

¹ Observation of the Higgs boson in the WW^*
² channel and search for Higgs boson pair
³ production in the $b\bar{b}b\bar{b}$ channel with the
⁴ ATLAS detector

⁵ A DISSERTATION PRESENTED
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²⁰ **Observation of the Higgs boson in the WW^* channel and search
²¹ for Higgs boson pair production in the $b\bar{b}b\bar{b}$ channel with the
²² ATLAS detector**

²³ ABSTRACT

²⁴ This dissertation presents the observation and measurement of the Higgs boson in the $H \rightarrow WW^* \rightarrow$
²⁵ $\ell\nu\ell\nu$ channel at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV and a search for Higgs pair production in the $HH \rightarrow$
²⁶ $b\bar{b}b\bar{b}$ channel at $\sqrt{s} = 13$ TeV with the ATLAS detector in pp collisions at the Large Hadron Collider.

²⁷ First, the discovery of a particle consistent with the Higgs boson in 4.8 fb^{-1} at $\sqrt{s} = 7$ TeV and
²⁸ 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV is discussed. Then, the measurement of the Higgs boson signal strength
²⁹ and cross section in both the gluon fusion and vector boson fusion (VBF) production modes using
³⁰ 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV data combined with 4.8 fb^{-1} of 7 TeV data is shown. The combined signal
³¹ strength is measured to be $\mu = 1.09^{+0.23}_{-0.21}$. The total observed significance of the $H \rightarrow WW^*$ process
³² is observed to be 6.1σ (with 5.8σ expected). Advanced methods for background reduction and estima-
³³ tion, particularly in same-flavor lepton final states, are shown. The VBF signal strength is measured to
³⁴ be $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$ with an observed significance of 3.2σ (with 2.7σ expected). In the VBF chan-
³⁵ nel, a selection requirement based method, the precursor to the final multivariate technique used for the
³⁶ result, is detailed.

³⁷ Finally, a search for Higgs pair production in the $b\bar{b}b\bar{b}$ final state with 3.2 fb^{-1} at $\sqrt{s} = 13$ TeV is
³⁸ presented. A particular focus is placed on a tailored signal region for resonant production of Higgs pairs
³⁹ at high masses. No significant excesses are observed, and upper limits on cross sections are placed for
⁴⁰ spin-2 Randall Sundrum gravitons (RSG) and narrow spin-0 resonances. The cross section of $\sigma(pp \rightarrow$
⁴¹ $G_{\text{KK}}^* \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ with $k/\bar{M}_{\text{Pl}} = 1$ is constrained to be less than 70 fb for masses in the range
⁴² $600 < m_{G_{\text{KK}}^*} < 3000$ GeV. The cross section upper limits for $\sigma(pp \rightarrow H \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ ranges
⁴³ from 30 to 300 fb in the mass range of $500 < m_H < 3000$ GeV.

Contents

44

45	o INTRODUCTION	I
46	I Theoretical and Experimental Background	5
47	I THE PHYSICS OF THE HIGGS BOSON	6
48	1.1 The Standard Model of Particle Physics	6
49	1.2 Electroweak Symmetry Breaking and the Higgs	8
50	1.3 Higgs Boson Production and Decay	10
51	1.4 Higgs Pair Production in the Standard Model	16
52	1.5 Higgs Pair Production in Theories Beyond the Standard Model	16
53	1.6 Conclusion	21
54	2 THE ATLAS DETECTOR AND THE LARGE HADRON COLLIDER	22
55	2.1 The Large Hadron Collider	23
56	2.2 The ATLAS Detector	25
57	2.3 The ATLAS Muon New Small Wheel Upgrade	36
58	2.4 Object Reconstruction in ATLAS	40
59	II Observation and measurement of Higgs boson decays to WW^* in LHC	
60	Run 1 at $\sqrt{s} = 7$ and 8 TeV	49
61	3 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ ANALYSIS STRATEGY	50
62	3.1 Introduction	50
63	3.2 The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal in ATLAS	51
64	3.3 Background processes	52
65	3.4 Shared signal region selection requirements	55
66	3.5 Background reduction in same-flavor final states	59
67	3.6 Parameters of interest and statistical treatment	63
68	4 THE DISCOVERY OF THE HIGGS BOSON AND THE ROLE OF THE $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ CHANNEL	69
69	4.1 Introduction	69

71	4.2	Data and simulation samples	70
72	4.3	$H \rightarrow WW \rightarrow e\nu\mu\nu$ search	70
73	4.4	$H \rightarrow \gamma\gamma$ search	75
74	4.5	$H \rightarrow ZZ \rightarrow 4\ell$ search	76
75	4.6	Combined results	77
76	4.7	Conclusion	79
77	5	OBSERVATION OF VECTOR BOSON FUSION PRODUCTION OF $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	82
78	5.1	Introduction	82
79	5.2	Data and simulation samples	83
80	5.3	Object selection	87
81	5.4	Analysis selection	90
82	5.5	Background estimation	99
83	5.6	Systematic uncertainties	109
84	5.7	Results	112
85	6	COMBINED RUN I $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ RESULTS	117
86	6.1	Introduction	117
87	6.2	Results of gluon fusion $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ search	118
88	6.3	Signal strength measurements in ggF and VBF production	120
89	6.4	Measurement of Higgs couplings to vector bosons and fermions	123
90	6.5	Higgs production cross section measurement	124
91	6.6	Conclusion	125
92	III	Search for Higgs pair production in the $HH \rightarrow b\bar{b}b\bar{b}$ channel in LHC	
93		Run 2 at $\sqrt{s} = 13$ TeV	127
94	7	SEARCH FOR HIGGS PAIR PRODUCTION IN BOOSTED $b\bar{b}b\bar{b}$ FINAL STATES	128
95	7.1	Introduction	128
96	7.2	Motivation	129
97	7.3	Data and simulation samples	131
98	7.4	Event reconstruction and object selection	133
99	7.5	Event selection	136
100	7.6	Data-driven background estimation	141
101	7.7	Systematic uncertainties	147
102	7.8	Results	150

103	8 COMBINED LIMITS FROM BOOSTED AND RESOLVED SEARCHES	152
104	8.1 Introduction	152
105	8.2 Resolved results	153
106	8.3 Search technique and results	153
107	8.4 Limit setting	154
108	IV Looking ahead	158
109	9 CONCLUSION	159
110	APPENDIX A <i>b</i>-TAGGING PERFORMANCE AT HIGH p_T	163
111	A.1 Changes in MV2 score at high p_T	163
112	A.2 Effect of multiple <i>b</i> -quarks inside one jet	165
113	A.3 Changes in track quality at high p_T	167
114	REFERENCES	170

Listing of figures

116	I.1	The particles of the Standard Model and their properties [6].	7
117	I.2	The four most common Higgs boson production modes at the LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c) $W/Z + H$ production, (d) $t\bar{t}H$ production	11
118	I.3	Higgs production cross sections as a function of center of mass energy (\sqrt{s}) at a pp collider [18].	12
119	I.4	Higgs boson branching ratios as a function of m_H [18].	14
120	I.5	The two leading diagrams for Standard Model di-Higgs production at the LHC: (a) box diagram, (b) Higgs self coupling	16
121	I.6	Diagrams with new vertices for non-resonant Higgs pair production arising in composite Higgs models	17
122	I.7	Generic Feynman diagram for resonant Higgs pair production in BSM theories	18
123	I.8	Branching ratios for a spin-2 Randall-Sundrum graviton as a function of mass computed in MadGraph with the CP ₃ -Origins implementation [25, 31]	19
124	I.9	$\sigma \times \text{BR}(HH)$ for RSG as a function of mass computed in MadGraph with the CP ₃ -Origins implementation [25, 31]	19
125	I.10	RSG width as a function of mass computed in MadGraph with the CP ₃ -Origins implementation [25, 31]	20
126	I.11	Branching ratios for heavy Higgs H in Type I (left) and Type II (right) 2HDM models with $\tan \beta = 1.5$ and $\cos(\beta - \alpha) = 0.1(0.01)$ for Type I (Type II). [29]	21
135	2.1	A schematic view of the LHC ring [37]	23
136	2.2	A full diagram of the ATLAS detector [33]	26
137	2.3	The ATLAS coordinate system	27
138	2.4	Layout of the ATLAS Inner Detector system [41]	28
139	2.5	Layout of the ATLAS calorimeter system [33]	30
140	2.6	Layout of the ATLAS muon system [33]	32
141	2.7	Predicted field integral as a function of $ \eta $ for the ATLAS magnet system [33]	34
142	2.8	ATLAS trigger rates for Level-1 triggers as a function of instantaneous luminosity in 2012 and 2015 operation. These are single object triggers for electromagnetic clusters (EM), muons (MU), jets (J), missing energy (XE), and τ leptons (TAU). The threshold of the trigger is given in the name in GeV. [43]	35

146	2.9	Instantaneous luminosity as a function of time for data recorded by ATLAS at different center of mass energies [44, 45]	36
148	2.10	MDT tube hit (solid) and segment (dashed) efficiency as a function of hit rate per tube [46]	37
149	2.11	Trigger rate as a function of p_T threshold with and without the NSW upgrade [46]	38
150	2.12	Illustrations of the geometry (left) and operating principle (right) of the micromegas detector [46]	39
152	2.13	Geometry of the sTGC detector [46]	39
153	2.14	Illustration of particle interactions in ATLAS [49]	41
154	2.15	Electron performance: (a) reconstruction efficiency as a function of electron E_T [51] (b) energy resolution in simulation as a function of $ \eta $ for different energy electrons [52]	42
155	2.16	Muon performance: (a) reconstruction efficiency as a function of muon p_T (b) dimuon mass resolution as a function of average p_T [53]	43
158	2.17	Jet energy response after calibration as a function of true p_T in simulation [57]	45
159	2.18	Summary of the inputs to the MV2 b -tagging algorithm	46
160	2.19	Light jet rejection (1/efficiency) vs. b -jet efficiency for MV1 and its input algorithms (a) [58] and MV2 (b) [59] in simulated $t\bar{t}$ events. The numbers in the algorithm names in (b) refer to the fraction of charm events used in the MV2 training.	46
163	2.20	Resolution of E_T^{miss} components as a function of $\sum E_T$ before pileup suppression with different pileup techniques [61]	48
165	3.1	Branching ratios for a WW system. q refers to quarks. ℓ can be either an electron or muon, and the leptonic branching ratios of the τ are included. For example, the $\ell\nu qq$ final state includes one W decaying to $e\nu$, $\mu\nu$, or $\tau\nu$. τ_h refer to hadronic decays of the τ	52
168	3.2	Feynman diagram for Standard Model WW production	53
169	3.3	Feynman diagrams for top pair production (left) and Wt production (right)	53
170	3.4	An example Feynman diagram of W +jets production	54
171	3.5	An example Feynman diagram of Z +jets production	55
172	3.6	An illustration of the unique analysis signal regions [62]. The most sensitive regions for both gluon fusion and vector boson fusion production are underlined.	56
174	3.7	A graphical illustration of the $E_{T,\text{rel}}^{\text{miss}}$ calculation	57
175	3.8	Predicted backgrounds (compared with data) as a function of n_j (a and b) and n_b (c) after pre-selection requirements	58
177	3.9	An event display of a Z/γ^* + jets event illustrating the effect of pileup interactions	60
178	3.10	The RMS of different missing transverse momentum definitions as a function of the average number of interactions per bunch crossing	60
180	3.11	The difference between the true and reconstructed values of the missing transverse momentum (a) and m_T (b) in a gluon fusion signal sample	62

182	3.12	Comparison of f_{recoil} distributions for $Z/\gamma^* + \text{jets}$, $H \rightarrow WW^*$, and other backgrounds with real neutrinos.	63
183			
184	3.13	Signal significance as a function of required value for f_{recoil} and $p_{\text{T},\text{rel}}^{\text{miss}(\text{trk})}$ in the ggF $H \rightarrow WW^*$ with $n_j = 0$	64
185			
186	4.1	Jet multiplicity distribution in data and MC after applying lepton, jet, and $E_{\text{T},\text{rel}}^{\text{miss}}$ selections. The WW and top backgrounds have been normalized using control samples, and the hashed band indicates the total uncertainty on the prediction. [1]	71
187			
188	4.2	Comparison of m_{T} between data and simulation in the $n_j = 0$ WW (a) and $n_j = 1$ top (b) control samples [1]	73
189			
190	4.3	m_{T} distribution in the $H \rightarrow WW \rightarrow e\nu\mu\nu$ $n_j \leq 1$ channels for 8 TeV data [1].	75
191			
192	4.4	Diphoton mass spectrum in 7 and 8 TeV data. Panel a) shows the unweighted data distribution superimposed on the background fit, while panel c) shows the data where each event category is weighted by its signal to background ratio. Panels b) and d) show the respective distributions with background subtracted [1].	76
193			
194	4.5	Four lepton invariant mass spectrum ($m_{4\ell}$) in 7 and 8 TeV data compared to background estimate. A 125 GeV SM Higgs signal is shown in blue [1].	77
195			
196	4.6	Local p_0 distribution as a function of hypothesized Higgs mass for the $H \rightarrow ZZ^* \rightarrow 4\ell$ (a), $H \rightarrow \gamma\gamma$ (b), and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ (c) channels. Dashed curves show expected results, while solid curves show observed. Red curves are from 7 TeV data, blue curves from 8 TeV, and black curved combined [1].	79
197			
198	4.7	Combined 95% CL limits (a), local p_0 values (b), and signal strength measurement (c) as a function of Higgs mass [1].	80
199			
200	4.8	Comparison of measured signal strength μ for a 126 GeV Higgs in the 7 and 8 TeV datasets [1].	81
201			
202	4.9	Two dimensional likelihood as a function of signal strength μ and Higgs mass m_H [1].	81
203			
204	5.1	A comparison of the subleading lepton p_{T} spectrum between VBF $H \rightarrow WW^*$ production and $t\bar{t}$ background	84
205			
206	5.2	Leading jet η in VBF $H \rightarrow WW^*$ (red) and $t\bar{t}$ (black)	92
207			
208	5.3	Distributions of (a) m_{jj} , (b) Δy_{jj} , (c) $C_{\ell 1}$, and (d) $\Sigma m_{\ell j}$, for the VBF analysis. The top panels compare simulation and data, while the bottom panels show normalized distributions for all background processes and signal [62].	94
209			
210	5.4	A cartoon of the WW final state. Momenta are represented with thin arrows, spins with thick arrows. [62]	95
211			
212	5.5	Event display of a VBF candidate event [62].	97
213			
214	5.6	Distributions of $m_{\ell\ell}$ (top left), $\Delta\phi_{\ell\ell}$ (top right), and m_{T} (bottom), Higgs topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [62].	98
215			
216			
217			

218	5.7	Distributions of m_{jj} (top left), Δy_{jj} (top right), $\sum C_\ell$ (bottom), VBF topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [62].	99
219			
220	5.8	Distributions of m_{jj} (a) and O_{BDT} (b) in the VBF $n_b = 1$ top CR [62].	102
221			
222	5.9	Comparison of m_{jj} shape in a same flavor $Z \rightarrow \ell\ell$ control region and the VBF cut-based signal region.	103
223			
224	5.10	General illustration of the ABCD region definitions for $Z/\gamma^* \rightarrow \ell\ell$ background estimation.	104
225			
226	5.11	Distribution of $m_{\text{T}2}$ in the WW validation region of the VBF analysis [62].	106
227			
228	5.12	Extrapolation factors for the $W + \text{jets}$ estimate derived for muons (a) and electrons (b) as a function of lepton p_T [62].	108
229			
230	5.13	Background composition in final VBF signal region [62].	109
231			
232	5.14	Variations in the top background extrapolation factor in the cut-based analysis due to PDF uncertainties, binned in m_{T}	III
233			
234	5.15	Variations in the top background extrapolation factor in the cut-based analysis due to QCD scale uncertainties, binned in m_{T}	III
235			
236	5.16	Post-fit distributions in the cut-based VBF analysis. Panel (a) shows the one-dimensional m_{T} distribution, while (b) shows the data candidates split into the bins of m_{T} and m_{jj} used in the final fit [62].	II4
237			
238	5.17	Postfit distributions in the BDT VBF analysis [62].	II5
239			
240	5.18	Overlap between cut-based and BDT VBF signal region candidates in the m_{jj} - m_{T} plane. .	II6
241			
242	6.1	Post-fit m_{T} distribution in the $n_j \leq 1$ regions [62].	II9
243			
244	6.2	Best fit signal strength $\hat{\mu}$ as a function of hypothesized m_H [62].	121
245			
246	6.3	Local p_0 as a function of m_H [62].	121
247			
248	6.4	Likelihood as a function of $\mu_{\text{VBF}}/\mu_{\text{ggF}}$ [62].	122
249			
250	6.5	Likelihood scan as a function of μ_{VBF} and μ_{ggF} [62].	123
251			
252	6.6	Likelihood scan as a function of κ_F and κ_V [62].	124
253			
254	6.7	Comparison of signal strength measurements in different Higgs decay channels on ATLAS [91].	126
255			
256	7.1	Parton luminosity ratios as a function of resonance mass M_X for 13/8 TeV and 7/8 TeV [92].	129
257			
258	7.2	Summary of HH branching ratios [93].	130
259			
260	7.3	Minimum ΔR between B decay vertices for different RSG masses in a $G_{\text{KK}}^* \rightarrow HH \rightarrow 4b$ sample with $c = 1$	131
261			
262	7.4	Trigger efficiency for events passing all signal region selections as a function of mass in $G_{\text{KK}}^* \rightarrow HH \rightarrow 4b$ samples with $c = 1$ [102]. In the trigger names, “j” refers to a jet or jets. “ht” refers to H_T , the scalar sum of transverse momenta in the event. “bloose” refers to a loose b -tagging requirement applied to the jet. “aor” refers to anti- k_T jets with $R = 1.0$. The numbers at the end are the thresholds on the given quantity in GeV.	133
263			

254	7.5	Comparison of untrimmed and trimmed jet masses for large radius jets in a RSG sample with $m_{G_{\text{KK}}^*} = 1 \text{ TeV}$. JES (JMS) refers to the standard jet energy (mass) scale calibration for ATLAS [57].	134
255			
256	7.6	Efficiency of finding two b -jets from each Higgs in an RSG event using calorimeter jets with $R = 0.3$ or different track jet radii [106]	135
257			
258	7.7	Illustration of the boosted selection requirements on Higgs candidates. Each large-radius calorimeter jet (Higgs candidate) must contain two track jets	137
259			
260	7.8	Estimated significance as a function of signal mass for RSG $c = 1$ models in the $3b$ (a) and $4b$ (b) regions for different b -tagging efficiency working points	138
261			
262	7.9	Acceptance \times efficiency as a function of mass for (a) RSG and (b) narrow heavy scalar signal models [109].	139
263			
264	7.10	Efficiency of requiring 3 or 4 b -tagged track jets vs. RSG mass. The efficiency quoted is relative to the previous selection requirements (rather than an absolute efficiency).	140
265			
266	7.11	MV2c20 b -tagging efficiency for each of the four track jets in the boosted $4b$ selection as a function of RSG mass for $c = 1$ models.	141
267			
268	7.12	M_J^{sublead} vs. M_J^{lead} in a $2 b$ -tag data sample. The signal region is defined by the inner black contour ($X_{hh} < 1.6$) and the sideband region is defined by the outer contour ($R_{hh} >$ 35.8 GeV). The region between the black contours is the control region. The mass region which is enriched in $t\bar{t}$ background is also shown for illustration. [109]	142
269			
270	7.13	An illustration of the data-driven background estimation technique for the boosted analysis	144
271			
272	7.14	Leading large-R jet mass in the $3b$ (a) and $4b$ (b) sideband regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above. Because their normalizations are derived in the sideband region, the total background normalization is constrained by default to match the normalization of the data [109].	145
273			
274	7.15	Di-jet invariant mass (M_{2J}) in the $3b$ (a) and $4b$ (b) control regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above [109].	146
275			
276	7.16	Di-jet invariant mass (M_{2J}) in the $3b$ (a) and $4b$ (b) signal regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above. In the $3b$ re- gion, a graviton signal with $m_{G_{\text{KK}}^*} = 1.8 \text{ TeV}$ and $c = 1$ is overlaid, with the cross section multiplied by a factor of 50 so that the signal is visible. In the $4b$ region, signals with $m_{G_{\text{KK}}^*} = 1.0 \text{ TeV}$ and $m_{G_{\text{KK}}^*} = 1.5 \text{ TeV}$ are overlaid, both with $c = 1$ and the yields multiplied by factors of 2 and 5 respectively [109].	151
277			
278	8.1	Di-jet invariant mass (M_{2J}) in the resolved signal region. A graviton signal with $m_{G_{\text{KK}}^*} =$ 800 GeV and $c = 1$ is overlaid. [109].	154
279			
280	8.2	Expected and observed upper limit as a function of mass for G_{KK}^* in the RSG model with (a) $c = 1$ and (b) $c = 2$, as well as (c) H with fixed $\Gamma_H = 1 \text{ GeV}$, at the 95% confidence level in the CL_s method. [109]	157
281			

291	9.1	Combined ATLAS and CMS measurements in Run 1 for (a) Higgs signal strength in gluon		
292		fusion and VBF and (b) Higgs couplings normalized to their SM predictions	161	
293	9.2	Discovery significance for RSG models at the HL-LHC in three different budget scenar-		
294		ios [116]. Systematic uncertainties on the background prediction (σ_B) of 2.5% and 5.0%		
295		are both tested.	162	
296	A.1	p_T of the leading track jet in the leading calorimeter jet for different signal masses in RSG		
297		$c = 1$ models	164	
298	A.2	MV _{2c2o} score for the leading track jet (a) and subleading track jet (b) of the leading calorime-		
299		ter jet for different signal masses in RSG $c = 1$ models	164	
300	A.3	IP _{3D} log-likelihood ratio ($\log(p_b/p_u)$) of the leading track jet in the leading calorimeter		
301		jet for different signal masses in RSG $c = 1$ models	165	
302	A.4	Mass (a) and number of tracks (b) for the secondary vertices computed with the SV1 algo-		
303		rithm. When no secondary vertex is found, the quantities are assigned to default negative		
304		values.	166	
305	A.5	Mass (a) and number of tracks (b) for vertices computed with the JetFitter algorithm.		
306		When no vertices are found, the quantities are assigned to default negative values.	166	
307	A.6	MV _{2c2o} score (a) and SV1 mass (b) for leading track jets with two truth b quarks ($n_{tb,lead} =$		
308		2) compared to those with only one truth b ($n_{tb,lead} = 1$).	167	
309	A.7	Track fit χ^2/n_{DOF} (a) and number of pixel detector hits (b) for the leading track of the		
310		leading track jet in different mass RSG $c = 1$ samples	168	
311	A.8	MV _{2c2o} score (a) and SV1 mass (b) for leading track jets whose leading track jet has at least		
312		four pixel hits ($N_{pix} \geq 4$) compared to those which do not ($N_{pix} < 4$).	169	

Listing of tables

313

314	1.1	Production cross sections for a 125 GeV Higgs boson at $\sqrt{s} = 8$ TeV with scale and PDF uncertainties [18].	13
315	1.2	Branching ratios for a 125 GeV Higgs boson [18].	15
316	1.3	Possible channels for Higgs searches. Checkmarks denote the most sensitive production modes [5].	15
317	1.4	Production cross sections for pair production of a 125 GeV Higgs boson at $\sqrt{s} = 14$ TeV with total uncertainty [20]. The uncertainties include QCD scale and PDF variations as well as uncertainties on α_S	17
318			
319	2.1	Evolution of LHC machine conditions [39, 40]	25
320	2.2	Performance requirements for the ATLAS detector [33].	36
321	2.3	Signal efficiencies for WH production with $H \rightarrow b\bar{b}$ and $H \rightarrow WW^* \rightarrow \mu\nu qq$ under different trigger configurations [46].	40
322			
323	3.1	A summary of backgrounds to the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal	55
324			
325	4.1	Monte carlo generators used to model signal and background for the Higgs search [1].	70
326	4.2	Normalization factors (ratio of data and MC yields in a control sample) for the Standard Model WW and top backgrounds in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis [1]. Only statistical uncertainties are shown.	73
327			
328	4.3	Data and expected yields for signal and background in the final $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal region. Uncertainties shown are both statistical and systematic. [1]	74
329			
330	4.4	Summary of the expected and observed significance and measured signal strengths in the combined 7 and 8 TeV datasets for the Higgs discovery analysis [1].	78
331			
332	5.1	Single lepton triggers used for electrons and muons. A logical “or” of the triggers listed for each lepton type is taken. Units are in GeV, and the i denotes an isolation requirement in the trigger.	84
333			
334	5.2	Di-lepton triggers used for different flavor combinations. The two thresholds listed refer to leading and sub-leading leptons, respectively. The di-muon trigger only requires a single lepton at level-1.	84
335			

341	5.3	Trigger efficiency for signal events and relative gain of adding a dilepton trigger on top of the single lepton trigger selection. The first lepton is the leading, while the second is the sub-leading. Efficiencies shown here are for the ggF signal in the $n_j = 0$ category but are comparable for the VBF signal.	85
342	5.4	Monte Carlo samples used to model the signal and background processes [62].	86
343	5.5	p_T dependent isolation requirements for muons. Muons are required to have the amount of calorimeter or track based cone sums be less than this fraction of their p_T	88
344	5.6	p_T dependent requirements for electrons. Electrons are required to have the amount of calorimeter or track based cone sums be less than this fraction of their E_T	89
345	5.7	Summary of event selection for the $n_j \geq 2$ VBF analysis in the 8 TeV cut-based analy- sis [62].	96
346	5.8	Background composition after each requirement in the $n_j \geq 2$ VBF analysis in the 8 TeV cut-based analysis [62].	96
347	5.9	Top normalization factors computed at each stage of the cut-based selection. Uncertainties are statistical only.	101
348	5.10	Top normalization factors computed for each bin of O_{BDT} . Uncertainties are statistical only.	101
349	5.11	$Z/\gamma^* \rightarrow \tau\tau$ correction factors for the VBF cut-based analysis. Uncertainties are statistical only.	104
350	5.12	$Z/\gamma^* \rightarrow \ell\ell$ normalization factors for cut-based and BDT analyses. Uncertainties are statistical only.	105
351	5.13	Systematic uncertainties for various processes in the cut-based VBF analysis, given in units of % change in yield. Values are given for the low m_{jj} signal region.	110
352	5.14	Composition of the post-fit uncertainties (in %) on the total signal (N_{sig}), total back- ground (N_{bkg}), and individual background yields in the VBF analysis [62].	113
353	5.15	Event selection for the VBF BDT analysis. The event yields in (a) are shown after the pre- selection and the additional requirements applied before the BDT classification (see text). The event yields in (b) are given in bins in O_{BDT} after the classification [62].	113
361	6.1	All signal regions definitions input into final statistical fit [62].	118
369	6.2	Post-fit yields in the different ggF and VBF dedicated signal regions [62].	119
371	7.1	Summary of requirements on objects used in the $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ search	136
372	7.2	Effect of boosted selection on data, RSG signal models, $t\bar{t}$, and $Z+\text{jets}$. The numbers from simulation are normalized with the MC generator cross section and do not take into account the data driven estimates described in section 7.6 [110].	141
374	7.3	Mass region definitions used for background estimation	143

376	7.4	Parameters derived for exponential fit to background M_{2J} shape in the $3b$ and $4b$ signal regions [10]	145
377	7.5	The number of events in data and predicted background events in the boosted 3-tag and 4-tag sideband and control regions. The uncertainties shown are statistical only. [109] . . .	146
378	7.6	Summary of systematic uncertainties in the total background and signal event yields (expressed in %) in the boosted 3-tag and 4-tag signal regions. Systematic uncertainties on the signal normalization are shown for models with $m_{G_{KK}^*} = 1.5$ TeV and both $c = 1$ and $c = 2$ as well as a narrow width heavy scalar.	148
379	7.7	Alternate fit functions used to model the M_{2J} distribution in the QCD multijet background. In the equations, $x = M_{2J}/\sqrt{s}$	149
380	7.8	Observed yields in the 3-tag and 4-tag signal regions for the boosted analysis compared to the predicted number of background events Errors correspond to the total uncertainties in the predicted event yields. The yields for a graviton with $m_{G_{KK}^*} = 1$ TeV and $c = 1$ are also shown. [109]	150
381	8.1	Observed yields in the resolve selection 4-tag signal region compared to the predicted number of background events Errors correspond to the total uncertainties in the predicted event yields. The yields for a graviton with $m_{G_{KK}^*} = 800$ GeV and $c = 1$ are also shown. [109]	153
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491

Introduction

492 The Higgs boson is often described as one of the cornerstones of the Standard Model. Since the concep-
493 tion of the Higgs mechanism as the source of electroweak symmetry breaking in the early 1960s, countless
494 collider experiments have searched for this elusive particle. This dissertation presents the story of the Higgs
495 boson from its discovery to its use as a tool in the search for physics beyond the Standard Model with the
496 ATLAS detector at the Large Hadron Collider (LHC).

497 One of the first priorities of the early LHC was the search for the Higgs boson. This search was first
498 tackled in three main channels: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, and $H \rightarrow WW^*$. Each channel has its own
499 merits, but the WW^* is particularly suited to searching over a wide range of masses. The $H \rightarrow WW^*$
500 branching ratio is large and it is the primary decay channel above the $2m_W$ mass threshold.

501 While the rate of events produced in $H \rightarrow WW^*$ is large, the channel poses some challenges. First,
502 the most common mode of study for this channel is $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. With neutrinos in the
503 final state, it is not possible to fully reconstruct the invariant mass of the parent Higgs like the $\gamma\gamma$ and

504 $ZZ \rightarrow 4\ell$ channels. Second, the final state topology is mimicked by a wide variety of backgrounds that
505 need to be properly estimated. This means tailored selection requirements for background reduction and
506 robust background estimation techniques must both be developed.

507 In 2012, the ATLAS and CMS experiments announced the discovery of a new particle consistent with
508 the Higgs boson [1, 2]. In ATLAS, this discovery was made with 4.8 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$ and
509 5.8 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis played an important role in this discovery.
510 After the discovery, measurement of the properties of the newly discovered particle and confirmation of its
511 consistency with the Standard Model Higgs were the main priorities. The WW^* channel is also uniquely
512 suited to these types of measurements. Because of its good rate, it offers some of the best cross section
513 measurements available among the various Higgs decay modes. It is also suited for measurement of mul-
514 tiple Higgs production modes, like the vector boson fusion (VBF) mode, where incoming quarks radiate
515 W/Z bosons which fuse to make a Higgs. In VBF production with the WW^* decay channel, the coupling
516 of the Higgs to the W boson is present in both the production and decay which allows for more precise
517 measurements of this coupling than other channels which rely on gluon fusion production (where gluons
518 couple to the Higgs through a top loop in the production). The measurement of VBF carries the addi-
519 tional challenge that its cross section is an order of magnitude smaller than that of gluon fusion, meaning
520 that the large branching ratio to WW^* offers an additional advantage in isolating this production mode.
521 In the final ATLAS Run 1 results, combining 20.3 fb^{-1} taken at $\sqrt{s} = 8 \text{ TeV}$ with the 4.8 fb^{-1} collected
522 at $\sqrt{s} = 7 \text{ TeV}$, the WW^* channel achieved its first observation of VBF production of the Higgs.

523 After Run 1 of the LHC, with the existence of the Higgs now firmly established, the focus shifted to
524 searches for physics beyond the Standard Model. In particular, searches for high mass resonances benefit
525 from the LHC's increase to $\sqrt{s} = 13 \text{ TeV}$ in Run 2. The cross section for a generic gluon-initiated reso-
526 nance with a mass of 2 TeV increases tenfold in Run 2, making searches for high mass resonances a high
527 priority. The newly discovered Higgs can be used as a tool in these searches. After the discovery, the Higgs
528 boson provides a large swath of unmeasured phase space where new physics could be discovered. Higgs
529 pair production in the Standard Model has a low cross section that requires large datasets (on the order of
530 the LHC's lifetime) for full measurement. However, new physics can modify this cross section, especially

531 through new resonances which decay to two Higgs bosons. Such high mass resonances also produce diffi-
532 cult to recognize final state topologies due to the merging of decay products from high momentum Higgs
533 bosons. A search for Higgs pair production in the $HH \rightarrow b\bar{b}b\bar{b}$ final state was performed with 3.2 fb^{-1}
534 collected with ATLAS at $\sqrt{s} = 13 \text{ TeV}$ in 2015. The results are presented in this dissertation with a focus
535 on a dedicated signal region for boosted final states. This signal region uses new techniques for recognizing
536 jet substructure and b -tagging to the improve signal acceptance of high mass resonances.

537 This dissertation begins by discussing the discovery of the Higgs and the role of the $H \rightarrow WW^* \rightarrow$
538 $\ell\nu\ell\nu$ channel. It then discusses the first observation of the VBF production mode in $H \rightarrow WW^* \rightarrow$
539 $\ell\nu\ell\nu$ with the full ATLAS Run 1 dataset, as well as the final combined Run 1 measurements from this
540 channel. Finally, it presents a search for Higgs pair production in the $HH \rightarrow b\bar{b}b\bar{b}$ channel. It is organized
541 into four parts.

542 Part 1 presents the theoretical and experimental background required for the subsequent parts. Chap-
543 ter 1 gives an overview of Higgs physics, particularly single and double Higgs production in the Standard
544 Model and beyond. Chapter 2 presents details regarding the Large Hadron Collider and the ATLAS exper-
545 iment. The evolution of machine conditions, descriptions of the ATLAS sub-detectors, and an overview
546 of object reconstruction in ATLAS are all shown. A brief interlude on the ATLAS Muon New Small
547 Wheel upgrade is also given, as this upgrade has been a focus of my graduate work and will have important
548 impact on ATLAS' ability to study the Higgs at the High Luminosity LHC.

549 Part 2 discusses the observation and measurement of the Higgs in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel
550 in the ATLAS Run 1 dataset at $\sqrt{s} = 7$ and 8 TeV . Because I worked in this channel from before the
551 discovery through to the final analysis of the Run 1 dataset, Part 2 is organized in such a way to allow easy
552 presentation of multiple analyses on different subsets of the full Run 1 dataset. Chapter 3 presents a general
553 overview of the $H \rightarrow WW^*$ analysis strategy and defines many of the variables and common elements
554 used in the rest of Part 2. Chapter 4 presents the discovery of the Higgs boson, focusing on the role of the
555 WW^* channel in this discovery. Chapter 5 presents the first observation of the VBF production mode of
556 the Higgs in the WW^* channel, a study which was done on the full Run 1 ATLAS dataset. In this chapter,
557 the focus is mainly on the selection cut-based VBF analysis. The cut-based analysis was an important first

558 step to the final VBF result which used a Boosted Decision Tree (BDT). Where appropriate, connections
559 between the cut-based and BDT analyses are shown and their compatibility is discussed. Finally, the VBF
560 analysis was an important input into the combined Run 1 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ result, which used
561 both the gluon fusion and VBF channels in a combined fit to infer properties of the Higgs, including its
562 couplings to the gauge bosons and its production cross section. This is the topic of Chapter 6.

563 Part 3 presents a search for Higgs pair production in the $HH \rightarrow b\bar{b}b\bar{b}$ channel. Chapter 7 presents
564 an overview of this search in the boosted regime, where the Higgs pairs are the result of the decay of a
565 heavy resonance. Chapter 8 shows the combined results between the boosted regime and the resolved
566 regime, which is sensitive to lower mass resonances and non-resonant Higgs pair production. Finally, Part
567 4 presents a conclusion and brief outlook of future Higgs physics with ATLAS.

Part I

Theoretical and Experimental Background

In modern physics, there is no such thing as “nothing.”

Richard Morris

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570

571

The Physics of the Higgs Boson

572 This chapter presents an overview of the Standard Model of Particle Physics and in particular the physics
573 of the Higgs boson. First, a brief overview of the Standard Model and its history are presented. Then, a
574 description of the Higgs mechanism of electroweak symmetry breaking is given. Next, the physics of single
575 Higgs boson production and decay is described. The Standard Model also allows for production of two
576 Higgs bosons and this is detailed as well. Finally, di-Higgs production in two beyond the Standard Model
577 (BSM) theories - Randall-Sundrum gravitons (RSG) and Two Higgs Doublet Models (2HDM) - is shown.

578 **I.I THE STANDARD MODEL OF PARTICLE PHYSICS**

579 The Standard Model (SM) of Particle Physics is a quantum field theory describing the fundamental
580 particles of nature and the forces that govern their interactions. Several comprehensive treatments of the
581 SM already exist in the literature [3–8] and this section will not rehash those. Rather, this section presents
582 a brief overview of the SM particles and forces in order to define them for subsequent discussions.

583 The Standard Model consists of two primary categories of fundamental particles: fermions (spin 1/2
 584 particles) and bosons (integer spin particles). The SM also describes three forces: electromagnetism, the
 585 weak nuclear force, and the strong nuclear force. Gravity is not included in the theory and is largely irrele-
 586 evant at the scales currently probed by collider experiments. Within the fermions, there are both quarks
 587 (which interact via all three forces) and the leptons. The charged leptons interact via electromagnetic and
 588 weak interactions, while neutrinos (neutral leptons) interact only via the weak force. Within the bosons,
 589 there are the W^\pm and Z bosons (the mediators of the weak force), the gluon (g , the mediator of the strong
 590 force), and the photon (γ), the mediator of the electromagnetic force. Finally, there is the Higgs boson,
 591 a fundamental spin-0 particle resulting from the Higgs mechanism of electroweak symmetry breaking.

592 Figure 1.1 summarizes the fermions and bosons of the SM.

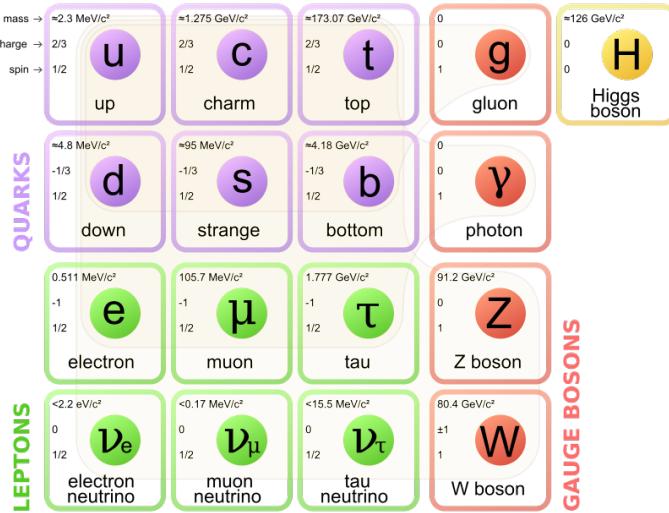


Figure 1.1: The particles of the Standard Model and their properties [6].

593 The Standard Model coalesced into a unified theoretical framework in the 1960s through the work
 594 of Glashow, Weinberg, Salam, and others on the theory of electroweak interactions [9–12]. This theory
 595 characterized both the electromagnetic and weak interactions as unified under a single gauge symmetry
 596 group, namely $SU(2) \times U(1)$. At low enough energy scales (on the order of the W and Z masses, the
 597 electroweak symmetry is broken, as evidenced by the fact that the weak bosons have mass while the photon
 598 does not. The discovery of the Higgs boson in 2012 confirmed the Higgs mechanism as the most likely
 599 candidate for this electroweak symmetry breaking [1, 2]. The electroweak theory is then combined with

600 the theory of quantum chromodynamics (which models the strong sector as a non-Abelian $SU(3)$ gauge
 601 group) to form the complete SM [13].

602 **I.2 ELECTROWEAK SYMMETRY BREAKING AND THE HIGGS**

603 In the Standard Model Lagrangian, it is difficult to include mass terms for the W and Z bosons without
 604 breaking the fundamental gauge symmetry of the Lagrangian. A traditional mass term does not preserve
 605 the $SU(2) \times U(1)$ symmetry. Additionally, scattering of massive W and Z bosons violate unitarity and
 606 these diagrams diverge at high energy scales. In the 1960s, Higgs, Brout, Englert, Guralnik, Kibble, and
 607 Hagen developed a mechanism for spontaneous symmetry breaking via the addition of a complex scalar
 608 doublet to the SM. Three of the four real degrees of freedom of this complex field would go to the lon-
 609 gitudinal modes of the W^\pm and Z , thus allowing them to have mass [14–17]. The remaining degree of
 610 freedom would manifest as an additional scalar, known now as the Higgs boson.

611 The mechanism works by introducing a Lagrangian for the newly introduced field that still respects the
 612 symmetry of the Standard Model inherently, but with a minimum at a non-zero vacuum expectation value
 613 for the field. In this minimum of the potential, the electroweak symmetry is broken. Specifically, consider
 614 a complex scalar doublet Φ with four degrees of freedom, as shown in equation I.1.

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ + i\phi_2^+ \\ \phi_1^0 + i\phi_2^0 \end{pmatrix} \quad (\text{I.1})$$

615 The minimal potential of a self-interacting Higgs that still respects the SM symmetry is given in equa-
 616 tion I.2.

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (\text{I.2})$$

617 If the μ^2 term of this potential is positive, then the potential has a minimum at $\Phi = 0$ and the SM
 618 symmetry is preserved. However, if instead $\mu^2 < 0$, then the minimum is at a finite value of Φ , namely

$$\Phi_{\min} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (\text{I.3})$$

⁶¹⁹ where $v = \sqrt{\mu^2/\lambda}$. Because this is the location of the minimum, it corresponds to the vacuum expecta-
⁶²⁰ tion value for the field ($\langle \Phi \rangle = \Phi_{\min}$). The excitations of the Higgs can then be parameterized as

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad (1.4)$$

⁶²¹ The full scalar Lagrangian, including the kinetic term, is then given as

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi) \quad (1.5)$$

⁶²² where the covariant derivative is defined as

$$D_\mu = \partial_\mu + \frac{ig}{2} \tau^a W_\mu^a + ig' Y B_\mu \quad (1.6)$$

⁶²³ and W^1, W^2, W^3 and B are the $SU(2)$ and $U(1)$ gauge fields of the electroweak theory, respectively. g
⁶²⁴ and g' are the corresponding coupling constants. With the scalar Lagrangian in place, the physical gauge
⁶²⁵ fields can then be written as

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2) \quad (1.7)$$

⁶²⁶

$$Z_\mu = \frac{-g'B_\mu + gW_\mu^3}{\sqrt{g^2 + g'^2}} \quad (1.8)$$

⁶²⁷

$$A_\mu = \frac{gB_\mu + g'W_\mu^3}{\sqrt{g^2 + g'^2}} \quad (1.9)$$

⁶²⁸ Equation 1.7 corresponds to the charged W^+ and W^- bosons, equation 1.8 corresponds to the neutral Z
⁶²⁹ boson, and equation 1.9 corresponds to the neutral photon. The masses of the particles also arise from the
⁶³⁰ Lagrangian. The photon has zero mass, while the masses of the W and Z bosons are given in equation 1.10.

⁶³¹

$$M_W^2 = \frac{1}{4} g^2 v^2$$

$$M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2 \quad (1.10)$$

632 The fermion masses also arise through a coupling with the Higgs via the Yukawa interaction (for a detailed
633 description, see [8]). In this case the coupling between the Higgs and the fermions goes as

$$g_{Hf\bar{f}} = \frac{m_f}{v} \quad (\text{i.ii})$$

634 The full Lagrangian of Higgs interactions can be written as

$$\mathcal{L}_{\text{Higgs}} = -g_{Hf\bar{f}}\bar{f}fH + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4 + \delta_V V_\mu V^\mu \left(g_{HV}VH + \frac{g_{HHV}}{2}H^2 \right) \quad (\text{i.12})$$

635 with

$$\begin{aligned} g_{HV} &= \frac{2m_V^2}{v} & g_{HHV} &= \frac{2m_V^2}{v^2} \\ g_{HHH} &= \frac{3m_H^2}{v} & g_{HHHH} &= \frac{3m_H^2}{v^2} \end{aligned} \quad (\text{i.13})$$

636 Here, V refers to the W^\pm and Z , and $\delta_W = 1$ while $\delta_Z = 1/2$. Phenomenologically, there are a few
637 features of this Lagrangian that are useful to note. First, note that the Higgs mass is a free parameter of the
638 theory that must be determined experimentally. Second, note that the coupling of the Higgs to the vector
639 bosons and fermions scales with the masses of these particles, a fact that is important when considering
640 both the production and decays of the particle. Also note that the branching ratio of the Higgs to W
641 bosons will be twice that of the branching ratio to Z if the Higgs mass is large enough to produce the
642 particles on shell because of the extra symmetry factor associated with the W coupling. Finally, note the
643 presence of the cubic and quartic Higgs self interaction terms, which can lead to final states with multiple
644 Higgs bosons produced.

645 1.3 HIGGS BOSON PRODUCTION AND DECAY

646 This section discusses the properties of Higgs production and decay mechanisms. The details presented
647 here will focus on the properties of a 125 GeV Higgs boson, as this is the mass closest to that of the newly
648 discovered Higgs.

649 1.3.1 HIGGS PRODUCTION

650 The Higgs is produced by four main production modes at the Large Hadron Collider - gluon-gluon
 651 fusion (ggF), vector boson fusion (VBF), associated production with a W or Z boson, or associated pro-
 652 duction with top quarks ($t\bar{t}H$). Figure 1.2 shows the Feynman diagrams for these four modes.

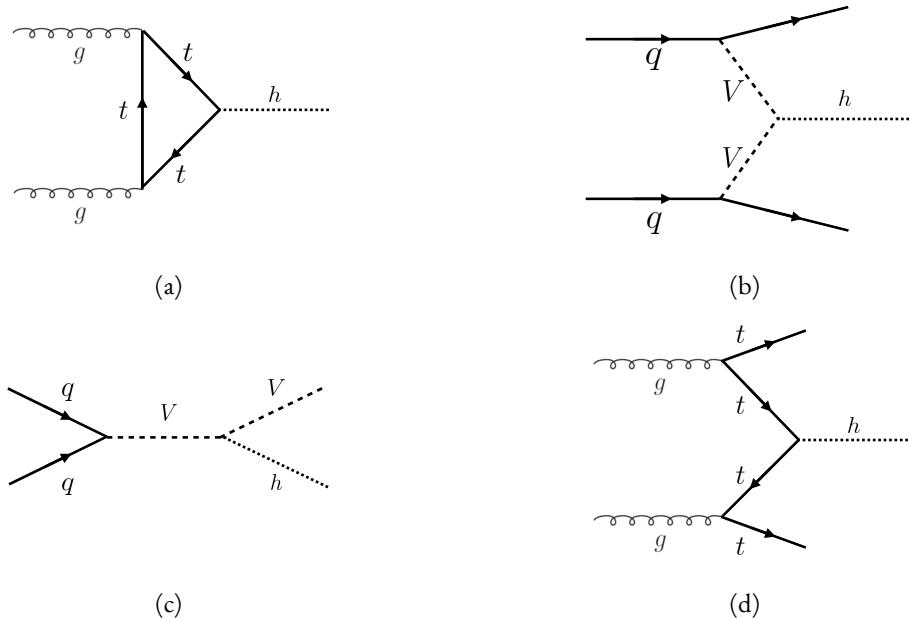


Figure 1.2: The four most common Higgs boson production modes at the LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c) $W/Z + H$ production, (d) $t\bar{t}H$ production

653 In gluon-gluon fusion, gluons from the incoming protons fuse via a top-quark loop to produce a Higgs.
 654 The top quark is the dominant contribution in the loop due to its heavy mass and the fact that the Higgs-
 655 fermion coupling constant scales with fermion mass. In vector boson fusion, the incoming quarks each
 656 radiate a W or Z boson which fuse to produce the Higgs. This production mode results in a final state
 657 with a Higgs boson and two additional jets which tend to be forward because they carry the longitudinal
 658 momentum of the incoming partons. The Higgs can also be produced in association with a W or Z boson.
 659 The W/Z is produced normally and then radiates a Higgs (this mode is also sometimes known as “Higgs-
 660 strahlung”). Finally, the Higgs can be produced in association with two top quarks. Each incoming gluon
 661 splits into a $t\bar{t}$ pair, and one of the top pairs combines to create a Higgs. Figure 1.3 shows the production
 662 cross section for a 125 GeV Higgs boson in each of these modes at a pp collider as a function of center of

663 mass energy.

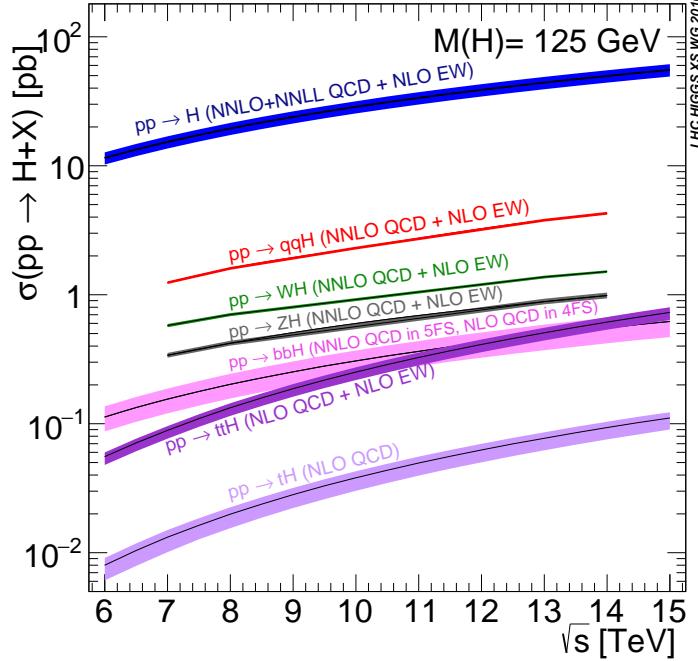


Figure 1.3: Higgs production cross sections as a function of center of mass energy (\sqrt{s}) at a pp collider [18].

664 In figure 1.3, note that gluon fusion has the largest cross section, while VBF is the second largest at
 665 approximately a factor of 10 smaller. The figure also includes the less commonly studied $b\bar{b}H$ and tH
 666 modes. The $b\bar{b}H$ and tH modes are not studied as commonly as $t\bar{t}H$ due to the larger background con-
 667 tributions and lower cross sections, respectively. At $\sqrt{s} = 8$ TeV, ggF production of a 125 GeV Higgs
 668 has a cross section of 19.47 pb, while VBF has a cross section of 1.601 pb [18]. The cross sections of all of
 669 the main Higgs production modes at this center of mass energy, as well as their uncertainties from varying
 670 the renormalization and factorization scales and PDFs, are summarized in table 1.1 for a 125 GeV Higgs.

671 1.3.2 HIGGS BRANCHING RATIOS

672 The fact that the Higgs couples more strongly to more massive particles is crucial for understanding its
 673 branching ratios. The width for Higgs decays to fermions is given in equation 1.14 [5].

$$\Gamma(H \rightarrow f\bar{f}) = \frac{N_c \sqrt{2} G_F m_f^2 m_H}{8\pi} \quad (1.14)$$

Production mode	σ (pb)	QCD scale uncert. (%)	PDF + α_s uncert. (%)
Gluon fusion	19.47	+7.3/ - 8.0	3.1
Vector boson fusion	1.601	+0.3/ - 0.2	2.2
WH	0.7026	+0.6/ - 0.9	2.0
ZH	0.4208	+2.9/ - 2.4	1.7
$t\bar{t}H$	0.1330	+4.1/ - 9.2	4.3
bbH	0.2021	+20.7/ - 22.3	
tH (t -channel)	0.01869	+7.3/ - 16.5	4.6
tH (s -channel)	1.214×10^{-3}	+2.8/ - 2.4	2.8

Table 1.1: Production cross sections for a 125 GeV Higgs boson at $\sqrt{s} = 8$ TeV with scale and PDF uncertainties [18].

674 In this case, N_c is the number of colors, G_F is the Fermi constant, m_f is the mass of the fermion, and
 675 m_H is the mass of the Higgs. Note that the width scales with the square of the fermion mass. (This also
 676 assumes that the Higgs mass is large enough to decay with both the fermions on shell.)

677 The decay width to WW , in the case where both W bosons are produced on shell ($m_H \geq 2m_W$), is
 678 given in equation 1.15 [5].

$$\Gamma(H \rightarrow W^+W^-) = \frac{\sqrt{2}G_FM_W^2m_H}{16\pi} \frac{\sqrt{1-x_W}}{x_W} (3x_W^2 - 4x_W + 4) \quad (1.15)$$

679 where m_W is the mass of the W and $x_W = 4M_W^2/m_H^2$. To get the branching ratio to ZZ (in the regime
 680 where $m_H \geq 2m_Z$), the equation is divided by 2 to account for identical particles in the final state, and
 681 x_W is replaced with $x_Z = 4M_Z^2/m_H^2$. This is shown in equation 1.16 [5].

$$\Gamma(H \rightarrow ZZ) = \frac{\sqrt{2}G_FM_Z^2m_H}{32\pi} \frac{\sqrt{1-x_Z}}{x_Z} (3x_Z^2 - 4x_Z + 4) \quad (1.16)$$

682 The more general formula for Higgs branching into WW or ZZ , taking into account the case where one
 683 or both vector bosons is off-shell, is shown in equation 1.17 [19].

$$\Gamma(H \rightarrow V^*V^*) = \frac{1}{\pi^2} \int_0^{M_H^2} \frac{dq_1^2 M_V \Gamma_V}{(q_1^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \int_0^{(M_H-q_1)^2} \frac{dq_2^2 M_V \Gamma_V}{(q_2^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \Gamma_0 \quad (1.17)$$

684 Here, q_1^2 and q_2^2 are the invariant masses of the virtual gauge bosons, M_V is the W or Z mass, and Γ_V is
 685 the W or Z width. Γ_0 is the squared matrix element, which is given in equation 1.18 [19].

$$\Gamma_0 = \frac{G_F M_H^3}{8\sqrt{2}\pi} \delta_V \sqrt{\lambda(q_1^2, q_2^2, M_H^2)} \left[\lambda(q_1^2, q_2^2, M_H^2) + \frac{12q_1^2 q_2^2}{M_H^4} \right] \quad (1.18)$$

686 The function λ is defined as $\lambda(x, y, z) = (1 - x/z - y/z)^2 - 4xy/z^2$. The integral in the general off-
 687 shell boson case is much more difficult to interpret than the simpler on-shell branching ratios, but it can be
 688 evaluated numerically. These formulas can also be visualized as a function of Higgs mass. Figure 1.4 shows
 the branching ratios as a function of the Higgs mass. There are a few interesting features to note in this

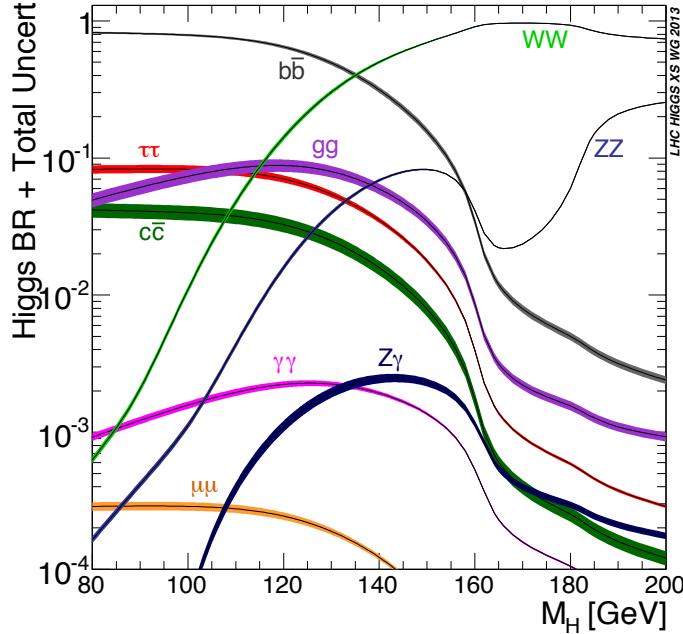


Figure 1.4: Higgs boson branching ratios as a function of m_H [18].

