

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 two studies: the observation and measurement of the Higgs boson in the
25 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV and a search for Higgs pair pro-
26 duction 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
27 Large Hadron Collider.

28 First, the discovery of a particle consistent with the Higgs in 4.8 fb^{-1} at $\sqrt{s} = 7$ TeV and 5.8 fb^{-1} at
29 $\sqrt{s} = 8$ TeV is discussed. Then, the measurement of the Higgs boson signal strength and cross section
30 in both the gluon fusion and vector boson fusion (VBF) production modes using 20.3 fb^{-1} of $\sqrt{s} =$
31 8 TeV data combined with 4.8 fb^{-1} of 7 TeV data is shown. The combined signal strength is measured
32 to be $\mu = 1.09^{+0.23}_{-0.21}$. The total observed significance of the $H \rightarrow WW^*$ process is observed to be
33 6.1σ (with 5.8σ expected). Advanced methods for background reduction and estimation, particularly in
34 same-flavor lepton final states, are shown. The VBF signal strength is measured to be $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$
35 with an observed significance of 3.2σ (with 2.7σ expected). In the VBF channel, a selection requirement
36 based method, the precursor to the final multivariate technique used for the 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
38 is presented. A particular focus is placed on a tailored signal region for resonant production of Higgs
39 pairs at high masses, utilizing novel techniques in object reconstruction to increase signal acceptance in
40 boosted final state topologies. No significant excesses are observed, and upper limits on cross sections are
41 placed for spin-2 Randall Sundrum gravitons (RSG) and narrow spin-0 resonances. The cross section of
42 $\sigma(pp \rightarrow G_{\text{KK}}^* \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ with $k/\bar{M}_{\text{Pl}} = 1$ is constrained to be less than 70 fb for masses in the
43 range $600 < m_{G_{\text{KK}}^*} < 3000 \text{ GeV}$. For the RSG model with $k/\bar{M}_{\text{Pl}} = 2$, cross sections limits between

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- ⁴⁴ 40 fb and 200 fb are set for the mass range of $500 < m_{G_{\text{KK}}^*} < 3000$ GeV. The cross section upper
⁴⁵ 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 $500 < m_H <$
⁴⁶ 3000 GeV.

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0

487

488

Introduction

489 The Higgs boson is often described as one of the cornerstones of the Standard Model. Since the con-
490 ception of the Higgs mechanism as the source of electroweak symmetry breaking in the early 1960s,
491 countless collider experiments have searched for this elusive particle. This dissertation presents multi-
492 ple studies of the Higgs boson with the ATLAS detector at the Large Hadron Collider (LHC).

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

497 While the rate of events produced in $H \rightarrow WW^*$ is large, the channel poses some challenges. First,
498 the most common mode of study for this channel is $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. With neutrinos in the
499 final state, it is not possible to fully reconstruct the invariant mass of the parent Higgs like the $\gamma\gamma$ and
500 $ZZ \rightarrow 4\ell$ channels. Second, the final state topology is mimicked by a wide variety of backgrounds that

501 need to be properly estimated. This means tailored selection requirements for background reduction
502 and robust background estimation techniques must both be developed.

503 In 2012, the ATLAS and CMS experiments announced the discovery of a new particle consistent with
504 the Higgs boson [1, 2]. In ATLAS, this discovery was made with 4.8 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$ and
505 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.
506 After the discovery, measurement of the properties of the newly discovered particle and confirmation
507 of its consistency with the Standard Model Higgs were the main priorities. The WW^* channel is also
508 uniquely suited to these types of measurements. Because of its good rate, it offers some of the best cross
509 section measurements available among the various Higgs decay modes. It is also suited for measurement
510 of multiple Higgs production modes, like the vector boson fusion (VBF) mode, where incoming quarks
511 radiate W/Z bosons which fuse to make a Higgs. In VBF production with the WW^* decay channel,
512 the coupling of the Higgs to the W boson is present in both the production and decay which allows for
513 more precise measurements of this coupling than other channels which rely on gluon fusion production
514 (where gluons couple to the Higgs through a top loop in the production). The measurement of VBF
515 carries the additional challenge that its cross section is an order of magnitude smaller than that of gluon
516 fusion, meaning that the large branching ratio to WW^* offers an additional advantage in isolating this
517 production mode. In the final ATLAS Run 1 results, combining 20.3 fb^{-1} taken at $\sqrt{s} = 8 \text{ TeV}$ with
518 the 4.8 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$, the WW^* channel achieved its first observation of VBF produc-
519 tion of the Higgs.

520 After Run 1 of the LHC, with the existence of the Higgs now firmly established, the focus shifted to
521 searches for physics beyond the Standard Model. In particular, searches for high mass resonances benefit
522 from the LHC's increase to $\sqrt{s} = 13 \text{ TeV}$ in Run 2. The newly discovered Higgs can be used as a tool
523 in these searches. Higgs pair production in the Standard Model has a low cross section that requires large
524 datasets (on the order of the LHC's lifetime) for full measurement. However, new physics can modify
525 this cross section, especially new resonances which decay to two Higgs bosons. A search for Higgs pair
526 production in the $HH \rightarrow b\bar{b}b\bar{b}$ final state was performed with 3.2 fb^{-1} collected with ATLAS at $\sqrt{s} =$
527 13 TeV in 2015.

528 This dissertation begins by discussing the discovery of the Higgs and the role of the $H \rightarrow WW^* \rightarrow$
529 $\ell\nu\ell\nu$ channel. It then discusses the first observation of the VBF production mode in $H \rightarrow WW^* \rightarrow$
530 $\ell\nu\ell\nu$ with the full ATLAS Run 1 dataset, as well as the final combined Run 1 measurements from this
531 channel. Finally, it presents a search for Higgs pair production in the $HH \rightarrow b\bar{b}b\bar{b}$ channel. It is orga-
532 nized into four parts.

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

540 Part 2 discusses the observation and measurement of the Higgs in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
541 channel in the ATLAS Run 1 dataset at $\sqrt{s} = 7$ and 8 TeV. Because I worked in this channel from
542 before the discovery through to the final analysis of the Run 1 dataset, Part 2 is organized in such a way
543 to allow easy presentation of multiple analyses on different subsets of the full Run 1 dataset. Chapter 3
544 presents a general overview of the $H \rightarrow WW^*$ analysis strategy and defines many of the variables and
545 common elements used in the rest of Part 2. Chapter 4 presents the discovery of the Higgs boson, fo-
546 cusing on the role of the WW^* channel in this discovery. Chapter 5 presents the first observation of the
547 VBF production mode of the Higgs in the WW^* channel, a study which was done on the full Run 1
548 ATLAS dataset. In this chapter, the focus is mainly on the selection cut-based VBF analysis. The cut-
549 based analysis was an important first step to the final VBF result which used a Boosted Decision Tree
550 (BDT). Where appropriate, connections between the cut-based and BDT analyses are shown and their
551 compatibility is discussed. Finally, the VBF analysis was an important input into the combined Run 1
552 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ result, which used both the gluon fusion and VBF channels in a combined
553 fit to infer properties of the Higgs, including its couplings to the gauge bosons and its production cross
554 section. This is the topic of Chapter 6.

555 Part 3 presents a search for Higgs pair production in the $HH \rightarrow b\bar{b}b\bar{b}$ channel. Chapter 7 presents
556 an overview of this search in the boosted regime, where the Higgs pairs are the result of the decay of a
557 heavy resonance. Chapter 8 shows the combined results between the boosted regime and the resolved
558 regime, which is sensitive to lower mass resonances and non-resonant Higgs pair production. Finally,
559 Part 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

1

562

563

The Physics of the Higgs Boson

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

571 I.I THE STANDARD MODEL OF PARTICLE PHYSICS

572 The Standard Model (SM) of Particle Physics is a quantum field theory describing the fundamental
573 particles of nature and the forces that govern their interactions. Several comprehensive treatments of
574 the SM already exist in the literature [3–8] and this section will not rehash those. Rather, this section

575 presents a brief overview of the SM particles and forces in order to define them for subsequent discussions.
 576

577 The Standard Model consists of two primary categories of fundamental particles: fermions (spin 1/2
 578 particles) and bosons (integer spin particles). The SM also describes three forces: electromagnetism, the
 579 weak nuclear force, and the strong nuclear force. Gravity is not included in the theory and is largely irrele-
 580 vant at the scales currently probed by collider experiments. Within the fermions, there are both quarks
 581 (which interact via all three forces) and the leptons. The charged leptons interact via electromagnetic and
 582 weak interactions, while neutrinos (neutral leptons) interact only via the weak force. Within the bosons,
 583 there are the W^\pm and Z bosons (the mediators of the weak force), the gluon (g , the mediator of the
 584 strong force), and the photon (γ), the mediator of the electromagnetic force. Finally, there is the Higgs
 585 boson, a fundamental spin-0 particle resulting from the Higgs mechanism of electroweak symmetry
 586 breaking. Figure 1.1 summarizes the fermions and bosons of the SM.

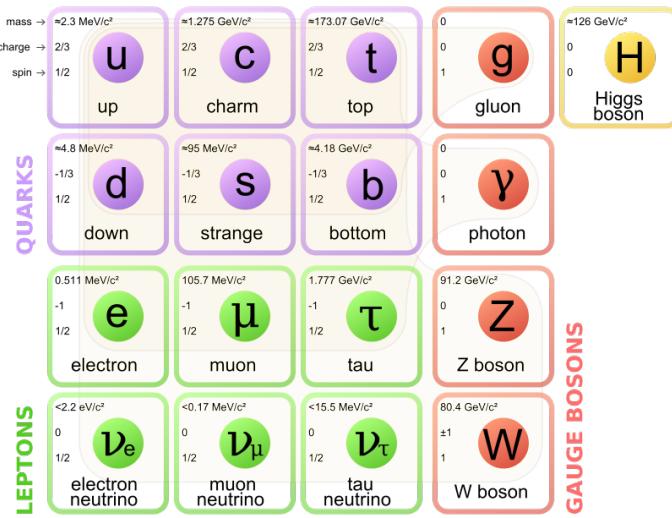


Figure 1.1: The particles of the Standard Model and their properties [6].

587 The Standard Model coalesced into a unified theoretical framework in the 1960s through the work
 588 of Glashow, Weinberg, Salam, and others on the theory of electroweak interactions [9–12]. This theory
 589 characterized both the electromagnetic and weak interactions as unified under a single gauge symmetry
 590 group, namely $SU(2) \times U(1)$. At low enough energy scales (on the order of the W and Z masses,
 591 the electroweak symmetry is broken, as evidenced by the fact that the weak bosons have mass while the

592 photon does not. The discovery of the Higgs boson in 2012 confirmed the Higgs mechanism as the most
 593 likely candidate for this electroweak symmetry breaking [1, 2]. The electroweak theory is then combined
 594 with the theory of quantum chromodynamics (which models the strong sector as a non-Abelian $SU(3)$
 595 gauge group) to form the complete SM [13].

596 1.2 ELECTROWEAK SYMMETRY BREAKING AND THE HIGGS

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

605 The mechanism works by introducing a Lagrangian for the newly introduced field that still respects
 606 the symmetry of the Standard Model inherently, but with a minimum at a non-zero vacuum expectation
 607 value for the field. In this minimum of the potential, the electroweak symmetry is broken. Specifically,
 608 consider a complex scalar doublet Φ with four degrees of freedom, as shown in equation 1.1.

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ + i\phi_2^+ \\ \phi_1^0 + i\phi_2^0 \end{pmatrix} \quad (1.1)$$

609 The minimal potential of a self-interacting Higgs that still respects the SM symmetry is given in equa-
 610 tion 1.2.

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (1.2)$$

611 If the μ^2 term of this potential is positive, then the potential has a minimum at $\Phi = 0$ and the SM

⁶¹² symmetry is preserved. However, if instead $\mu^2 < 0$, then the minimum is at a finite value of Φ , namely

$$\Phi_{\min} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (1.3)$$

⁶¹³ where $v = \sqrt{\mu^2/\lambda}$. Because this is the location of the minimum, it corresponds to the vacuum expecta-
⁶¹⁴ tion value for the field ($\langle \Phi \rangle = \Phi_{\min}$). The excitations of the Higgs can then be parameterized as

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

⁶¹⁵ The full scalar Lagrangian, including the kinetic term, is then given as

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

⁶¹⁶ where the covariant derivative is defined as

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

⁶¹⁷ and W^1, W^2, W^3 and B are the $SU(2)$ and $U(1)$ gauge fields of the electroweak theory, respectively. g
⁶¹⁸ and g' are the corresponding coupling constants. With the scalar Lagrangian in place, the physical gauge
⁶¹⁹ fields can then be written as

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

⁶²⁰

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

⁶²¹

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

⁶²² Equation 1.7 corresponds to the charged W^+ and W^- bosons, equation 1.8 corresponds to the neutral

623 Z boson, and equation 1.9 corresponds to the neutral photon. The masses of the particles also arise from
 624 the Lagrangian. The photon has zero mass, while the masses of the W and Z bosons are given in equa-
 625 tion 1.10.

$$\begin{aligned} M_W^2 &= \frac{1}{4}g^2v^2 \\ M_Z^2 &= \frac{1}{4}(g^2 + g'^2)v^2 \end{aligned} \tag{1.10}$$

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

$$g_{Hf\bar{f}} = \frac{m_f}{v} \tag{1.11}$$

628 The full Lagrangian of Higgs interactions can be written as

$$\mathcal{L}_{\text{Higgs}} = -g_{Hf\bar{f}}\bar{f}fH + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4 + \delta_V V_\mu V^\mu \left(g_{HV}VH + \frac{g_{HVV}}{2}H^2 \right) \tag{1.12}$$

629 with

$$\begin{aligned} g_{HV} &= \frac{2m_V^2}{v} & g_{HVV} &= \frac{2m_V^2}{v^2} \\ g_{HHH} &= \frac{3m_H^2}{v} & g_{HHHH} &= \frac{3m_H^2}{v^2} \end{aligned} \tag{1.13}$$

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

639 1.3 HIGGS BOSON PRODUCTION AND DECAY

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

643 1.3.1 HIGGS PRODUCTION

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

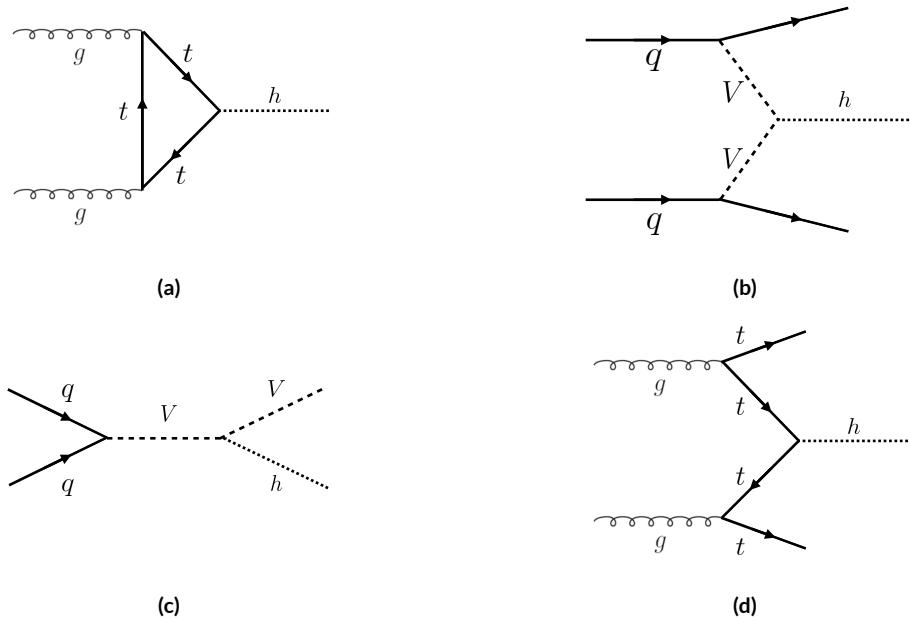


Figure 1.2: The four most common Higgs boson production modes at the LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c) $W/Z + H$ production, (d) $t\bar{t}H$ production

647 In gluon-gluon fusion, gluons from the incoming protons fuse via a top-quark loop to produce a
648 Higgs. The top quark is the dominant contribution in the loop due to its heavy mass and the fact that
649 the Higgs-fermion coupling constant scales with fermion mass. In vector boson fusion, the incoming
650 quarks each radiate a W or Z boson which fuse to produce the Higgs. This production mode results in
651 a final state with a Higgs boson and two additional jets which tend to be forward because they carry the

longitudinal momentum of the incoming partons. The Higgs can also be produced in association with a W or Z boson. The W/Z is produced normally and then radiates a Higgs (this mode is also sometimes known as “Higgs-strahlung”). Finally, the Higgs can be produced in association with two top quarks. Each incoming gluon splits into a $t\bar{t}$ pair, and one of the top pairs combines to create a Higgs. Figure 1.3 shows the production cross section for a 125 GeV Higgs boson in each of these modes at a pp collider as a function of center of mass energy.

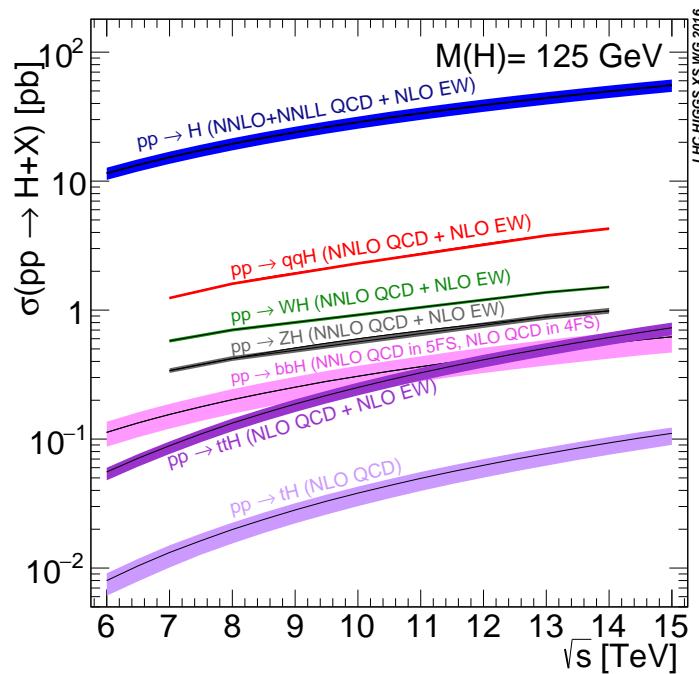


Figure 1.3: Higgs production cross sections as a function of center of mass energy (\sqrt{s}) at a pp collider [18].

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

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].

666 1.3.2 HIGGS BRANCHING RATIOS

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

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

669 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
 670 m_H is the mass of the Higgs. Note that the width scales with the square of the fermion mass. (This also
 671 assumes that the Higgs mass is large enough to decay with both the fermions on shell.)

672 The decay width to WW is given in equation 1.15 [5].

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

673 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 , the equa-
 674 tion is divided by 2 to account for identical particles in the final state, and x_W is replaced with $x_Z =$
 675 $4M_Z^2/m_H^2$. This is shown in equation 1.16 [5].

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

676 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. First, note that

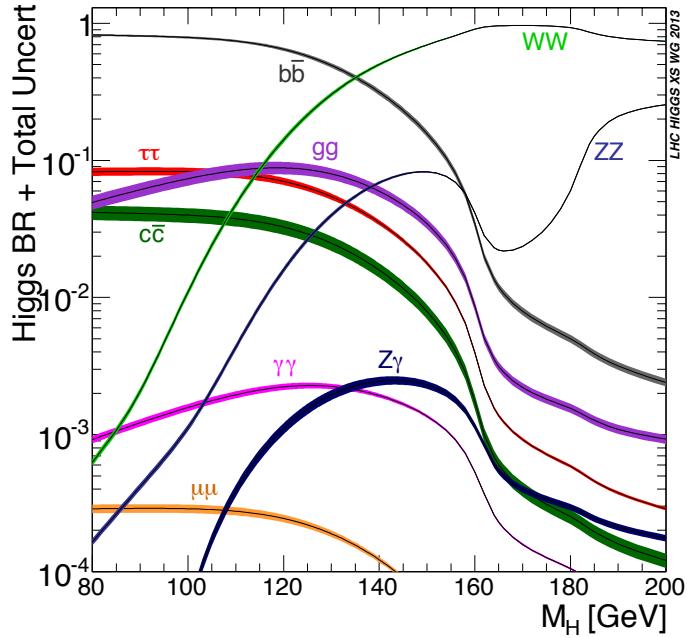


Figure 1.4: Higgs boson branching ratios as a function of m_H [18].

677
 678 at high Higgs masses, once on-shell production of both W and Z bosons is possible, these two decays
 679 are the dominant ones due to the large masses of the W/Z . Also note that the branching ratio to W s
 680 is twice that of Z s at these large masses due to the δ_V symmetry factor noted previously. At 125 GeV,
 681 the Higgs is accessible through many different decay modes. The largest branching ratio is the decay
 682 $H \rightarrow b\bar{b}$ at 58.24% [18]. This branching is larger than the WW/ZZ decays because one of the two
 683 bosons must be produced off-shell for $m_H = 125$ GeV. The second largest branching ratio is to WW^*
 684 at 21.37 % (before taking into account the branching ratios of the W). Table 1.2 summarizes the branch-
 685 ing ratios for a 125 GeV Higgs. Note that there is in fact a Higgs branching ratio to $\gamma\gamma$ even though
 686 photons are massless. This decay happens through a loop (the largest contributions to the loop are top
 687 and W) which suppresses the branching ratio.

688 Note that the branching ratios alone do not tell the full story of which Higgs channels are the most
 689 sensitive. For example, a $H \rightarrow b\bar{b}$ search in gluon fusion production is incredibly difficult due to the

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].

large QCD dijet background at the LHC. However, in associated production of the Higgs, where a W or Z gives additional final state particles that can be used to reduce background, a search for $H \rightarrow b\bar{b}$ can be sensitive. The combinations of production and decay modes that are most commonly studied are 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].

1.4 HIGGS PAIR PRODUCTION IN THE STANDARD MODEL

The Standard Model also allows for processes that produce two Higgs bosons in the final state, known 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 cross section for di-Higgs production at the LHC. Nevertheless, Higgs pair production is quite interesting to study because it gives direct access to the λ parameter of the Higgs potential, also known as the Higgs self coupling. The diagram in figure 1.5(b) is sensitive to this coupling through the triple Higgs

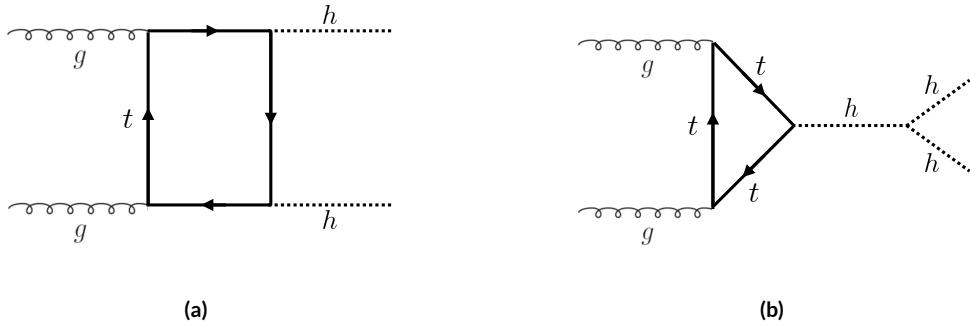


Figure 1.5: The two leading diagrams for Standard Model di-Higgs production at the LHC: (a) box diagram, (b) Higgs self coupling

701 vertex.

702 One can substitute the gluon fusion production of diagram 1.5(b) with any of the other production
 703 modes previously discussed. These other modes do not suffer from interference with the box diagram
 704 in figure 1.5(a) due to the presence of additional particles in the final state. They still have a lower cross
 705 section than the gluon fusion mode, however. The cross sections for di-Higgs production in the differ-
 706 ent modes, as well as their uncertainties, are shown in table 1.4 [19]. These are shown for $\sqrt{s} = 14$ TeV
 707 as the higher center of mass energy is more sensitive to this process. Note that the scale of cross section
 quoted is now in fb rather than pb.

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 [19]. The uncertainties include QCD scale and PDF variations as well as uncertainties on α_S .

708

709 1.5 HIGGS PAIR PRODUCTION IN THEORIES BEYOND THE STANDARD MODEL

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

712 However, the discovery of the Higgs also gives particle physicists a new tool that can be exploited in the
 713 search for new physics beyond the Standard Model. In particular, Higgs pair production is a promising
 714 channel in the search for new physics. The cross section for di-Higgs production can be altered through
 715 both resonant and non-resonant production of Higgs pairs. In non-resonant production, di-Higgs pro-
 716 duction vertices can arise from the presence of a new strong sector and additional colored particles [20–
 717 22]. Figure 1.6 shows examples of the types of vertices that can arise. In the resonant case, new heavy par-
 718 ticle can decay to Higgs pairs. Such new particles can include heavy Higgs bosons arising in two Higgs
 719 doublet models (2HDM) or Higgs portal models as well as heavy gravitons in Randall-Sundrum theo-
 720 ries [20, 23–29]. Figure 1.7 shows a generic diagram for a heavy resonance decaying to two Higgs bosons.
 721 In the 2HDM, X corresponds to the heavy CP-even scalar H . In the Randall-Sundrum model, X cor-
 722 responds to a heavy spin-2 graviton G . The next sections provide more detail on the phenomenology of

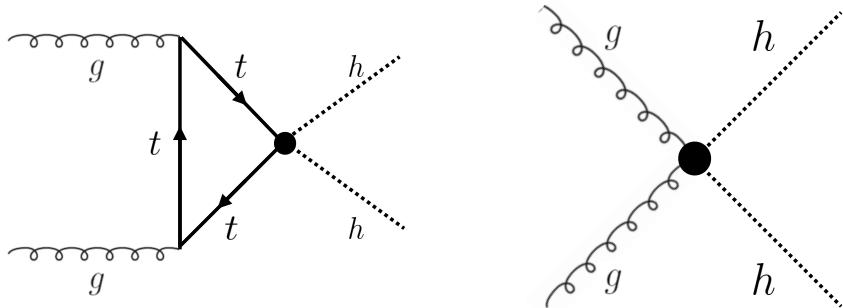


Figure 1.6: Diagrams with new vertices for non-resonant Higgs pair production arising in composite Higgs models

723 resonant Higgs production in Randall-Sundrum and 2HDM models, as these models will later be tested
 724 in a dedicated search for resonant production of boosted Higgs pairs.

725 1.5.1 RANDALL-SUNDRUM GRAVITONS

726 The Randall-Sundrum model is a proposed solution to the hierarchy problem that posits a five-dimensional
 727 warped spacetime that contains two branes: one where the force of gravity is very strong and a second
 728 brane at the TeV scale corresponding to the known Standard Model sector [23]. In the theory, the
 729 branes are weakly coupled and the graviton probability function drops exponentially going from the
 730 gravity brane to the SM brane, rendering gravity weak on the SM brane. The experimental consequence

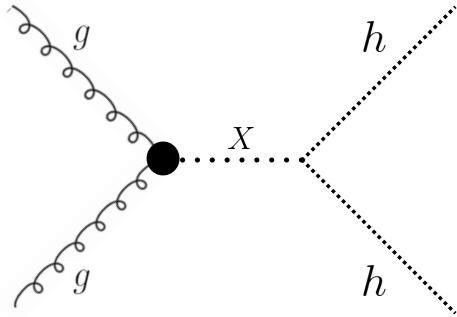


Figure 1.7: Generic Feynman diagram for resonant Higgs pair production in BSM theories

of this theory is a tower of widely spaced (in mass) Kaluza-Klein graviton resonances. In theories where the fermions are localized to the SM brane, production of gravitons from fermion pairs is suppressed and the primary mode of production is gluon fusion [24]. These gravitons have a substantial branching fraction to Higgs pairs, ranging from 6.43% for gravitons with a mass of 500 GeV to 7.66% at 3 TeV. Figure 1.8 shows the branching ratios of the spin-2 Randall Sundrum graviton (RSG) as a function of its mass. The predominant decays are to $t\bar{t}$ above the mass threshold for that channel.

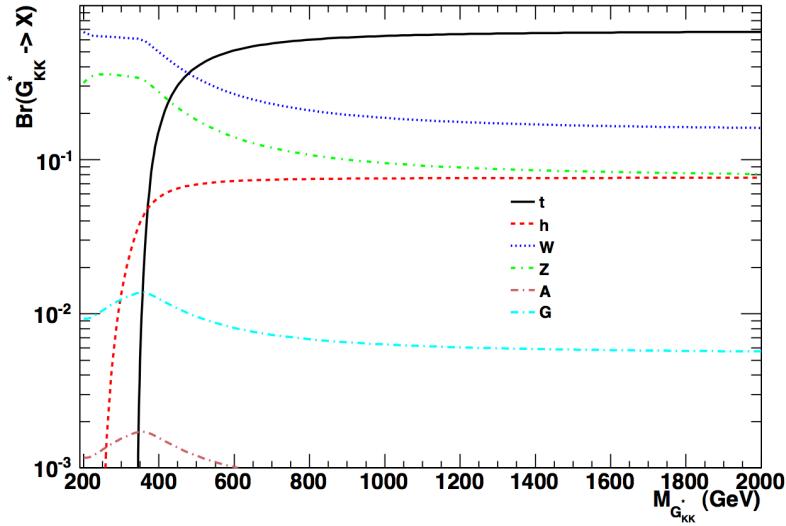


Figure 1.8: Branching ratios for a spin-2 Randall-Sundrum graviton as a function of mass computed in MadGraph with the CP3-Origins implementation [24, 30]

These models have two free parameters - the mass of the graviton and a curvature parameter k . Typically, 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 cross section for production of the RSG decreases as a function of mass and is strongly dependent on the gluon PDF. The increase in center of mass energy from 8 to 13 TeV in LHC Run 2 greatly increases the cross section at higher mass. Figure 1.9 shows the cross section as a function of graviton mass at $\sqrt{s} = 13$ TeV for RSG models with $c = 1.0$ and $c = 2.0$.

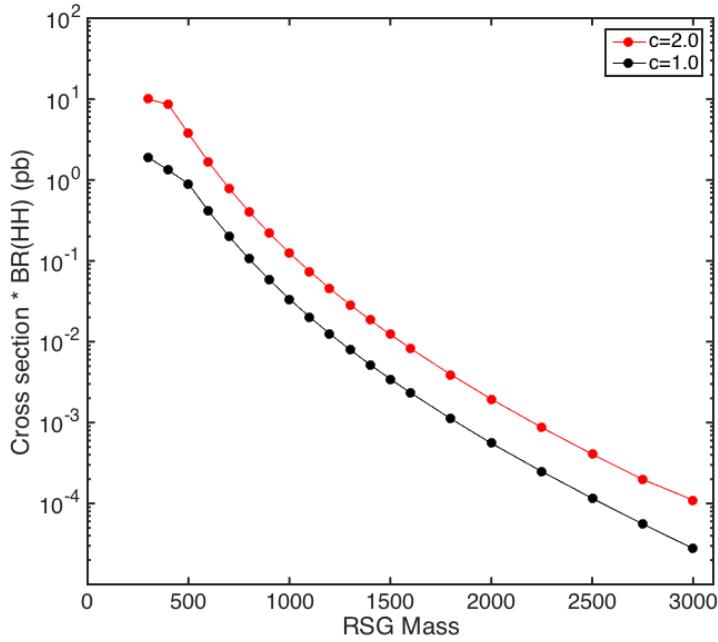


Figure 1.9: $\sigma \times \text{BR}(HH)$ for RSG as a function of mass computed in MadGraph with the CP3-Origins implementation [24, 30]

Another interesting feature of the theory is that the width of the graviton increases with both c and m_G . Figure 1.10 shows the graviton width for both $c = 1.0$ and $c = 2.0$ as a function of mass. In $c = 1.0$, 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. Similarly, with $c = 2.0$, the width starts at 33.46 GeV for $m_G = 300$ GeV and increases to 748.8 GeV at a mass of 3 TeV.

1.5.2 TWO HIGGS DOUBLET MODELS

In Two Higgs Doublet Models (2HDM), a second complex scalar doublet is added to SM [26–28]. In this case, all four degrees of freedom in the second doublet correspond to new particles, meaning that

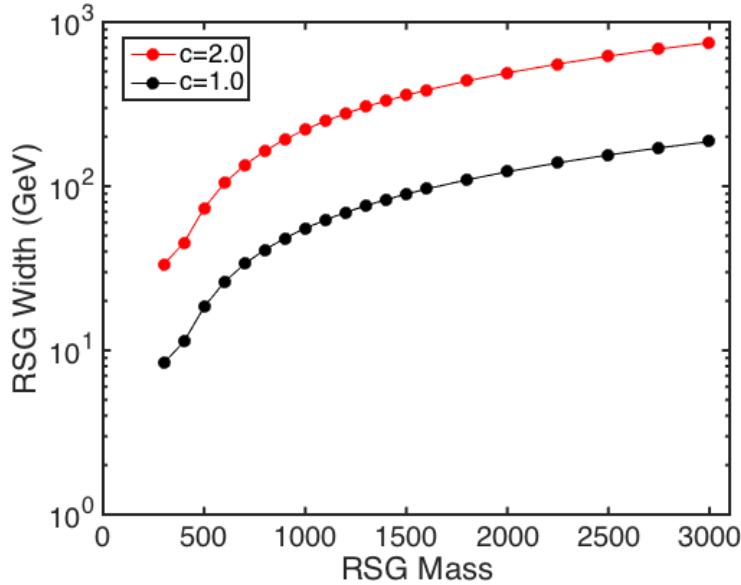


Figure 1.10: RSG width as a function of mass computed in MadGraph with the CP3-Origins implementation [24, 30]

there are five total scalars from the two Higgs doublets - h (light CP-even Higgs), H (heavy CP-even Higgs), A (heavy CP-odd Higgs), and H^\pm (charged Higgs). The model is parameterized by two main parameters. 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 corresponds to the v in the SM Higgs model described above). The second parameter is α , a mixing angle between the heavy and light Higgs fields. Models are also often parameterized with $\cos(\beta - \alpha)$ rather than α directly. The limit where $\cos(\beta - \alpha) = 0$ is called the alignment limit, and it is in this limit that the light Higgs h has the same couplings as a Standard Model Higgs.

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

Resonant di-Higgs production in this model can proceed through decays of the heavy CP-even Higgs $H \rightarrow hh$. The branching ratio for $H \rightarrow hh$ depends on the model type as well as the values of $\tan \beta$ and $\cos \beta - \alpha$. Figure 1.11 shows the branching ratios as a function of the mass of the heavy scalar H for

766 both Type I and Type II models. Depending on the type of model hh can be a substantial fraction of the
767 decays of H .

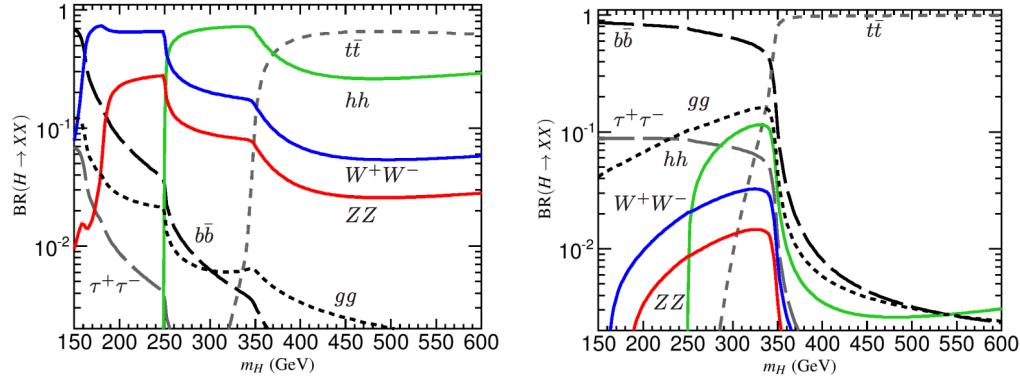


Figure 1.11: Branching ratios for heavy Higgs H in Type I (left) and Type II (right) 2HDM models with $\tan \beta = 1.5$ and $\cos(\beta - \alpha) = 0.1$ (0.01) for Type I (Type II). [28]

768 1.6 CONCLUSION

769 Studying the Higgs sector is essential for understanding the details of how mass arises in the Standard
770 Model and how the electroweak symmetry is broken. The discovery of the Higgs boson also opens the
771 door for its use as a tool to search for new physics, and Higgs pair production is an ideal candidate for
772 this study. Even if no BSM physics is found in Higgs pair production, searches for Higgs pairs will put
773 constraints on the Higgs self coupling and thus further knowledge of the Standard Model and the details
774 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

775

776

777

The ATLAS detector and the Large Hadron Collider

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

788 2.1 THE LARGE HADRON COLLIDER

789 The Large Hadron Collider (LHC) is a proton-proton collider at the CERN laboratory in Geneva,
790 Switzerland [31]. It is designed for a maximum collision center of mass energy of $\sqrt{s} = 14$ TeV and
791 has a circumference of 26.7 kilometers. Four main experiments are located at the interaction points (IP)
792 of the accelerator: ATLAS (A Toroidal LHC ApparatuS), CMS (the Compact Muon Solenoid), AL-
793 ICE (A Large Ion Collider Experiment), and LHCb [32–35]. The studies performed in this thesis were
794 all completed with the ATLAS detector. Figure 2.1 shows a schematic of the LHC ring and the various
795 experiments.

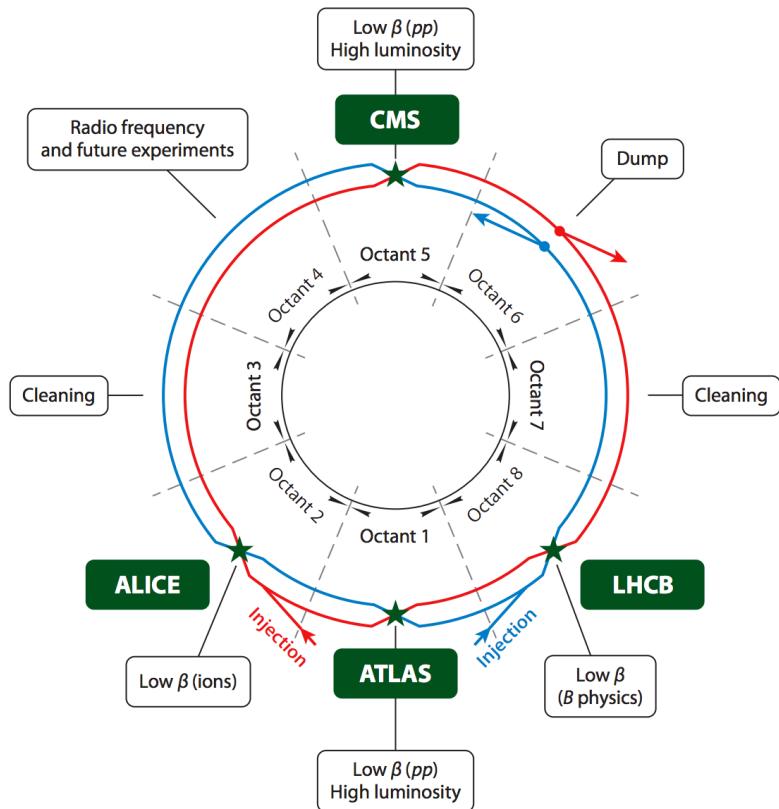


Figure 2.1: A schematic view of the LHC ring [36]

796 One of the most interesting features of the LHC is in its magnet design. Because the tunnel does not
797 have room for separate superconducting magnets for each of the beam pipes, the LHC employs a twin-
798 bore magnet design. Each magnet must hold an 8.3 Tesla magnetic field in order to bend the proton

⁷⁹⁹ beams at $\sqrt{s} = 14$ TeV. The superconducting magnets are cooled to a temperature of 1.9 Kelvin with
⁸⁰⁰ superfluid helium.

⁸⁰¹ 2.I.I INSTANTANEOUS LUMINOSITY

⁸⁰² The rate of physics events expected from the accelerator is dependent on the instantaneous luminosity
⁸⁰³ of the machine and the cross section of the physics process, $R_{\text{events}} = L\sigma$. Here, R_{events} is the number
⁸⁰⁴ of events per second, L is the instantaneous luminosity of the machine, and σ is the cross section for the
⁸⁰⁵ physics process being measured. The instantaneous luminosity of the LHC is determined by numerous
⁸⁰⁶ factors related to machine conditions. Equation 2.1 gives the equation for instantaneous luminosity of
⁸⁰⁷ Gaussian beam profile [36].

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

⁸⁰⁸ The LHC collides protons in bunches, and in the above equation N_b is the number of protons per
⁸⁰⁹ bunch while n_b is the number of bunches per beam. Nominally, the LHC can hold up to 2808 pro-
⁸¹⁰ ton bunches. f_{rev} is the revolution frequency. ϵ_n is the normalized transverse beam emittance, a mea-
⁸¹¹ surement of the average spread of the particles position-momentum space which has the dimension of
⁸¹² length. β^* is the value of the *beta* function for the beam at the interaction point. It relates the emittance
⁸¹³ to the Gaussian width of the beam with $\sigma_{\text{beam}} = \sqrt{\epsilon \cdot \beta}$. F is a reduction factor that corrects for the
⁸¹⁴ fact that the beams are colliding at an angle at the IP.

⁸¹⁵ Another way of writing the instantaneous luminosity is shown in equation 2.2. In this case, the in-
⁸¹⁶ stantaneous luminosity is written as the ratio of the rate of inelastic collisions with the inelastic cross
⁸¹⁷ section [37].

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

⁸¹⁸ In this case, μ is the average number of interactions per bunch crossing in the accelerator. μ is a useful
⁸¹⁹ parameter for characterizing the amount of activity recorded in an experiment. As the instantaneous
⁸²⁰ luminosity and thus μ increase, there are more interactions per bunch crossing and more activity in the
⁸²¹ detector. This is often characterized with $\langle \mu \rangle$, the measured per bunch crossing μ value averaged over

822 all bunch crossings. The interactions inside each bunch crossing that are not the main physics process of
 823 interest are often referred to as “pileup” interactions, and $\langle \mu \rangle$ is a measurement of the level of pileup in
 824 the detector.

825 **2.1.2 EVOLUTION OF MACHINE CONDITIONS**

826 This thesis uses datasets taken at three different center of mass energies: $\sqrt{s} = 7\text{ TeV}$ data taken in
 827 the year 2011, $\sqrt{s} = 8\text{ TeV}$ data taken in the year 2012, and $\sqrt{s} = 13\text{ TeV}$ data taken in the year
 828 2015. In addition to increasing center of mass energy, the instantaneous luminosity and parameters that
 829 determine 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}		1.15×10^{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 [38, 39]

830 **2.2 THE ATLAS DETECTOR**

831 The ATLAS detector is a multi-purpose particle detector experiment at the LHC’s Point 1 [32]. It has
 832 nearly 4π coverage in solid angle around the interaction point. It consists of an inner detector for mea-
 833 suring charged particles, electromagnetic and hadronic calorimeters, and a muon spectrometer. Fig-
 834 ure 2.2 gives an overview of the detector.

