $SU(2)_L$ and $U(1)_Y$ coupling constants, respectively. The field strength tensors $W_a^{\mu\nu}$ and $B^{\mu\nu}$ are given by the commutator of the covariant derivative associated to each field

$$B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu \quad (2.4)$$

$$W_a^{\mu\nu} = \partial^\mu W_a^\nu - \partial^\nu W_a^\mu - g\epsilon_{abc}W_a^\mu W_b^\nu, \quad i = 1, 2, 3$$

161

162 The terms in the Lagrangian 2.2 proportional to μ^2 and λ make up the “Higgs
163 potential” [50]. As normal (see Appendix ??), we restrict $\lambda > 0$ to guarantee our
164 potential is bounded from below, and we also require $\mu^2 < 0$, which gives us the
165 standard “sombrero” potential shown in 2.1.

This potential has infinitely many minima at $\langle \phi \rangle = \sqrt{2m/\lambda}$. The ground state is *spontaneously* broken by the choice of ground state, which induces a vacuum expectation value (VEV). Without loss of generality, we can choose the Higgs field ϕ to point in the real direction, and write the Higgs field ϕ in the following form :

$$\phi = \frac{1}{\sqrt{2}} \exp\left(\frac{i}{v} \sigma_a \theta_a\right) \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \quad (2.5)$$

We choose a gauge to rotate away the dependence on θ_a , such that we can write simply

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \quad (2.6)$$

Now, we can see how the masses of the vector bosons are generated from the application of the Higgs mechanism. We plug Eq.2.6 back into the electroweak Lagrangian, and only showing the relevant mass terms in the vacuum state where $h(x) = 0$ see that (dropping the Lorentz indices) :

$$\begin{aligned} \mathcal{L}_M &= \frac{1}{8} \left| \begin{pmatrix} gW_3 + g'B & g(W_1 - iW_2) \\ g(W_1 + iW_2) & -gW_3 + g'B \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} \right|^2 \\ &= \frac{g^2 v^2}{8} \left[W_1^2 + W_2^2 + \left(\frac{g'}{g} B - W_3 \right)^2 \right] \end{aligned} \quad (2.7)$$

Defining the *Weinberg* angle $\tan(\theta_W) = g'/g$ and the following *physical* fields :

$$W^\pm = \frac{1}{\sqrt{2}} (W_1 \mp iW_2) \quad (2.8)$$

$$Z^0 = \cos \theta_W W_3 - \sin \theta_W B$$

$$A^0 = \sin \theta_W W_3 + \cos \theta_W B$$

we can write the piece of the Lagrangian associated to the vector boson masses as

$$\mathcal{L}_{MV} = \frac{1}{4} g^2 v^2 W^+ W^- + \frac{1}{8} (g^2 + g'^2) v^2 Z^0 Z^0. \quad (2.9)$$

and we have the following values of the masses for the vector bosons :

$$\begin{aligned} m_W^2 &= \frac{1}{4}v^2g^2 \\ m_Z^2 &= \frac{1}{4}v^2(g^2 + g'^2) \\ m_A^2 &= 0 \end{aligned} \tag{2.10}$$

We thus see how the Higgs mechanism gives rise to the masses of the W^\pm and Z boson in the Standard Model. As expected, the mass of the photon is zero. The $SU(2)_L \otimes U(1)_Y$ symmetry of the initially massless $W_{1,2,3}$ and B fields is broken to the $U(1)_{EM}$. Of the four degrees of freedom in the complex Higgs doublet, three are “eaten” when we give mass to the W^\pm and Z_0 , while the other degree of freedom is the Higgs particle, as discovered in 2012 by the ATLAS and CMS collaborations [51, 52].

173 Quantum Chromodynamics

Quantum chromodynamics (or the theory of the *strong* force) characterizes the behavior of *colored* particles, collectively known as *partons*. The partons of the Standard Model are the (fermionic) quarks, and the (bosonic) gluons. The strong force is governed by $SU(3)_C$, an unbroken symmetry in the Standard Model, which implies the gluon remains massless. Defining the covariant derivative for QCD as

$$D^\mu = \partial^\mu + ig_s G_a^\mu L_a, a = 1, \dots, 8 \tag{2.11}$$

where L_a are the generators of $SU(3)_C$, and g_s is the coupling constant of the strong force. The QCD Lagrangian then is given by

$$\mathcal{L}_{\text{QCD}} = i\bar{\psi}_f D_\mu \gamma^\mu \psi_f - \frac{1}{4} G_{a,\mu\nu} G_a^{\mu\nu} \tag{2.12}$$

where the summation over f is for quarks *families*, and $G_a^{\mu\nu}$ is the gluon field strength tensor, given by

$$G_a^{\mu\nu} = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s f^{abc} G_b^\mu G_c^\nu, a, b, c = 1, \dots, 8 \tag{2.13}$$

174 where f^{abc} are the structure constants of $SU(3)_C$, which are analogous to ϵ_{abc} for
175 $SU(2)_L$. The kinetic term for the quarks is contained in the standard ∂_μ term, while
176 the field strength term contains the interactions between the quarks and gluons, as
177 well as the gluon self-interactions.

178 Written down in this simple form, the QCD Lagrangian does not seem much
179 different from the QED Lagrangian, with the proper adjustments for the different
180 group structures. The gluon is massless, like the photon, so one could naïvely expect
181 an infinite range force, and it pays to understand why this is not the case. The
182 reason for this fundamental difference is the gluon self-interactions arising in the
183 field strength tensor term of the Lagrangian. This leads to the phenomena of *color*
184 *confinement*, which describes how one only observes color-neutral particles alone in
185 nature. In contrast to the electromagnetic force, particles which interact via the
186 strong force experience a *greater* force as the distance between the particles increases.
187 At long distances, the potential is given by $V(r) = -kr$. At some point, it is more
188 energetically favorable to create additional partons out of the vacuum than continue
189 pulling apart the existing partons, and the colored particles undergo *fragmentation*.
190 This leads to *hadronization*. Bare quarks and gluons are actually observed as sprays
191 of hadrons (primarily kaons and pions). These sprays are known as *jets*, which are
192 what are observed by experiments.

193 It is important to recognize the importance of understanding these QCD inter-
194 actions in high-energy hadron colliders such as the LHC. Since protons are hadrons,
195 proton-proton collisions such as those produced by the LHC are primarily governed
196 by the processes of QCD. In particular, by far the most frequent process observed in
197 LHC experiments is dijet production from gluon-gluon interactions, as can be seen
198 (Fig.2.2). These gluons that interact are part of the *sea* particles inside the proton; the
199 simple $p = uud$ model does not apply. The main *valence uud* quarks are constantly
200 interacting via gluons, which can themselves radiate gluons or split into quarks, and

Standard Model Production Cross Section Measurements

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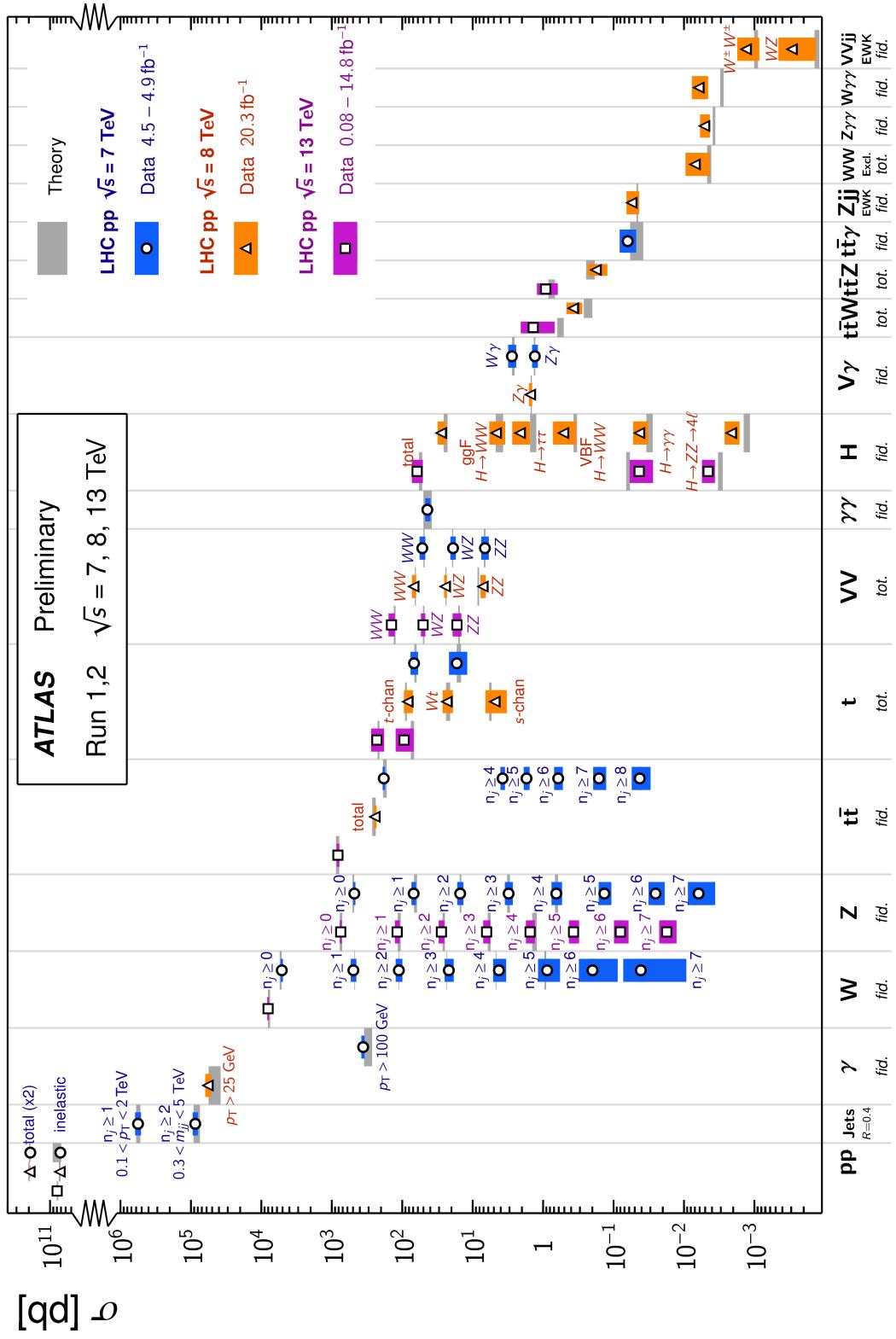


Figure 2.2: Cross-sections of various Standard Model processes

so on. A more useful understanding is given by the colloquially-known *bag* model [53, 54], where the proton is seen as a “bag” of (in principle) infinitely many partons, each with energy $E < \sqrt{s} = 6.5$ TeV. One then collides this (proton) bag with another, and views the products of this very complicated collision, where calculations include many loops in nonperturbative QCD calculations.

Fortunately, we are generally saved by the QCD factorization theorems [55]. This allows one to understand the hard (i.e. short distance or high energy) $2 \rightarrow 2$ parton process using the tools of perturbative QCD, while making series of approximations known as a *parton shower* model to understand the additional corrections from nonperturbative QCD. We will discuss the reconstruction of jets by experiments in Ch.5.

Fermions

We will now look more closely at the fermions in the Standard Model [56].

As noted earlier in Sec.2.2, the fermions of the Standard Model can be first distinguished between those that interact via the strong force (quarks) and those which do not (leptons).

There are six leptons in the Standard Model, which can be placed into three *generations*.

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \quad (2.14)$$

There is the electron (e), muon (μ), and tau (τ), each of which has an associated neutrino (ν_e, ν_μ, ν_τ). Each of the so-called charged (“electron-like”) leptons has electromagnetic charge -1 , while the neutrinos all have $q_{EM} = 0$.

Often in an experimental context, lepton is used to denote the stable electron and metastable muon, due to their striking experimental signatures. Taus are often treated separately, due to their much shorter lifetime of $\tau_\tau \sim 10^{-13}s$. These decay

223 through hadrons or the other leptons, so often physics analyses at the LHC treat
224 them as jets or leptons, as will be done in this thesis.

225 As the neutrinos are electrically neutral, nearly massless, and only interact via the
226 weak force, it is quite difficult to observe them directly. Since LHC experiments rely
227 overwhelmingly on electromagnetic interactions to observe particles, the presence of
228 neutrinos is not observed directly. Neutrinos are instead observed by the conservation
229 of four-momentum in the plane transverse to the proton-proton collisions, known as
230 *missing transverse energy*.

There are six quarks in the Standard Model : up, down, charm, strange, top, and bottom. Quarks are similar organized into three generations :

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \quad (2.15)$$

231 where we speak of “up-like” quarks and “down-like” quarks.

232 Each up-like quark has charge $q_{up} = 2/3$, while the down-like quarks have $q_{down} =$
233 $-1/3$. At the high energies of the LHC, one often makes the distinction between
234 the light quarks (u, d, c, s), the bottom quark, and top quark. In general, due to
235 the hadronization process described above, the light quarks, with masses $m_q < \sim$
236 1.5 GeV are indistinguishable by LHC experiments. Their hadronic decay products
237 generally have long lifetimes and they are reconstructed as jets.¹. The bottom quark
238 hadronizes primarily through the B -mesons, which generally travels a short distance
239 before decaying to other hadrons. This allows one to distinguish decays via b -quarks
240 from other jets. This procedure is known as *b-tagging* and will be discussed more in
241 Ch.5.

242 Due to its large mass, the top quark decays before it can hadronize. There are
243 no bound states associated to the top quark. The top is of particular interest at

¹In some contexts, charm quarks are also treated as a separate category, although it is quite difficult to distinguish charm quarks from the other light quarks at high energy colliders.

Standard Model Interactions (Forces Mediated by Gauge Bosons)



Figure 2.3: The interactions of the Standard Model

- 244 the LHC; it has a striking signature through its most common decay mode $t \rightarrow Wb$.
 245 Decays via tops, especially $t\bar{t}$ are frequently an important signal decay mode, or an
 246 important background process.

247 **Interactions in the Standard Model**

- 248 We briefly overview the entirety of the fundamental interactions of the Standard
 249 Model. These can also be found in [2.3](#).
- 250 The electromagnetic force, mediated by the photon, interacts with via a three-

251 point coupling all charged particles in the Standard Model. The photon thus interacts
252 with all the quarks, the charged leptons, and the charged W^\pm bosons.

253 The weak force is mediated by three particles : the W^\pm and the Z^0 . The Z^0 can
254 interacts with all fermions via a three-point coupling. A real Z_0 can thus decay to
255 a fermion-antifermion pair of all SM fermions except the top quark, due to its large
256 mass. The W^\pm has two important three-point interactions with fermions. First, the
257 W^\pm can interact with an up-like quark and a down-like quark; an important example
258 in LHC experiments is $t \rightarrow Wb$ The coupling constants for these interactions are
259 encoded in the unitary matrix known as the Cabibbo–Kobayashi–Maskawa (CKM)
260 matrix [57, 58], and are generally known as flavor-changing interactions. Secondly,
261 the W^\pm interacts with a charged lepton and its corresponding neutrino. In this case,
262 the unitary matrix that corresponds to CKM matrix for quarks is the identity matrix,
263 which forbids (fundamental) vertices such as $\mu \rightarrow We$. For leptons, instead this is
264 a two-step process : $\mu \rightarrow \nu_m u W \rightarrow \nu_m u \bar{\nu}_e e$. Finally, there are the self-interactions
265 of the weak gauge bosons. There is a three-point and four-point interaction. All
266 combinations are allowed which conserve electric charge.

267 The strong force is mediated by the gluon, which as discussed above also carries
268 the strong color charge. There is the fundamental three-point interaction, where a
269 quark radiates a gluon. Additionally, there are the three-point and four-point gluon-
270 only interactions.

271 2.3 Deficiencies of the Standard Model

272 The Standard Model has been enormously successful. This relatively simple theory is
273 capable of explaining a very wide range of phenomenom, which ultimately break down
274 to combinations of nine diagrams shown in Fig.2.3 at tree level. Unfortunately, there
275 are some unexplained problems with the Standard Model. We cannot go through all

m_e	Electron mass	511 keV
m_μ	Muon mass	105.7 MeV
m_τ	Tau mass	1.78 GeV
m_u	Up quark mass	1.9 MeV ($m_{\bar{MS}} = 2\text{GeV}$)
m_d	Down quark mass	4.4 MeV ($m_{\bar{MS}} = 2\text{GeV}$)
m_s	Strange quark mass	87 MeV ($m_{\bar{MS}} = 2\text{GeV}$)
m_c	Charm quark mass	1.32 GeV ($m_{\bar{MS}} = m_c$)
m_b	Bottom quark mass	4.24 GeV ($m_{\bar{MS}} = m_b$)
m_t	Top quark mass	172.7 GeV (on-shell renormalization)
θ_{12} CKM	12-mixing angle	13.1°
θ_{23} CKM	23-mixing angle	2.4°
θ_{13} CKM	13-mixing angle	0.2°
δ CKM	CP-violating Phase	0.995
g'	U(1) gauge coupling	0.357 ($m_{\bar{MS}} = m_Z$)
g	SU(2) gauge coupling	0.652 ($m_{\bar{MS}} = m_Z$)
g_s	SU(3) gauge coupling	1.221 ($m_{\bar{MS}} = m_Z$)
θ_{QCD}	QCD vacuum angle	~0
VEV	Higgs vacuum expectation value	246 GeV
m_H	Higgs mass	125 GeV

Table 2.1: Parameters of the Standard Model. For values dependent on the renormalization scheme, we use a combination of the on-shell normalization scheme [59–62] and modified minimal subtraction scheme with $m_{\bar{MS}}$ as indicated in the table[63]

276 of the potential issues in this thesis, but we will motivate the primary issues which
 277 naturally lead one to *supersymmetry*, as we will see in Ch.3.

The Standard Model has many free parameters; see Table 2.1. In general, we prefer models with less free parameters. A great example of this fact, and the primary experimental evidence for EWSB, is the relationship between the couplings of the weak force and the masses of the gauge bosons of the weak force :

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \stackrel{?}{=} 1 \quad (2.16)$$

278 where ? indicates that this is a testable prediction of the Standard Model (in
 279 particular, that the gauge bosons gain mass through EWSB). This relationship has
 280 been measured within experimental and theoretical predictions. We would like to
 281 produce additional such relationships, which would exist if the Standard Model is a

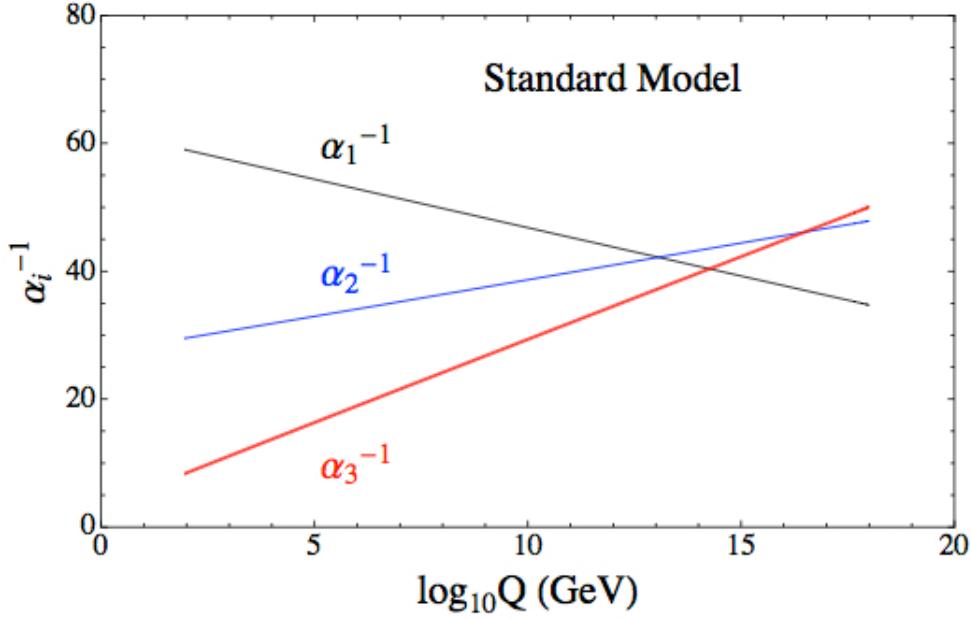


Figure 2.4: The running of Standard Model gauge couplings. The Standard Model couplings do not unify at high energies, which indicates it cannot completely describe nature through the Planck scale.

282 low-energy approximation of some other theory.

283 An additional issue is the lack of *gauge coupling unification*. The couplings of
 284 any quantum field theory “run” as a function of the distance scales (or inversely,
 285 energy scales) of the theory. The idea is closely related to the unification of the
 286 electromagnetic and weak forces at the so-called *electroweak scale* of $O(100$ GeV).
 287 One would hope this behavior was repeated between the electroweak forces and the
 288 strong force at some suitable energy scale. The Standard Model does not exhibit this
 289 behavior, as we can see in Fig.2.4.

But, the most significant problem with the Standard Model is the *hierarchy problem*. In its most straightforward incarnation, the Higgs scalar field is subject to quantum corrections through loop diagrams, as shown in Fig.2.5. For demonstration, we use the contributions from the top quark, since the top quark has the largest Higgs Yukawa coupling due to its large mass. In general, we should expect these corrections to quadratically depend on the scale of the ultraviolet physics, Λ . Briefly assume

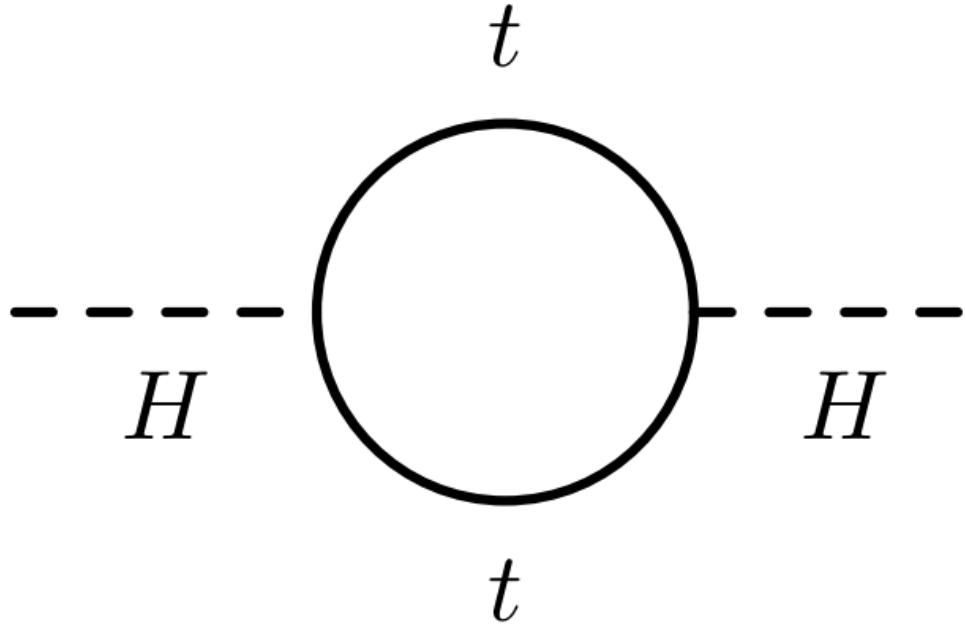


Figure 2.5: The dominant quantum loop correction to the Higgs mass in the Standard Model.

there is no new physics before the Planck scale of gravity, $\Lambda_{\text{Planck}} = 10^{19}$ GeV. In this case, we expect the corrections to the Higgs mass to be

$$\delta m_H^2 \approx \left(\frac{m_t}{8\pi^2 \langle \phi \rangle_{VEV}} \right)^2 \Lambda_{\text{Planck}}^2. \quad (2.17)$$

290 To achieve the miraculous cancellation required to get the observed Higgs mass of
 291 125 GeV, one needs to then set the bare Higgs mass m_0 , our input to the Standard
 292 Model Lagrangian, itself to a *precise* value $\sim 10^{19}$ GeV. This extraordinary level of
 293 parameter finetuning is quite undesirable, and within the framework of the Standard
 294 Model alone, there is little that can be done to alleviate this issue.

295 An additional concern, of a different nature, is the lack of a *dark matter* candidate
 296 in the Standard Model. Dark matter was discovered by observing galactic rotation
 297 curves, which showed that much of the matter that interacts gravitationally is invisible
 298 to our (electromagnetic) telescopes [16–22]. The postulation of the existence of dark
 299 matter, which interacts at least through gravity, allows one to understand these galactic

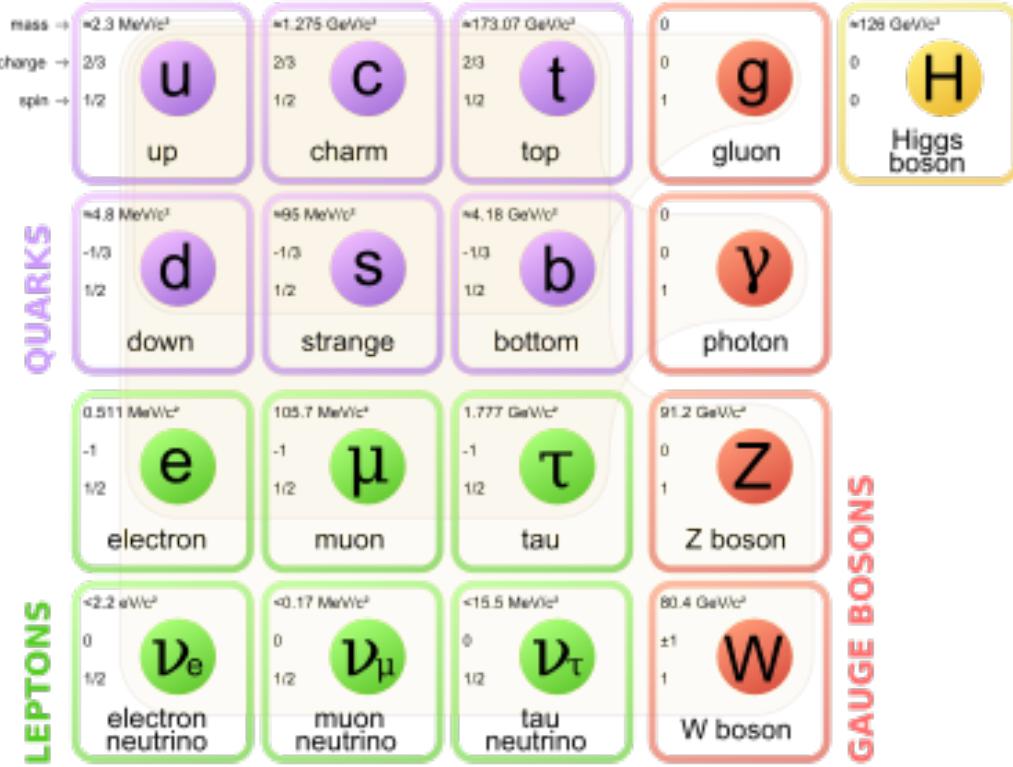


Figure 2.6: Particles of the Standard Model

300 rotation curves. Unfortunately, no particle in the Standard Model could possibly be
 301 the dark matter particle. The only candidate truly worth another look is the neutrino,
 302 but it has been shown that the neutrino content of the universe is simply too small
 303 to explain the galactic rotation curves [22, 64]. The experimental evidence from the
 304 galactic rotations curves thus show there *must* be additional physics beyond the
 305 Standard Model, which is yet to be understood.

306 In the next chapter, we will see how these problems can be alleviated by the theory
 307 of supersymmetry.

Supersymmetry

310 This chapter will introduce supersymmetry (SUSY) [15, 23–35]. We will begin by
 311 introducing the concept of a *superspace*, and discuss some general ingredients of
 312 supersymmetric theories. This will include a discussion of how the problems with the
 313 Standard Model described in Ch.2 are naturally fixed by these theories.

314 The next step is to discuss the particle content of the *Minimally Supersymmetric*
 315 *Standard Model* (MSSM). As its name implies, this theory contains the minimal
 316 additional particle content to make Standard Model supersymmetric. We then discuss
 317 the important phenomenological consequences of this theory, especially as it would
 318 be observed in experiments at the LHC.

319 **3.1 Supersymmetric theories : from space to
 320 superspace**

321 **Coleman-Mandula “no-go” theorem**

322 We begin the theoretical motivation for supersymmetry by citing the “no-go” theorem
 323 of Coleman and Mandula [65]. This theorem forbids *spin-charge unification*. It states
 324 that all quantum field theories which contain nontrivial interactions must be a direct
 325 product of the Poincaré group of Lorentz symmetries, the internal product of gauge
 326 symmetries, and the discrete symmetries of parity, charge conjugation, and time
 327 reversal. The assumptions which go into building the Coleman-Mandula theorem are

328 quite restrictive, but there is solution, which has become known as *supersymmetry* [26,
 329 66]. In particular, we must introduce a *spinorial* group generator Q . Alternatively,
 330 and equivalently, this can be viewed as the addition of anti-commuting coordinates.
 331 Space plus these new anti-commuting coordinates is then called *superspace* [67]. We
 332 will not investigate this view in detail, but it is also a quite intuitive and beautiful
 333 way to construct supersymmetry[15].

334 **Supersymmetry transformations**

A *supersymmetric* transformation Q transforms a bosonic state into a fermionic state,
 and vice versa :

$$Q |\text{Fermion}\rangle = |\text{Boson}\rangle \quad (3.1)$$

$$Q |\text{Boson}\rangle = |\text{Fermion}\rangle \quad (3.2)$$

To ensure this relation holds, Q must be an anticommuting spinor. Additionally, since
 spinors are inherently complex, Q^\dagger must also be a generator of the supersymmetry
 transformation. Since Q and Q^\dagger are spinor objects (with $s = 1/2$), we can see
 that supersymmetry must be a spacetime symmetry. The Haag-Lopuszanski-Sohnius
 extension [66] of the Coleman-Mandula theorem [65] is quite restrictive about the
 forms of such a symmetry. Here, we simply write the (anti-) commutation relations
 [15] :

$$Q_\alpha, Q_{\dot{\alpha}}^\dagger = -2\sigma_{\alpha\dot{\alpha}\mu} P_\mu \quad (3.3)$$

$$Q_\alpha, Q_{\dot{\beta}} = Q_{\dot{\alpha}}^\dagger, Q_{\dot{\beta}}^\dagger = 0 \quad (3.4)$$

$$[P^\mu, Q_\alpha] = [P^\mu, Q_{\dot{\alpha}}^\dagger] = 0 \quad (3.5)$$

335 **Supermultiplets**

336 In a supersymmetric theory, we organize single-particle states into irreducible
 337 representations of the supersymmetric algebra which are known as *supermultiplets*.

338 Each supermultiplet contains a fermion state $|F\rangle$ and a boson state $|B\rangle$. These two
339 states are known as *superpartners*. These are related by some combination of
340 Q and Q^\dagger , up to a spacetime transformation. Q and Q^\dagger commute with the mass-
341 squared operator $-P^2$ and the operators corresponding to the gauge transformations
342 [15]: in particular, the gauge interactions of the Standard Model. In an unbroken
343 supersymmetric theory, this means the states $|F\rangle$ and $|B\rangle$ have exactly the same mass,
344 electromagnetic charge, electroweak isospin, and color charges. One can also prove
345 [15] that each supermultiplet contains the exact same number of bosonic (n_B) and
346 fermion (n_F) degrees of freedom. We now explore the possible types of supermultiples
347 one can find in a renormalizable supersymmetric theory.

348 Since each supermultiplet must contain a fermion state, the simplest type of
349 supermultiplet contains a single Weyl fermion state ($n_F = 2$) which is paired with
350 $n_B = 2$ scalar bosonic degrees of freedom. This is most conveniently constructed
351 as single complex scalar field. We call this construction a *scalar supermultiplet* or
352 *chiral supermultiplet*. The second name is indicative, as only chiral supermultiplets
353 can contain fermions whose right-handed and left-handed components transform
354 differently under the gauge interactions (as of course happens in the Standard Model).

355 The second type of supermultiplet we construct is known as a *gauge supermul-*
356 *tiplet*. We take a spin-1 gauge boson (which must be massless due to the gauge
357 symmetry, so $n_B = 2$) and pair this with a single massless Weyl spinor¹. The gauge
358 bosons transform as the adjoint representation of their respective gauge groups
359 Their fermionic partners, which are known as gauginos, must also. In particular,
360 the left-handed and right-handed components of the gaugino fermions have the same
361 gauge transformation properties.

362 Excluding gravity, this is the entire list of supermultiplets which can participate
363 in renormalizable interactions in what is known as $N = 1$ supersymmetry. This

¹Choosing an $s = 3/2$ massless fermion leads to nonrenormalizable interactions.

means there is only one copy of the supersymmetry generators Q and Q^\dagger . This is essentially the only “easy” phenomenological choice, since it is the only option in four dimensions which allows for the chiral fermions and parity violations to be built into the Standard Model. We will not look further into $N > 1$ supersymmetry in this thesis.

The primary goal, after understanding the possible structures of the multiplets above, is to fit the Standard Model particles into a multiplet, and therefore make predictions about their supersymmetric partners. We explore this in the next section.

3.2 Minimally Supersymmetric Standard Model

To construct what is known as the MSSM [15, 68–71], we need a few ingredients and assumptions. First, we match the Standard Model particles with their corresponding superpartners of the MSSM. We will also introduce the naming of the superpartners (also known as *sparticles*). We discuss a very common additional restraint imposed on the MSSM, known as R –parity. We also discuss the concept of soft supersymmetry breaking and how it manifests itself in the MSSM.

Chiral supermultiplets

The first thing we deduce is directly from Sec.3.1. The bosonic superpartners associated to the quarks and leptons *must* be spin 0, since the quarks and leptons must be arranged in a chiral supermultiplet. This is essential, since the chiral supermultiplet is the only one which can distinguish between the left-handed and right-handed components of the Standard Model particles. The superpartners of the quarks and leptons are known as *squarks* and *sleptons*, or *sfermions* in aggregate. (for “scalar quarks”, “scalar leptons”, and “scalar fermion”). The “s-” prefix can also be added to the individual quarks i.e. *selectron*, *sneutrino*, and *stop*. The notation

388 is to add a \sim over the corresponding Standard Model particle i.e. \tilde{e} , the selectron is
 389 the superpartner of the electron. The two-component Weyl spinors of the Standard
 390 Model must each have their own (complex scalar) partner i.e. e_L, e_R have two distinct
 391 partners : \tilde{e}_L, \tilde{e}_R . As noted above, the gauge interactions of any of the sfermions are
 392 identical to those of their Standard Model partners.

Due to the scalar nature of the Higgs, it must obviously lie in a chiral supermultiplet. To avoid gauge anomalies and ensure the correct Yukawa couplings to the quarks and leptons [15], we must add additional Higgs bosons to any supersymmetric theory. In the MSSM, we have two chiral supermultiplets. The SM (SUSY) parts of the multiplets are denoted $H_u(\tilde{H}_u)$ and $H_d(\tilde{H}_d)$. Writing out H_u and H_d explicitly:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad (3.6)$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \quad (3.7)$$

393 we see that H_u looks very similar to the SM Higgs with $Y = 1$, and H_d is symmetric
 394 with $+ \rightarrow -$ and $Y = -1$. The SM Higgs boson, h_0 , is a linear superposition of the
 395 neutral components of these two doublets. The SUSY parts of the Higgs multiplets,
 396 \tilde{H}_u and \tilde{H}_d , are each left-handed Weyl spinors. For generic spin-1/2 sparticles, we
 397 add the “-ino” suffix. We then call the partners of the two Higgs collectively the
 398 *Higgsinos*.

399 Gauge supermultiplets

400 The superpartners of the gauge bosons must all be in gauge supermultiplets since
 401 they contain a spin-1 particle. Collectively, we refer to the superpartners of the
 402 gauge bosons as the gauginos.

403 The first gauge supermultiplet contains the gluon, and its superpartner, which is
 404 known as the *gluino*, denoted \tilde{g} . The gluon is of course the SM mediator of $SU(3)_C$

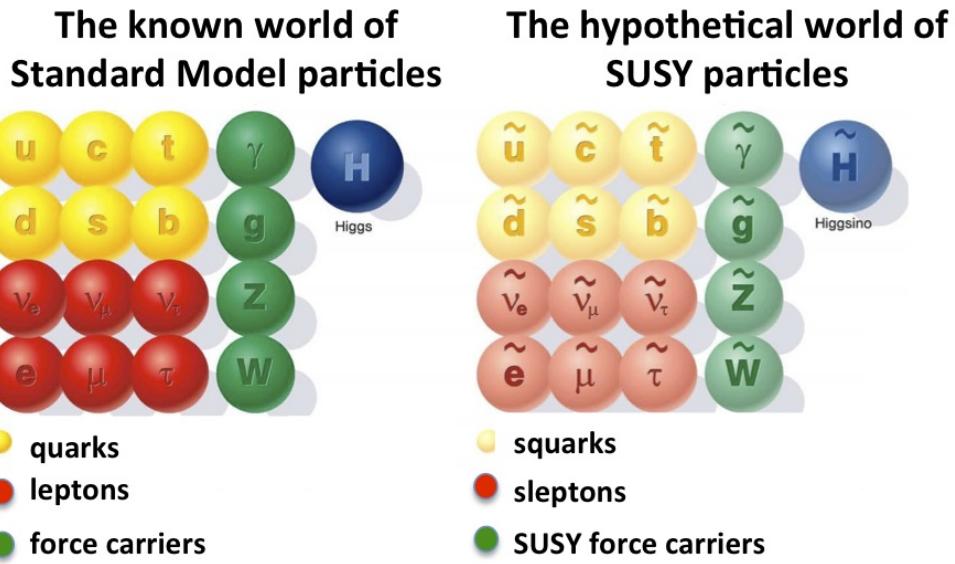


Figure 3.1: Particles of the MSSM

405 The gluino is also a colored particle, subject to $SU(3)_C$. From the SM before EWSB,
 406 we have the four gauge bosons of the electroweak symmetry group $SU(2)_L \otimes U(1)_Y$:
 407 $W^{1,2,3}$ and B^0 . The superpartners of these particles are thus the *winos* $\tilde{W}^{1,2,3}$ and
 408 *bino* \tilde{B}^0 , where each is placed in another gauge supermultiplet with its corresponding
 409 SM particle. After EWSB, without breaking supersymmetry, we would also have the
 410 zino \tilde{Z}^0 and photino $\tilde{\gamma}$.

411 The entire particle content of the MSSM can be seen in Fig.3.1.

412 At this point, it's important to take a step back. Where are these particles?
 413 As stated above, supersymmetric theories require that the masses and all quantum
 414 numbers of the SM particle and its corresponding sparticle are the same. Of course,
 415 we have not observed a selectron, squark, or wino. The answer, as it often is, is that
 416 supersymmetry is *broken* by the vacuum state of nature [15].



Figure 3.2: This Feynmann diagram shows how proton decay is induced in the MSSM, if one does not impose R -parity.

417 **R -parity**

This section is a quick aside to the general story. R – parity refers to an additional discrete symmetry which is often imposed on supersymmetric models. For a given particle state, we define

$$R = (-1)^{3(B-L)+2s} \quad (3.8)$$

418 where B, L is the baryon (lepton) number and s is the spin. The imposition of
419 this symmetry forbids certain terms from the MSSM Lagrangian that would violate
420 baryon and/or lepton number. This is required in order to prevent proton decay, as
421 shown in Fig.3.2². .

422 In supersymmetric models, this is a \mathbb{Z}_2 symmetry, where SM particles have $R = 1$
423 and sparticles have $R = -1$. We will take R – parity as part of the definition of
424 the MSSM. We will discuss later the *drastic* consequences of this symmetry on SUSY
425 phenomenology

426 **Soft supersymmetry breaking**

The fundamental idea of *soft* supersymmetry breaking [15, 34, 35, 72, 73] is that we would like to break supersymmetry without reintroducing the quadratic divergences

²Proton decay can actually be prevented by allowing only one of the four potential R-parity violating terms to survive.

we discussed at the end of Chapter 2. We write the Lagrangian in a form :

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}} \quad (3.9)$$

427 In this sense, the symmetry breaking is “soft”, since we have separated out the
 428 completely symmetric terms from those soft terms which will not allow the quadratic
 429 divergences to the Higgs mass.

430 The explicitly allowed terms in the soft-breaking Lagrangian are [35]:

431 • Mass terms for the scalar components of the chiral supermultipletss

432 • Mass terms for the Weyl spinor components of the gauge supermultipletss

433 • Trilinear couplings of scalar components of chiral supermultiplets

In particular, using the field content described above for the MSSM, the softly-broken portion of the MSSM Lagrangian can be written

$$\mathcal{L}_{\text{soft}} = -\frac{1}{2} \left(M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + c.c. \right) \quad (3.10)$$

$$- \left(\tilde{u} a_u \tilde{Q} H_u - \tilde{d} a_d \tilde{Q} H_d - \tilde{e} a_e \tilde{L} H_d + c.c. \right) \quad (3.11)$$

$$- \tilde{Q}^\dagger m_Q^2 \tilde{Q} - \tilde{L}^\dagger m_L^2 \tilde{L} - \tilde{u} m_u^2 \tilde{u}^\dagger - \tilde{d} m_d^2 \tilde{d}^\dagger - \tilde{e} m_e^2 \tilde{e}^\dagger \quad (3.12)$$

$$- m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + cc). \quad (3.13)$$

434 where we have introduced the following notations :

435 1. M_3, M_2, M_1 are the gluino, wino, and bino masses.

436 2. a_u, a_d, a_e are complex 3×3 matrices in family space.

437 3. $m_Q^2, m_u^2, m_d^2, m_L^2, m_e^2$ are hermitian 3×3 matrices in family space.

438 4. $m_{H_u}^2, m_{H_d}^2, b$ are the SUSY-breaking contributions to the Higgs potential.

439 We have written matrix terms without any sort of additional notational decoration to
 440 indicate their matrix nature, and we now show why. The first term 1 is the set of mass
 441 terms for the gluino, wino, and bino. The second term 2, containing a_u, a_d, a_e , has
 442 strong constraints from experiments [74, 75]. We will assume that each $a_i, i = u, d, e$
 443 is proportional to the Yukawa coupling matrix : $a_i = A_{i0}y_i$. The third term 3 can be
 444 similarly constrained by experiments [68, 75–82]. We will assume the elements of the
 445 fourth term 4 contributing to the Higgs potential as well as all of the 1 terms must
 446 be real, which limits the possible CP-violating interactions to those of the Standard
 447 Model. We thus only consider flavor-blind, CP-conserving interactions within the
 448 MSSM.

The important mixing for mass and gauge interaction eigenstates in the MSSM occurs within electroweak sector, in a process akin to EWSB in the Standard Model. The neutral portions of the Higgsinos doublets and the neutral gauginos ($\tilde{H}_u^0, \tilde{H}_d^0, \tilde{B}^0, \tilde{W}^0$) of the gauge interaction basis mix to form what are known as the *neutralinos* of mass basis :

$$M_{\tilde{\chi}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix} \quad (3.14)$$

449 where $s(c)$ are the sine and cosine of angles related to EWSB, which introduced
 450 masses to the gauginos and higgsinos. Diagonalization of this matrix gives the four
 451 neutralino mass states, listed without loss of generality in order of increasing mass :
 452 $\tilde{\chi}_{1,2,3,4}^0$.

453 The neutralinos, especially the lightest neutralino $\tilde{\chi}_1^0$, are important ingredients
 454 in SUSY phenomenology.

455 The same process can be done for the electrically charged gauginos with
 456 the charged portions of the Higgsino doublets along with the charged winos

457 $(\tilde{H}_u^+, \tilde{H}_d^+, \tilde{W}^+, \tilde{W}^-)$. This leads to the *charginos*, again in order of increasing mass :
458 $\tilde{\chi}_{1,2}^\pm$.

459

3.3 Phenomenology

460 We are finally at the point where we can discuss the phenomenology of the MSSM,
461 in particular as it manifests itself at the energy scales of the LHC.

462 As noted above in Sec.3.2, the assumption of R -parity has important conse-
463 quences for MSSM phenomenology. The SM particles have $R = 1$, while the sparticles
464 all have $R = -1$. Simply, this is the “charge” of supersymmetry. Since the particles of
465 LHC collisions (pp) have total incoming $R = 1$, we must expect that all sparticles will
466 be produced in *pairs*. An additional consequence of this symmetry is the fact that the
467 lightest supersymmetric particle (LSP) is *stable*. Off each branch of the Feynmann
468 diagram shown in Fig., we have $R = -1$, and this can only decay to another sparticle
469 and a SM particle. Once we reach the lightest sparticle in the decay, it is absolutely
470 stable. This leads to the common signature E_T^{miss} for a generic SUSY signal.

471 For this thesis, we will be presenting an inclusive search for squarks and gluinos
472 with zero leptons in the final state. This is a very interesting decay channel, due to
473 the high cross-sections of $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ decays, as can be seen in Fig.?? [83].

474 This is a direct consequence of the fact that these are the colored particles of the
475 MSSM. Since the sparticles interact with the gauge groups of the SM in the same way
476 as their SM partners, the colored sparticles, the squarks and gluinos, are produced
477 and decay as governed by the color group $SU(3)_C$ with the strong coupling g_S . The
478 digluino production is particularly copious, due to color factor corresponding to the
479 color octet of $SU(3)_C$.

480 In the case of disquark production, the most common decay mode of the squark in
481 the MSSM is a decay directly to the LSP plus a single SM quark [15]. This means the

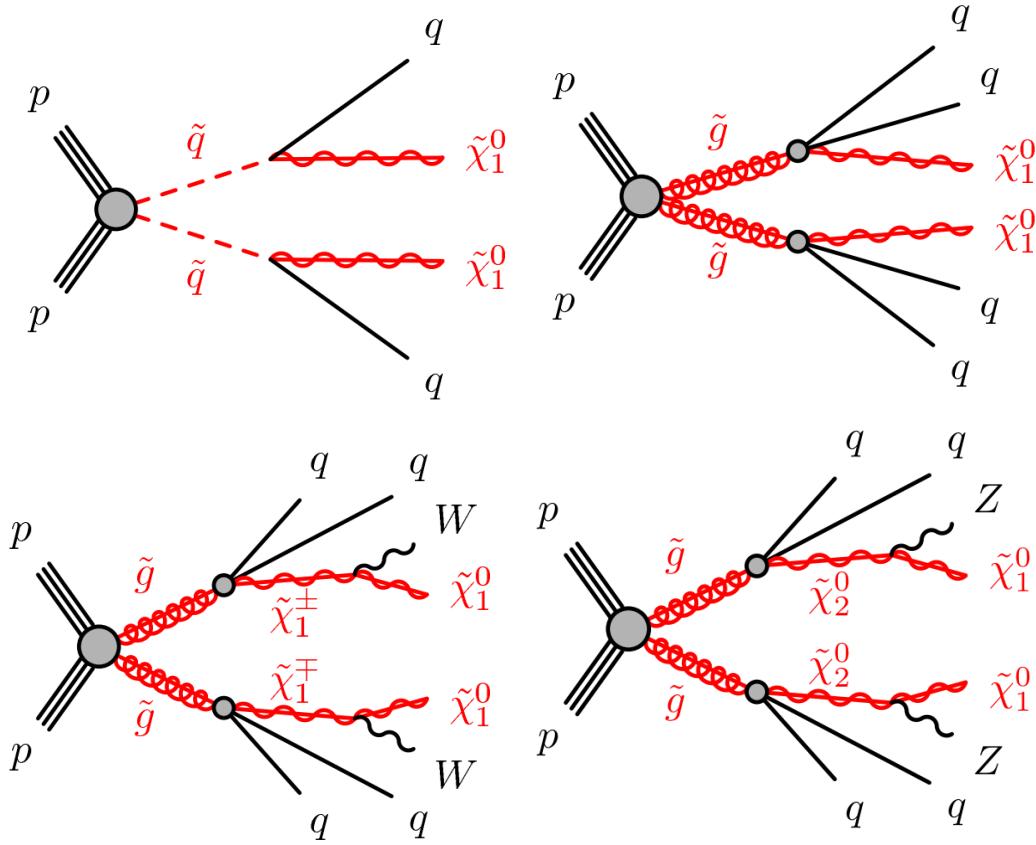


Figure 3.3: SUSY signals considered in this thesis

482 basic search strategy of disquark production is two jets from the final state quarks,
 483 plus missing transverse energy for the LSPs. There are also cascade decays, the most
 484 common of which, and the only one considered in this thesis, is $\tilde{q} \rightarrow q\chi_1^\pm \rightarrow qW^\pm\chi_1^0$.

485 For digluino production, the most common decay is $\tilde{g} \rightarrow g\tilde{q}$, due to the large g_S
 486 coupling. The squark then decays as listed above. In this case, we generically search
 487 for four jets and missing transverse energy from the LSPs.

488 In the context of experimental searches for SUSY, we often consider *simplified*
 489 *models*. These models make certain assumptions which allow easy comparisons of
 490 results by theorists and experimentalists. In the context of this thesis, the simplified
 491 models will make assumptions about the branching ratios described in the preceding
 492 paragraphs. In particular, we will often choose a model where the decay of interest
 493 occurs with 100% branching ratio. This is entirely for ease of interpretation, but it is

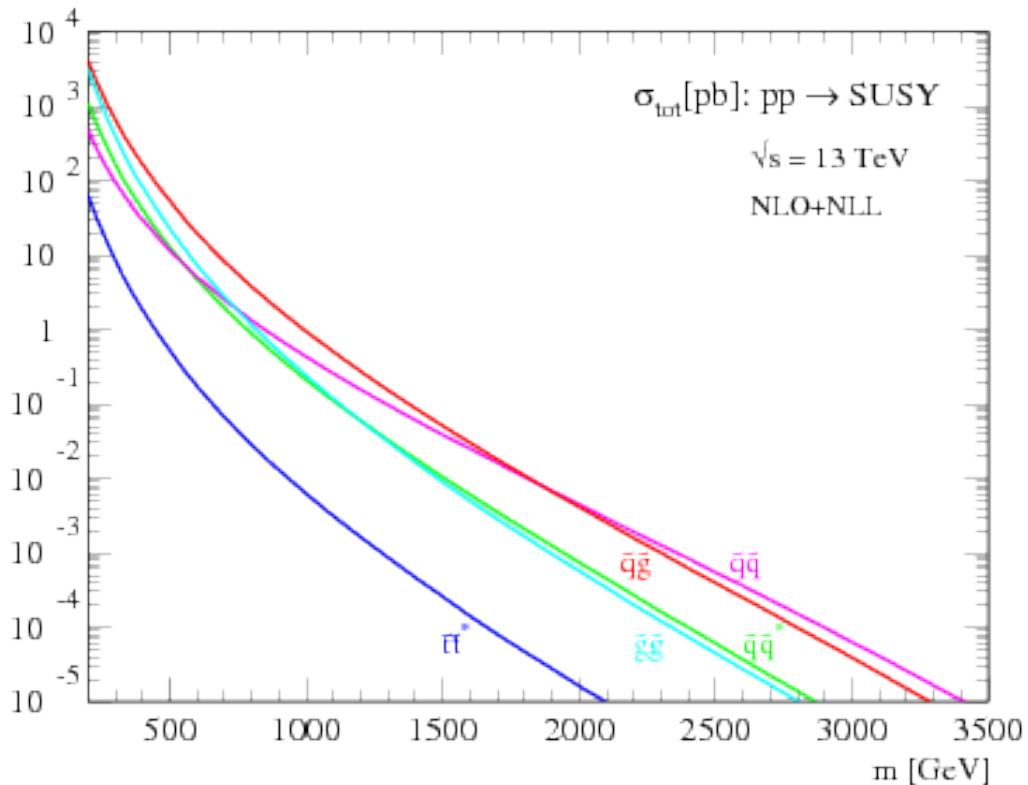


Figure 3.4: SUSY production cross-sections as a function of sparticle mass at $\sqrt{s} = 13$ TeV.

494 important to recognize that these are more a useful comparison tool, especially with
 495 for setting limits, than a strict statement about the potential masses of sought-after
 496 beyond the Standard Model particle.

497 3.4 How SUSY solves the problems with the SM

498 We now return to the issues with the Standard Model as described in Ch.2 to see
 499 how these issues are solved by supersymmetry.

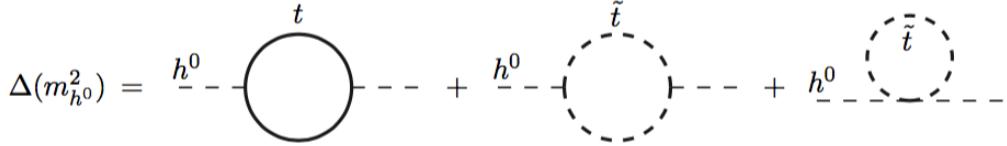


Figure 3.5: Loop diagrams correct the Higgs mass in the MSSM

500 Quadratic divergences to the Higgs mass

The quadratic divergences induced by the loop corrections to the Higgs mass, for example from the top Yukawa coupling, goes as

$$\delta m_H^2 \approx \left(\frac{m_t}{8\pi^2 \langle \phi \rangle_{VEV}} \right)^2 \Lambda_{Planck}^2. \quad (3.15)$$

501 The miraculous thing about SUSY is each of these terms *automatically* comes
 502 with a term which exactly cancels this contribution[15]. The fermions and bosons
 503 have opposite signs in this loop diagram to all orders in perturbation theory, which
 504 completely solves the hierarchy problem. This is the strongest motived reason for
 505 supersymmetry.

506 Gauge coupling unification

507 An additional motivation for supersymmetry is seen by the gauge coupling unification
 508 high scales. In the Standard Model, as we saw the gauge couplings fail to unify at
 509 high energies. In the MSSM and many other forms of supersymmetry, the gauge
 510 couplings unify at high energy, as can be seen in Fig.3.6. This provides additional
 511 aesthetic motivation for supersymmetric theories.

