

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

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

<sup>23</sup> ABSTRACT

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

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

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

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# 0

507

508

## Introduction

509 The Higgs boson is often described as one of the cornerstones of particle physics. When the Standard  
510 Model was first developed as a theory to describe the fundamental particles and forces of nature, physicists  
511 were faced with a dilemma. The electroweak theory beautifully characterized both electromagnetism and  
512 the weak force with a single underlying framework. However, the mass of the weak  $W$  and  $Z$  bosons  
513 was puzzling given the fact that their electromagnetic counterpart, the photon, is massless. The Higgs  
514 mechanism was developed as the leading theory for the origin of this electroweak symmetry breaking. It  
515 predicted the existence of an additional spin-0 boson in the Standard Model, the Higgs boson. Generations  
516 of collider experiments searched for this elusive particle. This dissertation presents research work on the  
517 Higgs boson from its discovery to its use as a tool in the search for physics beyond the Standard Model  
518 with the ATLAS detector at the Large Hadron Collider (LHC).

519 One of the first priorities for the LHC when it began colliding proton beams in 2010 was the search  
520 for the Higgs boson. This search was initially tackled in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel, followed by

521 the  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4\ell$  channels. Each channel has its own merits, but the  $WW^*$  mode is  
522 particularly suited to searching over a wide range of masses. The  $H \rightarrow WW^*$  branching ratio is large and it  
523 is the primary decay channel above the  $2m_W$  mass threshold. Despite the fact that the full Higgs invariant  
524 mass cannot be reconstructed in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel, its signal to background ratio makes  
525 it ideal for measurement of Higgs properties such as the production cross section and couplings.

526 In 2012, the ATLAS and CMS experiments announced the discovery of a new particle consistent with  
527 the Higgs boson [1, 2]. In ATLAS, this discovery was made with  $4.8 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 7 \text{ TeV}$   
528 and  $5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . This dissertation first presents the search for gluon fusion production  
529 of the Higgs in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel, which played an important role in this discovery.  
530 Selection requirements which were optimized to maximize the discovery significance in this channel, as  
531 well as background estimation procedures, are discussed.

532 After its discovery, interest in the Higgs shifted to focus on the measurement of its properties. As a result,  
533 extensions of the initial discovery analysis in larger datasets had two main goals. Improvement of signal to  
534 background ratio was important to allow for precision measurements. Also, searches for rarer production  
535 modes of the Higgs were a priority. The first such extension presented in this dissertation is a tailored  
536 selection for  $\ell\nu\ell\nu$  final states with same flavor leptons. Novel variables for the reduction of the  $Z+\text{jets}$   
537 background that could remain robust under increasing LHC instantaneous luminosities are shown. The  
538 second post-discovery result shown is the first evidence of Vector Boson Fusion (VBF) production of the  
539 Higgs boson.

540 VBF production of the Higgs boson is particularly interesting in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  final state.  
541 In this combination of production and decay modes, the Higgs boson couples exclusively to  $W$  bosons,  
542 allowing for precise measurement of the Higgs- $W$  coupling constant. However, it is challenging to observe  
543 VBF Higgs production because its cross section at the LHC is an order of magnitude lower than gluon  
544 fusion production. The large  $H \rightarrow WW^*$  branching ratio thus presents another advantage over other  
545 final states. Additionally, VBF production of the Higgs boson creates two forward jets in addition to the  
546 Higgs, and these jets can be used to isolate VBF Higgs events from other production modes. The VBF  
547  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis first created a selection requirement based signal region using variables

548 constructed specifically for the VBF Higgs production topology. This “cut-based” analysis is presented  
549 in detail in this dissertation. These VBF topology variables, once validated in the cut-based analysis, were  
550 then input into a multivariate boosted decision tree discriminant to achieve the first evidence of VBF Higgs  
551 production with the full  $20.3 \text{ fb}^{-1}$  of  $\sqrt{s} = 8 \text{ TeV}$  data in ATLAS.

552 After a two year shutdown, the LHC restarted in 2015 with a center of mass energy of  $\sqrt{s} = 13 \text{ TeV}$ .  
553 This increase improved the LHC’s ability to probe for physics beyond the Standard Model, and the Higgs  
554 sector remained one of the largest regions of unprobed phase space where such new physics could be dis-  
555 covered. Production of high mass resonances benefited most from the center of mass energy increase. In  
556 particular, the cross section for a generic gluon-initiated 2 TeV resonance increased tenfold with the in-  
557 crease from 8 to 13 TeV. Therefore, a natural next step in studies of the Higgs was a search for a new  
558 heavy resonance which decays into a pair of Higgs bosons. The final result shown in this dissertation is  
559 a search for resonant di-Higgs production in the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  final state with  $3.2 \text{ fb}^{-1}$  recorded  
560 by ATLAS at  $\sqrt{s} = 13 \text{ TeV}$ . This search has the unique advantage that it can both probe new physics  
561 and gain further understanding of the Higgs potential through constraints on SM pair production of the  
562 Higgs. It also extends the previous ATLAS results at  $\sqrt{s} = 8 \text{ TeV}$  and probes higher mass resonances  
563 that were not previously accessible. Additionally, it is an informative precursor to di-Higgs analyses at the  
564 future High Luminosity LHC (HL-LHC), where a projected dataset of  $3000 \text{ fb}^{-1}$  at  $\sqrt{s} = 14 \text{ TeV}$  will  
565 begin to become sensitive to the SM Higgs self coupling.

566 As mentioned above, this dissertation begins by discussing the discovery of the Higgs and the role of  
567 the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel. It then presents the first evidence for the VBF production mode using  
568 the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel with the full ATLAS Run 1 dataset. It also shows the final combined  
569 Run 1 measurements of gluon fusion Higgs production from this channel. Finally, it presents a search for  
570 Higgs pair production in the  $HH \rightarrow b\bar{b}b\bar{b}$  channel. It is organized into four parts.

571 Part 1 presents the theoretical and experimental background required for the subsequent parts. Chap-  
572 ter 1 gives an overview of Higgs physics, particularly single and double Higgs production in the Standard  
573 Model and beyond. Chapter 2 presents details regarding the Large Hadron Collider and the ATLAS experi-  
574 ment. The evolution of machine conditions, descriptions of the ATLAS sub-detectors, and an overview of

object reconstruction in ATLAS are all shown. A brief interlude on the ATLAS Muon New Small Wheel upgrade is also given, as this upgrade has been a focus of my graduate work and will have an important impact on ATLAS' ability to study the Higgs at the High Luminosity LHC.

Part 2 discusses the observation and measurement of the Higgs in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel in the ATLAS Run 1 dataset at  $\sqrt{s} = 7$  and 8 TeV. Because I worked in this channel from before the discovery through to the final analysis of the Run 1 dataset, Part 2 is organized in such a way to allow easy presentation of multiple analyses on different subsets of the full Run 1 dataset. Chapter 3 presents a general overview of the  $H \rightarrow WW^*$  analysis strategy and defines many of the variables and common elements used in the rest of Part 2. Chapter 4 presents the discovery and subsequent measurements of the Higgs boson, focusing on the role of the  $WW^*$  channel in this discovery. Chapter 5 presents the first evidence for the VBF production mode of the Higgs, a result from the  $WW^*$  channel in the full Run 1 ATLAS dataset. In this chapter, the focus is mainly on the cut-based VBF analysis. The cut-based analysis was an important first step to the final VBF result which used a boosted decision tree. Where appropriate, connections between the cut-based and BDT analyses are shown and their compatibility is discussed. Finally, the VBF analysis was an important input into the combined Run 1  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  result, which used both the gluon fusion and VBF channels in a combined fit to infer properties of the Higgs, including its couplings to the gauge bosons and its production cross section. This is the topic of Chapter 6.

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

600

601

## The Physics of the Higgs Boson

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

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

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

613      The Standard Model consists of two primary categories of fundamental particles: fermions (spin 1/2  
 614      particles) and bosons (integer spin particles). The SM also describes three forces: electromagnetism, the  
 615      weak nuclear force, and the strong nuclear force. Gravity is not included in the theory and is largely irrele-  
 616      vant at the scales currently probed by collider experiments. Within the fermions, there are both quarks  
 617      (which interact via all three forces) and leptons. The charged leptons interact via electromagnetic and weak  
 618      interactions, while neutrinos (neutral leptons) interact only via the weak force. Within the bosons, there  
 619      are the  $W^\pm$  and  $Z$  bosons (the mediators of the weak force), the gluon ( $g$ , the mediator of the strong  
 620      force), and the photon ( $\gamma$ , the mediator of the electromagnetic force). Finally, there is the Higgs boson,  
 621      a fundamental spin zero particle resulting from the Higgs mechanism of electroweak symmetry breaking.  
 622      Figure 1.1 summarizes the fermions and bosons of the SM.

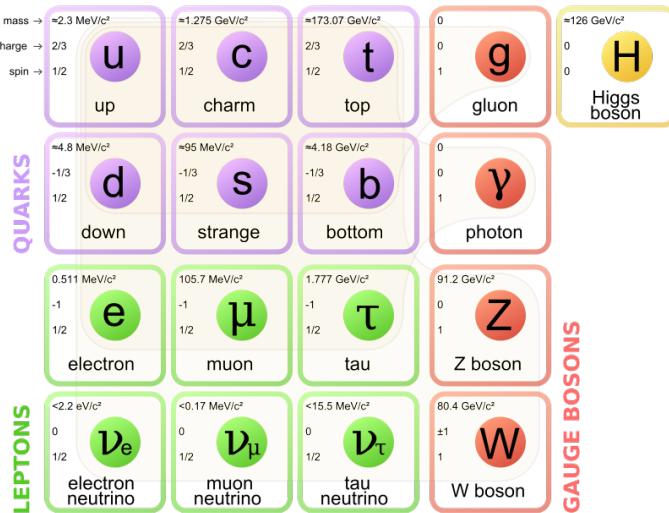


Figure 1.1: The particles of the Standard Model and their properties [6].

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

630 theory combined with the theory of quantum chromodynamics (which models the strong sector as a non-  
 631 Abelian  $SU(3)$  gauge group)<sup>1</sup>.

## 632 1.2 ELECTROWEAK SYMMETRY BREAKING AND THE HIGGS

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

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

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

645 The simplest potential of a self-interacting Higgs that still respects the SM symmetry is given in equa-  
 646 tion 1.2.

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

647 If the  $\mu^2$  term of this potential is positive, then the potential has a minimum at  $\Phi = 0$  and the electroweak

---

<sup>1</sup>For a pedagogical treatment of the physics of quantum chromodynamics, see reference [13].

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

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

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

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

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

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

652 where the covariant derivative is defined as

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

653 and  $W^1, W^2, W^3$  and  $B$  are the  $SU(2)$  and  $U(1)$  gauge fields of the electroweak theory, respectively.  $g$   
654 and  $g'$  are the corresponding coupling constants. The Pauli matrices are represented with  $\tau$ . With the  
655 scalar Lagrangian in place, the physical gauge fields can then be written as

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

656

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

657

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

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

661

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

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

$$g_{hf\bar{f}} = \frac{m_f}{v} \quad (1.11)$$

664 The full Lagrangian of Higgs interactions can be written as

$$\mathcal{L}_{\text{Higgs}} = -g_{hf\bar{f}}\bar{f}fh + \frac{g_{hhh}}{6}h^3 + \frac{g_{hhhh}}{24}h^4 + \delta_V V_\mu V^\mu \left( g_{hVV}H + \frac{g_{hhVV}}{2}h^2 \right) \quad (1.12)$$

665 with

$$\begin{aligned} g_{hVV} &= \frac{2m_V^2}{v} & g_{hhVV} &= \frac{2m_V^2}{v^2} \\ g_{hhh} &= \frac{3m_h^2}{v} & g_{hhHH} &= \frac{3m_h^2}{v^2} \end{aligned} \quad (1.13)$$

666 The last term of the Lagrangian appears twice, once for  $W$  bosons and once for  $Z$  bosons.  $V$  refers to  
 667 the  $W^\pm$  and  $Z$ , and  $\delta_W = 1$  while  $\delta_Z = 1/2$ . Phenomenologically, there are a few features of this  
 668 Lagrangian that are useful to note. First, note that the Higgs mass is a free parameter of the theory that  
 669 must be determined experimentally. Second, note that the coupling of the Higgs to the vector bosons and  
 670 fermions scales as a function of the masses of these particles, a fact that is important when considering  
 671 both the production and decays of the Higgs. Finally, note the presence of the cubic and quartic Higgs self  
 672 interaction terms, which can lead to final states with multiple Higgs bosons produced.

673 1.3 HIGGS BOSON PRODUCTION AND DECAY

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

677 1.3.1 HIGGS PRODUCTION

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

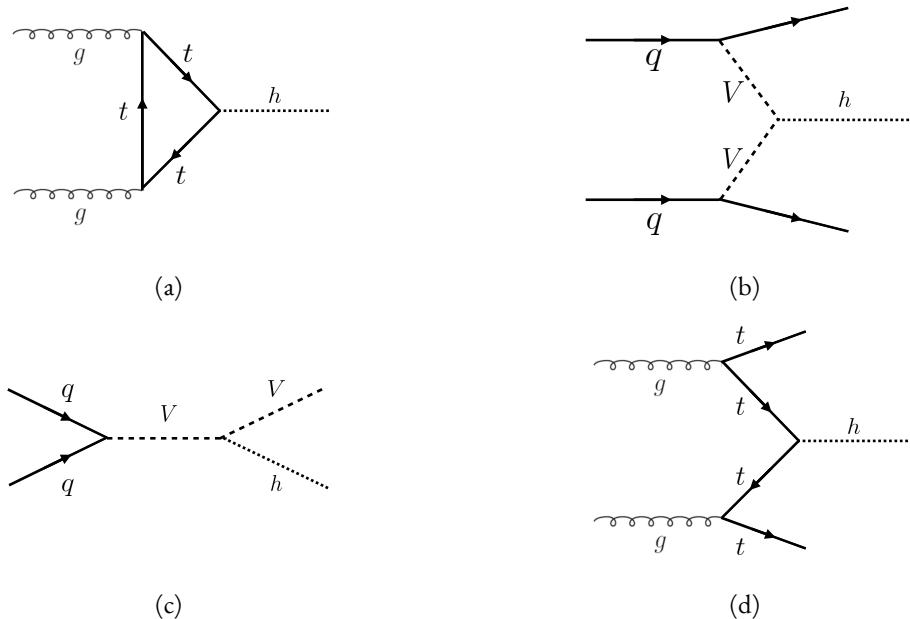


Figure 1.2: The four most common Higgs boson production modes at the LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c)  $W/Z + H$  production, (d)  $t\bar{t}H$  production

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

686 momentum of the incoming partons. The Higgs can also be produced in association with a  $W$  or  $Z$  boson.  
 687 The  $W/Z$  is produced normally and then radiates a Higgs<sup>2</sup>. Finally, the Higgs can be produced in associa-  
 688 tion with two top quarks. Each incoming gluon splits into a  $t\bar{t}$  pair, and one of the top pairs combines to  
 689 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. In figure 1.3, note that gluon fusion has the

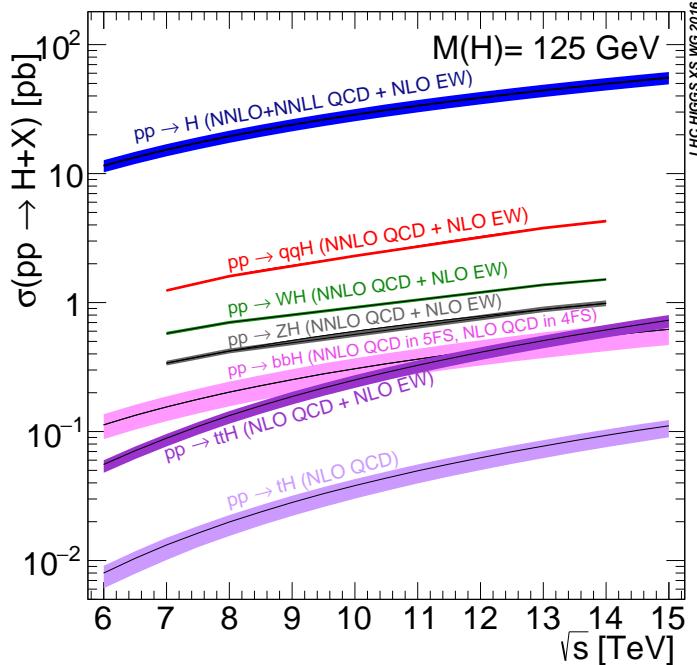


Figure 1.3: Higgs production cross sections as a function of center of mass energy ( $\sqrt{s}$ ) at a  $pp$  collider [18].

690  
 691 largest cross section, while VBF is the second largest at approximately a factor of 10 smaller. The figure also  
 692 includes the less commonly studied  $b\bar{b}H$  and  $tH$  modes. While the  $b\bar{b}H$  mode has a larger cross section  
 693 than  $t\bar{t}H$ , it also has larger backgrounds and is thus less sensitive. The  $tH$  mode is not as sensitive as  $t\bar{t}H$   
 694 due to its lower cross section. At  $\sqrt{s} = 8$  TeV, ggF production of a 125 GeV Higgs has a cross section  
 695 of  $19.47^{+1.54}_{-1.67}$  pb, while VBF has a cross section of  $1.601^{+0.036}_{-0.035}$  pb [18]. Both the gluon fusion and vector  
 696 boson fusion cross sections have been computed to next-to-next-to-leading order (NNLO) in the QCD  
 697 couplings and next-to-leading order in the electroweak couplings [19–26]. The gluon fusion cross section  
 698 also includes next-to-next-to-leading logarithm (NNLL) resummation [27]. The cross sections of all of

---

<sup>2</sup>This mode is also sometimes known as “Higgs-strahlung”.

699 the main Higgs production modes at this center of mass energy, as well as their uncertainties from varying  
 700 the QCD renormalization and factorization scales and PDFs, are summarized in table 1.1 for a 125 GeV  
 701 Higgs. The relative uncertainty of the gluon fusion mode is larger than the relative uncertainty in the  
 702 vector boson fusion mode due to the fact that gluon fusion production happens through a loop.

Production mode	$\sigma$ (pb)	QCD scale uncert. (%)	PDF + $\alpha_s$ 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
$b\bar{b}H$	0.2021	+20.7 / - 22.3	
$t\bar{t}H$	0.1330	+4.1 / - 9.2	4.3
$tH$ ( $t$ -channel)	0.01869	+7.3 / - 16.5	4.6
$tH$ ( $s$ -channel)	$1.214 \times 10^{-3}$	+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].

### 703 1.3.2 HIGGS BRANCHING RATIOS

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

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

706 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  
 707  $m_H$  is the mass of the Higgs. Note that the width scales with the square of the fermion mass. (This also  
 708 assumes that the Higgs mass is large enough to decay with both the fermions on shell.)

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

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

<sup>711</sup> where  $m_W$  is the mass of the  $W$  and  $x_W = 4M_W^2/m_H^2$ . To get the branching ratio to  $ZZ$  (in the regime  
<sup>712</sup> where  $m_H \geq 2m_Z$ ), the equation is divided by 2 to account for identical particles in the final state, and  
<sup>713</sup>  $x_W$  is replaced with  $x_Z = 4M_Z^2/m_H^2$ . This is shown in equation 1.16 [5].

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

<sup>714</sup> The more general formula for Higgs branching into  $WW$  or  $ZZ$ , taking into account the case where one  
<sup>715</sup> or both vector bosons is off-shell, is shown in equation 1.17 [28].

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

<sup>716</sup> Here,  $q_1^2$  and  $q_2^2$  are the invariant masses of the virtual gauge bosons,  $M_V$  is the  $W$  or  $Z$  mass, and  $\Gamma_V$  is  
<sup>717</sup> the  $W$  or  $Z$  width.  $\Gamma_0$  is the squared matrix element, which is given in equation 1.18 [28].

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

<sup>718</sup> The function  $\lambda$  is defined as  $\lambda(x, y, z) = (1 - x/z - y/z)^2 - 4xy/z^2$ . The integral in the general  
<sup>719</sup> off-shell boson case is much more difficult to interpret than the simpler on-shell branching ratios, but it  
<sup>720</sup> can be evaluated numerically. These branching ratio formulas can also be visualized as a function of Higgs  
<sup>721</sup> mass, as shown in figure 1.4. There are a few interesting features to note in this figure. First, note that at  
<sup>722</sup> high Higgs masses, once on-shell production of both  $W$  and  $Z$  bosons is possible, these two decays are  
<sup>723</sup> dominant due to the large masses of the  $W/Z$ . Also note that the branching ratio to  $W$ s is twice that of  
<sup>724</sup>  $Z$ s at these large masses due to the fact that there are two charged  $W$  bosons ( $W^\pm$ ) and only one  $Z$  boson<sup>3</sup>.  
<sup>725</sup> At 125 GeV, the Higgs is accessible through many different decay modes. The largest branching ratio is  
<sup>726</sup> the decay  $H \rightarrow b\bar{b}$  at 58.24% [18]. This branching is larger than the  $WW/ZZ$  decays because one of  
<sup>727</sup> the two bosons must be produced off-shell for  $m_h = 125$  GeV. The second largest branching ratio is  
<sup>728</sup> to  $WW^*$  at 21.37 % (before taking into account the branching ratios of the  $W$ ). Table 1.2 summarizes

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<sup>3</sup>In the Higgs Lagrangian, this extra symmetry factor is quantified by the  $\delta_V$  noted in equation 1.12.

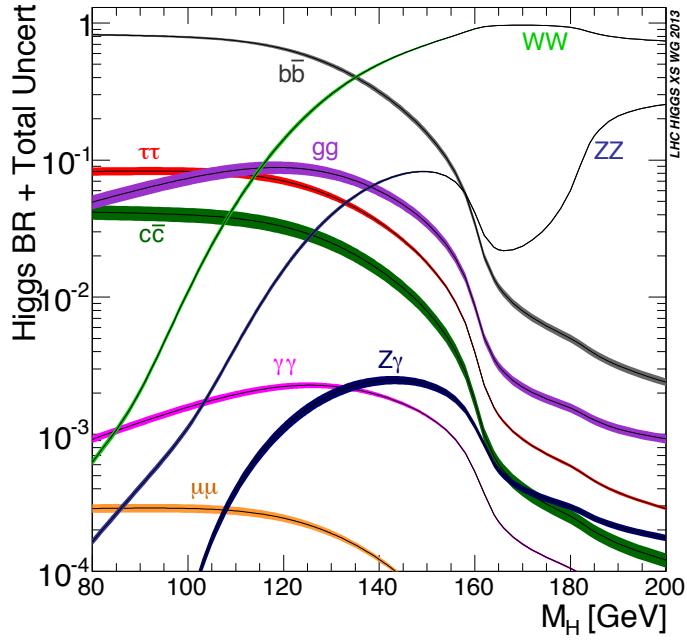


Figure 1.4: Higgs boson branching ratios as a function of  $m_H$  [18].

729 the theoretical branching ratios for a Higgs with a mass of 125 GeV. Note that there is a Higgs branching  
 730 ratio to  $\gamma\gamma$  even though photons are massless. This decay happens through a loop, which suppresses the  
 731 branching ratio<sup>4</sup>.

Decay	Branching ratio (%)	Relative uncertainty (%)
$bb$	58.24	+0.25 / -0.25
$WW^*$	21.37	+0.99 / -0.99
$gg$	8.187	+3.40 / -3.41
$\tau\tau$	6.272	+1.17 / -1.16
$cc$	2.891	+1.20 / -1.20
$ZZ^*$	2.619	+0.99 / -0.99
$\gamma\gamma$	0.2270	+1.73 / -1.72
$Z\gamma$	0.1533	+5.71 / -5.71
$\mu\mu$	0.02176	+1.23 / -1.23

Table 1.2: Theoretical branching ratios for a 125 GeV Higgs boson, quoted as a percentage of the total width of the Higgs. Uncertainties shown are relative to the branching ratio value [18].

732 Note that the branching ratios alone do not tell the full story of which Higgs channels are the most

---

<sup>4</sup>The largest contributions to the loop are the top quark and  $W$  boson.

733 sensitive. For example, the  $H \rightarrow b\bar{b}$  channel in gluon fusion production is incredibly difficult to observe  
 734 due to the large QCD dijet background at the LHC. However, in associated production of the Higgs,  
 735 where a  $W$  or  $Z$  gives additional final state particles that can be used to reduce background, a search for  
 736  $H \rightarrow b\bar{b}$  can be sensitive. The combinations of production and decay modes that are most commonly  
 737 studied at the LHC 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 for each decay channel [5].

#### 738 1.4 HIGGS PAIR PRODUCTION IN THE STANDARD MODEL

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

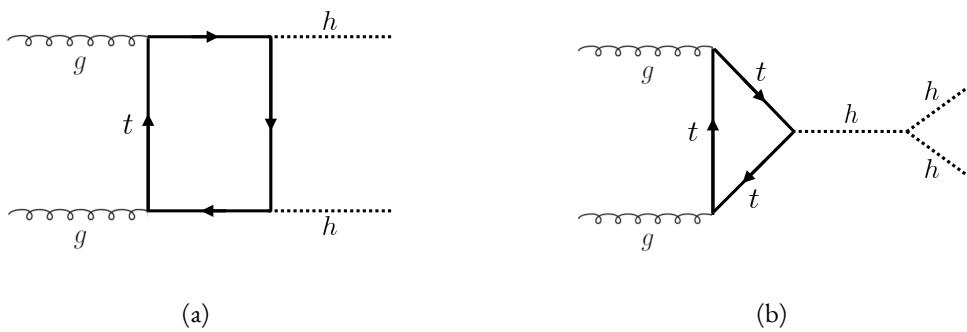


Figure 1.5: The two leading diagrams for Standard Model di-Higgs production at the LHC: (a) box diagram, (b) Higgs self coupling.

741  
 742 cross section for di-Higgs production at the LHC. Nevertheless, Higgs pair production is quite interesting

743 to study because it gives direct access to the  $\lambda$  parameter of the Higgs potential, also known as the Higgs  
744 self coupling. The diagram in figure 1.5(b) is sensitive to this coupling through the triple Higgs vertex.

745 One can substitute the gluon fusion production of diagram 1.5(b) with any of the other production  
746 modes previously discussed. These other modes do not suffer from interference with the box diagram in  
747 figure 1.5(a) due to the presence of additional particles in the final state. They still have a lower cross section  
748 than the gluon fusion mode, however. The cross sections for di-Higgs production in the different modes,  
749 as well as their uncertainties, are shown in table 1.4 [29]. These are shown for  $\sqrt{s} = 14$  TeV as this is the  
750 expected center of mass energy for the High Luminosity LHC and this energy is more sensitive to di-Higgs  
production. Note that the scale of cross section quoted is now in fb rather than pb.

Production mode	$\sigma$ (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 [29]. The uncertainties include QCD scale and PDF variations as well as uncertainties on  $\alpha_S$ .

751

## 752 1.5 HIGGS PAIR PRODUCTION IN THEORIES BEYOND THE STANDARD MODEL

753 The Higgs pair production cross section in the Standard Model is rather small, and datasets on the scale of  
754 the full  $3000 \text{ fb}^{-1}$  expected from the High Luminosity LHC will be required to obtain sensitive measure-  
755 ments of the Higgs self-coupling [29]. However, the discovery of the Higgs also gives particle physicists  
756 a new tool that can be exploited in the search for new physics beyond the Standard Model. In particular,  
757 Higgs pair production is a promising channel in the search for new physics. The cross section for di-Higgs  
758 production can be altered through both resonant and non-resonant production of Higgs pairs. In non-  
759 resonant production, di-Higgs production vertices can arise from the presence of a new strong sector and  
760 additional colored particles [30–32]. Figure 1.6 shows examples of the types of vertices that can arise. In  
761 the resonant case, new heavy particle can decay to Higgs pairs. Such new particles can include heavy Higgs

762 bosons arising in two Higgs doublet models (2HDM) or Higgs portal models as well as heavy gravitons in  
 763 Randall-Sundrum theories [30, 33–39]. Figure 1.7 shows a generic diagram for a heavy resonance decaying  
 764 to two Higgs bosons. In the 2HDM,  $X$  corresponds to the heavy CP-even scalar  $H$ . In the Randall-  
 Sundrum model,  $X$  corresponds to a heavy spin-2 graviton  $G_{KK}^*$ . The next sections provide more detail

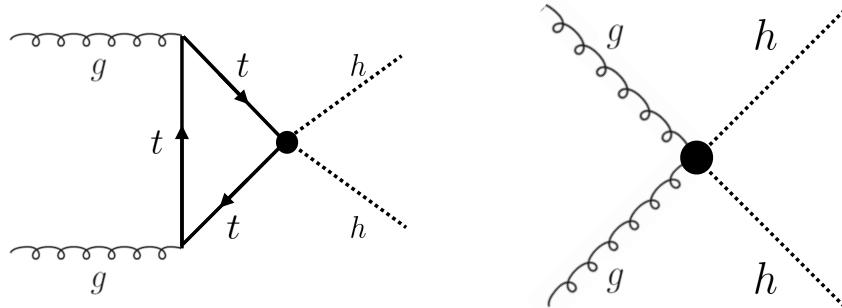


Figure 1.6: Diagrams with new vertices for non-resonant Higgs pair production arising in composite Higgs models.

765  
 766 on the phenomenology of resonant Higgs production in Randall-Sundrum and 2HDM models, as these  
 models will later be tested in a dedicated search for resonant production of boosted Higgs pairs.

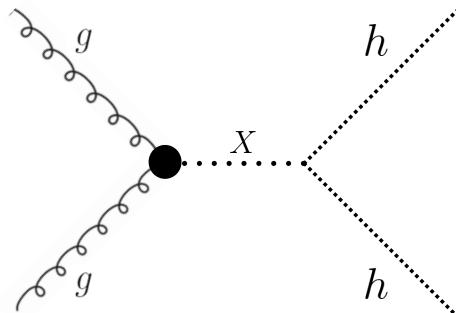


Figure 1.7: Generic Feynman diagram for resonant Higgs pair production in BSM theories.

767

### 768 1.5.1 RANDALL-SUNDRUM GRAVITONS

769 The Randall-Sundrum model is a proposed solution to the hierarchy problem that posits a five-dimensional  
 770 warped spacetime that contains two branes: one where the force of gravity is very strong and a second brane  
 771 at the TeV scale corresponding to the known Standard Model sector [33]. In the theory, the branes are

772 weakly coupled and the graviton probability function drops exponentially going from the gravity brane  
 773 to the SM brane, rendering gravity weak on the SM brane. The experimental consequence of this theory  
 774 is a tower of widely spaced (in mass) Kaluza-Klein graviton resonances. In theories where the fermions  
 775 are localized to the SM brane, production of gravitons from fermion pairs is suppressed and the primary  
 776 mode of production is gluon fusion [34]. These gravitons have a substantial branching fraction to Higgs  
 777 pairs, ranging from 6.43% for gravitons with a mass of 500 GeV to 7.66% at 3 TeV. Figure 1.8 shows the  
 778 branching ratios of the spin-2 Randall Sundrum graviton (RSG) as a function of its mass. The predomi-  
 779 nant decays are to  $t\bar{t}$  above the mass threshold for that channel.

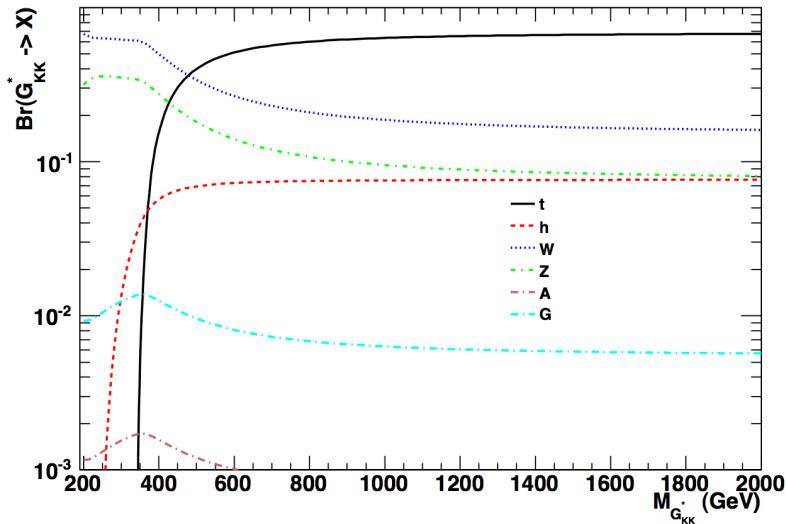


Figure 1.8: Branching ratios for a spin-2 Randall-Sundrum graviton as a function of mass computed in MadGraph with the CP3-Origins implementation [34, 40, 41].

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

786 Another interesting feature of the theory is that the width of the graviton increases with both  $c$  and  
 787  $m_{G_{\text{KK}}^*}$ . Figure 1.10 shows the graviton width for both  $c = 1.0$  and  $c = 2.0$  as a function of mass. In

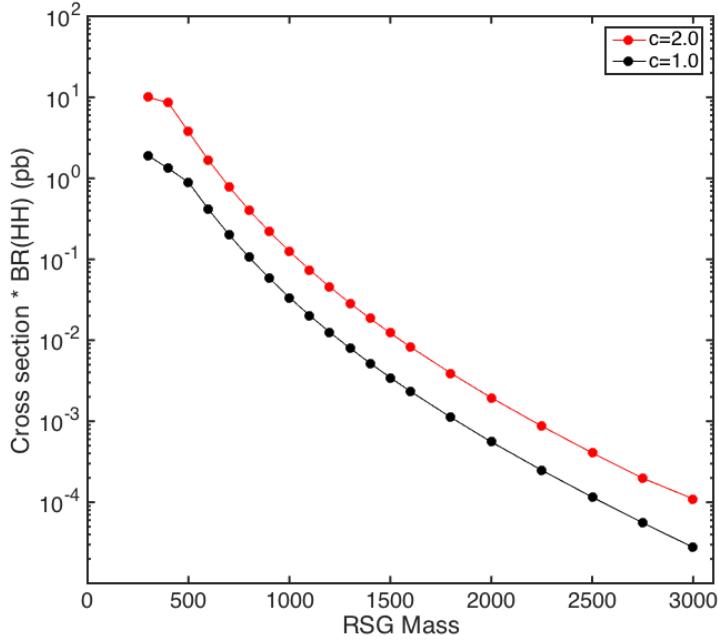


Figure 1.9:  $\sigma \times \text{BR}(HH)$  for Randall-Sundrum gravitons as a function of mass computed in MadGraph with the CP<sub>3</sub>-Origins implementation [34, 40, 41].

<sup>788</sup>  $c = 1.0$ , the width starts at 8.365 GeV for a mass of 300 GeV and increases to 187.2 GeV at a mass of  
<sup>789</sup> 3 TeV. Similarly, with  $c = 2.0$ , the width starts at 33.46 GeV for  $m_G = 300$  GeV and increases to  
<sup>790</sup> 748.8 GeV at a mass of 3 TeV.

### <sup>791</sup> 1.5.2 Two Higgs Doublet Models

<sup>792</sup> In Two Higgs Doublet Models (2HDM), a second complex scalar doublet is added to the Standard Model [36–  
<sup>793</sup> 38]. In this case, all four degrees of freedom in the second doublet correspond to new particles, meaning  
<sup>794</sup> that there are five total scalars from the two Higgs doublets -  $h$  (light CP-even Higgs),  $H$  (heavy CP-even  
<sup>795</sup> Higgs),  $A$  (heavy CP-odd Higgs), and  $H^\pm$  (charged Higgs). The model is parameterized by two main pa-  
<sup>796</sup> rameters. The first,  $\tan \beta \equiv \frac{v_2}{v_1}$ , is the ratio of the vacuum expectation values of the two Higgs doublets  
<sup>797</sup> (where  $v_1$  corresponds to the  $v$  in the SM Higgs model described above). The second parameter is  $\alpha$ , a mix-  
<sup>798</sup> ing angle between the heavy and light Higgs fields. Models are also often parameterized with  $\cos(\beta - \alpha)$   
<sup>799</sup> rather than  $\alpha$  directly. The limit where  $\cos(\beta - \alpha) = 0$  is called the alignment limit, and in this limit the

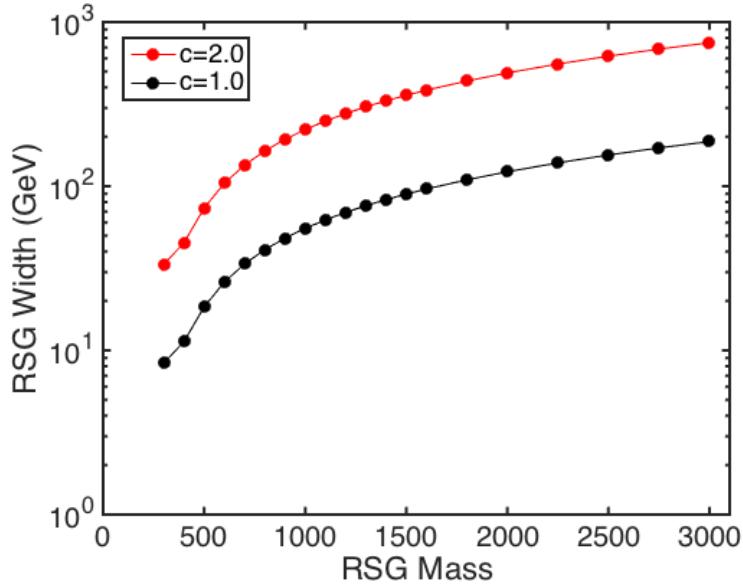


Figure 1.10: Randall-Sundrum graviton width as a function of mass computed in MadGraph with the CP3-Origins implementation [34, 40, 41]

800 light Higgs  $h$  has the same couplings as a Standard Model Higgs.

801 2HDM models are usually separated into two main types - Type I and Type II. In Type I models, the  
 802 charged fermions only couple to the second Higgs doublet, leading to a fermiophobic light Higgs. In  
 803 Type II models, up-type quarks couple to the first doublet while down-type quarks couple to the second  
 804 doublet. One specific realization of a Type II 2HDM is the Minimal Supersymmetric Standard Model  
 805 (MSSM).

806 Resonant di-Higgs production in 2HDM models can proceed through decays of the heavy CP-even  
 807 Higgs  $H \rightarrow hh$ . The branching ratio for  $H \rightarrow hh$  depends on the model type as well as the values of  
 808  $\tan \beta$  and  $\cos \beta - \alpha$ . Figure 1.11 shows the branching ratios as a function of the mass of the heavy scalar  
 809  $H$  for both Type I and Type II models. Depending on the type of model  $hh$  can be a substantial fraction  
 810 of the decays of  $H$ .

811 **1.6 CONCLUSION**

812 Studying the Higgs sector is essential for understanding the details of how mass arises in the Standard  
 813 Model and how the electroweak symmetry is broken. The discovery of the Higgs boson also opens the

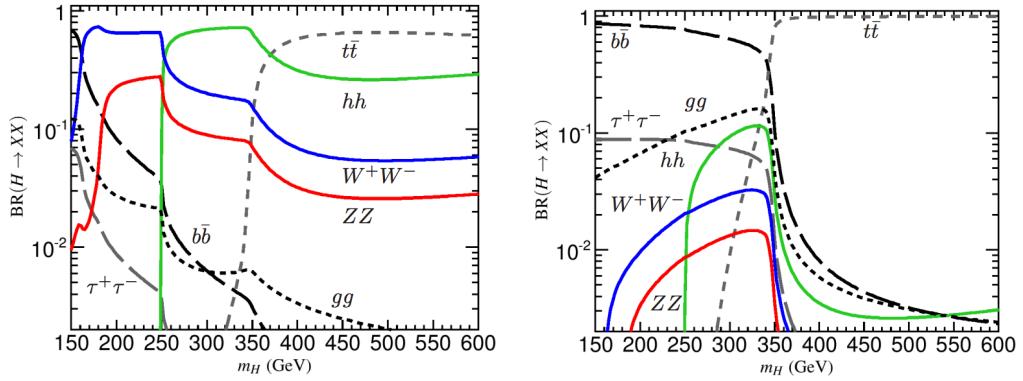


Figure 1.II: Branching ratios for heavy Higgs  $H$  in Type I (left) and Type II (right) 2HDM models with  $\tan \beta = 1.5$  and  $\cos(\beta - \alpha) = 0.1$ (0.01) for Type I (Type II) [38].

814 door for its use as a tool to search for new physics, and Higgs pair production is an ideal candidate for  
 815 this study. Even if no BSM physics is found in Higgs pair production, searches for Higgs pairs will put  
 816 constraints on the Higgs self coupling and thus improve knowledge of the Standard Model and the details  
 817 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

818

819

820

## The ATLAS detector and the Large Hadron Collider

821 This chapter presents an overview of the experimental systems used to conduct the measurements in this  
822 thesis. First, a brief overview of the accelerator, the Large Hadron Collider, will be given. In this section,  
823 the accelerator conditions relevant to data-taking are presented as well. Next, an overview of the ATLAS  
824 experiment is given. The basics of each sub-detector's role are summarized, as well as the details of the  
825 datasets accumulated. Then, a brief interlude on the ATLAS Muon New Small Wheel upgrade is pre-  
826 sented. While this new detector does not have a direct impact on any of the datasets recorded so far, it will  
827 have an impact on future analyses and the work done on it is briefly summarized here. Finally, an overview  
828 of object reconstruction in ATLAS is given. While the details of all of the algorithms will not be presented  
829 in detail, aspects of the reconstruction performance are shown as these are relevant to the results presented  
830 later in this thesis.

831    2.1 THE LARGE HADRON COLLIDER

832    The Large Hadron Collider (LHC) is a proton-proton collider at the CERN laboratory in Geneva, Switzer-  
833    land [42]. It was designed for a maximum collision center of mass energy of  $\sqrt{s} = 14 \text{ TeV}$  and has a  
834    circumference of 26.7 kilometers. Four main experiments are located at the interaction points (IP) of  
835    the accelerator: ATLAS (A Toroidal LHC ApparatuS), CMS (the Compact Muon Solenoid), ALICE (A  
836    Large Ion Collider Experiment), and LHCb [43–46]. Figure 2.1 shows a schematic of the LHC ring and  
837    its experiments.

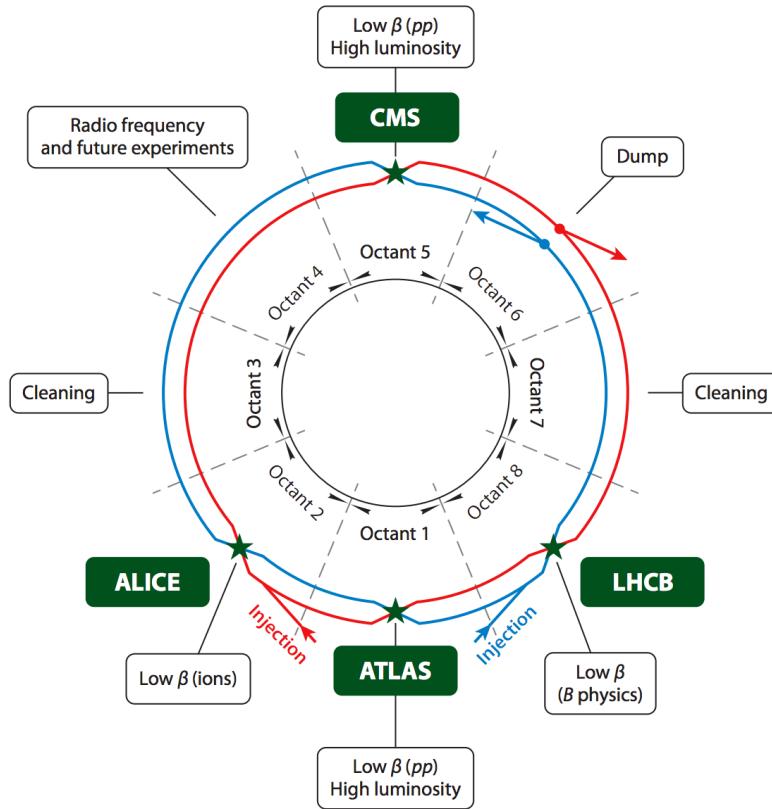


Figure 2.1: A schematic view of the LHC ring [47]. Four main experiments are located at interaction points along the ring. ATLAS and CMS are general purpose experiments, while ALICE is dedicated to heavy ion collisions and LHCb is dedicated to studying  $B$  physics.

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

841  $\sqrt{s} = 14 \text{ TeV}$ . The superconducting magnets are cooled to a temperature of 1.9 Kelvin with superfluid  
842 helium.

843 **2.1.1 INSTANTANEOUS LUMINOSITY**

844 The rate of physics events expected from the accelerator is dependent on the instantaneous luminosity  
845 of the machine and the cross section of the physics process,  $R_{\text{events}} = L\sigma$ . Here,  $R_{\text{events}}$  is the num-  
846 ber of events per second,  $L$  is the instantaneous luminosity of the machine, and  $\sigma$  is the cross section for  
847 the physics process being measured. The instantaneous luminosity of the LHC is determined by numer-  
848 ous factors related to beam conditions. Equation 2.1 gives the equation for instantaneous luminosity of a  
849 Gaussian beam profile [47].

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

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

857 Another way of writing the instantaneous luminosity is shown in equation 2.2. In this case, the instan-  
858 taneous luminosity is written as the ratio of the rate of inelastic collisions to the inelastic cross section [48].

859

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

860 In this case,  $\mu$  is the average number of interactions per bunch crossing in the accelerator.  $\mu$  is a useful  
861 parameter for characterizing the amount of activity recorded in an experiment. As the instantaneous lu-  
862 minosity and thus  $\mu$  increase, there are more interactions per bunch crossing and more activity is present  
863 in the detector. The level of activity is often characterized with  $\langle \mu \rangle$ , the measured per bunch crossing  $\mu$

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

867 **2.1.2 EVOLUTION OF MACHINE CONDITIONS**

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

	2011	2012	2015	Design
$\sqrt{s}$ [ TeV ]	7	8	13	14
Number of bunches	1380	1380	1825	2808
Max. protons per bunch	$1.45 \times 10^{11}$	$1.7 \times 10^{11}$	$1.2 \times 10^{11}$	$1.15 \times 10^{11}$
Bunch spacing [ns]	50	50	25	25
Max. instantaneous luminosity [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$3.7 \times 10^{33}$	$7.7 \times 10^{33}$	$5 \times 10^{33}$	$10^{34}$
$\beta^*$ [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 [49, 50].

872 **2.2 THE ATLAS DETECTOR**

873 The ATLAS detector is the multi-purpose particle detector experiment located at the LHC’s Point 1 [43].  
 874 It has nearly  $4\pi$  coverage in solid angle around the interaction point. It consists of an inner detector for  
 875 measuring charged particles, electromagnetic and hadronic calorimeters, and a muon spectrometer. Fig-  
 876 ure 2.2 gives an overview of the detector.