835 **2.2.1 COORDINATE SYSTEM**

836 Before defining the properties of the individual detectors, it is important to establish the coordinate
 837 system used. Figure 2.3 shows a schematic of the coordinate system. The azimuthal plane (perpendicular

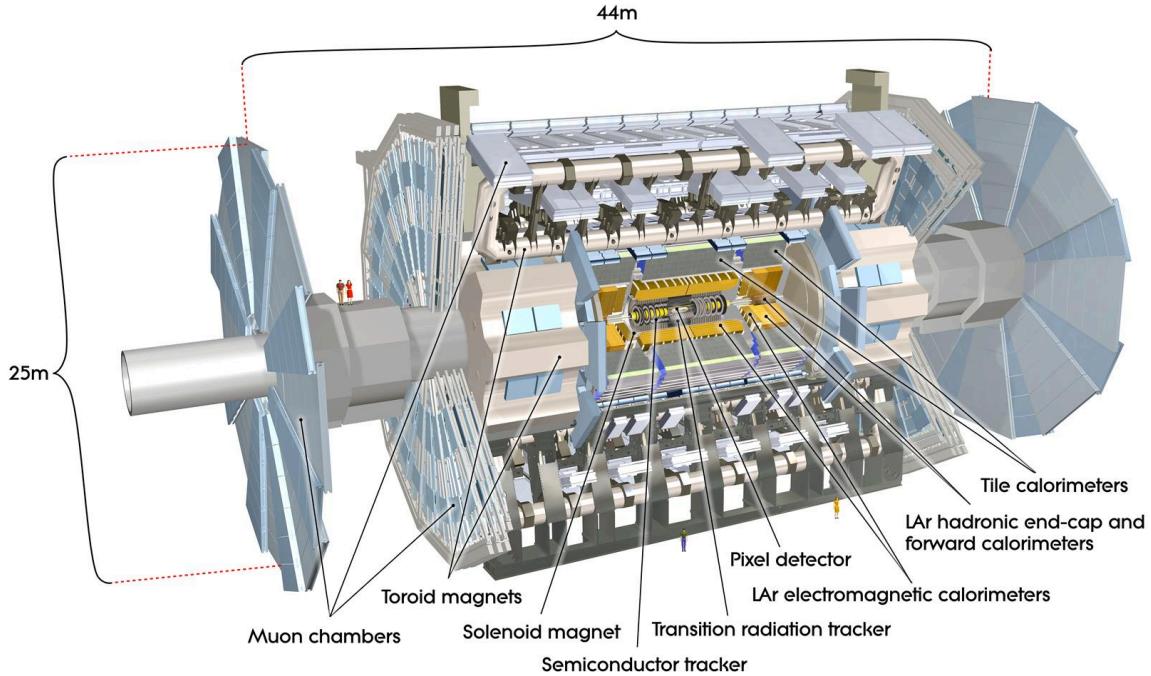


Figure 2.2: A full diagram of the ATLAS detector [32]

838 to the beam line) is defined as the x - y plane. The angle in this plane is referred to as ϕ . The angle relative
 839 to the beam axis is referred to as θ . Rather than using θ directly as a coordinate, the experiment often
 840 uses the pseudorapidity η . η is defined in equation 2.3.

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

841 Pseudorapidity is the massless approximation of rapidity, the angle used to parameterize boosts in
 842 special relativity. This is important for two reasons. First, it means that differences in η are Lorentz in-
 843 variant. Second, particle production is roughly constant in pseudorapidity. Particles with η close to zero
 844 are referred to as “central”, while those at high $|\eta|$ are called “forward”. In general, two main detector
 845 topologies can be seen in figure 2.2. There are “barrel” elements, which surround the beam line cylin-
 846 dically and are in the central region of the detector. In the forward region, there are “endcap” regions
 847 which are arranged as disks perpendicular to the beam line.

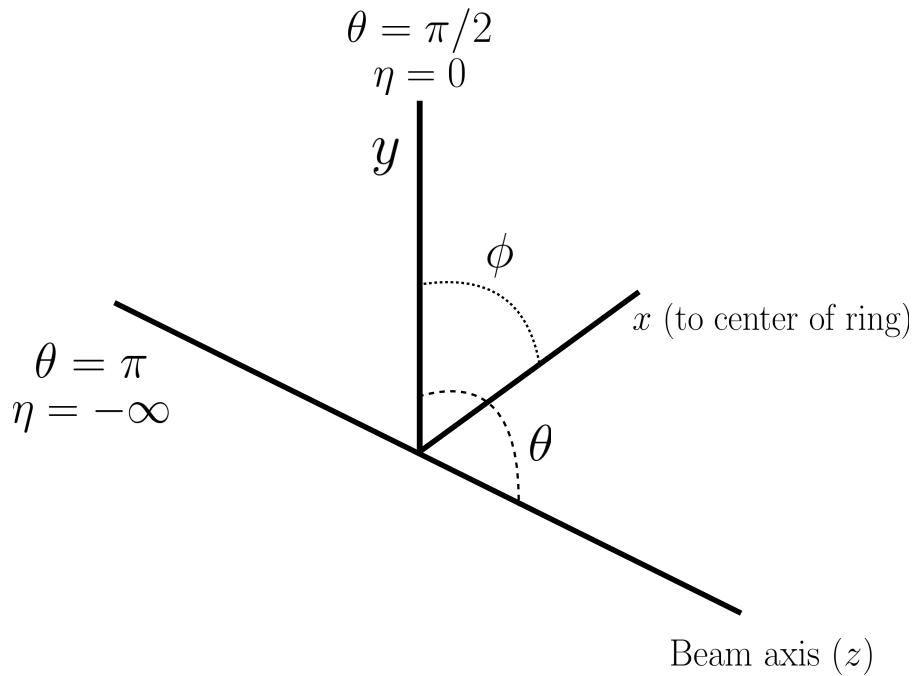


Figure 2.3: The ATLAS coordinate system

848 **2.2.2 INNER DETECTOR**

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

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

857 **PIXEL DETECTOR**

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

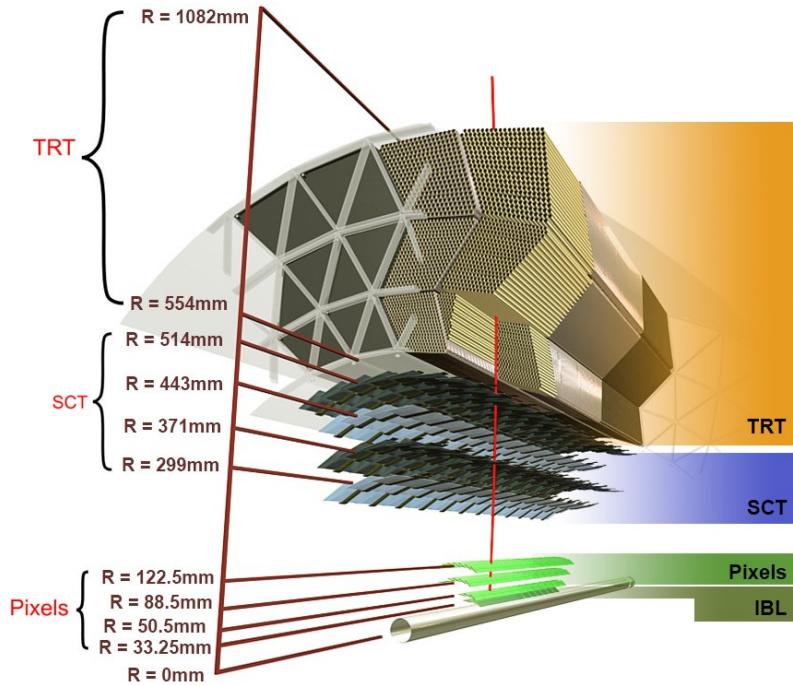


Figure 2.4: Layout of the ATLAS Inner Detector system [40]

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 [32]. 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 beam-line. In the endcap region, it consists of disks perpendicular to the beam axis. The detector is segmented in the $R-\phi$ 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 $R-\phi$ and $115 \mu\text{m}$ in z (or R for the endcap).

870 INSERTABLE B-LAYER

871 In Run 2, a new innermost pixel layer, known as the insertable B-layer (IBL), was added to the Inner
 872 Detector [41]. This layer was added to cope with the higher luminosities planned in LHC Run 2 and

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

876 **SEMICONDUCTOR TRACKER (SCT)**

877 The semiconductor tracker (SCT) consists of silicon microstrips and comprises the next four layers of
878 the ID. This sub-detector has 6.4cm long sensors that are daisy-chained into strips with a strip pitch
879 of $80\ \mu\text{m}$ [32]. Some of the strips have a small stereo angle to allow for measurement of both angular
880 coordinates. In total there are 6.3 million readout channels. The intrinsic accuracies are $17\ \mu\text{m}$ in $R\phi$
881 and $580\ \mu\text{m}$ in z (or R in the endcap).

882 **TRANSITION RADIATION TRACKER (TRT)**

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

891 **2.2.3 CALORIMETERS**

892 The calorimeter system consists of two main sub-components: a fine granularity electromagnetic calorime-
893 ter tailored for the measurement of photons and electrons and multiple coarser hadronic calorimeters
894 dedicated to the measurement of hadronic showers [32]. The calorimeter system has broader cover-
895 age than the inner detector, covering the region out to $|\eta| < 4.9$. It is also designed to deliver good
896 containment of showers so as to limit leakage into the muon system. Figure 2.5 shows the layout of the
897 calorimeter system.

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

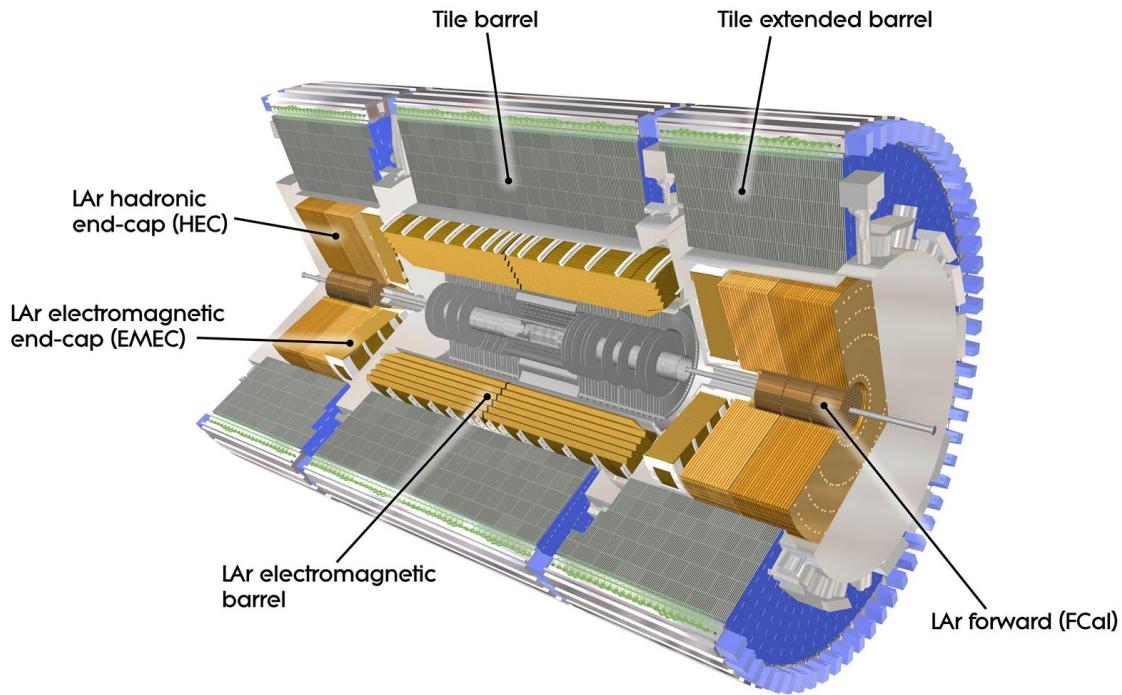


Figure 2.5: Layout of the ATLAS calorimeter system [32]

901 ELECTROMAGNETIC CALORIMETER

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

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

910 $I(x) = I_0 e^{-x/X_0}$, where I is the intensity, x is the distance traveled, and X_0 is the radiation length.

911 The ATLAS EM calorimeter is designed to have > 22 radiation lengths in the barrel and > 24 in the
912 endcap [32].

913 **HADRONIC CALORIMETERS**

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

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

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

924 The FCal covers the most forward regions of the calorimeter system, extending to the region of $3.1 <$
925 $|\eta| < 4.9$. It again uses liquid argon as its active material. For absorber, it consists of an innermost
926 module made of copper followed by a module made of tungsten.

927 The hadronic equivalent of radiation length is called the interaction length and is denoted as λ . In the
928 barrel, the hadronic calorimeter depth is approximately 9.7λ , while in the endcap is is 10λ . The outer
929 supports contribute an additional 1.3λ . This is been shown to be sufficient to limit punch-through of
930 showers to the muon system [32].

931 **2.2.4 MUON SPECTROMETER**

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

935 derives its name.) These magnets provide 1.5 to 5.5 Tm of bending power at $0 < |\eta| < 1.4$ and approx-
 936 imately 1 to 7.5 Tm in the endcap region of $1.6 < |\eta| < 2.7$. The entire muon system covers the range
 937 $0 < |\eta| < 2.7$. Monitored drift tubes (MDTs) are used for tracking in the barrel and the two outer
 938 layers of the endcap, while cathode strip chambers (CSCs) are used to provide tracking in the innermost
 939 endcap wheel. In the barrel, resistive plate chambers (RPCs) are used as trigger chambers while thin gap
 940 chambers (TGCs) are used in the endcap. Figure 2.6 shows the layout of the ATLAS muon system. The
 941 entire muon system is designed with the specification of providing a 10% momentum resolution for a
 942 1 TeV muon.

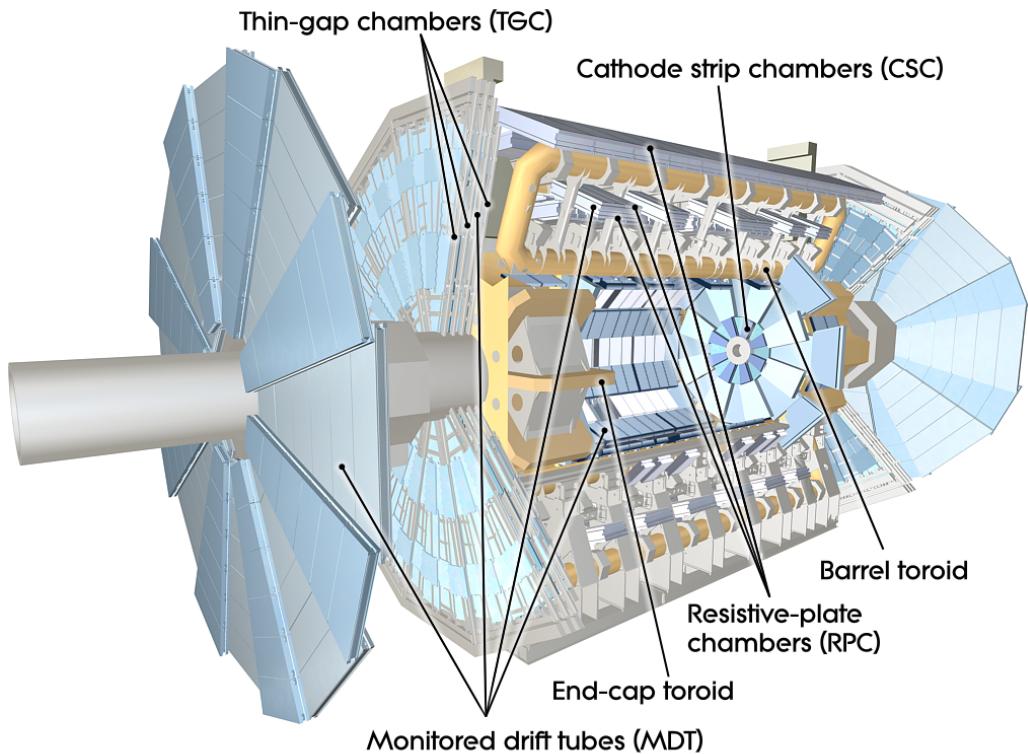


Figure 2.6: Layout of the ATLAS muon system [32]

943 MONITORED DRIFT TUBES (MDTs)

944 The monitored drift tubes (MDTs) are aluminum 3cm diameter tubes filled with a 93/7 % mixture of
 945 Argon and CO₂, with trace amounts of water. As a charged particle traverses the tube, it ionizes the gas

946 and the ions drift to a wire at the center of the tube. The radial distance of traversal of the particle in the
947 tube is determined by the drift time of the electrons, allowing for fine position resolution. The tubes
948 have an average resolution of $80 \mu\text{m}$ per tube and a maximum drift time of approximately 700ns. The
949 tubes are oriented so that they give precision measurement in η and run along ϕ . They cover $|\eta| < 2.7$,
950 except in the innermost layer of the endcap where they only go to $|\eta| < 2.0$ [32].

951 CATHODE STRIP CHAMBERS (CSCs)

952 The cathode strip chambers cover a narrow window of the innermost endcap region at $2.0 < |\eta| <$
953 2.7. In this region the background rates in the cavern are particularly high and the CSCs are designed
954 to handle these higher rates. The CSCs are multiwire proportional chambers with wires pointing in
955 the radial direction (away from the beam pipe). The wire serves as an anode and there are two types of
956 segmented cathode strip, one perpendicular to the wires which gives the precision measurement and one
957 parallel which provides the transverse coordinate. It has an 80/20 gas mixture of Argon and CO₂ [32].

958 RESISTIVE PLATE CHAMBERS (RPCs)

959 The resistive plate chambers (RPCs) are gaseous electrode-plate detectors covering the region $|\eta| <$
960 1.05. They consist of two resistive plates separated by a distance of 2 mm. The gas mixture used is a
961 94.7/5/0.3% mixture of C₂H₂F₄, Iso-C₄H₁₀, and SF₆. It has readout strips with a pitch of 23-35 mm
962 for both η and ϕ measurement and thus provides measurement of the azimuthal coordinate in the barrel
963 that the MDTs do not. The thin gas gap allows for a quick response time which makes it ideal for use in
964 the trigger. There are three layers of RPCs which are referred to as the three trigger stations. They allow
965 for both a low p_T and high p_T trigger. The coincidence of hits in the innermost chambers allows for
966 triggering of muons between 6 and 9 GeV, while the outermost layer allows the trigger to select high
967 momentum tracks in the range of 9 to 35 GeV [32].

968 THIN GAP CHAMBERS (TGCs)

969 The thin gap chambers (TGCs) are multiwire proportional chambers where the wire to cathode distance
970 (1.4mm) is smaller than the wire-to-wire distance (1.8 mm). They contain a gas mixture of CO₂ and

971 *n*-pentane and use a high electric field to gain good time resolution. They serve two functions in the
 972 end-cap system. First, they serve as the trigger chambers. Second, they also provide azimuthal coordi-
 973 nate measurement which the MDTs do not. They sit on the inner and middle layers of the endcap. The
 974 outermost layer's azimuthal coordinate is determined by extrapolation [32].

975 2.2.5 MAGNET SYSTEM

976 As mentioned previously, there are two independent magnet systems in ATLAS. The first is a 2 T solenoid
 977 field in the inner detector which provides bending in the azimuthal plane. The second is an approxi-
 978 mately 0.5 T toroidal field in the muon system which provides bending in η . Figure 2.7 shows the pre-
 979 dicted field integral as a function of $|\eta|$ [32].

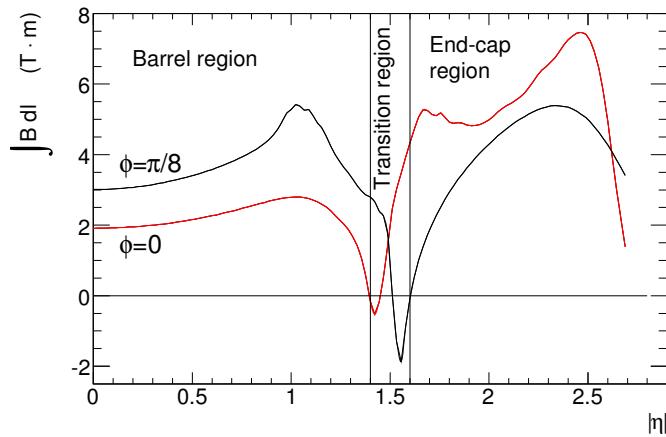


Figure 2.7: Predicted field integral as a function of $|\eta|$ for the ATLAS magnet system [32]

980 2.2.6 TRIGGER SYSTEM

981 The ATLAS trigger system searches for signatures of muons, electrons, photons, hadronically decay-
 982 ing τ leptons, and jets in order to save these events for further analysis. The trigger system in ATLAS
 983 is designed to reduce the maximum LHC event rate of 40 MHz to a more reasonable rate that can be
 984 recorded. The trigger first consists of a fast, hardware based system called the Level-1 (L1) trigger. The
 985 L1 trigger consists of independent dedicated detector sub-components that can seed regions of inter-
 986 est (RoIs) for further analysis downstream. For muons, the RPCs and TGCs are used, while in the

987 calorimeter coarsely grained sections of calorimeter cells called towers are used. Once regions of inter-
 988 est are seeded, a software based system called the High Level Trigger (HLT) is used to reconstruct objects
 989 and integrate information from different parts of the detector. In Run 1 of ATLAS, the HLT consisted
 990 of two separate stages: the level 2 (L2) trigger and the event filter (EF).

991 The maximum trigger rate that the L1 trigger can handle is 75 kHz. In the HLT, the rate of events
 992 written to disk is approximately 200 Hz. Figure 2.8 shows the trigger rates for different L1 triggers in
 993 2012 and 2015 for ATLAS [42].

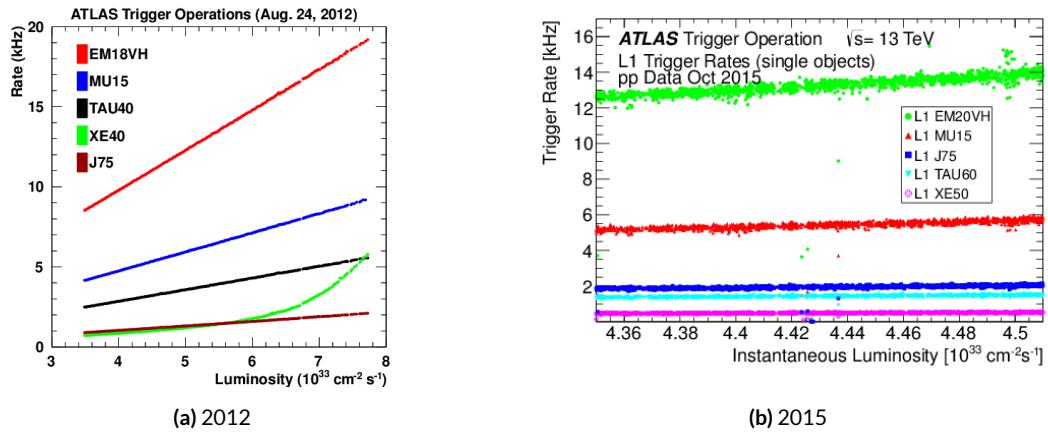


Figure 2.8: ATLAS trigger rates for Level-1 triggers as a function of instantaneous luminosity in 2012 and 2015 operation. These are single object triggers for electromagnetic clusters (EM), muons (MU), jets (J), missing energy (XE), and τ leptons (TAU). The threshold of the trigger is given in the name in GeV. [42]

994 2.2.7 ATLAS DATASETS

995 ATLAS has collected data at center of mass energies of 7, 8, and 13 TeV. Figure 2.9 shows the integrated
 996 luminosity as a function of time for each of the three collected datasets. At $\sqrt{s} = 7$ TeV, ATLAS
 997 recorded 5.08 fb^{-1} . Increased instantaneous luminosity in 2012 led to a larger dataset of 21.3 fb^{-1}
 998 recorded at $\sqrt{s} = 8$ TeV. After Long Shutdown 1 (LS1) of the LHC and a restart in 2015, ATLAS
 999 recorded 3.9 fb^{-1} of data at $\sqrt{s} = 13$ TeV. [43, 44]

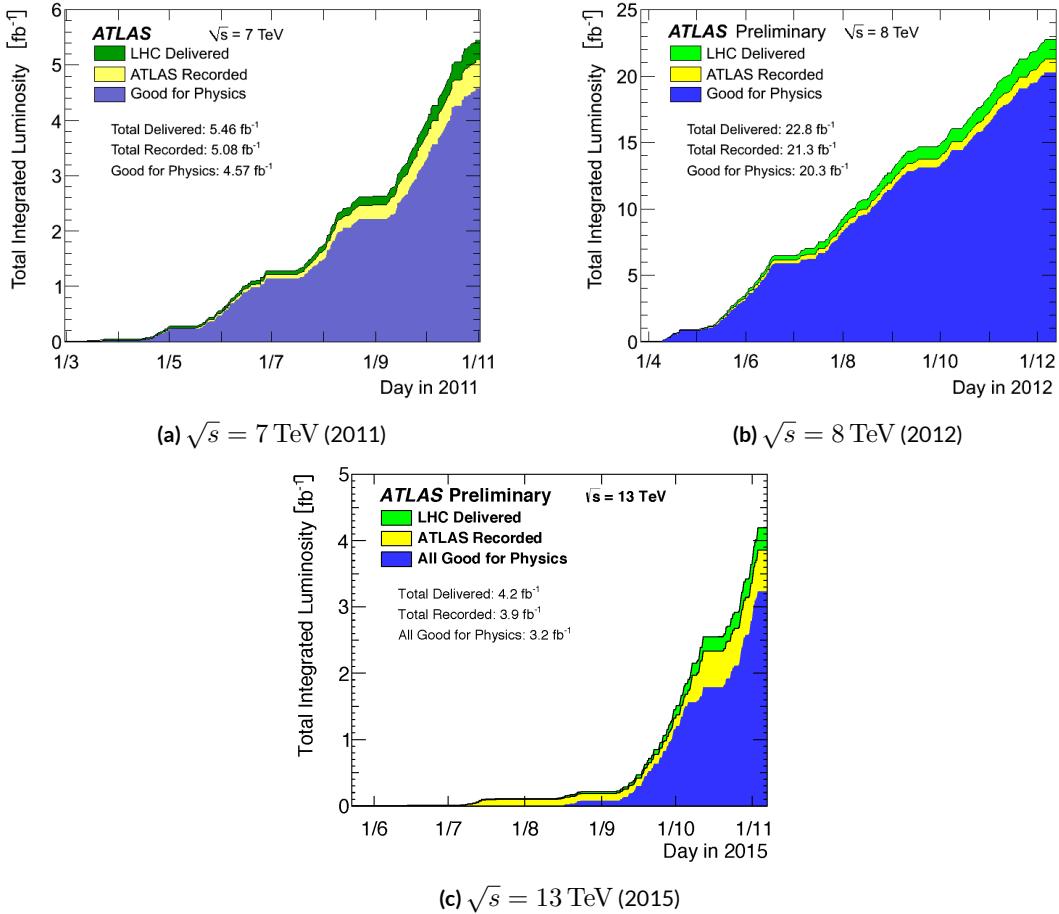


Figure 2.9: Instantaneous luminosity as a function of time for data recorded by ATLAS at different center of mass energies [43, 44]

2.2.8 DETECTOR PERFORMANCE

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

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 for study of rare physics processes but will also present interesting challenges that must be faced. ATLAS will require new detector technologies to cope with the increased background rates in the cavern in these

	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 $p_T = 1$ TeV

Table 2.2: Performance requirements for the ATLAS detector [32].

high luminosity conditions. One such upgrade, scheduled to be installed during Long Shutdown 2 (LS2) of the LHC in 2018, is the ATLAS Muon New Small Wheel (NSW) upgrade [45]. The NSW will replace the innermost end-cap wheel of the muon system with new technologies, as this is the part of the muon detector closest to the beam and thus suffers from the highest rates.

2.3.1 MOTIVATION

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

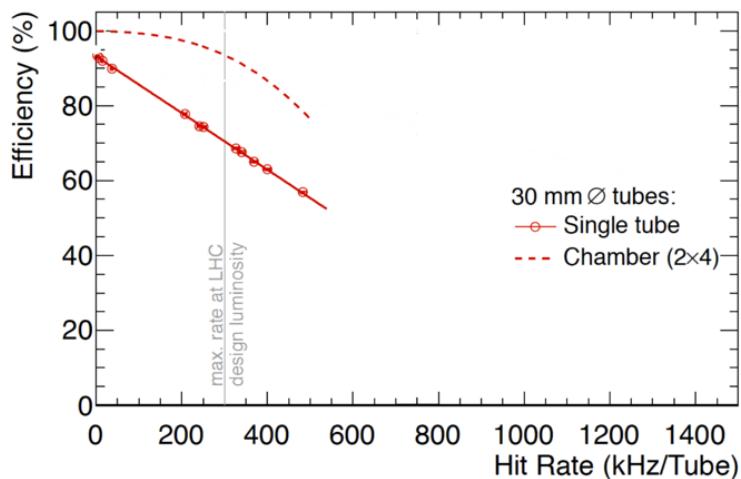


Figure 2.10: MDT tube hit (solid) and segment (dashed) efficiency as a function of hit rate per tube [45]

1017 Second, the NSW will work to alleviate the rate of fake triggers arising in the endcap. Figure 2.11
 1018 shows the extrapolated trigger rates as a function of the p_T threshold with and without the NSW up-
 1019 grade. As the figure shows, the NSW upgrade will reduce the trigger rate by an order of magnitude com-
 1020 pared to the current endcap trigger system.

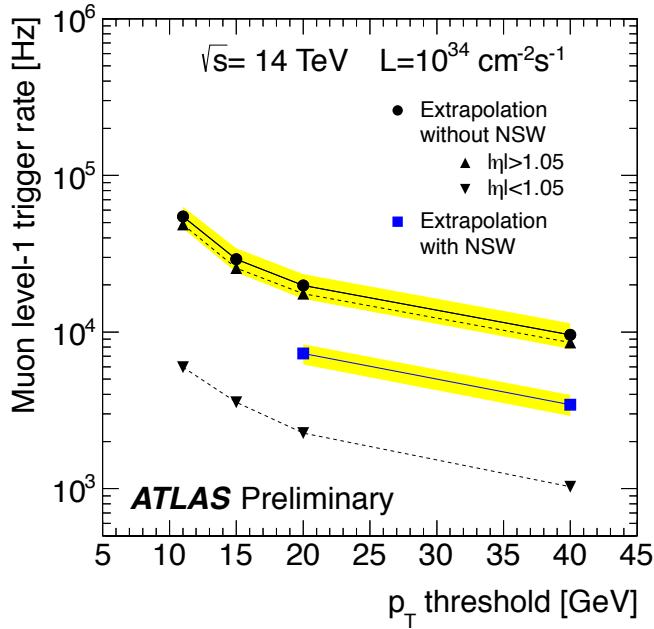


Figure 2.11: Trigger rate as a function of p_T threshold with and without the NSW upgrade [45]

1021 2.3.2 NSW DETECTOR TECHNOLOGIES

1022 The NSW will use two new detector technologies - micromesh gaseous structure detectors (micromegas)
 1023 and small-strip thin gap chambers (sTGCs) [45, 46]. Unlike the previous detectors, both of these detec-
 1024 tor technologies can be used for tracking or trigger. However, the micromegas is more suited to tracking
 1025 because of its good spatial resolution, while the sTGCs have better time resolution and are more suited
 1026 for the trigger. To maintain a fully redundant system, both technologies are used for both purposes.

1027 **MICROMEGAS**

1028 Micromegas detectors operate using a thin metallic mesh that sits approximately $100\ \mu\text{m}$ away from
1029 the readout electrodes to create the amplification region. Above this mesh, there is a drift region on the
1030 order of a few mm in length capped by a drift electrode. As a charged particle traverses the detector, it
1031 ionizes gas and the electrons drift down towards readout strips. The timing of the drift can be used to
1032 reconstruct the angle of traversal of the particle. This is illustrated in figure 2.12. The micromegas used in
1033 ATLAS will be resistive micromegas, where the readout electrodes are topped with resistive strips [47].
1034 This alleviates the risk of sparking in the large area detectors that ATLAS will use.

1035 In ATLAS, the micromegas drift gap will be 5 mm and the amplification gap will be $128\ \mu\text{m}$. They
1036 are filled with the same gas mixture as the MDTs. They will be stacked in an octuplet in an XXUV-
1037 UVXX geometry, where X refers to straight strips and U and V refer to stereo strips at an angle of $\pm 1.5^\circ$.
1038 This arrangement allows for measurement of the azimuthal coordinate and gives a large lever arm be-
1039 tween the straight strips for triggering purposes. Figure 2.12 shows the geometry of a single micromegas
1040 detector as well as its operating principle [45].

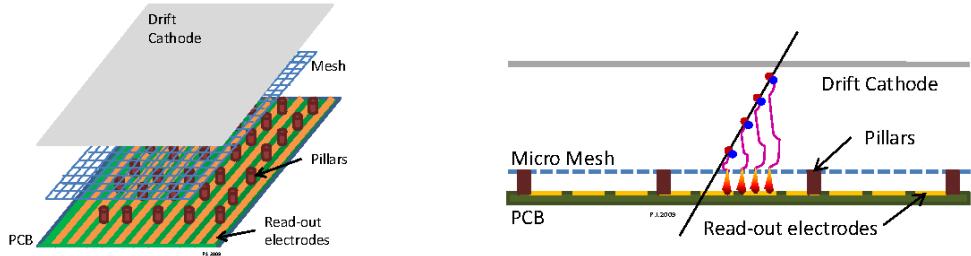


Figure 2.12: Illustrations of the geometry (left) and operating principle (right) of the micromegas detector [45]

1041 **sTGCs**

1042 The sTGCs are similar to the TGCs already described. They consist of gold-plated tungsten wires with
1043 a 1.8 mm pitch between two cathode planes 1.4 mm away from the wire plane. One cathode plane
1044 consists of strips with a 3.2 mm pitch (much smaller pitch than the TGCs), while the other consists
1045 of coarser pads that are used for defining regions of interest in the sTGC trigger algorithm. Figure 2.13
1046 shows the basic detector geometry.

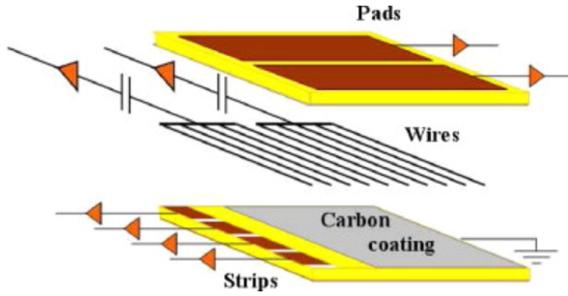


Figure 2.13: Geometry of the sTGC detector [45]

1047 2.3.3 PHYSICS IMPACT

1048 Maintaining low p_T thresholds for muons while still staying within the trigger rate budget at Level 1
 1049 (20 kHz) for the muon system is crucial for physics analyses to be successful in high luminosity condi-
 1050 tions. One realm where the lepton trigger threshold is especially important is in Higgs physics. In the
 1051 $H \rightarrow WW^*$ analysis, one of the W bosons is off shell and tends to decay to soft leptons. In associated
 1052 production of a Higgs with a W , the lepton is also important because the lepton provides the main han-
 1053 dle which allows the event to be triggered. Table 2.3 shows the impact of increasing the trigger thresholds
 1054 on these analyses. It shows that either raising the threshold or using only the barrel both have signifi-
 1055 cant impacts on the signal efficiency. With the NSW, the signal efficiency is largely maintained and the
 1056 triggers can be unprescaled.

Threshold	$H \rightarrow bb$ (%)	$H \rightarrow WW^*$ (%)
$p_T > 20$ GeV	93	94
$p_T > 40$ GeV	61	75
$p_T > 20$ GeV (barrel only)	43	72
$p_T > 20$ GeV (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 [45].

1057 2.4 OBJECT RECONSTRUCTION IN ATLAS

1058 ATLAS analyses first start by requiring the presence of certain reconstructed physics objects in the event.
 1059 This section will present a brief overview of the algorithms used to reconstruct electrons, muons, jets

1060 (including b -jets), and missing energy*. The performance of object reconstruction and measurement will
1061 also be discussed as these are relevant to the analyses presented later. Figure 2.14 gives an overview of the
1062 different sub-detectors that each type of particle will interact with in ATLAS.

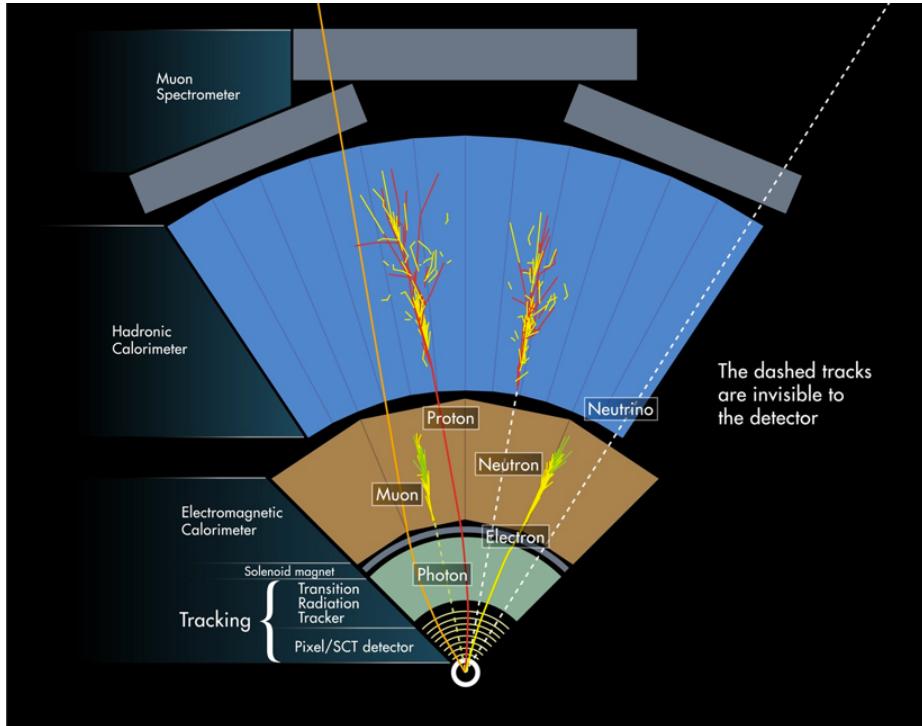


Figure 2.14: Illustration of particle interactions in ATLAS [48]

1063 2.4.I ELECTRONS

1064 Electrons in ATLAS will leave tracks in the inner detector and energy deposits in the electromagnetic
1065 calorimeter. The algorithm for recognizing the signature of electrons proceeds in two steps: reconstruc-
1066 tion and identification.

1067 In reconstruction, an electron candidate is formed by matching EM calorimeter deposits with ID
1068 tracks. The algorithm first chooses seed clusters in the EM calorimeter by using a sliding window algo-
1069 rithm that searches for towers with transverse energy larger than 2.5 GeV. In addition to seed clusters,
1070 track candidates must be identified in the ID. The algorithm selects seed tracks with $p_T > 1$ GeV that

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

1071 do not fit well with a pion hypothesis. Once candidate tracks are selected, they are re-fit with a Gaus-
 1072 sian Sum Filter (GSF) algorithm to estimate electron parameters [49]. Finally, an electron candidate is
 1073 formed if at least one track matches to a seed cluster in the calorimeter. The full details of the reconstruc-
 1074 tion algorithm can be found in reference [50].

1075 Once an electron candidate is present, identification criteria must be applied in order to reject fake
 1076 electrons from background. Many different variables are used for this identification, most of them re-
 1077 lated to the shower shape in the EM calorimeter and the amount of leakage into the hadronic calorime-
 1078 ter, as well as information from the ID and in particular the TRT. There are both cut-based and likelihood-
 1079 based criteria that range from “loose” to “very tight”. For details, see reference [50].

1080 Figure 2.15 shows the algorithm’s reconstruction efficiency of true electrons for different identification
 1081 criteria as well as the electron energy resolution in simulation [50, 51]. The reconstruction efficiency is
 1082 measured using both Z and J/ψ tag and probe techniques.

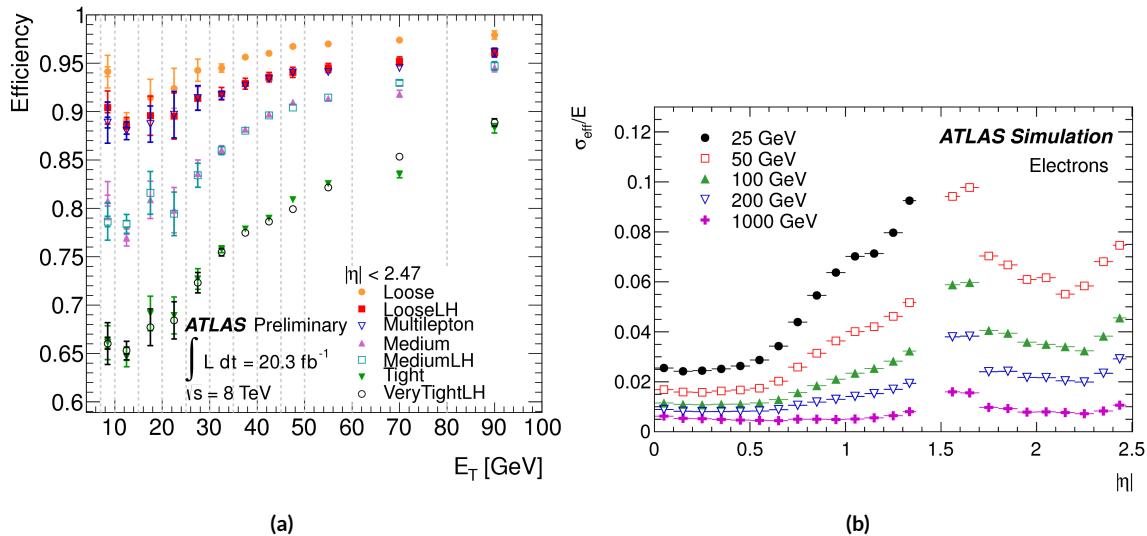


Figure 2.15: Electron performance: (a) reconstruction efficiency as a function of electron E_T [50] (b) energy resolution in simulation as a function of $|\eta|$ for different energy electrons [51]

1083 2.4.2 MUONS

1084 The ATLAS detector is designed to stop most particles before they reach the muon spectrometer. Muons,
 1085 however, are minimum ionizing particles, meaning that they will not lose a significant amount of energy

1086 through interactions with the detector and will thus pass through. Therefore, the muon reconstruction
1087 works to match tracks in the muon spectrometer with tracks in the inner detector.

1088 The first step of reconstruction is to reconstruct local straight line tracks, called segments, in each
1089 muon chamber. Segments are then fit to larger tracks that traverse the entire muon spectrometer. Such
1090 muon tracks are referred to as “standalone” tracks (SA) as they only use information from the muon
1091 spectrometer. The standalone tracks are then matched to tracks in the inner detector to form “com-
1092 bined” (CB) muons, where the combined ID and MS fit are used to determine the momentum and di-
1093 rection of the muon. To improve acceptance, segment-tagged and calorimeter-tagged muons are also
1094 reconstructed. In these cases, ID tracks are matched to segments in the MS and calorimeter deposits con-
1095 sistent with a minimum ionizing particle, respectively. The details of the reconstruction can be found in
1096 reference [52].

1097 As with electrons, once muon candidates are reconstructed they have identification criteria applied to
1098 reduce background. These criteria include the χ^2 match between the ID and MS tracks, the number of
1099 hits in the ID, overall ID and MS track fit quality, and additional variables [52]. The criteria range from
1100 “loose” to “tight” as with electrons.

1101 Figure 2.16 shows the muon reconstruction efficiency (measured with Z and J/ψ tag and probe) and
1102 invariant mass resolution [52].

1103 2.4.3 JETS

1104 When a quark or gluon is produced in collisions, it is not measured directly in ATLAS. Rather, due to
1105 QCD effects, it produces a collimated spray of hadrons in the direction of the original parton, which is
1106 known as a jet. Jets are reconstructed in ATLAS using energy deposits in the hadronic calorimeter. The
1107 first step is build “topological clusters” out of energy deposits in calorimeter cells [53, 54]. This is done
1108 using strategy where seed cells are chosen by picking cells whose energy measurements are four times the
1109 amount of noise expected for that cell. Adjacent cells with at least 2σ energy measurements are added
1110 to the cluster, then a final layer of clusters with energy above 0σ are added. Once calorimeter clusters
1111 are formed, they are clustered further into jet candidates using the anti- k_T jet clustering algorithm [55].