512 Dark matter

513 As we discussed previously, the lack of any dark matter candidate in the Standard
 514 Model naturally leads to beyond the Standard Model theories. In the Standard Model,
 515 there is a natural dark matter candidate in the lightest supersymmetric particle[15]



Figure 3.6: The running of Standard Model gauge couplings: compare to Fig.2.4. The MSSM gauge couplings nearly intersect at high energies.

516 The LSP would in dark matter experiments be called a *weakly-interacting massive*
 517 *particle* (WIMP), which is a type of cold dark matter [22, 84]. These WIMPS would
 518 only interact through the weak force and gravity, which is exactly as a model like the
 519 MSSM predicts for the neutralino. In Fig.3.7, we can see the current WIMP exclusions
 520 for a given mass. The range of allowed masses which have not been excluded for LSPs
 521 and WIMPs have significant overlap. This provides additional motivation outside of
 522 the context of theoretical details.

523 3.5 Conclusions

524 Supersymmetry is the most well-motivated theory for physics beyond the Standard
 525 Model. It provides a solution to the hierarchy problem, leads to gauge coupling
 526 unification, and provides a dark matter candidate consistent with galactic rotation
 527 curves. As noted in this chapter, due to the LSPs in the final state, most SUSY



Figure 3.7: WIMP exclusions from direct dark matter detection experiments.

528 searches require a significant amount of missing transverse energy in combination
 529 with jets of high transverse momentum. However, there is some opportunity to do
 530 better than this, especially in final states where one has two weakly-interacting LSPs
 531 on opposite sides of some potentially complicated decay tree. We will see how this is
 532 done in Ch. 7.

The Large Hadron Collider

535 The Large Hadron Collider (LHC) produces high-energy protons which are collided
 536 at the center of multiple large experiments at CERN on the outskirts of Geneva,
 537 Switzerland [85]. The LHC produces the highest energy collisions in the world,
 538 with design center-of-mass energy of $\sqrt{s} = 14$ TeV, which allows the experiments
 539 to investigate physics far beyond the reach of previous colliders. This chapter will
 540 summarize the basics of accelerator physics, especially with regards to discovering
 541 physics beyond the Standard Model. We will describe the CERN accelerator complex
 542 and the LHC.

543 **4.1 Basics of Accelerator Physics**

544 This section follows closely the presentation of [86].

Simple particle accelerators simply rely on the acceleration of charged particles in a static electric field. Given a field of strength E , charge q , and mass m , this is simply

$$a = \frac{qE}{m}. \quad (4.1)$$

545 For a given particle with a given mass and charge, this is limited by the static electric
 546 field which can be produced, which in turn is limited by electrical breakdown at high
 547 voltages.

548 There are two complementary solutions to this issue. First, we use the *radio*
 549 *frequency acceleration* technique. We call the devices used for this *RF cavities*. The

550 cavities produce a time-varied electric field, which oscillate such that the charged
 551 particles passing through it are accelerated towards the design energy of the RF
 552 cavity. This oscillation also induces the particles into *bunches*, since particles which
 553 are slightly off in energy from that induced by the RF cavity are accelerated towards
 554 the design energy.

Second, one bends the particles in a magnetic field, which allows them to pass through the same RF cavity over and over. This second process is often limited by *synchrotron radiation*, which describes the radiation produced when a charged particle is accelerated. The power radiated is

$$P \sim \frac{1}{r^2} \left(E/m \right)^4 \quad (4.2)$$

555 where r is the radius of curvature and E, m is the energy (mass) of the charged
 556 particle. Given an energy which can be produced by a given set of RF cavities (which
 557 is *not* limited by the mass of the particle), one then has two options to increase the
 558 actual collision energy : increase the radius of curvature or use a heavier particle.
 559 Practically speaking, the easiest options for particles in a collider are protons and
 560 electrons, since they are (obviously) copious in nature and do not decay¹. Given the
 561 dependence on mass, we can see why protons are used to reach the highest energies.
 562 The tradeoff for this is that protons are not point particles, and we thus we don't
 563 know the exact incoming four-vectors of the protons, as discussed in Ch.2.

The particle *beam* refers to the bunches all together. An important property of a beam of a particular energy E , moving in uniform magnetic field B , containing particles of momentum p is the *beam rigidity* :

$$R \equiv rB = p/c. \quad (4.3)$$

564 The linear relation between r and p , or alternatively B and p have important
 565 consequences for LHC physics. For hadron colliders, this is the limiting factor on

¹Muon colliders are a really cool option at high energies, since the relativistic γ factor gives them a relatively long lifetime in the lab frame.

566 going to higher energy scales; one needs a proportionally larger magnetic field to
567 keep the beam accelerating in a circle.

568 Besides the rigidity of the beam, the most important quantities to characterize
569 a beam are known as the (normalized) *emittance* ϵ_N and the *betatron function* β .
570 These quantities determine the transverse size σ of a relativistic beam $v \gtrsim c$ beam :
571 $\sigma^2 = \beta^* \epsilon_N / \gamma_{\text{rel}}$, where β^* is the value of the betatron function at the collision point
572 and γ_{rel} is the Lorentz factor.

These quantities determine the *instantaneous luminosity* L of a collider, which combined with the cross-section σ of a particular physics process, give the rate of this physics process :

$$R = L\sigma. \quad (4.4)$$

The instantaneous luminosity L is given by :

$$L = \frac{f_{\text{rev}} N_b^2 F}{4\pi\sigma^2} = \frac{f_{\text{rev}} n N_b^2 \gamma_{\text{rel}} F}{4\pi\beta^* \epsilon_N}. \quad (4.5)$$

573 Here we have introduced the frequency of revolutions f_{rev} , the number of bunches n ,
574 the number of protons per bunch N_b^2 , and a geometric factor F related to the crossing
575 angle of the beams.

The *integrated luminosity* $\int L$ gives the total number of a particular physics process P , with cross-section σ_P .

$$N_P = \sigma_P \int L. \quad (4.6)$$

576 Due to this simple relation, one can also quantify the “amount of data delivered” by
577 a collider simply by $\int L$.

578 4.2 Accelerator Complex

579 The Large Hadron Collider is the last accelerator in a chain of accelerators which
580 together form the CERN accelerator complex, which can be seen in 4.1. The protons



Figure 4.1: The CERN accelerator complex.

begin their journey to annihilation in a hydrogen source, where they are subsequently ionized. The first acceleration occurs in the Linac 2, a linear accelerator composed of RF cavities. The protons leave the Linac 2 at an energy of 50 MeV and enter the Proton Synchrotron Booster (PSB). The PSB contains four superimposed rings, which accelerate the protons to 1.4 GeV. The protons are then injected into the Proton Synchrotron (PS). This synchrotron increases the energy up to 25 GeV. After leaving the PS, the protons enter the Super Proton Synchrotron (SPS). This is the last step before entering the LHC ring, and the protons are accelerated to 450 GeV. From the SPS, the protons are injected into the beam pipes of the LHC. The process to fill the LHC rings with proton bunches from start to finish typically takes about four minutes.

592 **4.3 Large Hadron Collider**

The Large Hadron Collider is the final step in the CERN accelerator complex, and produces the collisions analyzed in this thesis. From the point of view of experimentalists on the general-purpose ATLAS and CMS experiments, the main goal of the LHC is to deliver collisions at the highest possible energy, with the highest possible instantaneous luminosity. The LHC was installed in the existing 27 km tunnel used by the Large Electron Positron (LEP) collider [87]. This allowed the existing accelerator complex at CERN, described in the previous section, to be used as the injection system to prepare the protons up to 450 GeV. Many aspects of the LHC design were decided by this very fact, and specified the options allowed to increase the energy or luminosity. In particular, the radius of the tunnel was already specified; from Eq.4.3, this implies the momentum (or energy) of the beam is entirely determined by the magnetic field. Given the 27 km circumference of the LEP tunnel, one can calculate the required magnetic field to reach the 7 TeV per proton design energy of the LHC :

$$r = C/2\pi = 4.3 \text{ km} \quad (4.7)$$

$$\rightarrow B = \frac{p}{rc} = 5 \text{ T} \quad (4.8)$$

593 In fact, the LHC consists of 8 528 m straight portions consisting of RF cavities, used
594 to accelerate the particles, and 8 circular portions which bend the protons around the
595 LHC ring. These circular portions actually have a slightly smaller radius of curvature
596 $r = 2804 \text{ m}$, and we require $B = 8.33 \text{ T}$. To produce this large field, we need to use
597 superconducting magnets, as discussed in the next section.

598 **Magnets**

599 There are many magnets used by the LHC machine, but the most important are the
600 1232 dipole magnets; a schematic is shown in Fig.4.2 and a photograph is shown in



CERN AC/DI/MM — 2001/06

Figure 4.2: Schematic of an LHC dipole magnet.

601 Fig.4.3.

602 The magnets are made of Niobium and Titanium. The maximum field strength is
 603 10 T when cooled to 1.9 Kelvin. The magnets are cooled by superfluid helium, which
 604 is supplied by a large cryogenic system. Due to heating between the eight helium
 605 refrigerators and the beampipe, the helium is cooled in the refrigerators to 1.8 K.

606 A failure in the cooling system can cause what is known as a *quench*. If the
 607 temperature goes above the critical superconducting temperature, the metal loses its
 608 superconducting properties, which leads to a large resistance in the metal. This leads
 609 to rapid temperature increases, and can cause extensive damages if not controlled.

610 The dipole magnets are 16.5 meters long with a diameter of 0.57 meters. There
 611 are two individual beam pipes inside each magnet, which allows the dipoles to house
 612 the beams travelling in both directions around the LHC ring. They curve slightly,
 613 at an angle of 5.1 mrad, which carefully matches the curvature of the ring. The

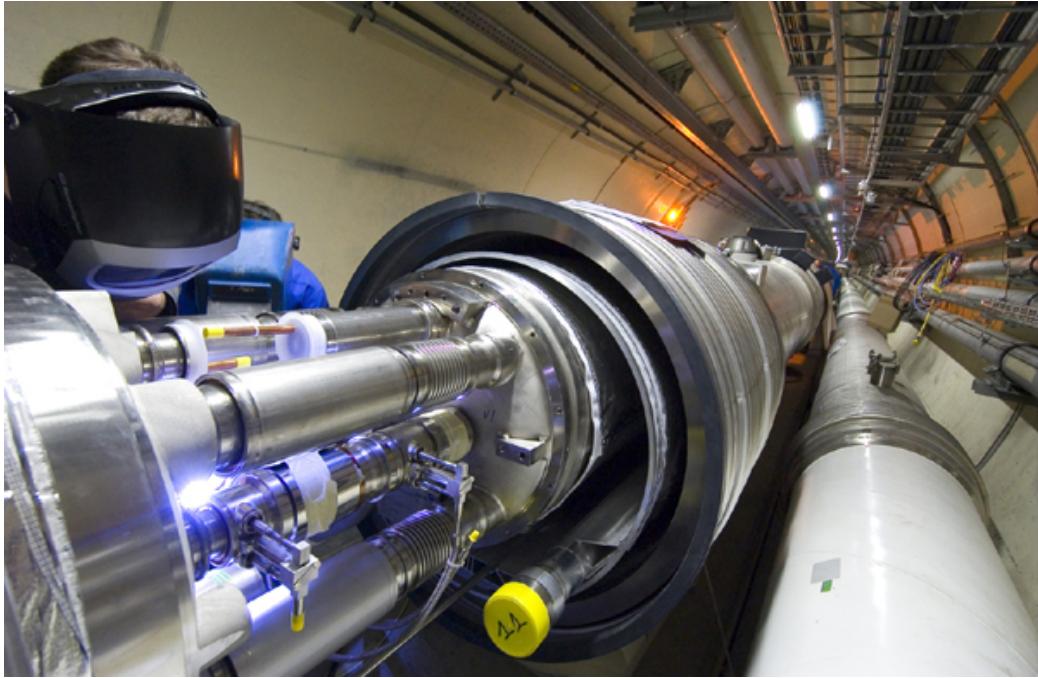


Figure 4.3: Photograph of a technician connecting an LHC dipole magnet.

614 beampipes inside of the magnets are held in high vacuum, to avoid stray particles
615 interacting with the beam.

616 **4.4 Dataset Delivered by the LHC**

617 In this thesis, we analyze the data delivered by the LHC to ATLAS in the 2015 and
618 2016 datasets. The beam parameters relevant to this dataset are available in Table
619 [4.1](#).

620 The peak instantaneous luminosity delivered in 2015 (2016) was $L =$
621 $5.2(11) \text{ cm}^{-2}\text{s}^{-1} \times 10^{33}$. One can note that the instantaneous luminosity delivered in
622 the 2016 dataset exceeds the design luminosity of the LHC. The total integrated
623 luminosity delivered was 13.3 fb^{-1} . In Figure [4.4](#), we display the integrated luminosity
624 as a function of day for 2015 and 2016.

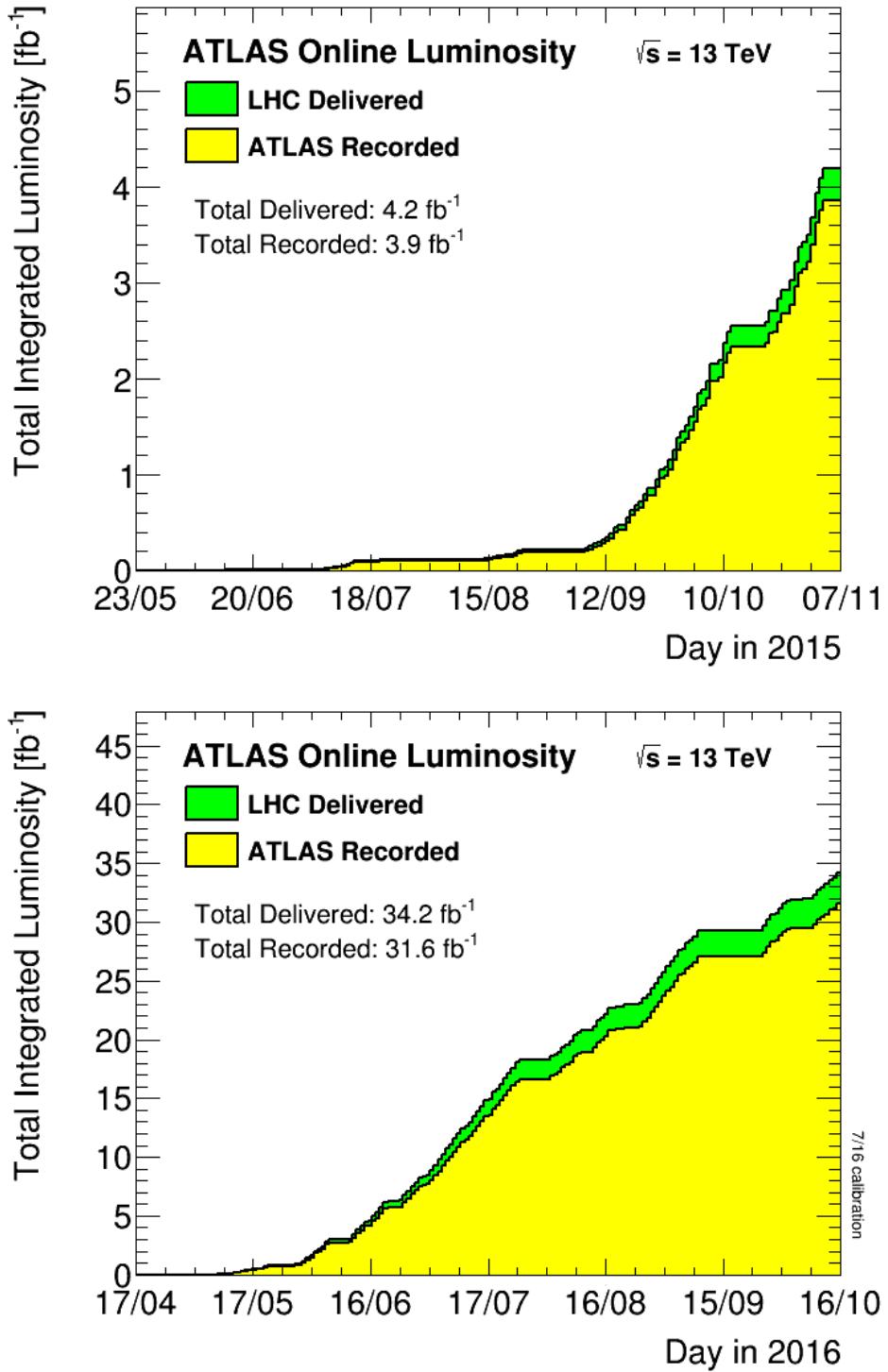


Figure 4.4: Integrated Luminosity delivered by the LHC and collected by ATLAS in the 2015 and 2016 datasets.

Parameter	Injection	Extraction
Energy (GeV)	450	7000
Rigidity (T-m)	3.8	23353
Bunch spacing (ns)	25	25
Design Luminosity ($\text{cm}^{-2}\text{s}^{-1} \times 10^3$)	-	1.0
Bunches per proton beam	2808	2808
Protons per bunch	1.15 e11	1.15 e11
Beam lifetime (hr)	-	10
Normalized Emittance ϵ_N (mm μrad)	3.3	3.75
Betatron function at collision point β^* (cm)	-	55

Table 4.1: Beam parameters of the Large Hadron Collider.

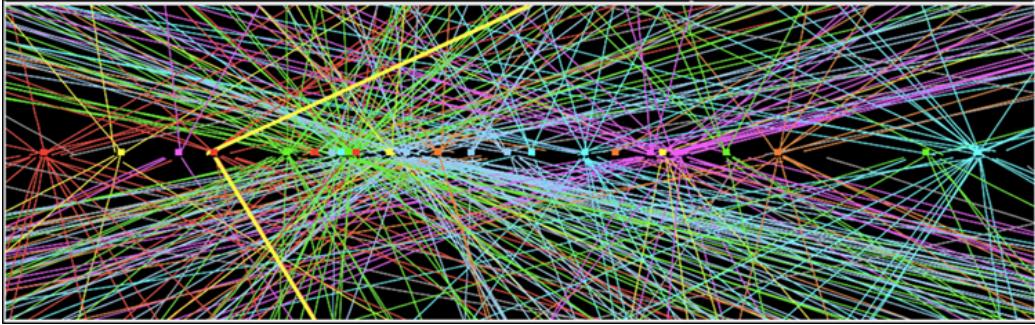


Figure 4.5: Simulated event with many pileup vertices.

625 Pileup

626 *Pileup* is the term for the additional proton-proton interactions which occur during
 627 each bunch crossing of the LHC. At the beginning of the LHC physics program, there
 628 had not been a collider which averaged more than a single interaction per bunch
 629 crossing. In the LHC, each bunch crossing (or *event*) generally contains multiple
 630 proton-proton interactions. An simulated event with many *vertices* can be seen in
 631 Fig.4.5. The so-called *primary vertex* (or *hard scatter vertex*) refers to the vertex
 632 which has the highest Σp_T^2 ; this summation occurs over the *tracks* in the detector,
 633 which we will describe later[**ATL-INDET-PUB-2009-001**]. We then distinguish
 634 between *in-time* pileup and *out-of-time* pileup. In-time pileup refers to the additional
 635 proton-proton interactions which occur in the event. Out-of-time pileup refers to
 636 effects related to proton-proton interactions previous bunch crossings.

637 We quantify in-time pileup by the number of “primary”² vertices in a particular
638 event. To quantify the out-of-time pileup, we use the average number of interactions
639 per bunch crossing $\langle \mu \rangle$ over some human-scale time. In Figure 4.6, we show the
640 distribution of μ for the dataset used in this thesis.

²The primary vertex is as defined above, but we unfortunately use the same name here.



Figure 4.6: Mean number of interactions per bunch crossing in the 2015 and 2016 datasets.

The ATLAS detector

643 The dataset analyzed in this thesis was taken by the ATLAS detector [88], which is
 644 located at the “Point 1” cavern of the LHC beampipe, just across the street from
 645 the main CERN campus. The much-maligned acronym stands for *A Toroidal LHC*
 646 *ApparatuS*. ATLAS is a massive cylindrical detector, with a radius of 12.5 m and a
 647 length of 44 m, with nearly hermitic coverage around the collision point. It consists
 648 of multiple subdetectors; each plays a role in ATLAS’s ultimate purpose of measuring
 649 the energy, momentum, and type of the particles produced in collisions delivered by
 650 the LHC. These subdetectors are immersed in a hybrid solenoid-toroid magnet system
 651 whichs forces charged particles to curve, which allows for precise measurements of
 652 their momenta. These magnetic fields are maximized in the central solenoid magnet,
 653 which contains a magnetic field of 2 T. A schematic of the detector can be seen in
 654 [5.1](#).

655 The *inner detector* (ID) lies closest to the collision point, and contains three
 656 separate subdetectors. It provides pseudorapidity¹coverage of $|\eta| < 2.5$ for charged
 657 particles to interact with the tracking material. The tracks reconstructed from the
 658 inner detector hits are used to reconstruct the primary vertices, as noted in Ch.??,

¹ATLAS uses a right-handed Cartesian coordinate system; the origin is defined by the nominal beam interaction point. The positive- z direction is defined by the incoming beam travelling counterclockwise around the LHC. The positive- x direction points towards the center of the LHC ring from the origin, and the positive- y direction points upwards towards the sky. For particles of transverse (in the $x - y$ plane) momentum $p_T = \sqrt{p_x^2 + p_y^2}$ and energy E , it is generally most convenient fully describe this particle’s kinematics as measured by the detector in the (p_T, ϕ, η, E) basis. The angle $\phi = \arctan(p_y/p_x)$ is the standard azimuthal angle, and $\eta = \ln \tan(\theta/2)$ is known as the pseudorapidity, and defined based on the standard polar angle $\theta = \arccos(p_z/p_T)$. For locations of i.e. detector elements, both (r, ϕ, η) and (z, ϕ, η) can be useful.



Figure 5.1: The ATLAS detector

and to determine the momemta of charged particles. The ATLAS *calorimeter* consists of two subdetectors, known as the *electromagnetic* and *hadronic* calorimeters. These detectors stop particles in their detector material, and measure the energy deposition inside, which measures the energy of the particles deposited. The calorimeters provide coverage out to pseudorapidity of $|\eta| < 4.9$. The muon spectrometer is aptly named; it is specifically used for muons, which are the only particles which generally reach the outer portions of the detector. In this region, we have the large tracking systems of the muon spectrometer, which provide precise measurements of muon momenta. The muon spectrometer has pseudorapidity coverage of $|\eta| < 2.7$.

5.1 Magnets

ATLAS contains multiple magnetic systems; primarily, we are concerned with the solenoid, used by the inner detector, and the toroids located outside of the ATLAS calorimeter. A schematic is shown in Fig.5.2. These magnetic fields are used to bend

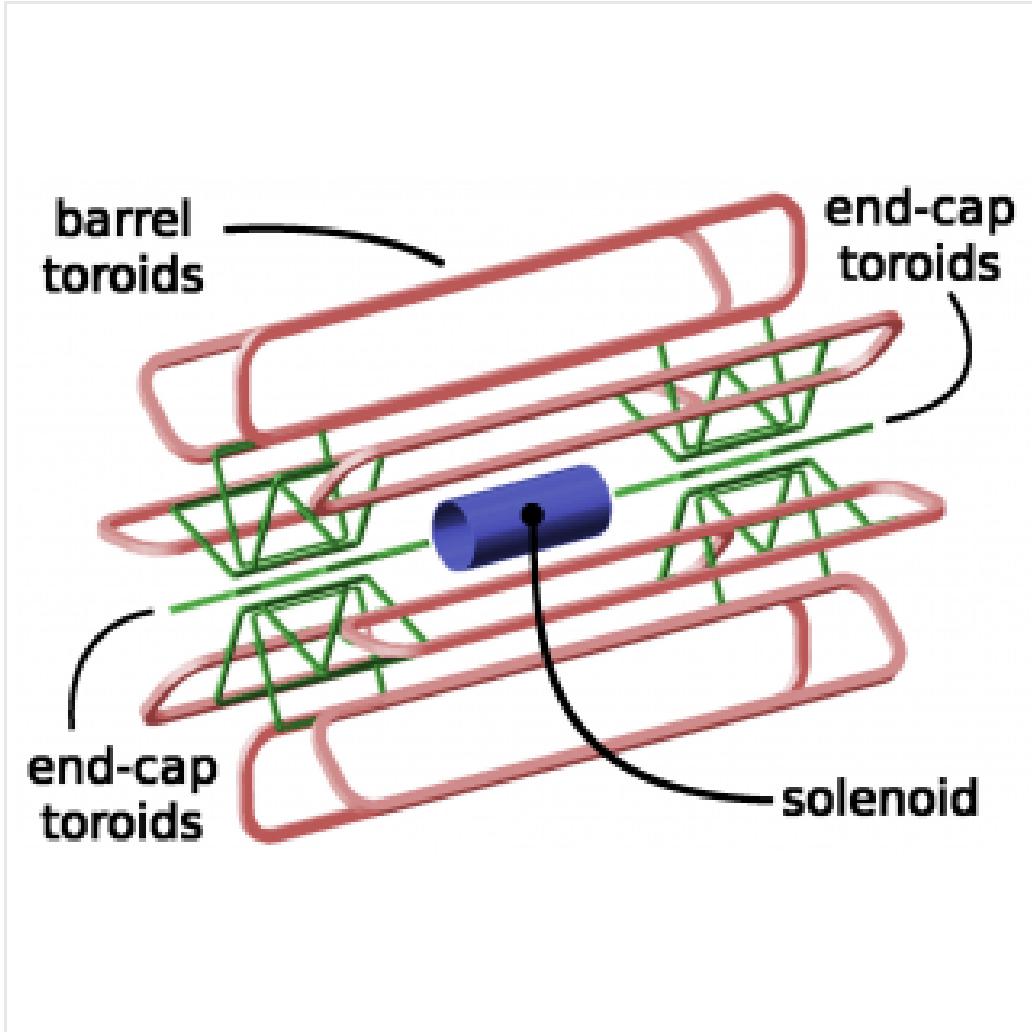


Figure 5.2: The ATLAS magnet system

672 charged particles under the Lorentz force, which subsequently allows one to measure
673 their momentum.

674 The ATLAS central solenoid is a 2.3 m diameter, 5.3 m long solenoid at the center
675 of the ATLAS detector. It produces a uniform magnetic field of 2 T; this strong field
676 is necessary to accurately measure the charged particles in this field. An important
677 design constraint for the central solenoid was the decision to place it in between the
678 inner detector and the calorimeters. To avoid excessive impacts on measurements in
679 the calorimetry, the central solenoid must be as transparent as possible².

²This is also one of the biggest functional differences between ATLAS and CMS; in CMS, the



Figure 5.3: The ATLAS inner detector

680 The toroid system consists of eight air-core superconducting barrel loops; these
 681 give ATLAS its distinctive shape. There are also two endcap air-core magnets. These
 682 produce a magnetic field in a region of approximately 26 m in length and 10 m of
 683 radius. The magnetic field in this region is non-uniform, due to the prohibitive costs
 684 of a solenoid magnet of that size.

685 **5.2 Inner Detector**

686 The ATLAS inner detector consists of three separate tracking detectors, which are
 687 known as, in order of increasing distance from the interaction point, the Pixel
 688 Detector, Semiconductor Tracker (SCT), and the Transition Radiation Tracker
 689 (TRT). When charged particles pass through these tracking layers, they produce
 690 *hits*, which using the known 2 T magnetic field, allows the reconstruction of *tracks*.
 691 Tracks are used as inputs for reconstruction of many higher-level physics objects,

solenoid is outside of the calorimeters.

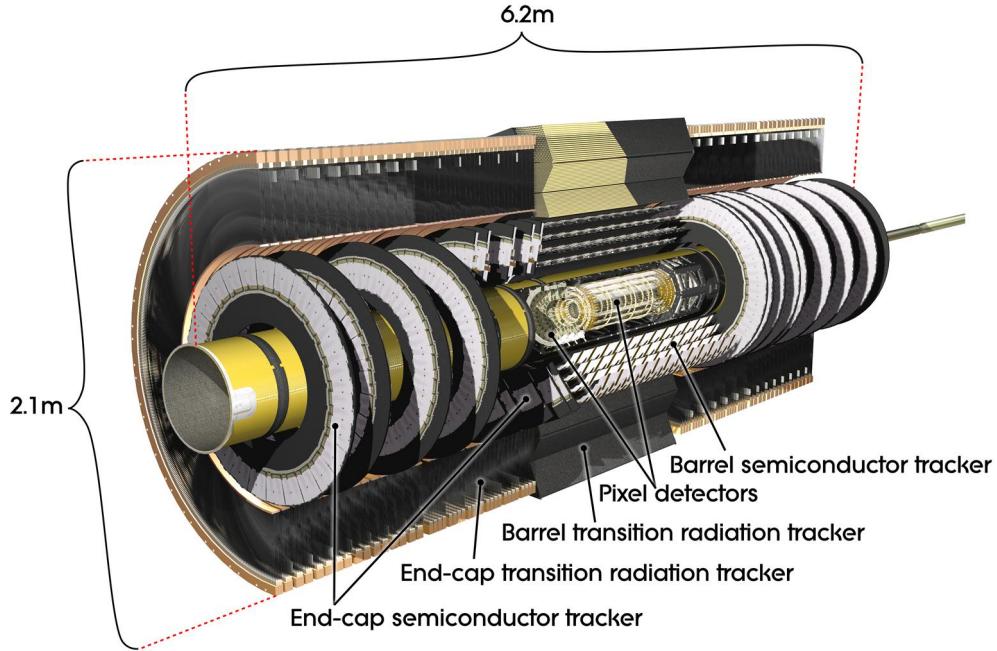


Figure 5.4: The ATLAS pixel detector

such as electrons, muons, photons, and E_T^{miss} . Accurate track reconstruction is thus crucial for precise measurements of charged particles.

Pixel Detector

The ATLAS pixel detector consists four layers of silicon “pixels”. This refers to the segmentation of the active medium into the pixels; compare to the succeeding silicon detectors, which will use silicon “strips”. This provides precise 3D hit locations. The layers are known as the “Insertable”³B-Layer (IBL), the B-Layer (or Layer-0), Layer-1, and Layer-2, in order of increasing distance from the interaction point. These layers are very close to the interaction point, and therefore experience a large amount of radiation.

Layer-1, Layer-2, and Layer-3 were installed with the initial construction of ATLAS. They contain front-end integrated electronics (FEI3s) bump-bonded to 1744

³Very often, the IBL is mistakenly called the Inner B-Layer, which would have been a much more sensible name.

704 silicon modules; each module is $250 \mu\text{m}$ in thickness and contains 47232 pixels. These
705 pixels have planar sizes of $50 \times 400 \mu\text{m}^2$ or $50 \times 600 \mu\text{m}^2$, to provide highly accurate
706 location information. The FEI3s are mounted on long rectangular structures known
707 as staves, which encircle the beam pipe. A small tilt to each stave allows full coverage
708 in ϕ even with readout systems which are installed. These layers are at radia of 50.5
709 mm, 88.5 mm, and 122.5 mm from the interaction point.

710 The IBL was added to ATLAS after Run1 in 2012 at a radius of 33 mm from the
711 interaction point. The entire pixel detector was removed from the center of ATLAS
712 to allow an additional pixel layer to be installed. The IBL was required to preserve
713 the integrity of the pixel detector as radiation damage leads to inoperative pixels in
714 the other layers. The IBL consists of 448 FEI4 chips, arranged onto 14 staves. Each
715 FEI4 has 26880 pixels, of planar size $50 \times 250 \mu\text{m}$. This smaller granularity was
716 required due to the smaller distance to the interaction point.

717 In total, a charged particle passing through the inner detector would expect to
718 leave four hits in the pixel detector.

719 Semiconductor Tracker

720 The SCT is directly beyond Layer-2 of the pixel detector. This is a silicon strip
721 detector, which do not provide the full 3D information of the pixel detector. The
722 dual-sensors of the SCT contain 2×768 individual strips; each strip has area 6.4 cm^2 .
723 The SCT dual-sensor is then double-layered, at a relative angle of 40 mrad;
724 together these layers provide the necessary 3D information for track reconstruction.
725 There are four of these double-layers, at radia of 284 mm, 355 mm, 427 mm, and 498
726 mm. These double-layers provide hits comparable to those of the pixel detector, and
727 we have four additional hits to reconstruct tracks for each charged particle.

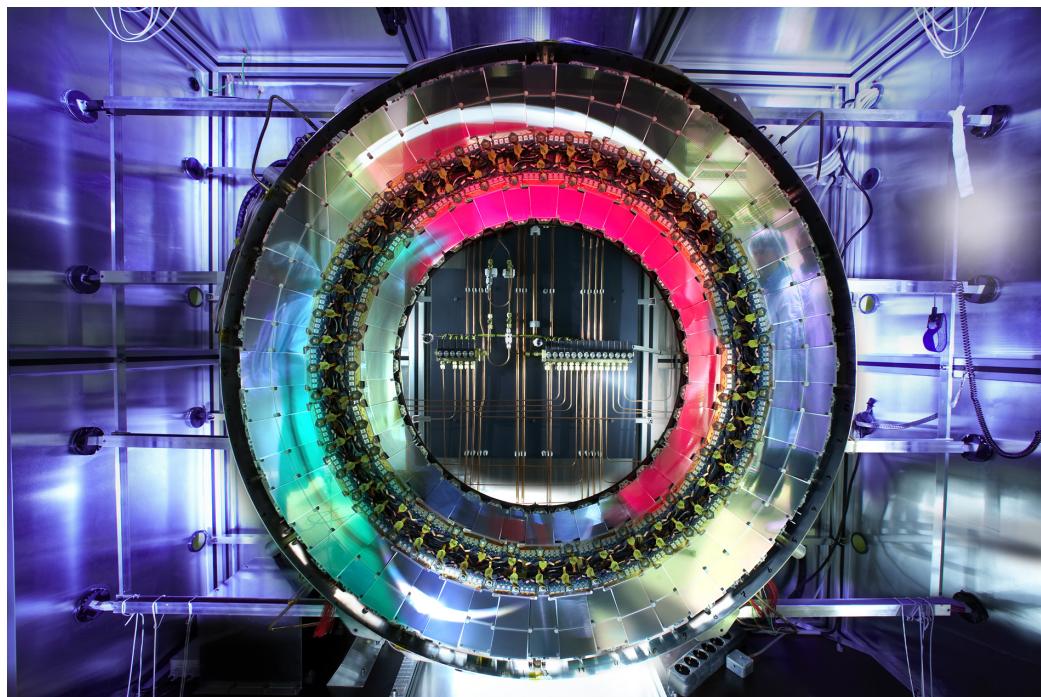


Figure 5.5: A ring of the Semiconductor Tracker

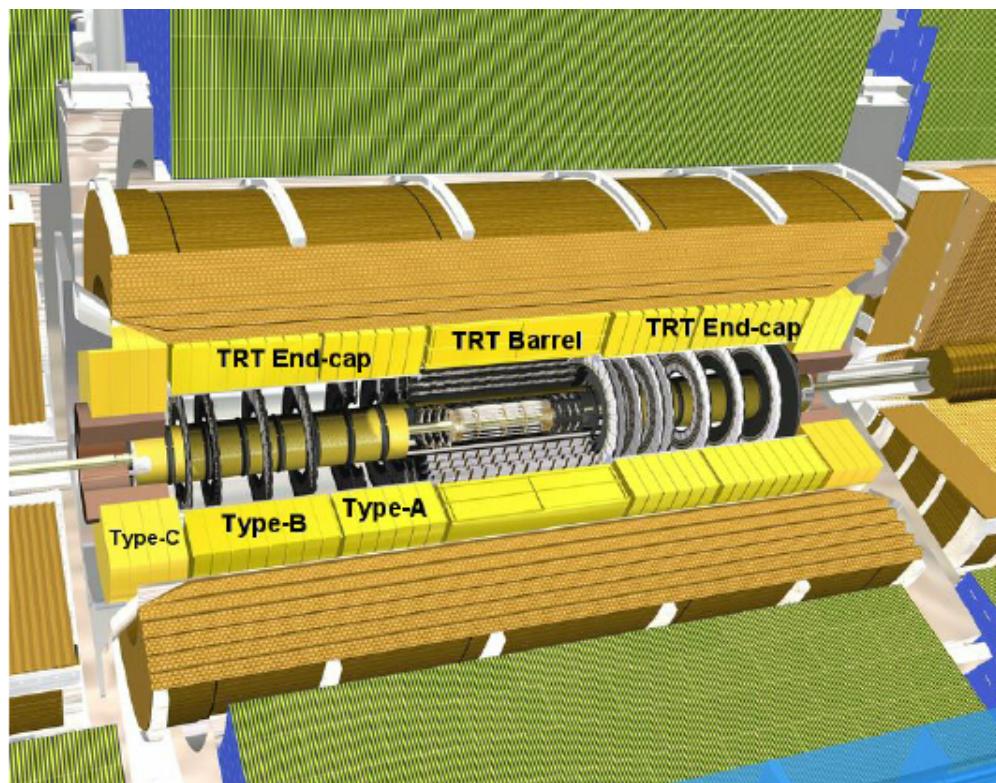


Figure 5.6: A schematic of the Transition Radiation Tracker

728 **Transition Radiation Tracker**

729 The Transition Radiation Tracker is the next detector radially outward from the SCT.
730 It contains straw drift tubes; these contain a tungsten gold-plated wire of $32 \mu\text{m}$
731 diameter held under high voltage (-1530 V) with the edge of the Kapton-aluminum
732 tube. They are filled with a gas mixture of primarily xenon that is ionized when
733 a charged particle passes through the tube. The ions are collected by the “drift”
734 due to the voltage inside the tubes, which is read out by the electronics. This gives
735 so-called “continuous tracking” throughout the tube, due to the large number of ions
736 produced.

737 The TRT is so-named due to the *transition radiation* (TR) it induces. Due to
738 the dielectric difference between the gas and tubes, TR is induced. This is important
739 for distinguishing electrons from their predominant background of minimum ionizing
740 particles. Generally, electrons have a much larger Lorentz factor than minimum
741 ionizing particles, which leads to additional TR. This can be used as an additional
742 handle for electron reconstruction.

743 **5.3 Calorimetry**

744 The calorimetry of the ATLAS detector also includes multiple subdetectors; these sub-
745 detectors allow precise measurements of the electrons, photons, and hadrons produced
746 by the ATLAS detector. Generically, calorimeters work by stopping particles in their
747 material, and measuring the energy deposition. This energy is deposited as a cascade
748 particles induce from interactions with the detector material known *showers*. ATLAS
749 uses *sampling* calorimeters; these alternate a dense absorbing material, which induces
750 showers, with an active layer which measures energy depositions by the induced
751 showers. Since some energy is deposited into the absorption layers as well, the energy
752 depositions must be properly calibrated for the detector.

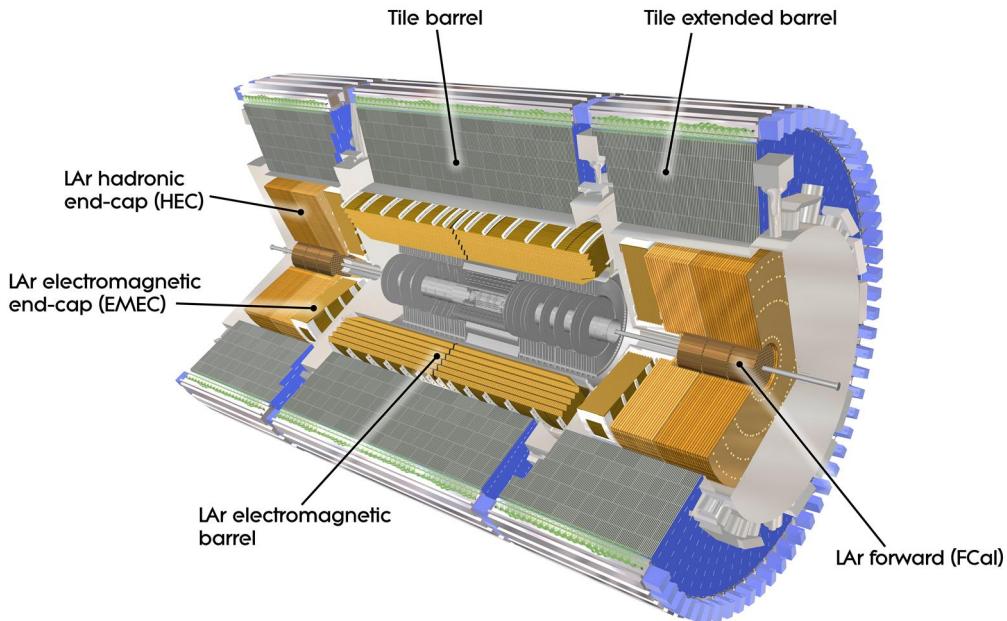


Figure 5.7: The ATLAS calorimeter

753 Electromagnetic objects (electrons and photons) and hadrons have much different
 754 interaction properties, and thus we need different calorimeters to accurately measure
 755 these different classes of objects; we can speak of the *electromagnetic* and *hadronic*
 756 calorimeters. ATLAS contains four separate calorimeters : the liquid argon (LAr)
 757 electromagnetic barrel calorimeter, the Tile barrel hadronic calorimeter, the LAr
 758 endcap electromagnetic calorimeter, the LAr endcap hadronic calorimeter, and the
 759 LAr Forward Calorimeter (FCal). Combined, these provide full coverage in ϕ up to
 760 $|\eta| < 4.9$, and can be seen in Fig.5.7.

761 **Electromagnetic Calorimeters**

762 The electromagnetic calorimeters of the ATLAS detector consist of the barrel and
 763 endcap LAr calorimeters. These are arranged into an ingenious “accordion” shape,
 764 shown in 5.8, which allows full coverage in ϕ and exceptional coverage in η while
 765 still allowing support structures for detector operation. The accordion is made of



Figure 5.8: A schematic of a subsection of the barrel LAr electromagnetic calorimeter

766 layers with liquid argon (active detection material) and lead (absorber) to induce
 767 electromagnetic showers. The LAr EM calorimeters are each more than 20 radiation
 768 lengths deep, which provides the high stopping power necessary to properly measure
 769 the electromagnetic showers.

770 The barrel component of the LAr EM calorimeter extends from the center of the
 771 detector out to $|\eta| < 1.475$. The calorimeter has a presampler, which measures the
 772 energy of any EM shower induced before the calorimeter. This has segmentation of
 773 $\Delta\eta = 0.025, \Delta\phi = .01$. There are three “standard” layers in the barrel, which have
 774 decreasing segmentation into calorimeter *cells* as one travels radially outward from
 775 the interaction point. The first layer has segmentation of $\Delta\eta = 0.003, \Delta\phi = .1$, and
 776 is quite thin relative to the other layers at only 4 radiation lengths deep. It provides
 777 precise η and ϕ measurements for incoming EM objects. The second layer is the
 778 deepest at 16 radiation lengths, with a segmentation of $\Delta\eta = 0.025, \Delta\phi = 0.025$. It



Figure 5.9: A schematic of Tile hadronic calorimeter

779 is primarily responsible for stopping the incoming EM particles, which dictates its
 780 large relative thickness, and measures most of the energy of the incoming particles.
 781 The third layer is only 2 radiation lengths deep, with a rough segmentation of $\Delta\eta =$
 782 0.05 , $\Delta\phi = .025$. The deposition in this layer is primarily used to distinguish hadrons
 783 interacting electromagnetically and entering the hadronic calorimeter from the strictly
 784 EM objects which are stopped in the second layer.

785 The barrel EM calorimeter has a similar overall structure, but extends from
 786 $1.4 < |\eta| < 3.2$. The segmentation in η is better in the endcap than the barrel;
 787 the ϕ segmentation is the same. In total, the EM calorimeters contain about 190000
 788 individual calorimeter cells.

789 Hadronic Calorimeters

790 The hadronic calorimetry of ATLAS sits directly outside the EM calorimetry. It
 791 contains three subdetectors : the barrel Tile calorimeter, the endcap LAr calorimeter,

792 and the Forward LAr Calorimeter. Similar to the EM calorimeters, these are
793 sampling calorimeters that alternate steel (dense material) with an active layer
794 (plastic scintillator).

795 The barrel Tile calorimeter extends out to $|\eta| < 1.7$. There are again three layers,
796 which combined give about 10 interactions length of distance, which provides excellent
797 stopping power for hadrons. This is critical to avoid excess *punchthrough* to the muon
798 spectrometer beyond the hadronic calorimeters. The first layer has a depth of 1.5
799 interaction lengths. The second layer is again the thickest at a depth of 4.1 interaction
800 lengths; most of the energy of incoming particle is deposited here. Both the first and
801 second layer have segmentation of about $\Delta\eta = 0.1, \Delta\phi = 0.1$. Generally, one does not
802 need as fine of granularity in the hadronic calorimeter, since the energy depositions
803 in the hadronic calorimeters will be summed into the composite objects we know as
804 jets. The third layer has a thickness of 1.8 interaction lengths, with a segmentation of
805 $\Delta\eta = 0.2, \Delta\phi = 0.1$. The use of multiple layers allows one to understand the induced
806 hadronic shower as it propagates through the detector material.

807 The endcap LAr hadronic calorimeter covers the region $1.5 < |\eta| < 3.2$. It is
808 again a sampling calorimeter; the active material is LAr with a copper absorbed. It
809 does not use the accordion shape of the other calorimeters; it has a “standard” flat
810 shape perpendicular to the interaction point. The segmentation varies with η . For
811 $1.5 < |\eta| < 2.5$, the cells are $\Delta\eta = 0.1, \Delta\phi = 0.1$; in the region $2.5 < |\eta| < 3.2$, the
812 cells are $\Delta\eta = 0.2, \Delta\phi = 0.2$ in size.

813 The final calorimeter in ATLAS is the forward LAr calorimeter. Of those
814 subdetectors which are used for standard reconstruction techniques, the FCal sits
815 at the most extreme values of $3.1 < |\eta| < 4.9$. The FCal itself is made of three
816 subdetectors; FCal1 is actually an electromagnetic module, while FCal2 and FCal3
817 are hadronic. The absorber in FCal1 is copper, with a liquid argon active medium.
818 FCal2 and FCal3 also use a liquid argon active medium, with a tungsten absorber.

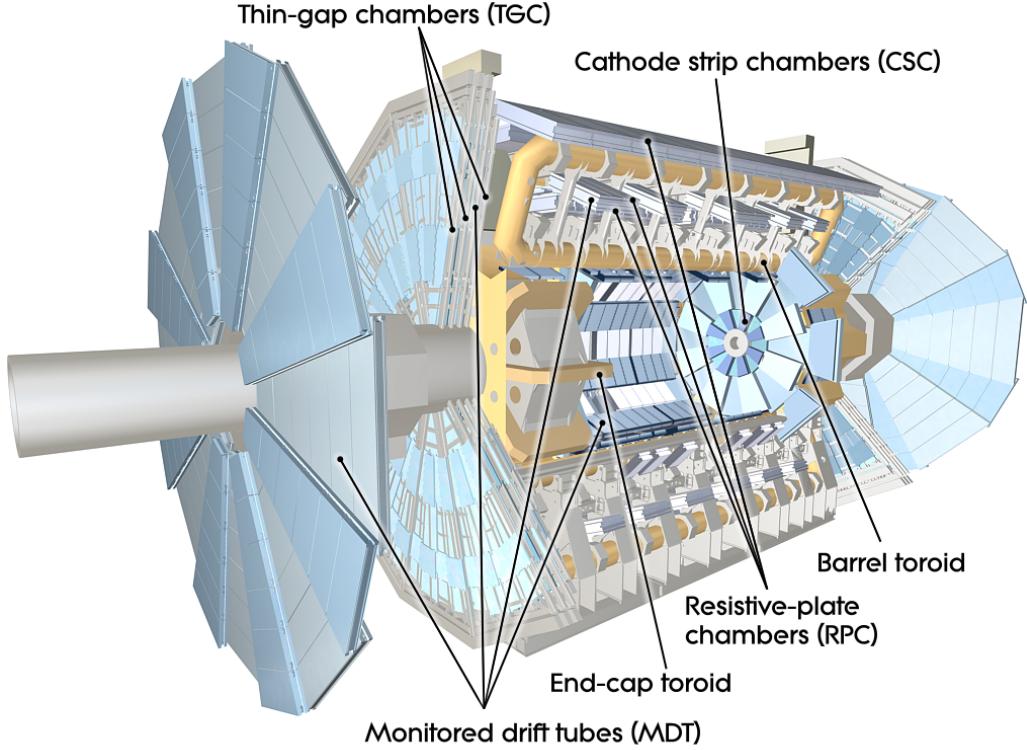


Figure 5.10: The ATLAS muon spectrometer

819 5.4 Muon Spectrometer

820 The muon spectrometer is the final major subdetector of the ATLAS detector.
 821 The muon spectrometer sits outside the hadronic calorimetry, with pseudorapidity
 822 coverage out to $|\eta| < 2.7$. The MS is a huge detector, with some detector elements
 823 existing as far as 11 m in radius from the interaction point. This system is used
 824 almost exclusively to measure the momenta of muons; these are the only measured
 825 SM particles which consistently exit the hadronic calorimeters. These systems provide
 826 a rough measurement, which is used in triggering (described in Ch.5.5), and a precise
 827 measurement to be used in offline event reconstruction as described in Ch.???. The
 828 MS produces tracks in a similar way to the ID; the hits in each subdetector are
 829 recorded and then tracks are produced from these hits. Muon spectrometer tracks are
 830 largely independent of the ID tracks due to the independent solenoidal and toroidal
 831 magnet systems used in the ID and MS respectively. The MS consists of four separate

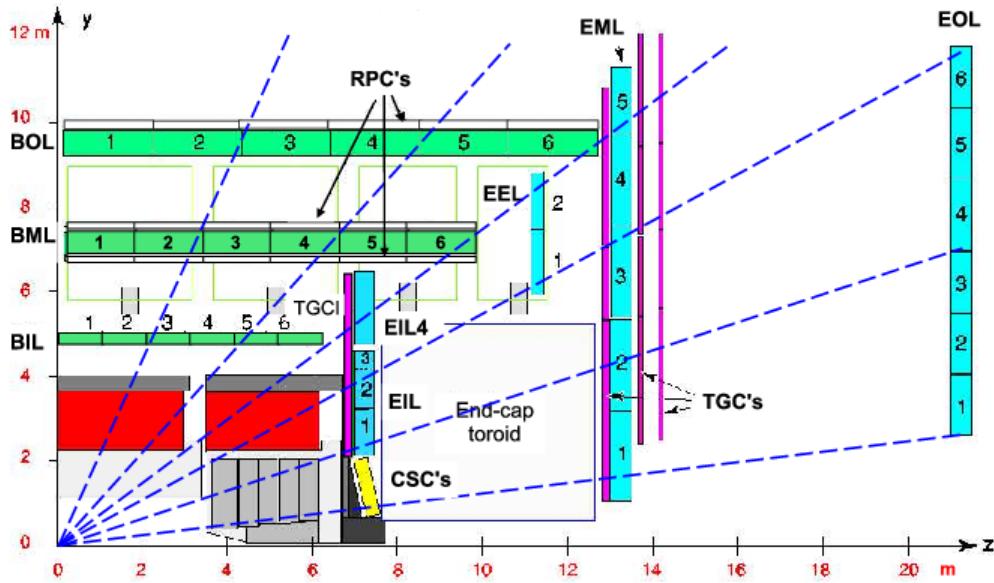


Figure 5.11: A schematic in z/η showing the location of the subdetectors of the muon spectrometer

832 subdetectors: the barrel region is covered by the Resistive Plate Chambers (RPCs)
 833 and Monitored Drift Tubes (MDTs) while the endcaps are covered by MDTs, Thin
 834 Gap Chambers (TGCs), and Cathode Strip Chambers (CSCs).

835 Monitored Drift Tubes

836 The MDT system is the largest individual subdetector of the MS. MDTs provide
 837 precision measurements of muon momenta as well as fast measurements used for
 838 triggers. There are 1088 MDT chambers providing coverage out to pseudorapidity
 839 $|\eta| < 2.7$; each consists of an aluminum tube containing an argon- CO_2 gas mixture.
 840 In the center of each tube there $50\mu\text{m}$ diameter tungsten-rhenium wire at a voltage of
 841 3080 V. A muon entering the tube will induce ionization in the gas, which will “drift”
 842 towards the wire due to the voltage. One measures this ionization as a current in the
 843 wire; this current comes with a time measurement related to how long it takes the
 844 ionization to drift to the wire.

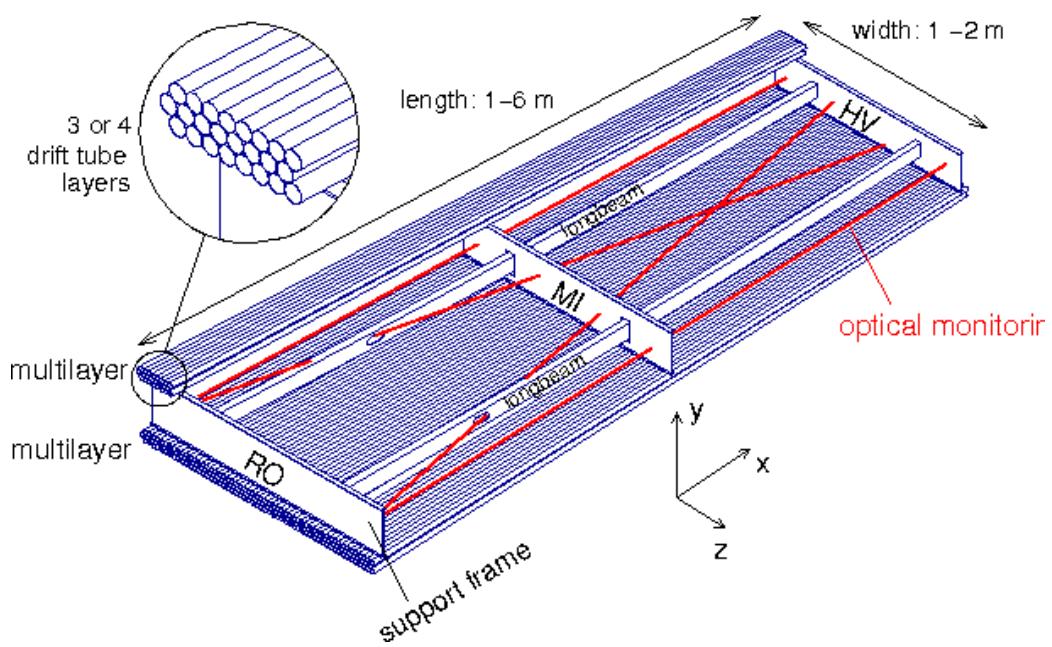


Figure 5.12: Schematic of a Muon Drift Tube chamber

845 These tubes are layered in a pattern shown in Fig.5.12. Combining the measure-
846 ments from the tubes in each layer gives good position resolution. The system consists
847 of three subsystems of these layers, at 5 m, 7m, and 9 m from the interaction point.
848 The innermost layer is directly outside the hadronic calorimeter. The combination of
849 these three measurements gives precise momenta measurements for muons.