689 figure. First, note that at high Higgs masses, once on-shell production of both W and Z bosons is possible,
 690 these two decays are the dominant ones due to the large masses of the W/Z . Also note that the branching
 691 ratio to W s is twice that of Z s at these large masses due to the δ_V symmetry factor noted previously. At
 692 125 GeV, the Higgs is accessible through many different decay modes. The largest branching ratio is the
 693 decay $H \rightarrow b\bar{b}$ at 58.24% [18]. This branching is larger than the WW/ZZ decays because one of the two
 694 bosons must be produced off-shell for $m_H = 125$ GeV. The second largest branching ratio is to WW^* at
 695

696 21.37 % (before taking into account the branching ratios of the W). Table 1.2 summarizes the branching
 697 ratios for a 125 GeV Higgs. Note that there is in fact a Higgs branching ratio to $\gamma\gamma$ even though photons
 698 are massless. This decay happens through a loop (the largest contributions to the loop are top and W)
 699 which suppresses the branching ratio.

Decay	Branching ratio (%)
$b\bar{b}$	58.24
WW^*	21.37
gg	8.187
$\tau\tau$	6.272
$c\bar{c}$	2.891
ZZ^*	2.619
$\gamma\gamma$	0.2270
$Z\gamma$	0.1533
$\mu\mu$	0.02176

Table 1.2: Branching ratios for a 125 GeV Higgs boson [18].

700 Note that the branching ratios alone do not tell the full story of which Higgs channels are the most
 701 sensitive. For example, a $H \rightarrow b\bar{b}$ search in gluon fusion production is incredibly difficult due to the
 702 large QCD dijet background at the LHC. However, in associated production of the Higgs, where a W
 703 or Z gives additional final state particles that can be used to reduce background, a search for $H \rightarrow b\bar{b}$
 704 can be sensitive. The combinations of production and decay modes that are most commonly studied are
 705 summarized in table 1.3 [5].

Decay	Inclusive (incl. ggF)	VBF	WH/ZH	$t\bar{t}H$
$H \rightarrow \gamma\gamma$	✓	✓	✓	✓
$H \rightarrow b\bar{b}$			✓	✓
$H \rightarrow \tau^+\tau^-$		✓		
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	✓	✓	✓	
$H \rightarrow ZZ \rightarrow 4\ell$	✓			
$H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$	very low			

Table 1.3: Possible channels for Higgs searches. Checkmarks denote the most sensitive production modes [5].

706 1.4 HIGGS PAIR PRODUCTION IN THE STANDARD MODEL

707 The Standard Model also allows for processes that produce two Higgs bosons in the final state, known
708 as Higgs pair production or di-Higgs production. The two main production mechanisms are shown in
figure 1.5. The two diagrams in figure 1.5 interfere destructively with one another, resulting in a low overall

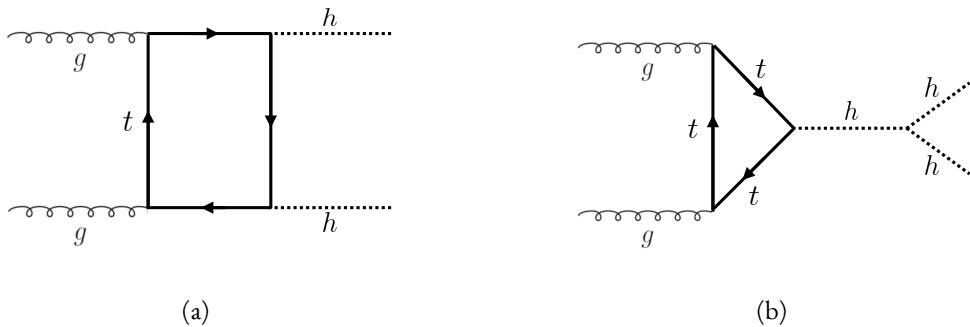


Figure 1.5: The two leading diagrams for Standard Model di-Higgs production at the LHC: (a) box diagram, (b) Higgs self coupling

709
710 cross section for di-Higgs production at the LHC. Nevertheless, Higgs pair production is quite interesting
711 to study because it gives direct access to the λ parameter of the Higgs potential, also known as the Higgs
712 self coupling. The diagram in figure 1.5(b) is sensitive to this coupling through the triple Higgs vertex.

713 One can substitute the gluon fusion production of diagram 1.5(b) with any of the other production
714 modes previously discussed. These other modes do not suffer from interference with the box diagram in
715 figure 1.5(a) due to the presence of additional particles in the final state. They still have a lower cross section
716 than the gluon fusion mode, however. The cross sections for di-Higgs production in the different modes,
717 as well as their uncertainties, are shown in table 1.4 [20]. These are shown for $\sqrt{s} = 14$ TeV as the higher
718 center of mass energy is more sensitive to this process. Note that the scale of cross section quoted is now
719 in fb rather than pb.

720 1.5 HIGGS PAIR PRODUCTION IN THEORIES BEYOND THE STANDARD MODEL

721 The Standard Model Higgs pair production cross section is rather small, and datasets on the scale of
722 the full lifetime of the LHC will be required to obtain sensitive measurements of the Higgs self-coupling.

Production mode	σ (fb)	Total uncert. (%)
Gluon fusion	33.89	+37.2/ - 27.8
Vector boson fusion	2.01	+7.6/ - 5.1
$W H H$	0.57	+3.7/ - 3.3
$Z H H$	0.42	+7.0/ - 5.5
$t \bar{t} H$	1.02	-

Table 1.4: Production cross sections for pair production of a 125 GeV Higgs boson at $\sqrt{s} = 14$ TeV with total uncertainty [20]. The uncertainties include QCD scale and PDF variations as well as uncertainties on α_S .

723 However, the discovery of the Higgs also gives particle physicists a new tool that can be exploited in the
 724 search for new physics beyond the Standard Model. In particular, Higgs pair production is a promising
 725 channel in the search for new physics. The cross section for di-Higgs production can be altered through
 726 both resonant and non-resonant production of Higgs pairs. In non-resonant production, di-Higgs pro-
 727 duction vertices can arise from the presence of a new strong sector and additional colored particles [21–23].
 728 Figure 1.6 shows examples of the types of vertices that can arise. In the resonant case, new heavy particle
 729 can decay to Higgs pairs. Such new particles can include heavy Higgs bosons arising in two Higgs doublet
 730 models (2HDM) or Higgs portal models as well as heavy gravitons in Randall-Sundrum theories [21, 24–
 731 30]. Figure 1.7 shows a generic diagram for a heavy resonance decaying to two Higgs bosons. In the 2HDM,
 732 X corresponds to the heavy CP-even scalar H . In the Randall-Sundrum model, X corresponds to a heavy
 733 spin-2 graviton G . The next sections provide more detail on the phenomenology of resonant Higgs pro-

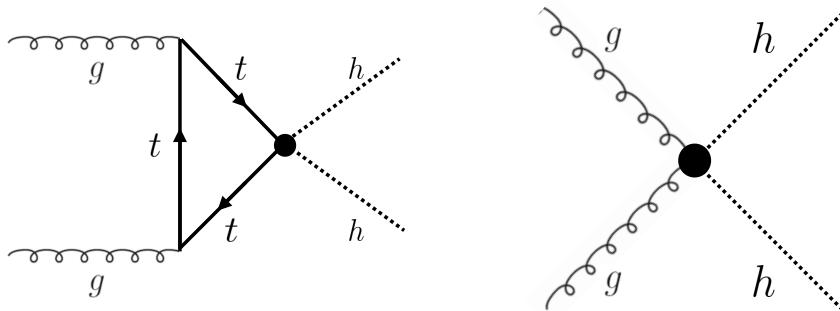


Figure 1.6: Diagrams with new vertices for non-resonant Higgs pair production arising in composite Higgs models

733
 734 duction in Randall-Sundrum and 2HDM models, as these models will later be tested in a dedicated search

for resonant production of boosted Higgs pairs.

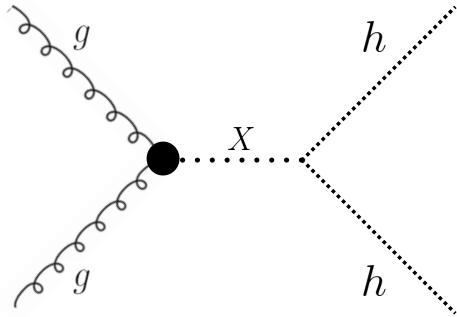


Figure 1.7: Generic Feynman diagram for resonant Higgs pair production in BSM theories

735

736 1.5.1 RANDALL-SUNDRUM GRAVITONS

737 The Randall-Sundrum model is a proposed solution to the hierarchy problem that posits a five-dimensional
 738 warped spacetime that contains two branes: one where the force of gravity is very strong and a second brane
 739 at the TeV scale corresponding to the known Standard Model sector [24]. In the theory, the branes are
 740 weakly coupled and the graviton probability function drops exponentially going from the gravity brane
 741 to the SM brane, rendering gravity weak on the SM brane. The experimental consequence of this theory
 742 is a tower of widely spaced (in mass) Kaluza-Klein graviton resonances. In theories where the fermions
 743 are localized to the SM brane, production of gravitons from fermion pairs is suppressed and the primary
 744 mode of production is gluon fusion [25]. These gravitons have a substantial branching fraction to Higgs
 745 pairs, ranging from 6.43% for gravitons with a mass of 500 GeV to 7.66% at 3 TeV. Figure 1.8 shows the
 746 branching ratios of the spin-2 Randall Sundrum graviton (RSG) as a function of its mass. The predomi-
 747 nant decays are to $t\bar{t}$ above the mass threshold for that channel.

748 These models have two free parameters - the mass of the graviton and a curvature parameter k . Typically,
 749 rather than k , the theory is parameterized using $c \equiv k/\bar{M}_{\text{pl}}$, where \bar{M}_{pl} is the reduced Planck mass. The
 750 cross section for production of the RSG decreases as a function of mass and is strongly dependent on the
 751 gluon PDF. The increase in center of mass energy from 8 to 13 TeV in LHC Run 2 greatly increases the
 752 cross section at higher mass. Figure 1.9 shows the cross section as a function of graviton mass at $\sqrt{s} =$
 753 13 TeV for RSG models with $c = 1.0$ and $c = 2.0$.

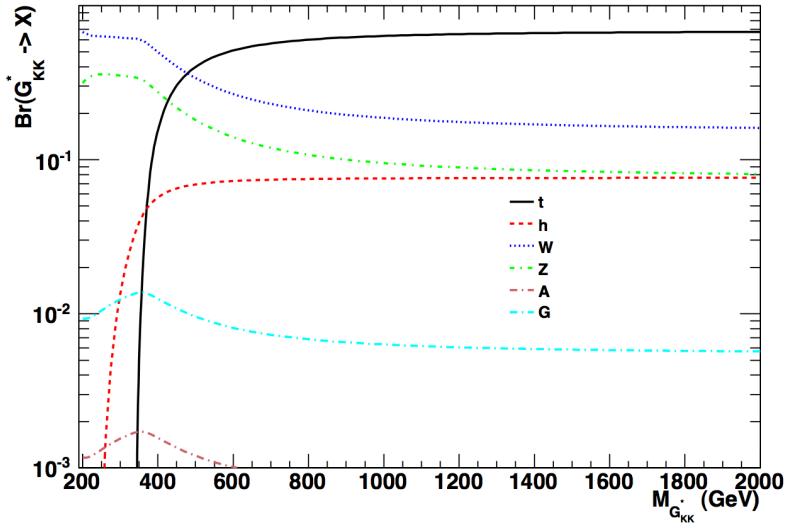


Figure 1.8: Branching ratios for a spin-2 Randall-Sundrum graviton as a function of mass computed in MadGraph with the CP₃-Origins implementation [25, 31]

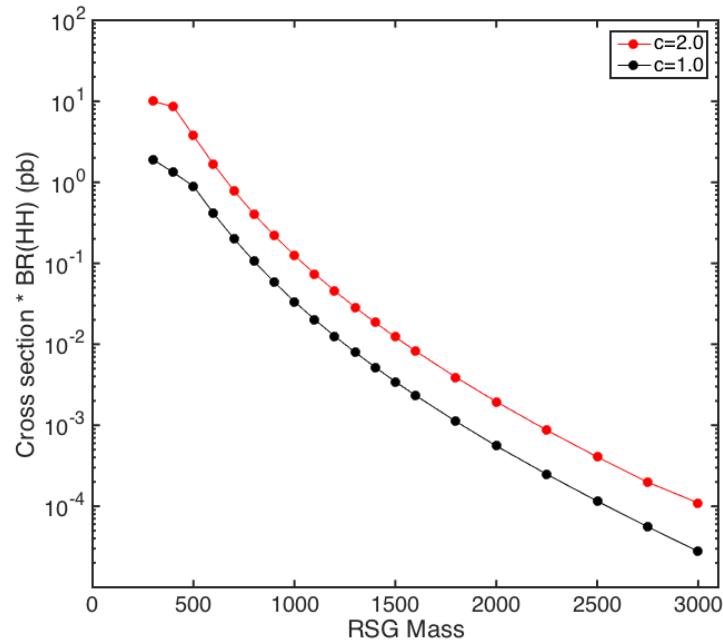


Figure 1.9: $\sigma \times \text{BR}(HH)$ for RSG as a function of mass computed in MadGraph with the CP₃-Origins implementation [25, 31]

754 Another interesting feature of the theory is that the width of the graviton increases with both c and m_G .

755 Figure 1.10 shows the graviton width for both $c = 1.0$ and $c = 2.0$ as a function of mass. In $c = 1.0$,

756 the width starts at 8.365 GeV for a mass of 300 GeV and increases to 187.2 GeV at a mass of 3 TeV.
 757 Similarly, with $c = 2.0$, the width starts at 33.46 GeV for $m_G = 300$ GeV and increases to 748.8 GeV
 758 at a mass of 3 TeV.

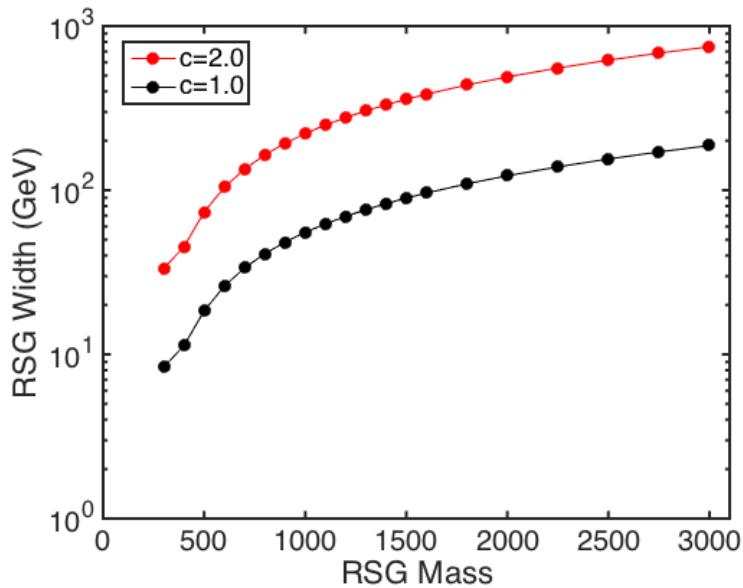


Figure 1.10: RSG width as a function of mass computed in MadGraph with the CP3-Origins implementation [25, 31]

759 1.5.2 TWO HIGGS DOUBLET MODELS

760 In Two Higgs Doublet Models (2HDM), a second complex scalar doublet is added to SM [27–29]. In
 761 this case, all four degrees of freedom in the second doublet correspond to new particles, meaning that there
 762 are five total scalars from the two Higgs doublets - h (light CP-even Higgs), H (heavy CP-even Higgs), A
 763 (heavy CP-odd Higgs), and H^\pm (charged Higgs). The model is parameterized by two main parameters.
 764 The first, $\tan \beta \equiv \frac{v_2}{v_1}$, is the ratio of the vacuum expectation values of the two Higgs doublets (where v_1
 765 corresponds to the v in the SM Higgs model described above). The second parameter is α , a mixing angle
 766 between the heavy and light Higgs fields. Models are also often parameterized with $\cos(\beta - \alpha)$ rather
 767 than α directly. The limit where $\cos(\beta - \alpha) = 0$ is called the alignment limit, and it is in this limit that
 768 the light Higgs h has the same couplings as a Standard Model Higgs.

769 2HDM models are usually separated into two main types - Type I and Type II. In Type I models, the
 770 charged fermions only couple to the second Higgs doublet, leading to a fermiophobic light Higgs. In
 771 Type II models, up-type quarks couple to the first doublet while down-type quarks couple to the second
 772 doublet. One specific realization of a Type II 2HDM is the Minimal Supersymmetric Standard Model
 773 (MSSM).

774 Resonant di-Higgs production in this model can proceed through decays of the heavy CP-even Higgs
 775 $H \rightarrow hh$. The branching ratio for $H \rightarrow hh$ depends on the model type as well as the values of $\tan \beta$ and
 776 $\cos \beta - \alpha$. Figure 1.II shows the branching ratios as a function of the mass of the heavy scalar H for both
 777 Type I and Type II models. Depending on the type of model hh can be a substantial fraction of the decays
 778 of H .

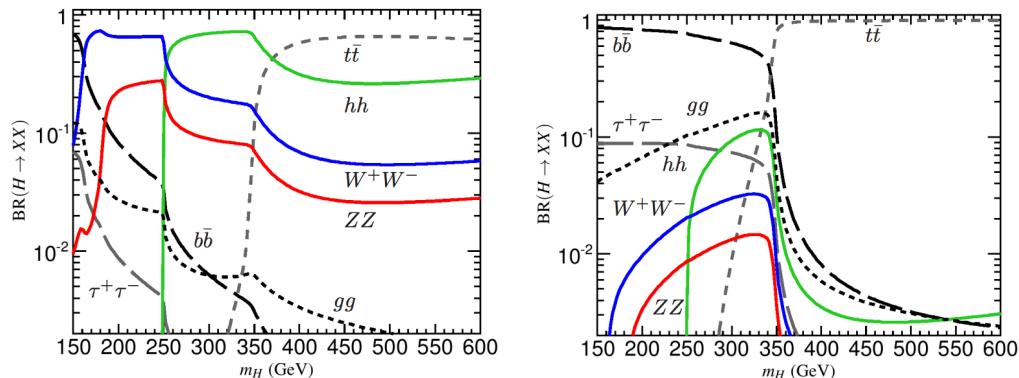


Figure 1.II: Branching ratios for heavy Higgs H in Type I (left) and Type II (right) 2HDM models with
 $\tan \beta = 1.5$ and $\cos(\beta - \alpha) = 0.1(0.01)$ for Type I (Type II). [29]

779 1.6 CONCLUSION

780 Studying the Higgs sector is essential for understanding the details of how mass arises in the Standard
 781 Model and how the electroweak symmetry is broken. The discovery of the Higgs boson also opens the
 782 door for its use as a tool to search for new physics, and Higgs pair production is an ideal candidate for
 783 this study. Even if no BSM physics is found in Higgs pair production, searches for Higgs pairs will put
 784 constraints on the Higgs self coupling and thus further knowledge of the Standard Model and the details
 785 of the Higgs potential.

*The enthusiasm and motivation to explore particle physics
at the high-energy frontier knows no borders between the
nations and regions of the planet.*

Peter Jenni

2

786

787

788

The ATLAS detector and the Large Hadron Collider

789 This chapter presents an overview of the experimental systems used to conduct the measurements pre-
790 sented in this thesis. First, a brief overview of the accelerator, the Large Hadron Collider, will be given.
791 In this section, the accelerator conditions relevant to data-taking are presented as well. Next, an overview
792 of the ATLAS experiment is given. The basics of each sub-detector's role are summarized, as well as the
793 details of the datasets accumulated. Then, a brief interlude on the ATLAS Muon New Small Wheel up-
794 grade is presented. While this new detector does not have a direct impact on any of the datasets taken so
795 far, it will have an impact on future analyses and the work done on it is briefly summarized here. Finally,
796 an overview of object reconstruction in ATLAS is given. While the details of all of the algorithms will not
797 be presented in detail, aspects of the reconstruction performance such as object resolutions are shown as
798 these are relevant to the two studies presented later in this thesis.

799 2.1 THE LARGE HADRON COLLIDER

800 The Large Hadron Collider (LHC) is a proton-proton collider at the CERN laboratory in Geneva,
801 Switzerland [32]. It is designed for a maximum collision center of mass energy of $\sqrt{s} = 14$ TeV and has a
802 circumference of 26.7 kilometers. Four main experiments are located at the interaction points (IP) of the
803 accelerator: ATLAS (A Toroidal LHC ApparatuS), CMS (the Compact Muon Solenoid), ALICE (A Large
804 Ion Collider Experiment), and LHCb [33–36]. The studies performed in this thesis were all completed with
805 the ATLAS detector. Figure 2.1 shows a schematic of the LHC ring and the various experiments.

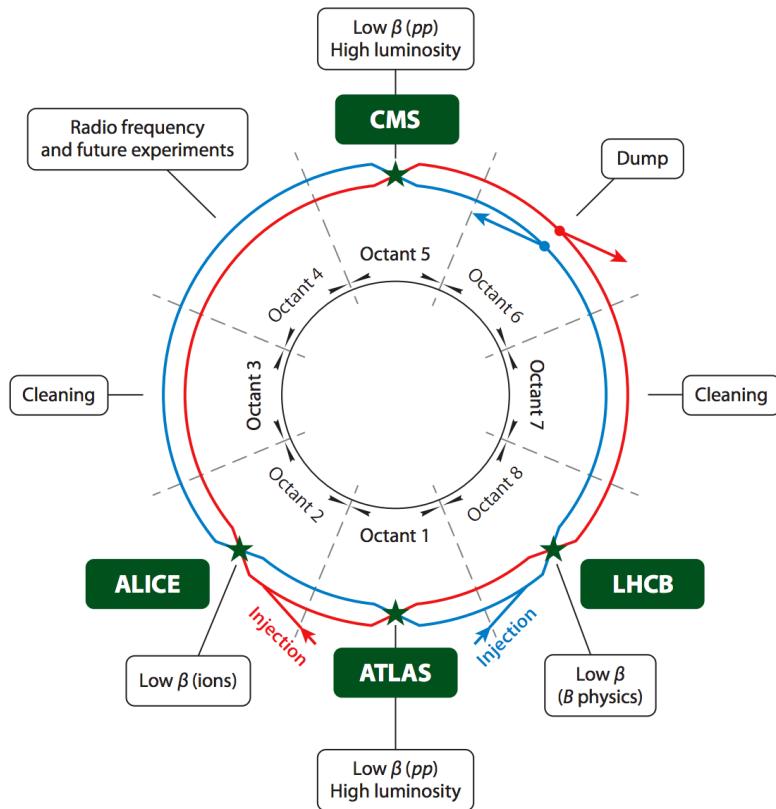


Figure 2.1: A schematic view of the LHC ring [37]

806 One of the most interesting features of the LHC is in its magnet design. Because the tunnel does not
807 have room for separate superconducting magnets for each of the beam pipes, the LHC employs a twin-bore
808 magnet design. Each magnet must hold an 8.3 Tesla magnetic field in order to bend the proton beams at
809 $\sqrt{s} = 14$ TeV. The superconducting magnets are cooled to a temperature of 1.9 Kelvin with superfluid

810 helium.

811 2.1.1 INSTANTANEOUS LUMINOSITY

812 The rate of physics events expected from the accelerator is dependent on the instantaneous luminosity
813 of the machine and the cross section of the physics process, $R_{\text{events}} = L\sigma$. Here, R_{events} is the number
814 of events per second, L is the instantaneous luminosity of the machine, and σ is the cross section for the
815 physics process being measured. The instantaneous luminosity of the LHC is determined by numerous
816 factors related to machine conditions. Equation 2.1 gives the equation for instantaneous luminosity of
817 Gaussian beam profile [37].

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (2.1)$$

818 The LHC collides protons in bunches, and in the above equation N_b is the number of protons per bunch
819 while n_b is the number of bunches per beam. Nominally, the LHC can hold up to 2808 proton bunches.
820 f_{rev} is the revolution frequency. ϵ_n is the normalized transverse beam emittance, a measurement of the
821 average spread of the particles position-momentum space which has the dimension of length. β^* is the
822 value of the *beta* function for the beam at the interaction point. It relates the emittance to the Gaussian
823 width of the beam with $\sigma_{\text{beam}} = \sqrt{\epsilon \cdot \beta}$. F is a reduction factor that corrects for the fact that the beams
824 are colliding at an angle at the IP.

825 Another way of writing the instantaneous luminosity is shown in equation 2.2. In this case, the instanta-
826 neous luminosity is written as the ratio of the rate of inelastic collisions with the inelastic cross section [38].

827

$$L = \frac{R_{\text{inel}}}{\sigma_{\text{inel}}} = \frac{\mu n_b f_{\text{rev}}}{\sigma_{\text{inel}}} \quad (2.2)$$

828 In this case, μ is the average number of interactions per bunch crossing in the accelerator. μ is a use-
829 ful parameter for characterizing the amount of activity recorded in an experiment. As the instantane-
830 ous luminosity and thus μ increase, there are more interactions per bunch crossing and more activity in the
831 detector. This is often characterized with $\langle \mu \rangle$, the measured per bunch crossing μ value averaged over all
832 bunch crossings. The interactions inside each bunch crossing that are not the main physics process of in-

833 terest are often referred to as “pileup” interactions, and $\langle \mu \rangle$ is a measurement of the level of pileup in the
834 detector.

835 **2.1.2 EVOLUTION OF MACHINE CONDITIONS**

836 This thesis uses datasets taken at three different center of mass energies: $\sqrt{s} = 7\text{ TeV}$ data taken in the
837 year 2011, $\sqrt{s} = 8\text{ TeV}$ data taken in the year 2012, and $\sqrt{s} = 13\text{ TeV}$ data taken in the year 2015. In
838 addition to increasing center of mass energy, the instantaneous luminosity and parameters that determine
839 it were evolving. Table 2.1 summarizes that machine conditions in each of these datasets.

	2011	2012	2015	Design
$\sqrt{s} [\text{TeV}]$	7	8	13	14
Number of bunches	1380	1380	1825	2808
Max. protons per bunch	1.45×10^{11}	1.7×10^{11}	1.2×10^{11}	1.15×10^{11}
Bunch spacing [ns]	50	50	25	25
Max. instantaneous luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	3.7×10^{33}	7.7×10^{33}	5×10^{33}	10^{34}
$\beta^* [\text{m}]$	1.0	0.6	0.8	0.55
$\langle \mu \rangle$	11.6	20.7	13.7	-

Table 2.1: Evolution of LHC machine conditions [39, 40]

840 **2.2 THE ATLAS DETECTOR**

841 The ATLAS detector is a multi-purpose particle detector experiment at the LHC’s Point 1 [33]. It has
842 nearly 4π coverage in solid angle around the interaction point. It consists of an inner detector for mea-
843 suring charged particles, electromagnetic and hadronic calorimeters, and a muon spectrometer. Figure 2.2
844 gives an overview of the detector.

845 **2.2.1 COORDINATE SYSTEM**

846 Before defining the properties of the individual detectors, it is important to establish the coordinate
847 system used. Figure 2.3 shows a schematic of the coordinate system. The azimuthal plane (perpendicular
848 to the beam line) is defined as the x - y plane. The angle in this plane is referred to as ϕ . The angle relative

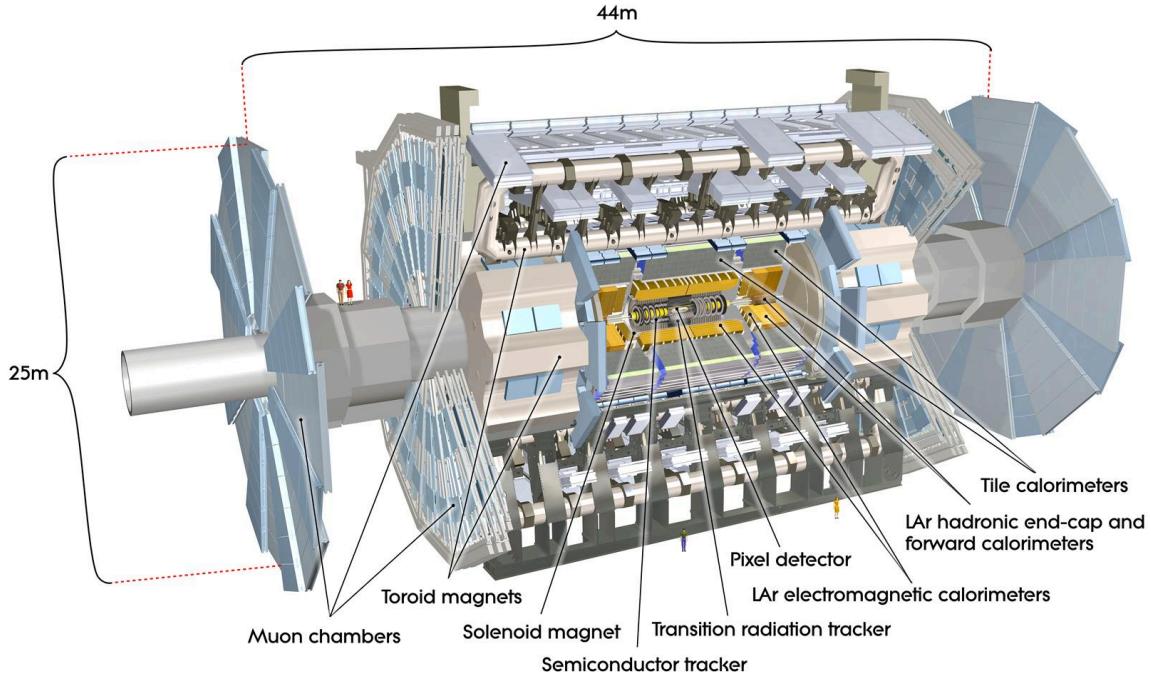


Figure 2.2: A full diagram of the ATLAS detector [33]

849 to the beam axis is referred to as θ . Rather than using θ directly as a coordinate, the experiment often uses
 850 the pseudorapidity η . η is defined in equation 2.3.

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

851 Pseudorapidity is the massless approximation of rapidity, the angle used to parameterize boosts in spe-
 852 cial relativity. This is important for two reasons. First, it means that differences in η are Lorentz invariant.
 853 Second, particle production is roughly constant in pseudorapidity. Particles with η close to zero are re-
 854 ferred to as “central”, while those at high $|\eta|$ are called “forward”. In general, two main detector topologies
 855 can be seen in figure 2.2. There are “barrel” elements, which surround the beam line cylindrically and are
 856 in the central region of the detector. In the forward region, there are “endcap” regions which are arranged
 857 as disks perpendicular to the beam line.

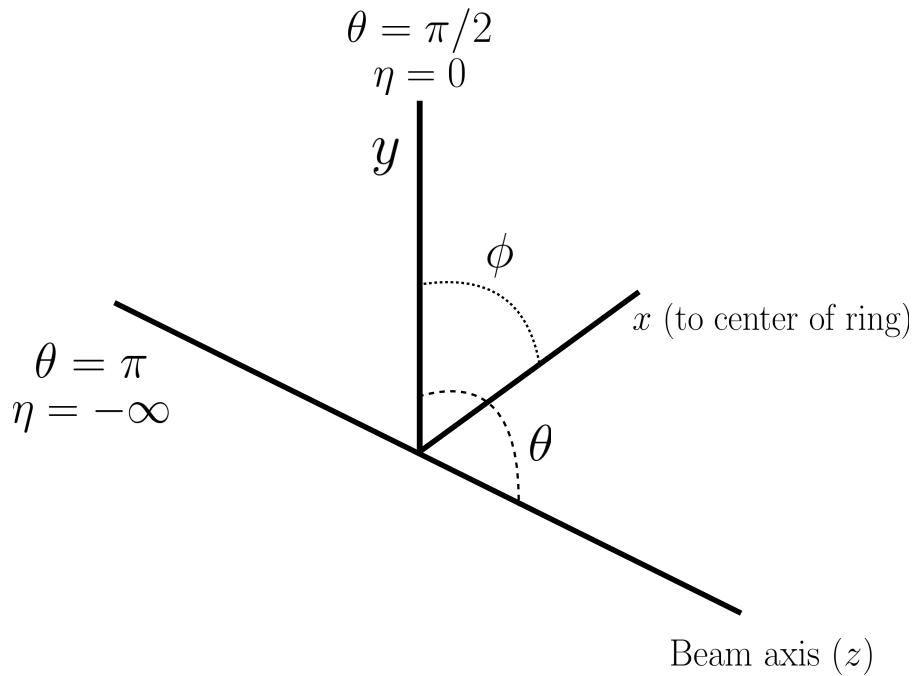


Figure 2.3: The ATLAS coordinate system

858 2.2.2 INNER DETECTOR

859 The ATLAS Inner Detector (ID) system is built for precision tracking of charged particles. It covers
 860 the range $|\eta| < 2.5$. In this range, approximately 1000 particles are generated every bunch crossing in the
 861 detector. This requires having fine granularity to achieve the resolutions required for good momentum
 862 measurement and vertex reconstruction.

863 The ID consists of three sub-components: the pixel detector, semiconductor tracker (SCT), and trans-
 864 sition radiation tracker (TRT). It is surrounded by a solenoid providing a 2 T axial magnetic field which
 865 bends particles in the transverse plane to allow for momentum measurement. Figure 2.4 shows the layout
 866 of each of these components.

867 PIXEL DETECTOR

868 The pixel detector is the first detector particles traverse after being generated in proton collisions and
 869 is the most granular detector. Its operation is crucial for precision tracking and vertex reconstruction as

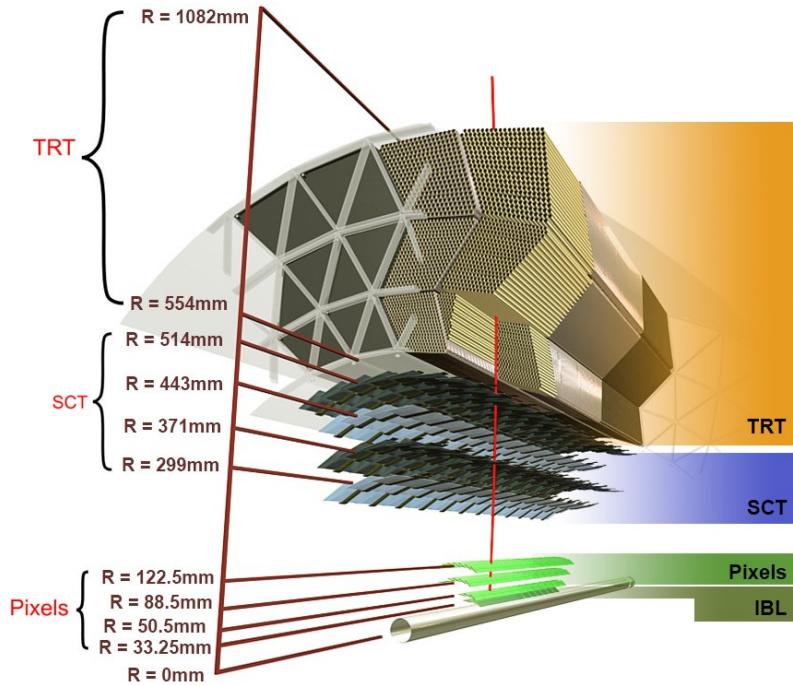


Figure 2.4: Layout of the ATLAS Inner Detector system [41]

well as higher level object reconstruction like tagging of jets from b -quarks. The basic sensing element in this subdetector is a silicon pixel detector. The operating principle for the silicon pixels is that of a p - n junction. When a charged particle passes through, it creates electron-hole pairs that are then separated by the electric field. The sensors are $250\ \mu\text{m}$ thick and use oxygenated n -type wafers with readout pixels on the n^+ side of the detector [33]. Overall, the pixel detector has 1744 sensors and 80.4 million readout channels.

In the barrel region, the pixel detector has three concentric layers of sensors surrounding the beamline. In the endcap region, it consists of disks perpendicular to the beam axis. The detector is segmented in the R - ϕ plane and in z . Usually, three pixel layers are crossed by a charged particle track. The intrinsic accuracies of the sensors are $10\ \mu\text{m}$ in R - ϕ and $115\ \mu\text{m}$ in z (or R for the endcap).

880 INSERTABLE B-LAYER

In Run 2, a new innermost pixel layer, known as the insertable B-layer (IBL), was added to the Inner Detector [42]. This layer was added to cope with the higher luminosities planned in LHC Run 2 and at the

883 high luminosity HL-LHC. Additionally it improves tracking position resolution which in turn improves
884 the vertexing and b -tagging capabilities in ATLAS. The detector sits directly on a new beam pipe, only
885 33.25 mm away from the collision points in the azimuthal plane.

886 **SEMICONDUCTOR TRACKER (SCT)**

887 The semiconductor tracker (SCT) consists of silicon microstrips and comprises the next four layers
888 of the ID. This sub-detector has 6.4cm long sensors that are daisy-chained into strips with a strip pitch
889 of $80\ \mu\text{m}$ [33]. Some of the strips have a small stereo angle to allow for measurement of both angular
890 coordinates. In total there are 6.3 million readout channels. The intrinsic accuracies are $17\ \mu\text{m}$ in $R\text{-}\phi$
891 and $580\ \mu\text{m}$ in z (or R in the endcap).

892 **TRANSITION RADIATION TRACKER (TRT)**

893 The transition radiation tracker (TRT) serves two purposes. First, it consists of 4mm diameter straw
894 tubes filled with a 70/27/3% gas mixture of xenon, carbon dioxide, and oxygen to provide tracking of
895 charged particles. Particles typically have 36 TRT straw tube hits per track. The material in between
896 the straws is designed to induce transition radiation which can be useful for particle identification. As
897 particles pass between media with different dielectric constants, they emit transition radiation that can
898 cause additional showers in the TRT. In particular it is useful for discrimination between electrons and
899 pions or other charged hadrons, as the amount of transition radiation is proportional to the Lorentz factor
900 of the particle.

901 **2.2.3 CALORIMETERS**

902 The calorimeter system consists of two main sub-components: a fine granularity electromagnetic calorime-
903 ter tailored for the measurement of photons and electrons and multiple coarser hadronic calorimeters ded-
904 icated to the measurement of hadronic showers [33]. The calorimeter system has broader coverage than
905 the inner detector, covering the region out to $|\eta| < 4.9$. It is also designed to deliver good containment of
906 showers so as to limit leakage into the muon system. Figure 2.5 shows the layout of the calorimeter system.

907 Both the electromagnetic and hadronic calorimeters are sampling calorimeters. They alternate active
908 material for energy measurement with passive material for energy absorption. The materials used for each
909 purpose vary based on the type of calorimeter and its location in the detector.

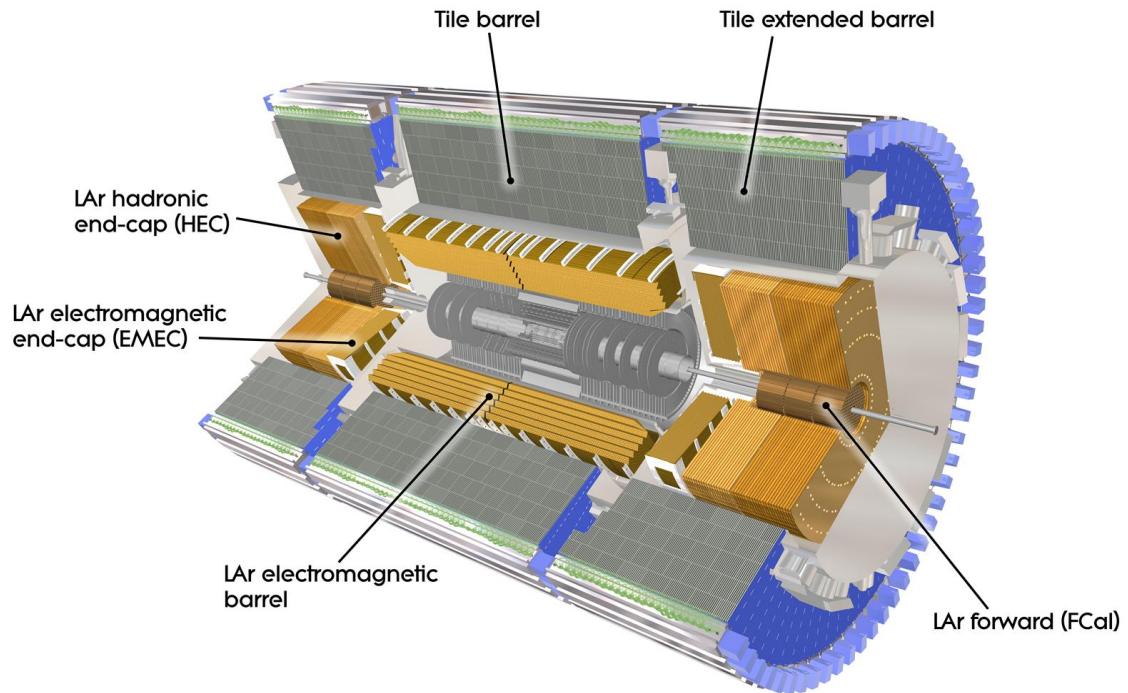


Figure 2.5: Layout of the ATLAS calorimeter system [33]

910 ELECTROMAGNETIC CALORIMETER

911 The electromagnetic calorimeter (EM calorimeter) use liquid Argon (LAr) as its active material and
912 lead as its passive material. It is arrange in an accordion geometry to increase the absorption area while still
913 allowing it to have no azimuthal cracks (complete symmetry in ϕ). The EM calorimeter is divided into a
914 barrel portion that extends to $|\eta| < 1.475$ and an endcap portion going from $1.375 < |\eta| < 3.2$. The
915 region where these two units overlap is called the “transition region”.

916 In order to provide good containment the calorimeter depth must be optimized. Typically, for elec-
917 tromagnetic calorimeters the depth is measured in radiation lengths. In general, the intensity of a par-
918 ticle beam attenuates exponentially in distance with a constant equal to the radiation length. That is,

919 $I(x) = I_0 e^{-x/X_0}$, where I is the intensity, x is the distance traveled, and X_0 is the radiation length.
920 The ATLAS EM calorimeter is designed to have > 22 radiation lengths in the barrel and > 24 in the
921 endcap [33].

922 **HADRONIC CALORIMETERS**

923 There are three types of hadronic calorimeters present in ATLAS: the tile calorimeter (TileCal), hadronic
924 endcap (HEC), and forward calorimeter (FCal). Each one is optimized for stopping of hadronic showers
925 and the materials chosen are specific to their placement in the detector.

926 The TileCal is a scintillating tile calorimeter placed directly outside the EM calorimeter. It uses steel as
927 the absorber and plastic scintillator tiles as the active material. It has coverage in the barrel at $|\eta| < 1.0$
928 and in the “extended barrel” region of $0.8 < |\eta| < 1.7$.

929 The HEC had two wheels perpendicular to the beam line per endcap and is located directly behind the
930 EM calorimeter endcap modules. The HEC covers the region from $1.5 < |\eta| < 3.2$, overlapping slightly
931 with both the tile calorimeter and the forward calorimeter. Like the EM calorimeter, it uses liquid Argon
932 as the active material, but it uses copper as the absorber.

933 The FCal covers the most forward regions of the calorimeter system, extending to the region of $3.1 <$
934 $|\eta| < 4.9$. It again uses liquid argon as its active material. For absorber, it consists of an innermost module
935 made of copper followed by a module made of tungsten.

936 The hadronic equivalent of radiation length is called the interaction length and is denoted as λ . In the
937 barrel, the hadronic calorimeter depth is approximately 9.7λ , while in the endcap is 10λ . The outer
938 supports contribute an additional 1.3λ . This is been shown to be sufficient to limit punch-through of
939 showers to the muon system [33].

940 **2.2.4 MUON SPECTROMETER**

941 The muon spectrometer is dedicated to measuring the momentum and position of muons. It consists
942 of tracking and trigger chambers which are unique in the barrel and endcap regions. The magnetic field
943 for bending of muons is provided by a system of three large air-core toroid magnets (from which ATLAS

944 derives its name.) These magnets provide 1.5 to 5.5 Tm of bending power at $0 < |\eta| < 1.4$ and approx-
 945 imately 1 to 7.5 Tm in the endcap region of $1.6 < |\eta| < 2.7$. The entire muon system covers the range
 946 $0 < |\eta| < 2.7$. Monitored drift tubes (MDTs) are used for tracking in the barrel and the two outer layers
 947 of the endcap, while cathode strip chambers (CSCs) are used to provide tracking in the innermost endcap
 948 wheel. In the barrel, resistive plate chambers (RPCs) are used as trigger chambers while thin gap chambers
 949 (TGCs) are used in the endcap. Figure 2.6 shows the layout of the ATLAS muon system. The entire muon
 950 system is designed with the specification of providing a 10% momentum resolution for a 1 TeV muon.

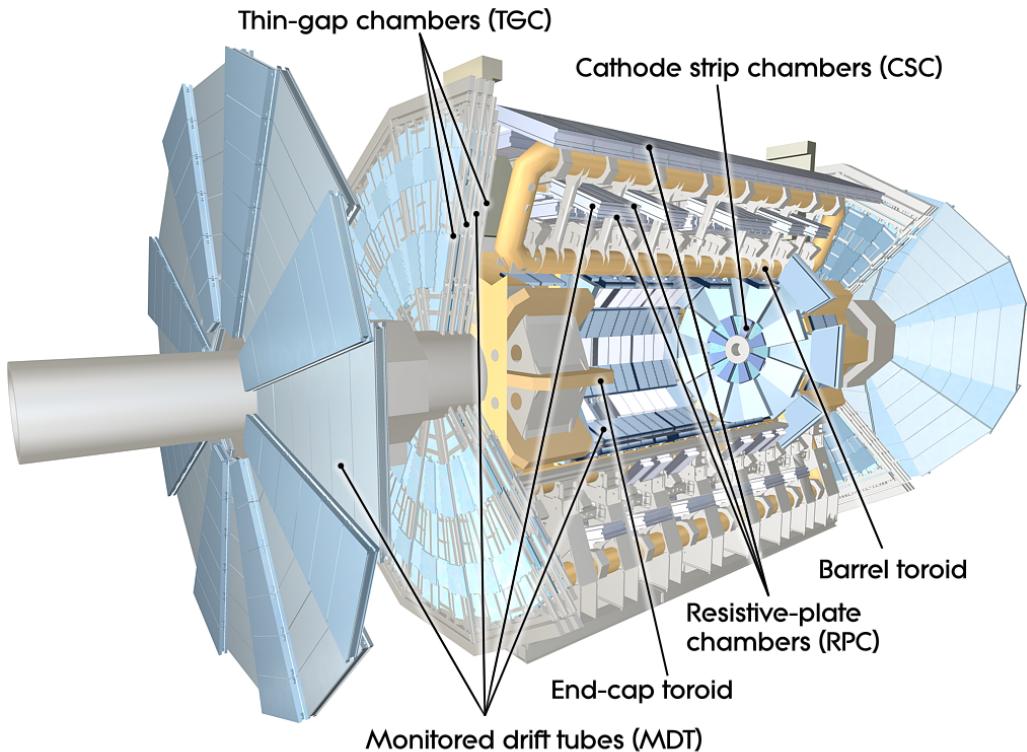


Figure 2.6: Layout of the ATLAS muon system [33]

951 MONITORED DRIFT TUBES (MDTs)

952 The monitored drift tubes (MDTs) are aluminum 3cm diameter tubes filled with a 93/7 % mixture of
 953 Argon and CO₂, with trace amounts of water. As a charged particle traverses the tube, it ionizes the gas
 954 and the ions drift to a wire at the center of the tube. The radial distance of traversal of the particle in the

955 tube is determined by the drift time of the electrons, allowing for fine position resolution. The tubes have
956 an average resolution of $80 \mu\text{m}$ per tube and a maximum drift time of approximately 700ns. The tubes
957 are oriented so that they give precision measurement in η and run along ϕ . They cover $|\eta| < 2.7$, except
958 in the innermost layer of the endcap where they only go to $|\eta| < 2.0$ [33].

959 **CATHODE STRIP CHAMBERS (CSCs)**

960 The cathode strip chambers cover a narrow window of the innermost endcap region at $2.0 < |\eta| <$
961 2.7. In this region the background rates in the cavern are particularly high and the CSCs are designed to
962 handle these higher rates. The CSCs are multiwire proportional chambers with wires pointing in the radial
963 direction (away from the beam pipe). The wire serves as an anode and there are two types of segmented
964 cathode strip, one perpendicular to the wires which gives the precision measurement and one parallel which
965 provides the transverse coordinate. It has an 80/20 gas mixture of Argon and CO₂ [33].

966 **RESISTIVE PLATE CHAMBERS (RPCs)**

967 The resistive plate chambers (RPCs) are gaseous electrode-plate detectors covering the region $|\eta| <$
968 1.05. They consist of two resistive plates separated by a distance of 2 mm. The gas mixture used is a
969 94.7/5/0.3% mixture of C₂H₂F₄, Iso-C₄H₁₀, and SF₆. It has readout strips with a pitch of 23-35 mm
970 for both η and ϕ measurement and thus provides measurement of the azimuthal coordinate in the barrel
971 that the MDTs do not. The thin gas gap allows for a quick response time which makes it ideal for use in the
972 trigger. There are three layers of RPCs which are referred to as the three trigger stations. They allow for
973 both a low p_T and high p_T trigger. The coincidence of hits in the innermost chambers allows for triggering
974 of muons between 6 and 9 GeV, while the outermost layer allows the trigger to select high momentum
975 tracks in the range of 9 to 35 GeV [33].

976 **THIN GAP CHAMBERS (TGCs)**

977 The thin gap chambers (TGCs) are multiwire proportional chambers where the wire to cathode dis-
978 tance (1.4mm) is smaller than the wire-to-wire distance (1.8 mm). They contain a gas mixture of CO₂
979 and *n*-pentane and use a high electric field to gain good time resolution. They serve two functions in the

end-cap system. First, they serve as the trigger chambers. Second, they also provide azimuthal coordinate measurement which the MDTs do not. They sit on the inner and middle layers of the endcap. The outermost layer's azimuthal coordinate is determined by extrapolation [33].

2.2.5 MAGNET SYSTEM

As mentioned previously, there are two independent magnet systems in ATLAS. The first is a 2 T solenoid field in the inner detector which provides bending in the azimuthal plane. The second is an approximately 0.5 T toroidal field in the muon system which provides bending in η . Figure 2.7 shows the predicted field integral as a function of $|\eta|$ [33].

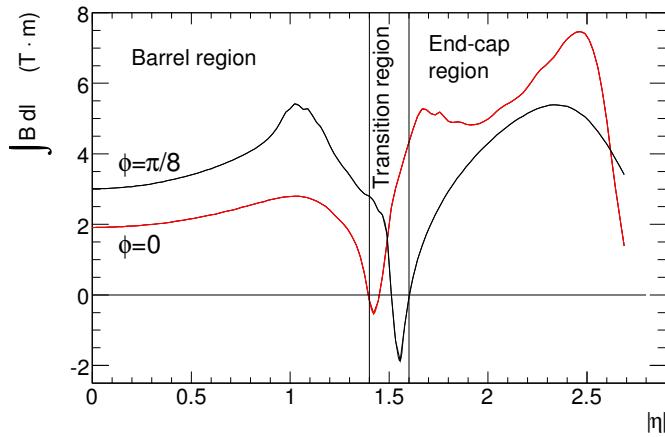


Figure 2.7: Predicted field integral as a function of $|\eta|$ for the ATLAS magnet system [33]

2.2.6 TRIGGER SYSTEM

The ATLAS trigger system searches for signatures of muons, electrons, photons, hadronically decaying τ leptons, and jets in order to save these events for further analysis. The trigger system in ATLAS is designed to reduce the maximum LHC event rate of 40 MHz to a more reasonable rate that can be recorded. The trigger first consists of a fast, hardware based system called the Level-1 (L1) trigger. The L1 trigger consists of independent dedicated detector sub-components that can seed regions of interest (RoIs) for further analysis downstream. For muons, the RPCs and TGCs are used, while in the calorimeter coarsely grained sections of calorimeter cells called towers are used. Once regions of interest are seeded, a software

996 based system called the High Level Trigger (HLT) is used to reconstruct objects and integrate information
 997 from different parts of the detector. In Run 1 of ATLAS, the HLT consisted of two separate stages: the
 998 level 2 (L2) trigger and the event filter (EF).

999 The maximum trigger rate that the L1 trigger can handle is 75 kHz. In the HLT, the rate of events
 1000 written to disk is approximately 200 Hz. Figure 2.8 shows the trigger rates for different L1 triggers in 2012
 1001 and 2015 for ATLAS [43].

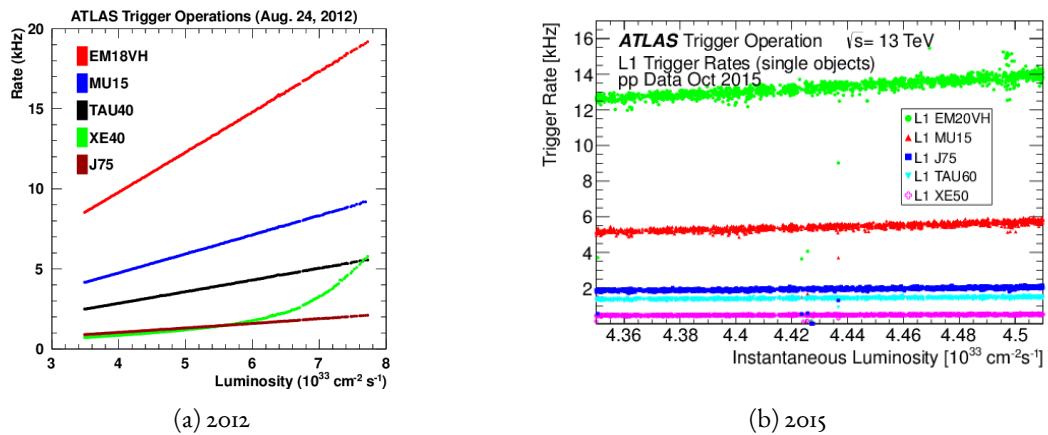


Figure 2.8: ATLAS trigger rates for Level-1 triggers as a function of instantaneous luminosity in 2012 and 2015 operation. These are single object triggers for electromagnetic clusters (EM), muons (MU), jets (J), missing energy (XE), and τ leptons (TAU). The threshold of the trigger is given in the name in GeV. [43]

1002 2.2.7 ATLAS DATASETS

1003 ATLAS has collected data at center of mass energies of 7, 8, and 13 TeV. Figure 2.9 shows the integrated
 1004 luminosity as a function of time for each of the three collected datasets. At $\sqrt{s} = 7$ TeV, ATLAS recorded
 1005 5.08 fb^{-1} . Increased instantaneous luminosity in 2012 led to a larger dataset of 21.3 fb^{-1} recorded at
 1006 $\sqrt{s} = 8$ TeV. After Long Shutdown 1 (LS1) of the LHC and a restart in 2015, ATLAS recorded 3.9 fb^{-1}
 1007 of data at $\sqrt{s} = 13$ TeV. [44, 45]

1008 2.2.8 DETECTOR PERFORMANCE

1009 Table 2.2 summarizes the design requirements for each of the different sub-detectors. This table shows
 1010 the energy and momentum resolution of each tracking, calorimetry, and muon measurements.