877 **2.2.1 COORDINATE SYSTEM**

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



Figure 2.2: A full diagram of the ATLAS detector [43].

beam line) is defined as the  $x$ - $y$  plane. The angle in this plane is referred to as  $\phi$ . The angle relative to the beam axis is referred to as  $\theta$ . Rather than using  $\theta$  directly as a coordinate, the experiment often uses the pseudorapidity  $\eta$ , defined in equation 2.3.

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

Pseudorapidity is the massless approximation of rapidity, the angle used to parameterize boosts in special relativity. This coordinate is useful in particle physics for two reasons. First, it means that differences in  $\eta$  are Lorentz invariant. Second, particle production is roughly constant in pseudorapidity. Particles with  $\eta$  close to zero are referred to as “central”, while those at high  $|\eta|$  are called “forward”. In general, two main detector configurations can be seen in figure 2.2. There are “barrel” elements, which surround the beam line cylindrically and are in the central region of the detector. In the forward region, there are “endcap” regions which are arranged as disks perpendicular to the beam line.

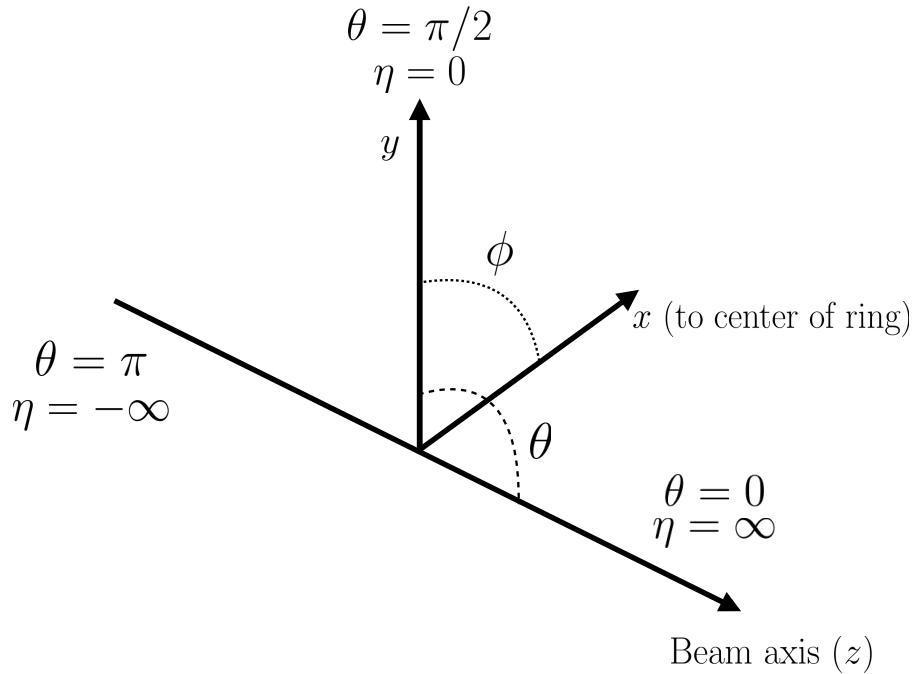


Figure 2.3: The ATLAS coordinate system. The  $z$  direction corresponds to the beam axis, while  $x$  and  $y$  define the transverse plane.  $\theta$  is the angle relative to the beam axis and  $\phi$  is the azimuthal angle.  $\eta$ , the pseudorapidity, approaches infinity at small angles relative to the beam axis.

#### 890 2.2.2 INNER DETECTOR

891 The ATLAS Inner Detector (ID) system is built for precision tracking of charged particles. It covers the  
 892 range  $|\eta| < 2.5$ . In this range, approximately 1000 particles are generated every bunch crossing in the de-  
 893 tector [43]. This requires having fine granularity to achieve the resolutions required for good momentum  
 894 measurement and vertex reconstruction.

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



Figure 2.4: Layout of the ATLAS Inner Detector system [51].

## 899 PIXEL DETECTOR

900 The pixel detector is the first detector particles traverse after being generated in proton collisions and is  
 901 the most granular detector. Its operation is crucial for precision tracking and vertex reconstruction as well  
 902 as higher level object reconstruction like tagging of jets from  $b$ -quarks. The basic sensing element in this  
 903 subdetector is a silicon pixel detector. The operating principle for the silicon pixels is that of a  $p-n$  junction.  
 904 When a charged particle passes through, it creates electron-hole pairs that are then separated by the electric  
 905 field. The sensors are  $250 \mu\text{m}$  thick and use oxygenated  $n$ -type wafers with readout pixels on the  $n^+$  side  
 906 of the detector [43]. Overall, the pixel detector has 1744 sensors and 80.4 million readout channels.

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

911 **INSERTABLE B-LAYER**

912 In Run 2, a new innermost pixel layer, known as the insertable B-layer (IBL), was added to the Inner  
913 Detector [52]. This layer was added to cope with the higher luminosities planned in LHC Run 2 and at the  
914 high luminosity HL-LHC. Additionally it improves tracking position resolution which in turn improves  
915 the vertexing and *b*-tagging capabilities in ATLAS. The detector sits directly on a new beam pipe, only  
916 33.25 mm away from the collision points in the azimuthal plane.

917 **SEMICONDUCTOR TRACKER (SCT)**

918 The semiconductor tracker (SCT) consists of silicon microstrips and comprises the next four layers of  
919 the ID. This sub-detector has 6.4 cm long sensors that are daisy-chained into strips with a strip pitch of  
920 80  $\mu\text{m}$  [43]. Some of the strips have a small stereo angle to allow for measurement of both angular coor-  
921 dinates. In total there are 6.3 million readout channels. The intrinsic accuracies are 17  $\mu\text{m}$  in  $R\text{-}\phi$  and  
922 580  $\mu\text{m}$  in  $z$  (or  $R$  in the endcap).

923 **TRANSITION RADIATION TRACKER (TRT)**

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

931 **2.2.3 CALORIMETERS**

932 The calorimeter system consists of two main sub-components: a fine granularity electromagnetic calorime-  
933 ter tailored for the measurement of photons and electrons and multiple coarser hadronic calorimeters ded-  
934 icated to the measurement of hadronic showers [43]. The calorimeter system has broader coverage than

935 the inner detector, covering the region out to  $|\eta| < 4.9$ . It is also designed to deliver good containment of  
936 showers so as to limit leakage into the muon system. Figure 2.5 shows the layout of the calorimeter system.

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

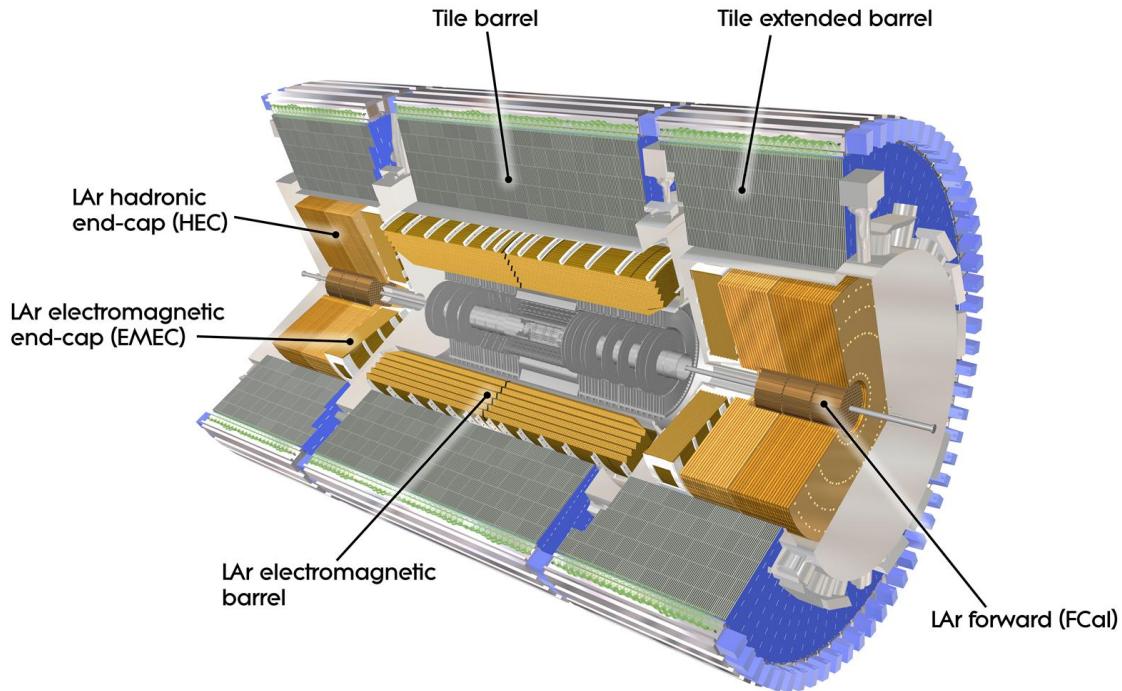


Figure 2.5: Layout of the ATLAS calorimeter system [43].

#### 940 ELECTROMAGNETIC CALORIMETER

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

946 In order to provide good containment the calorimeter depth must be optimized. Typically, for elec-  
947 tromagnetic calorimeters the depth is measured in radiation lengths. In general, the intensity of a particle  
948 beam attenuates exponentially in distance with an attenuation constant equal to the radiation length. That  
949 is,  $I(x) = I_0 e^{-x/X_0}$ , where  $I$  is the intensity,  $x$  is the distance traveled, and  $X_0$  is the radiation length.  
950 The ATLAS EM calorimeter is designed to have  $> 22$  radiation lengths in the barrel and  $> 24$  in the  
951 endcap [43].

952 **HADRONIC CALORIMETERS**

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

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

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

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

966 The hadronic equivalent of radiation length is called the interaction length and is denoted as  $\lambda$ . In the  
967 barrel, the hadronic calorimeter depth is approximately  $9.7\lambda$ , while in the endcap is is  $10\lambda$ . The outer  
968 supports contribute an additional  $1.3\lambda$ . This is been shown to be sufficient to limit punch-through of  
969 showers to the muon system [43].

970 2.2.4 MUON SPECTROMETER

971 The muon spectrometer is dedicated to measuring the momentum and position of muons. It consists  
972 of tracking and trigger chambers which are unique in the barrel and endcap regions. The magnetic field  
973 for bending of muons is provided by a system of three large air-core toroid magnets (from which ATLAS  
974 derives its name.) These magnets provide 1.5 to 5.5 Tm of bending power at  $0 < |\eta| < 1.4$  and approx-  
975 imately 1 to 7.5 Tm in the endcap region of  $1.6 < |\eta| < 2.7$ . The entire muon system covers the range  
976  $0 < |\eta| < 2.7$ . Monitored drift tubes (MDTs) are used for tracking in the barrel and the two outer layers  
977 of the endcap, while cathode strip chambers (CSCs) are used to provide tracking in the innermost endcap  
978 wheel. In the barrel, resistive plate chambers (RPCs) are used as trigger chambers while thin gap chambers  
979 (TGCs) are used in the endcap. Figure 2.6 shows the layout of the ATLAS muon system. The entire muon  
980 system is designed with the specification of providing a 10% momentum resolution for a 1 TeV muon.

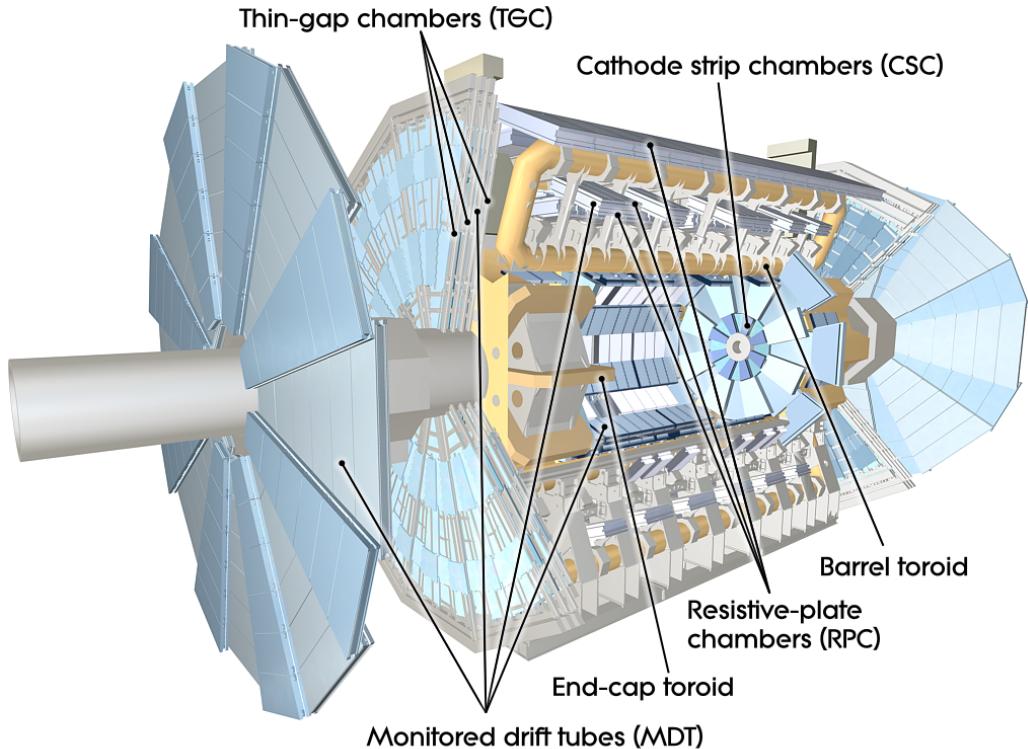


Figure 2.6: Layout of the ATLAS muon system [43].

981 MONITORED DRIFT TUBES (MDTs)

982 The monitored drift tubes (MDTs) are aluminum 3 cm diameter tubes filled with a 93/7 % mixture of  
983 Argon and CO<sub>2</sub>, with trace amounts of water. As a charged particle traverses the tube, it ionizes the gas  
984 and the ions drift to a wire at the center of the tube. The radial distance of traversal of the particle in the  
985 tube is determined by the drift time of the electrons, allowing for fine position resolution. The tubes have  
986 an average resolution of 80  $\mu\text{m}$  per tube and a maximum drift time of approximately 700 ns. The tubes  
987 are oriented so that they give precision measurement in  $\eta$  and run along  $\phi$ . They cover  $|\eta| < 2.7$ , except  
988 in the innermost layer of the endcap where they only go to  $|\eta| < 2.0$  [43].

989 CATHODE STRIP CHAMBERS (CSCs)

990 The cathode strip chambers cover a narrow window of the innermost endcap region at  $2.0 < |\eta| <$   
991 2.7. In this region the background rates in the cavern are particularly high and the CSCs are designed to  
992 handle these higher rates. The CSCs are multiwire proportional chambers with wires pointing in the radial  
993 direction (away from the beam pipe). The wire serves as an anode and there are two types of segmented  
994 cathode strip, one perpendicular to the wires which gives the precision measurement and one parallel which  
995 provides the transverse coordinate. It has an 80/20% gas mixture of Argon and CO<sub>2</sub> [43].

996 RESISTIVE PLATE CHAMBERS (RPCs)

997 The resistive plate chambers (RPCs) are gaseous electrode-plate detectors covering the region  $|\eta| < 1.05$ .  
998 They consist of two resistive plates separated by a distance of 2 mm. The gas mixture used is a 94.7/5/0.3%  
999 mixture of C<sub>2</sub>H<sub>2</sub>F<sub>4</sub>, Iso-C<sub>4</sub>H<sub>10</sub>, and SF<sub>6</sub>. It has readout strips with a pitch of 23-35 mm for both  $\eta$  and  
1000  $\phi$  measurement and thus provides measurement of the azimuthal coordinate in the barrel. The thin gas  
1001 gap allows for a quick response time which makes it ideal for use in the trigger. Signals in the RPC have  
1002 a width of approximately 5 ns. There are three layers of RPCs which are referred to as the three trigger  
1003 stations. They allow for programmable thresholds in both a low  $p_T$  and high  $p_T$  trigger. The coincidence  
1004 of hits in the innermost chambers allows for setting muon trigger thresholds between 6 and 9 GeV, while  
1005 the outermost layer allows the trigger to set trigger thresholds in the range of 9 to 40 GeV [43].

1006 THIN GAP CHAMBERS (TGCs)

1007 The thin gap chambers (TGCs) are multiwire proportional chambers where the wire to cathode distance  
1008 (1.4mm) is smaller than the wire-to-wire distance (1.8 mm). They contain a gas mixture of CO<sub>2</sub> and *n*-  
1009 pentane and use a high electric field to gain good time resolution. They serve two functions in the end-cap  
1010 system. First, they serve as the trigger chambers. Second, they also provide azimuthal coordinate measure-  
1011 ment. They sit on the inner and middle layers of the endcap. The outermost layer's azimuthal coordinate  
1012 is determined by extrapolation [43]. As with the RPCs, the TGCs also are capable of triggering with pro-  
1013 grammable thresholds in the same  $p_T$  range specified for the RPCs above.

1014 2.2.5 MAGNET SYSTEM

1015 As mentioned previously, there are two independent magnet systems in ATLAS. The first is a 2 T solenoid  
1016 field in the inner detector which provides bending in the azimuthal plane. The second is an approximately  
1017 0.5 T toroidal field in the muon system which provides bending in  $\eta$ . Figure 2.7 shows the predicted field  
1018 integral as a function of  $|\eta|$  [43].

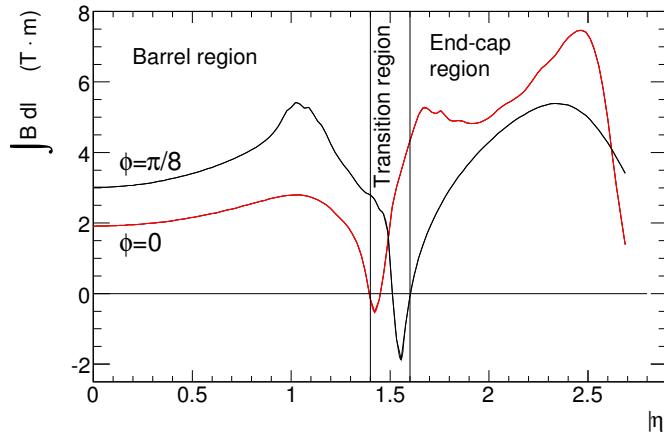


Figure 2.7: Predicted field integral as a function of  $|\eta|$  for the ATLAS magnet system [43].

1019    2.2.6    TRIGGER SYSTEM

1020    The ATLAS trigger system searches for signatures of muons, electrons, photons, hadronically decaying  $\tau$   
 1021    leptons, and jets in order to save these events for further analysis. The trigger system in ATLAS is designed  
 1022    to reduce the maximum LHC event rate of 40 MHz to a more reasonable rate that can be recorded. The  
 1023    trigger first consists of a fast, hardware based system called the Level-1 (L1) trigger. The L1 trigger consists  
 1024    of independent dedicated detector sub-components that can seed regions of interest (RoIs) for further  
 1025    analysis downstream. For muons, the RPCs and TGCs are used, while in the calorimeter coarsely grained  
 1026    sections of calorimeter cells called towers are used. Once regions of interest are seeded, a software based  
 1027    system called the High Level Trigger (HLT) is used to reconstruct objects and integrate information from  
 1028    different parts of the detector. In Run 1 of ATLAS, the HLT consisted of two separate stages: the level 2  
 1029    (L2) trigger and the event filter (EF).

1030    The maximum trigger rate that the L1 trigger can handle is 75 kHz. In the HLT, the rate of events  
 1031    written to disk is approximately 400 Hz. Figure 2.8 shows the trigger rates for different L1 triggers in 2012  
 1032    and 2015 for ATLAS [53].

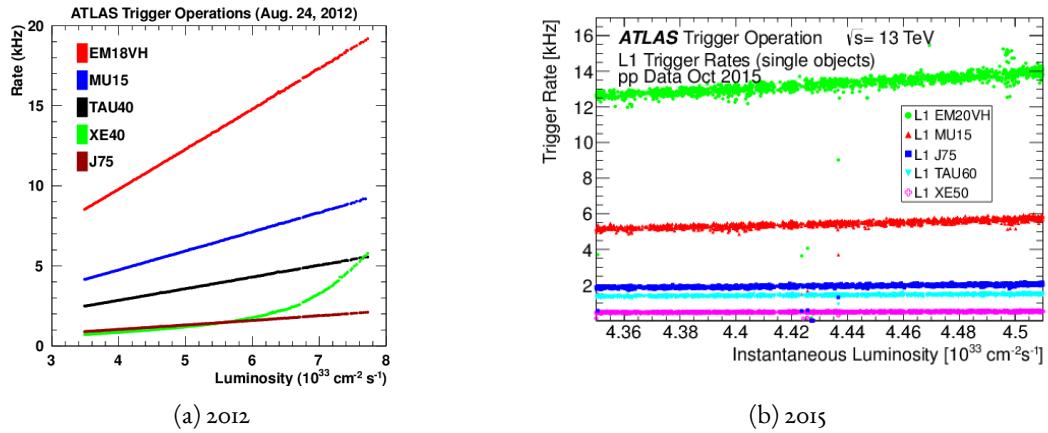


Figure 2.8: ATLAS trigger rates for Level-1 triggers as a function of instantaneous luminosity in 2012 and 2015 operation. These are single object triggers for electromagnetic clusters (EM), muons (MU), jets (J), missing energy (XE), and  $\tau$  leptons (TAU). The threshold of the trigger is given in the name in GeV [53].

1033 2.2.7 ATLAS DATASETS

1034 ATLAS has collected data at center of mass energies of 7, 8, and 13 TeV. Figure 2.9 shows the integrated  
1035 luminosity as a function of time for each of the three datasets. In the 2011 dataset with  $\sqrt{s} = 7$  TeV,  
1036 ATLAS recorded  $5.08 \text{ fb}^{-1}$ . Increased instantaneous luminosity in 2012 led to a larger dataset of  $21.3 \text{ fb}^{-1}$   
1037 recorded at  $\sqrt{s} = 8$  TeV. After Long Shutdown 1 (LS1) of the LHC and a restart in 2015, ATLAS  
1038 recorded  $3.9 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13$  TeV [54, 55]. The data recorded by ATLAS can only be used for  
1039 analysis if the required sub-detectors were in a stable state when the data was being taken. The fraction  
1040 of recorded ATLAS data that was labeled as being good for physics analysis was 90%, 95%, and 82% in  
1041 the 7, 8, and 13 TeV data respectively. Thus, the Run 1 results presented in this thesis use  $4.6 \text{ fb}^{-1}$  at  
1042  $\sqrt{s} = 7$  TeV and  $20.3 \text{ fb}^{-1}$  at  $\sqrt{s} = 8$  TeV<sup>1</sup>. The Run 2 results use  $3.2 \text{ fb}^{-1}$  at  $\sqrt{s} = 13$  TeV.

1043 2.2.8 DETECTOR PERFORMANCE

1044 Table 2.2 summarizes the design requirements for each of the different sub-detectors. This table shows the  
1045 energy and momentum resolution of tracking, calorimetry, and muon measurements.

	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	$\sigma_{p_T}/p_T$ at $p_T = 1$ TeV

Table 2.2: Performance requirements for the ATLAS detector [43].

1046 2.3 THE ATLAS MUON NEW SMALL WHEEL UPGRADE

1047 As the LHC continues operation, it is scheduled to be upgraded in several phases to allow it to reach higher  
1048 instantaneous luminosities and thus collect larger datasets. These conditions will open new doors for study

---

<sup>1</sup>The analyses combined in the Higgs discovery (presented in chapter 4) use between  $4.6$  and  $4.8 \text{ fb}^{-1}$  at  $7$  TeV depending on which detectors are required to be in a stable state. The discovery also only uses the  $5.8 \text{ fb}^{-1}$  of  $8$  TeV data that was available at the time of the analysis.

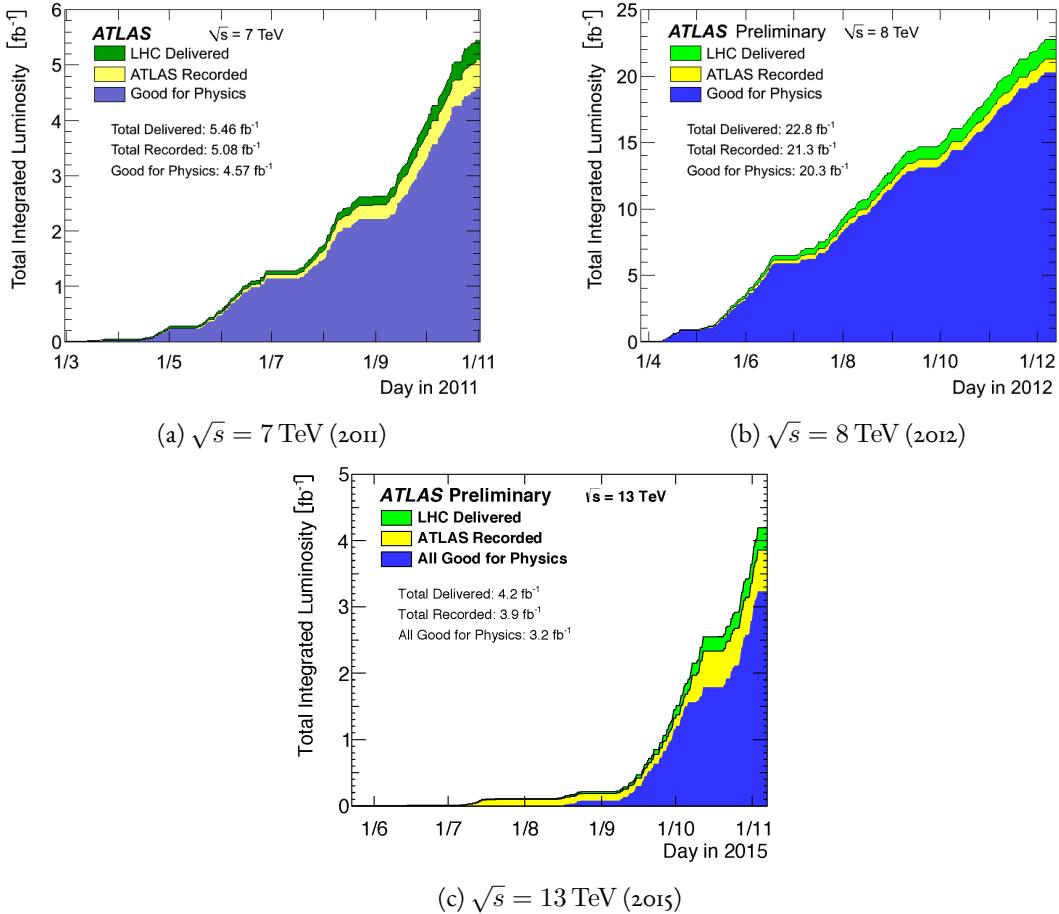


Figure 2.9: Instantaneous luminosity as a function of time for data recorded by ATLAS at different center of mass energies [54, 55].

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 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) [56]. The NSW will replace the innermost end-cap wheel of the muon system with new technologies. This is the part of the muon detector closest to the beam line and thus experiences the highest rates of particle flux in the muon system.

1055 2.3.1 MOTIVATION

1056 The motivation of the NSW is two-fold. The first objective is to alleviate the decreased tracking efficiency  
1057 that comes in a high rate environment. As shown in figure 2.10, at the LHC design luminosity both the  
1058 efficiency of recording hits and reconstructing track segments in the MDTs decreases. While the MDTs  
1059 were designed to cope with the hit rates at the LHC design luminosity, the High Luminosity LHC will  
1060 exceed these design specifications and the MDTs will have to be replaced.

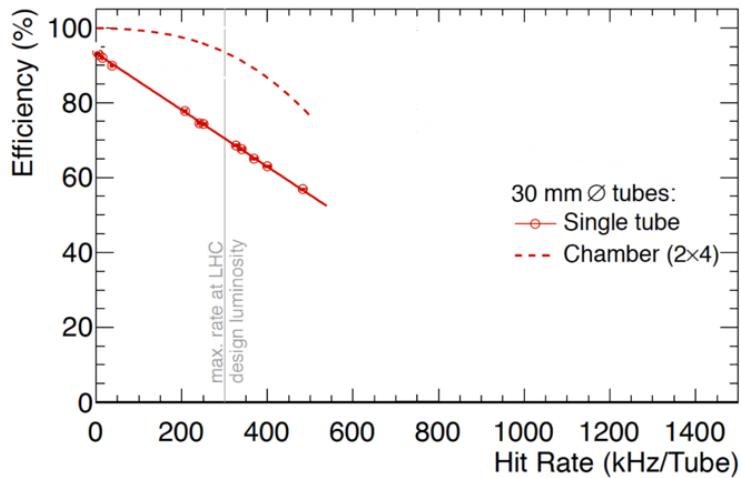


Figure 2.10: MDT tube hit (solid) and segment (dashed) efficiency as a function of hit rate per tube [56].

1061 The NSW will also work to alleviate the rate of fake triggers arising in the endcap. Figure 2.11 shows the  
1062 extrapolated trigger rates as a function of the  $p_T$  threshold with and without the NSW upgrade. As the  
1063 figure shows, the NSW upgrade will reduce the trigger rate considerably compared to the current endcap  
1064 trigger system. At a  $p_T$  threshold of 20 GeV, the level-1 trigger rate drops from 20 kHz to 7 kHz. This  
1065 reduction allows the  $p_T$  thresholds on muons to remain low, increasing the phase space of possible physics  
1066 studies and in particular maintaining good acceptance for Higgs physics.

1067 2.3.2 NSW DETECTOR TECHNOLOGIES

1068 The NSW will use two new detector technologies - micromesh gaseous structure detectors (micromegas)  
1069 and small-strip thin gap chambers (sTGCs) [56, 57]. The micromegas is more suited to tracking because

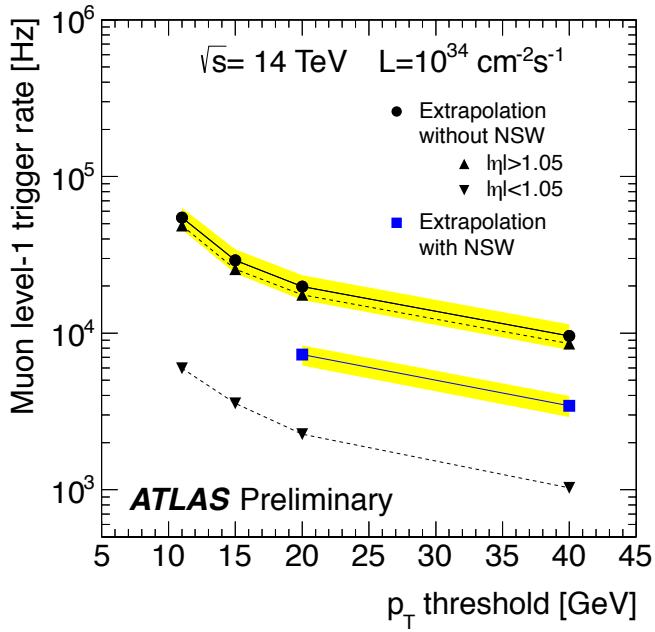


Figure 2.11: Trigger rate as a function of  $p_T$  threshold with and without the NSW upgrade [56].

of its good spatial resolution, while the sTGCs have better time resolution and are more suited for the trigger. However, both systems are capable of providing tracking and trigger information. To maintain full redundancy in cases of detector failure, both technologies will be used for tracking and trigger in the NSW.

#### 1074 MICROMEGAS

1075 Micromegas detectors operate using a thin metallic mesh that sits approximately  $100\ \mu\text{m}$  away from the  
 1076 readout electrodes to create the amplification region. Above this mesh, there is a drift region on the order  
 1077 of a few mm in length capped by a drift electrode. As a charged particle traverses the detector, it ionizes gas  
 1078 and the electrons drift down towards readout strips. The timing of the drift can be used to reconstruct the  
 1079 angle of traversal of the particle. This is illustrated in figure 2.12. The micromegas used in ATLAS will be  
 1080 resistive micromegas, where the readout electrodes are topped with resistive strips [58]. This alleviates the  
 1081 risk of sparking in the large area detectors that ATLAS will use.

1082 In ATLAS, the micromegas drift gap will be 5 mm and the amplification gap will be  $128\ \mu\text{m}$ . They are

1083 filled with the same gas mixture as the MDTs. They will be stacked in an octuplet in an XXUV-UVXX  
 1084 geometry, where X refers to nominal strips and U and V refer to stereo strips at an angle of  $\pm 1.5^\circ$ . This  
 1085 arrangement allows for measurement of the azimuthal coordinate and gives a large lever arm between the  
 1086 straight strips for triggering purposes. Figure 2.12 shows the geometry of a single micromegas detector as  
 1087 well as its operating principle [56].

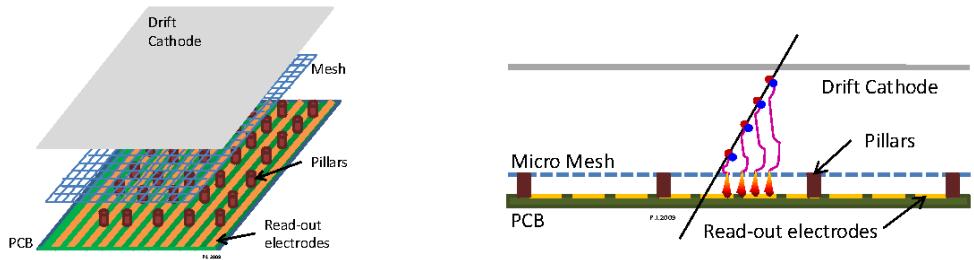


Figure 2.12: Illustrations of the geometry (left) and operating principle (right) of the micromegas detector [56].

## 1088 sTGCs

1089 The sTGCs are similar to the TGCs currently in the ATLAS endcap muon system [43]. They consist  
 1090 of gold-plated tungsten wires (with a 1.8 mm pitch) between two cathode planes 1.4 mm away from the  
 1091 wire plane. One cathode plane consists of strips with a 3.2 mm pitch (much smaller pitch than the TGCs),  
 1092 while the other consists of coarser pads that are used for defining regions of interest in the sTGC trigger  
 1093 algorithm. Figure 2.13 shows the basic detector geometry.

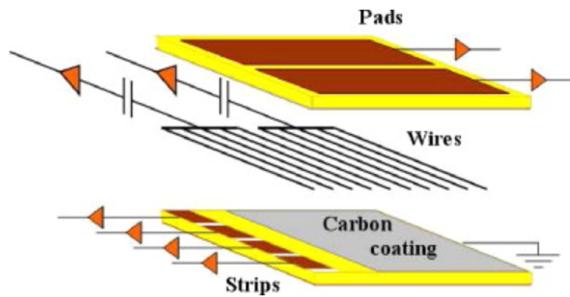


Figure 2.13: Geometry of the sTGC detector [56].

1094 2.3.3 PHYSICS IMPACT

1095 Maintaining low  $p_T$  thresholds for muons while still staying within the trigger rate budget at Level 1 for the  
1096 muon system (20 kHz) is crucial for physics analyses to be successful in high luminosity conditions. One  
1097 realm where the lepton trigger threshold is especially important is in Higgs physics. In the  $H \rightarrow WW^*$   
1098 analysis, one of the  $W$  bosons is off shell and tends to decay to soft leptons. In associated production of a  
1099 Higgs with a  $W$ , the lepton is also important because it provides the main handle which allows the event  
1100 to be triggered. Without the NSW, analyses would be required to either raise the muon  $p_T$  threshold or  
1101 only use muons triggered from the barrel muon system. Table 2.3 shows that both of these alternatives  
1102 significantly reduce the Higgs signal efficiency. With the NSW, the signal efficiency is largely maintained  
1103 and the triggers can remain unprescaled at lower  $p_T$  thresholds.

Threshold	$H \rightarrow b\bar{b}$ (%)	$H \rightarrow WW^*$ (%)
$p_T > 20$ 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 [56].

1104 2.4 OBJECT RECONSTRUCTION IN ATLAS

1105 ATLAS analyses first start by requiring the presence of certain reconstructed physics objects in the event.  
1106 This section will present a brief overview of the algorithms used to reconstruct electrons, muons, jets (in-  
1107 cluding  $b$ -jets), and missing energy<sup>2</sup>. The performance of physics object reconstruction and identification  
1108 will also be discussed as these are relevant to the analyses presented later. Figure 2.14 gives an overview of  
1109 the different sub-detectors that each type of particle will interact with in ATLAS.

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<sup>2</sup>Reconstruction algorithms for other objects, such as photons and hadronically decaying  $\tau$  leptons, are not detailed here as these objects are not used in the results presented in this dissertation.

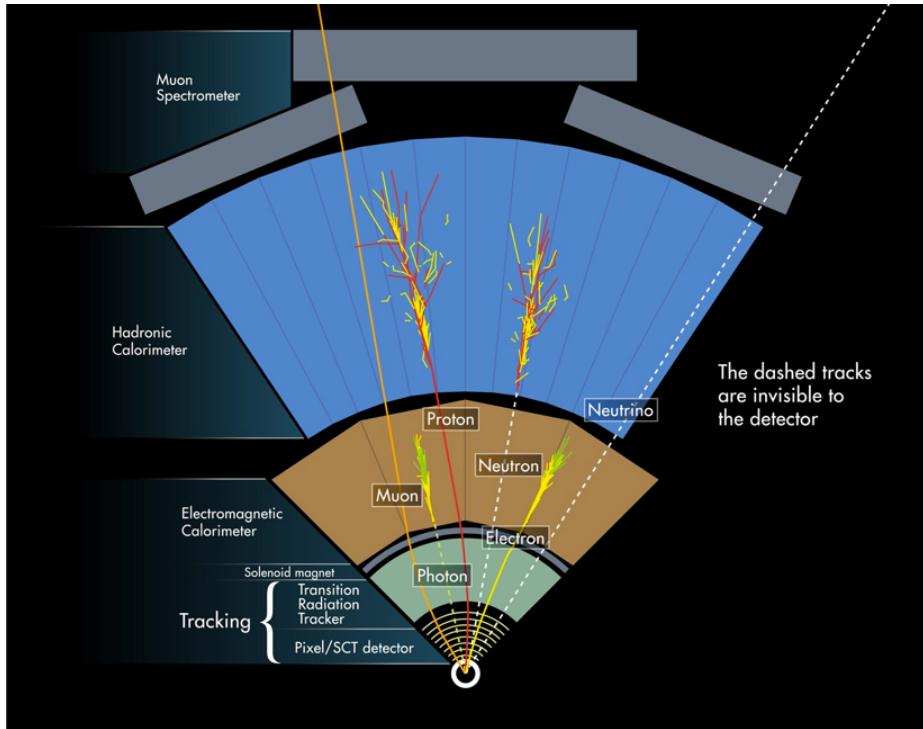


Figure 2.14: Illustration of particle interactions in ATLAS [59]

#### 1110 2.4.I ELECTRONS

1111 Electrons in ATLAS will leave tracks in the inner detector and energy deposits in the electromagnetic  
 1112 calorimeter. The algorithm for recognizing the signature of electrons proceeds in two steps: reconstruction  
 1113 and identification.

1114 In reconstruction, an electron candidate is formed by matching EM calorimeter deposits with ID tracks.  
 1115 The algorithm first chooses seed clusters in the EM calorimeter by using a sliding window algorithm that  
 1116 searches for towers with transverse energy larger than 2.5 GeV. In addition to seed clusters, track candi-  
 1117 dates must be identified in the ID. The algorithm selects seed tracks with  $p_T > 1$  GeV that do not fit  
 1118 well with a pion hypothesis. Once candidate tracks are selected, they are re-fit with a Gaussian Sum Filter  
 1119 (GSF) algorithm to estimate electron parameters [60]. Finally, an electron candidate is formed if at least  
 1120 one track matches to a seed cluster in the calorimeter. The full details of the reconstruction algorithm can  
 1121 be found in reference [61].

1122 Once an electron candidate is present, identification criteria must be applied in order to reject fake elec-

trons from background. Many different variables are used for this identification. They include information about the shower shape in the EM calorimeter and the amount of leakage into the hadronic calorimeter, as well as information from the ID and in particular the TRT. There are both selection requirement based and likelihood-based criteria that range from “loose” to “very tight”. For details, see reference [61]. In the  $H \rightarrow WW^*$  analysis, both medium and very tight likelihood electrons are used depending on the electron  $p_T$ .

Figure 2.15 shows the algorithm’s reconstruction efficiency for true electrons with different identification criteria as well as the electron energy resolution in simulation [61, 62]. The reconstruction efficiency is measured using both the  $Z$  and  $J/\psi$  with 8 TeV data.

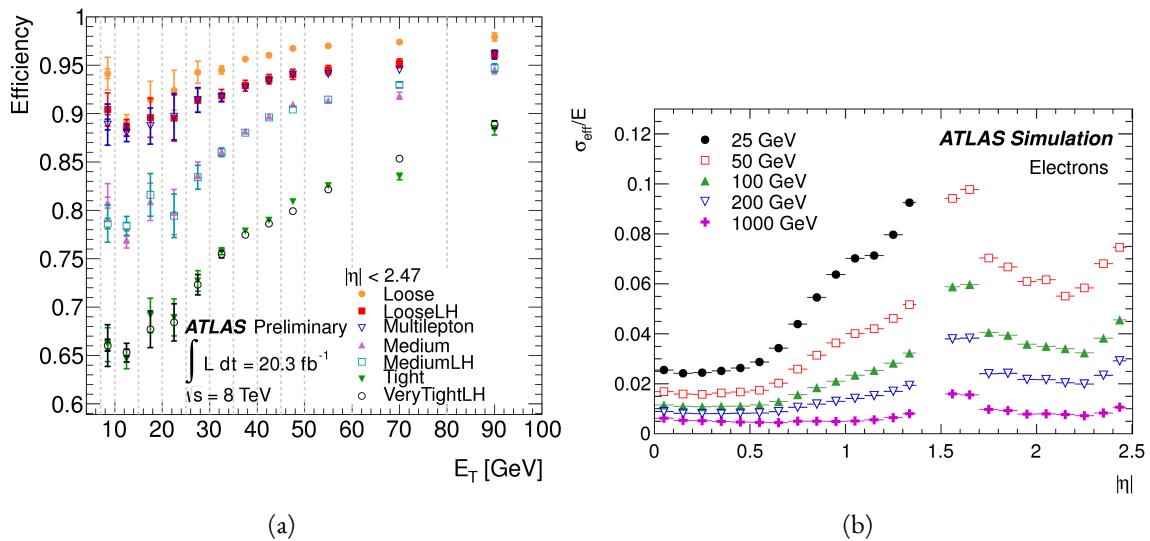


Figure 2.15: Electron performance: (a) reconstruction efficiency as a function of electron  $E_T$  [61] (b) energy resolution in simulation as a function of  $|\eta|$  for different energy electrons [62].

#### 2.4.2 MUONS

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

1137        The first step of reconstruction is to reconstruct local straight line tracks, called segments, in each muon  
1138        chamber. Segments are then fit to larger tracks that traverse the entire muon spectrometer. Such muon  
1139        tracks are referred to as “standalone” tracks (SA) as they only use information from the muon spectrometer.  
1140        The standalone tracks are then matched to tracks in the inner detector to form “combined” (CB) muons,  
1141        and both tracks are used to determine the momentum and direction of the muon. To improve acceptance,  
1142        segment-tagged and calorimeter-tagged muons are also reconstructed. In these cases, ID tracks are matched  
1143        to segments in the MS and calorimeter deposits consistent with a minimum ionizing particle, respectively.  
1144        The details of the reconstruction can be found in reference [63].

1145        As with electrons, once muon candidates are reconstructed they have identification criteria applied to  
1146        reduce background. These criteria include the  $\chi^2$  match between the ID and MS tracks, the number of  
1147        hits in the ID, overall ID and MS track fit quality, and additional variables. In Run 1, the muons used are  
1148        simply referred to as combined muons [63]. In Run 2, an improved reconstruction algorithm is used and  
1149        criteria ranging from “loose” to “tight” are defined (similar to what is done with electrons) [64]. Figure 2.16  
1150        shows the muon reconstruction efficiency (measured with the  $Z$  and  $J/\psi$ ) and invariant mass resolution  
1151        in  $\sqrt{s} = 8$  TeV data.

#### 1152        2.4.3 JETS

1153        When a quark or gluon is produced in collisions, it is not measured directly in ATLAS. Rather, due to  
1154        QCD effects, it produces a collimated spray of hadrons in the direction of the original parton, which is  
1155        known as a jet. Jets are reconstructed in ATLAS using energy deposits in the hadronic calorimeter. The  
1156        first step is build “topological clusters” out of energy deposits in calorimeter cells [65, 66]. This is done  
1157        using strategy where seed cells are chosen by picking cells whose energy measurements are four times the  
1158        amount of noise expected for that cell. Adjacent cells with at least  $2\sigma$  energy measurements are added to  
1159        the cluster, then a final layer of clusters with energy above  $0\sigma$  are added. Once calorimeter clusters are  
1160        formed, they are clustered further into jet candidates. The analyses presented in this thesis use the anti- $k_T$   
1161        jet clustering algorithm [67]. This algorithm defines a parameter  $R$  that appears in the denominator of  
1162        the clustering distance metric and defines the radial size of the jet in  $\eta$ - $\phi$  space.

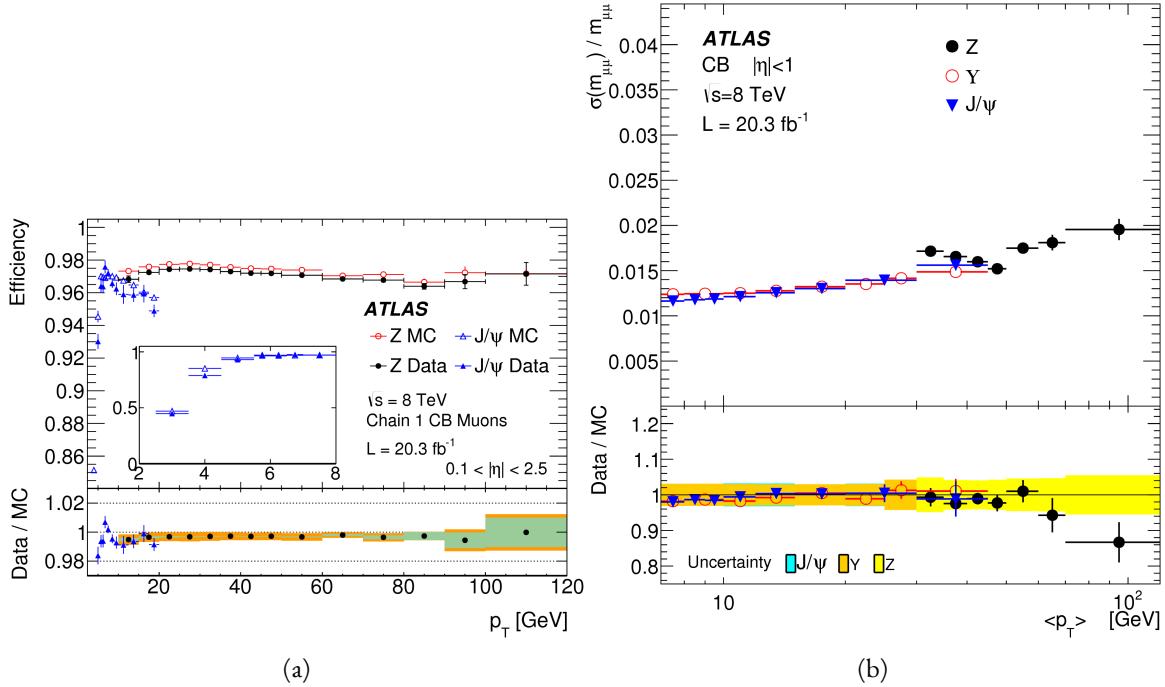


Figure 2.16: Muon performance in  $\sqrt{s} = 8$  TeV data: (a) reconstruction efficiency as a function of muon  $p_T$  (b) dimuon mass resolution as a function of average  $p_T$  [63].