850 Resistive Plate Chambers

851 The RPC system is alternated with the MDT system in the barrel; the first two layers
852 of RPC detectors surround the second MDT layer while the third is outside the final
853 MDT layer. The RPC system covers pseudorapidity $|\eta| < 1.05$. Each RPC consists
854 of two parallel plates at a distance of 2 mm surrounding a $\text{C}_2\text{H}_2\text{F}_4$ mixture. The
855 electric field between these plates is 4.9k kV/mm. Just as in the MDTs, an incoming
856 muon ionizes the gas, and the deposited ionization is collected by the detector (in this
857 case on the plates). It is quite fast, but with a relatively poor spatial resolution of
858 1 cm. Still, it can provide reasonable ϕ resolution due to its large distance from the
859 interaction point. This is most useful in triggering, where the timing requirements are
860 quite severe. The RPCs are also complement the MDTs by providing a measurement
861 of the non-bending coordinate.

862 Cathode Strip Chambers

863 The CSCs are used in place of MDTs in the first layer of the endcaps. This region, at
864 $2.0 < |\eta| < 2.7$, has higher particle multiplicity at the close distance to the interaction
865 point from low-energy photons and neutrons. The MDTs were not equip to deal with
866 the higher particle rate of this region, so the CSCs were designed to deal with this
867 deficiency.

868 Each CSC consists multiwire proportional chambers, oriented radially outward
869 from the interaction point. These chambers overlap partially in ϕ . The wires contain



Figure 5.13: Photo of the installation of Cathode Strip Chambers and Monitored Drift Tubes

870 a gas mixture of argon and CO₂, which is ionized when muons enter. The detectors
871 operate with a voltage of 1900 V, with much lower drift times than the MDTs. They
872 provide less hits than MDTs, but their lower drift times lower uptime and reduce the
873 amount of detector overload.

874 The CSCs are arranged into four planes on the wheels of the muon spectrometer,
875 as seen in Fig.???. There are 32 CSCs in total, with 16 on each side of the detector
876 in η .

877 Thin Gap Chambers

878 The TGCs serve the purpose of the RPCs in the endcap at pseudorapidity of $1.05 <$
879 $|\eta| < 2.4$; they provide fast measurements used in triggering. The TGCs are also
880 multiwire proportional chambers a la the CSCs. The fast readouts necessary for
881 trigger are provided by a high electric field and a small wire-to-wire distance of 1.8
882 mm. These detectors provide both η and ϕ information, allowing the trigger to use
883 as much information as possible when selecting events.



Figure 5.14: Photo of a muon Big Wheel, consisting of Thin Gap Chambers

884 5.5 Trigger System

885 The data rate delivered by the LHC is staggering [89]. In the 2016 dataset, the
886 collision rate was 40 MHz, meaning a *bunch spacing* of 25 ns. In each of the event,
887 as we saw in Ch.??, there are many proton-proton collisions. Most of the collisions
888 are uninteresting, such as elastic scattering of protons, or even inelastic scattering
889 leading to low-energy dijet events. These types of events have been studied in detail
890 in previous experiments.

891 Even if one is genuinely interested in these events, it's *impossible* to save all of
892 the information available in each event. If all events were written "to tape" (as the
893 jargon goes), ATLAS would store terabytes of data per second. We are limited to only
894 about 1000 Hz readout by computing processing time and storage space. We thus
895 implement a *trigger* which provides fast inspection of events to drastically reduce
896 the data rate from the 40 MHz provided by the LHC to the 1000 Hz we can write to
897 tape for further analysis.

898 The ATLAS trigger system consists of a two-level trigger, known as the Level-
899 1 trigger (L1 trigger) and the High-Level Trigger (HLT)⁴. Trigger selections are
900 organized into *trigger chains*, where events passing a particular L1 trigger are passed
901 to a corresponding HLT trigger. For example, one would require a particular high- p_T
902 muon at L1, with additional quality requirements at HLT. One can also use HLT
903 triggers as prerequisites for each other, as is done in some triggers requiring both jets
904 and E_T^{miss} .

905 **Level-1 Trigger**

906 The L1 trigger is hardware-based, and provides the very fast rejection needed to
907 quickly select events of interest. The L1 trigger uses only what is known as *prompt*
908 data to quickly identify interesting events. Only the calorimeters and the triggering
909 detectors (RPCs and TGCs) of the MS are fast enough to be considered at L1,
910 since the tracking reconstruction algorithms used by the ID and the more precise
911 MS detectors are very slow. This allows quick identification of events with the
912 most interesting physical objects : large missing transverse momentum and high-
913 p_T electrons, muons, and jets.

914 L1 trigger processing is done locally. This means that events are selected without
915 considering the entire available event. Energy deposits over some threshold are
916 reconstructed as *regions of interest*. These RoIs are then compared using pattern
917 recognition hardware to “expected” patterns for the given RoIs. Events with RoIs
918 matching these expected patterns are then handed to the HLT through the Central
919 Trigger Processor. This step alone lowers the data rate down by about three orders
920 of magnitude.

⁴In Run1, ATLAS ran with a three-level trigger system. The L1 was essentially as today; the HLT consisted of two separate systems known as the L2 trigger and the Event Filter (EF). This was changed to the simpler system used today during the shutdown between Run1 and Run2.

921 **High-Level Trigger**

922 The HLT performs the next step, taking the incoming data rate from the L1 trigger
923 of ~ 75 kHz down to the ~ 1 kHz that can be written to tape. The HLT really
924 performs much like a simplified offline reconstruction, using many common quality
925 and analysis cuts to eliminate uninteresting events. This is done by using computing
926 farms located close to the detector, which process events in parallel. Individually, each
927 event which enters the computing farms takes about 4 seconds to reconstruct; the
928 HLT reconstruction time also has a long tail, which necessitates careful monitoring
929 of the HLT to ensure smooth operation.

930 HLT triggers are targetted to a particular physics process, such as a E_T^{miss} trigger,
931 single muon trigger, or multijet trigger. The collection of all triggers is known as
932 the trigger *menu*. Since many low-energy particles are produced in collisions, it is
933 necessary to set a *trigger threshold* on the object of interest; this is really just a fancy
934 naming for a trigger p_T cut. Due to the changing luminosity conditions of the LHC,
935 these thresholds change constantly, mostly by increasing thresholds with increasing
936 instantaneous luminosity. This allows an approximately constant number of events to be
937 written for further analysis. Triggers which have rates higher than those designated
938 by the menu are *prescaled*. This means writing only some fraction of the triggered
939 events. Of course, for physics analyses, one wishes to investigate all data events
940 passing some set of analysis cuts, so often one uses the “lowest threshold unprescaled
941 trigger”. *Turn-on curves* allow one to select the needed offline analysis cut to ensure
942 the trigger is fully efficient. An example turn-on curve for the E_T^{miss} triggers used in
943 the signal region of this analysis is shown in ??.

944 The full set of the lowest threshold unprescaled triggers considered here can be
945 found in Table 5.1. These are the lowest unprescaled triggers associated to the SUSY
946 signal models and Standard Model backgrounds considered in this thesis. More
947 information can be found in [89].

Physics Object	Trigger	p_T (GeV)	Threshold	Level-1 Seed	Additional Requirements	Approximate Rate (Hz)
2015 Data						
E_T^{miss}	HLT_xe70	70	L1_XE50	-	60	
Muon	HLT_mu24_iloose_L1MU15	50	L1_MU15	isolated, loose	130	
Muon	HLT_mu50	50	L1_MU15	-	30	
Electron	HLT_e24_1hmedium_ll2base_L1EM20VH		L1_EM20VH	medium OR isolated, loose	140	
Electron	HLT_e60_1hmedium	60	L1_EM20VH	medium	10	
Electron	HLT_e120_1hloose	120	L1_EM20VH	loose	<10	
Photon	HLT_g120_loose	120	L1_EM20VH	loose	20	
2016 Data						
E_T^{miss}	HLT_xe100_mht_L1XE5000		L1_XE50	-	180	
Muon	HLT_mu24_ivarmedium4	50	L1_MU20	medium	120	
Muon	HLT_mu50	50	L1_MU20	-	40	
Electron	HLT_e24_1htight_noD1ivarloose		L1_EM22VHI	tight with no d_0 or loose	110	
Electron	HLT_e60_1hmedium_nd60		L1_EM22VHI	medium with no d_0	10	
Electron	HLT_e140_1hloose_noD0		L1_EM22VHI	loose with no d_0	<10	
Photon	HLT_g140_loose	140	L1_EM22VHI	loose	20	

Table 5.1: High-Level Triggers used in this thesis. Descriptions of loose, medium, tight, and isolated can be found in [89]. The d_0 cut refers to a quality cut on the vertex position; this was removed from many triggers in 2016 to increase sensitivity to displaced vertex signals. For most triggers, the increased thresholds in 2016 compared to 2016 were designed to keep the rate approximately equal. The exception is the E_T^{miss} triggers; see 5.5.

948 **Razor Triggers**

949 For the analysis presented in this thesis, the *razor triggers* were developed. These are
950 topological triggers, combining both jet and E_T^{miss} information to select interesting
951 events. In particular, they use the razor variable M_{Δ}^R which will be described in
952 Chapter ??.

953 Based on 2015 run conditions, these triggers would have allowed the use of a lower
954 offline E_T^{miss} cut with a similar rate to the nominal E_T^{miss} triggers. This can be seen
955 in the turn-on curves shown in Figure 5.15. The razor triggers are fully efficient at
956 nearly 100 GeV lower than the corresponding E_T^{miss} triggers in M_{Δ}^R .

957 There was a quite big change in the 2016 menu, which increased the rate given to
958 E_T^{miss} triggers drastically. This can be seen in the difference in rate shown between
959 E_T^{miss} triggers in 2015 and 2016 in Table 5.1. This allowed the E_T^{miss} triggers to
960 maintain a lower threshold throughout the dataset used in this thesis.

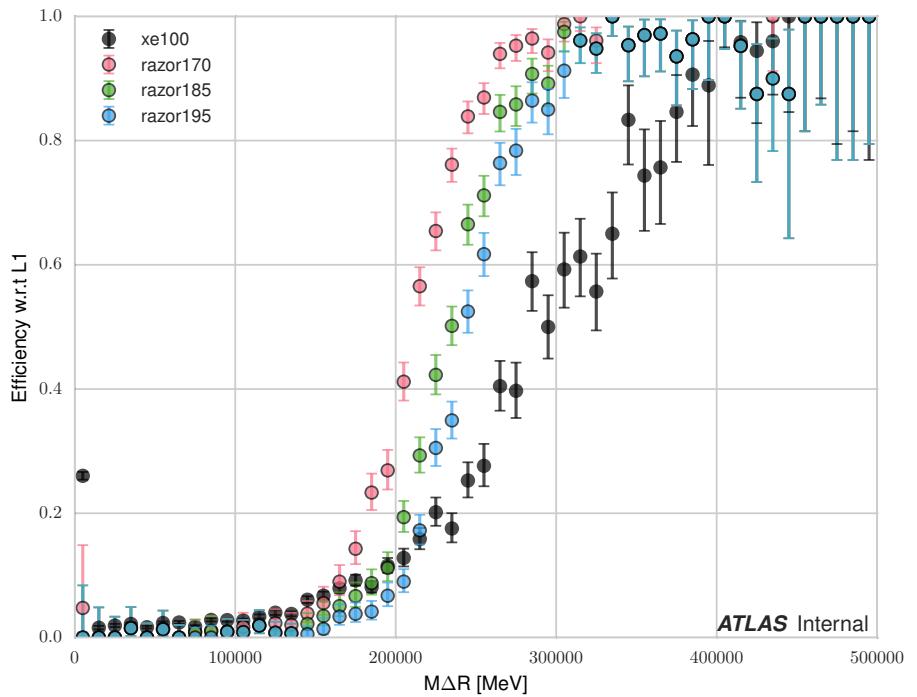
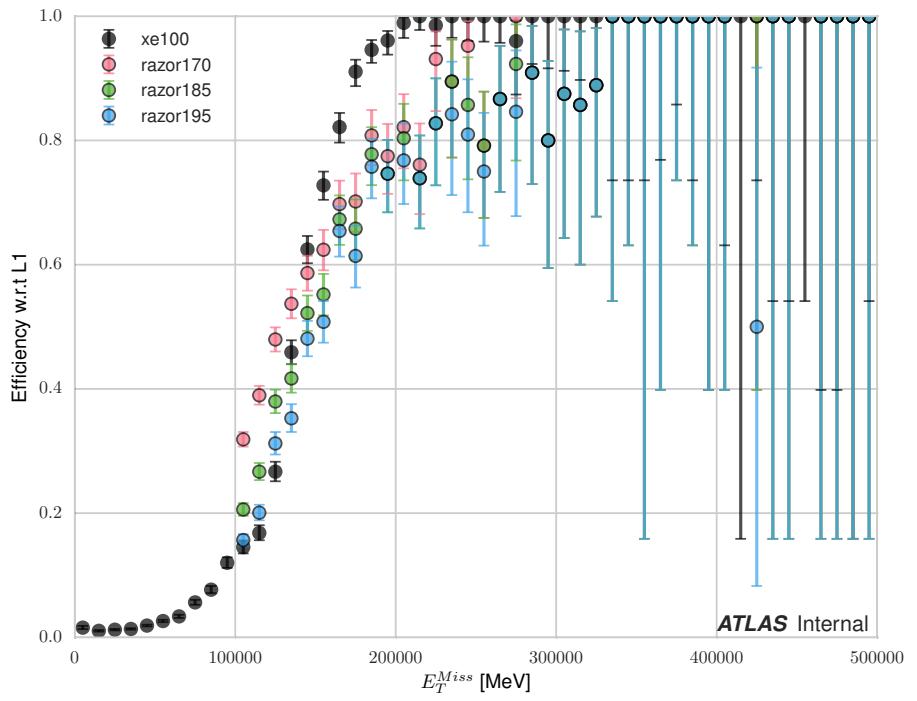


Figure 5.15: Turn-on curves for the razor triggers and nominal E_T^{miss} trigger. The razor triggers show a much sharper turn-on in M_D^R relative to the E_T^{miss} trigger. The converse is true for the E_T^{miss} triggers.

961

Chapter 6

962

Object Reconstruction

963 This chapter describes the reconstruction algorithms used within ATLAS. We will
964 make the distinction between the “primitive” objects which are reconstructed from
965 the detector signals from the “composite” physics objects we use in measurements
966 and searches for new physics.

967 **6.1 Primitive Object Reconstruction**

968 The primitive objects reconstructed by ATLAS are *tracks* and (calorimeter) *clusters*.
969 These are reconstructed directly from tracking hits and calorimeter energy deposits
970 into cells. Tracks can be further divided into inner detector and muon spectrom-
971 eter tracks. Calorimeter clusters can be divided into sliding-window clusters and
972 topological clusters (topoclusters).

973 **Inner Detector Tracks**

974 Inner detector tracks are reconstructed from hits in the inner detector [90, 91] These
975 hits indicate that a charged particle has passed through the detector material. Due
976 to the 2 T solenoid in the inner detector, the hits associated with any individual
977 particle will be curved. The amount of curvature determines the momentum of the
978 particle. In any given event, there are upwards of 10^4 hits, making it impossible to do
979 any sort of combinatorics to reconstruct tracks. There are two algorithms used by
980 ATLAS track reconstruction, known as *inside-out* and *outside-in*.

981 ATLAS first employs the inside-out algorithm. One assumes the track begins
982 at the interaction point. Moving out from the interaction point, one creates track
983 seeds. Track seeds are proto-tracks constructed from three hits. These hits can be
984 distributed as three pixel hits, two pixel hits and one SCT hit, or three SCT hits.
985 One extrapolates the track and uses a combinatorial Kalman filter[90], which adds
986 the rest of the pixel and SCT hits to the seeds. This is done seed by seed, so it
987 avoids the combinatorial complexity involved with checking all hits with all seeds.
988 At this point, the algorithm applies an additional filter to avoid ambiguities from
989 nearby tracks. The TRT hits are added to the seeds using the same method. After
990 this procedure, all hits are associated to a track.

991 The next step is to figure out the correct kinematics of the track. This is
992 done by applying a fitting algorithm which outputs the best-fit track parameters
993 by minimizing the track distance from hits, weighted by each hit's resolution. These
994 parameters are $(d_0, z_0, \eta, \phi, q/p)$ where d_0 (z_0) is the transverse (longitudinal) impact
995 parameter and q/p is the charge over the track momenta. This set of parameters
996 uniquely defines the measurement of the trajectory of the charged particle associated
997 to the track. An illustration of a track with these parameters is shown in Fig.6.1.

998 The other track reconstruction algorithm is the outside-in algorithm. As the
999 name implies, we start from the outside of the inner detector, in the TRT, and
1000 extend the tracks in toward the interaction point. One begins by seeding from
1001 TRT hits, and extending the track back towards the center of the detector. The
1002 same fitting procedure is used as in the inside-out algorithm to find the optimal
1003 track parameters. This algorithm is particularly important for finding tracks which
1004 originate from interactions with the detector material, especially the SCT. For tracks
1005 from primary vertices, this often finds the same tracks as the inside-out algorithm,
1006 providing an important check on the consistency of the tracking procedure.

1007 In the high luminosity environment of the LHC, even the tracks reconstructed

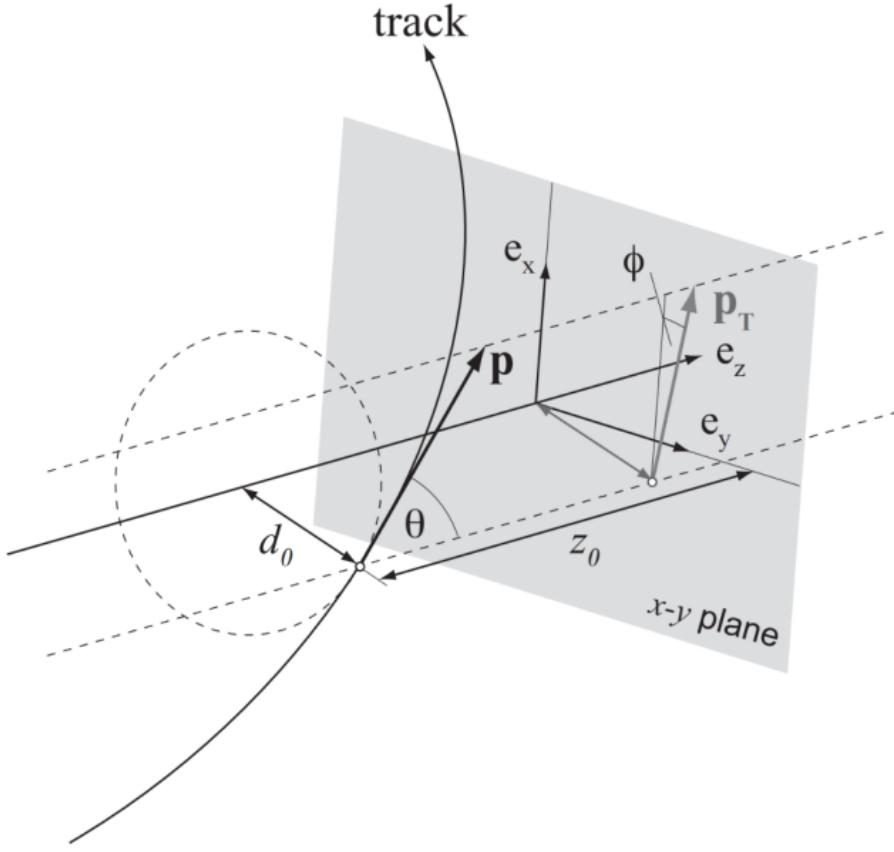


Figure 6.1: The parameters associated to a track.

from precision detectors such as those of ATLAS inner detector can sometimes lead to fake tracks from simple combinatoric chance. Several quality checks are imposed after track fitting which reduce this background. Seven silicon (pixel + SCT) hits are required for all tracks. No more than two *holes* are allowed in the pixel detector. Holes are expected measurements from the track that are missing in the pixel detector. Finally, tracks with poor fit quality, as measured by χ^2/ndf , are also rejected. Due to the high quality of the silicon measurements in the pixel detector and SCT, these requirements give good track reconstruction efficiency, as seen in Fig.6.2 for simulated events[92].



(a) Track reconstruction as a function of p_T . (b) Track reconstruction as a function of η .

Figure 6.2: Track reconstruction efficiency as a function of track p_T and η . The efficiency is defined as the number of reconstructed tracks divided by the number of generate charged particles.

1017 Sliding-window clusters

1018 The sliding-window algorithm is a way to combine calorimeter cells into composite
 1019 objects (clusters) to be used as inputs for other algorithms[93]. Sliding-window
 1020 clusters are the primary inputs to electron and photon reconstruction, as described
 1021 below. The electromagnetic calorimeter has high granularity, with a cell size of
 1022 $(\eta, \phi) = (.025, .025)$ in the coarsest second layer throughout most of the calorimeter.
 1023 The “window” consists of 3 by 5 cells in the (η, ϕ) space. All layers are added on
 1024 this same 2D space. One translates this window over the space and seeds a cluster
 1025 whenever the energy sum of the cells is maximized. If the seed energy is greater
 1026 than 2.5 GeV, this seed is called a sliding-window cluster. This choice was motivated
 1027 to optimize the reconstruction efficiency of proto-electrons and proto-photons while
 1028 rejecting fakes from electronic noise and additional particles from pileup vertices.

1029 Topological clusters

1030 Topoclusters are the output of the algorithm used within ATLAS to combine
1031 hadronic and electromagnetic calorimeter cells in a way which extracts signal from
1032 a background of significant electronic noise[94]. They are the primary input to the
1033 algorithms which reconstruct jets.

1034 Topological clusters are reconstructed from calorimeter cells in the following way.
1035 First, one maps all cells onto a single $\eta - \phi$ plane so one can speak of *neighboring*
1036 cells. Two cells are considered neighboring if they are in the same layer and directly
1037 adjacent, or if they are in adjacent layers and overlap in $\eta - \phi$ space. The *significance*
1038 ξ_{cell} of a cell during a given event is

$$\xi_{\text{cell}} = \frac{E_{\text{cell}}}{\sigma_{\text{noise},\text{cell}}} \quad (6.1)$$

1039 where $\sigma_{\text{noise},\text{cell}}$ is measured for each cell in ATLAS and E_{cell} measures the current
1040 energy level of the cell. One thinks of this as the measurement of the energy *over*
1041 *threshold* for the cell.

1042 Topocluster *seeds* are defined as calorimeter cells which have a significance $\xi_{\text{cell}} >$
1043 4. These are the inputs to the algorithm. One iteratively tests all cells adjacent
1044 to these seeds for $\xi_{\text{cell}} > 2$. Each cells passing this selection is then added to the
1045 topocluster, and the procedure is repeated. When the algorithm reaches the point
1046 where there are no additional adjacent cells with $\xi_{\text{cell}} > 2$, every positive-energy cell
1047 adjacent to the current proto-cluster is added. The collection of summed cells is a
1048 topocluster. An example of this procedure for a simulation dijet event is shown in
1049 Fig.6.3.

1050 There are two calibrations used for clusters[95]. These are known as the
1051 electromagnetic (EM) scale and the local cluster weighting (LCW) scale. The EM
1052 scale is the energy read directly out of the calorimeters as described. This scale
1053 is appropriate for electromagnetic processes. The LCW scale applies additional



Figure 6.3: Example of topoclustering on a simulated dijet event.

1054 scaling to the clusters based on the shower development. The cluster energy can be
1055 corrected for calorimeter non-compensation and the differences in the hadronic and
1056 electromagnetic calorimeters’ responses. This scale provides additional corrections
1057 that improve the accuracy of hadronic energy measurements. This thesis only uses
1058 the EM scale corrections. LCW scaling requires additional measurements that only
1059 became available with additional data. Due to the jet calibration procedure that
1060 we will describe below, it is also a relatively complicated procedure to rederive the
1061 “correct” jet energy.

1062 Muon Spectrometer Tracks

1063 Muon spectrometer tracks are fit using the same algorithms as the ID tracks, but
1064 different subdetectors. The tracks are seeded by hits in the MDTs or CSCs. After
1065 seeding in the MDTs and CSCs, the hits from all subsystems are refit as the final
1066 MS track. These tracks are used as inputs to the muon reconstruction, as we will see
1067 below.

1068 6.2 Physics Object Reconstruction and Quality

1069 Identification

1070 There are essentially six objects used in ATLAS searches for new physics: electrons,
1071 photons, muons, τ -jets, jets, and E_T^{miss} . The reconstruction of these objects is
1072 described here. In this thesis, τ lepton jets are not treated differently from other
1073 hadronic jets, and we will not consider their reconstruction algorithms. A very
1074 convenient summary plot is shown in Fig.6.4.

1075 One often wishes to understand “how certain” we are that a particular object
1076 is truly the underlying physics object. In ATLAS, we often generically consider, in



Figure 6.4: The interactions of particles with the ATLAS detector. Solid lines indicate the particle is interacting with the detector, while dashed lines are shown where the particle does not interact.

1077 order, *very loose*, *loose*, *medium*, and *tight* objects¹. These are ordered in terms of
 1078 decreasing object efficiency, or equivalently, decreasing numbers of fake objects. We
 1079 will also describe briefly the classification of objects into these categories.

1080 In this thesis, since we present a search for new physics in a zero lepton final state,
 1081 we will provide additional details about jet and E_T^{miss} reconstruction.

¹ These are not all used for all objects, but it's conceptually useful to think of these different categories.

1082 **Electrons and Photons**

1083 **Reconstruction**

1084 The reconstruction of electrons and photons (often for brevity called “electromagnetic
1085 objects”) is very similar [93, 96, 97]. This is because the reconstruction begins with
1086 the energy deposit in the calorimeter in the form of an electromagnetic shower. For
1087 any incoming e/γ , this induces many more electrons and photons in the shower. The
1088 measurement in the calorimeter is similar for these two objects.

1089 One begins the reconstruction of electromagnetic objects from the sliding-window
1090 clusters reconstructed from the EM calorimeter. These $E > 2.5$ GeV clusters the
1091 the primary seed for electrons and photons. One then looks for all ID tracks within
1092 $\Delta R < 0.3$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. We “match” the track and cluster if they are
1093 within $\Delta\phi < 0.2$ in the direction of track curvature, or $\Delta\phi < 0.05$ in the direction
1094 opposite the track curvature. Those track-cluster seeds with tracks pointing to the
1095 primary vertex are reconstructed as electrons.

1096 For photons, we have two options to consider, known as *converted* and *unconverted*
1097 photons. Due to the high energy of the LHC collisions, typical photons have energy
1098 $>\sim 1$ GeV. At this scale, photons interact almost exclusively via pair-production in
1099 the presence of the detector material, as shown in Fig.6.5 [56]. If the track-cluster seed
1100 has a track which does not point at the primary vertex, we reconstruct this object as a
1101 converted photon. This happens since the photon travels a distance before decay into
1102 two electrons, and see the tracks coming from this secondary vertex. Those clusters
1103 which do not have any associated tracks are then reconstruced as an unconverted
1104 photon.

1105 The final step in electromagnetic object reconstruction is the final energy value
1106 assigned to these objects. This process is different between electrons and photons due
1107 to their differing signatures in the EM calorimeter. In the barrel, electrons energies

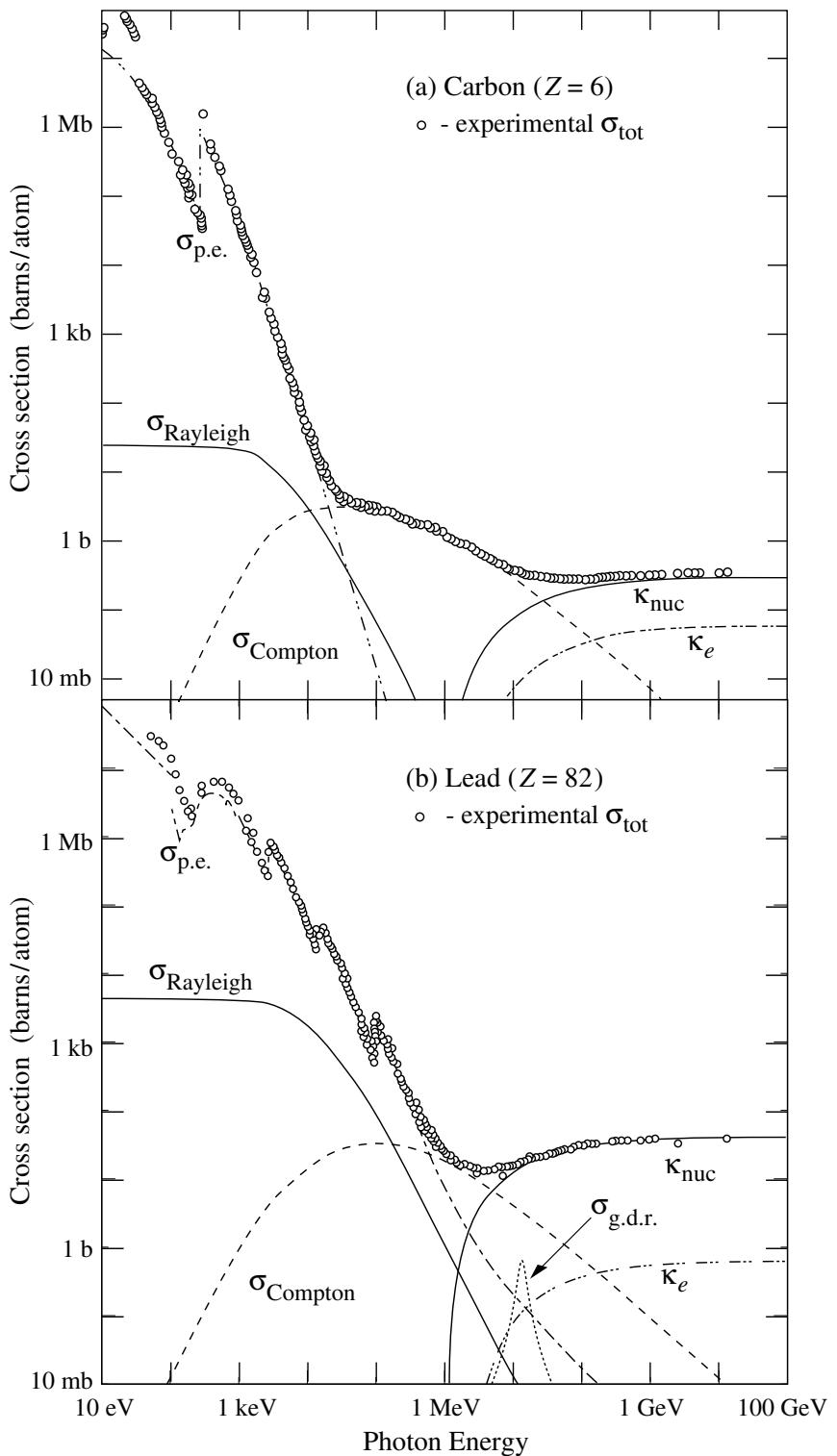


Figure 6.5: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes[56].

1108 are assigned as the sum of the 3 clusters in η and 7 clusters in ϕ to account for the
1109 electron curving in the ϕ direction. Barrel photons are assigned the energy sum of
1110 (3, 5) clusters in (η, ϕ) space. In the endcap, the effect of the magnetic field on the
1111 electrons is smaller, and there is a coarser granularity. Both objects sum the (5, 5)
1112 clusters for their final energy value.

1113 Quality Identification

1114 Electrons have a number of important backgrounds which can give fakes. Fake
1115 electrons come primarily from secondary vertices in hadron decays or misidentified
1116 hadronic jets. To reduce these backgrounds, quality requirements are imposed on
1117 electron candidates. Loose electrons have requirements imposed on the shower
1118 shapes in the electromagnetic calorimeter and on the quality of the associated ID
1119 track. There is also a requirement that there is a small energy deposition in the
1120 hadronic calorimeter behind the electron, to avoid jets being misidentified as electrons
1121 (low hadronic leakage). Medium and tight electrons have increasingly stronger
1122 requirements on these variables, and additional requirements on the isolation (as
1123 measured by ΔR) and matching of the ID track momentum and the calorimeter
1124 energy deposit.

1125 Photons are relatively straightforward to measure, since there are few background
1126 processes[98]. The primary one is pion decays to two photons, which can cause a jet
1127 to be misidentified as photon. Loose photons have requirements on the shower shape
1128 and hadronic leakage. Tight photons have tighter shower shape cuts, especially on
1129 the high granularity first layer of the EM calorimeter. The efficiency for unconverted
1130 tight photons as a function of p_T is shown in

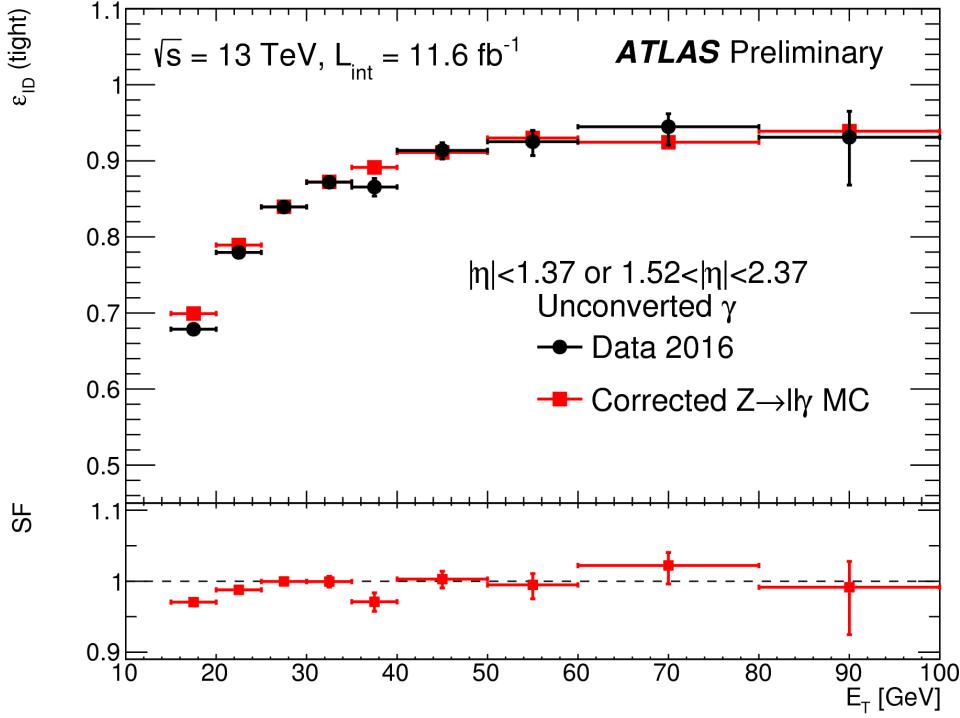


Figure 6.6: Unconverted photon efficiency as measured in [98].

1131 Muons

1132 Reconstruction

1133 Muons are reconstructed using measurements from all levels of the ATLAS detec-
 1134 tor[99]. They leave a ID track, a small, characteristic deposition in the EM calorime-
 1135 ter, and then a track in the muon spectrometer. The primary reconstruction technique
 1136 produces a so-called *combined* muon. “Combined” means using a combination of the
 1137 ID and MS tracks to produce the final reconstructed muon kinematics. This is done
 1138 by refitting the hits associated to both tracks, and using this refit track for the muon
 1139 kinematics. This process produces the best measured muons, although several other
 1140 worse algorithms are used when the full detector information is missing. An example
 1141 is in the region $2.5 < |\eta| < 2.7$ outside the ID acceptance, where MS tracks are used
 1142 without the corresponding ID tracks.

1143 **Quality Identification**

Several additional criteria are used to assure muon measurements are free of significant background contributions, especially from pion and kaon decays to muons. Muons produced via these decay processes are often characterized by a “kink”. Candidate muons with a poor fit quality, characterized by $\chi^2/\text{n.d.f.}$, are thus rejected. Additionally, the absolute difference in momentum measurements between the ID and MS provide another handle, since the other decay products from hadron decays carry away some amount of the initial hadron momentum. This is measured by

$$\rho' = \frac{|p_T^{\text{ID}} - p_T^{\text{MS}}|}{p_T^{\text{Combined}}}. \quad (6.2)$$

Additionally, there is a requirement on the q/p significance, defined as

$$S_{q/p} = \frac{|(q/p)^{\text{ID}} - (q/p)^{\text{MS}}|}{\sqrt{\sigma_{\text{ID}}^2 + \sigma_{\text{MS}}^2}}. \quad (6.3)$$

1144 The $\sigma_{\text{ID,MS}}$ in the denominator of Eq.6.3 are the uncertainties on the corresponding
1145 quantity from the numerator. Finally, cuts are placed on the number of hits in the
1146 various detector elements.

1147 Subsequently tighter cuts on these variables allow one to define the different muon
1148 identification criteria. Loose muons have the highest reconstruction efficiency, but
1149 the highest number of fake muons, since there are no requirements on the number
1150 of subdetector hits and the loosest requirements on the suite of quality variables.
1151 Medium muons consist of Loose muons with tighter cuts on the quality variables.
1152 They also require more than three MDT hits in at least two MDT layers. These are
1153 the default used by ATLAS analyses. Tight muons have stronger cuts than those of
1154 the medium selection, and reducing the reconstruction efficiency. The reconstruction
1155 efficiency as a function of p_T can be seen for Medium muons in Fig.6.7.

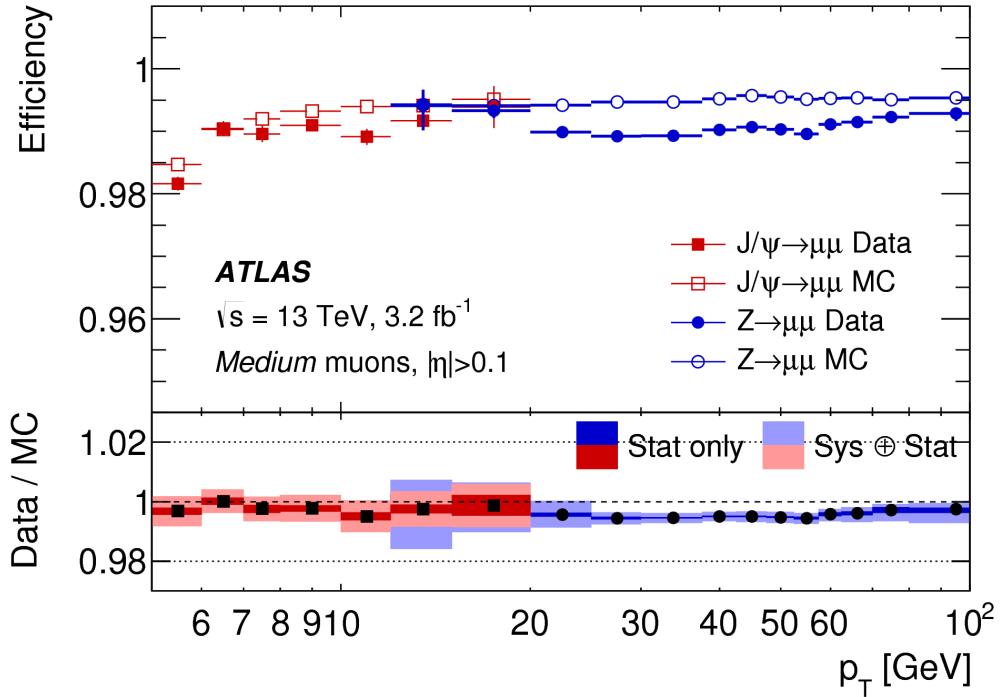


Figure 6.7: Medium muon efficiency as measured in [99].

1156 Jets

1157 Jets are composite objects corresponding to many physical particles [56, 100, 101]
 1158 This is a striking difference from the earlier particles. Fortunately, we normally (and
 1159 in this thesis) care about the original particle produced in primary collision. In the
 1160 SM, this corresponds to quarks and gluons. Due to the hadronization process, free
 1161 quarks and gluons spontaneously hadronize and produce a hadronic shower, which
 1162 we call a jet. These showers can be measured by the EM and hadronic calorimeters,
 1163 and the charged portions can be measured in the ID. The first question is how to
 1164 combine these measurements into a composite object representing the underlying
 1165 physical parton. This is done via jet algorithms.

1166 **Jet Algorithms**

1167 It might seem straightforward to combine the underlying physical particles into a
1168 jet. There are three important characteristics required for any jet reconstruction
1169 algorithm to be used by ATLAS.

- 1170 • Collinear safety - if any particle with four-vector p is replaced by two particles
1171 of p_1, p_2 with $p = p_1 + p_2$, the subsequent jet should not change

1172 • Radiative (infrared) safety - if any particle with four-vector p radiates a particle
1173 of energy $\alpha \rightarrow 0$, the subsequent jet should not change

1174 • Fast - the jet algorithm should be “fast enough” to be useable by ATLAS
1175 computing resources

1176 The first two requirements can be seen in terms of requirements on soft gluon emission.
1177 Since partons emit arbitrarily soft gluons freely, one should expect the algorithms
1178 to not be affected by this emission. The final requirement is of course a practical
1179 limitation.

The algorithms in use by ATLAS (and CMS) which satisfies these requirements are collectively known as the k_T algorithms [102–104]. These algorithms iteratively combine the “closest” objects, defined using the following distance measures :

$$d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p}) \frac{\Delta_{ij}^2}{R^2} \quad (6.4)$$
$$d_{iB} = k_{Ti}^{2p}$$

1180 In Eq.6.4, k_T, i is the transverse momentum of i -th jet *constituent*, Δ_{ij} is the angular
1181 distance between the constituents. Both R and p are adjustable parameters: R is
1182 known as the (jet) *cone size* and p regulates the power of the energy versus the
1183 geometrical scales. The algorithm sequence, for a given set of objects i with four-
1184 vector k :

- 1185 1. Find the minimum distance in the set of all d_{ij} and d_{iB} .

1186 2. If the distance is one of the d_{ij} , combine the input pair of object i, j and return
1187 to (1). If the distance is one of the d_{iB} , remove the object from the list, call it
1188 a jet, and return to (1).

1189 This process ends when all objects i have been added to a jet.

1190 Any choice of (p, R) has the requirements of collinear and radiative safety. In
1191 essence, the choice is then to optimize based on speed and the potential for new
1192 physics discoveries. In ATLAS, we make the choice of $p = -1$ which is also known
1193 as the *anti- k_T* algorithm. The choice of $R = 0.4$ is used for the distance parameter of
1194 the jets.

1195 The primary “nice” quality of this algorithm can be seen with the following
1196 example. Consider three inputs to an anti- k_T algorithm, all with $\eta = 0$:

- 1197 • Object 1 : $(p_T, \phi) = (30 \text{ GeV}, 0)$
- 1198 • Object 2 : $(p_T, \phi) = (20 \text{ GeV}, -0.2)$
- 1199 • Object 3 : $(p_T, \phi) = (10 \text{ GeV}, 0.2)$
- 1200 • Object 4 : $(p_T, \phi) = (1 \text{ GeV}, 0.5)$

1201 . In the case shown, it seems natural to first combine the “bigger” objects 1 and 2.
1202 These then pick up the extra small object 3, and object 4 is not included in the jet.
1203 This is exactly what is done by the anti- k_T algorithm. The (normal) k_T algorithm with
1204 $p = 1$ instead combines the smallest objects, 3 and 4, first. Object 1 and 2 combine
1205 to form their own jet, instead of these jets picking up object 3. This behavior is not
1206 ideal due to the effects of pileup, as we will see in the next section.

1207 Jet Reconstruction

1208 In ATLAS, jets are reconstructed using multiple different objects as inputs, including
1209 tracks, “truth” objects, calorimeter clusters, and *particle flow objects* (PFOs). For

1210 physics analyses, ATLAS primarily uses jets reconstructed from calorimeter clusters,
1211 but we will describe the others here, as they are often used for derivations of
1212 systematic uncertainties or future prospects.

1213 Calorimeter jets are reconstructed using topoclusters using the anti- k_T algorithm
1214 with $R = 0.4$. The jet reconstruction algorithm is run on the collection of all
1215 topoclusters reconstructed as in Sec.6.1. Both EM and LCW scale clusters are used
1216 in the ATLAS reconstruction software and produce two sets of jets for analysis. As
1217 stated above, this thesis presents an analysis using jets reconstructed using EM scale
1218 clusters, which we refer to these as *EM jets*.

1219 Tracks can be used as inputs to jet reconstruction algorithms. Jets reconstructed
1220 from tracks are known as *track jets*. Since the ID tracks do not measure neutral
1221 objects, these jets measure an incorrect energy. However, these are still useful for
1222 checks and derivations of systematic uncertainties.

1223 *Truth* jets are reconstructed from *truth* particles. In this case, truth is jargon for
1224 simulation. In simulation, the actual simulated particles are available and used as
1225 inputs to the jet reconstruction algorithms. Similarly to track jets, these are not useful
1226 in and of themselves. Instead, truth jets are used for comparisons and derivations of
1227 systematic uncertainties.

1228 The last object used as inputs to jet reconstruction algorithms are *particle flow*
1229 *objects* (PFOs). These are used extensively as the primary input to jet particle
1230 reconstruction algorithms by the CMS collaboration[105]. Particle flow objects are
1231 reconstructed by associating tracks and clusters through a combination of angular
1232 distance measures and detector response measurements to create a composite object
1233 which contains information from both the ID and the calorimeters. For calorimeter
1234 clusters which do not have any associated ID track, the cluster is simply the PFO.
1235 The natural association between tracks and clusters provides easy pileup subtraction
1236 since tracks are easily associated to the primary vertex. This technique is generally

1237 used in CMS, and ATLAS has been slow to adopt the same. As pileup has increased,
1238 the utility of using PFOs as inputs to jet reconstruction has increased as well.

1239 **Jet Calibration**

1240 Jets as described in the last section are still *uncalibrated*. Even correcting the cluster
1241 energies using the LCW does not fully correct the jet energy, due to particles losing
1242 energy in the calorimeters. The solution to this is the *jet energy scale* (JES). The
1243 JES is a series of calibrations which on average restore the correct truth jet energy
1244 for a given reconstructed jet. These steps are shown in Fig.6.8 and described here.

1245 The first step is the origin correction. This adjusts the jet to point at the
1246 primary vertex. Next, is the jet-area based pileup correction. This step subtracts
1247 the “average” pileup as measured by the energy density ρ outside of the jets and
1248 assumes this is a good approximation for the pileup inside the jet. One then removes
1249 energy $\Delta E = \rho \times A_{\text{jet}}$ in this step. The residual pileup correction makes a final offset
1250 correction by parametrizing the change in jet energy as a function of the number of
1251 primary vertices N_{PV} and the average number of interactions μ .

1252 The next step is the most important single correction, known as the AbsoluteEta-
1253 JES step. Due to the use of non-compensation and sampling calorimeters in ATLAS,
1254 the measured energy of a jet is a fraction of the true energy of the outgoing parton.
1255 Additionally, due to the use of different technologies and calorimeters throughout the
1256 detector, there are directional biases induced by these effects. The correction bins a
1257 multiplicative factor in p_{T} and η which scales the reconstructed jets to corresponding
1258 truth jet p_{T} . This step does not entirely correct the jets, since it is entirely a
1259 simulation-based approach.

1260 The final steps are known as the global sequential calibration (GSC) and the
1261 residual in-situ calibration. The GSC uses information about the jet showering shape
1262 to apply additional corrections based on the expected shape of gluon or quark jets.

1263 The final step is the residual in-situ calibration, which is only applied to data. This
1264 step uses well-measured objects recoiling off a jet to provide a final correction to the
1265 jets in data. In the low p_T region ($20 \text{ GeV} \sim < p_{T,\text{jet}} \sim < 200 \text{ GeV}$), $Z \rightarrow ll$ events are
1266 used as a reference object. In the middle p_T region ($100 \text{ GeV} \sim < p_{T,\text{jet}} \sim < 600 \text{ GeV}$),
1267 the reference object is a photon, while in the high p_T region ($p_{T,\text{jet}} \sim > 200 \text{ GeV}$),
1268 the high p_T jet is compared to multiple smaller p_T jets. The reference object is this
1269 group of multijets. After this final correction, the data and MC scales are identical
1270 up to the corresponding uncertainties. The combined JES uncertainty as a function
1271 of p_T is shown in Fig.6.9.

1272 Jet Vertex Tagger

1273 The *jet vertex tagger* (JVT) technique is used to separate pileup jets from those
1274 associated to the hard primary vertex[106]. The technique for doing so first involves
1275 *ghost association*[107]. Ghost association runs the anti- k_T jet clustering algorithm on
1276 a combined collection of the topoclusters and tracks. The tracks *only* momenta are
1277 set to zero², with only the directional information is included. As discussed above,
1278 the anti- k_T algorithm is “big to small”; tracks are associated to the “biggest” jet near
1279 them in (η, ϕ) . This method uniquely associates each track to a jet, without changing
1280 the final jet kinematics.

1281 The JVT technique uses a combination of these track variables to determine the
1282 likelihood that the jet originated at the primary vertex. For jets which have associated
1283 tracks from ghost association, this value ranges from 0 (likely pileup jet) to 1 (likely
1284 hard scatter jet). Jets without associated tracks are assigned $\text{JVT} = -.1$. The
1285 working point of $\text{JVT} > .59$ is used for jets in this thesis.

²Well, not exactly zero, since zero momentum tracks wouldn’t have a well-defined (η, ϕ) coordinate, but set to a value obeying $p_{T,\text{track}} << 400 \text{ MeV} = p_{\text{track,min}}$. This is the minimum momentum for a track to reach the ATLAS inner detector.

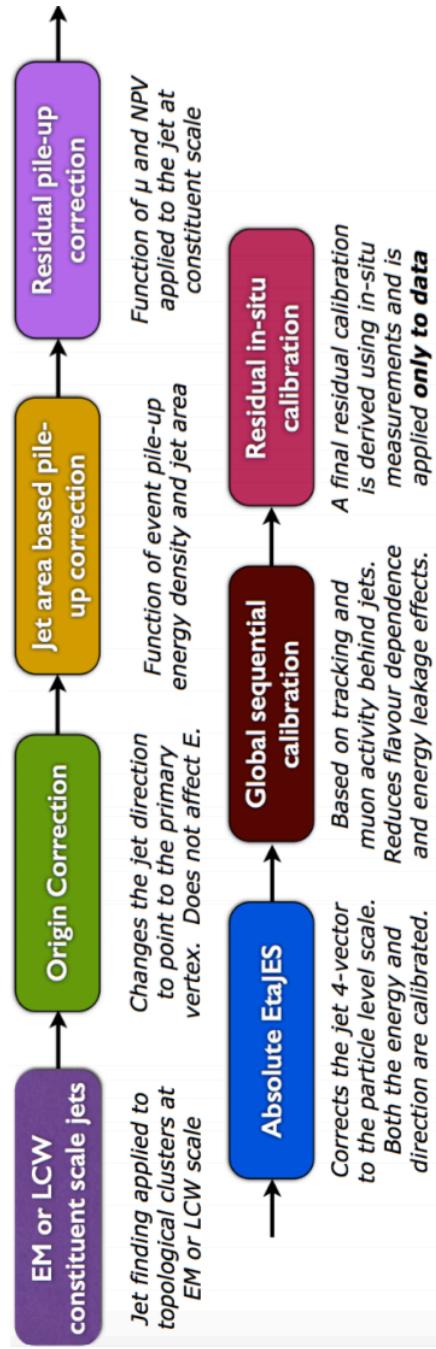


Figure 6.8: The steps used by ATLAS to calibrate jets

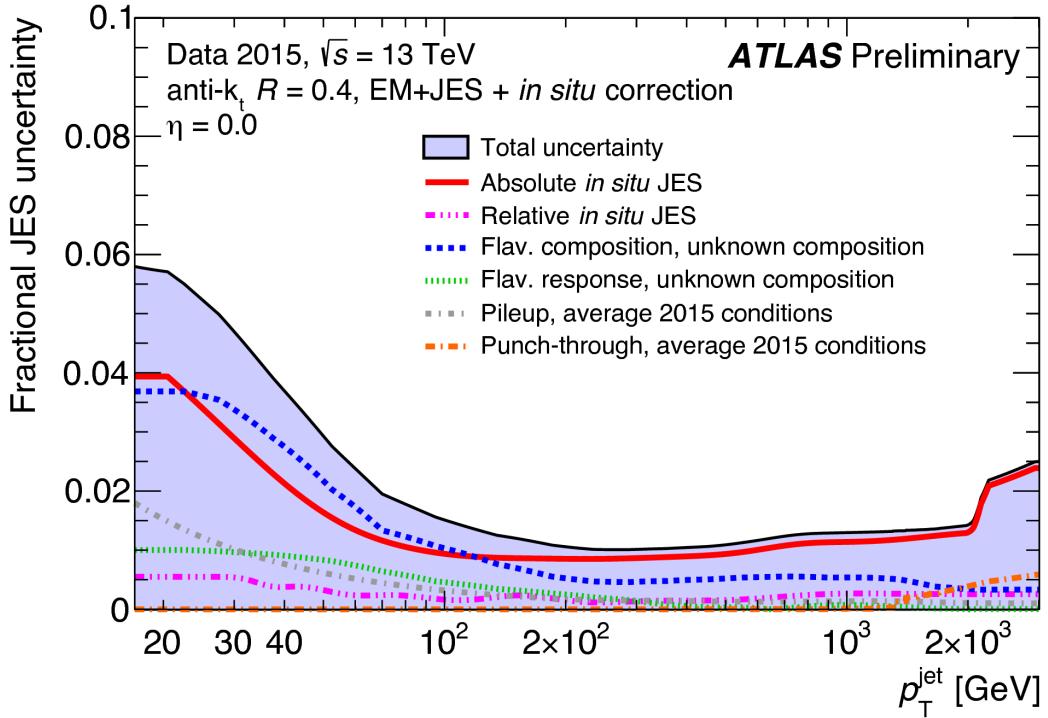


Figure 6.9: Combined jet energy scale uncertainty as a function of p_T at $\eta = 0$.

