

<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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541

## Introduction

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

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

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

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

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

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

581 constructed specifically for the VBF Higgs production topology. This “cut-based” analysis is presented  
582 in detail in this dissertation. These VBF topology variables, once validated in the cut-based analysis, were  
583 then input into a multivariate boosted decision tree discriminant to achieve the first evidence of VBF Higgs  
584 production with the full  $20.3 \text{ fb}^{-1}$  of  $\sqrt{s} = 8 \text{ TeV}$  data in ATLAS. Additionally, combining these results  
585 with the dedicated gluon fusion Higgs production analysis allowed for precise measurement of the Higgs  
586 couplings.

587 After a two year shutdown, the LHC restarted in 2015 with a center of mass energy of  $\sqrt{s} = 13 \text{ TeV}$ .  
588 This increase improved the LHC’s ability to probe for physics beyond the Standard Model, and the Higgs  
589 sector remained one of the largest regions of unprobed phase space where such new physics could be dis-  
590 covered. Production of high mass resonances benefit most from the center of mass energy increase. In  
591 particular, the cross section for a generic gluon-initiated 2 TeV resonance increased tenfold with the in-  
592 crease from 8 to 13 TeV. Therefore, a natural next step in studies of the Higgs was a search for a new  
593 heavy resonance which decays into a pair of Higgs bosons. The final result shown in this dissertation is  
594 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  
595 by ATLAS at  $\sqrt{s} = 13 \text{ TeV}$ . This search has the unique advantage that it can both probe new physics  
596 and gain further understanding of the Higgs potential through constraints on SM pair production of the  
597 Higgs. It also extends the previous ATLAS results at  $\sqrt{s} = 8 \text{ TeV}$  and probes higher mass resonances  
598 that were not previously accessible. Additionally, it is an informative precursor to di-Higgs analyses at the  
599 future High Luminosity LHC (HL-LHC), where a projected dataset of  $3000 \text{ fb}^{-1}$  at  $\sqrt{s} = 14 \text{ TeV}$  will  
600 begin to become sensitive to the SM Higgs self coupling.

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

606 Part 1 presents the theoretical and experimental background required for the subsequent parts. Chap-  
607 ter 1 gives an overview of Higgs physics, particularly single and double Higgs production in the Standard

608 Model and beyond. Chapter 2 presents details regarding the Large Hadron Collider and the ATLAS experi-  
609 ment. The evolution of machine conditions, descriptions of the ATLAS sub-detectors, and an overview of  
610 object reconstruction in ATLAS are all shown. A brief interlude on the ATLAS Muon New Small Wheel  
611 upgrade is also given, as this upgrade has been a focus of my graduate work and will have an important  
612 impact on ATLAS' ability to study the Higgs at the High Luminosity LHC.

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

628 Part 3 presents a search for Higgs pair production in the  $HH \rightarrow b\bar{b}b\bar{b}$  channel. Chapter 7 presents  
629 an overview of this search in the boosted regime, where the Higgs pairs are the result of the decay of a  
630 heavy resonance. Chapter 8 shows the combined results between the boosted regime and the resolved  
631 regime, which is sensitive to lower mass resonances and non-resonant Higgs pair production. Finally, Part  
632 4 presents a conclusion and brief outlook of future Higgs physics with ATLAS.

633

## Part I

634

### Theoretical and Experimental Background

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

Richard Morris

# 1

635

636

## The Physics of the Higgs Boson

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

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

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

648 The Standard Model consists of two primary categories of fundamental particles: fermions (spin 1/2  
 649 particles) and bosons (integer spin particles). The SM also describes three forces: electromagnetism, the  
 650 weak nuclear force, and the strong nuclear force. Gravity is not included in the theory and is largely irrele-  
 651 evant at the scales currently probed by collider experiments. Within the fermions, there are both quarks  
 652 (which interact via all three forces) and leptons. The charged leptons interact via electromagnetic and weak  
 653 interactions, while neutrinos (neutral leptons) interact only via the weak force. Within the bosons, there  
 654 are the  $W^\pm$  and  $Z$  bosons (the mediators of the weak force), the gluon ( $g$ , the mediator of the strong  
 655 force), and the photon ( $\gamma$ , the mediator of the electromagnetic force). Finally, there is the Higgs boson,  
 656 a fundamental spin zero particle resulting from the Higgs mechanism of electroweak symmetry breaking.

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

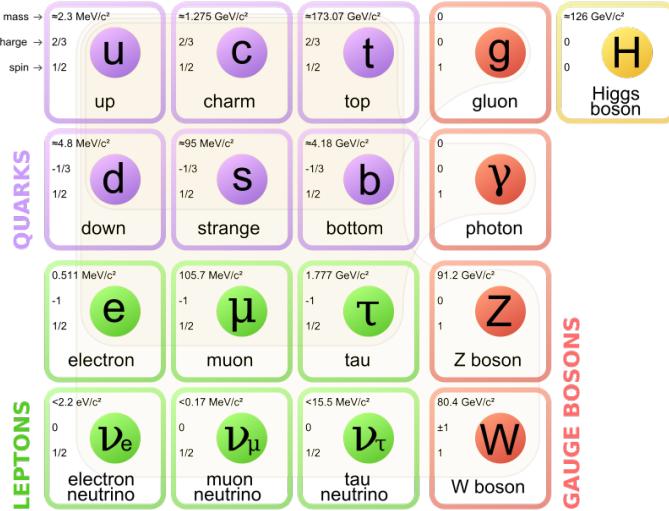


Figure 1.1: The particles of the Standard Model and their properties [6].

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

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

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

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

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

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

680 The simplest potential of a self-interacting Higgs that still respects the SM symmetry is given in equa-  
681 tion I.2.

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

682 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].