The energy response of the calorimeter must be properly characterized in order to reconstruct the true 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 discussed here and are presented in reference [68]. Figure 2.17 shows the jet energy response after calibration in Monte Carlo as a function of the true  $p_T$  of the jet [68]. Analyses often need to know how consistent a particular jet is with the primary vertex of the event in order to avoid contamination from pileup interactions. One measure of this consistency is known as the jet vertex fraction (JVF). The JVF is the ratio of tracks associated with a primary vertex to the total number of tracks inside a jet. Jets from the primary interaction in the event should have a large fraction of tracks consistent with the primary vertex and therefore have a large JVF value.

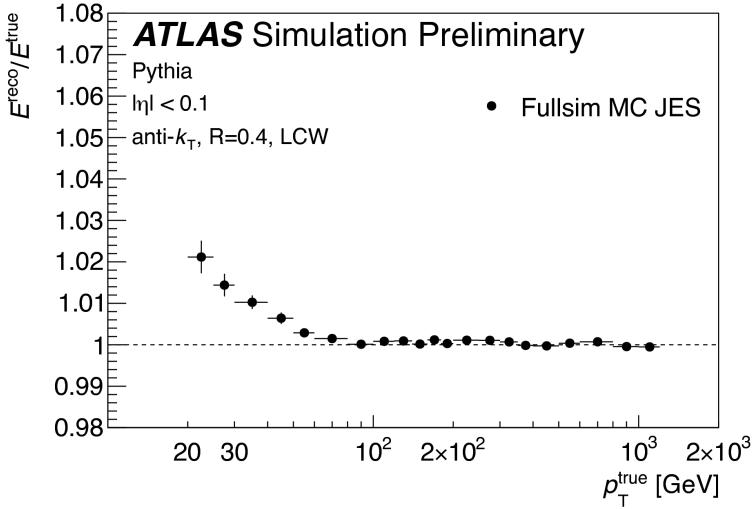


Figure 2.17: Jet energy response after calibration as a function of true  $p_T$  in simulation [68].

1174    2.4.4    *b*-TAGGING

1175    One important aspect of jet physics is the task of identifying the flavor of parton that produced the mea-  
 1176    sured jet. While in general this is very difficult, jets from *b*-quarks offer an interesting case where such  
 1177    identification is possible. *B* mesons have a lifetime on the order of  $10^{-12}$  seconds, which makes a  $c\tau$  of  
 1178    0.5 mm [6]. This type of displaced decay vertex can be identified in detectors like ATLAS and allows *b*-jets  
 1179    to be distinguished from other flavors of jets<sup>3</sup>. With boosts, *B* mesons can travel for several millimeters  
 1180    before decaying.

1181    ATLAS uses several algorithms, including a multivariate machine learning technique, to identify jets  
 1182    from *b*-quarks. The inputs to the multivariate algorithm are determined from lower level reconstruction  
 1183    algorithms. There are three distinct algorithms that reconstruct variables which are used as input to the  
 1184    multivariate technique.

1185    The first family of algorithms is referred to as IPxD (where the x can either be 2 or 3). These algorithms  
 1186    use the transverse and longitudinal impact parameters  $d_0$  and  $z_0$  of the tracks inside a jet to determine their  
 1187    consistency with the primary vertex. They use two or three dimensional (hence the x) templates for light

---

<sup>3</sup>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

1188 flavor, charm, and bottom jets and then evaluate the likelihood of the jet coming from each of these types.

1189 The likelihood ratios are used as inputs to the multivariate algorithm.

1190 The next two algorithms used as input are referred to as the secondary vertex (SV) and JetFitter (JF)  
1191 algorithms. The SV algorithm uses tracks inside the jet to fit for vertices that are displaced from the pri-  
1192 mary vertex. The JF algorithm attempts to reconstruct the full flight path of the  $b$  by looking for multiple  
1193 displaced vertices along the same line (as  $B$  decays often result in subsequent charm meson decays).

1194 In Run 1, the multivariate  $b$ -tagging algorithm used a neural network and was referred to as MV1. The  
1195 details of this algorithm and its inputs are given in reference [69]. This algorithm is used for defining a  
1196 veto on  $b$ -jets in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis presented in Part 2. In Run 2, the number of inputs  
1197 was simplified and a boosted decision tree with 24 input variables was used, referred to as MV2 [70].  
1198 The MV2 algorithm is a boosted decision tree incorporating twenty-four input variables constructed from  
1199 three lower level input algorithms described above. This algorithm is used for  $b$ -tagging in the  $X \rightarrow$   
1200  $HH \rightarrow b\bar{b}b\bar{b}$  search presented in Part 3. Figure 2.18 summarizes the inputs to MV2. Figure 2.19 shows the  
1201 performance of each of these algorithms in Run 1 and Run 2.

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
	$\Delta R$	$\Delta R$
Kinematics (2 inputs)		
	$p_T$	
	$\eta$	

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

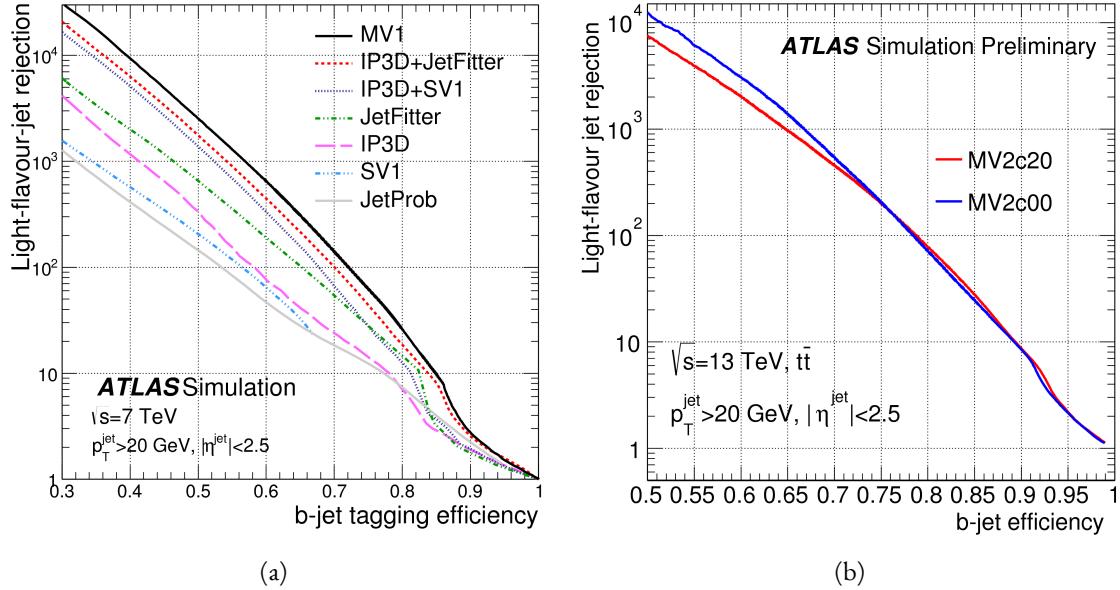


Figure 2.19: Light jet rejection (1/efficiency) vs.  $b$ -jet efficiency for MV1 and its input algorithms (a) [69] and MV2 (b) [70] in simulated  $t\bar{t}$  events. The numbers in the algorithm names in (b) refer to the fraction of charm events used in the MV2 training.

## 1202 2.4.5 MISSING TRANSVERSE ENERGY

1203 As noted in figure 2.14, neutrinos produced in ATLAS will pass through the detector without interacting.  
 1204 The only way of detecting the presence of weakly interacting particles like neutrinos (or BSM particles  
 1205 that are long-lived) is to use missing transverse momentum. The basic principle of missing transverse en-  
 1206 ergy is to use the momentum balance of the incoming protons to infer the presence of missing particles.  
 1207 The net longitudinal momentum of the incoming partons that collide is not known (since each carries  
 1208 an unknown fraction of the proton's momentum). However, the protons (and thus incoming partons)  
 1209 have essentially no net momentum in the plane transverse to the beam line (the  $x$ - $y$  plane). Therefore, if  
 1210 there are no undetected particles in the final state, the transverse momenta of all of the final state particles  
 1211 should balance. The magnitude of the imbalance in the transverse plane is known as missing transverse  
 1212 momentum ( $E_T^{\text{miss}}$ ).

1213 The basic calculation of missing transverse momentum from calorimeter cells is given in equation 2.4 [71].

1214

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

1215 The  $E_T^{\text{miss}}$  calculation is separated into different terms based on the objects that the calorimeter clusters  
 1216 are associated with. This way, each cell's contribution is calibrated appropriately according to the object.  
 1217 This separation of terms used to define the  $E_T^{\text{miss}}$  in Run 1 is shown in equation 2.5 [71].

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

1218 The CellOut term of the above equation corresponds to calorimeter cells with energy deposits that are  
 1219 not associated with other objects. The soft jets term comes from cells associated to jets with  $p_T$  between  
 1220 7 and 20 GeV, while the jets term comes from jets with  $p_T > 20$  GeV. Because muons do not deposit  
 1221 significant energy in the calorimeter, the muon momentum (after correction for the energy deposited in  
 1222 the calorimeter for non-isolated muons) is used for the muon term [71]. The final  $E_T^{\text{miss}}$  is calculated using  
 1223 equation 2.6.

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

1224 Figure 2.20 shows the resolution of the components of the  $E_T^{\text{miss}}$  with different pileup suppression tech-  
 1225 niques [72].

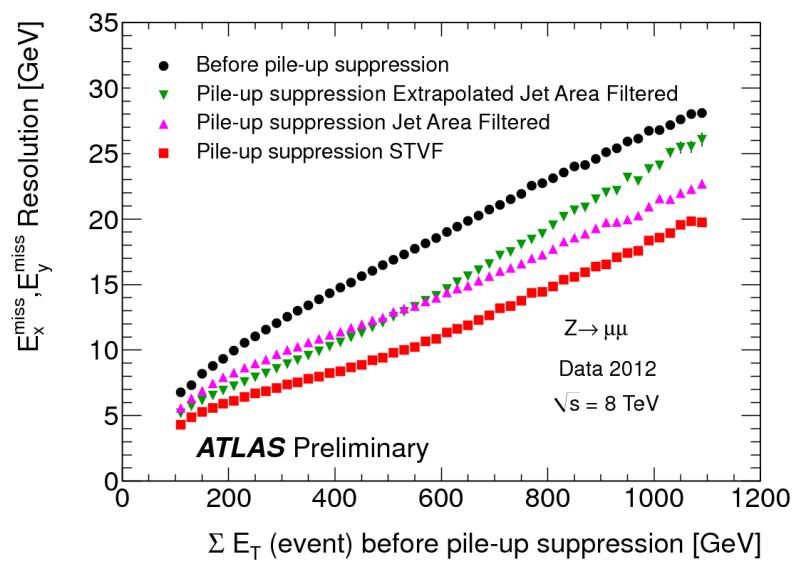


Figure 2.20: Resolution of  $E_T^{\text{miss}}$  components as a function of  $\sum E_T$  before pileup suppression with different pileup techniques [72].

1226

## Part II

1227

Observation and measurement of Higgs

1228

boson decays to  $WW^*$  in LHC Run I at

1229

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

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

Wernher von Braun

# 3

1230

## 1231 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ Analysis Strategy

### 1232 3.1 INTRODUCTION

1233 This chapter presents an overview of the strategy for searching for a Higgs boson in the  $H \rightarrow WW^* \rightarrow$   
1234  $\ell\nu\ell\nu$  decay topology. Its purpose is to define in broad terms how the search and measurement are under-  
1235 taken, before going into details on the specific sub-categories within the larger analysis. First, the properties  
1236 of the Higgs signal are discussed and the associated backgrounds are presented. Next, the observables used  
1237 to enhance the signal to background ratio are defined. Finally, the parameters of interest in the search  
1238 and measurement will be shown, along with a brief overview of the statistical treatment of the final Higgs  
1239 candidates.

1240 Following this chapter, three different results from the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel are shown.  
1241 Chapter 4 presents the discovery and subsequent measurement of Higgs boson production in gluon fusion  
1242 mode and the role of the  $H \rightarrow WW^*$  channel. Chapter 5 shows the search and first evidence in ATLAS  
1243 for the Vector Boson Fusion (VBF) production mode of the Higgs. Finally, chapter 6 shows the combined

1244 Run 1  $H \rightarrow WW^*$  results for the measurement of the Higgs cross section and relative coupling strengths  
1245 to other SM particles.

1246 3.2 THE  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  SIGNAL IN ATLAS

1247 The signal studied in this and subsequent chapters is the Higgs boson in the  $WW^*$  final state, where each  
1248  $W$  boson subsequently decays into a charged lepton and a neutrino. In the simplest decay path, the final  
1249 state consists of two neutrinos and two charged leptons, each of which can be either an electron or a muon.  
1250 If a  $W$  decays to a  $\tau$  lepton, only leptonic decays of the  $\tau$  are considered. The  $\tau$  lepton produce additional  
1251 neutrinos in the final state but still yield two charged leptons (where each lepton is an electron or muon).  
1252 Neutrinos are not detected in ATLAS, so the final state ultimately consists of two reconstructed leptons  
1253 and missing transverse momentum (denoted as  $E_T^{\text{miss}}$ ). Final states where both of the charged leptons are  
1254 electrons or muons are referred to as the “same flavor” ( $ee/\mu\mu$ ) final states, while those with one electron  
1255 and one muon are referred to as “different flavor” ( $e\mu$  or  $\mu e$ ).

1256 There can be additional jets produced in association with the Higgs boson. As described in detail in  
1257 Chapter 1, if the Higgs is produced via vector boson fusion production, there will be two additional forward  
1258 jets in the event. In gluon fusion, one or more jets can be produced through initial state radiation from  
1259 the incoming gluons. Because of the varying background composition as a function of jet multiplicity,  
1260 each bin in this variable has its own dedicated requirements applied in the search and measurement. The  
1261  $n_j = 0$  and  $n_j = 1$  bins are dedicated to gluon fusion production, while the  $n_j \geq 2$  bin has separate  
1262 dedicated searches for ggF and VBF production.

1263 Figure 3.1 shows the relative branching fractions for the  $H \rightarrow WW^*$  process, calculated from the Par-  
1264 ticle Data Group values for the  $W$  and  $\tau$  branching ratios [6]. The largest branching ratio corresponds  
1265 to both  $W$  bosons decaying to quark pairs at 45.44%. The second largest ratio is for one  $W$  decaying lep-  
1266 tonically and the other decaying to quarks, a branching ratio of 34.18%. In all cases,  $\ell$  denotes either an  
1267 electron or muon, and the leptonic branching ratios of the  $\tau$  are included. For example, the  $\ell\nu qq$  final  
1268 state includes one  $W$  decaying to  $e\nu$ ,  $\mu\nu$ , or  $\tau\nu$ . In the case of the  $W \rightarrow \tau\nu$  decay, the  $\tau$  lepton then  
1269 decays to an electron or muon via  $\tau \rightarrow \nu_\tau \ell \nu_\ell$ . Final states with a  $\tau_h$  refer to hadronic decays of the  $\tau$ . The

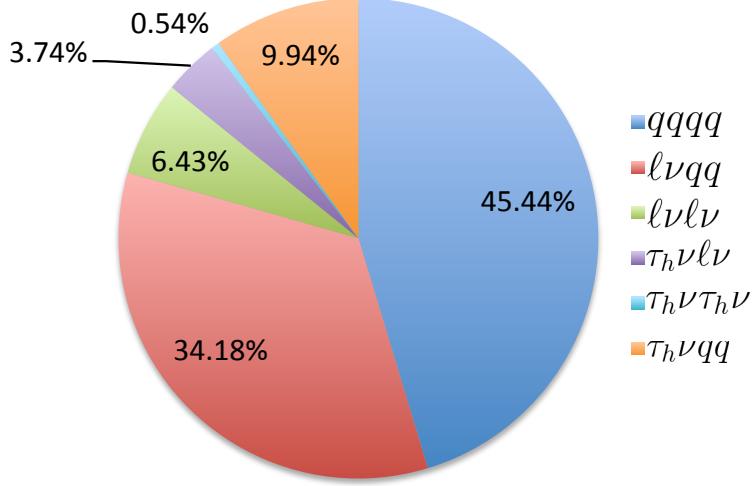


Figure 3.1: Branching ratios for a  $WW$  system.  $q$  refers to quarks.  $\ell$  can be either an electron or muon, and the leptonic branching ratios of the  $\tau$  are included. For example, the  $\ell\nu qq$  final state includes one  $W$  decaying to  $e\nu$ ,  $\mu\nu$ , or  $\tau\nu$ .  $\tau_h$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

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

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

### 3.3 BACKGROUND PROCESSES

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

#### 3.3.1 STANDARD MODEL WW PRODUCTION

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

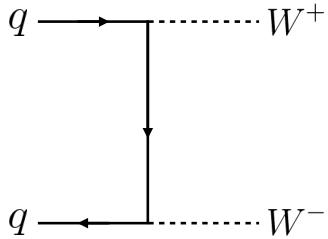


Figure 3.2: Feynman diagram for Standard Model  $WW$  production

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

### 3.3.2 TOP QUARK PRODUCTION

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

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

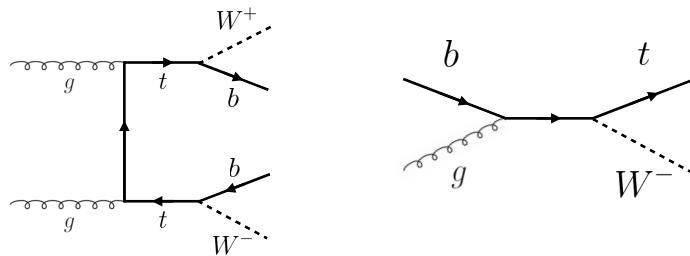


Figure 3.3: Feynman diagrams for top pair production (left) and  $Wt$  production (right)

1293 3.3.3  $W$ +JETS BACKGROUND

1294 Single  $W$  boson production in association with jets is a unique background to Higgs production. The  
1295 other backgrounds considered thus far have all included two prompt leptons, each decaying from a  $W$   
1296 boson, in the final state. In  $W$ +jets production, however, only one reconstructed lepton originates from  
1297 a  $W$ . The second reconstructed lepton is either an algorithmic “fake” or the result of non-prompt decays.  
1298 In the first case, the lepton is a jet misidentified as a lepton by either the electron or muon reconstruction  
1299 algorithms. In the second case, the lepton may be a real lepton but coming from semi-leptonic decays of  
1300 particles inside the shower of the jet. This background can be reduced by requiring that the reconstructed  
1301 lepton have little activity in the surrounding region of the calorimeter (also known as an “isolation”). Fig-  
1302 ure 3.4 shows the Feynman diagram for  $W$ +jets production.

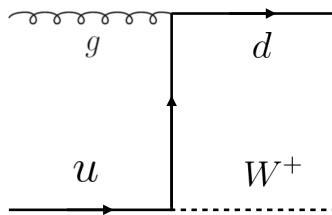


Figure 3.4: An example Feynman diagram of  $W$ +jets production

1303 3.3.4  $Z/\gamma^*$ +JETS BACKGROUND

1304 Production of a  $Z$  boson or virtual photon (also known as Drell-Yan and denoted with  $Z/\gamma^*$ ) in associa-  
1305 tion with jets is also a background to Higgs production. The  $Z$  boson decays to two leptons of the same  
1306 flavor. When the  $Z/\gamma^*$  decays directly to electrons or muons, the background enters the same flavor final  
1307 state. When the  $Z$  decays to two  $\tau$  leptons the background can enter the different flavor final state as well.  
1308 Figure 3.5 shows the production of a  $Z$  in association with one jet. Because there are no neutrinos in this  
1309 final state, variables like  $E_T^{\text{miss}}$  can be used to reduce the background<sup>i</sup>.

---

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

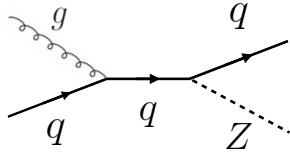


Figure 3.5: An example Feynman diagram of  $Z + \text{jets}$  production

### 3.3.5 SUBDOMINANT BACKGROUNDS

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

Category	Process	Description
SM $WW$	$WW \rightarrow \ell\nu\ell\nu$	Real leptons and neutrinos
Top quark production	$t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b\bar{b}\nu\bar{b}$	Real leptons, untagged $b$ s
	$tW \rightarrow WbW \rightarrow \ell\nu\ell\nu b$	Real leptons, untagged $b$
	$t\bar{b}, t\bar{q}\bar{b}$	Untagged $b$ , jet misidentified as lepton
Drell-Yan	$Z/\gamma^* \rightarrow ee, \mu\mu$	“Fake” $E_T^{\text{miss}}$
	$Z/\gamma^* \rightarrow \tau\tau \rightarrow \ell\nu\ell\nu\nu\nu$	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
	$W\gamma, Z\gamma$	$\gamma$ 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

### 3.4 SHARED SIGNAL REGION SELECTION REQUIREMENTS

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

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

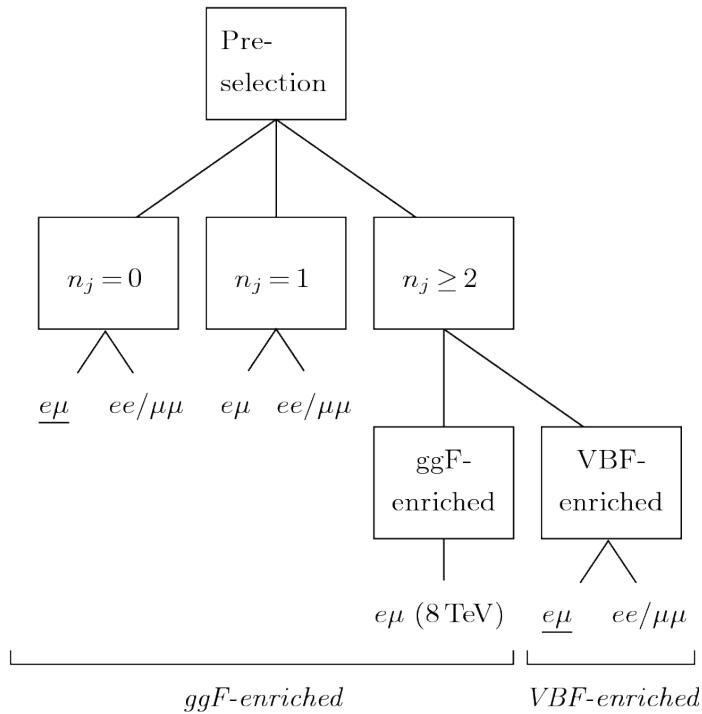


Figure 3.6: An illustration of the unique analysis signal regions [73]. The most sensitive regions for both gluon fusion and vector boson fusion production are underlined.

#### 3.4.1 EVENT PRE-SELECTION

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

1332 In general, it is expected that the signal should have a harder  $E_T^{\text{miss}}$  spectrum than backgrounds, espe-  
 1333 cially if these backgrounds do not contain neutrinos in the final state. When using  $E_T^{\text{miss}}$ , it is possible  
 1334 mis-measurements of objects in the detector can lead to imbalances in the transverse plane. When such a  
 1335 mis-measurement occurs, the  $E_T^{\text{miss}}$  vector in the transverse plane will often point in the same direction as  
 1336 the mis-measured object. Therefore, a new variable,  $E_{T,\text{rel}}^{\text{miss}}$ , is used in the pre-selection.  $E_{T,\text{rel}}^{\text{miss}}$  is defined  
 1337 in equation 3.1.

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

1338 If the closest object to the  $E_T^{\text{miss}}$  vector is within  $\pi/2$  radians in the transverse plane, the  $E_T^{\text{miss}}$  is projected  
 1339 away from this object. Otherwise, the normal  $E_T^{\text{miss}}$  vector is used. Figure 3.7 shows a graphical illustration  
 of this concept.

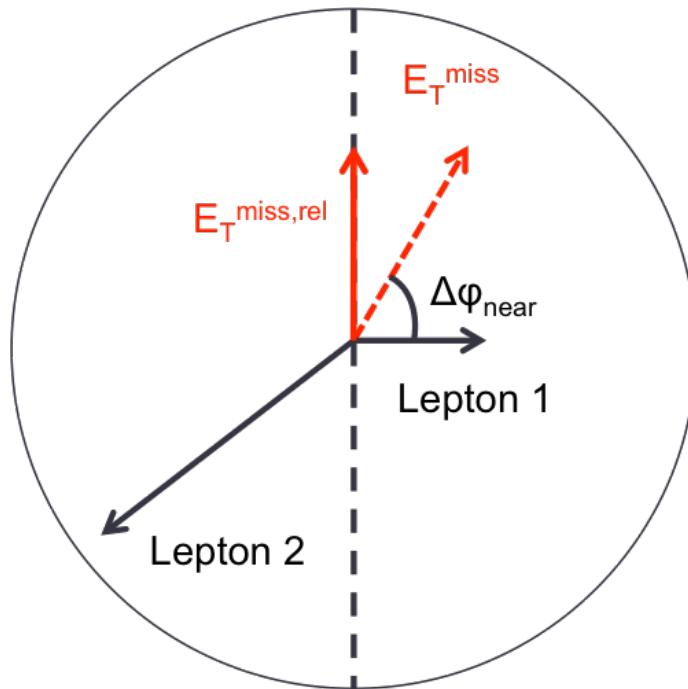


Figure 3.7: A graphical illustration of the  $E_{T,\text{rel}}^{\text{miss}}$  calculation

1340  
 1341 Once the lepton and  $E_T^{\text{miss}}$  pre-selections are made, the analysis is divided into different regions accord-  
 1342 ing to jet multiplicity.

1343 3.4.2 JET MULTIPLICITY

1344 Jet multiplicity, denoted as  $n_j$ , is used to sub-divide the analysis into distinct signal regions. By creating  
 1345 separate signal regions, each bin in jet multiplicity becomes sensitive to different modes of Higgs produc-  
 1346 tion and different backgrounds.

1347 For example, the  $n_j \geq 2$  region is more sensitive to VBF production because of the two high momen-  
 1348 tum jets produced at matrix element level. For gluon fusion production to enter this bin, two initial state  
 1349 radiation jets must be emitted.

1350 Figure 3.8 shows the jet multiplicity in both the different flavor and same flavor regions after the pre-  
 1351 selection. It also shows the background composition in the bins of  $n_b$ . A few trends from this distribution  
 1352 are worth noting. The first is that the Drell-Yan background dominates in the same flavor channels for  
 1353  $n_j \leq 1$ . Second, the top background becomes a clear contributor to the total background for  $n_j \geq$   
 1354 1. Lastly, the SM WW production dominates in the  $n_j = 0$  bin, as it is an irreducible background to  
 1355  $H \rightarrow WW^*$  production. Because of these distinct features, each jet multiplicity bin is treated separately.

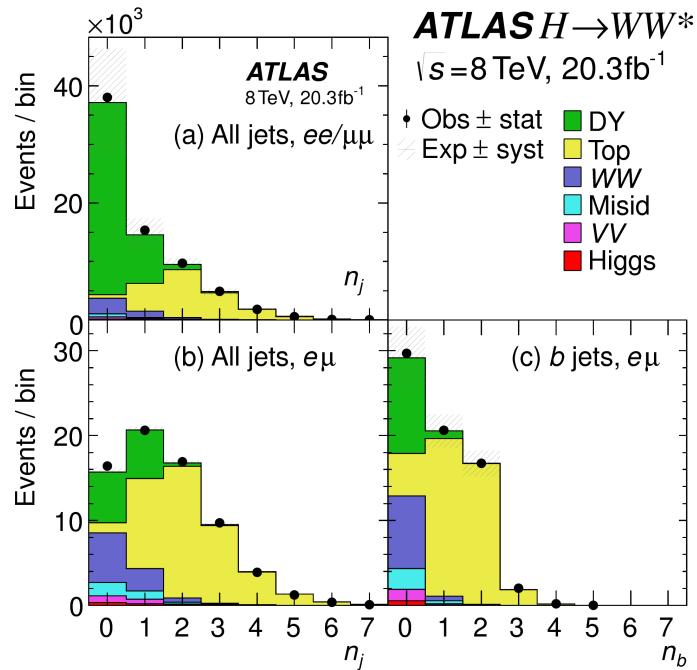


Figure 3.8: Predicted backgrounds (compared with data) as a function of  $n_j$  (a and b) and  $n_b$  (c) after pre-selection requirements

1356    3.5 BACKGROUND REDUCTION IN SAME-FLAVOR FINAL STATES

1357    As described in section 3.4.2, the background composition of the same flavor final states is different from  
1358    that of the different flavor states. In particular, Drell Yan processes play a much larger role because the  
1359     $Z/\gamma^*$  decays to same flavor leptons. Because real neutrinos are absent in the  $Z/\gamma^*$  decays to  $ee$  and  $\mu\mu$ , a  
1360    requirement on  $E_T^{\text{miss}}$  should largely reduce the background. However, as this section will demonstrate,  
1361    with increasing pileup conditions the resolution of the calorimeter-based  $E_T^{\text{miss}}$  degrades greatly. There-  
1362    fore, two new variables for  $Z/\gamma^*$  background reduction are constructed and described in this section.

1363    3.5.1 PILEUP AND  $E_T^{\text{miss}}$  RESOLUTION

1364    Secondary interactions of protons in the colliding bunches of the LHC (known as pileup interactions,  
1365    described in detail in Chapter 2) deposit energy into the ATLAS calorimeter in addition to the energy that  
1366    comes from the hard scatter process of interest. The calculation of  $E_T^{\text{miss}}$  is fundamentally Poissonian.  
1367    Summing up all of the energy deposits in individual calorimeter cells or clusters is similar to a counting  
1368    experiment. The error on a mean of  $N$  in a Poisson distribution is  $\sqrt{N}$ , so the energy resolution scales  
1369    as  $\sqrt{E}$ . As more energy is deposited in the calorimeter, the  $E_T^{\text{miss}}$  resolution degrades, meaning that the  
1370     $E_T^{\text{miss}}$  resolution is particularly sensitive to LHC instantaneous luminosity conditions.

1371    Figure 3.9 shows an event display of a  $Z/\gamma^* + \text{jets}$  event candidate with the twenty-five reconstructed  
1372    primary vertices. This display illustrates that while the interaction of interest only has tracks coming from  
1373    the hardest primary vertex, all of the secondary interactions deposit energy in the calorimeter as well.

1374    Figure 3.10 shows the RMS of the  $E_T^{\text{miss}}$  distribution in  $Z \rightarrow \mu\mu$  events (where there are no real neu-  
1375    trinos) as a function of the number of the average number of interactions. Under 2011 LHC conditions,  
1376    this RMS was approximately 9 GeV, while under 2012 running conditions the resolution worsened to 12  
1377    GeV. The increase in pileup dilutes the  $E_T^{\text{miss}}$  variable’s ability to reduce the  $Z/\gamma^*$  background.

1378    3.5.2 TRACK-BASED DEFINITIONS OF MISSING TRANSVERSE MOMENTUM

1379    Because the increasing number of secondary proton-proton interactions degrades calorimeter-based  $E_T^{\text{miss}}$   
1380    resolution, a new variable using only contributions from the primary interaction vertex is necessary to

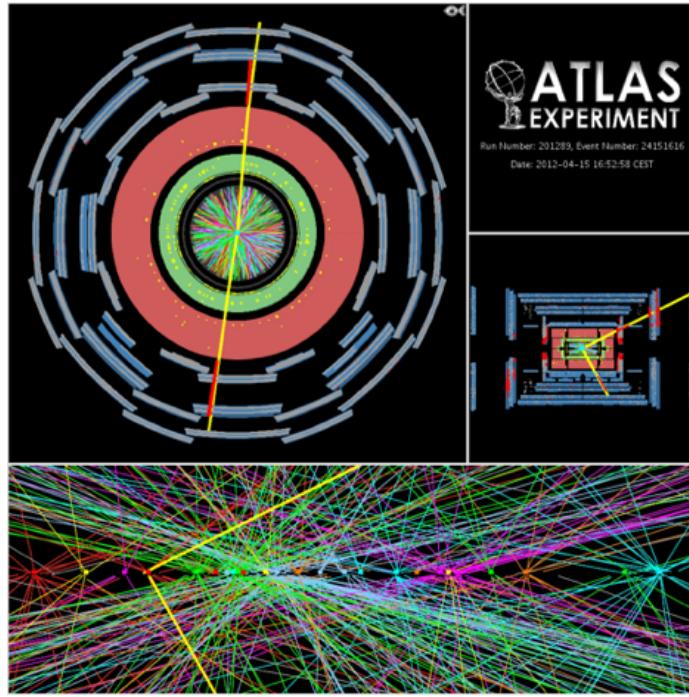


Figure 3.9: An event display of a  $Z/\gamma^*$  + jets event illustrating the effect of pileup interactions

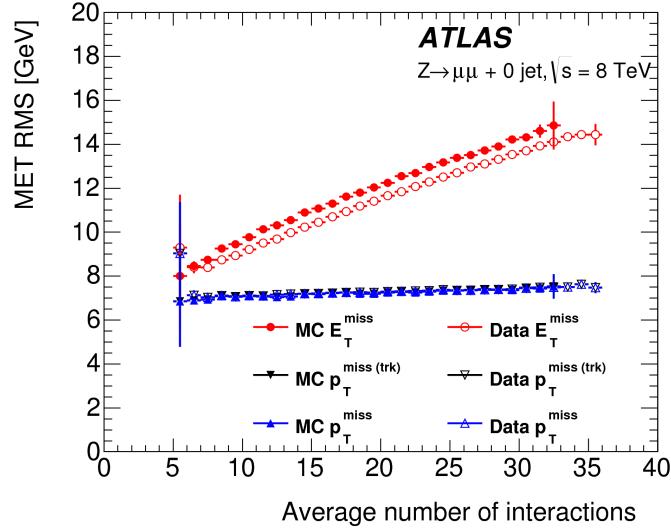


Figure 3.10: The RMS of different missing transverse momentum definitions as a function of the average number of interactions per bunch crossing

<sup>1381</sup> further reduce the  $Z/\gamma^*$  background. While it is not possible to associate calorimeter energy deposits  
<sup>1382</sup> with a particular vertex, individual charged particle tracks in the Inner Detector are associated to unique  
<sup>1383</sup> vertices. Thus, two track-based definitions of missing transverse momentum , using only tracks coming

1384 from the primary vertex in the event, are used in the analysis. The simplest variable,  $p_T^{\text{miss}(\text{trk})}$ , is the  
 1385 vectorial sum of the  $p_T$  of all of the tracks from the primary vertex and the selected leptons (excluding the  
 1386 tracks associated with the selected leptons to avoid double counting). Equation 3.2 defines  $p_T^{\text{miss}(\text{trk})}$ .

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

1387 To further improve the resolution on the missing transverse momentum, the variable  $p_T^{\text{miss}}$  is used as de-  
 1388 fined in equation 3.3. For selected leptons and jets, the nominal  $p_T$  measurements are used. Tracks are used  
 1389 to estimate the soft component of the missing transverse momentum instead of calorimeter measurements.

1390

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

1391 Figure 3.10 illustrates that these two new variables accomplish their intended purpose. The resolution as a  
 1392 function of mean number of interactions for both  $p_T^{\text{miss}(\text{trk})}$  and  $p_T^{\text{miss}}$  is much flatter than the dependence  
 1393 for  $E_T^{\text{miss}}$ . Figure 3.11a shows the difference between the true and reconstructed values of missing transverse  
 1394 momentum using both the track-based  $p_T^{\text{miss}}$  and calorimeter based  $E_T^{\text{miss}}$ . The RMS of the distribution  
 1395 improves by 3.5 GeV when using  $p_T^{\text{miss}}$ .

### 1396 3.5.3 DISTINGUISHING $Z/\gamma^*$ +JETS AND $H \rightarrow WW^*$ TOPOLOGIES

1397 In addition to measuring missing transverse momentum, another variable can be constructed to exploit  
 1398 kinematic and topological differences between the  $Z/\gamma^*$  background and  $H \rightarrow WW^*$  signal. Because  
 1399 there are no real neutrinos in the final state (in the case of  $Z/\gamma^* \rightarrow ee, \mu\mu$  decays), the dilepton system will  
 1400 be balanced with the jets produced in the hard scatter. A new variable,  $f_{\text{recoil}}$ , is constructed to estimate  
 1401 the balance between the dilepton system and recoiling jets and is defined in equation 3.4. The transverse  
 1402 plane is divided into four sections, or quadrants, with one quadrant centered on the dilepton vector. The  
 1403 numerator of  $f_{\text{recoil}}$  is the magnitude of the vectorial sum of the  $p_T$  of jets in the quadrant opposite the  
 1404 dilepton system, weighted by each jet's Jet Vertex Fraction (JVF, described in chapter 2). The denominator

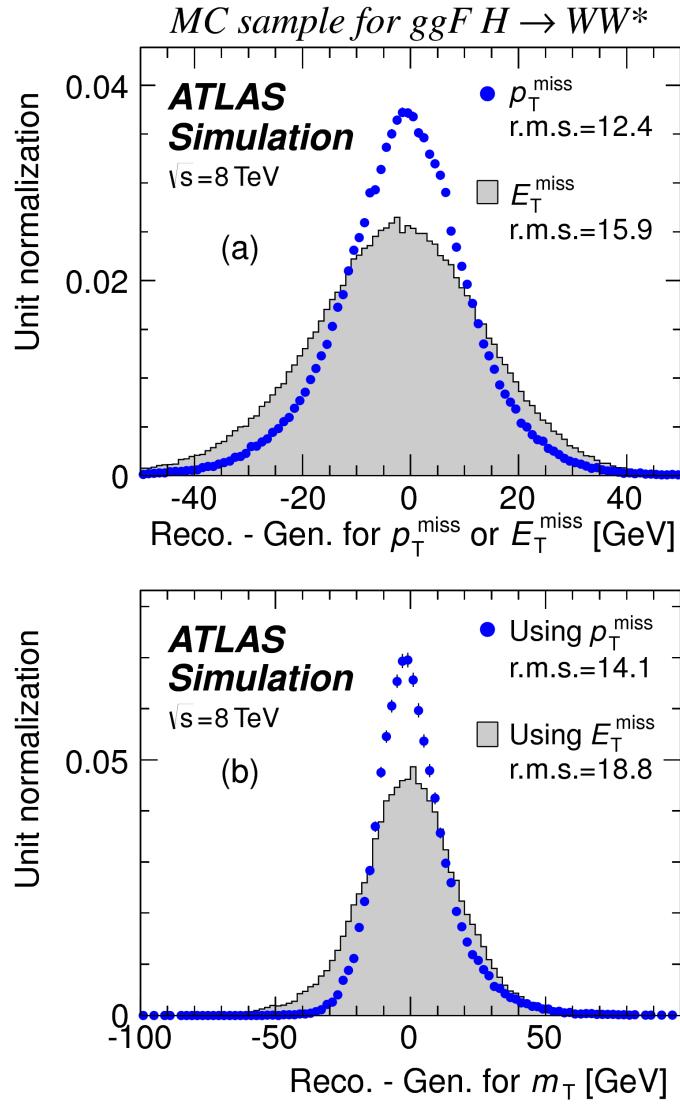


Figure 3.11: The difference between the true and reconstructed values of the missing transverse momentum (a) and  $m_T$  (b) in a gluon fusion signal sample

1405 is the magnitude of the dilepton  $p_T$ .

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

1406 Figure 3.12 shows a shape comparison of the  $f_{\text{recoil}}$  distribution in a simulated  $Z/\gamma^* + \text{jets}$  sample, a  
 1407  $H \rightarrow WW^*$  signal sample, and other backgrounds that contain real neutrinos. The  $Z/\gamma^* + \text{jets}$  events

<sup>1408</sup> tend to be more balanced between the dilepton system and recoiling jets, while the processes containing  
<sup>1409</sup> real neutrinos are less balanced in the transverse plane. Thus, a requirement on  $f_{\text{recoil}}$  will reduce the  $Z/\gamma^*$   
<sup>1410</sup> + jets background while maintaining a good signal efficiency.

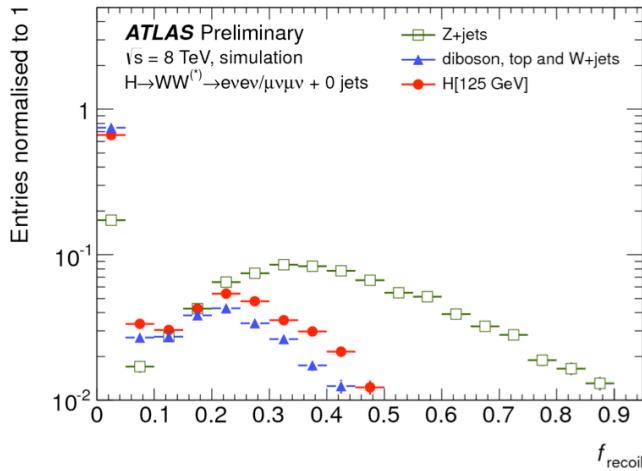


Figure 3.12: Comparison of  $f_{\text{recoil}}$  distributions for  $Z/\gamma^* + \text{jets}$ ,  $H \rightarrow WW^*$ , and other backgrounds with real neutrinos.

#### <sup>1411</sup> 3.5.4 OPTIMIZING BACKGROUND REDUCTION SELECTION REQUIREMENTS

<sup>1412</sup> The requirements on  $p_T^{\text{miss}(\text{trk})}$  and  $f_{\text{recoil}}$  used to reduce the  $Z + \text{jets}$  background must be optimized to  
<sup>1413</sup> maximize expected signal significance in the same flavor channels. Figure 3.13 shows an optimization of  
<sup>1414</sup> the combination of the two requirements in the gluon fusion zero jet bin. Each bin shows the expected  
<sup>1415</sup> signal significance if the  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  is required to be greater than the left edge of the bin and the  $f_{\text{recoil}}$  is  
<sup>1416</sup> required to be less than the top edge of the bin. The figure shows that the best signal significance comes  
<sup>1417</sup> from requiring low values of  $f_{\text{recoil}}$  ( $< 0.05$ ) and  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  values greater than 45 GeV.

#### <sup>1418</sup> 3.6 PARAMETERS OF INTEREST AND STATISTICAL TREATMENT

<sup>1419</sup> As with any search or measurement, there are particular parameters of the Higgs that the  $H \rightarrow WW^*$   
<sup>1420</sup> analysis is interested in measuring. In this case, the parameters of interest are the mass of the Higgs boson  
<sup>1421</sup> and its production cross section. Because the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  process does not have a closed final

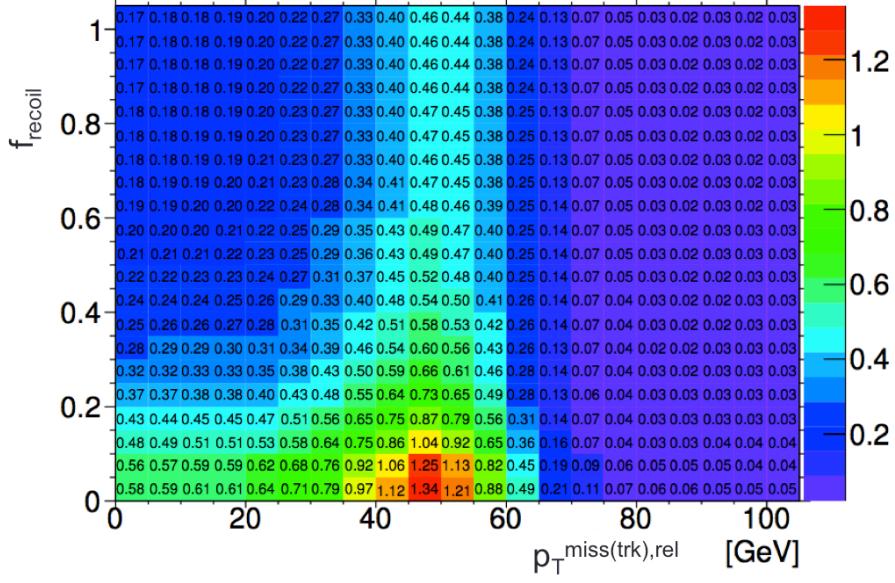


Figure 3.13: Signal significance as a function of required value for  $f_{\text{recoil}}$  and  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  in the ggF  $H \rightarrow WW^*$  with  $n_j = 0$

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

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

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

### 3.6.1 TRANSVERSE MASS

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

1432 information from the transverse plane. The transverse mass is defined in equation 3.6.

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

1433 Here the  $E_T^{\ell\ell}$  and  $\vec{p}_T^{\ell\ell}$  are the transverse energy and momentum of the dilepton system, while  $p_T^{\text{miss}}$  is a  
1434 proxy for the transverse momentum of the di-neutrino system. The track-based  $p_T^{\text{miss}}$  is used in the  $m_T$   
1435 rather than the calorimeter based  $E_T^{\text{miss}}$  because it has a better resolution on the true transverse mass.  
1436 Figure 3.11b shows the improvement in the RMS of the difference between the true and reconstructed  
1437 transverse mass in a ggF signal sample. The RMS improves by 4.7 GeV using  $p_T^{\text{miss}}$  in the  $m_T$  calculation.

1438 **3.6.2 STATISTICAL TREATMENT<sup>2</sup>**

1439 **LIKELIHOOD FUNCTION**

1440 The statistical analysis of final event candidates is framed as a hypothesis test, where the null hypothesis is  
1441 background-only (no Standard Model Higgs). The first step in the analysis is to form a likelihood function  
1442 for the data. In its simplest form, this likelihood is the probability of observing the number of events seen  
1443 in the final signal region given knowledge of the signal strength. Because observation of events is funda-  
1444 mentally a Poisson counting experiment, this simple likelihood can be expressed as a Poisson probability of  
1445 observing  $N$  events given a total number of predicted signal and background events. This basic likelihood  
1446 is shown in equation 3.7.