1286 B-jets

1287 Jets originating from bottom quarks (b-jets) are interesting physical phenomena that
 1288 can be *tagged* by the ATLAS detector[Aad:2015ydr, 108]. B-hadrons, which have
 1289 a comparatively long lifetime compared to hadrons consisting of lighter quarks, can
 1290 travel a macroscopic distance inside the ATLAS detector. The high-precision tracking
 1291 detectors identify the secondary vertices from these decays and the jet matched to
 1292 that vertex is called a *b-jet*. The “MV2c10” algorithm, based on boosted decision
 1293 trees, identifies these jets using a combination of variables sensitive to the difference
 1294 between light-quark and b-quark jets. The efficiency of this tagger is 77%, with a
 1295 rejection factor of 134 for light-quarks and 6 for charm jets.

1296 **Missing Transverse Momentum**

1297 Missing transverse momentum E_T^{miss} [109] is a key observable in searches for new
1298 physics, especially in SUSY searches[110, 111]. However, E_T^{miss} is not a uniquely
1299 defined object when considered from the detector perspective (as compared to the
1300 Feynammn diagram), and it is useful to understand the choices that affect the
1301 performance of this observable in searches for new physics.

1302 **E_T^{miss} Definitions**

Hard objects refers to all physical objects as defined in the previous sections. The
 E_T^{miss} reconstruction procedure uses these hard objects and the *soft term* to provide
a value and direction of the missing transverse momentum. The $E_{x(y)}^{\text{miss}}$ components
are calculated as:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss, } e} + E_{x(y)}^{\text{miss, } \gamma} + E_{x(y)}^{\text{miss, jets}} + E_{x(y)}^{\text{miss, } \mu} + E_{x(y)}^{\text{miss, soft}}, \quad (6.5)$$

1303 where each value $E_{x(y)}^{\text{miss, } i}$ is the negative vectorial sum of the calibrated objects defined
1304 in the previous sections.

1305 For purposes of E_T^{miss} reconstruction, we must assign an ordering of *overlap*
1306 *removal*. This is to avoid double counting of the underlying primitive objects (clusters
1307 and tracks) which are inputs to the reconstruction of the physics objects. We resolve
1308 this in the following order : electrons, photons , jets and muons. This is motivated
1309 by the performance of the reconstruction of these objects in the calorimeters.

1310 The soft term $E_{x(y)}^{\text{miss, soft}}$ contains all of the primitive objects which are not
1311 associated to any of the reconstructed physics objects. Of course, we need to choose
1312 which primitive object to use. The primary choices which have been used within
1313 ATLAS are the *calorimeter-based soft term* (CST) and the *track-based soft term*
1314 (TST). Based on the soft term choice, we then call E_T^{miss} built with a CST (TST)

1315 soft term simply CST (TST) E_T^{miss} . An additional option, which will be important
1316 as pileup continues to increase, particle flow E_T^{miss} (PFlow E_T^{miss}).

1317 The CST E_T^{miss} was used for much of the early ATLAS data-taking. CST E_T^{miss} is
1318 built from the calibrated hard objects, combined with the calorimeter clusters which
1319 are *not* assigned to any of those hard objects. In the absence of pileup, it provides the
1320 best answer for the “true” E_T^{miss} in a given event, due to the impressive hermiticity of
1321 the calorimeters. Unfortunately, the calorimeters do not know “where” from where
1322 their energy deposition came, and thus CST is susceptible to drastically reduced
1323 performance as pileup is increased.

1324 TST E_T^{miss} is the standard for ATLAS searches as currently performed by ATLAS.
1325 TST E_T^{miss} is built by using the calibrated hard objects and the soft term is built from
1326 the tracks which are not assigned to any of those hard objects. In particular, due
1327 to the impressive track-vertex association efficiency, one chooses tracks which only
1328 come from the primary vertex. This drastically reduces the pileup contributions to
1329 the E_T^{miss} measurement. However, since the ID tracking system is unable to measure
1330 neutral objects, the TST E_T^{miss} is “wrong”. This bias is important to understand for
1331 many measurements. However, in most searches for new physics, the soft E_T^{miss} is
1332 generally a small fraction of the total E_T^{miss} , and thus this bias is not particularly
1333 hurtful.

1334 PFlow E_T^{miss} uses the PFOs described above to build the E_T^{miss} . The PFOs which
1335 are assigned to hard objects are calibrated, and the PFOs which are not assigned
1336 to any hard object are added to the soft term. In this context, it is convenient to
1337 distinguish between “charged” and “neutral” PFOs. Charged PFOs can be seen as a
1338 topocluster which has an associated track, while neutral PFOs do not. This charged
1339 PFO is essentially a topocluster that we are “sure” comes from the primary vertex.
1340 The neutral PFOs are in the same status as the original topoclusters. Thus a “full”
1341 PFlow E_T^{miss} should have performance somewhere between TST E_T^{miss} and CST E_T^{miss} ³.

1342 A *charged* PFlow E_T^{miss} should for sanity be the same as TST.

1343 **Measuring E_T^{miss} Performance : event selection**

1344 The question is now straightforward: how do we compare these different algorithms?
1345 We compare these algorithms in $Z \rightarrow \ell\ell + \text{jets}$ and $W \rightarrow \ell\nu + \text{jets}$ events. Due to
1346 the presence of leptons, these events are well-measured “standard candles”. Here
1347 we present the results in early 2015 data with $Z \rightarrow \mu\mu$ and $W \rightarrow e\nu$ events, as
1348 shown in [112, 113]. This result was important to assure the integrity of the E_T^{miss}
1349 measurements at the higher energy and pileup environment of Run-2.

1350 The $Z \rightarrow \ell\ell$ selection is used to measure the intrinsic E_T^{miss} resolution of the
1351 detector. The only possible source of neutrinos in these decays is from heavy-flavor
1352 decays inside of jets, and thus $Z \rightarrow \ell\ell$ events they have very low E_T^{miss} . This provides
1353 an ideal event topology to understand the modelling of E_T^{miss} mismeasurement.
1354 Candidate $Z \rightarrow \mu\mu$ events are first required to pass a muon or electron trigger, as
1355 described in Table 5.1. Offline, the selection of $Z \rightarrow \mu\mu$ events requires exactly two
1356 medium muons. The muons are required to have opposite charge and $p_T > 25 \text{ GeV}$,
1357 and mass of the dimuon system is required to be consistent with the Z mass
1358 $|m_{ll} - m_Z| < 25 \text{ GeV}$.

$W \rightarrow \ell\nu$ events are an important topology to evaluate the E_T^{miss} modelling in
an event with real E_T^{miss} . This E_T^{miss} is from the neutrino, which is not detected.
The E_T^{miss} in these events has a characteristic distribution with a peak at $\frac{1}{2}m_W$. The
selection of $W \rightarrow e\nu$ events begins with the selection of exactly one electron of medium
quality. A selection on TST $E_T^{\text{miss}} > 25 \text{ GeV}$ drastically reduces the background from
multijet events where the jet fakes an electron. The transverse mass is used to select

³Naively, due to approximate isospin symmetry, about 2/3 of the hadrons will be charged and 1/3 will be neutral.

the $W \rightarrow e\nu$ events :

$$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \Delta\phi)}, \quad (6.6)$$

1359 where $\Delta\phi$ is the difference in the ϕ between the E_T^{miss} and the electron. m_T is required
1360 to be greater than 50 GeV.

1361 There are two main ingredients to investigate : the E_T^{miss} resolution and the E_T^{miss}
1362 scale.

1363 **Measuring E_T^{miss} Performance in early 2015 data : metrics**

1364 To compare these algorithms we use the E_T^{miss} resolution, E_T^{miss} scale, and the
1365 linearity. Representative distributions of TST E_x^{miss} , E_y^{miss} , and E_T^{miss} from early
1366 2015 datataking are shown in Fig.6.10.

The E_T^{miss} resolution is an important variable due to the fact that the bulk of the distributions associated to $E_{x(y)}^{\text{miss}}$ are Gaussian distributed [Aad2012]. However, to properly measure the tails of this distribution, especially when considering non-calorimeter based soft terms, it is important to use the root-mean square as the proper measure of the resolution. This is strictly larger than a resolution as measured using a fit to a Gaussian, due to the long tails from i.e. track mismeasurements. The resolution is measured with respect to two separate variables : $\sum E_T$ and N_{PV} . $\sum E_T$ is an important measure of the “total event activity”. It is defined as

$$\sum E_T = \sum p_T^e + \sum p_T^\gamma + \sum p_T^\tau + \sum p_T^{\text{jets}} + \sum p_T^\mu + \sum p_T^{\text{soft}}. \quad (6.7)$$

1367 The measurement as a function of N_{PV} is useful to understand the degradation of
1368 E_T^{miss} performance with increasing pileup. Figure 6.11 shows the E_T^{miss} resolution in
1369 the early 2015 data. The degradation of the E_T^{miss} performance is shown as a function
1370 of pileup N_{PV} and total event activity $\sum E_T$.

Another important performance metric is the E_T^{miss} scale, or how “right” we are in our E_T^{miss} calculation. This can be off in various directions, as CST E_T^{miss} contains

additional particles from pileup, while soft neutral particles⁴ are ignored by TST E_T^{miss} .

To measure this in data, we again use $Z \rightarrow \mu\mu$ events, where the $Z \rightarrow \mu\mu$ system is treated as a well-measured reference object. The component of E_T^{miss} which is in the same direction as the reconstructed $Z \rightarrow \mu\mu$ system is sensitive to potential biases in the detector response. The unit vector \mathbf{A}_Z of the Z system is defined as

$$\mathbf{A}_Z = \frac{\vec{p}_T^{\ell^+} + \vec{p}_T^{\ell^-}}{|\vec{p}_T^{\ell^+} + \vec{p}_T^{\ell^-}|}, \quad (6.8)$$

where $\vec{p}_T^{\ell^+}$ and $\vec{p}_T^{\ell^-}$ are the transverse momenta of the leptons from the Z boson decay. The relevant scale metric is then the mean value of the \vec{E}_T^{miss} projected onto \mathbf{A}_Z : $\langle \vec{E}_T^{\text{miss}} \cdot \mathbf{A}_Z \rangle$. In Figure 6.12, the scale is shown for the early 2015 dataset. The negative bias, which is maximized at about 5 GeV, is a reflection of two separate effects. The soft neutral particles are missed by the tracking system, and thus ignored in TST E_T^{miss} . Missed particles due to the limited ID acceptance can also affect the scale.

For events with real E_T^{miss} , one can also look at the *linearity* in simulation. This is defined as

$$\text{linearity} = \left\langle \frac{E_T^{\text{miss}} - E_T^{\text{miss,Truth}}}{E_T^{\text{miss,Truth}}} \right\rangle. \quad (6.9)$$

$E_T^{\text{miss,Truth}}$ refers to “truth” particles as defined before, or the magnitude of the vector sum of all noninteracting particles. The linearity is expected to be zero if the E_T^{miss} is reconstructed at the correct scale.

1381 Particle Flow Performance

As described above, the resolution, scale, and linearity are the most important metrics to understand the performance of the different E_T^{miss} algorithms. In this section, we present comparisons of the different algorithms, including particle flow, in simulation

⁴“Soft” here means those particles which are not hard enough to be reconstructed as their own particle, using the reconstruction algorithms above.

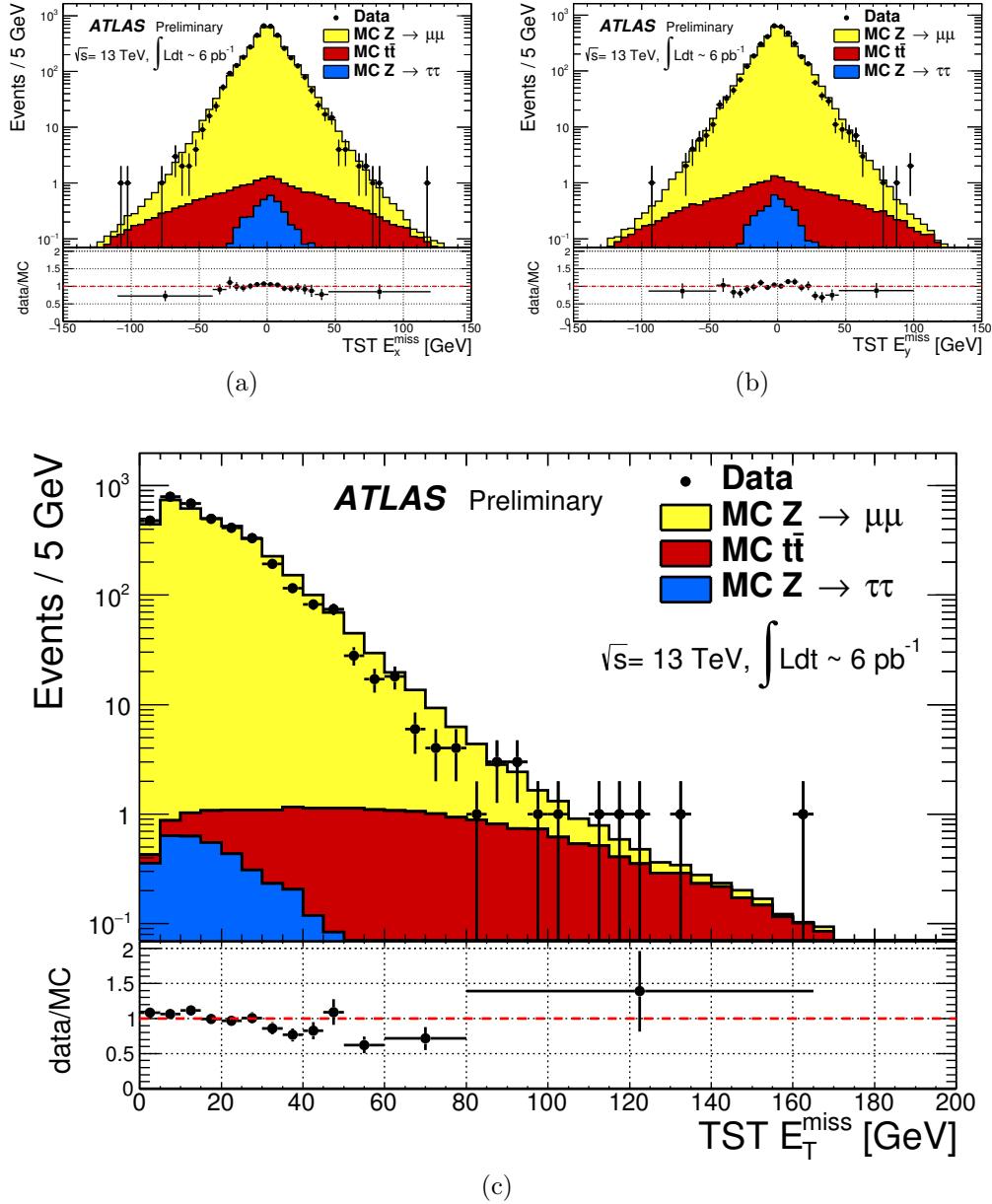


Figure 6.10: TST E_x^{miss} , E_y^{miss} , and E_T^{miss} distributions of early $\sqrt{s} = 13$ TeV data compared with simulation after the $Z \rightarrow \mu\mu$ selection described in Sec. 6.2. The data sample consists of 6 pb^{-1} .

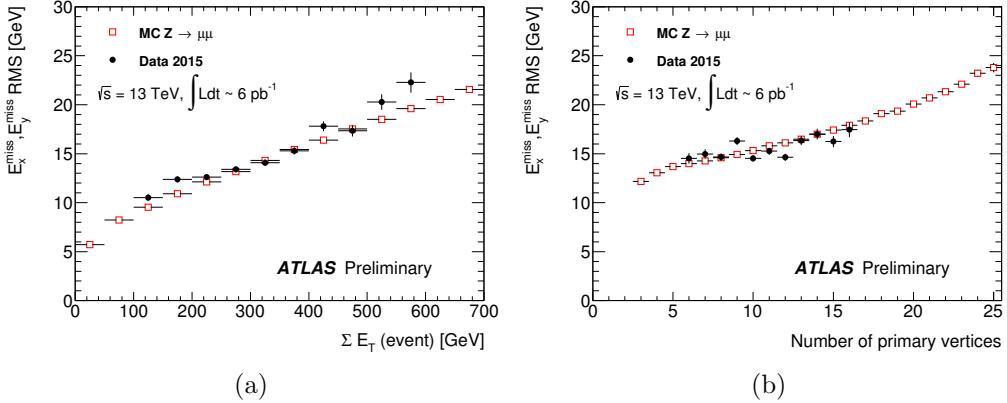


Figure 6.11: Resolution of TST E_T^{miss} of early $\sqrt{s} = 13$ TeV data compared with simulation after the $Z \rightarrow \mu\mu$ selection described in Sec.6.2. The data sample consists of 6 pb^{-1} .

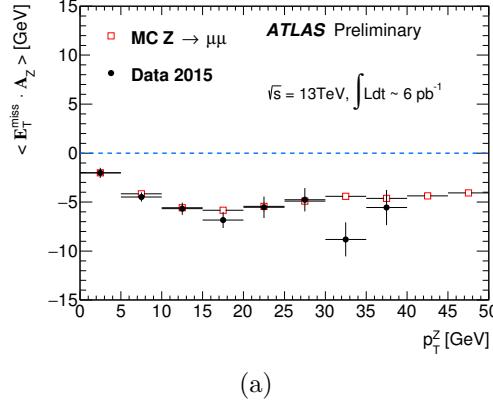


Figure 6.12: Scale of TST E_T^{miss} of early $\sqrt{s} = 13$ TeV data compared with simulation after the $Z \rightarrow \mu\mu$ selection described in Sec.6.2. The data sample consists of 6 pb^{-1} .

1385 and using a data sample from 2015 of 80 pb^{-1} . In these plots, ‘‘MET_PFlow-TST’’
1386 refers to charged PFlow E_T^{miss} , while the other algorithms are as described above.

1387 Figures ?? show the resolution and scale in simulated $Z \rightarrow \mu\mu$ events. The
1388 resolution curves follow the ‘‘intuitive’’ behavior discussed before. Due to the high
1389 pileup in 2015 run conditions, the CST E_T^{miss} resolution is poor, and becomes even
1390 poorer with increasing pileup and event activity. The ‘‘regular’’ PFlow E_T^{miss} shows
1391 reduces pileup and event activity dependence as compared to the CST. As stated
1392 earlier, the E_T^{miss} from the PFlow algorithm can be seen as a hybrid of TST E_T^{miss}

1393 and CST E_T^{miss} . The charged PFOs ($\sim 2/3$) are pileup suppressed, while the neutral
1394 PFOs (or topoclusters) are not. Both charged PFlow and TST E_T^{miss} show only a
1395 small residual dependence on N_{PV} and $\sum E_T$, since they have fully pileup suppressed
1396 inputs through the track associations.

1397 The scale plots are shown for $Z + \text{jets}$ events and Z events with no jets. For the
1398 nonsuppressed CST, the scale continues to worsen with increasing p_T^Z . It is almost
1399 always the worst performing algorithm. The standard PFlow algorithm performs the
1400 second worst in the region of high p_T^Z , but is the best at low p_T^Z . The most exciting note
1401 in this plot is the improved scale of the charged PFlow E_T^{miss} compared to the TST
1402 E_T^{miss} . Considering the resolution is essentially identical, the PFlow algorithm is better
1403 picking up the contributions from additional neutral particles. In events with no jets,
1404 the soft term is essentially the only indication of the E_T^{miss} mismeasurement, since
1405 the muons will be well-measured. In this case, the pileup effects cancel, on average,
1406 due to the $U(1)_\phi$ symmetry of the ATLAS detector, and CST performs rather well
1407 compared to the more complicated track-based algorithms. The full PFlow algorithm
1408 performs best, since it provides a small amount of pileup suppression on the neutral
1409 components from CST.

1410 The resolution and linearity are shown in simulated $W \rightarrow e\nu$ events in Figure ???.
1411 The resolution in $W \rightarrow e\nu$ events shows a similar qualitative behavior to that shown
1412 in $Z \rightarrow \mu\mu$ events. The CST E_T^{miss} has the worst performance, with charged PFlow
1413 E_T^{miss} performing best. The surprise here is that the scale associated to TST E_T^{miss} in
1414 these events is best throughout the space parameterized by $E_T^{\text{miss,Truth}}$, except for one
1415 bin at $40 \text{ GeV} < E_T^{\text{miss,Truth}} < 50 \text{ GeV}$. The scale in these events is best measured
1416 using a track-based soft term.

1417 The resolution also investigated in real data passing the $Z \rightarrow \mu\mu$ selection
1418 described above. A comparison of the E_T^{miss} between real data and simulation for
1419 each algorithm is presented in Figure 6.16. The resolution as a function of $\sum E_T$ and

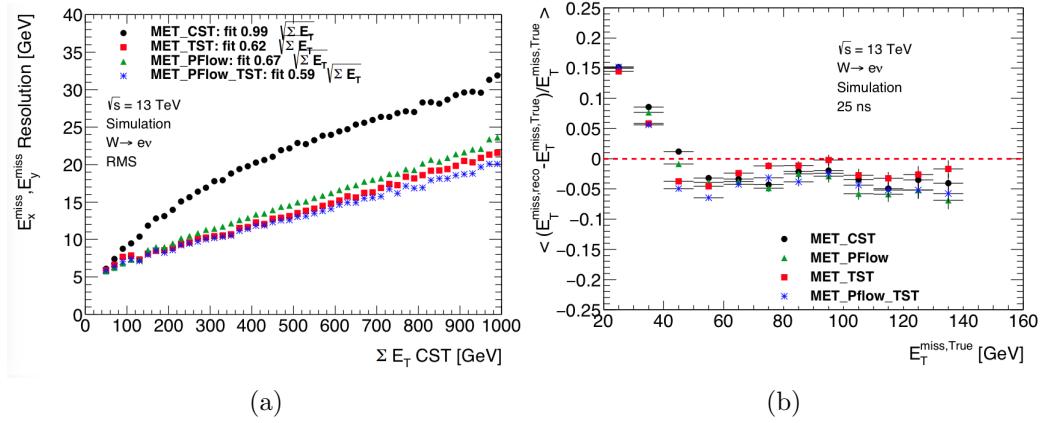


Figure 6.13: Comparison of E_T^{miss} resolution and linearity using different E_T^{miss} algorithms with simulated $W \rightarrow e\nu$ events.

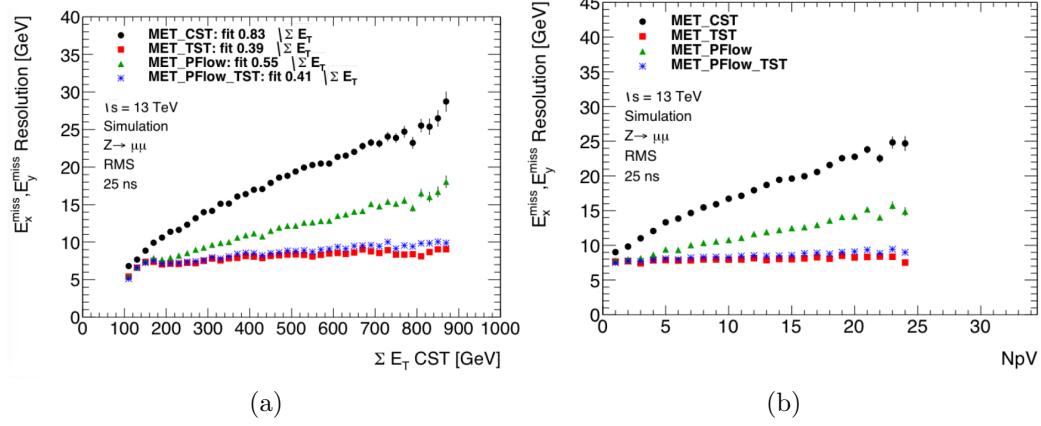


Figure 6.14: Comparison of E_T^{miss} resolution using different E_T^{miss} algorithms with simulated $Z \rightarrow \mu\mu$ events.

1420 N_{PV} is shown in Figure 6.17 for this dataset. Overall, this plot shows the same general
 1421 features as the simulation dataset in terms of algorithm performance. However, the
 1422 performance of all algorithms seems to be significantly worse in data. This is likely due
 1423 to simplifications made in the simulation: soft interactions that cannot be simulated
 1424 can have a significant effect on an event level variable such as the E_T^{miss} resolution.

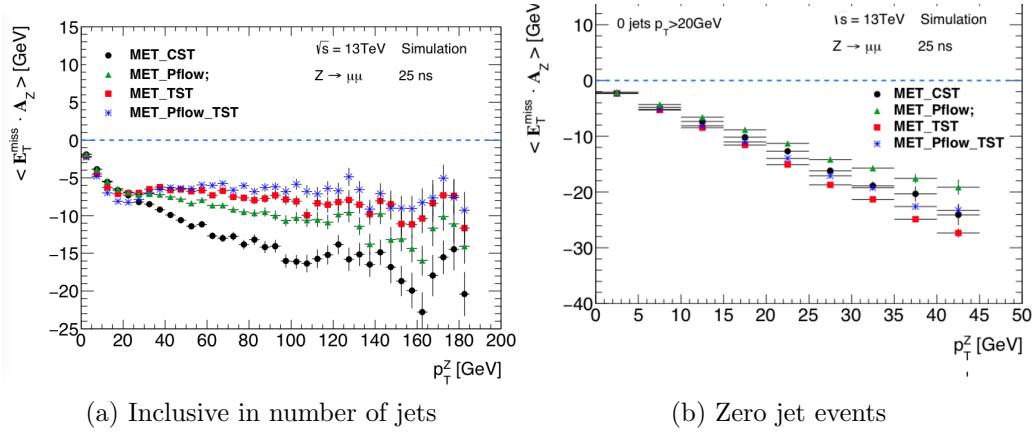


Figure 6.15: Comparison of E_T^{miss} scale using different E_T^{miss} algorithms with simulated $Z \rightarrow \mu\mu$ events.

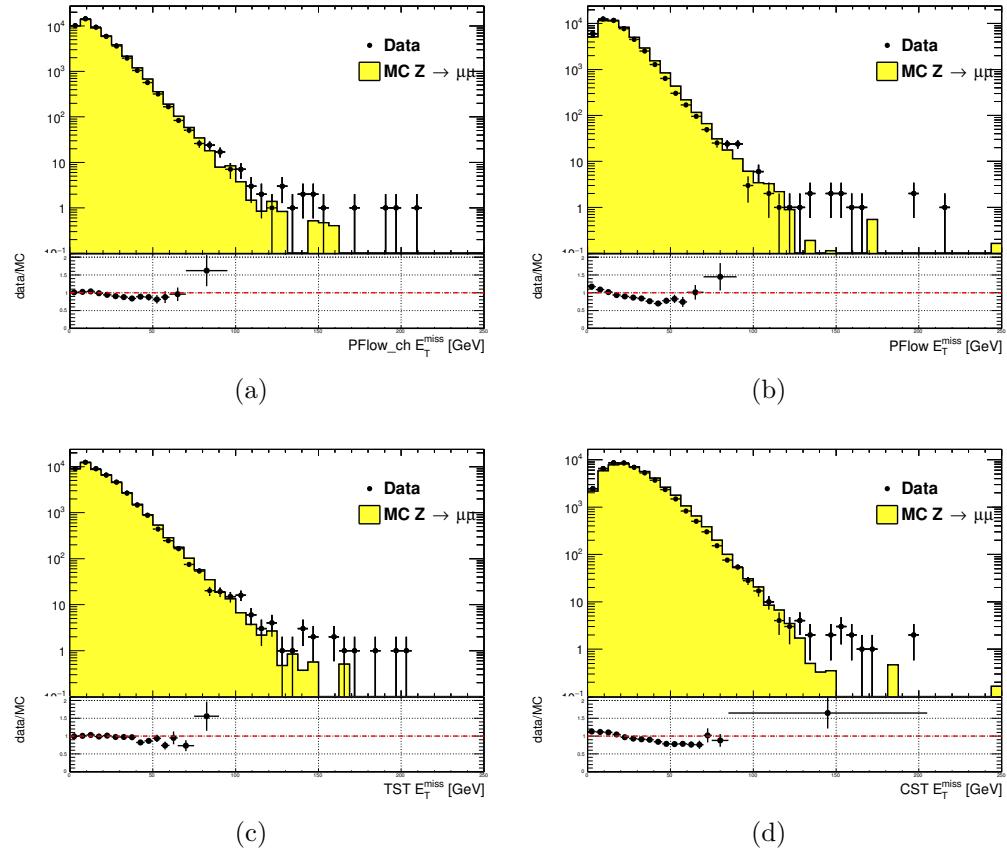


Figure 6.16: Comparison of E_T^{miss} distributions using different E_T^{miss} algorithms with a data sample of 80 pb^{-1} after the $Z \rightarrow \mu\mu$ selection described in Sec. 6.2

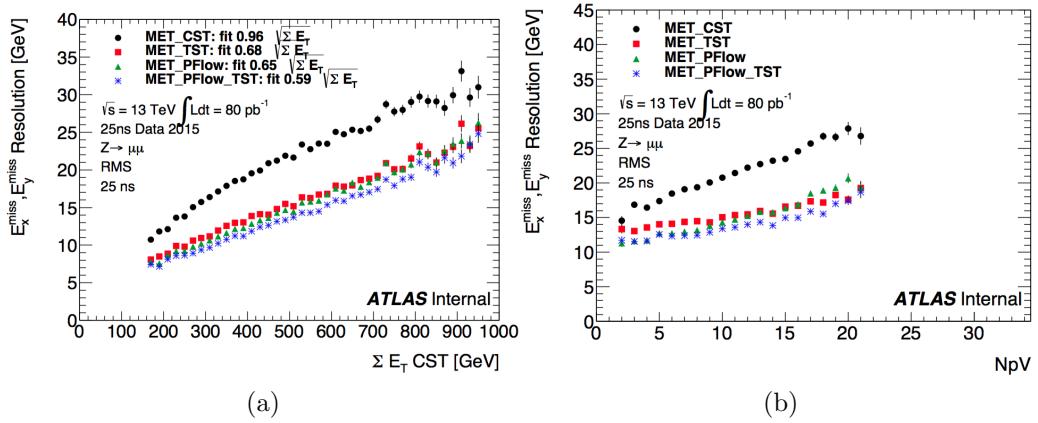


Figure 6.17: Comparison of E_T^{miss} resolution using different E_T^{miss} algorithms with a data sample of 80 pb^{-1} after the $Z \rightarrow \mu\mu$ selection described in Sec. 6.2

Recursive Jigsaw Reconstruction

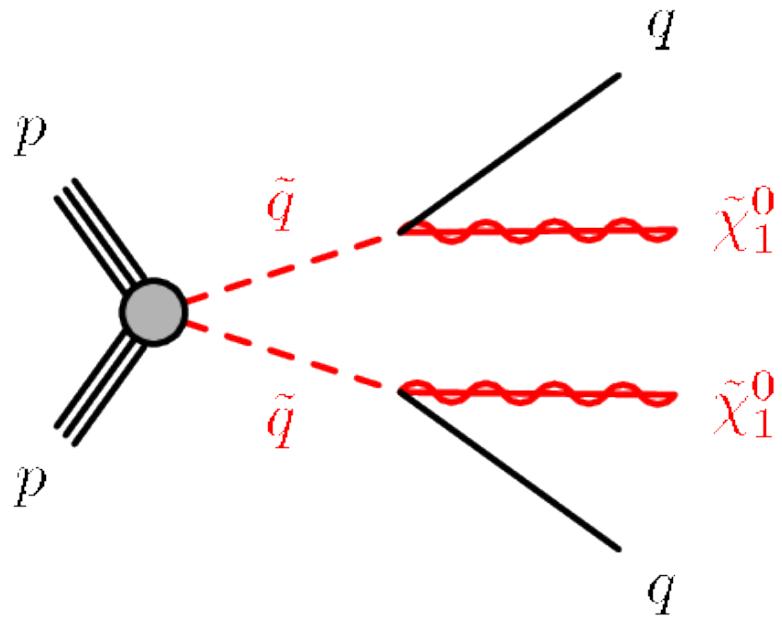
1427 *Recursive Jigsaw Reconstruction* (RJR) [114, 115] is a novel algorithm used for the
 1428 analysis presented in this thesis. RJR is the conceptual successor to the razor
 1429 technique [116, 117], which has been used successfully in many new physics searches
 1430 [37, 38, 40, 41, 47, 118]. In this chapter, we will first present the razor technique,
 1431 and describe the razor variables. We will then present the RJR algorithm. After the
 1432 description of the algorithm, we will describe the precise RJR variables used by this
 1433 thesis and attempt to provide some physical intuition of what they describe.

7.1 Razor variables

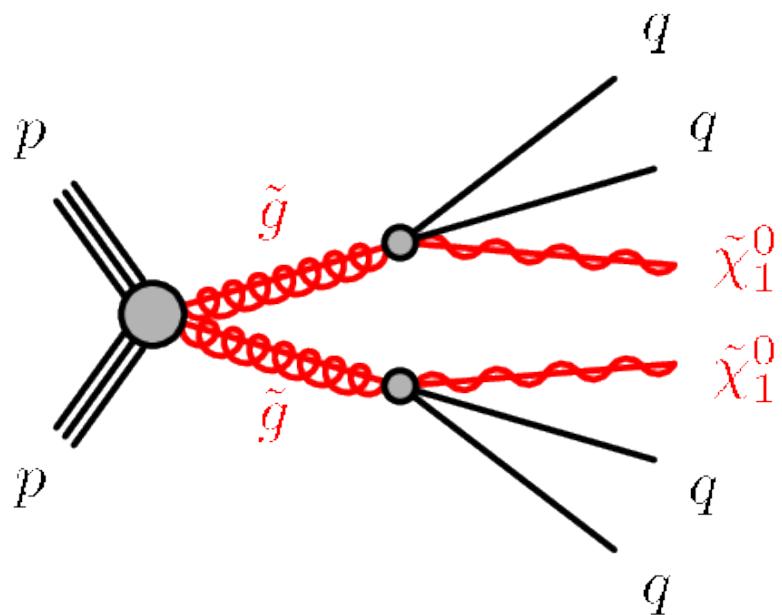
Motivation

1436 In this thesis, we consider SUSY models where gluinos and squarks are pair-produced.
 1437 Pair-production is a consequence of the R -parity imposed in many SUSY models.
 1438 R -parity violation is highly constrained by limits on proton decay[15], and is often
 1439 assumed in SUSY model building. The Feynman diagrams considered are shown in
 1440 Fig.7.1.

1441 As discussed previously, the consequences of this \mathbb{Z}_2 symmetry are drastic. To un-
 1442 derstand the utility of the razor variables, the stability of the lightest supersymmetric
 1443 particle is very important. In many SUSY models, including the ones considered in
 1444 this thesis, this is the lightest neutralino $\tilde{\chi}_1^0$. This means that on either side of a
 1445 SUSY decay process, where we begin with disparticle production, we have a final



(a) Disquark production



(b) Digluino production

Figure 7.1: Feynman diagrams for the SUSY signals considered in this thesis

1446 state particle which is not detected. Generically, this leads to E_T^{miss} . Selections based
1447 on E_T^{miss} are very good at reducing dominant backgrounds, for example from QCD
1448 backgrounds.

1449 However, there are limitations to searches based on E_T^{miss} . Due to jet mismeasurements,
1450 instrumental failures, finite detector acceptance, nongaussian tails in the
1451 detector response, and production of neutrinos inside of jets, there are many sources of
1452 “fake” E_T^{miss} which does not correspond to a Standard Model neutrino or new physics
1453 object such as an LSP. An additional limitation is the complete lack of longitudinal
1454 information. As events from i.e. QCD backgrounds tend to have higher boosts along
1455 the z -direction, this is ignoring an important handle in searches for new physics.
1456 Finally, E_T^{miss} is only one object, which is a measurement for *two* separate LSPs. If one
1457 could factorize this information somehow, this would provide additional information
1458 to potentially discriminate against backgrounds. The *razor variables* (M_{Δ}^R, R^2) are
1459 more robust than standard variables against these effects[[116](#), [117](#)].

1460 Derivation of the razor variables

1461 To derive the razor variables (M_{Δ}^R, R^2), we start with a generic situation of the pair
1462 production of heavy sparticles with mass m_{Heavy} .¹ Each sparticle decays to a number
1463 of observable objects (in this thesis, jets), and an unobservable $\tilde{\chi}_1^0$ of mass $m_{\tilde{\chi}_1^0}$. We
1464 will combine all of the jets into a *megajet*; this process will be described below. We
1465 begin by analyzing the decay in the “rough-approximation”, or in modern parlance,
1466 *razor frame* (*R-frame*). This is the frame where each sparticle is at rest. The complete
1467 set of frames considered in the case of the razor variables is shown in [7.2](#).

In the *R-frame*, the decay is straightforward to analyze. By construction, there
are in fact two *R-frame* s, and they have identical kinematics. Each megajet has

¹The razor variables have undergone confusing notational changes over the years. We will be self-consistent, but the notation used here may be different from references.

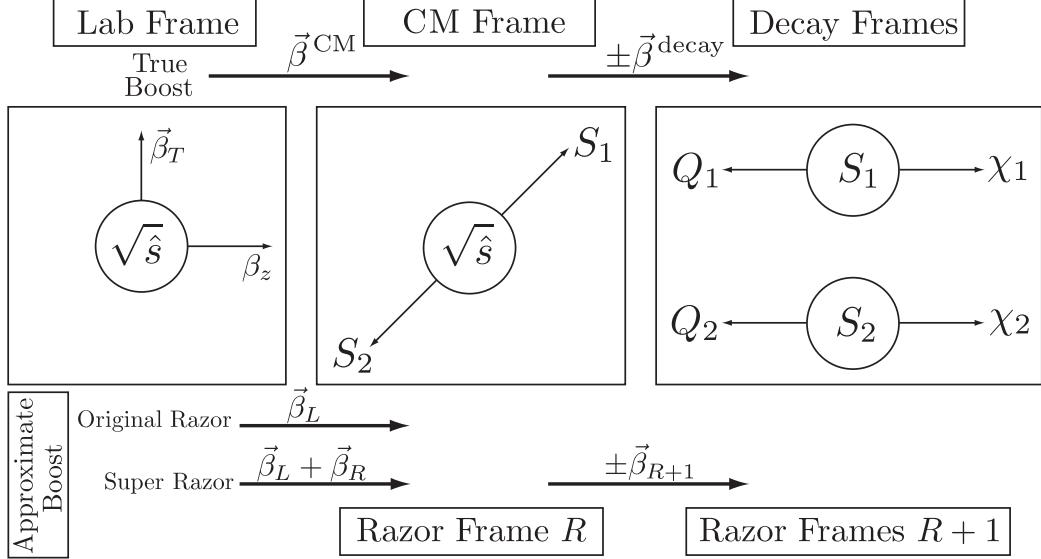


Figure 7.2: Frames considered when applying the razor technique, from [117].

energy E_1^R, E_2^R in the frame of its parent sparticle, and we define a characteristic mass M_R :

$$E_1^R = E_2^R = \frac{m_{\text{Heavy}}^2 - m_{\tilde{\chi}_1^0}^2}{2m_{\text{Heavy}}} \quad (7.1)$$

$$M_R = 2 \times E_1^R = 2 \times E_2^R = \frac{m_{\text{Heavy}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\text{Heavy}}} \quad (7.2)$$

For cases where $m_{\text{Heavy}} \gg m_{\tilde{\chi}_1^0}$, M_R is an estimator of m_{Heavy} . This scenario happens in the SM, such as in $t\bar{t}$ and WW events, where the $\tilde{\chi}_1^0$ is instead a neutrino.

The question now is how to use this simple derivation in the lab frame, where we actually have measurements. There are two related issues: how to combine the jets into the megajets, and how to “transform” (or *boost*) to the R -frame.

To construct the megajets, the procedure is the following. For a given set of jets $j_i, i = 0, \dots, n_{\text{jet}}$, we construct *all* combinations of their four-momenta such that there is at least one jet inside each megajet. Among this set of possible megajets $\{J_{1,2}\}$, we make the following unique choice for the megajets. We minimize the following quantity:

$$m_{J_1}^2 + m_{J_2}^2. \quad (7.3)$$

1473 In modern parlance, this is known as a *jigsaw*. It is important to note, this is a
 1474 *choice*. It may have nice physical qualities or satisfy some convenient intuition about
 1475 the events, but as we will see later, other choices are possible.

We now describe how we translate our megajet kinematics, measured in the lab frame, to the R -frame. This is a two-step procedure. We perform two *boosts*: a longitudinal boost β_L and a transverse boost β_T . Schematically,

$$J_1^R \xrightarrow{\beta_T} J_1^{CM} \xrightarrow{\beta_L} J_1^{\text{lab}} \quad (7.4)$$

$$J_2^R \xrightarrow{-\beta_T} J_2^{CM} \xrightarrow{\beta_L} J_2^{\text{lab}} \quad (7.5)$$

$$(7.6)$$

1476 The $J_{1,2}^{\text{lab}}$ correspond directly to those in the megajet construction. We drop the
 1477 “lab” designation for the rest of the discussion. The question is how to compute the
 1478 magnitudes of these boosts, given the missing degrees of freedom.

For the transverse boost β_T , recall the two megajets have equal energies in their R -frame by construction. This constraint can be reexpressed as a constraint on the magnitude of this boost, in terms of the boost velocity β_L (and Lorentz factor γ_L):

$$\beta_T = \frac{\gamma_L(E_1 - E_2) - \gamma_L\beta_L(p_{1,z} - p_{2,z})}{\hat{\beta}_T \cdot (\vec{p}_{1,T} + \vec{p}_{2,T})} \quad (7.7)$$

where we have denoted the lab frame four-vectors as $p_i = (E_i, \vec{p}_{i,T}, p_z)$. We now make the *choice* for the direction of the transverse boost $\hat{\beta}_T$:

$$\hat{\beta}_T = \frac{\vec{p}_{1,T} + \vec{p}_{2,T}}{|\vec{p}_{1,T} + \vec{p}_{2,T}|}. \quad (7.8)$$

1479 This choice forces the denominator of 7.7 to unity, and corresponds to aligning the
 1480 transverse boost direction with the sum of the two megajets transverse directions.

For the longitudinal boost, we choose $\vec{\beta}_L$ along the z -direction, with magnitude:

$$\beta_L = \frac{p_{1,z} + p_{2,z}}{E_1 + E_2}. \quad (7.9)$$

1481 Viewed in terms of the original parton-parton interactions, this is the choice which
 1482 “on average” gives $p_{z,\text{CM}} = 0$, as we would expect. This well-motivated choice due to
 1483 the total z symmetry.

We now have well-motivated guesses for both boosts, which allow us write our original characteristic mass M_R in terms of the lab frame variables, by application of these two Lorentz boosts to the energies of 7.1:

$$M_R^2 \xrightarrow{\beta_T} M_{R,\text{CM}}^2 \xrightarrow{\beta_L} M_{R,\text{lab}}^2 = (E_1 + E_2)^2 - (p_{1,z} + p_{2,z})^2. \quad (7.10)$$

Finally, we define an additional mass variable, which include the missing transverse energy $E_{\text{T}}^{\text{miss}}$. Importantly, note that we did not use the $E_{\text{T}}^{\text{miss}}$ in the definition of M_R , which depends only on the energies of the megajets. Backgrounds with no invisible particles (such as multijet events) must have J_1 and J_2 back to back. Thus, we define the transverse mass:

$$(M_R^T)^2 = \frac{1}{2} \left[E_{\text{T}}^{\text{miss}}(p_{1,T} + p_{2,T}) - \vec{E}_{\text{T}}^{\text{miss}} \cdot (\vec{p}_{1,T} + \vec{p}_{2,T}) \right]. \quad (7.11)$$

Generally, we have $M_R^T < M_R$, so we define a dimensionless ratio (“the razor”):

$$R^2 = \left(\frac{M_R^T}{M_R} \right)^2. \quad (7.12)$$

1484 For signal events, we expect R to peak around $R \sim 1/4$, while backgrounds without
 1485 real $E_{\text{T}}^{\text{miss}}$ are expected to have $R \sim 0$.

1486 7.2 Recursive Jigsaw Reconstruction

1487 Recursive Jigsaw Reconstruction is an algorithm allowing the imposition of a decay
 1488 tree interpretation on an particular event[114, 115]. The idea is to construct the
 1489 underlying kinematic variables (the masses and decay angles) on an event-by-event
 1490 level. This is done “recursively” through a decay tree which corresponds (sometimes
 1491 approximately) to the Feynmann diagram for the signal process of interest. After

1492 each step of the recursive procedure, the objects are “placed” into one bucket (or
1493 branch) of the decay tree, and the process is repeated on each frame we have imposed.
1494 The imposition of these decay trees is done by *jigsaw* rule: a procedure to resolve
1495 combinatoric or kinematic ambiguities while traversing the decay tree. This procedure
1496 is performed by the `RestFrames` software packages [119]

1497 In events where all objects are fully reconstructed, this is straightforward, and
1498 of course has been used for many years in particle physics experiments. Events
1499 which contain E_T^{miss} are more difficult, due to the loss of information: the potential
1500 for multiple mismeasured or simply unmeasureable objects, such as neutrinos or the
1501 LSP in SUSY searches. There can also be combinatoric ambiguities in deciding how
1502 to group objects of the same type; specifically here, we will be concerned with the
1503 jigsaw rule to associate jets to a particular branch of a decay tree. The jigsaw rules
1504 we impose will remove these ambiguities. First, we will describe the decay trees used
1505 in this thesis, and then describe the jigsaw rules we will use. Finally, we will describe
1506 the variables used in the all-hadronic SUSY search presented in this thesis.

1507 Decay Trees

1508 The decay trees imposed in this thesis are shown in 7.3. Leaving temporarily the
1509 question of “how” we apply the jigsaw rules, let us compare these trees to the signal
1510 processes of interest. In particular, we want to compare the Feynman diagrams of 7.1
1511 with the decay trees of 7.3. The decay tree in ?? corresponds exactly to that expected
1512 from disquark production, and matches very closely with the principles of the razor
1513 approach. We first apply a jigsaw rule, indicated by a line, to the kinematics of the
1514 objects in the *lab* frame. This outputs the kinematics of our event in the *parent-parent*
1515 (*PP*) frame, or in the razor terminology, the CM frame. That is, the kinematics of
1516 this frame are an estimator for the kinematics in the center of mass frame of the
1517 disquark system. We apply another jigsaw, which splits the objects in the *PP* frame

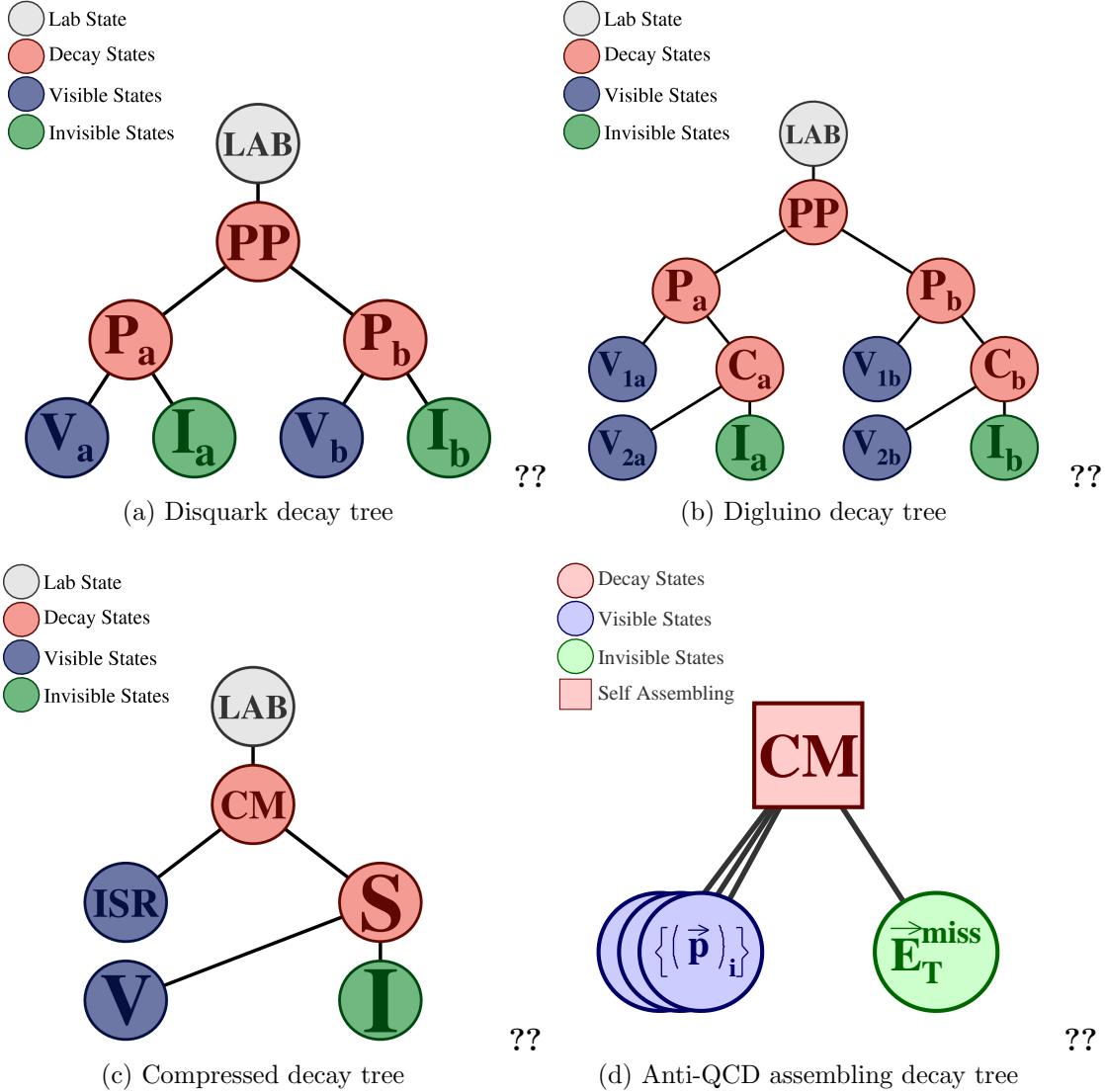


Figure 7.3: RJR decay trees imposed in this thesis

1518 into two new frames, known as the P_a and P_b systems. These are equivalent to the
 1519 razor frames of the razor technique, and represent proxy frames where each squark
 1520 is at rest. In $P_a(P_b)$, the decay is symmetric between the visible $V_a(V_b)$ objects and
 1521 the invisible system $I_a(I_b)$. To generate the estimator of the kinematics of the V_a , V_b ,
 1522 I_a , and I_b systems in the P_a and P_b systems, we apply another jigsaw rule to split the
 1523 total E_T^{miss} between P_a and P_b , which allows calculations of these kinematics in these
 1524 frames. For the case of disquark production, this is the expected decay tree, and we

1525 stop the recursive calculation at that level.

1526 In the case of digluino production, we expect two additional jets, and we can
1527 perform an additional boost in each of P_a and P_b , to what we call the C_a and C_b frames.
1528 The decay tree is shown in ?? . In this case we apply a jigsaw at the level of $P_a(P_b)$
1529 which separates a single visible object V_{1a} (V_{2a}) from the child frame $C_a(C_b)$. This
1530 child frame represents the hypothesized squark after the decay $\tilde{g} \rightarrow g\tilde{q}$, which then
1531 decays as in the squark case. This gives additional information which will be exploited
1532 for the gluino specific search regions.

The third decay tree used in this thesis is the *compressed* decay tree. Compressed refers to signal models which have a small splitting between the mass of the proposed sparticle and the $\tilde{\chi}_1^0$. In this case, the sparticle decay products (i.e. the jets and E_T^{miss}) do not generally have large scale[114]. Instead, the strategy is generally to look for a large-scale initial state radiation (ISR) jet which is recoiling off the disparticle system. In the case where the LSPs receive no momentum from the sparticle decays, the following approximation holds:

$$E_T^{\text{miss}} \sim -p_T^{\text{ISR}} \times \frac{m_{\tilde{\chi}_1^0}}{m_{\text{sparticle}}} \quad (7.13)$$

1533 where p_T^{ISR} is the transverse momentum associated to the entire ISR system.

1534 RJR offers a natural and straightforward way to exploit this feature in events
1535 containing ISR. One imposes the simple decay tree in ?? with associated jigsaw rules.
1536 With suitable jigsaw rules, this decay tree “picks out” the large p_T ISR jet, recoiling
1537 off the E_T^{miss} and additional radiation from the sparticle decays. This provides a
1538 convenient set of variables to understand compressed scenarios.