<sup>683</sup> symmetry is preserved. However, if instead  $\mu^2 < 0$ , then the minimum is at a finite value of  $\Phi$ , namely

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

<sup>684</sup> where  $v = \sqrt{\mu^2/\lambda}$ . Because this is the location of the minimum, it corresponds to the vacuum expecta-  
<sup>685</sup> tion value for the field ( $\langle \Phi \rangle = \Phi_{\min}$ ). The excitations of the Higgs can then be parameterized as

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

<sup>686</sup> The full scalar Lagrangian, including the kinetic term, is then given as

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

<sup>687</sup> where the covariant derivative is defined as

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

<sup>688</sup> and  $W^1, W^2, W^3$  and  $B$  are the  $SU(2)$  and  $U(1)$  gauge fields of the electroweak theory, respectively.  $g$   
<sup>689</sup> and  $g'$  are the corresponding coupling constants. The Pauli matrices are represented with  $\tau$ . With the  
<sup>690</sup> scalar Lagrangian in place, the physical gauge fields can then be written as

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

<sup>691</sup>

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

<sup>692</sup>

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

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

696

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

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

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

699 The full Lagrangian of Higgs interactions can be written as

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

700 with

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

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

708 1.3 HIGGS BOSON PRODUCTION AND DECAY

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

712 1.3.1 HIGGS PRODUCTION

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

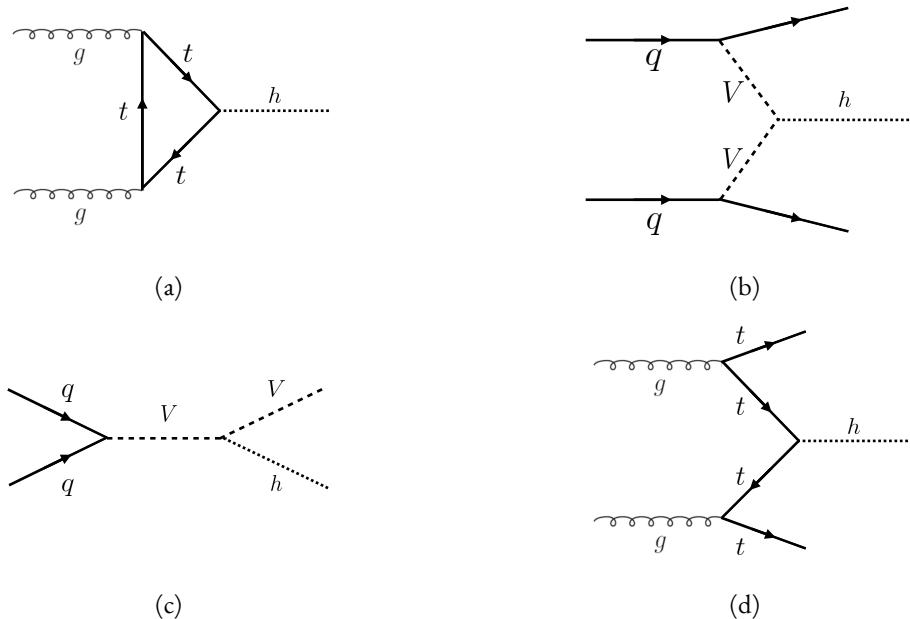


Figure 1.2: The four most common Higgs boson production modes at the LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c)  $W/Z + H$  production, (d)  $t\bar{t}H$  production

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

721 momentum of the incoming partons. The Higgs can also be produced in association with a  $W$  or  $Z$  boson.  
 722 The  $W/Z$  is produced normally and then radiates a Higgs<sup>2</sup>. Finally, the Higgs can be produced in associa-  
 723 tion with two top quarks. Each incoming gluon splits into a  $t\bar{t}$  pair, and one of the top pairs combines to  
 724 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

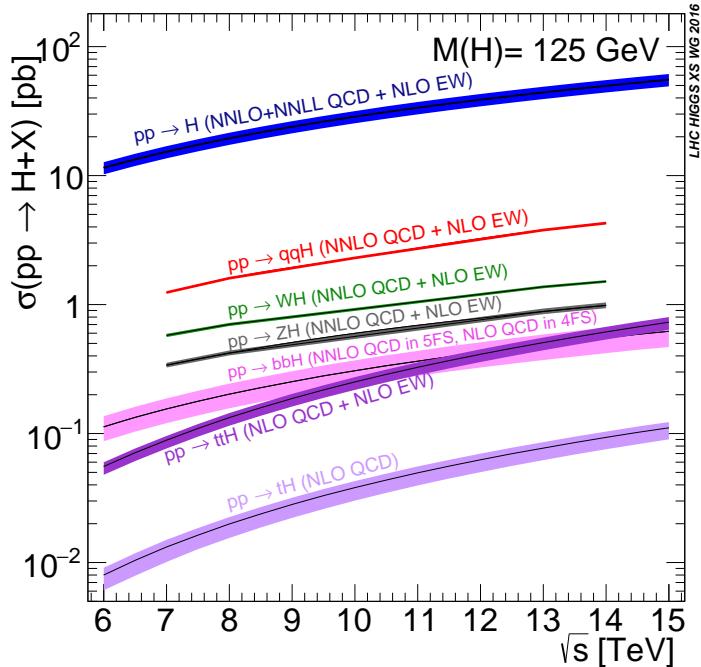


Figure 1.3: Higgs production cross sections as a function of center of mass energy ( $\sqrt{s}$ ) at a  $pp$  collider [18].

725  
 726 largest cross section, while VBF is the second largest at approximately a factor of 10 smaller. The figure also  
 727 includes the less commonly studied  $b\bar{b}H$  and  $tH$  modes. While the  $b\bar{b}H$  mode has a larger cross section  
 728 than  $t\bar{t}H$ , it also has larger backgrounds and is thus less sensitive. The  $tH$  mode is not as sensitive as  $t\bar{t}H$   
 729 due to its lower cross section. At  $\sqrt{s} = 8$  TeV, ggF production of a 125 GeV Higgs has a cross section  
 730 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  
 731 boson fusion cross sections have been computed to next-to-next-to-leading order (NNLO) in the QCD  
 732 couplings and next-to-leading order in the electroweak couplings [19–26]. The gluon fusion cross section  
 733 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”.

734 the main Higgs production modes at this center of mass energy, as well as their uncertainties from varying  
 735 the QCD renormalization and factorization scales and PDFs, are summarized in table 1.1 for a 125 GeV  
 736 Higgs. The relative uncertainty of the gluon fusion mode is larger than the relative uncertainty in the  
 737 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].