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

1447 Here,  $P$  is the Poisson probability density function,  $N$  is the total number of observed events,  $\mu$  is the  
1448 signal strength,  $S$  is the predicted number of signal events, and  $B$  is the predicted number of background  
1449 events.

1450 In particle physics, certain background estimates are commonly normalized in so-called “control” re-  
1451 gions and those predictions are scaled by the same normalization factor in the signal region. This leads to a  
1452 slightly more complicated likelihood, which is a function of both the signal strength and the background

---

<sup>2</sup>Many thanks to Aaron Armbruster, whose thesis [74] inspired parts of this section.

1453 normalization. This is shown in equation 3.8.

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

1454 Here,  $\theta$  serves as a “nuisance parameter”, or a parameter that is not of primary interest but still enters the  
1455 likelihood. The second Poisson term enforces that the background normalization be consistent with the  
1456 number of observed events in data in the control region,  $N_{\text{CR}}$ .

1457 So far, these two formulations of likelihoods have assumed a single signal region and do not take into  
1458 account any shape information of potential discriminating variables. The  $H \rightarrow WW^*$  analysis is divided  
1459 into many different categories, the counting experiment described above can be performed in each individ-  
1460 ual category. As mentioned in section 3.6.1, the transverse mass is used as the primary discriminating vari-  
1461 able in many of the  $H \rightarrow WW^*$  sub-analyses. The same counting experiment can be performed in each  
1462 bin of the  $m_T$  distribution to incorporate some shape information. Thus, the total likelihood becomes a  
1463 product over signal regions and bins of the  $m_T$  distribution. Finally, there are usually many backgrounds  
1464 that are normalized in control regions. The new formulation of the likelihood takes this into account by  
1465 including a product over control regions in the second Poisson term. All of these modifications are shown  
1466 in equation 3.9.

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

1467 The final step to obtain the full likelihood used in the analysis is to add nuisance parameters for the  
1468 systematic uncertainties. In cases where the uncertainty does not affect the shape of  $m_T$  bin-by-bin, each  
1469 systematic uncertainty  $\epsilon$  is allowed to affect the expected event yields through a linear response function  
1470 of the nuisance parameter, namely  $\nu(\theta) = (1 + \epsilon)\theta$ . If instead the uncertainty does affect the shape, the  
1471 effect is instead parameterized by  $\nu_b(\theta) = 1 + \epsilon_b\theta$ . The value of the nuisance parameters for the systematic  
1472 uncertainty are constrained with a Gaussian term that is added to the likelihood as well. This is of the form  
1473  $g(\delta|\theta) = e^{-(\delta-\theta)^2/2}/\sqrt{2\pi}$ , where  $\delta$  is the central value and  $\theta$  is a nuisance parameter. Finally, a last term is  
1474 added to account for the statistical uncertainty in the Monte Carlo samples used, which adds an additional

<sup>1475</sup> poisson term. The full likelihood used in the final statistical analysis is defined in equation 3.10.

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

<sup>1476</sup> The fourth term of the equation quantifies the uncertainty due to finite Monte Carlo sample size. Here,  
<sup>1477</sup>  $\xi$  represents the central value of the background prediction,  $\theta$  is the associated nuisance parameter,  $\zeta =$   
<sup>1478</sup>  $(B/\delta B)^2$ , where  $\delta B$  is the statistical uncertainty of  $B$ .

<sup>1479</sup> The best fit value of the signal strength  $\mu$  is determined by finding the values of  $\mu$  and  $\boldsymbol{\theta}$  that maximize  
<sup>1480</sup> the likelihood, while setting  $\delta = 0$  and  $\xi = \zeta$ . Once the likelihood is defined, a test statistic must be built  
<sup>1481</sup> for use in hypothesis testing.

## <sup>1482</sup> TEST STATISTIC

<sup>1483</sup> To distinguish whether the data match a background only or background and signal hypothesis, a test  
<sup>1484</sup> statistic must be used. The  $H \rightarrow WW^*$  analysis uses the profile likelihood technique [75]. The first step  
<sup>1485</sup> in formulating this test statistic is to define the profile likelihood ratio, shown in equation 3.11.

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

<sup>1486</sup> Here  $\hat{\theta}_\mu$  is the value of  $\theta$  that maximizes the likelihood for the choice of  $\mu$  being tested. Additionally,  $\hat{\theta}$   
<sup>1487</sup> and  $\hat{\mu}$  represent the values of  $\theta$  and  $\mu$  that gives the overall maximum value of the likelihood.

<sup>1488</sup> Once this is defined, a test statistic  $q_\mu$  is constructed. This is shown in equation 3.12.

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

1489 A higher value of  $q_\mu$  indicates that the data are more incompatible with the hypothesized value of  $\mu$ , and  
1490  $q_0$  then corresponds to the value of the test statistic for the background only hypothesis. A  $p_0$  value is  
1491 then defined to quantify the compatibility between the data and the null hypothesis. The  $p_0$  value is the  
1492 probability of obtaining a value of  $q_0$  larger than the observed value, and this is shown in equation 3.13.

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

1493 Here  $f(q_\mu)$  is the probability distribution function of the test statistic. Finally, the  $p_0$  value can be con-  
1494 verted into a signal significance, using the formula in equation 3.14, or the one-sided tail of the Gaussian  
1495 distribution.

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

1496 The threshold for discovery used in particle physics is  $Z_0 \geq 5$ , more commonly known as a value of  $5\sigma$ .

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

Marcel Proust

# 4

1497

## 1498 The discovery of the Higgs boson and the role 1499 of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel

### 1500 4.1 INTRODUCTION

1501 This chapter presents the results of the search for the Higgs boson in  $4.8 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 7 \text{ TeV}$   
1502 and  $5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . The results of three searches at  $\sqrt{s} = 8 \text{ TeV}$  in the  $H \rightarrow WW^* \rightarrow$   
1503  $\ell\nu\ell\nu$ ,  $H \rightarrow \gamma\gamma$ , and  $H \rightarrow ZZ \rightarrow 4\ell$  channels are shown. These results at  $8 \text{ TeV}$  are combined  
1504 with the results of searches at  $\sqrt{s} = 7 \text{ TeV}$  in the same channels along with  $H \rightarrow \tau\tau$  production and  
1505 associated production searches for  $H \rightarrow b\bar{b}$ . The results of this combination are a  $5.9\sigma$  detection of a  
1506 new particle consistent with a Higgs boson produced via gluon fusion. Rather than going into detail for  
1507 all of the different Higgs decay searches, this chapter will discuss the three most sensitive channels and in  
1508 particular focus on  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ . While the focus is on  $WW^*$ , some of the  $ZZ^*$  and  $\gamma\gamma$  results

1509 are shown for completeness. The results not discussed here can be found in the ATLAS Higgs discovery  
1510 publication [1].

1511 **4.2 DATA AND SIMULATION SAMPLES**

1512 The data sample used for the following results was taken in 2011 and 2012 at center of mass energies of 7 and  
1513 8 TeV, respectively, with  $4.8 \text{ fb}^{-1}$  collected at 7 TeV and  $5.8 \text{ fb}^{-1}$  collected at 8 TeV. Higgs production  
1514 in the gluon fusion and vector boson fusion modes is modeled with POWHEG for the hard scattering event  
1515 and PYTHIA for the showering and hadronization. Associated production of a Higgs with a vector boson  
1516 or top quarks is modeled via PYTHIA . Table 4.1 shows the Monte Carlo generators used for modeling the  
1517 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].

1518 **4.3  $H \rightarrow WW \rightarrow e\nu\mu\nu$  SEARCH**

1519 The  $H \rightarrow WW \rightarrow e\nu\mu\nu$  search is unique compared to the  $ZZ$  and  $\gamma\gamma$  channels. The Higgs mass  
1520 cannot be fully reconstructed due to the presence of neutrinos in the final state, so the transverse mass  $m_T$   
1521 is used as the final discriminating variable. This channel also has a wider variety of backgrounds compared  
1522 to other channels, as discussed in chapter 3. The same flavor final states are excluded from the 8 TeV dataset

1523 due to high pileup conditions<sup>1</sup>. These final states are later included in results with the full Run 1 dataset,  
1524 as discussed in chapters 5 and 6.

1525 **4.3.1 EVENT SELECTION**

1526 The analysis requires to opposite charge isolated leptons, with the leading (sub-leading) lepton required to  
1527 have  $p_T > 25(15)$  GeV. The events are separated into different signal regions depending on which flavor  
1528 of lepton is leading ( $e\mu$  for leading electron,  $\mu e$  for leading muon). Strict lepton quality cuts are applied  
1529 to the sample to reduce backgrounds from mis-reconstructed leptons.

1530 Jets are reconstructed with the anti- $k_T$  algorithm with a radius parameter  $R = 0.4$ . The jets are re-  
1531 quired to have  $p_T > 25$  GeV and  $|\eta| < 4.5$ , with jets in the tracking volume required to have a jet vertex  
1532 fraction of 0.5 and jets in the forward region required to have  $p_T > 30$  GeV. The analysis is separated  
1533 into three different signal regions based on jet multiplicity:  $n_j = 0, 1, \geq 2$ .

1534 To indicate the presence of neutrinos in the event, a requirement of  $E_{T,\text{rel}}^{\text{miss}} > 25$  GeV is made<sup>2</sup>. This  
1535 requirement significantly reduces the QCD multijet and  $Z/\gamma^*$  + jets backgrounds. Figure 4.1 shows the  
1536 distribution of  $n_j$  in data and simulation after applying these “pre-selection” requirements.

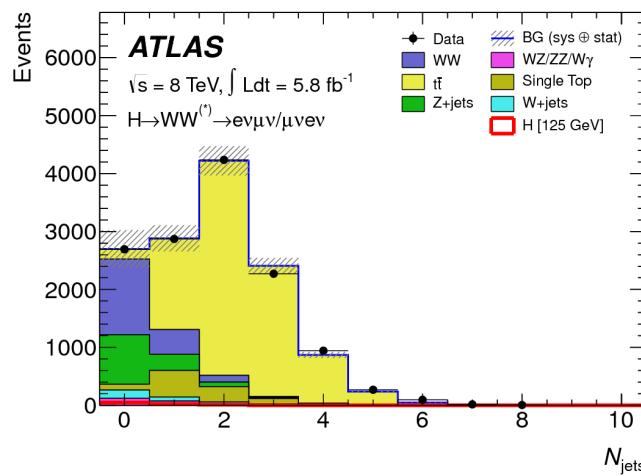


Figure 4.1: Jet multiplicity distribution in data and MC after applying lepton, jet, and  $E_{T,\text{rel}}^{\text{miss}}$  selections. The  $WW$  and top backgrounds have been normalized using control samples, and the hashed band indicates the total uncertainty on the prediction [1].

<sup>1</sup>The less sensitive 7 TeV search result includes both different flavor and same flavor final states.

<sup>2</sup>For the definition of  $E_{T,\text{rel}}^{\text{miss}}$ , see section 3.4.1.

1537        Additional selections are applied to require the dilepton topology to correspond to that of a Standard  
1538        Model Higgs boson. The requirements are presented here - more detailed discussion on the motivation  
1539        for each requirement is saved for Chapter 5. In all of the jet multiplicity channels, the dilepton system  
1540        is required to have a small gap in azimuthal angle,  $\Delta\phi_{\ell\ell} < 1.8$ . Similarly, the dilepton invariant mass,  
1541         $m_{\ell\ell}$ , is required to be less than 50 GeV in the lower jet multiplicity channels and less than 80 GeV in the  
1542         $n_j \geq 2$  channel. In the  $n_j = 0$  channel, the magnitude of the dilepton  $p_T$ ,  $p_T^{\ell\ell}$ , is required to be greater  
1543        than 30 GeV.

1544        In the higher jet multiplicity channels ( $n_j \geq 1$ ), the top background is a larger fraction of the total  
1545        background and must be reduced more carefully. The total transverse momentum  $p_T^{\text{sum}}$  is thus required  
1546        to be less than 30 GeV. Additionally, the di- $\tau$  invariant mass  $m_{\tau\tau}$  (dilepton mass computed under the  
1547        assumption that the neutrinos from the  $\tau$  decay are emitted collinear to the charged leptons [76]) is used  
1548        to reject  $Z \rightarrow \tau\tau$  events by requiring  $|m_{\tau\tau} - m_Z| > 25$  GeV. These variables are also discussed in more  
1549        detail in Chapter 5.

1550        In the  $n_j \geq 2$  channel, requirements are made to isolate the VBF contribution to Higgs production.  
1551        The kinematics of the two leading jets are used to make these requirements. In particular, the event must  
1552        have  $\Delta y_{jj} > 3.8$  and  $m_{jj} > 500$  GeV, along with a veto on having any additional jets with rapidity  
1553        between the two leading jets.

#### 1554        4.3.2 BACKGROUND ESTIMATION

1555        The details of the background estimation techniques used in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis are  
1556        discussed in section 5.5. The dominant backgrounds are SM  $WW$  production and top (both pair and  
1557        single) production, and these backgrounds have their normalizations estimated from dedicated control  
1558        regions while their shapes are taken from simulation.

1559        The control sample for the Standard Model  $WW$  background is defined by making the same require-  
1560        ments as the signal region with the  $m_{\ell\ell}$  requirement inverted (now requiring  $m_{\ell\ell} > 80$  GeV) and remov-  
1561        ing the  $\Delta\phi_{\ell\ell}$  requirement. This creates a control sample that is 70% (40%) pure in the 0(1)-jet region. The  
1562        correction to the pure MC-based background estimate is quantified by defining a normalization factor  $\beta$

1563 which is the ratio of the data yield to the MC yield ( $N_{\text{data}}/N_{\text{MC}}$ ) in this control sample. Table 4.2 shows  
 1564 the  $WW$  normalization factors in the  $n_j = 0$  and  $n_j = 1$  bins (the  $n_j \geq 2$  estimate is taken directly  
 1565 from MC).

$n_j$	$\beta_{WW}$	$\beta_t$
= 0	$1.06 \pm 0.06$	$1.11 \pm 0.06$
= 1	$0.99 \pm 0.15$	$1.11 \pm 0.05$
$\geq 2$	-	$1.01 \pm 0.26$

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.

1566 The top background estimate is also computed separately in each jet multiplicity bin. In the  $n_j = 0$   
 1567 channel, the background is first normalized using data after pre-selection requirements with no selection  
 1568 on  $n_j$ . Then, a dedicated  $b$ -tagged control sample is used to evaluate the ratio of one-jet to two-jet events in  
 1569 data. The details of this technique are shown in reference [77]. In the  $n_j = 1$  and the  $n_j \geq 2$  regions, the  
 1570 top background is normalized in a control sample where the signal region selections are applied, but the  
 1571  $b$ -jet veto is reversed and the Higgs topology requirements on  $m_{\ell\ell}$  and  $\Delta\phi_{\ell\ell}$  are removed. The resulting  
 1572 normalization factors for these techniques are shown in table 4.2.

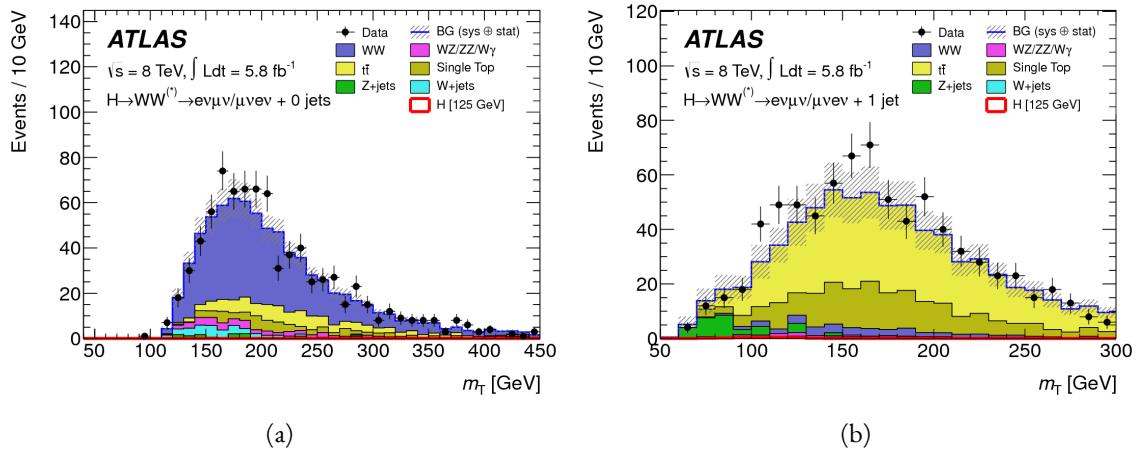


Figure 4.2: Comparison of  $m_T$  between data and simulation in the  $n_j = 0$   $WW$  (a) and  $n_j = 1$  top (b) control samples [1].

1573 The control samples which are used for background normalization can also be used to validate the mod-  
 1574 eling of the  $m_T$  distribution for each background. Figure 4.2 shows the comparison between data and MC

1575 for the  $m_T$  distribution after correcting the normalization of the backgrounds in the  $WW$  and top control  
1576 regions. Good agreement between data and simulation is seen in both cases.

1577 The  $W + \text{jets}$  background estimate is taken entirely from data using a control sample with one well recon-  
1578 structed lepton and one anti-identified lepton. All other backgrounds are taken purely from simulation.

#### 1579 4.3.3 SYSTEMATIC UNCERTAINTIES

1580 The systematic uncertainties that have the largest impact on the analysis are the theoretical uncertainties  
1581 associated with the signal cross section. These are shared with the  $ZZ^*$  and  $\gamma\gamma$  channels. The uncertainties  
1582 resulting from variations of the QCD scale are  $+7\% / -8\%$  on the final signal yield. Those coming from  
1583 variations of the parton distribution function (PDF) used in the simulation add a  $\pm 8\%$  uncertainty on  
1584 the yield. The uncertainties on the branching ratios of the Higgs are  $\pm 5\%$ .

1585 The main experimental uncertainties come from variations of the jet energy scale (JES), jet energy reso-  
1586 lution, pile-up,  $E_T^{\text{miss}}$ ,  $b$ -tagging efficiency,  $W + \text{jets}$  background estimate, and integrated luminosity. For  
1587 more details, see reference [1].

#### 1588 4.3.4 RESULTS

1589 Table 4.3 shows the signal and background yields in the final signal region after normalizing the back-  
1590 grounds according to the methods described above.

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

1591     Figure 4.3 shows the  $m_T$  distribution in the  $n_j \leq 1$  channels for 8 TeV data. (No events are observed  
 1592     in data in the  $n_j \geq 2$  channels in this dataset). The excess shown here relatively flat as a function of  
 1593     hypothesized Higgs mass. The combined 7 and 8 TeV data gives an excess with local significance of  $2.8\sigma$   
 1594     with an expected significance of  $2.3\sigma$ , corresponding to a  $\mu$  measurement of  $1.3 \pm 0.5$ .

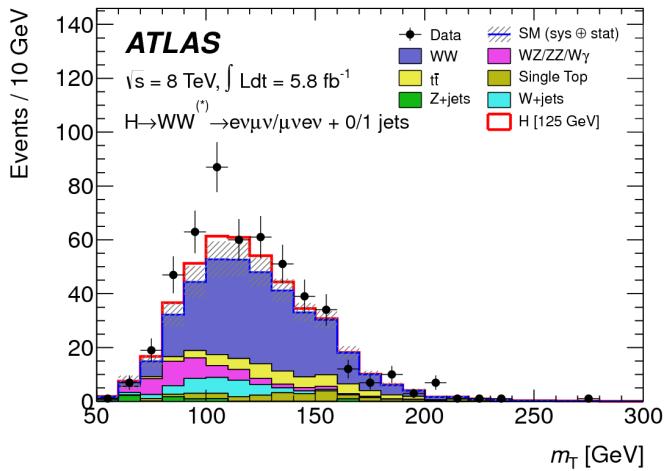


Figure 4.3:  $m_T$  distribution in the  $H \rightarrow WW \rightarrow e\nu\mu\nu$   $n_j \leq 1$  channels for 8 TeV data [1].

#### 1595    4.4    $H \rightarrow \gamma\gamma$ SEARCH

1596     The  $H \rightarrow \gamma\gamma$  search is a search for a peaked excess above the falling SM diphoton mass spectrum, with  
 1597      $m_{\gamma\gamma}$  as the ultimate discriminating variable. Events are selected by requiring two isolated photons, with  
 1598     the leading (sub-leading) photon required to have  $E_T > 40(30)$  GeV. In the 8 TeV data, the photons are  
 1599     required to pass identification criteria consistent with a photonic shower in the electromagnetic calorimeter  
 1600     and little leakage in the hadronic calorimeter.

1601     The main challenges for this analysis are accurate mass reconstruction and background estimation. In  
 1602     order to accurately reconstruct the invariant mass of the di-photon system, both the energy and direction  
 1603     of the photons must be measured well. Therefore, the identification of the primary vertex of the hard  
 1604     interaction is particularly important, and is done using a multivariate likelihood which combines informa-  
 1605     tion about the photon direction and vertex position. The background is modeled with a falling spectrum  
 1606     in  $m_{\gamma\gamma}$  that is parameterized by different functions depending on the category of the event.

1607    4.4.1    RESULTS

1608    The resulting diphoton mass spectrum is shown in figure 4.4. The best fit mass value in the  $\gamma\gamma$  channel  
 1609    alone in the combined 7 and 8 TeV data is 126.5 GeV. The local significance at this point is  $4.5\sigma$ , with  
 1610    an expected significance of  $2.5\sigma$ . Therefore, the measured signal strength  $\mu$  is  $1.8 \pm 0.5$  in this channel.

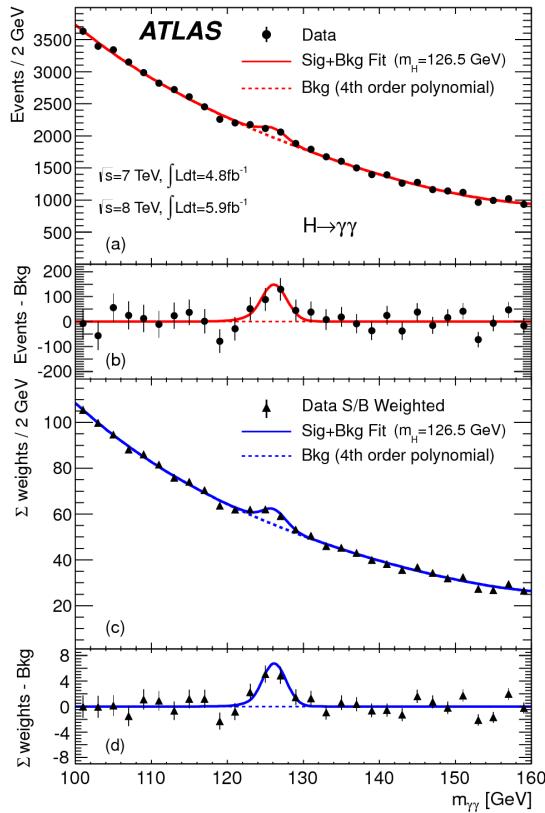


Figure 4.4: Diphoton mass spectrum in 7 and 8 TeV data. Panel a) shows the unweighted data distribution superimposed on the background fit, while panel c) shows the data where each event category is weighted by its signal to background ratio. Panels b) and d) show the respective distributions with background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

1611    4.5     $H \rightarrow ZZ \rightarrow 4\ell$  SEARCH

1612    The  $H \rightarrow ZZ \rightarrow 4\ell$  analysis searches for a Standard Model Higgs boson decaying to two  $Z$  bosons, each  
 1613    of which decays to a pair of same flavor, opposite charge isolated leptons. The ultimate discriminating  
 1614    variable is  $m_{4\ell}$ , or the invariant mass of the four selected leptons. The  $\ell$  denotes an  $e$  or  $\mu$  as with the  
 1615     $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis.

1616 Four distinct signal regions are constructed depending on the flavors of the final state, additionally sep-  
1617 arated by the flavor of the leading lepton pair. These are referred to as  $4e$ ,  $2e2\mu$ ,  $2\mu2e$ ,  $4\mu$ .

1618 The main backgrounds in the  $H \rightarrow ZZ \rightarrow 4\ell$  search are continuum  $ZZ^*$  production,  $Z + \text{jets}$  pro-  
1619 duction, and  $t\bar{t}$ . The  $m_{4\ell}$  distribution for background is estimated from simulation. The normalization  
1620 of the SM  $ZZ^*$  background is also taken from MC simulation, while the  $Z + \text{jets}$  and  $t\bar{t}$  normalizations are  
1621 taken from data-driven methods.

1622 **4.5.1 RESULTS**

1623 Figure 4.5 shows the  $m_{4\ell}$  spectrum measured in the 7 and 8 TeV datasets. The total number of events  
1624 observed in the window between 120 and 130 GeV is 13, with 6 events in the  $4\mu$  channel, 2 events in  
1625 the  $4e$  channel, and 5 events in the  $2e2\mu/2\mu2e$ . The best fit  $\mu$  value in the combined 7 and 8 TeV data  
1626 occurs at 125 GeV and is measured to be  $1.2 \pm 0.6$ . The observed significance at this mass is  $3.6\sigma$ , with  
1627 an expected significance of  $2.7\sigma$ .

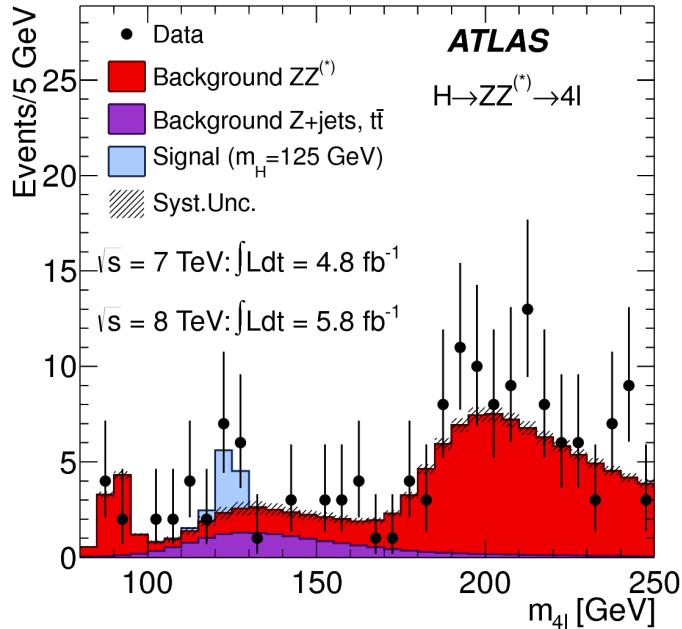


Figure 4.5: Four lepton invariant mass spectrum ( $m_{4\ell}$ ) in 7 and 8 TeV data compared to background estimate. A 125 GeV SM Higgs signal is shown in blue [1].

1628    4.6 COMBINED RESULTS

1629    The statistical interpretation of the combined results is undertaken as described in section 3.6.2, with a hy-  
 1630    pothesis test based on a likelihood ratio parameterized by the Higgs signal strength  $\mu$ . The null hypothesis  
 1631    corresponds to  $\mu = 0$ , while the SM Higgs corresponds to  $\mu = 1$ .

1632    Table 4.4 summarizes the properties of the individual channels as well as the significances of the excesses  
 1633    seen. The most significant observed local excess comes from the  $\gamma\gamma$  channel. Figure 4.6 shows a com-  
 1634    parison of the observed local  $p_0$  values as a function of hypothesized mass for the three different search  
 1635    channels. Both the  $ZZ^*$  and  $\gamma\gamma$  channels have very peaked excesses, while the  $WW^*$  excess can be seen as  
 1636    very broad because the  $m_T$  distribution does not provide detailed information about the true Higgs mass.  
 1637    Figure 4.7 shows the combined exclusion limit,  $p_0$ , and signal strength. The highest local excess comes at  
 1638    a value of 126.5 GeV and corresponds to a  $6.0\sigma$  observed excess.

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

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].

1639    Figure 4.8 shows a comparison of the measured signal strengths between the different Higgs search  
 1640    channels. All measured  $\mu$  are consistent with unity within their uncertainty, and the combined  $\mu$  mea-  
 1641    surement is  $1.4 \pm 0.3$ .

1642    The likelihood can also be computed in a two-dimensional plane of  $m_H$  and  $\mu$ , and this is shown in  
 1643    figure 4.9. The figure shows that while the  $\gamma\gamma$  and  $ZZ^*$  channels have very good mass resolution, the  
 1644    excess in  $WW^*$  covers a broad mass range. The banana shape of the  $WW^*$  result is due to the fact that  
 1645    the excess in this channel can either be explained by increasing the signal strength or by changing the mass  
 1646    (and thus the cross section). The two parameters are correlated due to the lack of mass sensitivity in this  
 1647    channel.

1648    Because multiple Higgs mass points are searched for, the local significance must be corrected for a look-

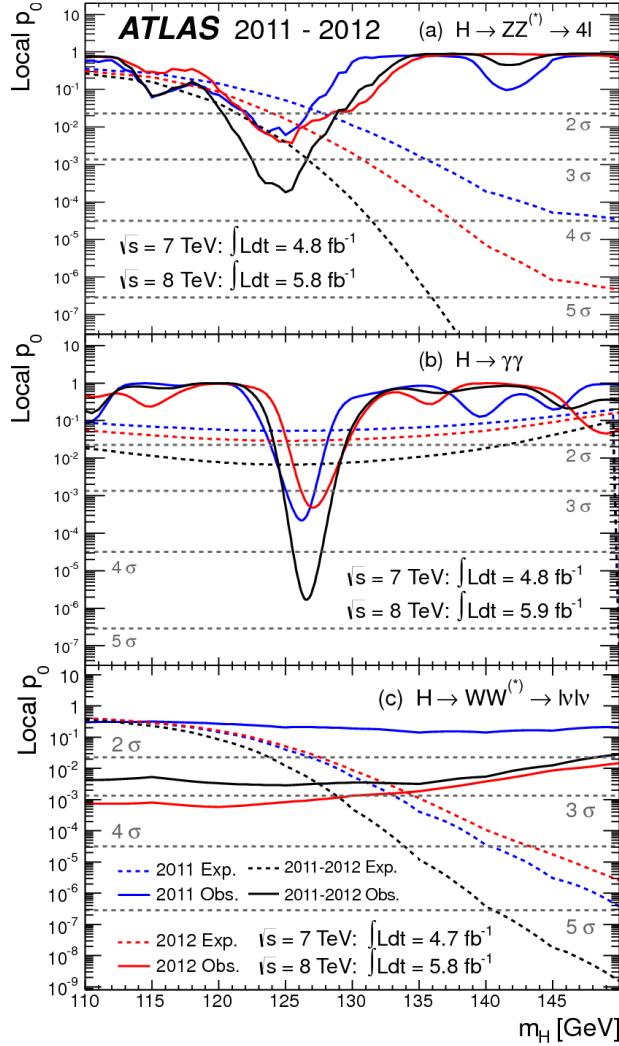


Figure 4.6: Local  $p_0$  distribution as a function of hypothesized Higgs mass for the  $H \rightarrow ZZ^* \rightarrow 4\ell$  (a),  $H \rightarrow \gamma\gamma$  (b), and  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  (c) channels. Dashed curves show expected results, while solid curves show observed.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

1649 elsewhere effect to compute a true global significance. The global significance for finding a Higgs anywhere  
1650 in the mass range of 110 GeV to 600 GeV is  $5.1\sigma$ . This increases slightly to  $5.3\sigma$  if only mass range from  
1651 110 to 150 GeV.

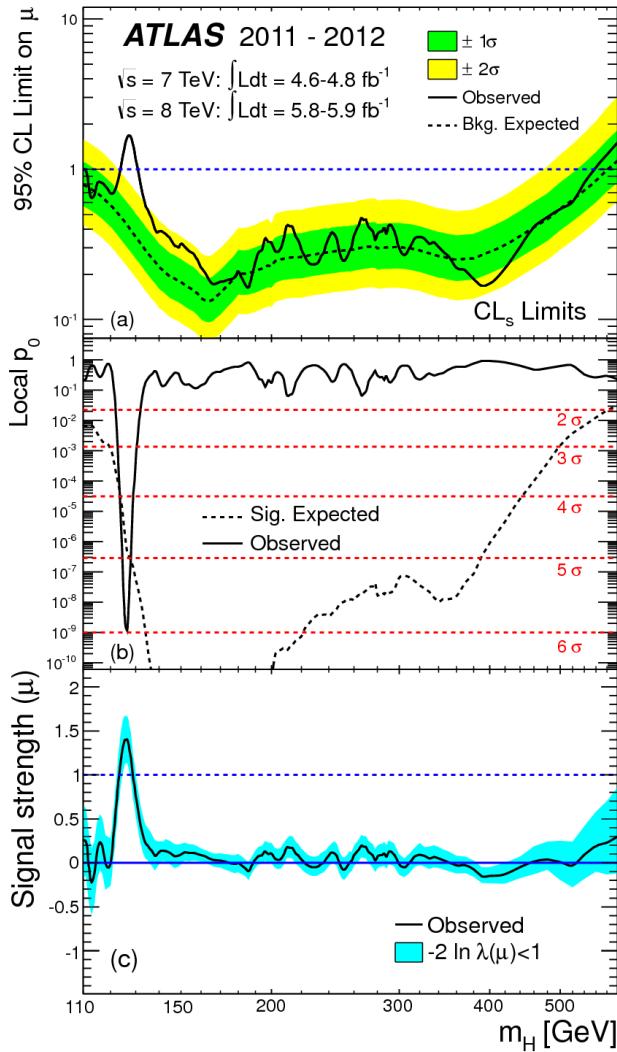


Figure 4.7: Combined 95% CL limits (a), local  $p_0$  values (b), and signal strength measurement (c) as a function of Higgs mass [1].

1652    4.7 CONCLUSION

1653    A search for the production of a Standard Model Higgs boson was conducted in  $4.8 \text{ fb}^{-1}$  collected at  
 1654     $\sqrt{s} = 7 \text{ TeV}$  and  $5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . A new particle consistent with the Higgs boson was observed,  
 1655    with a mass of  $126.5 \text{ GeV}$  and a global (local) significance of  $5.1(6.0)\sigma$ . This is the first discovery level  
 1656    observation of a particle consistent with the Higgs.

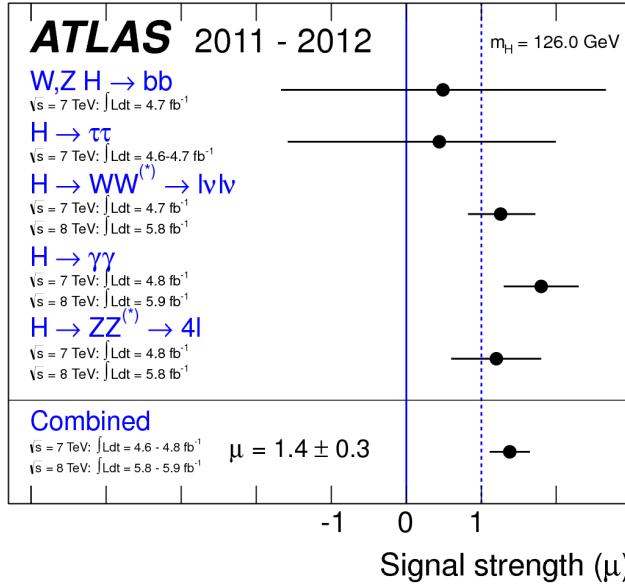


Figure 4.8: Comparison of measured signal strength  $\mu$  for a 126 GeV Higgs in the 7 and 8 TeV datasets [1].

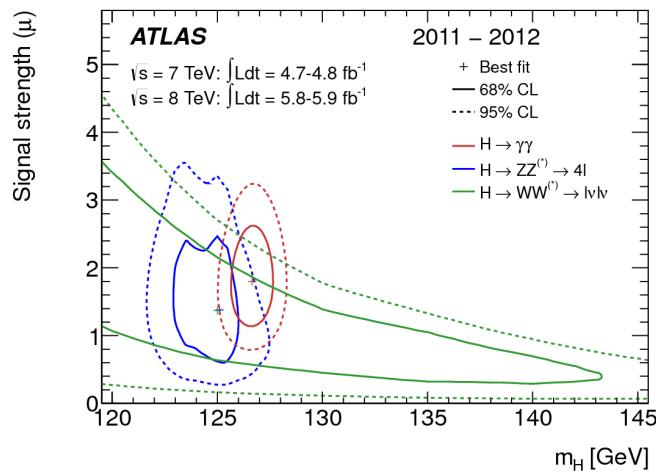


Figure 4.9: Two dimensional likelihood as a function of signal strength  $\mu$  and Higgs mass  $m_H$  [1].

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

Richard Feynman

# 5

1657

## 1658 Evidence for Vector Boson Fusion production

1659

$$\text{of } H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$$

### 1660 5.1 INTRODUCTION

1661 After the discovery of the Higgs boson, the  $H \rightarrow WW^*$  analysis had two main goals. The first goal was  
1662 to increase the sensitivity of the analysis to fully confirm that the  $H \rightarrow WW^*$  process did indeed exist.  
1663 The second goal was to characterize the particle as much as possible, including searching for the lower  
1664 cross-section production modes. This chapter presents a dedicated search for Vector Boson Fusion (VBF)  
1665 production of a Higgs boson decaying via the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  mode. First, the data and Monte  
1666 Carlo samples are detailed, along with trigger and physics object selections. Then, the details of the analysis  
1667 are shown, including signal region definition, background estimation techniques, and systematic uncer-  
1668 tainties. Finally, the results of the analysis are presented. As will be shown, this analysis is the first and

1669 most sensitive evidence for VBF production of the Higgs at the LHC.

1670 The VBF  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis defines two signal regions. The first is a more standard  
1671 selection, referred to as “cut-based”, that applies requirements on VBF topology variables and uses  $m_T$  as  
1672 the final discriminating variable. The second is a looser selection that uses an algorithm known as a Boosted  
1673 Decision Tree (BDT). A BDT is a multivariate technique that uses an ensemble of decision trees to split the  
1674 phase space of input variables into signal-like and background-like regions in order to provide separation  
1675 power [78–80]. The output score of a BDT trained to distinguish the VBF Higgs signal from background  
1676 processes is used as the final discriminating variable in the second signal region. While the BDT-based  
1677 signal region is ultimately more sensitive, the cut-based result is an important component of the analysis.  
1678 First, the cut-based analysis allows for confirming the modeling and validity of the variables used as input  
1679 to the BDT. Second, because this is the first use of a multivariate technique in the  $H \rightarrow WW^*$  analysis,  
1680 the cut-based selection allows confirmation of the final BDT result with a more traditional analysis. The  
1681 cut-based techniques are the focus of this chapter, but connections to the BDT result will be illustrated  
1682 when appropriate.

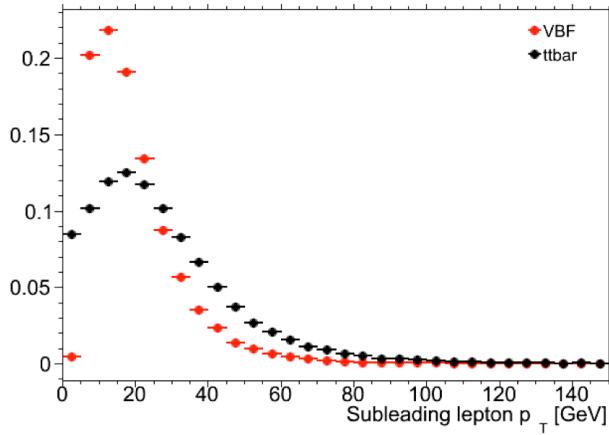
1683 One important note is that because this analysis is dedicated to the measurement of the VBF pro-  
1684 duction mode of the Higgs, events coming from gluon fusion production with the Higgs decaying via  
1685  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  are treated as background events. This will be seen throughout the background  
1686 predictions shown below.

## 1687 5.2 DATA AND SIMULATION SAMPLES

1688 The results presented here are with  $20.3 \text{ fb}^{-1}$  taken at  $\sqrt{s} = 8 \text{ TeV}$  and  $4.5 \text{ fb}^{-1}$  taken at  $\sqrt{s} = 7 \text{ TeV}$ .  
1689 The details of the LHC and detector conditions during this period are given in Chapter 2. The trigger  
1690 selection defining the dataset is discussed in section 5.2.1. The simulation samples used for signal and back-  
1691 ground modeling are given in section 5.2.2.

1692    5.2.1    TRIGGERS

1693    The analysis uses a combination of single lepton and dilepton triggers to allow lowering of the  $p_T$  thresh-  
1694    olds and increased signal acceptance. The  $p_T$  threshold on the leptons is a particularly important con-  
1695    sideration for this signal. Because the  $W^*$  produced in the decay is off-shell, it tends to produce lower  
1696    momentum leptons. Thus, being able to lower the  $p_T$  threshold while still maintaining a low background  
1697    rate is critical. Figure 5.1 shows an example of the subleading lepton  $p_T$  for a VBF  $H \rightarrow WW^*$  signal com-  
1698    pared to the corresponding  $t\bar{t}$  background. Note that the lepton  $p_T$  spectrum is considerably softer in the  
1699    signal sample. The spectrum shown here is also similar in gluon fusion production of the Higgs as well.



1700    Figure 5.1: A comparison of the subleading lepton  $p_T$  spectrum between VBF  $H \rightarrow WW^*$  production and  $t\bar{t}$   
1701    background.

1702    As discussed in Chapter 2, there are multiple levels in the ATLAS trigger system, and there are different  
1703     $p_T$  thresholds imposed for the leptons at each level. Additionally, some triggers have a loose selection on  
1704    the isolation of the lepton (looser than that applied offline in the analysis object selection). Table 5.1 shows  
1705    the  $p_T$  thresholds used for single lepton triggers, while table 5.2 shows the  $p_T$  thresholds coming from  
1706    di-lepton triggers. The single lepton trigger efficiency for muons that pass the analysis object selection is  
1707    70% for muons in the barrel region ( $|\eta| < 1.05$ ) and 90% in the endcap region. The electron trigger  
efficiency increases with electron  $p_T$  but the average is approximately 90%. These efficiencies are measured  
by combined performance and trigger signature groups [81, 82].

	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 in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis. 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 in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis. The two thresholds listed refer to leading and sub-leading leptons, respectively. The di-muon trigger only requires a single lepton at level-1.

1708        The combination of all listed triggers gives good efficiency for signal events. This efficiency is summa-  
 1709        rized in table 5.3. The relative improvement in efficiency by adding the dilepton triggers is also shown  
 1710        in the same table. The largest gain comes in the  $\mu\mu$  channel. Overall the trigger selection shows a good  
 1711        efficiency for  $H \rightarrow WW^*$  signal events.

Channel	Trigger efficiency	Gain from $2\ell$ trigger
$ee$	97%	9.1%
$\mu\mu$	89%	18.5%
$e\mu$	95%	8.3%
$\mu e$	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.

### 1712     5.2.2 MONTE CARLO SAMPLES

1713        In both the gluon fusion and vector boson fusion focused analyses, modeling of signal and background  
 1714        processes in the signal region is an important consideration for the final interpretation of the analysis.  
 1715        Therefore, careful consideration must be paid to which Monte Carlo (MC) generators are used for specific

1716 processes. With the exception of the  $W + \text{jet}$  and multijet backgrounds, the  $m_T$  shape used as the final  
1717 discriminant is taken from simulation<sup>1</sup>.

1718 Table 5.4 shows the MC generators used for the signal and background processes, as well as the cross  
1719 sections of each process. In order to include corrections up to next-to-leading order (NLO) in the QCD  
1720 coupling constant  $\alpha_s$ , the **POWHEG** [83] generator is often used. In some cases, only leading order gener-  
1721 ators like **ACERMC** [84] and **GG2VV** [85] are available for the process in question. If the process requires  
1722 good modeling for very high parton multiplicities, the **SHERPA** [86] and **ALPGEN** [87] generators are used  
1723 to provide merged calculations for five or fewer additional partons. These matrix element level calculations  
1724 must then be additionally matched to models of the underlying event, hadronization, and parton shower.  
1725 There are four generators used for this purpose: **SHERPA**, **PYTHIA 6** [88], **PYTHIA 8** [89], or **HERWIG**  
1726 [90] + **JIMMY** [91]. The simulation additionally requires an input parton distribution function (PDF).  
1727 The **CT10** [92] PDFs are used for **SHERPA** and **POWHEG** simulated samples, while **CTEQ6Li** [93] is used for  
1728 **ALPGEN + HERWIG** and **ACERMC** simulations. The Drell-Yan samples are reweighted to the **MRST** [94]  
1729 PDFs, as these are found to give the best agreement between data and simulation. The branching ratio  
1730 for Higgs to  $WW^*$  and  $ZZ^*$  is computed with **PROPHECY4f** [95], while the width of all other decays is  
1731 computed with **HDECAY**[96].

1732 Once the basic hard scattering process is simulated, it must be passed through a detector simulation and  
1733 additional pile-up events must be overlaid. The pile-up events are modeled with **PYTHIA 8**, and the ATLAS  
1734 detector is simulated with **GEANT4** [97]. Because of the unique phase space of the  $H \rightarrow WW^*$  analysis,  
1735 events are sometimes filtered at generator level to allow for more efficient generation of relevant events.  
1736 The efficiency of the trigger in MC simulation does not always match the measured efficiency in data, so  
1737 trigger scale factors are applied to correct the MC efficiency to the data. The details of these corrections are  
1738 given in reference [81] for muons and reference [82] for electrons.

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<sup>1</sup>Many backgrounds are normalized from data, as described in section 5.5.

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 [73]. The table lists the cross section for each process, taking into account the branching ratio for the process producing two leptons.

### 1739 5.3 OBJECT SELECTION

1740 In order to define the signal region, the analysis must first select the reconstructed physics objects to be  
 1741 considered. The details of the object reconstruction algorithms were discussed in Chapter 2, while this

1742 section gives specific selection requirements used in the  $H \rightarrow WW^*$  analysis. The first step in this process  
1743 is to select a primary vertex candidates. The event's primary vertex is chosen to be the vertex with the largest  
1744 sum of  $p_T^2$  for its associated tracks. It is required to have at least three tracks with  $p_T > 450$  MeV. Many  
1745 of the object selection cuts are then made relative to this chosen primary vertex.

1746 **5.3.1 MUONS**

1747 The analysis uses combined muon candidates, where a track in the Inner Detector has been matched to a  
1748 standalone track in the Muon Spectrometer. The track parameters are combined statistically in the muon  
1749 reconstruction algorithm [63]. The muons are required to be within  $|\eta| < 2.5$  and have a  $p_T > 10$  GeV.  
1750 To reduce backgrounds coming from mis-reconstructed leptons, there are requirements on the impact  
1751 parameter of the muon relative to the primary vertex. The transverse impact parameter  $d_0$  is required to  
1752 be small relative to its estimated uncertainty, the exact cut value being  $d_0/\sigma_{d_0} < 3$ . The longitudinal  
1753 impact parameter  $z_0$  must satisfy  $|z_0 \sin \theta| < 1$  mm.