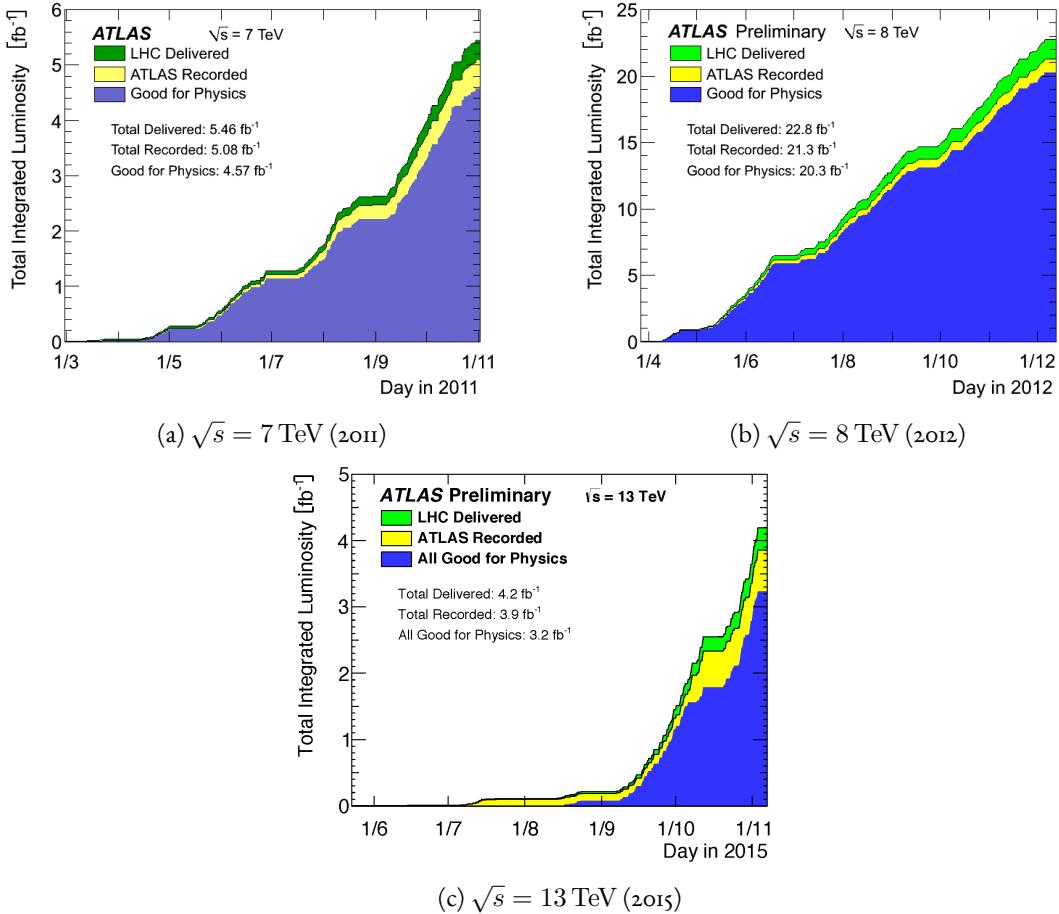


Figure 2.9: Instantaneous luminosity as a function of time for data recorded by ATLAS at different center of mass energies [44, 45]

	Required resolution
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
Hadronic calorimetry	
Barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$
Forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$
Muon spectrometer	σ_{p_T}/p_T at $p_T = 1 \text{ TeV}$

Table 2.2: Performance requirements for the ATLAS detector [33].

2.3 THE ATLAS MUON NEW SMALL WHEEL UPGRADE

As the LHC continues operation, it is scheduled to be upgraded in several phases to allow it to reach higher instantaneous luminosities and thus collect larger datasets. These conditions will open new doors

1014 for study of rare physics processes but will also present interesting challenges that must be faced. ATLAS
 1015 will require new detector technologies to cope with the increased background rates in the cavern in these
 1016 high luminosity conditions. One such upgrade, scheduled to be installed during Long Shutdown 2 (LS2)
 1017 of the LHC in 2018, is the ATLAS Muon New Small Wheel (NSW) upgrade [46]. The NSW will replace
 1018 the innermost end-cap wheel of the muon system with new technologies, as this is the part of the muon
 1019 detector closest to the beam and thus suffers from the highest rates.

1020 2.3.1 MOTIVATION

1021 The motivation of the NSW is two-fold. First, the objective is to alleviate the decreased tracking ef-
 1022 ficiency that comes in a high rate environment. As figure 2.10, at the LHC design luminosity both the
 1023 efficiency of recording hits and reconstructing track segments in the MDTs decreases at the LHC design
 1024 luminosity.

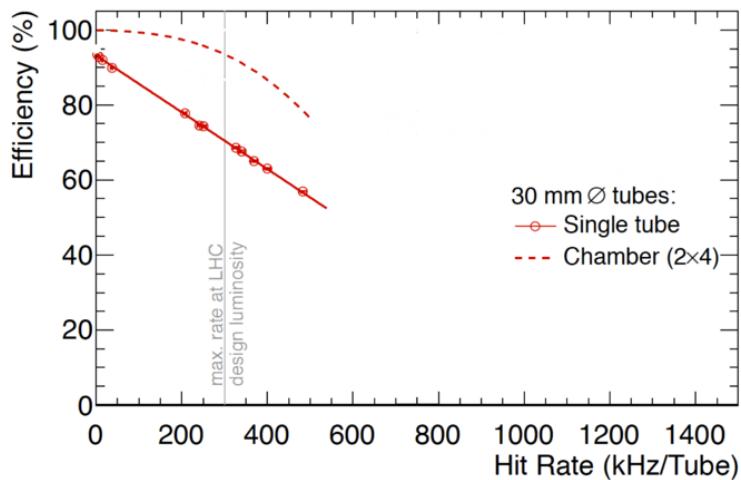


Figure 2.10: MDT tube hit (solid) and segment (dashed) efficiency as a function of hit rate per tube [46]

1025 Second, the NSW will work to alleviate the rate of fake triggers arising in the endcap. Figure 2.11 shows
 1026 the extrapolated trigger rates as a function of the p_T threshold with and without the NSW upgrade. As
 1027 the figure shows, the NSW upgrade will reduce the trigger rate by an order of magnitude compared to the
 1028 current endcap trigger system.

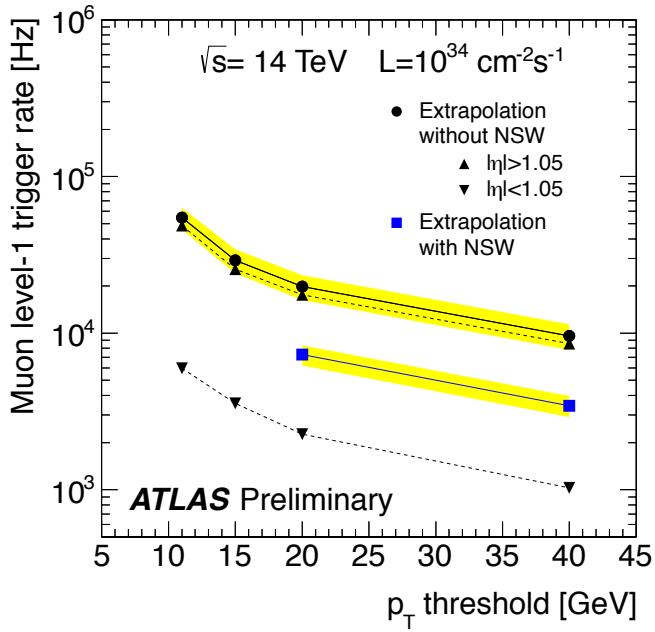


Figure 2.11: Trigger rate as a function of p_T threshold with and without the NSW upgrade [46]

1029 2.3.2 NSW DETECTOR TECHNOLOGIES

1030 The NSW will use two new detector technologies - micromesh gaseous structure detectors (micromegas)
 1031 and small-strip thin gap chambers (sTGCs) [46, 47]. Unlike the previous detectors, both of these detector
 1032 technologies can be used for tracking or trigger. However, the micromegas is more suited to tracking be-
 1033 cause of its good spatial resolution, while the sTGCs have better time resolution and are more suited for
 1034 the trigger. To maintain a fully redundant system, both technologies are used for both purposes.

1035 MICROMEGAS

1036 Micromegas detectors operate using a thin metallic mesh that sits approximately $100 \mu\text{m}$ away from the
 1037 readout electrodes to create the amplification region. Above this mesh, there is a drift region on the order
 1038 of a few mm in length capped by a drift electrode. As a charged particle traverses the detector, it ionizes gas
 1039 and the electrons drift down towards readout strips. The timing of the drift can be used to reconstruct the
 1040 angle of traversal of the particle. This is illustrated in figure 2.12. The micromegas used in ATLAS will be
 1041 resistive micromegas, where the readout electrodes are topped with resistive strips [48]. This alleviates the

1042 risk of sparking in the large area detectors that ATLAS will use.

1043 In ATLAS, the micromegas drift gap will be 5 mm and the amplification gap will be $128 \mu\text{m}$. They are
1044 filled with the same gas mixture as the MDTs. They will be stacked in an octuplet in an XXUV-UVXX
1045 geometry, where X refers to straight strips and U and V refer to stereo strips at an angle of $\pm 1.5^\circ$. This
1046 arrangement allows for measurement of the azimuthal coordinate and gives a large lever arm between the
1047 straight strips for triggering purposes. Figure 2.12 shows the geometry of a single micromegas detector as
1048 well as its operating principle [46].

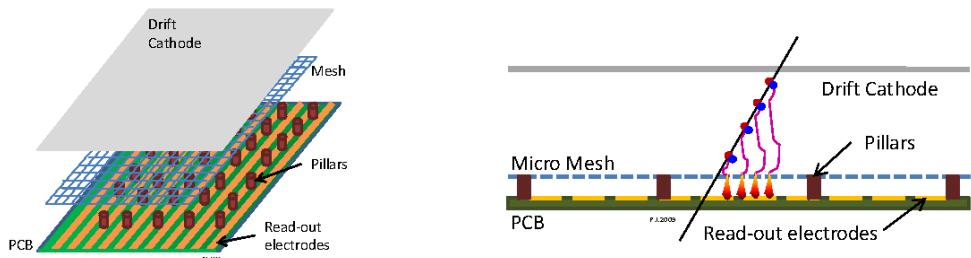


Figure 2.12: Illustrations of the geometry (left) and operating principle (right) of the micromegas detector [46]

1049 sTGCs

1050 The sTGCs are similar to the TGCs already described. They consist of gold-plated tungsten wires with a
1051 1.8 mm pitch between two cathode planes 1.4 mm away from the wire plane. One cathode plane consists
1052 of strips with a 3.2 mm pitch (much smaller pitch than the TGCs), while the other consists of coarser
1053 pads that are used for defining regions of interest in the sTGC trigger algorithm. Figure 2.13 shows the
1054 basic detector geometry.

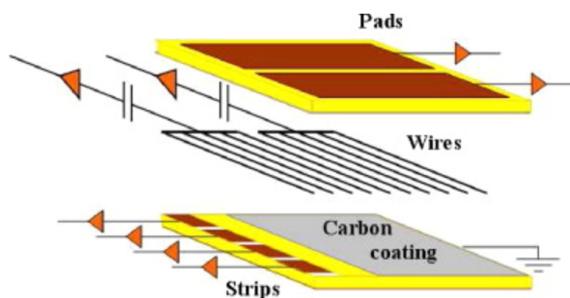


Figure 2.13: Geometry of the sTGC detector [46]

1055 2.3.3 PHYSICS IMPACT

1056 Maintaining low p_T thresholds for muons while still staying within the trigger rate budget at Level 1
1057 (20 kHz) for the muon system is crucial for physics analyses to be successful in high luminosity condi-
1058 tions. One realm where the lepton trigger threshold is especially important is in Higgs physics. In the
1059 $H \rightarrow WW^*$ analysis, one of the W bosons is off shell and tends to decay to soft leptons. In associated
1060 production of a Higgs with a W , the lepton is also important because the lepton provides the main han-
1061 dle which allows the event to be triggered. Table 2.3 shows the impact of increasing the trigger thresholds
1062 on these analyses. It shows that either raising the threshold or using only the barrel both have significant
1063 impacts on the signal efficiency. With the NSW, the signal efficiency is largely maintained and the triggers
1064 can be unprescaled.

Threshold	$H \rightarrow b\bar{b}$ (%)	$H \rightarrow WW^*$ (%)
$p_T > 20 \text{ GeV}$	93	94
$p_T > 40 \text{ GeV}$	61	75
$p_T > 20 \text{ GeV} (\text{barrel only})$	43	72
$p_T > 20 \text{ GeV} (\text{with NSW})$	90	92

Table 2.3: Signal efficiencies for WH production with $H \rightarrow b\bar{b}$ and $H \rightarrow WW^* \rightarrow \mu\nu qq$ under different trigger configurations [46].

1065 2.4 OBJECT RECONSTRUCTION IN ATLAS

1066 ATLAS analyses first start by requiring the presence of certain reconstructed physics objects in the event.
1067 This section will present a brief overview of the algorithms used to reconstruct electrons, muons, jets (in-
1068 cluding b -jets), and missing energy¹. The performance of object reconstruction and measurement will also
1069 be discussed as these are relevant to the analyses presented later. Figure 2.14 gives an overview of the differ-
1070 ent sub-detectors that each type of particle will interact with in ATLAS.

¹Reconstruction algorithms for other objects, such as photons and τ leptons, are not detailed here as these objects are not used in the presented studies.

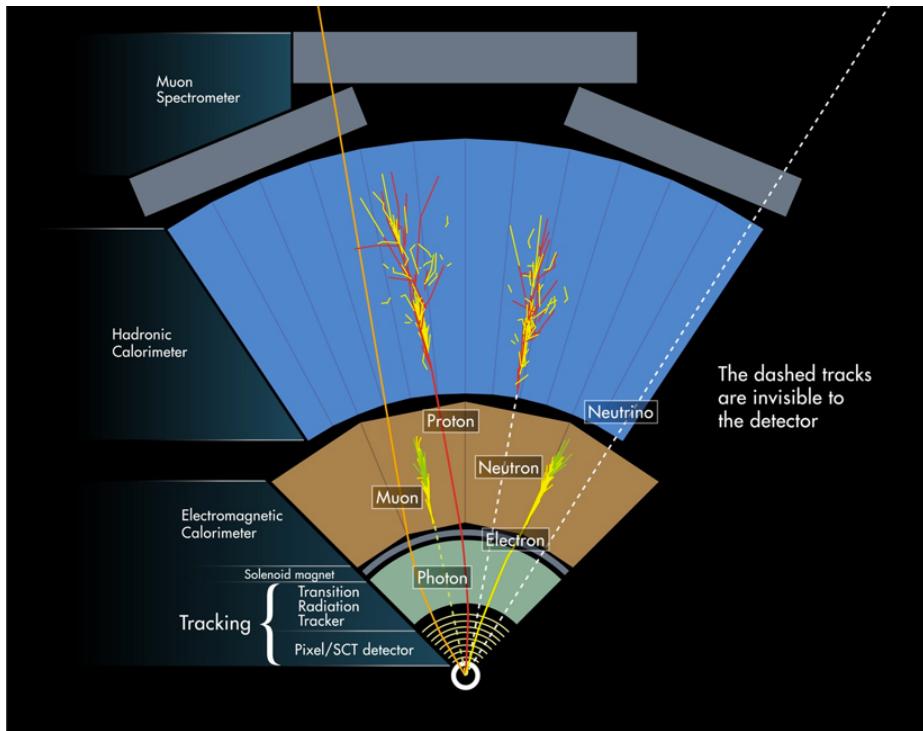


Figure 2.14: Illustration of particle interactions in ATLAS [49]

1071 2.4.I ELECTRONS

1072 Electrons in ATLAS will leave tracks in the inner detector and energy deposits in the electromagnetic
 1073 calorimeter. The algorithm for recognizing the signature of electrons proceeds in two steps: reconstruction
 1074 and identification.

1075 In reconstruction, an electron candidate is formed by matching EM calorimeter deposits with ID tracks.
 1076 The algorithm first chooses seed clusters in the EM calorimeter by using a sliding window algorithm that
 1077 searches for towers with transverse energy larger than 2.5 GeV. In addition to seed clusters, track candi-
 1078 dates must be identified in the ID. The algorithm selects seed tracks with $p_T > 1$ GeV that do not fit well
 1079 with a pion hypothesis. Once candidate tracks are selected, they are re-fit with a Gaussian Sum Filter (GSF)
 1080 algorithm to estimate electron parameters [50]. Finally, an electron candidate is formed if at least one track
 1081 matches to a seed cluster in the calorimeter. The full details of the reconstruction algorithm can be found
 1082 in reference [51].

1083 Once an electron candidate is present, identification criteria must be applied in order to reject fake elec-

1084 trons from background. Many different variables are used for this identification, most of them related to
 1085 the shower shape in the EM calorimeter and the amount of leakage into the hadronic calorimeter, as well
 1086 as information from the ID and in particular the TRT. There are both cut-based and likelihood-based
 1087 criteria that range from “loose” to “very tight”. For details, see reference [51].

1088 Figure 2.15 shows the algorithm’s reconstruction efficiency of true electrons for different identification
 1089 criteria as well as the electron energy resolution in simulation [51, 52]. The reconstruction efficiency is
 1090 measured using both Z and J/ψ tag and probe techniques.

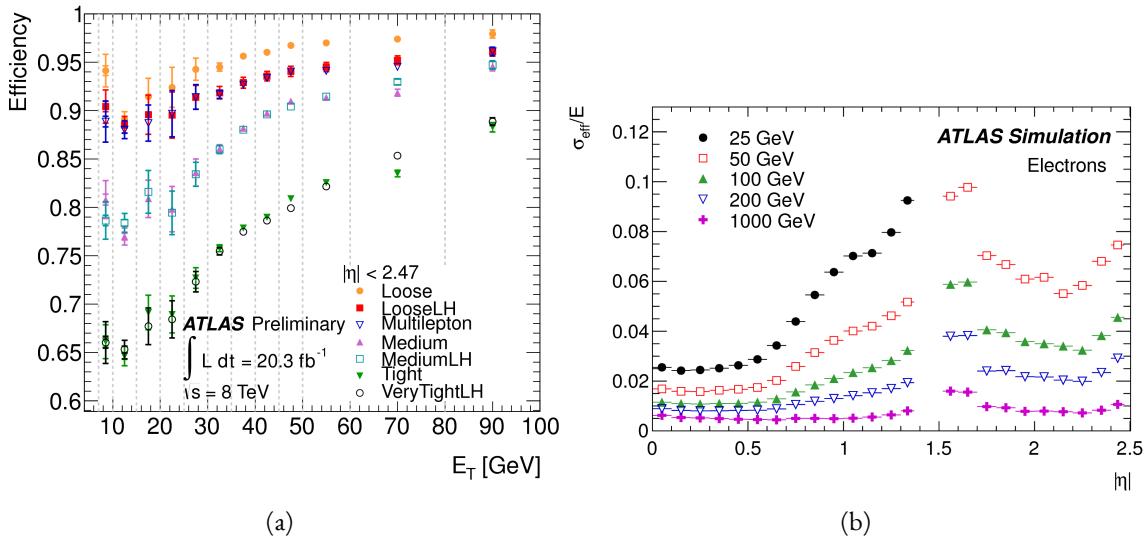


Figure 2.15: Electron performance: (a) reconstruction efficiency as a function of electron E_T [51] (b) energy resolution in simulation as a function of $|\eta|$ for different energy electrons [52]

1091 2.4.2 MUONS

1092 The ATLAS detector is designed to stop most particles before they reach the muon spectrometer. Muons,
 1093 however, are minimum ionizing particles, meaning that they will not lose a significant amount of energy
 1094 through interactions with the detector and will thus pass through. Therefore, the muon reconstruction
 1095 works to match tracks in the muon spectrometer with tracks in the inner detector.

1096 The first step of reconstruction is to reconstruct local straight line tracks, called segments, in each muon
 1097 chamber. Segments are then fit to larger tracks that traverse the entire muon spectrometer. Such muon
 1098 tracks are referred to as “standalone” tracks (SA) as they only use information from the muon spectrometer.

1099 The standalone tracks are then matched to tracks in the inner detector to form “combined” (CB) muons,
 1100 where the combined ID and MS fit are used to determine the momentum and direction of the muon. To
 1101 improve acceptance, segment-tagged and calorimeter-tagged muons are also reconstructed. In these cases,
 1102 ID tracks are matched to segments in the MS and calorimeter deposits consistent with a minimum ionizing
 1103 particle, respectively. The details of the reconstruction can be found in reference [53].

1104 As with electrons, once muon candidates are reconstructed they have identification criteria applied to
 1105 reduce background. These criteria include the χ^2 match between the ID and MS tracks, the number of
 1106 hits in the ID, overall ID and MS track fit quality, and additional variables [53]. The criteria range from
 1107 “loose” to “tight” as with electrons.

1108 Figure 2.16 shows the muon reconstruction efficiency (measured with Z and J/ψ tag and probe) and
 1109 invariant mass resolution [53].

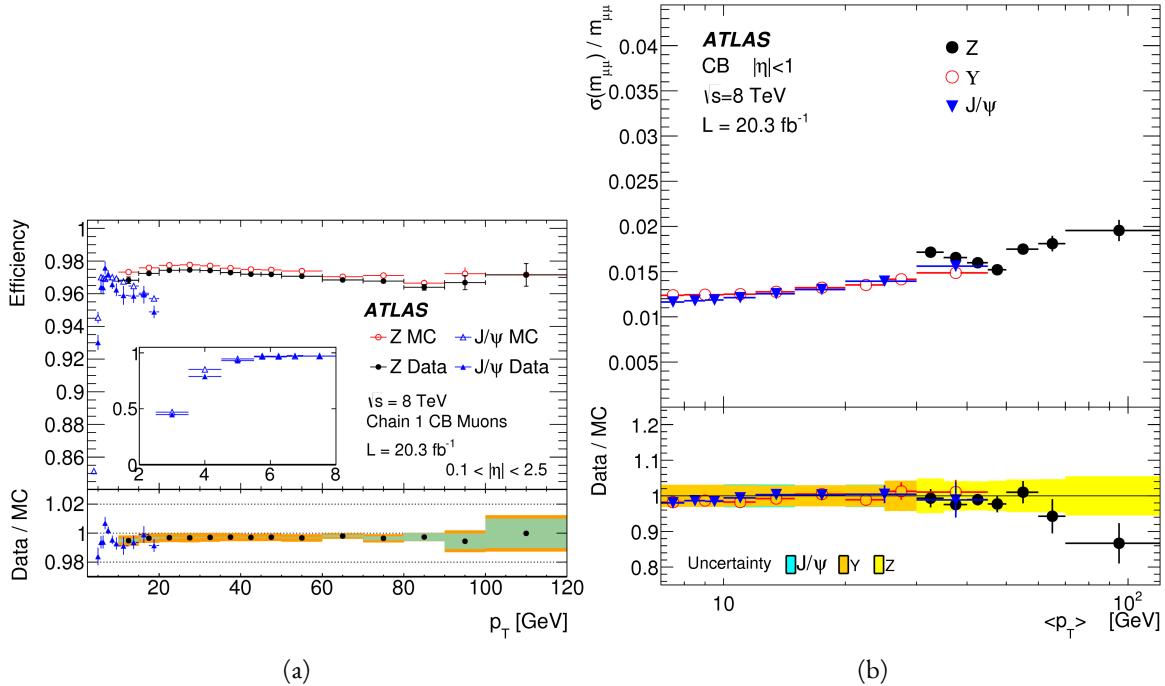


Figure 2.16: Muon performance: (a) reconstruction efficiency as a function of muon p_T (b) dimuon mass resolution as a function of average p_T [53]

1110 2.4.3 JETS

1111 When a quark or gluon is produced in collisions, it is not measured directly in ATLAS. Rather, due to
1112 QCD effects, it produces a collimated spray of hadrons in the direction of the original parton, which is
1113 known as a jet. Jets are reconstructed in ATLAS using energy deposits in the hadronic calorimeter. The
1114 first step is build “topological clusters” out of energy deposits in calorimeter cells [54, 55]. This is done
1115 using strategy where seed cells are chosen by picking cells whose energy measurements are four times the
1116 amount of noise expected for that cell. Adjacent cells with at least 2σ energy measurements are added to
1117 the cluster, then a final layer of clusters with energy above 0σ are added. Once calorimeter clusters are
1118 formed, they are clustered further into jet candidates using the anti- k_T jet clustering algorithm [56]. This
1119 algorithm uses a parameter R that appears in the denominator of the clustering distance metric and defines
1120 the radial size of the jet in η - ϕ space.

1121 The energy response of the calorimeter must be properly characterized in order to reconstruct jet energy.
1122 Calorimeter clusters can be calibrated either with the EM calibration, where each cluster is assumed to have
1123 come from the energy deposit of an electron or photon, or the LCW calibration, where local cluster weights
1124 are computed to allow for local calibration of clusters as hadronic or electromagnetic. The details of the
1125 jet energy calibration are not detailed here and are discussed in reference [57].

1126 Figure 2.17 shows the jet energy response after calibration in Monte Carlo as a function of the true p_T
1127 of the jet [57].

1128 2.4.4 b -TAGGING

1129 One important aspect of jet physics is the task of identifying the flavor of parton that produced the
1130 measured jet. While in general this is very difficult, jets from b -quarks offer an interesting case where such
1131 identification is possible. B mesons have a lifetime on the order of 10^{-12} seconds, which makes a $c\tau$ on
1132 the order of millimeters [6]. This type of displaced decay vertex can be identified in detectors like ATLAS
1133 and allows b -jets to be distinguished from other flavors of jets².

²Jets from charm quarks can also be detected in this way but they do not live quite as long so the displacement of the vertex is harder to distinguish

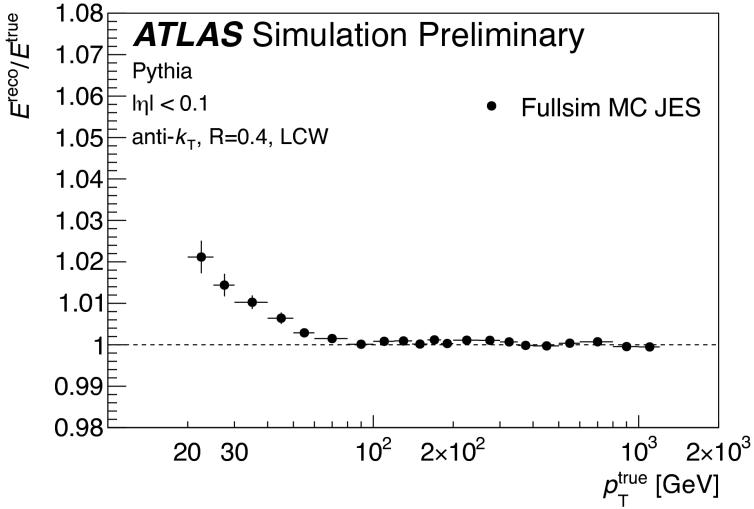


Figure 2.17: Jet energy response after calibration as a function of true p_T in simulation [57]

1134 ATLAS uses a multivariate machine learning algorithm to identify jets from b -quarks. The inputs to this
 1135 algorithm are determined from lower level reconstruction algorithms. There are three distinct algorithms
 1136 that reconstruct variables which are used as input to the multivariate technique.

1137 The first family is referred to as IPxD (where the x can either be 2 or 3). These algorithms use the trans-
 1138 verse and longitudinal impact parameters d_0 and z_0 of the tracks inside a jet to determine their consistency
 1139 with the primary vertex. They two or three dimensional (hence the x) templates for light flavor, charm,
 1140 and bottom jets and then evaluate the likelihood of the jet coming from each of these types. The likelihood
 1141 ratios are used as inputs to the multivariate algorithm.

1142 The next two algorithms used as input are referred to as the secondary vertex (SV) and JetFitter (JF)
 1143 algorithms. The SV algorithm uses tracks inside the jet to fit for vertices that are displaced from the pri-
 1144 mary vertex. The JF algorithm attempts to reconstruct the full flight path of the b by looking for multiple
 1145 displaced vertices along the same line (as B decays often result in subsequent c decays).

1146 In Run 1, the multivariate b -tagging algorithm used a neural network and was referred to as MV1.
 1147 The details of this algorithm and its inputs are given in reference [58]. In Run 2, the number of inputs
 1148 was simplified and a boosted decision tree with 24 input variables was used, referred to as MV2 [59]. The
 1149 MV2 algorithm is a boosted decision tree incorporating twenty-four input variables constructed from three

lower level input algorithms described above. Figure 2.18 summarizes the inputs to MV2. Figure 2.19 shows the performance of each of these algorithms.

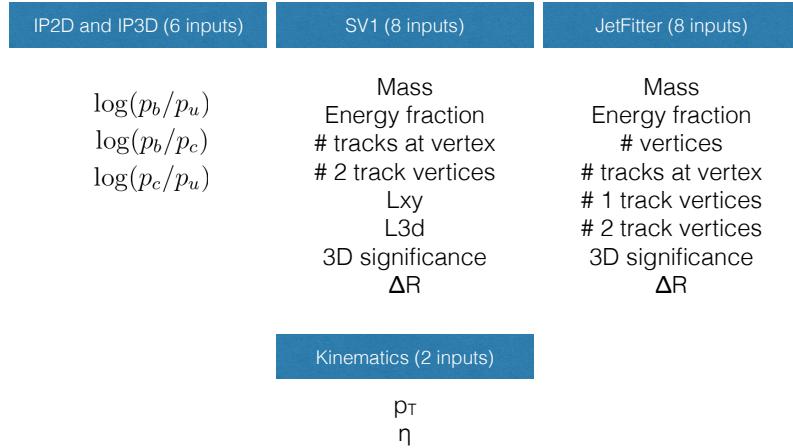


Figure 2.18: Summary of the inputs to the MV2 b -tagging algorithm

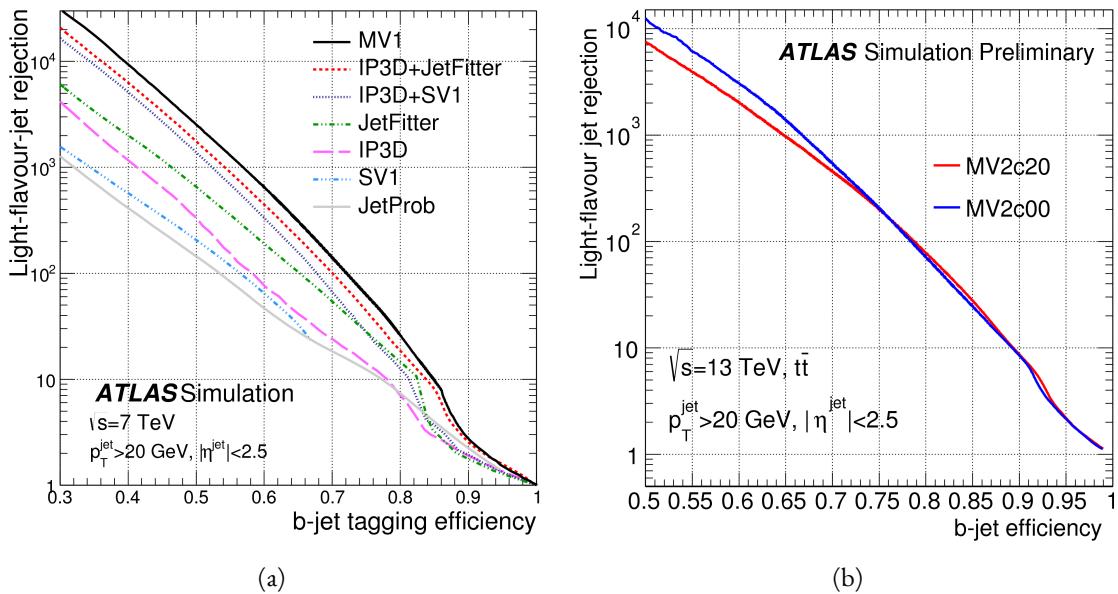


Figure 2.19: Light jet rejection (1/efficiency) vs. b -jet efficiency for MV1 and its input algorithms (a) [58] and MV2 (b) [59] in simulated $t\bar{t}$ events. The numbers in the algorithm names in (b) refer to the fraction of charm events used in the MV2 training.

1152 2.4.5 MISSING TRANSVERSE ENERGY

1153 As noted in figure 2.14, neutrinos produced in ATLAS will pass through the detector without interact-
1154 ing. The only way of detecting the presence of particles like neutrinos (or BSM particles that are long-lived)
1155 is to use missing transverse momentum. The basic principle of missing transverse energy is to use the mo-
1156 mentum balance of the incoming protons to infer the presence of missing particles. The net longitudinal
1157 momentum of the incoming partons that collide is not known (since each carries an unknown fraction of
1158 the proton's momentum). However, the protons (and thus incoming partons) have no net momentum
1159 in the plane transverse to the beam line (the x - y) plane. Therefore, if there are no un-measured particles
1160 in the final state, the transverse momenta of all of the final state particles should balance. The magnitude
1161 of this imbalance is known as missing transverse momentum (E_T^{miss}).

1162 The basic calculation of missing transverse momentum from calorimeter cells is given in equation 2.4 [60].

1163

$$\begin{aligned} E_x^{\text{miss}} &= -\sum_{i=1}^{N_{\text{cell}}} E_i \sin \theta_i \cos \phi_i \\ E_y^{\text{miss}} &= -\sum_{i=1}^{N_{\text{cell}}} E_i \sin \theta_i \sin \phi_i \end{aligned} \quad (2.4)$$

1164 The E_T^{miss} calculation is separated into different terms based on the objects that the calorimeter clusters
1165 are associated with. This way, each cell's contribution is calibrated appropriately according to the object.
1166 This separation of terms is shown in equation 2.5 [60].

$$\begin{aligned} E_{x(y)}^{\text{miss,calo}} &= E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} \\ &\quad + E_{x(y)}^{\text{miss,softjets}} + E_{x(y)}^{\text{miss},\mu} + E_{x(y)}^{\text{miss,CellOut}} \end{aligned} \quad (2.5)$$

1167 The CellOut term of the above equation corresponds to calorimeter cells with energy deposits that are
1168 not associated with other objects. The soft jets term comes from cells associated to jets with p_T between
1169 7 and 20 GeV, while the jets term comes from jets with $p_T > 20$ GeV. Because muons do not deposit
1170 significant energy in the calorimeter, the muon momentum is used for the muon term [60]. The final
1171 E_T^{miss} is calculated using equation 2.6.

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (2.6)$$

¹¹⁷² Figure 2.20 shows the resolution of the components of the E_T^{miss} under different pileup suppression techniques [61].

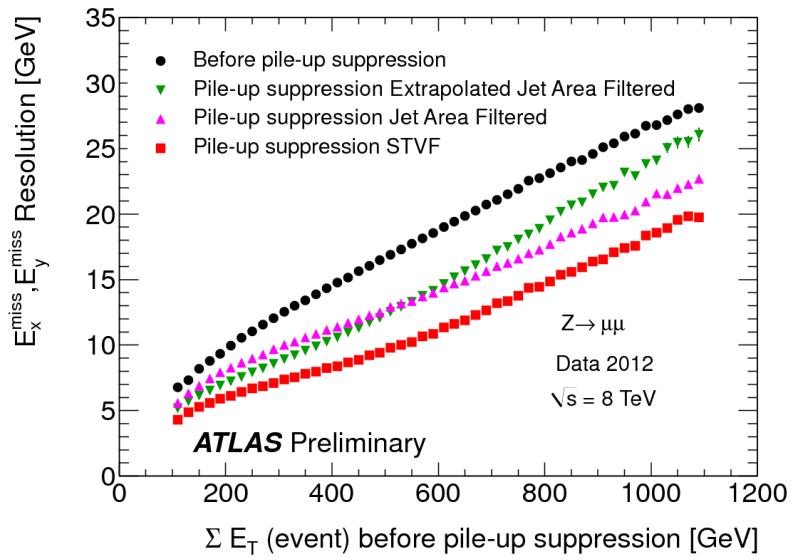


Figure 2.20: Resolution of E_T^{miss} components as a function of $\sum E_T$ before pileup suppression with different pileup techniques [61]

¹¹⁷³

¹¹⁷⁴

Part II

¹¹⁷⁵

Observation and measurement of Higgs

¹¹⁷⁶

boson decays to WW^* in LHC Run I at

¹¹⁷⁷

$\sqrt{s} = 7$ and 8 TeV

*Basic research is what I am doing when I don't know what
I am doing.*

Wernher von Braun

3

1178

1179 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ Analysis Strategy

1180 3.1 INTRODUCTION

1181 This chapter presents an overview of the strategy for searching for a Higgs boson in the $H \rightarrow WW^* \rightarrow$
1182 $\ell\nu\ell\nu$ decay topology. Its purpose is to define in broad terms how the search and measurement are under-
1183 taken, before going into details on the specific sub-categories within the larger analysis. First, the properties
1184 of the Higgs signal are discussed and the associated backgrounds are presented. Next, the observables used
1185 to enhance the signal to background ratio are defined. Finally, the parameters of interest in the search
1186 and measurement will be shown, along with a brief overview of the statistical treatment of the final Higgs
1187 candidates.

1188 Following this chapter, the results of three different studies within the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel
1189 are shown. Chapter 4 presents a search for Higgs boson production in gluon fusion mode and the role of
1190 the $H \rightarrow WW^*$ channel in its discovery. Chapter 5 shows the search and first observation in ATLAS of
1191 the Vector Boson Fusion (VBF) production mode of the Higgs in the $H \rightarrow WW^*$ decay channel. Finally,

1192 chapter 6 shows the combined Run 1 $H \rightarrow WW^*$ results for the measurement of the Higgs cross section
1193 and relative coupling strengths to other SM particles.

1194 3.2 THE $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ SIGNAL IN ATLAS

1195 The signal studied in this and subsequent chapters is the Higgs boson in the WW^* final state, where
1196 each W boson subsequently decays into a charged lepton and a neutrino. In the simplest decay path, the
1197 final state consists of two neutrinos and two charged leptons, each of which can be either an electron or a
1198 muon. If a W decays to a τ lepton, only leptonic decays of the τ are considered. The τ lepton produce
1199 additional neutrinos in the final state but still yield two charged leptons (where each lepton is an electron or
1200 muon). Neutrinos are not detected in ATLAS, so the final state ultimately consists of two reconstructed
1201 leptons and missing transverse momentum (denoted as E_T^{miss}). Final states where both of the charged
1202 leptons are electrons or muons are referred to as the “same flavor” ($ee/\mu\mu$) final states, while those with
1203 one electron and one muon are referred to as “different flavor” ($e\mu$ or μe).

1204 There can be additional jets produced in association with the Higgs boson. As described in detail in
1205 Chapter 1, if the Higgs is produced via vector boson fusion production, there will be two additional forward
1206 jets in the event. In gluon fusion, one or more jets can be produced through initial state radiation from
1207 the incoming gluons. Because of the varying background composition as a function of jet multiplicity,
1208 each bin in this variable has its own dedicated requirements applied in the search and measurement. The
1209 $n_j = 0$ and $n_j = 1$ bins are dedicated to gluon fusion production, while the $n_j \geq 2$ bin has separate
1210 dedicated searches for ggF and VBF production.

1211 Figure 3.1 shows the relative branching fractions for the $H \rightarrow WW^*$ process, calculated from the Par-
1212 ticle Data Group values for the W and τ branching ratios [6]. The largest branching ratio corresponds
1213 to both W bosons decaying to quark pairs at 45.44%. The second largest ratio is for one W decaying lep-
1214 tonically and the other decaying to quarks, a branching ratio of 34.18%. In all cases, ℓ denotes either an
1215 electron or muon, and the leptonic branching ratios of the τ are included. For example, the $\ell\nu qq$ final
1216 state includes one W decaying to $e\nu$, $\mu\nu$, or $\tau\nu$. In the case of the $W \rightarrow \tau\nu$ decay, the τ lepton then
1217 decays to an electron or muon via $\tau \rightarrow \nu_\tau \ell \nu_\ell$. Final states with a τ_h refer to hadronic decays of the τ . The

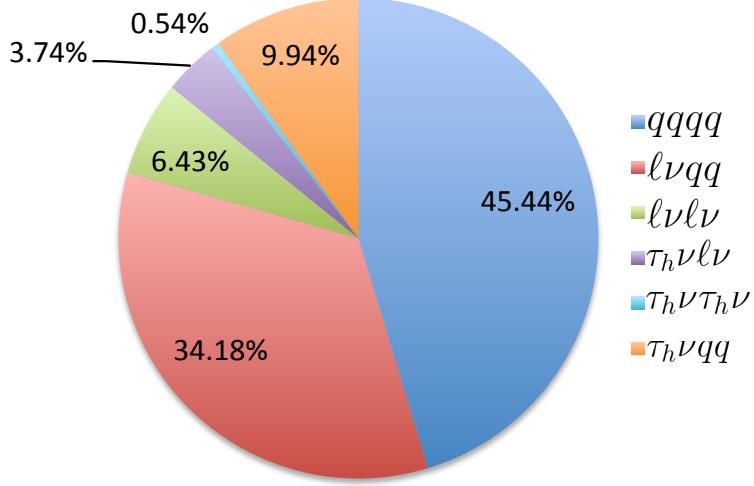


Figure 3.1: Branching ratios for a WW system. q refers to quarks. ℓ can be either an electron or muon, and the leptonic branching ratios of the τ are included. For example, the $\ell\nu qq$ final state includes one W decaying to $e\nu$, $\mu\nu$, or $\tau\nu$. τ_h refer to hadronic decays of the τ .

branching ratio of the $\ell\nu\ell\nu$ final state is 6.43%.

While the $\ell\nu\ell\nu$ final state is not a large fraction of the branching ratio, there are significant advantages to using this channel in an analysis. First, both the $qqqq$ and $\ell\nu qq$ channels suffer from a large QCD multijet background, which is often difficult to model. Second, events in the the $\ell\nu\ell\nu$ channel in data can be triggered more efficiently due to the presence of two leptons.

3.3 BACKGROUND PROCESSES

Many processes from the Standard Model can also produce a final state with two leptons and missing transverse momentum. This section describes the dominant backgrounds to Higgs production and further explains how they can be reduced. Table 3.1 summarizes the different background processes.

3.3.1 STANDARD MODEL WW PRODUCTION

Non-resonant Standard Model diboson production, as shown in figure 3.2, is an irreducible background to Higgs boson production in the WW final state. It produces the same exact final state objects, namely

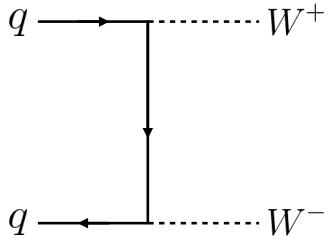


Figure 3.2: Feynman diagram for Standard Model WW production

leptonically decaying W bosons. There are no additional objects in the final state that allow for background reduction. Therefore the analysis solely relies on the correlations between the leptons to reduce this background.

3.3.2 TOP QUARK PRODUCTION

Top quark production can mimic the Higgs in the WW^* final state as well. Top quarks can be produced either in pairs ($t\bar{t}$ production) or singly (s -channel, t -channel, or associated production Wt). The dominant top background are $t\bar{t}$ and Wt production.

Because top quarks decay via $t \rightarrow Wb$, top pair production can produce a final state with two W bosons that then decay leptonically. In Wt production, there are two real W bosons produced, as with $t\bar{t}$. In both cases, there is at least one b -jet in the final state. By vetoing on the presence of b -jets, these top quark backgrounds can be reduced. Figure 3.3 shows the Feynman diagrams for $t\bar{t}$ and Wt production.

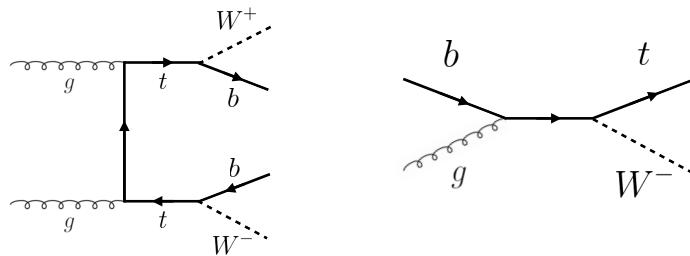


Figure 3.3: Feynman diagrams for top pair production (left) and Wt production (right)

1241 3.3.3 W +JETS BACKGROUND

1242 Single W boson production in association with jets is a unique background to Higgs production. The
1243 other backgrounds considered thus far have all included two prompt leptons, each decaying from a W
1244 boson, in the final state. In W +jets production, however, only one reconstructed lepton originates from
1245 a W . The second reconstructed lepton is either an algorithmic “fake” or the result of non-prompt decays.
1246 In the first case, the lepton is a jet misidentified as a lepton by either the electron or muon reconstruction
1247 algorithms. In the second case, the lepton may be a real lepton but coming from semi-leptonic decays of
1248 particles inside the shower of the jet. This background can be reduced by requiring that the reconstructed
1249 lepton have little activity in the surrounding region of the calorimeter (also known as an “isolation”). Fig-
1250 ure 3.4 shows the Feynman diagram for W +jets production.

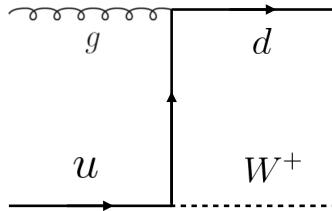


Figure 3.4: An example Feynman diagram of W +jets production

1251 3.3.4 Z/γ^* +JETS BACKGROUND

1252 Production of a Z boson or virtual photon (also known as Drell-Yan and denoted with Z/γ^*) in as-
1253 sociation with jets is also a background to Higgs production. The Z boson decays to two leptons of the
1254 same flavor. When the Z/γ^* decays directly to electrons or muons, the background enters the same flavor
1255 final state. When the Z decays to two τ leptons the background can enter the different flavor final state as
1256 well. Figure 3.5 shows the production of a Z in association with one jet. Because there are no neutrinos in
1257 this final state, variables like E_T^{miss} can be used to reduce the background¹.

¹The E_T^{miss} cut is much more effective for the reduction of Z/γ^* production in the same flavor final state. If the background enters the different flavor final state through τ decays, there will be neutrinos present. Other requirements on the lepton invariant mass are made to reduce the $Z/\gamma^* \rightarrow \tau\tau$ background.

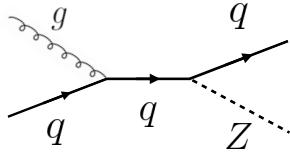


Figure 3.5: An example Feynman diagram of $Z + \text{jets}$ production

1258 3.3.5 SUBDOMINANT BACKGROUNDS

1259 There are additional processes which contribute to the background composition. These backgrounds
 1260 are subdominant and contribute less to the total background estimate than those discussed previously.
 1261 The first process is referred to as VV or “Other diboson” processes and includes multiple Standard Model
 1262 diboson processes, including WZ , ZZ , $W\gamma$, $W\gamma^*$, and $Z\gamma$ production. Additionally, there is a back-
 1263 ground contribution from QCD multijet production. While the cross section for this process is large, its
 1264 contribution to the WW^* final state is small because two jets must be misidentified as leptons.

Category	Process	Description
SM WW	$WW \rightarrow \ell\nu\ell\nu$	Real leptons and neutrinos
Top quark production	$t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b\bar{\nu} b$	Real leptons, untagged b s
	$tW \rightarrow WbW \rightarrow \ell\nu\ell\nu b$	Real leptons, untagged b
	$t\bar{b}, t\bar{q}\bar{b}$	Untagged b , jet misidentified as lepton
Drell-Yan	$Z/\gamma^* \rightarrow ee, \mu\mu$	“Fake” E_T^{miss}
	$Z/\gamma^* \rightarrow \tau\tau \rightarrow \ell\nu\ell\nu\nu$	Real leptons and neutrinos
Other dibosons	$ZZ \rightarrow \ell\ell\nu\nu$	Real leptons and neutrinos
	$W\gamma^*, WZ \rightarrow \ell\nu\ell\ell, ZZ \rightarrow \ell\ell\ell\ell$	Unreconstructed leptons
	$W\gamma, Z\gamma$	γ reconstructed as e , unreconstructed lepton
$W + \text{jets}$	$Wj \rightarrow \ell\nu j$	Jet reconstructed as lepton
QCD multijet	jj	Jets reconstructed as leptons

Table 3.1: A summary of backgrounds to the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal

1265 3.4 SHARED SIGNAL REGION SELECTION REQUIREMENTS

1266 As presented in section 3.2, there are many different combinations of physics objects that can define a
 1267 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ final state. The multiplicity of jets and the flavor combinations of the leptons

1268 both lead to many potential signal regions. Additionally, signal regions can be optimized separately to be
 1269 sensitive to the distinct production modes of the Higgs. Gluon fusion, vector boson fusion, and associated
 1270 production of a Higgs all lead to unique final state topologies. Figure 3.6 delineates the different signal
 1271 regions used in the gluon fusion and vector boson fusion $H \rightarrow WW^*$ analyses. While there are different
 1272 optimizations possible in each signal region, there are also some commonly shared selections that will be
 1273 described here.

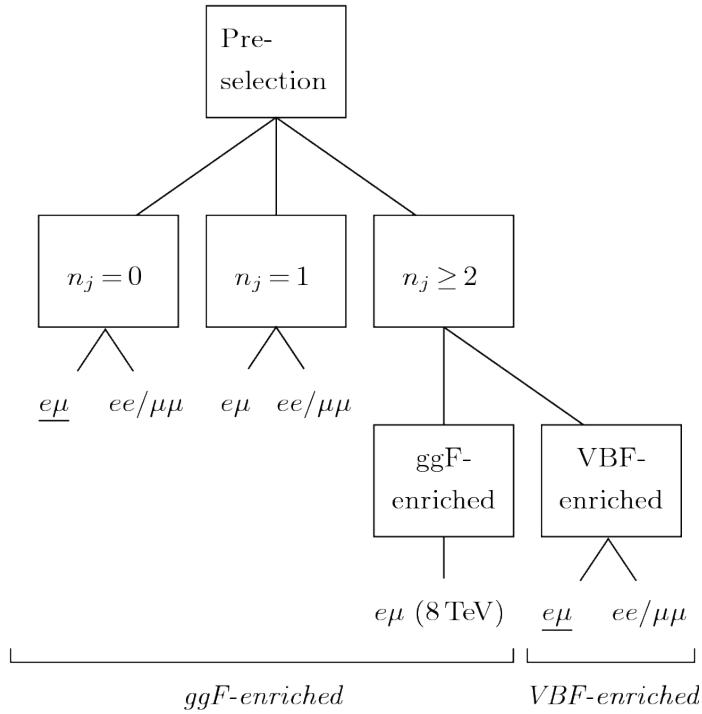


Figure 3.6: An illustration of the unique analysis signal regions [62]. The most sensitive regions for both gluon fusion and vector boson fusion production are underlined.

1274 3.4.1 EVENT PRE-SELECTION

1275 Before being sorted into the distinct signal regions, basic requirements are applied to the reconstructed
 1276 objects in the event to select Higgs-like event candidates. First, two oppositely charged leptons are required.
 1277 Once the leptons are selected, the last requirement for event pre-selection is the presence of neutrinos. As
 1278 neutrinos cannot be detected directly in ATLAS, E_T^{miss} can be used as a proxy for the combined neutrino
 1279 momentum in the transverse plane.

1280 In general, it is expected that the signal should have a harder E_T^{miss} spectrum than backgrounds, espe-
 1281 cially if these backgrounds do not contain neutrinos in the final state. When using E_T^{miss} , it is possible
 1282 mis-measurements of objects in the detector can lead to imbalances in the transverse plane. When such a
 1283 mis-measurement occurs, the E_T^{miss} vector in the transverse plane will often point in the same direction as
 1284 the mis-measured object. Therefore, a new variable, $E_{T,\text{rel}}^{\text{miss}}$, is used in the pre-selection. $E_{T,\text{rel}}^{\text{miss}}$ is defined
 1285 in equation 3.1.

$$E_{T,\text{rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} \sin \Delta\phi_{\text{near}} & \text{if } \Delta\phi_{\text{near}} < \pi/2 \\ E_T^{\text{miss}} & \text{otherwise,} \end{cases} \quad (3.1)$$

1286 If the closest object to the E_T^{miss} vector is within $\pi/2$ radians in the transverse plane, the E_T^{miss} is projected
 1287 away from this object. Otherwise, the normal E_T^{miss} vector is used. Figure 3.7 shows a graphical illustration
 of this concept.

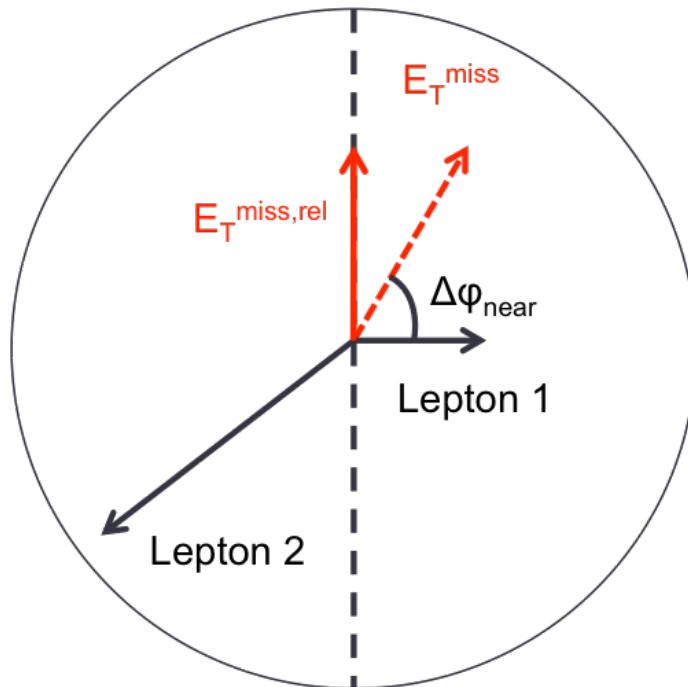


Figure 3.7: A graphical illustration of the $E_{T,\text{rel}}^{\text{miss}}$ calculation

1288 Once the lepton and E_T^{miss} pre-selections are made, the analysis is divided into different regions accord-
 1289 ing to jet multiplicity.

1291 3.4.2 JET MULTIPLICITY

1292 Jet multiplicity, denoted as n_j , is used to sub-divide the analysis into distinct signal regions. By creating
 1293 separate signal regions, each bin in jet multiplicity becomes sensitive to different modes of Higgs produc-
 1294 tion and different backgrounds.

1295 For example, the $n_j \geq 2$ region is more sensitive to VBF production because of the two high momen-
 1296 tum jets produced at matrix element level. For gluon fusion production to enter this bin, two initial state
 1297 radiation jets must be emitted.

1298 Figure 3.8 shows the jet multiplicity in both the different flavor and same flavor regions after the pre-
 1299 selection. It also shows the background composition in the bins of n_b . A few trends from this distribution
 1300 are worth noting. The first is that the Drell-Yan background dominates in the same flavor channels for
 1301 $n_j \leq 1$. Second, the top background becomes a clear contributor to the total background for $n_j \geq$
 1302 1. Lastly, the SM WW production dominates in the $n_j = 0$ bin, as it is an irreducible background to
 1303 $H \rightarrow WW^*$ production. Because of these distinct features, each jet multiplicity bin is treated separately.