1539 There is one other decay tree, shown in ?? . This is special, as it is only used for
1540 the purpose of QCD rejection, and does not directly map to a sparticle decay chain.
1541 Due to the large production cross-sections of QCD events, even very rare large jet
1542 mismeasurements can lead to significant E_T^{miss} which can enter the signal region. To
1543 reduce these backgrounds, one usually rejects events which contain jets which are

1544 “too close” by some distance metric to the E_T^{miss} in the event. Generally, in the past,
1545 the distance metric has been defined as simply the angular distance ΔR .

1546 The *self-assembling tree* can be seen as defining a distance metric which depends
1547 on the magnitudes of the E_T^{miss} and jets rather than simply their distance in angular
1548 space. Depending on the exact kinematics, the one or two closest jets are found, and
1549 label the E_T^{miss} *siblings*.

1550 In this section, we have seen how one imposes particular decay trees on an event
1551 to produce a basis of kinematic variables in the approximated frames relevant to
1552 the hypothesized sparticle decay chain. This explains why we call this procedure
1553 “recursive”: we can continue the procedure through as many steps of a decay tree as
1554 we want, and each application of a jigsaw rule is dependent on the variables produced
1555 in the last step. The question, of course, is *what are these jigsaw rules?*.

1556 Jigsaw Rules

1557 Jigsaw rules are the fundamental step that allow the recursive definitions of the
1558 variables of interest. We want rules which allow us to fully define kinematic variables
1559 at each step in a decay tree. The only possible solution to fully define the event
1560 kinematics in terms of the frames of the hypothesized decays is the imposition of
1561 external constraints to eliminate additional degrees of freedom. In principle, these
1562 need not have any particular physical motivation. Instead, the jigsaw rules are a
1563 way to resolve the mathematical ambiguities to fully reconstruct the full decay chain
1564 kinematics. However, most practical jigsaw rules also have some reasonable physical
1565 motivation, which we will also elucidate.

1566 In the original razor point of view, some jigsaw rules can be seen as the definitions
1567 of the boosts which relate the different frames of interest, while other rules allow one
1568 to combine multiple objects and place them into a particular hemisphere (previously
1569 megajet). These are the two forms of jigsaw rules: combinatoric and kinematic. As

1570 we have stressed before, the jigsaw rules are a *choice*; as long as a particular jigsaw
1571 rule allows the definition of variables at each step in a decay tree, it is “as valid” as
1572 any other rule.

Practically speaking, in this thesis we use only a small subset of possible jigsaw rules. The combinatoric jigsaw rule we use has already been introduced as megajet construction above. The minimization of

$$m_{J_1}^2 + m_{J_2}^2. \quad (7.14)$$

1573 is a jigsaw rule to deal with the combinatoric ambiguity implicit in which jets go in
1574 which hemisphere. This is the jigsaw rule used in the decay trees when going from
1575 one frame to two frames such as $PP \rightarrow P_a, P_b$.

1576 We will use three other jigsaw rules, which are both kinematic jigsaw rules. One
1577 has already been used in the razor technique. The minimization of β_L will be used
1578 as the jigsaw rule in the first step of each decay tree: the lab frame to the PP/CM
1579 frame. This is in effect the imposition of longitudinal boost invariance, as we expect
1580 on average $p_{z,PP,\text{CM}} = 0$. One defines a unique longitudinal boost by imposition of
1581 this external constraint.

1582 The final two jigsaw rules used in this thesis was not used in the razor technique.
1583 We describe them here.

The first kinematic ambiguity is the total mass of the invisible system M_I . We
guess this to be:

$$M_I^2 = M_V^2 - 4M_{V_a}M_{V_b}. \quad (7.15)$$

1584 As we stated above, there is no need to “justify” the jigsaw rules, as they are in some
1585 ways a mathematical trick to fully resolve the event kinematics. However in this case,
1586 there is a nice property of this guess. The symmetry of the production mechanism,
1587 where we have two decay products V_i and I_i produced from the decay of the same
1588 heavy sparticle, is explicit with this jigsaw choice.

1589 The final jigsaw rule we employ in this thesis is used to resolve the “amount” of
1590 E_T^{miss} that “belongs” to each hemisphere, and therefore how to impose the transverse
1591 boost onto each of i.e. P_a and P_b from PP . Equivalently, it can be seen as the
1592 resolution of the kinematics of the I_a and I_b objects in the disquark and digluino
1593 decay trees. Recall that at this point, we have already approximated the boost
1594 of the PP frame. The choice we use is to minimize the masses P_a and P_b , while
1595 simultaneously constraining $P_a = P_b$. As is the case in the last step, there is a
1596 straightforward physical interpretation of this choice. In the signal models we are
1597 considering, P_a and P_b are the estimated frames of the squark or gluino pair-produced
1598 as a heavy resonance. We then of course expect $M_{P_a} = M_{P_b}$.

1599 The imposition of the decay trees, with ambiguities resolved through the jigsaw
1600 rules, give a full set of boosts relating the frames of each decay tree. In each frame,
1601 we have estimates for the frame mass and decay angles, which can be used in searches
1602 for new physics. In the next section, we describe the variables that are used in this
1603 thesis in more details.

1604 **7.3 Variables used in the search for zero lepton**

1605 **SUSY**

1606 We describe here the variables used in the search described in ???. These were
1607 reconstructed using the RJR algorithm as just described, using the RestFrames
1608 packages[119]. In these frames, the momenta of all objects placed into that branch
1609 of the decay tree are available (after application of the approximated boost), and in
1610 principle we can calculate any variable of interest such as invariant masses or the
1611 angles between these objects. The truly useful set of variables are highly dependent
1612 on the signal process, and we leave their discussion to the subsequent chapters. It is
1613 useful to understand the philosophy employed in the construction of these variables.

1614 In general, we can split variables useful for searches for new physics into two
1615 categories: *scaleful* and *scaleless* variables. In this search, we will use a set of scaleful
1616 variables called the H variables. The scaleless variables will consists of ratios and
1617 angles. In general, we want to limit the number of scaleful cuts we apply, for two
1618 reasons. Different scaleful variables are often highly correlated, and this of course
1619 limits the utility of additional cuts. Addtionally, selections based on many scaleful
1620 variables often “over-optimize” for particular signal model of interest, especially as
1621 related to the mass difference chosen between the sparticle and the LSP. To avoid
1622 this, each decay tree will only use two scale variables, one of which quantifies the
1623 overall mass scale of the event, and another which acts as a measure of the event
1624 balance.

1625 **Squark and gluino variables**

1626 Taking our general philosophy to a particular case, we here describe the variables
1627 used by the squark and gluino searches. We have a suite of scale variables which we
1628 will call the H variables, and a suite of angles and ratios.

1629 As we have described above, the RJR algorithm gives us access to the masses of
1630 each frame of interest. It maybe seem natural, then, that these variables would be the
1631 most useful for discrimination of the signal from background processes. However, due
1632 to the all hadronic state considered in this thesis, the that can be constructed such
1633 as M_{PP} can be affected by extra QCD radiation, which can promote the background
1634 processes to large scales. The H variables show a resilience to this effect. They
1635 take their name from the commonly used variable H_T , which is the scalar sum of
1636 the visible momentum. However, due to the RJR technique, we can evaluate these
1637 variables in the non-lab frame, including longitudinal information. They are also
1638 constructed with *aggregate* momenta using a similar mass minimization procedure
1639 as we have already described.

We label these variables as $H_{n,m}^F$. The frame from where they are evaluated is denoted F ; practically, this means $F \in \{\text{lab}, PP, P_a, P_b\}$. When the discussion applies to both P_a and P_b , we will write P_i . The subscripts n and m denote the number of visible and invisible vectors considered, respectively. When there are more vectors available than n or m , we add up vectors using the hemisphere (megajet) jigsaw rule until there are n (m) objects.² In the opposite case, where n or m is greater than the number of available objects, one simply considers the available objects. The $H_{n,m}^F$ variables are then defined as

$$H_{n,m}^F = \sum_i^n |\vec{p}_{\text{vis},i}^F| + \sum_j^m |\vec{p}_{\text{inv},i}^F|. \quad (7.16)$$

It may not be clear that these variables encode independent information. Fundamentally, this is just an expression of the triangle inequality $\sum |\vec{p}| \geq |\sum \vec{p}|$. The different combinations can then include independent information. The final note on the H variables is that we can also consider purely transverse versions of these variables, which we will denote $H_{T,n,m}^F$. Including this view, it is easy to see how the H variables are extensions of the normal H_T variables, as

$$H_T = H_{T,\infty,0}^{\text{lab}}. \quad (7.17)$$

1640 Although the H variables are interesting in their own right, the true power of the
 1641 RJR technique comes from the construction of scaleless variables with the technique.
 1642 This is because the scaleless ratios and angles are in fact measured in the “right”
 1643 frame, where right here means an approximation of the correct frame. This provides
 1644 a less correlated set of variables than those measured in the lab frame, due to the
 1645 corrections to the disparticle or sparticle system boosts from the RJR technique.
 1646 For the search for noncompressed disquark production, we use will use the
 1647 following set of RJR variables.

²Recall that these vectors are constructed by the imposition of the decay tree with the relevant jigsaw rules.

- 1648 • $H_{1,1}^{PP}$ - scale variable useful for discrimination against QCD backgrounds and
 1649 used in a similar way to E_T^{miss}

- 1650 • $H_{T,2,1}^{PP}$ - scale variable providing information on the overall mass scale of the
 1651 event for disquark signal production. We will often call this the *full* scale
 1652 variable.

- 1653 • $H_{T,1,1}^{PP}/H_{2,1}^{PP}$ - ratio used to prevent imbalanced events where the scale variable
 1654 is dominated by one high p_T jet or high E_T^{miss}

- 1655 • $p_{PP,z}^{\text{LAB}}/(p_{PP,z}^{\text{LAB}} + H_{T,2,1}^{PP})$ - ratio used to prevent significant boosts in the
 1656 z -direction. $p_{PP,z}^{\text{LAB}}$ is a measure of the total boost of the PP system from the lab
 1657 frame

- 1658 • $p_{T,j2}^{PP}/H_{T,2,1}^{PP}$ - ratio to force the second leading jet in the PP frame to carry a
 1659 significant portion of the total scalar sum in that frame. This requirement is
 1660 another balance requirement, on the total p_T of that second jet in the PP frame.

1661 First, we note that there is an implicit requirement that each hemisphere has at least
 1662 one jet (to even reconstruct the P_a and P_b frames), these variables are implicitly using
 1663 two or more jets, as we expect in disquark production. The other important thing
 1664 to note is that all of the ratios use the full scale variable as the denominator. This
 1665 is sensible, as we expect all of these effects to be scaled with the full scale variable
 1666 $H_{T,2,1}^{PP}$. We will see a similar behavior for the gluino regions, with a new full scale
 1667 variable.

1668 For the search for noncompressed digluino production, we use will use the following
 1669 set of RJR variables. Due to the increased complexity of the event topology with four
 1670 jets, there are additional handles we can exploit:

- 1671 • $H_{1,1}^{PP}$ - same as disquark production

- 1672 • $H_{T,4,1}^{PP}$ - scale variable providing information on the overall mass scale of the
 1673 event for digluino signal production. As before, we often call this the *full* scale
 1674 variable. Since this variable allows the jets to be separated in the *PP* frame, it
 1675 is more appropriate for digluino production.
- 1676 • $H_{T,1,1}^{PP}/H_{4,1}^{PP}$ - ratio used to prevent imbalanced events where the scale variable
 1677 is dominated by one high p_T jet or high E_T^{miss}
- 1678 • $H_{T,4,1}^{PP}/H_{4,1}^{PP}$ - ratio used to measure the fraction of the total scalar sum of the
 1679 momentum in the transverse plane. Digluino production is expected to be fairly
 1680 central
- 1681 • $p_{PP,z}^{\text{LAB}}/(p_{PP,z}^{\text{LAB}} + H_{T,4,1}^{PP})$ - ratio used to prevent significant boosts in the
 1682 z -direction
- 1683 • $\min(p_{T,j2_i}^{PP}/H_{T,2,1_i}^{PP})$ - ratio to require the second leading jet in *both* squark-like
 1684 hemispheres C_a and C_b to contain a significant portion of *that frame's* momenta.
 1685 This is similar to the $p_{T,j2}^{PP}/H_{T,2,1}^{PP}$ disquark discriminator, but applied to both
 1686 hemispheres C_a and C_b .
- 1687 • $\max(H_{1,0}^{P_i}/H_{2,0}^{P_i})$ - ratio requiring one jet in each of the P_i to not take too much
 1688 of the total momentum of that frame. This ratio is generally a very loose cut.

1689 Compressed variables

1690 As we saw above, the decay tree imposed for compressed spectra is simpler. We do
 1691 not attempt to fully reconstruct the details of the system recoiling of the ISR system,
 1692 but use a straightforward set of variables in this case. One additional simplification
 1693 is that all variables are force to be transverse in this case; we simply do not include
 1694 the η/z information of the objects as inputs to the RJR reconstruction. We still use
 1695 the philosophy of limiting our scaleful variables to just two. The compressed scenario
 1696 uses the following set of RJR variables:

- 1697 • $p_{T,S}^{\text{ISR}}$ - scale variable that is the magnitude of the total transverse momenta of all
 1698 jets associated to the ISR system, as evaluated in the CM frame

- 1699 • $R_{\text{ISR}} \equiv p_I^{\hat{C}\text{M}} \cdot p_{T,S}^{\hat{C}\text{M}} / p_{T,S}^{\text{CM}}$ - this ratio is our measurement for the ratio of the LSP
 1700 mass to the compressed sparticle mass. These are the values in the CM frame
 1701 In compressed cases, this should be large, as this estimates the amount of the
 1702 total CM $\rightarrow S$ boost is carried by the invisible system.

- 1703 • $M_{T,S}$ - the transverse mass of the S system

- 1704 • N_{jet}^V - the number of jets associated to the visible system V

- 1705 • $\Delta\phi_{\text{ISR},I}$ - the opening angle between the ISR system and the invisible system
 1706 measured in the lab frame. As the invisible system is expected to carry much
 1707 of the total S system momentum, this should be large, as we expect the ISR
 1708 system to recoil directly opposite the I system in that case.

1709 Anti-QCD variables

1710 For the self-assembling tree, we construct two variables, which we combine to form a
 1711 single variable which rejects QCD events. In this case, we use the mass minimization
 1712 jigsaw, with a fully transverse version of the event (i.e. we set all jet z/η components
 1713 to 0). This jigsaw defines the distance metric, and provides us with one or two jets
 1714 known as the $E_{\text{T}}^{\text{miss}}$ siblings. We define \vec{p}_{sib} as the sum of these jets, and define the
 1715 following quantities.

We calculate a ratio observable which examines the relative magnitude of the sibling vector \vec{p}_{sib} and $E_{\text{T}}^{\text{miss}}$, and an angle relating \vec{p}_{sib} and $E_{\text{T}}^{\text{miss}}$:

$$R(\vec{p}_{\text{sib}}, E_{\text{T}}^{\text{miss}}) \equiv \frac{\vec{p}_{\text{sib}} \cdot \hat{E}_{\text{T}}^{\text{miss}}}{\vec{p}_{\text{sib}} \cdot \hat{E}_{\text{T}}^{\text{miss}} + |\vec{E}_{\text{T}}^{\text{miss}}|} \quad (7.18)$$

$$\cos \theta(\vec{p}_{\text{sib}}, E_{\text{T}}^{\text{miss}}) \equiv \frac{(\vec{p}_{\text{sib}} + \vec{E}_{\text{T}}^{\text{miss}}) \cdot \vec{p}_{\text{sib}}^{\text{miss}}}{|\vec{p}_{\text{sib}}| + E_{\text{T}}^{\text{miss}}} \quad (7.19)$$

These observables are highly correlated, but taking the following fractional difference provides strong discrimination between SUSY signal and QCD background events:

$$\Delta_{\text{QCD}} \equiv \frac{1 + \cos \theta(\vec{p}_{\text{sib}}, E_{\text{T}}^{\text{miss}}) - 2R(\vec{p}_{\text{sib}}, E_{\text{T}}^{\text{miss}})}{1 + \cos \theta(\vec{p}_{\text{sib}}, E_{\text{T}}^{\text{miss}}) + 2R(\vec{p}_{\text{sib}}, E_{\text{T}}^{\text{miss}})}. \quad (7.20)$$

1716 We will use this variable in the next chapter.

1718 *A search for supersymmetric particles in zero lepton final
 1719 states with the Recursive Jigsaw Technique*

1720 This section presents the details of the first search employing RJR variables as
 1721 discriminating variables, as described in [115]. We will describe the simulation
 1722 samples used, and then define the selections where we search for new SUSY
 1723 phenomena, which we call the *signal regions* (SRs) Afterwards, we describe the
 1724 background estimation techniques used in the analysis. Finally, we discuss the
 1725 treatment of systematic uncertainties, and how we combine them using a likelihood
 1726 method[120].

1727 **8.1 Simulation samples**

1728 We discussed the collision data sample provided by the LHC for the analysis in this
 1729 thesis. We analyze a dataset of 13.3 fb^{-1} of collision data, at $\sqrt{s} = 13 \text{ TeV}$. To select
 1730 events in data, we use the trigger system as previously discussed, and use the lowest
 1731 unprescaled trigger which is available for a particular Standard Model background.
 1732 We now discuss the simulation samples used for this search.

1733 Simulated data is fundamentally important to the ATLAS physics program.
 1734 Calibrations, measurements, and searches use Monte Carlo (MC) simulations¹ to
 1735 compare with collision data. In this thesis, MC samples are used to optimize the
 1736 signal region selections, assist in background estimation, and assess the sensitivity to

¹In jargon, often just called “Monte Carlo” or MC.

1737 specific SUSY signal models. The details of Monte Carlo production, accuracy, and
1738 utility are far beyond the scope of this thesis, but we provide a short description here.

1739 The first step is MC *generation*. A program is run which does a matrix-element
1740 calculation, sometimes with additional corrections, which produces a set of output
1741 particles from the parton interactions. These output particles are then decayed via
1742 another (or the same) simulation program. This produces a set of *truth* particles,
1743 which are the output of event generation. The details of which generator to use are
1744 the subject of much discussion, and generally (many) comparisons are made between
1745 them, for different processes of interest. Additionally, differences between generators
1746 are often a starting point for the calculation of systematic uncertainties.

1747 The next step is the *simulation*. The detector response to the truth particles
1748 is simulated, and simulated hits are produced. After simulation, the standard
1749 reconstruction algorithms described previously are run with the simulated hits. This
1750 procedure ensures “as close as possible” treatment of simulation and collision data.

1751 We give a brief description of which samples use which generators; additional
1752 details are available in [115].

MAKE 1753 Signal (diguino and disquark) samples are generated with up to two ex-
BETTER 1754 tra partons in the matrix element using MG5_aMC@NLO 2.2.2 event genera-
1755 tor [Alwall:2014hca] interfaced to PYTHIA 8.186 [Sjostrand:2014zea]. The
1756 nominal cross-section is taken from an envelope of cross-section predictions using
1757 different PDF sets and factorization and renormalization scales, as described in
1758 Ref. [Kramer:2012bx], considering only light-flavour quarks (u, d, s, c). For the
1759 light-flavour squarks (gluinos) in case of gluino- (squark-) pair production, cross-
1760 sections are evaluated assuming masses of 450 TeV. The free parameters are $m_{\tilde{\chi}_1^0}$ and
 $m_{\tilde{g}} (m_{\tilde{s}})$ for gluino-pair (squark-pair) production models.

explain 1761 Boson (W, Z, γ) plus jet events are simulated using different SHERPAGenerators,
we have a 1762 with COMIX and OPENLOOPS matrix-element generators[comix, openloops, 121].
“grid” of 1763 these signal
models
samples

1764 Photons are required to have transverse momentum of > 35 GeV. Importantly, the
1765 $W(Z)$ +jet events are calculated at NLO while the the γ +jet events are calculated
1766 at LO. The $W/Z +$ jets events are normalized to their NNLO cross-sections
1767 [Catani:2009sm]. The γ +jets LO cross-section is taken directly from **SHERPA**; we
1768 will apply a correction factor to be described later.

1769 The various $t\bar{t}$ and single-top processes[122] are generated using two versions of
1770 **POWHEG-Box** [**powheg-box**, 122]. These are calculated at NLO and normalized
1771 to various orders ranging from NLO to NNLO+NNLL in the different processes,
1772 which can be seen in 8.1[Czakon:2013goa, Czakon:2011xx, Aliev:2010zk,
1773 Kant:2014oha, Kidonakis:2010ux, Kidonakis:2011wy].

1774 Diboson processes (WW , WZ , ZZ) [123] are simulated using the **SHERPA** 2.1.1
1775 generator. For processes with four charged leptons (4ℓ), three charged leptons and
1776 a neutrino ($3\ell+1\nu$) or two charged leptons and two neutrinos ($2\ell+2\nu$), the matrix
1777 elements contain all diagrams with four electroweak vertices, and are calculated for
1778 up to one (4ℓ , $2\ell+2\nu$) or no partons ($3\ell+1\nu$) at NLO and up to three partons at LO
1779 using the **COMIX** and **OPENLOOPS** matrix-element generators, and merged with the
1780 **SHERPA** parton shower using the ME+PS@NLO prescription. For processes in which
1781 one of the bosons decays hadronically and the other leptonically, matrix elements
1782 are calculated for up to one (ZZ) or no (WW , WZ) additional partons at NLO
1783 and for up to three additional partons at LO using the **COMIX** and **OPENLOOPS**
1784 matrix-element generators, and merged with the **SHERPA** parton shower using the
1785 ME+PS@NLO prescription. In all cases, the CT10 PDF set is used in conjunction
1786 with a dedicated parton-shower tuning developed by the authors of **SHERPA**. The
1787 generator cross-sections are used in this case.

1788 The multi-jet background is generated with **PYTHIA** 8.186 using the A14
1789 underlying-event tune and the NNPDF2.3LO parton distribution functions.

1790 A summary of the SM background processes together with the MC generators,

1791 cross-section calculation orders in α_s , PDFs, parton shower and tunes used is given
 1792 in Table 8.1.

Physics process	Generator	Cross-section normalization	PDF set	Parton shower	Tune
$W(\rightarrow \ell\nu) + \text{jets}$	SHERPA 2.2.0	NNLO	NNPDF3.0NNLO	SHERPA	SHERPA default
$Z/\gamma^*(\rightarrow \ell\bar{\ell}) + \text{jets}$	SHERPA 2.2.0	NNLO	NNPDF3.0NNLO	SHERPA	SHERPA default
$\gamma + \text{jets}$	SHERPA 2.1.1	LO	CT10	SHERPA	SHERPA default
$t\bar{t}$	Powheg-Box v2	NNLO+NNLL	CT10	PYTHIA 6.428	PERUGIA2012
Single top (Wt -channel)	Powheg-Box v2	NNLO+NNLL	CT10	PYTHIA 6.428	PERUGIA2012
Single top (s -channel)	Powheg-Box v2	NLO	CT10	PYTHIA 6.428	PERUGIA2012
Single top (t -channel)	Powheg-Box v1	NLO	CT10f4	PYTHIA 6.428	PERUGIA2012
$t\bar{t} + W/Z/WW$	MG5_aMC@NLO 2.2.3	NLO	NNPDF2.3LO	PYTHIA 8.186	A14
WW, WZ, ZZ	SHERPA 2.1.1	NLO	CT10	SHERPA	SHERPA default
Multi-jet	PYTHIA 8.186	LO	NNPDF2.3LO	PYTHIA 8.186	A14

Table 8.1: The Standard Model background Monte Carlo simulation samples used in this thesis. The generators, the order in α_s of cross-section calculations used for yield normalization, PDF sets, parton showers and tunes used for the underlying event are shown.

1793 For all SM background samples the response of the detector to particles is
 1794 modelled with a full ATLAS detector simulation [:2010wqa] based on GEANT4
 1795 [Agostinelli:2002hh]. Signal samples are prepared using a fast simulation based on
 1796 a parameterization of the performance of the ATLAS electromagnetic and hadronic
 1797 calorimeters [ATLAS:2010bfa] and on GEANT4 elsewhere.

1798 All simulated events are overlaid with multiple pp collisions simulated with
 1799 the soft QCD processes of PYTHIA 8.186 using the A2 tune [A14tune] and the
 1800 MSTW2008LO parton distribution functions [Martin:2009iq]. The simulations are
 1801 reweighted to match the distribution of the mean number of interactions observed in
 1802 data.

1803 **8.2 Event selection**

1804 This section describes the selection of the signal region events. We begin by describing
1805 the *preselection*, which is used to remove problematic events and reduce the dataset
1806 to a manageable size. We then describe the signal region strategy, and present the
1807 signal regions used in the analysis.

1808 **Preselection**

1809 The preselection is used to reduce the dataset to that of interest in this thesis. The
1810 table containing the preselection cuts is shown in 8.2. This selection is also used for
1811 the samples used for background estimation, except for the lepton veto.

1812 The cuts [1] and [4] are a set of cleaning cuts to remove problematic events.
1813 The *Good Runs List* is a centrally-maintained list of data runs which have been
1814 determined to be “good for physics”. This determination is made by analysis of the
1815 various subdetectors, and monitoring of their status. Event cleaning is used to veto
1816 events which could be affected by noncollision background, noise bursts, or cosmic
1817 rays.

1818 We require the lowest unprescaled E_T^{miss} trigger for the data run of interest, as
1819 described previously, in cut [2]. The lepton veto is applied in cut [5]. These two cuts
1820 are only used for the signal region selection.

1821 The rest of the preselection is used for the signal region and control regions used
1822 for background estimation. These cuts on scaleful variables used by previous searches
1823 are mostly used for the reduction of the dataset to a manageable size. Signal models
1824 with sensitivity to lower values of these scaleful variables have been ruled out by
1825 previous searches[124]. The final cut is on m_{eff} , which is the scalar sum of all jets and
1826 E_T^{miss} . This is the final discriminating variable used in the complementary search to
1827 this thesis, which is also presented in [115].

Cut	Description	
1	Good Runs List	Veto events with intolerable detector errors
2	Trigger	HLT_xe70 (2015), HLT_xe80_tclcw_L1XE50, or HLT_xe100_mht_L1XE50 (2016)
3	Event cleaning	Veto for noncollision background, noise bursts, and cosmic rays
4	Lepton veto	No leptons with $p_T > 10$ GeV after overlap removal
5	E_T^{miss} [GeV] >	250
6	$p_T(j_1)$ [GeV] >	200
7	$p_T(j_2)$ [GeV] >	50
8	m_{eff} [GeV] >	800

Table 8.2: Preselection for the various event topologies used in the analysis.

1828 Signal regions

1829 We define a set of signal regions using the RJR variables previously described.
 1830 These signal regions are split into three general categories: squark pair production
 1831 SRs, gluino pair production SRs, and compressed production SRs. Within these
 1832 general SRs, we have a set of signal regions targetting different mass splittings of the
 1833 sparticle and LSP.

1834 A schematic of this strategy is shown in 8.1. This type of plane is how most
 1835 (R -parity conserving) SUSY searches are organized in both ATLAS and CMS. The
 1836 horizontal axis is the mass of the sparticle considered. In the case of this thesis,
 1837 this will be the squark or gluino mass. On the horizontal axis, we place the LSP mass.
 1838 These are the two free parameters of the simplified models considered here. Our
 1839 search occurs in this two-parameter space. Each signal region targets some portion
 1840 of this plane. As shown in the figure, a new iteration of a search will use a set of
 1841 signal regions which have sensitivity just beyond those of the previous exclusions.
 1842 The choice of how many signal regions to use to fully cover this plane is in many
 1843 ways a matter of judgment, as it is important to avoid over or under/over-fitting
 1844 to the signal models of interest. To take the extreme examples, One signal region

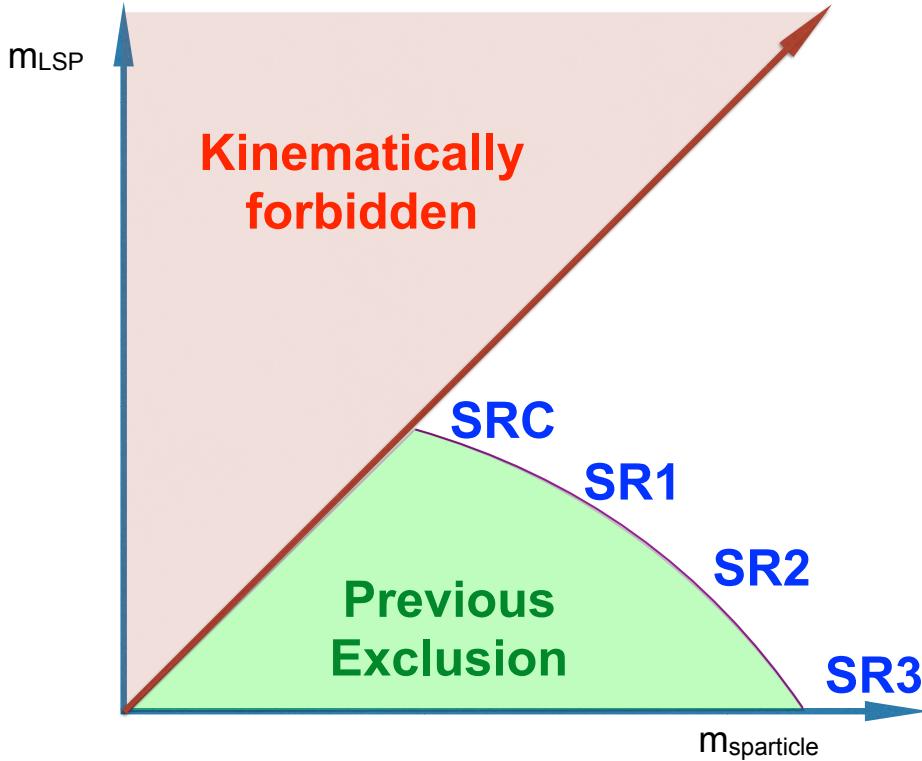


Figure 8.1: Schematic leading the development of the SUSY signal regions in this thesis. A variant of this schematic is used for most SUSY searches on ATLAS and CMS.

1845 will obscure the different phenomena in signal events with large versus small mass
 1846 splittings, leading to underfitting. Binning as finely as possible² leads to overfitting
 1847 due to the fluctuations present in the signal and background events passing the various
 1848 selections selection. In this thesis, we use six squark signal regions, six gluino signal
 1849 regions, and five compressed regions.

1850 The full table defining all signal regions is shown in 8.3. In all cases, the signal
 1851 region selections contain a combination of scaleful and scaleless cuts. Emphasis
 1852 on cuts on scaleful variables provide stronger sensitivity to larger mass splittings,
 1853 while additional sensitivity to smaller mass splittings is found using stronger cuts on
 1854 scaleless variables. One envisions walking from SR1 (with tight scaleless cuts and

²This can be defined as having a signal region for each simulated signal sample, which for this analysis is ~ 100 .

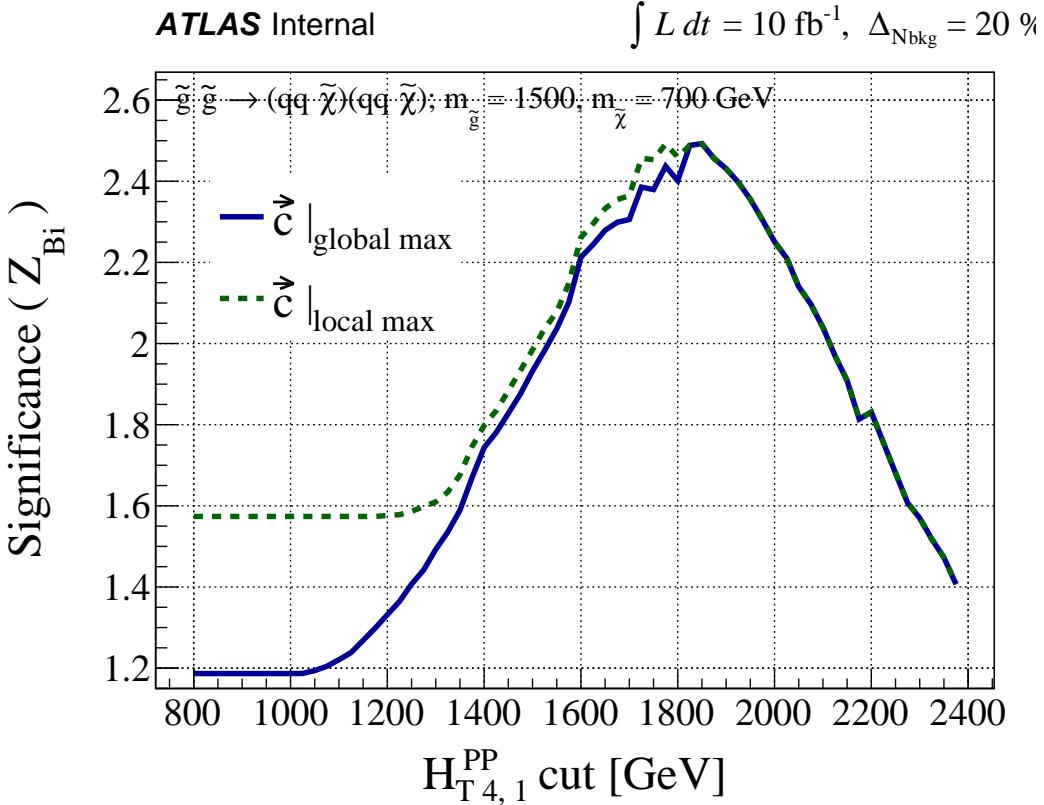


Figure 8.2: Optimization of the $H_{T,4,1}^{PP}$ cut for a gluino signal model with $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (1500, 700)$ GeV assuming 10 fb^{-1} and an uncertainty of 20% on the background estimate.

1855 loose scaleful cuts) in 8.1 towards SR3 by loosening the scaleless cuts and tightening
 1856 the scaleful cuts. We will see this strategy at work in each set of signal regions.

1857 We have already described the useful variables in the previous chapter. The
 1858 question is how to choose the optimal cuts for a given set of signal models, which are
 1859 grouped in the mass splitting space. This was done by a brute force scan over the
 1860 cut values, using a guess of integrated luminosity with a fixed systematic uncertainty
 1861 scenario; the value of the systematic uncertainty is motivated by that from previous
 1862 analyses. We choose the lowest cut value that maximizes the Z_{Bi} , as described in
 1863 [125]. This figure of merit gives conservative estimates, as compared to i.e. S/\sqrt{B} .
 1864 A figure showing an example of this selection tuning procedure is shown in 8.2.

1865 The compressed selections are split into five regions (SRC1-5), and due to the

1866 simplified nature of the compressed decay tree, has sensitivity in both the gluino
1867 and squark planes. The compressed regions target mass splittings with $m_{\text{sparticle}} -$
1868 $m_{\text{LSP}} \tilde{<} 200 \text{ GeV}$. For the compressed region, $M_{T,S}$ is the primary scaleful variable.
1869 We can see the general strategy of lowering increasing scale cuts while decreasing the
1870 scaleless cuts here. SRC1 targets the most compressed scenarios, with mass splittings
1871 of less than 25 GeV, and has the loosest $M_{T,S}$ cut coupled with the tightest R_{ISR} and
1872 $\Delta\phi_{\text{ISR},I}$ cuts. SRC4 and SRC5 target mass splittings of ~ 200 GeV, and are coupled
1873 with the loosest scaleless cuts on R_{ISR} and $\Delta\phi_{\text{ISR},I}$. We also note that SRC4 and
1874 SRC5 have differing cuts on N_{jet}^V , since these SRs are closest to the noncompressed
1875 regions, and can be seen as the “crossover” where the differences between squark and
1876 gluino production begins to become manifest.

1877 The squark regions (for noncompressed spectra) are organized into six signal
1878 regions. These are labeled by a numeral 1-3 and letter a/b. SRs sharing a common
1879 numeral i.e. SRS1a and SRS1b share a common set of scaleless cuts, while differing in
1880 the main scale variable $H_{T,2,1}^{PP}$. The two SRs for each set of scaleless cuts, only differing
1881 in the main scale variable, can be seen in a naïve way as providing sensitivity to a
1882 range of luminosity scenarios³. As before, we see that the scaleless cuts are loosened
1883 as we tighten the scaleful cuts, as we move across the table from SRS1a to SRS3b.
1884 This provides strong sensitivity to signal models with intermediate mass splittings with
1885 SRS1a to large mass splittings with SR3b.

1886 The gluino signal regions are organized entirely analogously to the squark signal
1887 regions. There are six gluino signal regions, again labeled via a numeral 1-3 and letter
1888 a/b. Those SRs sharing a common numeral have a common set of scaleless cuts, but
1889 differ in their main scale variable $H_{T,4,1}^{PP}$. The SRs follow scaleless vs scaleful strategy,
1890 with SRG1 having the loosest scaleful cut cuts coupled with the strongest scaleless

³These SRs were defined before the entire collision dataset was produced, and thus needed to be robust in cases where the LHC provided significantly different than expected performance.

1891 cuts, and the converse being true in SRG3. As in the squark case, this strategy
1892 provides strong expected sensitivity throughout the gluino-LSP plane.

Targeted signal	$\tilde{s}\tilde{s}, \tilde{s} \rightarrow q\tilde{\chi}_1^0$									
Requirement	Signal Region									
	RJR-S1		RJR-S2		RJR-S3					
$H_{1,1}^{PP}/H_{2,1}^{PP} \geq$	0.6		0.55		0.5					
$H_{1,1}^{PP}/H_{2,1}^{PP} \leq$	0.95		0.96		0.98					
$p_{PP, z}/(p_{PP, z}^{lab} + H_{T, 2,1}^{PP}) \leq$	0.5		0.55		0.6					
$p_{j2, T}^{PP}/H_{T, 2,1}^{PP} \geq$	0.16		0.15		0.13					
$\Delta_{QCD} >$	0.001									
	RJR-S1a	RJR-S1b	RJR-S2a	RJR-S2b	RJR-S3a	RJR-S3b				
$H_{T, 2,1}^{PP}$ [GeV] >	1000	1200	1400	1600	1800	2000				
$H_{1,1}^{PP}$ [GeV] >	1000		1400		1600					
Targeted signal	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$									
Requirement	Signal Region									
	RJR-G1		RJR-G2		RJR-G3					
$H_{1,1}^{PP}/H_{4,1}^{PP} \geq$	0.35		0.25		0.2					
$H_{T, 4,1}^{PP}/H_{4,1}^{PP} \geq$	0.8		0.75		0.65					
$p_{PP, z}/(p_{PP, z}^{lab} + H_{T, 4,1}^{PP}) \leq$	0.5		0.55		0.6					
$\min(p_{j2, T, i}^{PP}/H_{T, 2,1}^{PP}) \geq$	0.12		0.1		0.08					
$\max(H_{1,0}^{Pi}/H_{2,0}^{Pi}) \leq$	0.95		0.97		0.98					
$ \frac{2}{3}\Delta\phi_{V,P}^{PP} - \frac{1}{3}\cos\theta_p \leq$	0.5		—		—					
$\Delta_{QCD} >$	0									
	RJR-G1a	RJR-G1b	RJR-G2a	RJR-G2b	RJR-G3a	RJR-G3b				
$H_{T, 4,1}^{PP}$ [GeV] >	1000	1200	1500	1900	2300	2700				
$H_{1,1}^{PP}$ [GeV] >	600		800		900					
Targeted signal	compressed spectra in $\tilde{s}\tilde{s}$ ($\tilde{s} \rightarrow q\tilde{\chi}_1^0$); $\tilde{g}\tilde{g}$ ($\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$)									
Requirement	Signal Region									
	RJR-C1	RJR-C2₁₅₃	RJR-C3	RJR-C4	RJR-C5					
$R_{ISR} \geq$	0.9	0.85	0.8	0.75	0.70					
$\Delta\phi_{ISR, I} >$	3.1	3.07	2.95	2.95	2.95					

Requirement	Signal Region				
	RJR-C1	RJR-C2₁₅₃	RJR-C3	RJR-C4	RJR-C5
$R_{ISR} \geq$	0.9	0.85	0.8	0.75	0.70
$\Delta\phi_{ISR, I} >$	3.1	3.07	2.95	2.95	2.95

1893 8.3 Background estimation

1894 We describe here the method of background estimation. In this thesis, we detail what
 1895 is colloquially called a “cut-and-count” analysis. This is in contrast to a “shape fit”
 1896 analysis, where one needs to consider the details of the variable distribution shapes.
 1897 Instead, we must ensure the overall normalization of the Standard Model backgrounds
 1898 are correct in the regions of phase space considered in the analysis. In order to
 1899 do this, we define a set of *control regions* which are free of SUSY contamination
 1900 based on the previously excluded analysis. We compare the number of events present
 1901 in the control regions in simulation with that in data to define a *transfer factor*
 1902 (TF). We extrapolate the number of expected events from each background using
 1903 this transfer factor to translate from the , which provides our final estimate of the
 1904 SM background in the corresponding signal region. To be explicit, each signal region
 1905 SR has a corresponding set of control regions.

More precisely, for a given signal region, we are attempting to estimate the value $N_{\text{SR}}^{\text{data}}$ for a given background. This value is estimated using the following equation:

$$N_{\text{SR}}^{\text{data,est}} = N_{\text{CR}}^{\text{data,obs}} \times \text{TF}_{\text{CR}} \equiv N_{\text{CR}}^{\text{data,obs}} \times \left(\frac{N_{\text{SR}}^{\text{MC}}}{N_{\text{CR}}^{\text{MC}}} \right) \quad (8.1)$$

1906 where the transfer factor TF is taken directly from MC. The two ingredients to our
 1907 estimation of $N_{\text{SR}}^{\text{data,obs}}$ is thus $N_{\text{CR}}^{\text{data,obs}}$ and the transfer factor taken from MC.

The transfer factor method is potentially more straightforward written in the following way:

$$N_{\text{SR}}^{\text{data,est}} = N_{\text{SR}}^{\text{MC}} \times \left(\frac{N_{\text{CR}}^{\text{data,obs}}}{N_{\text{CR}}^{\text{MC}}} \right) \equiv N_{\text{SR}}^{\text{MC}} \times \mu_{\text{CR}}. \quad (8.2)$$

1908 In this form, the correction to the overall normalization is explicit. The ratio $\frac{N_{\text{CR}}^{\text{data,obs}}}{N_{\text{CR}}^{\text{MC}}}$
 1909 which we call μ informs us how to scale $N_{\text{SR}}^{\text{MC}}$ in order to get the right overall
 1910 normalization. The assumption made with this method is that the overall shape of
 1911 the distribution should not change “that much” as one extrapolates to the signal
 1912 region.

1913 The CR definitions are motivated and designed according to two (generally
1914 competing) requirements:

- 1915 1. Statistical uncertainties due to low CR statistics
1916 2. Systematic uncertainties related to the extrapolation from the CR to the SR.

1917 This motivates the desire to make the control regions as similar as possible
1918 to the signal regions without risking signal contamination while ensuring high
1919 purity in the targeted SM background.

1920 In principle, one can also apply data-driven corrections to the TF obtained for each
1921 CR.

1922 In order to validate the transfer factors obtained from MC, we also develop a series
1923 of *validation regions* (VRs). These regions are generally designed to be “in between”
1924 the control region and signal region selections in phase space, and thus provide a
1925 check on the extrapolation from the control regions into the signal regions. Despite
1926 their closeness in phase space to the signal regions, they are also designed to have
1927 low signal contamination.

1928 In practice, we perform this estimation procedure simultaneously across all control
1929 regions; we describe this later. We only note this here since we can also apply
1930 Eq.8.1 to measure the contamination of a control region with another background as
1931 well. This procedure accounts for the correlations between regions due to correlated
1932 systematic uncertainties. We next describe the control region selection for the major
1933 SM backgrounds for the analysis.

1934 **Control Regions**

1935 As was hinted at in the discussion of Monte Carlo generators, the primary back-
1936 grounds of note in this analysis are $Z + \text{jets}$, $W + \text{jets}$, $t\bar{t}$, and QCD events. There is
1937 also a minor background from diboson events which is taken directly from MC with an

1938 uncertainty of 50%. We describe the strategy to estimate these various backgrounds
 1939 here. A summary table is shown in 8.4. All distributions shown in this section use
 1940 the scaling factors μ from the background fits, which we describe later.

CR	SM background	CR process	CR event selection
Meff/RJR-CR γ	$Z(\rightarrow \nu\bar{\nu}) + \text{jets}$	$\gamma + \text{jets}$	Isolated photon
Meff/RJR-CRQ	Multi-jet	Multi-jet	$\Delta_{\text{QCD}} < 0$ reversed requirement on $H_{1,1}^{PP}$ (RJR-S/G) or $R_{\text{ISR}} < 0.5$ (RJR-C)
Meff/RJR-CRW	$W(\rightarrow \ell\nu) + \text{jets}$	$W(\rightarrow \ell\nu) + \text{jets}$	$30 \text{ GeV} < m_T(\ell, E_T^{\text{miss}}) < 100 \text{ GeV}$, b -veto
Meff/RJR-CRT	$t\bar{t}(\text{+EW})$ and single top	$t\bar{t} \rightarrow b\bar{b}qq'\ell\nu$	$30 \text{ GeV} < m_T(\ell, E_T^{\text{miss}}) < 100 \text{ GeV}$, b -tag

Table 8.4: Control regions used in this thesis.

1941 Events with a Z boson decaying to neutrinos in association with jets are the
 1942 primary irreducible background in the analysis. These events have true E_T^{miss} from
 1943 the decaying neutrinos, and can have significant values of the scaleful variables of
 1944 interest. Naively, one might expect us to use $Z \rightarrow \ell\ell$ as the control process of interest,
 1945 as $Z \rightarrow \ell\ell$ events are quite well-measured. Unfortunately, the $Z \rightarrow \ell\ell$ branching ratio
 1946 is about half of from $Z \rightarrow \nu\nu$, which necessitates loosening the control region selection
 1947 significantly. This leads to unacceptably large systematic uncertainties in the transfer
 1948 factor.

1949 Instead, photon events are used as the control region for the $Z \rightarrow \nu\nu$ events. We
 1950 label this photon control region as CRY. The photon is required to have $p_T > 150 \text{ GeV}$
 1951 to ensure the trigger is fully efficient. The kinematic properties of photon events
 1952 strongly resemble those of Z events when the boson p_T is significantly above the
 1953 mass of the Z boson. In this regime, the neutral bosons are both scaleless, and can be
 1954 treated interchangeably, up to the differences in coupling strengths. Additionally, the

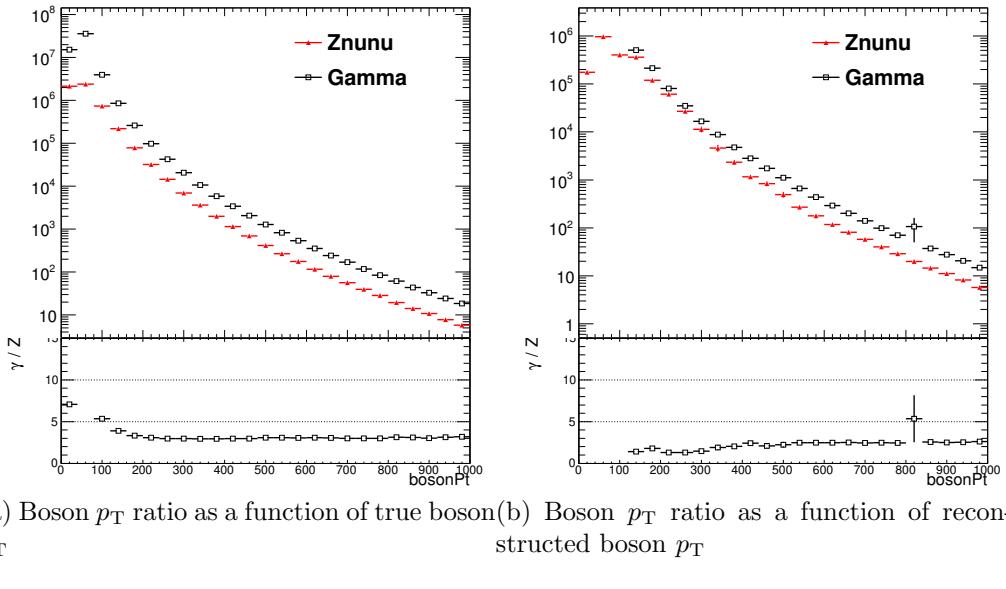


Figure 8.3

1955 cross-section for $\gamma + \text{jets}$ events is significantly larger than $Z + \text{jets}$ events above the Z
 1956 mass. These features are shown in 8.3 in simulated $Z \rightarrow \nu\nu$ truth and reconstructed
 1957 events. The reconstructed $Z \rightarrow \nu\nu$ events define the boson p_T as simply the E_T^{miss} .
 1958 In truth events, one clearly sees the effect of the Z mass below ~ 100 GeV, with a
 1959 flattening of the ratio above ~ 300 GeV. In reconstructed events, the effects are less
 1960 clear at low boson p_T , primarily due to cut sculpting from i.e. the trigger requirement
 1961 on photon events, which necessitates a higher p_T cut on photon events for the trigger
 1962 to remain fully efficient. Still, it is clear that the ratio flattens out at high boson p_T ,
 1963 and we are justified in the use of CRY to model the $Z + \text{jets}$ background.

1964 The CRY kinematic selection is slightly looser in the scaleful variables for the
 1965 noncompressed regions to provide sufficient control region statistics. This is chosen
 1966 to be $H_{1,1}^{PP} > 900$ GeV ($H_{1,1}^{PP} > 550$ GeV) for the squark (gluino) regions to minimize
 1967 the corresponding statistical and systematic uncertainties.

1968 One additional correction scale factor is applied to $\gamma + \text{jets}$ events before calculat-
 1969 ing the transfer factors. This is known as the κ method, which is used to determine
 1970 the disagreement arising from the use of a LO generator for photon events vs. a NLO

1971 generator for Z +jets events, which can reduce the theoretical uncertainties from
1972 this disagreement. One can see this as a measurement of the k-factor for the LO
1973 γ +jets sample. This is effectively done with an auxiliary CRZ region, defined using
1974 two leptons with an invariant mass close with 25 GeV of the Z mass. The correction
1975 factor derived for this purpose is $\kappa = 1.39 \pm 0.05$.

1976 Distributions of CRY in squark, gluino, and compressed regions are shown in ??.
1977 One can see the quite high purity of CRY in photon events from these plots.

Event with a W boson decaying leptonically via $W \rightarrow \ell\nu$ can also enter the signal region. In this case, we use leptonically to include all leptons (e, μ, τ). The W +jets events passing the event selection either have a hadronically-decaying τ , with a neutrino supplying E_T^{miss} , or the case where a muon or electron is misidentified as a jet or missed completely due to the limited detector acceptance. To model this background, we use a sample of one-lepton events with a veto on b-jets, which we label CRW. The lepton is required to have $p_T > 27$ GeV to guarantee a fully efficient trigger. We then treat this single lepton as a jet for purposes of the RJR variable calculations. We apply a kinematic selection on the transverse mass:

$$m_T = \sqrt{2p_{T,\ell}E_T^{\text{miss}}(1 - \cos\phi_e - E_\phi^{\text{miss}})}, \quad (8.3)$$

1978 around the W mass: $30 \text{ GeV} < m_T < 100 \text{ GeV}$. Checks in simulation shows that
1979 these requirements give a sample of high purity $W \rightarrow \ell\nu$ background. Due to low
1980 statistics using the kinematic cuts imposed in the signal regions, the control region
1981 kinematic cuts are slightly loosened with respect to the signal region cuts. We use
1982 the loosest cut in any signal region as the control region selection for all signal
1983 regions. More clearly, the control region selection corresponding to each signal region
1984 is the *same*. As discussed above, this leads to a tolerable increase in the systematic
1985 uncertainty from the extrapolation from the CR to the SR when compared to the
1986 resulting statistical uncertainty.

1987 Distributions of CRW in squark, gluino, and compressed regions are shown in ??.

1988 There is high purity in $W+\text{jets}$ events in the control region corresponding to all

1989 signal regions.

1990 Top events are also an important background, for the same reasons as the

1991 $W+\text{jets}$ background, due to the dominant top decay channel of $t \rightarrow Wb$. For a

1992 top event to be selected by the analysis criteria, as in the case of $W+\text{jets}$, we expect

1993 a W to decay via a τ lepton which decays hadronically or one a muon or electron to

1994 be misidentified as a jet or be outside the detector acceptance. We are not so worried

1995 about hadronic or all dileptonic tops: hadronic $t\bar{t}$ events generally have low E_T^{miss}

1996 (and $H_{1,1}^{PP}$) so they will not pass the kinematic cuts, while dileptonic $t\bar{t}$ events have a

1997 lower cross-section and good reconstruction efficiency from the two leptons. We are

1998 thus primarily concerned with semileptonic $t\bar{t}$ events with E_T^{miss} from the neutrino.

1999 To model this background, we use the same selection as the W selection, but require

2000 that one of the jets chosen by the analysis has at least one b -tag. This selection has

2001 quite high purity, as we expect the $t\bar{t}$ background to have two b -jets. Thus with

2002 the 70% b -tagging efficiency working point used in this analysis, ignoring (small)

2003 correlations between the two b -tags, we expect to tag one of the b -jets greater than

2004 90% of the time. As with CRW, we need to loosen the cuts applied to CRT with

2005 respect to the signal region in order to gain sufficient expected data statistics. We

2006 use exactly the same scheme; the CRT corresponding to each SR is identical, due to

2007 using the loosest set of cuts among the SRs. This comes at the cost of an increased

2008 systematic uncertainty for this extrapolation, but it was determined that this tradeoff

2009 resulted in the lowest overall uncertainty.