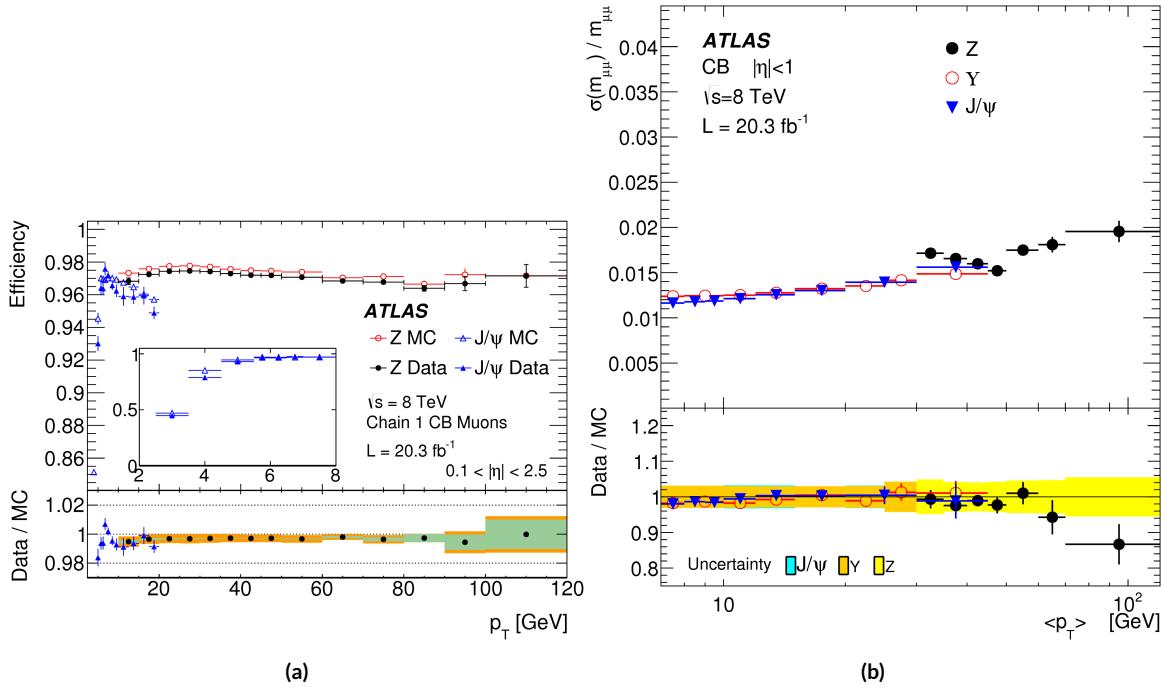


Figure 2.16: Muon performance: (a) reconstruction efficiency as a function of muon p_T (b) dimuon mass resolution as a function of average p_T [52]

This algorithm uses a parameter R that appears in the denominator of the clustering distance metric and defines the radial size of the jet in η - ϕ space.

The energy response of the calorimeter must be properly characterized in order to reconstruct jet energy. Calorimeter clusters can be calibrated either with the EM calibration, where each cluster is assumed to have come from the energy deposit of an electron or photon, or the LCW calibration, where local cluster weights are computed to allow for local calibration of clusters as hadronic or electromagnetic.

The details of the jet energy calibration are not detailed here and are discussed in reference [56].

Figure 2.17 shows the jet energy response after calibration in Monte Carlo as a function of the true p_T of the jet [56].

2.4.4 b -TAGGING

One important aspect of jet physics is the task of identifying the flavor of parton that produced the measured jet. While in general this is very difficult, jets from b -quarks offer an interesting case where such identification is possible. B mesons have a lifetime on the order of 10^{-12} seconds, which makes a $c\tau$

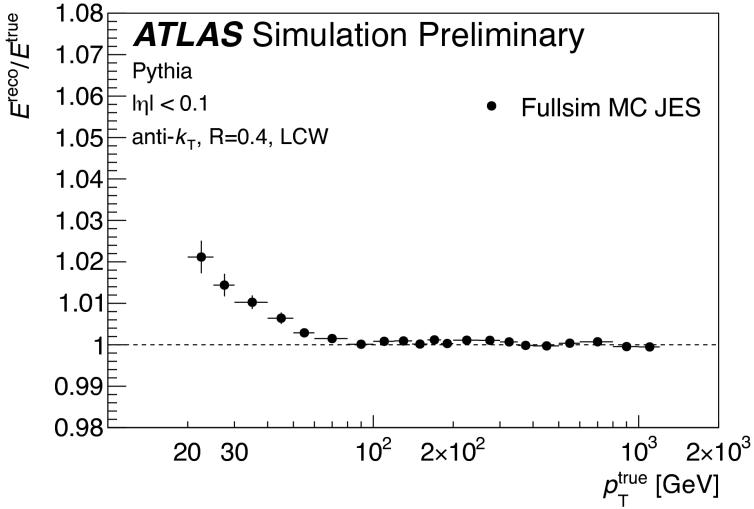


Figure 2.17: Jet energy response after calibration as a function of true p_T in simulation [56]

on the order of millimeters [6]. This type of displaced decay vertex can be identified in detectors like ATLAS and allows b -jets to be distinguished from other flavors of jets[†].

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

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

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

In Run 1, the multivariate b -tagging algorithm used a neural network and was referred to as MV1.

[†]Jets 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

1140 The details of this algorithm and its inputs are given in reference [57]. In Run 2, the number of inputs
 1141 was simplified and a boosted decision tree with 24 input variables was used, referred to as MV2. The
 1142 details of this algorithm are in reference [58]. Figure 2.18 shows the performance of each of these algo-
 1143 rithms.

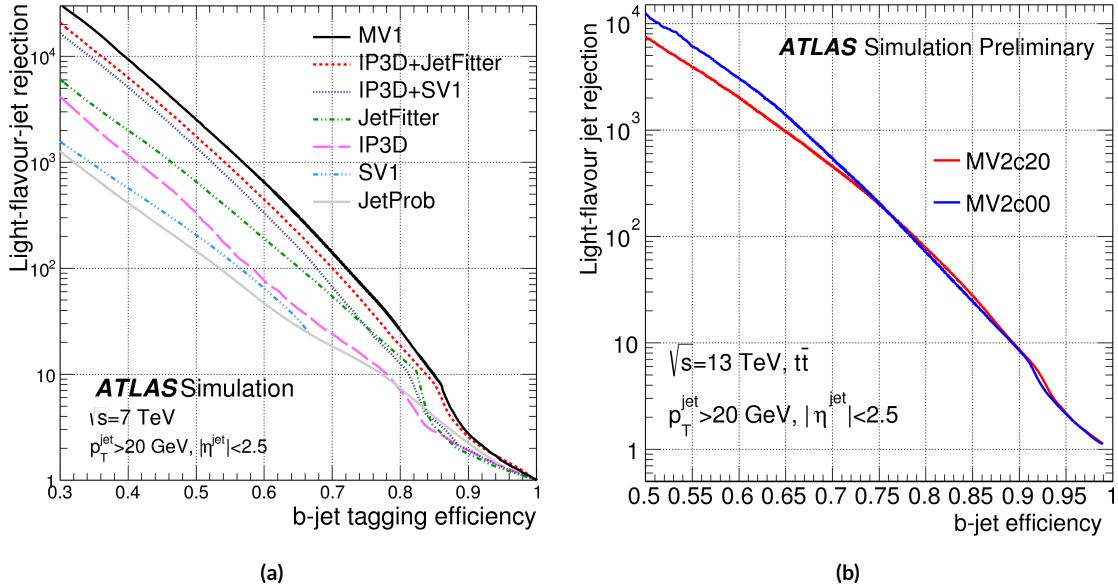


Figure 2.18: Light jet rejection ($1/\text{efficiency}$) vs. b -jet efficiency for MV1 and its input algorithms (a) [57] and MV2 (b) [58] in simulated $t\bar{t}$ events. The numbers in the algorithm names in (b) refer to the fraction of charm events used in the MV2 training.

1144 2.4.5 MISSING TRANSVERSE ENERGY

1145 As noted in figure 2.14, neutrinos produced in ATLAS will pass through the detector without inter-
 1146 acting. The only way of detecting the presence of particles like neutrinos (or BSM particles that are
 1147 long-lived) is to use missing transverse momentum. The basic principle of missing transverse energy is
 1148 to use the momentum balance of the incoming protons to infer the presence of missing particles. The
 1149 net longitudinal momentum of the incoming partons that collide is not known (since each carries an un-
 1150 known fraction of the proton's momentum). However, the protons (and thus incoming partons) have
 1151 no net momentum in the plane transverse to the beam line (the x - y plane). Therefore, if there are no
 1152 un-measured particles in the final state, the transverse momenta of all of the final state particles should

balance. The magnitude of this imbalance is known as missing transverse momentum (E_T^{miss}).

The basic calculation of missing transverse momentum from calorimeter cells is given in equation 2.4 [59].

1155

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

1156 The E_T^{miss} calculation is separated into different terms based on the objects that the calorimeter clusters
1157 are associated with. This way, each cell's contribution is calibrated appropriately according to the object.

1158 This separation of terms is shown in equation 2.5 [59].

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

1159 The CellOut term of the above equation corresponds to calorimeter cells with energy deposits that are
1160 not associated with other objects. The soft jets term comes from cells associated to jets with p_T between
1161 7 and 20 GeV, while the jets term comes from jets with $p_T > 20$ GeV. Because muons do not deposit
1162 significant energy in the calorimeter, the muon momentum is used for the muon term [59]. The final
1163 E_T^{miss} is calculated using equation 2.6.

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

1164 Figure 2.19 shows the resolution of the components of the E_T^{miss} under different pileup suppression
1165 techniques [60].

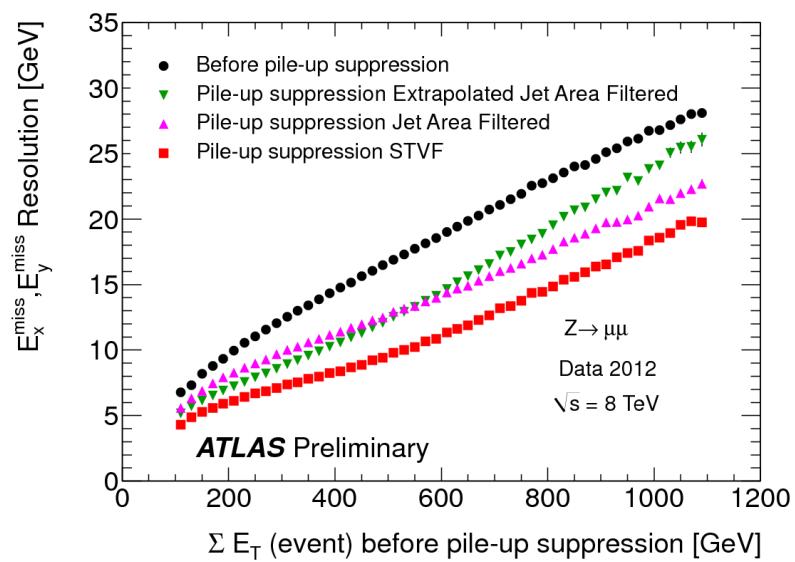


Figure 2.19: Resolution of E_T^{miss} components as a function of $\sum E_T$ before pileup suppression with different pileup techniques [60]

1166

Part II

1167

Observation and measurement of Higgs

1168

boson decays to WW^* in LHC Run I at

1169

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

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

Wernher von Braun

3

1170

1171 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ Analysis Strategy

1172 3.1 INTRODUCTION

1173 This chapter presents an overview of the strategy for searching for a Higgs boson in the $H \rightarrow WW^* \rightarrow$
1174 $\ell\nu\ell\nu$ decay topology. Its purpose is to define in broad terms how the search and measurement are un-
1175 dertaken, before going into details on the specific sub-categories within the larger analysis. First, the
1176 properties of the Higgs signal are discussed and the associated backgrounds are presented. Next, the ob-
1177 servables used to enhance the signal to background ratio are defined. Finally, the parameters of interest
1178 in the search and measurement will be shown, along with a brief overview of the statistical treatment of
1179 the final Higgs candidates.

1180 Following this chapter, the results of three different studies within the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel
1181 are shown. Chapter 4 presents a search for Higgs boson production in gluon fusion mode and the role
1182 of the $H \rightarrow WW^*$ channel in its discovery. Chapter 5 shows the search and first observation in ATLAS
1183 of the Vector Boson Fusion (VBF) production mode of the Higgs in the $H \rightarrow WW^*$ decay channel.

1184 Finally, chapter 6 shows the combined Run 1 $H \rightarrow WW^*$ results for the measurement of the Higgs
1185 cross section and relative coupling strengths to other SM particles.

1186 3.2 THE $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ SIGNAL IN ATLAS

1187 The signal studied in this and subsequent chapters is the Higgs boson in the WW^* final state, where
1188 each W boson subsequently decays into a charged lepton and a neutrino. In its simplest decay path, the
1189 final state consists of two neutrinos and two charged leptons, each of which can be either an electron or
1190 a muon. If one or both of the W s decay to τ leptons, only leptonic decays of the τ are considered. This
1191 decay path produces additional neutrinos in the final state but still gives two charged leptons as before.
1192 Neutrinos are not detected in ATLAS, so the final state ultimately consists of two reconstructed leptons
1193 and missing transverse momentum (denoted as E_T^{miss}). Final states where both of the charged leptons
1194 are electrons or muons are referred to as the “same flavor” ($ee/\mu\mu$) final states, while those with one
1195 electron and one muon are referred to as “different flavor” ($e\mu$ or μe).

1196 While the basic final state consists of two leptons and E_T^{miss} , there can be additional objects depend-
1197 ing on the production mode of the Higgs. As described in detail in Chapter 1, if the Higgs is produced
1198 via vector boson fusion production, there will be two additional forward jets in the event. Even in gluon
1199 fusion, one or more jets can be produced through initial state radiation from the incoming gluons. Be-
1200 cause of the varying background composition as a function of jet multiplicity, each bin in this variable
1201 has its own dedicated requirements applied in the search and measurement. The $n_j = 0$ and $n_j = 1$
1202 bins are dedicated to gluon fusion production, while the $n_j \geq 2$ bin has separate dedicated searches for
1203 ggF and VBF production.

1204 Figure 3.1 shows the relative branching fractions for the $H \rightarrow WW^*$ process, calculated from the
1205 Particle Data Group values for the W and τ branching ratios [?]. The largest branching ratio is both
1206 W bosons decaying to quark pairs at 45.44%. The next largest is one W decaying leptonically and the
1207 other decaying to quarks, a branching ratio of 34.18%. In all cases, ℓ denotes either an electron or muon,
1208 and the leptonic branching ratios of the τ are included. For example, the $\ell\nu qq$ final state includes one W
1209 decaying to $e\nu$, $\mu\nu$, or $\tau\nu$. In the case of the $W \rightarrow \tau\nu$ decay, the τ lepton then decays to an electron or

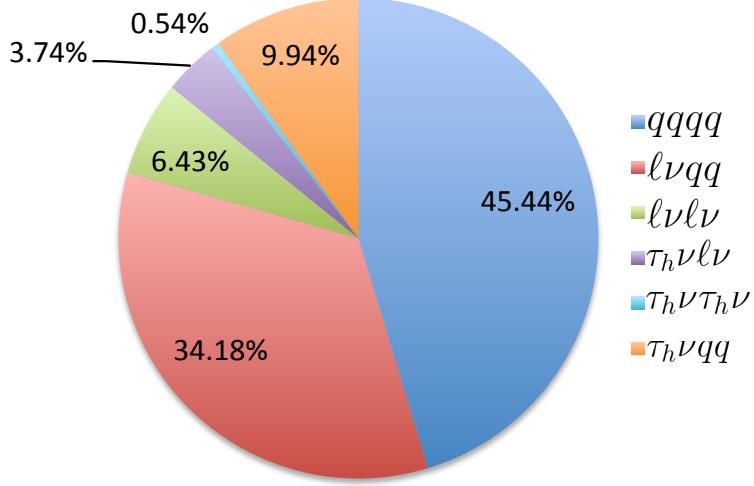


Figure 3.1: Branching ratios for a WW system. q refers to quarks. ℓ can be either an electron or muon, and the leptonic branching ratios of the τ are included. For example, the $\ell\nu qq$ final state includes one W decaying to $e\nu$, $\mu\nu$, or $\tau\nu$. τ_h refer to hadronic decays of the τ .

1210 muon via $\tau \rightarrow \nu_\tau \ell \nu_\ell$. Final states with a τ_h refer to hadronic decays of the τ . The branching ratio to the
1211 $\ell\nu\ell\nu$ final state is 6.43%.

1212 While the $\ell\nu\ell\nu$ final state is not a large fraction of the branching ratio, there are significant advantages
1213 in this channel. First, both the $qqqq$ and $\ell\nu qq$ channels suffer from a large QCD multijet background,
1214 which is often difficult to model. Second, events in the the $\ell\nu\ell\nu$ channel in data can be triggered more
1215 efficiently due to the presence of two leptons.

1216 **3.3 BACKGROUND PROCESSES**

1217 Many processes from the Standard Model can also produce a final state with two leptons and missing
1218 transverse momentum . This section lists the dominant backgrounds to Higgs production. It gives gen-
1219 eral descriptions of how the backgrounds mimic Higgs production and how they can be reduced. Ta-
1220 ble3.1 summarizes the different processes.

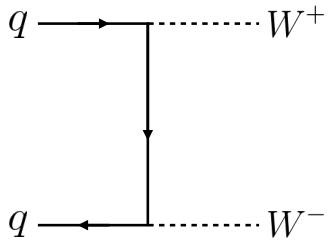


Figure 3.2: Feynman diagram for Standard Model WW production

1221 3.3.1 STANDARD MODEL WW PRODUCTION

1222 Non-resonant Standard Model diboson production, as shown in figure 3.2, is an irreducible background
1223 to Higgs boson production in the WW final state. It produces the same exact final state objects, namely
1224 leptonically decaying W bosons. There are no additional objects in the final state that allow for back-
1225 ground reduction. Therefore the analysis solely relies on the correlations between the leptons to reduce
1226 this background.

1227 3.3.2 TOP QUARK PRODUCTION

1228 Production of top quarks, either in pairs ($t\bar{t}$ production) or singly (e.g. Wt production), can also mimic
1229 Higgs production. Because top quarks decay via $t \rightarrow Wb$, top pair production can produce a final state
1230 with two W bosons that then decay leptonically. In this case, however, there are two additional jets from
1231 the bottom quarks in the final state. This allows the analysis to veto on the presence of jets identified as
1232 originating from a b in order to reduce the size of the background.

1233 Single top production can occur via s -channel, t -channel, or associated production (Wt). The mode
1234 which most closely resembles the Higgs final state is Wt . In this case, there are two real W bosons pro-
1235 duced, as with $t\bar{t}$. However, the decay of the single top quark will still also produce one b -jet, meaning
1236 a b veto will reduce this background as well. Figure 3.3 shows the Feynman diagrams for $t\bar{t}$ and Wt pro-
1237 duction.

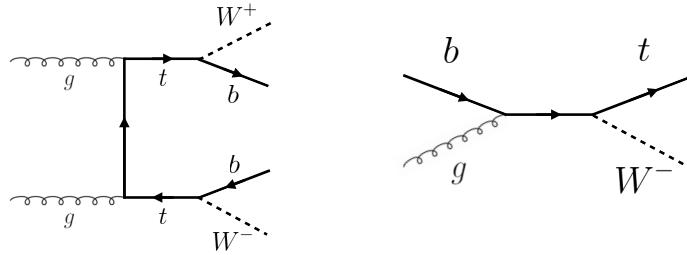


Figure 3.3: Feynman diagrams for top pair production (left) and Wt production (right)

1238 3.3.3 W +JETS BACKGROUND

1239 Single W boson production, in association with jets, is a unique background. The other background
 1240 considered so far have all included real leptons in the final state. In this case, however, only one real lep-
 1241 ton from the decay of a W exists in the final state. The second reconstructed lepton can arise from two
 1242 different cases. First, the lepton may truly be an algorithm “fake”, or a jet misidentified as a lepton by
 1243 either the electron or muon reconstruction algorithms. Second, the lepton may be a real lepton but
 1244 coming from semi-leptonic decays of particles inside the shower of the jet. This background can be re-
 1245 duced by requiring that the reconstructed lepton have little activity surrounding it in the calorimeter
 1246 (also known as an “isolated” lepton). Figure 3.4 shows the Feynman diagram for W +jets production.

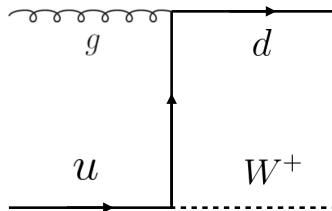


Figure 3.4: An example Feynman diagram of W +jets production

1247 3.3.4 Z/γ^* +JETS BACKGROUND

1248 Production of a Z/γ^* in association with jets (also known as Drell-Yan) is also a background to Higgs
 1249 production. In particular, the same flavor final states have a large Z +jets background, as the Z decays
 1250 into two leptons of the same flavor. (This background also enters the different flavor final state through

1251 the leptonic decays of $Z \rightarrow \tau\tau$). Figure 3.5 shows the production of a Z in association with one jet. Be-
1252 cause there are no neutrinos in this final state, variables like E_T^{miss} can be used to reduce the background.

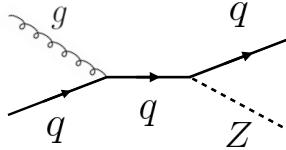


Figure 3.5: An example Feynman diagram of $Z + \text{jets}$ production

1253 3.3.5 OTHER (SUBDOMINANT) BACKGROUNDS

1254 There are additional processes which contribute to the background composition but are not produced
1255 as frequently as those listed already. The first of these are referred to as VV or “Other diboson” pro-
1256 cesses and include multiple Standard Model diboson processes, including WZ , ZZ , $W\gamma$, $W\gamma^*$, and
1257 $Z\gamma$ production. Additionally, there is background from QCD multijet production, where two jets are
1258 misidentified as leptons.

Category	Process	Description
SM WW	$WW \rightarrow \ell\nu\ell\nu$	Real leptons and neutrinos
Top quark production	$t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b\ell\nu b$	Real leptons, untagged $b s$
	$tW \rightarrow WbW \rightarrow \ell\nu\ell\nu b$	Real leptons, untagged b
	$t\bar{b}, t q \bar{b}$	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

1259 3.4 SHARED SIGNAL REGION SELECTION REQUIREMENTS

1260 As presented in section 3.2, there are many different combinations of objects that can define a $H \rightarrow$
1261 $WW^* \rightarrow \ell\nu\ell\nu$ final state. The multiplicity of jets and the flavor combinations of the leptons both lead
1262 to many potential signal regions. Additionally, signal regions can be optimized separately to be sensi-
1263 tive to the distinct production modes of the Higgs. Gluon fusion, vector boson fusion, and associated
1264 production of a Higgs all lead to unique final state topologies. Figure 3.6 delineates the different signal
1265 regions used in the gluon fusion and vector boson fusion $H \rightarrow WW^*$ analyses. While there are different
1266 optimizations possible in each signal region, there are also some commonly shared selections that will be
1267 described here.

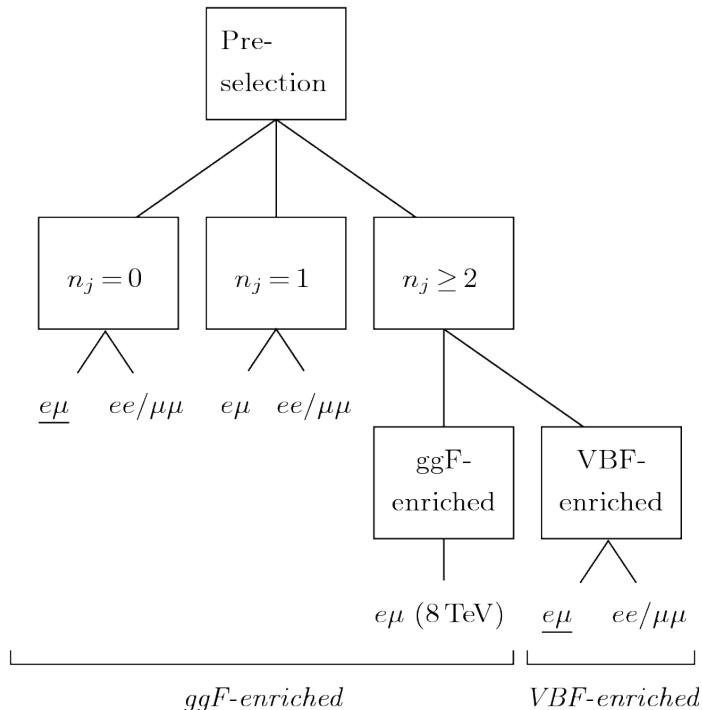


Figure 3.6: An illustration of the unique analysis signal regions [61]

1268 3.4.I EVENT PRE-SELECTION

1269 Before being sorted into the distinct signal regions, basic requirements are applied on the reconstructed
1270 objects in the event to select Higgs-like event candidates. First, two oppositely charged leptons are re-

1271 quired.

1272 Once the leptons are selected, the last requirement for event pre-selection is the presence of neutrinos.

1273 As neutrinos cannot be detected directly in ATLAS, E_T^{miss} can be used as a proxy for the combined neutrino momentum in the transverse plane. In general, it is expected that the signal should have a harder 1274 E_T^{miss} spectrum than backgrounds, especially if those backgrounds did not contain neutrinos. One additional consideration when using E_T^{miss} is the fact that mis-measurements of objects in the detector 1275 can lead to imbalances in the transverse plane that are not due to real particles escaping the detector.

1276 One indicator that this is the case is that the E_T^{miss} vector in the transverse plane will be pointing in the 1277 same direction as the mis-measured object. Therefore, a new variable, $E_{T,\text{rel}}^{\text{miss}}$, is used in the pre-selection. 1278 $E_{T,\text{rel}}^{\text{miss}}$ is defined in equation 3.1.

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

1281 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 1282 away from this object. Otherwise, the normal E_T^{miss} vector is used. Figure 3.7 shows a graphical 1283 illustration of this concept.

1284 Once both the lepton and E_T^{miss} pre-selections are made, the analysis can be divided into different 1285 regions according to jet multiplicity.

1286 3.4.2 JET MULTIPLICITY

1287 Jet multiplicity, denoted as n_j , is used to sub-divide the analysis into its distinct signal regions. The reason 1288 for this is twofold. First, different jet multiplicity bins will be more or less sensitive to different Higgs 1289 production modes. For example, the $n_j \geq 2$ region is more sensitive to VBF production because of 1290 the two high momentum jets produced at matrix element level. For gluon fusion production to enter 1291 this bin, two initial state radiation jets must be emitted. Second, background composition varies greatly 1292 in different bins of n_j . Figure 3.8 shows the jet multiplicity in both the different flavor and same flavor 1293 regions. It also shows the background composition in the bins of n_b . There are a few clear trends from

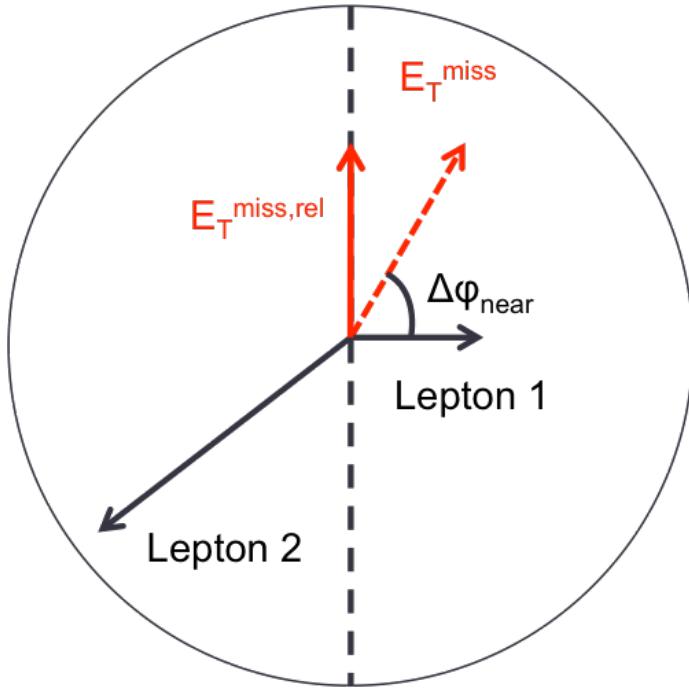


Figure 3.7: A graphical illustration of the $E_{T,\text{rel}}^{\text{miss}}$ calculation

1294 this distribution. The first is that the Drell-Yan background dominates in the same flavor channels for
 1295 $n_j \leq 1$. Second, the top background becomes a clear contributor to the total background for $n_j \geq 1$.
 1296 Lastly, the SM WW production dominates in the $n_j = 0$ bin, as it is an irreducible background to
 1297 $H \rightarrow WW^*$ production. Because of these distinct features, each jet multiplicity bin is treated separately.

1298 3.5 BACKGROUND REDUCTION IN SAME-FLAVOR FINAL STATES

1299 As described in section 3.4.2, the background composition of the same flavor final states is unique to that
 1300 of the different flavor states. In particular, Drell Yan processes play a much larger role because the Z/γ^*
 1301 decays to same flavor leptons. Because real neutrinos are absent in the Z/γ^* decays to ee and $\mu\mu$, a re-
 1302 quirement on E_T^{miss} should largely reduce the background. However, as this section will demonstrate,
 1303 with increasing pileup conditions the resolution of the calorimeter-based E_T^{miss} degrades greatly. There-
 1304 fore, two new variables for Z/γ^* background reduction are constructed and described in this section.

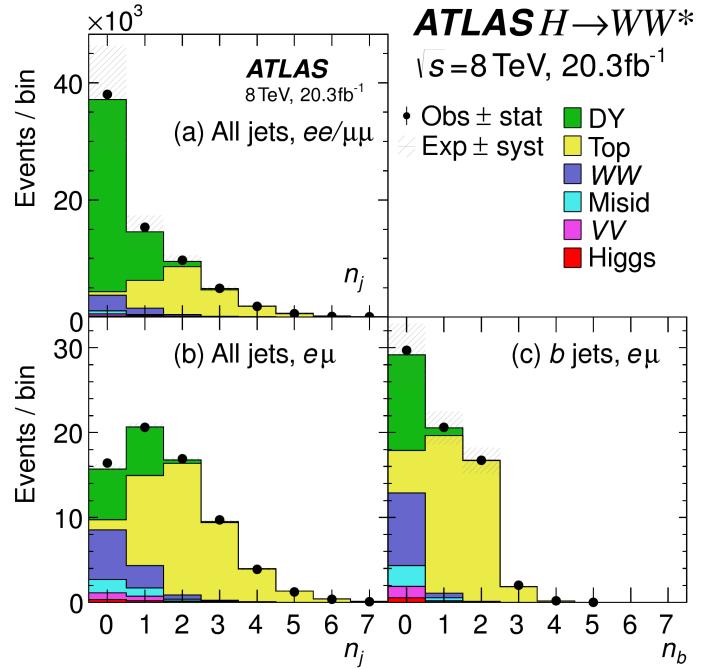


Figure 3.8: Predicted backgrounds (compared with data) as a function of n_j (a and b) and n_b (c)

3.5.1 PILEUP AND E_T^{miss} RESOLUTION

Secondary interactions of protons in the colliding bunches of the LHC (known as pileup interactions, described in detail in Chapter 2) deposit energy into the ATLAS calorimeter on top of the energy that comes from the hard scatter process that is being searched for or analyzed. The calculation of E_T^{miss} is fundamentally Poissonian, as summing up all of the energy deposits in individual calorimeter cells or clusters is similar to a counting experiment. Thus, the energy resolution scales as \sqrt{E} , just as the error on a mean of N in a Poisson distribution is \sqrt{N} . As more energy is deposited in the calorimeter, the E_T^{miss} resolution degrades, meaning that the E_T^{miss} resolution is particularly sensitive to LHC instantaneous luminosity conditions.

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

Figure 3.10 shows the RMS of the E_T^{miss} distribution in $Z \rightarrow \mu\mu$ events (where there are no real neu-

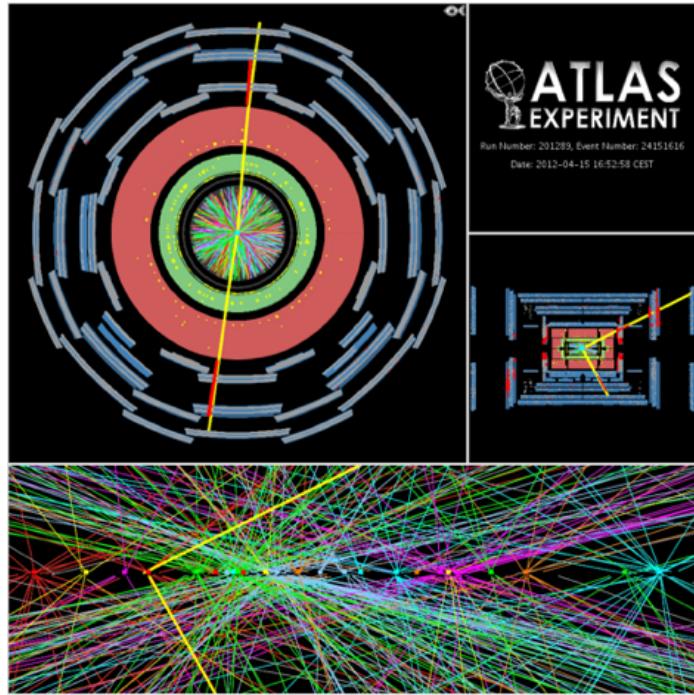


Figure 3.9: An event display of a Z/γ^* + jets event illustrating the effect of pileup interactions

trinos) as a function of the number of the average number of interactions. Under 2011 LHC conditions, this RMS was approximately 9 GeV, while under 2012 running conditions the resolution worsened to 12 GeV. This worsening dilutes the E_T^{miss} variable's ability to reduce the Z/γ^* background.

3.5.2 TRACK-BASED DEFINITIONS OF MISSING TRANSVERSE MOMENTUM

Because the increasing number of secondary proton-proton interactions degrades calorimeter-based E_T^{miss} resolution, a new variable using only contributions from the primary interaction vertex is necessary to further reduce the Z/γ^* background. While it is not possible to associate calorimeter energy deposits with a particular vertex, individual charged particle tracks in the Inner Detector are associated to unique vertices. Thus, two track-based definitions of missing transverse momentum , using only tracks coming from the primary vertex in the event, are used in the analysis. The simplest variable, $p_T^{\text{miss}(\text{trk})}$, is the vectorial sum of the p_T of all of the tracks from the primary vertex and the selected leptons (excluding the tracks associated with the selected leptons to avoid double counting). This is defined in equa-

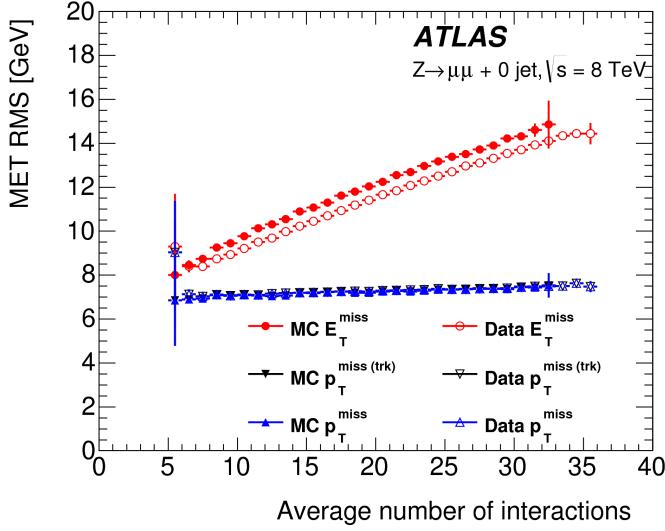


Figure 3.10: The RMS of different missing transverse momentum definitions as a function of the average number of interactions per bunch crossing

1331 tion 3.2.

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

1332 In events with hard jets, a better resolution on the missing transverse momentum is obtained by includ-
 1333 ing the calorimeter based measurement of the hard jets rather than the track based measurements. Thus,
 1334 another variable, p_T^{miss} , is defined, using the nominal measurements of p_T for the selected leptons and
 1335 jets and using tracks rather than calorimeter clusters for the soft component of the missing transverse
 1336 momentum . This is defined in equation 3.3.

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

1337 Figure 3.10 illustrates that these two new variables accomplish their intended purpose. The resolution
 1338 as a function of mean number of interactions for both $p_T^{\text{miss}(\text{trk})}$ and p_T^{miss} is much flatter compared to
 1339 the dependence for E_T^{miss} . Figure 3.11a shows the difference between the true and reconstructed values of
 1340 missing transverse momentum using both the track-based p_T^{miss} and calorimeter based E_T^{miss} . The RMS
 1341 of the distribution improves by 3.5 GeV when using p_T^{miss} .

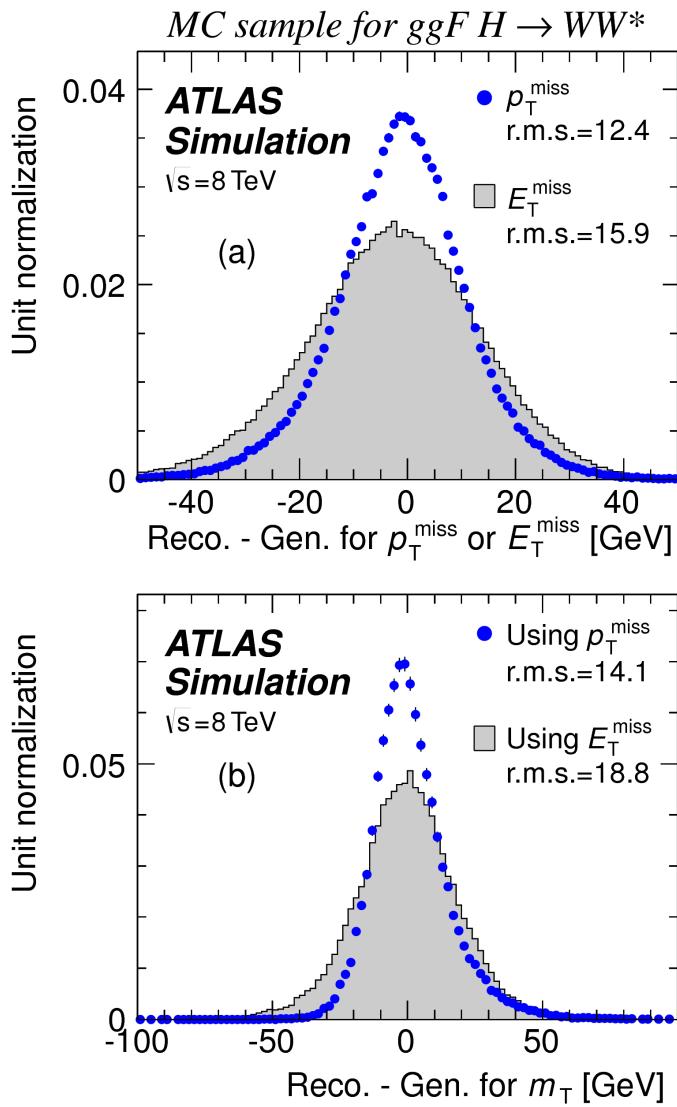


Figure 3.11: The difference between the true and reconstructed values of the missing transverse momentum (a) and m_T (b) in a gluon fusion signal sample

1342 3.5.3 DISTINGUISHING Z/γ^* +JETS AND $H \rightarrow WW^*$ TOPOLOGIES

1343 The track-based definitions of missing transverse momentum were constructed to mitigate degrading
 1344 performance as a function of pileup. However, an additional variable can be constructed to exploit kine-
 1345 matic and topological differences between the Z/γ^* background and $H \rightarrow WW^*$ signal. Because there
 1346 are no real neutrinos in the final state (in the case of $Z/\gamma^* \rightarrow ee, \mu\mu$ decays), the dilepton system of a
 1347 Z/γ^* will be balanced with the jets produced in the hard scatter. A new variable, f_{recoil} , is constructed

1348 to estimate the balance between the dilepton system and the jets in the quadrant opposite the dilepton
 1349 vector in the transverse plane. It is defined in equation 3.4. The numerator of f_{recoil} is the magnitude of
 1350 the vectorial sum of the p_T of jets in the quadrant opposite the dilepton system, weighted by each jet's Jet
 1351 Vertex Fraction (JVF, described in chapter 2). The denominator is the magnitude of the dilepton p_T .

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

1352 Figure 3.12 shows a shape comparison of the distribution of f_{recoil} in a simulated $Z/\gamma^* + \text{jets}$ sample, a
 1353 $H \rightarrow WW^*$ signal sample, and other backgrounds that contain real neutrinos. The $Z/\gamma^* + \text{jets}$ events
 1354 tend to be more balanced between the dilepton system and recoiling jets, while the processes containing
 1355 real neutrinos are less balanced in the transverse plane. Thus, a requirement on f_{recoil} will also reduce
 1356 the $Z/\gamma^* + \text{jets}$ background while maintaining a good signal efficiency.

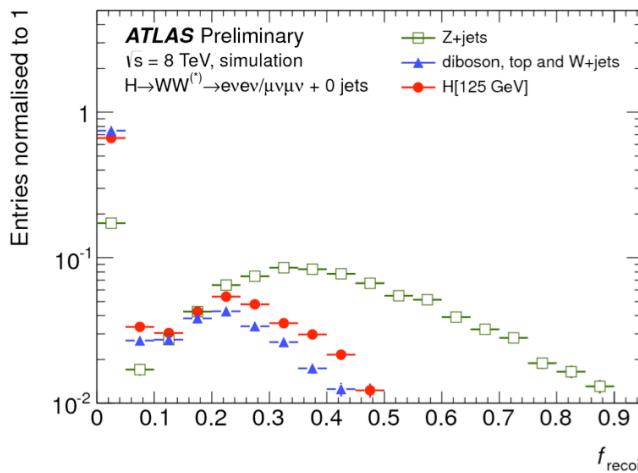


Figure 3.12: Comparison of f_{recoil} distributions for $Z/\gamma^* + \text{jets}$, $H \rightarrow WW^*$, and other backgrounds with real neutrinos.

1357 3.5.4 OPTIMIZING BACKGROUND REDUCTION SELECTION REQUIREMENTS

1358 The requirements on $p_T^{\text{miss}(\text{trk})}$ and f_{recoil} used to reduce the $Z + \text{jets}$ background must be optimized
 1359 to maximize their efficacy. Figure 3.13 shows an early attempt to optimize the combination of the two
 1360 requirements in the gluon fusion zero jet bin. Each bin shows the expected signal significance if the

1361 $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$ is required to be greater than the left edge of the bin and the f_{recoil} is required to be less than
 1362 the top edge of the bin. The figure shows that the best signal significance comes from requiring low val-
 1363 ues of f_{recoil} (< 0.05) and $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$ values greater than 45 GeV.

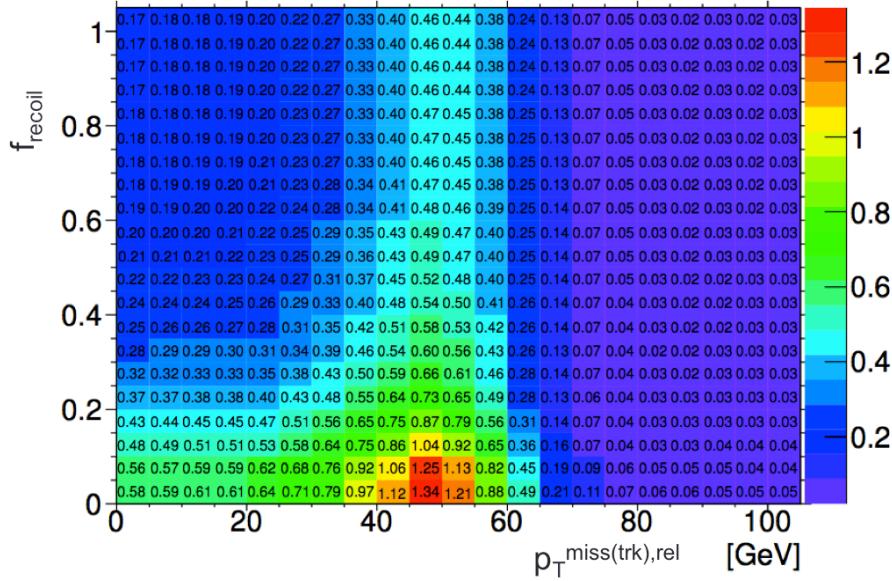


Figure 3.13: Signal significance as a function of required value for f_{recoil} and $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$ in the ggF $H \rightarrow WW^*$ with $n_j = 0$

1364 3.6 PARAMETERS OF INTEREST AND STATISTICAL TREATMENT

1365 As with any search or measurement, there are particular parameters of the Higgs that the $H \rightarrow WW^*$
 1366 analysis is interested in measuring. In this case, the parameters of interest are the mass of the Higgs bo-
 1367 son and its production cross section. Because the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ process does not have a closed
 1368 final state, it is not possible to measure the full invariant mass of the particle that may have produced
 1369 the final state. However, a proxy for the invariant mass using transverse plane information can be de-
 1370 fined. This is described in more detail in section 3.6.1. The second parameter of interest is the ratio of the
 1371 measured cross section to that expected from the Standard Model Higgs, which is denoted a μ . This is
 1372 defined in equation 3.5.