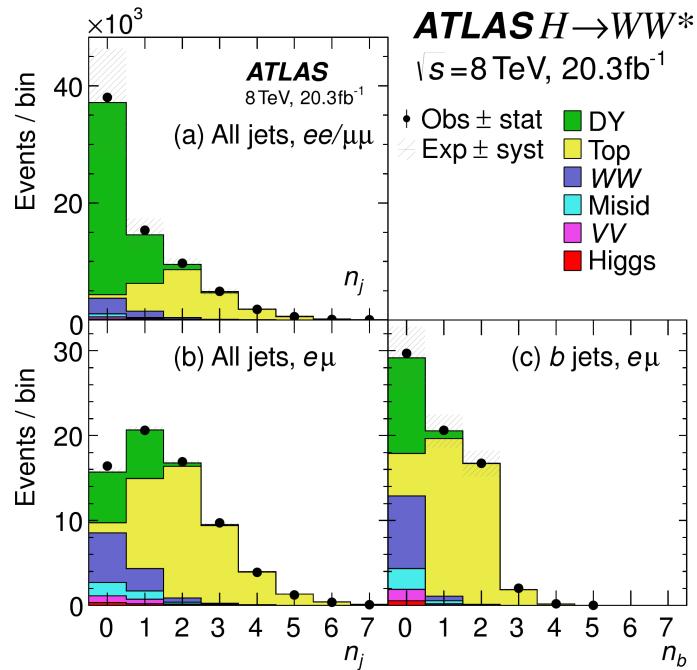


Figure 3.8: Predicted backgrounds (compared with data) as a function of n_j (a and b) and n_b (c) after pre-selection requirements

1304 3.5 BACKGROUND REDUCTION IN SAME-FLAVOR FINAL STATES

1305 As described in section 3.4.2, the background composition of the same flavor final states is different
1306 from that of the different flavor states. In particular, Drell Yan processes play a much larger role because
1307 the Z/γ^* decays to same flavor leptons. Because real neutrinos are absent in the Z/γ^* decays to ee and $\mu\mu$,
1308 a requirement on E_T^{miss} should largely reduce the background. However, as this section will demonstrate,
1309 with increasing pileup conditions the resolution of the calorimeter-based E_T^{miss} degrades greatly. There-
1310 fore, two new variables for Z/γ^* background reduction are constructed and described in this section.

1311 3.5.1 PILEUP AND E_T^{miss} RESOLUTION

1312 Secondary interactions of protons in the colliding bunches of the LHC (known as pileup interactions,
1313 described in detail in Chapter 2) deposit energy into the ATLAS calorimeter in addition to the energy that
1314 comes from the hard scatter process of interest. The calculation of E_T^{miss} is fundamentally Poissonian.
1315 Summing up all of the energy deposits in individual calorimeter cells or clusters is similar to a counting
1316 experiment. The error on a mean of N in a Poisson distribution is \sqrt{N} , so the energy resolution scales
1317 as \sqrt{E} . As more energy is deposited in the calorimeter, the E_T^{miss} resolution degrades, meaning that the
1318 E_T^{miss} resolution is particularly sensitive to LHC instantaneous luminosity conditions.

1319 Figure 3.9 shows an event display of a $Z/\gamma^* + \text{jets}$ event candidate with the twenty-five reconstructed
1320 primary vertices. This display illustrates that while the interaction of interest only has tracks coming from
1321 the hardest primary vertex, all of the secondary interactions deposit energy in the calorimeter as well.

1322 Figure 3.10 shows the RMS of the E_T^{miss} distribution in $Z \rightarrow \mu\mu$ events (where there are no real neu-
1323 trinos) as a function of the number of the average number of interactions. Under 2011 LHC conditions,
1324 this RMS was approximately 9 GeV, while under 2012 running conditions the resolution worsened to 12
1325 GeV. The increase in pileup dilutes the E_T^{miss} variable's ability to reduce the Z/γ^* background.

1326 3.5.2 TRACK-BASED DEFINITIONS OF MISSING TRANSVERSE MOMENTUM

1327 Because the increasing number of secondary proton-proton interactions degrades calorimeter-based
1328 E_T^{miss} resolution, a new variable using only contributions from the primary interaction vertex is necessary

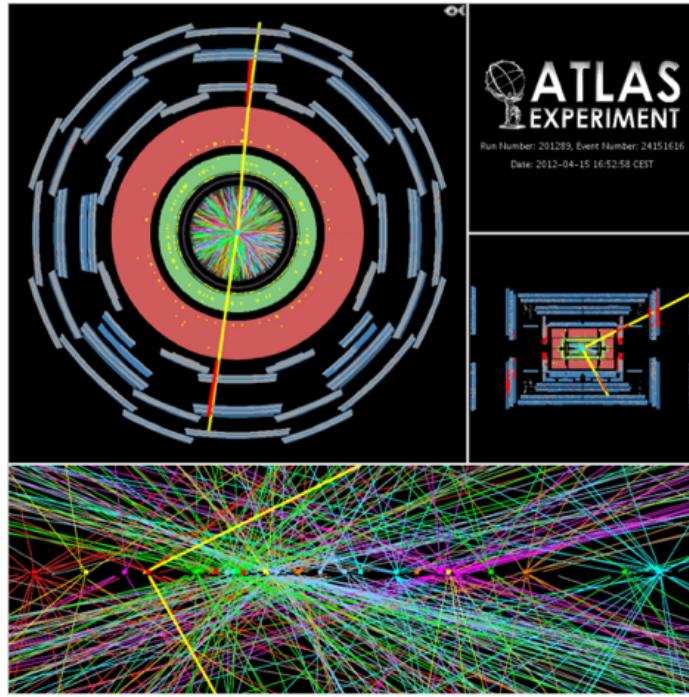


Figure 3.9: An event display of a Z/γ^* + jets event illustrating the effect of pileup interactions

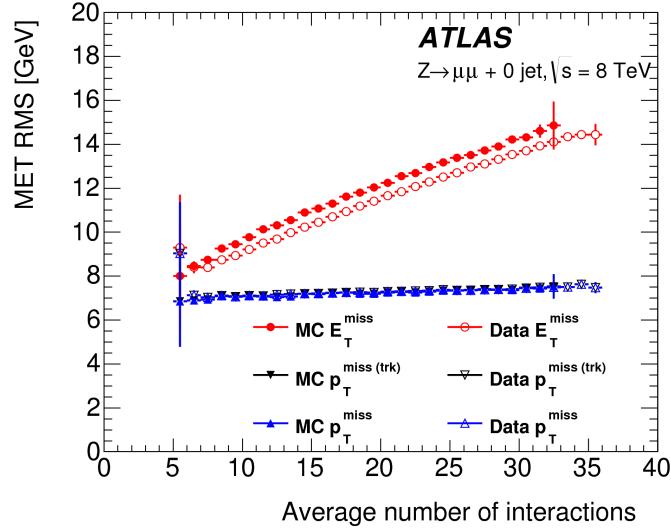


Figure 3.10: The RMS of different missing transverse momentum definitions as a function of the average number of interactions per bunch crossing

¹³²⁹ to further reduce the Z/γ^* background. While it is not possible to associate calorimeter energy deposits
¹³³⁰ with a particular vertex, individual charged particle tracks in the Inner Detector are associated to unique
¹³³¹ vertices. Thus, two track-based definitions of missing transverse momentum , using only tracks coming

1332 from the primary vertex in the event, are used in the analysis. The simplest variable, $p_T^{\text{miss}(\text{trk})}$, is the vec-
 1333 torial sum of the p_T of all of the tracks from the primary vertex and the selected leptons (excluding the
 1334 tracks associated with the selected leptons to avoid double counting). Equation 3.2 defines $p_T^{\text{miss}(\text{trk})}$.

$$p_T^{\text{miss}(\text{trk})} = - \left(\sum_{\text{selected leptons}} p_T + \sum_{\text{other tracks}} p_T \right), \quad (3.2)$$

1335 To further improve the resolution on the missing transverse momentum, the variable p_T^{miss} is used as de-
 1336 fined in equation 3.3. For selected leptons and jets, the nominal p_T measurements are used. Tracks are used
 1337 to estimate the soft component of the missing transverse momentum instead of calorimeter measurements.

1338

$$p_T^{\text{miss}} = - \left(\sum_{\text{selected leptons}} p_T + \sum_{\text{selected jets}} p_T + \sum_{\text{other tracks}} p_T \right), \quad (3.3)$$

1339 Figure 3.10 illustrates that these two new variables accomplish their intended purpose. The resolution as a
 1340 function of mean number of interactions for both $p_T^{\text{miss}(\text{trk})}$ and p_T^{miss} is much flatter than the dependence
 1341 for E_T^{miss} . Figure 3.11a shows the difference between the true and reconstructed values of missing transverse
 1342 momentum using both the track-based p_T^{miss} and calorimeter based E_T^{miss} . The RMS of the distribution
 1343 improves by 3.5 GeV when using p_T^{miss} .

1344 3.5.3 DISTINGUISHING Z/γ^* +JETS AND $H \rightarrow WW^*$ TOPOLOGIES

1345 In addition to measuring missing transverse momentum, another variable can be constructed to exploit
 1346 kinematic and topological differences between the Z/γ^* background and $H \rightarrow WW^*$ signal. Because
 1347 there are no real neutrinos in the final state (in the case of $Z/\gamma^* \rightarrow ee, \mu\mu$ decays), the dilepton system will
 1348 be balanced with the jets produced in the hard scatter. A new variable, f_{recoil} , is constructed to estimate
 1349 the balance between the dilepton system and recoiling jets and is defined in equation 3.4. The transverse
 1350 plane is divided into four sections, or quadrants, with one quadrant centered on the dilepton vector. The
 1351 numerator of f_{recoil} is the magnitude of the vectorial sum of the p_T of jets in the quadrant opposite the
 1352 dilepton system, weighted by each jet's Jet Vertex Fraction (JVF, described in chapter 2). The denominator

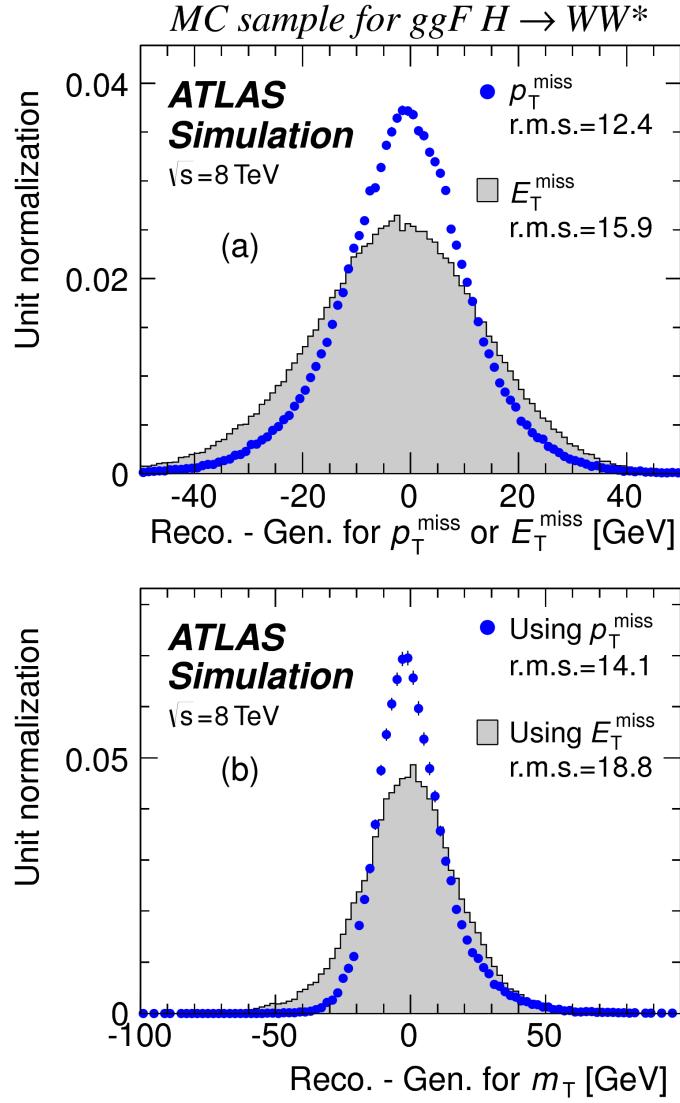


Figure 3.11: The difference between the true and reconstructed values of the missing transverse momentum (a) and m_T (b) in a gluon fusion signal sample

1353 is the magnitude of the dilepton p_T .

$$f_{\text{recoil}} = \left| \sum_{\text{jets } j \text{ in } \wedge} \text{JVF}_j \cdot p_T^j \right| / p_T^{\ell\ell}. \quad (3.4)$$

1354 Figure 3.12 shows a shape comparison of the f_{recoil} distribution in a simulated $Z/\gamma^* + \text{jets}$ sample, a
 1355 $H \rightarrow WW^*$ signal sample, and other backgrounds that contain real neutrinos. The $Z/\gamma^* + \text{jets}$ events

1356 tend to be more balanced between the dilepton system and recoiling jets, while the processes containing
 1357 real neutrinos are less balanced in the transverse plane. Thus, a requirement on f_{recoil} will reduce the Z/γ^*
 1358 + jets background while maintaining a good signal efficiency.

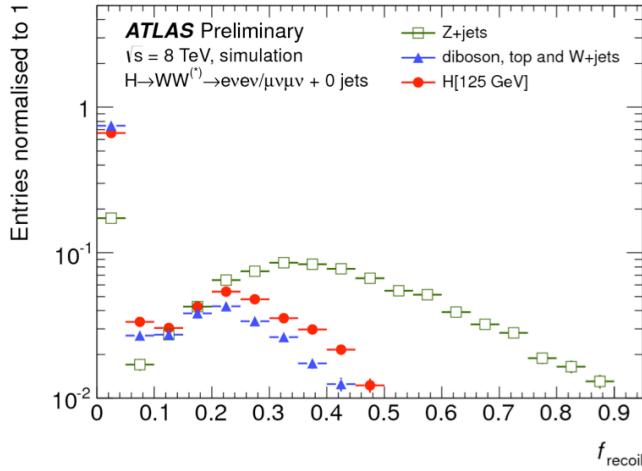


Figure 3.12: Comparison of f_{recoil} distributions for $Z/\gamma^* + \text{jets}$, $H \rightarrow WW^*$, and other backgrounds with real neutrinos.

1359 3.5.4 OPTIMIZING BACKGROUND REDUCTION SELECTION REQUIREMENTS

1360 The requirements on $p_T^{\text{miss}(\text{trk})}$ and f_{recoil} used to reduce the $Z + \text{jets}$ background must be optimized
 1361 to maximize expected signal significance in the same flavor channels. Figure 3.13 shows an optimization of
 1362 the combination of the two requirements in the gluon fusion zero jet bin. Each bin shows the expected
 1363 signal significance if the $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$ is required to be greater than the left edge of the bin and the f_{recoil} is
 1364 required to be less than the top edge of the bin. The figure shows that the best signal significance comes
 1365 from requiring low values of f_{recoil} (< 0.05) and $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$ values greater than 45 GeV.

1366 3.6 PARAMETERS OF INTEREST AND STATISTICAL TREATMENT

1367 As with any search or measurement, there are particular parameters of the Higgs that the $H \rightarrow WW^*$
 1368 analysis is interested in measuring. In this case, the parameters of interest are the mass of the Higgs boson
 1369 and its production cross section. Because the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ process does not have a closed final

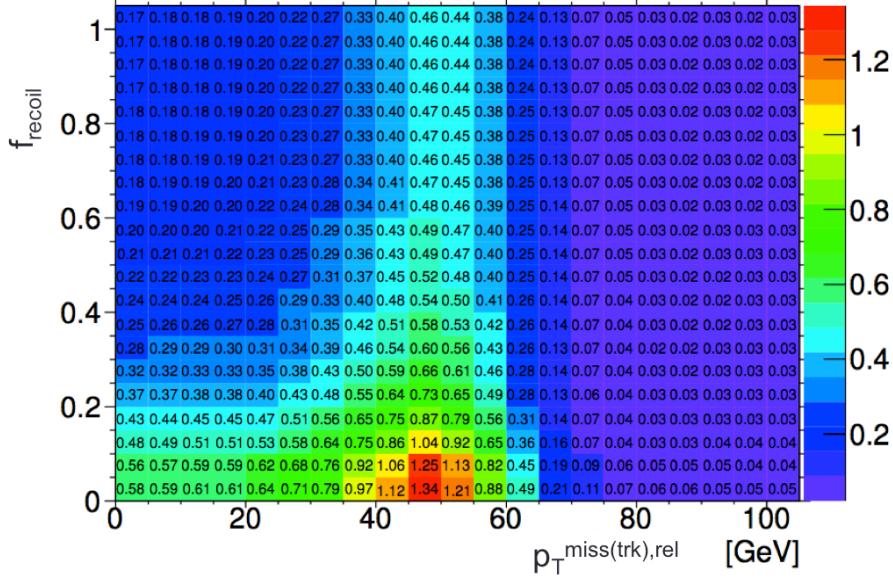


Figure 3.13: Signal significance as a function of required value for f_{recoil} and $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$ in the ggF $H \rightarrow WW^*$ with $n_j = 0$

state, it is not possible to measure the full invariant mass of the particle that may have produced the final state. However, a proxy for the invariant mass is defined using transverse plane information and detailed in section 3.6.1. The second parameter of interest is the ratio of the measured cross section to that expected from the Standard Model Higgs, which is denoted a μ . This is defined in equation 3.5.

$$\mu = \frac{\sigma}{\sigma_{\text{SM}}} \quad (3.5)$$

All of the likelihoods used in the statistical analysis of the final signal region events are parameterized as a function of μ . μ is a natural variable for hypothesis testing, as $\mu = 0$ corresponds to a background only hypothesis and $\mu = 1$ corresponds exactly to a Standard Model Higgs.

3.6.1 TRANSVERSE MASS

The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis cannot reconstruct the full invariant mass of the Higgs because of the neutrinos in the final state. The transverse mass serves as a proxy for the full invariant mass by

1380 exploiting information from the transverse plane. The transverse mass is defined in equation 3.6.

$$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{\text{miss}})^2 - |\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}}|^2}, \quad (3.6)$$

1381 Here the $E_T^{\ell\ell}$ and $\vec{p}_T^{\ell\ell}$ are the transverse energy and momentum of the dilepton system, while p_T^{miss} is a
1382 proxy for the transverse momentum of the di-neutrino system. The track-based p_T^{miss} is used in the m_T
1383 rather than the calorimeter based E_T^{miss} because it has a better resolution on the true transverse mass.
1384 Figure 3.11b shows the improvement in the RMS of the difference between the true and reconstructed
1385 transverse mass in a ggF signal sample. The RMS improves by 4.7 GeV using p_T^{miss} in the m_T calculation.

1386 **3.6.2 STATISTICAL TREATMENT²**

1387 **LIKELIHOOD FUNCTION**

1388 The statistical analysis of final event candidates is framed as a hypothesis test, where the null hypoth-
1389 esis is background-only (no Standard Model Higgs). The first step in the analysis is to form a likelihood
1390 function for the data. In its simplest form, this likelihood is the probability of observing the number of
1391 events seen in the final signal region given knowledge of the signal strength. Because observation of events
1392 is fundamentally a Poisson counting experiment, this simple likelihood can be expressed as a Poisson prob-
1393 ability of observing N events given a total number of predicted signal and background events. This basic
1394 likelihood is shown in equation 3.7.

$$\mathcal{L}(\mu) = P(N|\mu S + B) \quad (3.7)$$

1395 Here, P is the Poisson probability density function, N is the total number of observed events, μ is the
1396 signal strength, S is the predicted number of signal events, and B is the predicted number of background
1397 events.

1398 In particle physics, certain background estimates are commonly normalized in so-called “control” re-
1399 gions and those predictions are scaled by the same normalization factor in the signal region. This leads to a

²Many thanks to Aaron Armbruster, whose thesis [63] inspired parts of this section.

1400 slightly more complicated likelihood, which is a function of both the signal strength and the background
1401 normalization. This is shown in equation 3.8.

$$\mathcal{L}(\mu, \theta) = P(N|\mu S + \theta B) P(N_{\text{CR}}|\theta B_{\text{CR}}) \quad (3.8)$$

1402 Here, θ serves as a “nuisance parameter”, or a parameter that is not of primary interest but still enters the
1403 likelihood. The second Poisson term enforces that the background normalization be consistent with the
1404 number of observed events in data in the control region, N_{CR} .

1405 So far, these two formulations of likelihoods have assumed a single signal region and do not take into
1406 account any shape information of potential discriminating variables. The $H \rightarrow WW^*$ analysis is divided
1407 into many different categories, the counting experiment described above can be performed in each individ-
1408 ual category. As mentioned in section 3.6.1, the transverse mass is used as the primary discriminating vari-
1409 able in many of the $H \rightarrow WW^*$ sub-analyses. The same counting experiment can be performed in each
1410 bin of the m_T distribution to incorporate some shape information. Thus, the total likelihood becomes a
1411 product over signal regions and bins of the m_T distribution. Finally, there are usually many backgrounds
1412 that are normalized in control regions. The new formulation of the likelihood takes this into account by
1413 including a product over control regions in the second Poisson term. All of these modifications are shown
1414 in equation 3.9.

$$\mathcal{L}(\mu, \theta) = \prod_{\substack{\text{SRs } i \\ \text{bins } b}} P\left(N_{ib} \middle| \mu S_{ib} + \sum_{\text{bkg } k} \theta_k B_{kib}\right) \prod_{\text{CRs } l} P\left(N_l \middle| \sum_{\text{bkg } k} \theta_k B_{kl}\right) \quad (3.9)$$

1415 The final step to obtain the full likelihood used in the analysis is to add nuisance parameters for the
1416 systematic uncertainties. In cases where the uncertainty does not affect the shape of m_T bin-by-bin, each
1417 systematic uncertainty ϵ is allowed to affect the expected event yields through a linear response function
1418 of the nuisance parameter, namely $\nu(\theta) = (1 + \epsilon)\theta$. If instead the uncertainty does affect the shape, the
1419 effect is instead parameterized by $\nu_b(\theta) = 1 + \epsilon_b\theta$. The value of the nuisance parameters for the systematic
1420 uncertainty are constrained with a Gaussian term that is added to the likelihood as well. This is of the form
1421 $g(\delta|\theta) = e^{-(\delta-\theta)^2/2}/\sqrt{2\pi}$, where δ is the central value and θ is a nuisance parameter. Finally, a last term is

¹⁴²² added to account for the statistical uncertainty in the Monte Carlo samples used, which adds an additional
¹⁴²³ poisson term. The full likelihood used in the final statistical analysis is defined in equation 3.10.

$$\begin{aligned} \mathcal{L}(\mu, \boldsymbol{\theta}) = & \prod_{\substack{\text{SRs i} \\ \text{bins b}}} P \left(N_{ib} \middle| \mu S_{ib} \cdot \prod_{\substack{\text{sig.} \\ r}} \nu_{br}(\theta_r) + \sum_{\text{bkg k}} \theta_k B_{kib} \cdot \prod_{\substack{\text{bkg.} \\ s \\ \text{syst.}}} \nu_{bs}(\theta_s) \right) \\ & \cdot \prod_{\text{CRs l}} P \left(N_l \middle| \sum_{\text{bkg k}} \theta_k B_{kl} \right) \\ & \cdot \prod_{\substack{\text{syst} \\ t}} g(\delta_t | \theta_t) \cdot \prod_{\text{bkg k}} P(\xi_k | \zeta_k \theta_k) \end{aligned} \quad (3.10)$$

¹⁴²⁴ The fourth term of the equation quantifies the uncertainty due to finite Monte Carlo sample size. Here,
¹⁴²⁵ ξ represents the central value of the background prediction, θ is the associated nuisance parameter, $\zeta =$
¹⁴²⁶ $(B/\delta B)^2$, where δB is the statistical uncertainty of B .

¹⁴²⁷ The best fit value of the signal strength μ is determined by finding the values of μ and $\boldsymbol{\theta}$ that maximize
¹⁴²⁸ the likelihood, while setting $\delta = 0$ and $\xi = \zeta$. Once the likelihood is defined, a test statistic must be built
¹⁴²⁹ for use in hypothesis testing.

¹⁴³⁰ TEST STATISTIC

¹⁴³¹ To distinguish whether the data match a background only or background and signal hypothesis, a test
¹⁴³² statistic must be used. The $H \rightarrow WW^*$ analysis uses the profile likelihood technique [64]. The first step
¹⁴³³ in formulating this test statistic is to define the profile likelihood ratio, shown in equation 3.11.

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \quad (3.11)$$

¹⁴³⁴ Here $\hat{\theta}_\mu$ is the value of θ that maximizes the likelihood for the choice of μ being tested. Additionally, $\hat{\theta}$
¹⁴³⁵ and $\hat{\mu}$ represent the values of θ and μ that gives the overall maximum value of the likelihood.

₁₄₃₆ Once this is defined, a test statistic q_μ is constructed. This is shown in equation 3.12.

$$q_\mu = -2 \ln \lambda(\mu) \quad (3.12)$$

₁₄₃₇ A higher value of q_μ indicates that the data are more incompatible with the hypothesized value of μ , and
₁₄₃₈ q_0 then corresponds to the value of the test statistic for the background only hypothesis. A p_0 value is
₁₄₃₉ then defined to quantify the compatibility between the data and the null hypothesis. The p_0 value is the
₁₄₄₀ probability of obtaining a value of q_0 larger than the observed value, and this is shown in equation 3.13.

$$p_0 = \int_{q_0^{\text{obs}}}^{\infty} f(q_\mu | \mu = 0) dq_\mu \quad (3.13)$$

₁₄₄₁ Here $f(q_\mu)$ is the probability distribution function of the test statistic. Finally, the p_0 value can be con-
₁₄₄₂ verted into a signal significance, using the formula in equation 3.14, or the one-sided tail of the Gaussian
₁₄₄₃ distribution.

$$Z_0 = \sqrt{2} \operatorname{erf}^{-1}(1 - 2p_0) \quad (3.14)$$

₁₄₄₄ The threshold for discovery used in particle physics is $Z_0 \geq 5$, more commonly known as a value of 5σ .

The real voyage of discovery consists not in seeking new landscapes, but in having new eyes.

Marcel Proust

4

1445

1446 The discovery of the Higgs boson and the role 1447 of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel

1448 4.1 INTRODUCTION

1449 This chapter presents the results of the search for the Higgs boson in 4.8 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$
1450 and 5.8 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. The results of three searches at $\sqrt{s} = 8 \text{ TeV}$ in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
1451, $H \rightarrow \gamma\gamma$, and $H \rightarrow ZZ \rightarrow 4\ell$ channels are combined with results of searches at $\sqrt{s} = 7 \text{ TeV}$
1452 in the same search channels (as well as the $H \rightarrow \tau\tau$ production and associated production searches for
1453 $H \rightarrow b\bar{b}$). The results of this combination are a 5.9σ detection of a new particle consistent with a Higgs
1454 boson. Rather than going into detail for all of the different Higgs decay searches, this chapter will discuss
1455 the three most sensitive channels and in particular focus on $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. While the focus is on
1456 WW^* , some of the ZZ^* and $\gamma\gamma$ results are shown for completeness. The results not discussed here can

1457 be found in the ATLAS Higgs discovery publication [1].

1458 **4.2 DATA AND SIMULATION SAMPLES**

1459 The data sample used for the following results was taken in 2011 and 2012 at center of mass energies
1460 of 7 and 8 TeV, respectively, with 4.8 fb^{-1} collected at 7 TeV and 5.8 fb^{-1} collected at 8 TeV. Higgs
1461 production in the gluon fusion and vector boson fusion modes is modeled with **POWHEG** for the hard
1462 scattering event and **PYTHIA** for the showing and hadronization. Associated production of a Higgs with a
1463 vector boson or top quarks is modeled via **PYTHIA**. Table 4.1 shows the Monte Carlo generators used for
1464 modeling the signal and background processes relevant for the three analyses to be discussed.

Process	Generator
ggF, VBF H	POWHEG + PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
$W + \text{jets}, Z/\gamma^* + \text{jets}$	ALPGEN + HERWIG
$t\bar{t}, tW, tb$	MC@NLO + HERWIG
tqb	ACERMC + PYTHIA
$q\bar{q} \rightarrow WW$	MC@NLO + HERWIG
$gg \rightarrow WW$	GG2WW+ HERWIG
$q\bar{q} \rightarrow ZZ$	POWHEG + PYTHIA
$gg \rightarrow ZZ$	GG2ZZ+ HERWIG
WZ	MADGRAPH+ PYTHIA , HERWIG
$W\gamma + \text{jets}$	ALPGEN + HERWIG
$W\gamma^*$	MADGRAPH+ PYTHIA
$q\bar{q}/gg \rightarrow \gamma\gamma$	SHERPA

Table 4.1: Monte carlo generators used to model signal and background for the Higgs search [1].

1465 **4.3 $H \rightarrow WW \rightarrow e\nu\mu\nu$ SEARCH**

1466 The $H \rightarrow WW \rightarrow e\nu\mu\nu$ search is unique compared to the ZZ and $\gamma\gamma$ channels. The Higgs mass
1467 cannot be fully reconstructed due to the presence of neutrinos in the final state, so the transverse mass m_T
1468 is used as the final discriminating variable. Compared to the other channels, there are more backgrounds
1469 here as well, as discussed in chapter 3. The same flavor final states are excluded from this search due to high
1470 pileup in the 8 TeV dataset.

1471 4.3.I EVENT SELECTION

1472 The analysis requires two opposite charge isolated leptons, with the leading (sub-leading) lepton required
 1473 to have $p_T > 25(15)$ GeV. The events are separated into different signal regions depending on which
 1474 flavor of lepton is leading ($e\mu$ for leading electron, μe for leading muon). Strict lepton quality cuts are
 1475 applied to the sample to reduce backgrounds from fake leptons.

1476 Jets are reconstructed with the anti- k_T algorithm with a radius parameter $R = 0.4$. The jets are re-
 1477 quired to have $p_T > 25$ GeV and $|eta| < 4.5$, with jets in the tracking volume required to have a jet
 1478 vertex fraction of 0.5 and jets in the forward region required to have $p_T > 30$ GeV. The analysis is sepa-
 1479 rated into three different signal regions based on jet multiplicity: $n_j = 0, 1, \geq 2$.

1480 To indicate the presence of neutrinos in the event, a requirement of $E_{T,\text{rel}}^{\text{miss}} > 25$ GeV is made¹. This
 1481 requirement significantly reduces the QCD multijet and $Z/\gamma^* + \text{jets}$ backgrounds. Figure 4.1 shows the
 1482 distribution of n_j in data and simulation after applying these “pre-selection” requirements.

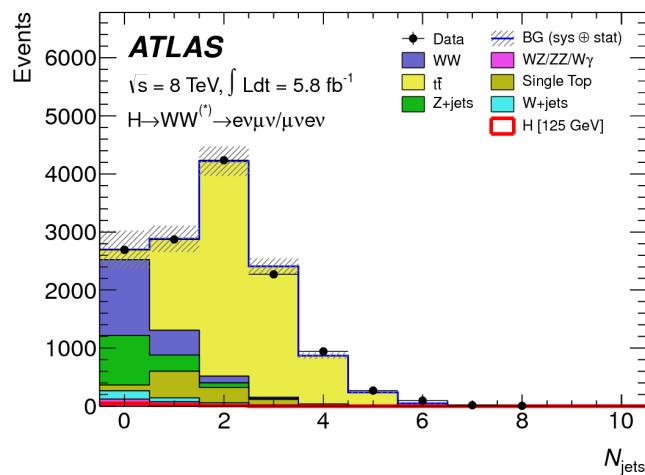


Figure 4.1: Jet multiplicity distribution in data and MC after applying lepton, jet, and $E_{T,\text{rel}}^{\text{miss}}$ selections. The WW and top backgrounds have been normalized using control samples, and the hashed band indicates the total uncertainty on the prediction. [1]

1483 Additional selections are applied to require the dilepton topology to correspond to that of a SM Higgs.
 1484 The requirements are presented here - more detailed discussion on the motivation for each requirement is
 1485 saved for Chapter 5. In all of the jet multiplicity channels, the dilepton system is required to have a small

¹For the definition of $E_{T,\text{rel}}^{\text{miss}}$, see chapter 3

1486 gap in azimuthal angle, $\Delta\phi_{\ell\ell} < 1.8$. Similarly, the $m_{\ell\ell}$ is required to be less than 50 GeV in the lower jet
1487 multiplicity channels and less than 80 GeV in the $n_j \geq 2$ channel. In the $n_j = 0$ channel, the magnitude
1488 of the dilepton p_T , $p_T^{\ell\ell}$, is required to be greater than 30 GeV.

1489 In the higher jet multiplicity channels ($n_j \geq 1$), the top background is a more important component
1490 and must be reduced. The total transverse momentum p_T^{sum} is thus required to be less than 30 GeV. Ad-
1491 ditionally, the di- τ invariant mass $m_{\tau\tau}$ (dilepton mass computed under the assumption that the neutrinos
1492 from the τ decay are emitted collinear to the charged leptons) is used to reject $Z \rightarrow \tau\tau$ events by requiring
1493 $|m_{\tau\tau} - m_Z| > 25$ GeV. These variables are also discussed in more detail in Chapter 5.

1494 In the $n_j \geq 2$ channel, requirements are made to isolate the VBF contribution to Higgs production.
1495 The kinematics of the two leading jets are used to make these requirements. In particular, the event must
1496 have $\Delta y_{jj} > 3.8$ and $m_{jj} > 500$ GeV, along with a veto on having any additional jets with rapidity
1497 between the two leading jets.

1498 **4.3.2 BACKGROUND ESTIMATION**

1499 The details of the background estimation techniques used in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis are
1500 discussed in section 5.5. As that section refers to a later iteration of the analysis, a general discussion is given
1501 here for completeness. The dominant backgrounds are SM WW production and top (both pair and
1502 single) production, and these backgrounds have their normalizations estimated from dedicated control
1503 regions while their shapes are taken from simulation.

1504 The control sample for the Standard Model WW background is defined by making the same require-
1505 ments as the signal region with the $m_{\ell\ell}$ requirement inverted (now requiring $m_{\ell\ell} > 80$ GeV) and remov-
1506 ing the $\Delta\phi_{\ell\ell}$ requirement. This creates a control sample that is 70% (40%) pure in the 0(1)-jet region. The
1507 correction to the pure MC-based background estimate is quantified by defining a normalization factor β
1508 which is the ratio of the data yield to the MC yield ($N_{\text{data}}/N_{\text{MC}}$) in this control sample. Table 4.2 shows
1509 the WW normalization factors in the $n_j = 0$ and $n_j = 1$ bins (the $n_j \geq 2$ estimate is taken directly
1510 from MC).

1511 The top background estimate is also computed separately in each jet multiplicity bin. In the $n_j = 0$

n_j	β_{WW}	β_t
= 0	1.06 ± 0.06	1.11 ± 0.06
= 1	0.99 ± 0.15	1.11 ± 0.05
≥ 2	-	1.01 ± 0.26

Table 4.2: Normalization factors (ratio of data and MC yields in a control sample) for the Standard Model WW and top backgrounds in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis [1]. Only statistical uncertainties are shown.

channel, the background is first normalized using data after pre-selection requirements with no selection on n_j . Then, a dedicated b -tagged control sample is used to evaluate the ratio of one-jet to two-jet events in data. The details of this technique are shown in reference [65]. In the $n_j = 1$ and the $n_j \geq 2$ regions, the top background is normalized in a control sample where the signal region selections are applied, but the b -jet veto is reversed and the Higgs topology requirements on $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ are removed. The resulting normalization factors for these techniques are shown in table 4.2.

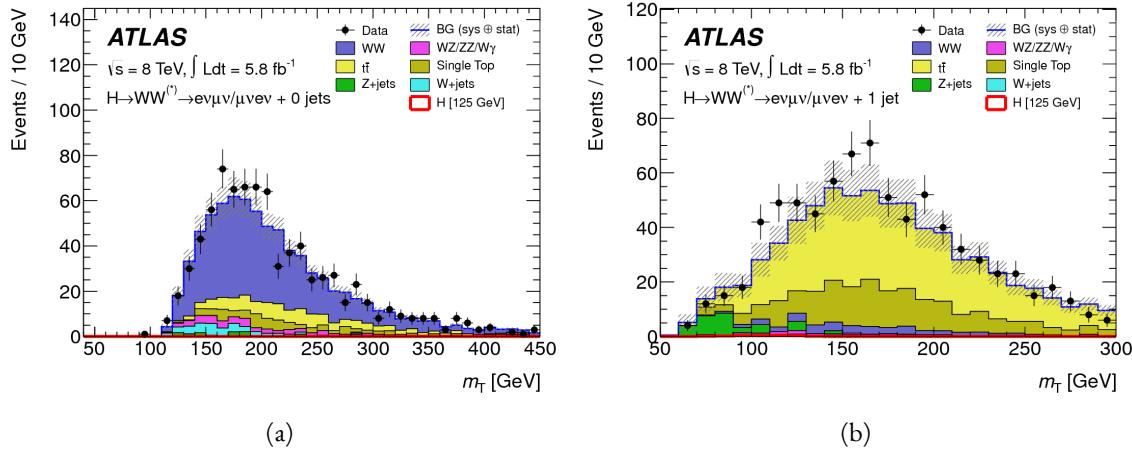


Figure 4.2: Comparison of m_T between data and simulation in the $n_j = 0$ WW (a) and $n_j = 1$ top (b) control samples [1]

The control samples which are used for background normalization can also be used to validate the modeling of the m_T distribution for each background. Figure 4.2 shows the comparison between data and MC for the m_T distribution after correcting the normalization of the backgrounds in the WW and top control regions. Good agreement between data and simulation is seen in both cases.

The $W + \text{jets}$ background estimate is taken entirely from data using a control sample with one well reconstructed lepton and one anti-identified lepton. All other backgrounds are taken purely from simulation.

1524 4.3.3 SYSTEMATIC UNCERTAINTIES

1525 The systematic uncertainties that have the largest impact on the analysis are the theoretical uncertainties
1526 associated with the signal cross section, and these are shared with the ZZ^* and $\gamma\gamma$ channels. The uncer-
1527 tainties resulting from variations of the QCD scale are $+7\%/-8\%$ on the final singal yield. Those coming
1528 from variations of the parton distribution function (PDF) used in the simulation add a $\pm 8\%$ uncertainty
1529 on the yield. The uncertainties on the branching ratios of the Higgs are $\pm 5\%$.

1530 The main experimental uncertainties come from variations of the jet energy scale (JES), jet energy reso-
1531 lution, pile-up, E_T^{miss} , b -tagging efficiency, W +jets background estimate, and integrated luminosity. For
1532 more details, see reference [1].

1533 4.3.4 RESULTS

1534 Table 4.3 shows the signal and background yields in the final signal region after normalizing the back-
1535 grounds according to the methods described above.

	$n_j = 0$	$n_j = 1$	$n_j \geq 2$
Signal	20 ± 4	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
Other dibosons	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
$t\bar{t}$	8 ± 2	6 ± 2	0.15 ± 0.10
Single top	3.4 ± 1.5	3.7 ± 1.6	-
$Z/\gamma^* + \text{jets}$	1.9 ± 1.3	0.10 ± 0.10	-
$W + \text{jets}$	15 ± 7	2 ± 1	-
Total background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed in data	185	38	0

Table 4.3: Data and expected yields for signal and background in the final $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal region.
Uncertainties shown are both statistical and systematic. [1]

1536 Figure 4.3 shows the m_T distribution in the $n_j \leq 1$ channels for 8 TeV data. (No events are observed
1537 in data in the $n_j \geq 2$ channels in this dataset). The excess shown here relatively flat as a function of
1538 hypothesized Higgs mass. The combined 7 and 8 TeV data gives an excess with local significance of 2.8σ
1539 with an expected significance of 2.3σ , corresponding to a μ measurement of 1.3 ± 0.5 .

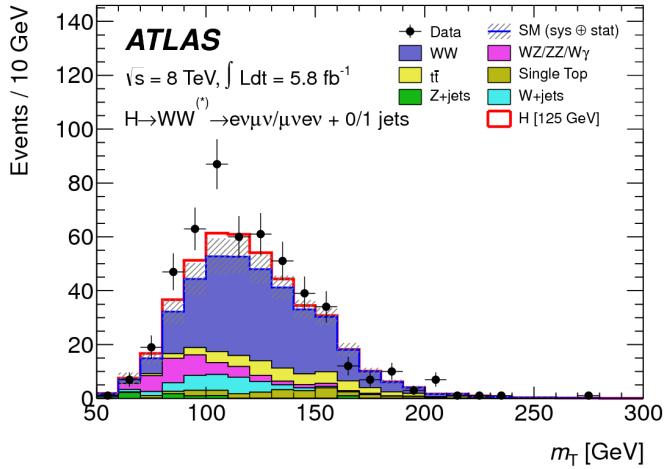


Figure 4.3: m_T distribution in the $H \rightarrow WW \rightarrow e\nu\mu\nu n_j \leq 1$ channels for 8 TeV data [1].

1540 4.4 $H \rightarrow \gamma\gamma$ SEARCH

1541 The $H \rightarrow \gamma\gamma$ search is in essence a search for a peaked excess above the falling SM diphoton mass
 1542 spectrum, with $m_{\gamma\gamma}$ as the ultimate discriminating variable. Events are selected by requiring two isolated
 1543 photons, with the leading (sub-leading) photon required to have $E_T > 40(30)$ GeV. In the 8 TeV data,
 1544 the photons are required to pass cut-based identification criteria consistent with a photon in the electro-
 1545 magnetic calorimeter and little leakage in the hadronic calorimeter.

1546 The main challenges for this analysis are accurate mass reconstruction and background estimation. In
 1547 order to accurately reconstruct the invariant mass of the di-photon system, both the energy and direction
 1548 of the photons must be measured well. Therefore, the identification of the primary vertex of the hard
 1549 interaction is particularly important, and is done using a multivariate likelihood which combines informa-
 1550 tion about the photon direction and vertex position. The background is modeled with a falling spectrum
 1551 in $m_{\gamma\gamma}$ that is parameterized by different functions depending on the category of the event.

1552 4.4.1 RESULTS

1553 The resulting diphoton mass spectrum is shown in figure 4.4. The best fit mass value in the $\gamma\gamma$ channel
 1554 alone in the combined 7 and 8 TeV data is 126.5 GeV. The local significance at this point is 4.5σ , with
 1555 an expected significance of 2.5σ . Therefore, the measured signal strength μ is 1.8 ± 0.5 in this channel.

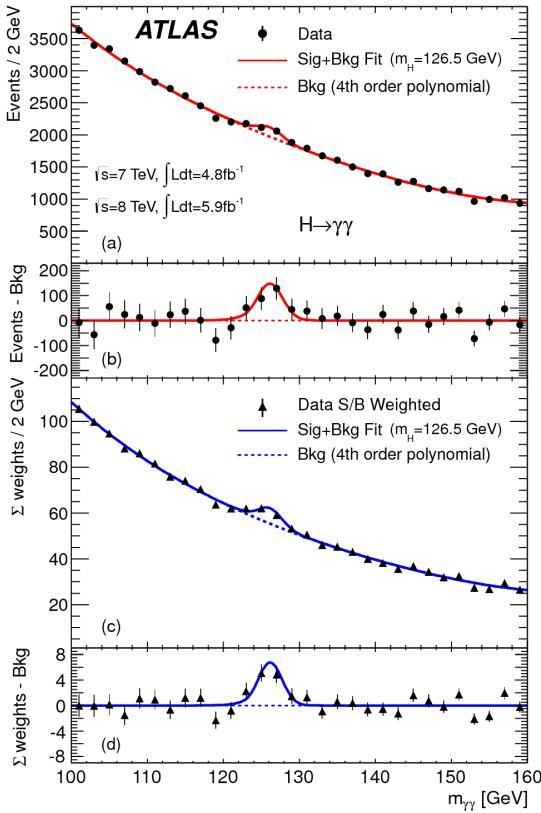


Figure 4.4: Diphoton mass spectrum in 7 and 8 TeV data. Panel a) shows the unweighted data distribution superimposed on the background fit, while panel c) shows the data where each event category is weighted by its signal to background ratio. Panels b) and d) show the respective distributions with background subtracted [1].

1556 4.5 $H \rightarrow ZZ \rightarrow 4\ell$ SEARCH

1557 The $H \rightarrow ZZ \rightarrow 4\ell$ analysis searches for a Standard Model Higgs boson decaying to two Z bosons,
 1558 each of which decays to a pair of same flavor, opposite charge isolated leptons. The ultimate discriminating
 1559 variable is $m_{4\ell}$, or the invariant mass of the four selected leptons. The ℓ denotes an e or μ as with the
 1560 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis.

1561 Four distinct signal regions are constructed depending on the flavors of the final state, additionally sep-
 1562 arated by the flavor of the leading lepton pair. These are referred to as $4e$, $2e2\mu$, $2\mu2e$, 4μ .

1563 The main backgrounds in the $H \rightarrow ZZ \rightarrow 4\ell$ search are continuum ZZ^* production, $Z +$ jets pro-
 1564 duction, and $t\bar{t}$. The $m_{4\ell}$ distribution for background is estimated from simulation. The normalization
 1565 of the SM ZZ^* background is also taken from MC simulation, while the $Z +$ jets and $t\bar{t}$ normalizations are

1566 taken from data-driven methods.

1567 **4.5.1 RESULTS**

1568 Figure 4.5 shows the $m_{4\ell}$ spectrum measured in the 7 and 8 TeV datasets. The total number of events
1569 observed in the window between 120 and 130 GeV is 13, with 6 events in the 4μ channel, 2 events in
1570 the $4e$ channel, and 5 events in the $2e2\mu/2\mu2e$. The best fit μ value in the combined 7 and 8 TeV data
1571 occurs at 125 GeV and is measured to be 1.2 ± 0.6 . The observed significance at this mass is 3.6σ , with
1572 an expected significance of 2.7σ .

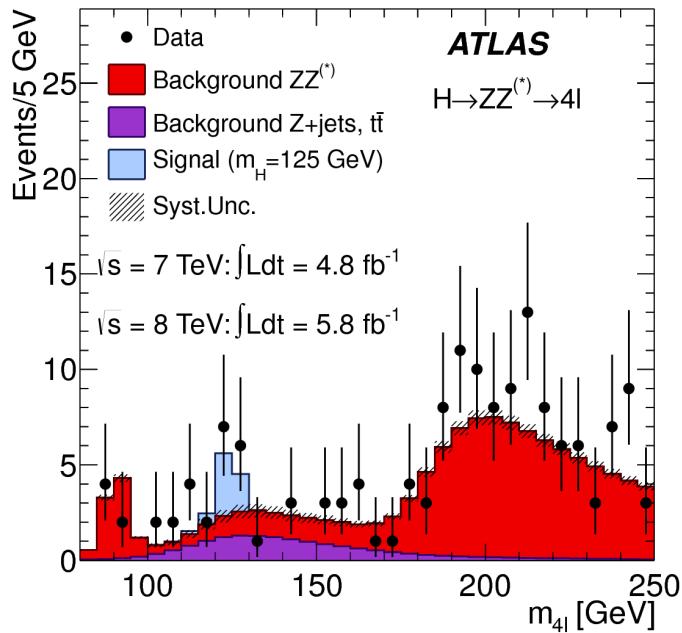


Figure 4.5: Four lepton invariant mass spectrum ($m_{4\ell}$) in 7 and 8 TeV data compared to background estimate. A 125 GeV SM Higgs signal is shown in blue [1].

1573 **4.6 COMBINED RESULTS**

1574 The statistical interpretation of the combined results is undertaken as described in section 3.6.2, with a
1575 hypothesis test based on a likelihood ratio parameterized by the Higgs signal strength μ . The null hypoth-
1576 esis corresponds to $\mu = 0$, while the SM Higgs corresponds to $\mu = 1$.

1577 Table 4.4 summarizes the properties of the individual channels as well as the significances of the excesses
 1578 seen. The most significant observed local excess comes from the $\gamma\gamma$ channel. Figure 4.6 shows a compari-
 1579 son of the observed local p_0 values as a function of hypothesized mass for the three different search chan-
 1580 nels. Both the ZZ^* and $\gamma\gamma$ channels have very peaked excesses, while the WW^* excess can be seen as very
 1581 broad because the m_T distribution does not provide detailed information about the true Higgs mass.

Channel	Fit var.	Observed Z_l	Expected Z_l	$\hat{\mu}$
$H \rightarrow ZZ^* \rightarrow 4\ell$	$m_{4\ell}$	3.6	2.7	1.2 ± 0.6
$H \rightarrow \gamma\gamma$	$m_{\gamma\gamma}$	4.5	2.5	1.8 ± 0.5
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$	m_T	2.8	2.3	1.3 ± 0.5
Combined	-	6.0	4.9	1.4 ± 0.3

Table 4.4: Summary of the expected and observed significance and measured signal strengths in the combined 7 and 8 TeV datasets for the Higgs discovery analysis [1].

1582 Figure 4.7 shows the combined exclusion limit, p_0 , and signal strength. The highest local excess comes
 1583 at a value of 126.5 GeV and corresponds to a 6.0σ observed excess.

1584 Figure 4.8 shows a comparison of the measured signal strengths between the different Higgs search
 1585 channels. All measured μ are consistent with unity within their uncertainty, and the combined μ mea-
 1586 surement is 1.4 ± 0.3 .

1587 The likelihood can also be computed in a two-dimensional plane of m_H and μ , and this is shown in
 1588 figure 4.9. The figure shows that while the $\gamma\gamma$ and ZZ^* channels have very good mass resolution, the
 1589 excess in WW^* covers a broad mass range. The banana shape of the WW^* result is due to the fact that
 1590 the excess in this channel can either be explained by increasing the signal strength or by changing the mass
 1591 (and thus the cross section). The two parameters are correlated due to the lack of mass sensitivity in this
 1592 channel.

1593 Because multiple Higgs mass points are searched for, the local significance must be corrected for a look-
 1594 elsewhere effect to compute a true global significance. The global significance for finding a Higgs anywhere
 1595 in the mass range of 110 GeV to 600 GeV is 5.1σ . This increases slightly to 5.3σ if only mass range from
 1596 110 to 150 GeV.

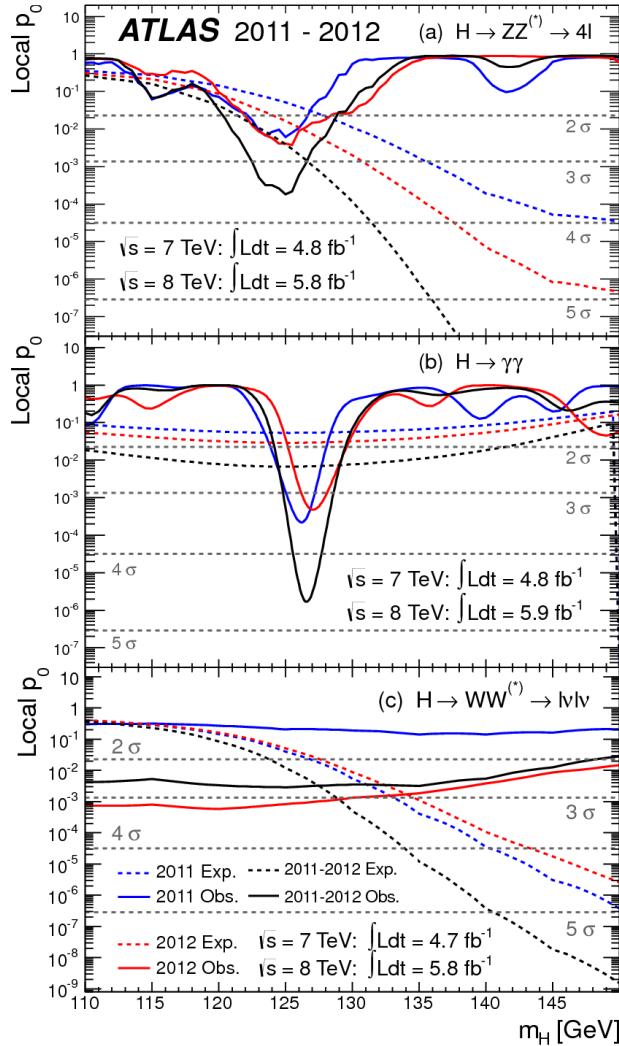


Figure 4.6: Local p_0 distribution as a function of hypothesized Higgs mass for the $H \rightarrow ZZ^* \rightarrow 4\ell$ (a), $H \rightarrow \gamma\gamma$ (b), and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ (c) channels. Dashed curves show expected results, while solid curves show observed. Red curves are from 7 TeV data, blue curves from 8 TeV, and black curved combined [1].

1597 4.7 CONCLUSION

1598 A search for the production of a Standard Model Higgs boson was conducted in 4.8 fb^{-1} collected at
 1599 $\sqrt{s} = 7 \text{ TeV}$ and 5.8 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. A new particle consistent with the Higgs boson was observed,
 1600 with a mass of 126.5 GeV and a global (local) significance of $5.1(6.0)\sigma$. This is the first discovery level
 1601 observation of a particle consistent with the Higgs.

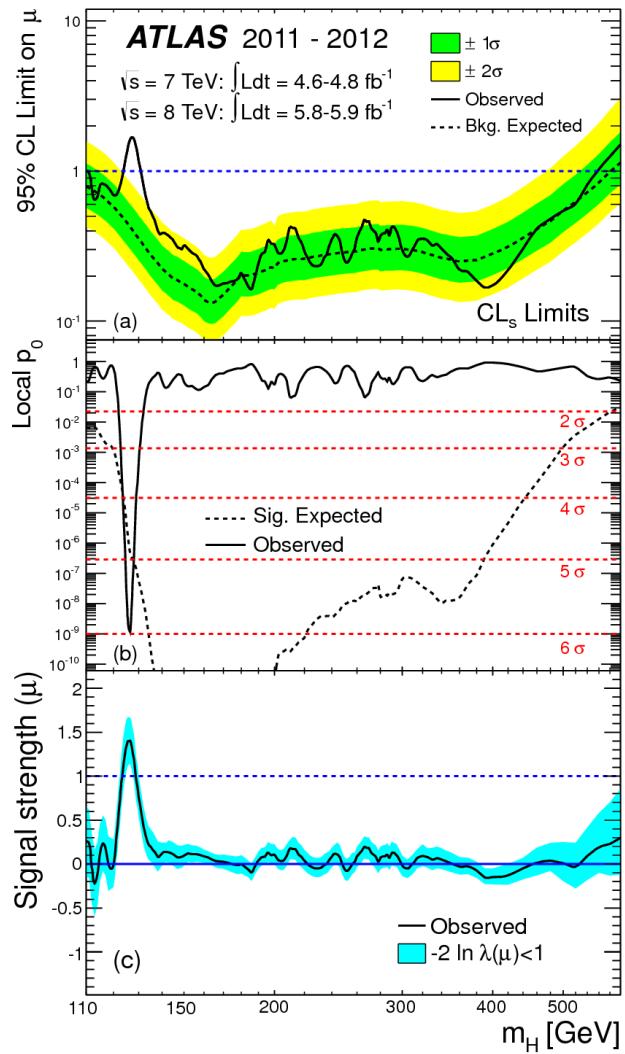


Figure 4.7: Combined 95% CL limits (a), local p_0 values (b), and signal strength measurement (c) as a function of Higgs mass [1].

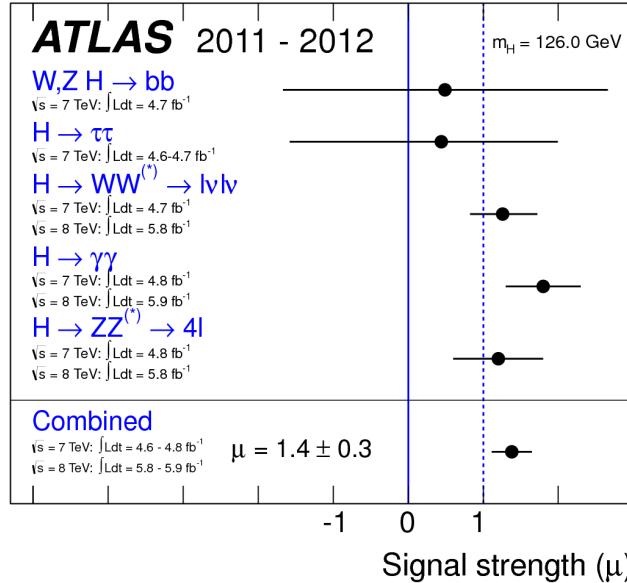


Figure 4.8: Comparison of measured signal strength μ for a 126 GeV Higgs in the 7 and 8 TeV datasets [1].