### 738 1.3.2 HIGGS BRANCHING RATIOS

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

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

741 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  
 742  $m_H$  is the mass of the Higgs. Note that the width scales with the square of the fermion mass. (This also  
 743 assumes that the Higgs mass is large enough to decay with both the fermions on shell.)

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

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

746 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  
747 where  $m_H \geq 2m_Z$ ), the equation is divided by 2 to account for identical particles in the final state, and  
748  $x_W$  is replaced with  $x_Z = 4M_Z^2/m_H^2$ . This is shown in equation 1.16 [5].

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

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

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

751 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  
752 the  $W$  or  $Z$  width.  $\Gamma_0$  is the squared matrix element, which is given in equation 1.18 [28].

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

753 The function  $\lambda$  is defined as  $\lambda(x, y, z) = (1 - x/z - y/z)^2 - 4xy/z^2$ . The integral in the general  
754 off-shell boson case is much more difficult to interpret than the simpler on-shell branching ratios, but it  
755 can be evaluated numerically. These branching ratio formulas can also be visualized as a function of Higgs  
756 mass, as shown in figure 1.4. There are a few interesting features to note in this figure. First, note that at  
757 high Higgs masses, once on-shell production of both  $W$  and  $Z$  bosons is possible, these two decays are  
758 dominant due to the large masses of the  $W/Z$ . Also note that the branching ratio to  $W$ s is twice that of  
759  $Z$ 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>.  
760 At 125 GeV, the Higgs is accessible through many different decay modes. The largest branching ratio is  
761 the decay  $H \rightarrow b\bar{b}$  at 58.24% [18]. This branching is larger than the  $WW/ZZ$  decays because one of  
762 the two bosons must be produced off-shell for  $m_h = 125$  GeV. The second largest branching ratio is  
763 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.

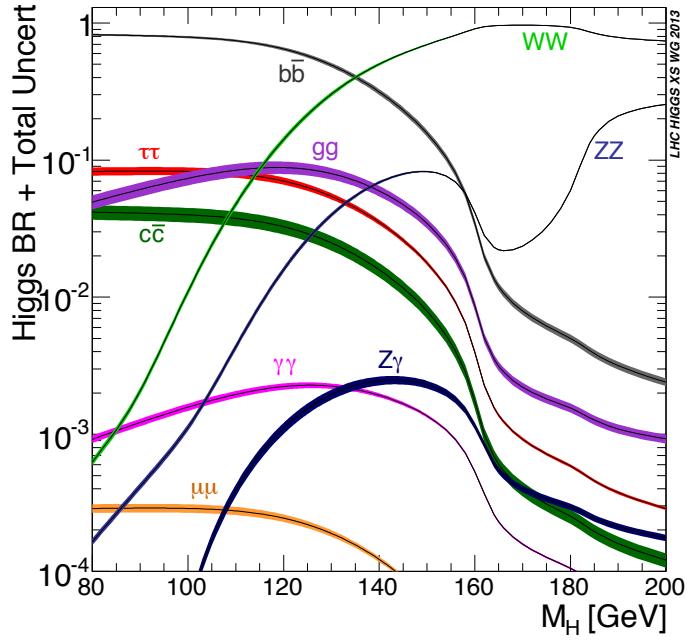


Figure 1.4: Higgs boson branching ratios as a function of  $m_H$  [18].

theoretical branching ratios for a Higgs with a mass of 125 GeV. Note that there is a Higgs branching ratio to  $\gamma\gamma$  even though photons are massless. This decay happens through a loop, which suppresses the 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].

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.

768 sensitive. For example, the  $H \rightarrow b\bar{b}$  channel in gluon fusion production is incredibly difficult to observe  
 769 due to the large QCD dijet background at the LHC. However, in associated production of the Higgs,  
 770 where a  $W$  or  $Z$  gives additional final state particles that can be used to reduce background, a search for  
 771  $H \rightarrow b\bar{b}$  can be sensitive. The combinations of production and decay modes that are most commonly  
 772 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].

#### 773 1.4 HIGGS PAIR PRODUCTION IN THE STANDARD MODEL

774 The Standard Model also allows for processes that produce two Higgs bosons in the final state, known  
 775 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

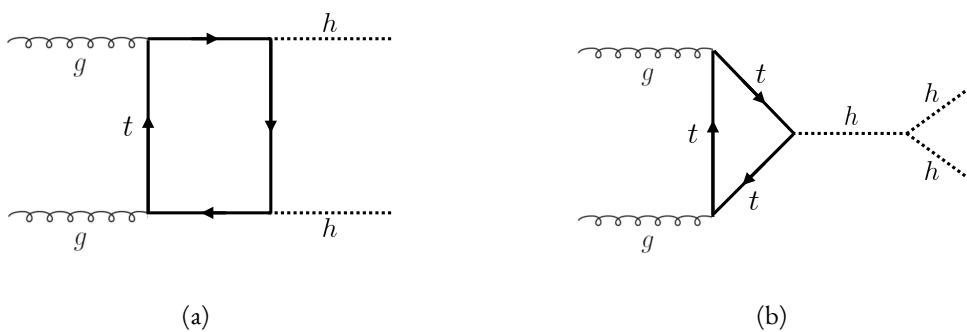


Figure 1.5: The two leading diagrams for Standard Model di-Higgs production at the LHC: (a) box diagram, (b) Higgs self coupling.

776  
 777 cross section for di-Higgs production at the LHC. Nevertheless, Higgs pair production is quite interesting

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

780 One can substitute the gluon fusion production of diagram 1.5(b) with any of the other production  
781 modes previously discussed. These other modes do not suffer from interference with the box diagram in  
782 figure 1.5(a) due to the presence of additional particles in the final state. They still have a lower cross section  
783 than the gluon fusion mode, however. The cross sections for di-Higgs production in the different modes,  
784 as well as their uncertainties, are shown in table 1.4 [29]. These are shown for  $\sqrt{s} = 14$  TeV as this is the  
785 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  $\alpha_S$ .