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

1373 All of the likelihoods used in the statistical analysis of the final signal region events are parameterized as a
1374 function of μ . μ is a natural variable for hypothesis testing, as $\mu = 0$ corresponds to a background only
1375 hypothesis and $\mu = 1$ corresponds exactly to a Standard Model Higgs.

1376 **3.6.1 TRANSVERSE MASS**

1377 Because the longitudinal information about the neutrinos is not attainable, the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
1378 analysis uses a mass variable, the transverse mass, that exploits information in the transverse plane as a
1379 proxy for the full invariant mass. The transverse mass is defined in equation 3.6.

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

1380 Here the $E_T^{\ell\ell}$ and $p_T^{\ell\ell}$ are the transverse energy and momentum of the dilepton system, while p_T^{miss} is a
1381 proxy for the transverse momentum of the di-neutrino system. The track-based p_T^{miss} is used in the m_T
1382 rather than the calorimeter based E_T^{miss} because it has a better resolution on the true transverse mass.
1383 Figure 3.11b shows the improvement in the RMS of the difference between the true and reconstructed
1384 transverse mass in a ggF signal sample. The RMS improves by 4.7 GeV using p_T^{miss} in the m_T calcula-
1385 tion.

1386 **3.6.2 STATISTICAL TREATMENT^{*}**

1387 **LIKELIHOOD FUNCTION**

1388 The statistical analysis of final event candidates is framed as a hypothesis test, where the null hypothe-
1389 sis 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
1391 of events seen in the final signal region given knowledge of the signal strength. Because observation of
1392 events is fundamentally a Poisson counting experiment, this simple likelihood can be expressed as a Pois-
1393 son probability of observing N events given a total number of predicted signal and background events.

*Many thanks to Aaron Armbruster, whose thesis [62] inspired parts of this section.

1394 This basic 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 back-
1397 ground 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
1400 to a slightly more complicated likelihood, which is a function of both the signal strength and the back-
1401 ground 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 is a so-called “nuisance parameter”, a parameter that is not a primary parameter of interest but
1403 still enters the likelihood. The second Poisson term adds an extra term to the likelihood, enforcing the
1404 fact that the background normalization must be consistent with the number of observed events in data
1405 in the control region, N_{CR} .

1406 So far, these two formulations of likelihoods have assumed a single signal region and do not take into
1407 account any shape information of potential discriminating variables. The $H \rightarrow WW^*$ analysis is di-
1408 vided into many different categories, and we can perform the same counting experiment described above
1409 in each individual category. As mentioned in section 3.6.1, the transverse mass is used as the primary dis-
1410 criminating variable in many of the $H \rightarrow WW^*$ sub-analyses, so additionally we can perform the same
1411 counting experiment in each bin of the m_T distribution to incorporate some shape information. Thus,
1412 the total likelihood becomes a product over signal regions and bins of the m_T distribution. Finally, there
1413 are usually many backgrounds that are normalized in control regions, so the new formulation of the like-
1414 lihood takes this into account as well by including a product over control regions in the second Poisson

¹⁴¹⁵ term. All of these modifications are shown in equation 3.9.

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

¹⁴¹⁶ The final step to get the full likelihood used in the analysis is to add nuisance parameters for the sys-
¹⁴¹⁷ tematic uncertainties. In cases where the uncertainty does not affect the shape of m_T bin-by-bin, each
¹⁴¹⁸ systematic uncertainty ϵ is allowed to affect the expected event yields through a linear response function
¹⁴¹⁹ of the nuisance parameter, namely $\nu(\theta) = (1 + \epsilon)^{\theta}$. If instead the uncertainty does affect the shape,
¹⁴²⁰ the effect is instead parameterized by $\nu_b(\theta) = 1 + \epsilon_b \theta$. The value of the nuisance parameters for the
¹⁴²¹ systematic uncertainty are constrained with a Gaussian term that is added to the likelihood as well. This
¹⁴²² is of the form $g(\delta|\theta) = e^{-(\delta-\theta)^2/2}/\sqrt{2\pi}$, where δ is the central value and θ is a nuisance parameter.
¹⁴²³ Finally, a last term is added to account for the statistical uncertainty in the Monte Carlo samples used,
¹⁴²⁴ which adds an additional poisson term. The full likelihood used in the final statistical analysis is defined
¹⁴²⁵ in equation 3.10.

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

¹⁴²⁶ In the fourth term of the equation, quantifying uncertainty due to finite Monte Carlo sample size, ξ
¹⁴²⁷ represents the central value of the background prediction, θ is the associated nuisance parameter, $\zeta =$
¹⁴²⁸ $(B/\delta B)^2$, where δB is the statistical uncertainty of B .

¹⁴²⁹ The best fit value of the signal strength μ is determined by finding the values of μ and $\boldsymbol{\theta}$ that maxi-
¹⁴³⁰ mize the likelihood, while setting $\delta = 0$ and $\xi = \zeta$. Once the likelihood is defined, a test statistic must

¹⁴³¹ be built for use in hypothesis testing.

¹⁴³² TEST STATISTIC

¹⁴³³ To distinguish whether the data match a background only or background and signal hypothesis, a test
¹⁴³⁴ statistic must be used. The $H \rightarrow WW^*$ analysis used the profile likelihood technique [63]. The first
¹⁴³⁵ step in formulating this test statistic is to define the profile likelihood ratio, shown in equation 3.11.

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

¹⁴³⁶ Here $\hat{\theta}_\mu$ is the value of θ that maximizes the likelihood for the choice of μ being tested. Additionally, $\hat{\theta}$
¹⁴³⁷ and $\hat{\mu}$ represent the values of θ and μ that gives the overall maximum value of the likelihood.

¹⁴³⁸ Once this is defined, a test statistic q_μ is constructed. This is shown in equation 3.12.

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

¹⁴³⁹ A higher value of q_μ means that the data are more incompatible with the hypothesized value of μ , and
¹⁴⁴⁰ q_0 then corresponds to the value of the test statistic for the background only hypothesis. A p_0 value is
¹⁴⁴¹ then defined to quantify the compatibility between the data and the null hypothesis. The p_0 value is the
¹⁴⁴² probability of obtaining a value of q_0 larger than the observed value, and this is shown in equation 3.13.

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

¹⁴⁴³ Here $f(q_\mu)$ is the probability distribution function of the test statistic. Finally, the p_0 value can be con-
¹⁴⁴⁴ verted into a signal significance, using the formula in equation 3.14, or the one-sided tail of the Gaussian
¹⁴⁴⁵ distribution.

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

¹⁴⁴⁶ 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

1447

1448

The discovery of the Higgs boson and the 1449 role of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel

1450

4.1 INTRODUCTION

1451 This chapter presents the results of the search for the Higgs boson in 4.8 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$
1452 and 5.8 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. The results of three searches at $\sqrt{s} = 8 \text{ TeV}$ in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$,
1453 $H \rightarrow \gamma\gamma$, and $H \rightarrow ZZ \rightarrow 4\ell$ channels are combined with results of searches at $\sqrt{s} = 7 \text{ TeV}$
1454 in the same search channels (as well as the $H \rightarrow \tau\tau$ production and associated production searches for
1455 $H \rightarrow b\bar{b}$). The results of this combination are a 5.9σ detection of a new particle consistent with a Higgs
1456 boson. Rather than going into detail for all of the different Higgs decay searches, this chapter will discuss
1457 the three most sensitive channels and in particular focus on $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. While the focus is
1458 on WW^* , some of the ZZ^* and $\gamma\gamma$ results are shown for completeness. The results not discussed here

¹⁴⁵⁹ can be found in the ATLAS Higgs discovery publication [1].

¹⁴⁶⁰ 4.2 DATA AND SIMULATION SAMPLES

¹⁴⁶¹ The data sample used for the following results was taken in 2011 and 2012 at center of mass energies of 7
¹⁴⁶² and 8 TeV, respectively, with 4.8 fb^{-1} collected at 7 TeV and 5.8 fb^{-1} collected at 8 TeV. Higgs pro-
¹⁴⁶³ duction in the gluon fusion and vector boson fusion modes is modeled with **POWHEG** for the hard scat-
¹⁴⁶⁴ tering event and **PYTHIA** for the showing and hadronization. Associated production of a Higgs with a
¹⁴⁶⁵ vector boson or top quarks is modeled via **PYTHIA**. Table 4.1 shows the Monte Carlo generators used for
¹⁴⁶⁶ 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].

¹⁴⁶⁷ 4.3 $H \rightarrow WW \rightarrow e\nu\mu\nu$ SEARCH

¹⁴⁶⁸ The $H \rightarrow WW \rightarrow e\nu\mu\nu$ search is unique compared to the ZZ and $\gamma\gamma$ channels. The Higgs mass can-
¹⁴⁶⁹ not be fully reconstructed due to the presence of neutrinos in the final state, so the transverse mass m_T
¹⁴⁷⁰ is used as the final discriminating variable. Compared to the other channels, there are more backgrounds
¹⁴⁷¹ here as well, as discussed in chapter 3. The same flavor final states are excluded from this search due to
¹⁴⁷² high pileup in the 8 TeV dataset.

1473 4.3.I EVENT SELECTION

1474 The analysis requires two opposite charge isolated leptons, with the leading (sub-leading) lepton required
 1475 to have $p_T > 25(15)$ GeV. The events are separated into different signal regions depending on which
 1476 flavor of lepton is leading ($e\mu$ for leading electron, μe for leading muon). Strict lepton quality cuts are
 1477 applied to the sample to reduce backgrounds from fake leptons.

1478 Jets are reconstructed with the anti- k_T algorithm with a radius parameter $R = 0.4$. The jets are
 1479 required to have $p_T > 25$ GeV and $|eta| < 4.5$, with jets in the tracking volume required to have a
 1480 jet vertex fraction of 0.5 and jets in the forward region required to have $p_T > 30$ GeV. The analysis is
 1481 separated into three different signal regions based on jet multiplicity: $n_j = 0, 1, \geq 2$.

1482 To indicate the presence of neutrinos in the event, a requirement of $E_{T,\text{rel}}^{\text{miss}} > 25$ GeV is made*. This
 1483 requirement significantly reduces the QCD multijet and Z/γ^* + jets backgrounds. Figure 4.1 shows the
 1484 distribution of n_j in data and simulation after applying these “pre-selection” requirements.

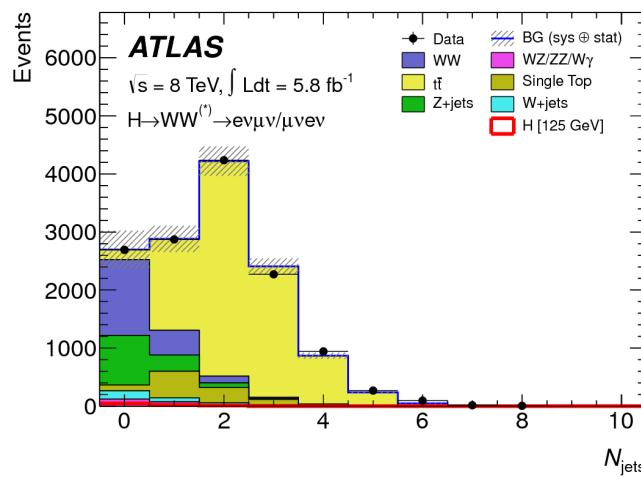


Figure 4.1: Jet multiplicity distribution in data and MC after applying lepton, jet, and $E_{T,\text{rel}}^{\text{miss}}$ selections. The WW and top backgrounds have been normalized using control samples, and the hashed band indicates the total uncertainty on the prediction. [1]

1485 Additional selections are applied to require the dilepton topology to correspond to that of a SM
 1486 Higgs. The requirements are presented here - more detailed discussion on the motivation for each re-
 1487 quirement is saved for Chapter 5. In all of the jet multiplicity channels, the dilepton system is required to

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

1488 have a small gap in azimuthal angle, $\Delta\phi_{\ell\ell} < 1.8$. Similarly, the $m_{\ell\ell}$ is required to be less than 50 GeV
1489 in the lower jet multiplicity channels and less than 80 GeV in the $n_j \geq 2$ channel. In the $n_j = 0$ chan-
1490 nel, the magnitude of the dilepton p_T , $p_T^{\ell\ell}$, is required to be greater than 30 GeV.

1491 In the higher jet multiplicity channels ($n_j \geq 1$), the top background is a more important component
1492 and must be reduced. The total transverse momentum p_T^{sum} is thus required to be less than 30 GeV.
1493 Additionally, the di- τ invariant mass $m_{\tau\tau}$ (dilepton mass computed under the assumption that the neu-
1494 trinos from the τ decay are emitted collinear to the charged leptons) is used to reject $Z \rightarrow \tau\tau$ events by
1495 requiring $|m_{\tau\tau} - m_Z| > 25$ GeV. These variables are also discussed in more detail in Chapter 5.

1496 In the $n_j \geq 2$ channel, requirements are made to isolate the VBF contribution to Higgs production.
1497 The kinematics of the two leading jets are used to make these requirements. In particular, the event must
1498 have $\Delta y_{jj} > 3.8$ and $m_{jj} > 500$ GeV, along with a veto on having any additional jets with rapidity
1499 between the two leading jets.

1500 4.3.2 BACKGROUND ESTIMATION

1501 The details of the background estimation techniques used in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis are dis-
1502 cussed in section 5.5. As that section refers to a later iteration of the analysis, a general discussion is given
1503 here for completeness. The dominant backgrounds are SM WW production and top (both pair and
1504 single) production, and these backgrounds have their normalizations estimated from dedicated control
1505 regions while their shapes are taken from simulation.

1506 The control sample for the Standard Model WW background is defined by making the same require-
1507 ments as the signal region with the $m_{\ell\ell}$ requirement inverted (now requiring $m_{\ell\ell} > 80$ GeV) and
1508 removing the $\Delta\phi_{\ell\ell}$ requirement. This creates a control sample that is 70% (40%) pure in the 0(1)-jet
1509 region. The correction to the pure MC-based background estimate is quantified by defining a normal-
1510 ization factor β which is the ratio of the data yield to the MC yield ($N_{\text{data}}/N_{\text{MC}}$) in this control sample.
1511 Table 4.2 shows the WW normalization factors in the $n_j = 0$ and $n_j = 1$ bins (the $n_j \geq 2$ estimate is
1512 taken directly from MC).

1513 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 [64]. 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.

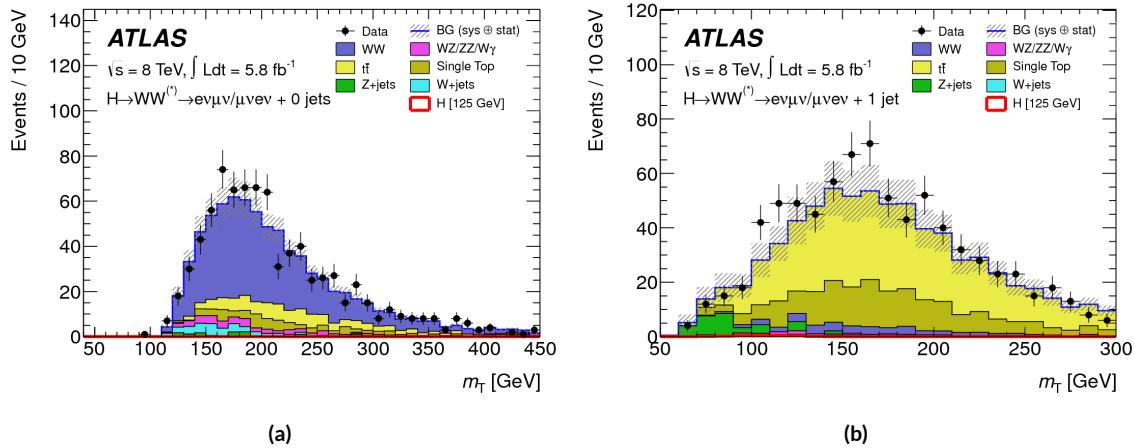


Figure 4.2: Comparison of m_T between data and simulation in the $n_j = 0$ WW (a) and $n_j = 1$ top (b) control samples [1]

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 $W+jets$ 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 simu-

1526 lation.

1527 **4.3.3 SYSTEMATIC UNCERTAINTIES**

1528 The systematic uncertainties that have the largest impact on the analysis are the theoretical uncertainties
1529 associated with the signal cross section, and these are shared with the ZZ^* and $\gamma\gamma$ channels. The un-
1530 certainties resulting from variations of the QCD scale are $+7\% / -8\%$ on the final singal yield. Those
1531 coming from variations of the parton distribution function (PDF) used in the simulation add a $\pm 8\%$
1532 uncertainty on the yield. The uncertainties on the branching ratios of the Higgs are $\pm 5\%$.

1533 The main experimental uncertainties come from variations of the jet energy scale (JES), jet energy
1534 resolution, pile-up, E_T^{miss} , b -tagging efficiency, $W + \text{jets}$ background estimate, and integrated luminosity.
1535 For more details, see reference [1].

1536 **4.3.4 RESULTS**

1537 Table 4.3 shows the signal and background yields in the final signal region after normalizing the back-
1538 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]

1539 Figure 4.3 shows the m_T distribution in the $n_j \leq 1$ channels for 8 TeV data. (No events are observed
1540 in data in the $n_j \geq 2$ channels in this dataset). The excess shown here relatively flat as a function of
1541 hypothesized Higgs mass. The combined 7 and 8 TeV data gives an excess with local significance of 2.8σ
1542 with an expected significance of 2.3σ , corresponding to a μ measurement of 1.3 ± 0.5 .

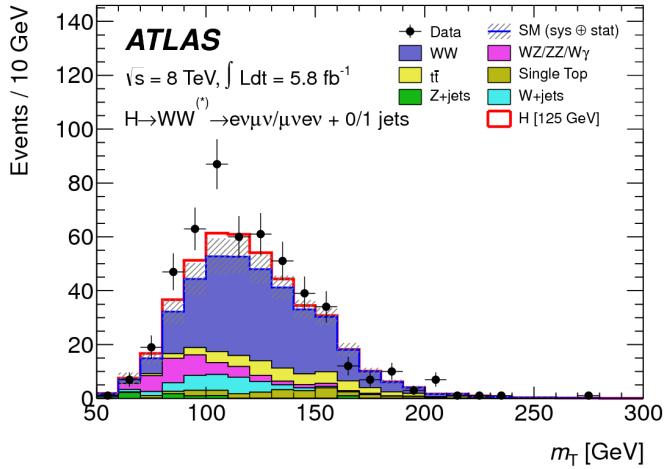


Figure 4.3: m_T distribution in the $H \rightarrow WW \rightarrow e\nu\mu\nu n_j \leq 1$ channels for 8 TeV data [1].

1543 4.4 $H \rightarrow \gamma\gamma$ SEARCH

1544 The $H \rightarrow \gamma\gamma$ search is in essence a search for a peaked excess above the falling SM diphoton mass spec-
 1545 trum, with $m_{\gamma\gamma}$ as the ultimate discriminating variable. Events are selected by requiring two isolated
 1546 photons, with the leading (sub-leading) photon required to have $E_T > 40(30)$ GeV. In the 8 TeV
 1547 data, the photons are required to pass cut-based identification criteria consistent with a photon in the
 1548 electromagnetic calorimeter and little leakage in the hadronic calorimeter.

1549 The main challenges for this analysis are accurate mass reconstruction and background estimation.
 1550 In order to accurately reconstruct the invariant mass of the di-photon system, both the energy and di-
 1551 rection of the photons must be measured well. Therefore, the identification of the primary vertex of the
 1552 hard interaction is particularly important, and is done using a multivariate likelihood which combines
 1553 information about the photon direction and vertex position. The background is modeled with a falling
 1554 spectrum in $m_{\gamma\gamma}$ that is parameterized by different functions depending on the category of the event.

1555 4.4.1 RESULTS

1556 The resulting diphoton mass spectrum is shown in figure 4.4. The best fit mass value in the $\gamma\gamma$ channel
 1557 alone in the combined 7 and 8 TeV data is 126.5 GeV. The local significance at this point is 4.5σ , with
 1558 an expected significance of 2.5σ . Therefore, the measured signal strength μ is 1.8 ± 0.5 in this channel.

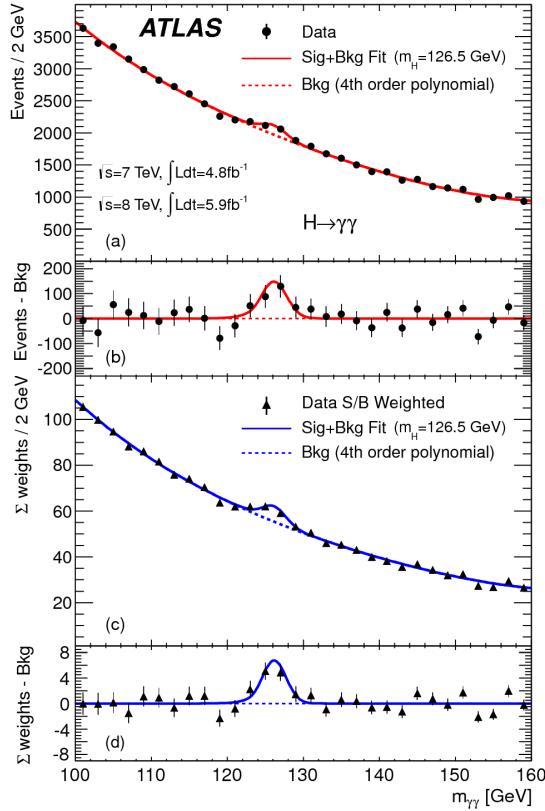


Figure 4.4: Diphoton mass spectrum in 7 and 8 TeV data. Panel a) shows the unweighted data distribution superimposed on the background fit, while panel c) shows the data where each event category is weighted by its signal to background ratio. Panels b) and d) show the respective distributions with background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

1559 4.5 $H \rightarrow ZZ \rightarrow 4\ell$ SEARCH

1560 The $H \rightarrow ZZ \rightarrow 4\ell$ analysis searches for a Standard Model Higgs boson decaying to two Z bosons,
 1561 each of which decays to a pair of same flavor, opposite charge isolated leptons. The ultimate discriminat-
 1562 ing variable is $m_{4\ell}$, or the invariant mass of the four selected leptons. The ℓ denotes an e or μ as with the
 1563 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis.

1564 Four distinct signal regions are constructed depending on the flavors of the final state, additionally
 1565 separated by the flavor of the leading lepton pair. These are referred to as $4e$, $2e2\mu$, $2\mu2e$, 4μ .

1566 The main backgrounds in the $H \rightarrow ZZ \rightarrow 4\ell$ search are continuum ZZ^* production, $Z + \text{jets}$ pro-
 1567 duction, and $t\bar{t}$. The $m_{4\ell}$ distribution for background is estimated from simulation. The normalization
 1568 of the SM ZZ^* background is also taken from MC simulation, while the $Z + \text{jets}$ and $t\bar{t}$ normalizations

1569 are taken from data-driven methods.

1570 **4.5.1 RESULTS**

1571 Figure 4.5 shows the $m_{4\ell}$ spectrum measured in the 7 and 8 TeV datasets. The total number of events
1572 observed in the window between 120 and 130 GeV is 13, with 6 events in the 4μ channel, 2 events in
1573 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
1574 occurs at 125 GeV and is measured to be 1.2 ± 0.6 . The observed significance at this mass is 3.6σ , with
1575 an expected significance of 2.7σ .

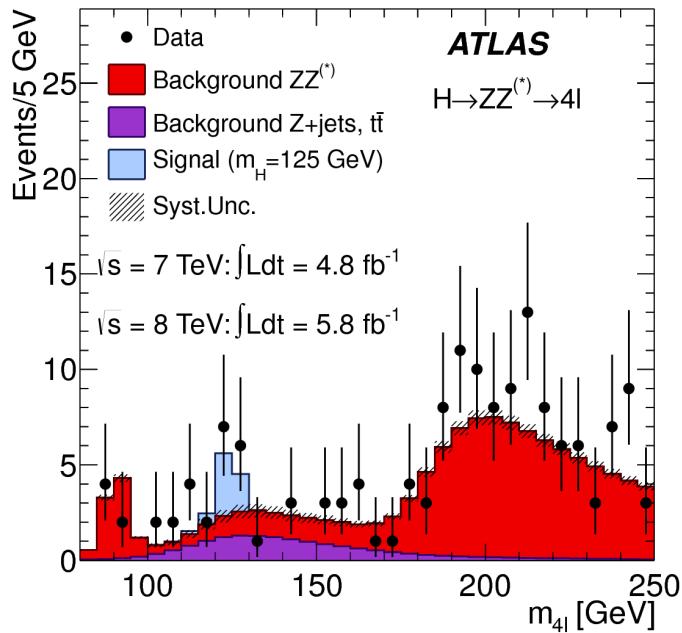


Figure 4.5: Four lepton invariant mass spectrum ($m_{4\ell}$) in 7 and 8 TeV data compared to background estimate. A 125 GeV SM Higgs signal is shown in blue [1].

1576 **4.6 COMBINED RESULTS**

1577 The statistical interpretation of the combined results is undertaken as described in section 3.6.2, with a
1578 hypothesis test based on a likelihood ratio parameterized by the Higgs signal strength μ . The null hy-
1579 pothesis corresponds to $\mu = 0$, while the SM Higgs corresponds to $\mu = 1$.

1580 Table 4.4 summarizes the properties of the individual channels as well as the significances of the ex-
 1581 cesses seen. The most significant observed local excess comes from the $\gamma\gamma$ channel. Figure 4.6 shows a
 1582 comparison of the observed local p_0 values as a function of hypothesized mass for the three different
 1583 search channels. Both the ZZ^* and $\gamma\gamma$ channels have very peaked excesses, while the WW^* excess can
 1584 be seen as very broad because the m_T distribution does not provide detailed information about the true
 1585 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].

1586 Figure 4.7 shows the combined exclusion limit, p_0 , and signal strength. The highest local excess comes
 1587 at a value of 126.5 GeV and corresponds to a 6.0σ observed excess.

1588 Figure 4.8 shows a comparison of the measured signal strengths between the different Higgs search
 1589 channels. All measured μ are consistent with unity within their uncertainty, and the combined μ mea-
 1590 surement is 1.4 ± 0.3 .

1591 The likelihood can also be computed in a two-dimensional plane of m_H and μ , and this is shown in
 1592 figure 4.9. The figure shows that while the $\gamma\gamma$ and ZZ^* channels have very good mass resolution, the
 1593 excess in WW^* covers a broad mass range. The banana shape of the WW^* result is due to the fact that
 1594 the excess in this channel can either be explained by increasing the signal strength or by changing the
 1595 mass (and thus the cross section). The two parameters are correlated due to the lack of mass sensitivity in
 1596 this channel.

1597 Because multiple Higgs mass points are searched for, the local significance must be corrected for a
 1598 look-elsewhere effect to compute a true global significance. The global significance for finding a Higgs
 1599 anywhere in the mass range of 110 GeV to 600 GeV is 5.1σ . This increases slightly to 5.3σ if only mass
 1600 range from 110 to 150 GeV.

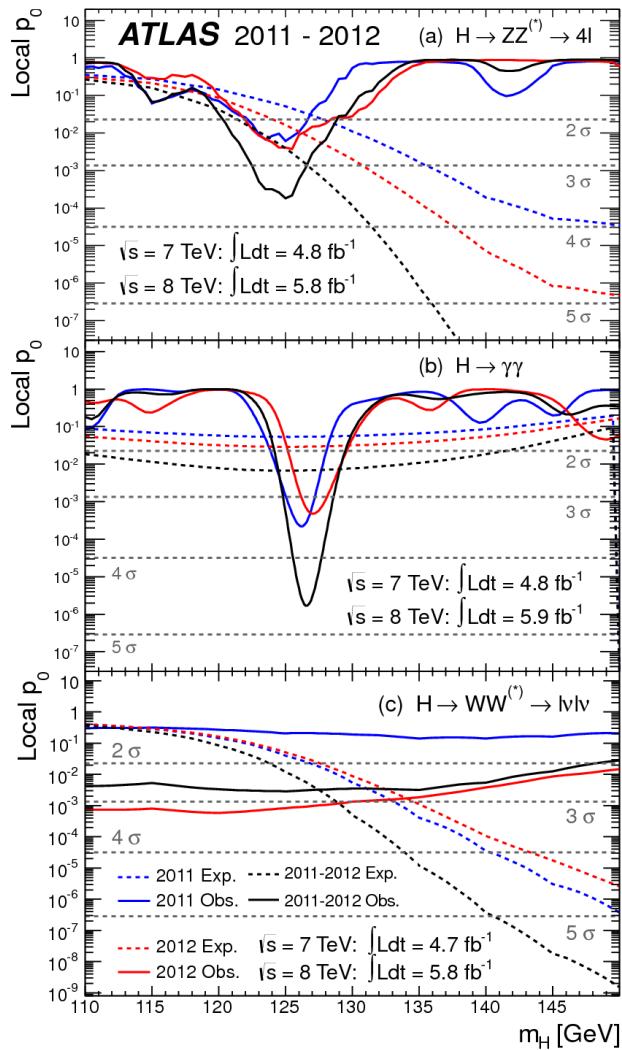


Figure 4.6: Local p_0 distribution as a function of hypothesized Higgs mass for the $H \rightarrow ZZ^* \rightarrow 4\ell$ (a), $H \rightarrow \gamma\gamma$ (b), and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ (c) channels. Dashed curves show expected results, while solid curves show observed. Red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

4.7 CONCLUSION

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

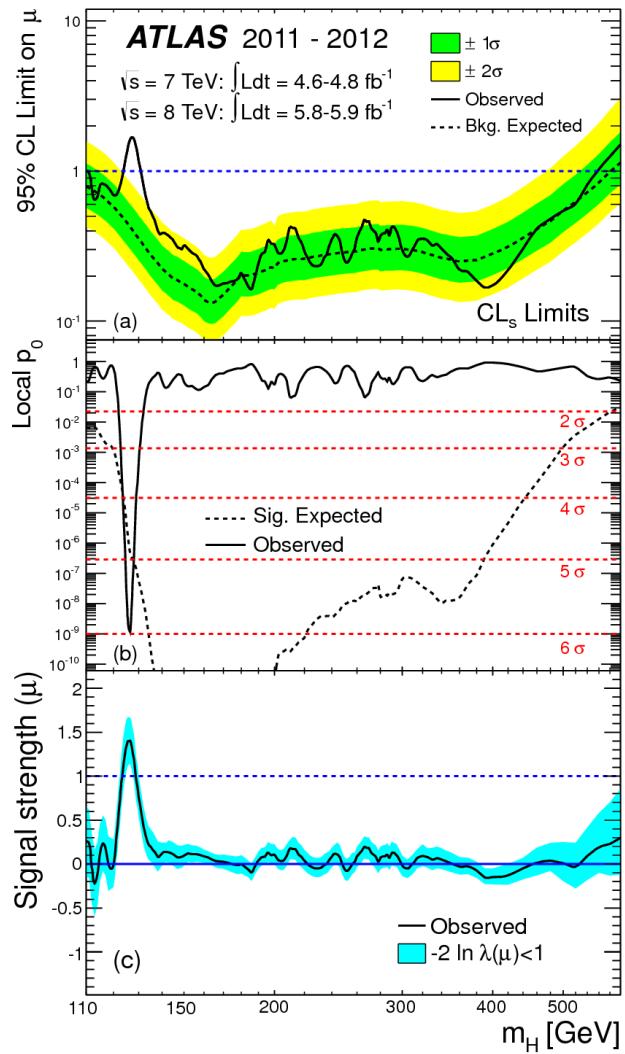


Figure 4.7: Combined 95% CL limits (a), local p_0 values (b), and signal strength measurement (c) as a function of Higgs mass [1].

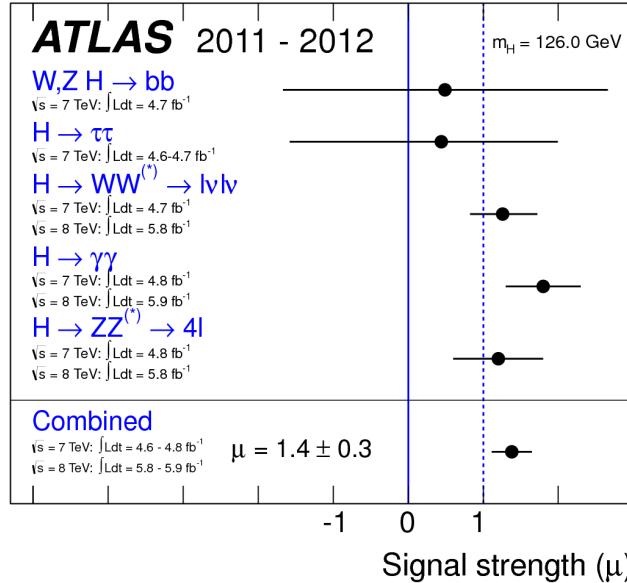


Figure 4.8: Comparison of measured signal strength μ for a 126 GeV Higgs in the 7 and 8 TeV datasets [1].

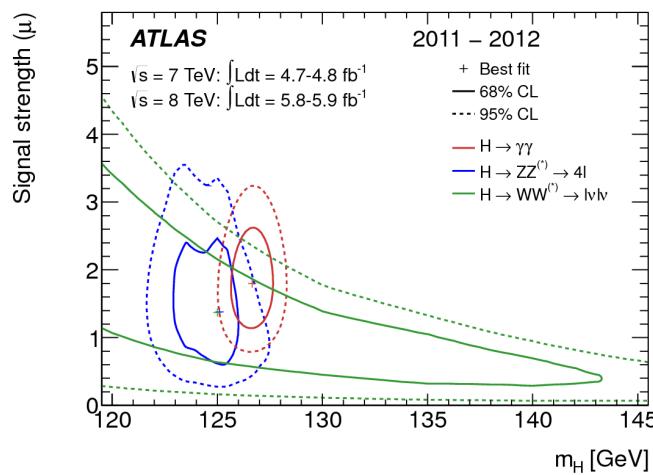


Figure 4.9: Two dimensional likelihood as a function of signal strength μ and Higgs mass m_H [1].

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

Richard Feynman

5

1606

1607

Observation of Vector Boson Fusion

1608

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

1609

5.1 INTRODUCTION

1610 After the discovery of a particle consistent with the Higgs boson, the $H \rightarrow WW^*$ analysis had two main
1611 goals. The first goal was to increase the sensitivity of the analysis to fully confirm that the $H \rightarrow WW^*$
1612 process did indeed exist. The second goal was to characterize the particle as much as possible, including
1613 searching for the lower cross-section production modes, in order to confirm that it was indeed a Higgs
1614 boson. This chapter presents a dedicated search for Vector Boson Fusion (VBF) production of a Higgs
1615 boson decaying via the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ mode. First, basics of the topology of VBF production
1616 are presented. Then, the details of the analysis are shown, including signal region definition, background
1617 estimation techniques, and systematic uncertainties. Finally, the results of the analysis are presented. As

1618 will be shown, this analysis is the first and most sensitive observation of the VBF production mode of the
1619 Higgs on ATLAS.

1620 In the VBF channel, there are both a selection requirement based signal region analysis (known as the
1621 “cut-based”) and a multivariate analysis which uses a boosted decision tree (known as the BDT analysis).
1622 The focus of this chapter will be on the cut-based signal region, as this is an important component of the
1623 VBF analysis and in particular acts as strong validation for the final BDT result. Connections between
1624 the cut-based and BDT analyses will be discussed where appropriate.

1625 5.2 DATA AND SIMULATION SAMPLES

1626 The results presented here are with 20.3 fb^{-1} taken at $\sqrt{s} = 8 \text{ TeV}$ and 4.5 fb^{-1} taken at $\sqrt{s} = 7 \text{ TeV}$.
1627 The details of the LHC and detector conditions during this period are given in Chapter 2. The trigger
1628 selection defining the dataset is discussed in section 5.2.1. The simulation samples used for signal and
1629 background modeling are given in section 5.2.2.

1630 5.2.1 TRIGGERS

1631 The analysis uses a combination of single lepton and dilepton triggers to allow lowering of the p_T thresh-
1632 olds and increased signal acceptance. The p_T threshold on the leptons is a particularly important consid-
1633 eration for this signal. Because the second W produced in the decay can be off-shell, it tends to pro-
1634 duce lower momentum leptons. Thus, being able to lower the p_T threshold while still maintaining
1635 a low background rate is critical. Figure 5.1 shows an example of the subleading lepton p_T for a VBF
1636 $H \rightarrow WW^*$ signal compared to the corresponding $t\bar{t}$ background. Note that the lepton p_T spectrum is
1637 considerably softer in the signal sample.

1638 As discussed in Chapter 2, there are multiple levels in the ATLAS trigger system, and there are differ-
1639 ent p_T thresholds imposed for the leptons at each level. Additionally, some triggers have a loose selection
1640 on the isolation of the lepton (looser than that applied offline in the analysis object selection). Table 5.1
1641 shows the thresholds used for single lepton triggers, while table 5.2 shows the thresholds coming from
1642 di-lepton triggers. The single lepton trigger efficiency for muons that pass the analysis object selection is

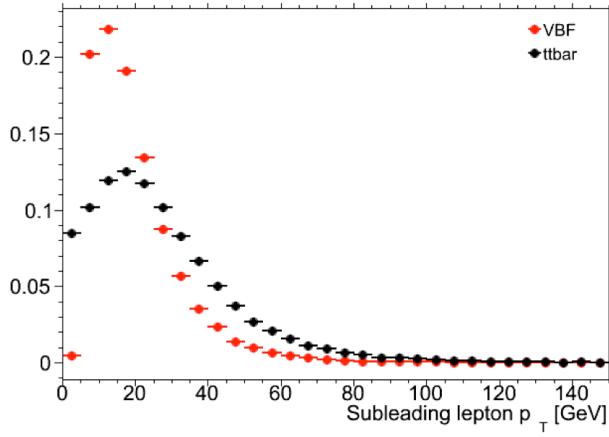


Figure 5.1: A comparison of the subleading lepton p_T spectrum between VBF $H \rightarrow WW^*$ production and $t\bar{t}$ background

1643 70% for muons in the barrel region ($|\eta| < 1.05$) and 90% in the endcap region. The electron trigger ef-
1644 ficiency increases with electron p_T but the average is approximately 90%. These efficiencies are measured
1645 by combined performance and trigger signature groups [65, 66].

	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.

1646 The combination of all triggers shown gives good efficiency for signal events. This efficiency is sum-
1647 marized in table 5.3. The relative improvement in efficiency by adding the dilepton triggers is also shown
1648 in the same table. The largest gain comes in the $\mu\mu$ channel. Overall the trigger selection shows a good
1649 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.

1650 5.2.2 MONTE CARLO SAMPLES

1651 Modeling of signal and background processes in the signal region, in particular for the m_T distribution,
 1652 is an important consideration for the final interpretation of the analysis. Therefore, careful consideration
 1653 must be paid to which Monte Carlo (MC) generators are used for specific processes. With the exception
 1654 of the $W + \text{jet}$ and multijet backgrounds, the m_T shape used as the final discriminant is taken from simu-
 1655 lation. (Many backgrounds are normalized from data, as described in section 5.5).

1656 Table 5.4 shows the MC generators used for the signal and background processes, as well as their cross
 1657 sections. In order to include corrections up to next-to-leading order (NLO) in the QCD coupling con-
 1658 stant α_s , the POWHEG [67] generator is often used. In some cases, only leading order generators like
 1659 ACERMC [68] and GG2VV [69] are available for the process in question. If the process requires good
 1660 modeling for very high parton multiplicities, the SHERPA [70] and ALPGEN [71] generators are used
 1661 to provide merged calculations for five or fewer additional partons. These matrix element level calcula-
 1662 tions must then be additionally matched to models of the underlying event, hadronization, and parton
 1663 shower. There are four possible generators for this: SHERPA, PYTHIA 6 [72], PYTHIA 8 [73], or HERWIG
 1664 [74] + JIMMY [75]. The simulation additionally requires an input parton distribution function (PDF).
 1665 The CT10 [76] PDFs are used for SHERPA and POWHEG simulated samples, while CTEQ6L1 [77] is used
 1666 for ALPGEN +HERWIG and ACERMC simulations. The Drell-Yan samples are reweighted to the MRST
 1667 [78] PDFs, as these are found to give the best agreement between data and simulation.

1668 Once the basic hard scattering process is simulated, it must be passed through a detector simulation
 1669 and additional pile-up events must be overlaid. The pile-up events are modeled with PYTHIA 8, and the

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 [61].

ATLAS detector is simulated with **GEANT4** [79]. Because of the unique phase space of the $H \rightarrow WW^*$ analysis, events are sometimes filtered at generator level to allow for more efficient generation of relevant events. The efficiency of the trigger in MC simulation does not always match the measured efficiency in

1673 data, so trigger scale factors are applied to correct the MC efficiency to the data. These are derived by the
1674 combined performance groups [65, 66].

1675 **5.3 OBJECT SELECTION**

1676 In order to define the signal region, the analysis must first select the objects to be considered. The de-
1677 tails of the object reconstruction algorithms are discussed in Chapter 2, while this section gives specific
1678 selection cuts used in the $H \rightarrow WW^*$ analysis.

1679 The first step in this process is to select a primary vertex candidates. The event's primary vertex is the
1680 vertex with the largest sum of p_T^2 for associated tracks and is required to have at least three tracks with
1681 $p_T > 450$ MeV. Many of the object selection cuts are then made relative to this chosen primary vertex.

1682 **5.3.1 MUONS**

1683 The analysis uses combined muon candidates, where a track in the Inner Detector has been matched
1684 to a standalone track in the Muon Spectrometer. The track parameters are combined statistically in the
1685 muon reconstruction algorithm [52]. The muons are required to be within $|\eta| < 2.5$ and have a $p_T >$
1686 10 GeV. To reduce backgrounds coming from mis-reconstructed leptons, there are requirements on
1687 the impact parameter of the muon relative to the primary vertex. The transverse impact parameter d_0
1688 is required to be small relative to its estimated uncertainty, the exact cut value being $d_0/\sigma_{d_0} < 3$. The
1689 longitudinal impact parameter z_0 must satisfy $|z_0 \sin \theta| < 1$ mm.

1690 As discussed previously, the muons must also be isolated. There are two types of lepton isolations
1691 that are calculated: track-based and calorimeter-based. For muons, the track-based isolation is defined
1692 using the scalar sum $\sum p_T$ for tracks with $p_T > 1$ GeV (excluding the muon's track) within a cone of
1693 $\Delta R = 0.3$ (0.4) for muon with $p_T > 15$ GeV ($10 < p_T < 15$ GeV). The final isolation requirement
1694 is made my requiring that this scalar sum be no more than a certain fraction of the muon's p_T . This re-
1695 quirement varies with muon p_T and the exact cuts are defined in table 5.5.

1696 The calorimeter-based muon isolation is defined using as a $\sum E_T$ calculated from calorimeter cells
1697 using the same cone size as the track-based isolation but excluding cells with $\Delta R < 0.05$ around the

1698 muon. This requirement is also defined as a cut on the ratio of the sum to the muon p_T and varies with
1699 muon p_T . The cut values are also given in table 5.5.

1700 The isolation requirements loosen as a function of p_T to allow for larger signal acceptance. At low p_T ,
1701 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 .

1702 5.3.2 ELECTRONS

1703 Electrons are identified by matching reconstructed clusters in the electromagnetic calorimeter with tracks
1704 in the inner detector. The electrons are identified using a likelihood based method [49, 50] which takes
1705 into account the shower shapes in the calorimeter, the matching of tracks to clusters, and the amount of
1706 transition radiation in the TRT. The electrons are required to have $|\eta| < 2.47$, and candidates in the
1707 transition region between the barrel and endcap ($1.37 < |\eta| < 1.52$) are excluded. As the muons, the
1708 electrons are required to have transverse impact parameter significance < 3 , while in the longitudinal
1709 direction they must have $|z_0 \sin \theta| < 0.4$ mm. Some electron requirements also vary with electron E_T ,
1710 and these requirements are summarized in table 5.6.