1754 As discussed previously, the muons must also be isolated. There are two types of lepton isolations  
1755 that are calculated: track-based and calorimeter-based. For muons, the track-based isolation is defined  
1756 using the scalar sum  $\sum p_T$  for tracks with  $p_T > 1$  GeV (excluding the muon track) within a cone of  
1757  $\Delta R = 0.3$  (0.4) around the track for muons with  $p_T > 15$  GeV ( $10 < p_T < 15$  GeV). The final  
1758 isolation requirement is made by requiring that this scalar sum be no more than a certain fraction of the  
1759 muon  $p_T$ . This requirement varies with muon  $p_T$  and the exact requirements are defined in table 5.5.

1760 The calorimeter-based muon isolation is defined using the  $\sum E_T$  calculated from calorimeter cells with  
1761 the same cone size as the track-based isolation but excluding cells within  $\Delta R < 0.05$  around the muon.  
1762 This isolation is also defined as a requirement on the ratio of the sum to the muon  $p_T$  and varies with  
1763 muon  $p_T$ . The requirement values as a function of  $p_T$  are also given in table 5.5.

1764 The isolation requirements loosen as a function of  $p_T$  to allow for larger signal acceptance. At low  $p_T$ ,  
1765 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 their calorimeter based or track based cone sums be less than this fraction of their  $p_T$ .

1766    5.3.2 ELECTRONS

1767    Electrons are identified and reconstructed using the methods previously described in chapter 2. The elec-  
 1768    trons are required to have  $|\eta| < 2.47$ , and candidates in the transition region between the barrel and  
 1769    endcap ( $1.37 < |\eta| < 1.52$ ) are excluded. As the muons, the electrons are required to have transverse  
 1770    impact parameter significance  $< 3$ , while in the longitudinal direction they must have  $|z_0 \sin \theta| < 0.4$   
 1771    mm. Some electron requirements also vary with electron  $E_T$ , and these requirements are summarized in  
 1772    table 5.6.

1773    The isolation for electrons is defined similarly to the muons but with unique requirements on the ob-  
 1774    jects included. The track-based isolation is constructed using tracks with  $p_T > 400$  MeV with cone sizes  
 1775    as defined for the muons. The calorimeter-based isolation also uses the same cone size as the muon, but  
 1776    here the cells within a  $0.125 \times 0.175$  area in  $\eta \times \phi$  around the electron cluster's barycenter are excluded.  
 1777    The other difference with respect to muons is that the denominator of the isolation ratio is the electron  
 1778     $E_T$  rather than  $p_T$ . The isolation cuts very with electron  $E_T$  and are defined in table 5.6. The electron is  
 1779    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 their calorimeter based or track based cone sums be less than this fraction of their  $E_T$ .

1780 5.3.3 JETS

1781 Jets are clustered with the anti- $k_T$  reconstruction algorithm using a radius parameter of  $R = 0.4$ . They  
1782 are required to have a jet vertex fraction (JVF) of at least 50%, meaning that half of the tracks associated with  
1783 the jet originated from the primary vertex. Jets with no tracks associated (i.e. those outside the acceptance  
1784 of the ID) do not have this requirement applied. Jets are required to have  $p_T > 25$  GeV if they are within  
1785 the tracking acceptance ( $|\eta| < 2.4$ ). Jets with  $2.4 < |\eta| < 4.5$  are required to have  $p_T > 30$  GeV. This  
1786 tighter requirement reduces jets from pileup in the region where JVF requirements cannot be applied. The  
1787 two highest  $p_T$  jets in the event are referred to as the “VBF” jets and used to compute variables used in the  
1788 analysis selection.

1789 Identification of  $b$ -jets is done using the MV1 algorithm and is limited to the acceptance of the ID ( $|\eta| <$   
1790 2.5) [69]. The operating point of MV1 used is 85% efficient for identifying true  $b$ -jets. This operating point  
1791 has a 10.3% probability of mis-tagging a light quark jet as a  $b$ -jet. The analysis vetoes events that contain  
1792  $b$ -tagged jets with  $p_T > 20$  GeV.

1793 5.3.4 OVERLAP REMOVAL

1794 There are some cases where reconstructed objects will overlap and one will have to be chosen (for example,  
1795 an electron and a jet in the calorimeter). First, the case of lepton overlap is dealt with. If an electron  
1796 candidate extends into the muon spectrometer, it is removed. If a muon and electron are within  $\Delta R < 0.1$   
1797 of each other, the electron is removed and the muon is kept. If two electron candidates overlap within the  
1798 same radius, then the higher  $E_T$  electron is kept. Next, the overlap between leptons and jets is considered.  
1799 If an electron and jet are within  $\Delta R < 0.3$  of one another, the electron is kept and the jet is removed.  
1800 However, if a muon and jet overlap within  $\Delta R < 0.3$ , the jet is kept (as it is likely that the muon is the  
1801 result of a semileptonic decay inside the jet). Once the overlap removal is complete, the final set of objects  
1802 used in the analysis is defined.

1803    5.4 ANALYSIS SELECTION

1804    This section discusses the variables used to distinguish VBF production of the Higgs in the  $H \rightarrow WW^* \rightarrow$   
1805     $\ell\nu\ell\nu$  final state. First, pre-selection requirements are presented. Then, the definitions of analysis variables  
1806    and the cut-based signal region are shown. Finally, the BDT signal region is defined and the commonalities  
1807    between the two signal regions are discussed.

1808    5.4.1 PRE-SELECTION

1809    Both the cut-based and BDT analyses have a common pre-selection that is applied before the signal region  
1810    requirements. The requirements on leptons are common to all  $n_j$  bins. The analysis requires two oppo-  
1811    sitely charged leptons, with the leading lepton required to have  $p_T > 22$  GeV while the subleading lepton  
1812    must have  $p_T > 10$  GeV. Next, to remove low mass  $Z/\gamma^*$  events, a requirement on the dilepton mass  
1813     $m_{\ell\ell} > 10$  (12) GeV is applied in the different (same) flavor channel. In the same flavor channels, there is  
1814    an additional veto placed on the region around the Z peak, requiring that  $|m_{\ell\ell} - m_Z| > 15$  GeV.

1815    There are also requirements on the amount of missing transverse momentum in the event. These  
1816    are only applied in the same flavor channels, where  $Z/\gamma^* + \text{jets}$  production is one of the dominant back-  
1817    grounds. The BDT analysis requires  $p_T^{\text{miss}} > 40$  GeV and  $E_T^{\text{miss}} > 45$  GeV. The cut-based analysis  
1818    must select more tightly on these variables to have maximal sensitivity and thus requires  $p_T^{\text{miss}} > 50$  GeV  
1819    and  $E_T^{\text{miss}} > 55$  GeV.

1820    Finally, because this analysis is focused on VBF Higgs production, a requirement on the jet multiplicity  
1821    is placed, with  $n_j \geq 2$ . Additionally, the analysis requires that there are no jets identified as b-quarks in  
1822    the event, or  $n_b = 0$ .

1823    5.4.2 ANALYSIS VARIABLE DEFINITIONS AND CUT-BASED SELECTION

1824    The cut-based selection places sequential requirements on variables reconstructed from the VBF jets in  
1825    order to increase the signal to background ratio. This section defines the variables that are used in the  
1826    cut-based selection and details the requirements that are placed on these variables.

1827 GENERAL BACKGROUND REDUCTION

1828 Top pair production is the primary background in the  $n_j \geq 2$  bin. Even though  $n_b = 0$  is required, an  
1829 additional variable is constructed to further suppress the top background. There is often additional QCD  
1830 radiation that accompanies the  $t\bar{t}$  system when it is produced. Therefore, a variable which tests for the  
1831 presence of this additional radiation,  $p_T^{\text{sum}}$ , is constructed. It is defined in equation 5.1.

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

1832 After pre-selection, the cut-based analysis requires the event to have  $p_T^{\text{sum}} < 15$  GeV to further suppress  
1833  $t\bar{t}$  production.

1834 In the different flavor channels, a requirement is made to reduce the contamination from  $Z \rightarrow \tau\tau$   
1835 decays. The di- $\tau$  invariant mass,  $m_{\tau\tau}$ , is constructed by assuming that the neutrinos from the  $\tau$  decays  
1836 were collinear with the leptons [76]. The analysis requires that this mass satisfy  $m_{\tau\tau} < m_Z - 25$  GeV so  
1837 that it is not consistent with the mass of the  $Z$  boson.

1838 VBF TOPOLOGICAL CUTS

1839 The characteristic feature of VBF production of the Higgs is the presence of two additional forward jets  
1840 coming from the incoming partons which radiate the vector bosons that make the Higgs. These jets are  
1841 forward because the outgoing partons still carry the longitudinal momentum of the incoming partons.  
1842 Figure 5.2 shows the distribution of the  $\eta$  for the leading jet in a VBF event compared to a background top  
1843 pair production event. As can be seen, the VBF jets tend to be more forward in  $\eta$ , while the  $t\bar{t}$  jets are more  
1844 central. Because the cross section for VBF production is an order of magnitude smaller than gluon fusion  
1845 production, these forward jets must be used in order to reduce background and achieve a good signal to  
1846 background ratio. The dedicated VBF search selection requirements are constructed to maximally exploit  
1847 the features of the unique VBF topology.

1848 Requirements on the VBF jets are collectively referred to as the “VBF topological cuts”. First, a require-  
1849 ment on the dijet invariant mass of the VBF jets,  $m_{jj}$ , is placed, requiring  $m_{jj} > 600$  GeV. Next, the

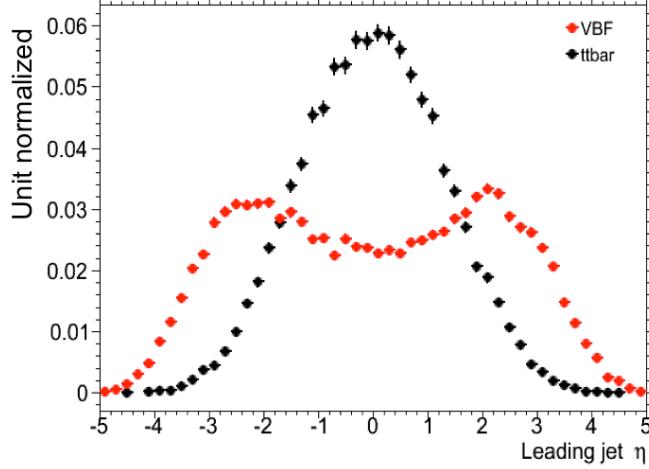


Figure 5.2: Leading jet  $\eta$  in VBF  $H \rightarrow WW^*$  (red) and  $t\bar{t}$  (black)

event is required to have a large gap in rapidity between the two VBF jets, or  $\Delta y_{jj} > 3.6$ . Both of these are tight requirements on the presence of two forward, high  $p_T$  jets moving in opposite directions in the longitudinal plane.

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

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

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

The decay products of the Higgs tend to be central as well. Thus, the analysis also requires that both

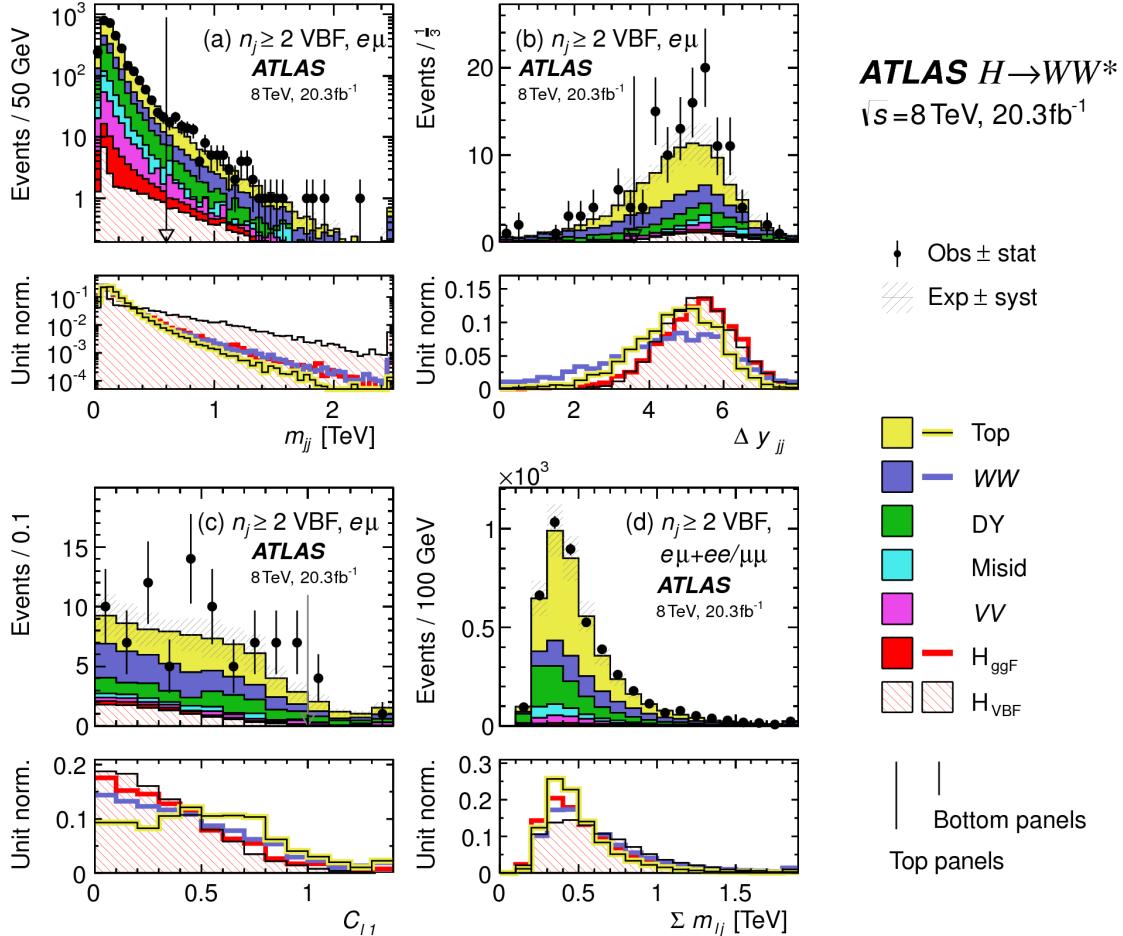


Figure 5.3: Distributions of (a)  $m_{jj}$ , (b)  $\Delta y_{jj}$ , (c)  $C_{\ell 1}$ , and (d)  $\Sigma m_{\ell j}$ , for the cut-based VBF analysis. The top panels compare simulation and data, while the bottom panels show normalized distributions for all background processes and signal for shape comparisons [73].

leptons in the analysis fall within the rapidity gap defined by the jets. This cut is referred to as the outside lepton veto, or OLV. Stated another way, leptons are required to have a centrality (defined analogously to that of the third jet in equation 5.2) within the jet rapidity gap, or  $C_{\ell} < 1$  for both leptons.

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

The final signal region is also split into two bins of  $m_{jj}$ , with the first bin corresponding to  $600 \text{ GeV} < m_{jj} < 1 \text{ TeV}$  and the second bin corresponding to  $m_{jj} > 1 \text{ TeV}$ . The first bin has more events but also

1871 a larger contribution from background, while the second bin has a lower expected number of events but a  
1872 1:1 signal to background ratio.

1873 HIGGS TOPOLOGICAL CUTS

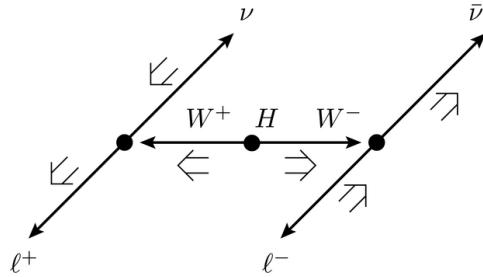


Figure 5.4: A cartoon of the WW final state. Momenta are represented with thin arrows, spins with thick arrows [73].

1874 The final state leptons will exhibit unique correlations due to the fact that they arise from the decay of  
1875 a spin zero resonance. These characteristics are present in  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  decays regardless of the  
1876 production mode being studies. In particular, the spins of the final state leptons and neutrinos must all  
1877 cancel, as shown in figure 5.4. Because the neutrino has a left handed chirality and the anti-neutrino has a  
1878 right handed chirality (in the massless neutrino approximation), the spin and momentum of the particles  
1879 will be anti-aligned and aligned, respectively. In the transverse plane, the momenta of all four final state  
1880 objects must cancel as well. With the constraint of having both the momenta and the spin alignments  
1881 cancel, the final state kinematics strongly prefer having a small angle between the leptons in the transverse  
1882 plane (low  $\Delta\phi_{\ell\ell}$ ). This angular correlation will also lead to low values of the di-lepton invariant mass  $m_{\ell\ell}$ .  
1883 These unique signal final state kinematic correlations are exploited to define the ultimate signal region.

1884 Two requirements on dilepton kinematics are made that are common with lower multiplicity jet bins  
1885 as well. The angle between leptons in the transverse plane,  $\Delta\phi_{\ell\ell}$ , is required to be less than 1.8 radians.  
1886 Additionally, the dilepton invariant mass,  $m_{\ell\ell}$ , is required to be less than 50 GeV.

1887 The cut-based analysis uses  $m_T$  as the final discriminating variable as in the ggF focused analysis. The  
1888 optimal number of bins in  $m_T$  was found to be three bins, with the bin boundaries at 80 and 130 GeV.

1889 Table 5.7 shows a summary of the data and estimated signal and background yields from simulation  
 1890 as each requirement described above is made. The table shows how the overall signal to background ra-  
 1891 tio grows through the various selection requirements. Table 5.8 shows the background composition after  
 1892 each selection requirement, illustrating which backgrounds are reduced most by certain requirements. Fig-  
 1893 ure 5.5 shows an ATLAS event display of a candidate event in the final signal region.

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

Table 5.7: Summary of event selection for the  $n_j \geq 2$  VBF analysis in the 8 TeV cut-based analysis [73].

### 1894 5.4.3 BDT-BASED SELECTION

1895 The boosted decision tree based analysis uses many of the variables defined in the cut-based selection as  
 1896 inputs to the BDT. The output BDT score ( $O_{\text{BDT}}$ ) is used as the final discriminant rather than  $m_T$ <sup>2</sup>.  
 1897 The BDT is trained with the VBF  $H \rightarrow WW^*$  simulation as the signal samples and all other processes as  
 1898 background, including ggF  $H \rightarrow WW^*$  production. While the BDT based analysis is ultimately treated  
 1899 as a separate result, it has significant overlap with the cut-based selection.

<sup>2</sup>For the final discriminant analysis, the  $O_{\text{BDT}}$  distribution is divided into four bins, with boundaries at  $[-1, -0.48, -0.3, 0.78, 1]$ .

	Composition of $N_{\text{bkg}}$									
	$N_{WW}$		$N_{\text{top}}$		$N_{\text{misid}}$		$N_{VV}$		$N_{\text{Drell-Yan}}$	
	$N_{WW}^{\text{QCD}}$	$N_{WW}^{\text{EW}}$	$N_{t\bar{t}}$	$N_t$	$N_{Wj}$	$N_{jj}$	$N_{VV}^{\text{QCD}}$	$N_{ee/\mu\mu}$	$N_{\tau\tau}^{\text{QCD}}$	$N_{\tau\tau}^{\text{EW}}$
$e\mu$ sample	1350	68	51810	2970	847	308	380	51	3260	46
$n_b = 0$	993	43	3000	367	313	193	273	35	2400	29
$p_T^{\text{sum}} < 15$	781	38	1910	270	216	107	201	27	2010	23
$m_{\tau\tau} < m_Z - 25$	484	22	1270	177	141	66	132	7.6	627	5.8
$m_{jj} > 600$	18	8.9	40	5.3	1.8	2.4	5.1	0.1	15	1.0
$\Delta y_{jj} > 3.6$	11.7	6.9	35	5.0	1.6	2.3	3.3	—	11.6	0.8
$C_{j3} > 1$	6.9	5.6	14	3.0	1.3	1.3	2.0	—	6.8	0.6
$C_{\ell 1} < 1, C_{\ell 2} < 1$	5.9	5.2	10.8	2.5	1.3	1.3	1.6	—	5.7	0.6
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_T$	1.0	0.5	1.1	0.3	0.3	0.3	0.6	—	0.5	0.2
$ee/\mu\mu$ sample	594	37	23440	1320	230	8.6	137	690	679	16
$n_b, p_T^{\text{sum}}, m_{\tau\tau}$	229	12.0	633	86	26	0.9	45	187	76	1.5
$m_{jj}, \Delta y_{jj}, C_{j3}, C_\ell$	3.1	3.1	5.5	1.0	0.2	0.0	0.7	3.8	0.7	0.1
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_T$	0.4	0.2	0.6	0.2	0.2	0.0	0.1	1.5	0.3	0.1

Table 5.8: Background composition after each requirement in the  $n_j \geq 2$  VBF analysis in the 8 TeV cut-based analysis [73].

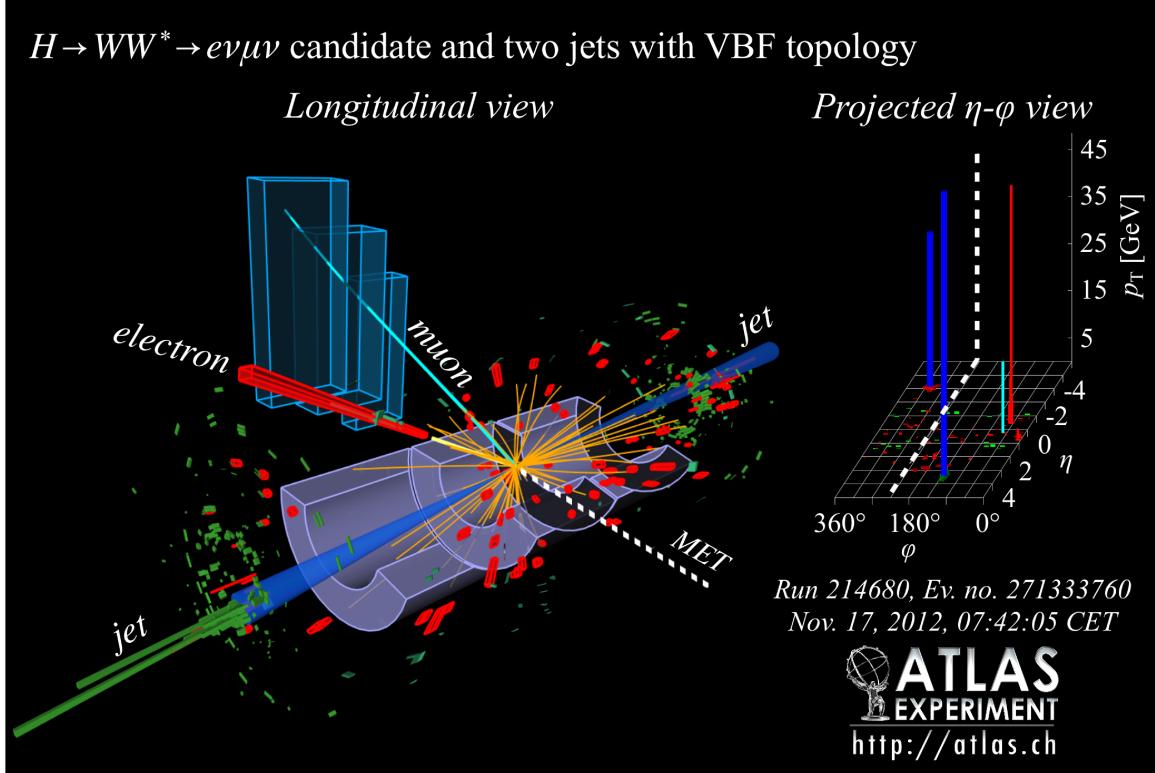


Figure 5.5: Event display of a VBF candidate event [73].

1900 PRE-TRAINING SELECTION AND BDT INPUTS

1901 Before training, the common pre-selection cuts described in section 5.4.1 are applied. Additionally, the  
1902 central jet veto and outside lepton veto described in section 5.4.2 are applied. The BDT has eight input  
1903 variables, six of which are also variables that are used in the cut-based analysis. The six shared variables  
1904 are  $p_T^{\text{sum}}$ ,  $m_{jj}$ ,  $\Delta y_{jj}$ ,  $m_{\ell\ell}$ ,  $\Delta\phi_{\ell\ell}$ , and  $m_T$ . The seventh variable input in the BDT is a combination of  
1905 the variables used to define the OLV in the cut-based analysis. The BDT uses as input the sum of lepton  
1906 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  
1907 the correlations between the jets and leptons in the event. It is the sum of the invariant masses of all four  
1908 possible lepton-jet combinations.

1909 Figure 5.3d shows the agreement between data and simulation for the  $\Sigma m_{\ell j}$  variable, as well as showing  
1910 its discriminating power. Figure 5.6 shows the distributions of the Higgs topological variables that are  
1911 shared between the cut-based and BDT analyses. Figure 5.7 shows the distributions of the VBF topological  
1912 variables shared between the cut-based and BDT analyses. In both cases, the VBF yield has been scaled by  
1913 a factor of 50 to better show the shape difference compared to the backgrounds.

1914 5.5 BACKGROUND ESTIMATION

1915 This section describes the procedures used to estimate backgrounds for the VBF analysis in both the cut-  
1916 based and BDT analyses.

1917 5.5.1 GENERAL STRATEGY

1918 Most of the backgrounds in both the gluon fusion and VBF Higgs analyses have shapes estimated from  
1919 Monte Carlo simulation but normalizations derived from control regions in data. In essence, a normaliza-  
1920 tion factor (denoted with  $\beta$  or abbreviated as NF) is derived by scaling the MC yield in the control region  
1921 to the corresponding yield in data. Once this factor is derived, it can be used to scale the MC estimate of  
1922 the background in the signal region. This is illustrated in equation 5.3.

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

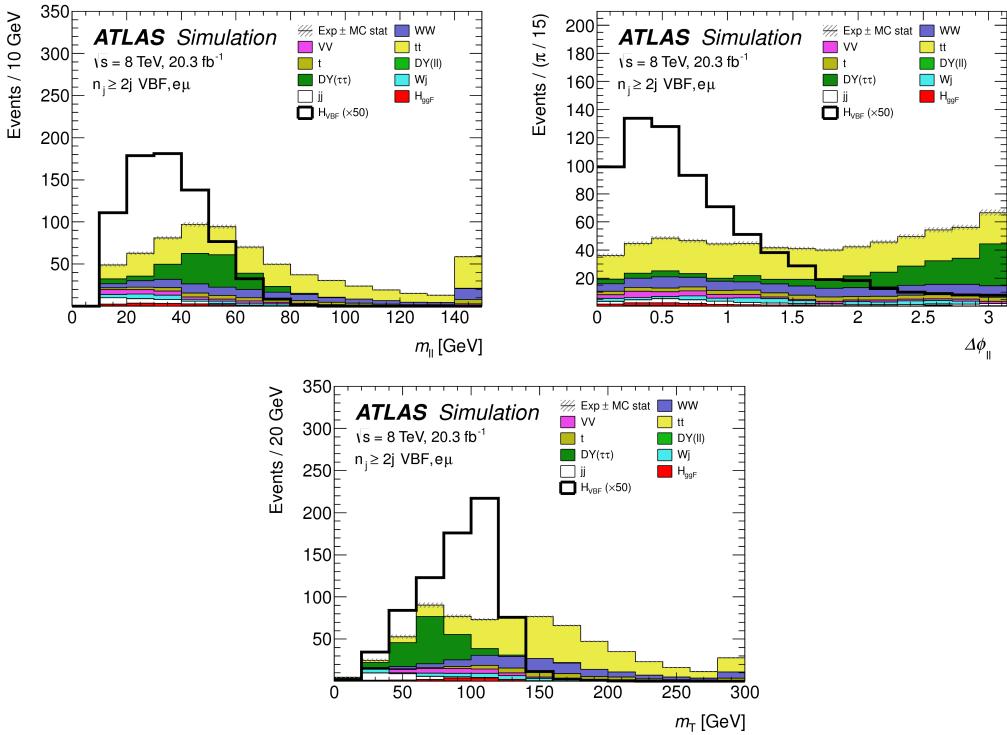


Figure 5.6: Higgs topology variables -  $m_{\ell\ell}$  (top left),  $\Delta\phi_{\ell\ell}$  (top right), and  $m_T$  (bottom) - used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [73]. The VBF Higgs signal cross section is multiplied by a factor of 50 to allow for shape comparisons.

1923 Here,  $B$  is the MC yield prediction in the denoted region, while  $N$  is the observed number of events in  
 1924 data in the denoted region.

1925 There is an alternative way of writing the same equation in terms of an extrapolation factor  $\alpha$  rather  
 1926 than a normalization factor  $\beta$ . The overall calculation is exactly the same. However, when phrased in  
 1927 this way, it shows how the uncertainty on the background estimation can be reduced. This is shown in  
 1928 equation 5.4.

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

1929 Phrased this way, the equation shows that with enough events in the control region, a large theoretical  
 1930 uncertainty on the overall background yield in the signal region can be replaced by a small statistical un-  
 1931 certainty coming from the number of data events in the CR and a smaller theoretical uncertainty on the  
 1932 extrapolation from the control region to the signal region.

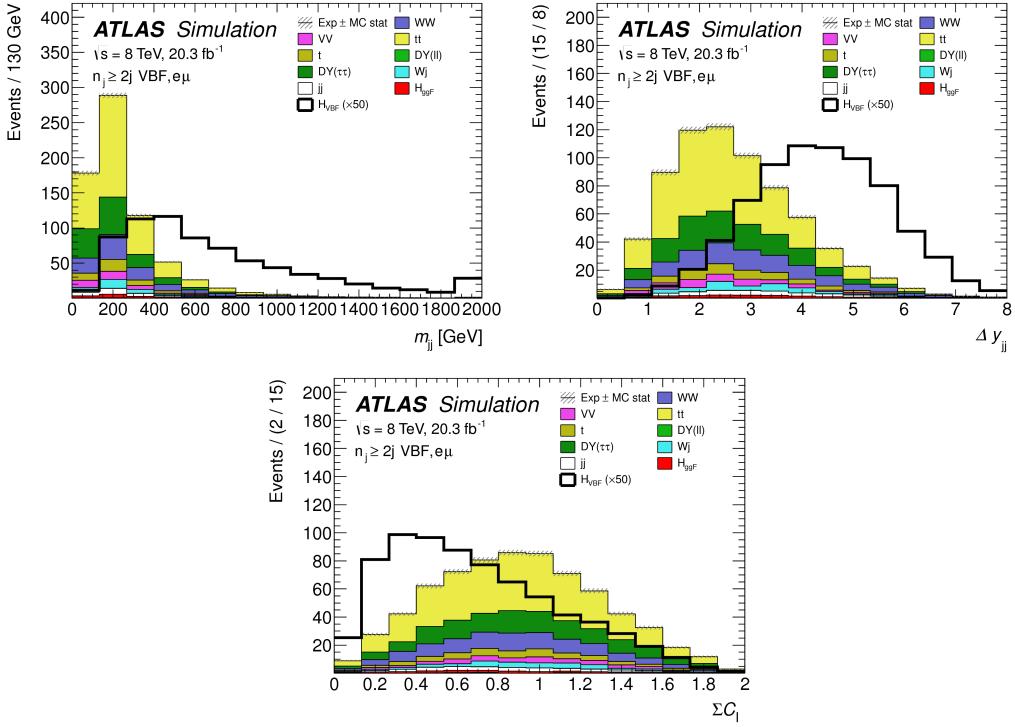


Figure 5.7: VBF topology variables -  $m_{jj}$  (top left),  $\Delta y_{jj}$  (top right),  $\sum C_\ell$  (bottom) - used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [73]. The VBF Higgs signal cross section is multiplied by a factor of 50 to allow for shape comparisons.

### 5.5.2 TOP BACKGROUND

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

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

<sup>1944</sup> consistent with those derived in the cut-based signal region, increasing confidence in the BDT estimation.

Figure 5.8 shows the  $m_{jj}$  and  $O_{\text{BDT}}$  distributions in the top control region. Overall the modeling looks

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

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

$O_{\text{BDT}}$	$\beta_t$
Bin 0	$1.09 \pm 0.02$
Bin 1	$1.58 \pm 0.15$
Bin 2	$0.95 \pm 0.31$
Bin 3	$0.95 \pm 0.31$

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

<sup>1945</sup>

<sup>1946</sup> consistent with the data. While these normalization factors can be computed and applied to the expected background yields listed in tables like table 5.8, the final normalization of the top background is profiled <sup>1947</sup> (meaning there is a dedicated Poisson constraint) and allowed to float in the final statistical fit. <sup>1948</sup>

### <sup>1949</sup> 5.5.3 $Z/\gamma^* \rightarrow \tau\tau$ BACKGROUND

<sup>1950</sup> In the different flavor channels, the  $Z/\gamma^* \rightarrow \tau\tau$  background is an important one. Di-tau production can <sup>1951</sup> produce an  $e\mu$  final state if each  $\tau$  lepton decays to a different flavor lepton.

<sup>1952</sup> In the BDT analysis, a single normalization factor for the background is derived. A control region <sup>1953</sup> is defined using the pre-training selection cuts, except requiring that  $|m_{\tau\tau} - m_Z| < 25 \text{ GeV}$  so that <sup>1954</sup> the region is enriched in  $Z/\gamma^* \rightarrow \tau\tau$  background. Additional requirements of  $m_{\ell\ell} < 80(75) \text{ GeV}$  <sup>1955</sup> in the different (same) flavor channel, as well as  $O_{\text{BDT}} > -0.48$  are applied to increase the purity of the

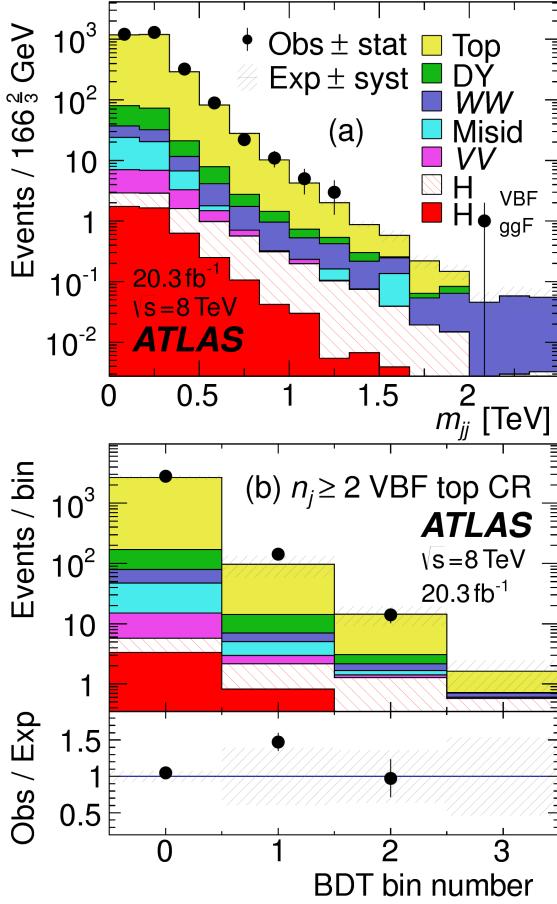


Figure 5.8: Distributions of  $m_{jj}$  (a) and  $O_{\text{BDT}}$  (b) in the VBF  $n_b = 1$  top CR [73].

region. The final  $\beta_{Z/\gamma^* \rightarrow \tau\tau}$  is calculated to be  $0.9 \pm 0.3$  (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  $\beta$  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 control region is defined including all SR requirements up to the  $Z/\gamma^* \rightarrow \tau\tau$  veto, which is instead turned into a Z mass peak requirement as for the BDT region. The  $m_{\ell\ell}$  cut from the BDT region is included as well. The cut-based approach aims to correct the normalization of the  $Z/\gamma^* \rightarrow \tau\tau$  background in two ways. First, an overall normalization factor is computed from the control region. However, the VBF topological cuts are not included in this region, and applying them as is done in the top CR is not feasible due to limited statistics. So, instead, correction

1966 factors (CF) to the cut efficiencies of the VBF cuts are derived in a same flavor  $Z \rightarrow \ell\ell$  control region,  
 1967 which has significantly more statistics. The CF is simply the ratio of the cut efficiencies in data and MC  
 1968 derived in this region. In the end, the overall background estimate is given by equation 5.5.

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

1969 The hypothesis is that while the normalization correction must be derived in a dedicated region, the effi-  
 1970 ciency of the VBF topology requirements should not be sensitive to the type of  $Z/\gamma^*$  process and thus the  
 1971 higher number of events can be exploited to derive the CF. Figure 5.9 shows a shape comparison for the  
 1972  $m_{jj}$  variable in  $Z \rightarrow \tau\tau$  events in the signal region and  $Z \rightarrow \ell\ell$  events in the control region. The figure  
 1973 shows that the shapes are indeed comparable and thus any CF derived in the same flavor control region  
 1974 can reliably be applied in the signal region.

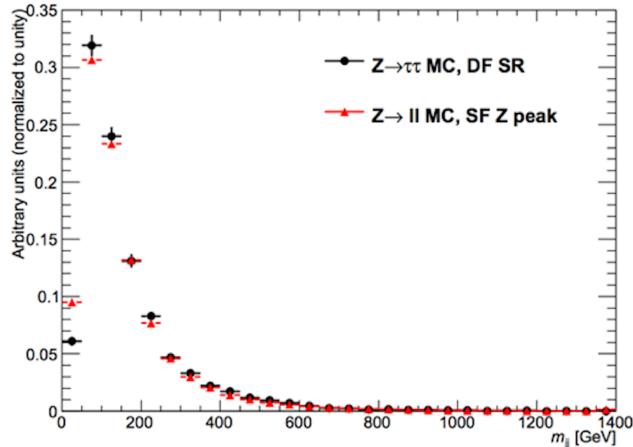


Figure 5.9: Comparison of  $m_{jj}$  shape in a same flavor  $Z \rightarrow \ell\ell$  control region and the VBF cut-based signal region.

1975 Table 5.11 shows the overall normalization factor  $\beta_{\tau\tau}$  and the efficiency correction factors for the various  
 1976 VBF topological cuts. In general, the statistical uncertainties on the cut efficiency corrections are quite  
 1977 good, and the MC tends to underestimate the efficiency of the VBF cuts for the  $Z/\gamma^* \rightarrow \tau\tau$  background.  
 1978 The overall normalization factor is also consistent with that calculated for the BDT analysis.

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

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

1979    5.5.4     $Z/\gamma^* \rightarrow \ell\ell$  BACKGROUND

1980    In the same flavor channels, the  $Z/\gamma^* \rightarrow \ell\ell$  background is dominant and thus must be estimated cor-  
 1981    rectly. In both the BDT and cut-based analyses, the background is estimated using the so-called “ABCD”  
 1982    method. The ABCD method creates four different regions by defining requirements on two variables.  
 1983    One of the regions (A) is the signal region, while the other regions are defined by inverting one of both of  
 1984    the requirements. in this case, the two variables used are  $m_{\ell\ell}$  and  $E_T^{\text{miss}}$ , because inverting either of the  
 1985    SR cuts on these variables will give regions rich in the  $Z/\gamma^* \rightarrow \ell\ell$  background. Figure 5.10 illustrates the  
 1986    definitions of each region.

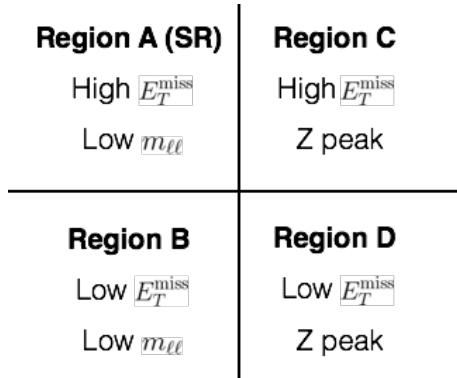


Figure 5.10: General illustration of the ABCD region definitions for  $Z/\gamma^* \rightarrow \ell\ell$  background estimation.

1987    In both of the cut-based and BDT analyses, the Z peak region is defined with  $|m_{\ell\ell} - m_Z| < 15 \text{ GeV}$ .  
 1988    In the cut-based analysis, low  $m_{\ell\ell}$  corresponds to  $m_{\ell\ell} < 50 \text{ GeV}$  (this defines the cut-based SR) while  
 1989    in the BDT it is  $m_{\ell\ell} < 75 \text{ GeV}$ . In the cut-based, high and low  $E_T^{\text{miss}}$  are defined as opposite ends of

1990 the 55 GeV cut applied for the signal region definition. The BDT low  $E_T^{\text{miss}}$  region is between 25 and  
 1991 45 GeV, while the high  $E_T^{\text{miss}}$  region is  $E_T^{\text{miss}} > 45$  GeV.

1992 Once the regions are defined, the background in the signal region is estimated by extrapolating the  
 1993 estimate in region B to region A. This extrapolation is done by multiplying the number of events in region  
 1994 B by the ratio of the number of events in regions C and D. Effectively, the Z peak region is used to estimate  
 1995 the efficiency of the  $E_T^{\text{miss}}$  requirement in data, and then this efficiency is applied in the low  $m_{\ell\ell}$  region.  
 1996 An additional correction is also applied for the non-closure of the method in MC. This is summarized in  
 1997 equations 5.6 and 5.7.

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

1998

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

1999 Here, the  $N$  refer to data yields in each region with the non  $Z/\gamma^*$  backgrounds subtracted, while  $B$  refer  
 2000 to the  $Z/\gamma^*$  yields in MC in each region.

2001 A normalization factor  $\beta_{\ell\ell}$  is computed for each analysis as the ratio of the predicted data yield to the  
 2002 MC yield in the SR. The shape of the BDT distribution is taken from data region B, while the shape of  
 2003 the  $m_T$  distribution in the cut-based analysis is taken from  $Z/\gamma^*$  MC in the SR. The values of  $\beta_{\ell\ell}$  in the  
 2004 cut-based and BDT analyses from this method are summarized in table 5.12. They are quite consistent with  
 2005 one another within the statistical uncertainties. In the cut-based analysis, the same cut efficiency correction  
 2006 factors shown in table 5.11 are also applied (in product with the  $\beta_{\ell\ell}$ ) in the same flavor channels to the  $Z/\gamma^*$   
 2007 background.

	$\beta_t$
BDT Bin 1	$1.01 \pm 0.15$
BDT Bin 2	$0.89 \pm 0.28$
Cut-based	$0.81 \pm 0.21$

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

### 2008 5.5.5 $WW$ AND OTHER DIBOSON BACKGROUNDS

2009 The Standard Model  $WW$  and other diboson backgrounds have both their shape and normalization taken  
 2010 from MC simulation. They are validated in dedicated control regions and found to agree with data well.

2011 As SM  $WW$  production is the largest of these backgrounds and is irreducible, validating the estimate  
 2012 is of particular importance. A validation region is constructed by requiring the pre-selection requirements  
 2013 on leptons and  $m_{\ell\ell}$ ,  $n_b = 0$ , and  $m_T > 100$  GeV. The  $m_{T2}$  variable [98] is an additional discriminant  
 2014 that will isolate the SM  $WW$  background, and a requirement of  $m_{T2} > 160$  GeV is placed to define  
 2015 the  $WW$  validation region. This requirement gives a 60% purity for the validation region. The derived  
 2016 normalization factor in the region is  $1.15 \pm 0.19$  and is thus consistent with unity. Figure 5.11 shows the  
 2017  $m_{T2}$  distribution and how it distinguishes the  $WW$  background.

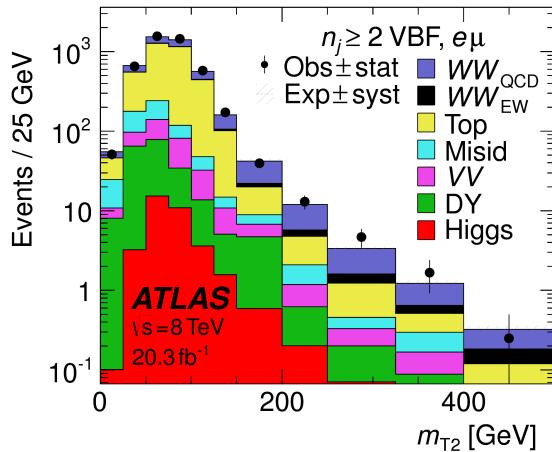


Figure 5.11: Distribution of  $m_{T2}$  in the  $WW$  validation region of the VBF analysis [73].

### 2018 5.5.6 HIGGS PRODUCTION VIA GLUON-GLUON FUSION

2019 Because this analysis is dedicated to measuring the VBF contribution to Higgs production, the compo-  
 2020 nent of Higgs production from gluon-gluon fusion is treated as a background. The shape is taken directly  
 2021 from simulation, using the generators described in table 5.4. In the final combined fit of all different signal  
 2022 regions, the normalization is controlled by either a combined signal strength parameter  $\mu$ , which controls  
 2023 the normalization of both ggF and VBF production, or a separate parameter  $\mu_{ggF}$  depending on the in-

2024 interpretation being presented in the final results.

### 2025 5.5.7 BACKGROUNDS WITH MISIDENTIFIED LEPTONS

2026 As discussed previously, the  $W$ +jets and QCD multijet backgrounds are derived with fully data-driven  
2027 methods. These backgrounds do not make a large contribution to the final VBF signal region but their  
2028 estimation methods are discussed briefly here.

#### 2029 $W$ +JETS BACKGROUND

2030 The  $W$ +jets background enters the signal region by having one of the jets mis-reconstructed as a lepton.  
2031 The background is estimated by constructing a control sample with two leptons, where one lepton passes  
2032 the usual lepton quality requirements but the second lepton fails one of those requirements (also known  
2033 as the “anti-identified” lepton). This control region is rich in the  $W$ +jets contribution because if a second  
2034 lepton is reconstructed in a  $W$ +jets event it is likely to be poor quality. The purity of this  $W$ +jets control  
2035 sample is 85% to 90% depending on the exact configuration of leptons in the final state.

2036 The signal region estimate of  $W$ +jets is estimated by extrapolation from the control sample to the sig-  
2037 nal region using extrapolation factors derived in a  $Z$ +jets control sample in data. The extrapolation factor  
2038 is the ratio of the number of lepton candidates satisfying all quality criteria to the number of lepton can-  
2039 didates anti-identified. This ratio is measured in bins of  $p_T$  and  $\eta$ . Thus, the final signal region estimate  
2040 (binned as the extrapolation factor is binned) is simply the number of events in the anti-identified lepton  
2041 control sample multiplied by the extrapolation factor derived from the  $Z$ +jets control sample. Figure 5.12  
2042 shows the extrapolation factors derived for electrons and muons.