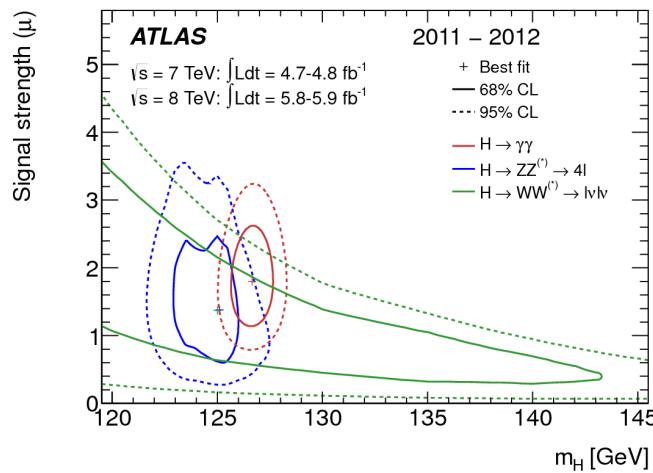


Figure 4.9: Two dimensional likelihood as a function of signal strength μ and Higgs mass m_H [1].

*The imagination of nature is far, far greater than the
imagination of man.*

Richard Feynman

1602

5

1603

Observation of Vector Boson Fusion

1604

production of $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

1605

5.1 INTRODUCTION

1606

After the discovery of a particle consistent with the Higgs boson, the $H \rightarrow WW^*$ analysis had two main goals. The first goal was to increase the sensitivity of the analysis to fully confirm that the $H \rightarrow WW^*$ process did indeed exist. The second goal was to characterize the particle as much as possible, including searching for the lower cross-section production modes, in order to confirm that it was indeed a Higgs boson. This chapter presents a dedicated search for Vector Boson Fusion (VBF) production of a Higgs boson decaying via the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ mode. First, basics of the topology of VBF production are presented. Then, the details of the analysis are shown, including signal region definition, background estimation techniques, and systematic uncertainties. Finally, the results of the analysis are presented. As

1614 will be shown, this analysis is the first and most sensitive observation of the VBF production mode of the
1615 Higgs on ATLAS.

1616 In the VBF channel, there are both a selection requirement based signal region analysis (known as the
1617 “cut-based”) and a multivariate analysis which uses a boosted decision tree (known as the BDT analysis).
1618 The focus of this chapter will be on the cut-based signal region, as this is an important component of the
1619 VBF analysis and in particular acts as strong validation for the final BDT result. Connections between the
1620 cut-based and BDT analyses will be discussed where appropriate.

1621 5.2 DATA AND SIMULATION SAMPLES

1622 The results presented here are with 20.3 fb^{-1} taken at $\sqrt{s} = 8 \text{ TeV}$ and 4.5 fb^{-1} taken at $\sqrt{s} = 7 \text{ TeV}$.
1623 The details of the LHC and detector conditions during this period are given in Chapter 2. The trigger
1624 selection defining the dataset is discussed in section 5.2.1. The simulation samples used for signal and back-
1625 ground modeling are given in section 5.2.2.

1626 5.2.1 TRIGGERS

1627 The analysis uses a combination of single lepton and dilepton triggers to allow lowering of the p_T
1628 thresholds and increased signal acceptance. The p_T threshold on the leptons is a particularly important
1629 consideration for this signal. Because the second W produced in the decay can be off-shell, it tends to pro-
1630 duce lower momentum leptons. Thus, being able to lower the p_T threshold while still maintaining a low
1631 background rate is critical. Figure 5.1 shows an example of the subleading lepton p_T for a VBF $H \rightarrow WW^*$
1632 signal compared to the corresponding $t\bar{t}$ background. Note that the lepton p_T spectrum is considerably
1633 softer in the signal sample.

1634 As discussed in Chapter 2, there are multiple levels in the ATLAS trigger system, and there are different
1635 p_T thresholds imposed for the leptons at each level. Additionally, some triggers have a loose selection
1636 on the isolation of the lepton (looser than that applied offline in the analysis object selection). Table 5.1
1637 shows the thresholds used for single lepton triggers, while table 5.2 shows the thresholds coming from
1638 di-lepton triggers. The single lepton trigger efficiency for muons that pass the analysis object selection is

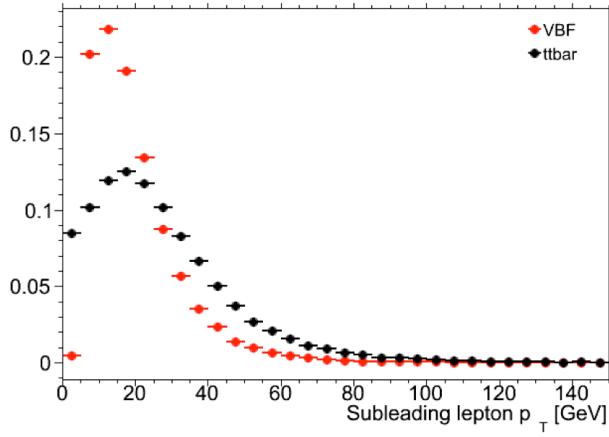


Figure 5.1: A comparison of the subleading lepton p_T spectrum between VBF $H \rightarrow WW^*$ production and $t\bar{t}$ background

1639 70% for muons in the barrel region ($|\eta| < 1.05$) and 90% in the endcap region. The electron trigger
1640 efficiency increases with electron p_T but the average is approximately 90%. These efficiencies are measured
1641 by combined performance and trigger signature groups [66, 67].

	Level-1 threshold	High-level threshold
Electron	18	$24i$
	30	60
Muon	15	$24i$
		36

Table 5.1: Single lepton triggers used for electrons and muons. A logical “or” of the triggers listed for each lepton type is taken. Units are in GeV, and the i denotes an isolation requirement in the trigger.

	Level-1 threshold	High-level threshold
ee	10 and 10	12 and 12
$\mu\mu$	15	18 and 8
$e\mu$	10 and 6	12 and 8

Table 5.2: Di-lepton triggers used for different flavor combinations. The two thresholds listed refer to leading and sub-leading leptons, respectively. The di-muon trigger only requires a single lepton at level-1.

1642 The combination of all triggers shown gives good efficiency for signal events. This efficiency is sum-
1643 marized in table 5.3. The relative improvement in efficiency by adding the dilepton triggers is also shown

1644 in the same table. The largest gain comes in the $\mu\mu$ channel. Overall the trigger selection shows a good
1645 efficiency for $H \rightarrow WW^*$ signal events.

Channel	Trigger efficiency	Gain from 2ℓ trigger
ee	97%	9.1%
$\mu\mu$	89%	18.5%
$e\mu$	95%	8.3%
μe	81%	8.2%

Table 5.3: Trigger efficiency for signal events and relative gain of adding a dilepton trigger on top of the single lepton trigger selection. The first lepton is the leading, while the second is the sub-leading. Efficiencies shown here are for the ggF signal in the $n_j = 0$ category but are comparable for the VBF signal.

1646 5.2.2 MONTE CARLO SAMPLES

1647 Modeling of signal and background processes in the signal region, in particular for the m_T distribution,
1648 is an important consideration for the final interpretation of the analysis. Therefore, careful consideration
1649 must be paid to which Monte Carlo (MC) generators are used for specific processes. With the exception of
1650 the $W + \text{jet}$ and multijet backgrounds, the m_T shape used as the final discriminant is taken from simulation.
1651 (Many backgrounds are normalized from data, as described in section 5.5).

1652 Table 5.4 shows the MC generators used for the signal and background processes, as well as their cross
1653 sections. In order to include corrections up to next-to-leading order (NLO) in the QCD coupling constant
1654 α_s , the POWHEG [68] generator is often used. In some cases, only leading order generators like ACERMC
1655 [69] and GG2VV [70] are available for the process in question. If the process requires good modeling for
1656 very high parton multiplicities, the SHERPA [71] and ALPGEN [72] generators are used to provide merged
1657 calculations for five or fewer additional partons. These matrix element level calculations must then be
1658 additionally matched to models of the underlying event, hadronization, and parton shower. There are
1659 four possible generators for this: SHERPA, PYTHIA 6 [73], PYTHIA 8 [74], or HERWIG [75] + JIMMY [76].
1660 The simulation additionally requires an input parton distribution function (PDF). The CTEQ [77] PDFs
1661 are used for SHERPA and POWHEG simulated samples, while CTEQ6Li [78] is used for ALPGEN + HERWIG
1662 and ACERMC simulations. The Drell-Yan samples are reweighted to the MRST [79] PDFs, as these are
1663 found to give the best agreement between data and simulation.

Process	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
Signal		
ggF $H \rightarrow WW^*$	POWHEG +PYTHIA 8	0.435
VBF $H \rightarrow WW^*$	POWHEG +PYTHIA 8	0.0356
VH $H \rightarrow WW^*$	PYTHIA 8	0.0253
WW		
$q\bar{q} \rightarrow WW$ and $qg \rightarrow WW$	POWHEG +PYTHIA 6	5.68
$gg \rightarrow WW$	GG2VV +HERWIG	0.196
$(q\bar{q} \rightarrow W) + (q\bar{q} \rightarrow W)$	PYTHIA 8	0.480
$q\bar{q} \rightarrow WW$	SHERPA	5.68
VBS $WW + 2$ jets	SHERPA	0.0397
Top quarks		
$t\bar{t}$	POWHEG +PYTHIA 6	26.6
Wt	POWHEG +PYTHIA 6	2.35
$t\bar{q}\bar{b}$	ACERMC +PYTHIA 6	28.4
$t\bar{b}$	POWHEG +PYTHIA 6	1.82
Other dibosons (VV)		
$W\gamma$ ($p_T^\gamma > 8$ GeV)	ALPGEN +HERWIG	369
$W\gamma^*$ ($m_{\ell\ell} \leq 7$ GeV)	SHERPA	12.2
WZ ($m_{\ell\ell} > 7$ GeV)	POWHEG +PYTHIA 8	12.7
VBS $WZ + 2$ jets	SHERPA	0.0126
($m_{\ell\ell} > 7$ GeV)		
$Z\gamma$ ($p_T^\gamma > 8$ GeV)	SHERPA	163
$Z\gamma^*$ (min. $m_{\ell\ell} \leq 4$ GeV)	SHERPA	7.31
ZZ ($m_{\ell\ell} > 4$ GeV)	POWHEG +PYTHIA 8	0.733
$ZZ \rightarrow \ell\ell\nu\nu$ ($m_{\ell\ell} > 4$ GeV)	POWHEG +PYTHIA 8	0.504
Drell-Yan		
Z ($m_{\ell\ell} > 10$ GeV)	ALPGEN +HERWIG	16500
VBF $Z + 2$ jets	SHERPA	5.36
($m_{\ell\ell} > 7$ GeV)		

Table 5.4: Monte Carlo samples used to model the signal and background processes [62].

Once the basic hard scattering process is simulated, it must be passed through a detector simulation and additional pile-up events must be overlaid. The pile-up events are modeled with PYTHIA 8, and the ATLAS detector is simulated with GEANT4 [80]. Because of the unique phase space of the $H \rightarrow WW^*$

1667 analysis, events are sometimes filtered at generator level to allow for more efficient generation of relevant
1668 events. The efficiency of the trigger in MC simulation does not always match the measured efficiency in
1669 data, so trigger scale factors are applied to correct the MC efficiency to the data. These are derived by the
1670 combined performance groups [66, 67].

1671 5.3 OBJECT SELECTION

1672 In order to define the signal region, the analysis must first select the objects to be considered. The details
1673 of the object reconstruction algorithms are discussed in Chapter 2, while this section gives specific selection
1674 cuts used in the $H \rightarrow WW^*$ analysis.

1675 The first step in this process is to select a primary vertex candidates. The event’s primary vertex is the
1676 vertex with the largest sum of p_T^2 for associated tracks and is required to have at least three tracks with
1677 $p_T > 450$ MeV. Many of the object selection cuts are then made relative to this chosen primary vertex.

1678 5.3.1 MUONS

1679 The analysis uses combined muon candidates, where a track in the Inner Detector has been matched to
1680 a standalone track in the Muon Spectrometer. The track parameters are combined statistically in the muon
1681 reconstruction algorithm [53]. The muons are required to be within $|\eta| < 2.5$ and have a $p_T > 10$ GeV.
1682 To reduce backgrounds coming from mis-reconstructed leptons, there are requirements on the impact
1683 parameter of the muon relative to the primary vertex. The transverse impact parameter d_0 is required to
1684 be small relative to its estimated uncertainty, the exact cut value being $d_0/\sigma_{d_0} < 3$. The longitudinal
1685 impact parameter z_0 must satisfy $|z_0 \sin \theta| < 1$ mm.

1686 As discussed previously, the muons must also be isolated. There are two types of lepton isolations that
1687 are calculated: track-based and calorimeter-based. For muons, the track-based isolation is defined using the
1688 scalar sum $\sum p_T$ for tracks with $p_T > 1$ GeV (excluding the muon’s track) within a cone of $\Delta R = 0.3$
1689 (0.4) for muon with $p_T > 15$ GeV ($10 < p_T < 15$ GeV). The final isolation requirement is made my
1690 requiring that this scalar sum be no more than a certain fraction of the muon’s p_T . This requirement varies
1691 with muon p_T and the exact cuts are defined in table 5.5.

1692 The calorimeter-based muon isolation is defined using as a $\sum E_T$ calculated from calorimeter cells us-
 1693 ing the same cone size as the track-based isolation but excluding cells with $\Delta R < 0.05$ around the muon.
 1694 This requirement is also defined as a cut on the ratio of the sum to the muon p_T and varies with muon p_T .
 1695 The cut values are also given in table 5.5.

 1696 The isolation requirements loosen as a function of p_T to allow for larger signal acceptance. At low p_T ,
 1697 the isolation is tightened to reduce the $W + \text{jets}$ background which arises from a misidentified lepton.

p_T range (GeV)	Calorimeter isolation	Track isolation
10 – 15	0.06	0.06
15 – 20	0.12	0.08
20 – 25	0.18	0.12
> 25	0.30	0.12

Table 5.5: p_T dependent isolation requirements for muons. Muons are required to have the amount of calorimeter or track based cone sums be less than this fraction of their p_T .

1698 5.3.2 ELECTRONS

1699 Electrons are identified by matching reconstructed clusters in the electromagnetic calorimeter with tracks
 1700 in the inner detector. The electrons are identified using a likelihood based method [50, 51] which takes into
 1701 account the shower shapes in the calorimeter, the matching of tracks to clusters, and the amount of transi-
 1702 tion radiation in the TRT. The electrons are required to have $|\eta| < 2.47$, and candidates in the transition
 1703 region between the barrel and endcap ($1.37 < |\eta| < 1.52$) are excluded. As the muons, the electrons
 1704 are required to have transverse impact parameter significance < 3 , while in the longitudinal direction
 1705 they must have $|z_0 \sin \theta| < 0.4$ mm. Some electron requirements also vary with electron E_T , and these
 1706 requirements are summarized in table 5.6.

1707 The isolation for electrons are defined similarly to the muons but with unique cuts on the objects in-
 1708 cluded. The track-based isolation is defined using tracks with $p_T > 400$ MeV with cone sizes as defined
 1709 previously. The calorimeter-based isolation also uses the same cone size as the muon, but here the cells
 1710 within a 0.125×0.175 area in $\eta \times \phi$ around the electron cluster's barycenter are excluded. The other
 1711 difference with respect to muons is that the denominator of the isolation ratio is the electron's E_T rather
 1712 than p_T . The isolation cuts very with electron E_T and are defined in table 5.6.

1713 The electron is also required to not be consistent with a vertex coming from a photon conversion.

p_T range (GeV)	Quality cut	Calorimeter isolation	Track isolation
10 – 15	Very tight LH	0.20	0.06
15 – 20	Very tight LH	0.24	0.08
20 – 25	Very tight LH	0.28	0.10
> 25	Medium	0.28	0.10

Table 5.6: p_T dependent requirements for electrons. Electrons are required to have the amount of calorimeter or track based cone sums be less than this fraction of their E_T .

1714 5.3.3 JETS

1715 Jets are clustered with the anti- k_T reconstruction algorithm using a radius parameter of $R = 0.4$. They
1716 are required to have a jet vertex fraction (JVF) of at least 50%, meaning that half of the tracks associated with
1717 the jet originated from the primary vertex. Jets with no tracks associated (i.e. those outside the acceptance
1718 of the ID) do not have this requirement applied. Jets are required to have $p_T > 25$ GeV if they are within
1719 the tracking acceptance ($|\eta| < 2.4$). Jets with $2.4 < |\eta| < 4.5$ are required to have $p_T > 30$ GeV.
1720 This tighter requirement reduces jets from pileup in the region where JVF requirements cannot be applied.
1721 The two highest p_T jets in the event are referred to as the “VBF” jets and used to compute various analysis
1722 selections later.

1723 Identification of b -jets is done using the MV1 algorithm and is limited to the acceptance of the ID ($|\eta| <$
1724 2.5). The operating point of MV1 that is used is the one that is 85% efficient for identifying true b -jets. This
1725 operating point has a 10.3% of mis-tagging a light quark jet as a b -jet. In order to improve the rejection of b -
1726 jets, a lower threshold than the nominal p_T threshold described above is used. For the purposes of counting
1727 the number of b -jets, jets with p_T down to 20 GeV are used.

1728 5.3.4 OVERLAP REMOVAL

1729 There are some cases where certain reconstructed objects will overlap and one will have to be chosen
1730 (for example, an electron and a jet in the calorimeter). First, the case of lepton overlap is dealt with. If
1731 an electron candidate extends into the muon spectrometer, it is removed. If a muon or electron have a
1732 $\Delta R < 0.1$, the electron is removed and the muon is kept. If two electron candidates overlap within the

1733 same radius, then the higher E_T electron is kept. Next, the overlap between leptons and jets is considered.
1734 If an electron and jet are within $\Delta R < 0.3$ of one another, the electron is kept and the jet is removed.
1735 However, if a muon and jet overlap within $\Delta R < 0.3$, the jet is kept (as it is likely that the muon is the
1736 result of a semileptonic decay inside the jet).

1737 Once the overlap removal is complete, the final set of objects used in the analysis is defined.

1738 5.4 ANALYSIS SELECTION

1739 The VBF analysis uses two distinct selections. The first is a more standard selection, referred to as “cut-
1740 based”, that applies requirements on the VBF variables and uses m_T as the final discriminating variable.
1741 The second is a looser selection that uses a Boosted Decision Tree (BDT) score as the final discriminator in
1742 order to take advantage of the detailed correlations between the VBF variables. While the BDT analysis is
1743 ultimately more sensitive, the cut-based serves as an important component of the analysis. First, the cut-
1744 based allows for confirming the modeling and validity of many variables used as input to the BDT. Second,
1745 because this is the first use of such an MVA technique in the $H \rightarrow WW^*$ analysis, the cut-based selection
1746 allows confirmation of the final BDT result with a more traditional analysis. The cut-based techniques are
1747 the focus of this chapter, but connections to the BDT result will be illustrated when appropriate.

1748 One important note is that because this analysis is dedicated to the measurement of the VBF pro-
1749 duction mode of the Higgs, events coming from gluon fusion production with the Higgs decaying via
1750 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ are treated as background events. This will be seen throughout the various predic-
1751 tions shown.

1752 5.4.1 COMMON PRE-SELECTION

1753 Both the cut-based and BDT analyses have a common pre-selection that is applied before the main signal
1754 region requirements. The requirements on leptons are common to all n_j bins. The analysis requires two
1755 oppositely charged leptons, with the leading lepton required to have $p_T > 22$ GeV while the subleading
1756 lepton must have $p_T > 10$ GeV. Next, to remove low mass Z/γ^* events, a cut on the dilepton mass
1757 $m_{\ell\ell} > 10$ (12) GeV is applied in the different (same) flavor channel. In the same flavor channels, there is

1758 an additional veto placed on the region around the Z peak, requiring that $|m_{\ell\ell} - m_Z| > 15$ GeV.

1759 There are also requirements on the amount of missing transverse momentum in the event. These are
1760 only applied in the same flavor channels, as in the different flavor channels $t\bar{t}$ is the dominant background
1761 in $n_j \geq 2$. The BDT analysis requires $p_T^{\text{miss}} > 40$ GeV and $E_T^{\text{miss}} > 45$ GeV. The cut-based analysis
1762 must select more tightly on these variables to have maximal sensitivity and thus requires $p_T^{\text{miss}} > 50$ GeV
1763 and $E_T^{\text{miss}} > 55$ GeV.

1764 Finally, because this analysis is focused on VBF, a requirement on the jet multiplicity is placed, with
1765 $n_j \geq 2$. Additionally, the analysis requires that there are no jets identified as b-quarks in the event, or
1766 $n_b = 0$.

1767 5.4.2 CUT-BASED SELECTION

1768 The cut-based selection places sequential requirements on variables reconstructed from the VBF jets in
1769 order to increase the signal to background ratio.

1770 GENERAL BACKGROUND REDUCTION

1771 Top pair production is the primary background in the $n_j \geq 2$ bin. Even though $n_b = 0$ is required, an
1772 additional variable is constructed to further suppress the top background. There is often additional QCD
1773 radiation that accompanies the $t\bar{t}$ system when it is produced. Therefore, a variable which tests for the
1774 presence of this additional radiation, p_T^{sum} , is constructed. It is defined in equation 5.1.

$$p_T^{\text{sum}} = p_T^{\ell\ell} + p_T^{\text{miss}} + \sum p_T^j \quad (5.1)$$

1775 The first cut after pre-selection in the cut-based analysis requires $p_T^{\text{sum}} < 15$ GeV to further suppress $t\bar{t}$
1776 production.

1777 In the different flavor channels, a cut is made to reduce the contamination from $Z \rightarrow \tau\tau$ decays.
1778 The di- τ invariant mass, $m_{\tau\tau}$, is constructed by assuming that the neutrinos from the τ decays were
1779 collinear with the leptons [81]. The analysis requires that this mass not be consistent with a Z by requiring
1780 $m_{\tau\tau} < m_Z - 25$ GeV.

1781 VBF TOPOLOGICAL CUTS

1782 The characteristic feature of VBF production of the Higgs is the presence of two additional forward
1783 jets coming from the incoming partons which radiate the vector bosons that make the Higgs. These jets
1784 are forward because the outgoing partons still carry the longitudinal momentum of the incoming partons.
1785 Figure 5.2 shows the distribution of the η for the leading jet in a VBF event compared to a background top
1786 pair production event. As can be seen, the VBF jets tend to be more forward in η , while the $t\bar{t}$ jets are more
1787 central.

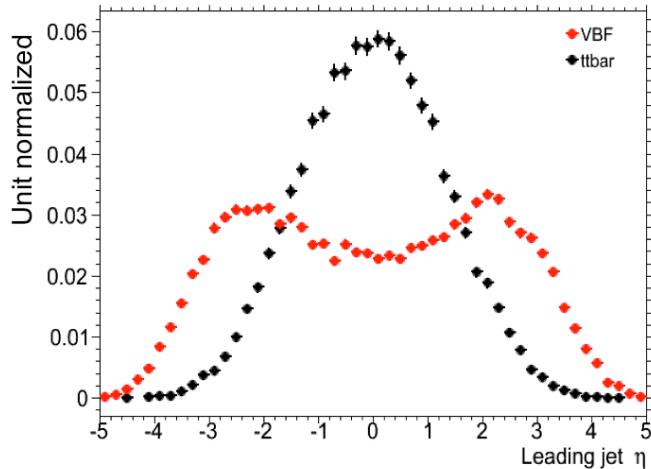


Figure 5.2: Leading jet η in VBF $H \rightarrow WW^*$ (red) and $t\bar{t}$ (black)

1788 Because the cross section for VBF production is an order of magnitude smaller than gluon fusion pro-
1789 duction, these forward jets must be used in order to better reduce background and achieve a good signal to
1790 background ratio. The dedicated VBF search selection requirements are constructed to maximally exploit
1791 the features of the unique VBF topology.

1792 Requirements on the VBF jets are collectively referred to as the “VBF topological cuts”. First, a require-
1793 ment on the dijet invariant mass of the VBF jets, m_{jj} , is placed, requiring $m_{jj} > 600$ GeV. Next, the
1794 event is required to have a large gap in rapidity between the two VBF jets, or $\Delta y_{jj} > 3.6$. Both of these
1795 cuts put tight requirements on the presence of two forward, high p_T jets moving in opposite directions in

1796 the longitudinal plane.

1797 Beyond requiring the presence of the two forward VBF jets, the analysis also vetoes on the presence
1798 of any additional jets that fall between the two VBF jets. This cut is referred to as the central jet veto, or
1799 CJV. Any events with a third jet with $p_T > 20$ GeV whose rapidity is between the region defined by the
1800 two VBF jets are vetoed. This can be expressed in terms of a variable called the jet centrality, defined in
1801 equation 5.2.

$$C_{j3} = \left| \eta_{j3} - \frac{\eta_{j1} + \eta_{j2}}{2} \right| / \frac{|\eta_{j1} - \eta_{j2}|}{2}, \quad (5.2)$$

1802 Here, η_{j1} and η_{j2} are the pseudorapidities of the leading and subleading jets, respectively, while η_{j3} is
1803 the pseudorapidity of the extra jet in the event (if one exists). Intuitively, C_{j3} is zero when η_{j3} is directly
1804 centered between the two jets and unity when η_{j3} is aligned with either of the VBF jets. Thus, the CJV
1805 can be expressed as a requirement that $C_{j3} > 1$.

1806 The decay products of the Higgs tend to be central as well. Thus, the analysis also requires that both
1807 leptons in the analysis fall within the rapidity gap defined by the jets. This cut is referred to as the outside
1808 lepton veto, or OLV. A quantitative way to define the cut is to require that the centrality of each lepton
1809 (defined analogously to that of the third jet in equation 5.2) correspond to the lepton being within the jet
1810 rapidity gap, or $C_\ell < 1$ for both leptons.

1811 Figure 5.3a-c shows the m_{jj} , Δy_{jj} , and $C_{\ell 1}$ variables at the stage where all previous cuts in the sequence
1812 have been made. The agreement between data and Monte Carlo is good, and the bottom panels show their
1813 power in discriminating the VBF signal from the background processes.

1814 The final signal region is also split into two bins of m_{jj} , with the first bin corresponding to $600 \text{ GeV} <$
1815 $m_{jj} < 1 \text{ TeV}$ and the second bin corresponding to $m_{jj} > 1 \text{ TeV}$. The first bin has more statistics but
1816 also a larger contribution from background, while the second bin has lower statistics but a 1:1 signal to
1817 background ratio.

1818 HIGGS TOPOLOGICAL CUTS

1819 The final state leptons will exhibit unique correlations due to the fact that they are arising from the
1820 decay of a spin zero resonance. In particular, the spins of the final state leptons and neutrinos must all

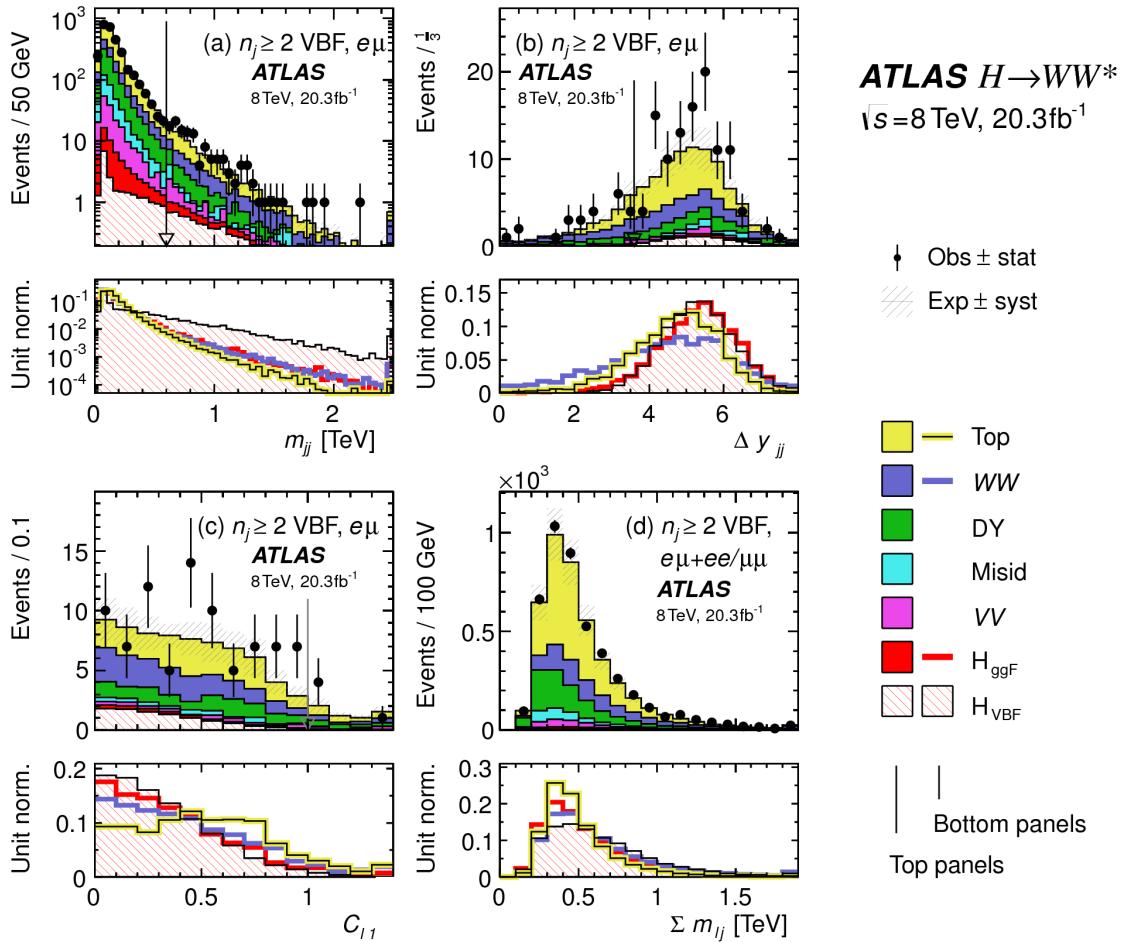


Figure 5.3: Distributions of (a) m_{jj} , (b) Δy_{jj} , (c) $C_{\ell 1}$, and (d) $\Sigma m_{\ell j}$, for the VBF analysis. The top panels compare simulation and data, while the bottom panels show normalized distributions for all background processes and signal [62].

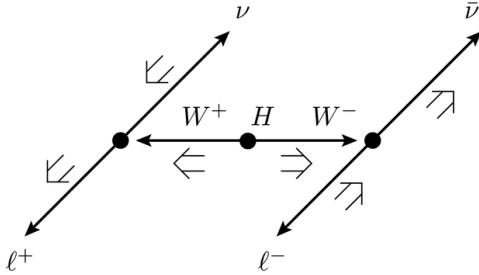


Figure 5.4: A cartoon of the WW final state. Momenta are represented with thin arrows, spins with thick arrows.
[62]

cancel, as shown in figure 5.4. Because the neutrino has a left handed chirality and the anti-neutrino has a right handed chirality (in the massless neutrino approximation), the spin and momentum of the particles will be anti-aligned and aligned, respectively. In the transverse plane, the momenta of all four final state objects must cancel as well. With the constraint of having both the momenta and the spin alignments cancel, the final state kinematics strongly prefer having a small angle between the leptons in the transverse plane (low $\Delta\phi_{\ell\ell}$). This angular correlation will also lead to low values of the di-lepton invariant mass $m_{\ell\ell}$. These unique signal final state kinematic correlations will be exploited to define the ultimate signal region.

The analysis places additional requirements on the final state leptons. Two requirements on dilepton kinematics are made that are common with lower multiplicity jet bins as well. The angle between leptons in the transverse plane, $\Delta\phi_{\ell\ell}$, is required to be less than 1.8 radians. Additionally, the dilepton mass $m_{\ell\ell}$ is required to be less than 50 GeV.

The cut-based analysis uses m_T as the final discriminating variable as in the ggF focused analysis. The optimal number of bins in m_T was found to be three bins, with the bin boundaries at 80 and 130 GeV.

Table 5.7 shows a summary of the data and estimated signal and background yields from simulation as each requirement described above is made. The table shows how the overall signal to background ratio grows through the various selection requirements. Table 5.8 shows the background composition after each selection requirement, illustrating which backgrounds are reduced most by certain requirements. Figure 5.5 shows an ATLAS event display of a candidate event in the final signal region.

Selection	Summary					
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{signal}		
				N_{ggF}	N_{VBF}	N_{VH}
$e\mu$ sample	1.00 ± 0.00	61434	61180	85	32	26
$n_b = 0$	1.02 ± 0.01	7818	7700	63	26	16
$p_T^{\text{sum}} < 15$	1.03 ± 0.01	5787	5630	46	23	13
$m_{\tau\tau} < m_Z - 25$	1.05 ± 0.02	3129	2970	40	20	9.9
$m_{jj} > 600$	1.31 ± 0.12	131	100	2.3	8.2	—
$\Delta y_{jj} > 3.6$	1.33 ± 0.13	107	80	2.1	7.9	—
$C_{j3} > 1$	1.36 ± 0.18	58	43	1.3	6.6	—
$C_{\ell 1} < 1, C_{\ell 2} < 1$	1.42 ± 0.20	51	36	1.2	6.4	—
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_T$	2.53 ± 0.71	14	5.5	0.8	4.7	—
$ee/\mu\mu$ sample	0.99 ± 0.01	26949	27190	31	14	10.1
$n_b, p_T^{\text{sum}}, m_{\tau\tau}$	1.03 ± 0.03	1344	1310	13	8.0	4.0
$m_{jj}, \Delta y_{jj}, C_{j3}, C_\ell$	1.39 ± 0.28	26	19	0.4	2.9	0.0
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_T$	1.63 ± 0.69	6	3.7	0.3	2.2	0.0

Table 5.7: Summary of event selection for the $n_j \geq 2$ VBF analysis in the 8 TeV cut-based analysis [62].

	Composition of N_{bkg}								
	N_{WW}		N_{top}		N_{misid}		N_{VV}	$N_{\text{Drell-Yan}}$	
	N_{WW}^{QCD}	N_{WW}^{EW}	$N_{t\bar{t}}$	N_t	N_{Wj}	N_{jj}	N_{VV}	$N_{ee/\mu\mu}^{\text{QCD}}$	$N_{\tau\tau}^{\text{EW}}$
$e\mu$ sample	1350	68	51810	2970	847	308	380	51	3260
$n_b = 0$	993	43	3000	367	313	193	273	35	2400
$p_T^{\text{sum}} < 15$	781	38	1910	270	216	107	201	27	2010
$m_{\tau\tau} < m_Z - 25$	484	22	1270	177	141	66	132	7.6	627
$m_{jj} > 600$	18	8.9	40	5.3	1.8	2.4	5.1	0.1	15
$\Delta y_{jj} > 3.6$	11.7	6.9	35	5.0	1.6	2.3	3.3	—	11.6
$C_{j3} > 1$	6.9	5.6	14	3.0	1.3	1.3	2.0	—	6.8
$C_{\ell 1} < 1, C_{\ell 2} < 1$	5.9	5.2	10.8	2.5	1.3	1.3	1.6	—	5.7
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_T$	1.0	0.5	1.1	0.3	0.3	0.3	0.6	—	0.5
$ee/\mu\mu$ sample	594	37	23440	1320	230	8.6	137	690	679
$n_b, p_T^{\text{sum}}, m_{\tau\tau}$	229	12.0	633	86	26	0.9	45	187	76
$m_{jj}, \Delta y_{jj}, C_{j3}, C_\ell$	3.1	3.1	5.5	1.0	0.2	0.0	0.7	3.8	0.7
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_T$	0.4	0.2	0.6	0.2	0.2	0.0	0.1	1.5	0.3

Table 5.8: Background composition after each requirement in the $n_j \geq 2$ VBF analysis in the 8 TeV cut-based analysis [62].

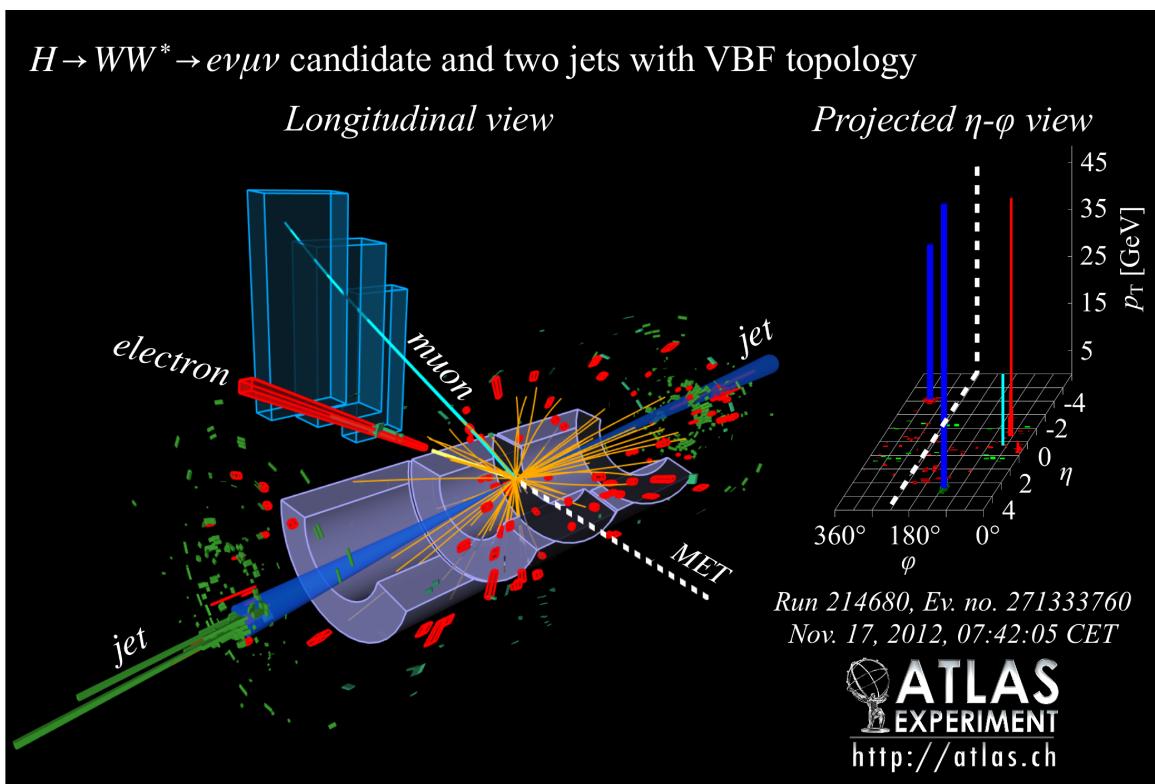


Figure 5.5: Event display of a VBF candidate event [62].

1839 5.4.3 BDT-BASED SELECTION

1840 The boosted decision tree based analysis takes a different philosophy compared to the cut-based. Rather
 1841 than cutting sequentially on many variables, the BDT analysis uses many of these variables as inputs to
 1842 the BDT and the output BDT score (O_{BDT}) as the final discriminant. The BDT is trained with the
 1843 VBF $H \rightarrow WW^*$ simulation as the signal samples and all other processes as background, including ggF
 1844 $H \rightarrow WW^*$ production. While the BDT based analysis is treated as a separate result, it has significant
 1845 overlap with the cut-based selection.

1846 PRE-TRAINING SELECTION AND BDT INPUTS

1847 Before training, the common pre-selection cuts described in section 5.4.1 are applied. Additionally, the
 1848 central jet veto and outside lepton veto described in section 5.4.2 are applied. The BDT has eight input
 1849 variables, six of which are also variables that are used in the cut-based analysis. The six shared variables

1850 are p_T^{sum} , m_{jj} , Δy_{jj} , $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, and m_T . The seventh variable input in the BDT is a combination of
 1851 the variables used to do the OLV in the cut-based analysis. The BDT uses as input the sum of lepton
 1852 centralities, or $\sum C_\ell = C_{\ell 1} + C_{\ell 2}$. The final BDT input variable, $\Sigma m_{\ell j}$, is constructed to account for
 1853 the correlations between the jets and leptons in the event. It is the sum of the invariant masses of all four
 1854 possible lepton-jet combinations.

1855 Figure 5.3d shows the agreement between data and simulation for the $\Sigma m_{\ell j}$ variable, as well as showing
 1856 its discriminating power. Figure 5.6 shows the distributions of the Higgs topological variables that are
 1857 shared between the cut-based and BDT analyses. Figure 5.7 shows the distributions of the VBF topological
 1858 variables shared between the cut-based and BDT analyses. In both cases, the VBF yield has been scaled by
 1859 a factor of 50 to better show the shape difference compared to the backgrounds.

1860 Table ?? summarizes the cuts applied for the cut-based and analyses, as well as which variables are used
 1861 as input to the BDT.

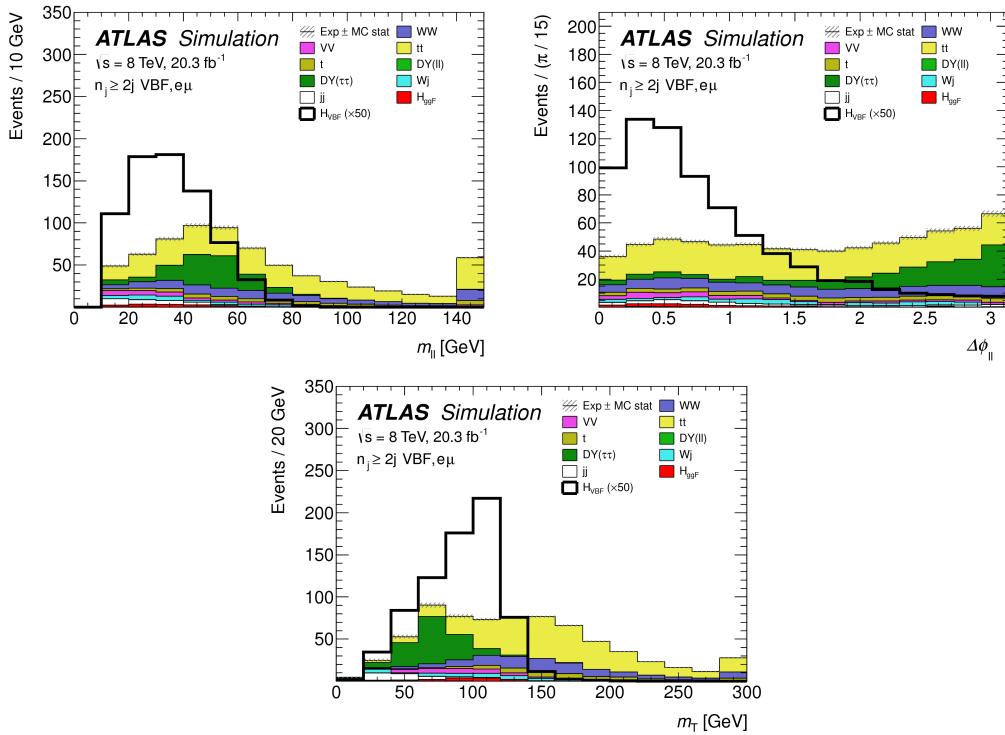


Figure 5.6: Distributions of $m_{\ell\ell}$ (top left), $\Delta\phi_{\ell\ell}$ (top right), and m_T (bottom), Higgs topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [62].

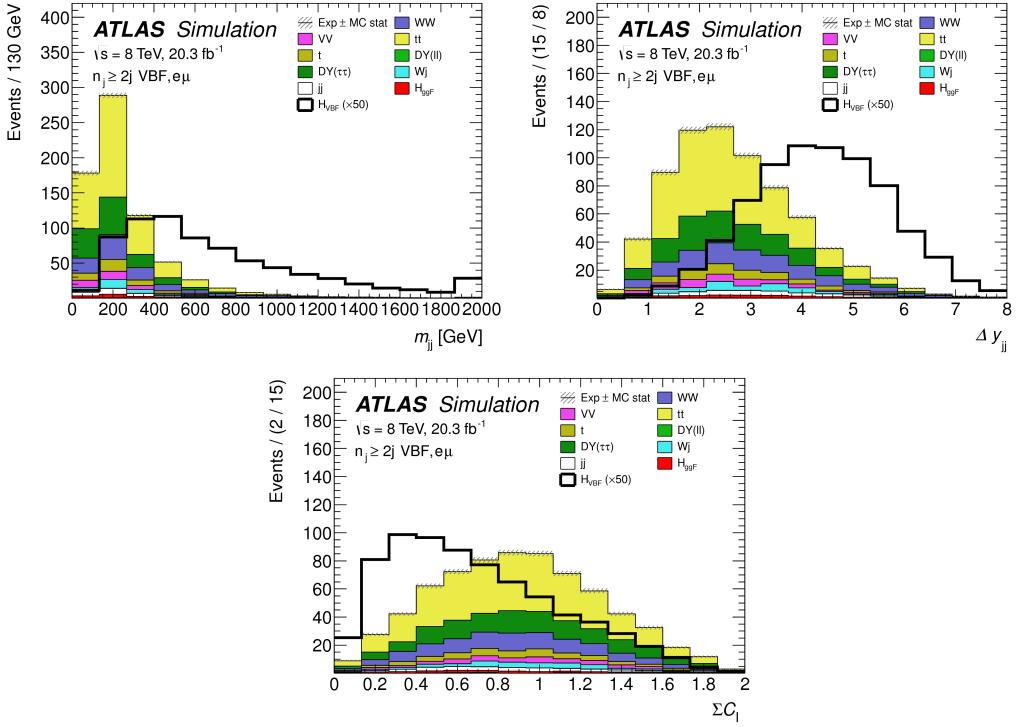


Figure 5.7: Distributions of m_{jj} (top left), Δy_{jj} (top right), $\sum C_\ell$ (bottom), VBF topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [62].

1862 5.5 BACKGROUND ESTIMATION

1863 This section describes the procedures used to estimate backgrounds for the VBF analysis in both the
 1864 cut-based and BDT analyses.

1865 5.5.1 GENERAL STRATEGY

1866 Most of the backgrounds in the VBF analysis have shapes estimated from Monte Carlo simulation but
 1867 normalizations derived from control regions in data. In essence, a normalization factor (denoted with β
 1868 or abbreviated as NF) is derived by scaling the MC yield in the control region to the corresponding yield
 1869 in data. Once this factor is derived, it can be used to scale the MC estimate of the background in the signal

1870 region. This is illustrated in equation 5.3.

$$B_{\text{SR}}^{\text{est}} = B_{\text{SR}} \times \frac{N_{\text{CR}}}{B_{\text{CR}}} \equiv B_{\text{SR}} \times \beta \quad (5.3)$$

1871 Here, B denotes the MC yield prediction in the denoted region, while N denotes the observed number of
1872 events in data in the denoted region.

1873 Another way of writing the same equation, in terms of an extrapolation factor α rather than a normal-
1874 ization factor β . The overall calculation is exactly the same. However, when phrased in this way, it shows
1875 how the uncertainty on the background estimation can be reduced. This is shown in equation 5.4.

$$B_{\text{SR}}^{\text{est}} = N_{\text{CR}} \times \frac{B_{\text{SR}}}{B_{\text{CR}}} \equiv N_{\text{CR}} \times \alpha \quad (5.4)$$

1876 Phrased this way, the equation shows that with enough statistics in the control region, a large theoretical
1877 uncertainty on the overall background yield in the signal region can be replaced by a small statistical un-
1878 certainty coming from the number of data events in the CR and a smaller theoretical uncertainty on the
1879 extrapolation from the control region to the signal region.

1880 5.5.2 TOP BACKGROUND

1881 The normalization factor β_t for the top background in the VBF analysis is derived in a region required
1882 to have one b-tagged jet, or $n_b = 1$. In the cut-based analysis, normalization factors are computed at every
1883 stage of the cutflow by applying the appropriate cuts in the CR. These NF are then applied to the $t\bar{t}$ and
1884 single top event yields in the SR. In the BDT analysis, a single normalization factor is computed for each
1885 bin of O_{BDT} after applying the BDT pre-training cuts described previously. The computed normaliza-
1886 tion factors are derived with all flavor combinations combined in order to decrease statistical uncertainty.
1887 Additionally, in the BDT analysis, BDT bins 2 and 3 are merged for the same reason.

1888 Table 5.9 shows the evolution of the β_t through the cut-based selection. Table 5.10 shows the value of
1889 the β_t in each bin of O_{BDT} . In all cases, the computed factors are relatively consistent with unity, with
1890 the largest discrepancy coming in bin 1 of O_{BDT} . The normalization factors in the bins of O_{BDT} are also

1891 consistent with those derived in teh cut-based sisgnal region, increasing confidence in the BDT estimation.

Cut	β_t
$p_T^{\text{sum}} < 15 \text{ GeV}$	1.03 ± 0.01
$m_{\tau\tau} < m_Z - 25$	1.05 ± 0.01
$m_{jj} > 600 \text{ GeV}$	0.96 ± 0.06
$\Delta y_{jj} > 3.6$	1.02 ± 0.08
CJV	1.13 ± 0.16
OLV	1.01 ± 0.19
$m_{jj} < 1 \text{ TeV}$	0.94 ± 0.19
$m_{jj} > 1 \text{ TeV}$	1.48 ± 0.66

Table 5.9: Top normalization factors computed at each stage of the cut-based selection. Uncertainties are statistical only.

O_{BDT}	β_t
Bin0	1.09 ± 0.02
Bin1	1.58 ± 0.15
Bin2	0.95 ± 0.31
Bin3	0.95 ± 0.31

Table 5.10: Top normalization factors computed for each bin of O_{BDT} . Uncertainties are statistical only.

1892 Figure 5.8 shows the m_{jj} and O_{BDT} distributions in the top control region. Overall the modeling looks
1893 consistent with the data.

1894 While these normalization factors can be computed and applied to the expected background yields listed
1895 in tables like table ??, in the end the normalization of the top background is profiled (meaning there is a
1896 dedicated Poisson constraint) and allowed to float in the final statistical fit.

1897 5.5.3 $Z/\gamma^* \rightarrow \tau\tau$ BACKGROUND

1898 In the different flavor channels, the $Z/\gamma^* \rightarrow \tau\tau$ background is an important one. Di-tau production
1899 can produce an $e\mu$ final state if each τ lepton decays to a different flavor lepton.

1900 In the BDT analysis, a single normalization factor for the background is derived. A control region
1901 is defined using the pre-training selection cuts, except requiring that $|m_{\tau\tau} - m_Z| < 25 \text{ GeV}$ so that
1902 the region is enriched in $Z/\gamma^* \rightarrow \tau\tau$ background. Additional requirements of $m_{\ell\ell} < 80(75) \text{ GeV}$

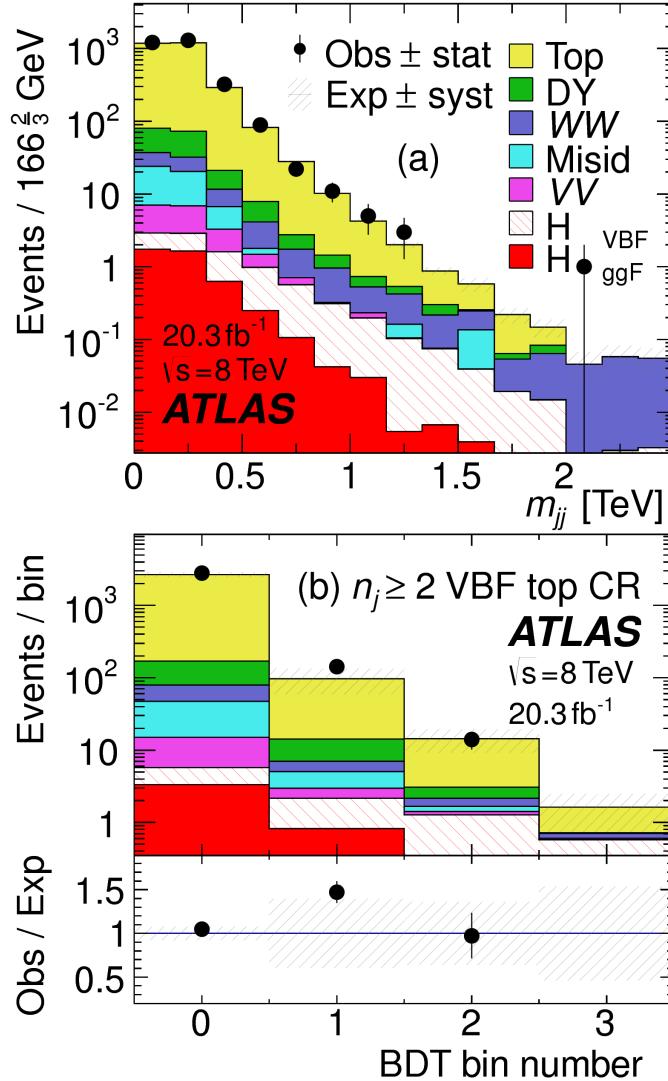


Figure 5.8: Distributions of m_{jj} (a) and O_{BDT} (b) in the VBF $n_b = 1$ top CR [62].

in the different (same) flavor channel, as well as $O_{\text{BDT}} > -0.48$ are applied to increase the purity of the region. The final $\beta_{Z/\gamma^* \rightarrow \tau\tau}$ is calculated to be 0.9 ± 0.3 (statistical uncertainty only). Because of the small contribution of this background in the BDT analysis and the large statistical uncertainty, no additional systematics are calculated. The final SR estimate is scaled by this β and not allowed to float in the fit.

The cut-based corrections are a bit more involved because they need to be applied selection by selection, as well as in the final signal region for the fit. The region is defined including all SR cuts up to the $Z/\gamma^* \rightarrow \tau\tau$ veto, which is instead made into a Z mass peak requirement as for the BDT region. The $m_{\ell\ell}$ cut from

1910 the BDT region is included as well. The cut-based approach aims to correct the normalization of the
 1911 $Z/\gamma^* \rightarrow \tau\tau$ background in two ways. First, an overall normalization factor is computed from the control
 1912 region. However, the VBF topological cuts are not included in this region, and applying them as is done in
 1913 the top CR is not feasible due to limited statistics. So, instead, correction factors (CF) to the cut efficiencies
 1914 of the VBF cuts are derived in a same flavor $Z \rightarrow \ell\ell$ control region, which has significantly more statistics.
 1915 The CF is simply the ratio of the cut efficiencies in data and MC derived in this region. In the end, the
 1916 overall background estimate is given by equation 5.5.

$$N_{Z/\gamma^* \rightarrow \tau\tau}^{\text{est}} = B_{Z/\gamma^* \rightarrow \tau\tau}^{\text{SR}} \times \beta_{\tau\tau} \times \frac{\epsilon_{\text{VBF cuts}}^{\text{data}}}{\epsilon_{\text{VBF cuts}}^{\text{MC}}} \quad (5.5)$$

1917 The hypothesis is that while the normalization correction must be derived in a dedicated region, the ef-
 1918 ficiency of the VBF cuts should not be sensitive to the type of Z/γ^* process and thus the larger control
 1919 region can be exploited to derive the CF. Figure 5.9 shows a shape comparison for the m_{jj} variable in
 1920 $Z \rightarrow \tau\tau$ events in the signal region and $Z \rightarrow \ell\ell$ events in the control region. The figure shows that the
 1921 shapes are indeed comparable and thus any CF derived in the same flavor control region can reliably be
 1922 applied in the signal region.