1711 The isolation for electrons are defined similarly to the muons but with unique cuts on the objects in-
1712 cluded. The track-based isolation is defined using tracks with $p_T > 400$ MeV with cone sizes as defined
1713 previously. The calorimeter-based isolation also uses the same cone size as the muon, but here the cells
1714 within a 0.125×0.175 area in $\eta \times \phi$ around the electron cluster's barycenter are excluded. The other
1715 difference with respect to muons is that the denominator of the isolation ratio is the electron's E_T rather
1716 than p_T . The isolation cuts very with electron E_T and are defined in table 5.6.

1717 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 .

1718 5.3.3 JETS

1719 Jets are clustered with the anti- k_T reconstruction algorithm using a radius parameter of $R = 0.4$. They
 1720 are required to have a jet vertex fraction (JVF) of at least 50%, meaning that half of the tracks associated
 1721 with the jet originated from the primary vertex. Jets with no tracks associated (i.e. those outside the ac-
 1722 ceptance of the ID) do not have this requirement applied. Jets are required to have $p_T > 25$ GeV if
 1723 they are within the tracking acceptance ($|\eta| < 2.4$). Jets with $2.4 < |\eta| < 4.5$ are required to have
 1724 $p_T > 30$ GeV. This tighter requirement reduces jets from pileup in the region where JVF requirements
 1725 cannot be applied. The two highest p_T jets in the event are referred to as the “VBF” jets and used to com-
 1726 pute various analysis selections later.

1727 Identification of b -jets is done using the MV1 algorithm and is limited to the acceptance of the ID
 1728 ($|\eta| < 2.5$). The operating point of MV1 that is used is the one that is 85% efficient for identifying true
 1729 b -jets. This operating point has a 10.3% of mis-tagging a light quark jet as a b -jet. In order to improve
 1730 the rejection of b -jets, a lower threshold than the nominal p_T threshold described above is used. For the
 1731 purposes of counting the number of b -jets, jets with p_T down to 20 GeV are used.

1732 5.3.4 OVERLAP REMOVAL

1733 There are some cases where certain reconstructed objects will overlap and one will have to be chosen
 1734 (for example, an electron and a jet in the calorimeter). First, the case of lepton overlap is dealt with. If
 1735 an electron candidate extends into the muon spectrometer, it is removed. If a muon or electron have a
 1736 $\Delta R < 0.1$, the electron is removed and the muon is kept. If two electron candidates overlap within
 1737 the same radius, then the higher E_T electron is kept. Next, the overlap between leptons and jets is con-

1738 sidered. If an electron and jet are within $\Delta R < 0.3$ of one another, the electron is kept and the jet is
1739 removed. However, if a muon and jet overlap within $\Delta R < 0.3$, the jet is kept (as it is likely that the
1740 muon is the result of a semileptonic decay inside the jet).

1741 Once the overlap removal is complete, the final set of objects used in the analysis is defined.

1742 5.4 ANALYSIS SELECTION

1743 The VBF analysis uses two distinct selections. The first is a more standard selection, referred to as “cut-
1744 based”, that applies requirements on the VBF variables and uses m_T as the final discriminating variable.
1745 The second is a looser selection that uses a Boosted Decision Tree (BDT) score as the final discriminator
1746 in order to take advantage of the detailed correlations between the VBF variables. While the BDT analy-
1747 sis is ultimately more sensitive, the cut-based serves as an important component of the analysis. First, the
1748 cut-based allows for confirming the modeling and validity of many variables used as input to the BDT.
1749 Second, because this is the first use of such an MVA technique in the $H \rightarrow WW^*$ analysis, the cut-based
1750 selection allows confirmation of the final BDT result with a more traditional analysis. The cut-based
1751 techniques are the focus of this chapter, but connections to the BDT result will be illustrated when ap-
1752 propriate.

1753 One important note is that because this analysis is dedicated to the measurement of the VBF pro-
1754 duction mode of the Higgs, events coming from gluon fusion production with the Higgs decaying via
1755 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ are treated as background events. This will be seen throughout the various
1756 predictions shown.

1757 5.4.1 COMMON PRE-SELECTION

1758 Both the cut-based and BDT analyses have a common pre-selection that is applied before the main signal
1759 region requirements. The requirements on leptons are common to all n_j bins. The analysis requires two
1760 oppositely charged leptons, with the leading lepton required to have $p_T > 22$ GeV while the subleading
1761 lepton must have $p_T > 10$ GeV. Next, to remove low mass Z/γ^* events, a cut on the dilepton mass
1762 $m_{\ell\ell} > 10$ (12) GeV is applied in the different (same) flavor channel. In the same flavor channels, there is

1763 an additional veto placed on the region around the Z peak, requiring that $|m_{\ell\ell} - m_Z| > 15$ GeV.

1764 There are also requirements on the amount of missing transverse momentum in the event. These
1765 are only applied in the same flavor channels, as in the different flavor channels $t\bar{t}$ is the dominant back-
1766 ground in $n_j \geq 2$. The BDT analysis requires $p_T^{\text{miss}} > 40$ GeV and $E_T^{\text{miss}} > 45$ GeV. The cut-
1767 based analysis must select more tightly on these variables to have maximal sensitivity and thus requires
1768 $p_T^{\text{miss}} > 50$ GeV and $E_T^{\text{miss}} > 55$ GeV.

1769 Finally, because this analysis is focused on VBF, a requirement on the jet multiplicity is placed, with
1770 $n_j \geq 2$. Additionally, the analysis requires that there are no jets identified as b-quarks in the event, or
1771 $n_b = 0$.

1772 5.4.2 CUT-BASED SELECTION

1773 The cut-based selection places sequential requirements on variables reconstructed from the VBF jets in
1774 order to increase the signal to background ratio.

1775 GENERAL BACKGROUND REDUCTION

1776 Top pair production is the primary background in the $n_j \geq 2$ bin. Even though $n_b = 0$ is required,
1777 an additional variable is constructed to further suppress the top background. There is often additional
1778 QCD radiation that accompanies the $t\bar{t}$ system when it is produced. Therefore, a variable which tests for
1779 the presence of this additional radiation, p_T^{sum} , is constructed. It is defined in equation 5.1.

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

1780 The first cut after pre-selection in the cut-based analysis requires $p_T^{\text{sum}} < 15$ GeV to further suppress $t\bar{t}$
1781 production.

1782 In the different flavor channels, a cut is made to reduce the contamination from $Z \rightarrow \tau\tau$ decays.
1783 The di- τ invariant mass, $m_{\tau\tau}$, is constructed by assuming that the neutrinos from the τ decays were
1784 collinear with the leptons [?]. The analysis requires that this mass not be consistent with a Z by requir-
1785 ing $m_{\tau\tau} < m_Z - 25$ GeV.

1786 VBF TOPOLOGICAL CUTS

1787 The characteristic feature of VBF production of the Higgs is the presence of two additional forward jets
1788 coming from the incoming partons which radiate the vector bosons that make the Higgs. These jets are
1789 forward because the outgoing partons still carry the longitudinal momentum of the incoming partons.
1790 Figure 5.2 shows the distribution of the η for the leading jet in a VBF event compared to a background
1791 top pair production event. As can be seen, the VBF jets tend to be more forward in η , while the $t\bar{t}$ jets are
1792 more central.

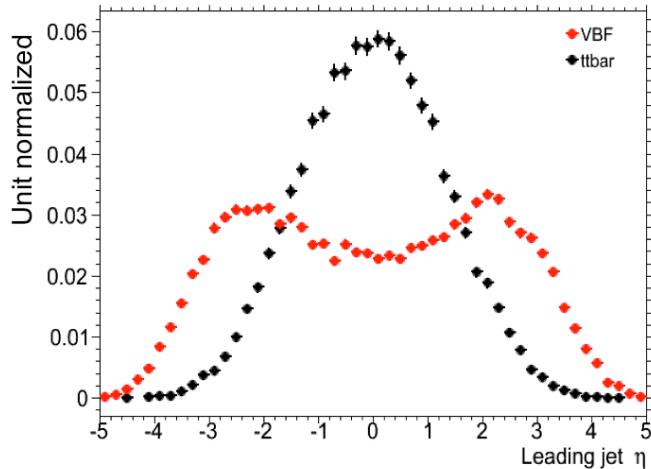


Figure 5.2: Leading jet η in VBF $H \rightarrow WW^*$ (red) and $t\bar{t}$ (black)

1793 Because the cross section for VBF production is an order of magnitude smaller than gluon fusion pro-
1794 duction, these forward jets must be used in order to better reduce background and achieve a good signal
1795 to background ratio. The dedicated VBF search selection requirements are constructed to maximally
1796 exploit the features of the unique VBF topology.

1797 Requirements on the VBF jets are collectively referred to as the “VBF topological cuts”. First, a re-
1798 quirement on the dijet invariant mass of the VBF jets, m_{jj} , is placed, requiring $m_{jj} > 600$ GeV. Next,
1799 the event is required to have a large gap in rapidity between the two VBF jets, or $\Delta y_{jj} > 3.6$. Both
1800 of these cuts put tight requirements on the presence of two forward, high p_T jets moving in opposite

1801 directions in the longitudinal plane.

1802 Beyond requiring the presence of the two forward VBF jets, the analysis also vetoes on the presence
1803 of any additional jets that fall between the two VBF jets. This cut is referred to as the central jet veto, or
1804 CJV. Any events with a third jet with $p_T > 20$ GeV whose rapidity is between the region defined by the
1805 two VBF jets are vetoed. This can be expressed in terms of a variable called the jet centrality, defined in
1806 equation 5.2.

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

1807 Here, η_{j1} and η_{j2} are the pseudorapidities of the leading and subleading jets, respectively, while η_{j3} is
1808 the pseudorapidity of the extra jet in the event (if one exists). Intuitively, C_{j3} is zero when η_{j3} is directly
1809 centered between the two jets and unity when η_{j3} is aligned with either of the VBF jets. Thus, the CJV
1810 can be expressed as a requirement that $C_{j3} > 1$.

1811 The decay products of the Higgs tend to be central as well. Thus, the analysis also requires that both
1812 leptons in the analysis fall within the rapidity gap defined by the jets. This cut is referred to as the outside
1813 lepton veto, or OLV. A quantitative way to define the cut is to require that the centrality of each lepton
1814 (defined analogously to that of the third jet in equation 5.2) correspond to the lepton being within the jet
1815 rapidity gap, or $C_\ell < 1$ for both leptons.

1816 Figure 5.3a-c shows the m_{jj} , Δy_{jj} , and $C_{\ell 1}$ variables at the stage where all previous cuts in the se-
1817 quence have been made. The agreement between data and Monte Carlo is good, and the bottom panels
1818 show their power in discriminating the VBF signal from the background processes.

1819 The final signal region is also split into two bins of m_{jj} , with the first bin corresponding to $600 \text{ GeV} <$
1820 $m_{jj} < 1 \text{ TeV}$ and the second bin corresponding to $m_{jj} > 1 \text{ TeV}$. The first bin has more statistics but
1821 also a larger contribution from background, while the second bin has lower statistics but a 1:1 signal to
1822 background ratio.

1823 HIGGS TOPOLOGICAL CUTS

1824 The final state leptons will exhibit unique correlations due to the fact that they are arising from the decay
1825 of a spin zero resonance. In particular, the spins of the final state leptons and neutrinos must all cancel,

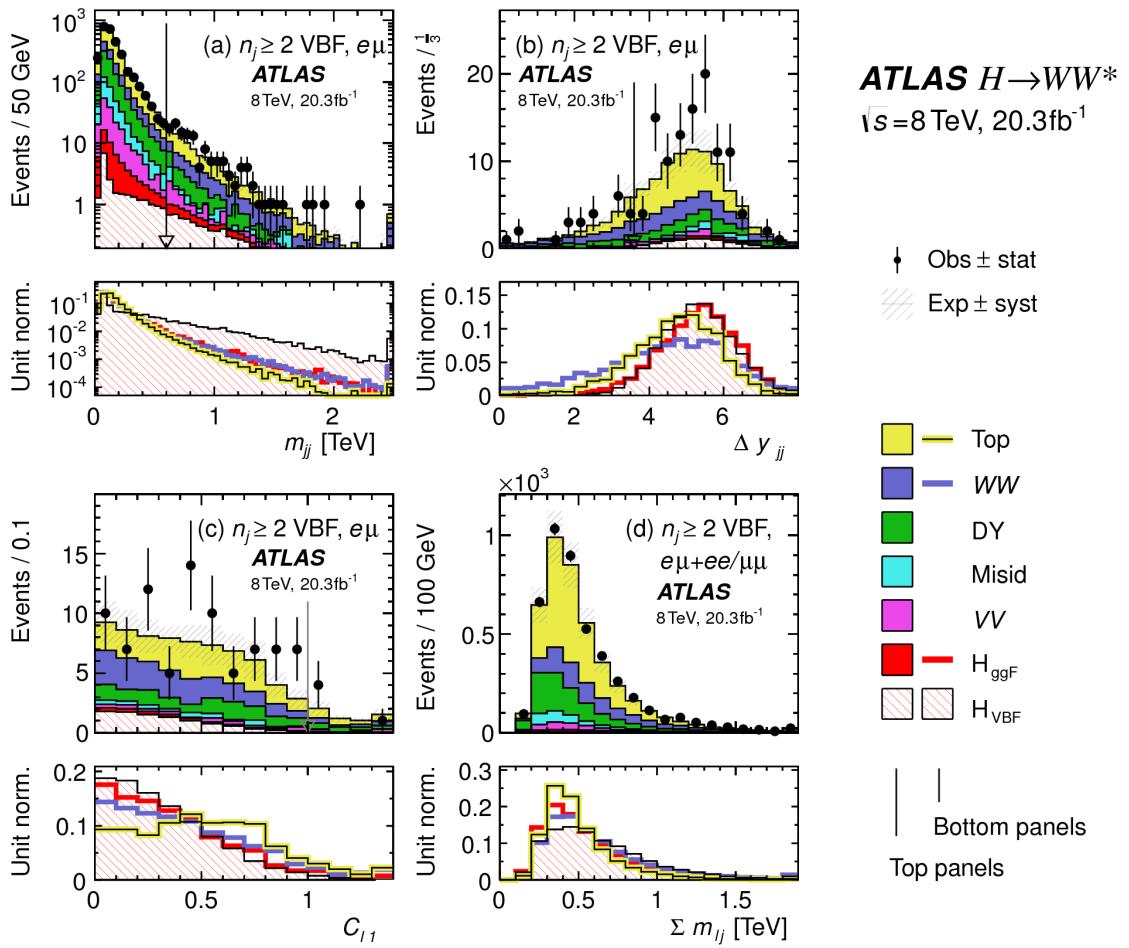


Figure 5.3: Distributions of (a) m_{jj} , (b) Δy_{jj} , (c) $C_{\ell 1}$, and (d) $\Sigma m_{\ell j}$, for the VBF analysis. The top panels compare simulation and data, while the bottom panels show normalized distributions for all background processes and signal [61].

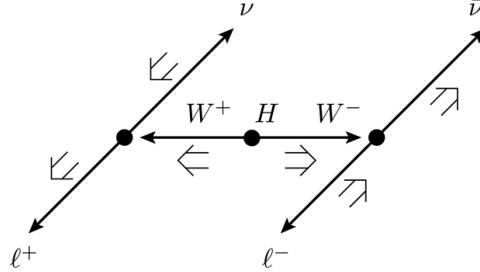


Figure 5.4: A cartoon of the WW final state. Momenta are represented with thin arrows, spins with thick arrows. [61]

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 the data and estimated signal and background yields from simulation as each cut described above is made. The table shows how each cut reduces specific backgrounds and how the overall signal to background ratio grows through the various selection requirements.

Figure 5.5 shows an ATLAS event display of a candidate event in the final signal region.

Table 5.7: Event selection for the $n_j \geq 2$ VBF analysis in the 8 TeV cut-based analysis [61].

Selection	Summary										Composition of N_{bkg}								
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{ggF}	N_{VBF}	N_{signal}	N_{WW}	N_{WW}^{EW}	$N_{t\bar{t}}$	N_t	N_{top}	N_{Wj}	N_{jj}	N_{misid}	$N_{e\mu/\mu\mu}$	$N_{\tau\tau}^{\text{QCD}}$	$N_{\tau\tau}^{\text{EW}}$	$N_{\text{Drell-Yan}}$	$N_{e\tau}^{\text{QCD}}$
$e\mu$ sample	1.00 ± 0.00	61434	61180	85	32	26	1350	68	51810	2970	847	308	380	51	3260	46			
$n_b = 0$	1.02 ± 0.01	7818	7700	63	26	16	993	43	3000	367	313	193	273	35	2400	29			
$p_T^{\text{sum}} < 15$	1.03 ± 0.01	5787	5630	46	23	13	781	38	1910	270	216	107	201	27	2010	23			
$m_{\tau\tau} < m_Z - 25$	1.05 ± 0.02	3129	2970	40	20	9.9	484	22	1270	177	141	66	132	7.6	627	5.8			
$m_{jj} > 600$	1.31 ± 0.12	131	100	2.3	8.2	—	18	8.9	40	5.3	1.8	2.4	5.1	0.1	15	1.0			
$\Delta y_{jj} > 3.6$	1.33 ± 0.13	107	80	2.1	7.9	—	11.7	6.9	35	5.0	1.6	2.3	3.3	—	11.6	0.8			
$C_{j3} > 1$	1.36 ± 0.18	58	43	1.3	6.6	—	6.9	5.6	14	3.0	1.3	1.3	2.0	—	6.8	0.6			
$C_{\ell 1} < 1, C_{\ell 2} < 1$	1.42 ± 0.20	51	36	1.2	6.4	—	5.9	5.2	10.8	2.5	1.3	1.3	1.6	—	5.7	0.6			
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_{\tau\tau}$	2.53 ± 0.71	14	5.5	0.8	4.7	—	1.0	0.5	1.1	0.3	0.3	0.3	0.6	—	0.5	0.2			
$ee/\mu\mu$ sample	0.99 ± 0.01	26949	27190	31	14	10.1	594	37	23440	1320	230	8.6	137	690	679	16			
$n_b, p_T^{\text{sum}}, m_{\tau\tau}$	1.03 ± 0.03	1344	1310	13	8.0	4.0	229	12.0	633	86	26	0.9	45	187	76	1.5			
$m_{jj}, \Delta y_{jj}, C_{j3}, C_\ell$	1.39 ± 0.28	26	19	0.4	2.9	0.0	3.1	5.5	1.0	0.2	0.0	0.7	3.8	0.7	0.1				
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_{\tau\tau}$	1.63 ± 0.69	6	3.7	0.3	2.2	0.0	0.4	0.2	0.6	0.2	0.0	0.1	1.5	0.3	0.1				

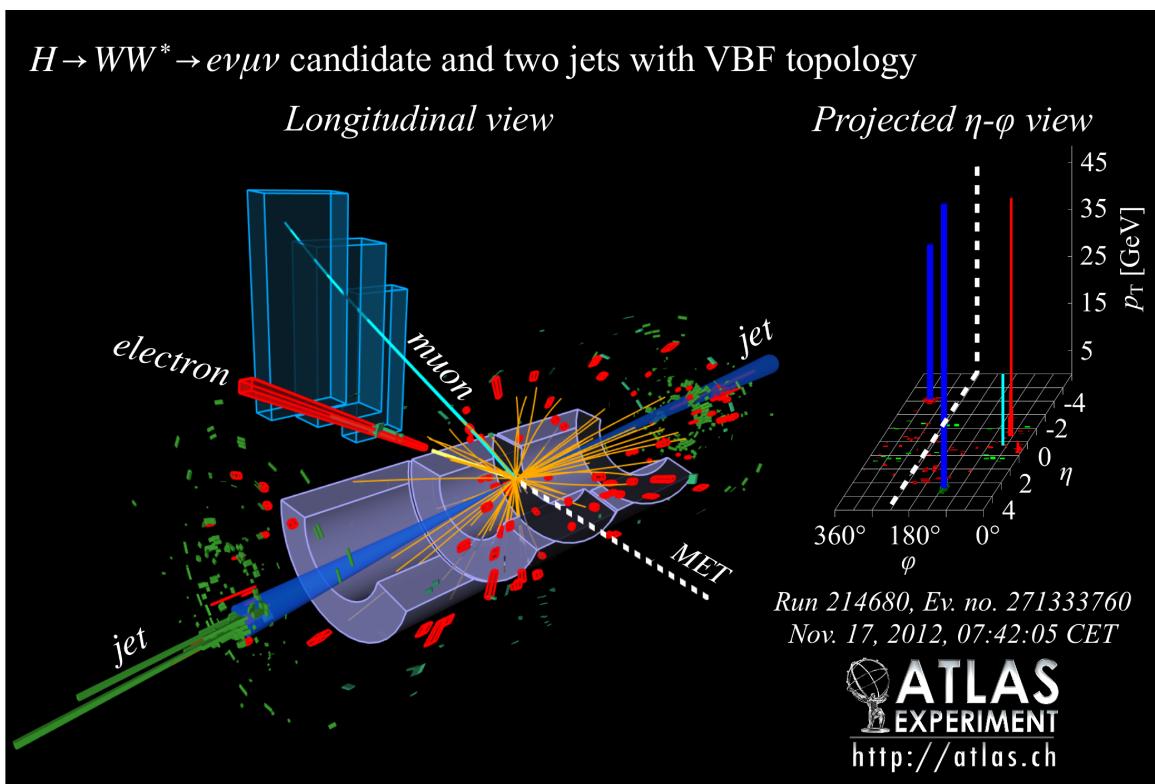


Figure 5.5: Event display of a VBF candidate event [61].

1844 5.4.3 BDT-BASED SELECTION

1845 The boosted decision tree based analysis takes a different philosophy compared to the cut-based. Rather
 1846 than cutting sequentially on many variables, the BDT analysis uses many of these variables as inputs
 1847 to the BDT and the output BDT score (O_{BDT}) as the final discriminant. The BDT is trained with the
 1848 VBF $H \rightarrow WW^*$ simulation as the signal samples and all other processes as background, including ggF
 1849 $H \rightarrow WW^*$ production. While the BDT based analysis is treated as a separate result, it has significant
 1850 overlap with the cut-based selection.

1851 PRE-TRAINING SELECTION AND BDT INPUTS

1852 Before training, the common pre-selection cuts described in section 5.4.1 are applied. Additionally, the
 1853 central jet veto and outside lepton veto described in section 5.4.2 are applied. The BDT has eight input
 1854 variables, six of which are also variables that are used in the cut-based analysis. The six shared variables

1855 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
 1856 the variables used to do the OLV in the cut-based analysis. The BDT uses as input the sum of lepton
 1857 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
 1858 the correlations between the jets and leptons in the event. It is the sum of the invariant masses of all four
 1859 possible lepton-jet combinations.

1860 Figure 5.3d shows the agreement between data and simulation for the $\Sigma m_{\ell j}$ variable, as well as show-
 1861 ing its discriminating power. Figure 5.6 shows the distributions of the Higgs topological variables that
 1862 are shared between the cut-based and BDT analyses. Figure 5.7 shows the distributions of the VBF topo-
 1863 logical variables shared between the cut-based and BDT analyses. In both cases, the VBF yield has been
 1864 scaled by a factor of 50 to better show the shape difference compared to the backgrounds.

1865 Table ?? summarizes the cuts applied for the cut-based and analyses, as well as which variables are used
 1866 as input to the BDT.

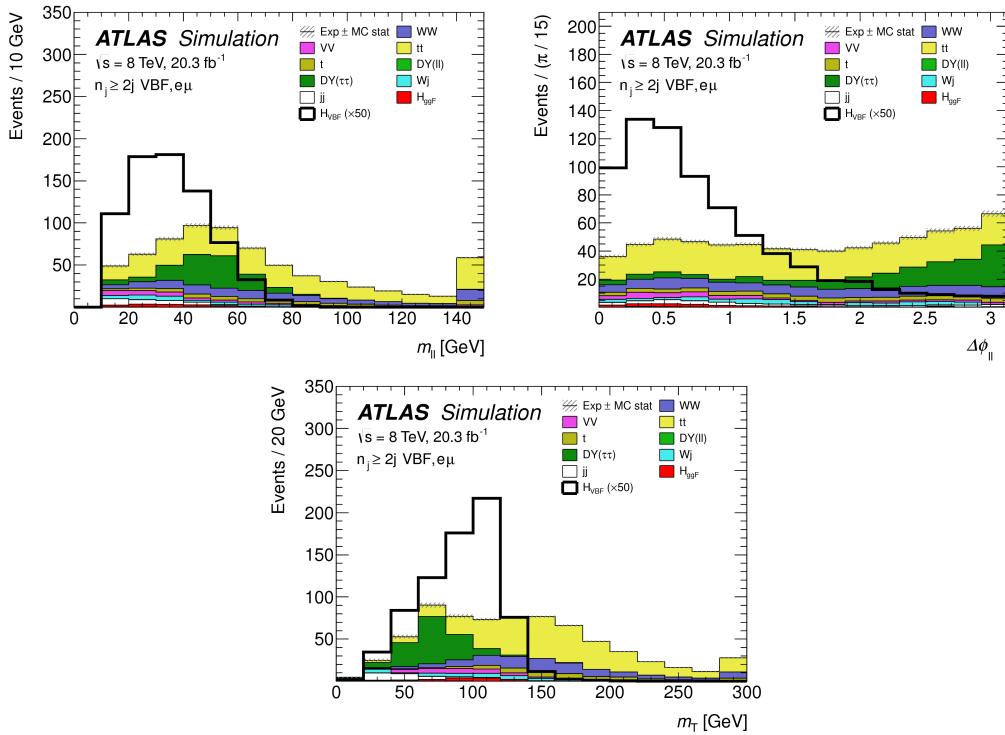


Figure 5.6: Distributions of $m_{\ell\ell}$ (top left), $\Delta\phi_{\ell\ell}$ (top right), and m_T (bottom), Higgs topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [61].

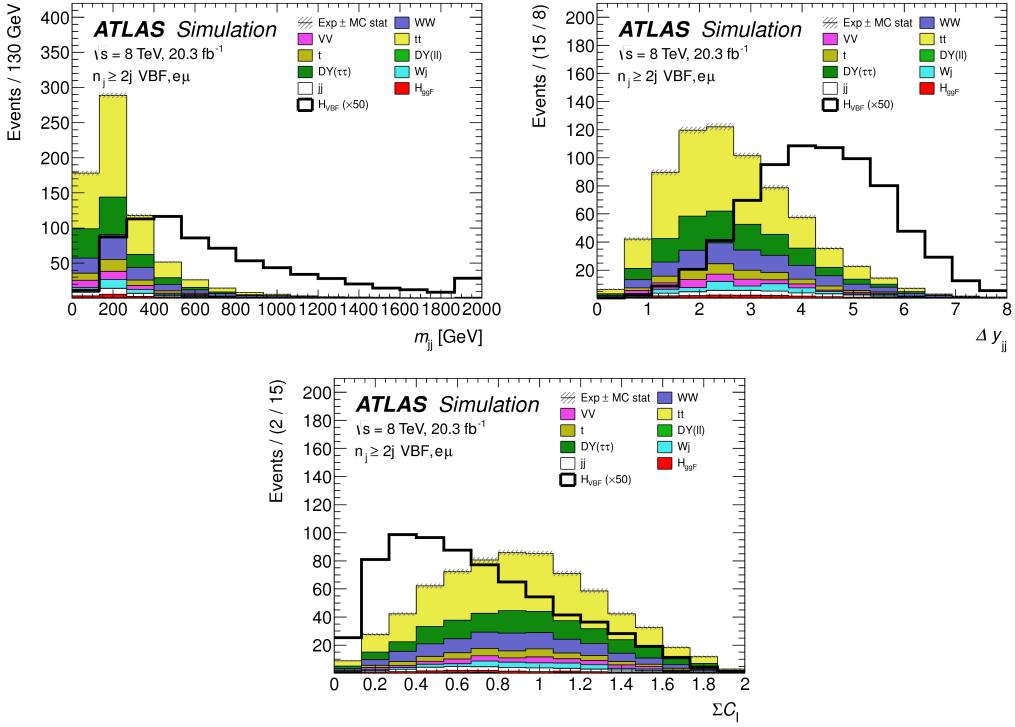


Figure 5.7: Distributions of m_{jj} (top left), Δy_{jj} (top right), $\sum C_l$ (bottom), VBF topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [61].

1867 5.5 BACKGROUND ESTIMATION

1868 This section describes the procedures used to estimate backgrounds for the VBF analysis in both the
 1869 cut-based and BDT analyses.

1870 5.5.1 GENERAL STRATEGY

1871 Most of the backgrounds in the VBF analysis have shapes estimated from Monte Carlo simulation but
 1872 normalizations derived from control regions in data. In essence, a normalization factor (denoted with
 1873 β or abbreviated as NF) is derived by scaling the MC yield in the control region to the corresponding
 1874 yield in data. Once this factor is derived, it can be used to scale the MC estimate of the background in the

1875 signal region. This is illustrated in equation 5.3.

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

1876 Here, B denotes the MC yield prediction in the denoted region, while N denotes the observed number
1877 of events in data in the denoted region.

1878 Another way of writing the same equation, in terms of an extrapolation factor α rather than a nor-
1879 malization factor β . The overall calculation is exactly the same. However, when phrased in this way, it
1880 shows how the uncertainty on the background estimation can be reduced. This is shown in equation 5.4.

1881

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

1882 Phrased this way, the equation shows that with enough statistics in the control region, a large theoretical
1883 uncertainty on the overall background yield in the signal region can be replaced by a small statistical
1884 uncertainty coming from the number of data events in the CR and a smaller theoretical uncertainty on
1885 the extrapolation from the control region to the signal region.

1886 5.5.2 TOP BACKGROUND

1887 The normalization factor β_t for the top background in the VBF analysis is derived in a region required
1888 to have one b-tagged jet, or $n_b = 1$. In the cut-based analysis, normalization factors are computed at
1889 every stage of the cutflow by applying the appropriate cuts in the CR. These NF are then applied to the
1890 $t\bar{t}$ and single top event yields in the SR. In the BDT analysis, a single normalization factor is computed
1891 for each bin of O_{BDT} after applying the BDT pre-training cuts described previously. The computed
1892 normalization factors are derived with all flavor combinations combined in order to decrease statistical
1893 uncertainty. Additionally, in the BDT analysis, BDT bins 2 and 3 are merged for the same reason.

1894 Table 5.8 shows the evolution of the β_t through the cut-based selection. Table 5.9 shows the value
1895 of the β_t in each bin of O_{BDT} . In all cases, the computed factors are relatively consistent with unity,
1896 with the largest discrepancy coming in bin 1 of O_{BDT} . The normalization factors in the bins of O_{BDT}

1897 are also consistent with those derived in teh cut-based sisignal region, increasing confidence in the BDT
1898 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 5.8: 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 5.9: Top normalization factors computed for each bin of O_{BDT} . Uncertainties are statistical only.

1899 Figure 5.8 shows the m_{jj} and O_{BDT} distributions in the top control region. Overall the modeling
1900 looks consistent with the data.

1901 While these normalization factors can be computed and applied to the expected background yields
1902 listed in tables like table 5.7, in the end the normalization of the top background is profiled (meaning
1903 there is a dedicated Poisson constraint) and allowed to float in the final statistical fit.

1904 5.5.3 $Z/\gamma^* \rightarrow \tau\tau$ BACKGROUND

1905 In the different flavor channels, the $Z/\gamma^* \rightarrow \tau\tau$ background is an important one. Di-tau production
1906 can produce an $e\mu$ final state if each τ lepton decays to a different flavor lepton.

1907 In the BDT analysis, a single normalization factor for the background is derived. A control region is
1908 defined using the pre-training selection cuts, except requiring that $|m_{\tau\tau} - m_Z| < 25 \text{ GeV}$ so that
1909 the region is enriched in $Z/\gamma^* \rightarrow \tau\tau$ background. Additional requirements of $m_{\ell\ell} < 80(75) \text{ GeV}$

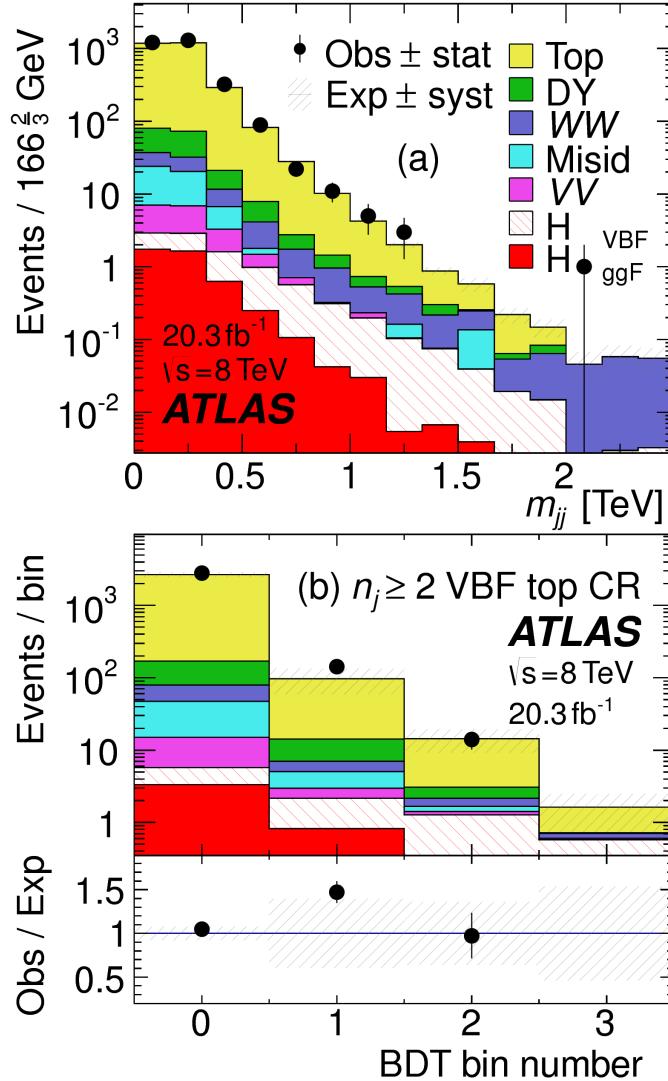


Figure 5.8: Distributions of m_{jj} (a) and O_{BDT} (b) in the VBF $n_b = 1$ top CR [61].

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

1917 $Z/\gamma^* \rightarrow \tau\tau$ veto, which is instead made into a Z mass peak requirement as for the BDT region. The
 1918 $m_{\ell\ell}$ cut from the BDT region is included as well. The cut-based approach aims to correct the normal-
 1919 ization of the $Z/\gamma^* \rightarrow \tau\tau$ background in two ways. First, an overall normalization factor is computed
 1920 from the control region. However, the VBF topological cuts are not included in this region, and apply-
 1921 ing them as is done in the top CR is not feasible due to limited statistics. So, instead, correction factors
 1922 (CF) to the cut efficiencies of the VBF cuts are derived in a same flavor $Z \rightarrow \ell\ell$ control region, which has
 1923 significantly more statistics. The CF is simply the ratio of the cut efficiencies in data and MC derived in
 1924 this region. In the end, the overall background estimate is given by equation 5.5.

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

1925 The hypothesis is that while the normalization correction must be derived in a dedicated region, the
 1926 efficiency of the VBF cuts should not be sensitive to the type of Z/γ^* process and thus the larger control
 1927 region can be exploited to derive the CF. Figure 5.9 shows a shape comparison for the m_{jj} variable in
 1928 $Z \rightarrow \tau\tau$ events in the signal region and $Z \rightarrow \ell\ell$ events in the control region. The figure shows that the
 1929 shapes are indeed comparable and thus any CF derived in the same flavor control region can reliably be
 1930 applied in the signal region.

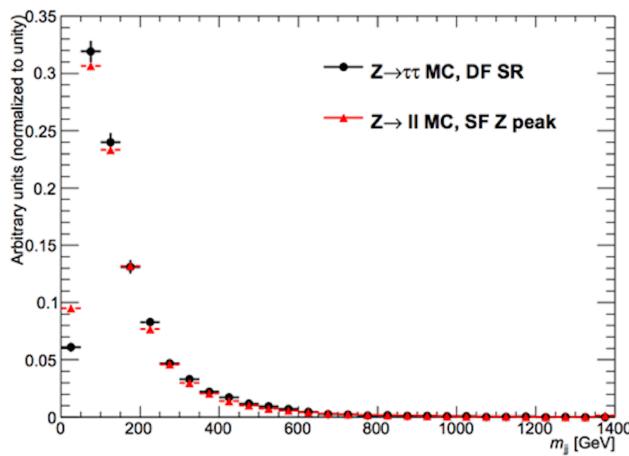


Figure 5.9: Comparison of m_{jj} shape in a same flavor $Z \rightarrow \ell\ell$ control region and the VBF cut-based signal region.

1931 Table 5.10 shows the overall normalization factor $\beta_{\tau\tau}$ and the efficiency correction factors for the var-

¹⁹³² ious VBF topological cuts. In general, the statistical uncertainties on the cut efficiency corrections are
¹⁹³³ quite good, and the MC tends to underestimate the efficiency of the VBF cuts for the $Z/\gamma^* \rightarrow \tau\tau$ back-
¹⁹³⁴ ground. 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 5.10: $Z/\gamma^* \rightarrow \tau\tau$ correction factors for the VBF cut-based analysis. Uncertainties are statistical only.

¹⁹³⁵ 5.5.4 $Z/\gamma^* \rightarrow \ell\ell$ BACKGROUND

¹⁹³⁶ In the same flavor channels, the $Z/\gamma^* \rightarrow \ell\ell$ background is dominant and thus must be estimated
¹⁹³⁷ correctly. In both the BDT and cut-based analyses, the background is estimated using the so-called
¹⁹³⁸ “ABCD” method. The ABCD method creates four different regions by defining cuts on two variables.
¹⁹³⁹ One of the regions (A) is the signal region, while the other regions are defined by inverting one of both
¹⁹⁴⁰ of the cuts. in this case, the two variables used are $m_{\ell\ell}$ and E_T^{miss} , because inverting either of the SR cuts
¹⁹⁴¹ on these variables will give regions rich in the $Z/\gamma^* \rightarrow \ell\ell$ background. Figure 5.10 illustrates the general
¹⁹⁴² strategy for each region.

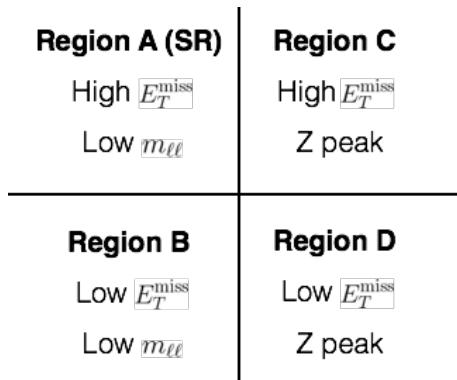


Figure 5.10: General illustration of the ABCD region definitions for $Z/\gamma^* \rightarrow \ell\ell$ background estimation.

1943 In both of the cut-based and BDT analyses, the Z peak region is defined with $|m_{\ell\ell} - m_Z| < 15$ GeV.
 1944 In the cut-based analysis, low $m_{\ell\ell}$ corresponds to $m_{\ell\ell} < 50$ GeV (this defines the cut-based SR) while
 1945 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
 1946 the 55 GeV cut applied for the signal region definition. The BDT low E_T^{miss} region is between 25 and
 1947 45 GeV, while the high E_T^{miss} region is $E_T^{\text{miss}} > 45$ GeV.

1948 Once the regions are defined, the final signal region background estimate is done by taking the esti-
 1949 mate in region B and extrapolating it to the signal region (A) by multiplying it by the ratio of regions
 1950 C and D. Effectively, the Z peak region is used to estimate the efficiency of the E_T^{miss} cut in data, and
 1951 then this efficiency is applied in the low $m_{\ell\ell}$ region. An additional correction is also applied for the non-
 1952 closure of the method in MC. This is summarized in equations 5.6 and 5.7.

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

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

1953 Here, the N refer to data yields in each region with the non Z/γ^* backgrounds subtracted, while B
 1954 refer to the Z/γ^* yields in MC in each region.

1955 A normalization factor $\beta_{\ell\ell}$ is computed for each analysis as the ratio of the predicted data yield to
 1956 the MC yield in the SR. The shape of the BDT distribution is taken from data region B, while the shape
 1957 of the m_T distribution in the cut-based analysis is taken from Z/γ^* MC in the SR. The values of the
 1958 $\beta_{\ell\ell}$ in the cut-based and BDT analyses from this method are summarized in table 5.11. They are quite
 1959 consistent with one another within the statistical uncertainties. In the cut-based analysis, the same cut
 1960 efficiency correction factors shown in table 5.10 are also applied (in product with the $\beta_{\ell\ell}$) in the same
 1961 flavor channels to this background, as they were derived in the Z peak region.

	β_t
BDT Bin 1	1.01 ± 0.15
BDT Bin 2	0.89 ± 0.28
Cut-based	0.81 ± 0.21

Table 5.11: $Z/\gamma^* \rightarrow \ell\ell$ normalization factors for cut-based and BDT analyses. Uncertainties are statistical only.

1962 5.5.5 WW AND OTHER DIBOSON BACKGROUNDS

1963 The WW and other diboson backgrounds have both their shape and normalization taken from MC
 1964 simulation. They are validated in dedicated control regions and found to agree with data well.

1965 As WW is the largest of these backgrounds and is irreducible, validating the estimate is of particular
 1966 importance. The validation region is constructed by requiring the pre-selection cuts on leptons and $m_{\ell\ell}$,
 1967 $n_b = 0$, and $m_T > 100$ GeV. The m_{T2} variable [?] is an additional discriminant that will isolate
 1968 the WW background, and a requirement of $m_{T2} > 160$ GeV is placed to define the WW validation
 1969 region. This cut gives a 60% purity for the validation region. The derived normalization factor in the
 1970 region is 1.15 ± 0.19 and is thus consistent with unity. Figure 5.11 shows the m_{T2} distribution and how
 1971 it distinguishes the WW background.

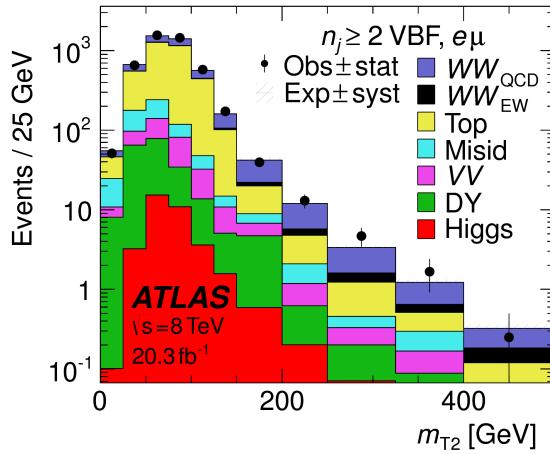


Figure 5.11: Distribution of m_{T2} in the WW validation region of the VBF analysis [61].

1972 5.5.6 HIGGS PRODUCTION VIA GLUON-GLUON FUSION

1973 Because this analysis is dedicated to measuring the VBF contribution to Higgs production, the com-
1974 ponent of Higgs production from gluon-gluon fusion is treated as a background. The shape is taken
1975 directly from simulation, using the generators described in table 5.4. In the final combined fit of all dif-
1976 ferent signal regions, the normalization is controlled by either a combined signal strength parameter μ ,
1977 which controls the normalization of both ggF and VBF production, or a separate parameter μ_{ggF} de-
1978 pending on the interpretation being presented in the final results.

1979 5.5.7 BACKGROUNDS WITH MISIDENTIFIED LEPTONS

1980 As discussed previously, the $W + \text{jets}$ and QCD multijet backgrounds are derived with fully data-driven
1981 methods. These backgrounds do not make a large contribution to the final VBF signal region but their
1982 estimation methods are discussed briefly here.

1983 $W + \text{jets}$ BACKGROUND

1984 The $W + \text{jets}$ background enters the signal region by having one of the jets mis-reconstructed as a lep-
1985 ton. The background is estimated by constructing a control sample with two leptons, where one lepton
1986 passes the usual lepton quality cuts but the second lepton fails one of those cuts (also known as the “anti-
1987 identified” lepton). This control region is rich in the $W + \text{jets}$ contribution because if a second lepton is
1988 reconstructed in a $W + \text{jets}$ event it is likely to be poor quality. The purity of this $W + \text{jets}$ control sample
1989 is 85% to 90% depending on the exact configuration of leptons in the final state.