#### 2043 QCD MULTIJET BACKGROUND

2044 The method for estimating the multijet background is very similar to the  $W$ +jets estimation method. The  
2045 control sample in this case has two anti-identified leptons but otherwise satisfies all signal region require-  
2046 ments. The extrapolation factor is estimated from a multijet sample and applied twice to the control sam-  
2047 ple.

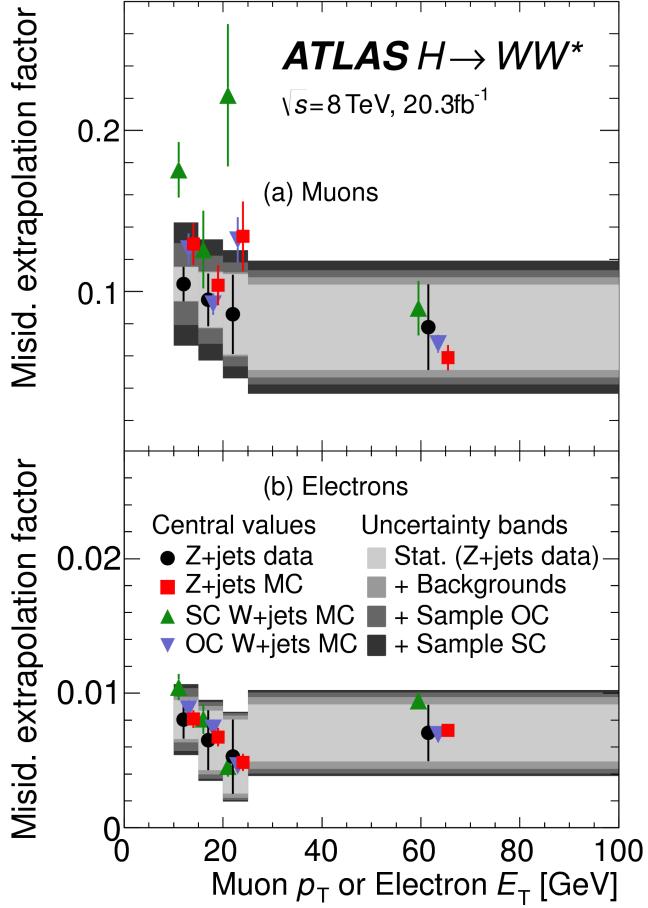


Figure 5.12: Extrapolation factors for the  $W + \text{jets}$  estimate derived for muons (a) and electrons (b) as a function of lepton  $p_T$  [73].

### 2048 5.5.8 BACKGROUND COMPOSITION IN SIGNAL REGION

2049 After all of these estimation procedures, the signal region background composition can be calculated. The  
 2050 estimated yields are all shown in table 5.8. Figure 5.13 shows the relative percentages of the different back-  
 2051 ground for the different flavor and same flavor final states. In  $e\mu$ , the leading backgrounds are top back-  
 2052 grounds, ggF Higgs, and SM  $WW$  production. In  $ee/\mu\mu$ , the leading background is Drell-Yan, followed  
 2053 by top and ggF Higgs.

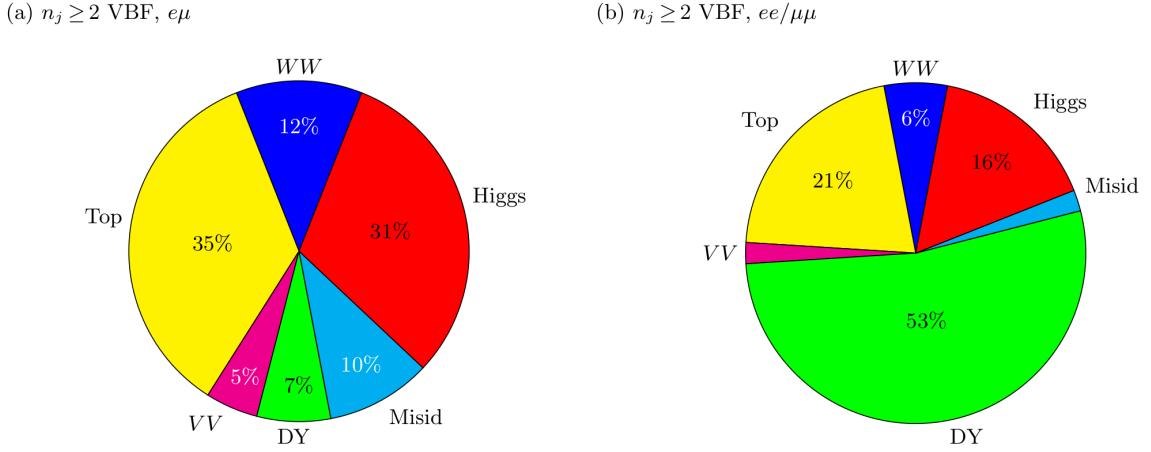


Figure 5.13: Background composition in final VBF signal region [73].

2054 **5.6 SYSTEMATIC UNCERTAINTIES**

2055 There are two main types of systematic uncertainties that are assessed for the analysis. First, theoretical  
 2056 uncertainties associated with the signal and background yield estimates are discussed. Then, experimental  
 2057 uncertainties due to detector effects are shown. Normalization uncertainties refer to uncertainties that  
 2058 affect the cross section of the process in question in the signal region being probed. Shape uncertainties  
 2059 refer to systematic uncertainties that affect the shape of the final discriminating variable (either  $m_T$  or  
 2060  $O_{\text{BDT}}$ ).

2061 **5.6.1 THEORETICAL UNCERTAINTIES**

2062 There are four main components to theoretical uncertainties assigned to signal and background processes  
 2063 taken from Monte Carlo. Each one is a different source of variation in the overall acceptance for that  
 2064 process. The first involves variation of the QCD renormalization and factorization scales used in the cal-  
 2065 culation. In this case, the two scales are varied both independently and simultaneously by factors of two  
 2066 high or low. The resulting variation in normalization and shape for the process is taken as a systematic  
 2067 uncertainty (referred to as scale uncertainty). This uncertainty approximates the level of the correction  
 2068 to the cross section that would come from including the next order of the QCD calculation. Next, there  
 2069 is an uncertainty associated with the PDF set used in generating the events. The uncertainty eigenvec-

tors for the given PDF set are inspected, and the envelope of maximal variation is taken as an uncertainty (referred to as PDF uncertainty). Finally, there are two uncertainties associated with the choice of MC software. 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  $\alpha$  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 [18, 99] for ggF events and the Stewart-Tackmann (ST) method [100] for VBF production. Table 5.13 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 5.13: Systematic uncertainties for various processes in the cut-based VBF analysis, given in units of % change in yield. Values are given for the low  $m_{jj}$  signal region.

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 was no significant shape uncertainty but normalization uncertainties were assigned according to the maximal variation. These uncertainties enter into the 26% total uncertainty on top quark production quoted in table 5.13

2092 While the estimate for the same-flavor  $Z/\gamma^* \rightarrow \ell\ell$  background is data-driven, there is still a systematic  
 2093 uncertainty taken for the non-closure of the method in Monte Carlo. This is taken as the maximum of the  
 2094 deviation of the non-closure factor  $f_{\text{corr}}$  from unity and its uncertainty, or  $\max(|1 - f_{\text{corr}}|, \delta f_{\text{corr}})$ . For  
 2095 the cut-based analysis this non-closure uncertainty 23%, while for the BDT analysis it is 17%.

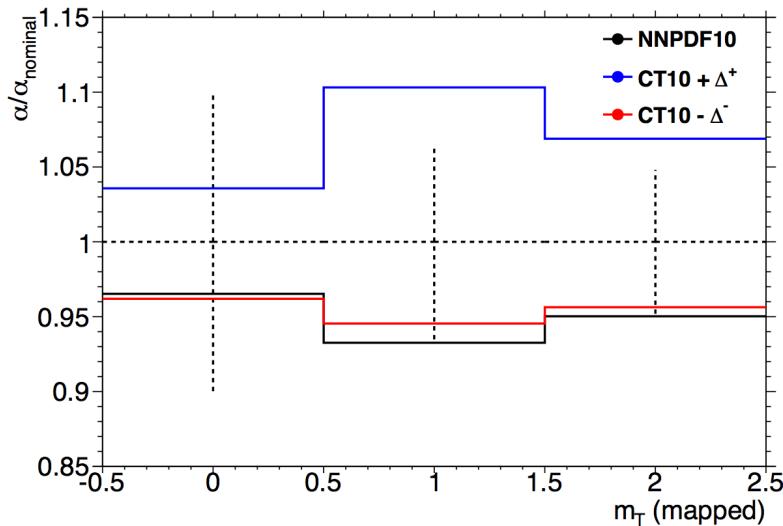


Figure 5.14: Variations in the top background extrapolation factor in the cut-based analysis due to PDF uncertainties. The uncertainties are shown in the three bins of  $m_T$  used in the final cut-based statistical fit. Variations from the eigenvector of the nominal PDF, CT10, as well as the result from an alternate PDF (NNPDF10), are compared.

### 2096 5.6.2 EXPERIMENTAL UNCERTAINTIES

2097 In this analysis, the theoretical uncertainties are the most dominant after statistical, but there are some ex-  
 2098 perimental uncertainties that make a contribution as well. The first is the uncertainty on the measured in-  
 2099 tegrated luminosity, which affects backgrounds whose normalizations are taken from MC and is measured  
 2100 to be 2.8% in the 8 TeV dataset [101]. The dominant sources of uncertainty overall are uncertainties on the  
 2101 jet energy scale and resolution and the  $b$ -tagging efficiency. Additional sources include lepton uncertain-  
 2102 ties on identification, resolution, and trigger efficiency, as well as uncertainties on the missing transverse  
 2103 momentum.

2104 The jet energy scale uncertainty is split into several independent components, including jet-flavor de-  
 2105 pendent calorimeter response uncertainties, uncertainties on modeling of pile-up interactions, uncertain-

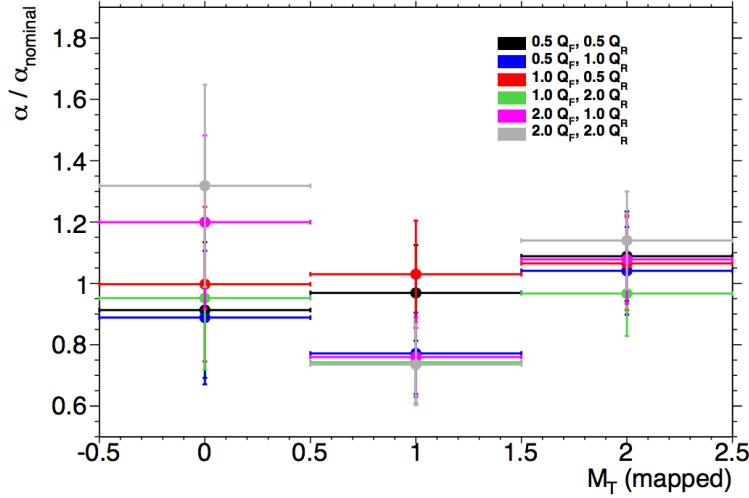


Figure 5.15: Variations in the top background extrapolation factor in the cut-based analysis due to QCD scale uncertainties. The uncertainties are shown in the three bins of  $m_T$  used in the final cut-based statistical fit.  $Q_F$  is the QCD factorization scale, while  $Q_R$  is the QCD renormalization scale.

ties on extrapolation from the central to forward detector regions, and MC non-closure [102]. The uncertainty on energy scale for jets used in this analysis ranges from 1% to 7% depending on the jet  $p_T$  and  $\eta$ . 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 [103, 104]. The efficiencies and their uncertainties are binned in  $p_T$  and decomposed into uncorrelated components using an eigenvector method [105]. 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 mistagging ranges from 9-19% depending on  $p_T$  and  $\eta$ .

The total experimental uncertainties on different signal and background components are summarized in table 5.14. 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				
$N_{\text{sig}}$	13	—	6.8	12
$N_{\text{bkg}}$	9.2	4.7	6.4	4.5
$N_{WW}$	32	—	14	28
$N_{\text{top}}$	15	9.6	7.6	8.5
$N_{\text{misid}}$	22	—	12	19
$N_{VV}$	20	—	12	15
$N_{\tau\tau}$ (DY)	40	25	31	2.9
$N_{ee/\mu\mu}$ (DY)	19	11	15	—

Table 5.14: Composition of the post-fit uncertainties (in %) on the total signal ( $N_{\text{sig}}$ ), total background ( $N_{\text{bkg}}$ ), and individual background yields in the VBF analysis [73].

## 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  $O_{\text{BDT}}$  are shown in table 5.15.

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  $O_{\text{BDT}}$  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 5.18 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 signal candidates from the lower  $m_{jj}$  region due to its ability to recognize correlations with other variables.

(a) Before the BDT classification

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

(b) Bins in  $O_{\text{BDT}}$ 

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

Table 5.15: Event selection for the VBF BDT analysis. The event yields in (a) are shown after the pre-selection and the additional requirements applied before the BDT classification (see text). The event yields in (b) are given in bins in  $O_{\text{BDT}}$  after the classification [73].

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

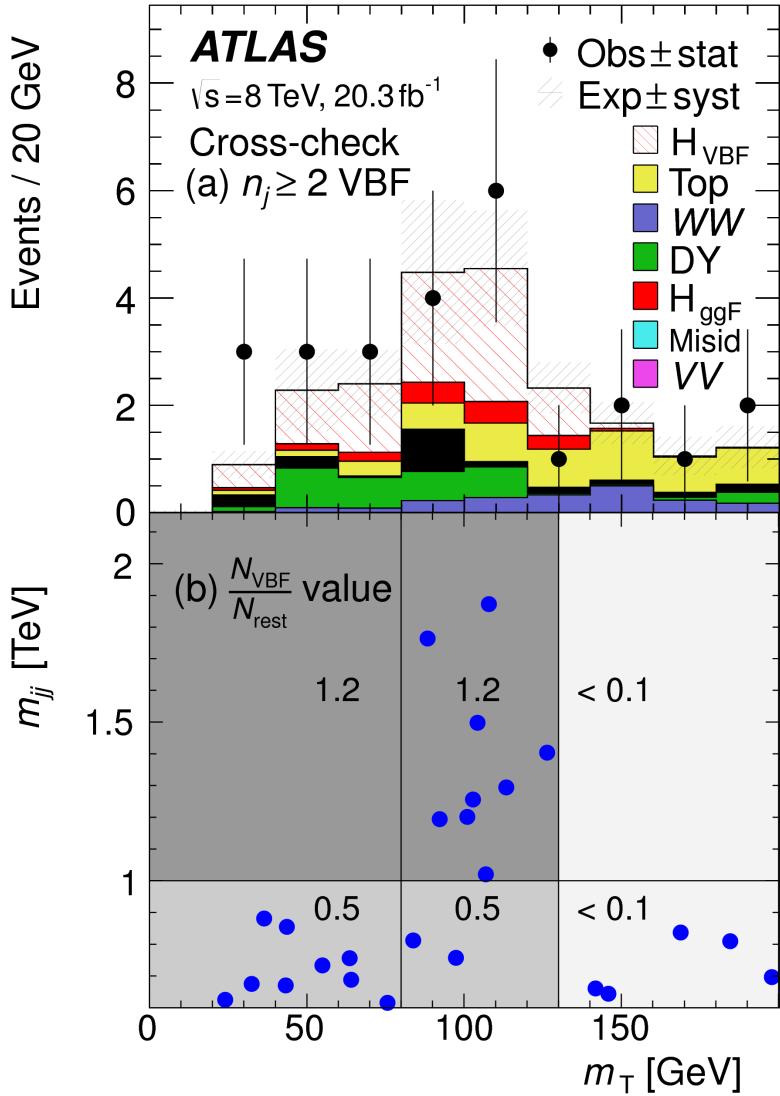


Figure 5.16: Post-fit distributions in the cut-based VBF analysis. Panel (a) shows the one-dimensional  $m_T$  distribution, while (b) shows the data candidates split into the bins of  $m_T$  and  $m_{jj}$  used in the final fit [73].

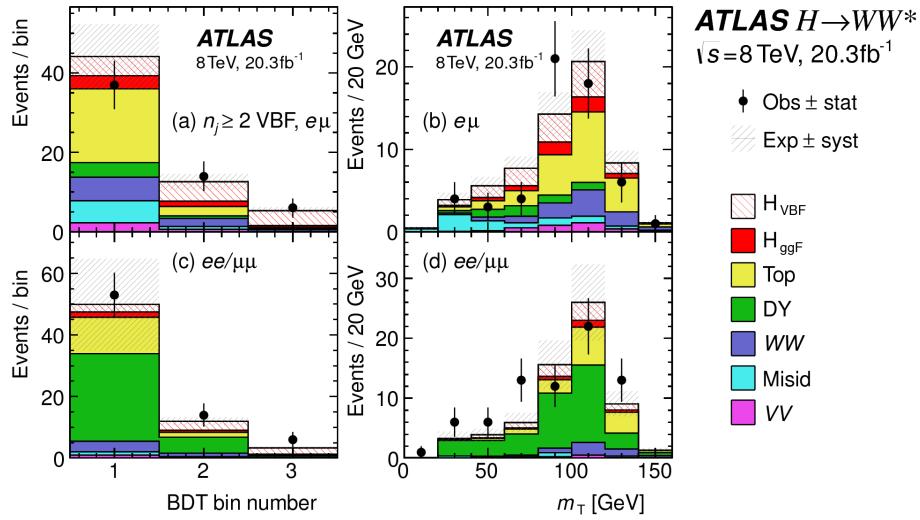


Figure 5.17: Postfit distributions in the BDT VBF analysis [73].

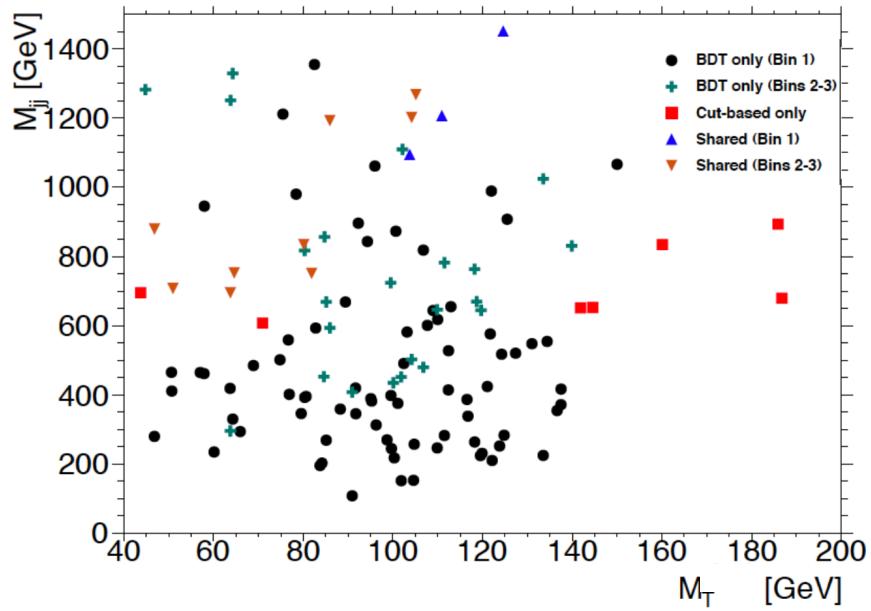


Figure 5.18: Overlap between cut-based and BDT VBF signal region candidates in the  $m_{jj}$ - $m_T$  plane.

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

Chuck Palahniuk

# 6

2145

2146

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

2147

## results

2148

### 6.1 INTRODUCTION

2149 In the final statistical analysis of  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ , the dedicated gluon-gluon fusion and vector  
2150 boson fusion sensitive signal regions are all combined into a single fit to determine the main parameters of  
2151 interest, the Higgs signal strength  $\mu$  and mass  $m_H$ . Therefore, while the specific requirements applied for  
2152 the VBF sensitive analysis are discussed in chapter 5, the final measurement of these parameters can only be  
2153 discussed in combination with the results of the ggF dedicated analysis. For example, because ggF Higgs  
2154 production is considered a background in the VBF analysis, the ggF dedicated signal regions can actually  
2155 constrain the normalization of this background in the VBF dedicated region.

2156 This chapter presents the combined interpretation of results in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis

2157 for gluon fusion and vector boson fusion Higgs production. First, the results of the dedicated gluon fu-  
 2158 sion search are presented. Then, a comparison of the individual production mode signal strengths ( $\mu_{\text{ggF}}$   
 2159 and  $\mu_{\text{VBF}}$ ) and a measurement of the combined signal strength ( $\mu$ ) are shown. Subsequently, the mea-  
 2160 sured values of the Higgs couplings to fermions and vector bosons is presented. Finally, the cross section  
 2161 measurement for ggF and VBF production are shown.

## 2162 6.2 RESULTS OF DEDICATION GLUON FUSION $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ ANALYSIS

2163 The details of the dedicated gluon fusion  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis are not discussed in this thesis  
 2164 and instead left to more comprehensive sources [73]. However, a brief summary of the results is essential  
 2165 for describing the measurements of Higgs properties and interpreting the the dedicated VBF Higgs pro-  
 2166 duction search in a broader context. Additionally, the final Run I results on gluon fusion production make  
 2167 use of the dedicated variables for same flavor final states developed in section 3.5. The results in the same  
 2168 flavor final states will be shown here as well.

### 2169 6.2.1 RESULTS IN SAME FLAVOR ( $ee/\mu\mu$ ) FINAL STATES

2170 Final states of the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel where both leptons have the same flavor ( $ee/\mu\mu$ )  
 2171 were not included in the discovery result due to increased pileup conditions in the  $\sqrt{s} = 8$  TeV data.  
 2172 Dedicated techniques for background reduction in the same flavor final states were developed, as described  
 2173 in section 3.5. The results shown in this section are the first published results using the same flavor channels  
 2174 in the  $H \rightarrow WW^*$  analysis.

2175 Table 6.1 shows the background estimate, expected signal yield, and event count in data for the same  
 2176 flavor channels in the  $n_j \leq 1$  signal regions. The dedicated same flavor background reduction techniques  
 2177 allow this channel to preserve a signal to background ratio similar to that of the different flavor channels.

	$N_{\text{obs}}$	$N_{\text{bkg}}$	$N_{\text{ggF}}$	$N_{\text{VBF}}$
$n_j = 0$	1108	$1040 \pm 40$	$77 \pm 15$	$2.4 \pm 1.7$
$n_j = 1$	467	$427 \pm 21$	$22 \pm 6$	$3.6 \pm 1.8$

Table 6.1: Post-fit yields in ggF dedicated signal regions for the  $ee/\mu\mu$  final states [73].

2178     Figure 6.1 shows the final  $m_T$  distribution in data for the  $n_j \leq 1$  same flavor channels. The data is very  
 2179     consistent with the Higgs hypothesis and it can be seen that the same flavor channels are indeed sensitive  
 2180     to gluon fusion production of the Higgs.

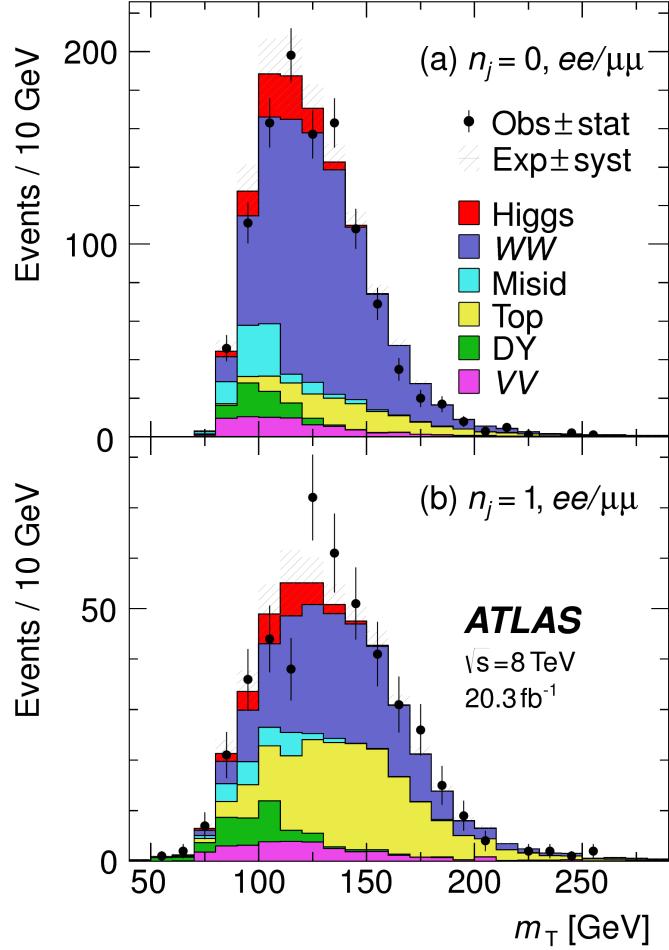


Figure 6.1: Post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions for the same flavor ( $ee/\mu\mu$ ) final states [73].

### 2181     6.2.2 COMBINED GLUON FUSION RESULTS

2182     Table 6.2 shows the individual signal regions that were input into the final statistical fit. The ggF dedicated  
 2183     bins use  $m_T$  as their discriminating variable and are separated into bins of  $p_T$  of the subleading lepton as  
 2184     well. The VBF dedicated bin uses the  $O_{BDT}$  distribution as its final discriminant.

2185     Table 6.3 shows the yields in the various signal regions in both data and expected signal and back-  
 2186     grounds. The yields for signal and background are all scaled according to the final normalizations cal-

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	$e\mu$	$\otimes [10, 50]$	$\otimes [10, \infty]$		$O_{\text{BDT}}$
	$ee/\mu\mu$	$\otimes [12, 50]$	$\otimes [10, \infty]$		$O_{\text{BDT}}$

Table 6.2: All signal regions definitions input into final statistical fit [73].

2187 culated in the fit.

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

Table 6.3: Post-fit yields in the both ggF and VBF dedicated signal regions with all lepton flavor final states combined [73].

2188 Figure 6.2 shows the final post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions. The data are very consistent  
 2189 with the hypothesis of ggF Higgs production. These yields are used as input, along with the VBF results  
 2190 in chapter 5, for the physical interpretation of results presented in subsequent sections.

### 2191 6.3 SIGNAL STRENGTH MEASUREMENTS IN GGF AND VBF PRODUCTION

2192 When all of the signal regions are combined in the fit, there can be a combined measurement of the signal  
 2193 strength as well as the individual ggF and VBF signal strengths. The combined signal strength is the ratio of  
 2194 the measured cross section in the combined gluon fusion and VBF signal regions to the theory prediction

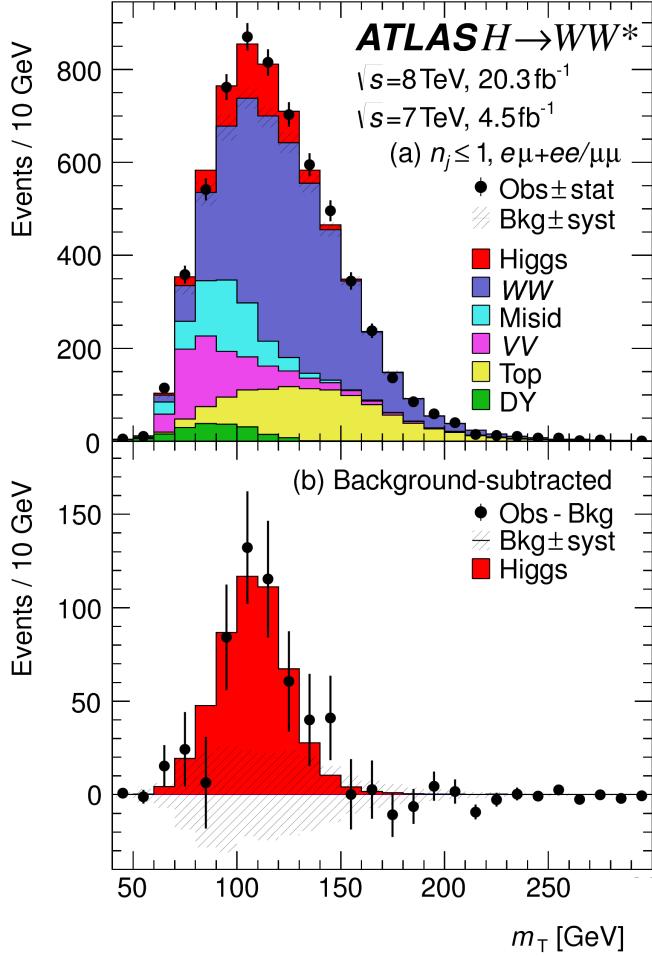


Figure 6.2: Post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions [73].

for the sum of of these two processes. It is a signal strength measurement for the total Higgs production cross section that this analysis is sensitive to. The final measured combined signal strength  $\mu$  is measured shown in equation 6.1.

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

2198 Figure 6.3 gives the best fit signal strength  $\hat{\mu}$  as a function of the hypothesized Higgs mass. The value at  
 2199 a mass of 125.36 GeV corresponds to the  $\mu$  quoted in equation 6.1. This value of the Higgs mass is used  
 2200 because it is the most precise mass measurement from ATLAS, a result of the combined  $\gamma\gamma$  and  $ZZ$  mass  
 2201 measurements [106].

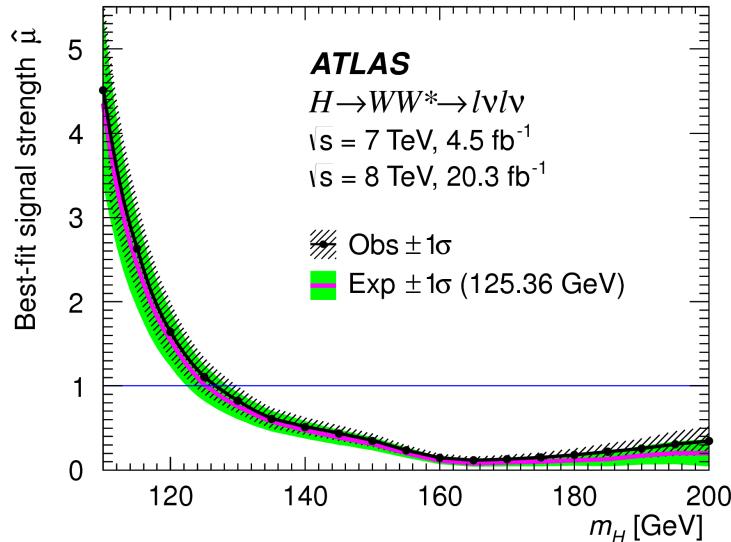


Figure 6.3: Best fit signal strength  $\hat{\mu}$  as a function of hypothesized  $m_H$  [73].

2202 As explained in chapter 3, a probability  $p_0$  can be computed using the test statistic  $q_0$  to quantify the  
 2203 probability that the background could fluctuate to produce an excess at least as large as the one observed  
 2204 in the data. The local  $p_0$  value is shown in figure 6.4 as a function of  $m_H$ . The minimum  $p_0$  value is at  
 2205  $m_H = 130$  GeV and corresponds to a significance of  $6.1\sigma$ . The curve is relatively flat and the significance  
 2206 is the same at 125.36 GeV within the quoted precision. The expected significance for a signal with strength  
 2207  $\mu = 1.0$  is  $5.8\sigma$ . This represents the first discovery level observation of Higgs production using only the  
 2208  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis.

2209 All the results presented so far in this section have been for the combined gluon fusion and VBF  
 2210 production modes. However, each signal strength can be calculated separately in the likelihood as well. There  
 2211 are two ways to do this. First, the likelihood can be parameterized in terms of a single parameter, the ratio  
 2212 of the VBF and gluon fusion signal strengths. With this method, the statistical significance of the VBF  
 2213 Higgs result can be evaluated. Figure 6.5 shows the likelihood as a function of the ratio  $\mu_{\text{VBF}}/\mu_{\text{ggF}}$ .

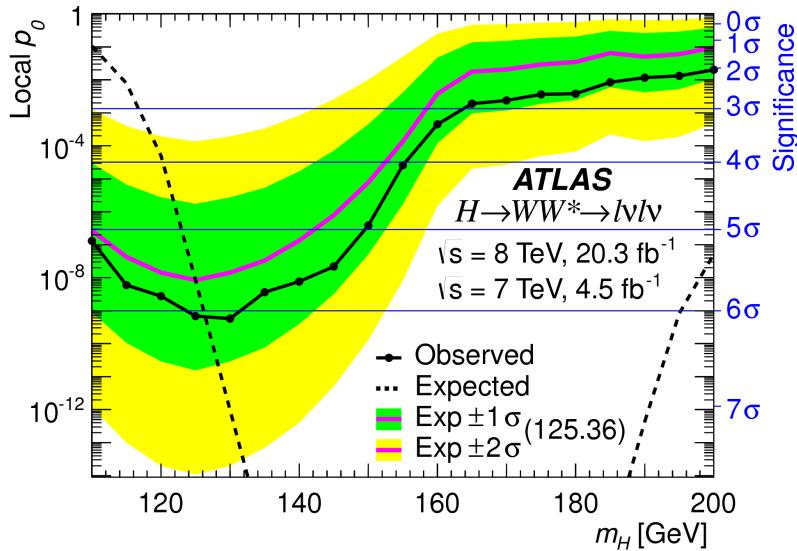


Figure 6.4: Local  $p_0$  as a function of  $m_H$  [73].

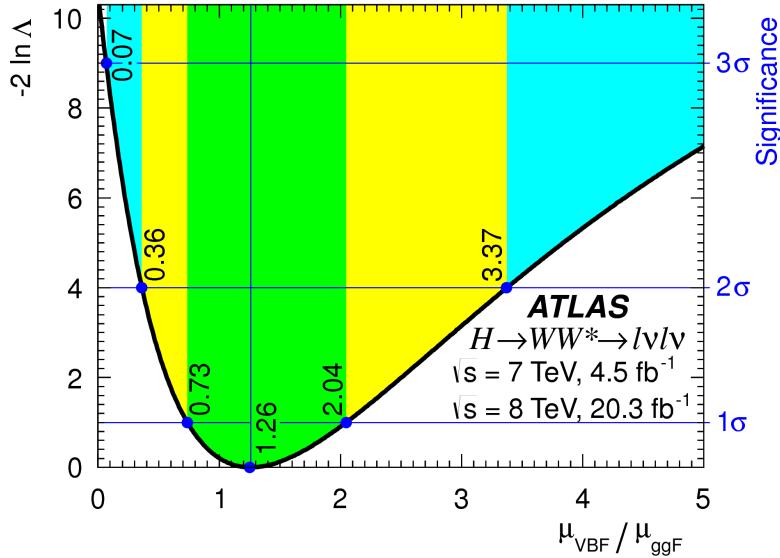


Figure 6.5: Likelihood as a function of  $\mu_{\text{VBF}} / \mu_{\text{ggF}}$  [73].

<sup>2214</sup> The best fit value of the ratio of signal strengths is shown in equation 6.2. Within the quoted uncer-  
<sup>2215</sup> tainties, it is consistent with a ratio of unity.

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

2216 The null hypothesis for VBF production corresponds to a ratio of  $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ . The likelihood in  
 2217 figure 6.5 gives a significance of  $3.2\sigma$  at  $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ , as quoted in chapter 5.

2218 In addition to the ratio of signal strengths, each signal strength can be varied independently in the like-  
 2219 lihood as well. Figure 6.6 shows the two dimensional likelihood scan in the  $\mu_{\text{ggF}}-\mu_{\text{VBF}}$  plane. The best fit  
 2220 values of the two signal strengths are shown in equation 6.3. Both are consistent with unity within their  
 2221 uncertainties.

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

(stat.) (syst.)

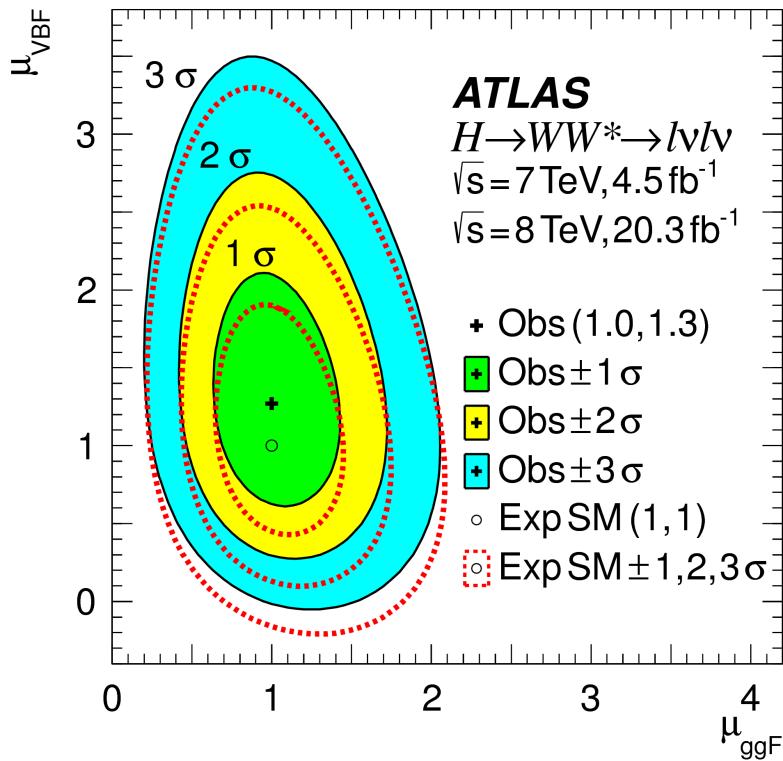


Figure 6.6: Two dimensional likelihood scan as a function of  $\mu_{\text{VBF}}$  and  $\mu_{\text{ggF}}$  [73].

2222 6.4 MEASUREMENT OF HIGGS COUPLINGS TO VECTOR BOSONS AND FERMIONS

2223 Similar to the parameterization of signal strength, the couplings of the Higgs to fermions and bosons can  
 2224 also be parameterized. The parameter of interest in this case is  $\kappa$ , or the ratio of the measured coupling to  
 2225 the Standard Model expectation. Both the fermion and boson couplings have these so-called scale factors,  
 2226  $\kappa_F$  for fermions and  $\kappa_V$  for bosons. Gluon fusion production is sensitive to the fermion couplings through  
 2227 the top quark loops in its production, while VBF production is sensitive to the vector boson couplings in  
 2228 its production. Both modes are sensitive to the vector boson couplings in their decays. The signal strengths  
 2229 will have dependence on the coupling scale factors as described in equation 6.4 [18].

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

2230 Figure 6.7 shows the two-dimensional likelihood scan of  $\kappa_F$  and  $\kappa_V$ . The best-fit values are given in equa-  
 2231 tion 6.5. The best-fit values are consistent with unity within their uncertainties.

$$\begin{aligned}\kappa_F &= 0.93 & {}^{+0.24}_{-0.18} & {}^{+0.21}_{-0.14} & = 0.93 & {}^{+0.32}_{-0.23} \\ \kappa_V &= 1.04 & {}^{+0.07}_{-0.08} & {}^{+0.07}_{-0.08} & = 1.04 & \pm 0.11.\end{aligned}\quad (6.5)$$

(stat.) (syst.)

2232

2233 6.5 HIGGS PRODUCTION CROSS SECTION MEASUREMENT

2234 Another measurement that comes naturally from the signal strength measurements quoted earlier is the  
 2235 production cross section and 7 and 8 TeV for both gluon fusion and VBF production. The general equa-

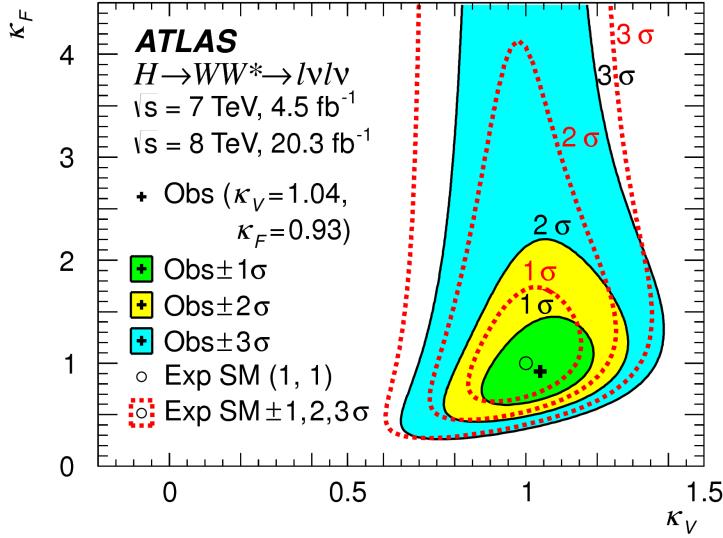


Figure 6.7: Likelihood scan as a function of  $\kappa_F$  and  $\kappa_V$ , the Higgs coupling scale factors [73].

tion for calculating the cross section is given in equation 6.6.

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

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

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

(stat.) (syst.)

2242 The predicted cross section values (including the branching ratio of  $H \rightarrow WW^*$ ) for gluon fusion are  
2243  $3.3 \pm 0.4$  pb at 7 TeV and  $4.2 \pm 0.5$  pb at 8 TeV, consistent with the measured values within their uncer-  
2244 tainties. For vector boson fusion, the predicted cross section is  $0.35 \pm 0.02$  pb, again consistent with the  
2245 measured value.

2246 **6.6 CONCLUSION**

2247 The combined analysis of the gluon fusion and vector boson fusion processes in  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  in  
2248 the 7 and 8 TeV datasets has yielded the first discovery level significance for Higgs production in this decay  
2249 channel. Additionally, precise measurements of the couplings to vector bosons and fermions are given.  
2250 Finally, signal strengths and cross sections for each production mode are measured. Figure 6.8 shows the  
2251  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  measurements in comparison with other Higgs decay channels in ATLAS. The  
2252 measurement of signal strength from this channel remains the most sensitive in both the gluon fusion and  
2253 VBF production modes for the Run 1 dataset.

**ATLAS**

### Individual analysis

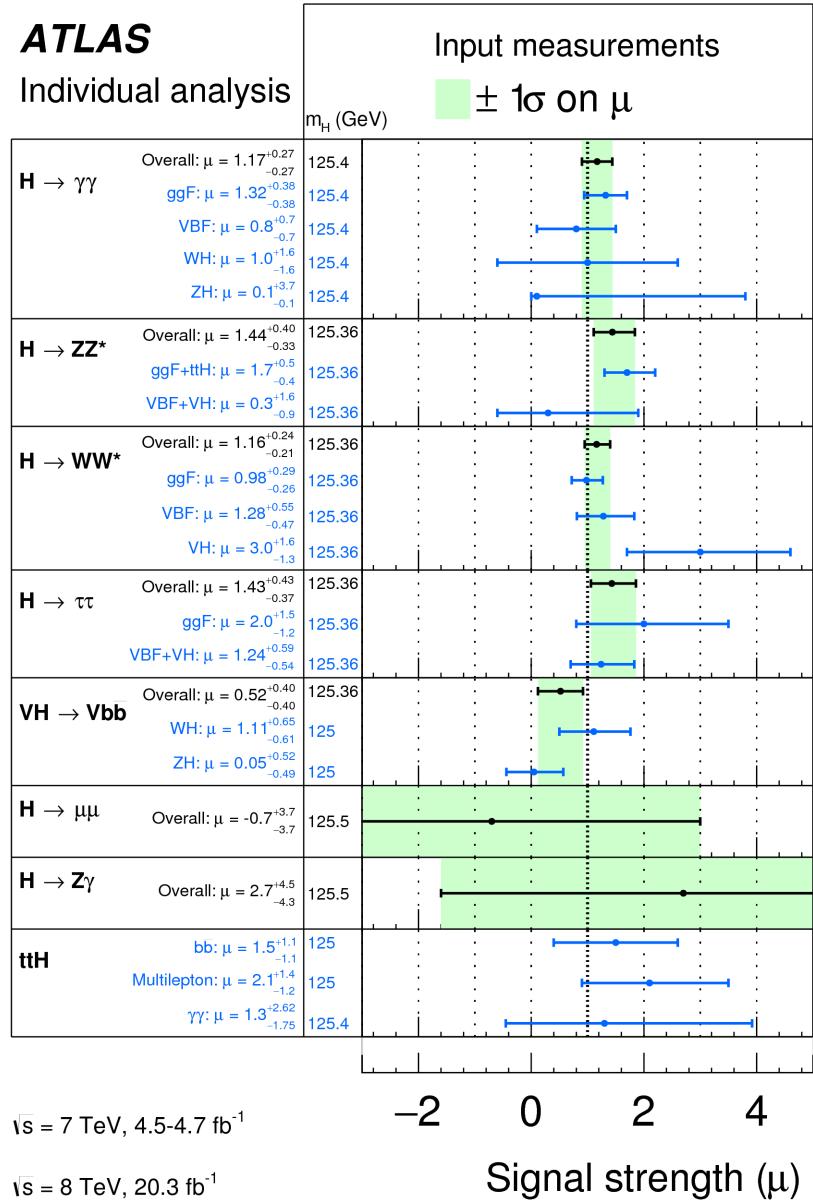


Figure 6.8: Comparison of signal strength measurements in different Higgs decay channels on ATLAS [107].

2254

## Part III

2255

Search for Higgs pair production in the

2256

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

2257

13 TeV

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

W. Eugene Smith

# 7

2258

## 2259 Search for Higgs pair production in boosted 2260 $b\bar{b}b\bar{b}$ final states

### 2261 7.1 INTRODUCTION

2262 This chapter presents a search for resonant production of a Higgs pair in the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  final  
2263 state in  $3.2 \text{ fb}^{-1}$  of data collected at  $\sqrt{s} = 13 \text{ TeV}$ . In particular, this chapter focuses on a search for this  
2264 final state in the regime where  $m_X$  is large ( $\gtrsim 1 \text{ TeV}$ ) and the Higgs bosons in the decay are significantly  
2265 boosted. A tailored selection for this boosted selection, using novel techniques in jet substructure and  $b$ -  
2266 tagging, is discussed. Then, the data-driven background estimate is presented. Finally, the results of the  
2267 search are shown. The signal models used as benchmarks are a spin-2 Randall Sundrum graviton (RSG)  
2268 and a narrow width spin zero resonance. These models are described in more detail in Chapter 1. Limits  
2269 on signal models are reserved for the next chapter where the results of this chapter are combined with the

2270 results of a separate selection dedicated to the lower  $m_X$  regime.

2271 **7.2 MOTIVATION**

2272 With the center of mass energy increase from  $\sqrt{s} = 8 \text{ TeV}$  to  $\sqrt{s} = 13 \text{ TeV}$ , the LHC and ATLAS are  
2273 able to probe new resonances at higher mass scales than previously accessible in Run 1. This is a powerful  
2274 motivator for searching for a new resonance in the early 13 TeV data. Figure 7.1 shows the ratios of parton  
2275 luminosities between 8 and 13 TeV for different resonance masses. For a resonance of  $M_X = 2 \text{ TeV}$ , the  
2276 cross section at  $\sqrt{s} = 13 \text{ TeV}$  is roughly a factor of 10 larger than at  $\sqrt{s} = 8 \text{ TeV}$ .