786

## 787 1.5 HIGGS PAIR PRODUCTION IN THEORIES BEYOND THE STANDARD MODEL

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

797 bosons arising in two Higgs doublet models (2HDM) or Higgs portal models as well as heavy gravitons in  
 798 Randall-Sundrum theories [30, 33–39]. Figure 1.7 shows a generic diagram for a heavy resonance decaying  
 799 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

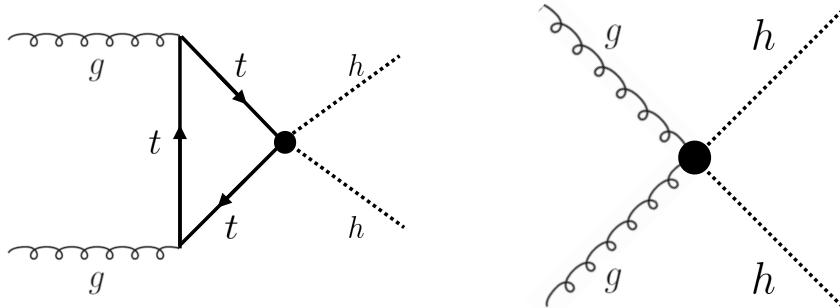


Figure 1.6: Diagrams with new vertices for non-resonant Higgs pair production arising in composite Higgs models.

800  
 801 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.

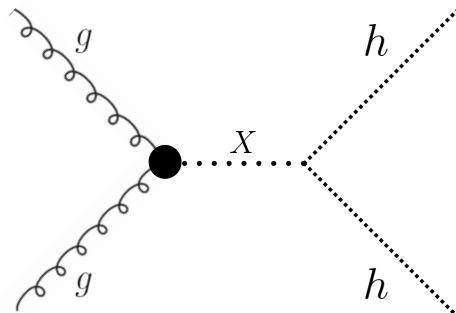


Figure 1.7: Generic Feynman diagram for resonant Higgs pair production in BSM theories.

802  
 803 **1.5.1 RANDALL-SUNDRUM GRAVITONS**  
 804 The Randall-Sundrum model is a proposed solution to the hierarchy problem that posits a five-dimensional  
 805 warped spacetime that contains two branes: one where the force of gravity is very strong and a second brane  
 806 at the TeV scale corresponding to the known Standard Model sector [33]. In the theory, the branes are

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

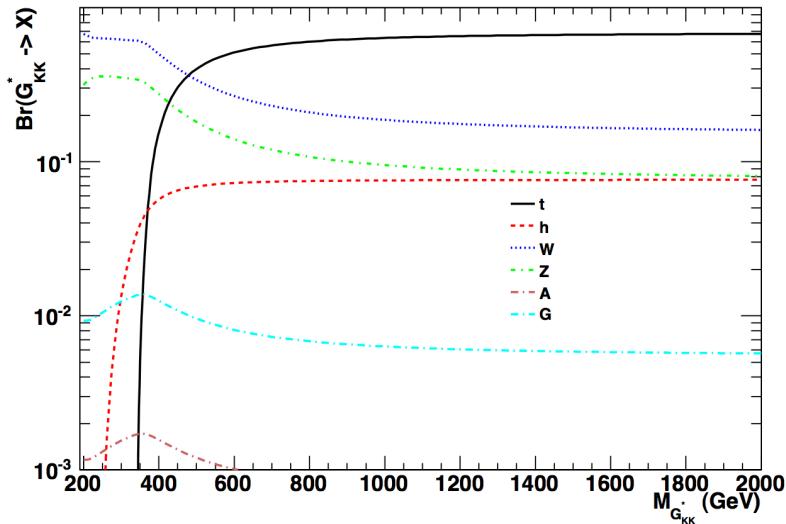


Figure 1.8: Branching ratios for a spin-2 Randall-Sundrum graviton as a function of mass computed in MadGraph with the CP3-Origins implementation [34, 40, 41].

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

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

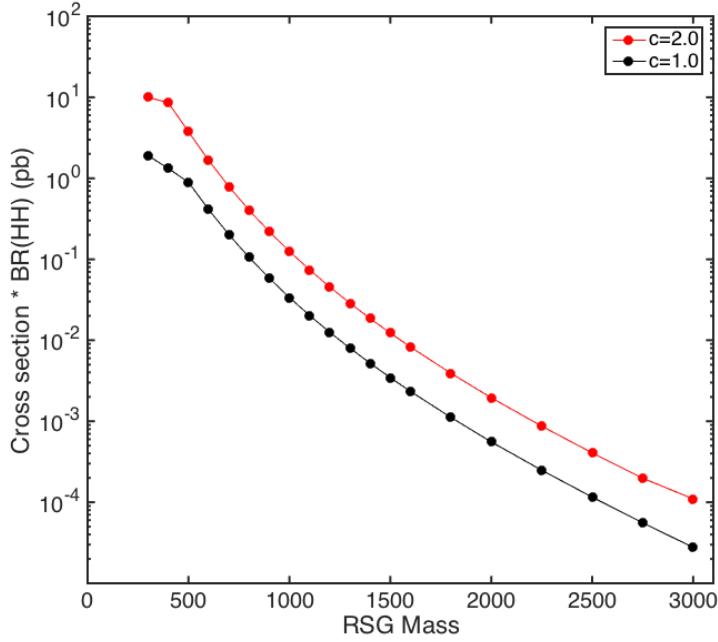


Figure 1.9:  $\sigma \times \text{BR}(HH)$  for Randall-Sundrum gravitons as a function of mass computed in MadGraph with the CP3-Origins implementation [34, 40, 41].

823     $c = 1.0$ , the width starts at 8.365 GeV for a mass of 300 GeV and increases to 187.2 GeV at a mass of  
 824    3 TeV. Similarly, with  $c = 2.0$ , the width starts at 33.46 GeV for  $m_G = 300$  GeV and increases to  
 825    748.8 GeV at a mass of 3 TeV.