1990 The signal region estimate of $W + \text{jets}$ is estimated by extrapolation from the control sample to the sig-
1991 nal region using extrapolation factors derived in a $Z + \text{jets}$ control sample in data. The extrapolation fac-
1992 tor is the ratio of the number of lepton candidates satisfying all quality criteria to the number of lepton
1993 candidates anti-identified. This ratio is measured in bins of p_T and η . Thus, the final signal region esti-
1994 mate (binned as the extrapolation factor is binned) is simply the number of events in the anti-identified
1995 lepton control sample multiplied by the extrapolation factor derived from the $Z + \text{jets}$ control sample.

1996 Figure 5.12 shows the extrapolation factors derived for electrons and muons.

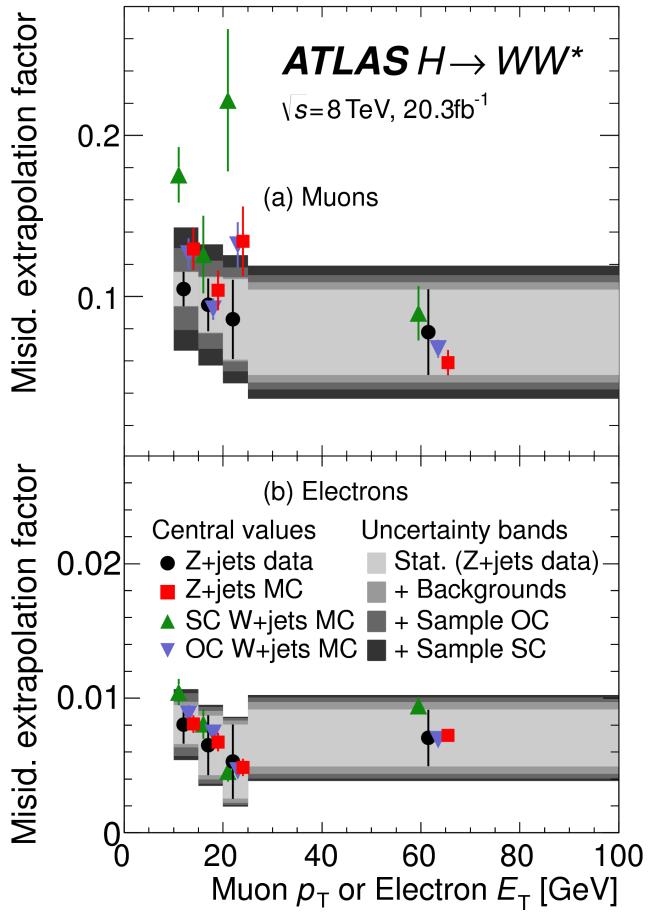


Figure 5.12: Extrapolation factors for the $W + \text{jets}$ estimate derived for muons (a) and electrons (b) as a function of lepton p_T [61].

1997 QCD MULTIJET BACKGROUND

1998 The method for estimating the multijet background is very similar to the $W + \text{jets}$ estimation method.
 1999 The control sample in this case has two anti-identified leptons but otherwise satisfies all signal region
 2000 requirements. The extrapolation factor is estimated from a multijet sample and applied twice to the
 2001 control sample.

2002 5.5.8 BACKGROUND COMPOSITION IN FINAL SIGNAL REGION

2003 After all of these estimation procedures, the final signal region composition can be calculated. The esti-
 2004 mated yields are all shown in table 5.7. Figure 5.13 shows the relative percentages of the different back-

ground for the different flavor and same flavor final states. In $e\mu$, the leading backgrounds are top backgrounds, ggF Higgs, and SM WW production. In $ee/\mu\mu$, the leading background is Drell-Yan, followed by top and ggF Higgs.

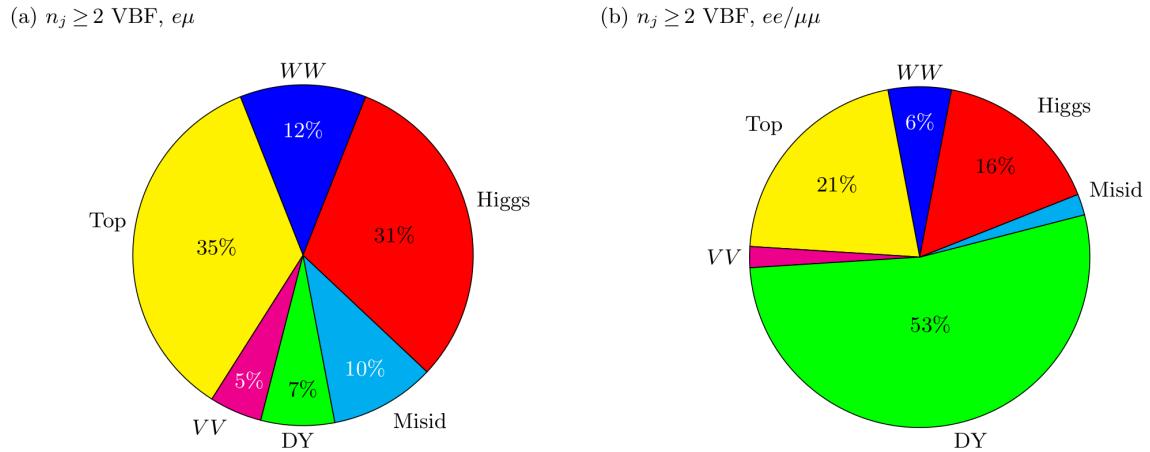


Figure 5.13: Background composition in final VBF signal region [61].

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

There are two additional uncertainties that are applied to the Higgs processes as well. First, there are uncertainties assigned to the Higgs total production cross section. Then, there are uncertainties assigned based on the fact that the analysis is done in exclusive jet bins and it is possible for signal events to migrate from one bin to the next depending on the presence or absence of jets. These are assigned using the Jet Veto Efficiency (JVE) procedure [?] for ggF events and the Stewart-Tackmann (ST) method [80] for VBF production.

Table 5.12 shows the total theory uncertainties on the backgrounds in the cut-based analysis. These are 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 5.12: 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.

Figures 5.14 and 5.15 show the variations in the extrapolation factor from the PDF and QCD uncertainties on the top background estimate, binned in m_T , for the cut-based analysis. In both cases, there

2043 was no significant shape uncertainty but normalization uncertainties were assigned according to the
 2044 maximal variation. These uncertainties enter into the 26% total uncertainty on top quoted in table 5.12
 2045 While the estimate for the same-flavor $Z/\gamma^* \rightarrow \ell\ell$ background is data-driven, there is still a sys-
 2046 tematic uncertainty taken for the non-closure of the method in Monte Carlo. This is taken as the max-
 2047 imum of the deviation of the non-closure factor f_{corr} from unity and its uncertainty, or $\max(|1 -$
 2048 $|f_{\text{corr}}|, \delta f_{\text{corr}})$. For the cut-based analysis this non-closure uncertainty 23%, while for the BDT analy-
 2049 sis it is 17%.

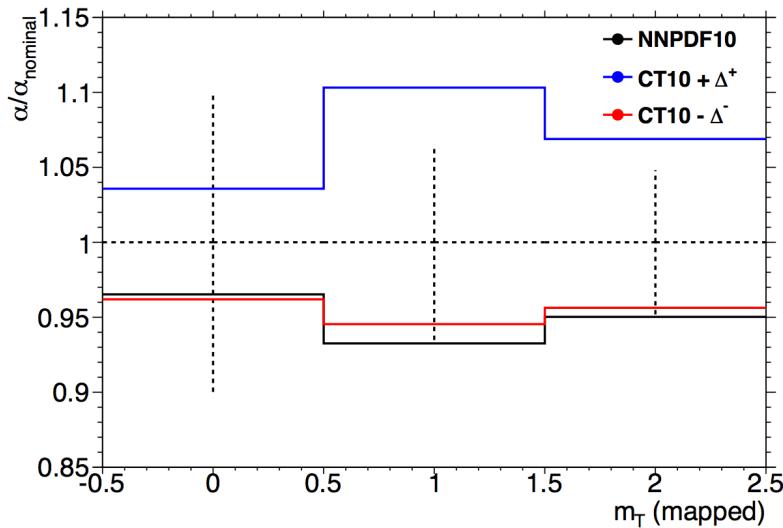


Figure 5.14: Variations in the top background extrapolation factor in the cut-based analysis due to PDF uncertainties, binned in m_T .

2050 5.6.2 EXPERIMENTAL UNCERTAINTIES

2051 In this analysis, the theoretical uncertainties end up being the most dominant, but there are some ex-
 2052 perimental uncertainties that make a contribution as well. The first is the uncertainty on the measured
 2053 integrated luminosity, which affects backgrounds whose normalization is taken from MC and is mea-
 2054 sured to be 2.8% in the 8 TeV dataset [81]. The dominant sources of uncertainty overall are uncertainties
 2055 on the jet energy scale and resolution and the b -tagging efficiency. Additional sources include lepton
 2056 uncertainties on identification, resolution, and trigger efficiency, as well as uncertainties on the missing
 2057 transverse momentum .

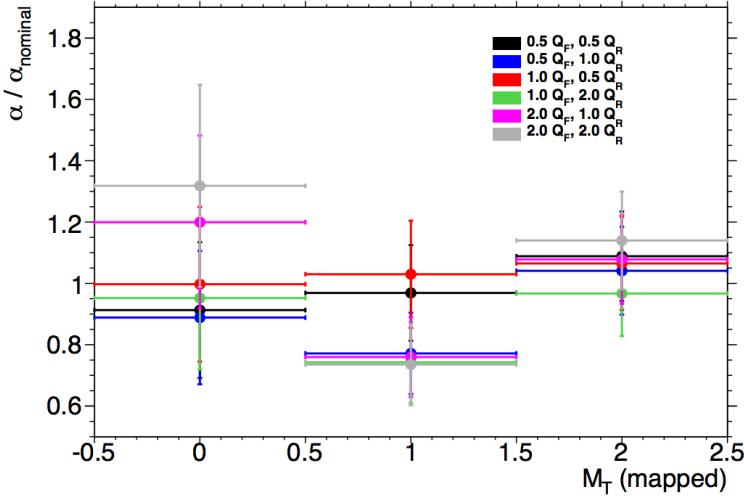


Figure 5.15: Variations in the top background extrapolation factor in the cut-based analysis due to QCD scale uncertainties, binned in m_T .

The jet energy scale uncertainty is split into several independent components, including jet-flavor dependent calorimeter response uncertainties, uncertainties on modeling of pile-up interactions, uncertainties on extrapolation from the central to forward detector regions, and MC non-closure [82]. The uncertainty on energy scale for jets used in this analysis ranges from 1% to 7% depending on the jet p_T and η . The jet energy resolution varies from 5% to 20%, with uncertainties ranging from 2% to 40% (the largest uncertainties occurring at the selection threshold).

The b-tagging efficiency is independently measured in data samples enriched in dileptonic decays of $t\bar{t}$ events or in events where a muon is reconstructed in the vicinity of a jet [83, 84]. The efficiencies and their uncertainties are binned in p_T and decomposed into uncorrelated components using an eigenvector method [?]. Uncertainties on the efficiency range from 1% to 7.8%. The uncertainty on the rate of misidentification of c -jets as b -jets ranges from 6-14%, while the uncertainty on the rate of light jet mis-tagging ranges from 9-19% depending on p_T and η .

The total experimental uncertainties on different signal and background components are summarized in table 5.13. They are compared to the level of other statistical and systematic uncertainties as well. Overall, the experimental uncertainties are sub-dominant compared to the statistical and theoretical uncertainties.

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 5.13: 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 [61].

5.7 RESULTS

While the combined results of all the $H \rightarrow WW^*$ sub-analyses will be discussed in the next chapter, this section presents the results of the VBF specific analysis and interpretations. As table 5.7 shows, the final cut-based signal region contains 20 events in data with $m_T < 150$ GeV, 14 coming from the $e\mu$ channel and 6 coming from the $ee + \mu\mu$ channel. The BDT analysis has many more candidates due to its looser selection, and the yields in each bin of O_{BDT} are shown in table 5.14.

Figure 5.16(a) shows the final distribution of data candidates compared to the expected m_T distribution for signal and background. The data are very consistent with a VBF Higgs hypothesis. Figure 5.16(b) shows where the data candidates fall in the two-dimensional binning of m_T and m_{jj} used in the fit for the cut-based analysis.

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

Because the cut-based result is used as a validation for the BDT analysis and the two signal regions are not fully orthogonal, it is interesting to explore which events overlap between the two analyses. Of the twenty events in the cut-based signal region, only seven were not selected by the BDT analysis, while the other thirteen also enter the BDT signal region. Figure ?? shows where the different analysis candidates lie in the m_{jj} - m_T plane. This shows clearly that the advantage of the BDT analysis is that it can extract

(a) Before the BDT classification

Selection	Summary						Composition of N_{bkg}						
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{signal}	N_{eggF}	N_{VBF}	N_{VH}	N_{WW}^{SD}	N_{WW}^{EW}	$N_{t\bar{t}}$	N_t	N_{Wj}	N_{jj}
$e\mu$ sample	1.04 ± 0.04	718	689	13	15	2.0	90	II	327	42	29	23	31
$ee/\mu\mu$ sample	1.18 ± 0.08	469	397	6.0	7.7	0.9	37	3	132	17	5.2	1.2	10.1

(b) Bins in O_{BDT}

$e\mu$ sample	Summary													Composition of N_{bkg}				
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{signal}	N_{eggF}	N_{VBF}	N_{VH}	N_{WW}^{SD}	N_{WW}^{EW}	$N_{t\bar{t}}$	N_t	N_{Wj}	N_{jj}	N_{missid}	N_{VV}	$N_{\text{Drell-Yan}}$	$N_{e\mu/\mu e}$	$N_{\tau\tau}^{\text{SD}}$
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	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	Summary													Composition of N_{bkg}				
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{signal}	N_{eggF}	N_{VBF}	N_{VH}	N_{WW}^{SD}	N_{WW}^{EW}	$N_{t\bar{t}}$	N_t	N_{Wj}	N_{jj}	N_{missid}	N_{VV}	$N_{\text{Drell-Yan}}$	$N_{e\mu/\mu e}$	$N_{\tau\tau}^{\text{SD}}$
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	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	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	4.4	0.3	0.1	
Bin 3	6.32 ± 2.87	6	0.9	0.2	1.7	—	0.1	0.2	0.2	—	—	—	—	0.7	—	—	—	

Table 5.14: 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 [61].

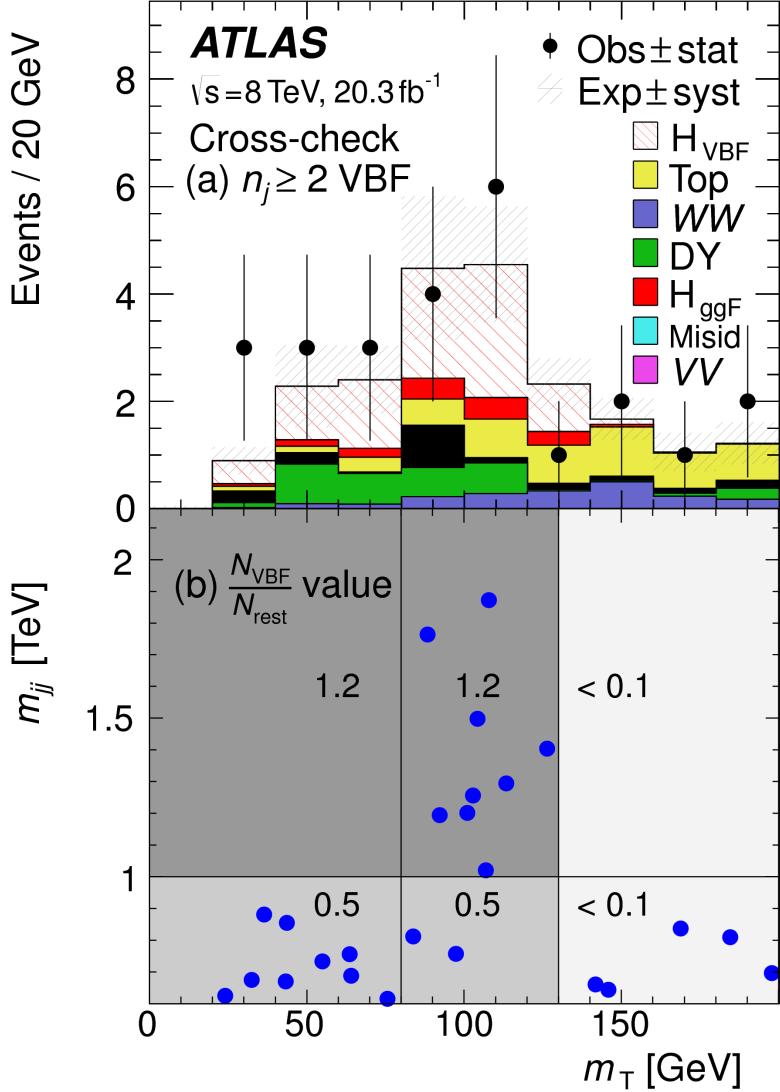


Figure 5.16: Post-fit distributions in the cut-based VBF analysis. Panel (a) shows the one-dimensional m_T distribution, while (b) shows the data candidates split into the bins of m_T and m_{jj} used in the final fit [6.1].

signal candidates lower m_{jj} region due to its ability to recognize correlations with other variables.
 While the context of these results in the broader $H \rightarrow WW^*$ statistical analysis will be presented in the next chapter, the significance of the VBF observation can be shown here. In the BDT analysis, the expected signal significance was 2.7σ , while the observed significance was 3.1σ . In the cut-based analysis, the expected significance was 2.1σ and the observed significance was 3.0σ . The compatibility between these two results can be evaluated by computing the probability of observing a larger difference

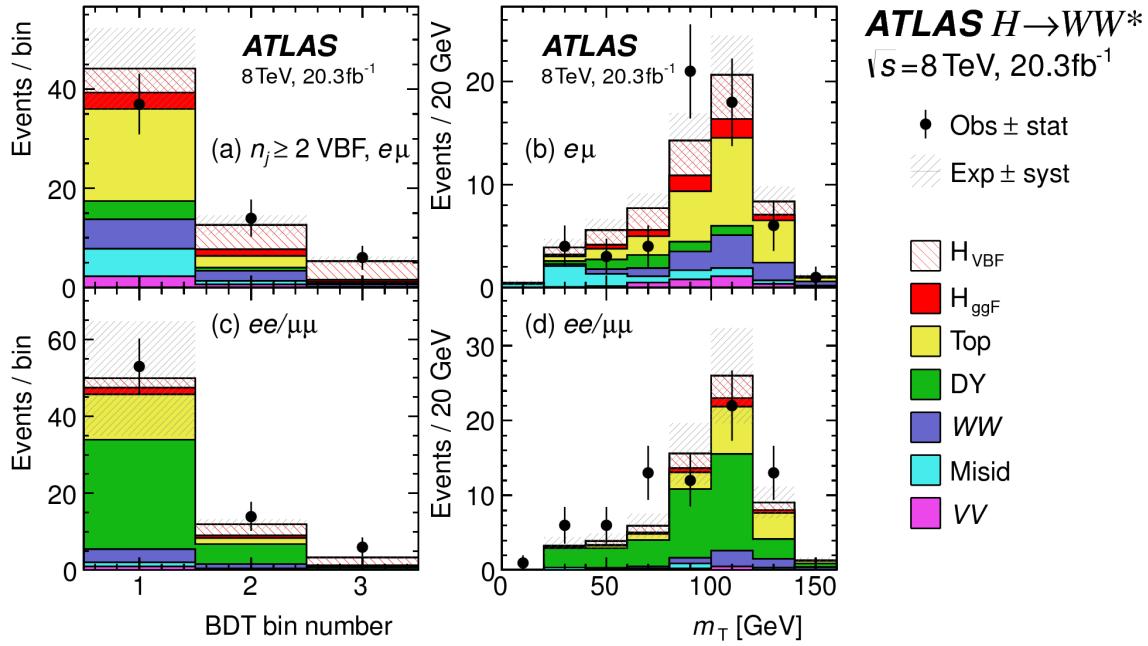


Figure 5.17: Postfit distributions in the BDT VBF analysis [61].

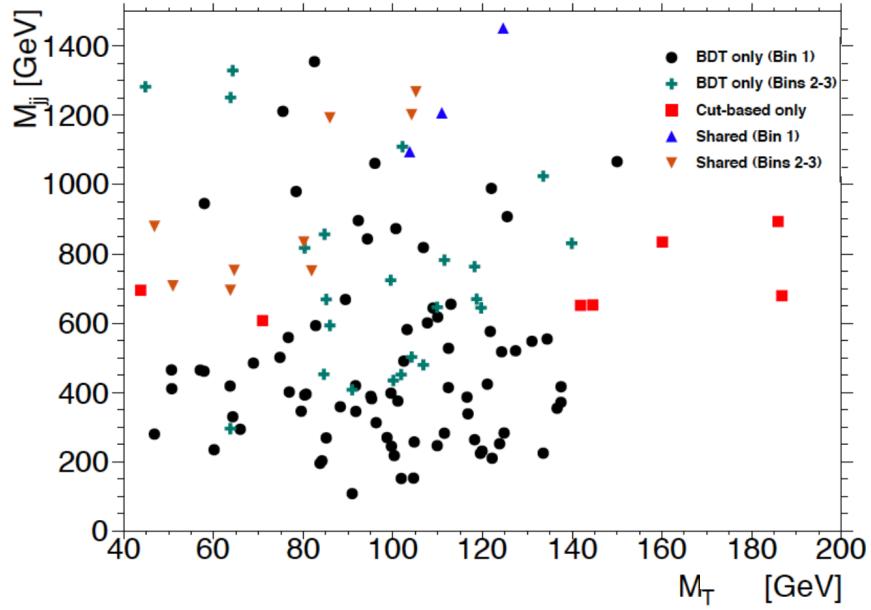


Figure 5.18: Overlap between cut-based and BDT VBF signal region candidates in the m_{jj} - m_T plane.

2097 in Z_0 values than the one measured. Using toy Monte Carlo with the ggF signal strength fixed to unity
2098 and considering only statistical uncertainties, this probability is computed to be 79%, indicating good
2099 agreement between the analyses. This result represents the first observation of the vector boson fusion
2100 production of a Higgs boson.

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

Chuck Palahniuk

6

2101

2102

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

2103

results

2104

6.1 INTRODUCTION

2105 In the final statistical analysis of $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, the dedicated gluon-gluon fusion and vector
2106 boson fusion sensitive signal regions are all combined into a single fit to determine the main parameters
2107 of interest, the Higgs signal strength μ and mass m_H . Therefore, while the specific requirements applied
2108 for the VBF sensitive analysis are discussed in chapter 5, the final measurement of these parameters can
2109 only be discussed in combination with the results of the ggF dedicated analysis. For example, because
2110 ggF Higgs production is considered a background in the VBF analysis, the ggF dedicated signal regions
2111 can actually constrain the normalization of this background in the VBF dedicated region.

2112 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	$\otimes m_{\ell\ell}$	$\otimes p_T^{\ell 2}$	$\otimes \ell_2$		
$n_j = 0$	$e\mu$	$\otimes [10, 30, 55]$	$\otimes [10, 15, 20, \infty]$	$\otimes [e, \mu]$	m_T
	$ee/\mu\mu$	$\otimes [12, 55]$	$\otimes [10, \infty]$		m_T
$n_j = 1$	$e\mu$	$\otimes [10, 30, 55]$	$\otimes [10, 15, 20, \infty]$	$\otimes [e, \mu]$	m_T
	$ee/\mu\mu$	$\otimes [12, 55]$	$\otimes [10, \infty]$		m_T
$n_j \geq 2$ ggF	$e\mu$	$\otimes [10, 55]$	$\otimes [10, \infty]$		m_T
$n_j \geq 2$ VBF	$e\mu$	$\otimes [10, 50]$	$\otimes [10, \infty]$		O_{BDT}
	$ee/\mu\mu$	$\otimes [12, 50]$	$\otimes [10, \infty]$		O_{BDT}

Table 6.1: All signal regions definitions input into final statistical fit [61].

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 [61]. 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-

2127 grounds. The yields for signal and background are all scaled according to the final normalizations calcu-
2128 lated 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 [61].

2129 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

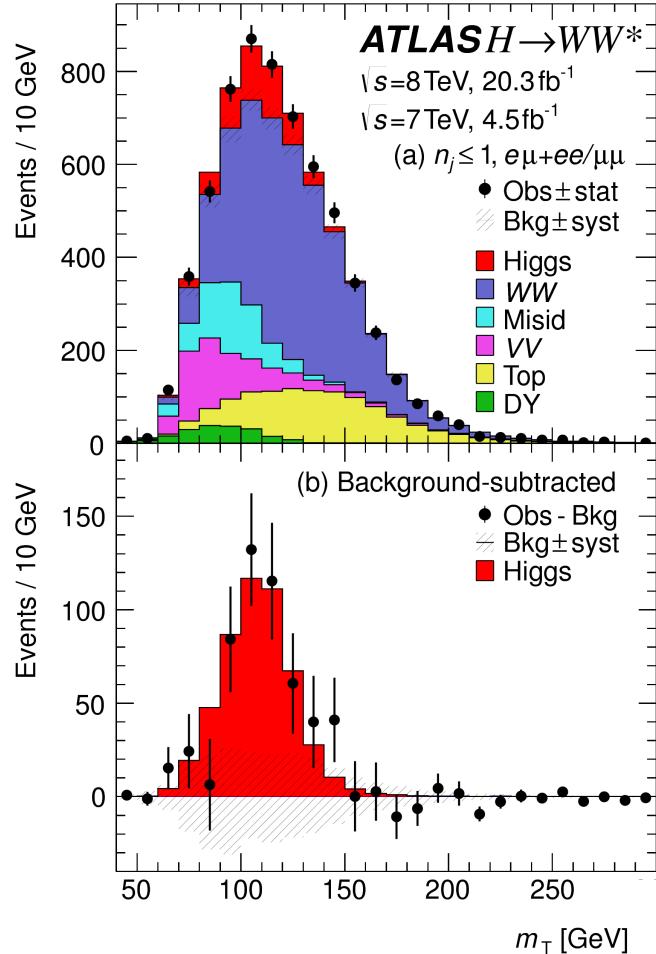


Figure 6.1: Post-fit m_T distribution in the $n_j \leq 1$ regions [61].

2130

2131 in chapter 5, for the physical interpretation of results presented in subsequent sections.

2132 **6.3 SIGNAL STRENGTH MEASUREMENTS IN ggF AND VBF PRODUCTION**

2133 When all of the signal regions are combined in the fit, there can be a combined measurement of the sig-
 2134 nal strength as well as the individual ggF and VBF signal strengths. The combined signal strength is the
 2135 ratio of the sum of the gluon fusion and VBF cross sections to the theory prediction, or a signal strength
 2136 for the total Higgs production cross section that this analysis is sensitive to. The final measured com-
 2137 bined signal strength μ is measured shown in equation 6.1.

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

2138 Figure 6.2 gives the best fit signal strength $\hat{\mu}$ as a function of the hypothesized Higgs mass. The value
 2139 at 125.36 GeV corresponds to the μ quoted in equation 6.1. This value of the Higgs mass is used because
 2140 it is the most precise mass measurement from ATLAS, a result of the combined $\gamma\gamma$ and ZZ mass mea-
 2141 surements [?].

2142 As explained in chapter 3, a probability p_0 can be computed using the test statistic q_0 to quantify the
 2143 probability that the background could fluctuate to produce an excess at least as large as the one observed
 2144 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
 2145 at $m_H = 130$ GeV and corresponds to a significance of 6.1σ . The curve is relatively flat and the sig-
 2146 nificance is the same at 125.36 GeV within the quoted precision. The expected significance for a signal
 2147 with strength $\mu = 1.0$ is 5.8σ . This represents the first discovery level significance measurement in the
 2148 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis.

2149 All the results presented so far in this section have been for the combined gluon fusion and VBF pro-
 2150 duction modes. However, each signal strength can be calculated separately in the likelihood as well.
 2151 There are two ways to do this. First, the likelihood can be parameterized in terms of a single parameter,

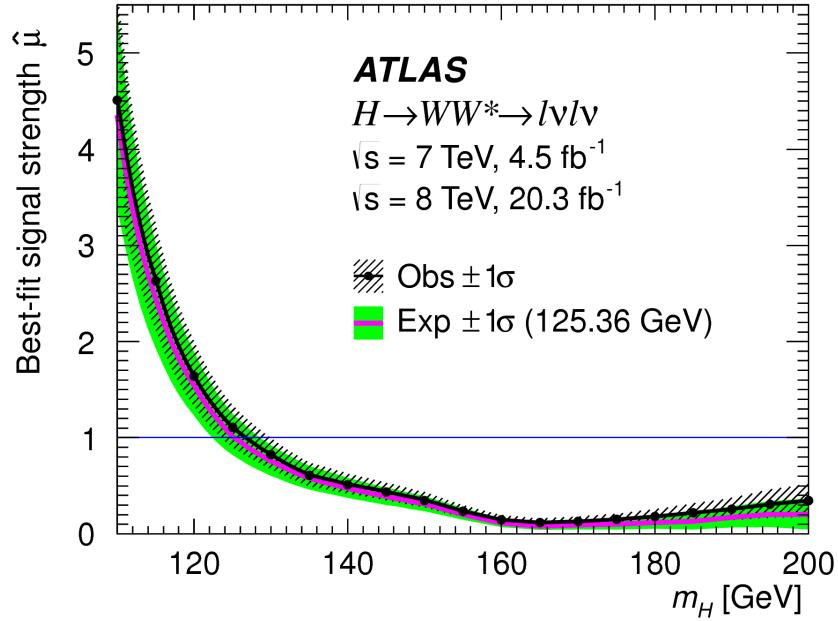


Figure 6.2: Best fit signal strength $\hat{\mu}$ as a function of hypothesized m_H [61].

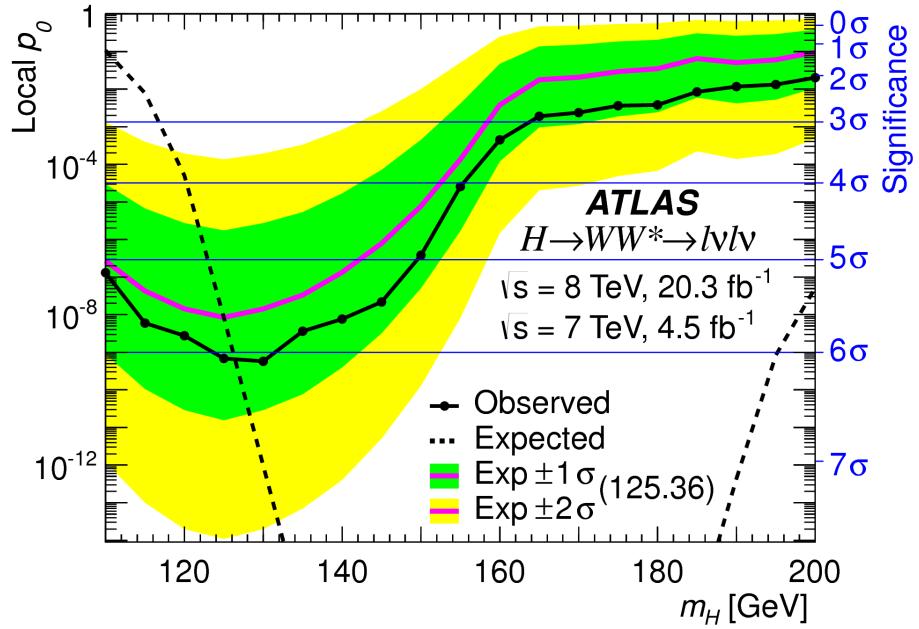


Figure 6.3: Local p_0 as a function of m_H [61].

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

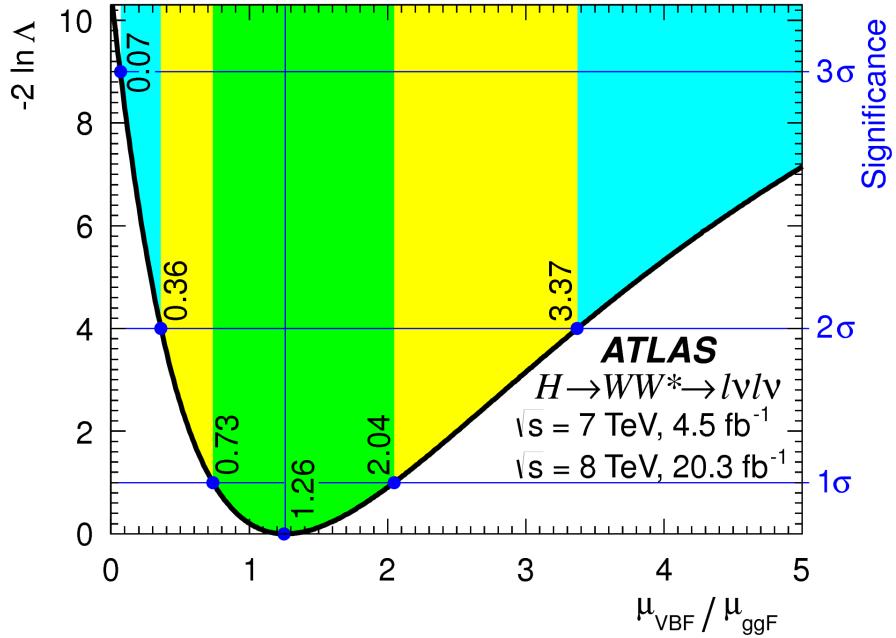


Figure 6.4: Likelihood as a function of $\mu_{\text{VBF}} / \mu_{\text{ggF}}$ [61].

2154 The best fit value of the ratio of signal strengths is shown in equation 6.2. Within the quoted uncer-
 2155 tainties, it is consistent with a ratio of unity.

$$\frac{\mu_{\text{VBF}}}{\mu_{\text{ggF}}} = 1.26^{+0.61}_{-0.45} (\text{stat.})^{+0.50}_{-0.26} (\text{syst.}) = 1.26^{+0.79}_{-0.53} \quad (6.2)$$

2156 The null hypothesis for VBF production corresponds to a ratio of $\mu_{\text{VBF}} / \mu_{\text{ggF}} = 0$. The likelihood in
 2157 figure 6.4 gives a significance of 3.2σ at $\mu_{\text{VBF}} / \mu_{\text{ggF}} = 0$, as quoted in chapter 5.

2158 In addition to the ratio of signal strengths, each signal strength can be varied independently in the
 2159 likelihood as well. Figure 6.5 shows the two dimensional likelihood scan in the $\mu_{\text{ggF}}-\mu_{\text{VBF}}$ plane. The
 2160 best fit values of the two signal strengths are shown in equation 6.3. Both are consistent with unity
 2161 within their 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.)

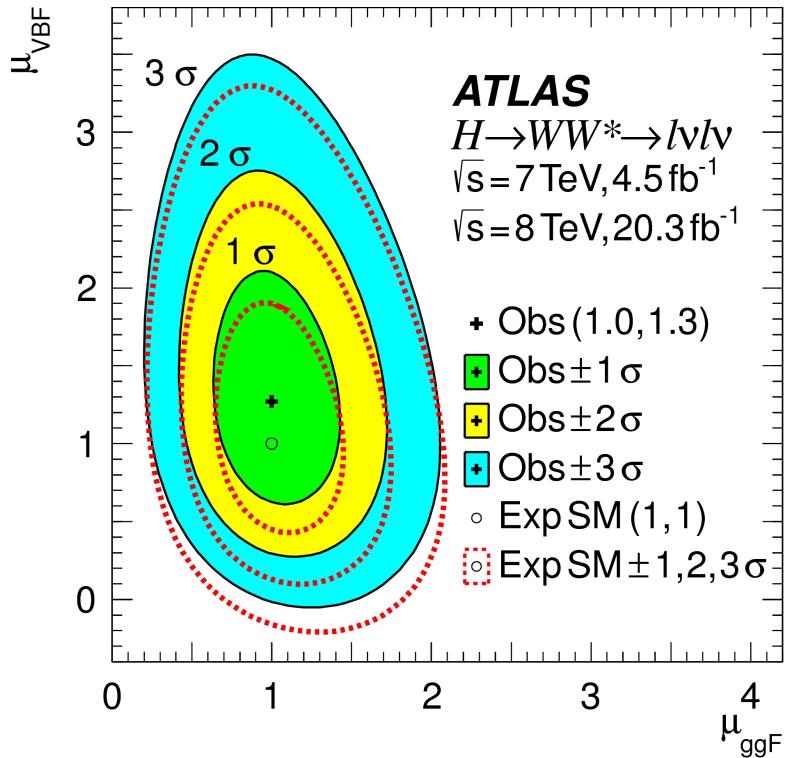


Figure 6.5: Likelihood scan as a function of μ_{VBF} and μ_{ggF} [61].

2162 6.4 MEASUREMENT OF HIGGS COUPLINGS TO VECTOR BOSONS AND FERMIONS

2163 Similar to the parameterization of signal strength, the couplings of the Higgs to fermions and bosons can
 2164 also be parameterized. The parameter of interest in this case is κ , or the ratio of the measured coupling
 2165 to the standard model expectation. Both the fermion and boson couplings have these so-called scale fac-
 2166 tors, κ_F for fermions and κ_V for bosons. Gluon fusion production is sensitive to the fermion couplings
 2167 through the top quark loops in its production, while VBF production is sensitive to the vector boson
 2168 couplings in its production. Both modes are sensitive to the vector boson couplings in their decays. The
 2169 signal strengths will have dependence on the coupling scale factors as described in equation 6.4 [18].

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

2170 Figure 6.6 shows the two-dimensional likelihood scan of κ_F and κ_V . The best-fit values are given in
 2171 equation 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.)

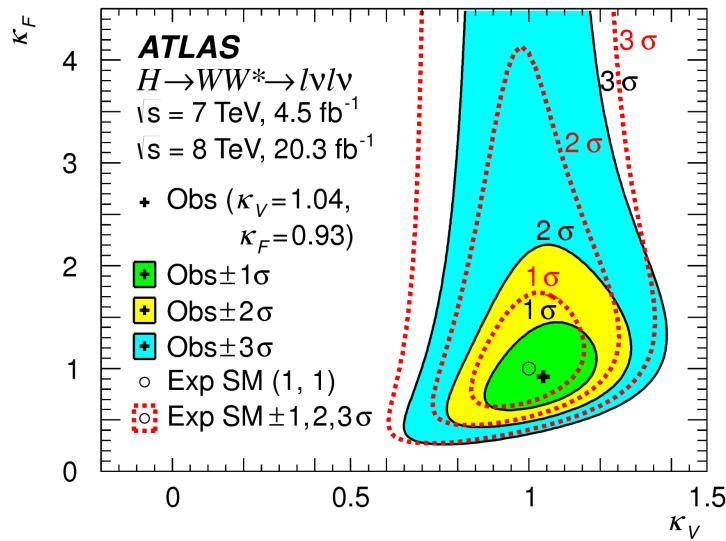


Figure 6.6: Likelihood scan as a function of κ_F and κ_V [61].

2172

2173 6.5 HIGGS PRODUCTION CROSS SECTION MEASUREMENT

2174 Another measurement that comes naturally from the signal strength numbers quoted earlier is the pro-
 2175 duction cross section and 7 and 8 TeV for both gluon fusion and VBF production. The general equa-
 2176 tion for calculating the cross section is given in equation 6.6.

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

2177 $(N_{\text{sig}})_{\text{obs}}$ is the number of events observed in data. \mathcal{A} is the geometric and kinematic acceptance of the
 2178 detector, while \mathcal{C} is the efficiency of the signal region selection for events that are reconstructed in the
 2179 detector. The branching ratio of a WW system to leptons must also be divided out. The production
 2180 cross section depends on the center of mass energy and the production mode desired (gluon fusion or
 2181 VBF), and so three separate cross section measurements are quoted in equation 6.7.

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

(stat.) (syst.)

2182 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,
 2183 consistent with the measured values within their uncertainties. For vector boson fusion, the predicted
 2184 cross section is 0.35 ± 0.02 pb, again consistent with the measured value.

2185 6.6 CONCLUSION

2186 The combined analysis of the gluon fusion and vector boson fusion processes in $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
 2187 in the 7 and 8 TeV datasets has yielded the first discovery level significance for Higgs production in this
 2188 decay channel. Additionally, precise measurements of the couplings to vector bosons and fermions are
 2189 given. Finally, signal strengths and cross sections for each production mode are measured. Figure 6.7
 2190 shows the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ measurements in comparison with other Higgs decay channels in
 2191 ATLAS. The measurement of signal strength from this channel remains the most sensitive in both the
 2192 gluon fusion and VBF production modes for the Run 1 dataset.

ATLAS

Individual analysis

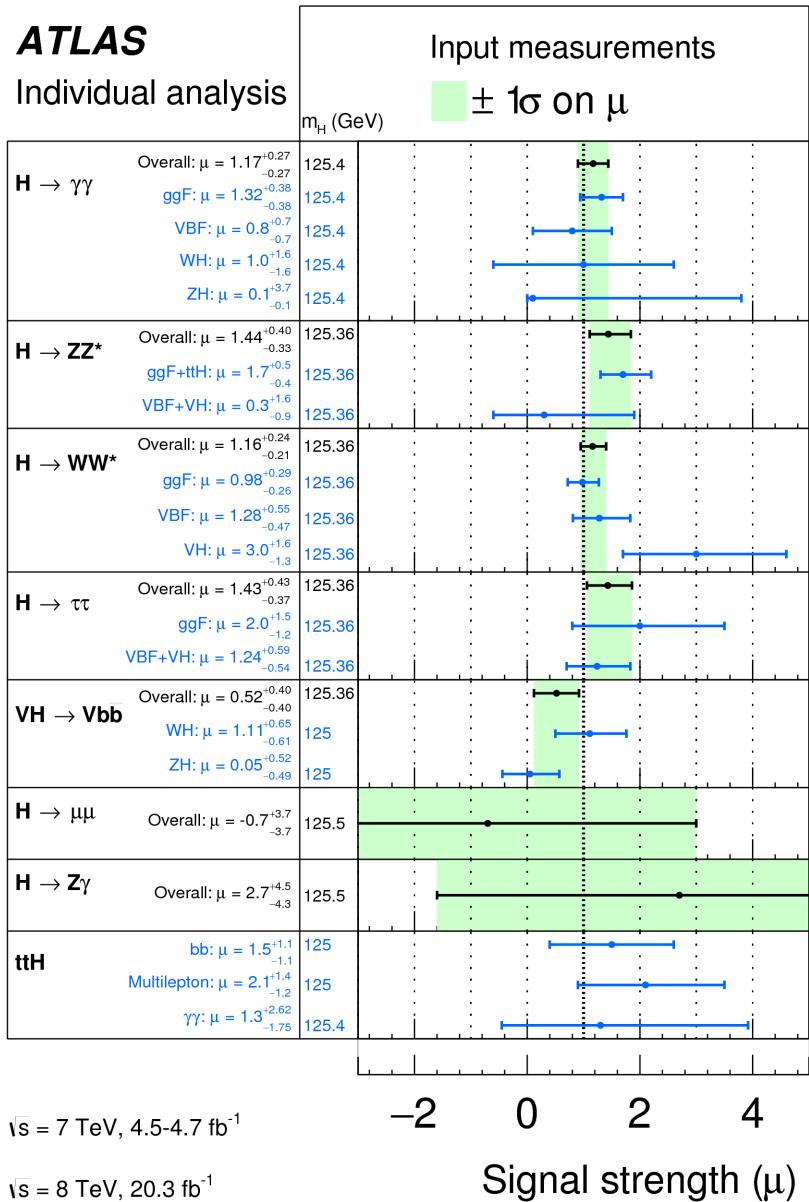


Figure 6.7: Comparison of signal strength measurements in different Higgs decay channels on ATLAS [85].