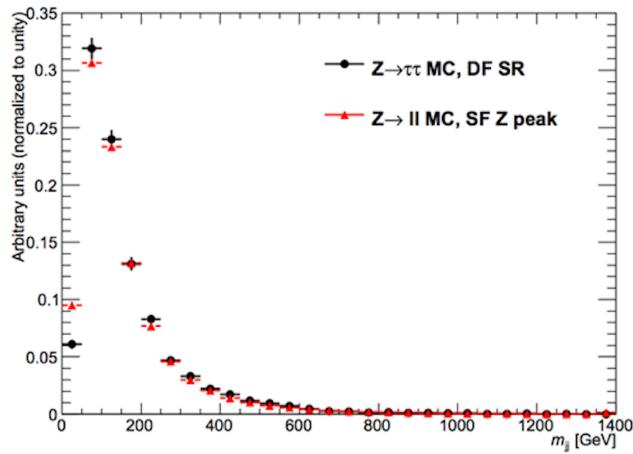


Figure 5.9: Comparison of m_{jj} shape in a same flavor $Z \rightarrow \ell\ell$ control region and the VBF cut-based signal region.

1923 Table 5.11 shows the overall normalization factor $\beta_{\tau\tau}$ and the efficiency correction factors for the various
 1924 VBF topological cuts. In general, the statistical uncertainties on the cut efficiency corrections are quite

₁₉₂₅ good, and the MC tends to underestimate the efficiency of the VBF cuts for the $Z/\gamma^* \rightarrow \tau\tau$ background.
₁₉₂₆ The overall normalization factor is also consistent with that calculated for the BDT analysis.

$\beta_{\tau\tau}$	0.97 ± 0.04
Cut	Correction factors
$m_{jj} > 600 \text{ GeV}$	1.09 ± 0.01
$\Delta y_{jj} > 3.6$	1.14 ± 0.02
CJV	1.20 ± 0.02
OLV	1.17 ± 0.03
$m_{jj} < 1 \text{ TeV}$	1.17 ± 0.06
$m_{jj} > 1 \text{ TeV}$	1.18 ± 0.13

Table 5.II: $Z/\gamma^* \rightarrow \tau\tau$ correction factors for the VBF cut-based analysis. Uncertainties are statistical only.

₁₉₂₇ **5.5.4 $Z/\gamma^* \rightarrow \ell\ell$ BACKGROUND**

₁₉₂₈ In the same flavor channels, the $Z/\gamma^* \rightarrow \ell\ell$ background is dominant and thus must be estimated cor-
₁₉₂₉ rectly. In both the BDT and cut-based analyses, the background is estimated using the so-called “ABCD”
₁₉₃₀ method. The ABCD method creates four different regions by defining cuts on two variables. One of the
₁₉₃₁ regions (A) is the signal region, while the other regions are defined by inverting one of both of the cuts.
₁₉₃₂ in this case, the two variables used are $m_{\ell\ell}$ and E_T^{miss} , because inverting either of the SR cuts on these
₁₉₃₃ variables will give regions rich in the $Z/\gamma^* \rightarrow \ell\ell$ background. Figure 5.10 illustrates the general strategy
₁₉₃₄ for each region.

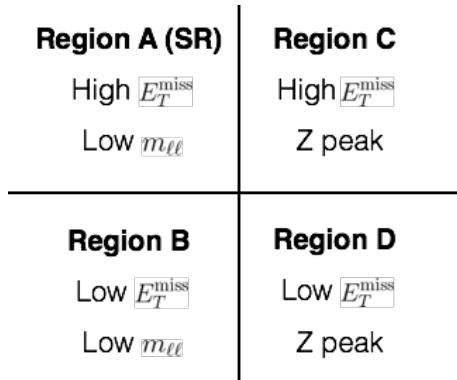


Figure 5.10: General illustration of the ABCD region definitions for $Z/\gamma^* \rightarrow \ell\ell$ background estimation.

₁₉₃₅ In both of the cut-based and BDT analyses, the Z peak region is defined with $|m_{\ell\ell} - m_Z| < 15 \text{ GeV}$.

1936 In the cut-based analysis, low $m_{\ell\ell}$ corresponds to $m_{\ell\ell} < 50$ GeV (this defines the cut-based SR) while
 1937 in the BDT it is $m_{\ell\ell} < 75$ GeV. In the cut-based, high and low E_T^{miss} are defined as opposite ends of
 1938 the 55 GeV cut applied for the signal region definition. The BDT low E_T^{miss} region is between 25 and
 1939 45 GeV, while the high E_T^{miss} region is $E_T^{\text{miss}} > 45$ GeV.

1940 Once the regions are defined, the final signal region background estimate is done by taking the estimate
 1941 in region B and extrapolating it to the signal region (A) by multiplying it by the ratio of regions C and
 1942 D. Effectively, the Z peak region is used to estimate the efficiency of the E_T^{miss} cut in data, and then this
 1943 efficiency is applied in the low $m_{\ell\ell}$ region. An additional correction is also applied for the non-closure of
 1944 the method in MC. This is summarized in equations 5.6 and 5.7.

$$N_{Z/\gamma^* \rightarrow \ell\ell}^{\text{SR}} = N_{Z/\gamma^* \rightarrow \ell\ell}^B \times \frac{N_{Z/\gamma^* \rightarrow \ell\ell}^C}{N_{Z/\gamma^* \rightarrow \ell\ell}^D} \times f_{\text{corr}} \quad (5.6)$$

$$f_{\text{corr}} = \frac{B_{\text{MC}}^A / B_{\text{MC}}^B}{B_{\text{MC}}^C / B_{\text{MC}}^D} \quad (5.7)$$

1945 Here, the N refer to data yields in each region with the non Z/γ^* backgrounds subtracted, while B
 1946 refer to the Z/γ^* yields in MC in each region.

1947 A normalization factor $\beta_{\ell\ell}$ is computed for each analysis as the ratio of the predicted data yield to the
 1948 MC yield in the SR. The shape of the BDT distribution is taken from data region B, while the shape of
 1949 the m_T distribution in the cut-based analysis is taken from Z/γ^* MC in the SR. The values of the $\beta_{\ell\ell}$ in
 1950 the cut-based and BDT analyses from this method are summarized in table 5.12. They are quite consistent
 1951 with one another within the statistical uncertainties. In the cut-based analysis, the same cut efficiency
 1952 correction factors shown in table 5.11 are also applied (in product with the $\beta_{\ell\ell}$) in the same flavor channels
 1953 to this background, as they were derived in the Z peak region.

	$\beta_{\ell\ell}$
BDT Bin 1	1.01 ± 0.15
BDT Bin 2	0.89 ± 0.28
Cut-based	0.81 ± 0.21

Table 5.12: $Z/\gamma^* \rightarrow \ell\ell$ normalization factors for cut-based and BDT analyses. Uncertainties are statistical only.

1954 5.5.5 WW AND OTHER DIBOSON BACKGROUNDS

1955 The WW and other diboson backgrounds have both their shape and normalization taken from MC
1956 simulation. They are validated in dedicated control regions and found to agree with data well.

1957 As WW is the largest of these backgrounds and is irreducible, validating the estimate is of particular
1958 importance. The validation region is constructed by requiring the pre-selection cuts on leptons and $m_{\ell\ell}$,
1959 $n_b = 0$, and $m_T > 100$ GeV. The m_{T2} variable [82] is an additional discriminant that will isolate
1960 the WW background, and a requirement of $m_{T2} > 160$ GeV is placed to define the WW validation
1961 region. This cut gives a 60% purity for the validation region. The derived normalization factor in the
1962 region is 1.15 ± 0.19 and is thus consistent with unity. Figure 5.11 shows the m_{T2} distribution and how it
1963 distinguishes the WW background.

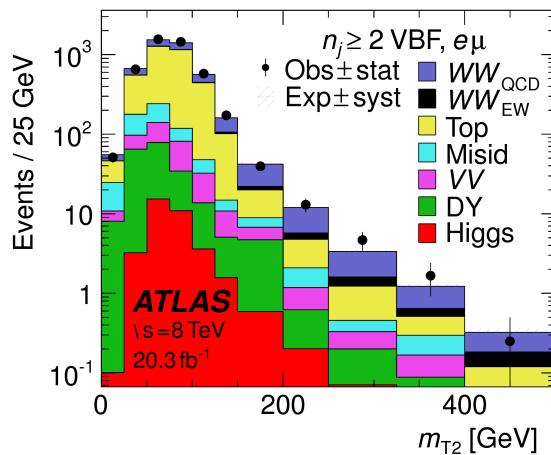


Figure 5.11: Distribution of m_{T2} in the WW validation region of the VBF analysis [62].

1964 5.5.6 HIGGS PRODUCTION VIA GLUON-GLUON FUSION

1965 Because this analysis is dedicated to measuring the VBF contribution to Higgs production, the compo-
1966 nent of Higgs production from gluon-gluon fusion is treated as a background. The shape is taken directly
1967 from simulation, using the generators described in table 5.4. In the final combined fit of all different signal
1968 regions, the normalization is controlled by either a combined signal strength parameter μ , which controls
1969 the normalization of both ggF and VBF production, or a separate parameter μ_{ggF} depending on the in-

1970 terpretation being presented in the final results.

1971 5.5.7 BACKGROUNDS WITH MISIDENTIFIED LEPTONS

1972 As discussed previously, the $W + \text{jets}$ and QCD multijet backgrounds are derived with fully data-driven
1973 methods. These backgrounds do not make a large contribution to the final VBF signal region but their
1974 estimation methods are discussed briefly here.

1975 $W + \text{jets}$ BACKGROUND

1976 The $W + \text{jets}$ background enters the signal region by having one of the jets mis-reconstructed as a lep-
1977 ton. The background is estimated by constructing a control sample with two leptons, where one lepton
1978 passes the usual lepton quality cuts but the second lepton fails one of those cuts (also known as the “anti-
1979 identified” lepton). This control region is rich in the $W + \text{jets}$ contribution because if a second lepton is
1980 reconstructed in a $W + \text{jets}$ event it is likely to be poor quality. The purity of this $W + \text{jets}$ control sample is
1981 85% to 90% depending on the exact configuration of leptons in the final state.

1982 The signal region estimate of $W + \text{jets}$ is estimated by extrapolation from the control sample to the sig-
1983 nal region using extrapolation factors derived in a $Z + \text{jets}$ control sample in data. The extrapolation factor
1984 is the ratio of the number of lepton candidates satisfying all quality criteria to the number of lepton can-
1985 didates anti-identified. This ratio is measured in bins of p_T and η . Thus, the final signal region estimate
1986 (binned as the extrapolation factor is binned) is simply the number of events in the anti-identified lepton
1987 control sample multiplied by the extrapolation factor derived from the $Z + \text{jets}$ control sample. Figure 5.12
1988 shows the extrapolation factors derived for electrons and muons.

1989 QCD MULTIJET BACKGROUND

1990 The method for estimating the multijet background is very similar to the $W + \text{jets}$ estimation method.
1991 The control sample in this case has two anti-identified leptons but otherwise satisfies all signal region re-
1992 quirements. The extrapolation factor is estimated from a multijet sample and applied twice to the control
1993 sample.

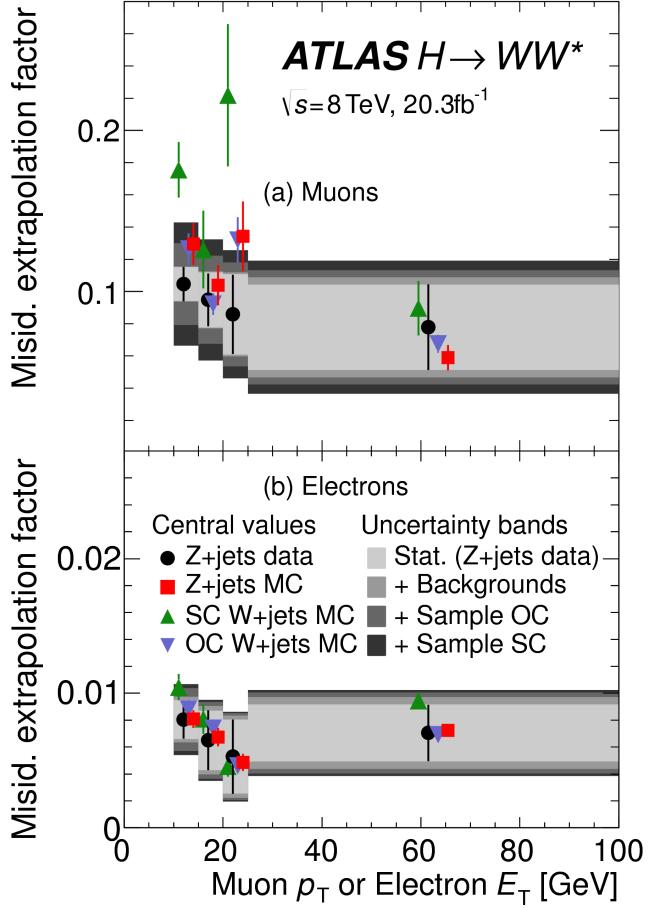


Figure 5.12: Extrapolation factors for the $W+jets$ estimate derived for muons (a) and electrons (b) as a function of lepton p_T [62].

1994 5.5.8 BACKGROUND COMPOSITION IN FINAL SIGNAL REGION

1995 After all of these estimation procedures, the final signal region composition can be calculated. The esti-
 1996 mated yields are all shown in table ???. Figure 5.13 shows the relative percentages of the different background
 1997 for the different flavor and same flavor final states. In $e\mu$, the leading backgrounds are top backgrounds,
 1998 ggF Higgs, and SM WW production. In $ee/\mu\mu$, the leading background is Drell-Yan, followed by top
 1999 and ggF Higgs.

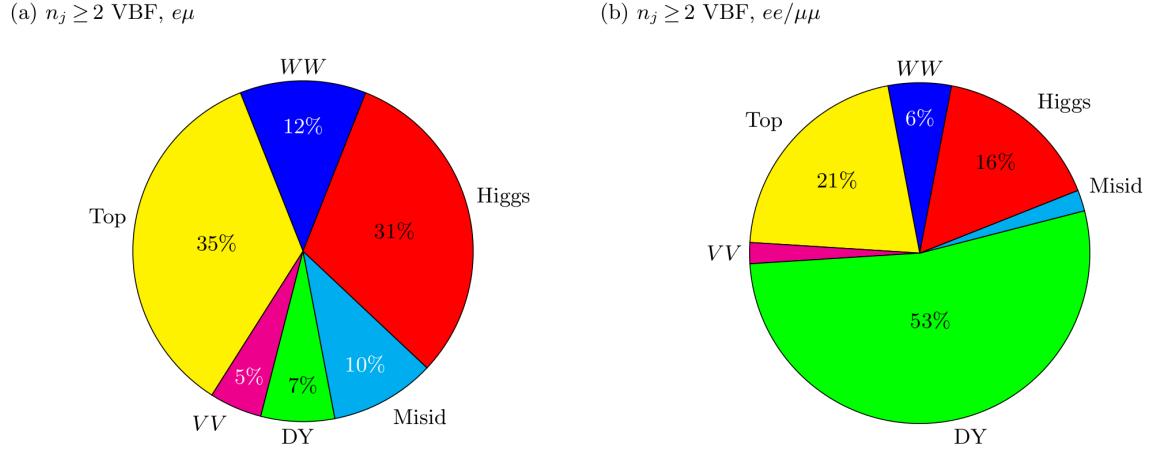


Figure 5.13: Background composition in final VBF signal region [62].

5.6 SYSTEMATIC UNCERTAINTIES

There are two main types of systematic uncertainties that are assessed for the analysis. First, theoretical uncertainties associated with the various signal and background yield estimates are discussed. Then, experimental uncertainties due to detector effects are shown. Normalization uncertainties refer to uncertainties that affect the cross section of the process in question in the signal region being probed. Shape uncertainties refer to systematic uncertainties that affect the shape of the final discriminating variable (either m_T or O_{BDT}).

5.6.1 THEORETICAL UNCERTAINTIES

There are four main components to theoretical uncertainties assigned to signal and background processes taken from Monte Carlo. Each one is a different source of variation in the overall acceptance for that process. The first involves variation of the QCD renormalization and factorization scales used in the calculation. In this case, the two scales are varied independently and simultaneously by factors of two high or low and quantifying the resulting variation in normalization and shape for the process. This approximates the correction to the cross section that would come from including the next order of the QCD calculation (referred to as scale uncertainty). Next, there is an uncertainty associated with the PDF set used in generating the events. The uncertainty eigenvectors for the given PDF set are studied, and the en-

2016 envelope of maximal variation is taken as an uncertainty. Finally, there are two uncertainties associated with
 2017 the choice of MC software (referred to as PDF uncertainty). An uncertainty associated with the generator
 2018 chosen for the hard scattering process is evaluated by keeping the parton showering software constant but
 2019 varying the matrix element generator and taking the maximal variation as an uncertainty (referred to as
 2020 the generator uncertainty). The converse variation can also be done, where the matrix element generator
 2021 remains constant and the generator used for the underlying event/parton shower modeling is varied (re-
 2022 ferred to as the UE/PS uncertainty). In cases where the background is normalized in a control region, the
 2023 systematic uncertainty arises from variations of the extrapolation factor α between the CR and the SR,
 2024 which can affect the normalization of the background in the SR.

2025 There are two additional uncertainties that are applied to the Higgs processes as well. First, there are
 2026 uncertainties assigned to the Higgs total production cross section. Then, there are uncertainties assigned
 2027 based on the fact that the analysis is done in exclusive jet bins and it is possible for signal events to migrate
 2028 from one bin to the next depending on the presence or absence of jets. These are assigned using the Jet
 2029 Veto Efficiency (JVE) procedure [18, 83] for ggF events and the Stewart-Tackmann (ST) method [84] for
 2030 VBF production.

2031 Table 5.13 shows the total theory uncertainties on the backgrounds in the cut-based analysis. These are
 2032 the sum in quadrature of the uncertainties from each of the variations described above.

Process	Theory syst. (%)
ggF H	48
Top	26
QCD WW	37
$Z/\gamma^* \rightarrow \tau\tau$	6.1

Table 5.13: Systematic uncertainties for various processes in the cut-based VBF analysis, given in units of % change
in yield. Values are given for the low m_{jj} signal region.

2033 Figures 5.14 and 5.15 show the variations in the extrapolation factor from the PDF and QCD uncertain-
 2034 ties on the top background estimate, binned in m_T , for the cut-based analysis. In both cases, there was
 2035 no significant shape uncertainty but normalization uncertainties were assigned according to the maximal
 2036 variation. These uncertainties enter into the 26% total uncertainty on top quoted in table 5.13

2037 While the estimate for the same-flavor $Z/\gamma^* \rightarrow \ell\ell$ background is data-driven, there is still a systematic
 2038 uncertainty taken for the non-closure of the method in Monte Carlo. This is taken as the maximum of the
 2039 deviation of the non-closure factor f_{corr} from unity and its uncertainty, or $\max(|1 - f_{\text{corr}}|, \delta f_{\text{corr}})$. For
 2040 the cut-based analysis this non-closure uncertainty 23%, while for the BDT analysis it is 17%.

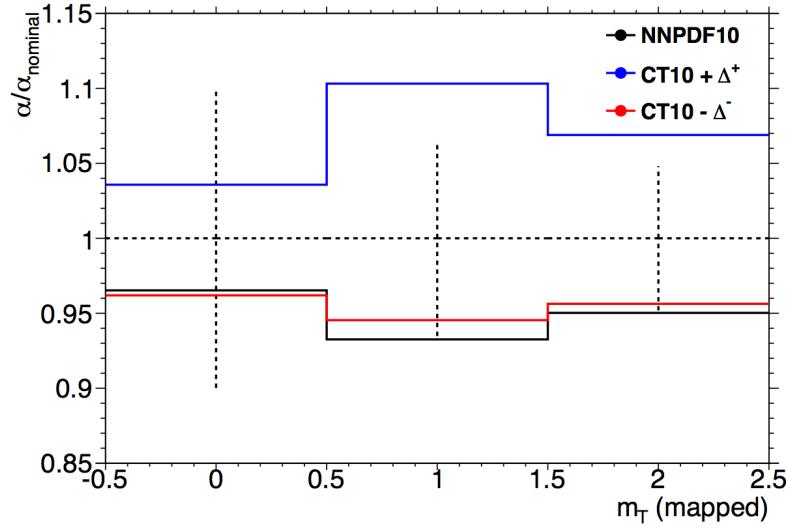


Figure 5.14: Variations in the top background extrapolation factor in the cut-based analysis due to PDF uncertainties, binned in m_T .

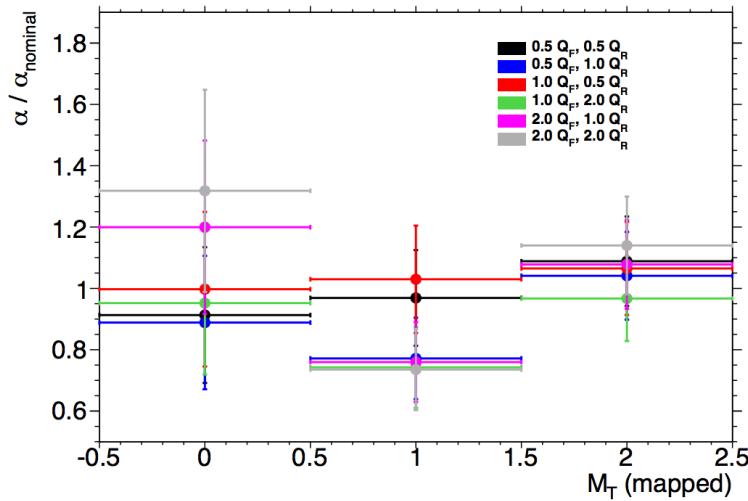


Figure 5.15: Variations in the top background extrapolation factor in the cut-based analysis due to QCD scale uncertainties, binned in m_T .

2041 5.6.2 EXPERIMENTAL UNCERTAINTIES

2042 In this analysis, the theoretical uncertainties end up being the most dominant, but there are some ex-
2043 perimental uncertainties that make a contribution as well. The first is the uncertainty on the measured
2044 integrated luminosity, which affects backgrounds whose normalization is taken from MC and is measured
2045 to be 2.8% in the 8 TeV dataset [85]. The dominant sources of uncertainty overall are uncertainties on the
2046 jet energy scale and resolution and the b -tagging efficiency. Additional sources include lepton uncertain-
2047 ties on identification, resolution, and trigger efficiency, as well as uncertainties on the missing transverse
2048 momentum .

2049 The jet energy scale uncertainty is split into several independent components, including jet-flavor de-
2050 pending calorimeter response uncertainties, uncertainties on modeling of pile-up interactions, uncertain-
2051 ties on extrapolation from the central to forward detector regions, and MC non-closure [86]. The uncer-
2052 tainty on energy scale for jets used in this analysis ranges from 1% to 7% depending on the jet p_T and η .
2053 The jet energy resolution varies from 5% to 20%, with uncertainties ranging from 2% to 40% (the largest
2054 uncertainties occurring at the selection threshold).

2055 The b -tagging efficiency is independently measured in data samples enriched in dileptonic decays of $t\bar{t}$
2056 events or in events where a muon is reconstructed in the vicinity of a jet [87, 88]. The efficiencies and
2057 their uncertainties are binned in p_T and decomposed into uncorrelated components using an eigenvector
2058 method [89]. Uncertainties on the efficiency range from 1% to 7.8%. The uncertainty on the rate of
2059 misidentification of c -jets as b -jets ranges from 6-14%, while the uncertainty on the rate of light jet mis-
2060 tagging ranges from 9-19% depending on p_T and η .

2061 The total experimental uncertainties on different signal and background components are summarized
2062 in table 5.14. They are compared to the level of other statistical and systematic uncertainties as well. Overall,
2063 the experimental uncertainties are sub-dominant compared to the statistical and theoretical uncertainties.

2064 5.7 RESULTS

2065 While the combined results of all the $H \rightarrow WW^*$ sub-analyses will be discussed in the next chapter,
2066 this section presents the results of the VBF specific analysis and interpretations. As table ?? shows, the final

Sample	Total error	Stat. error	Expt. syst. err.	Theo. syst. err.
$n_j \geq 2$ VBF-enriched				
N_{sig}	13	—	6.8	12
N_{bkg}	9.2	4.7	6.4	4.5
N_{WW}	32	—	14	28
N_{top}	15	9.6	7.6	8.5
N_{misid}	22	—	12	19
N_{VV}	20	—	12	15
$N_{\tau\tau}$ (DY)	40	25	31	2.9
$N_{ee/\mu\mu}$ (DY)	19	11	15	—

Table 5.14: Composition of the post-fit uncertainties (in %) on the total signal (N_{sig}), total background (N_{bkg}), and individual background yields in the VBF analysis [62].

2067 cut-based signal region contains 20 events in data with $m_T < 150$ GeV, 14 coming from the $e\mu$ channel
 2068 and 6 coming from the $ee + \mu\mu$ channel. The BDT analysis has many more candidates due to its looser
 2069 selection, and the yields in each bin of O_{BDT} are shown in table 5.15.

(a) Before the BDT classification

Selection	Summary						Composition of N_{bkg}									
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{signal}			N_{WW}^{QCD}	N_{WW}^{EW}	N_{tt}	N_t	N_{Wj}	N_{jj}	N_{VV}	Drell-Yan		
				N_{ggF}	N_{VBF}	N_{VH}								$N_{ee/\mu\mu}$	$N_{\tau\tau}^{\text{QCD}}$	$N_{\tau\tau}^{\text{EW}}$
$e\mu$ sample	1.04 ± 0.04	718	689	13	15	2.0	90	11	327	42	29	23	31	2.2	130	2
$ee/\mu\mu$ sample	1.18 ± 0.08	469	397	6.0	7.7	0.9	37	3	132	17	5.2	1.2	10.1	168	23	1

(b) Bins in O_{BDT}

$e\mu$ sample																
Bin 0 (not used)	1.02 ± 0.04	661	650	8.8	3.0	1.9	83	9	313	40	26	21	28	2.2	126	1
Bin 1	0.99 ± 0.16	37	37	3.0	4.2	0.1	5.0	1.0	17	3.1	3.3	1.8	2.6	—	4.0	0.2
Bin 2	2.26 ± 0.63	14	6.2	1.2	4.2	—	1.5	0.5	1.8	0.3	0.4	0.3	0.8	—	0.3	0.3
Bin 3	5.41 ± 2.32	6	1.1	0.4	3.1	—	0.3	0.2	0.3	0.1	—	—	0.1	—	0.1	0.1
$ee/\mu\mu$ sample																
Bin 0 (not used)	1.91 ± 0.08	396	345	3.8	1.3	0.8	33	2	123	16	4.1	1.1	8.8	137	20.5	0.5
Bin 1	0.82 ± 0.14	53	45	1.5	2.2	0.1	3.0	0.5	10.4	1.8	0.8	0.2	0.9	26	1.7	0.1
Bin 2	1.77 ± 0.49	14	7.9	0.6	2.5	—	0.8	0.3	1.1	0.2	0.2	—	0.3	4.4	0.3	0.1
Bin 3	6.52 ± 2.87	6	0.9	0.2	1.7	—	0.1	0.2	0.2	—	—	—	—	0.7	—	—

Table 5.15: Event selection for the VBF BDT analysis. The event yields in (a) are shown after the pre-selection and the additional requirements applied before the BDT classification (see text). The event yields in (b) are given in bins in O_{BDT} after the classification [62].

2070 Figure 5.16(a) shows the final distribution of data candidates compared to the expected m_T distribution
 2071 for signal and background. The data are very consistent with a VBF Higgs hypothesis. Figure 5.16(b) shows

2072 where the data candidates fall in the two-dimensional binning of m_T and m_{jj} used in the fit for the cut-
 2073 based analysis.

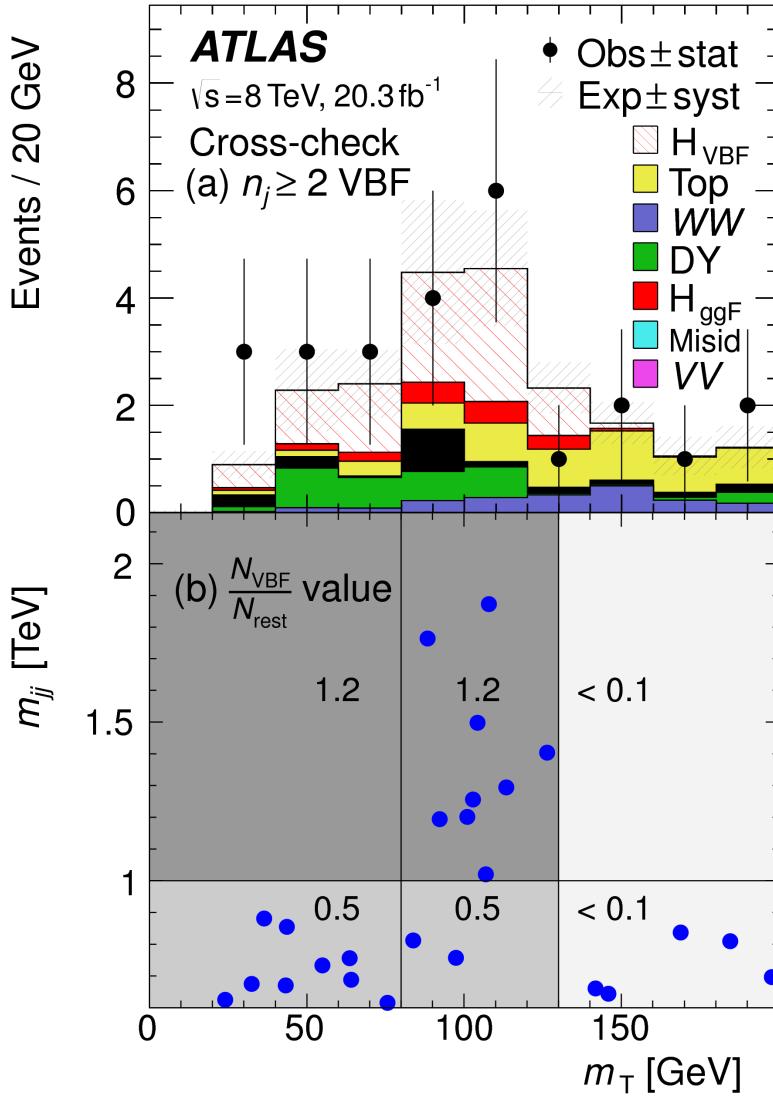


Figure 5.16: Post-fit distributions in the cut-based VBF analysis. Panel (a) shows the one-dimensional m_T distribution, while (b) shows the data candidates split into the bins of m_T and m_{jj} used in the final fit [62].

2074 Figure 5.17 shows the distributions of O_{BDT} and m_T in the VBF BDT analysis. Again the data are quite
 2075 consistent with a VBF Higgs hypothesis.

2076 Because the cut-based result is used as a validation for the BDT analysis and the two signal regions are
 2077 not fully orthogonal, it is interesting to explore which events overlap between the two analyses. Of the

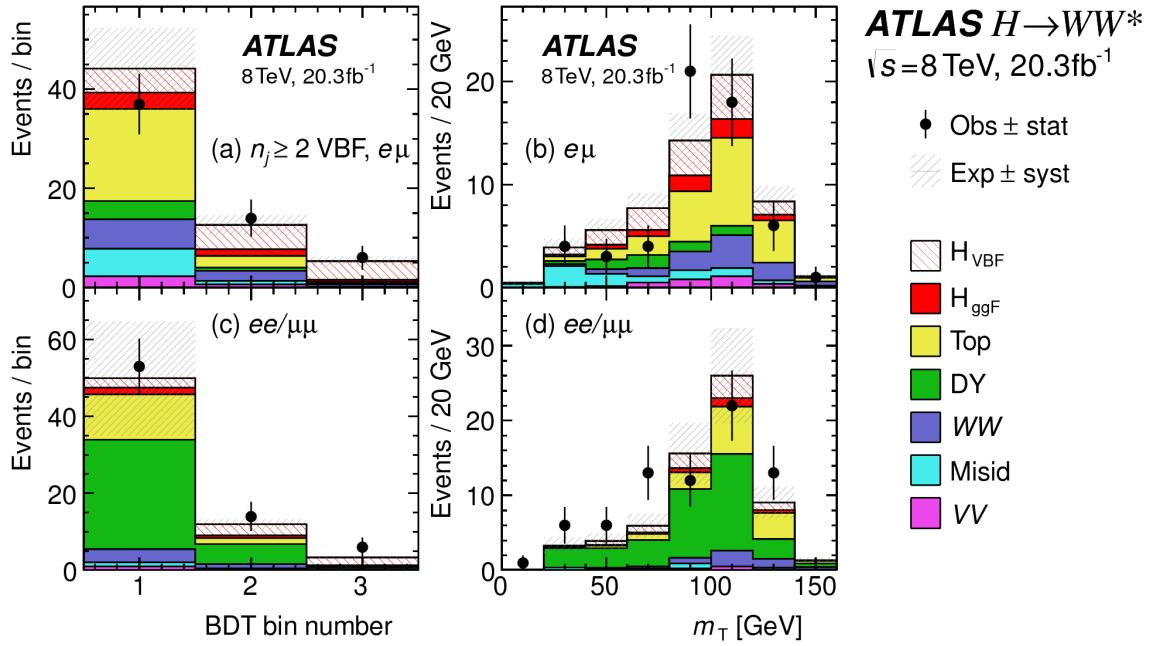


Figure 5.17: Postfit distributions in the BDT VBF analysis [62].

2078 twenty events in the cut-based signal region, only seven were not selected by the BDT analysis, while the
 2079 other thirteen also enter the BDT signal region. Figure 5.18 shows where the different analysis candidates
 2080 lie in the m_{jj} - m_T plane. This shows clearly that the advantage of the BDT analysis is that it can extract
 2081 signal candidates lower m_{jj} region due to its ability to recognize correlations with other variables.

2082 While the context of these results in the broader $H \rightarrow WW^*$ statistical analysis will be presented in
 2083 the next chapter, the significance of the VBF observation can be shown here. In the BDT analysis, the
 2084 expected signal significance was 2.7σ , while the observed significance was 3.1σ . In the cut-based analysis,
 2085 the expected significance was 2.1σ and the observed significance was 3.0σ . The compatibility between
 2086 these two results can be evaluated by computing the probability of observing a larger difference in Z_0 values
 2087 than the one measured. Using toy Monte Carlo with the ggF signal strength fixed to unity and considering
 2088 only statistical uncertainties, this probability is computed to be 79%, indicating good agreement between
 2089 the analyses. This result represents the first observation of the vector boson fusion production of a Higgs
 2090 boson.

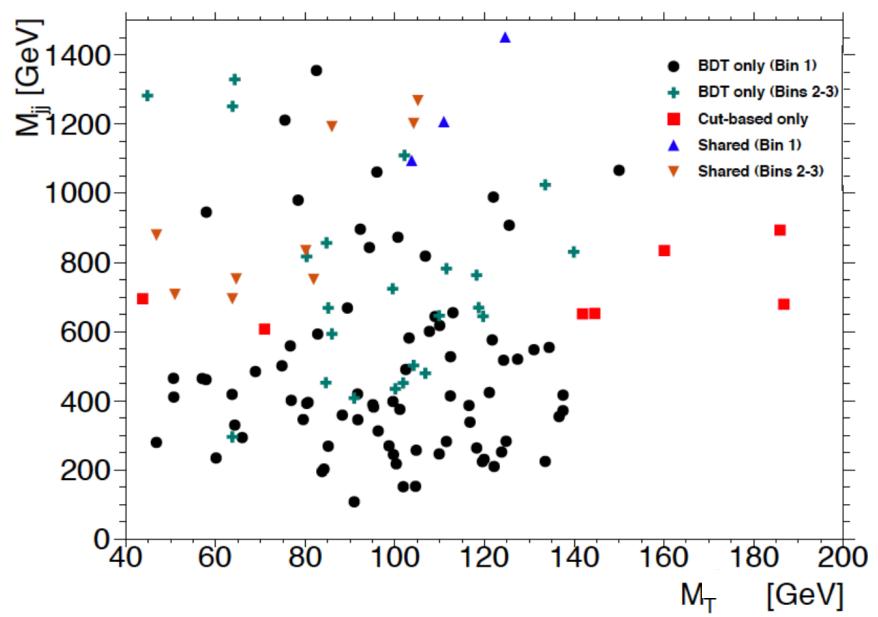


Figure 5.18: Overlap between cut-based and BDT VBF signal region candidates in the m_{jj} - m_T plane.

*The feeling is less like an ending than just another starting
point.*

Chuck Palahniuk

6

2091

2092

Combined Run I $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

2093

results

2094

6.1 INTRODUCTION

2095

In the final statistical analysis of $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, the dedicated gluon-gluon fusion and vector boson fusion sensitive signal regions are all combined into a single fit to determine the main parameters of interest, the Higgs signal strength μ and mass m_H . Therefore, while the specific requirements applied for the VBF sensitive analysis are discussed in chapter 5, the final measurement of these parameters can only be discussed in combination with the results of the ggF dedicated analysis. For example, because ggF Higgs production is considered a background in the VBF analysis, the ggF dedicated signal regions can actually constrain the normalization of this background in the VBF dedicated region.

2102

This chapter presents the combined interpretation of results in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis

SR category i			Fit var.
n_j , flavor	$\otimes m_{\ell\ell}$	$\otimes p_T^{\ell 2}$	
$n_j = 0$	$e\mu$	$\otimes [10, 30, 55]$	$\otimes [10, 15, 20, \infty]$
	$ee/\mu\mu$	$\otimes [12, 55]$	$\otimes [10, \infty]$
			m_T
$n_j = 1$	$e\mu$	$\otimes [10, 30, 55]$	$\otimes [10, 15, 20, \infty]$
	$ee/\mu\mu$	$\otimes [12, 55]$	$\otimes [10, \infty]$
			m_T
$n_j \geq 2$ ggF	$e\mu$	$\otimes [10, 55]$	$\otimes [10, \infty]$
$n_j \geq 2$ VBF	$e\mu$	$\otimes [10, 50]$	$\otimes [10, \infty]$
	$ee/\mu\mu$	$\otimes [12, 50]$	$\otimes [10, \infty]$
			O_{BDT}

Table 6.1: All signal regions definitions input into final statistical fit [62].

for gluon fusion and vector boson fusion Higgs production. First, the results of the dedicated gluon fusion search are presented. Then, a comparison of the individual production mode signal strengths (μ_{ggF} and μ_{VBF}) and a measurement of the combined signal strength (μ) are shown. Subsequently, the measured values of the Higgs couplings to fermions and vector bosons is presented. Finally, the cross section measurement for ggF and VBF production are shown.

6.2 RESULTS OF DEDICATION GLUON FUSION $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ SEARCH

The details of the dedicated gluon fusion $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ search are not discussed in this thesis and instead left to more comprehensive sources [62]. However, a brief summary of the results are essential for describing the results of the full analysis and interpreting the results of the dedicated VBF search in this broader context.

Table 6.1 shows the individual signal regions that were input into the final statistical fit. The ggF dedicated bins use m_T as their discriminating variable and are separated into bins of p_T of the subleading lepton as well. The VBF dedicated bin uses the O_{BDT} distribution as its final discriminant.

Table 6.2 shows the yields in the various signal regions in both data and expected signal and back-

2117 grounds. The yields for signal and background are all scaled according to the final normalizations cal-
2118 culated in the fit.

	N_{obs}	N_{bkg}	N_{ggF}	N_{VBF}
$n_j = 0$	3750	3430 ± 90	300 ± 50	8 ± 4
$n_j = 1$	1596	1470 ± 40	102 ± 26	17 ± 5
$n_j \geq 2, \text{ggF } e\mu$	1017	960 ± 40	37 ± 11	13 ± 1.4
$n_j \geq 2, \text{VBF}$	130	99 ± 9	7.7 ± 2.6	21 ± 3

Table 6.2: Post-fit yields in the different ggF and VBF dedicated signal regions [62].

2119 Figure 6.1 shows the final post-fit m_T distribution in the $n_j \leq 1$ regions. The data are very consistent with the hypothesis of ggF Higgs production. These yields are used as input, along with the VBF results

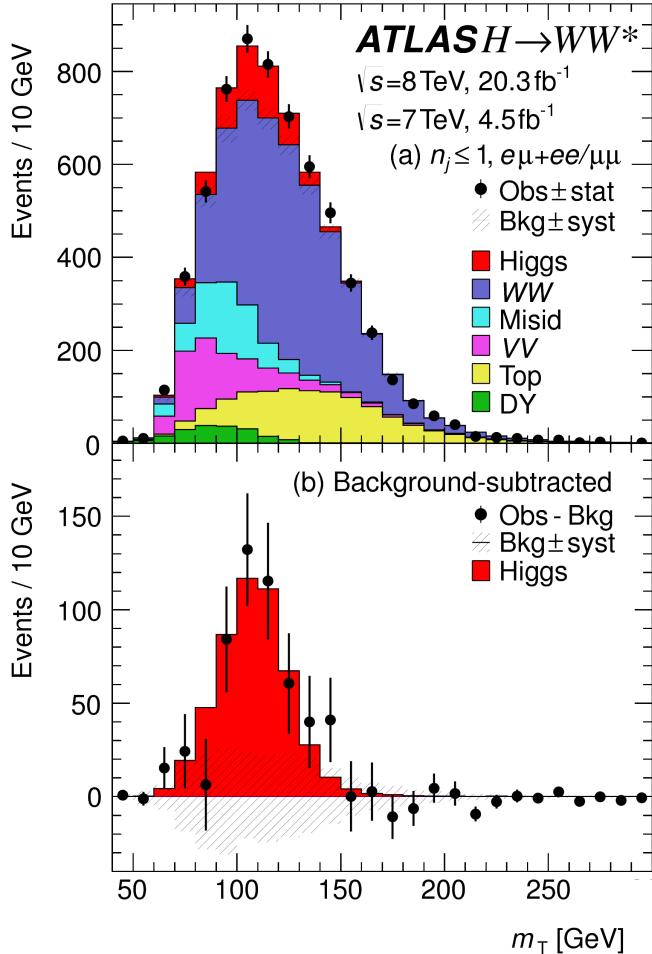


Figure 6.1: Post-fit m_T distribution in the $n_j \leq 1$ regions [62].

2120

2121 in chapter 5, for the physical interpretation of results presented in subsequent sections.

2122 **6.3 SIGNAL STRENGTH MEASUREMENTS IN ggF AND VBF PRODUCTION**

2123 When all of the signal regions are combined in the fit, there can be a combined measurement of the
 2124 signal strength as well as the individual ggF and VBF signal strengths. The combined signal strength is the
 2125 ratio of the sum of the gluon fusion and VBF cross sections to the theory prediction, or a signal strength
 2126 for the total Higgs production cross section that this analysis is sensitive to. The final measured combined
 2127 signal strength μ is measured shown in equation 6.1.

$$\begin{aligned} \mu &= 1.09 \quad {}^{+0.16}_{-0.15} \text{ (stat.)} \quad {}^{+0.08}_{-0.07} \left(\begin{array}{l} \text{expt} \\ \text{syst} \end{array} \right) \quad {}^{+0.15}_{-0.12} \left(\begin{array}{l} \text{theo} \\ \text{syst} \end{array} \right) \quad \pm 0.03 \left(\begin{array}{l} \text{lumi} \\ \text{syst} \end{array} \right) \\ &= 1.09 \quad {}^{+0.16}_{-0.15} \text{ (stat)} \quad {}^{+0.17}_{-0.14} \text{ (syst)} \\ &= 1.09 \quad {}^{+0.23}_{-0.21}. \end{aligned} \tag{6.1}$$

2128 Figure 6.2 gives the best fit signal strength $\hat{\mu}$ as a function of the hypothesized Higgs mass. The value
 2129 at 125.36 GeV corresponds to the μ quoted in equation 6.1. This value of the Higgs mass is used because it
 2130 is the most precise mass measurement from ATLAS, a result of the combined $\gamma\gamma$ and ZZ mass measure-
 2131 ments [90].

2132 As explained in chapter 3, a probability p_0 can be computed using the test statistic q_0 to quantify the
 2133 probability that the background could fluctuate to produce an excess at least as large as the one observed
 2134 in the data. The local p_0 value is shown in figure 6.3 as a function of m_H . The minimum p_0 value is at
 2135 $m_H = 130$ GeV and corresponds to a significance of 6.1σ . The curve is relatively flat and the significance
 2136 is the same at 125.36 GeV within the quoted precision. The expected significance for a signal with strength
 2137 $\mu = 1.0$ is 5.8σ . This represents the first discovery level significance measurement in the $H \rightarrow WW^* \rightarrow$
 2138 $\ell\nu\ell\nu$ analysis.

2139 All the results presented so far in this section have been for the combined gluon fusion and VBF pro-
 2140 duction modes. However, each signal strength can be calculated separately in the likelihood as well. There
 2141 are two ways to do this. First, the likelihood can be parameterized in terms of a single parameter, the ratio

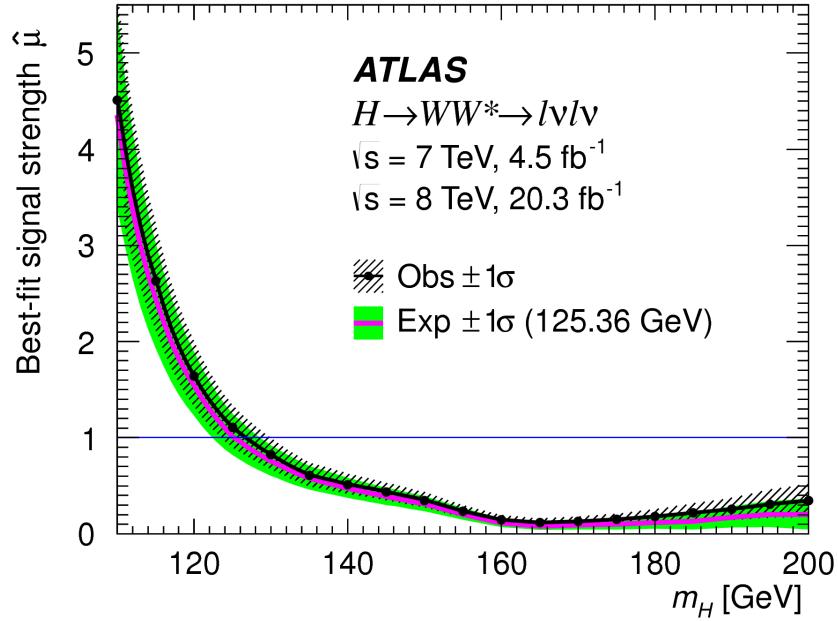


Figure 6.2: Best fit signal strength $\hat{\mu}$ as a function of hypothesized m_H [62].

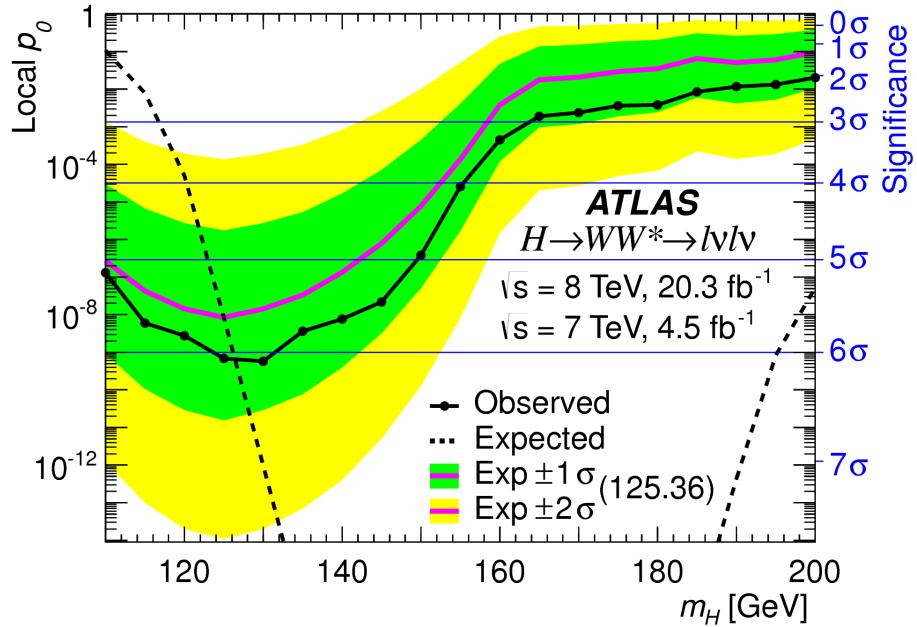


Figure 6.3: Local p_0 as a function of m_H [62].

²¹⁴² of the VBF and gluon fusion signal strengths. With this method, the significance of the VBF observation
²¹⁴³ can be evaluated. Figure 6.4 shows the likelihood as a function of the ratio $\mu_{\text{VBF}}/\mu_{\text{ggF}}$.

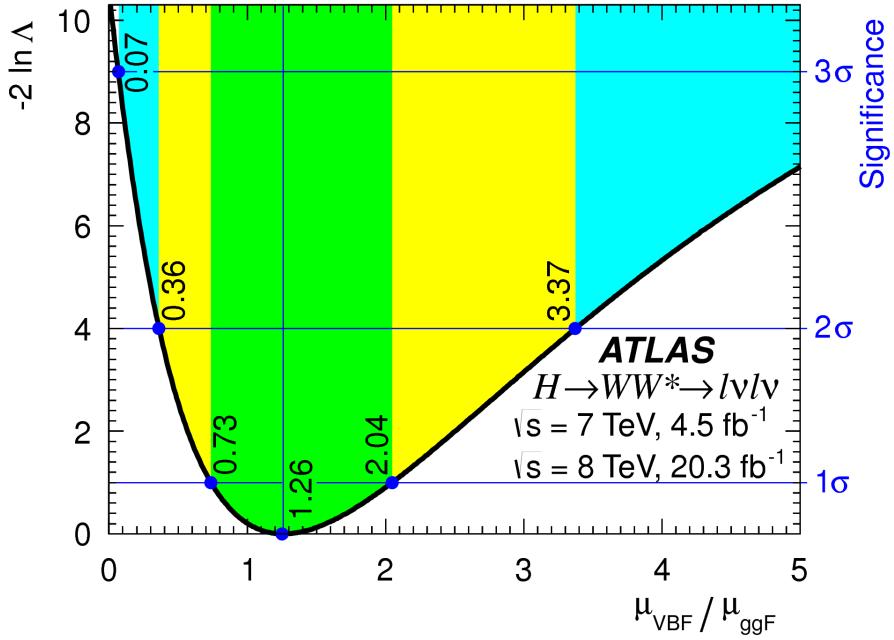


Figure 6.4: Likelihood as a function of $\mu_{\text{VBF}} / \mu_{\text{ggF}}$ [62].

2144 The best fit value of the ratio of signal strengths is shown in equation 6.2. Within the quoted uncer-
 2145 tainties, it is consistent with a ratio of unity.

$$\frac{\mu_{\text{VBF}}}{\mu_{\text{ggF}}} = 1.26^{+0.61} (\text{stat.})^{+0.50} (\text{syst.}) = 1.26^{+0.79}_{-0.53} \quad (6.2)$$

2146 The null hypothesis for VBF production corresponds to a ratio of $\mu_{\text{VBF}} / \mu_{\text{ggF}} = 0$. The likelihood in
 2147 figure 6.4 gives a significance of 3.2σ at $\mu_{\text{VBF}} / \mu_{\text{ggF}} = 0$, as quoted in chapter 5.

2148 In addition to the ratio of signal strengths, each signal strength can be varied independently in the like-
 2149 lihood as well. Figure 6.5 shows the two dimensional likelihood scan in the $\mu_{\text{ggF}}-\mu_{\text{VBF}}$ plane. The best fit
 2150 values of the two signal strengths are shown in equation 6.3. Both are consistent with unity within their
 2151 uncertainties.

$$\begin{aligned} \mu_{\text{ggF}} &= 1.02 \pm 0.19^{+0.22}_{-0.18} = 1.02^{+0.29}_{-0.26} \\ \mu_{\text{VBF}} &= 1.27 \pm 0.40^{+0.44}_{-0.21} = 1.27^{+0.53}_{-0.45}. \end{aligned} \quad (6.3)$$

(stat.) (syst.)

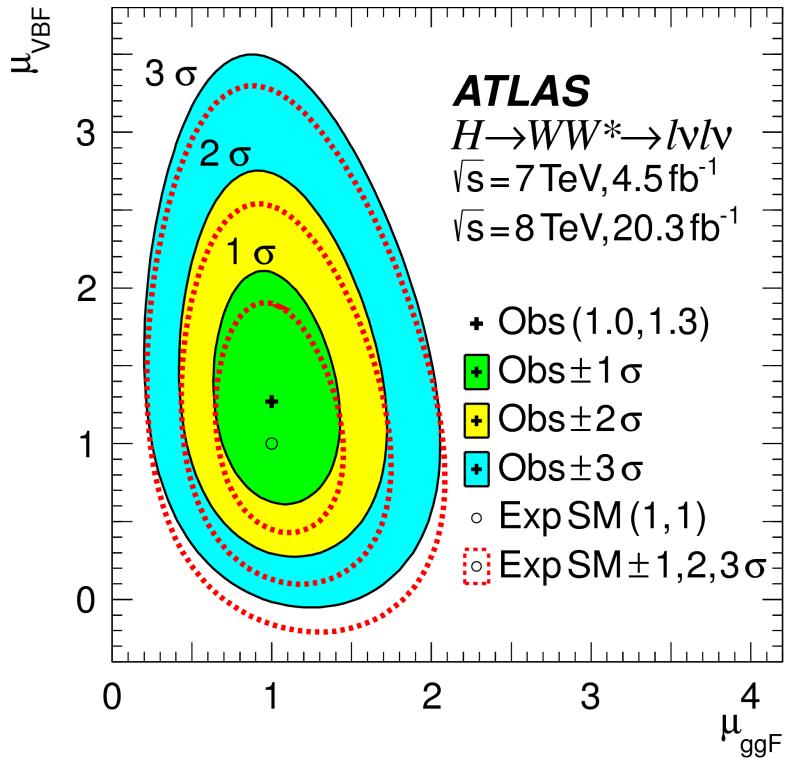


Figure 6.5: Likelihood scan as a function of μ_{VBF} and μ_{ggF} [62].

2152 6.4 MEASUREMENT OF HIGGS COUPLINGS TO VECTOR BOSONS AND FERMIONS

2153 Similar to the parameterization of signal strength, the couplings of the Higgs to fermions and bosons
 2154 can also be parameterized. The parameter of interest in this case is κ , or the ratio of the measured coupling
 2155 to the standard model expectation. Both the fermion and boson couplings have these so-called scale factors,
 2156 κ_F for fermions and κ_V for bosons. Gluon fusion production is sensitive to the fermion couplings through
 2157 the top quark loops in its production, while VBF production is sensitive to the vector boson couplings in
 2158 its production. Both modes are sensitive to the vector boson couplings in their decays. The signal strengths
 2159 will have dependence on the coupling scale factors as described in equation 6.4 [18].

$$\begin{aligned} \mu_{\text{ggF}} &\propto \frac{\kappa_F^2 \cdot \kappa_V^2}{(\mathcal{B}_{H \rightarrow f\bar{f}} + \mathcal{B}_{H \rightarrow gg}) \kappa_F^2 + (\mathcal{B}_{H \rightarrow VV}) \kappa_V^2} \\ \mu_{\text{VBF}} &\propto \frac{\kappa_V^4}{(\mathcal{B}_{H \rightarrow f\bar{f}} + \mathcal{B}_{H \rightarrow gg}) \kappa_F^2 + (\mathcal{B}_{H \rightarrow VV}) \kappa_V^2}. \end{aligned} \quad (6.4)$$

2160 Figure 6.6 shows the two-dimensional likelihood scan of κ_F and κ_V . The best-fit values are given in equa-
 2161 tion 6.5. The best-fit values are consistent with unity within their uncertainties.

$$\begin{aligned} \kappa_F &= 0.93 & +0.24 & +0.21 & = 0.93 & +0.32 \\ \kappa_V &= 1.04 & +0.07 & +0.07 & = 1.04 & \pm 0.11. \end{aligned} \quad (6.5)$$

(stat.) (syst.)