### 826    1.5.2    TWO HIGGS DOUBLET MODELS

827    In Two Higgs Doublet Models (2HDM), a second complex scalar doublet is added to the Standard Model [36–  
 828    38]. In this case, all four degrees of freedom in the second doublet correspond to new particles, meaning  
 829    that there are five total scalars from the two Higgs doublets -  $h$  (light CP-even Higgs),  $H$  (heavy CP-even  
 830    Higgs),  $A$  (heavy CP-odd Higgs), and  $H^\pm$  (charged Higgs). The model is parameterized by two main pa-  
 831    rameters. The first,  $\tan \beta \equiv \frac{v_2}{v_1}$ , is the ratio of the vacuum expectation values of the two Higgs doublets  
 832    (where  $v_1$  corresponds to the  $v$  in the SM Higgs model described above). The second parameter is  $\alpha$ , a mix-  
 833    ing angle between the heavy and light Higgs fields. Models are also often parameterized with  $\cos(\beta - \alpha)$   
 834    rather than  $\alpha$  directly. The limit where  $\cos(\beta - \alpha) = 0$  is called the alignment limit, and in this limit the

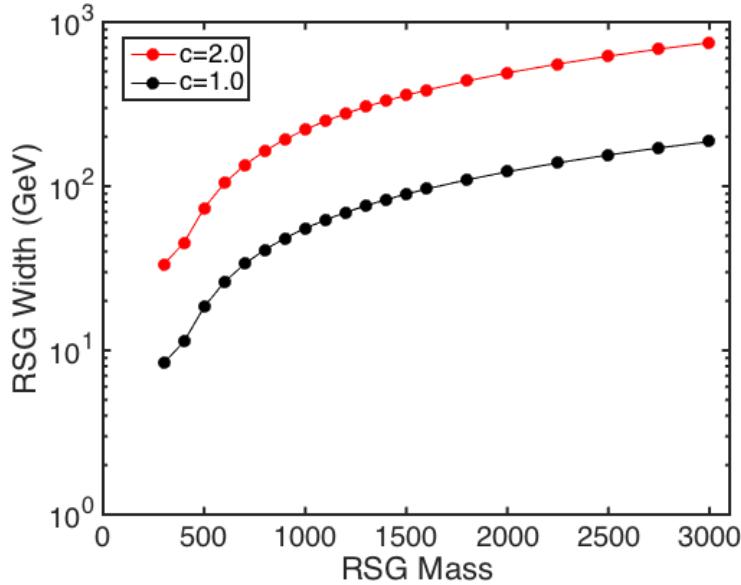


Figure 1.10: Randall-Sundrum graviton width as a function of mass computed in MadGraph with the CP3-Origins implementation [34, 40, 41]

835 light Higgs  $h$  has the same couplings as a Standard Model Higgs. Measurements of the Higgs boson have  
 836 put constraints on these two parameters, but near the alignment limit there is still much unprobed phase  
 837 space depending on the exact models and values of  $\tan \beta$  being considered [42].

838 2HDM models are usually separated into two main types - Type I and Type II. In Type I models, the  
 839 charged fermions only couple to the second Higgs doublet, leading to a fermiophobic light Higgs. In  
 840 Type II models, up-type quarks couple to the first doublet while down-type quarks couple to the second  
 841 doublet. One specific realization of a Type II 2HDM is the Minimal Supersymmetric Standard Model  
 842 (MSSM).

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

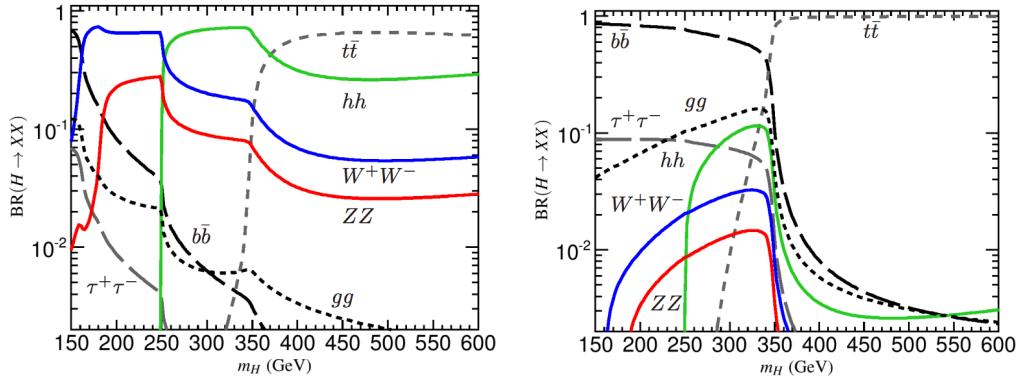


Figure 1.II: Branching ratios for heavy Higgs  $H$  in Type I (left) and Type II (right) 2HDM models with  $\tan \beta = 1.5$  and  $\cos(\beta - \alpha) = 0.1$  (0.01) for Type I (Type II) [38].

## 848 1.6 CONCLUSION

849 Studying the Higgs sector is essential for understanding the details of how mass arises in the Standard  
 850 Model and how the electroweak symmetry is broken. The discovery of the Higgs boson also opens the  
 851 door for its use as a tool to search for new physics, and Higgs pair production is an ideal candidate for  
 852 this study. Even if no BSM physics is found in Higgs pair production, searches for Higgs pairs will put  
 853 constraints on the Higgs self coupling and thus improve knowledge of the Standard Model and the details  
 854 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

855

856

857

## The ATLAS detector and the Large Hadron Collider

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

868 2.1 THE LARGE HADRON COLLIDER

869 The Large Hadron Collider (LHC) is a proton-proton collider at the CERN laboratory in Geneva, Switzer-  
870 land [43]. It was designed for a maximum collision center of mass energy of  $\sqrt{s} = 14 \text{ TeV}$  and has a  
871 circumference of 26.7 kilometers. Four main experiments are located at the interaction points (IP) of  
872 the accelerator: ATLAS (A Toroidal LHC ApparatuS), CMS (the Compact Muon Solenoid), ALICE (A  
873 Large Ion Collider Experiment), and LHCb [44–47]. Figure 2.1 shows a schematic of the LHC ring and  
874 its experiments.