2010 Distributions of CRT in squark, gluino, and compressed regions are shown in ??.

2011 There is high purity in top events in the control region corresponding to all signal

2012 regions.

2013 The final important background is the QCD background. As briefly discussed in

2014 the previous chapter, QCD backgrounds are difficult, for a few reasons we describe
2015 here. The large cross-section for QCD events means that even very rare extreme
2016 mismeasurements can be seen in our signal regions. However, as these events are
2017 very rare, one requires extreme confidence in the tails of the distributions to use
2018 simulation as an input for background estimation. To avoid this, the strategy in
2019 these cases is to apply a strong enough cut to expect *zero* QCD events in the signal
2020 regions to avoid this issue. To produce a sample enriched in QCD, which we call CRQ,
2021 we reverse the Δ_{QCD} and $H_{1,1}^{PP}$ cuts. This analysis uses the jet smearing method, as
2022 described in [126]. This is a data-driven method which applies a resolution function
2023 to well-measured QCD events, which also an estimate of the impact of the jet energy
2024 mismeasurement on $E_{\text{T}}^{\text{miss}}$ and subsequently the RJR variables.

2025 Distributions of CRQ in squark, gluino, and compressed regions are shown in ??.
2026 There is high purity in top events in the control region corresponding to all signal
2027 regions.

2028 The final background of note in this background is the diboson background. This
2029 background is estimated directly from simulation. Due to the low cross-section of
2030 electroweak processes, this background is not significant in the signal regions. We
2031 assign a large ad-hoc 50% systematic on the cross-section, and do not attempt to
2032 define a control region for this background.

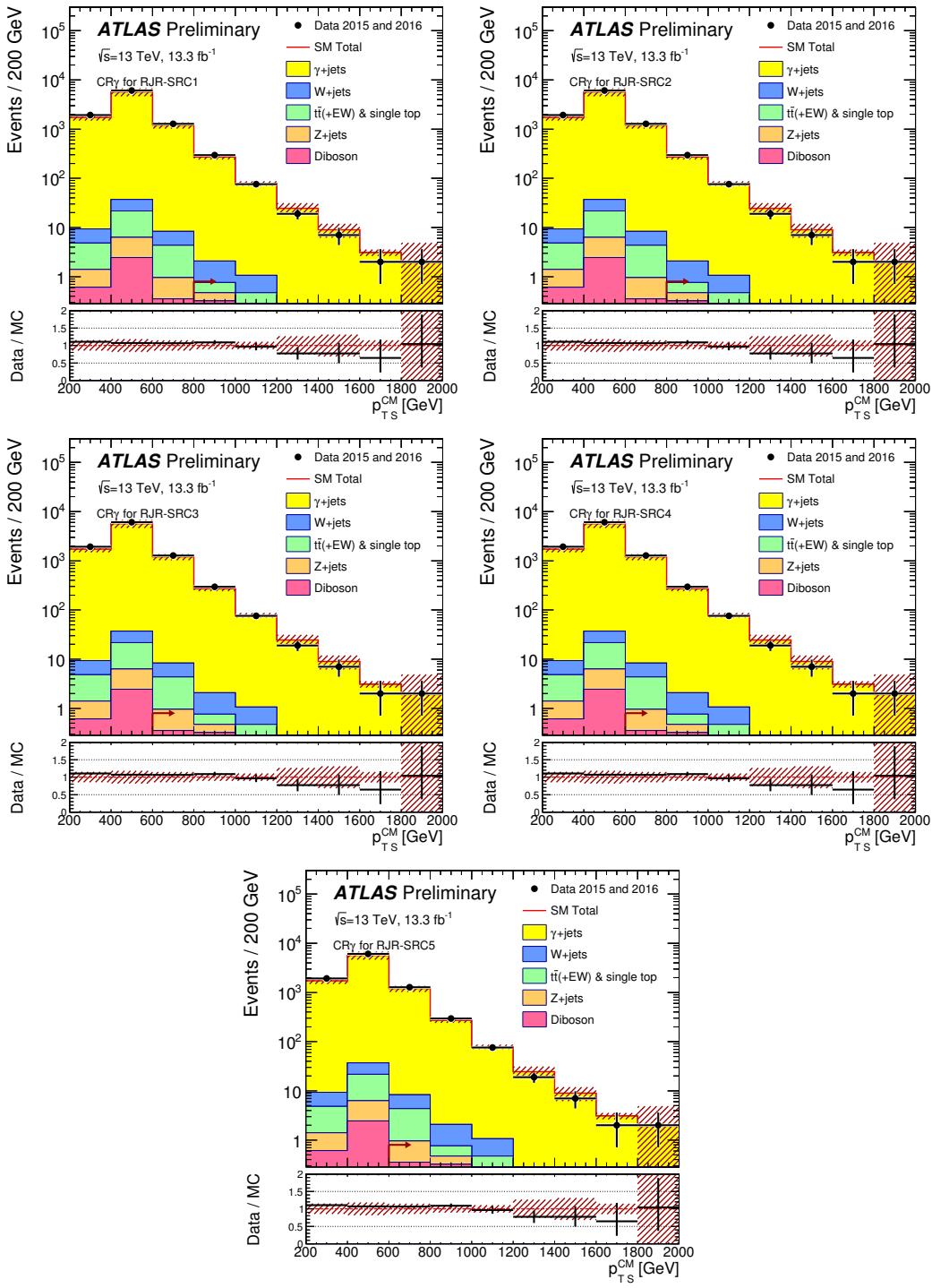


Figure 8.4: Scale variable distributions for the compressed CRY regions.

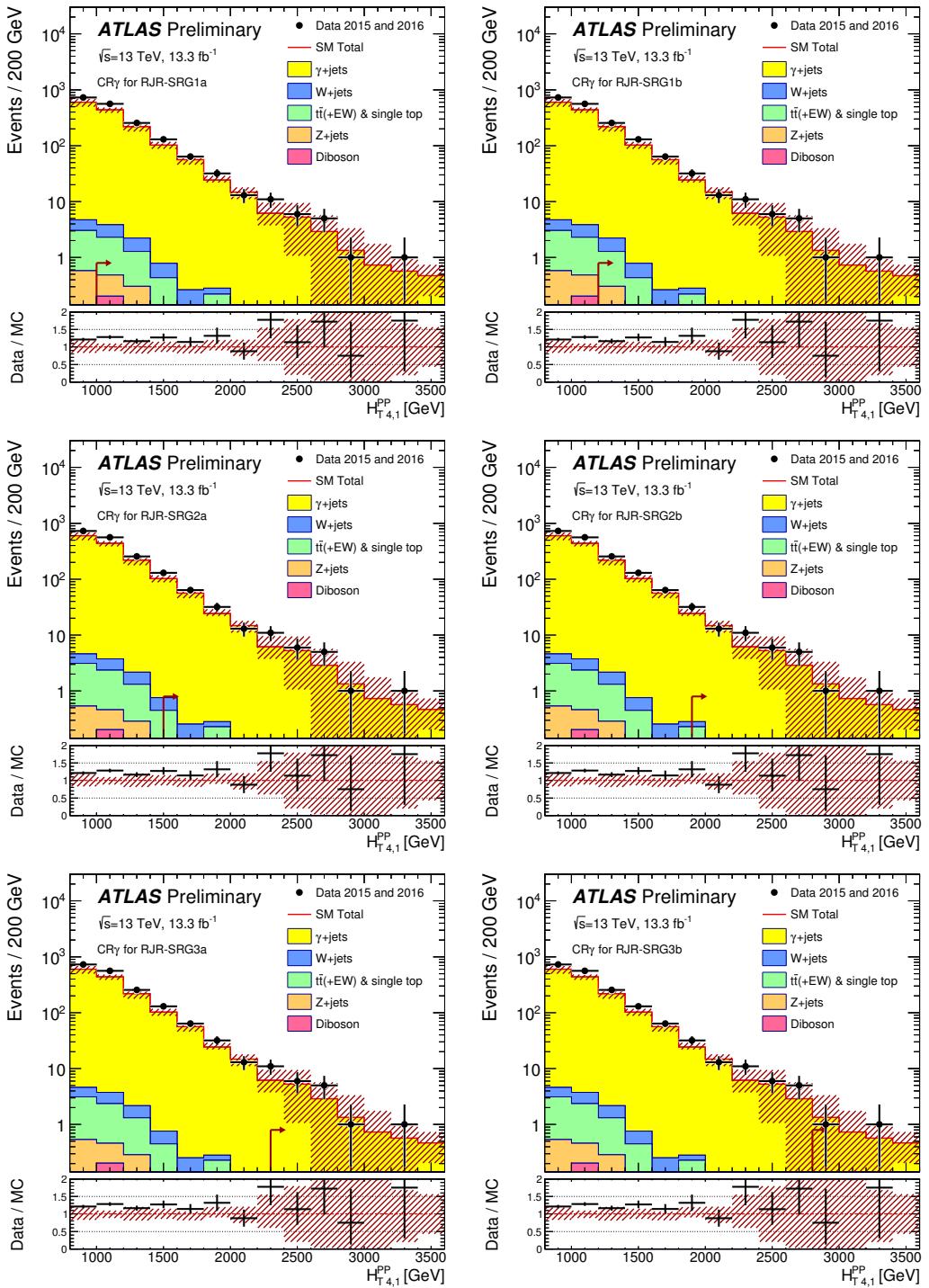


Figure 8.5: Scale variable distributions for the gluino CRY regions.

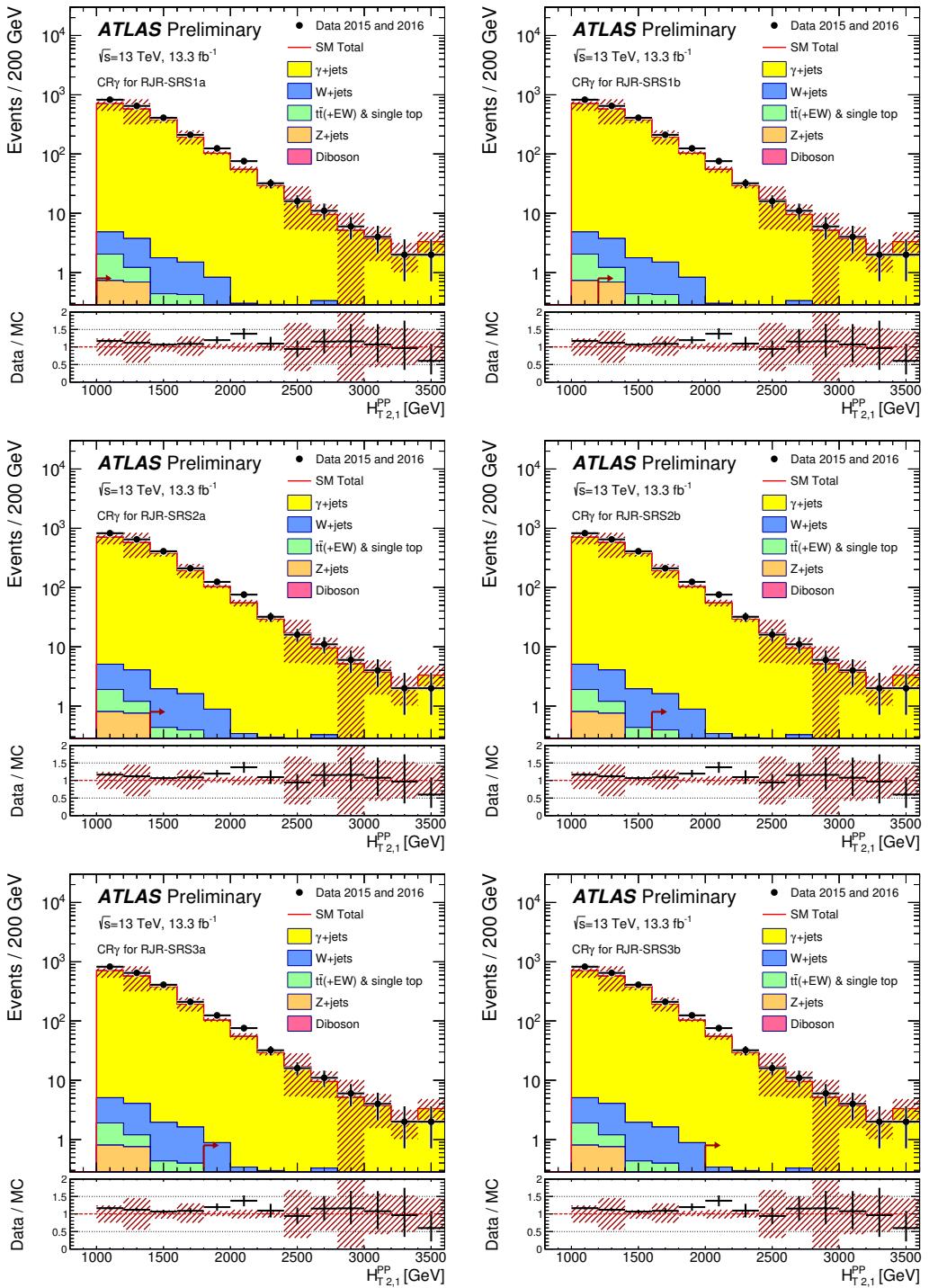


Figure 8.6: Scale variable distributions for the squark CRY regions.

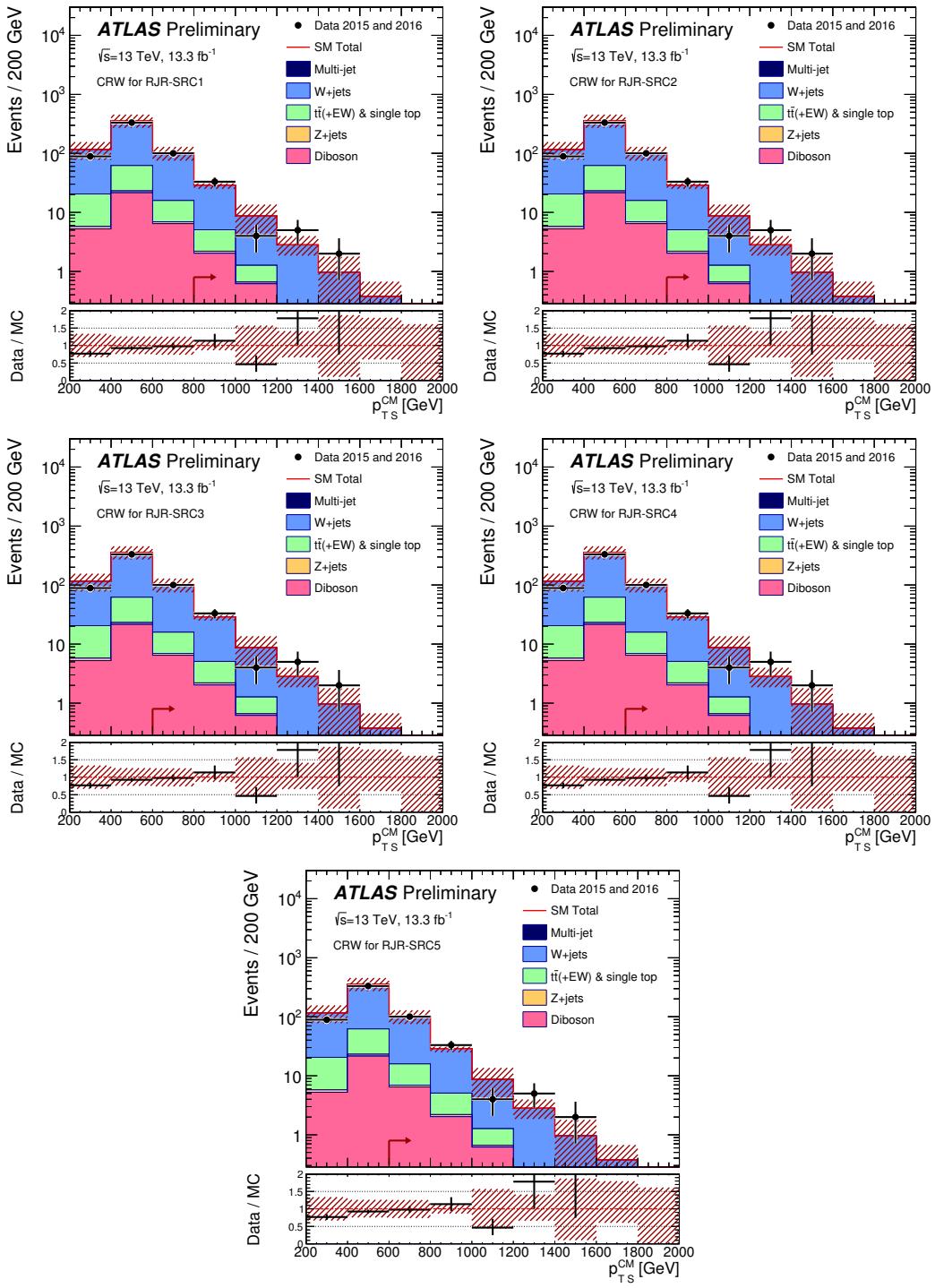


Figure 8.7: Scale variable distributions for the compressed CRW regions.

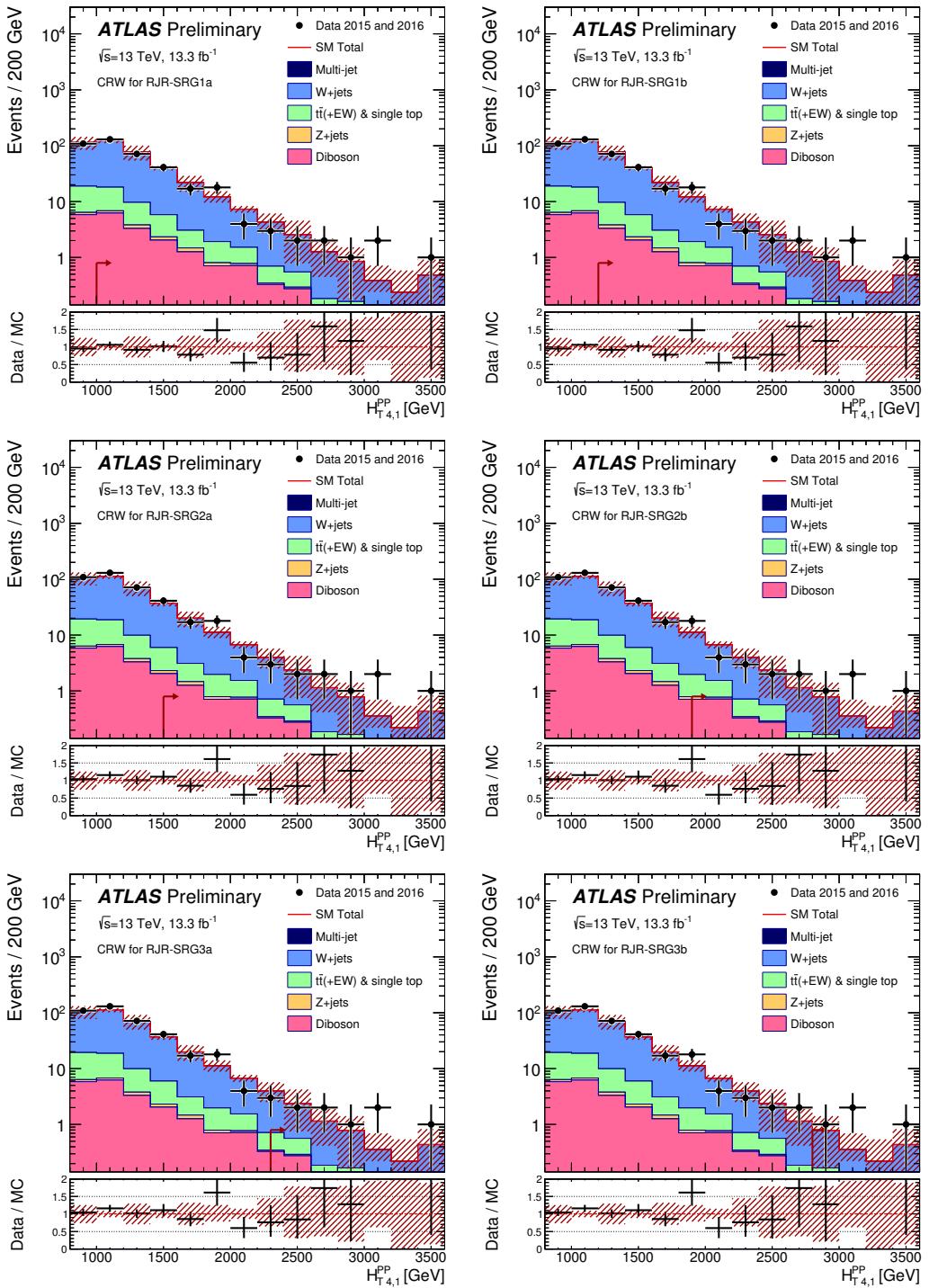


Figure 8.8: Scale variable distributions for the gluino CRW regions.

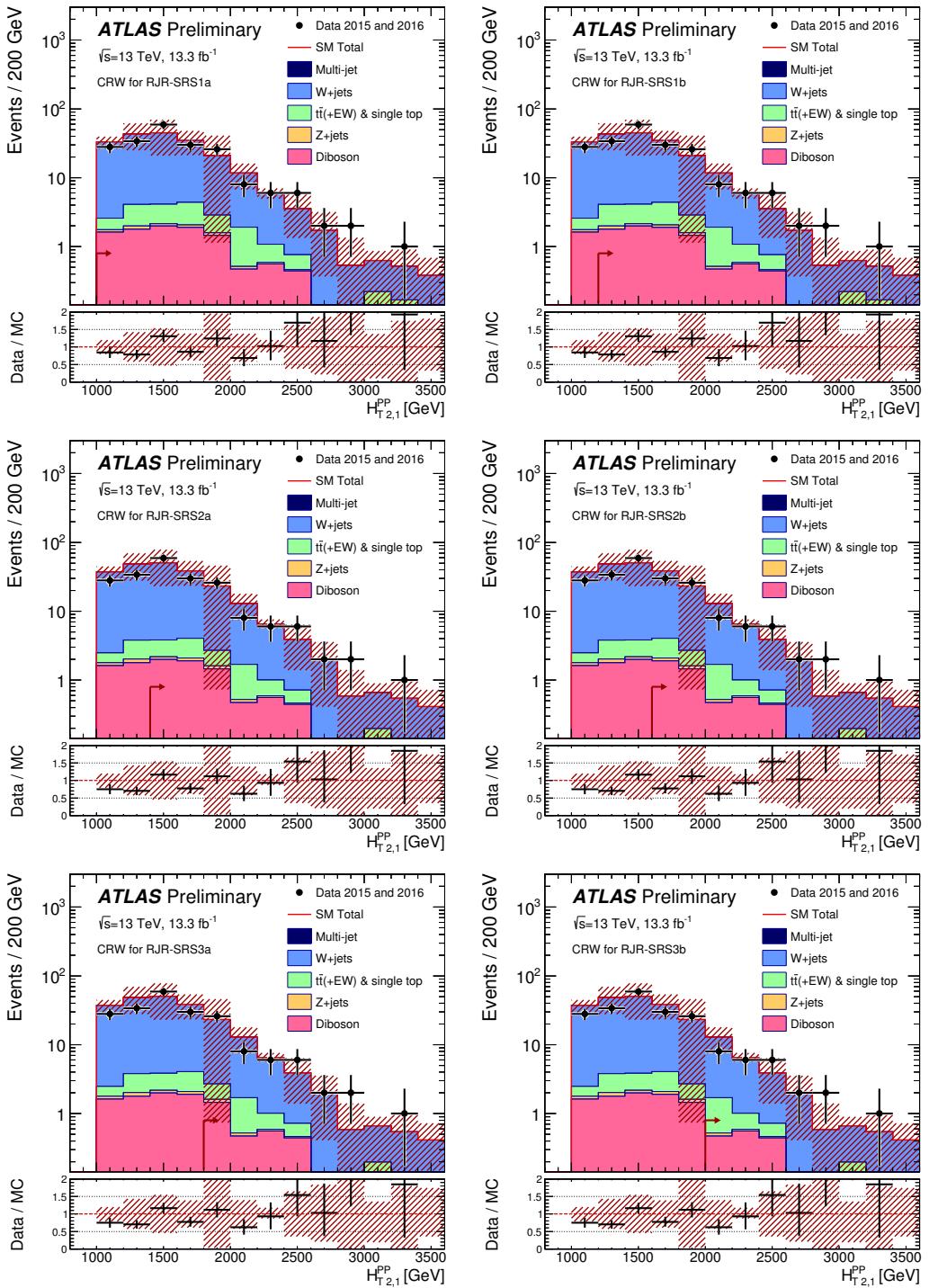


Figure 8.9: Scale variable distributions for the squark CRW regions.

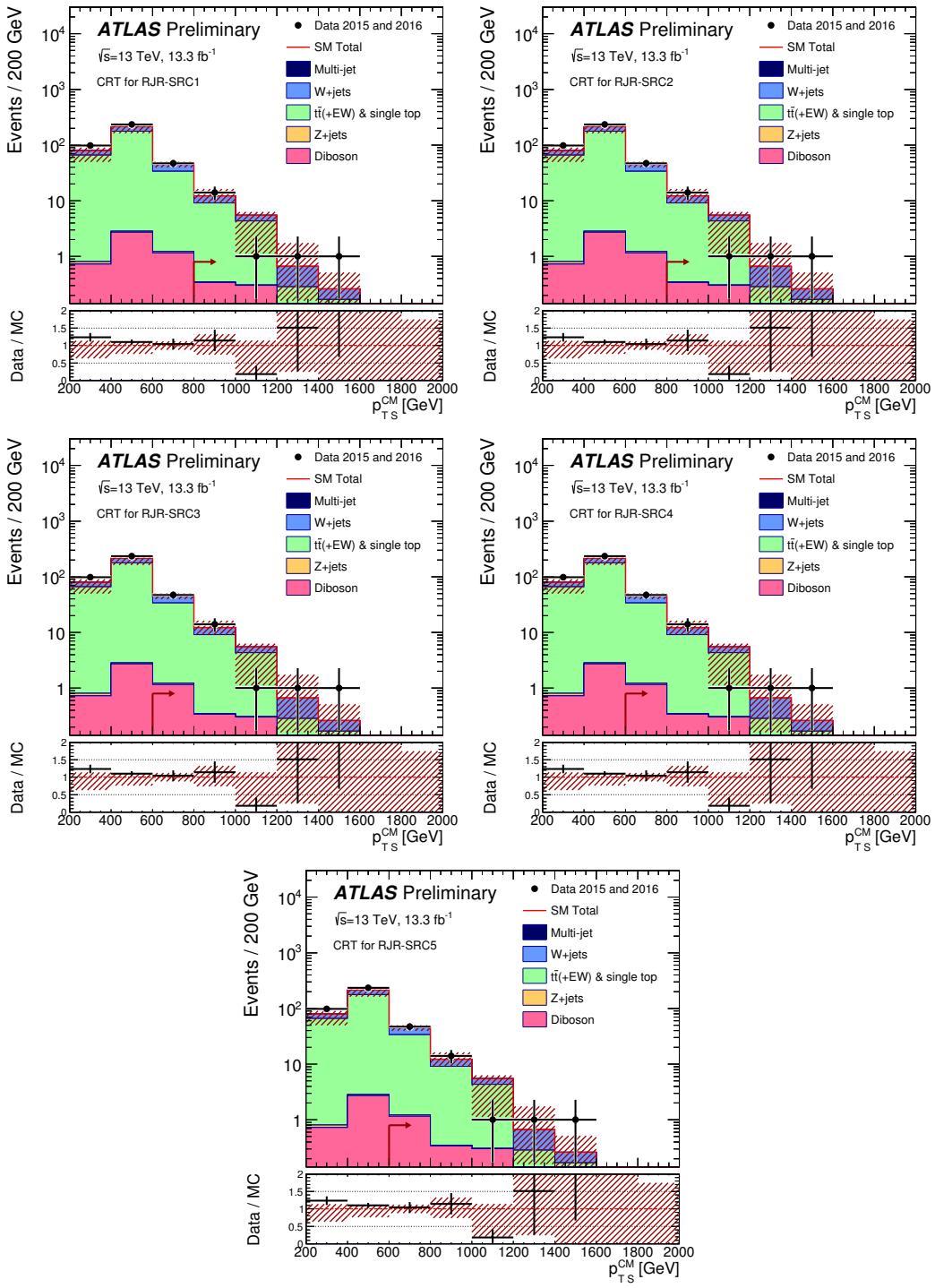


Figure 8.10: Scale variable distributions for the compressed CRT regions.

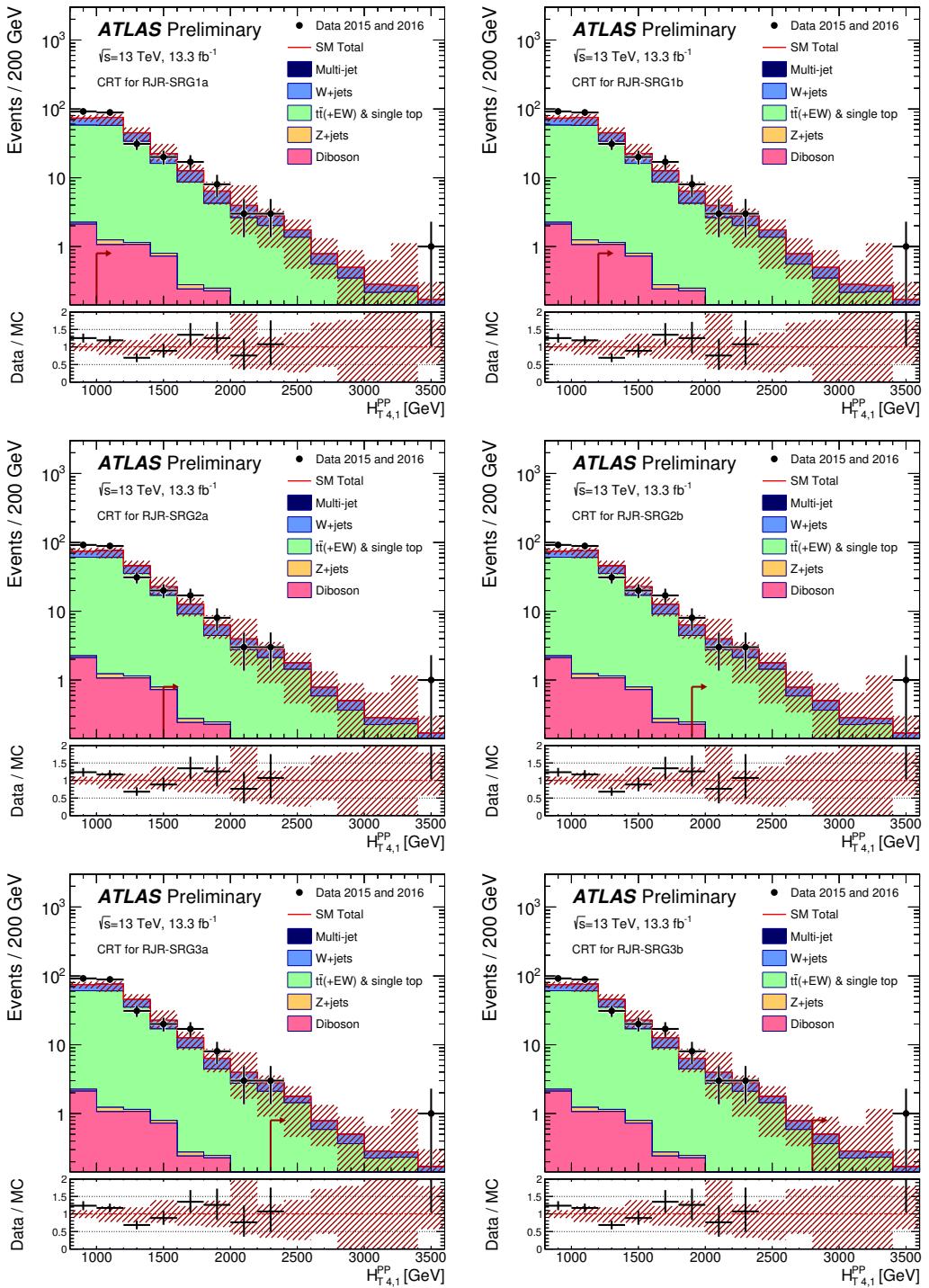


Figure 8.11: Scale variable distributions for the gluino CRT regions.

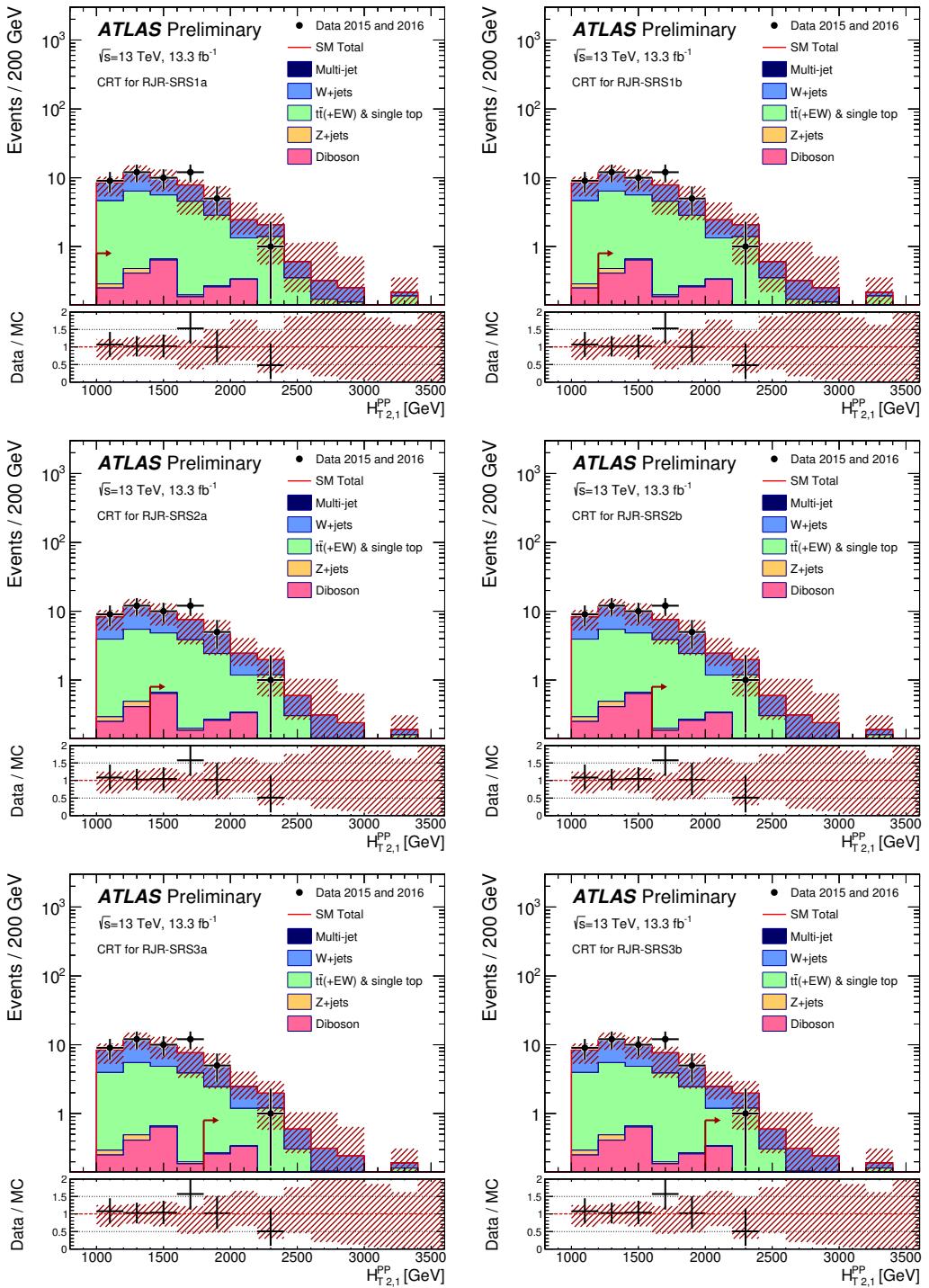


Figure 8.12: Scale variable distributions for the squark CRT regions.

2033 **Validation Regions**

2034 As discussed in general terms above, we define a set of validation regions to ensure
2035 we can properly model the particular backgrounds as we move closer to the SRs in
2036 phase space. We define at least one validation region for each major background.

2037 For the most important background $Z \rightarrow \nu\nu$, we use a series of validation regions.
2038 The primary validation region, which we label as VRZ, is defined by selecting lepton
2039 pairs of opposite sign and identical flavor which lie within $\pm 25\text{ GeV}$ of the Z boson mass.
2040 This selection has high purity for $Z \rightarrow \ell\ell$ events as seen in simulation. We treat the
2041 two leptons as contributions to the E_T^{miss} (as we did with the photon in CRY). This
2042 selection uses the same kinematic cuts as the signal region. We also define two VRs
2043 using the same event selection but looser kinematic cuts, which we label VRZa and
2044 VRZb. VRZa has a loosened selection on $H_{1,1}^{PP}$, again to the loosest value among the
2045 signal regions, as was done for CRW and CRt. VRZa has a loosened selection on
2046 the primary scaleful variable ($H_{T,2,1}^{PP}$ or $H_{T,4,1}^{PP}$), again to the loosest value among the
2047 signal regions, as was done for CRW and CRT. These two validation regions allow us
2048 to test the modeling of each of these variables individually, as well as allowing more
2049 validation region statistics in the signal regions with tighter cuts on these variables.

2050 For the compressed regions, these Z validation region were found lacking. The
2051 leptons are highly boosted in the compressed case, and the lepton acceptance was
2052 quite low due to lepton isolation requirements in ΔR . Instead, two fully hadronic
2053 validation region were developed for the compressed regions. The first, VRZc has
2054 identical requirements to the signal regions with an inverted requirement on $\Delta\phi_{ISR,I}$.
2055 From simulation, this region was found to be at least 50% pure in Z events, which
2056 was considered enough to validate this background in this extreme portion of phase
2057 space. For additional validation region statistics, we also developed VRZca, which
2058 takes again uses the loosest set of cuts from each signal region. Note this means that
2059 each compressed signal region has an identical VRZca.

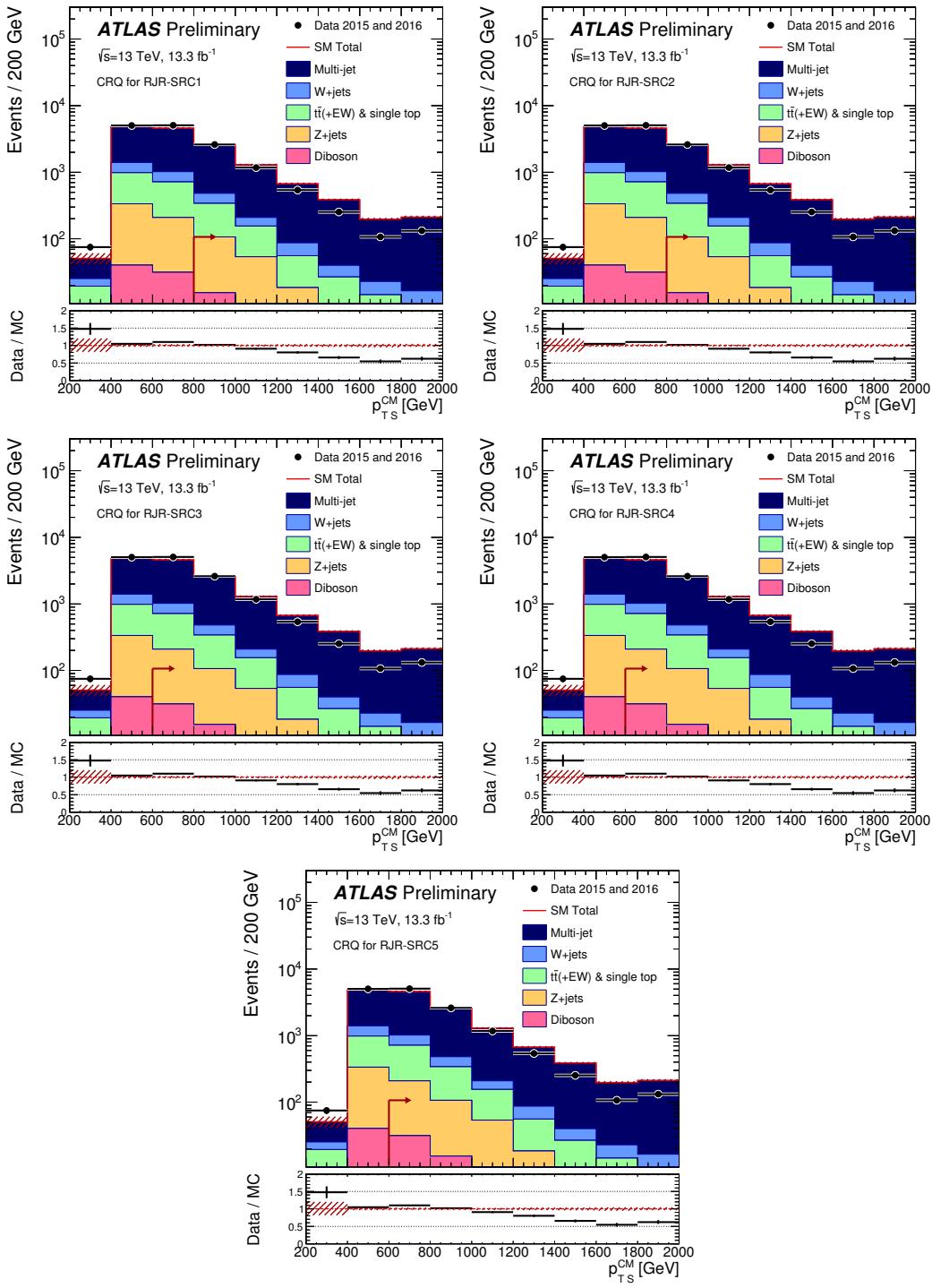


Figure 8.13: Scale variable distributions for the compressed CRQ regions.

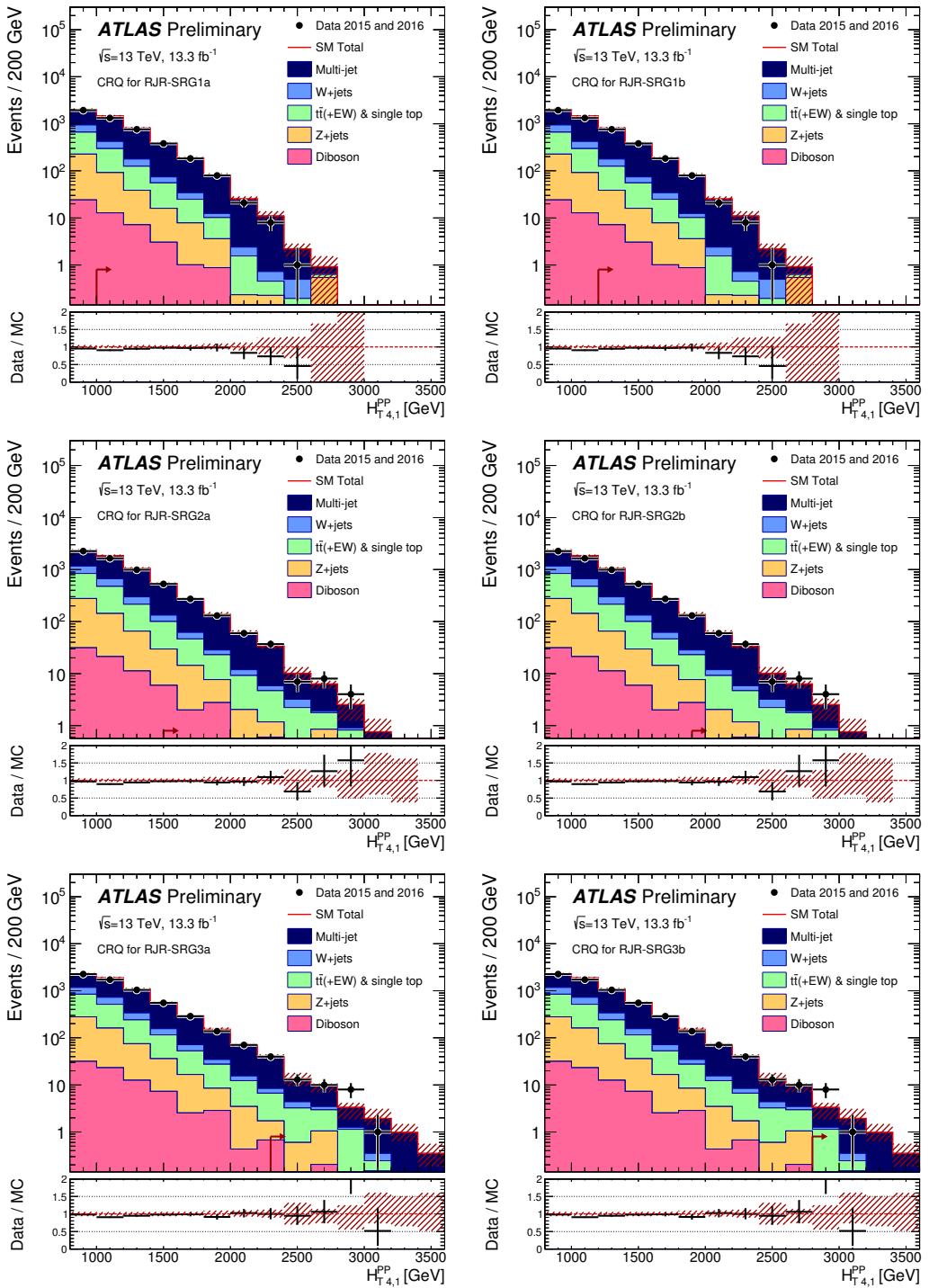


Figure 8.14: Scale variable distributions for the gluino CRQ regions.

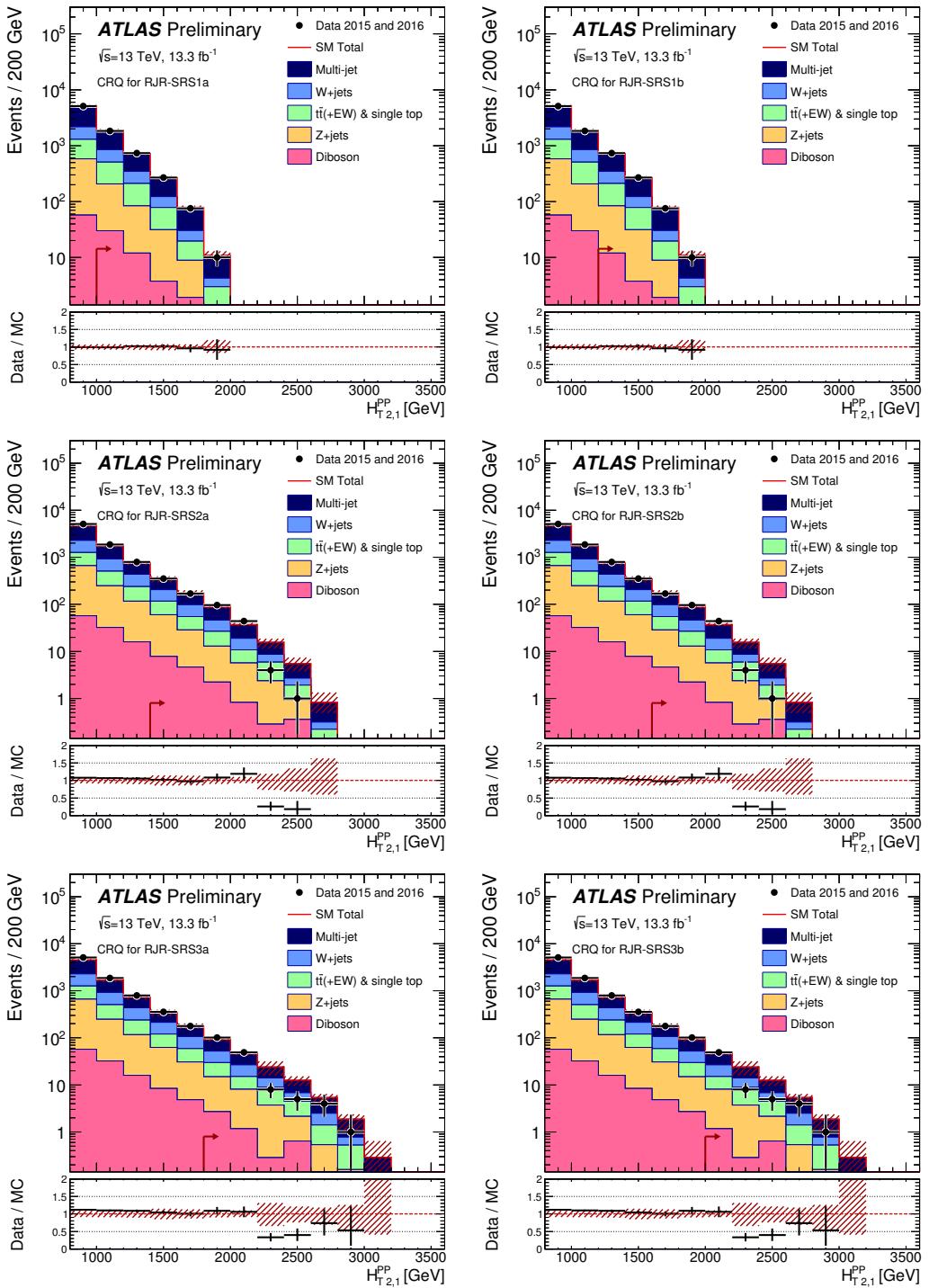


Figure 8.15: Scale variable distributions for the squark CRQ regions.

2060 The top and W validation regions use the same event selection as the correspond-
 2061 ing control regions, as described above. However, unlike the control regions, these
 2062 validation regions reimpose the SR scaleful variable selections, to be closer in phase
 2063 space to the hadronic signal regions. In the same way as we did for VRZa and
 2064 VRZb, we also define auxiliary VRs which loosen the cuts on the scale variables. We
 2065 define VRTa (VRWa) as VRT (VRW) with the same loosened cut on $H_{1,1}^{PP}$ and VRTb
 2066 (VRWb) as VRT (VRW) with the same loosened cut on the primary scale variable.

2067 The final set of validation regions are those defined to check the estimation of
 2068 the QCD background. VRQ is defined to be identical to the corresponding CRQ,
 2069 but again we use the full SR region cuts for the scaleful variables. This selection is
 2070 then closer to the corresponding signal region to validate the CRQ estimate. We also
 2071 define the auxiliary validation regions VRQa and VRQb for the noncompressed signal
 2072 regions. In this case, we reimpose one of the two inverted cuts in CRQ with respect
 2073 to the signal regions, to make each one even closer to the SRs. In CRQa (CRQb), we
 2074 reimpose the $H_{1,1}^{PP}$ (Δ_{QCD}).

2075 For the compressed case, we again define a separate validation region, due to
 2076 the special kinematics probed. We construct a validation region which is the same as
 2077 CRQ, with $.5 < R_{\text{ISR}} < R_{\text{ISR, SR}}$, where $R_{\text{ISR, SR}}$ is the cut on R_{ISR} in the corresponding
 2078 SR. Again, this can be seen as probing “in between” the CR and SR in phase space.

The results of this validation can be seen in [8.16](#). Each bin is *pull* of the validation
 region corresponding to a particular signal region. This is defined

$$\text{Pull} = \frac{N_{\text{obs}} - N_{\text{pred}}}{\sigma_{\text{tot}}} \quad (8.4)$$

2079 where σ_{tot} is the total uncertainty folding in all systematic uncertainties, which we
 2080 will describe later. Assuming we have well-measured our backgrounds, we expect a
 2081 Gaussian distribution of the pulls around 0, with a standard deviation of 1, as this
 2082 is measuring the number of standard deviations around the mean. We can see there
 2083 are few positive pulls (indicating an underestimation of the background), indicating

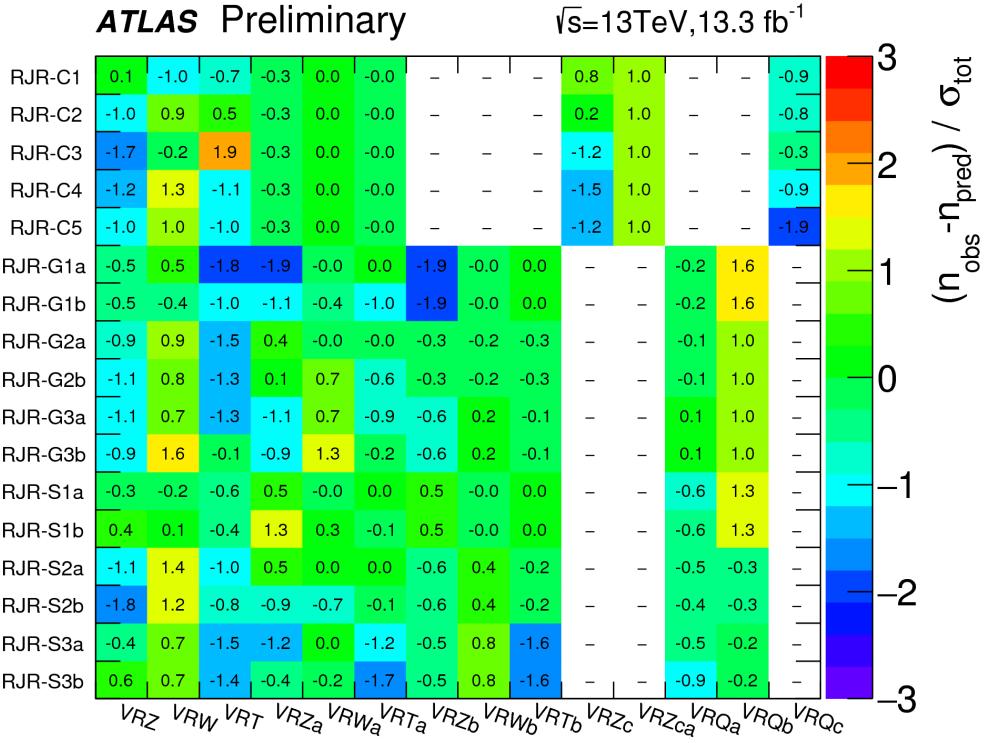


Figure 8.16: Summary of the validation region pulls

2084 we have conservatively measured the Standard Model backgrounds with our control

2085 regions.