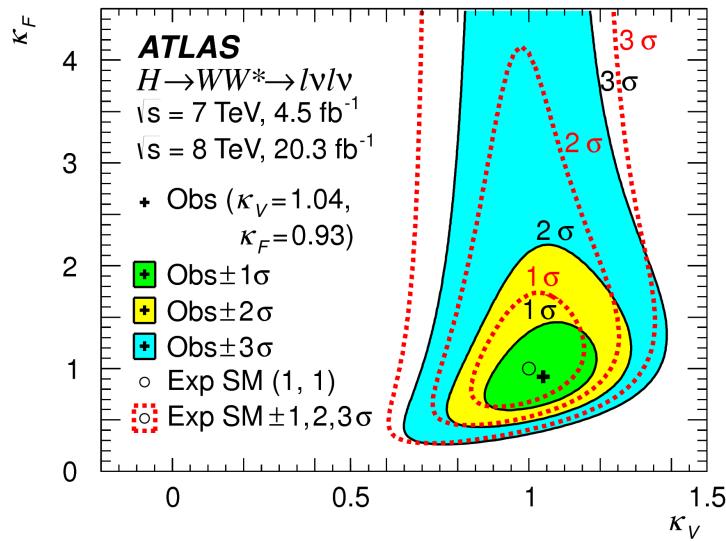


Figure 6.6: Likelihood scan as a function of κ_F and κ_V [62].

2162

2163 6.5 HIGGS PRODUCTION CROSS SECTION MEASUREMENT

2164 Another measurement that comes naturally from the signal strength numbers quoted earlier is the pro-
 2165 duction cross section and 7 and 8 TeV for both gluon fusion and VBF production. The general equation
 2166 for calculating the cross section is given in equation 6.6.

$$\begin{aligned} (\sigma \cdot \mathcal{B}_{H \rightarrow WW^*})_{\text{obs}} &= \frac{(N_{\text{sig}})_{\text{obs}}}{\mathcal{A} \cdot \mathcal{C} \cdot \mathcal{B}_{WW \rightarrow \ell\nu\ell\nu}} \cdot \frac{1}{\int L dt} \\ &= \hat{\mu} \cdot (\sigma \cdot \mathcal{B}_{H \rightarrow WW^*})_{\text{exp}} \end{aligned} \quad (6.6)$$

2167 $(N_{\text{sig}})_{\text{obs}}$ is the number of events observed in data. \mathcal{A} is the geometric and kinematic acceptance of the
 2168 detector, while \mathcal{C} is the efficiency of the signal region selection for events that are reconstructed in the
 2169 detector. The branching ratio of a WW system to leptons must also be divided out. The production
 2170 cross section depends on the center of mass energy and the production mode desired (gluon fusion or
 2171 VBF), and so three separate cross section measurements are quoted in equation 6.7.

$$\begin{aligned}
 \sigma_{\text{ggf}}^{\text{7TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 2.0 \pm 1.7^{+1.2}_{-1.1} = 2.0^{+2.1}_{-2.0} \text{ pb} \\
 \sigma_{\text{ggf}}^{\text{8TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 4.6 \pm 0.9^{+0.8}_{-0.7} = 4.6^{+1.2}_{-1.1} \text{ pb} \\
 \sigma_{\text{vbf}}^{\text{8TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 0.51^{+0.17}_{-0.15} {}^{+0.13}_{-0.08} = 0.51^{+0.22}_{-0.17} \text{ pb.}
 \end{aligned} \tag{6.7}$$

(stat.) (syst.)

2172 The predicted cross section values for gluon fusion are 3.3 ± 0.4 pb at 7 TeV and 4.2 ± 0.5 pb at 8 TeV,
 2173 consistent with the measured values within their uncertainties. For vector boson fusion, the predicted
 2174 cross section is 0.35 ± 0.02 pb, again consistent with the measured value.

2175 6.6 CONCLUSION

2176 The combined analysis of the gluon fusion and vector boson fusion processes in $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
 2177 in the 7 and 8 TeV datasets has yielded the first discovery level significance for Higgs production in this
 2178 decay channel. Additionally, precise measurements of the couplings to vector bosons and fermions are
 2179 given. Finally, signal strengths and cross sections for each production mode are measured. Figure 6.7 shows
 2180 the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ measurements in comparison with other Higgs decay channels in ATLAS. The
 2181 measurement of signal strength from this channel remains the most sensitive in both the gluon fusion and
 2182 VBF production modes for the Run 1 dataset.

ATLAS

Individual analysis

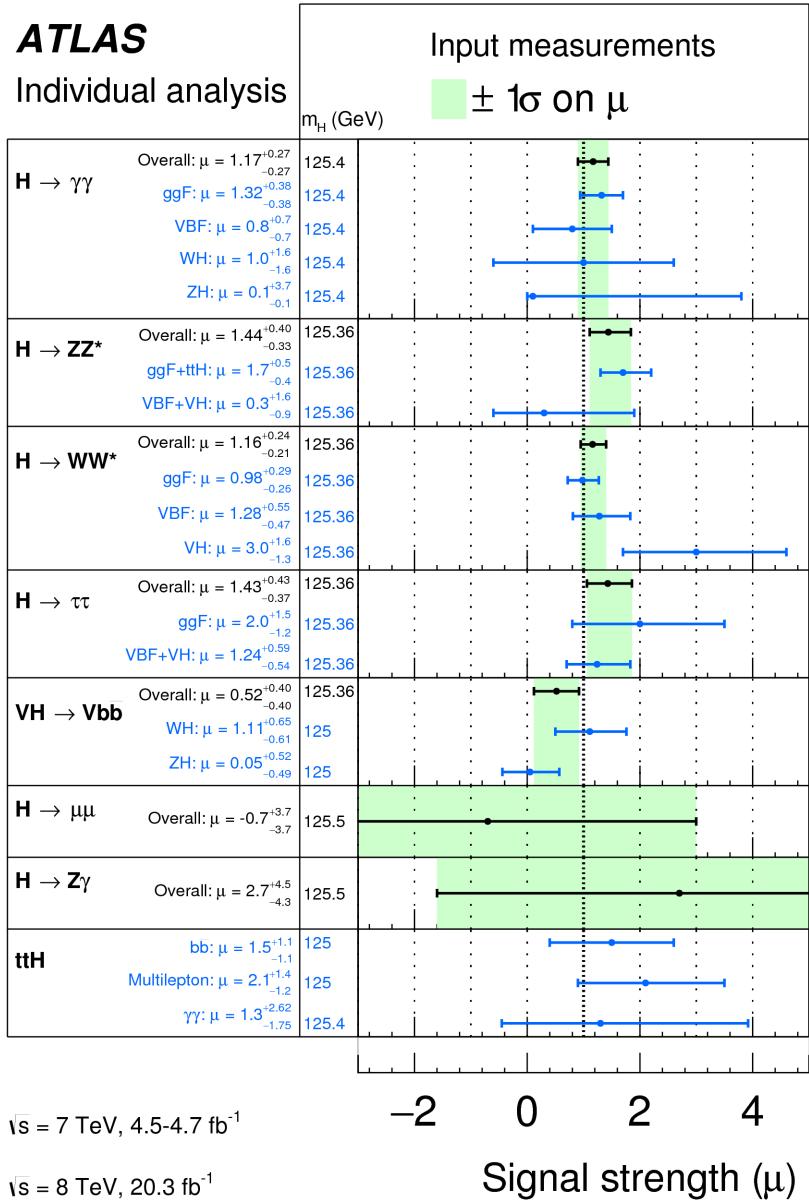


Figure 6.7: Comparison of signal strength measurements in different Higgs decay channels on ATLAS [91].

2183

Part III

2184

Search for Higgs pair production in the

2185

$HH \rightarrow b\bar{b}b\bar{b}$ channel in LHC Run 2 at $\sqrt{s} =$

2186

13 TeV

Passion is in all great searches and is necessary to all creative endeavors.

W. Eugene Smith

7

2187

2188 Search for Higgs pair production in boosted 2189 $b\bar{b}b\bar{b}$ final states

2190 7.1 INTRODUCTION

2191 After the discovery of the Higgs boson in the ATLAS Run 1 dataset and the subsequent measurements
2192 of its properties, the Higgs transformed into a potential tool in searches for physics beyond the Standard
2193 Model. The pair production cross section of the Higgs can be enhanced through BSM physics. Studying
2194 di-Higgs production also probes the Higgs self-coupling, shedding light on the structure of the Higgs po-
2195 tential. This chapter presents a search for resonant production of a Higgs pair in the $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$
2196 final state in 3.2 fb^{-1} of data collected at $\sqrt{s} = 13 \text{ TeV}$. In particular, this chapter focuses on a search for
2197 this final state in the regime where m_X is large ($\gtrsim 1 \text{ TeV}$) and the Higgs bosons in the decay are signifi-
2198 cantly boosted. A tailored selection for this boosted selection, using novel techniques in jet substructure

and b -tagging, is discussed. Then, the data-driven background estimate is presented. Finally, the results of the search are shown. The signal models used as benchmarks are a spin-2 Randall Sundrum graviton (RSG) and a narrow width spin-0 resonance. These models are described in more detail in Chapter 1. Limits on signal models are reserved for the next chapter where the results of this chapter are combined with the results of a separate selection dedicated to the lower m_X regime.

7.2 MOTIVATION

With the center of mass energy increase from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 13$ TeV, the LHC and ATLAS are able to probe new resonances at higher mass scales than previously accessible in Run 1. This is a powerful motivator for searching for a new resonance in the early 13 TeV data. Figure 7.1 shows the ratios of parton luminosities between 8 and 13 TeV for different resonance masses. For a resonance of $M_X = 2$ TeV, the cross section at $\sqrt{s} = 13$ TeV is roughly a factor of 10 larger than at $\sqrt{s} = 8$ TeV.

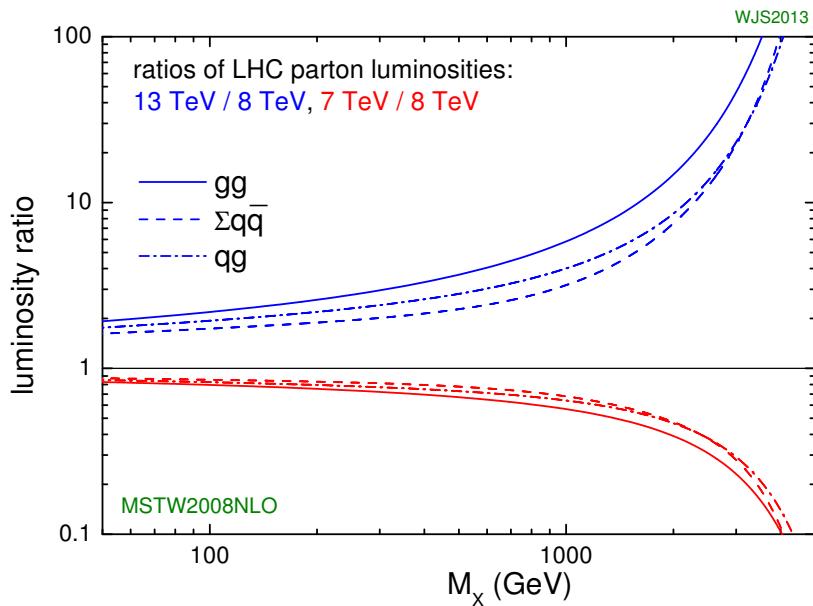


Figure 7.1: Parton luminosity ratios as a function of resonance mass M_X for 13/8 TeV and 7/8 TeV [92].

Higgs pair production offers a vast array of unprobed regions of phase space where searches for BSM physics can be made. Chapter 1 discusses some possibilities for both resonant and non-resonant enhance-

2212 ment of the di-Higgs production cross section. Given the increased mass reach of the LHC in Run 2, it is
 2213 particularly important to focus on resonant searches at high m_X . One consideration when conducting a
 2214 search in the HH final state is which decay modes of the Higgs to consider. Figure 7.2 shows the branching
 2215 ratio of the HH final state for different combinations of decays of each individual Higgs. As the largest
 2216 branching ratio for the 125 GeV Higgs is $H \rightarrow b\bar{b}$, the $HH \rightarrow b\bar{b}b\bar{b}$ branching ratio is also the largest at
 2217 33%.

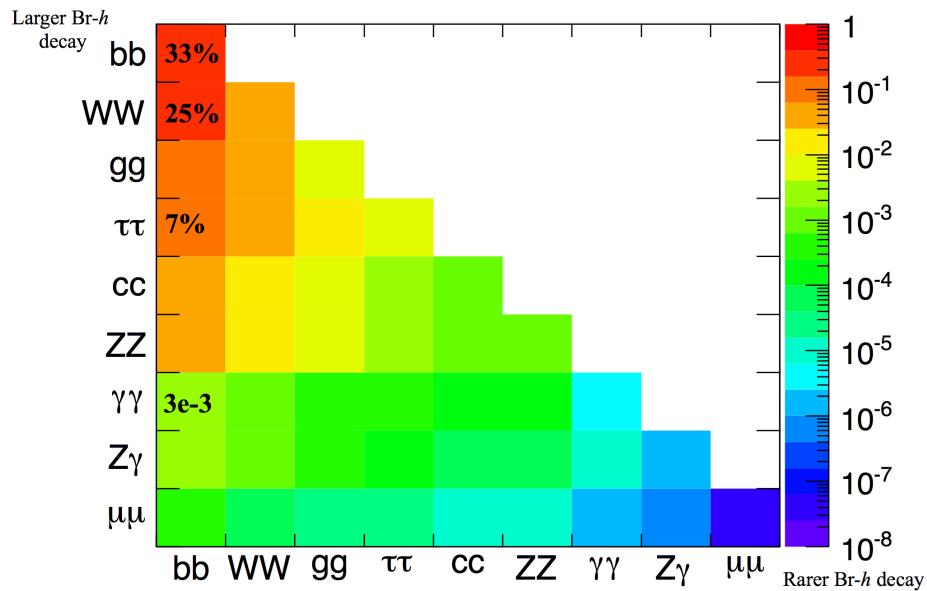


Figure 7.2: Summary of HH branching ratios [93].

2218 At high m_X , the Higgs bosons resulting from the decay of a heavy resonance will have large p_{T} ¹. The
 2219 ΔR between the decay products of the Higgs is inversely proportional to the Higgs p_{T} , as shown in equa-
 2220 tion 7.1.

$$\Delta R \approx \frac{2m}{p_{\text{T}}} \quad (7.1)$$

2221 Figure 7.3 shows the minimum ΔR between truth level B decay vertices in simulation samples for Randall-
 2222 Sundrum gravitons of different masses. The figure shows that as the mass of the graviton increases, the ΔR
 2223 distribution between the b quarks in the Higgs decay tends to shift to lower values. Because of this effect,
 2224 it is necessary to tailor a selection to target these merged b -jets.

¹In the limit that $m_H \ell \ell m_X$, the Higgs p_{T} is roughly $m_X/2$.

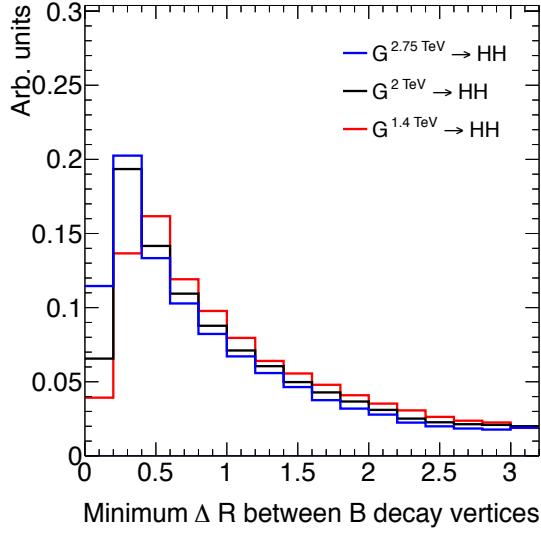


Figure 7.3: Minimum ΔR between B decay vertices for different RSG masses in a $G_{KK}^* \rightarrow HH \rightarrow 4b$ sample with $c = 1$

2225 7.3 DATA AND SIMULATION SAMPLES

2226 7.3.1 SIGNAL MODELS

2227 While the resonance search is by its nature generic (as it is a simple search for a peak in the $4b$ invariant
 2228 mass spectrum), there are two signal models that the selection requirements have been optimized for.
 2229 The first is Randall-Sundrum (RSG) model, where a tower of massive spin-2 Kaluza-Klein gravitons is
 2230 predicted. The second is a heavy narrow spin-0 resonance, the so-called “heavy Higgs”. This type of res-
 2231 onance arises, for example, in the two Higgs doublet model (2HDM). More details about the physics of
 2232 these models and their motivation is given in chapter 1.

2233 Signal graviton (G_{KK}^*) events are generated at leading order (LO) with **MADGRAPH5 v2.2.2** [94]. The
 2234 PDF set used is the **NNPDF2.3 LO** set [95]. For modeling parton shower and hadronization in jets, **PYTHIA**
 2235 8.186 is used with the A14 tune [74, 96]. The free parameters in the RSG model are the graviton mass
 2236 and the coupling constant $c \equiv k/\bar{M}_{\text{Pl}}^2$. Both the production cross section and width of the graviton are
 2237 proportional to c^2 . Samples are generated at both $c = 1$ and $c = 2$ for a variety of mass points between

² k is the curvature constant for the warped extra dimension and \bar{M}_{Pl} is the Planck mass divided by 8π

2238 300 GeV and 3 TeV.

2239 The second signal sample is a heavy spin-0 resonance H with a fixed width of $\Gamma_H = 1$ GeV. This
2240 is generated with **MADGRAPH5** and uses the **CTEQ10** PDF set [77]. The parton shower and hadronization
2241 are handled by **HERWIG ++** with the **CTEQ6L1** PDF set and the **UEEE5** event tune [78, 97, 98]. Because
2242 the width and branching ratios depend on 2HDM parameters, each mass point generated with this fixed
2243 width corresponds to a different point in the 2HDM parameter phase space. Mass points are generated
2244 between 300 GeV and 1 TeV as with the RSG signal samples.

2245 **7.3.2 BACKGROUND SAMPLES**

2246 While the dominant **QCD** multijet background is estimated with a fully data-driven method, the sub-
2247 dominant backgrounds $t\bar{t}$ and Z +jets are modeled with some input from simulation.

2248 $t\bar{t}$ events are simulated at next-to-leading order (NLO) with the **POWHEG-BOX** version 1 generator us-
2249 ing the **CTEQ10** PDF set [99]. The parton shower, hadronization, and underlying event are simulated with
2250 **PYTHIA 6.428** with the **CTEQ6L1** PDF set [73]. The Perugia 2012 tune is used [100]. NNLO **QCD** cor-
2251 rections to the cross sections are computed in **Top++ 2.0** [101]. The top quark mass is set to 172.5 GeV.
2252 The shapes of distributions in $t\bar{t}$ are taken from MC while the normalization is taken from data.

2253 Finally, the Z +jets background is simulated with **PYTHIA 8.186** and the **NNPDF2.3** LO PDF set. This
2254 background is negligible compared to the others and is taken fully from MC.

2255 **7.3.3 DATA SAMPLE AND TRIGGER**

2256 This analysis is done on 3.2 fb^{-1} of data taken in 2015 at $\sqrt{s} = 13$ TeV. The details of the machine
2257 conditions during this time can be found in Chapter 2. Only data which was taken during stable beam con-
2258 ditions with all detectors functioning is used. Events must pass a trigger which requires a single 360 GeV
2259 large radius ($R = 1.0$) jet to be reconstructed in the HLT. Figure 7.4 shows the trigger efficiency for vari-
2260 ous trigger options as a function of graviton mass. Above $m_G > 1$ TeV, the single large radius jet trigger
2261 is 99% efficient for events passing the signal selection.

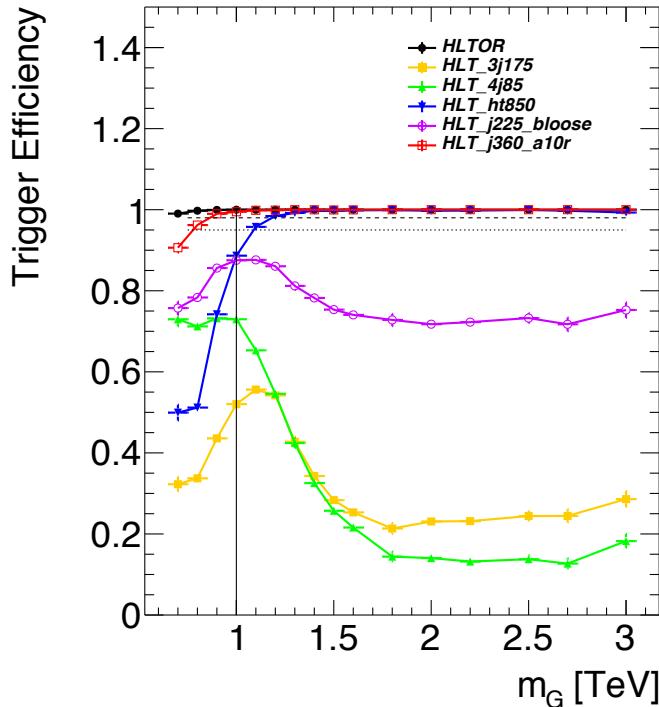


Figure 7.4: Trigger efficiency for events passing all signal region selections as a function of mass in $G_{\text{KK}}^* \rightarrow HH \rightarrow 4b$ samples with $c = 1$ [102]. In the trigger names, “j” refers to a jet or jets. “ht” refers to H_T , the scalar sum of transverse momenta in the event. “bloose” refers to a loose b -tagging requirement applied to the jet. “a10r” refers to anti- k_T jets with $R = 1.0$. The numbers at the end are the thresholds on the given quantity in GeV.

2262 7.4 EVENT RECONSTRUCTION AND OBJECT SELECTION

2263 The boosted selection first begins by defining a unique set of objects that can be exploited to increase
 2264 signal efficiency in the kinematic regime where the final state b -jets are very merged.

2265 7.4.1 LARGE RADIUS ($R = 1.0$) JETS

2266 The first step towards reconstructing the final state is to define objects that can be used to measure the
 2267 kinematics of the Higgs bosons. In the boosted selection anti- k_T jets with a radius parameter of 1.0 are
 2268 used. These jets are much larger in angular size than the typical $R = 0.4$ jets and are intended to encompass
 2269 both jets resulting from the Higgs decay³. The jets are built from clusters in the calorimeter calibrated with

³This is in contrast to the resolved selection, which uses two $R = 0.4$ anti- k_T jets for each Higgs

local calibration weighting [57].

Because of the large extent of these jets, great care must be taken to remove potential contributions of calorimeter clusters from pile-up. This is done using a technique called jet trimming [103]. With trimming, the constituents of the large radius jet are re-clustered with a smaller radius with the k_T algorithm. Then, these so-called subjets are removed from the larger jet if $p_T^{\text{subjett}}/p_T^{\text{jet}} < f_{\text{cut}}$. In this analysis, the subjet radius is $R = 0.2$ and $f_{\text{cut}} = 0.05$. Trimming has been shown to improve the mass resolution of large radius jets. Figure 7.5 shows the effect of trimming on the large radius jet mass (M_J). Because the large radius jet fully contains the higgs decay products, its invariant mass should correspond to the 125 GeV mass of the Higgs. The trimming algorithm brings the jet mass much closer to the expected Higgs mass and improves the mass resolution.

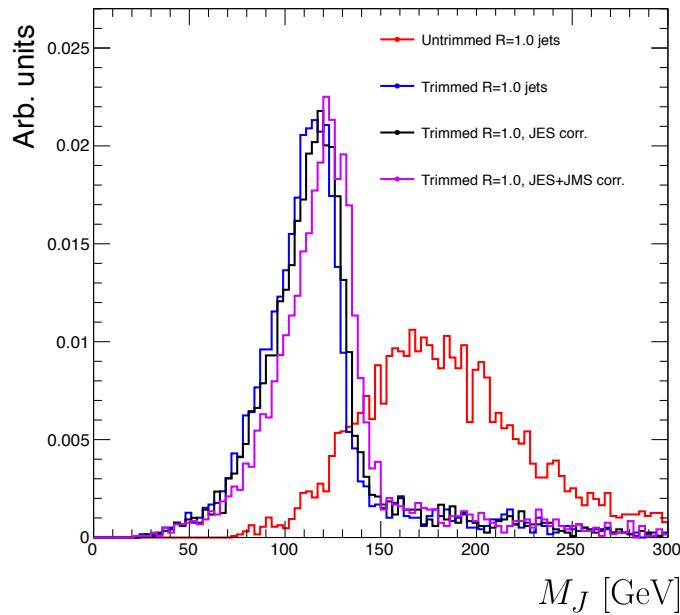


Figure 7.5: Comparison of untrimmed and trimmed jet masses for large radius jets in a RSG sample with $m_{G_{KK}^*} = 1 \text{ TeV}$. JES (JMS) refers to the standard jet energy (mass) scale calibration for ATLAS [57].

The large radius jets are required to satisfy $250 < p_T < 1500 \text{ GeV}$. They must also be within $|\eta| < 2.0$ in order to ensure that the full jet is within the inner detector tracking volume. Finally, they are required to have $M_J > 50 \text{ GeV}$. The upper p_T cut and lower threshold on mass are applied to correspond to the kinematic range where uncertainties are available in ATLAS calibrations [104, 105].

2284 7.4.2 TRACK JETS AND b -TAGGING

2285 Because the b -jets from boosted Higgs decays are so close together (as illustrated in figure 7.3), narrow ra-
2286 dius jets are required to fully resolve both b -jets. The minimum radius feasible for jets based on calorimeter
2287 deposits is determined by the calorimeter granularity. However, because b -tagging relies on information
2288 from the inner detector, it is possible to define another type of jet that can have a smaller radius and better
2289 b -tagging resolution. These jets are called “track jets” [105, 106].

2290 Track jets are formed by applying the usual anti- k_T clustering algorithm to tracks that are required to be
2291 consistent with the primary vertex. After the jet axis has been determined using these tracks, a second step
2292 of track association is also performed to add tracks that can be useful for b -tagging [106]. In this analysis,
2293 the tracks are clustered with a radius parameter of $R = 0.2$. This radius has been shown to give good
2294 performance in boosted Higgs tagging [105, 106]. Figure 7.6 shows a comparison among different track jet
2295 radii of the efficiency for reconstructing two b -jets from each Higgs in a RSG sample as a function of mass.
Track jets with radius of 0.2 give the best performance, especially at high mass. In this analysis, track jets

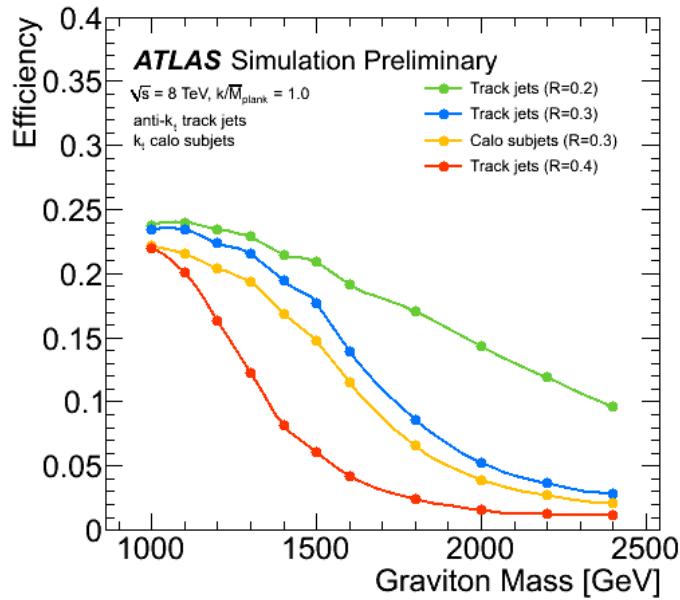


Figure 7.6: Efficiency of finding two b -jets from each Higgs in an RSG event using calorimeter jets with $R = 0.3$ or
2296 different track jet radii [106]

2297 are required to have $p_T > 10$ GeV and $|\eta| < 2.5$. They must also have at least two tracks.

2298 7.4.3 MUONS

2299 Muons are used in this study to correct the four-momenta of calorimeter jets by accounting for semi-
2300 leptonic b decays. The muons used are combined ID and MS muons which must satisfy tight identification
2301 requirements [53]. The muons must have $p_T > 4 \text{ GeV}$ and $|\eta| < 2.5$. Table 7.1 summarizes the object
2302 requirements described in this section.

	R	p_T	$ \eta $	M
Calorimeter jets	1.0	$250 < p_T < 1500 \text{ GeV}$	< 2.0	$> 50 \text{ GeV}$
Track jets	0.2	$> 10 \text{ GeV}$	< 2.5	-
Muons	-	4 GeV	< 2.5	-

Table 7.1: Summary of requirements on objects used in the $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ search

2303 7.5 EVENT SELECTION

2304 The first requirement in the boosted selection is for ≥ 2 large radius jets satisfying the selections out-
2305 lined above. The two highest momentum large-R jets in the event are referred to as “Higgs candidates”.
2306 The leading jet is required to have $p_T > 350 \text{ GeV}$.

2307 Track jets satisfying the object selections are matched to Higgs candidate jets via ghost association [107].
2308 Each Higgs candidate must have at least 2 track jets associated with it. These basic requirements are illus-
2309 trated in figure 7.7.

2310 The QCD multijet background produces less central jets than high mass resonances, so there is an ad-
2311 ditional requirement that the two Higgs candidates be close together in η . The large-R jets are required to
2312 satisfy $|\Delta\eta(JJ)| < 1.7$.

2313 7.5.1 MASS REQUIREMENTS

2314 The final set of requirements ensures that the Higgs candidates are consistent with expected properties
2315 of the 125.0 GeV Higgs. First, a variable (X_{hh}) is defined to measure the consistency of both of the Higgs

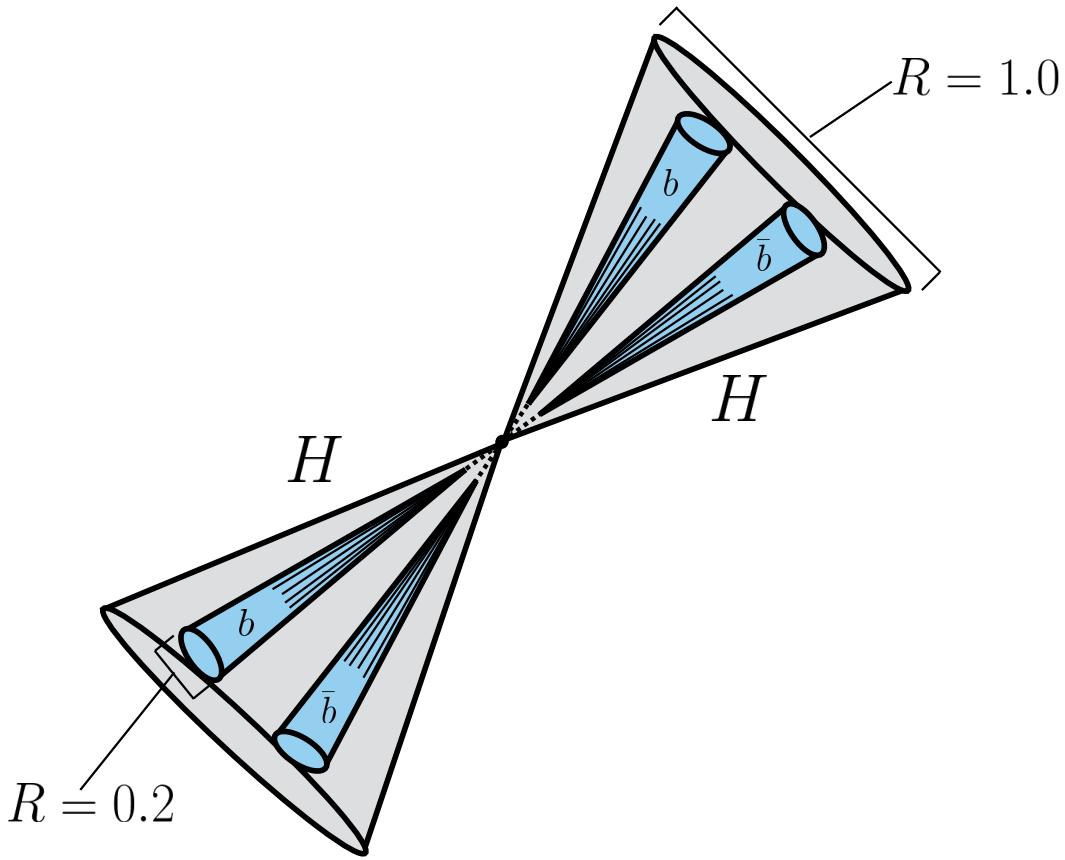


Figure 7.7: Illustration of the boosted selection requirements on Higgs candidates. Each large-radius calorimeter jet (Higgs candidate) must contain two track jets

²³¹⁶ candidate jets with the SM Higgs mass. This is shown in equation 7.2.

$$X_{hh} = \sqrt{\left(\frac{M_J^{\text{lead}} - 124 \text{ GeV}}{0.1 M_J^{\text{lead}}}\right)^2 + \left(\frac{M_J^{\text{sublead}} - 115 \text{ GeV}}{0.1 M_J^{\text{sublead}}}\right)^2} \quad (7.2)$$

²³¹⁷ The mass values in the X_{hh} formula are optimized to maximize signal efficiency. The sub-leading jet
²³¹⁸ typically has a lower mass due to semi-leptonic b decays and final state radiation. X_{hh} effectively acts as
²³¹⁹ a χ^2 measurement of the consistency of the two Higgs candidate masses with the signal hypothesis. The
²³²⁰ denominators of each term ($0.1M$) give the uncertainty on the mass measurement for the large radius jets.
²³²¹ Events are required to satisfy $X_{hh} < 1.6$.

²³²² Before making the requirement on X_{hh} , the masses of the Higgs candidates are corrected for semi-

leptonic b decays using muons with the criteria outlined in the previous section. Any muons within a $\Delta R < 0.2$ of a b -tagged track jet (as described in the next section) have their four-momenta added to the four-momentum of the Higgs candidate. This correction does not affect the pre-selection requirements but does affect the X_{hh} requirement and the final invariant mass distribution used.

7.5.2 b -TAGGING REQUIREMENTS

The last requirement applied is on the number of b -tagged track jets. There are two signal regions defined. The first requires exactly four b -tagged track jets, two in each Higgs candidate (known as the $4b$ signal region). At high resonance masses, this requirement is inefficient, so an additional signal region requiring only three b -tagged track jets is also defined (known as the $3b$ signal region). While this has a larger background it is also more efficient for high resonance masses. For both signal regions, the MV2c20 algorithm, where the training sample for the algorithm has 20% charm events is used. More details for this algorithm can be found in Chapter 2.

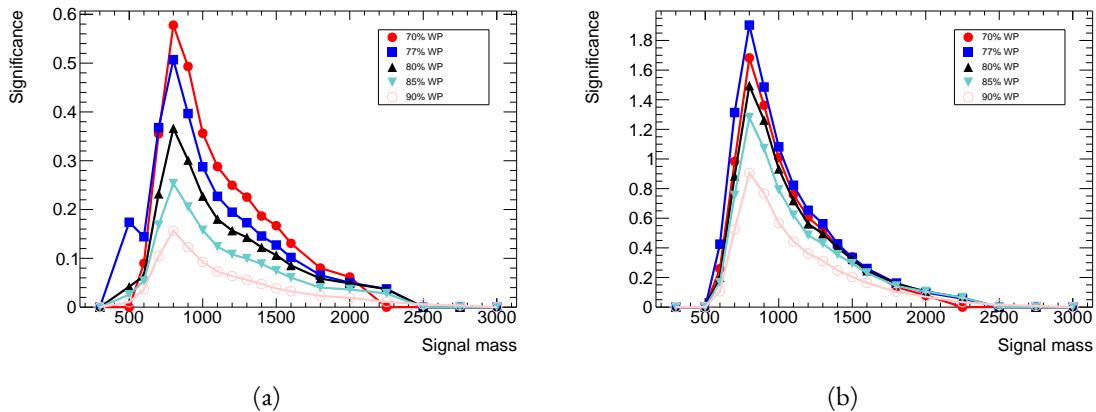


Figure 7.8: Estimated significance as a function of signal mass for RSG $c = 1$ models in the $3b$ (a) and $4b$ (b) regions for different b -tagging efficiency working points

Once the algorithm is selected, an efficiency working point must also be chosen. This working point defines the efficiency with which true b -jets are tagged and also fixes the overall background rejection of the algorithm. Higher efficiency working points accept more true b -jets but also allow for more background. Five different working points (70%, 77%, 80%, 85%, 90%) are tested. With each working point, the full data driven background estimation method is run to quantify the amount of background that will be

present in the final signal region. The significance is quantified using the median discovery significance for signal and background with Poisson errors, given in equation 7.3 [108].

$$Z = \sqrt{2 \left((s + b) \ln \left(1 + \frac{s}{b} \right) - s \right)} \quad (7.3)$$

Here, s is the expected number of signal events and b is the expected number of background events. This formula is derived using Poisson statistics with errors on both the signal and background. It is used because it is valid in the regime where s and b are of the same order. Note that in the limit where s is much smaller than b , this equation reduces to the more well known s/\sqrt{b} . Figure 7.8 shows the estimated significance as a function of signal mass in RSG $c = 1$ models for the $3b$ and $4b$ signal regions. The 77% working point gives the best performance over a wide range of masses in the $4b$ signal region. As this is the region which contributes the most to the total discovery significance, the 77% efficiency working point is chosen for the analysis.

7.5.3 SELECTION EFFICIENCY

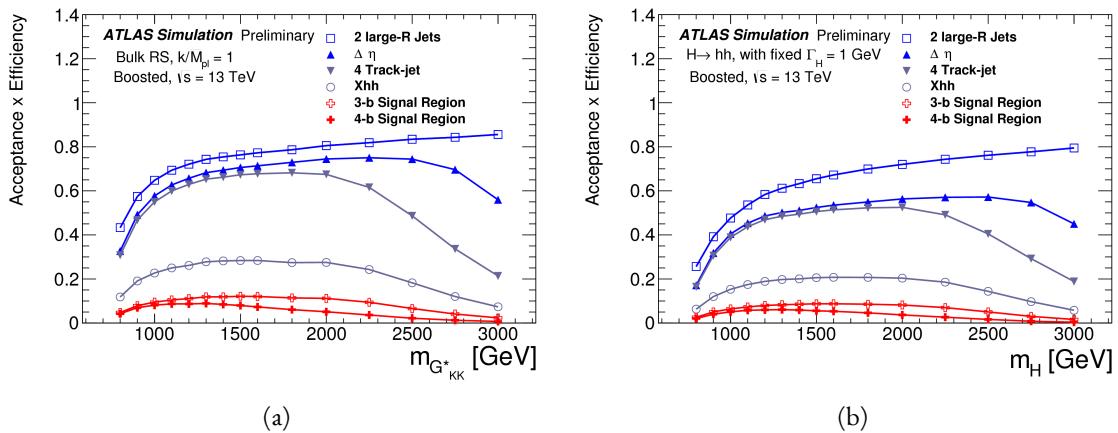


Figure 7.9: Acceptance \times efficiency as a function of mass for (a) RSG and (b) narrow heavy scalar signal models [109].

Figure 7.9 shows the product of acceptance and efficiency as a function of mass for both the RSG and narrow heavy scalar resonance signal models. After $m_X > 1$ TeV, the efficiency of the $4b$ requirement begins to decline. After $m_X > 2$ TeV, the efficiency of requiring two track jets in each Higgs candidate

begins to decline as well. Both of these behaviors illustrate the difficulty of resolving the merged decay products at high mass. Figure 7.10 shows a more detailed comparison of the signal efficiency in the $3b$ vs $4b$ signal regions for the RSG model. The efficiencies shown here are relative to all prior selection requirements. It can be seen there that at high masses the $3b$ signal region is more efficient for signal.

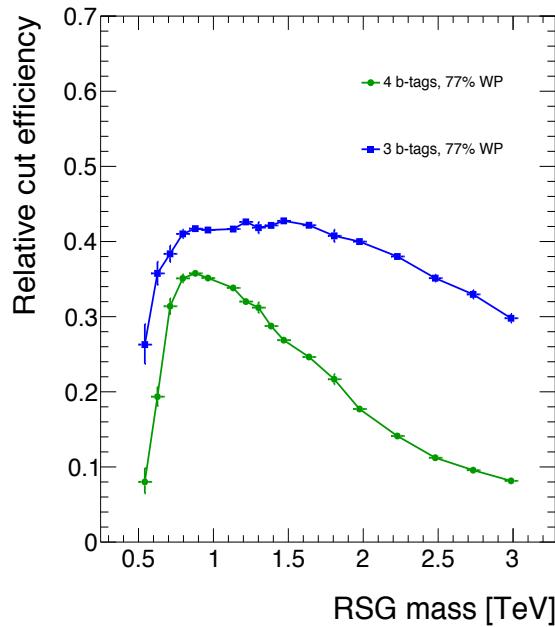


Figure 7.10: Efficiency of requiring 3 or 4 b -tagged track jets vs. RSG mass. The efficiency quoted is relative to the previous selection requirements (rather than an absolute efficiency).

To investigate the degradation of b -tagging efficiency at high p_T , the individual jet tagging efficiencies can be compared as a function of signal mass. This is shown in figure 7.11. The figure shows that the leading jet tagging efficiency in both calorimeter jets degrades heavily, while the sub-lead jet tagging efficiency remains relatively constant. More details on the cause of this degradation are shown in appendix A.

The final discriminating variable used in the boosted analysis is M_{2J} , the invariant mass of the two Higgs candidates. In order to improve the mass resolution, the four-momenta of each Higgs candidate are scaled by m_h/M_J . The effect of this correction is small in the boosted analysis but is done for consistency with the resolved selection. Table 7.2 shows the effect of the selection requirements on signal and background simulations as well as data.

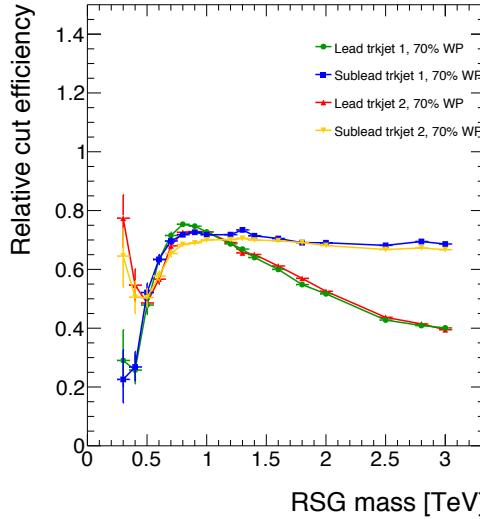


Figure 7.11: MV2c20 b -tagging efficiency for each of the four track jets in the boosted $4b$ selection as a function of RSG mass for $c = 1$ models.

Selection	Data	$m_{G_{KK}^*} = 1\text{TeV}$	$m_{G_{KK}^*} = 2\text{TeV}$	$t\bar{t}$	$Z + \text{jets}$
$N(\text{fiducial large-R jets}) \geq 2$	2202396	23.3	0.48	32345.2	4255.7
leading large-R jet $p_T > 350\text{ GeV}$	1873741	22.9	0.48	26511.7	3649.9
Both large-R jet $m > 50\text{ GeV}$	1854625	21.2	0.47	24369.8	3575.8
Both large-R jet $p_T < 1500\text{ GeV}$	1853601	21.2	0.46	24346.5	3572.9
$ \Delta\eta(JJ) < 1.7$	1435273	20.8	0.44	20751.0	3265.8
≥ 2 track-jets per large-R jet	1224727	19.8	0.40	18234.5	2692.6
3 b -tags, $X_{hh} < 1.6$	316	3.4	0.067	46.7	2.0
4 b -tags, $X_{hh} < 1.6$	20	2.9	0.030	1.4	0.0

Table 7.2: Effect of boosted selection on data, RSG signal models, $t\bar{t}$, and $Z + \text{jets}$. The numbers from simulation are normalized with the MC generator cross section and do not take into account the data driven estimates described in section 7.6 [110].

2367 7.6 DATA-DRIVEN BACKGROUND ESTIMATION

2368 The largest background to this final state is QCD multijet production, constituting 80-90% of the to-
 2369 total background. Because of the difficulties in modeling higher order QCD processes, this background is
 2370 estimated with a fully data-driven method. The only other non-negligible background is $t\bar{t}$, constituting
 2371 the other 10-20%⁴. Due to the presence of $t\bar{t}$ in the sideband region where the QCD background will be

⁴The $Z + \text{jets}$ background is a sub-percent level contribution

2372 estimated, the normalization of the QCD and $t\bar{t}$ backgrounds are simultaneously estimated.

2373 7.6.1 MASS REGION DEFINITIONS

2374 The first step in the data-driven background estimate is to define a sideband mass region where the
2375 background normalization can be derived. Additionally, a control region is defined where the background
2376 estimate can be validated. The control (CR) and sideband (SB) regions are defined using a radial distance
2377 in the two-dimensional large-R jet mass plane, R_{hh} , which is defined in equation 7.4.

$$R_{hh} = \sqrt{(M_J^{\text{lead}} - 124 \text{ GeV})^2 + (M_J^{\text{sublead}} - 115 \text{ GeV})^2} \quad (7.4)$$

2378 Events in the sideband region are required to fail the signal region $X_{hh} < 1.6$ requirement and have
2379 $R_{hh} > 35.8 \text{ GeV}$. The control region consists of those events which are not in the signal or sideband
regions. Figure 7.12 shows the definition of the signal, control, and sideband mass regions. Table 7.3 sum-

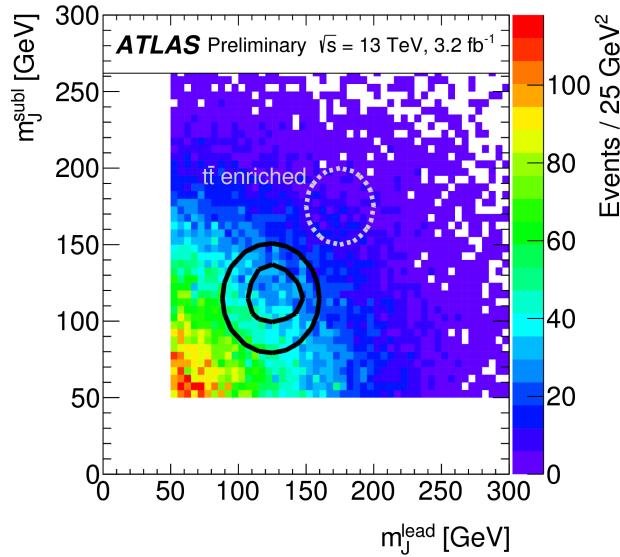


Figure 7.12: M_J^{sublead} vs. M_J^{lead} in a 2 b -tag data sample. The signal region is defined by the inner black contour ($X_{hh} < 1.6$) and the sideband region is defined by the outer contour ($R_{hh} > 35.8 \text{ GeV}$). The region between the black contours is the control region. The mass region which is enriched in $t\bar{t}$ background is also shown for illustration. [109]

2380

2381 marizes the mass region selections for the three different regions used in the analysis.

Region	Requirement	Notes
Signal Region (SR)	$X_{hh} < 1.6$	-
Control Region (CR)	$R_{hh} < 35.8 \text{ GeV}$ and $X_{hh} > 1.6$	Used for validation of background estimates
Sideband Region (SB)	$R_{hh} > 35.8 \text{ GeV}$	Used to derive background normalization

Table 7.3: Mass region definitions used for background estimation

2382 7.6.2 BACKGROUND ESTIMATION

2383 The method for estimating the background in this analysis is similar to the ABCD method presented in
 2384 Chapter 5. In this case, the two handles used to define different regions for the estimate are the number of
 2385 b -tagged track jets and the mass regions. A region requiring exactly two b -tagged track jets in one large-R
 2386 jet (referred to as the 2-tag or $2b$ region) is defined for use in the background estimate. The number of
 2387 expected background events in the $3b$ and $4b$ signal regions is then given by equation 7.5.

$$N_{\text{bkg}}^{3(4)-\text{tag},\text{SR}} = \mu_{\text{Multijet}} N_{\text{Multijet}}^{2-\text{tag},\text{SR}} + \beta_{t\bar{t}} N_{t\bar{t}}^{3(4)-\text{tag},\text{SR}} + N_{Z+\text{jets}}^{3(4)-\text{tag},\text{SR}} \quad (7.5)$$

2388 In this equation, $N_{\text{bkg}}^{3(4)-\text{tag}}$ is the expected number of background events in the $3b$ or $4b$ signal regions.
 2389 $N_{\text{Multijet}}^{2-\text{tag}}$ is the number of multijet events in the 2-tag region. $N_{t\bar{t}}^{3(4)-\text{tag}}$ is the number of $t\bar{t}$ events pre-
 2390 dicted in the MC for the $3b$ or $4b$ signal region, and the variable is similarly defined for the $Z+\text{jets}$ back-
 2391 ground. The $\beta_{t\bar{t}}$ parameter is a scale factor used to correct the normalization of the $t\bar{t}$ estimate in the signal
 2392 region. μ_{Multijet} is an extrapolation factor that is derived in the sideband region and used to estimate the
 2393 ratio of 2-tag events to 3(4)-tag events in the signal region. It is defined in equation 7.6.

$$\mu_{\text{Multijet}} = \frac{N_{\text{Multijet}}^{3(4)-\text{tag},\text{SB}}}{N_{\text{Multijet}}^{2-\text{tag},\text{SB}}} = \frac{N_{\text{data}}^{3(4)-\text{tag},\text{SB}} - \beta_{t\bar{t}} N_{t\bar{t}}^{3(4)-\text{tag},\text{SB}} - N_{Z+\text{jets}}^{3(4)-\text{tag},\text{SB}}}{N_{\text{data}}^{2-\text{tag},\text{SB}} - \beta_{t\bar{t}} N_{t\bar{t}}^{2-\text{tag},\text{SB}} - N_{Z+\text{jets}}^{2-\text{tag},\text{SB}}} \quad (7.6)$$

2394 The $t\bar{t}$ scale factor ($\beta_{t\bar{t}}$) and the QCD multijet extrapolation factor (μ_{Multijet}) are estimated together in
 2395 a simultaneous fit in the sideband region. Then, the number of events in the 2-tag signal region is used,
 2396 along with the $t\bar{t}$ estimate in the $3b$ and $4b$ signal regions and μ_{Multijet} , to estimate the total number
 2397 of background events in the two final signal regions. The shape of the final discriminant M_{2J} is also

2398 taken from the 2-tag signal region where there are more statistics. This method is illustrated graphically in
2399 figure 7.13.

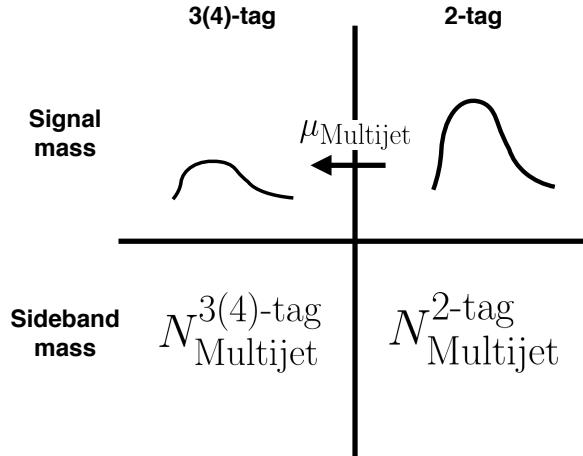


Figure 7.13: An illustration of the data-driven background estimation technique for the boosted analysis

2400 In the $3b$ region, the fit yields values of $\mu_{\text{Multijet}} = 0.160 \pm 0.03$ and $\beta_{t\bar{t}} = 1.02 \pm 0.09$. In the $4b$
2401 region, the fit gives $\mu_{\text{Multijet}} = 0.0091 \pm 0.0007$ and $\beta_{t\bar{t}} = 0.82 \pm 0.39$. The uncertainties quoted are
2402 statistical only. The larger uncertainties in the $4b$ values indicate the lower statistics available in that region.

2403 Figure 7.14 shows the distributions of data and background estimates in the $3b$ and $4b$ sideband regions
2404 after the background fit has been done. The normalizations are constrained from the fit to match that of
2405 the data, but good modeling of the shape of the mass of the leading large-R jet is seen as well. The shapes
2406 of the kinematic distributions in the $4b$ region are taken from the $3b$ region due to the better MC statistics
2407 in that region.

2408 7.6.3 BACKGROUND SHAPE FIT

2409 As mentioned in the previous section, the background shape in the 3-tag and 4-tag signal regions is
2410 taken from the 2-tag signal mass region. Due to the limited statistics available, the background shapes are
2411 additionally smoothed after being extrapolated to the 3-tag and 4-tag signal regions. Only the data in the
2412 range $900 < M_{2J} < 2000$ GeV is included in the fit due to the limited statistics available above 2 TeV.
2413 Both the $t\bar{t}$ and QCD multijet background are independently fit with an exponential shape, $y = e^{ax+b}$.

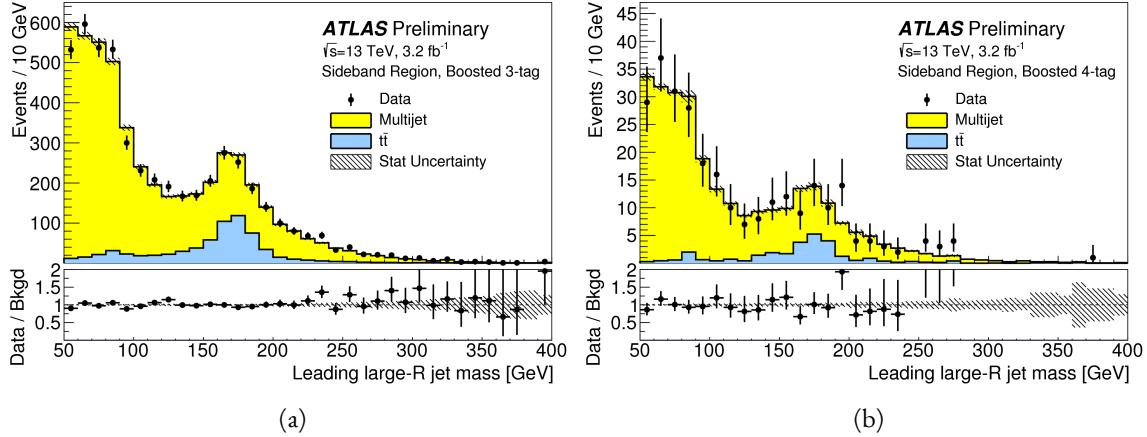


Figure 7.14: Leading large-R jet mass in the $3b$ (a) and $4b$ (b) sideband regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above. Because their normalizations are derived in the sideband region, the total background normalization is constrained by default to match the normalization of the data [109].