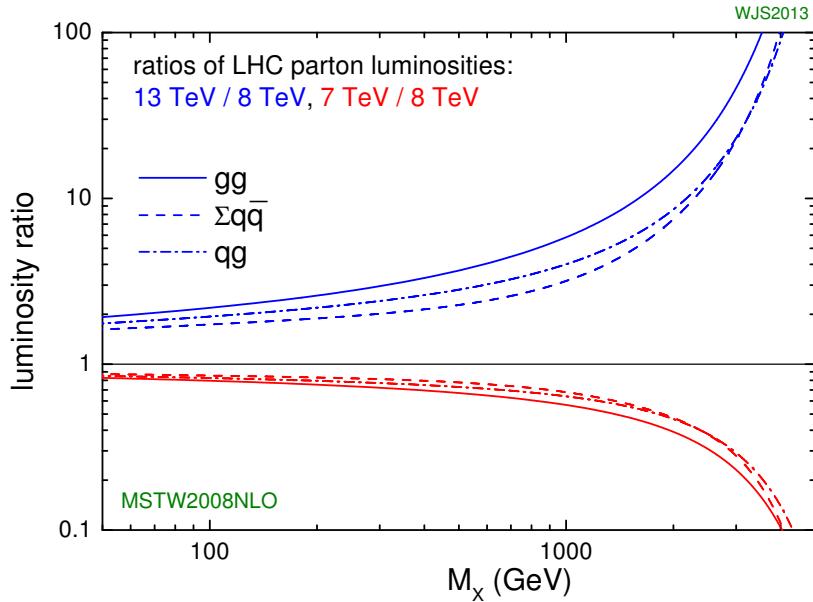


Figure 7.1: Parton luminosity ratios as a function of resonance mass  $M_X$  for 13/8 TeV and 7/8 TeV [108].

2277 Higgs pair production offers a vast array of unprobed regions of phase space where searches for BSM  
2278 physics can be made. Chapter 1 discusses some possibilities for both resonant and non-resonant enhance-  
2279 ment of the di-Higgs production cross section. Given the increased mass reach of the LHC in Run 2, it is  
2280 particularly important to focus on resonant searches at high  $m_X$ . When conducting a search in the  $HH$   
2281 final state, the different possible decay modes of each Higgs must be considered. Figure 7.2 shows the  
2282 branching ratio of the  $HH$  final state for different combinations of decays of each individual Higgs. As

2283 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  
 2284 largest at 33%.

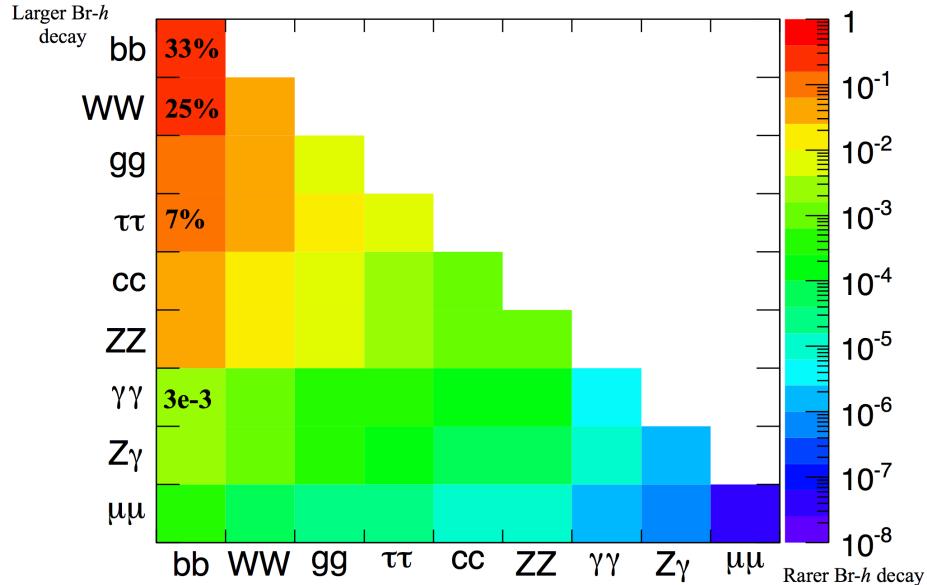


Figure 7.2: Summary of  $HH$  branching ratios [109].

2285 At high  $m_X$ , the Higgs bosons resulting from the decay of a heavy resonance will have large  $p_T$ <sup>1</sup>. The  
 2286 angular separation between the decay products of the Higgs,  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ , is inversely  
 2287 proportional to the Higgs  $p_T$ , as shown in equation 7.1.

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

2288 Figure 7.3 shows the minimum  $\Delta R$  between truth level  $B$  decay vertices in simulation samples for Randall-  
 2289 Sundrum gravitons of different masses. The figure shows that as the mass of the graviton increases, the  $\Delta R$   
 2290 distribution between the  $b$  quarks in the Higgs decay tends to shift to lower values. Because of this effect,  
 2291 it is necessary to tailor a selection to target these merged  $b$ -jets.

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<sup>1</sup>In the limit that the resonance mass is much larger than the Higgs mass, the Higgs  $p_T$  is roughly  $m_X/2$ .

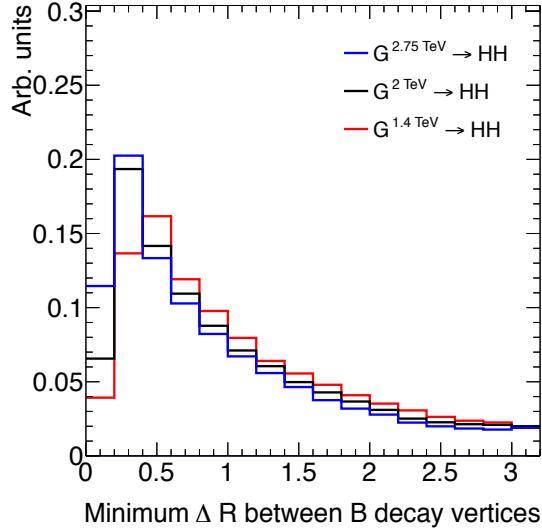


Figure 7.3: Minimum  $\Delta R$  between  $B$  decay vertices for different RSG masses in a  $G_{KK}^* \rightarrow HH \rightarrow 4b$  sample with  $c = 1$ .

2292    7.3 DATA AND SIMULATION SAMPLES

2293    7.3.1 SIGNAL MODELS

2294    While the resonance search is by its nature generic (as it is a simple search for a peak in the  $4b$  invariant mass  
 2295    spectrum), there are two signal models that the selection requirements have been optimized for. The first  
 2296    is Randall-Sundrum (RSG) model, where a tower of massive spin-2 Kaluza-Klein gravitons is predicted.  
 2297    The second is a heavy narrow scalar resonance, the so-called “heavy Higgs”. This type of resonance arises,  
 2298    for example, in the two Higgs doublet model (2HDM). More details about the physics of these models  
 2299    and their motivation is given in chapter 1.

2300    Signal graviton ( $G_{KK}^*$ ) events are generated at leading order (LO) with **MADGRAPH5 v2.2.2** [110]. The  
 2301    PDF set used is the **NNPDF2.3 LO** set [111]. For modeling parton shower and hadronization in jets, **PYTHIA**  
 2302    8.186 is used with the A14 tune [89, 112]. The free parameters in the RSG model are the graviton mass  
 2303    and the coupling constant  $c \equiv k/\bar{M}_{\text{Pl}}^2$ . Both the production cross section and width of the graviton are  
 2304    proportional to  $c^2$ . Samples are generated at both  $c = 1$  and  $c = 2$  for a variety of mass points between

---

<sup>2</sup> $k$  is the curvature constant for the warped extra dimension and  $\bar{M}_{\text{Pl}}$  is the Planck mass divided by  $8\pi$

2305 300 GeV and 3 TeV.

2306 The second signal sample is a heavy spin-0 resonance  $H$  with a fixed width of  $\Gamma_H = 1 \text{ GeV}$ . This  
2307 is generated with **MADGRAPH5** and uses the **CT10** PDF set [92]. The parton shower and hadronization  
2308 are handled by **HERWIG ++** with the **CTEQ6L1** PDF set and the **UEEE5** event tune [93, 113, 114]. Because  
2309 the width and branching ratios depend on 2HDM parameters, each mass point generated with this fixed  
2310 width corresponds to a different point in the 2HDM parameter phase space. Mass points are generated  
2311 between 300 GeV and 1 TeV as with the RSG signal samples.

### 2312 7.3.2 BACKGROUND SAMPLES

2313 While the dominant **QCD** multijet background is estimated with a fully data-driven method, the sub-  
2314 dominant backgrounds  $t\bar{t}$  and  $Z+\text{jets}$  are modeled with some input from simulation.

2315  $t\bar{t}$  events are simulated at next-to-leading order (NLO) with the **POWHEG-BOX** version 1 generator us-  
2316 ing the **CT10** PDF set [115]. The parton shower, hadronization, and underlying event are simulated with  
2317 **PYTHIA 6.428** with the **CTEQ6L1** PDF set [88]. The Perugia 2012 tune is used [116]. **NNLO QCD** correc-  
2318 tions to the cross sections are computed in **Top++ 2.0** [117]. The top quark mass is set to 172.5 GeV. The  
2319 shapes of distributions in  $t\bar{t}$  are taken from MC while the normalization is taken from data.

2320 Finally, the  $Z+\text{jets}$  background is simulated with **PYTHIA 8.186** and the **NNPDF2.3 LO** PDF set. This  
2321 background is negligible compared to the others and is taken fully from MC.

### 2322 7.3.3 DATA SAMPLE AND TRIGGER

2323 This analysis is done on  $3.2 \text{ fb}^{-1}$  of data taken in 2015 at  $\sqrt{s} = 13 \text{ TeV}$ . The details of the machine  
2324 conditions during this time can be found in Chapter 2. Only data which was taken during stable beam  
2325 conditions with all detectors functioning is used. Events must pass a trigger which requires a single large  
2326 radius ( $R = 1.0$ ) jet with  $p_T > 360 \text{ GeV}$  to be reconstructed in the HLT. Figure 7.4 shows the trigger  
2327 efficiency for various trigger options as a function of graviton mass. Above  $m_{G_{KK}^*} > 1 \text{ TeV}$ , the single  
2328 large radius jet trigger is 99% efficient for events passing the signal selection.

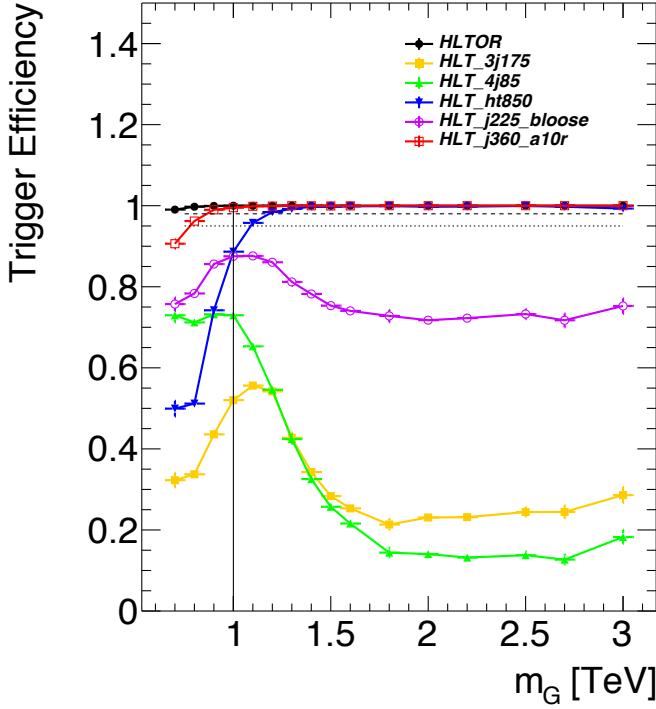


Figure 7.4: Trigger efficiency for events passing all signal region selections as a function of mass in  $G_{KK}^* \rightarrow HH \rightarrow 4b$  samples with  $c = 1$  [118]. In the trigger names, “j” refers to a jet or jets. “ht” refers to  $H_T$ , the scalar sum of transverse momenta in the event. “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 of each trigger name are the thresholds on the given quantity in GeV.

## 2329 7.4 EVENT RECONSTRUCTION AND OBJECT SELECTION

2330 The boosted selection first begins by defining a unique set of objects that can be exploited to increase signal  
 2331 efficiency in the kinematic regime where the final state  $b$ -jets are very merged.

### 2332 7.4.1 LARGE RADIUS ( $R = 1.0$ ) JETS

2333 The first step towards reconstructing the final state is to define objects that can be used to measure the  
 2334 kinematics of the Higgs bosons. In the boosted selection anti- $k_T$  jets with a radius parameter of 1.0 are  
 2335 used. These jets are much larger in angular size than the typical  $R = 0.4$  jets and are intended to encompass  
 2336 all of the products of the Higgs decay<sup>3</sup>. The jets are built from clusters in the calorimeter calibrated with

---

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

local calibration weighting [68].

Because of the large extent of these jets, great care must be taken to remove potential contributions of calorimeter clusters from pile-up. This is done using a technique called jet trimming [119]. With trimming, the constituents of the large radius jet are re-clustered with a smaller radius using the  $k_T$  algorithm. Then, these so-called subjets are removed from the larger jet if  $p_T^{\text{subjett}} / p_T^{\text{jet}} < f_{\text{cut}}$ . In this analysis, the subjet radius is  $R = 0.2$  and  $f_{\text{cut}} = 0.05$ . Trimming has been shown to improve the mass resolution of large radius jets. Figure 7.5 shows the effect of trimming on the large radius jet mass ( $M_J$ ). Because the large radius jet fully contains the Higgs decay products, its invariant mass should correspond to the 125 GeV mass of the Higgs. The trimming algorithm brings the jet mass much closer to the expected Higgs mass and improves the mass resolution.

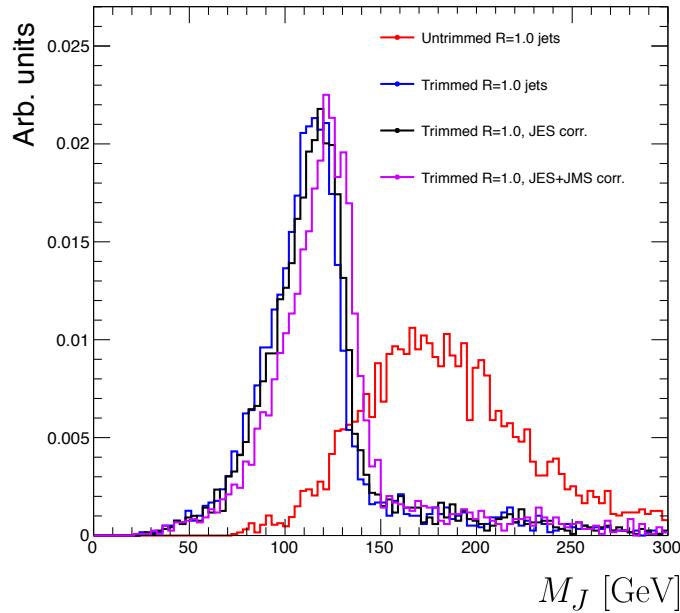


Figure 7.5: Comparison of untrimmed and trimmed jet masses for large radius jets in a RSG sample with  $m_{G_{KK}^*} = 1$  TeV. JES (JMS) refers to the standard jet energy (mass) scale calibration for ATLAS [68].

The large radius jets are required to satisfy  $250 < p_T < 1500$  GeV. They must also be within  $|\eta| < 2.0$  in order to ensure that the full jet is within the inner detector tracking volume. Finally, they are required to have  $M_J > 50$  GeV. The upper  $p_T$  cut and lower threshold on mass are applied to correspond to the kinematic range where uncertainties are available in ATLAS calibrations [120, 121].

2351    7.4.2 TRACK JETS AND  $b$ -TAGGING

2352    Because the  $b$ -jets from boosted Higgs decays are so close together (as illustrated in figure 7.3), narrow radius  
 2353    jets are required to fully resolve both  $b$ -jets. The minimum radius feasible for jets based on calorimeter  
 2354    deposits is determined by the calorimeter granularity. However, because  $b$ -tagging relies on information  
 2355    from the inner detector, it is possible to define another type of jet that can have a smaller radius and better  
 2356     $b$ -tagging resolution. These jets are called “track jets” [121, 122].

2357    Track jets are formed by applying the usual anti- $k_T$  clustering algorithm to tracks that are required to be  
 2358    consistent with the primary vertex. After the jet axis has been determined using these tracks, a second step  
 2359    of track association is also performed to add tracks that can be useful for  $b$ -tagging [122]. In this analysis,  
 2360    the tracks are clustered with a radius parameter of  $R = 0.2$ . This radius has been shown to give good  
 2361    performance in boosted Higgs tagging [121, 122]. Figure 7.6 shows a comparison among different track jet  
 2362    radii of the efficiency for reconstructing two  $b$ -jets from each Higgs in a RSG sample as a function of mass.

Track jets with radius of 0.2 give the best performance, especially at high mass. In this analysis, track jets

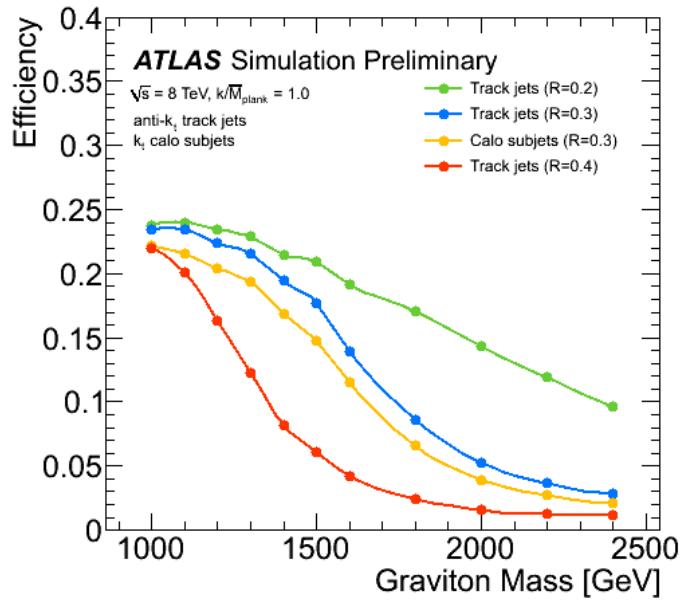


Figure 7.6: Efficiency of finding two  $b$ -jets from each Higgs in an RSG event using calorimeter jets with  $R = 0.3$  and track jet radii of  $R = [0.2, 0.3, 0.4]$  [122].

2363

2364    are required to have  $p_T > 10 \text{ GeV}$  and  $|\eta| < 2.5$ . They must also have at least two tracks.

2365 **7.4.3 MUONS**

2366 Muons are used in this study to correct the four-momenta of calorimeter jets by accounting for semi-  
2367 leptonic  $b$  decays. The muons used are combined ID and MS muons which must satisfy tight identification  
2368 requirements [64]. The muons must have  $p_T > 4 \text{ GeV}$  and  $|\eta| < 2.5$ . Table 7.1 summarizes the object  
2369 requirements described in this section.

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

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

2370 **7.5 EVENT SELECTION**

2371 The first requirement in the boosted event selection is for  $\geq 2$  large radius jets satisfying the selections  
2372 outlined above. The two highest momentum large-R jets in the event are referred to as “Higgs candidates”.  
2373 The leading jet is required to have  $p_T > 350 \text{ GeV}$ .

2374 Track jets satisfying the object selections are matched to Higgs candidate jets via ghost association [123].  
2375 Each Higgs candidate must have at least 2 track jets associated with it. These basic requirements are illus-  
2376 trated graphically in figure 7.7.

2377 The QCD multijet background produces less central jets than high mass resonances, so there is an ad-  
2378 dditional requirement that the two Higgs candidates be close together in  $\eta$ . The large-R jets are required to  
2379 satisfy  $|\Delta\eta(JJ)| < 1.7$ .

2380 **7.5.1 MASS REQUIREMENTS**

2381 The final set of requirements ensures that the Higgs candidates are consistent with expected properties of  
2382 the 125.0 GeV Higgs. First, a variable ( $X_{hh}$ ) is defined to measure the consistency of both of the Higgs

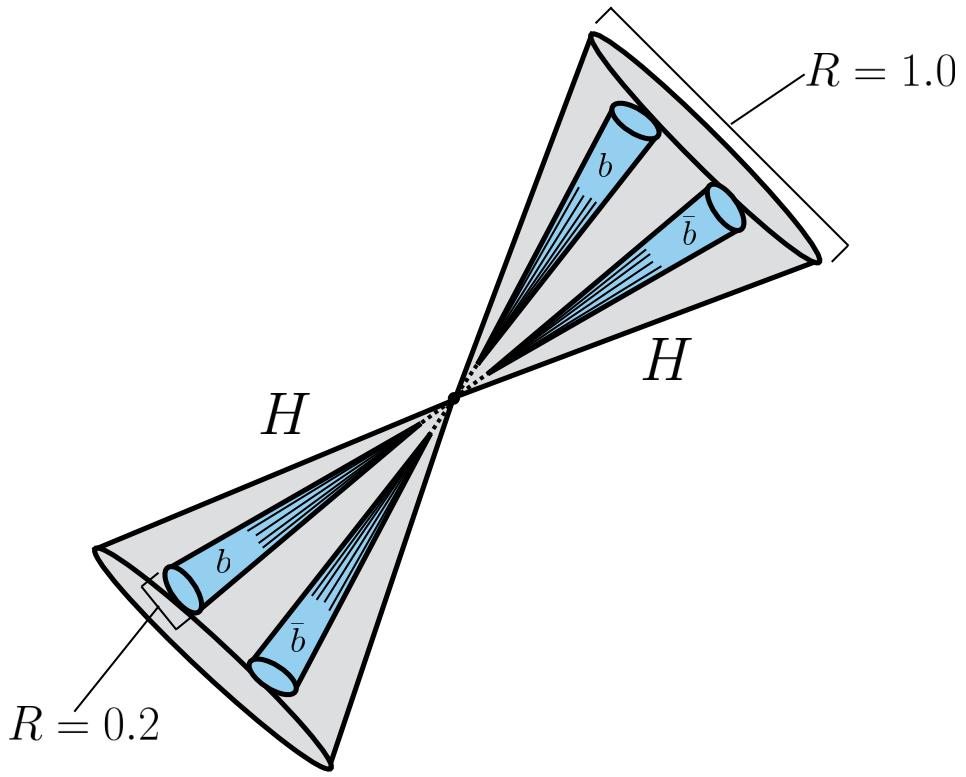


Figure 7.7: Illustration of the boosted selection requirements on Higgs candidates. Each large-radius calorimeter jet (Higgs candidate) must contain two track jets.

2383 candidate jets with the SM Higgs mass. This is shown in equation 7.2.

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

2384 The mass values in the  $X_{hh}$  formula are optimized to maximize signal efficiency. The sub-leading jet typ-  
2385 ically has a lower mass due to semi-leptonic  $b$  decays and final state radiation.  $X_{hh}$  effectively acts as a  $\chi^2$   
2386 measurement of the consistency of the two Higgs candidate masses with the signal hypothesis. The de-  
2387 nominators of each term ( $0.1 M$ ) give the uncertainty on the mass measurement for the large radius jets.  
2388 Events are required to satisfy  $X_{hh} < 1.6$ .

2389 Before making the requirement on  $X_{hh}$ , the masses of the Higgs candidates are corrected for semi-  
2390 leptonic  $b$  decays using muons with the criteria outlined in the previous section. Any muons within a  
2391  $\Delta R < 0.2$  of a  $b$ -tagged track jet (as described in the next section) have their four-momenta added to the

2392 four-momentum of the Higgs candidate. This correction does not affect the pre-selection requirements  
 2393 but does affect the  $X_{hh}$  requirement and the final invariant mass discriminant.

2394 **7.5.2 b-TAGGING REQUIREMENTS**

2395 The last requirement applied is on the number of  $b$ -tagged track jets. There are two signal regions defined.  
 2396 The first requires exactly four  $b$ -tagged track jets, two in each Higgs candidate (known as the  $4b$  signal re-  
 2397 gion). At high resonance masses, this requirement is inefficient, so an additional signal region requiring  
 2398 only three  $b$ -tagged track jets is also defined (known as the  $3b$  signal region). While this has a larger back-  
 2399 ground it is also more efficient for high resonance masses. For both signal regions, the MV2c2o algorithm,  
 2400 where the training sample for the algorithm has 20% charm events is used. More details for this algorithm  
 2401 can be found in Chapter 2.

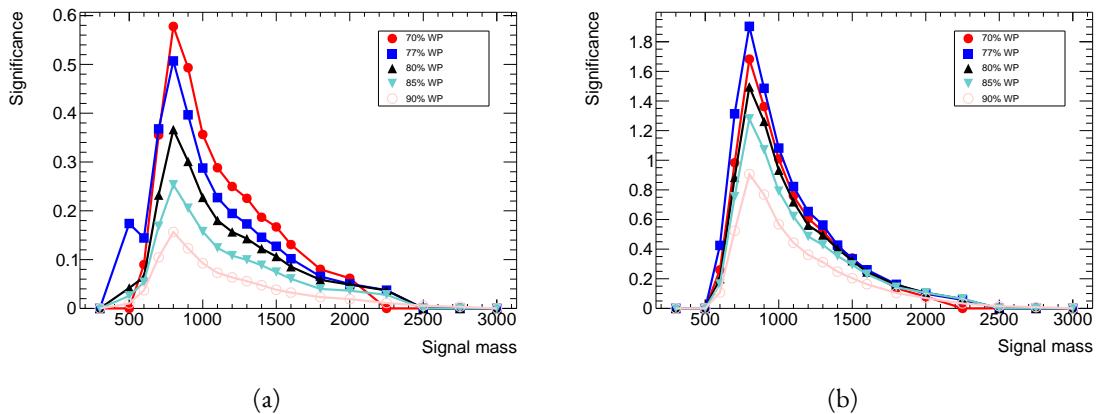


Figure 7.8: Estimated significance as a function of signal mass for RSG  $c = 1$  models in the  $3b$  (a) and  $4b$  (b)  
 regions for different  $b$ -tagging efficiency working points

2402 Once the algorithm is selected, an efficiency working point must also be chosen. This working point  
 2403 defines the efficiency with which true  $b$ -jets are tagged and also fixes the overall background rejection of the  
 2404 algorithm. Higher efficiency working points accept more true  $b$ -jets but also allow for more background.  
 2405 Five different working points (70%, 77%, 80%, 85%, 90%) are tested. With each working point, the  
 2406 full data driven background estimation method is run to quantify the amount of background that will be  
 2407 present in the final signal region. The significance is quantified using the median discovery significance for

2408 signal and background with Poisson errors, given in equation 7.3 [124].

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

2409 Here,  $s$  is the expected number of signal events and  $b$  is the expected number of background events. This  
2410 formula is derived using Poisson statistics with errors on both the signal and background. It is used because  
2411 it is valid in the regime where  $s$  and  $b$  are of the same order. Note that in the limit where  $s$  is much smaller  
2412 than  $b$ , this equation reduces to the more well known  $s/\sqrt{b}$ . Figure 7.8 shows the estimated significance as  
2413 a function of signal mass in RSG  $c = 1$  models for the  $3b$  and  $4b$  signal regions. The 77% working point  
2414 gives the best performance over a wide range of masses in the  $4b$  signal region. As this is the region which  
2415 contributes the most to the total discovery significance, the 77% efficiency working point is chosen for the  
2416 analysis.

### 2417 7.5.3 SELECTION EFFICIENCY

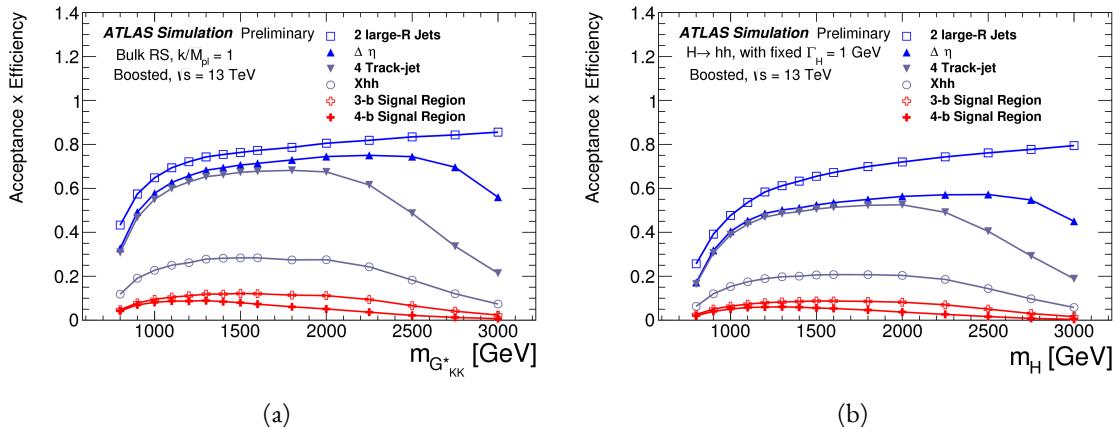


Figure 7.9: Acceptance  $\times$  efficiency as a function of mass for (a) RSG and (b) narrow heavy scalar signal models [125].

2418 Figure 7.9 shows the product of acceptance and efficiency as a function of mass for both the RSG and  
2419 narrow heavy scalar resonance signal models. After  $m_X > 1$  TeV, the efficiency of the  $4b$  requirement  
2420 begins to decline. After  $m_X > 2$  TeV, the efficiency of requiring two track jets in each Higgs candidate  
2421 begins to decline as well. Both of these behaviors illustrate the difficulty of resolving the merged decay

products at high mass. Figure 7.10 shows a more detailed comparison of the signal efficiency in the  $3b$  vs  $4b$  signal regions for the RSG model. The efficiencies shown here are relative to all prior selection requirements. It can be seen there that at high masses the  $3b$  signal region is more efficient for signal.

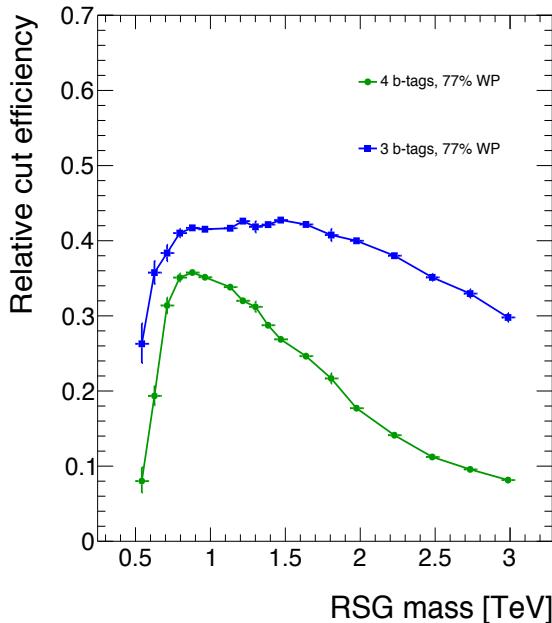


Figure 7.10: Efficiency of requiring 3 or 4  $b$ -tagged track jets vs. RSG mass. The efficiency quoted is relative to the previous selection requirements (rather than an absolute efficiency).

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

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

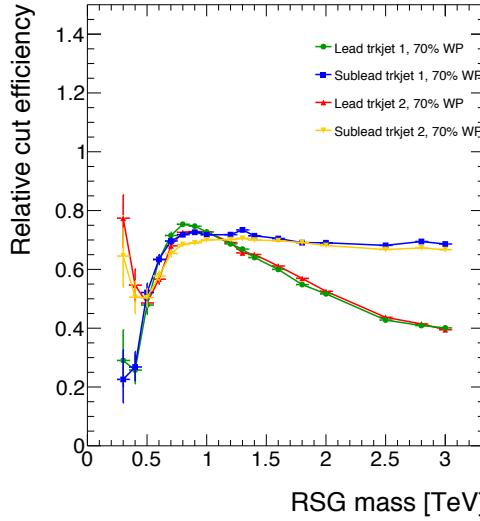


Figure 7.11: MV2c20  $b$ -tagging efficiency for each of the four track jets in the boosted  $4b$  selection as a function of RSG mass for  $c = 1$  models.

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

Table 7.2: Effect of boosted selection on data, RSG signal models,  $t\bar{t}$ , and  $Z + \text{jets}$ . The numbers from simulation are normalized with the MC generator cross section and do not take into account the data driven estimates described in section 7.6 [126].

## 2434 7.6 DATA-DRIVEN BACKGROUND ESTIMATION

2435 The largest background to the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  final state is QCD multijet production, constitut-  
 2436 ing 80-90% of the total background. Because of the difficulties in modeling higher order QCD processes,  
 2437 this background is estimated with a fully data-driven method. The only other non-negligible background  
 2438 is  $t\bar{t}$ , constituting the other 10-20%. Due to the presence of  $t\bar{t}$  in the sideband region where the QCD

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

<sup>2439</sup> background will be estimated, the normalization of the QCD and  $t\bar{t}$  backgrounds are simultaneously es-  
<sup>2440</sup> timated.

#### <sup>2441</sup> 7.6.1 MASS REGION DEFINITIONS

<sup>2442</sup> The first step in the data-driven background estimate is to define a sideband mass region where the back-  
<sup>2443</sup> ground normalization can be derived. Additionally, a control region is defined where the background  
<sup>2444</sup> estimate can be validated. The control (CR) and sideband (SB) regions are defined using a radial distance  
<sup>2445</sup> in the two-dimensional large-R jet mass plane,  $R_{hh}$ , which is defined in equation 7.4.

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

<sup>2446</sup> Events in the control region are required to fail the signal region  $X_{hh} < 1.6$  requirement and have  
<sup>2447</sup>  $R_{hh} < 35.8 \text{ GeV}$ . The sideband region consists of those events which are not in the signal or control  
regions. Figure 7.12 shows the definition of the signal, control, and sideband mass regions. Table 7.3 sum-

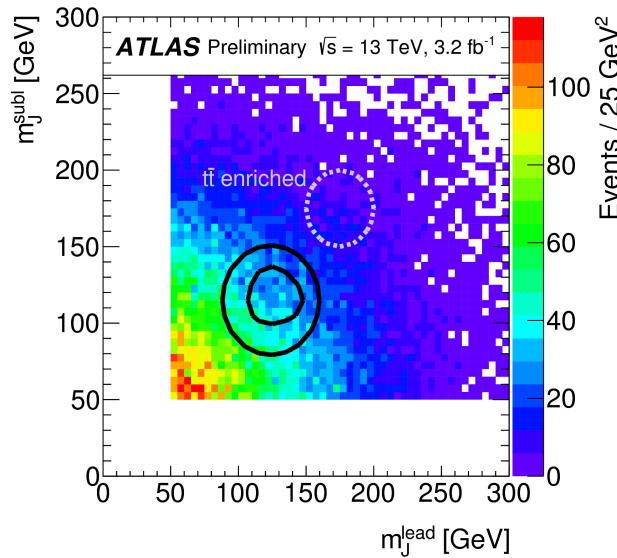


Figure 7.12:  $M_J^{\text{sublead}}$  vs.  $M_J^{\text{lead}}$  in a 2  $b$ -tag data sample. The signal region is defined by the inner black contour ( $X_{hh} < 1.6$ ) and the sideband region is defined by the outer contour ( $R_{hh} > 35.8 \text{ GeV}$ ). The region between the black contours is the control region. The mass region which is enriched in  $t\bar{t}$  background is also shown for illustration [[125](#)].

<sup>2448</sup> marizes the mass region selections for the three different regions used in the analysis.  
<sup>2449</sup>

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.

2450    7.6.2 BACKGROUND ESTIMATION

2451    The method for estimating the background in this analysis is similar to the ABCD method presented in  
 2452    Chapter 5. In this case, the two handles used to define different regions for the estimate are the number  
 2453    of  $b$ -tagged track jets and the mass requirements. A region requiring exactly two  $b$ -tagged track jets in one  
 2454    large-R jet (referred to as the 2-tag or  $2b$  region) is defined for use in the background estimate. The number  
 2455    of expected background events in the  $3b$  and  $4b$  signal regions is then given by equation 7.5.

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

2456    In this equation,  $N_{\text{bkg}}^{3(4)-\text{tag}}$  is the expected number of background events in the  $3b$  or  $4b$  signal regions.  
 2457     $N_{\text{Multijet}}^{2-\text{tag}}$  is the number of multijet events in the 2-tag region.  $N_{t\bar{t}}^{3(4)-\text{tag}}$  is the number of  $t\bar{t}$  events pre-  
 2458    dicted in the MC for the  $3b$  or  $4b$  signal region, and the variable is similarly defined for the  $Z+\text{jets}$  back-  
 2459    ground. The  $\beta_{t\bar{t}}$  parameter is a scale factor used to correct the normalization of the  $t\bar{t}$  estimate in the signal  
 2460    region.  $\mu_{\text{Multijet}}$  is an extrapolation factor that is derived in the sideband region and used to estimate the  
 2461    ratio of 2-tag events to 3(4)-tag events in the signal region. It is defined in equation 7.6.

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

2462    The  $t\bar{t}$  scale factor ( $\beta_{t\bar{t}}$ ) and the QCD multijet extrapolation factor ( $\mu_{\text{Multijet}}$ ) are estimated together in  
 2463    a simultaneous fit in the sideband region. Then, the number of events in the 2-tag signal region is used,  
 2464    along with the  $t\bar{t}$  estimate in the  $3b$  and  $4b$  signal regions and  $\mu_{\text{Multijet}}$ , to estimate the total number  
 2465    of background events in the two final signal regions. The shape of the final discriminant  $M_{2J}$  is also

<sup>2466</sup> taken from the 2-tag signal region where there are more events. This method is illustrated graphically in figure 7.13. In the  $3b$  region, the fit yields values of  $\mu_{\text{Multijet}} = 0.160 \pm 0.03$  and  $\beta_{t\bar{t}} = 1.02 \pm 0.09$ .

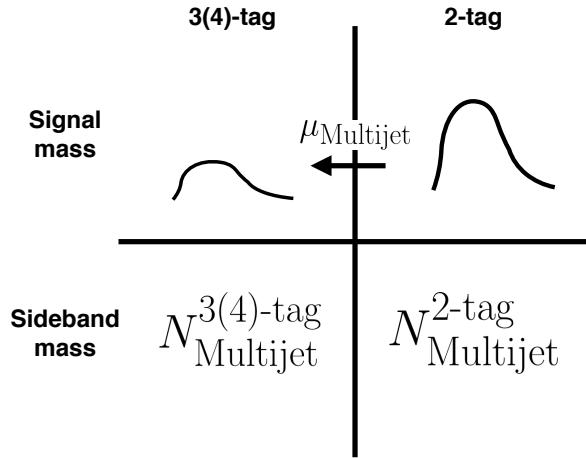


Figure 7.13: An illustration of the data-driven background estimation technique for the boosted analysis

<sup>2467</sup>

<sup>2468</sup> In the  $4b$  region, the fit gives  $\mu_{\text{Multijet}} = 0.0091 \pm 0.0007$  and  $\beta_{t\bar{t}} = 0.82 \pm 0.39$ . The uncertainties  
<sup>2469</sup> quoted are statistical only. The larger uncertainties in the  $4b$  values indicate the lower statistics available in  
<sup>2470</sup> that region.

<sup>2471</sup> Figure 7.14 shows the distributions of data and background estimates in the  $3b$  and  $4b$  sideband regions  
<sup>2472</sup> after the background fit has been done. The normalizations are constrained from the fit to match that of  
<sup>2473</sup> the data, but good modeling of the shape of the mass of the leading large-R jet is seen as well. The shapes  
<sup>2474</sup> of the kinematic distributions for the  $t\bar{t}$  background in the  $4b$  region are taken from the  $3b$  region due to  
<sup>2475</sup> the better MC statistics in that region.

### <sup>2476</sup> 7.6.3 BACKGROUND SHAPE FIT

<sup>2477</sup> As mentioned in the previous section, the background shape in the 3-tag and 4-tag signal regions is taken  
<sup>2478</sup> from the 2-tag signal mass region. Due to the limited statistics available, the background shapes are addi-  
<sup>2479</sup> tionally smoothed after being extrapolated to the 3-tag and 4-tag signal regions. Only the data in the range  
<sup>2480</sup>  $900 < M_{2J} < 2000$  GeV is included in the shape fit due to the limited statistics available above 2 TeV.  
<sup>2481</sup> Both the  $t\bar{t}$  and QCD multijet background are independently fit with an exponential shape,  $y = e^{ax+b}$ .

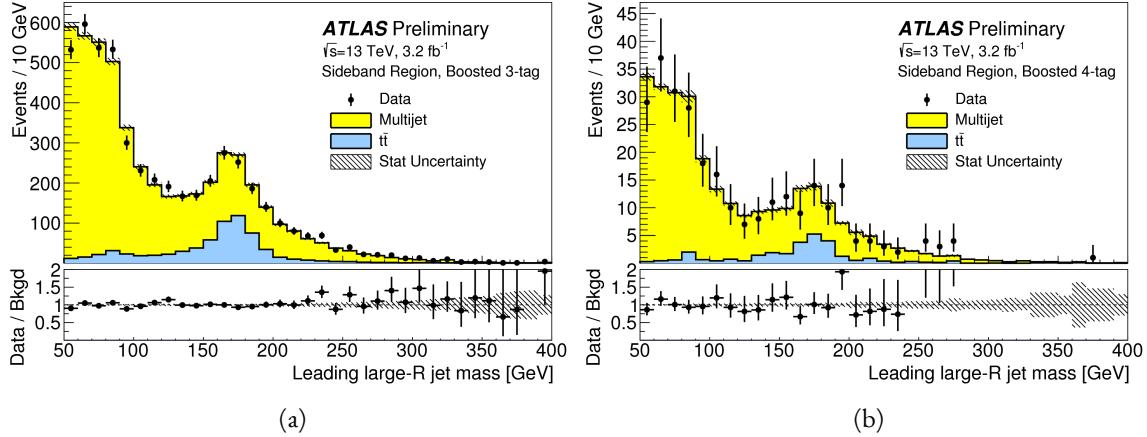


Figure 7.14: Leading large-R jet mass in the 3b (a) and 4b (b) sideband regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above. Because their normalizations are derived in the sideband region, the total background normalization is constrained by default to match the normalization of the data [125].

2482 Other shapes are considered and used for the systematic uncertainties. Table 7.4 shows the fit values for  
 2483 the parameters. Because both the 3b and 4b QCD shapes come from the 2-tag region, the slopes derived  
 2484 are very similar.

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

Table 7.4: Parameters derived for exponential fit to background  $M_{2J}$  shape in the 3b and 4b signal regions [126].

#### 2485 7.6.4 VALIDATION OF BACKGROUND ESTIMATE

2486 The background estimate can be validated by using the method to estimate the number of events in the  
 2487 control mass region rather than the signal mass region. Figure 7.15 shows the  $M_{2J}$  distribution in the 3b  
 2488 and 4b control regions, comparing data and background estimates. In both cases, both the background  
 2489 shape and normalization are consistent with the data, indicating good agreement. The ratio of data to the  
 2490 background estimates is also fit to a line in the figure to test for any shape difference. The slope of the  
 2491 line is within  $1\sigma$  (from the fit uncertainties) of flat, further indicating that the data is consistent with the  
 2492 background estimate in the control region.

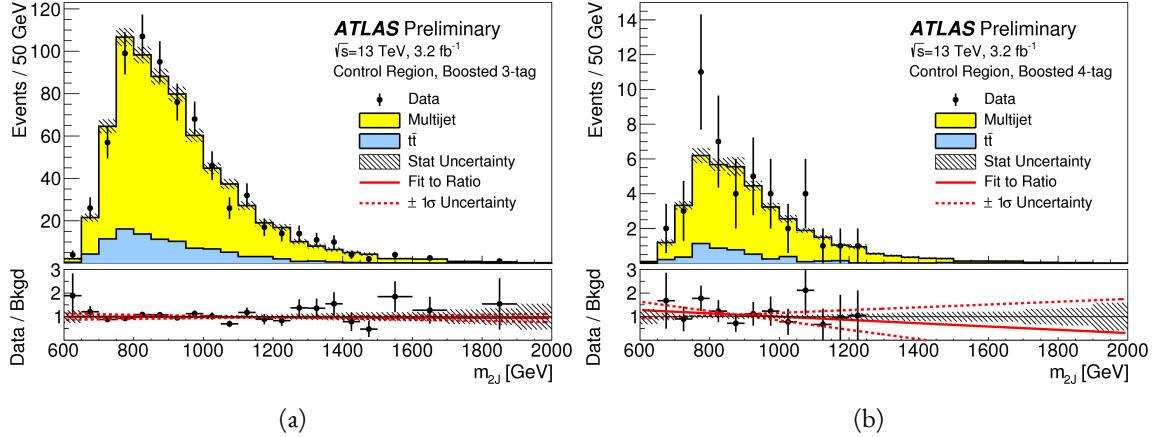


Figure 7.15: Di-jet invariant mass ( $M_{2J}$ ) in the 3b (a) and 4b (b) control regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above [125].

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

Sample (3-tag)	Sideband Region	Control Region
Multijet	$4328 \pm 27$	$607 \pm 10$
$t\bar{t}$	$683.5 \pm 8.1$	$99.6 \pm 3.1$
Z+jets	$31.8 \pm 3.7$	$7.7 \pm 1.8$
Total	$5043 \pm 28$	$715 \pm 11$
Data	5043	724
Sample (4-tag)	Sideband Region	Control Region
Multijet	$247.4 \pm 1.5$	$34.7 \pm 0.6$
$t\bar{t}$	$28.4 \pm 1.5$	$5.1 \pm 0.7$
Z+jets	$3.4 \pm 1.2$	$0.6 \pm 0.5$
Total	$279.2 \pm 2.5$	$40.3 \pm 1.0$
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 [125]. The uncertainties shown are statistical only.

2496 7.7 SYSTEMATIC UNCERTAINTIES

2497 The systematic uncertainties in this analysis can be divided into two broad categories. The first type is  
2498 uncertainties associated with the modeling of the signal processes. The second type of uncertainty is asso-  
2499 ciated with both the shape and normalization of the background prediction.

2500 7.7.1 SIGNAL MODELING UNCERTAINTIES

2501 The signal modeling uncertainty has three main components: theoretical uncertainty on the acceptance,  
2502 experimental uncertainties on the large-R jets, and experimental uncertainties on the track jets related to  
2503  $b$ -tagging. In this analysis the experimental uncertainties are the most significant.