2086 Systematic Uncertainties

2087 In this section, we discuss the uncertainties considered. These generally fall into

2088 four categories: theoretical generator uncertainties, uncertainties on the CR to SR

2089 extrapolations, uncertainties on the data-driven transfer factor corrections, and object

2090 reconstruction uncertainties. We discuss each of these categories here. A table

2091 summarizing this section is in 8.5

Systematic	Uncertainty Description
alpha_GeneratorZ	Theoretical on Z cross-section
alpha_generatorW	Theoretical on W cross-section
alpha_generatorTop	Theoretical on t cross-section
alpha_radiationTop	Theoretical on t radiation tune
alpha_Pythia8Top	Theoretical on t fragmentation tune
alpha_FlatDiboson	Flat on diboson cross-section
mu_Zjets	CRY extrapolation to SR
mu_Wjets	CRW extrapolation to SR
mu_Top	CRT extrapolation to SR
mu_Multijets	CRQ extrapolation to SR
alpha_Kappa	κ factor
alpha_QCDError	Jet smearing
alpha_JET_GroupedNP_1	JES NP group 1
alpha_JET_GroupedNP_2	JES NP group 2
alpha_JET_GroupedNP_3	JES NP group 3
alpha_JER	JER
alpha_MET_SoftTrk_ResoPerp	Soft E_T^{miss} resolution perpendicular to hard object system
alpha_MET_SoftTrk_ResoPara	Soft E_T^{miss} resolution parallel to hard object system
alpha_MET_SoftTrk_Scale	Soft E_T^{miss} scale

Table 8.5: Description of the systematic uncertainties in the analysis.

2092 The theoretical generator uncertainties are evaluated by using alternative sim-
 2093 ulation samples or varying scale uncertainties. In the case of the $Z+jets$ and
 2094 $W+jets$ backgrounds, the related theoretical uncertainties are estimated by varying
 2095 the renormalization, factorization, and resummation scales by two, and decreasing
 2096 the nominal CKKW matching scale by 5 GeV and 10 GeV respectively. In
 2097 the case of $t\bar{t}$ production, we compare the nominal POWHEG-Box generator with
 2098 MG5_aMC@NLO, as well as comparing different radiation and generator tunes. As
 2099 stated above, we account for the uncertainty on the small diboson background by
 2100 imposition of a flat 50% uncertainty.

2101 The CR to SR extrapolation uncertainties, or what could be called the transfer

2102 factor uncertainties, are listed in 8.5 as μ_- . There is one normalization factor μ for
2103 each major background, and their uncertainties, especially μ_Z , are often dominant
2104 for the measurement in many signal regions. This uncertainty is generally dominated
2105 by the statistical uncertainty in the CR.

2106 There are two uncertainties from the data-driven corrections to the transfer
2107 factors. The first is the uncertainty on κ , which is measured using an auxiliary $Z \rightarrow \ell\ell$
2108 control region. This is labeled alpha_Kappa. The other is the uncertainty is that
2109 assigned to the jet smearing method, which is seen in the table as alpha_QCDError.

2110 The final set of uncertainties are those related to object reconstruction. In the
2111 case of the hadronic search presented, the important uncertainties are those assigned
2112 to the jet energy and E_T^{miss} . The uncertainties on the lepton reconstruction and
2113 b -tagging uncertainties were found to be negligible in all SRs. The measurement
2114 of the jet energy scale (JES) uncertainty is quite complicated, and described in
2115 [Aad:2011he, Aad:2012vm, 127]. After a complicated procedure to decorrelate
2116 the various components of the JES uncertainty, there are three components which
2117 remain, which are labeled as alpha_JET_GroupedNP_1,2,3. The jet energy resolution
2118 uncertainty is estimated using the methods discussed in Refs. [Aad:2012ag, 127],
2119 and is labeled alpha_JER.

2120 The E_T^{miss} soft term uncertainties are described in [112, 113, 128]. The
2121 uncertainty on the E_T^{miss} soft term resolution is parameterized into a component
2122 parallel to direction of the rest of the event (the sum of the hard objects p_T)
2123 and a component perpendicular to this direction. There is also an uncertainty
2124 on the E_T^{miss} soft term scale. These are labeled as alpha_MET_SoftTrk_ResoPara,
2125 alpha_MET_SoftTrk_ResoPerp, and alpha_MET_SoftTrk_Scale.

2126 **Fitting procedure**

2127 In this section, we describe the fitting procedure employed, which properly accounts
2128 for the correlations between the uncertainties through the use of a likelihood fit
2129 as described in [120]. We use three classes of likelihood fits: *background-only*,
2130 *model-independent*, and *model-dependent* fits. The background-only fits estimate the
2131 background yields in each signal region. These fits use only the control region event
2132 yields as inputs; they do not include the information from the signal regions besides
2133 the simulation event yield. The cross-contamination between CRs is also fit by this
2134 procedure. The systematic uncertainties described in the previous section are used as
2135 nuisance parameters. This background only fit also estimates the background event
2136 yields in the validation regions. When designing the analysis (before unblinding
2137 the signal regions), checking the validation region agreement is the primary way to
2138 validate the consistency and accuracy of the background estimation procedure.

2139 In the case no excess is observed, we use a model-independent fit to set upper limits
2140 on the possible number of possible beyond the Standard Model events in each SR.
2141 These limits are derived using the same procedure as the background-only fit, with
2142 two additional pieces of information included in the fitting procedure. We include
2143 the SR event count, and a parameter known as the *signal strength*, defined as $\mu =$
2144 $\sigma/\sigma_{\text{BG}}$. Using the CL_s procedure[129] and neglecting the possible (small) signal
2145 contamination in control regions, we derive the the observed and expected limits on
2146 the number of events from BSM phenomena in each signal region.

2147 Model-dependent fits are used to set exclusion limits on the specific SUSY
2148 models considered in this thesis, particular the gluino or squark pair production
2149 with various mass splittings. This can be seen as identical to the background-only
2150 fit with an additional simulation input from the particular model of interest, with its
2151 corresponding systematic uncertainties from detector effects accounted for as in the
2152 background-only fit. As noted when we introduced 8.1, the exclusion contours from

2153 previous model-dependent fits are the primary motivating factor in the design of our
2154 signal regions. If no excess is found, we set limits on each of the simplified signal
2155 models with various mass splittings.

Results

2158 This chapter presents the results of the analysis presented in the previous chapter.
 2159 We present the full set of signal region distributions after applying the μ factors
 2160 derived from the fitting procedure. We also present the systematic uncertainties in
 2161 each signal region properly accounting for the correlations of the uncertainties. As
 2162 no excess is observed, we show exclusion limits in the sparticle- $\tilde{\chi}_1^0$ plane based on
 2163 the results of the model-dependent fits and present the model-independent limits.

2164 **9.1 Signal region distributions**

2165 In figs. 9.1 to 9.3, we can see the unblinded distributions of the last scale cut used
 2166 for each signal region. These distributions include the μ normalization scale factors
 2167 derived from the fitting procedure. The systematic uncertainties are also shown.
 2168 Each plot shows the distribution from a signal model which is targetted by the given
 2169 signal region.

2170 These distributions have all cuts applied except for the cut on this scale variable,
 2171 which allows us to see the additional discrimination provided by the given variable.
 2172 Since signal regions with the same numeral have identical cuts except for that on the
 2173 main scale variable, we show (a) and (b) on the same figure. The left-most (right-
 2174 most) arrow shown is the location of the a (b) cut applied in the analysis. We call
 2175 these plot $N - 1$ plots, where N refers to the number of cuts applied in the analysis.
 2176 The full set of $N - 1$ plots in the signal regions for the other variables used in the

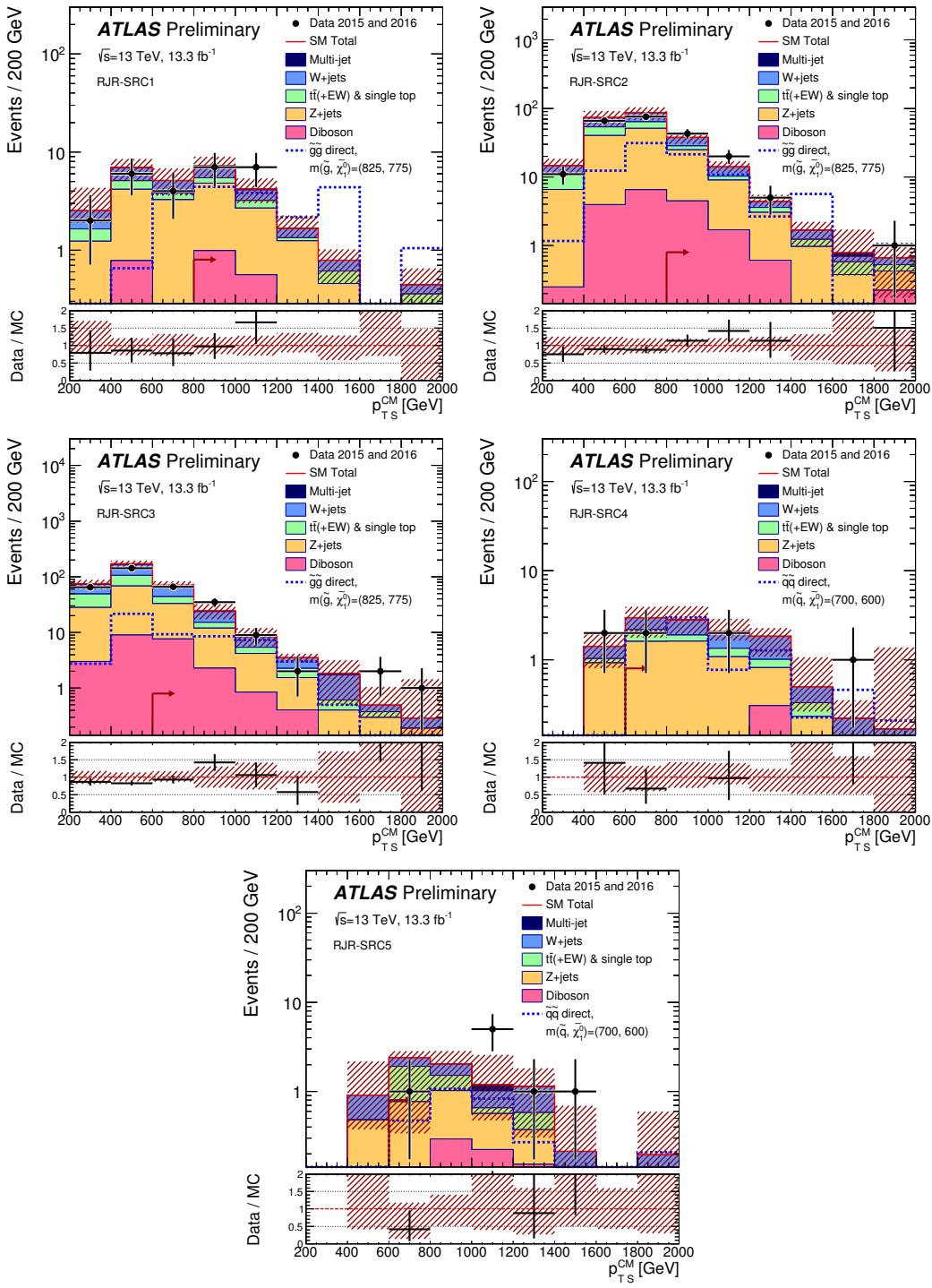


Figure 9.1: Scale variable distributions for the compressed signal regions.

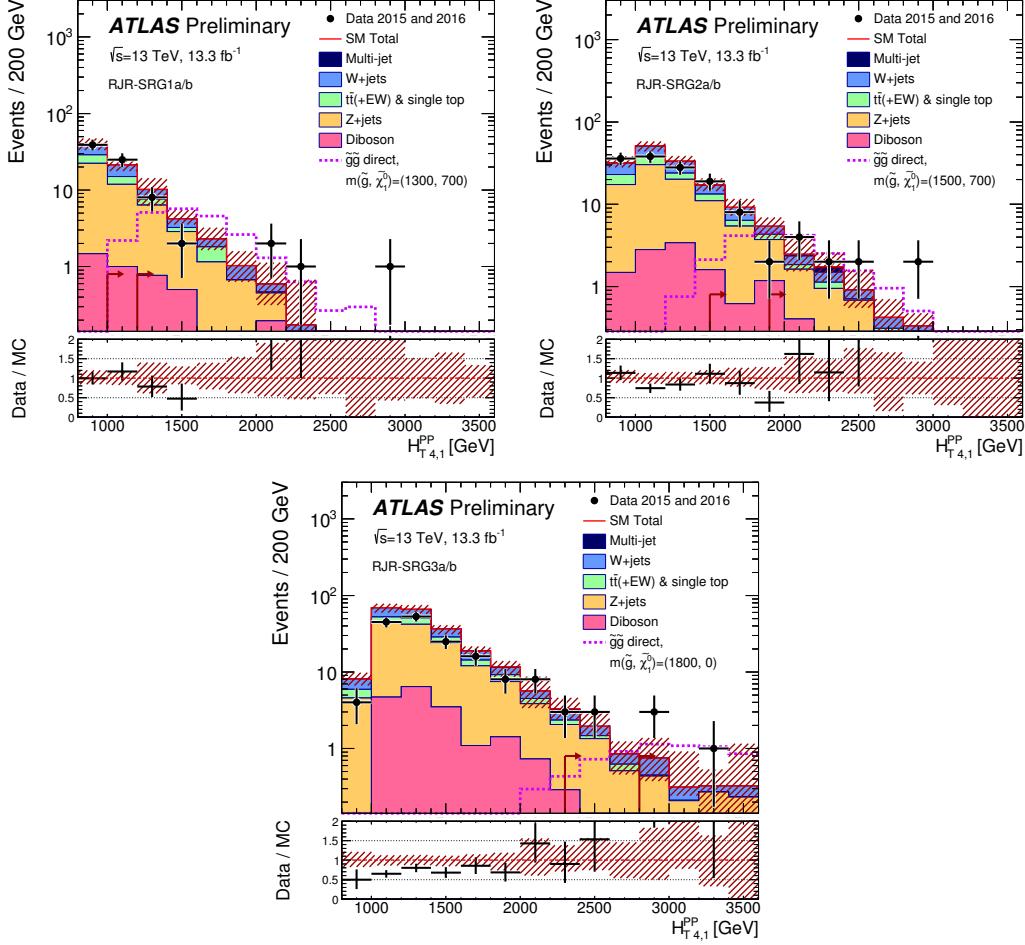


Figure 9.2: Scale variable distributions for the gluino signal regions.

analysis are shown in 9.4.

A figure showing a summary of the pulls in all of the SRs is shown in 9.4. This figure shows the integrated data and simulation values above the cut values in the N-1 plots, with the corresponding statistical and systematic uncertainties, for all signal regions simultaneously. The systematic uncertainties will be discussed in the next section. From this plot, we can see there is no significant excess of events over the Standard Model background.

This information is also presented in 9.2. The table includes the expectations from simulation before applying the μ normalization factor, as well as the model-independent limits we will discuss later.

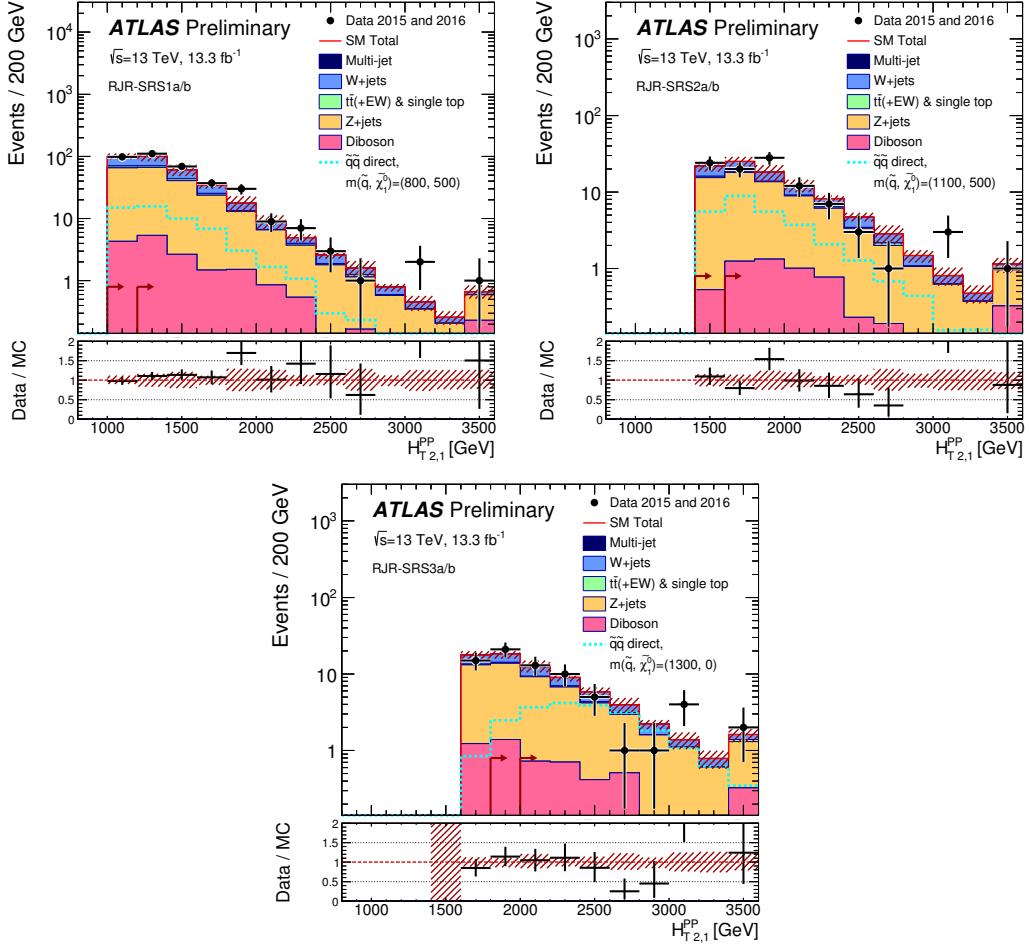


Figure 9.3: Scale variable distributions for the squark signal regions.

2187

We now consider the final values of the systematic uncertainties.

2188

9.2 Systematic Uncertainties

2189 This section considers the results of 9.1. This table is a summary of the resulting
 2190 systematic uncertainties on the background estimation in each signal region, properly
 2191 accounting for systematic uncertainties. These uncertainties are expressed both as a
 2192 relative uncertainty and absolute uncertainty. As correlations are properly treated,
 2193 the absolute uncertainties do not add in quadrature, although most uncertainties are
 2194 relatively uncorrelated. We discuss the general trends in the systematic uncertainties

2195 for each type of signal region.

2196 In the squark regions, the total uncertainties range from 10% to 11%. We note
2197 that the uncertainties on the Z , both theoretical and $\Delta_{\mu, Z+jets}$ account for the largest
2198 on the background estimate in each signal region. The κ factor uncertainty, which is
2199 also an uncertainty on the Z estimate, is also significant at 4% in each region. The
2200 $Z \rightarrow \nu\nu$ contribution to the squark regions is the primary irreducible background, so
2201 even when relatively well-measured, the uncertainty on its event yield dominates the
2202 overall uncertainty. There are also significant uncertainties from the W , top, and flat
2203 diboson uncertainties, although these are subdominant. We note that the uncertainty
2204 due to statistics of the MC simulation samples are very small for the squark case; this
2205 is a reflection of the “looseness” of these regions, as the MC statistics are sufficient
2206 for all of the major backgrounds.

2207 The gluino regions have overall larger uncertainties than the squark regions,
2208 between 10% and 25%, due to a multitude of factors. The Z related uncertainties
2209 all contribute significantly to the final background yield uncertainties. These
2210 are relatively similar to the squark Z uncertainties. The W , top, and diboson
2211 uncertainties are all significantly more important than in the squark case however. In
2212 the gluino case, we also see that the limited simulation statistics begin to significantly
2213 affect the measurement of the Standard Model background. These are all reflections
2214 of the overall “tighter” quality of the gluino regions, as indicated by the event yields.
2215 The Δ_{μ} uncertainties are affected by this due to the need to use overall looser
2216 control regions, while the theory uncertainties are more affected by small statistical
2217 fluctuations between different generators. The low statistics is particularly clear in
2218 SRG3b, where the simulation statistics account for a very large 14% uncertainty.

2219 The compressed regions have systematic uncertainties ranging from 10% to 19%.
2220 For the tighter regions, SRC1, SRC4, and SRC5, we see a large contribution from
2221 the lack of MC statistics. SRC1 and SRC4 should a large value for the W theory

uncertainty, while all compressed regions show a large uncertainty on the Z estimate. These large uncertainties result from the fact that we are probing extreme phase space in boson p_T with the compressed regions. SRC5 shows large top and jet/ E_T^{miss} uncertainties; these uncertainties are more pronounced in this region than the other compressed region due to the $N_{\text{jet}}^V > 3$ cut, and thus the uncertainty in this region is quite affected by fluctuations in the top, jet, or E_T^{miss} uncertainties.

9.3 Limits and Model-dependent Exclusions

In Table 9.1, we show the statistical significance Z for each signal region. We calculate this using the fitted simulation mean compared with the observed event counts in each region. There is no significant excess in each region; the highest excess is in SRG3b, which is only $Z_{\text{SRG3b}} = 1.55$. This information is summarized in 9.4. We thus set model-independent and model-dependent limits.

As no significant excess is observed in any of the signal regions of this analysis after estimating the background using the background-only fit, we set limits on the model-independent and model-dependent cross sections.

The model-independent limits are shown in 9.1. We present the limits on the new physics cross section in each SR. The observed and expected limits S_{obs}^{95} and S_{exp}^{95} are reported for the potential contribution from new physics in each region. Including the acceptance ϵ , the model-independent limits in most signal regions are of $\sim 1 - 2$ fb. One should note that the (b) version of each signal region is strictly tighter in the primary scale cut, and thus provides a stronger limit when we observe no excess, as seen here.

Additionally, we derive exclusion limits for the simplified models considered in this thesis. These are the models with pair-production of squark pairs with inaccessible gluinos, and gluino pairs with inaccessible squarks. They correspond directly to the

Channel	RJR-S1a	RJR-S1b	RJR-S2a	RJR-S2b	RJR-S3a	RJR-S3b
Total bkg	334	233	96	75	56	37
Total bkg unc.	± 35 [10%]	± 25 [11%]	± 10 [10%]	± 8 [11%]	± 6 [11%]	± 4 [11%]
MC statistics	—	± 2.6 [1%]	± 1.5 [2%]	± 1.3 [2%]	± 1.0 [2%]	± 0.7 [2%]
$\Delta\mu_{Z,+jets}$	± 20 [6%]	± 14 [6%]	± 4 [4%]	± 2.9 [4%]	± 2.2 [4%]	± 1.5 [4%]
$\Delta\mu_{W,+jets}$	± 10 [3%]	± 7 [3%]	± 3.1 [3%]	± 2.3 [3%]	± 1.6 [3%]	± 1.1 [3%]
$\Delta\mu_{Top}$	± 6 [2%]	± 4 [2%]	± 1.5 [2%]	± 1.1 [1%]	± 0.9 [2%]	± 0.6 [2%]
$\Delta\mu_{Multijet}$	± 0.09 [0%]	± 0.05 [0%]	± 0.02 [0%]	—	—	—
CR γ corr. factor	± 12 [4%]	± 8 [3%]	± 4 [4%]	± 2.9 [4%]	± 2.2 [4%]	± 1.4 [4%]
Theory Z	± 23 [7%]	± 16 [7%]	± 7 [7%]	± 6 [8%]	± 4 [7%]	± 2.8 [8%]
Theory W	± 4 [1%]	± 5 [2%]	± 0.4 [0%]	± 0.11 [0%]	± 1.5 [3%]	± 1.2 [3%]
Theory Top	± 4 [1%]	± 2.7 [1%]	± 0.8 [1%]	± 0.7 [1%]	± 0.6 [1%]	± 0.4 [1%]
Theory Diboson	± 9 [3%]	± 6 [3%]	± 2.8 [3%]	± 2.6 [3%]	± 2.1 [4%]	± 1.4 [4%]
Jet/MET	± 3.3 [1%]	± 1.5 [1%]	± 0.6 [1%]	± 0.6 [1%]	± 1.2 [2%]	± 1.0 [3%]
Multijet method	± 0.7 [0%]	± 0.4 [0%]	± 0.08 [0%]	—	—	—
Channel	RJR-G1a	RJR-G1b	RJR-G2a	RJR-G2b	RJR-G3a	RJR-G3b
Total bkg	40	18.8	27.8	8.5	5.8	1.7
Total bkg unc.	± 4 [10%]	± 2.5 [13%]	± 3.4 [12%]	± 1.4 [16%]	± 1.1 [19%]	± 0.4 [24%]
MC statistics	± 1.6 [4%]	± 1.0 [5%]	± 1.2 [4%]	± 0.6 [7%]	± 0.4 [7%]	± 0.23 [14%]
$\Delta\mu_{Z,+jets}$	± 1.5 [4%]	± 0.7 [4%]	± 1.6 [6%]	± 0.5 [6%]	± 0.4 [7%]	± 0.1 [6%]
$\Delta\mu_{W,+jets}$	± 0.9 [2%]	± 0.4 [2%]	± 1.2 [4%]	± 0.31 [4%]	± 0.28 [5%]	± 0.1 [6%]
$\Delta\mu_{Top}$	± 0.8 [2%]	± 0.33 [2%]	± 0.9 [3%]	± 0.23 [3%]	± 0.07 [1%]	± 0.1 [6%]
$\Delta\mu_{Multijet}$	± 0.1 [0%]	—	± 0.03 [0%]	± 0.02 [0%]	—	—
CR γ corr. factor	± 1.2 [3%]	± 0.6 [3%]	± 0.8 [3%]	± 0.26 [3%]	± 0.19 [3%]	± 0.05 [3%]
Theory Z	± 2.3 [6%]	± 1.1 [6%]	± 1.6 [6%]	± 0.5 [6%]	± 0.4 [7%]	± 0.1 [6%]
Theory W	± 1.1 [3%]	± 1.3 [7%]	± 0.3 [1%]	± 0.7 [8%]	± 0.6 [10%]	± 0.16 [9%]
Theory Top	± 1.2 [3%]	± 0.7 [4%]	± 1.0 [4%]	± 0.4 [5%]	± 0.4 [7%]	± 0.26 [15%]
Theory Diboson	± 1.3 [3%]	± 0.8 [4%]	± 1.5 [5%]	± 0.6 [7%]	± 0.31 [5%]	± 0.13 [8%]
Jet/MET	± 1.0 [3%]	± 0.6 [3%]	± 0.4 [1%]	± 0.17 [2%]	± 0.22 [4%]	± 0.05 [3%]
Multijet method	± 0.24 [1%]	± 0.12 [1%]	± 0.5 [2%]	± 0.4 [5%]	—	—
Channel	RJR-C1	RJR-C2	RJR-C3	RJR-C4	RJR-C5	
Total bkg	14.5	59	110	10.5	7.3	
Total bkg unc.	± 2.2 [15%]	± 6 [10%]	± 11 [10%]	± 1.5 [14%]	± 1.4 [19%]	
MC statistics	± 0.7 [5%]	± 1.7 [3%]	± 2.4 [2%]	± 0.6 [6%]	± 0.6 [8%]	
$\Delta\mu_{Z,+jets}$	± 0.5 [3%]	± 1.9 [3%]	± 2.5 [2%]	± 0.31 [3%]	± 0.13 [2%]	
$\Delta\mu_{W,+jets}$	± 0.4 [3%]	± 1.7 [3%]	± 5 [5%]	± 0.4 [4%]	± 0.25 [3%]	
$\Delta\mu_{Top}$	± 0.33 [2%]	± 1.3 [2%]	± 4 [4%]	± 0.31 [3%]	± 0.4 [5%]	
$\Delta\mu_{Multijet}$	—	± 0.1 [0%]	± 0.06 [0%]	—	± 0.1 [1%]	
CR γ corr. factor	± 0.5 [3%]	± 1.8 [3%]	± 2.3 [2%]	± 0.29 [3%]	± 0.13 [2%]	
Theory Z	± 0.8 [6%]	± 3.5 [6%]	± 4 [4%]	± 0.6 [6%]	± 0.24 [3%]	
Theory W	± 1.3 [9%]	± 0.03 [0%]	± 2.0 [2%]	± 1.0 [10%]	± 0.13 [2%]	
Theory Top	± 0.5 [3%]	± 1.3 [2%]	± 3.2 [3%]	± 0.6 [6%]	± 0.9 [12%]	
Theory Diboson	± 1.0 [7%]	± 4 [7%]	± 6 [5%]	± 0.27 [3%]	± 0.4 [5%]	
Jet/MET	± 0.5 [3%]	± 1.5 [3%]	± 3.1 [3%]	± 0.24 [2%]	± 0.5 [7%]	
Multijet method	± 0.09 [1%]	± 0.4 [1%]	± 2.1 [2%]	—	± 0.18 [2%]	

Table 9.1: Breakdown of the dominant systematic uncertainties in the background estimates for the RJR-based search. The individual uncertainties can be correlated, and do not necessarily add in quadrature to the total background uncertainty. Δ_μ uncertainties are the result of the control region statistical uncertainties and the systematic uncertainties entering a specific control region. In brackets, uncertainties are given relative to the expected total background yield, also presented in the Table. Empty cells (indicated by a ‘-’) correspond to uncertainties $< 0.1\%$.

Signal Region	RJR-S1a	RJR-S1b	RJR-S2a	RJR-S2b	RJR-S3a	RJR-S3b
MC expected events						
Diboson	17	13	5.6	5.1	4.2	2.8
Z/ γ^* +jets	231	163	63	48	36	24
W+jets	97	66	22	16	11	7.8
$t\bar{t}$ (+EW) + single top	15	10	2.9	2.1	1.7	1.1
Fitted background events						
Diboson	17 ± 9	13 ± 7	5.6 ± 2.8	5.1 ± 2.6	4.2 ± 2.1	2.8 ± 1.4
Z/ γ^* +jets	207 ± 33	146 ± 23	65 ± 9	50 ± 7	37 ± 5	25.0 ± 3.5
W+jets	95 ± 9	65 ± 7	24.1 ± 2.9	18.3 ± 2.3	12.8 ± 2.8	8.7 ± 2.0
$t\bar{t}$ (+EW) + single top	14 ± 7	9 ± 5	2.1 ± 1.7	1.6 ± 1.3	1.3 ± 1.0	0.8 ± 0.7
Multi-jet	$0.71^{+0.71}_{-0.71}$	$0.41^{+0.41}_{-0.41}$	$0.08^{+0.09}_{-0.08}$	—	—	—
Total Expected MC	362	253	93	72	53	36
Total Fitted bkg	334 ± 35	233 ± 25	96 ± 10	75 ± 8	56 ± 6	37 ± 4
Observed	368	270	99	75	57	36
$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb]	7.6	6.5	2.2	1.7	1.6	1.1
S_{obs}^{95}	101	86	29	23	22	15
S_{exp}^{95}	78^{+27}_{-21}	61^{+22}_{-16}	28^{+11}_{-8}	23^{+9}_{-7}	20^{+8}_{-6}	16^{+7}_{-5}
p_0 (Z)	0.20 (0.84)	0.12 (1.17)	0.44 (0.15)	0.50 (0.00)	0.44 (0.14)	0.50 (0.00)
Signal Region	RJR-G1a	RJR-G1b	RJR-G2a	RJR-G2b	RJR-G3a	RJR-G3b
MC expected events						
Diboson	2.6	1.6	2.9	1.1	0.62	0.26
Z/ γ^* +jets	18	8.8	13	4.2	3.1	0.83
W+jets	11	4.7	7.7	2.0	1.9	0.63
$t\bar{t}$ (+EW) + single top	7.4	3.1	4.4	1.1	0.34	0.03
Fitted background events						
Diboson	2.6 ± 1.3	1.6 ± 0.8	2.9 ± 1.5	1.1 ± 0.6	0.6 ± 0.4	0.26 ± 0.14
Z/ γ^* +jets	21.1 ± 3.1	10.2 ± 1.6	14.3 ± 2.5	4.5 ± 0.8	3.3 ± 0.6	0.88 ± 0.19
W+jets	10.8 ± 1.7	4.6 ± 1.4	6.7 ± 1.3	1.7 ± 0.7	1.6 ± 0.7	0.55 ± 0.2
$t\bar{t}$ (+EW) + single top	5.4 ± 1.6	2.3 ± 0.9	3.4 ± 1.4	0.8 ± 0.5	$0.26^{+0.45}_{-0.26}$	$0.02^{+0.26}_{-0.02}$
Multi-jet	0.24 ± 0.24	0.12 ± 0.12	0.5 ± 0.5	0.4 ± 0.4	—	—
Total Expected MC	39	18	29	8.7	5.9	1.7
Total Fitted bkg	40 ± 4	18.8 ± 2.5	27.8 ± 3.4	8.5 ± 1.4	5.8 ± 1.1	1.7 ± 0.4
Observed	39	14	30	10	8	4
$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb]	1.1	0.56	1.1	0.71	0.64	0.55
S_{obs}^{95}	15	7.5	15	9.4	8.5	7.3
S_{exp}^{95}	16^{+7}_{-4}	10^{+5}_{-3}	14^{+6}_{-4}	$7.6^{+3.5}_{-2.0}$	$7.0^{+2.5}_{-2.1}$	$4.2^{+1.9}_{-0.5}$
p_0 (Z)	0.50 (0.00)	0.50 (0.00)	0.36 (0.35)	0.31 (0.50)	0.21 (0.81)	0.06 (1.55)
Signal Region	RJR-C1	RJR-C2	RJR-C3	RJR-C4	RJR-C5	
MC expected events						
Diboson	1.9	7.1	11	0.54	0.75	
Z/ γ^* +jets	8.8	36	46	5.8	2.5	
W+jets	3.5	16	43	3.8	2.3	
$t\bar{t}$ (+EW) + single top	1.9	7.2	20	1.7	2.5	
Fitted background events						
Diboson	1.9 ± 1.0	7 ± 4	11 ± 6	0.54 ± 0.29	0.8 ± 0.5	
Z/ γ^* +jets	7.7 ± 1.1	32 ± 5	40 ± 6	5.0 ± 0.8	2.2 ± 0.4	
W+jets	3.3 ± 1.4	14.5 ± 1.7	40 ± 5	3.56 ± 1.0	2.14 ± 0.35	
$t\bar{t}$ (+EW) + single top	1.5 ± 0.6	5.8 ± 1.8	16 ± 5	1.4 ± 0.7	2.0 ± 1.1	
Multi-jet	0.09 ± 0.09	0.4 ± 0.4	2.1 ± 2.1	—	0.18 ± 0.18	
Total Expected MC	16	67	124	12	8.3	
Total Fitted bkg	14.5 ± 2.2	59 ± 6	110 ± 11	10.5 ± 1.5	7.3 ± 1.4	
Observed	14	69	115	5	8	
$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb]	0.76	2.2	2.5	0.35	0.61	
S_{obs}^{95}	10	29	34	4.7	8.1	
S_{exp}^{95}	11^{+5}_{-3}	21^{+9}_{-6}	30^{+12}_{-8}	$8.1^{+3.0}_{-2.3}$	$7.4^{+2.9}_{-1.8}$	
p_0 (Z)	0.50 (0.00)	0.18 (0.92)	0.37 (0.32)	0.50 (0.00)	0.39 (0.30)	

Table 9.2: Numbers of events observed in the signal regions used in the RJR-based analysis compared with background expectations obtained from the fits described in the text. Empty cells (indicated by a ‘-’) correspond to estimates lower than 0.01. The p-values (p_0) give the probabilities of the observations being consistent with the estimated backgrounds. For an observed number of events lower than expected, the p-value is truncated at 0.5. Between parentheses, p -values are also given as the number of equivalent Gaussian standard deviations (Z). Also shown are 95% CL upper limits on the visible cross-section ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$), the visible number of signal events (S_{obs}^{95}) and the number of signal events (S_{exp}^{95}) given the expected number of background events (and $\pm 1\sigma$ excursions of the expectation).

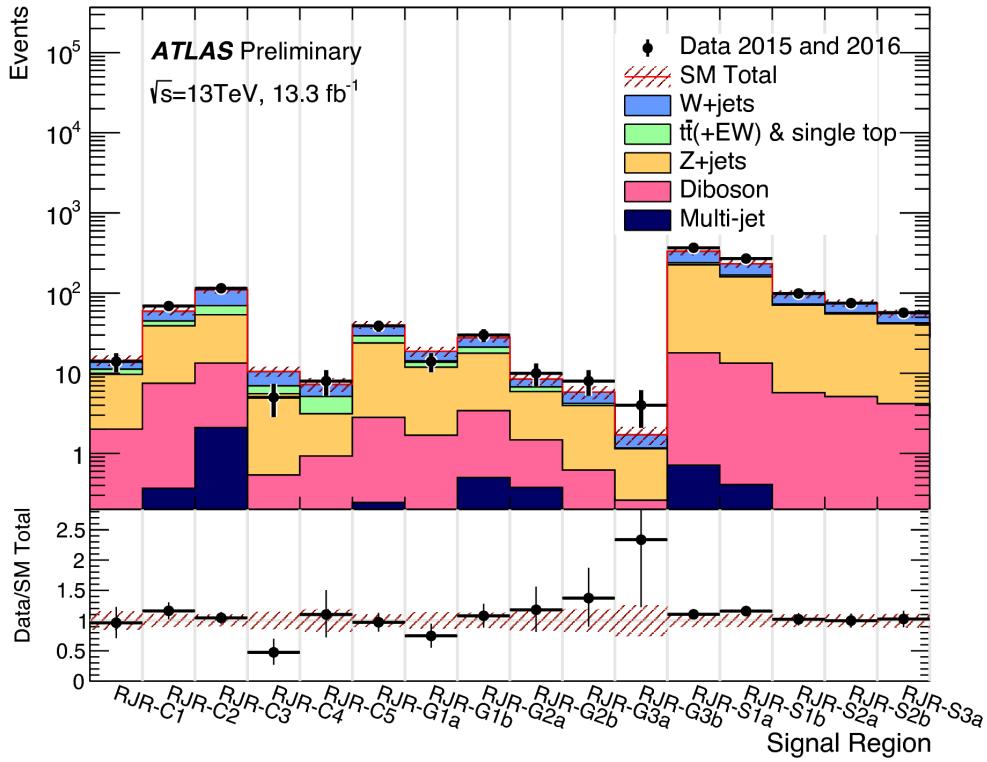


Figure 9.4: Summary of the signal region pulls

2247 Feynman diagrams shown previously. The free parameters of these simplified models
 2248 are the relevant sparticle mass and the mass of the LSP $\tilde{\chi}_1^0$. We set limits in a plane
 2249 of these free parameters.

2250 The exclusion limits are shown in 9.5. Gray text is imposed on the plane at the
 2251 point of each simplified model with masses $(m_{\text{sparticle}}, m_{\tilde{\chi}_1^0})$. This gray text indicates
 2252 the signal region which provided the best sensitivity at that point, as measured by the
 2253 background-only fit. For each simplified signal model, we run the model-dependent fit
 2254 described in the last chapter, where the signal model signal strength μ_{sig} is included
 2255 as an additional free parameter. The signal sample is also allowed to freely contribute
 2256 to the control regions due to signal contamination. This produces a CL_s p -value for
 2257 each signal model in the plane, and we can find those with $p = 0.05$ to set a 95%
 2258 exclusion limit.

2259 In the squark- $\tilde{\chi}_1^0$ plane, we observe that the limits from the 2015 dataset are far
2260 extended in all directions. The expected and observed exclusions are similar, which
2261 is a reflection of the compatibility of the expected Standard Model event counts and
2262 observed event counts in the squark regions. A squark with mass of 1350 GeV or less
2263 is excluded by the analysis in direct decays to a quark and LSP. In the compressed
2264 spectra, we have extended limits significantly over the 2015 result in the region of 600-
2265 700 GeV in squark mass with an LSP of 450 GeV to 600 GeV. We note that directly
2266 along the kinematically-forbidden diagonal, the shape of the exclusions is affected
2267 by the interpolation between the signal models considered. This could be rectified
2268 by inclusion of additional compressed signal models. The limits in the intermediate
2269 with an LSP of \sim 450-500 GeV are not far extended beyond the previous dataset. We
2270 also note that every signal region designed to provide sensitivity to this simplified
2271 model (all SRS regions and SRC1-4) is chosen as the best region at least once in
2272 the plane, indicating that each signal region provided additional sensitivity to squark
2273 phenomena.

2274 Another curiosity is the fact that a gluino region, SRG2a is chosen as the optimal
2275 region in the squark- $\tilde{\chi}_1^0$ plane, when the squark mass is \sim 700 GeV. Generally, the
2276 squark regions are looser than the gluino regions, as seen in their overall event counts.
2277 One could see this as an indication that the next iteration of the analysis should have
2278 an additional tight squark region here. Another possibility is that this region also
2279 benefits from the compressed region strategy of using an ISR jet. As the gluino
2280 regions require four jets from the imposition of the gluino decay tree, these could be
2281 capturing events where a two jet ISR system recoils off the disquark system.

2282 In the gluino- $\tilde{\chi}_1^0$ plane, the limits on gluino masses in the simplified model where
2283 gluinos decay to two jets and an $\tilde{\chi}_1^0$ are again far extended beyond the 2015 dataset.
2284 We note in most of the plane, the expected limit is significantly stronger than the
2285 observed limit; for example, the gluino mass limit is more than 50 GeV stronger in

2286 the case of a massless $\tilde{\chi}_1^0$. As much of the phase space is covered by SRG3a and
2287 SRG3b, this results from the small statistical fluctuation upward in these regions.
2288 Again, we note that every gluino signal region is the best choice at some point in this
2289 plane. This is an indication of the utility of the signal region strategy employed in
2290 this thesis, as each point provides additional sensitivity to new SUSY models.

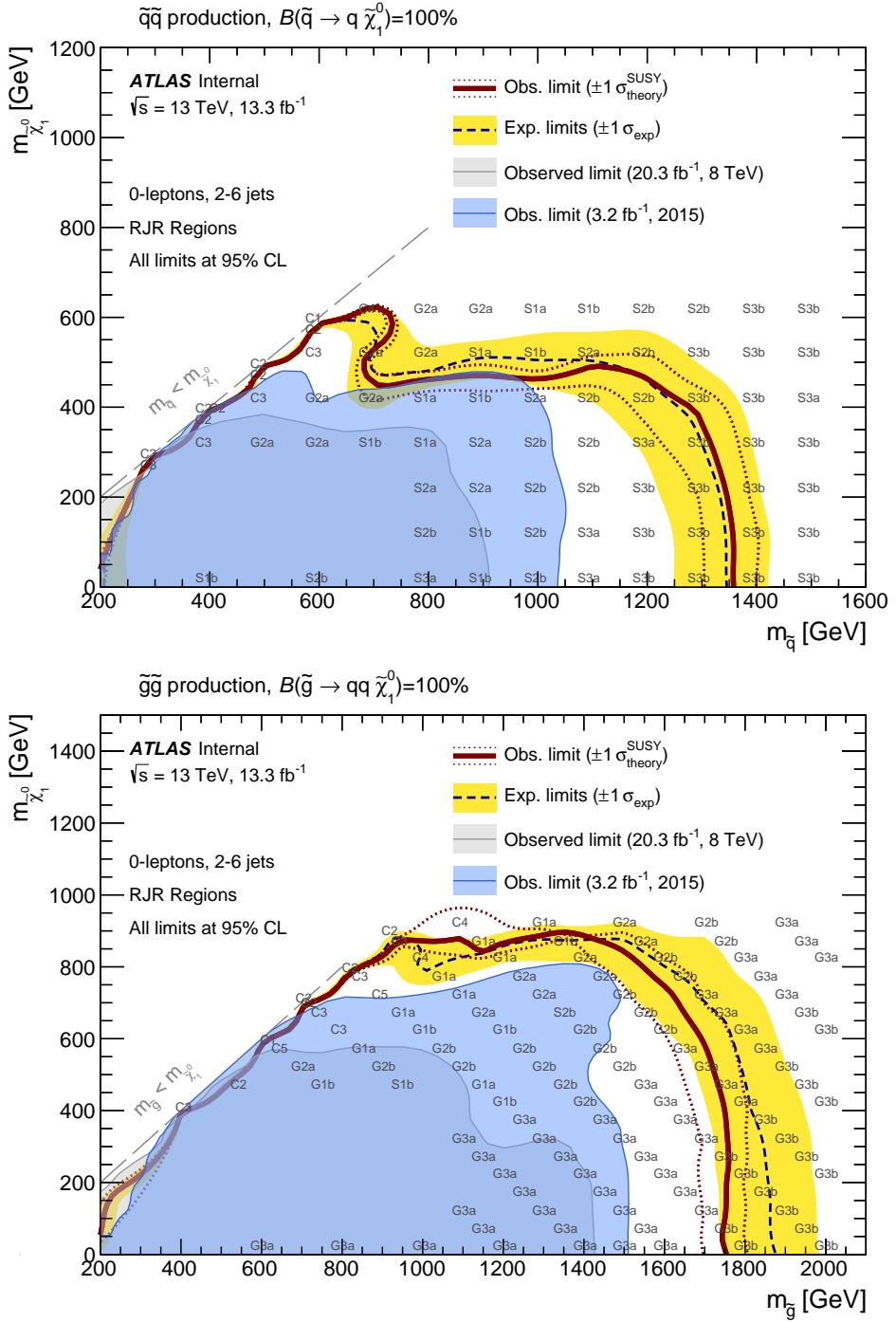


Figure 9.5: Exclusion limits for direct production of (a) light-flavour squark pairs with decoupled gluinos and (b) gluino pairs with decoupled squarks. Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. The blue dashed lines show the expected limits at 95% CL, with the yellow bands indicating the 1σ excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by maroon curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross-section by the renormalization and factorization scale and PDF uncertainties. Results are compared with the observed limits obtained by the previous ATLAS searches with no leptons, jets and missing transverse momentum [124, 130].

2291

Conclusion

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2293 sentence its own line.

2294 When you need a new paragraph, just skip an extra line.

2295 **9.4 New Section**

2296 By using the asterisk to start a new section, I keep the section from appearing in the
2297 table of contents. If you want your sections to be numbered and to appear in the
2298 table of contents, remove the asterisk.