2414 Other shapes are considered and used for the systematic uncertainties. Table 7.4 shows the fit values for
 2415 the parameters. Because both the $3b$ and $4b$ QCD shapes come from the 2-tag region, the slopes derived
 2416 are very similar.

	a	b
QCD ($4b$)	0.00545 ± 0.00021	5.44 ± 0.24
$t\bar{t}$ ($4b$)	0.00746 ± 0.00021	4.88 ± 0.36
QCD ($3b$)	0.00545 ± 0.00021	8.30 ± 0.24
$t\bar{t}$ ($3b$)	0.00746 ± 0.00021	8.58 ± 0.36

Table 7.4: Parameters derived for exponential fit to background M_{2J} shape in the $3b$ and $4b$ signal regions [109]

2417 7.6.4 VALIDATION OF BACKGROUND ESTIMATE

2418 The background estimate can be validated by using the method to estimate the number of events in the
 2419 control mass region rather than the signal mass region. Figure 7.15 shows the M_{2J} distribution in the $3b$
 2420 and $4b$ control regions, comparing data and background estimates. In both cases, both the background
 2421 shape and normalization are consistent with the data, indicating good agreement. The ratio of data to the
 2422 background estimates is also fit to a line in the figure to test for any shape difference. The slope of the
 2423 line is within 1σ (from the fit uncertainties) of flat, further indicating that the data is consistent with the
 2424 background estimate in the control region.

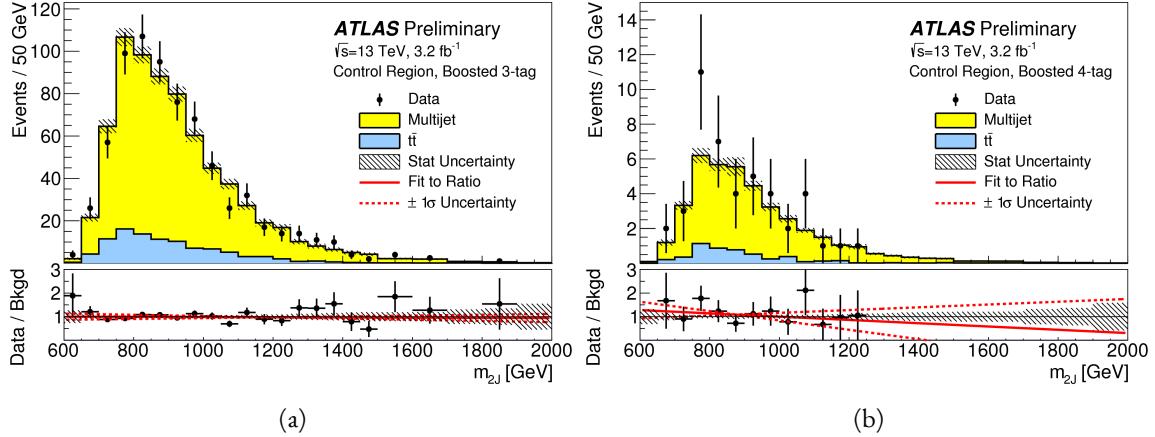


Figure 7.15: Di-jet invariant mass (M_{2J}) in the 3b (a) and 4b (b) control regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above [109].

Table 7.5 shows the yields in data and background estimates in the 3-tag and 4-tag sideband and control regions. Again, here, it can be seen that the total number of predicted background events from the data driven method is consistent with the number of data events in the region.

Sample (3-tag)	Sideband Region	Control Region
Multijet	4328 ± 27	607 ± 10
$t\bar{t}$	683.5 ± 8.1	99.6 ± 3.1
Z+jets	31.8 ± 3.7	7.7 ± 1.8
Total	5043 ± 28	715 ± 11
Data	5043	724
Sample (4-tag)	Sideband Region	Control Region
Multijet	247.4 ± 1.5	34.7 ± 0.6
$t\bar{t}$	28.4 ± 1.5	5.1 ± 0.7
Z+jets	3.4 ± 1.2	0.6 ± 0.5
Total	279.2 ± 2.5	40.3 ± 1.0
Data	279	45

Table 7.5: The number of events in data and predicted background events in the boosted 3-tag and 4-tag sideband and control regions. The uncertainties shown are statistical only. [109]

2428 7.7 SYSTEMATIC UNCERTAINTIES

2429 The systematic uncertainties in this analysis can be divided into two broad categories. The first type
2430 is uncertainties associated with the modeling of the signal processes. The second type of uncertainty is
2431 associated with both the shape and normalization of the background prediction.

2432 7.7.1 SIGNAL MODELING UNCERTAINTIES

2433 The signal modeling uncertainty has three main components: theoretical uncertainty on the acceptance,
2434 experimental uncertainties on the large-R jets, and experimental uncertainties on the track jets related to
2435 b -tagging. In this analysis the experimental uncertainties are the most significant.

2436 The first uncertainty on signal modeling is the theoretical uncertainty on the acceptance. As explained
2437 in section 5.6.1, there are four components to this uncertainty. The first is related to missing higher order
2438 terms from the matrix element calculations which is estimated by varying the QCD renormalization and
2439 factorization scales. The second is uncertainty due to the PDF set used. The third is a generator uncer-
2440 tainty which is estimated by modifying the generator used to model the underlying event and hadroniza-
2441 tion. Finally, there is an uncertainty associated with the modeling of the initial state and final state radia-
2442 tion (ISR/FSR). The total theoretical uncertainty on the signal yield is 3%, and this is dominated by the
2443 ISR/FSR modeling.

2444 There are uncertainties on the large-R jets in both the jet energy scale (JES) and jet energy resolution
2445 (JER) as well as the jet mass scale (JMS) and jet mass resolution (JMR). These are evaluated using $\sqrt{s} =$
2446 8 TeV data from Run 1 of ATLAS and extrapolated to the Run 2 beam and detector conditions using
2447 MC^s. The details of these uncertainties can be found in reference [111].

2448 Uncertainties on the track jets are related to the b -tagging efficiency. The total uncertainty on the signal
2449 yield due to b -tagging is evaluated by propagating variations of the b -tagging efficiency through the boosted
2450 selection requirements. The uncertainties are calculated jet-by-jet and parameterized as a function of b -jet
2451 p_T and η [89]. For high p_T b -jets (with $p_T > 300$ GeV), the uncertainties are extrapolated using MC
2452 simulation from the lower p_T b -jets [112].

^sThe uncertainties are correspondingly larger due to the uncertainty of this extrapolation.

2453 Table 7.6 shows the systematic uncertainties on the signal normalization for models with $m_{G_{\text{KK}}^*} =$
 2454 1.5 TeV and both $c = 1$ and $c = 2$ as well as a narrow width heavy scalar. The dominant uncertainty
 2455 comes from b -tagging and this uncertainty is larger in the 4-tag region than the 3-tag region.

Source	Background	G_{KK}^*		H
		$c = 1$	$c = 2$	
Luminosity	-	5.0	5.0	5.0
3-tag				
JER	< 1	< 1	< 1	< 1
JES	2	< 1	< 1	< 1
JMR	1	12	12	11
JMS	5	14	13	17
b -tagging	1	23	22	23
Theoretical	-	3	3	3
Multijet Normalization	3	-	-	-
Statistical	2	1	1	1
Total	7	31	30	33
4-tag				
JER	< 1	< 1	< 1	< 1
JES	< 1	< 1	< 1	< 1
JMR	4	12	13	13
JMS	5	13	13	14
b -tagging	2	36	36	36
Theoretical	-	3	3	3
Multijet Normalization	14	-	-	-
Statistical	3	1	1	1
Total	15	42	42	43

Table 7.6: Summary of systematic uncertainties in the total background and signal event yields (expressed in %) in the boosted 3-tag and 4-tag signal regions. Systematic uncertainties on the signal normalization are shown for models with $m_{G_{\text{KK}}^*} = 1.5 \text{ TeV}$ and both $c = 1$ and $c = 2$ as well as a narrow width heavy scalar.

2456 **7.7.2 BACKGROUND UNCERTAINTIES**

2457 Uncertainties on the QCD multijet background normalization and shape are estimated using the con-
 2458 trol mass region. As shown previously, the background predictions in the control region match with the

2459 data yields within the statistical uncertainty in both the 3-tag and 4-tag control regions. As an additional
 2460 protection, the statistical uncertainty on the background prediction in the control region is assigned as a
 2461 systematic uncertainty on the normalization of the QCD background.

2462 Additional robustness tests are done by varying the definition of the control mass region and the b -
 2463 tagging requirements used to define the 2-tag sample. In all cases, the effect of the variations is found to be
 2464 within the statistical uncertainties on the background normalization in the control region.

2465 Shape uncertainties on the background are evaluated using two techniques. First, as shown in fig-
 2466 ure 7.15, the ratio between the data and background prediction is fit with a linear function. The uncer-
 2467 tainties on the slope of this fit are assigned as shape uncertainties. An additional uncertainty is assigned by
 2468 using alternate power law fit functions for the smoothing of the background shape. Table 7.7 shows the
 2469 alternate shapes used. The largest difference between the nominal fit function and the alternates, taking
 2470 into account the 1σ uncertainty band on each fit as well, is taken as a shape uncertainty.

Functional Form
$f_1(x) = p_0(1 - x)^{p_1}x^{p_2}$
$f_2(x) = p_0(1 - x)^{p_1}e^{p_2 x^2}$
$f_3(x) = p_0(1 - x)^{p_1}x^{p_2}x$
$f_4(x) = p_0(1 - x)^{p_1}x^{p_2} \ln x$
$f_5(x) = p_0(1 - x)^{p_1}(1 + x)^{p_2}x$
$f_6(x) = p_0(1 - x)^{p_1}(1 + x)^{p_2} \ln x$
$f_7(x) = \frac{p_0}{x}(1 - x)^{p_1-p_2} \ln x$
$f_8(x) = \frac{p_0}{x^2}(1 - x)^{p_1-p_2} \ln x$

Table 7.7: Alternate fit functions used to model the M_{2J} distribution in the QCD multijet background. In the equations, $x = M_{2J}/\sqrt{s}$.

2471 The uncertainties on the $t\bar{t}$ background are obtained by propagating the various experimental variations
 2472 (JES, JER, JMS, JMR, b -tagging) through the analysis selection requirements. Table 7.6 summarizes the
 2473 background uncertainties in the 3-tag and 4-tag regions.

2474 7.8 RESULTS

2475 Table 7.8 shows the observed yields in the 3-tag and 4-tag signal regions for the boosted analysis com-
 2476 pared to the predicted number of background events. In the 3-tag region, 316 events are observed with
 2477 a predicted background of 285 ± 19 . In the 4-tag region, 20 events are observed with a predicted back-
 2478 ground of 14.6 ± 2.4 . Figure 7.16 shows the M_{2J} distribution in the 3-tag and 4-tag regions. There are
 2479 some small excesses in the data, in particular in the 3-tag region around $M_{2J} \approx 900$ GeV and in the region
 2480 of $1.6 < M_{2J} < 2.0$ TeV. The significance of these excesses will be evaluated in the next chapter in the
 2481 statistical combination with the resolved results.

Sample	Signal Region (3-tag)	Signal Region (4-tag)
Multijet	235 ± 14	13.5 ± 2.4
$t\bar{t}$	48 ± 22	1.2 ± 1.0
$Z + \text{jets}$	2.0 ± 2.2	-
Total	285 ± 19	14.6 ± 2.4
Data	316	20
G_{KK}^* (1000 GeV), $c = 1$	3.4 ± 0.9	2.9 ± 1.1

Table 7.8: Observed yields in the 3-tag and 4-tag signal regions for the boosted analysis compared to the predicted number of background events Errors correspond to the total uncertainties in the predicted event yields. The yields for a graviton with $m_{G_{\text{KK}}^*} = 1$ TeV and $c = 1$ are also shown. [109]

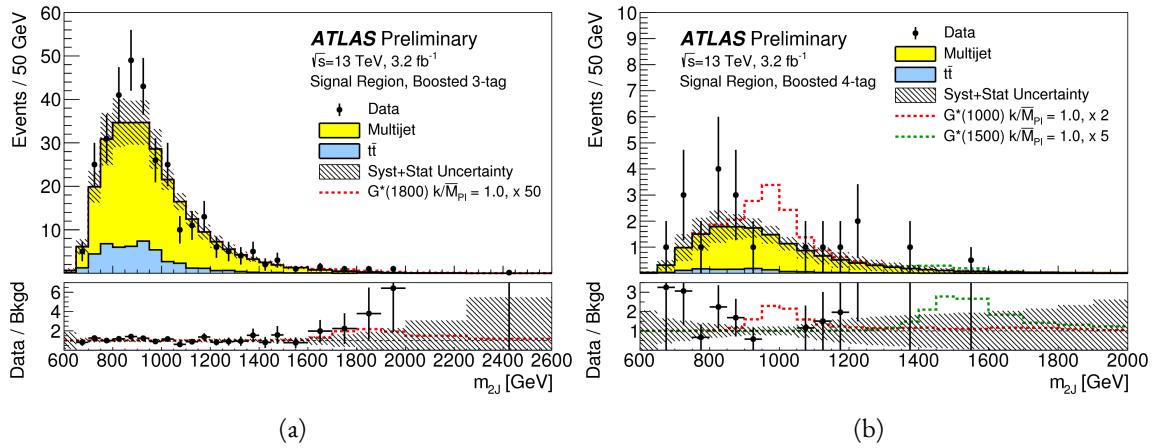


Figure 7.16: Di-jet invariant mass (M_{2J}) in the $3b$ (a) and $4b$ (b) signal regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above. In the $3b$ region, a graviton signal with $m_{G_{KK}^*} = 1.8 \text{ TeV}$ and $c = 1$ is overlaid, with the cross section multiplied by a factor of 50 so that the signal is visible. In the $4b$ region, signals with $m_{G_{KK}^*} = 1.0 \text{ TeV}$ and $m_{G_{KK}^*} = 1.5 \text{ TeV}$ are overlaid, both with $c = 1$ and the yields multiplied by factors of 2 and 5 respectively [109].

*There is no real ending. It's just the place where you stop
the story.*

Frank Herbert

8

2482

2483

Combined limits from boosted and resolved searches

2484

2485

8.1 INTRODUCTION

2486 In order to cover the full mass range of possible resonances decaying to di-Higgs final states, two distinct
2487 tailored selections were produced. The resolved selection is more sensitive in the mass range of $400 < m_X < 1100$ GeV while the boosted selection is more sensitive to masses in the range $1100 < m_X <$
2488 3000 GeV. Chapter 7 presents the details of the boosted selection and results. In setting limits on spin-2
2489 Randall-Sundrum graviton (RSG) and narrow width heavy scalar (H) models, the results of the boosted
2490 selection are combined with the results of the resolved selection to cover the full mass range.
2491

2492 This chapter presents limits on signal models resulting from the $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ search in both
2493 the resolved and boosted selections. It first presents a brief overview of the resolved results that go into

2494 the limit setting. Then, an overview of the statistical methods used for the search and limit setting is given.
2495 Finally, limits on the RSG and heavy scalar models are presented.

2496 **8.2 RESOLVED RESULTS**

2497 The details of the resolved selection will not be presented here and can be found in reference [109]. In
2498 basic terms, the selection searches for four $R = 0.4$ b-tagged calorimeter jets (where each pair of jets is
2499 one Higgs candidate). This is distinct from the boosted methodology which searches for merged decay
2500 products. The backgrounds to the resolved selection are the same as those presented in Chapter 7 for the
2501 boosted analysis.

2502 Table 8.1 shows the results for data yields and expected background in the resolved signal region. Fig-
2503 ure 8.1 shows the M_{2J} distribution in the resolved signal region. The total number of events is consistent
2504 with the prediction and no significant excess is seen. One event in the boosted 4-tag signal is shared with
2505 the resolved signal region and has a mass of 852 GeV.

Sample	Signal Region Yield
Multijet	43.3 ± 2.3
$t\bar{t}$	4.3 ± 3.0
$Z + \text{jets}$	-
Total	47.6 ± 3.8
Data	46
SM hh	0.25 ± 0.07
$G_{\text{KK}}^*(800 \text{ GeV}), c = 1$	5.7 ± 1.5

Table 8.1: Observed yields in the resolve selection 4-tag signal region compared to the predicted number of background events Errors correspond to the total uncertainties in the predicted event yields. The yields for a graviton with $m_{G_{\text{KK}}^*} = 800$ GeV and $c = 1$ are also shown. [109]

2506 **8.3 SEARCH TECHNIQUE AND RESULTS**

2507 The statistical technique used for the search in this analysis is the same as that used in the $H \rightarrow WW^*$
2508 analysis presented in section 3.6.2. The test statistic q_0 is used to define the p -values which measure the

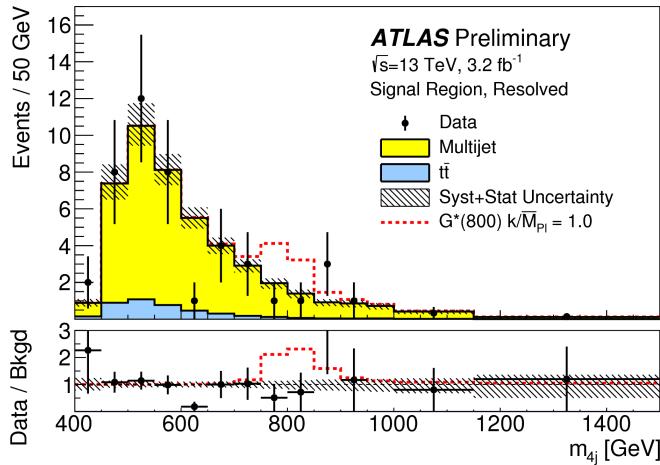


Figure 8.1: Di-jet invariant mass (M_{2J}) in the resolved signal region. A graviton signal with $m_{G_{KK}^*} = 800$ GeV and $c = 1$ is overlaid. [109].

compatibility of the data with the background-only hypothesis corresponding to a signal strength $\mu = 0$.

Local p_0 values are computed to quantify the probability that the background could produce a fluctuation greater than or equal to the one observed in the data. In the resolved analysis, no significant excesses are observed. The largest discrepancy with respect to the background only hypothesis occurs near a resonance mass of 900 GeV and is found to be less than 2σ in significance.

In the boosted selection, the largest local excess is a broad excess in the $3b$ signal region that begins near $M_{2J} \approx 1.7$ GeV. Assuming a G_{KK}^* with this mass and $c = 1.0$, the local significance of this excess is 2.0σ .

8.4 LIMIT SETTING

In the absence of any significant excess observed in the data, limits on different signal models can be set. This section describes the limit setting procedure and presents combined results of the resolved and boosted analyses.

8.4.1 LIMIT SETTING PROCEDURE

The procedure used for setting exclusion limits in this analysis is the CL_s method [113]. The first step in setting the limits is to define a test statistic which will be used. For limit setting, the test statistic is shown

2524 in equation 8.1.

$$\tilde{q}_\mu = \begin{cases} -2 \ln \frac{L(\mu, \hat{\theta}(\mu))}{L(0, \hat{\theta}(0))} & \hat{\mu} < 0 \\ -2 \ln \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} & 0 \leq \hat{\mu} < \mu \\ 0 & \hat{\mu} > \mu \end{cases} \quad (8.1)$$

2525 In the above equation, μ is the value of the signal strength under test, $\hat{\mu}$ is the best fit μ , $\hat{\theta}$ is the
2526 best fit value of the nuisance parameters, $\hat{\theta}$ is the best fit value of the nuisance parameters under the fixed
2527 μ value, and L is the Poisson likelihood of the data (as described in section 3.6.2).

2528 The test statistic \tilde{q}_μ is constructed to protect against two interesting corner cases when setting the upper
2529 limit on the cross section. First, it protects against negative signal strengths μ which are unphysical. Second,
2530 it does not count excesses in the data larger than those expected by a signal strength μ as evidence against
2531 the μ hypothesis.

2532 The CL_s statistic is constructed by taking a ratio of two probabilities. CL_{s+b} is the probability that the
2533 signal+background hypothesis would produce a value of the test statistic that is less than or equal to the
2534 observed value¹. CL_b is the probability that the background only hypothesis will produce a value
2535 of the test statistics less than or equal to the observed. The CL_s statistic is then the ratio CL_{s+b}/CL_b . A
2536 95% upper limit on the cross section is set at the value of μ that makes the CL_s statistic less than 5%.

2537 In practice, the limits are computed numerically within an asymptotic approximation for the distribu-
2538 tion of the test statistic \tilde{q}_μ . The details of this approximation can be found in reference [64].

2539 The resolved and boosted analyses are combined using a very simple procedure rather than a full statis-
2540 tical combination. For each mass point tested, the limit which gives the most stringent constraint is used.
2541 This means that for mass points below 1.1 TeV the resolved signal region is used, while at and above this
2542 point the combination of the orthogonal 3b and 4b boosted signal regions is used.

2543 8.4.2 LIMIT SETTING RESULTS

2544 Figure 8.2 shows the combined 95% upper bounds as a function of mass for three different models:
2545 G_{KK}^* with $c = 1$, G_{KK}^* with $c = 2$, and a narrow heavy scalar H .

¹Lower values of \tilde{q}_μ mean better compatibility

2546 The cross section of $\sigma(pp \rightarrow G_{\text{KK}}^* \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ with $c = 1$ is constrained to be less than 70 fb
2547 for masses in the range $600 < m_{G_{\text{KK}}^*} < 3000$ GeV. For the RSG model with $c = 2$, cross sections limits
2548 between 40 fb and 200 fb are set for the mass range of $500 < m_{G_{\text{KK}}^*} < 3000$ GeV. Masses in the range
2549 of $475 < m_{G_{\text{KK}}^*} < 785$ GeV are excluded with $c = 1$ (with an exclusion of the range 465 to 745 GeV
2550 expected). Masses less than 980 GeV are excluded with $c = 2$ (with an exclusion for masses less than
2551 1 TeV expected).

2552 In the heavy Higgs model, the cross section upper limits for $\sigma(pp \rightarrow H \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ ranges from
2553 30 to 300 fb in the mass range of $500 < m_H < 3000$ GeV. The resolved analysis can also set an upper
2554 limit on the Standard Model di-Higgs production cross section discussed in chapter 3. The upper limit on
2555 $\sigma(pp \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ in the Standard Model is constrained to be less than 1.22 pb.

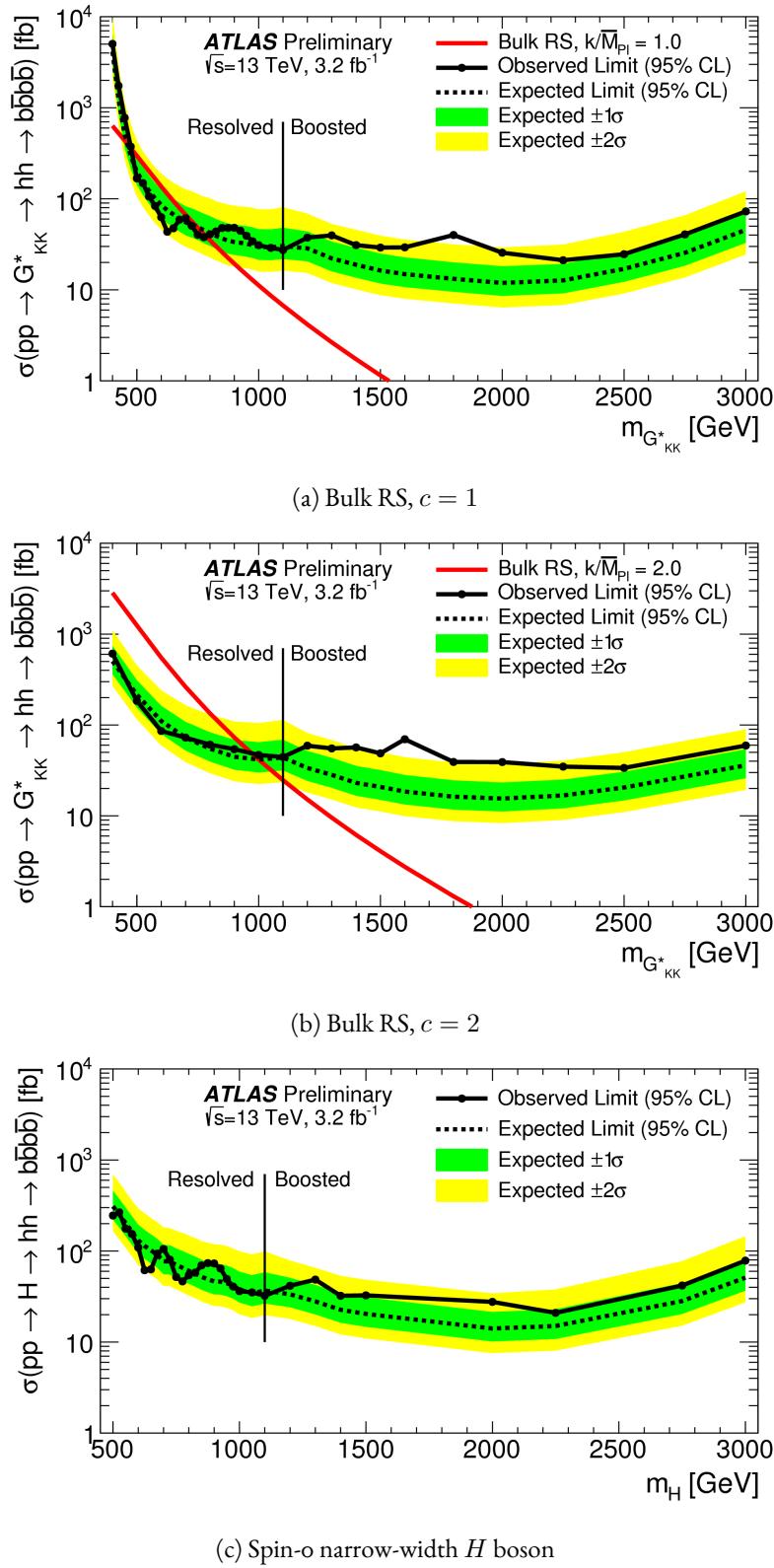


Figure 8.2: Expected and observed upper limit as a function of mass for G_{KK}^* in the RSG model with (a) $c = 1$ and (b) $c = 2$, as well as (c) H with fixed $\Gamma_H = 1$ GeV, at the 95% confidence level in the CL_s method. [109]

2556

Part IV

2557

Looking ahead

9

2558

2559

Conclusion

2560 After being sought for many years at different collider experiments, the Higgs boson was discovered by
2561 the ATLAS and CMS experiments in 2012, confirming the leading theory for the source of electroweak
2562 symmetry breaking and filling in the last missing piece of the Standard Model. After its discovery, mea-
2563 surements of the particle's detailed properties and searches for new particles decaying to Higgs final states
2564 were both extremely important in constraining physics beyond the Standard Model. This dissertation
2565 presented this evolution through two results: the observation and measurement of the Higgs boson in the
2566 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV and a search for Higgs pair production
2567 in the $HH \rightarrow b\bar{b}b\bar{b}$ channel at $\sqrt{s} = 13$ TeV with the ATLAS detector in pp collisions at the Large
2568 Hadron Collider.

2569 In the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, results from both the discovery of the Higgs boson and the full ATLAS
2570 Run 1 dataset were presented. The Higgs boson was discovered with a 6.1σ significance in a combina-
2571 tion of the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ4\ell$, $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ with 4.2 fb^{-1} at $\sqrt{s} = 7$ TeV and

2572 5.2 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. With the full 20.3 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ and 4.2 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$,
2573 ATLAS achieved discovery level significance in the $H \rightarrow WW^*$ channel alone and obtained the first ob-
2574 servation of vector boson fusion production in that channel. The combined signal strength is measured
2575 to be $\mu = 1.09^{+0.23}_{-0.21}$. The total observed significance of the $H \rightarrow WW^*$ process is observed to be 6.1σ
2576 (with 5.8σ expected). Advanced methods for background reduction and estimation, particularly in same-
2577 flavor lepton final states, are shown. The VBF signal strength is measured to be $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$ with
2578 an observed significance of 3.2σ (with 2.7σ expected).

2579 These results required many novel innovations. The increase of pileup interactions in the higher in-
2580 stantaneous luminosity LHC conditions of 2012 led to a degradation of missing transverse momentum
2581 resolution. As a result, the prominent $Z/\gamma^* + \text{jets}$ background of the same flavor $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
2582 final states increased greatly. New variables, including a track-based missing transverse momentum and a
2583 measurement of the balance between the dilepton system and recoiling jets, allowed for significant reduc-
2584 tion of this background. In the VBF channel, selections were optimized to exploit the unique VBF final
2585 state topology. Incorporating these variables into a boosted decision tree technique allowed the analysis
2586 to exceed the 3σ observation threshold.

2587 After the end of Run 1, the results of Higgs measurements from ATLAS were combined with those
2588 from CMS to produce the most precise measurements of the Higgs boson so far [114]. Figure 9.1 shows the
2589 combination of ATLAS and CMS data for the Higgs signal strength in and coupling measurements. In the
2590 signal strength measurements of gluon fusion and vector boson fusion, the $H \rightarrow WW^*$ channel provides
2591 the tightest constraints. Additionally, the Higgs coupling to W bosons is the most precisely measured with
2592 a relative uncertainty of 10%.

2593 With the discovery of the Higgs firmly established and its properties measured, a natural next step was
2594 to search for new physics with Higgs final states. At $\sqrt{s} = 13 \text{ TeV}$, a search for Higgs pair production
2595 in the $b\bar{b}b\bar{b}$ final state with 3.2 fb^{-1} was conducted. A signal region optimized for the boosted final states
2596 arising from high mass resonances was constructed. This signal region utilized large-radius calorimeter jets
2597 and b -tagging with small radius track jets to maximize the signal acceptance. No significant excesses were
2598 observed, and upper limits on cross sections are placed for spin-2 Randall Sundrum gravitons (RSG) and

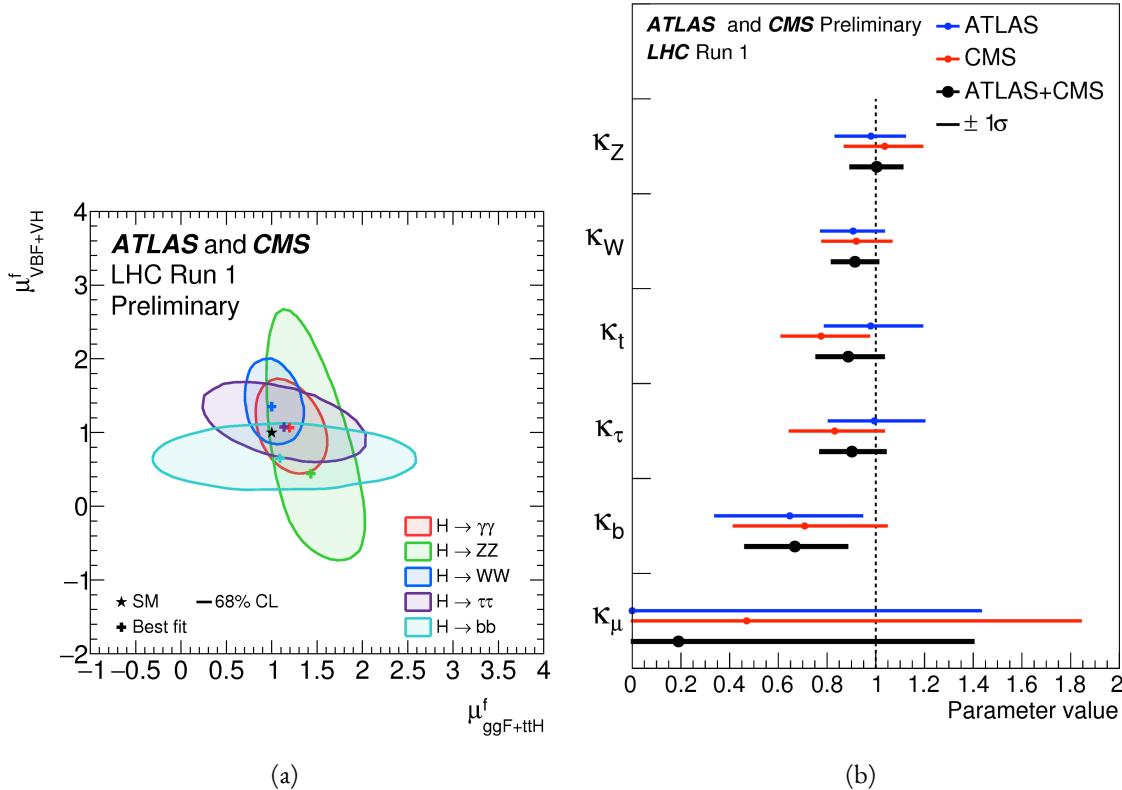


Figure 9.1: Combined ATLAS and CMS measurements in Run 1 for (a) Higgs signal strength in gluon fusion and VBF and (b) Higgs couplings normalized to their SM predictions

narrow spin-0 resonances. The increase in center of mass energy in Run 2 allowed this analysis to extend upper limits up to 3 TeV, while previous results from ATLAS in Run 1 only quotes limits up to 2 TeV. The cross section of $\sigma(pp \rightarrow G_{KK}^* \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ with $k/\bar{M}_{\text{Pl}} = 1$ is constrained to be less than 70 fb for masses in the range $600 < m_{G_{KK}^*} < 3000$ GeV. For the RSG model with $k/\bar{M}_{\text{Pl}} = 2$, cross sections limits between 40 fb and 200 fb are set for the mass range of $500 < m_{G_{KK}^*} < 3000$ GeV. The cross section upper limits for $\sigma(pp \rightarrow H \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ ranges from 30 to 300 fb in the mass range of $500 < m_H < 3000$ GeV.

While there has been a rigorous program of measurements and searches involving the Higgs, there is still much room for improvement at the High Luminosity LHC (HL-LHC) and beyond. The measured signal strength for VBF production in $H \rightarrow WW^*$ still has a relative error at the level of 40%, largely dominated by statistical uncertainty. Projections for the HL-LHC show that the uncertainty on the VBF signal strength can be reduced to approximately 15% with 3000 fb^{-1} [n5, n6]. This uncertainty also

2611 assumes that theoretical uncertainties on the signal, which would be the largest contribution in this dataset,
 2612 remain as they are now. Improvements in the theoretical understanding of the Higgs signal would also
 2613 reduce the signal strength uncertainty dramatically. Such precision measurements allow for measurements
 2614 of the Higgs coupling to vector bosons precise to the few percent level, therefore giving much power to
 2615 constrain or discover new physics.

2616 The prospects for detection of beyond the Standard Model resonant di-Higgs production at the HL-
 2617 LHC are also quite promising. Figure 9.2 shows projections for the discovery significance of RSG signals at
 2618 the HL-LHC in the $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ search [ii6]. In all detector budget scenarios, a 1.5 TeV resonance
 is above or near 5σ significance, while a 2 TeV resonance is between $4-5\sigma$ except for the lowest budget.

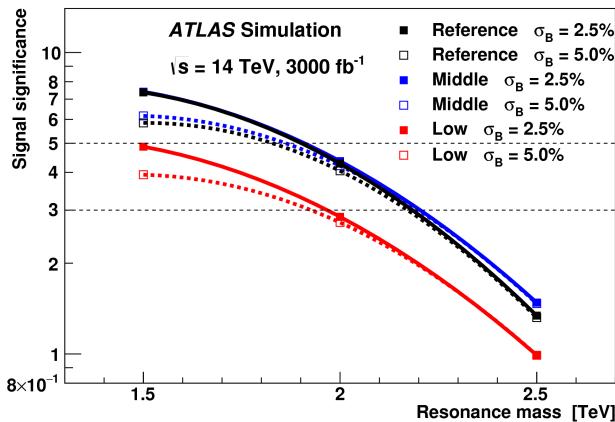


Figure 9.2: Discovery significance for RSG models at the HL-LHC in three different budget scenarios [ii6]. Systematic uncertainties on the background prediction (σ_B) of 2.5% and 5.0% are both tested.

2619
 2620 The Higgs will continue to be an incredibly powerful tool in the understanding of nature at the HL-
 2621 LHC and beyond. Through both precision measurements and searches, the nature of electroweak symme-
 2622 try breaking will be better understood and the potential for the discovery of physics beyond the Standard
 2623 Model has never been greater.

A

2624

2625

b-tagging performance at high p_T

2626 One of the limiting factors of the signal acceptance in the $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ search at high resonance
2627 masses is the degradation of the *b*-tagging efficiency for high p_T jets. This appendix presents a study of the
2628 underlying causes of this degradation.

2629 A.I CHANGES IN MV₂ SCORE AT HIGH p_T

2630 The degradation of *b*-tagging at high p_T was studied in particular in the context of RSG models at high
2631 mass. Figure A.I shows the p_T of the leading track jet inside of the leading calorimeter jet in RSG events.
2632 At high $m_{G_{KK}^*}$, the p_T spectrum of track jets is much harder than at lower masses due to the increased
2633 Higgs p_T .

2634 Figure A.2 shows the MV_{2c2o} algorithm score for the leading and subleading track jets inside of the
2635 leading calorimeter jet. In both cases, it can be seen that at higher RSG masses the MV₂ score shifts towards
2636 more background like (negative) values. Additionally, this effect is more pronounced in the leading track

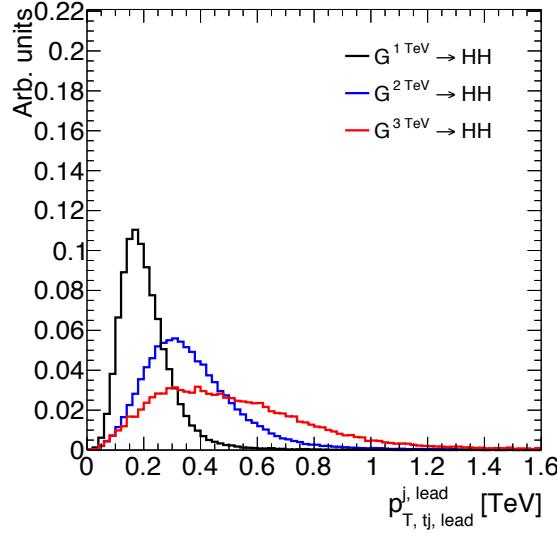


Figure A.1: p_T of the leading track jet in the leading calorimeter jet for different signal masses in RSG $c = 1$ models

2637 jet than the subleading.

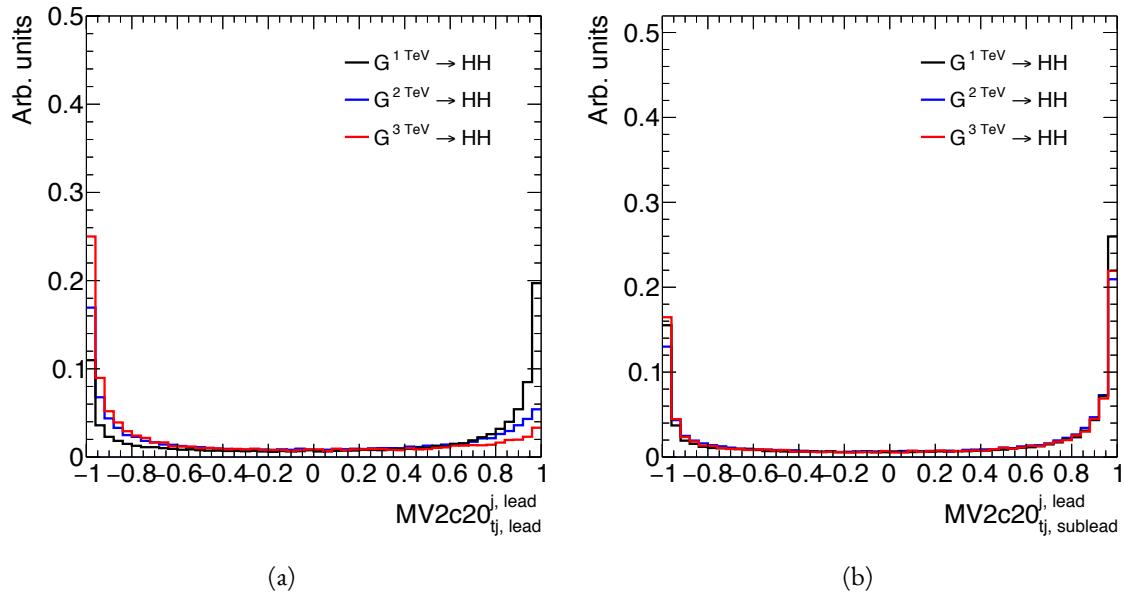


Figure A.2: MV2c20 score for the leading track jet (a) and subleading track jet (b) of the leading calorimeter jet for different signal masses in RSG $c = 1$ models

2638 To understand what is causing this change in the MV2c20 score, the same comparisons can be made for
 2639 the input variables of MV2c20. The focus in these comparisons will be on the leading track jet as this is the
 2640 one seen to have the largest difference in MV2 score. Figure A.3 shows the log likelihood ratio $\log(p_b/p_u)$

from the IP₃D (three dimensional impact parameter) algorithm. At higher masses, the IP₃D likelihood ratio distribution does become more background-like.

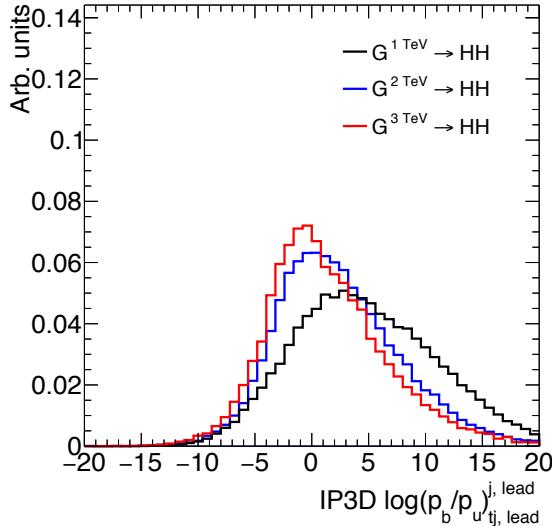


Figure A.3: IP₃D log-likelihood ratio ($\log(p_b/p_u)$) of the leading track jet in the leading calorimeter jet for different signal masses in RSG $c = 1$ models

Figure A.4 shows the mass and number of tracks at the secondary vertex computed by the SV1 algorithm. When there is no secondary vertex found, the algorithm assigns a default negative value for these quantities. Both of these distributions show that there is a significantly larger fraction of jets where no secondary vertex is found in the high mass samples compared to the $m_{G_{KK}^*} = 1$ TeV sample. The SV1 algorithm's inability to find a secondary vertex could be an important factor in the overall MV₂ score shift, as this eliminates eight of the input variables that would normally contribute information to the algorithm.

Figure A.5 shows the same quantities for the JetFitter algorithm. In this case, there is also a change in the fraction of jets which have their secondary vertices successfully reconstructed, but this change is not as drastic as that seen in SV1. There is also an increase in the number of jets which have high values of mass.

A.2 EFFECT OF MULTIPLE b -QUARKS INSIDE ONE JET

One hypothesis for why the efficiency of b -tagging the leading track jet degrades is that at high masses, the b quarks get close enough together that both of them are inside of the leading track jet. Because MV₂

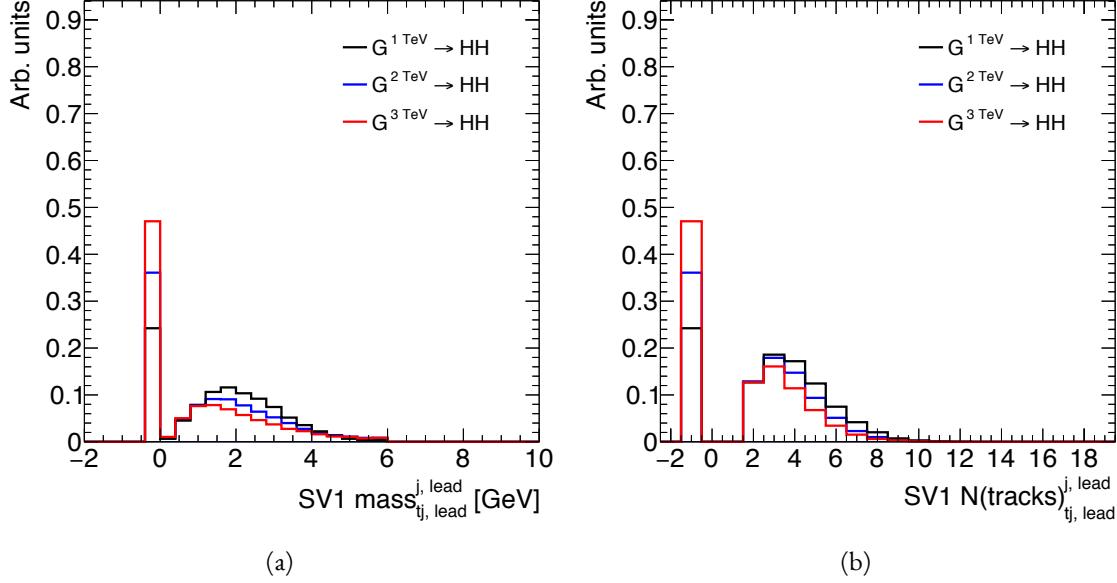


Figure A.4: Mass (a) and number of tracks (b) for the secondary vertices computed with the SV1 algorithm. When no secondary vertex is found, the quantities are assigned to default negative values.

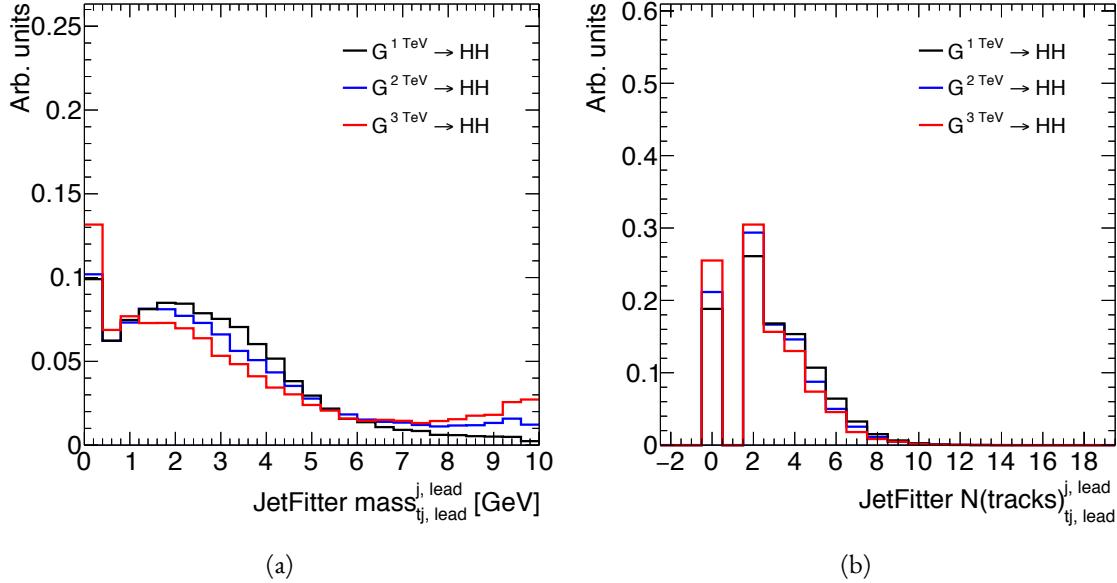


Figure A.5: Mass (a) and number of tracks (b) for vertices computed with the JetFitter algorithm. When no vertices are found, the quantities are assigned to default negative values.

2655 is not tuned for tagging multiple b quarks inside one jet, the tagging efficiency could degrade. Figure A.6
 2656 shows MV₂ scores and SV1 mass for cases where there are two b quarks at truth level within the radius of

the leading track jet compared to cases where there is only one true b^l . This figure suggests that the presence

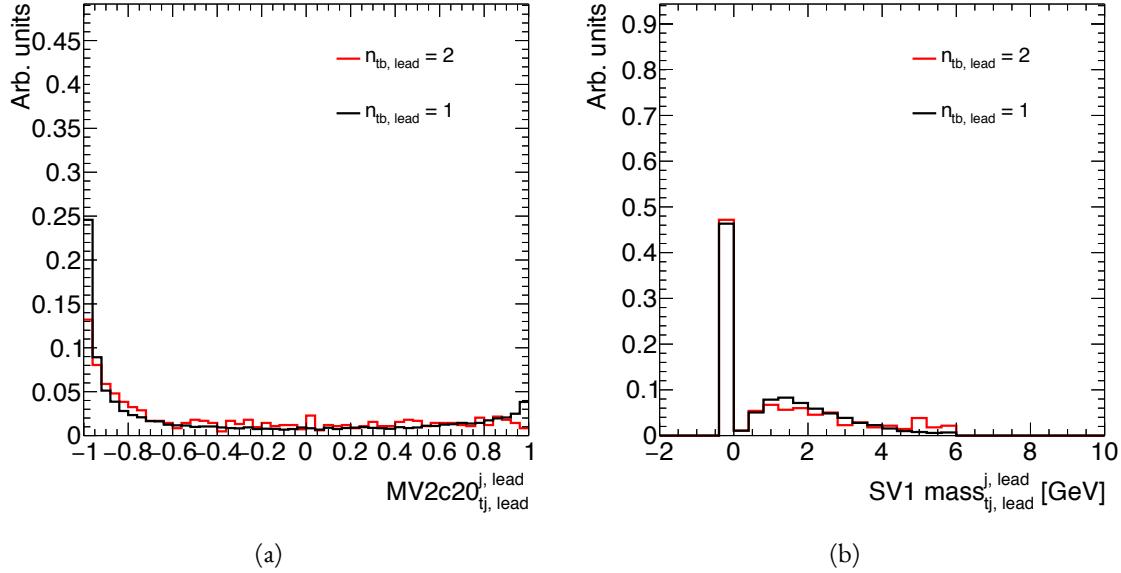


Figure A.6: MV₂c20 score (a) and SV1 mass (b) for leading track jets with two truth b quarks ($n_{tb,\text{lead}} = 2$) compared to those with only one truth b ($n_{tb,\text{lead}} = 1$).

of two b -quarks inside the leading jet is not the cause of the degradation in efficiency. There is a change in the shape of the MV₂ score distribution, but it is not nearly as pronounced as that seen in A.2 at higher masses. Additionally, the fraction of jets with no secondary vertex found is nearly identical in the track jets with two truth b -quarks.

A.3 CHANGES IN TRACK QUALITY AT HIGH p_T

Another hypothesis for the degradation of the b -tagging efficiency is a decrease in track quality for high p_T b jets. One way to check the overall quality of the tracking inside the jet is to investigate quantities related to the leading track inside of the track jet. Figure A.7 shows the fit χ^2/n_{DOF} and number of hits in the pixel detector for the leading track of the leading track jet. In both cases, the figure shows that in higher mass samples, the quality of the leading track inside of the track jet degrades substantially. The fit quality is lessened and the tracks have less hits in the pixel detector. This is likely due to the fact that at higher p_T ,

¹When two truth b quarks are required in the leading jet, the subleading jet is required to have zero. When one is required for the leading, one is also required for the subleading.

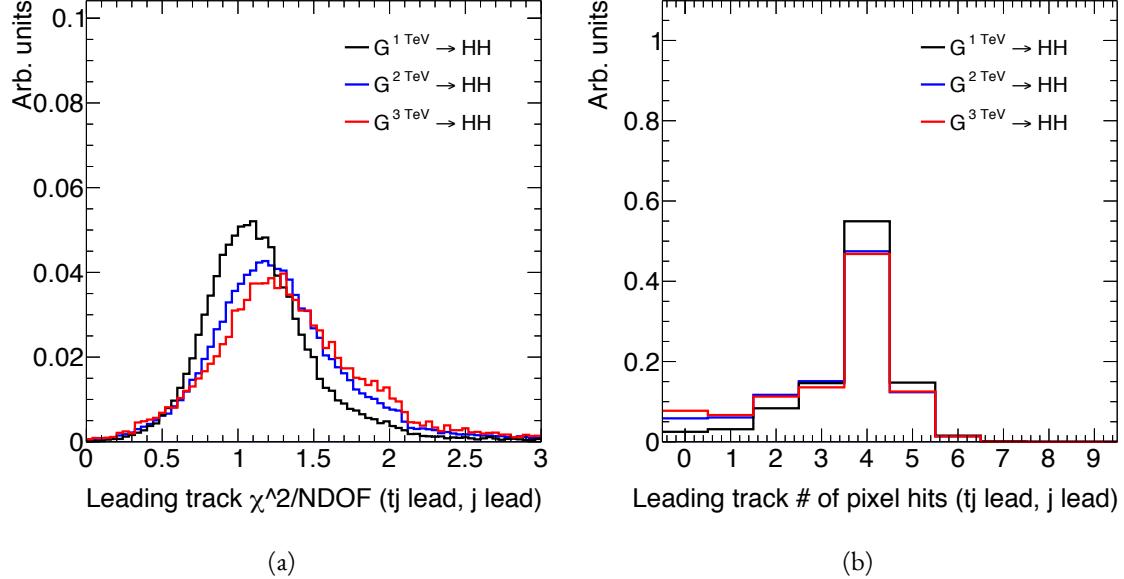


Figure A.7: Track fit χ^2/nDOF (a) and number of pixel detector hits (b) for the leading track of the leading track jet in different mass RSG $c = 1$ samples

the B -hadron will sometimes live long enough to miss the IBL and first pixel layer, thus decreasing the number of hits on the track.

To check whether this is the cause for the shift in the MV_2 score and the higher difficulty in reconstructing secondary vertices, jets whose leading track have at least four pixel hits are compared with those whose tracks have less than four pixel hits. The results for the MV_2 score and SV_1 mass are shown in figure A.8. Track jets where the leading track does not have at least four pixel hits are more likely to not have a secondary vertex reconstructed. Additionally, their $\text{MV}_{2\text{c}2\text{o}}$ score is shifted more significantly to background-like values. This seems to confirm the hypothesis that degrading track quality is responsible for the lowered b -tagging efficiency at high p_T .

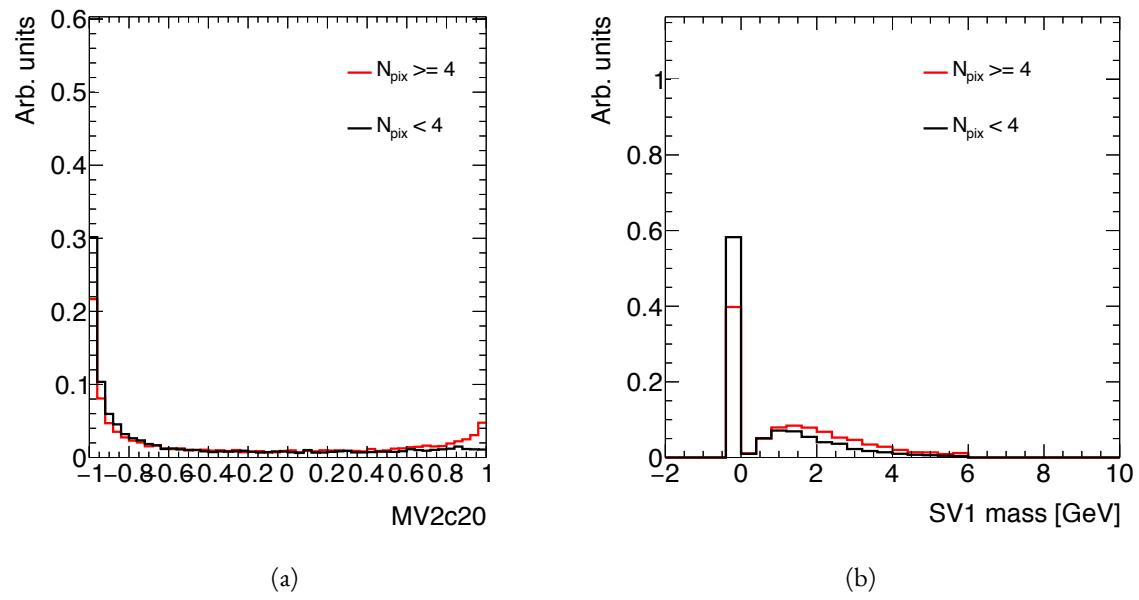


Figure A.8: MV₂c₂₀ score (a) and SV₁ mass (b) for leading track jets whose leading track jet has at least four pixel hits ($N_{\text{pix}} \geq 4$) compared to those which do not ($N_{\text{pix}} < 4$).

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2951

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