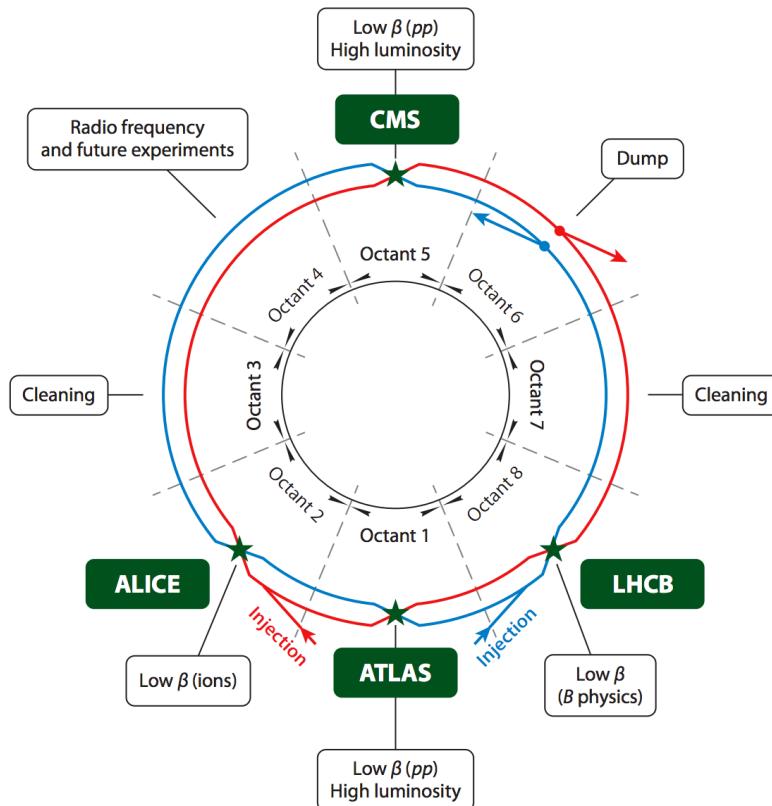


Figure 2.1: A schematic view of the LHC ring [48]. Four main experiments are located at interaction points along the ring. ATLAS and CMS are general purpose experiments, while ALICE is dedicated to heavy ion collisions and LHCb is dedicated to studying  $B$  physics.

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

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

880 2.1.1 INSTANTANEOUS LUMINOSITY

881 The rate of physics events expected from the accelerator is dependent on the instantaneous luminosity  
882 of the machine and the cross section of the physics process,  $R_{\text{events}} = L\sigma$ . Here,  $R_{\text{events}}$  is the num-  
883 ber of events per second,  $L$  is the instantaneous luminosity of the machine, and  $\sigma$  is the cross section for  
884 the physics process being measured. The instantaneous luminosity of the LHC is determined by numer-  
885 ous factors related to beam conditions. Equation 2.1 gives the equation for instantaneous luminosity of a  
886 Gaussian beam profile [48].

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

887 The LHC collides protons in bunches, and in the above equation  $N_b$  is the number of protons per bunch  
888 while  $n_b$  is the number of bunches per beam. Nominally, the LHC can hold up to 2808 proton bunches.  
889  $f_{\text{rev}}$  is the revolution frequency.  $\epsilon_n$  is the normalized transverse beam emittance, a measurement of the  
890 average spread of the particles in position-momentum space which has the dimension of length.  $\beta^*$  is the  
891 value of the  $\beta$  function for the beam at the interaction point. It relates the emittance to the Gaussian  
892 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  
893 are colliding at an angle at the IP.

894 Another way of writing the instantaneous luminosity is shown in equation 2.2. In this case, the instan-  
895 taneous luminosity is written as the ratio of the rate of inelastic collisions to the inelastic cross section [49].

896

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

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

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

### 2.1.2 EVOLUTION OF MACHINE CONDITIONS

This thesis uses datasets taken at three different center of mass energies:  $\sqrt{s} = 7$  TeV data taken in the year 2011,  $\sqrt{s} = 8$  TeV data taken in the year 2012, and  $\sqrt{s} = 13$  TeV data taken in the year 2015. In addition to increasing center of mass energy, the instantaneous luminosity and parameters that determine 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 [50, 51].

## 2.2 THE ATLAS DETECTOR

The ATLAS detector is the multi-purpose particle detector experiment located at the LHC’s Point 1 [44]. It has nearly  $4\pi$  coverage in solid angle around the interaction point. It consists of an inner detector for measuring charged particles, electromagnetic and hadronic calorimeters, and a muon spectrometer. Figure 2.2 gives an overview of the detector.