2504 The first uncertainty on signal modeling is the theoretical uncertainty on the acceptance. As explained  
2505 in section 5.6.1, there are four components to this uncertainty. The first is related to missing higher order  
2506 terms from the matrix element calculations which is estimated by varying the QCD renormalization and  
2507 factorization scales. The second is uncertainty due to the PDF set used. The third is a generator uncer-  
2508 tainty which is estimated by modifying the generator used to model the underlying event and hadroniza-  
2509 tion. Finally, there is an uncertainty associated with the modeling of the initial state and final state radia-  
2510 tion (ISR/FSR). The total theoretical uncertainty on the signal yield is 3%, and this is dominated by the  
2511 ISR/FSR modeling.

2512 There are uncertainties on the large-R jets in both the jet energy scale (JES) and jet energy resolution  
2513 (JER) as well as the jet mass scale (JMS) and jet mass resolution (JMR). These are evaluated using  $\sqrt{s} =$   
2514 8 TeV data from Run 1 of ATLAS and extrapolated to the Run 2 beam and detector conditions using  
2515 MC<sup>5</sup>. The details of these uncertainties can be found in reference [127].

2516 Uncertainties on the track jets are related to the  $b$ -tagging efficiency. The total uncertainty on the signal  
2517 yield due to  $b$ -tagging is evaluated by propagating variations of the  $b$ -tagging efficiency through the boosted  
2518 selection requirements. The uncertainties are calculated jet-by-jet and parameterized as a function of  $b$ -jet  
2519  $p_T$  and  $\eta$  [105]. For high  $p_T$   $b$ -jets (with  $p_T > 300$  GeV), the uncertainties are extrapolated using MC  
2520 simulation from the lower  $p_T$   $b$ -jets [128].

---

<sup>5</sup>The uncertainties are correspondingly larger due to the uncertainty of this extrapolation.

2521 Table 7.6 shows the systematic uncertainties on the signal normalization for models with  $m_{G_{\text{KK}}^*} =$   
 2522  $1.5 \text{ TeV}$  and both  $c = 1$  and  $c = 2$  as well as a narrow width heavy scalar. The dominant uncertainty  
 2523 comes from  $b$ -tagging and this uncertainty is larger in the 4-tag region than the 3-tag region.

Source	Background	$G_{\text{KK}}^*$		$H$
		$c = 1$	$c = 2$	
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.

2524 **7.7.2 BACKGROUND UNCERTAINTIES**

2525 Uncertainties on the QCD multijet background normalization and shape are estimated using the con-  
 2526 trol mass region. As shown previously, the background predictions in the control region match with the

2527 data yields within the statistical uncertainty in both the 3-tag and 4-tag control regions. As an additional  
 2528 protection, the statistical uncertainty on the background prediction in the control region is assigned as a  
 2529 systematic uncertainty on the normalization of the QCD background.

2530 Additional robustness tests are done by varying the definition of the control mass region and the  $b$ -  
 2531 tagging requirements used to define the 2-tag sample. In all cases, the effect of the variations is found to be  
 2532 within the statistical uncertainties on the background normalization in the control region.

2533 Shape uncertainties on the background are evaluated using two techniques. First, as shown in fig-  
 2534 ure 7.15, the ratio between the data and background prediction is fit with a linear function. The uncer-  
 2535 tainties on the slope of this fit are assigned as shape uncertainties. An additional uncertainty is assigned by  
 2536 using alternate power law fit functions for the smoothing of the background shape. Table 7.7 shows the  
 2537 alternate shapes used. The largest difference between the nominal fit function and the alternates, taking  
 2538 into account the  $1\sigma$  uncertainty band on each fit as well, is taken as a shape uncertainty.

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

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

2539 The uncertainties on the  $t\bar{t}$  background are obtained by propagating the various experimental variations  
 2540 (JES, JER, JMS, JMR,  $b$ -tagging) through the analysis selection requirements. Table 7.6 summarizes the  
 2541 background uncertainties in the 3-tag and 4-tag regions.

2542    7.8 RESULTS

2543    Table 7.8 shows the observed yields in the 3-tag and 4-tag signal regions for the boosted analysis compared  
 2544    to the predicted number of background events. In the 3-tag region, 316 events are observed with a pre-  
 2545    dicted background of  $285 \pm 19$ . In the 4-tag region, 20 events are observed with a predicted background  
 2546    of  $14.6 \pm 2.4$ . Figure 7.16 shows the  $M_{2J}$  distribution in the 3-tag and 4-tag regions. There are some  
 2547    small excesses in the data, in particular in the 3-tag region around  $M_{2J} \approx 900$  GeV and in the region of  
 2548     $1.6 < M_{2J} < 2.0$  TeV. The significance of these excesses will be evaluated in the next chapter in the  
 2549    statistical combination with the resolved results.

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

Table 7.8: Observed yields in the 3-tag and 4-tag signal regions for the boosted analysis compared to the predicted number of background events Errors correspond to the total uncertainties in the predicted event yields. The yields for a graviton with  $m_{G_{\text{KK}}^*} = 1$  TeV and  $c = 1$  are also shown [125].

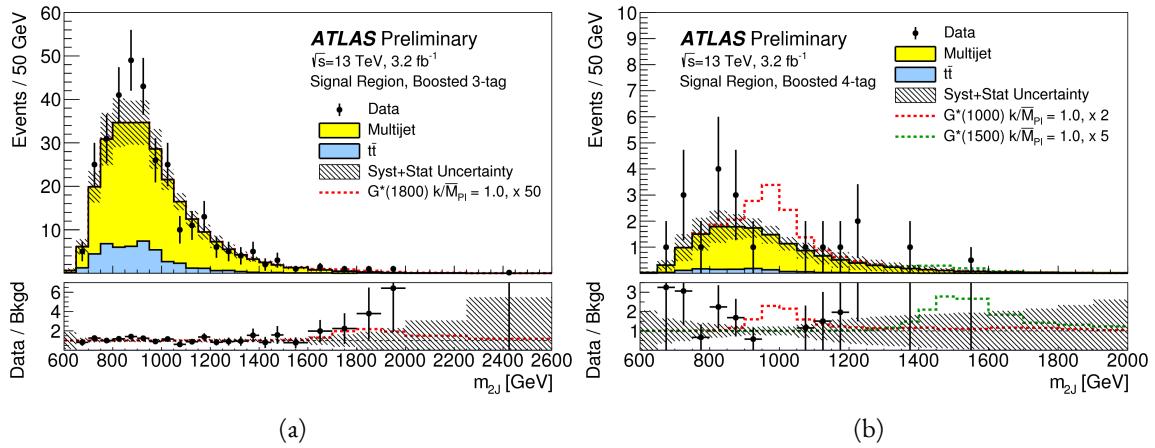


Figure 7.16: Di-jet invariant mass ( $M_{2J}$ ) in the  $3b$  (a) and  $4b$  (b) signal regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above. In the  $3b$  region, a graviton signal with  $m_{G_{KK}^*} = 1.8$  TeV and  $c = 1$  is overlaid, with the cross section multiplied by a factor of 50 so that the signal is visible. In the  $4b$  region, signals with  $m_{G_{KK}^*} = 1.0$  TeV and  $m_{G_{KK}^*} = 1.5$  TeV are overlaid, both with  $c = 1$  and the yields multiplied by factors of 2 and 5 respectively [125].

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

Frank Herbert

# 8

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2551

## Combined limits from boosted and resolved searches

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### 8.1 INTRODUCTION

2554 In order to cover the full mass range of possible resonances decaying to di-Higgs final states, two distinct  
2555 tailored selections were produced. The resolved selection is more sensitive in the mass range of  $400 < m_X <$   
2556  $1100 \text{ GeV}$  while the boosted selection is more sensitive to masses in the range  $1100 < m_X <$   
2557  $3000 \text{ GeV}$ . Chapter 7 presents the details of the boosted selection and results. In setting limits on spin-2  
2558 Randall-Sundrum graviton (RSG) and narrow width heavy scalar ( $H$ ) models, the results of the boosted  
2559 selection are combined with the results of the resolved selection to cover the full mass range.

2560 This chapter presents limits on signal models resulting from the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  search in both  
2561 the resolved and boosted selections. It first presents a brief overview of the resolved results that go into

2562 the limit setting. Then, an overview of the statistical methods used for the search and limit setting is given.  
2563 Finally, limits on the RSG and heavy scalar models are presented.

2564 **8.2 RESOLVED RESULTS**

2565 The details of the resolved selection will not be presented here and can be found in reference [125]. In  
2566 basic terms, the selection searches for four  $R = 0.4$  b-tagged calorimeter jets (where each pair of jets is  
2567 one Higgs candidate). This is distinct from the boosted methodology which searches for merged decay  
2568 products. The backgrounds to the resolved selection are the same as those presented in Chapter 7 for the  
2569 boosted analysis.

2570 Table 8.1 shows the results for data yields and expected background in the resolved signal region. Fig-  
2571 ure 8.1 shows the  $M_{2J}$  distribution in the resolved signal region. The total number of events is consistent  
2572 with the prediction and no significant excess is seen. One event in the boosted 4-tag signal is shared with  
2573 the resolved signal region and has a mass of 852 GeV.

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

Table 8.1: Observed yields in the resolved selection 4-tag signal region compared to the predicted number of background events Errors correspond to the total uncertainties in the predicted event yields. The yields for a graviton with  $m_{G_{\text{KK}}^*} = 800$  GeV and  $c = 1$  are also shown [125].

2574 **8.3 SEARCH TECHNIQUE AND RESULTS**

2575 The statistical technique used for the search in this analysis is the same as that used in the  $H \rightarrow WW^*$   
2576 analysis presented in section 3.6.2. The test statistic  $q_0$  is used to define the  $p$ -values which measure the

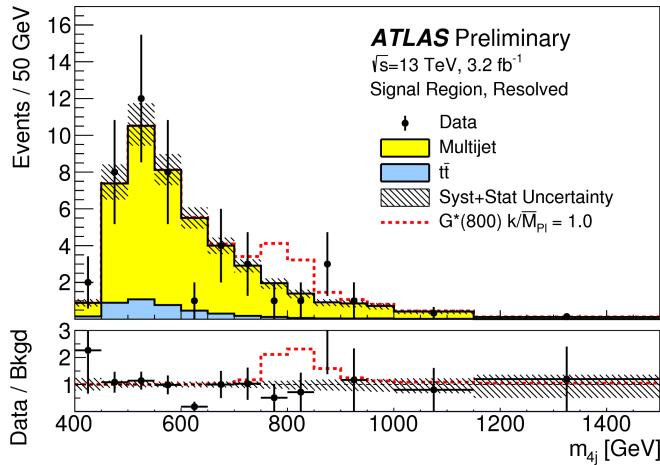


Figure 8.1: Di-jet invariant mass ( $M_{2J}$ ) in the resolved signal region. A graviton signal with  $m_{G_{KK}^*} = 800$  GeV and  $c = 1$  is overlaid. [125].

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

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

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

#### 8.4 LIMIT SETTING

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

##### 8.4.1 LIMIT SETTING PROCEDURE

The procedure used for setting exclusion limits in this analysis is the  $CL_s$  method [129]. The first step in setting the limits is to define a test statistic which will be used. For limit setting, the test statistic is shown

2592 in equation 8.1.

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

2593 In the above equation,  $\mu$  is the value of the signal strength under test,  $\hat{\mu}$  is the best fit  $\mu$ ,  $\hat{\theta}$  is the best fit  
2594 value of the nuisance parameters,  $\hat{\theta}$  is the best fit value of the nuisance parameters under the fixed  $\mu$  value,  
2595 and  $L$  is the Poisson likelihood of the data (as described in section 3.6.2).

2596 The test statistic  $\tilde{q}_\mu$  is constructed to protect against two interesting corner cases when setting the upper  
2597 limit on the cross section. First, it protects against negative signal strengths  $\mu$  which are unphysical. Second,  
2598 it does not count excesses in the data larger than those expected by a signal strength  $\mu$  as evidence against  
2599 the  $\mu$  hypothesis.

2600 The  $CL_s$  statistic is constructed by taking a ratio of two probabilities.  $CL_{s+b}$  is the probability that the  
2601 signal+background hypothesis would produce a value of the test statistic that is less than or equal to the  
2602 observed value<sup>1</sup>.  $CL_b$  is the probability that the background only hypothesis will produce a value  
2603 of the test statistic less than or equal to the observed. The  $CL_s$  statistic is the ratio  $CL_{s+b}/CL_b$ . A 95%  
2604 upper limit on the cross section is set at the value of  $\mu$  that makes the  $CL_s$  statistic less than 5%. In practice,  
2605 the limits are computed numerically within an asymptotic approximation for the distribution of the test  
2606 statistic  $\tilde{q}_\mu$ . The details of this approximation can be found in reference [75].

2607 The resolved and boosted analyses are combined using a very simple procedure rather than a full statis-  
2608 tical combination. For each mass point tested, the limit which gives the most stringent constraint is used.  
2609 This means that for mass points below 1.1 TeV the resolved signal region is used, while at and above this  
2610 point the combination of the orthogonal 3b and 4b boosted signal regions is used.

#### 2611 8.4.2 LIMIT SETTING RESULTS

2612 Figure 8.2 shows the combined 95% upper bounds as a function of mass for three different models:  $G_{KK}^*$   
2613 with  $c = 1$ ,  $G_{KK}^*$  with  $c = 2$ , and a narrow heavy scalar  $H$ .

---

<sup>1</sup>Lower values of  $\tilde{q}_\mu$  mean better compatibility.

2614      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  
2615 for masses in the range  $600 < m_{G_{\text{KK}}^*} < 3000$  GeV. For the RSG model with  $c = 2$ , cross sections limits  
2616 between 40 fb and 200 fb are set for the mass range of  $500 < m_{G_{\text{KK}}^*} < 3000$  GeV. Masses in the range  
2617 of  $475 < m_{G_{\text{KK}}^*} < 785$  GeV are excluded with  $c = 1$  (with an exclusion of the range 465 to 745 GeV  
2618 expected). Masses less than 980 GeV are excluded with  $c = 2$  (with an exclusion for masses less than  
2619 1 TeV expected).

2620      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  
2621 30 to 300 fb in the mass range of  $500 < m_H < 3000$  GeV. The resolved analysis can also set an upper  
2622 limit on the Standard Model di-Higgs production cross section discussed in chapter 3. The upper limit on  
2623  $\sigma(pp \rightarrow hh \rightarrow b\bar{b}b\bar{b})$  in the Standard Model is constrained to be less than 1.22 pb.

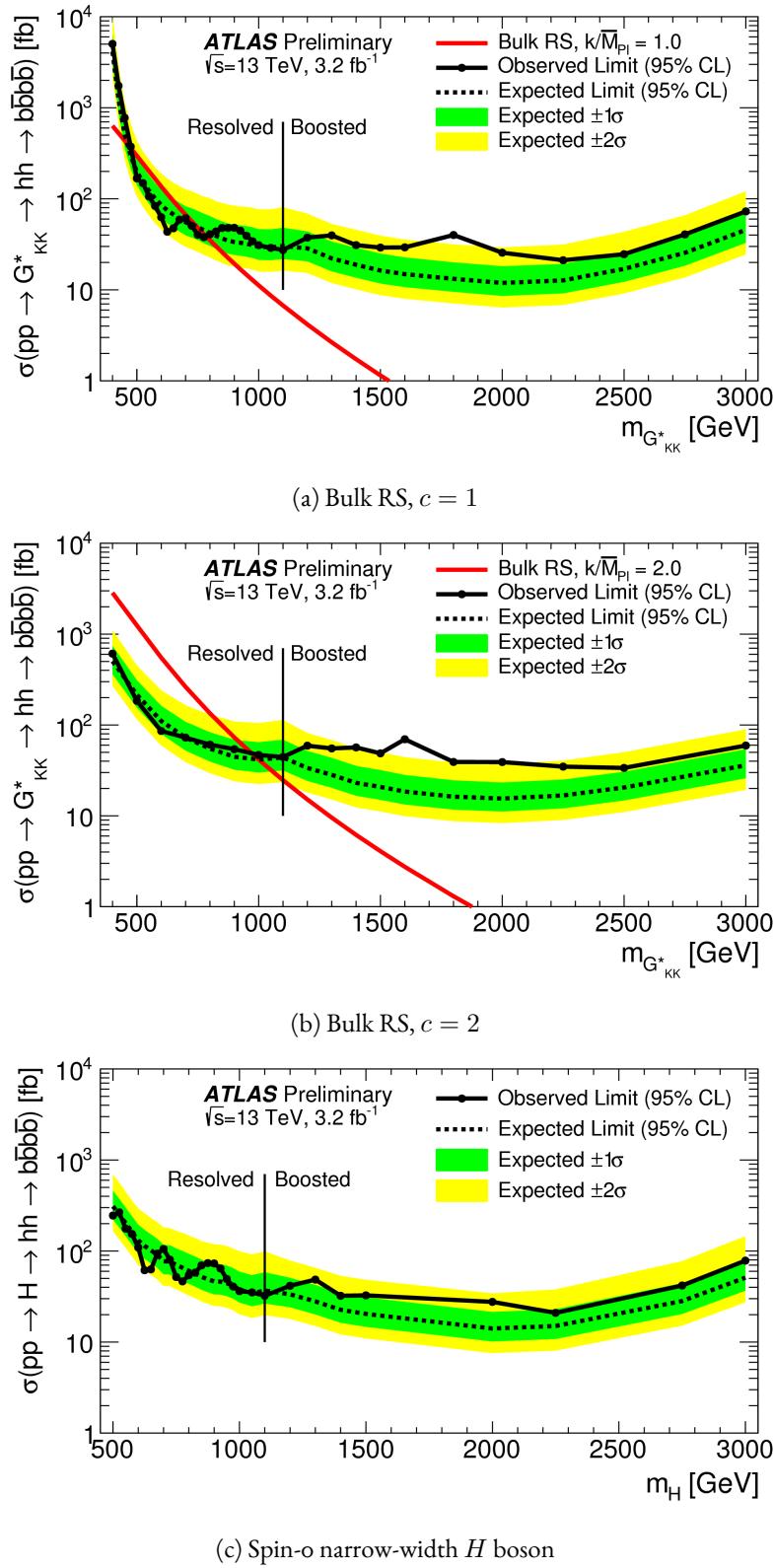


Figure 8.2: Expected and observed upper limit as a function of mass for  $G^*_{KK}$  in the RSG model with (a)  $c = 1$  and (b)  $c = 2$ , as well as (c)  $H$  with fixed  $\Gamma_H = 1$  GeV, at the 95% confidence level in the  $CL_s$  method [125].

2624

## Part IV

2625

## Looking ahead

# 9

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2627

## Conclusion

2628 After being sought for many years at different collider experiments, the Higgs boson was discovered by  
2629 the ATLAS and CMS experiments in 2012, confirming the leading theory for the source of electroweak  
2630 symmetry breaking and filling in the last missing piece of the Standard Model. After its discovery, mea-  
2631 surements of the particle's detailed properties and searches for new particles decaying to Higgs final states  
2632 were both extremely important in constraining physics beyond the Standard Model. This dissertation  
2633 presented this evolution through two results: the observation and measurement of the Higgs boson in the  
2634  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel at  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV and a search for Higgs pair production  
2635 in the  $HH \rightarrow b\bar{b}b\bar{b}$  channel at  $\sqrt{s} = 13$  TeV with the ATLAS detector in  $pp$  collisions at the Large  
2636 Hadron Collider.

2637 In the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ , results from both the discovery of the Higgs boson and the full ATLAS  
2638 Run 1 dataset were presented. The Higgs boson was discovered with a  $5.9\sigma$  significance in a combination  
2639 of the  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ \rightarrow 4\ell$ ,  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  with  $4.2 \text{ fb}^{-1}$  at  $\sqrt{s} = 7$  TeV and  $5.2 \text{ fb}^{-1}$  at

2640     $\sqrt{s} = 8$  TeV. With the full  $20.3 \text{ fb}^{-1}$  at  $\sqrt{s} = 8$  TeV and  $4.2 \text{ fb}^{-1}$  at  $\sqrt{s} = 7$  TeV, ATLAS achieved dis-  
2641    covery level significance in the  $H \rightarrow WW^*$  channel alone and obtained the first evidence of vector boson  
2642    fusion production in that channel. The combined signal strength was measured to be  $\mu = 1.09^{+0.23}_{-0.21}$ . The  
2643    total observed significance of the  $H \rightarrow WW^*$  process was observed to be  $6.1\sigma$  (with  $5.8\sigma$  expected). Ad-  
2644    vanced methods for background reduction and estimation, particularly in same-flavor lepton final states,  
2645    were shown. The VBF signal strength was measured to be  $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$  with an observed signifi-  
2646    cance of  $3.2\sigma$  (with  $2.7\sigma$  expected).

2647    These results required many novel innovations. The increase of pileup interactions in the higher in-  
2648    stantaneous luminosity LHC conditions of 2012 led to a degradation of missing transverse momentum  
2649    resolution. As a result, the prominent  $Z/\gamma^* + \text{jets}$  background of the same flavor  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$   
2650    final states increased greatly. New variables, including a track-based missing transverse momentum and a  
2651    measurement of the balance between the dilepton system and recoiling jets, allowed for significant reduc-  
2652    tion of this background. In the VBF channel, selections were optimized to exploit the unique VBF final  
2653    state topology. Incorporating these variables into a boosted decision tree technique allowed the analysis  
2654    to exceed the  $3\sigma$  statistical significance threshold.

2655    After the end of Run 1, the results of Higgs measurements from ATLAS were combined with those  
2656    from CMS to produce the most precise measurements of the Higgs boson so far [130]. Figure 9.1 shows the  
2657    combination of ATLAS and CMS data for the Higgs signal strength in and coupling measurements. In the  
2658    signal strength measurements of gluon fusion and vector boson fusion, the  $H \rightarrow WW^*$  channel provides  
2659    the tightest constraints. Additionally, the Higgs coupling to  $W$  bosons is the most precisely measured with  
2660    a relative uncertainty of 10%.

2661    With the discovery of the Higgs firmly established and its properties measured, a natural next step was  
2662    to search for new physics with Higgs final states. At  $\sqrt{s} = 13$  TeV, a search for Higgs pair production  
2663    in the  $b\bar{b}b\bar{b}$  final state with  $3.2 \text{ fb}^{-1}$  was conducted. A signal region optimized for the boosted final states  
2664    arising from high mass resonances was constructed. This signal region utilized large-radius calorimeter jets  
2665    and  $b$ -tagging with small radius track jets to maximize the signal acceptance. No significant excesses were  
2666    observed, and upper limits on cross sections are placed for spin-2 Randall Sundrum gravitons (RSG) and

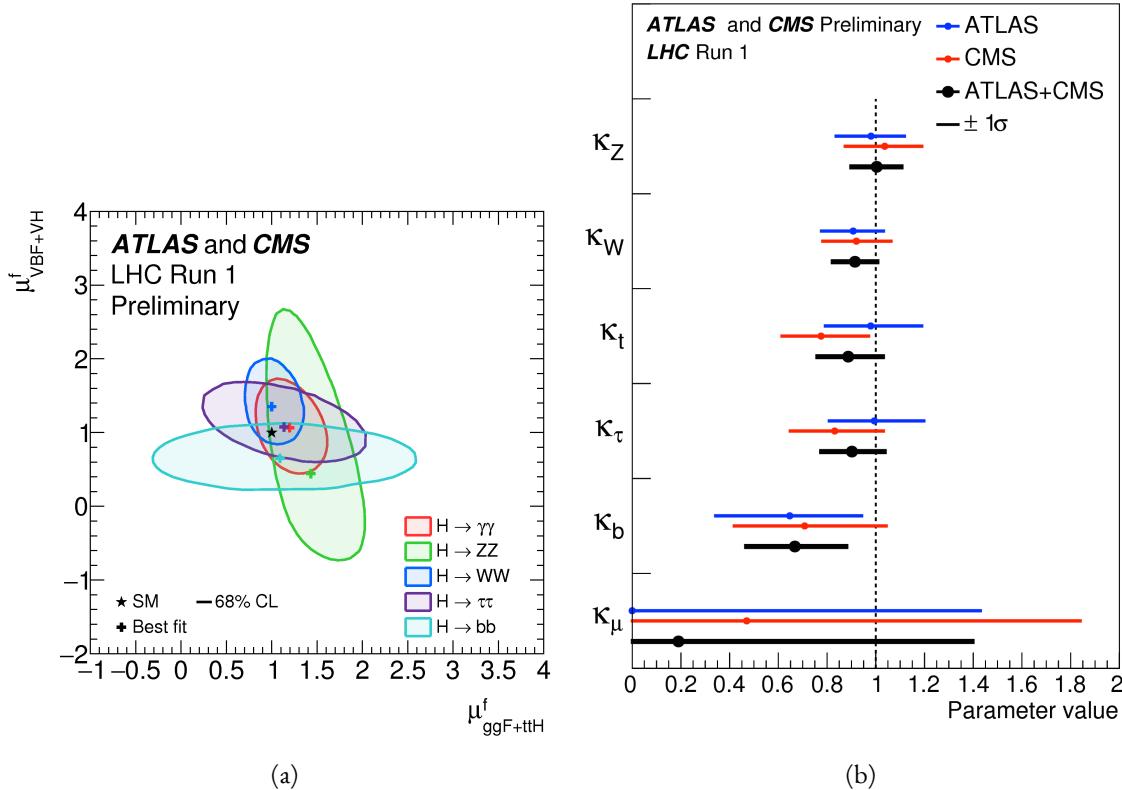


Figure 9.1: Combined ATLAS and CMS measurements in Run 1 for (a) Higgs signal strength in gluon fusion and VBF and (b) Higgs couplings normalized to their SM predictions

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

While there has been a rigorous program of measurements and searches involving the Higgs, there is still much room for improvement at the High Luminosity LHC (HL-LHC) and beyond. The measured signal strength for VBF production in  $H \rightarrow WW^*$  still has a relative error at the level of 40%, largely dominated by statistical uncertainty. Projections for the HL-LHC show that the uncertainty on the VBF signal strength can be reduced to approximately 15% with  $3000 \text{ fb}^{-1}$  [131, 132]. This projection also assumes

2679 that theoretical uncertainties on the signal, which would be the largest contribution in the future dataset,  
 2680 remain as they are now. Improvements in the theoretical understanding of the Higgs signal would also  
 2681 reduce the signal strength uncertainty dramatically. Such precision results allow for measurements of the  
 2682 Higgs coupling to vector bosons precise to the few percent level, therefore giving much power to constrain  
 2683 or discover new physics.

2684 The prospects for detection of beyond the Standard Model resonant di-Higgs production at the HL-  
 2685 LHC are also quite promising. Figure 9.2 shows projections for the discovery significance of RSG signals at  
 2686 the HL-LHC in the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  search [132]. In all detector budget scenarios, a 1.5 TeV resonance  
 is above or near  $5\sigma$  significance, while a 2 TeV resonance is between  $4-5\sigma$  except for the lowest budget.

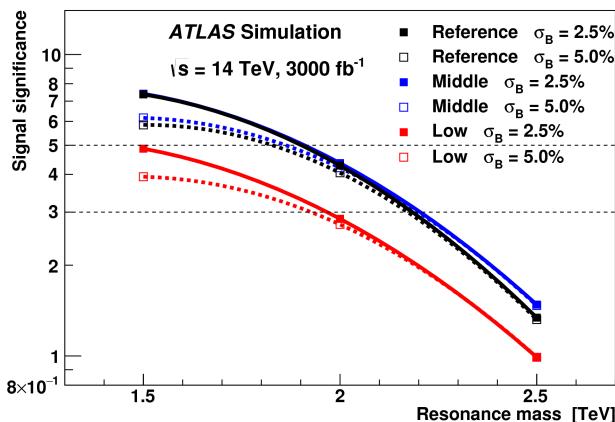


Figure 9.2: Discovery significance for RSG models at the HL-LHC in three different budget scenarios [132].  
 Systematic uncertainties on the background prediction ( $\sigma_B$ ) of 2.5% and 5.0% are both tested.

2687  
 2688 The Higgs will continue to be an incredibly powerful tool in the understanding of nature at the HL-  
 2689 LHC and beyond. Through both precision measurements and searches, the nature of electroweak symme-  
 2690 try breaking will be better understood and the potential for the discovery of physics beyond the Standard  
 2691 Model has never been greater.

# A

2692

2693

## *b*-tagging performance at high $p_T$

2694 One of the limiting factors of the signal acceptance in the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  search at high resonance  
2695 masses is the degradation of the *b*-tagging efficiency for high  $p_T$  jets. This appendix presents a study of the  
2696 underlying causes of this degradation.

### 2697 A.I CHANGES IN MV2 SCORE AT HIGH $p_T$

2698 The degradation of *b*-tagging at high  $p_T$  was studied in particular in the context of RSG models at high  
2699 mass. Figure A.I shows the  $p_T$  of the leading track jet inside of the leading calorimeter jet in RSG events.  
2700 At high  $m_{G_{KK}^*}$ , the  $p_T$  spectrum of track jets is much harder than at lower masses due to the increased  
2701 Higgs  $p_T$ .

2702 Figure A.2 shows the MV2c2o algorithm score for the leading and subleading track jets inside of the  
2703 leading calorimeter jet. In both cases, it can be seen that at higher RSG masses the MV2 score shifts towards  
2704 more background like (negative) values. Additionally, this effect is more pronounced in the leading track

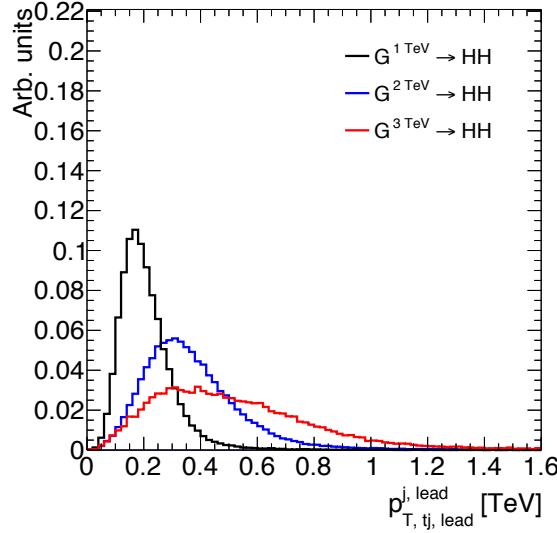


Figure A.1:  $p_T$  of the leading track jet in the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

jet than the subleading.

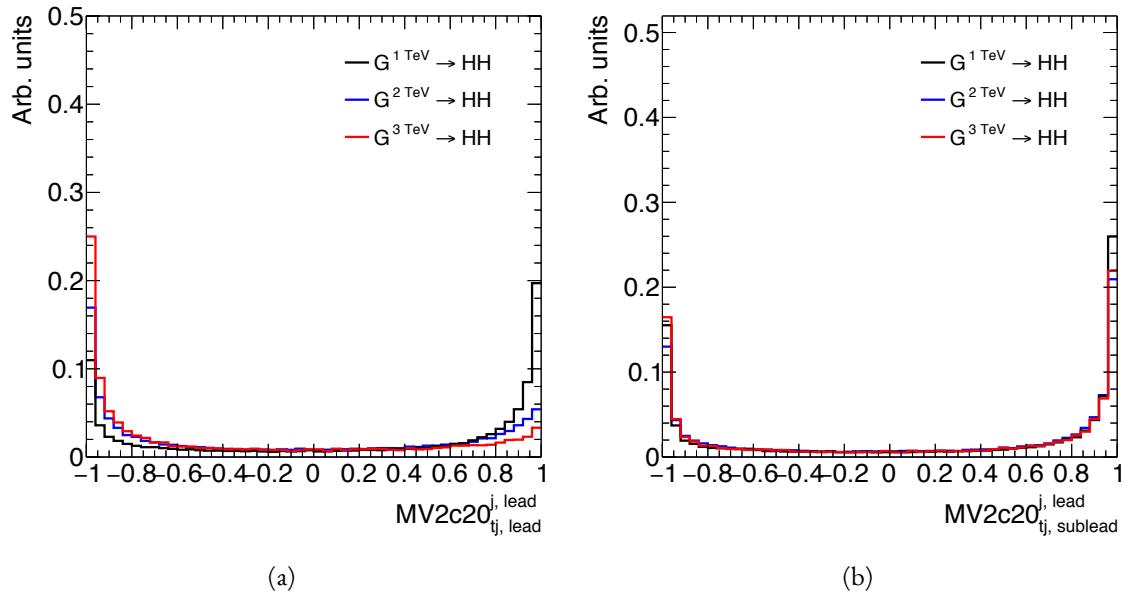


Figure A.2: MV2c20 score for the leading track jet (a) and subleading track jet (b) of the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

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

from the IP<sub>3</sub>D (three dimensional impact parameter) algorithm. At higher masses, the IP<sub>3</sub>D likelihood ratio distribution does become more background-like.

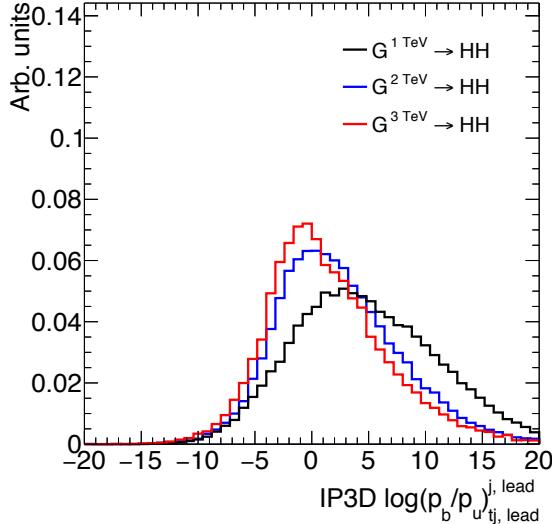


Figure A.3: IP<sub>3</sub>D log-likelihood ratio ( $\log(p_b/p_u)$ ) of the leading track jet in the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

Figure A.4 shows the mass and number of tracks at the secondary vertex computed by the SV1 algorithm. When there is no secondary vertex found, the algorithm assigns a default negative value for these quantities. Both of these distributions show that there is a significantly larger fraction of jets where no secondary vertex is found in the high mass samples compared to the  $m_{G_{KK}^*} = 1$  TeV sample. The SV1 algorithm's inability to find a secondary vertex could be an important factor in the overall MV<sub>2</sub> score shift, as this eliminates eight of the input variables that would normally contribute information to the algorithm.

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

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

One hypothesis for why the efficiency of  $b$ -tagging the leading track jet degrades is that at high masses, the  $b$  quarks get close enough together that both of them are inside of the leading track jet. Because MV<sub>2</sub> is not

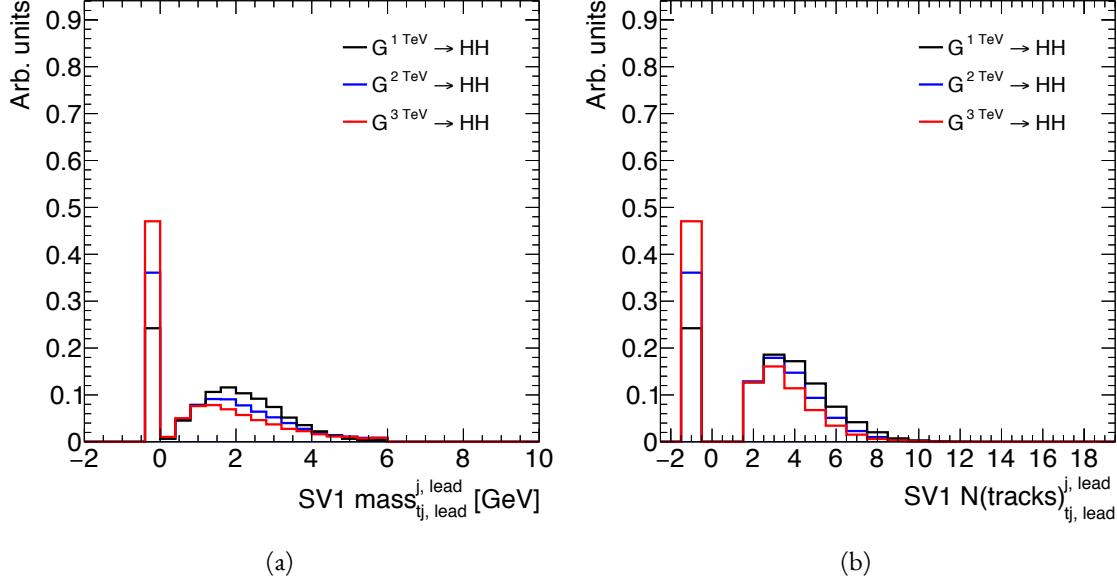


Figure A.4: Mass (a) and number of tracks (b) for the secondary vertices computed with the SV1 algorithm. When no secondary vertex is found, the quantities are assigned to default negative values.

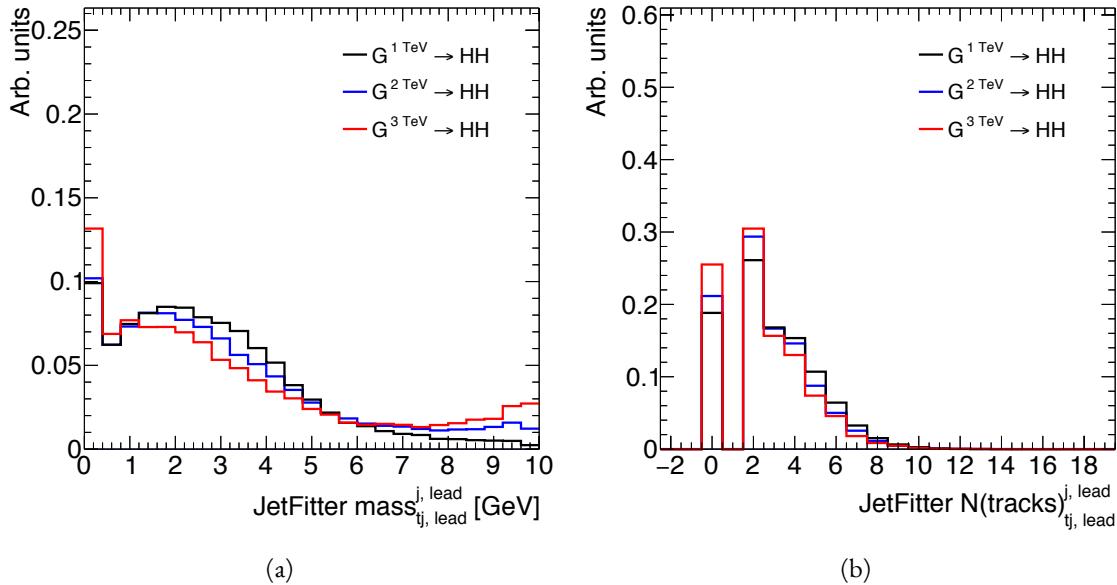


Figure A.5: Mass (a) and number of tracks (b) for vertices computed with the JetFitter algorithm. When no vertices are found, the quantities are assigned to default negative values.

tuned for tagging multiple  $b$  quarks inside one jet, the tagging efficiency could degrade. Figure A.6 shows MV2 scores and SV1 mass for cases where there are two  $b$  quarks at truth level within the radius of the

leading track jet compared to cases where there is only one true  $b$ <sup>1</sup>. This figure suggests that the presence

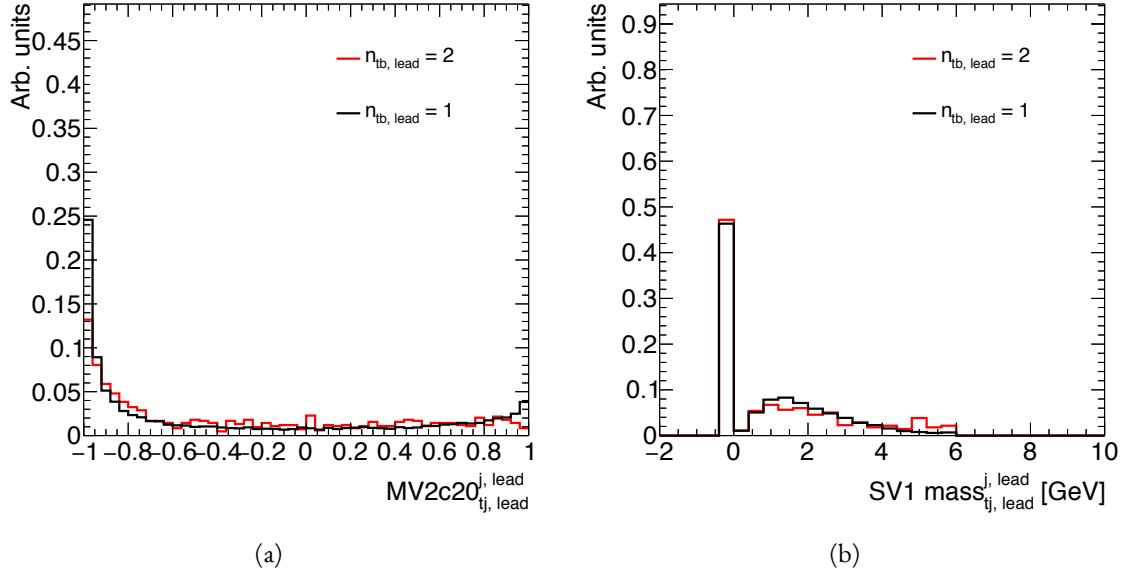


Figure A.6: MV<sub>2</sub>c20 score (a) and SV1 mass (b) for leading track jets with two truth  $b$  quarks ( $n_{tb, \text{lead}} = 2$ ) compared to those with only one truth  $b$  ( $n_{tb, \text{lead}} = 1$ ).

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

### A.3 CHANGES IN TRACK QUALITY AT HIGH $p_T$

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

<sup>1</sup>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.

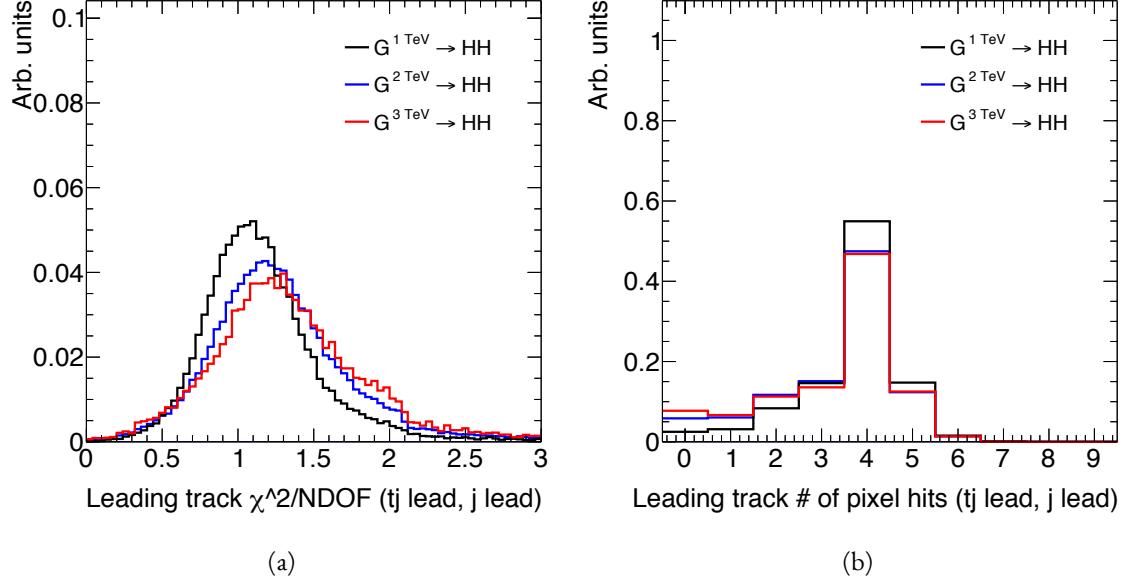


Figure A.7: Track fit  $\chi^2/\text{nDOF}$  (a) and number of pixel detector hits (b) for the leading track of the leading track jet in different mass RSG  $c = 1$  samples

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

To check whether this is the cause for the shift in the  $\text{MV}_2$  score and the higher difficulty in reconstructing secondary vertices, jets whose leading track have at least four pixel hits are compared with those whose tracks have less than four pixel hits. The results for the  $\text{MV}_2$  score and  $\text{SV}_1$  mass are shown in figure A.8. Track jets where the leading track does not have at least four pixel hits are more likely to not have a secondary vertex reconstructed. Additionally, their  $\text{MV}_{2c2o}$  score is shifted more significantly to background-like values. This seems to confirm the hypothesis that degrading track quality is responsible for the lowered  $b$ -tagging efficiency at high  $p_T$ .

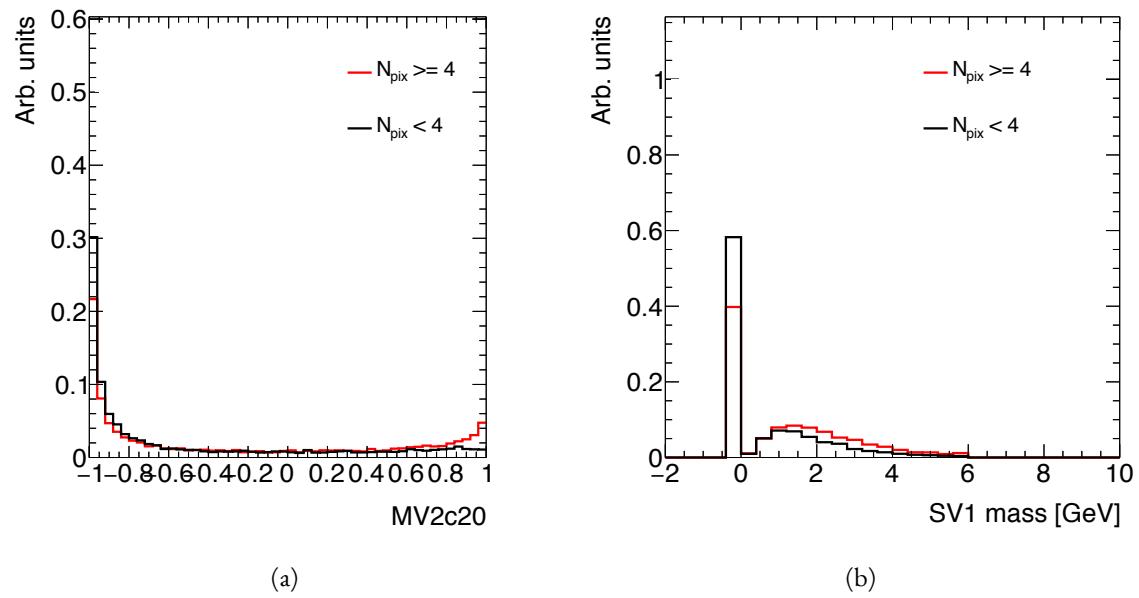


Figure A.8: MV<sub>2</sub>c<sub>20</sub> score (a) and SV<sub>1</sub> mass (b) for leading track jets whose leading track jet has at least four pixel hits ( $N_{\text{pix}} \geq 4$ ) compared to those which do not ( $N_{\text{pix}} < 4$ ).

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