2193

Part III

2194

Search for Higgs pair production in the

2195

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

2196

13 TeV

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

W. Eugene Smith

7

2197

2198 Search for Higgs pair production in boosted 2199 $b\bar{b}b\bar{b}$ final states

2200 7.1 INTRODUCTION

2201 After the discovery of the Higgs boson in the ATLAS Run 1 dataset and the subsequent measurements
2202 of its properties, the Higgs transformed into a potential tool in searches for physics beyond the Stan-
2203 dard Model. The pair production cross section of the Higgs can be enhanced through BSM physics.
2204 Studying di-Higgs production also probes the Higgs self-coupling, shedding light on the structure
2205 of the Higgs potential. This chapter presents a search for resonant production of a Higgs pair in the
2206 $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ final state in 3.2 fb^{-1} of data collected at $\sqrt{s} = 13 \text{ TeV}$. In particular, this
2207 chapter focuses on a search for this final state in the regime where m_X is large ($\gtrsim 1 \text{ TeV}$) and the Higgs
2208 bosons in the decay are significantly boosted. A tailored selection for this boosted selection, using novel

2209 techniques in jet substructure and b -tagging, is discussed. Then, the data-driven background estimate is
 2210 presented. Finally, the results of the search are shown. The signal models used as benchmarks are a spin-
 2211 2 Randall Sundrum graviton (RSG) and a narrow width spin-0 resonance. These models are described
 2212 in more detail in Chapter 1. Limits on signal models are reserved for the next chapter where the results of
 2213 this chapter are combined with the results of a separate selection dedicated to the lower m_X regime.

2214 7.2 MOTIVATION

2215 With the center of mass energy increase from $\sqrt{s} = 8 \text{ TeV}$ to $\sqrt{s} = 13 \text{ TeV}$, the LHC and ATLAS
 2216 are able to probe new resonances at higher mass scales than previously accessible in Run 1. This is a
 2217 powerful motivator for searching for a new resonance in the early 13 TeV data. Figure 7.1 shows the
 2218 ratios of parton luminosities between 8 and 13 TeV for different resonance masses. For a resonance of
 2219 $M_X = 2 \text{ TeV}$, the cross section at $\sqrt{s} = 13 \text{ TeV}$ is roughly a factor of 10 larger than at $\sqrt{s} = 8 \text{ TeV}$.

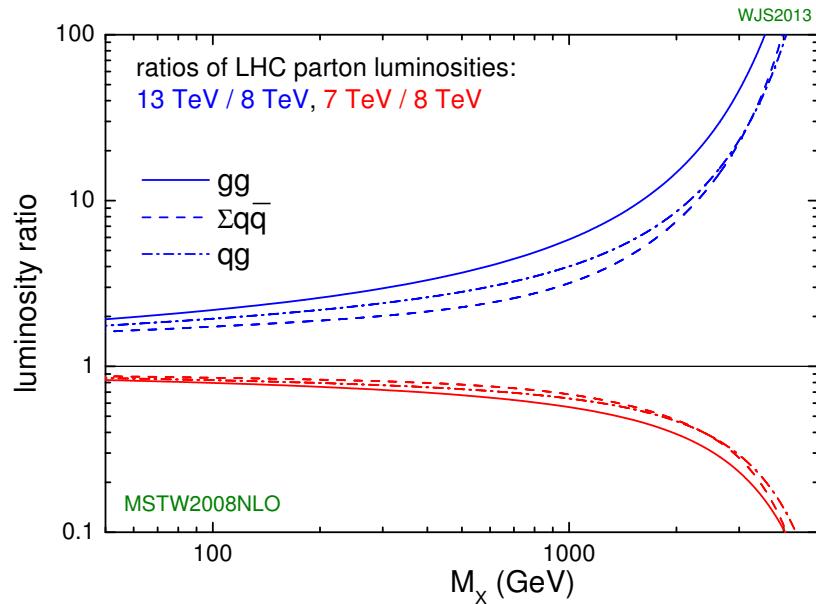


Figure 7.1: Parton luminosity ratios as a function of resonance mass M_X for 13/8 TeV and 7/8 TeV [86].

2220 Higgs pair production offers a vast array of unprobed regions of phase space where searches for BSM
 2221 physics can be made. Chapter 1 discusses some possibilities for both resonant and non-resonant enhance-

ment of the di-Higgs production cross section. Given the increased mass reach of the LHC in Run 2, it is particularly important to focus on resonant searches at high m_X . One consideration when conducting a search in the HH final state is which decay modes of the Higgs to consider. Figure 7.2 shows the branching ratio of the HH final state for different combinations of decays of each individual Higgs. As the largest 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 33%.

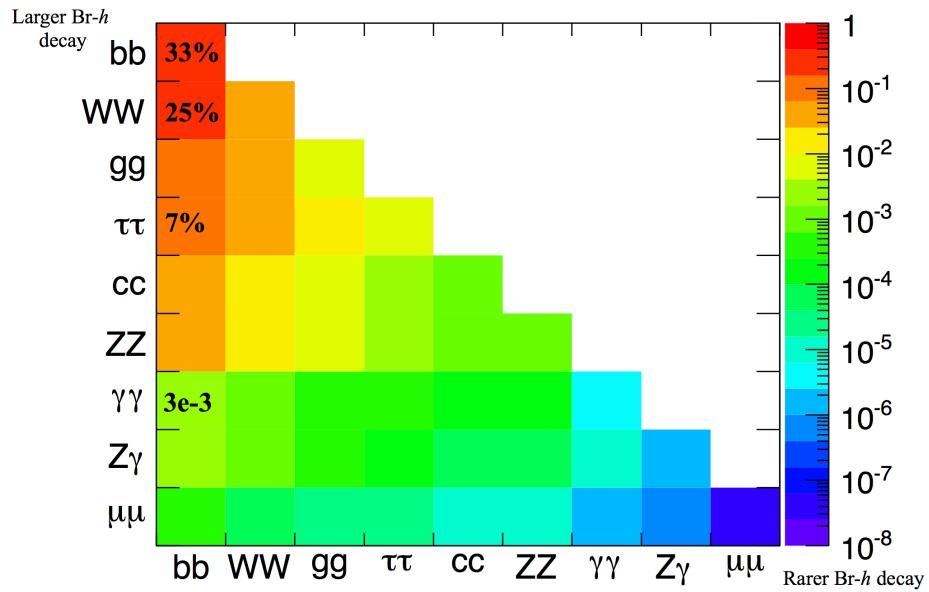


Figure 7.2: Summary of HH branching ratios [87].

At high m_X , the Higgs bosons resulting from the decay of a heavy resonance will have large p_T^* . The ΔR between the decay products of the Higgs is inversely proportional to the Higgs p_T , as shown in equation ??.

$$\Delta R \approx \frac{2m}{p_T} \quad (7.1)$$

Figure 7.3 shows the minimum ΔR between truth level B decay vertices in simulation samples for Randall-Sundrum gravitons of different masses. The figure shows that as the mass of the graviton increases, the ΔR distribution between the b quarks in the Higgs decay tends to shift to lower values. Be-

*In the limit that $m_H \ell \ell m_X$, the Higgs p_T is roughly $m_X/2$.

cause of this effect, it is necessary to tailor a selection to target these merged b -jets.

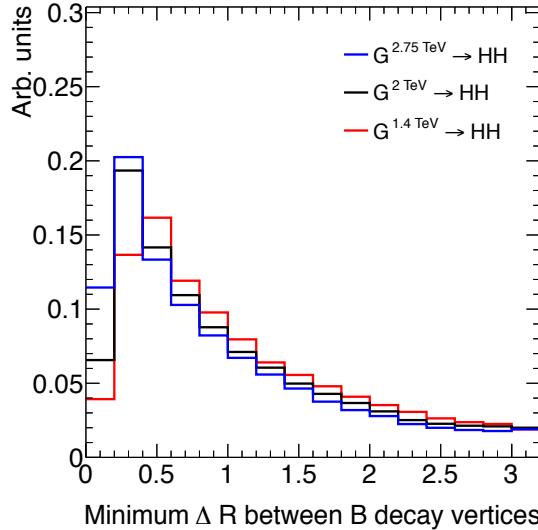


Figure 7.3: Minimum ΔR between B decay vertices for different RSG masses in a $G_{KK}^* \rightarrow HH \rightarrow 4b$ sample with $c = 1$

7.3 DATA AND SIMULATION SAMPLES

7.3.1 SIGNAL MODELS

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

Signal graviton (G_{KK}^*) events are generated at leading order (LO) with **MADGRAPH5 v2.2.2** [88]. The PDF set used is the **NNPDF2.3** LO set [89]. For modeling parton shower and hadronization in jets, **PYTHIA 8.186** is used with the A14 tune [73, 90]. The free parameters in the RSG model are the graviton mass and the coupling constant $c \equiv k/\bar{M}_{\text{Pl}}$ [†]. Both the production cross section and width of the

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

2247 graviton are proportional to c^2 . Samples are generated at both $c = 1$ and $c = 2$ for a variety of mass
2248 points between 300 GeV and 3 TeV.

2249 The second signal sample is a heavy spin-0 resonance H with a fixed width of $\Gamma_H = 1$ GeV. This
2250 is generated with **MADGRAPH5** and uses the **CT10** PDF set [76]. The parton shower and hadronization
2251 are handled by **HERWIG ++** with the **CTEQ6L1** PDF set and the **UEEE5** event tune [77, 91, 92]. Because
2252 the width and branching ratios depend on 2HDM parameters, each mass point generated with this fixed
2253 width corresponds to a different point in the 2HDM parameter phase space. Mass points are generated
2254 between 300 GeV and 1 TeV as with the RSG signal samples.

2255 7.3.2 BACKGROUND SAMPLES

2256 While the dominant **QCD** multijet background is estimated with a fully data-driven method, the sub-
2257 dominant backgrounds $t\bar{t}$ and Z +jets are modeled with some input from simulation.

2258 $t\bar{t}$ events are simulated at next-to-leading order (NLO) with the **POWHEG-BOX** version 1 generator us-
2259 ing the **CT10** PDF set [93]. The parton shower, hadronization, and underlying event are simulated with
2260 **PYTHIA 6.428** with the **CTEQ6L1** PDF set [72]. The Perugia 2012 tune is used [94]. NNLO **QCD** cor-
2261 rections to the cross sections are computed in **Top++ 2.0** [95]. The top quark mass is set to 172.5 GeV.
2262 The shapes of distributions in $t\bar{t}$ are taken from MC while the normalization is taken from data.

2263 Finally, the Z +jets background is simulated with **PYTHIA 8.186** and the **NNPDF2.3** LO PDF set. This
2264 background is negligible compared to the others and is taken fully from MC.

2265 7.3.3 DATA SAMPLE AND TRIGGER

2266 This analysis is done on 3.2 fb^{-1} of data taken in 2015 at $\sqrt{s} = 13$ TeV. The details of the machine
2267 conditions during this time can be found in Chapter 2. Only data which was taken during stable beam
2268 conditions with all detectors functioning is used. Events must pass a trigger which requires a single
2269 360 GeV large radius ($R = 1.0$) jet to be reconstructed in the HLT. Figure 7.4 shows the trigger effi-
2270 ciency for various trigger options as a function of graviton mass. Above $m_G > 1$ TeV, the single large
2271 radius jet trigger is 99% efficient for events passing the signal selection.

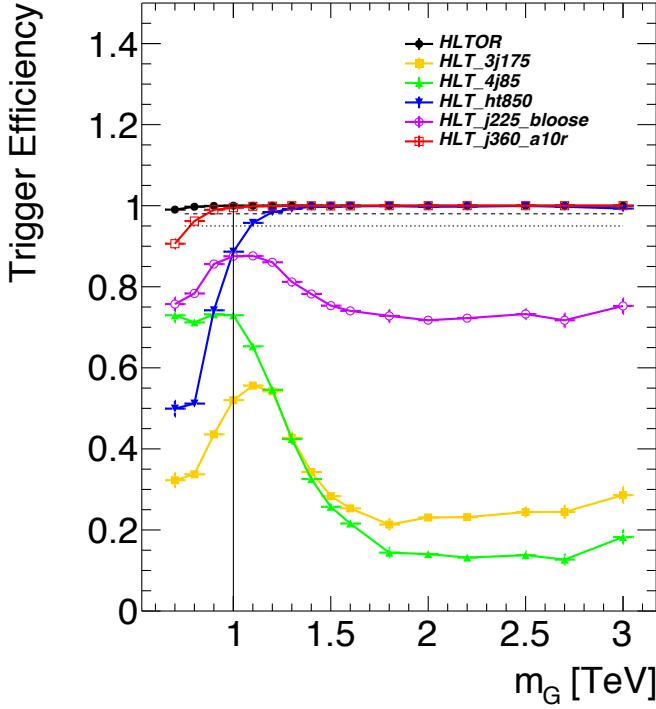


Figure 7.4: Trigger efficiency for events passing all signal region selections as a function of mass in $G_{KK}^* \rightarrow HH \rightarrow 4b$ samples with $c = 1$ [96]. In the trigger names, “j” refers to a jet or jets. “ht” refers to H_T , the scalar sum of transverse momenta in the event. “bloose” 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.

2272 7.4 EVENT RECONSTRUCTION AND OBJECT SELECTION

2273 The boosted selection first begins by defining a unique set of objects that can be exploited to increase
 2274 signal efficiency in the kinematic regime where the final state b -jets are very merged.

2275 7.4.1 LARGE RADIUS ($R = 1.0$) JETS

2276 The first step towards reconstructing the final state is to define objects that can be used to measure the
 2277 kinematics of the Higgs bosons. In the boosted selection anti- k_T jets with a radius parameter of 1.0
 2278 are used. These jets are much larger in angular size than the typical $R = 0.4$ jets and are intended to
 2279 encompass both jets resulting from the Higgs decay[‡]. The jets are built from clusters in the calorimeter

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

2280 calibrated with local calibration weighting [56].

2281 Because of the large extent of these jets, great care must be taken to remove potential contributions
2282 of calorimeter clusters from pile-up. This is done using a technique called jet trimming [97]. With trim-
2283 ming, the constituents of the large radius jet are re-clustered with a smaller radius with the k_T algorithm.
2284 Then, these so-called subjets are removed from the larger jet if $p_T^{\text{subjet}}/p_T^{\text{jet}} < f_{\text{cut}}$. In this analysis, the
2285 subjet radius is $R = 0.2$ and $f_{\text{cut}} = 0.05$. Trimming has been shown to improve the mass resolution
2286 of large radius jets. Figure 7.5 shows the effect of trimming on the large radius jet mass (M_J). Because
2287 the large radius jet fully contains the higgs decay products, its invariant mass should correspond to the
2288 125 GeV mass of the Higgs. The trimming algorithm brings the jet mass much closer to the expected
2289 Higgs mass and improves the mass resolution.

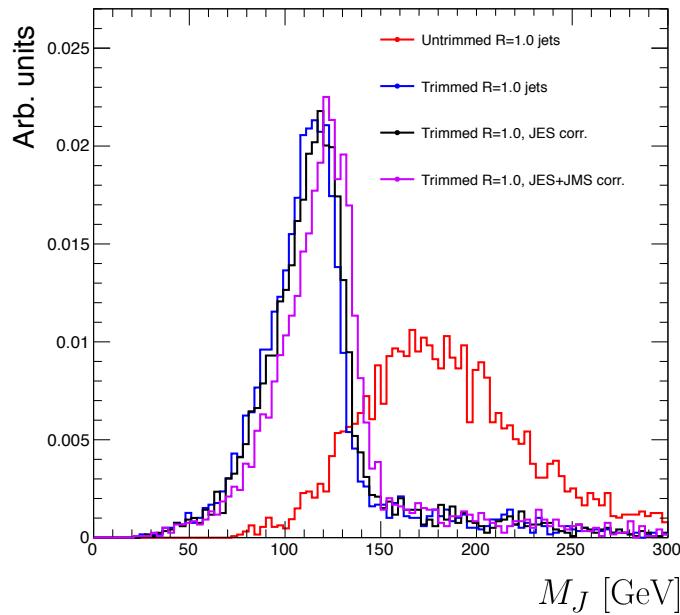


Figure 7.5: Comparison of untrimmed and trimmed jet masses for large radius jets in a RSG sample with $m_{G_{KK}^*} = 1 \text{ TeV}$. JES (JMS) refers to the standard jet energy (mass) scale calibration for ATLAS [56].

2290 The large radius jets are required to satisfy $250 < p_T < 1500 \text{ GeV}$. They must also be within
2291 $|\eta| < 2.0$ in order to ensure that the full jet is within the inner detector tracking volume. Finally, they
2292 are required to have $M_J > 50 \text{ GeV}$. The upper p_T cut and lower threshold on mass are applied to
2293 correspond to the kinematic range where uncertainties are available in ATLAS calibrations [98, 99].

2294 7.4.2 TRACK JETS AND b -TAGGING

2295 Because the b -jets from boosted Higgs decays are so close together (as illustrated in figure 7.3), narrow ra-
2296 dius jets are required to fully resolve both b -jets. The minimum radius feasible for jets based on calorime-
2297 ter deposits is determined by the calorimeter granularity. However, because b -tagging relies on informa-
2298 tion from the inner detector, it is possible to define another type of jet that can have a smaller radius and
2299 better b -tagging resolution. These jets are called “track jets” [99, 100].

2300 Track jets are formed by applying the usual anti- k_T clustering algorithm to tracks that are required
2301 to be consistent with the primary vertex. After the jet axis has been determined using these tracks, a sec-
2302 ond step of track association is also performed to add tracks that can be useful for b -tagging [100]. In this
2303 analysis, the tracks are clustered with a radius parameter of $R = 0.2$. This radius has been shown to
2304 give good performance in boosted Higgs tagging [99, 100]. Figure 7.6 shows a comparison among dif-
2305 ferent track jet 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

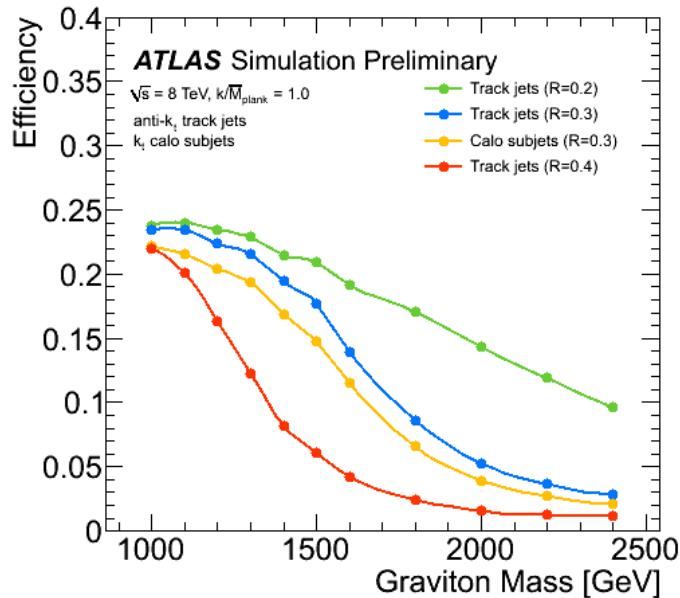


Figure 7.6: Efficiency of finding two b -jets from each Higgs in an RSG event using calorimeter jets with $R = 0.3$ or different track jet radii [100]

2306

2307 analysis, track jets are required to have $p_T > 10$ GeV and $|\eta| < 2.5$. They must also have at least two
2308 tracks.

2309 **7.4.3 MUONS**

2310 Muons are used in this study to correct the four-momenta of calorimeter jets by accounting for semi-
2311 leptonic b decays. The muons used are combined ID and MS muons which must satisfy tight identifica-
2312 tion requirements [52]. The muons must have $p_T > 4$ GeV and $|\eta| < 2.5$. Table 7.1 summarizes the
2313 object requirements described in this section.

	R	p_T	$ \eta $	M
Calorimeter jets	1.0	$250 < p_T < 1500$ GeV	< 2.0	> 50 GeV
Track jets	0.2	> 10 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

2314 **7.5 EVENT SELECTION**

2315 The first requirement in the boosted selection is for ≥ 2 large radius jets satisfying the selections outlined
2316 above. The two highest momentum large-R jets in the event are referred to as “Higgs candidates”. The
2317 leading jet is required to have $p_T > 350$ GeV.

2318 Track jets satisfying the object selections are matched to Higgs candidate jets via ghost association [101].
2319 Each Higgs candidate must have at least 2 track jets associated with it. These basic requirements are illus-
2320 trated in figure 7.7

2321 The QCD multijet background produces less central jets than high mass resonances, so there is an ad-
2322 ditional requirement that the two Higgs candidates be close together in η . The large-R jets are required
2323 to satisfy $|\Delta\eta(JJ)| < 1.7$.

2324 The final set of requirements ensures that the Higgs candidates are consistent with expected proper-
2325 ties of the 125.0 GeV Higgs. First, a variable (X_{hh}) is defined to measure the consistency of both of the

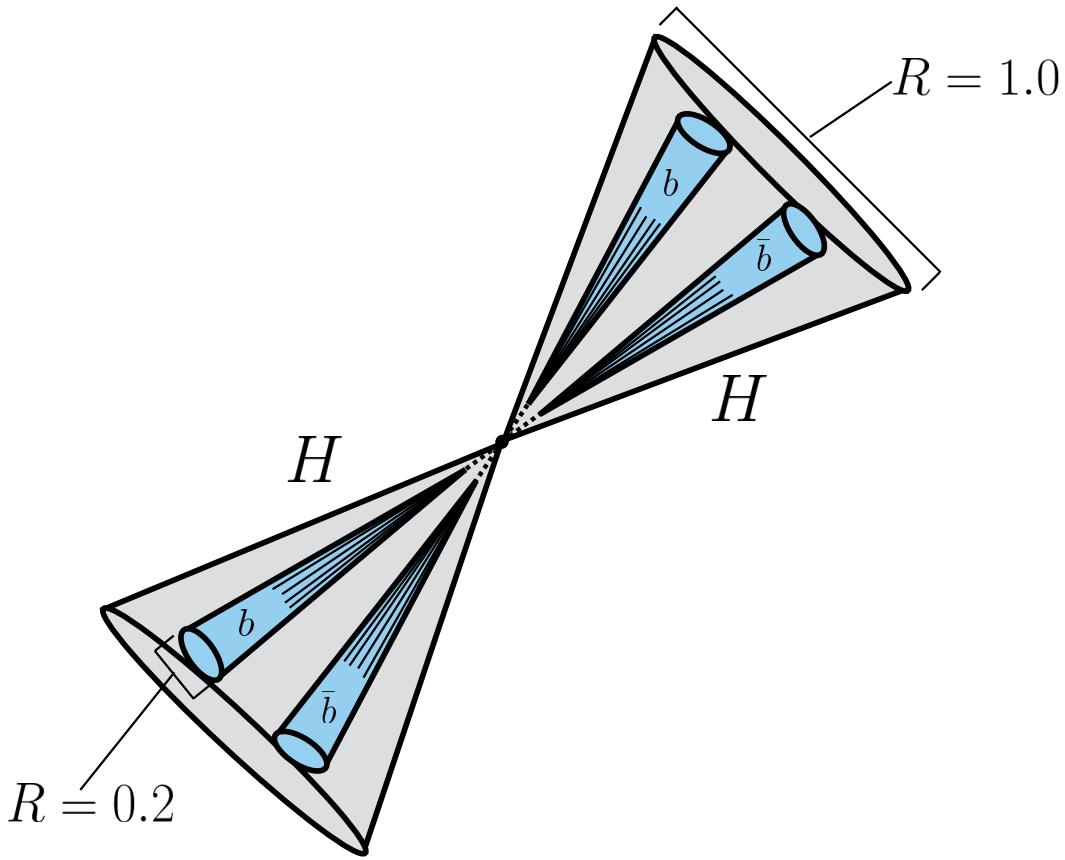


Figure 7.7: Illustration of the boosted selection requirements on Higgs candidates. Each large-radius calorimeter jet (Higgs candidate) must contain two track jets

²³²⁶ Higgs candidate jets with the SM Higgs mass. This is shown in equation 7.2.

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

²³²⁷ The mass values in the X_{hh} formula are optimized to maximize signal efficiency. The sub-leading jet
²³²⁸ typically has a lower mass due to semi-leptonic b decays and final state radiation. X_{hh} effectively acts as
²³²⁹ a χ^2 measurement of the consistency of the two Higgs candidate masses with the signal hypothesis. The
²³³⁰ denominators of each term ($0.1 M$) give the uncertainty on the mass measurement for the large radius
²³³¹ jets. Events are required to satisfy $X_{hh} < 1.6$.

²³³² The last requirement applied is on the number of b -tagged track jets. There are two signal regions de-

2333 fined. The first requires exactly four b -tagged track jets, two in each Higgs candidate (known as the $4b$
 2334 signal region). At high resonance masses, this requirement is inefficient, so an additional signal region
 2335 requiring only three b -tagged track jets is also defined (known as the $3b$ signal region). While this has
 2336 a larger background it is also more efficient for high resonance masses. For both signal regions, thresh-
 2337 old on MV₂ score is chosen such that the algorithm is 77% efficiency in finding true b -jets[§]. Different
 2338 working points were tested and this was found to be optimal. Appendix A has more details on this opti-
 2339 mization.

2340 Before making the requirement on X_{hh} , the masses of the Higgs candidates are corrected for semi-
 2341 leptonic b decays using muons with the criteria outlined in the previous section. Any muons within a
 2342 $\Delta R < 0.2$ of a b -tagged track jet have their four-momenta added to the four-momentum of the Higgs
 2343 candidate. This correction does not affect the pre-selection requirements but does affect the X_{hh} re-
 2344 quirement and the final invariant mass distribution used.

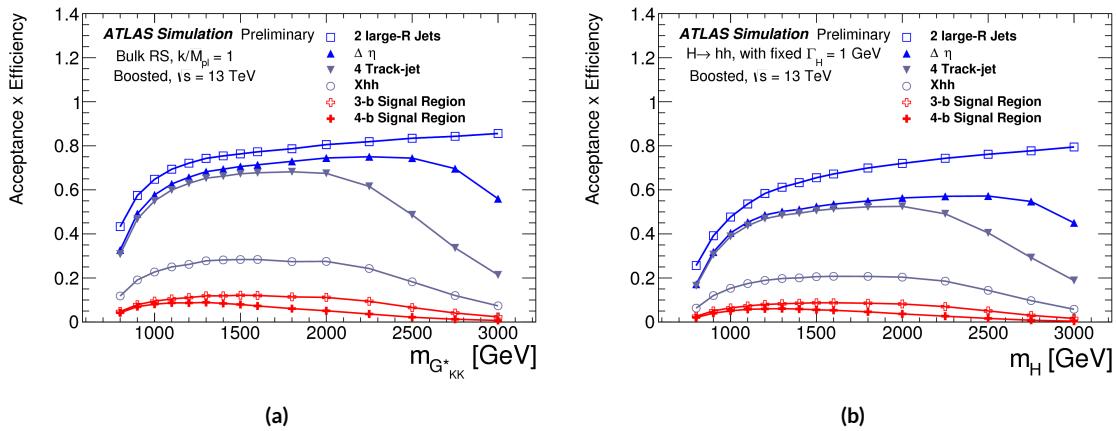


Figure 7.8: Acceptance \times efficiency as a function of mass for (a) RSG and (b) narrow heavy scalar signal models [102].

2345 Figure 7.8 shows the product of acceptance and efficiency as a function of mass for both the RSG and
 2346 narrow heavy scalar resonance signal models. After $m_X > 1$ TeV, the efficiency of the $4b$ requirement
 2347 begins to decline. After $m_X > 2$ TeV, the efficiency of requiring two track jets in each Higgs candidate
 2348 begins to decline as well. Both of these behaviors illustrate the difficulty of resolving the merged decay

[§]The specific MV₂ algorithm chosen is MV_{2c2o}, where the fraction of charm events used in the training is 20%

2349 products at high mass. More details on the degradation of the b -tagging efficiency at high masses are
2350 shown in appendix B.

2351 Figure 7.9 shows a more detailed comparison of the signal efficiency in the $3b$ vs $4b$ signal regions for
2352 the RSG model. The efficiencies shown here are relative to all prior selection requirements.

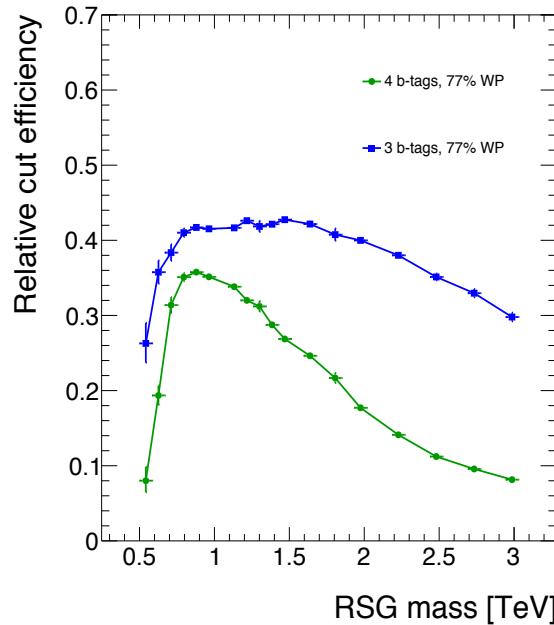


Figure 7.9: Efficiency of requiring 3 or 4 b -tagged track jets vs. RSG mass. The efficiency quoted is relative to the previous selection requirements (rather than an absolute efficiency).

2353 The final discriminating variable used in the boosted analysis is M_{2J} , the invariant mass of the two
2354 Higgs candidates. In order to improve the mass resolution, the four-momenta of each Higgs candidate
2355 are scaled by m_h/M_J . The effect of this correction is small in the boosted analysis but is done for consistency
2356 with the resolved selection.

2357 Table 7.2 shows the effect of the selection requirements on signal and background simulations as well
2358 as data.

2359 7.6 DATA-DRIVEN BACKGROUND ESTIMATION

2360 The largest background to this final state is QCD multijet production, constituting 80-90% of the total
2361 background. Because of the difficulties in modeling higher order QCD processes, this background is

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
$3 b\text{-tags}, X_{hh} < 1.6$	316	3.4	0.067	46.7	2.0
$4 b\text{-tags}, X_{hh} < 1.6$	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 [103].

estimated with a fully data-driven method. The only other non-negligible background is $t\bar{t}$, constituting the other 10-20%. Due to the presence of $t\bar{t}$ in the sideband region where the QCD background will be estimated, the normalization of the QCD and $t\bar{t}$ backgrounds are simultaneously estimated.

7.6.1 MASS REGION DEFINITIONS

The first step in the data-driven background estimate is to define a sideband mass region where the background normalization can be derived. Additionally, a control region is defined where the background estimate can be validated. The control (CR) and sideband (SB) regions are defined using a radial distance in the two-dimensional large-R jet mass plane, R_{hh} , which is defined in equation 7.3.

$$R_{hh} = \sqrt{(M_J^{\text{lead}} - 124\text{ GeV})^2 + (M_J^{\text{sublead}} - 115\text{ GeV})^2} \quad (7.3)$$

Events in the sideband region are required to fail the signal region $X_{hh} < 1.6$ requirement and have $R_{hh} > 35.8\text{ GeV}$. The control region consists of those events which are not in the signal or sideband regions. Figure 7.10 shows the definition of the signal, control, and sideband mass regions. Table 7.3 summarizes the mass region selections for the three different regions used in the analysis.

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

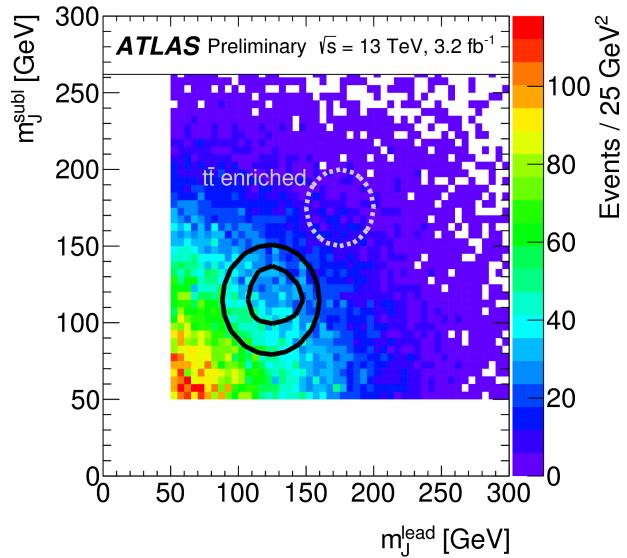


Figure 7.10: M_j^{sublead} vs. M_j^{lead} in a 2 b -tag data sample. The signal region is defined by the inner black contour ($X_{hh} < 1.6$) and the sideband region is defined by the outer contour ($R_{hh} > 35.8 \text{ GeV}$). The region between the black contours is the control region. The mass region which is enriched in $t\bar{t}$ background is also shown for illustration. [102]

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

2374 7.6.2 BACKGROUND ESTIMATION

2375 The method for estimating the background in this analysis is similar to the ABCD method presented in
 2376 Chapter 5. In this case, the two handles used to define different regions for the estimate are the number
 2377 of b -tagged track jets and the mass regions. A region requiring exactly two b -tagged track jets in one large-
 2378 R jet (referred to as the 2-tag or 2 b region) is defined for use in the background estimate. The number of
 2379 expected background events in the 3 b and 4 b signal regions is then given by equation 7.4.

$$N_{\text{bkg}}^{3(4)-\text{tag},\text{SR}} = \mu_{\text{Multijet}} N_{\text{Multijet}}^{2-\text{tag},\text{SR}} + \beta_{t\bar{t}} N_{t\bar{t}}^{3(4)-\text{tag},\text{SR}} + N_{Z+\text{jets}}^{3(4)-\text{tag},\text{SR}} \quad (7.4)$$

2380 In this equation, $N_{\text{bkg}}^{3(4)-\text{tag}}$ is the expected number of background events in the $3b$ or $4b$ signal regions.
 2381 $N_{\text{Multijet}}^{2-\text{tag}}$ 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
 2382 predicted in the MC for the $3b$ or $4b$ signal region, and the variable is similarly defined for the $Z+\text{jets}$
 2383 background. The $\beta_{t\bar{t}}$ parameter is a scale factor used to correct the normalization of the $t\bar{t}$ estimate in
 2384 the signal region. μ_{Multijet} is an extrapolation factor that is derived in the sideband region and used to
 2385 estimate the ratio of 2-tag events to 3(4)-tag events in the signal region. It is defined in equation 7.5.

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

2386 The $t\bar{t}$ scale factor ($\beta_{t\bar{t}}$) and the QCD multijet extrapolation factor (μ_{Multijet}) are estimated together in
 2387 a simultaneous fit in the sideband region. Then, the number of events in the 2-tag signal region is used,
 2388 along with the $t\bar{t}$ estimate in the $3b$ and $4b$ signal regions and μ_{Multijet} , to estimate the total number of
 2389 background events in the two final signal regions. The shape of the final discriminant M_{2J} is also taken
 2390 from the 2-tag signal region where there are more statistics. This method is illustrated graphically in
 2391 figure 7.11.

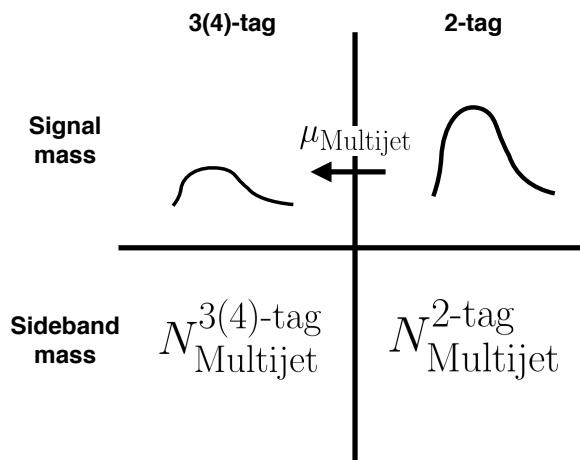


Figure 7.11: An illustration of the data-driven background estimation technique for the boosted analysis

2392 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 $4b$
 2393 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

2394 are statistical only. The larger uncertainties in the $4b$ values indicate the lower statistics available in that
 2395 region.

2396 Figure 7.12 shows the distributions of data and background estimates in the $3b$ and $4b$ sideband re-
 2397 gions after the background fit has been done. The normalizations are constrained from the fit to match
 2398 that of the data, but good modeling of the shape of the mass of the leading large-R jet is seen as well. The
 2399 shapes of the kinematic distributions in the $4b$ region are taken from the $3b$ region due to the better MC
 2400 statistics in that region.

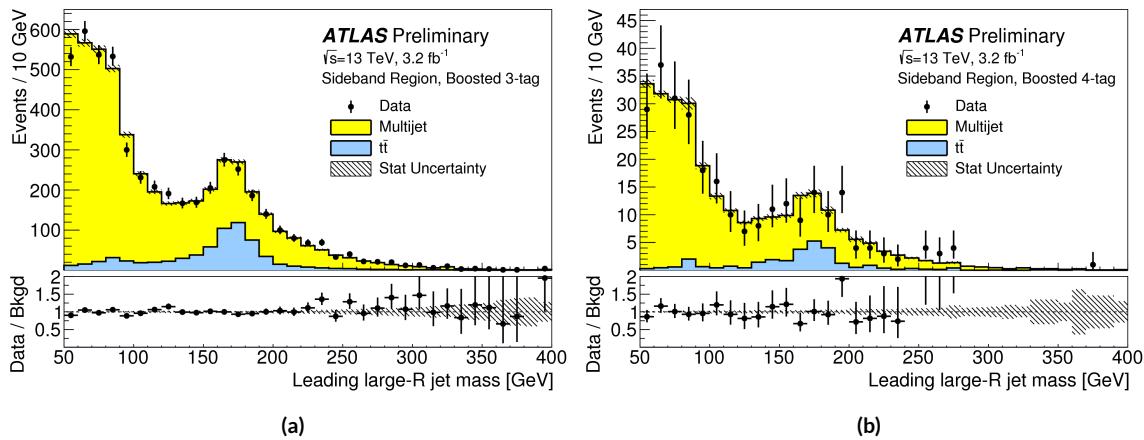


Figure 7.12: Leading large-R jet mass in the $3b$ (a) and $4b$ (b) sideband regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above. Because their normalizations are derived in the sideband region, the total background normalization is constrained by default to match the normalization of the data [102].

2401 7.6.3 BACKGROUND SHAPE FIT

2402 As mentioned in the previous section, the background shape in the 3-tag and 4-tag signal regions is taken
 2403 from the 2-tag signal mass region. Due to the limited statistics available, the background shapes are ad-
 2404 ditionally smoothed after being extrapolated to the 3-tag and 4-tag signal regions. Only the data in the
 2405 range $900 < M_{2J} < 2000$ GeV is included in the fit due to the limited statistics available above 2 TeV.
 2406 Both the $t\bar{t}$ and QCD multijet background are independently fit with an exponential shape, $y = e^{ax+b}$.
 2407 Other shapes are considered and used for the systematic uncertainties. Table 7.4 shows the fit values for
 2408 the parameters. Because both the $3b$ and $4b$ QCD shapes come from the 2-tag region, the slopes derived
 2409 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 [103]

2410 7.6.4 VALIDATION OF BACKGROUND ESTIMATE

2411 The background estimate can be validated by using the method to estimate the number of events in the
 2412 control mass region rather than the signal mass region. Figure 7.13 shows the M_{2J} distribution in the $3b$
 2413 and $4b$ control regions, comparing data and background estimates. In both cases, both the background
 2414 shape and normalization are consistent with the data, indicating good agreement. The ratio of data to
 2415 the background estimates is also fit to a line in the figure to test for any shape difference. The slope of the
 2416 line is within 1σ (from the fit uncertainties) of flat, further indicating that the data is consistent with the
 2417 background estimate in the control region.

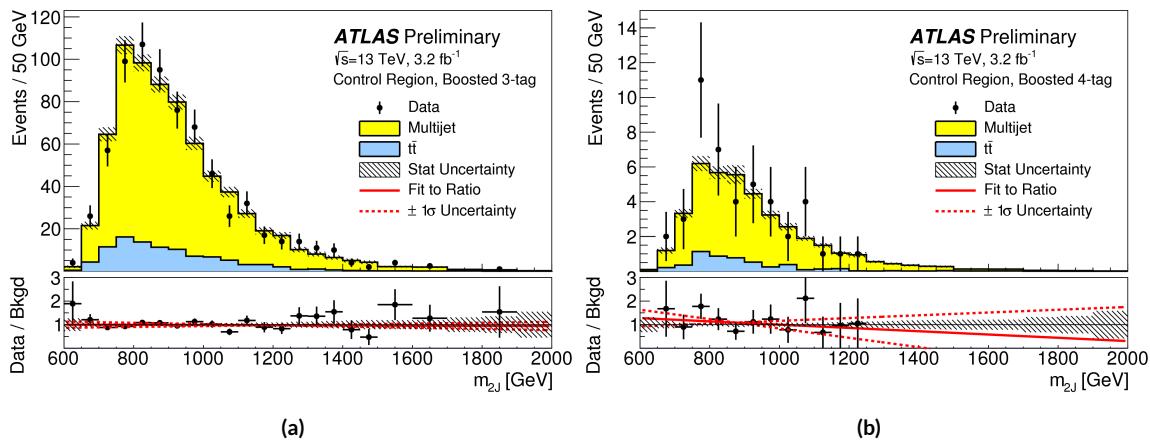


Figure 7.13: Di-jet invariant mass (M_{2J}) in the $3b$ (a) and $4b$ (b) control regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above [102].

2418 Table 7.5 shows the yields in data and background estimates in the 3-tag and 4-tag sideband and con-
 2419 trol regions. Again, here, it can be seen that the total number of predicted background events from the
 2420 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. [102]

2421 7.7 SYSTEMATIC UNCERTAINTIES

2422 The systematic uncertainties in this analysis can be divided into two broad categories. The first type is
 2423 uncertainties associated with the modeling of the signal processes. The second type of uncertainty is
 2424 associated with both the shape and normalization of the background prediction.

2425 7.7.1 SIGNAL MODELING UNCERTAINTIES

2426 The signal modeling uncertainty has three main components: theoretical uncertainty on the acceptance,
 2427 experimental uncertainties on the large-R jets, and experimental uncertainties on the track jets related to
 2428 b -tagging. In this analysis the experimental uncertainties are the most significant.

2429 The first uncertainty on signal modeling is the theoretical uncertainty on the acceptance. As explained
 2430 in section 5.6.1, there are four components to this uncertainty. The first is related to missing higher order
 2431 terms from the matrix element calculations which is estimated by varying the QCD renormalization and
 2432 factorization scales. The second is uncertainty due to the PDF set used. The third is a generator uncer-
 2433 tainty which is estimated by modifying the generator used to model the underlying event and hadroniza-

2434 tion. Finally, there is an uncertainty associated with the modeling of the initial state and final state radia-
2435 tion (ISR/FSR). The total theoretical uncertainty on the signal yield is 3%, and this is dominated by the
2436 ISR/FSR modeling.

2437 There are uncertainties on the large-R jets in both the jet energy scale (JES) and jet energy resolution
2438 (JER) as well as the jet mass scale (JMS) and jet mass resolution (JMR). These are evaluated using $\sqrt{s} =$
2439 8 TeV data from Run 1 of ATLAS and extrapolated to the Run 2 beam and detector conditions using
2440 MC[¶]. The details of these uncertainties can be found in reference [104].

2441 Uncertainties on the track jets are related to the b -tagging efficiency. The total uncertainty on the sig-
2442 nal yield due to b -tagging is evaluated by propagating variations of the b -tagging efficiency through the
2443 boosted selection requirements. The uncertainties are calculated jet-by-jet and parameterized as a func-
2444 tion of b -jet p_T and η [105]. For high p_T b -jets (with $p_T > 300$ GeV), the uncertainties are extrapolated
2445 using MC simulation from the lower p_T b -jets [106].

2446 Table 7.6 shows the systematic uncertainties on the signal normalization for models with $m_{G_{KK}^*} =$
2447 1.5 TeV and both $c = 1$ and $c = 2$ as well as a narrow width heavy scalar. The dominant uncertainty
2448 comes from b -tagging and this uncertainty is larger in the 4-tag region than the 3-tag region.

2449 7.7.2 BACKGROUND UNCERTAINTIES

2450 Uncertainties on the QCD multijet background normalization and shape are estimated using the control
2451 mass region. As shown previously, the background predictions in the control region match with the
2452 data yields within the statistical uncertainty in both the 3-tag and 4-tag control regions. As an additional
2453 protection, the statistical uncertainty on the background prediction in the control region is assigned as a
2454 systematic uncertainty on the normalization of the QCD background.