### 2.2.1 COORDINATE SYSTEM

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

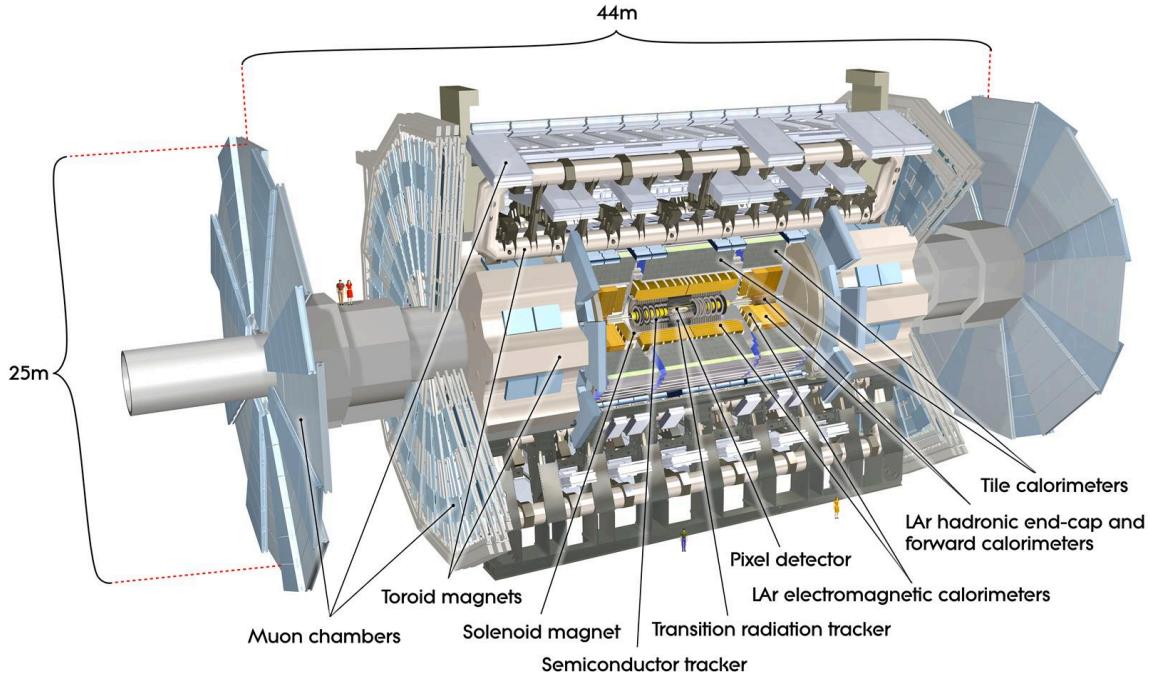


Figure 2.2: A full diagram of the ATLAS detector [44].

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.

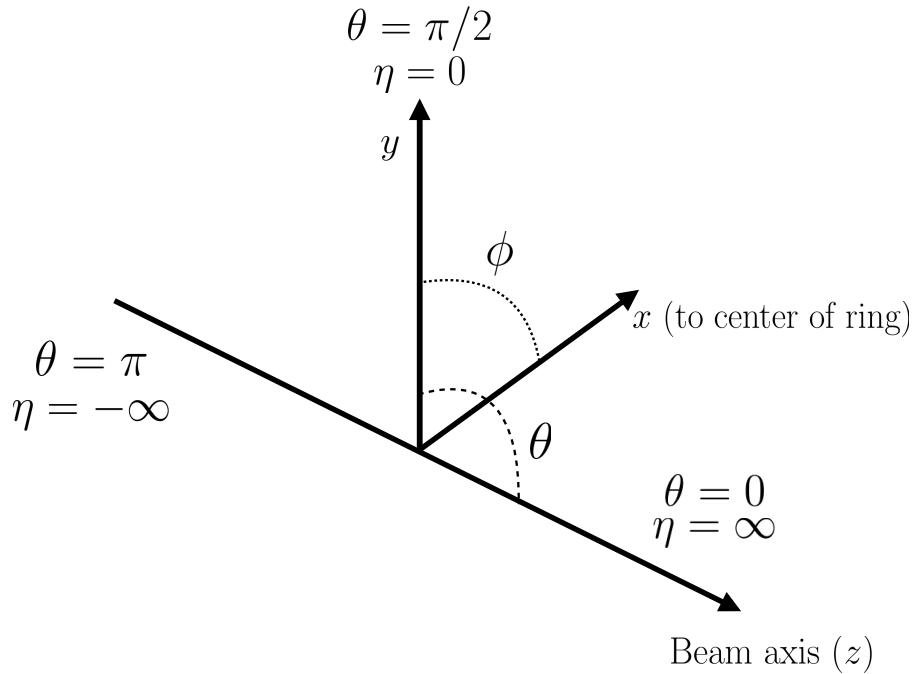


Figure 2.3: The ATLAS coordinate system. The  $z$  direction corresponds to the beam axis, while  $x$  and  $y$  define the transverse plane.  $\theta$  is the angle relative to the beam axis and  $\phi$  is the azimuthal angle.  $\eta$ , the pseudorapidity, approaches infinity at small angles relative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

927    2.2.2 INNER DETECTOR

928    The ATLAS Inner Detector (ID) system is built for precision tracking of charged particles. It covers the  
 929    range  $|\eta| < 2.5$ . In this range, approximately 1000 particles are generated every bunch crossing in the de-  
 930    tector [44]. This requires having fine granularity to achieve the resolutions required for good momentum  
 931    measurement and vertex reconstruction.

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

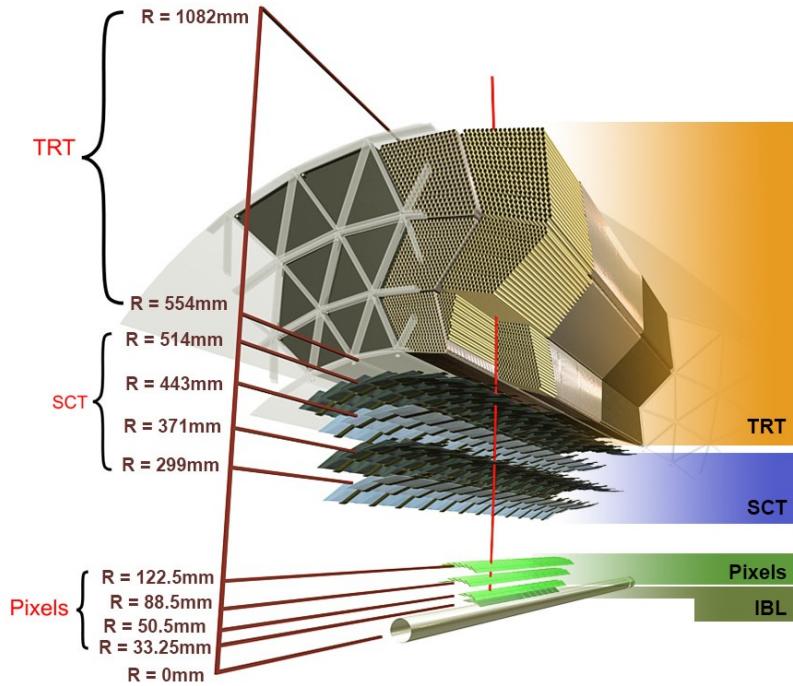


Figure 2.4: Layout of the ATLAS Inner Detector system [52].