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2678

The Standard Model

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2680 **Compressed region N-1 plots**

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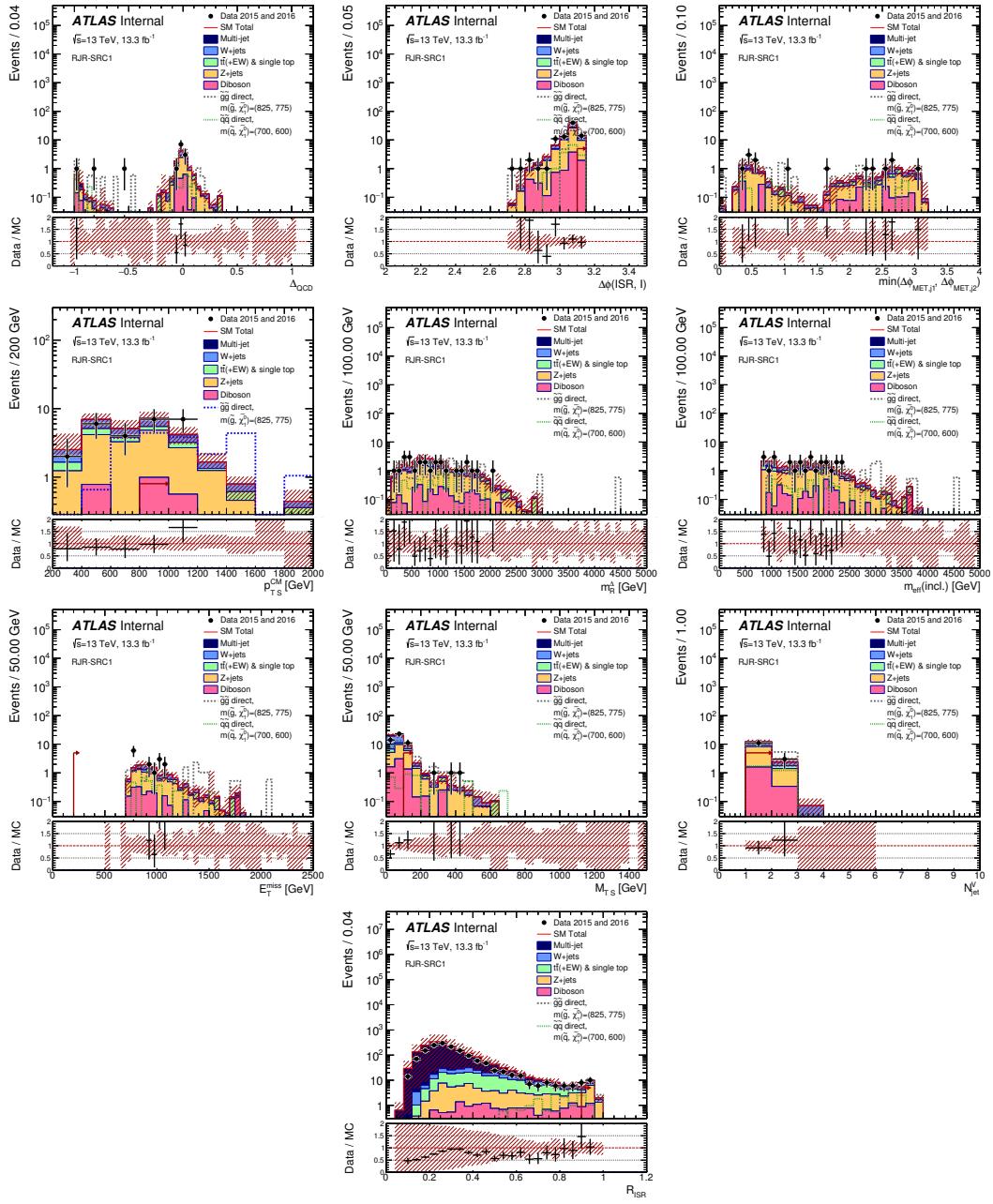


Figure 1

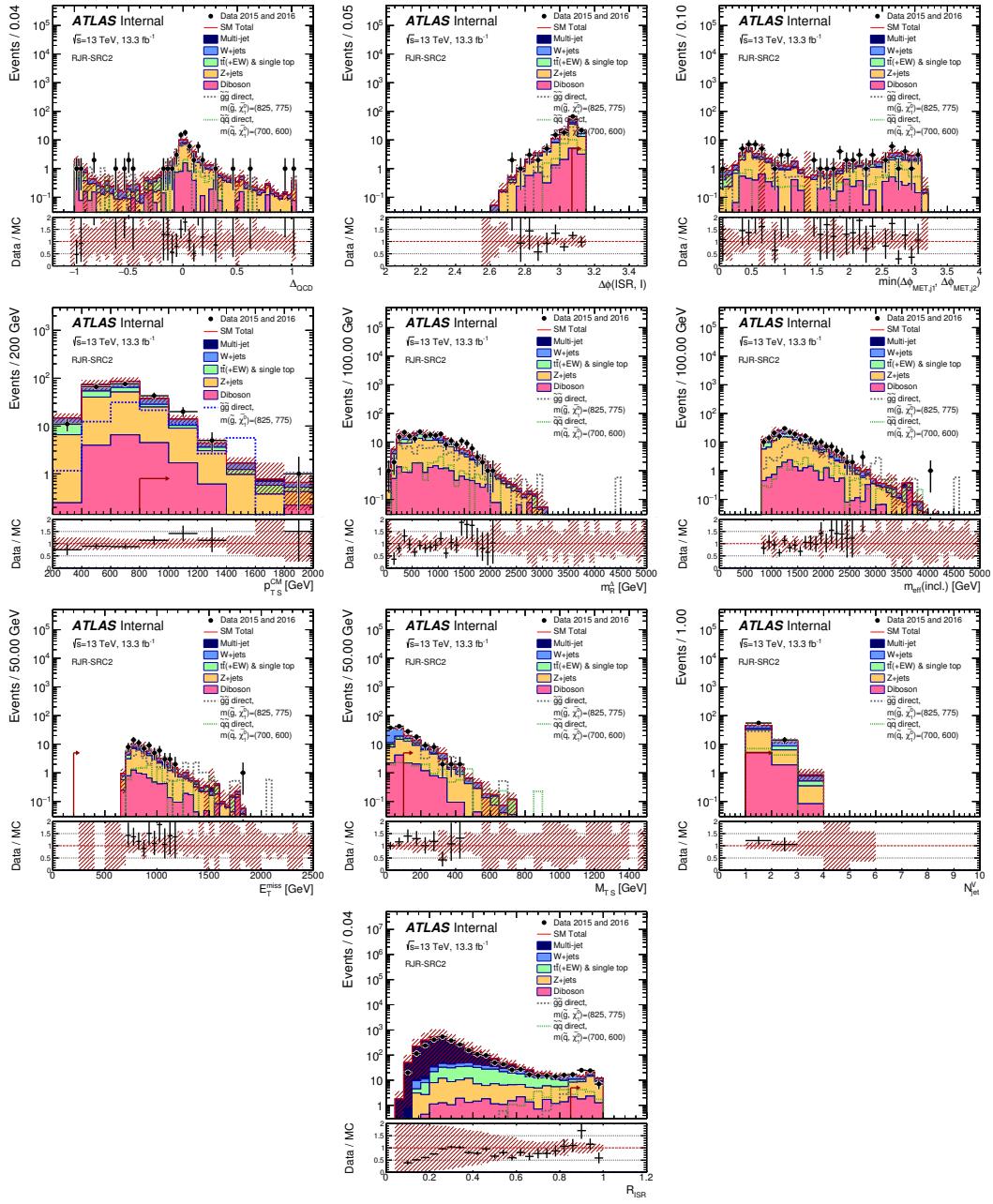


Figure 2

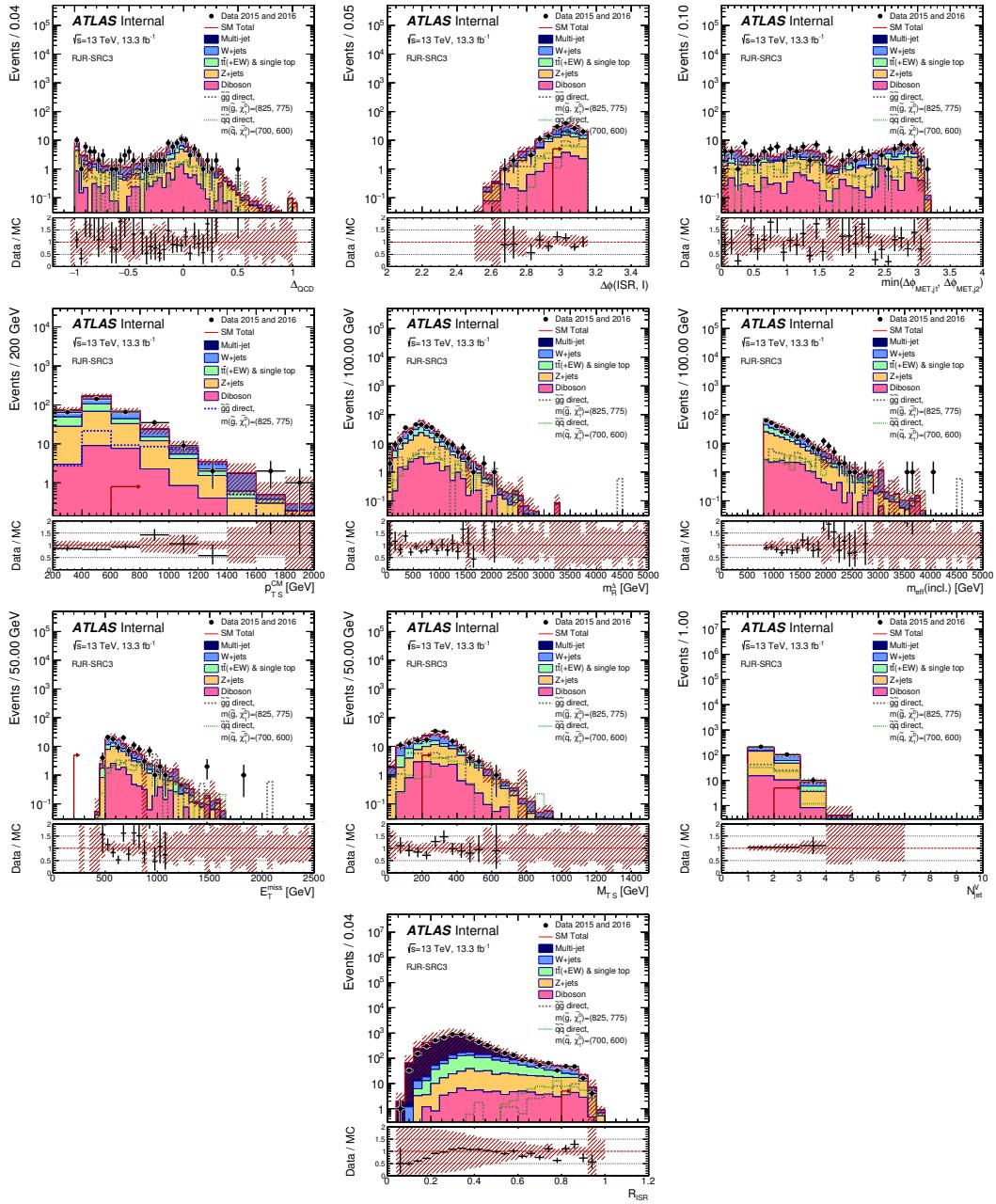


Figure 3

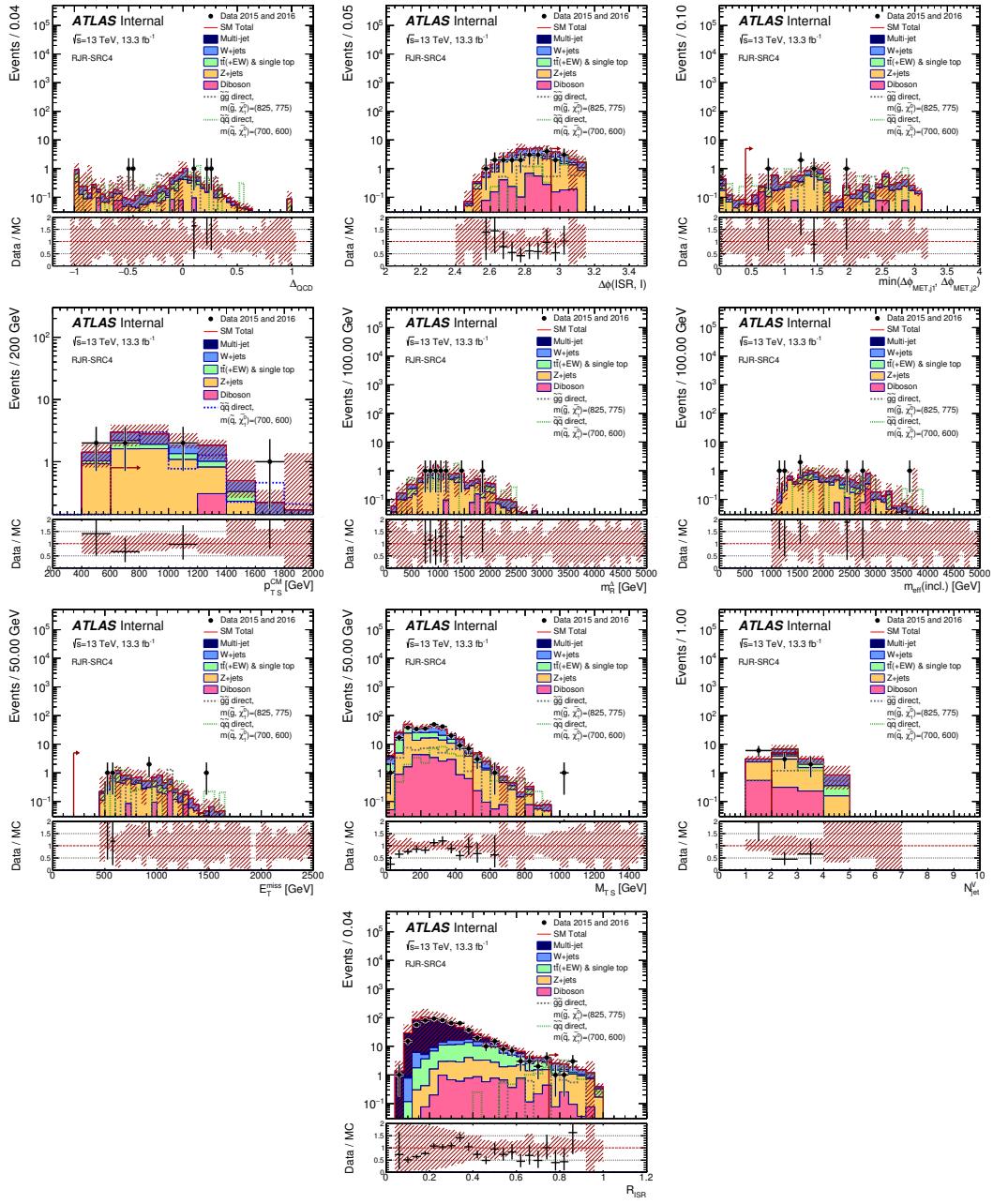


Figure 4

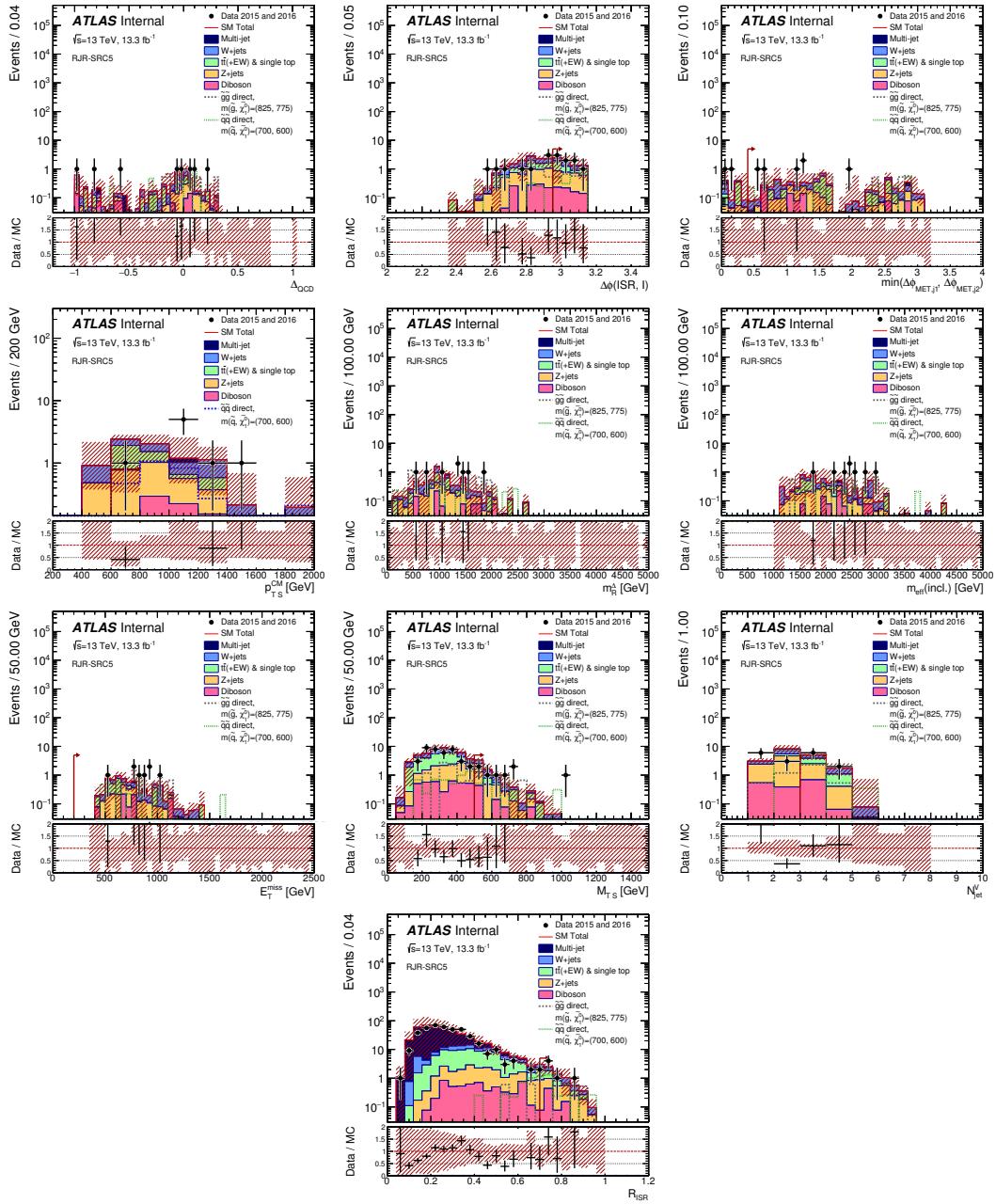


Figure 5

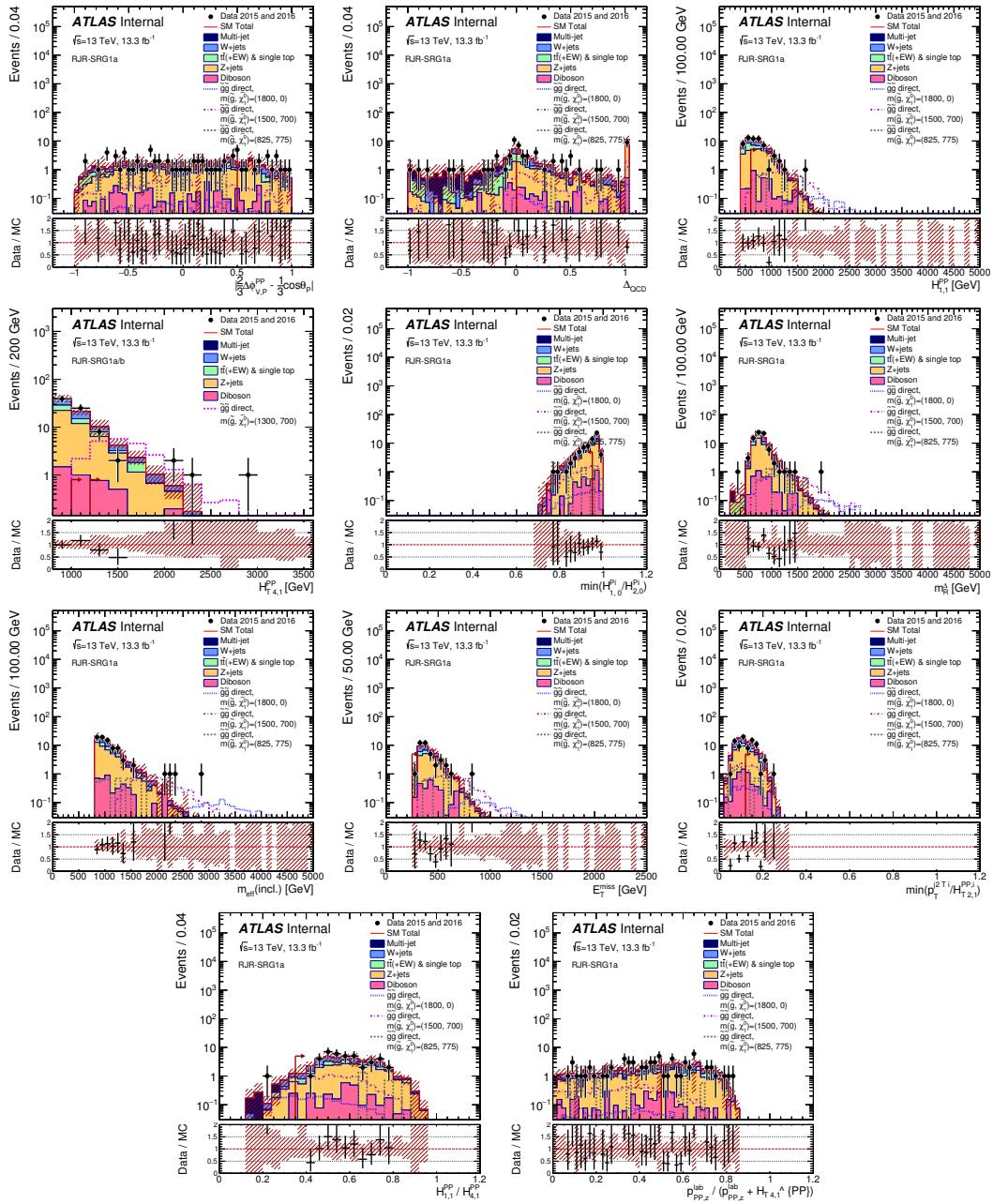


Figure 6

Figure 7

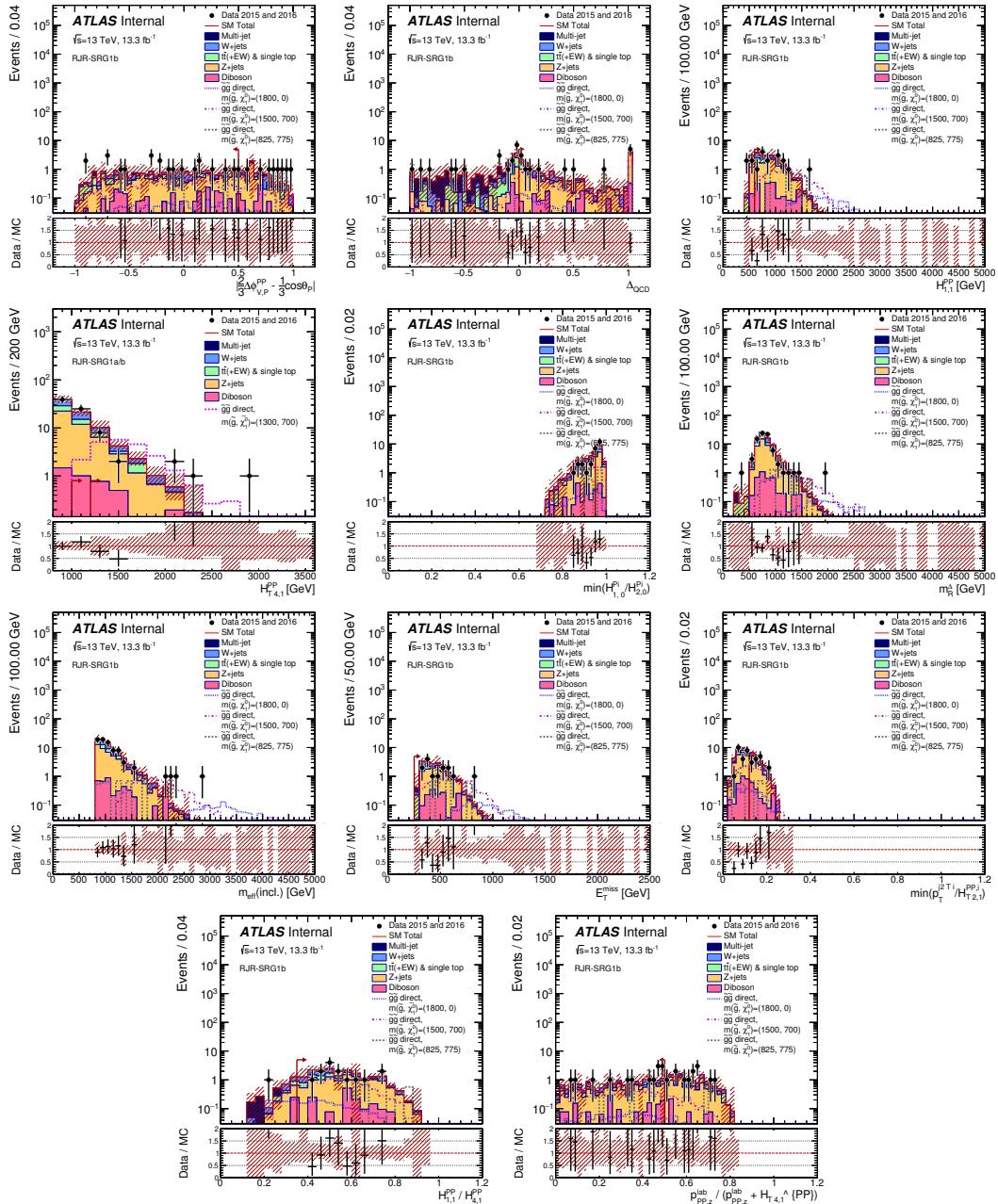


Figure 8

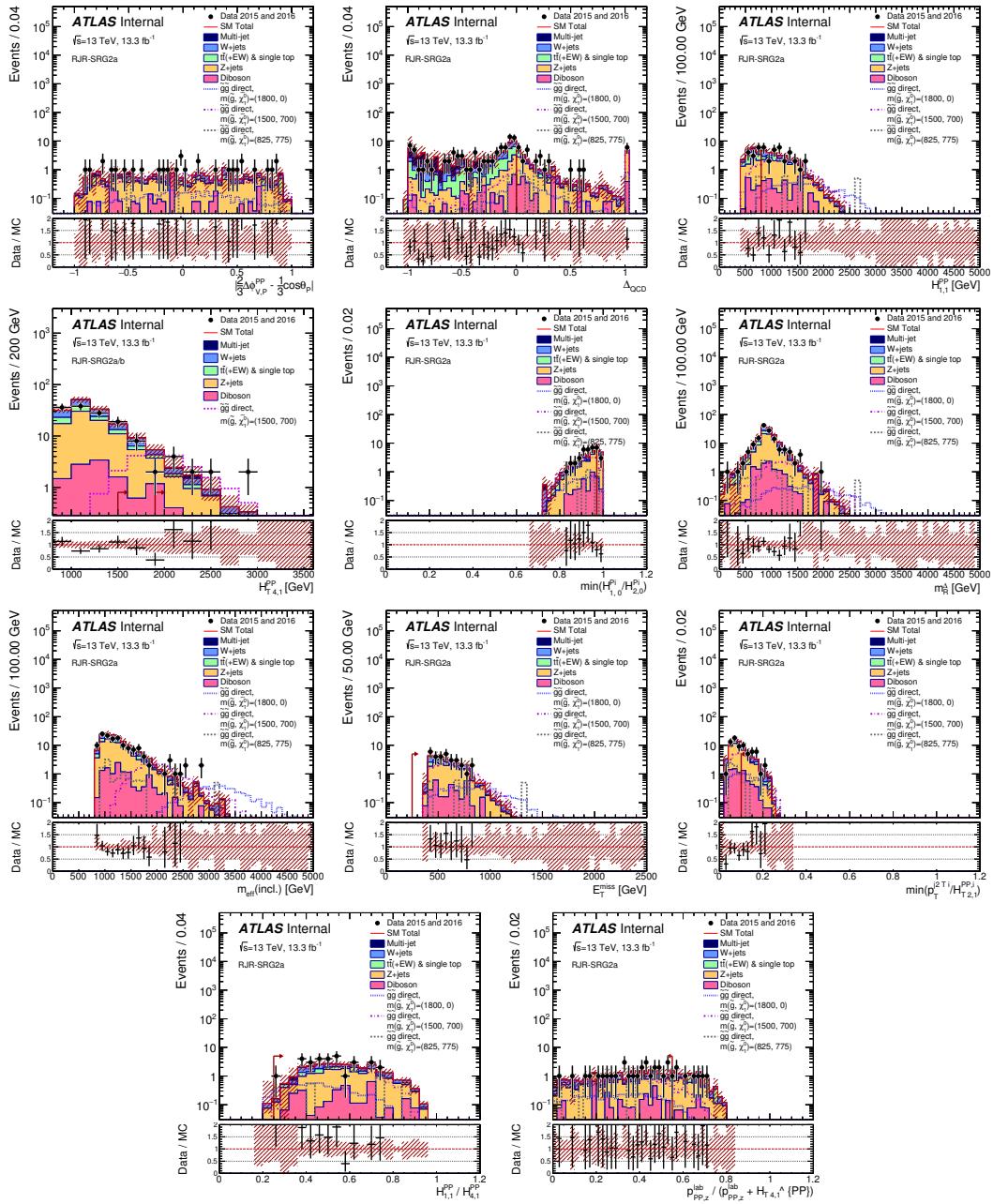


Figure 9

Figure 10

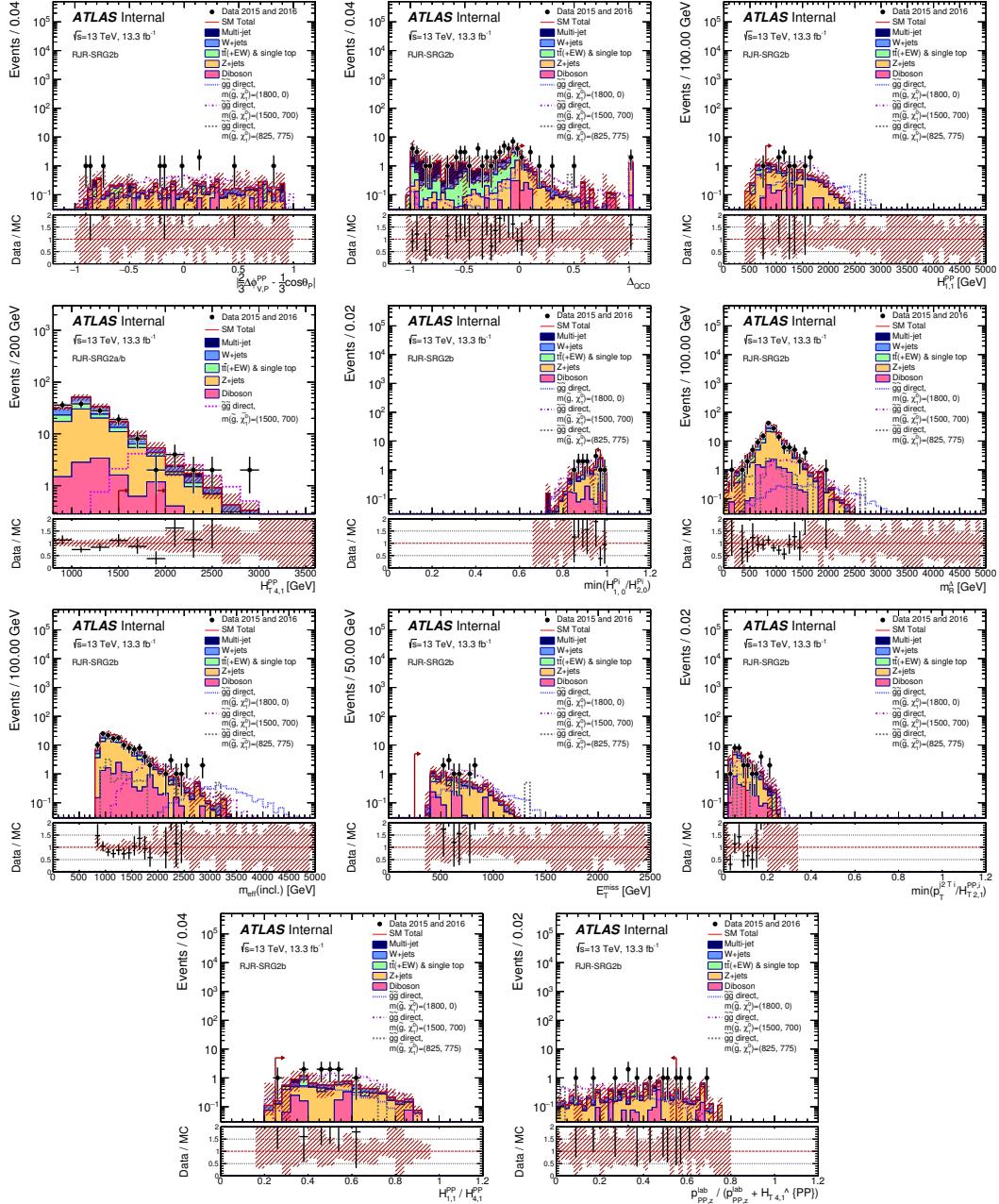


Figure 11

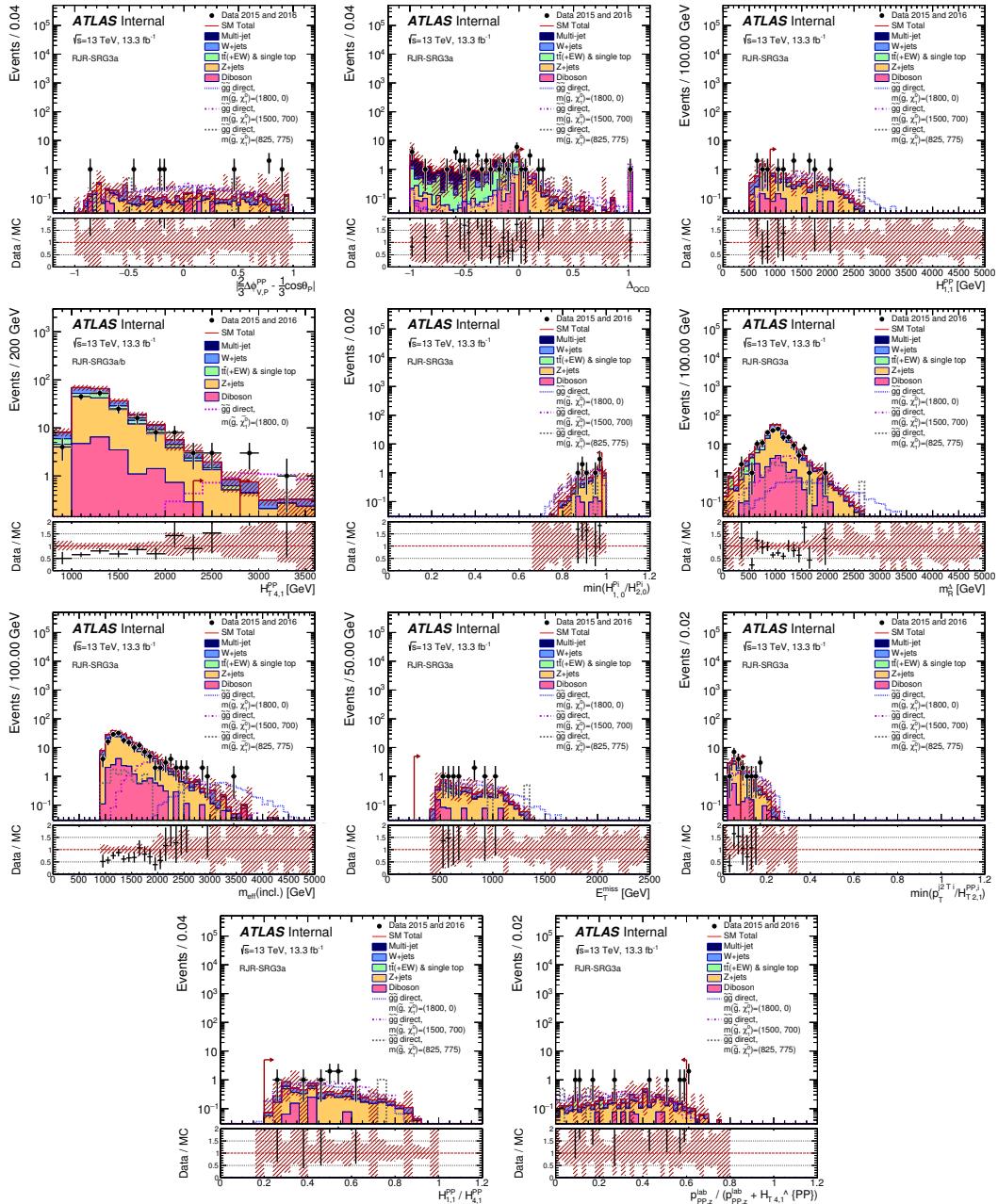


Figure 12

Figure 13

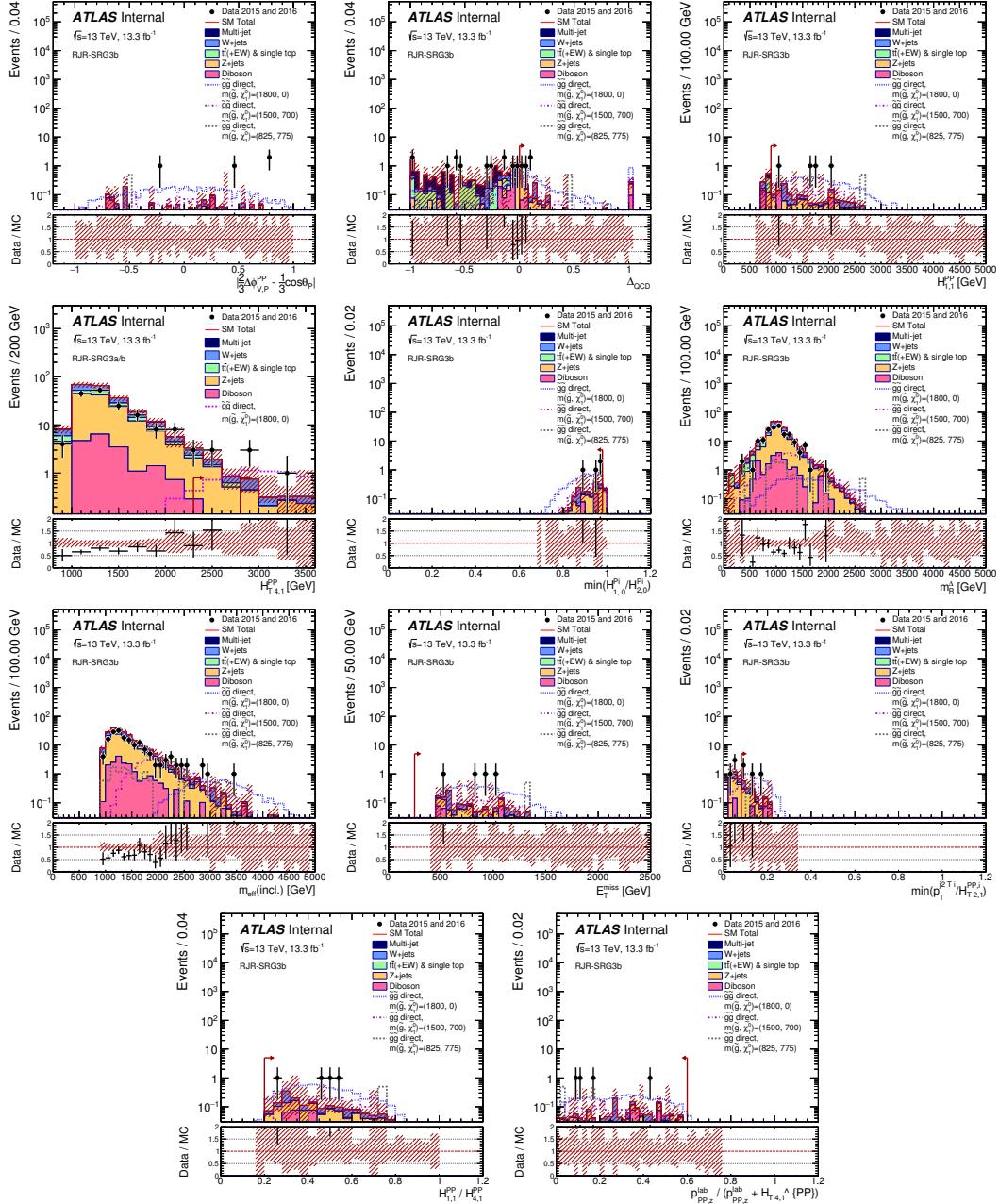


Figure 14

Figure 15

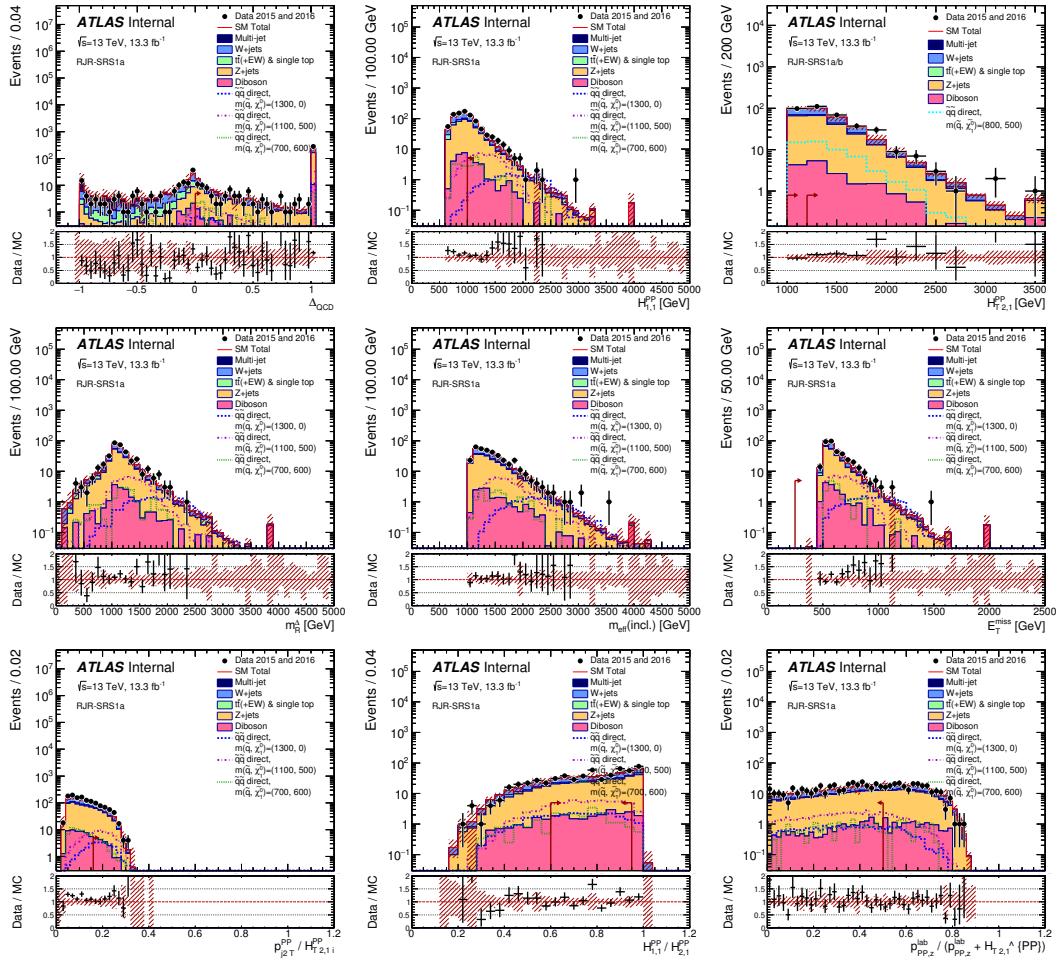


Figure 16

Figure 17

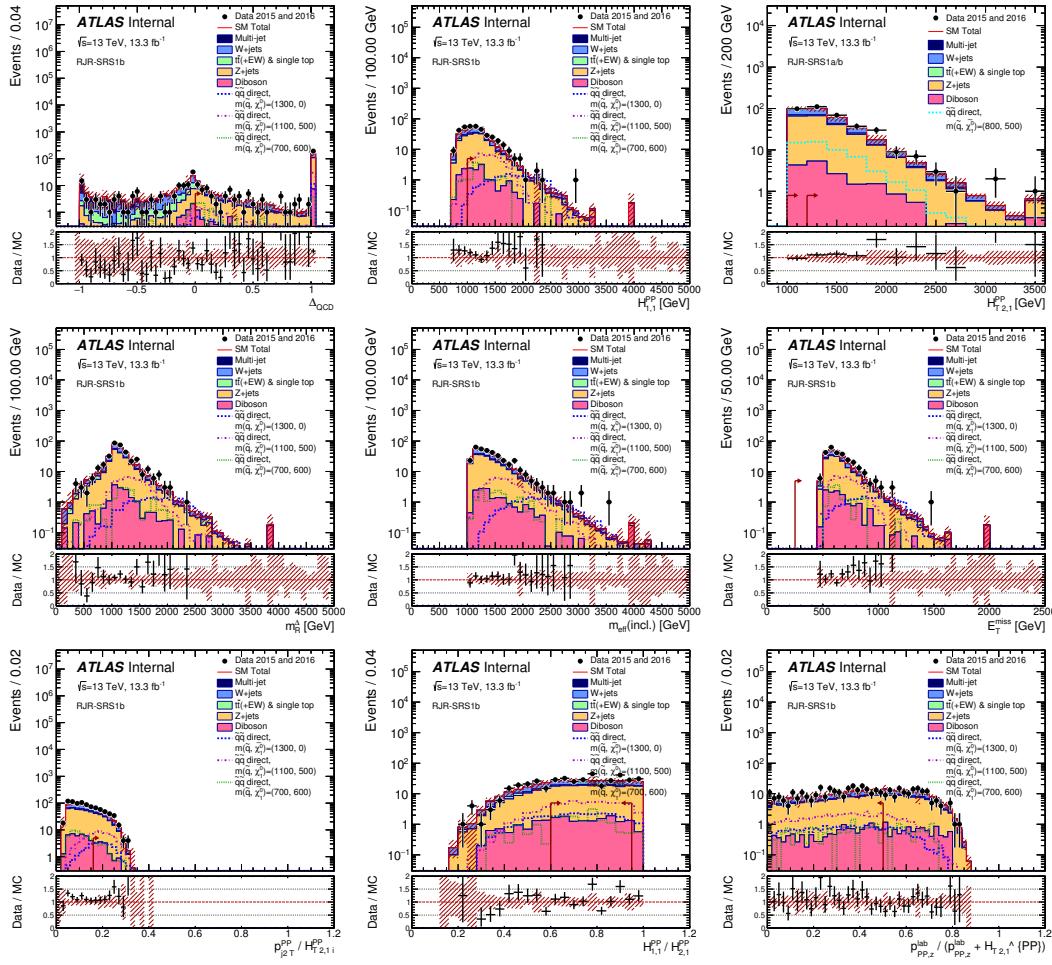


Figure 18

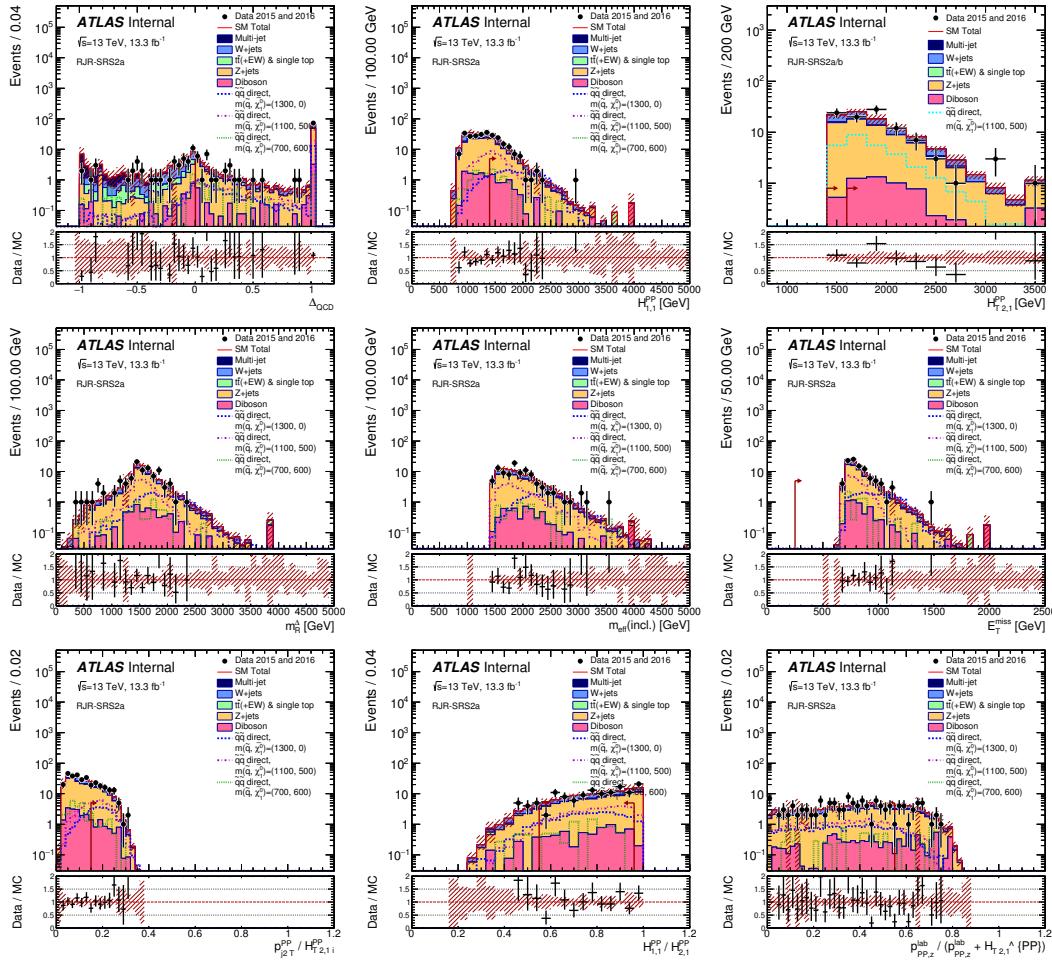


Figure 19

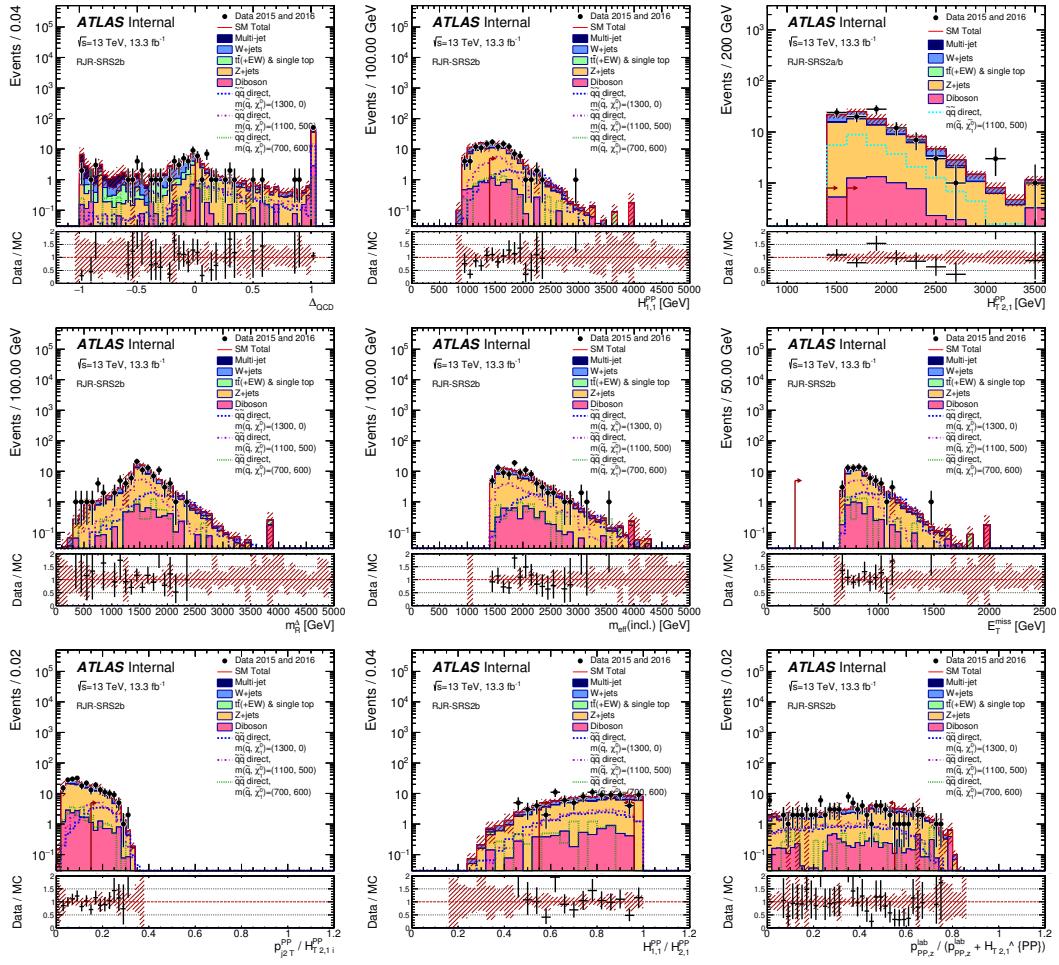


Figure 20

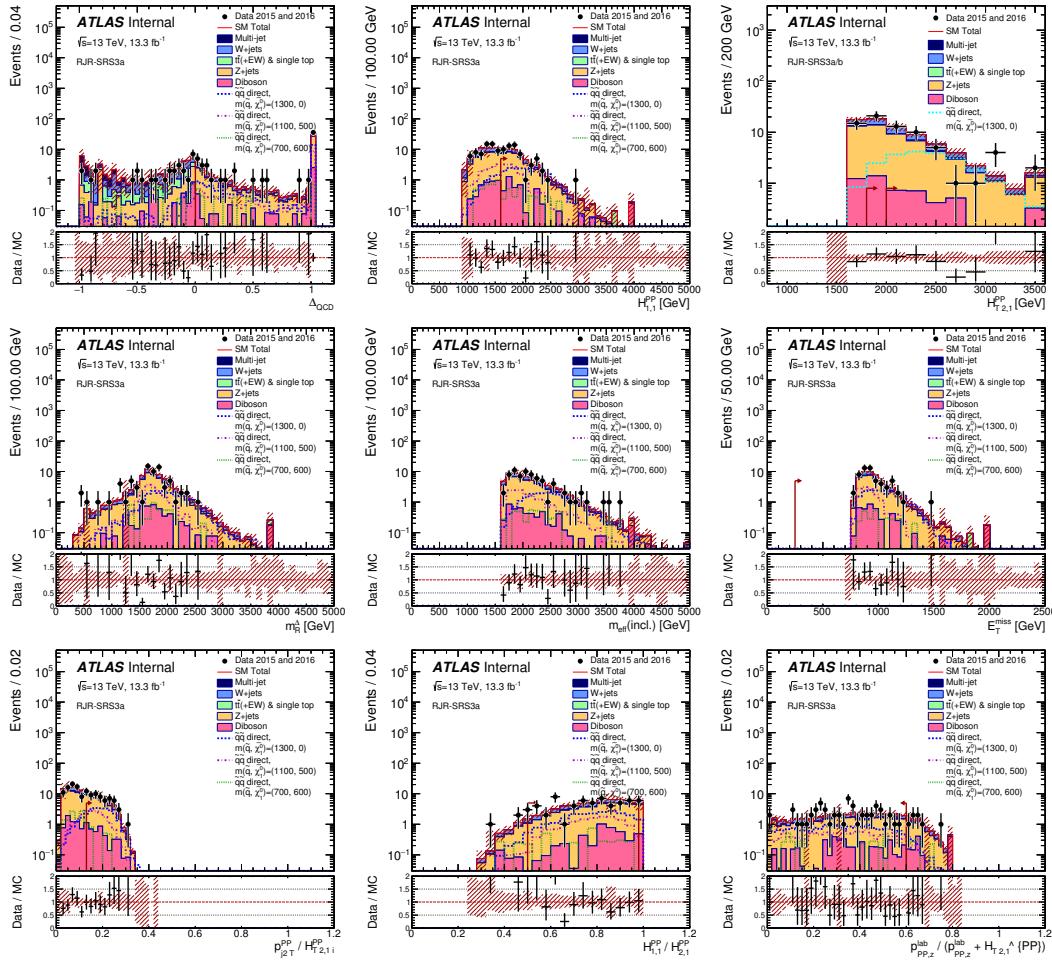


Figure 21

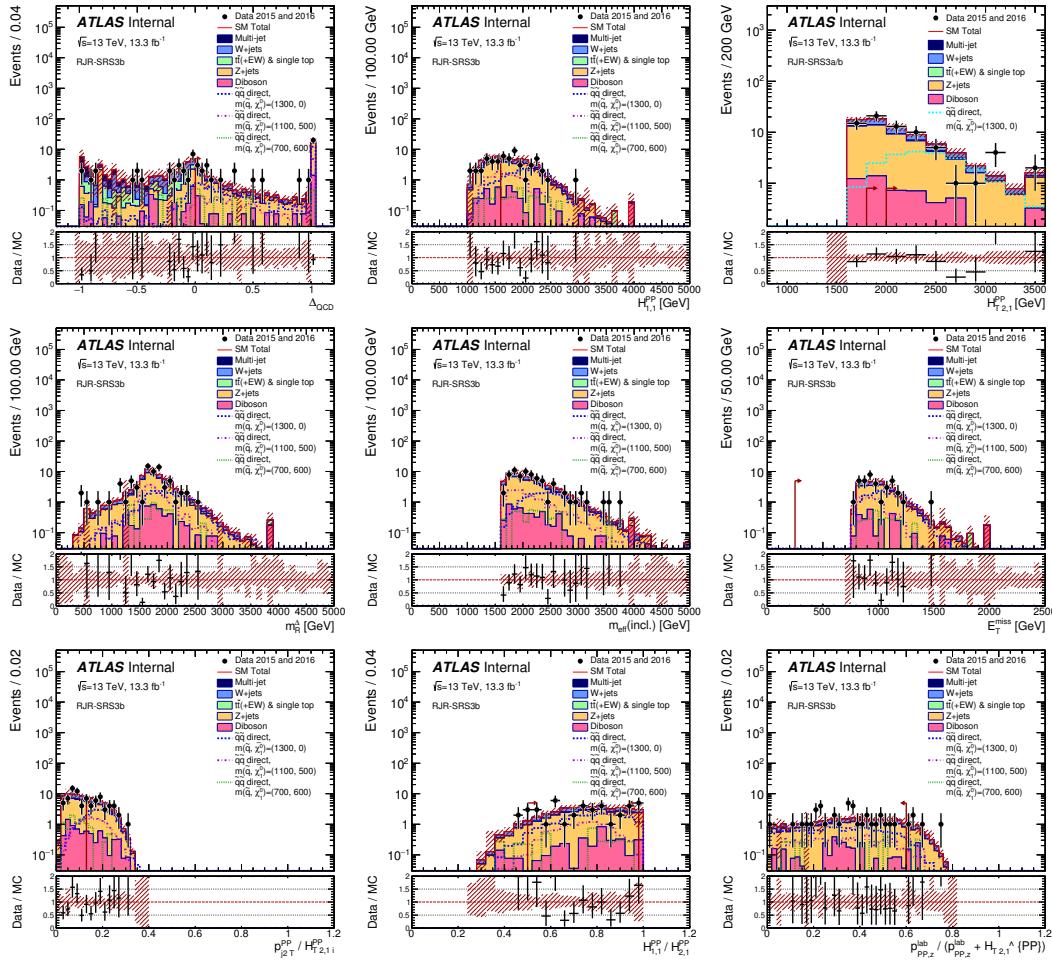


Figure 22