2455 Additional robustness tests are done by varying the definition of the control mass region and the b -
2456 tagging requirements used to define the 2-tag sample. In all cases, the effect of the variations is found to
2457 be within the statistical uncertainties on the background normalization in the control region.

2458 Shape uncertainties on the background are evaluated using two techniques. First, as shown in fig-

[¶]The uncertainties are correspondingly larger due to the uncertainty of this extrapolation.

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.

ure 7.13, the ratio between the data and background prediction is fit with a linear function. The uncertainties on the slope of this fit are assigned as shape uncertainties. An additional uncertainty is assigned by using alternate power law fit functions for the smoothing of the background shape. Table 7.7 shows the alternate shapes used. The largest difference between the nominal fit function and the alternates, taking into account the 1σ uncertainty band on each fit as well, is taken as a shape uncertainty.

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

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_{JJ} distribution in the QCD multijet background. In the equations, $x = M_{JJ}/\sqrt{s}$.

²⁴⁶⁶ the background uncertainties in the 3-tag and 4-tag regions.

²⁴⁶⁷ 7.8 RESULTS

²⁴⁶⁸ Table 7.8 shows the observed yields in the 3-tag and 4-tag signal regions for the boosted analysis com-
²⁴⁶⁹ pared to the predicted number of background events. In the 3-tag region, 316 events are observed with
²⁴⁷⁰ a predicted background of 285 ± 19 . In the 4-tag region, 20 events are observed with a predicted back-
²⁴⁷¹ground of 14.6 ± 2.4 . Figure 7.14 shows the M_{JJ} distribution in the 3-tag and 4-tag regions. There are
²⁴⁷² some small excesses in the data, in particular in the 3-tag region around $M_{JJ} \approx 900$ GeV and in the
²⁴⁷³ region of $1.6 < M_{JJ} < 2.0$ TeV. The significance of these excesses will be evaluated in the next chapter
²⁴⁷⁴ in the 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
$G_{\text{KK}}^*(1000 \text{ GeV}), c = 1$	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 $m_{G_{\text{KK}}^*} = 1 \text{ TeV}$ and $c = 1$ are also shown. [102]

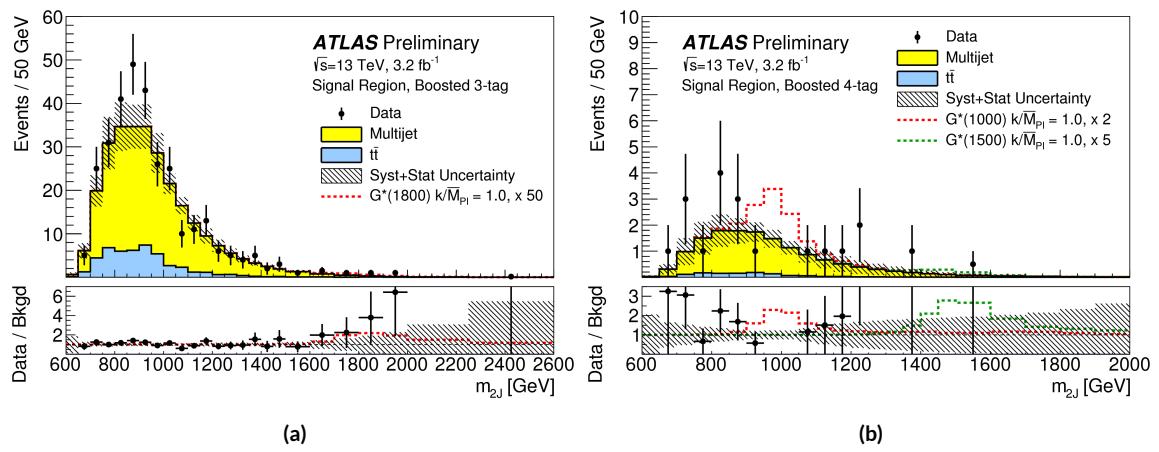


Figure 7.14: Di-jet invariant mass (M_{2J}) in the $3b$ (a) and $4b$ (b) signal regions. The multijet and $t\bar{t}$ backgrounds are estimated using the data-driven methods described above. In the $3b$ region, a graviton signal with $m_{G_{\text{KK}}^*} = 1.8 \text{ TeV}$ and $c = 1$ is overlaid, with 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 [102].

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

Frank Herbert

8

2475

2476

Combined limits from boosted and resolved searches

2477

2478

8.1 INTRODUCTION

2479 In order to cover the full mass range of possible resonances decaying to di-Higgs final states, two distinct
2480 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 $1100 < m_X <$
2481 3000 GeV. Chapter 7 presents the details of the boosted selection and results. In setting limits on spin-2
2482 Randall-Sundrum graviton (RSG) and narrow width heavy scalar (H) models, the results of the boosted
2483 selection are combined with the results of the resolved selection to cover the full mass range.
2484

2485 This chapter presents limits on signal models resulting from the $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ search in both
2486 the resolved and boosted selections. It first presents a brief overview of the resolved results that go into

2487 the limit setting. Then, an overview of the statistical methods used for the search and limit setting is
2488 given. Finally, limits on the RSG and heavy scalar models are presented.

2489 **8.2 RESOLVED RESULTS**

2490 The details of the resolved selection will not be presented here and can be found in reference [102]. In
2491 basic terms, the selection searches for four $R = 0.4$ b-tagged calorimeter jets (where each pair of jets is
2492 one Higgs candidate). This is distinct from the boosted methodology which searches for merged decay
2493 products. The backgrounds to the resolved selection are the same as those presented in Chapter 7 for the
2494 boosted analysis.

2495 Table 8.1 shows the results for data yields and expected background in the resolved signal region. Fig-
2496 ure 8.1 shows the M_{2J} distribution in the resolved signal region. The total number of events is consis-
2497 tent with the prediction and no significant excess is seen. One event in the boosted 4-tag signal is shared
2498 with 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 $m_{G_{\text{KK}}^*} = 800 \text{ GeV}$ and $c = 1$ are also shown. [102]

2499 **8.3 SEARCH TECHNIQUE AND RESULTS**

2500 The statistical technique used for the search in this analysis is the same as that used in the $H \rightarrow WW^*$
2501 analysis presented in section 3.6.2. The test statistic q_0 is used to define the p -values which measure the

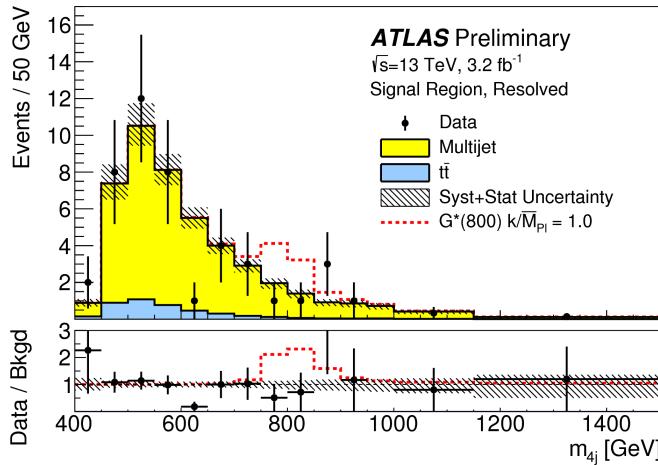


Figure 8.1: Di-jet invariant mass (M_{2J}) in the resolved signal region. A graviton signal with $m_{G_{KK}^*} = 800$ GeV and $c = 1$ is overlaid. [102].

2502 compatibility of the data with the background-only hypothesis corresponding to a signal strength $\mu =$
 2503 0.

2504 Local p_0 values are computed to quantify the probability that the background could produce a fluc-
 2505 tuation greater than or equal to the one observed in the data. In the resolved analysis, no significant ex-
 2506 cesses are observed. The largest discrepancy with respect to the background only hypothesis occurs near
 2507 a resonance mass of 900 GeV and is found to be less than 2σ in significance.

2508 In the boosted selection, the largest local excess is a broad excess in the $3b$ signal region that begins
 2509 near $M_{2J} \approx 1.7$ GeV. Assuming a G_{KK}^* with this mass and $c = 1.0$, the local significance of this excess
 2510 is 2.0σ .

2511 8.4 LIMIT SETTING

2512 In the absence of any significant excess observed in the data, limits on different signal models can be set.
 2513 This section describes the limit setting procedure and presents combined results of the resolved and
 2514 boosted analyses.

2515 8.4.1 LIMIT SETTING PROCEDURE

2516 The procedure used for setting exclusion limits in this analysis is the CL_s method [107]. The first step in
 2517 setting the limits is to define a test statistic which will be used. For limit setting, the test statistic is shown
 2518 in equation 8.1.

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

2519 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
 2520 best fit value of the nuisance parameters, $\hat{\theta}$ is the best fit value of the nuisance parameters under the fixed
 2521 μ value, and L is the Poisson likelihood of the data (as described in section 3.6.2).

2522 The test statistic \widetilde{q}_μ is constructed to protect against two interesting corner cases when setting the
 2523 upper limit on the cross section. First, it protects against negative signal strengths μ which are unphys-
 2524 ical. Second, it does not count excesses in the data larger than those expected by a signal strength μ as
 2525 evidence against the μ hypothesis.

2526 The CL_s statistic is constructed by taking a ratio of two probabilities. CL_{s+b} is the probability that
 2527 the signal+background hypothesis would produce a value of the test statistic that is less than or equal
 2528 to the observed value*. CL_b is the probability that the background only hypothesis will pro-
 2529 duce a value of the test statistics less than or equal to the observed. The CL_s statistic is then the ratio
 2530 $\text{CL}_{s+b}/\text{CL}_b$. A 95% upper limit on the cross section is set at the value of μ that makes the CL_s statistic
 2531 less than 5%.

2532 In practice, the limits are computed numerically within an asymptotic approximation for the distri-
 2533 bution of the test statistic \widetilde{q}_μ . The details of this approximation can be found in reference [63].

2534 The resolved and boosted analyses are combined using a very simple procedure rather than a full sta-
 2535 tistical combination. For each mass point tested, the limit which gives the most stringent constraint is
 2536 used. This means that for mass points below 1.1 TeV the resolved signal region is used, while at and

*Lower values of \widetilde{q}_μ mean better compatibility

2537 above this point the combination of the orthogonal $3b$ and $4b$ boosted signal regions is used.

2538 **8.4.2 LIMIT SETTING RESULTS**

2539 Figure 8.2 shows the combined 95% upper bounds as a function of mass for three different models:

2540 G_{KK}^* with $c = 1$, G_{KK}^* with $c = 2$, and a narrow heavy scalar H .

2541 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
2542 for masses in the range $600 < m_{G_{\text{KK}}^*} < 3000$ GeV. For the RSG model with $c = 2$, cross sections
2543 limits between 40 fb and 200 fb are set for the mass range of $500 < m_{G_{\text{KK}}^*} < 3000$ GeV. Masses in
2544 the range of $475 < m_{G_{\text{KK}}^*} < 785$ GeV are excluded with $c = 1$ (with an exclusion of the range 465
2545 to 745 GeV expected). Masses less than 980 GeV are excluded with $c = 2$ (with an exclusion for masses
2546 less than 1 TeV expected).

2547 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
2548 30 to 300 fb in the mass range of $500 < m_H < 3000$ GeV. The resolved analysis can also set an upper
2549 limit on the Standard Model di-Higgs production cross section discussed in chapter 3. The upper limit
2550 on $\sigma(pp \rightarrow hh \rightarrow b\bar{b}b\bar{b})$ in the Standard Model is constrained to be less than 1.22 pb.

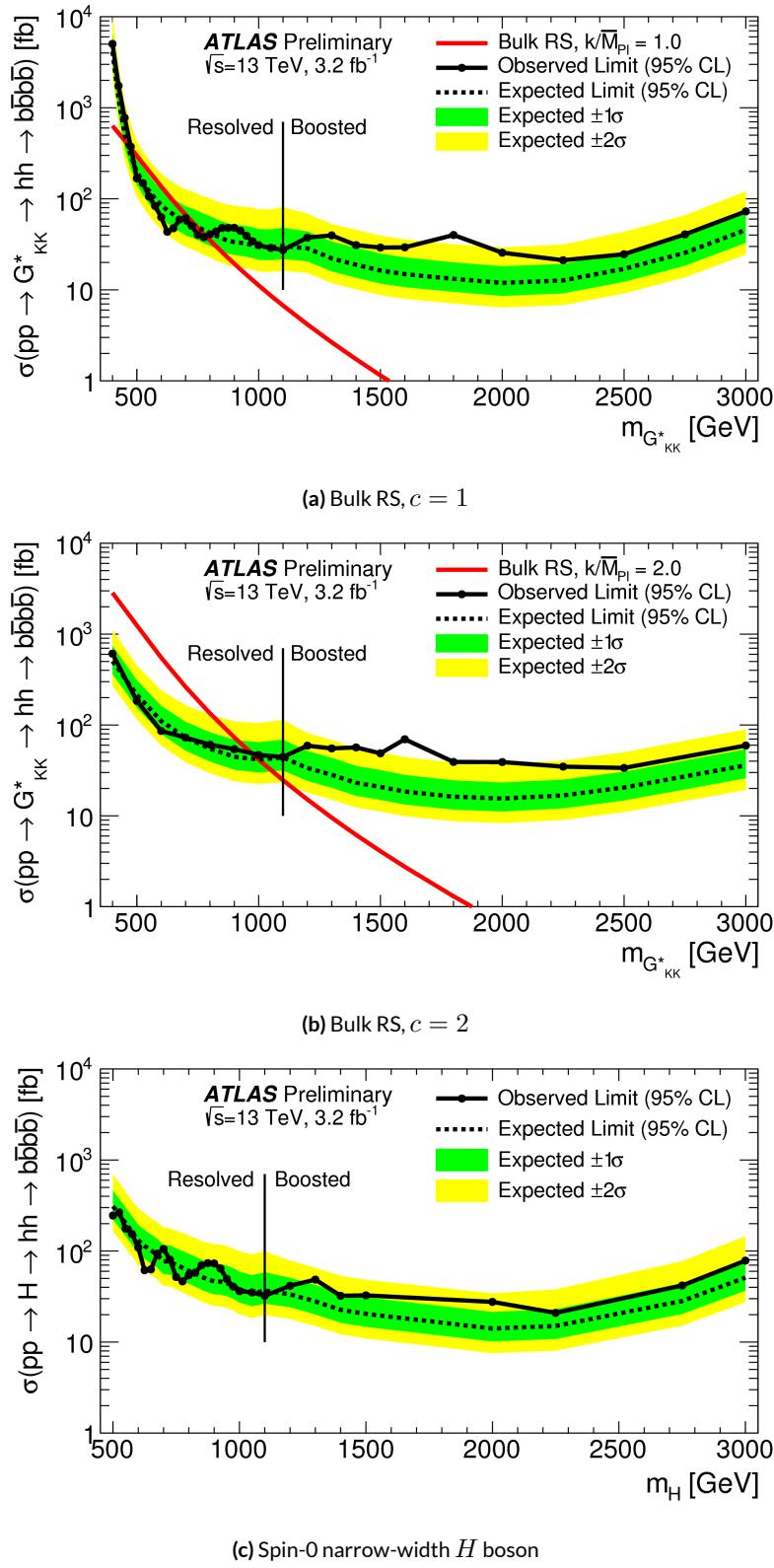


Figure 8.2: Expected and observed upper limit as a function of mass for G_{KK}^* in the RSG model with (a) $c = 1$ and (b) $c = 2$, as well as (c) H with fixed $\Gamma_H = 1$ GeV, at the 95% confidence level in the CL_s method. [102]

2551

Part IV

2552

Looking ahead

9

2553

Conclusion

2554

2555 This dissertation presented two distinct studies: the observation and measurement of the Higgs boson
2556 in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV and a search for Higgs pair
2557 production in the $HH \rightarrow b\bar{b}b\bar{b}$ channel at $\sqrt{s} = 13$ TeV with the ATLAS detector in pp collisions at
2558 the Large Hadron Collider.

2559 In the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, results from both the discovery of the Higgs boson and the full
2560 ATLAS Run 1 dataset were presented. With the full 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV and 4.2 fb^{-1} at $\sqrt{s} =$
2561 7 TeV, ATLAS achieved discovery level significance in the $H \rightarrow WW^*$ channel alone and obtained
2562 the first observation of vector boson fusion production in that channel. The combined signal strength
2563 is measured to be $\mu = 1.09^{+0.23}_{-0.21}$. The total observed significance of the $H \rightarrow WW^*$ process is ob-
2564 served to be 6.1σ (with 5.8σ expected). Advanced methods for background reduction and estimation,
2565 particularly in same-flavor lepton final states, are shown. The VBF signal strength is measured to be
2566 $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$ with an observed significance of 3.2σ (with 2.7σ expected).

2567 These results required many novel innovations. The increase of pileup interactions in the higher in-
2568 stantaneous luminosity LHC conditions of 2012 led to a degradation of missing transverse momentum
2569 resolution. As a result, the prominent Z/γ^* +jets background of the same flavor $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
2570 final states increased greatly. New variables, including a track-based missing transverse momentum and
2571 a measurement of the balance between the dilepton system and recoiling jets, allowed for significant re-
2572 duction of this background. In the VBF channel, selections were optimized to exploit the unique VBF
2573 final state topology. Incorporating these variables into a boosted decision tree technique allowed the
2574 analysis to exceed the 3σ observation threshold.

2575 At $\sqrt{s} = 13$ TeV, a search for Higgs pair production in the $b\bar{b}b\bar{b}$ final state with 3.2 fb^{-1} was con-
2576 ducted. A signal region optimized for the boosted final states arising from high mass resonances was
2577 constructed. This signal region utilized large-radius calorimeter jets and b -tagging with small radius track
2578 jets to maximize the signal acceptance. No significant excesses were observed, and upper limits on cross
2579 sections are placed for spin-2 Randall Sundrum gravitons (RSG) and narrow spin-0 resonances. The
2580 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
2581 masses in the range $600 < m_{G_{KK}^*} < 3000 \text{ GeV}$. For the RSG model with $k/\bar{M}_{\text{Pl}} = 2$, cross sections
2582 limits between 40 fb and 200 fb are set for the mass range of $500 < m_{G_{KK}^*} < 3000 \text{ GeV}$. The cross
2583 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
2584 $500 < m_H < 3000 \text{ GeV}$.

A

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2587

Optimization of b -tagging working point in $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ search

2588 To the $3b$ and $4b$ signal regions in the boosted $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ search, the MV₂ algorithm with a
2589 20% fraction of charm events in training is used (MV_{2c20}). Once the algorithm is selected, an efficiency
2590 working point must also be chosen. This working point defines the efficiency with which true b -jets
2591 are tagged and also fixes the overall background rejection of the algorithm. Higher efficiency working
2592 points accept more true b -jets but also allow for more background. Five different working points (70%,
2593 77%, 80%, 85%, 90%) are tested. With each working point, the full data driven background estimation
2594 method is run to quantify the amount of background that will be present in the final signal region. The
2595 significance is quantified using the median discovery significance for signal and background with Poisson

2596 errors, given in equation A.1 [108].

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

2597 Note that in the limit where s is much smaller than b , this equation reduces to the more well known
 2598 s/\sqrt{b} .

2599 Figure A.1 shows the estimated significance as a function of signal mass in RSG $c = 1$ models for
 2600 the $3b$ and $4b$ signal regions. The 77% working point gives the best performance over a wide range of
 2601 masses in the $4b$ signal region. As this is the region which contributes the most to the total discovery
 2602 significance, the 77% efficiency working point is chosen for the analysis.

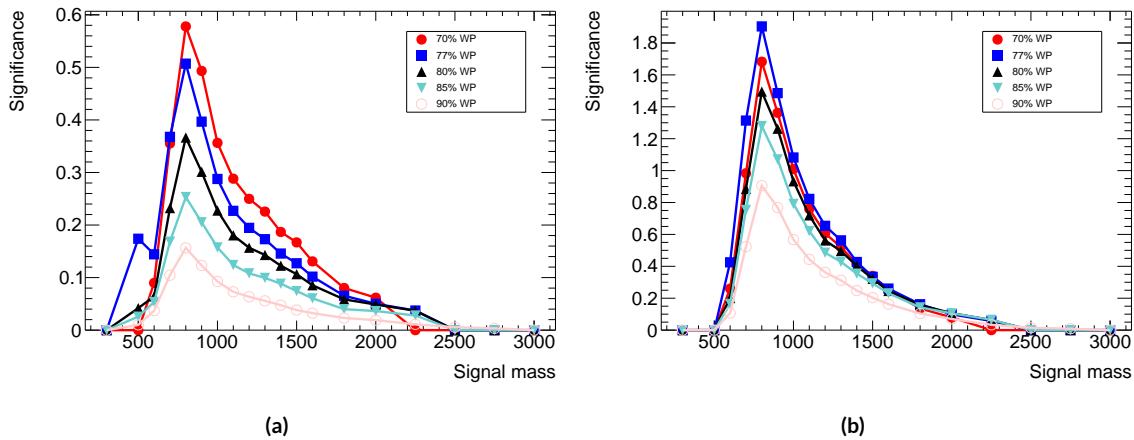


Figure A.1: Estimated significance as a function of signal mass for RSG $c = 1$ models in the $3b$ (a) and $4b$ (b) regions for different b -tagging efficiency working points

B

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b-tagging performance at high p_T

2605 One of the limiting factors of the signal acceptance in the *FourB full* search at high resonance masses is
2606 the degradation of the *b*-tagging efficiency for high p_T jets. This appendix presents a study of the under-
2607 lying causes of this degradation.

2608 B.I MV₂ ALGORITHM OVERVIEW

2609 The MV₂ algorithm is a boosted decision tree incorporating twenty-four input variables constructed
2610 from three lower level input algorithms: IPxD, SVI, and JetFitter. IPxD uses the two and three dimen-
2611 sional impact parameter information of tracks in the jet to construct templates for light, charm, and bot-
2612 tom quarks and compute likelihood ratios. SVI is a secondary vertex reconstruction algorithm. JetFitter
2613 attempts to fit to the full decay chain of the *B* hadron, looking for multiple decay vertices aligned along a
2614 single axis. Figure B.1 summarizes the inputs to MV₂.

IP2D and IP3D (6 inputs)	SV1 (8 inputs)	JetFitter (8 inputs)
$\log(p_b/p_u)$	Mass	Mass
$\log(p_b/p_c)$	Energy fraction	Energy fraction
$\log(p_c/p_u)$	# tracks at vertex	# vertices
	# 2 track vertices	# tracks at vertex
	Lxy	# 1 track vertices
	L3d	# 2 track vertices
	3D significance	3D significance
	ΔR	ΔR
Kinematics (2 inputs)		
	p_T	
	η	

Figure B.1: Summary of the inputs to the MV2 b -tagging algorithm

2615 **B.2 CHANGES IN MV2 SCORE AT HIGH p_T**

2616 The degradation of b -tagging at high p_T was studied in particular in the context of RSG models at high
 2617 mass. Figure B.2 shows the p_T of the leading track jet inside of the leading calorimeter jet in RSG events.
 2618 At high $m_{G_K^*}$, the p_T spectrum of track jets is much harder than at lower masses due to the increased
 2619 Higgs p_T .

2620 Figure B.3 shows the MV2c2o algorithm score for the leading and subleading track jets inside of the
 2621 leading calorimeter jet. In both cases, it can be seen that at higher RSG masses the MV2 score shifts to-
 2622 wards more background like (negative) values. Additionally, this effect is more pronounced in the lead-
 2623 ing track jet than the subleading.

2624 To understand what is causing this change in the MV2c2o score, the same comparisons can be made
 2625 for the input variables of MV2c2o. The focus in these comparisons will be on the leading track jet as
 2626 this is the one seen to have the largest difference in MV2 score. Figure B.4 shows the log likelihood ratio
 2627 $\log(p_b/p_u)$ from the IP3D (three dimensional impact parameter) algorithm. At higher masses, the IP3D
 2628 likelihood ratio distribution does become more background-like.

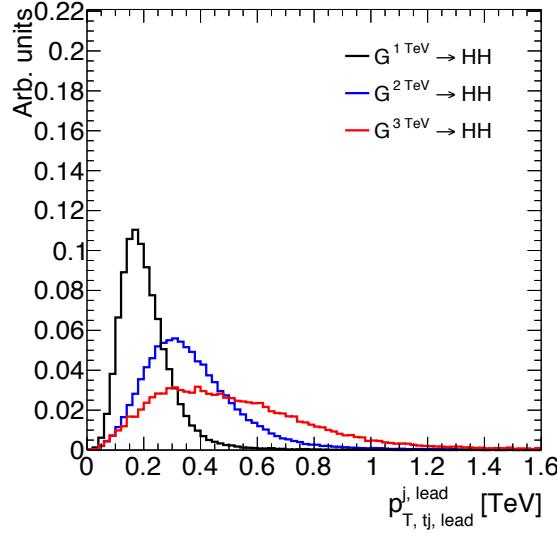


Figure B.2: p_T of the leading track jet in the leading calorimeter jet for different signal masses in RSG $c = 1$ models

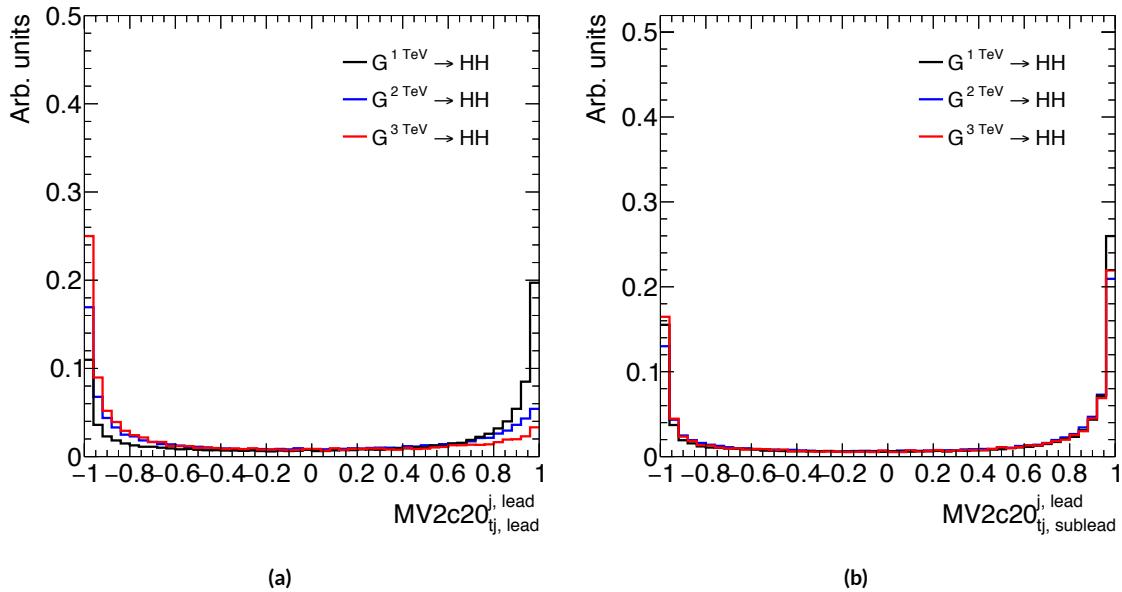


Figure B.3: MV2c20 score for the leading track jet (a) and subleading track jet (b) of the leading calorimeter jet for different signal masses in RSG $c = 1$ models

2629 Figure B.5 shows the mass and number of tracks at the secondary vertex computed by the SV1 algo-
 2630 rithm. When there is no secondary vertex found, the algorithm assigns a default negative value for these
 2631 quantities. Both of these distributions show that there is a significantly larger fraction of jets where no
 2632 secondary vertex is found in the high mass samples compared to the $m_{G_{KK}^*} = 1$ TeV sample. The SV1

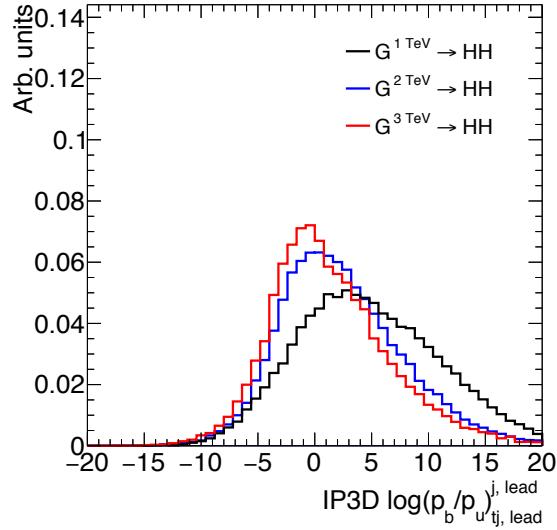


Figure B.4: IP3D log-likehood ratio ($\log(p_b/p_u)$) of the leading track jet in the leading calorimeter jet for different signal masses in RSG $c = 1$ models

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.

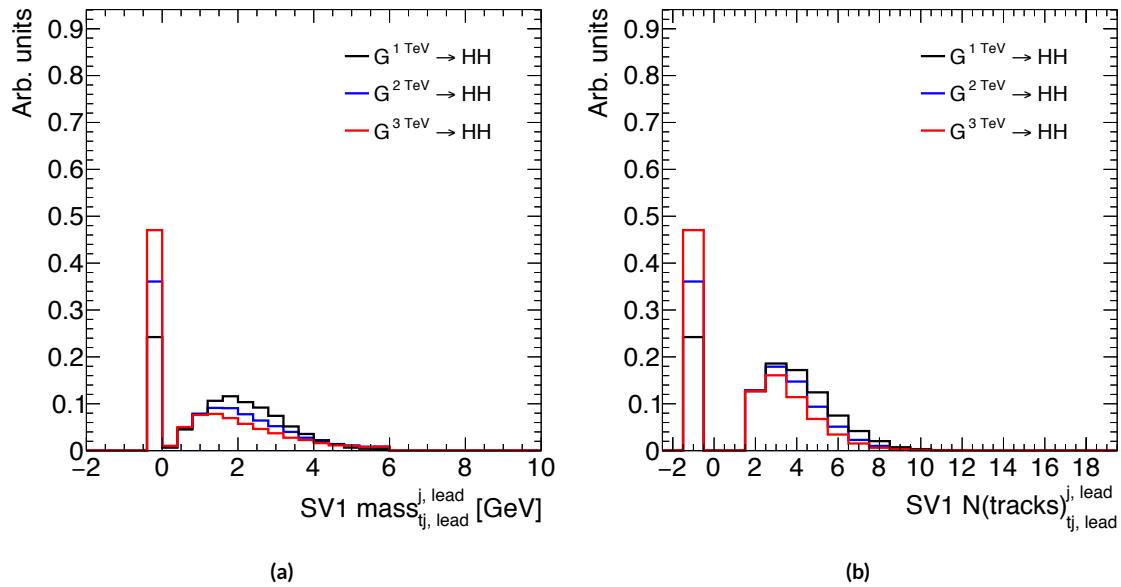


Figure B.5: Mass (a) and number of tracks (b) for the secondary vertices computed with the SV1 algorithm. When no secondary vertex is found, the quantites are assigned to default negative values.

2636 Figure B.6 shows the same quantities for the JetFitter algorithm. In this case, there is also a change in
 2637 the fraction of jets which have their secondary vertices successfully reconstructed, but this change is not
 2638 as drastic as that seen in SVI. There is also an increase in the number of jets which have high values of
 2639 mass.

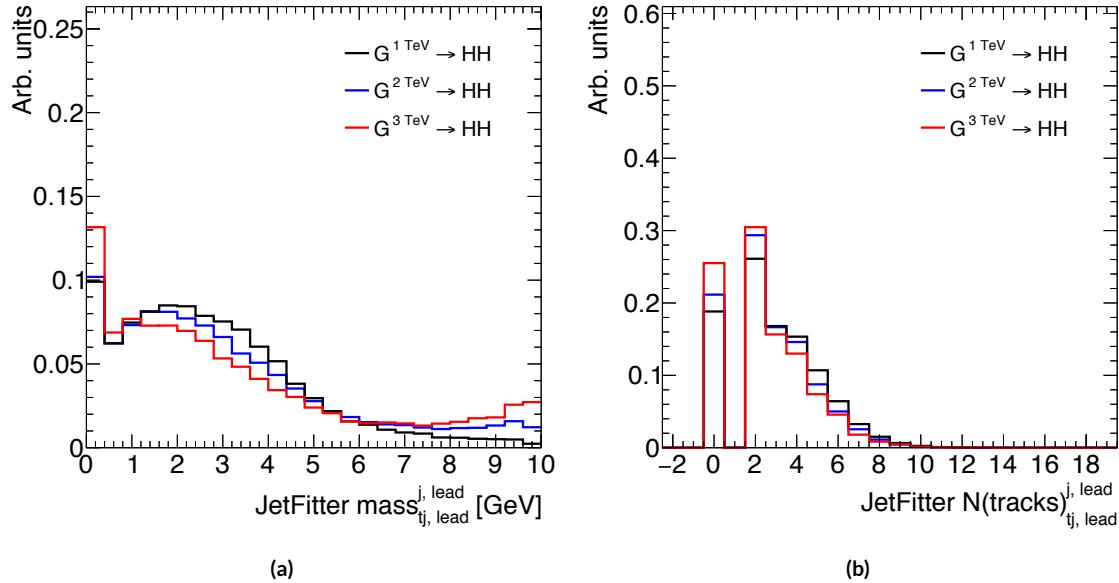


Figure B.6: Mass (a) and number of tracks (b) for vertices computed with the JetFitter algorithm. When no vertices are found, the quantities are assigned to default negative values.

2640 B.3 TAGGING EFFICIENCY BY INDIVIDUAL JET

2641 In the last section, the largest changes in MV₂ score were seen for the leading track jet inside the leading
 2642 calorimeter jet. To confirm that the overall 4*b* tagging efficiency is indeed degrading because of degra-
 2643 dation of the leading track jet efficiency, the tagging efficiency for each individual jet as a function of mass
 2644 can be compared. This is shown in figure B.7. The figure shows that the leading jet tagging efficiency
 2645 in both calorimeter jets degrades heavily, while the sub-lead jet tagging efficiency remains relatively con-
 2646 stant.

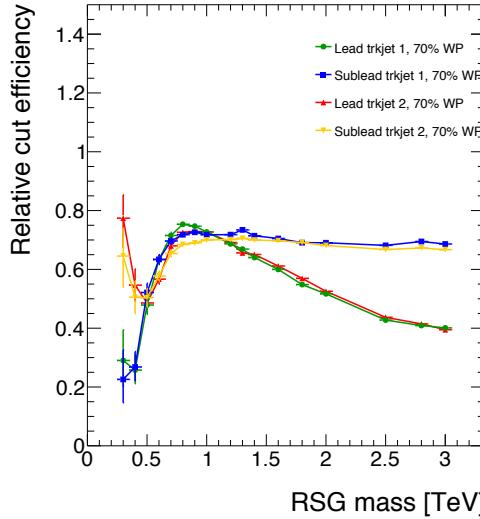


Figure B.7: MV2c20 b -tagging efficiency for each of the four track jets in the boosted $4b$ selection as a function of RSG mass for $c = 1$ models.

2647 **B.4 EFFECT OF MULTIPLE b -QUARKS INSIDE ONE JET**

2648 One hypothesis for why the efficiency of b -tagging the leading track jet degrades is that at high masses,
 2649 the b quarks get close enough together that both of them are inside of the leading track jet. Because MV2
 2650 is not tuned for tagging multiple b quarks inside one jet, the tagging efficiency could degrade. Figure B.8
 2651 shows MV2 scores and SV1 mass for cases where there are two b quarks at truth level within the radius
 2652 of the leading track jet compared to cases where there is only one true b^* . This figure suggests that the
 2653 presence of two b -quarks inside the leading jet is not the cause of the degradation in efficiency. There is a
 2654 change in the shape of the MV2 score distribution, but it is not nearly as pronounced as that seen in B.3
 2655 at higher masses. Additionally, the fraction of jets with no secondary vertex found is nearly identical in
 2656 the track jets with two truth b -quarks.

*When 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.

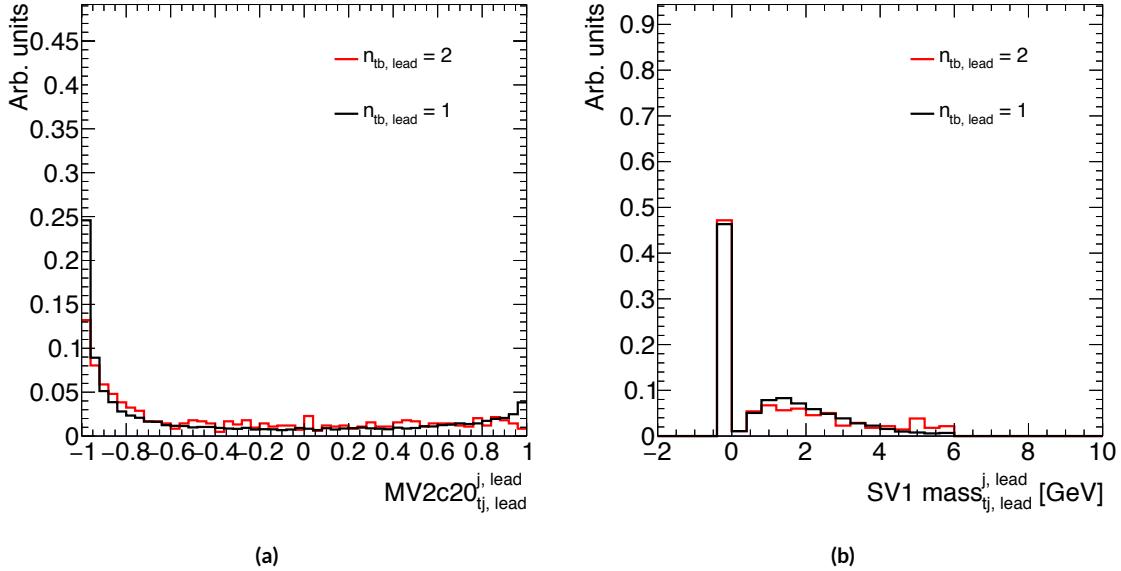


Figure B.8: MV2c20 score (a) and SV1 mass (b) for leading track jets with two truth b quarks ($n_{tb,\text{lead}} = 2$) compared to those with only one truth b ($n_{tb,\text{lead}} = 1$).

2657 B.5 CHANGES IN TRACK QUALITY AT HIGH p_T

2658 Another hypothesis for the degradation of the b -tagging efficiency is a decrease in track quality for high
 2659 p_T b jets. One way to check the overall quality of the tracking inside the jet is to investigate quantities
 2660 related to the leading track inside of the track jet. Figure B.9 shows the fit χ^2/n_{DOF} and number of hits
 2661 in the pixel detector for the leading track of the leading track jet. In both cases, the figure shows that in
 2662 higher mass samples, the quality of the leading track inside of the track jet degrades substantially. The
 2663 fit quality is lessened and the tracks have less hits in the pixel detector. This is likely due to the fact that
 2664 at higher p_T , the B -hadron will sometimes live long enough to miss the IBL and first pixel layer, thus
 2665 decreasing the number of hits on the track.

2666 To check whether this is the cause for the shift in the MV2 score and the higher difficulty in recon-
 2667 structing secondary vertices, jets whose leading track have at least four pixel hits are compared with those
 2668 whose tracks have less than four pixel hits. The results for the MV2 score and SV1 mass are shown in fig-
 2669 ure B.10. Track jets where the leading track does not have at least four pixel hits are more likely to not
 2670 have a secondary vertex reconstructed. Additionally, their MV2c20 score is shifted more significantly to

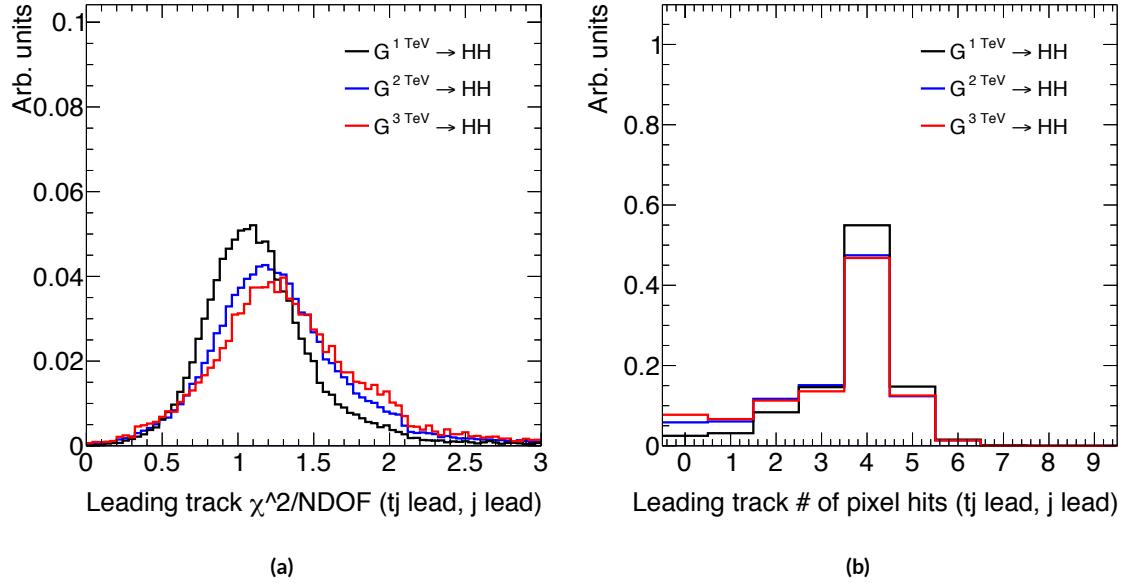


Figure B.9: Track fit χ^2/n_{DOF} (a) and number of pixel detector hits (b) for the leading track of the leading track jet in different mass RSG $c = 1$ samples

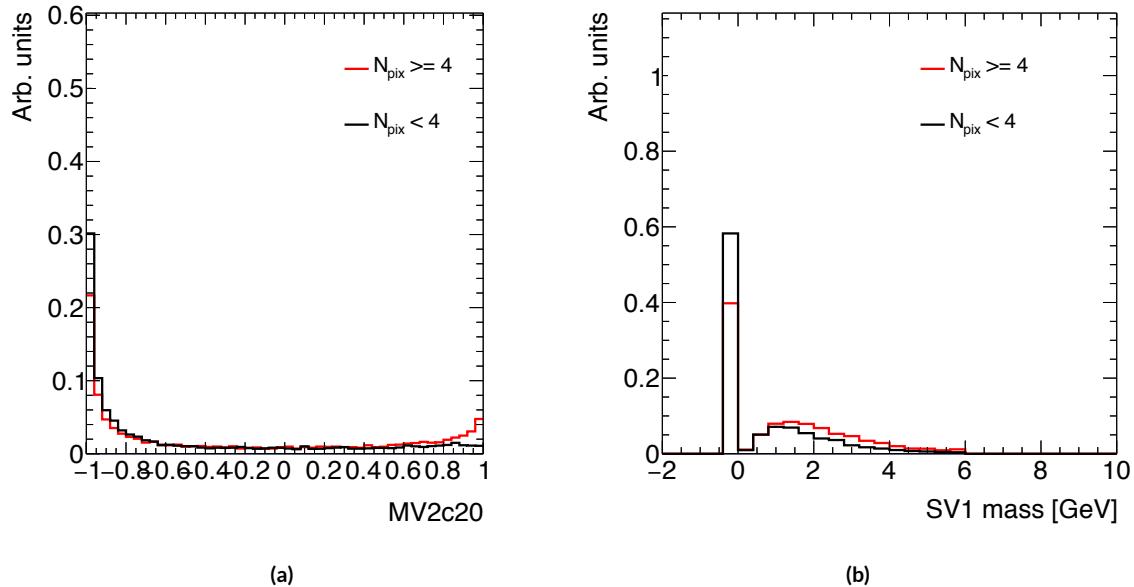


Figure B.10: MV2c20 score (a) and SV1 mass (b) for leading track jets whose leading track jet has at least four pixel hits ($N_{\text{pix}} \geq 4$) compared to those which do not ($N_{\text{pix}} < 4$).

²⁶⁷¹ background-like values. This seems to confirm the hypothesis that degrading track quality is responsible
²⁶⁷² for the lowered b -tagging efficiency at high p_{T} .

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