#### 936    PIXEL DETECTOR

937    The pixel detector is the first detector particles traverse after being generated in proton collisions and is  
 938    the most granular detector. Its operation is crucial for precision tracking and vertex reconstruction as well  
 939    as higher level object reconstruction like tagging of jets from  $b$ -quarks. The basic sensing element in this  
 940    subdetector is a silicon pixel detector. The operating principle for the silicon pixels is that of a  $p-n$  junction.  
 941    When a charged particle passes through, it creates electron-hole pairs that are then separated by the electric  
 942    field. The sensors are  $250 \mu\text{m}$  thick and use oxygenated  $n$ -type wafers with readout pixels on the  $n^+$  side  
 943    of the detector [44]. Overall, the pixel detector has 1744 sensors and 80.4 million readout channels.

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

948 **INSERTABLE B-LAYER**

949 In Run 2, a new innermost pixel layer, known as the insertable B-layer (IBL), was added to the Inner  
950 Detector [53]. This layer was added to cope with the higher luminosities planned in LHC Run 2 and at the  
951 high luminosity HL-LHC. Additionally it improves tracking position resolution which in turn improves  
952 the vertexing and *b*-tagging capabilities in ATLAS. The detector sits directly on a new beam pipe, only  
953 33.25 mm away from the collision points in the azimuthal plane.

954 **SEMICONDUCTOR TRACKER (SCT)**

955 The semiconductor tracker (SCT) consists of silicon microstrips and comprises the next four layers of  
956 the ID. This sub-detector has 6.4 cm long sensors that are daisy-chained into strips with a strip pitch of  
957 80  $\mu\text{m}$  [44]. Some of the strips have a small stereo angle to allow for measurement of both angular co-  
958 ordinates. In total there are 6.3 million readout channels. The intrinsic accuracies are 17  $\mu\text{m}$  in  $R\text{-}\phi$  and  
959 580  $\mu\text{m}$  in  $z$  (or  $R$  in the endcap).

960 **TRANSITION RADIATION TRACKER (TRT)**

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

968 **2.2.3 CALORIMETERS**

969 The calorimeter system consists of two main sub-components: a fine granularity electromagnetic calorime-  
970 ter tailored for the measurement of photons and electrons and multiple coarser hadronic calorimeters ded-  
971 icated to the measurement of hadronic showers [44]. The calorimeter system has broader coverage than

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

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

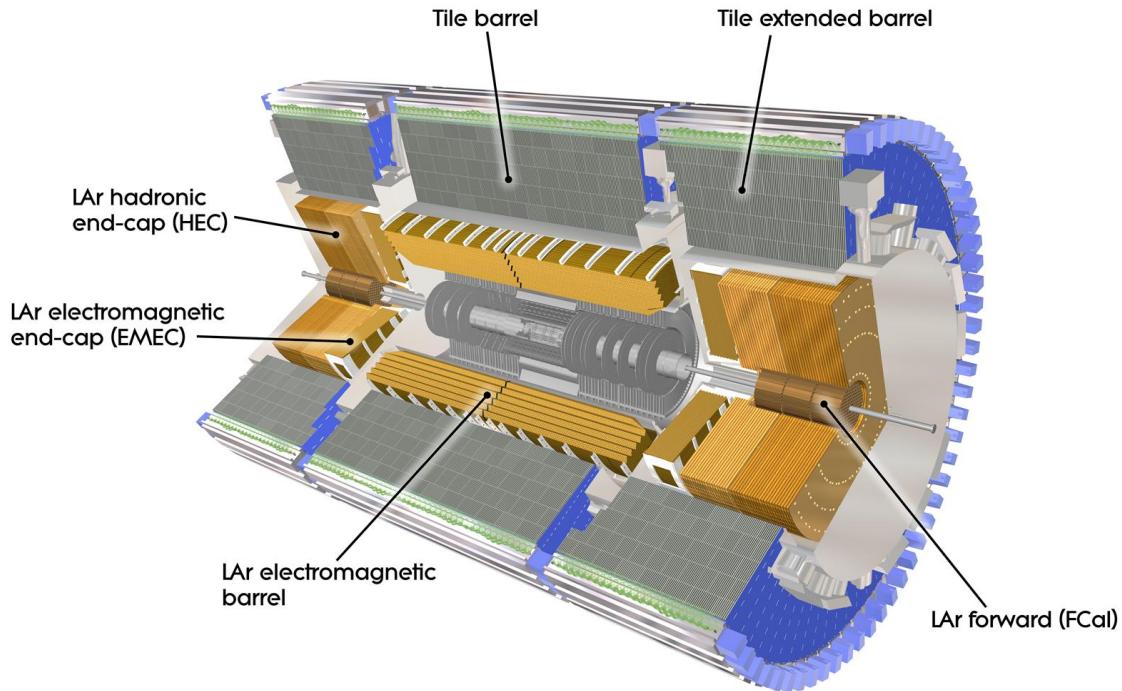


Figure 2.5: Layout of the ATLAS calorimeter system [44].

## 977 ELECTROMAGNETIC CALORIMETER

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

983 In order to provide good containment the calorimeter depth must be optimized. Typically, for elec-  
984 tromagnetic calorimeters the depth is measured in radiation lengths. In general, the intensity of a particle  
985 beam attenuates exponentially in distance with an attenuation constant equal to the radiation length. That  
986 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.  
987 The ATLAS EM calorimeter is designed to have  $> 22$  radiation lengths in the barrel and  $> 24$  in the  
988 endcap [44].

989 **HADRONIC CALORIMETERS**

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

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

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

1000 The FCal covers the most forward regions of the calorimeter system, extending to the region of  $3.1 <$   
1001  $|\eta| < 4.9$ . It again uses liquid argon as its active material. For absorber, it consists of an innermost module  
1002 made of copper followed by a module made of tungsten.

1003 The hadronic equivalent of radiation length is called the interaction length and is denoted as  $\lambda$ . In the  
1004 barrel, the hadronic calorimeter depth is approximately  $9.7\lambda$ , while in the endcap is is  $10\lambda$ . The outer  
1005 supports contribute an additional  $1.3\lambda$ . This is been shown to be sufficient to limit punch-through of  
1006 showers to the muon system [44].

1007    2.2.4    MUON SPECTROMETER

1008    The muon spectrometer is dedicated to measuring the momentum and position of muons. It consists  
1009    of tracking and trigger chambers which are unique in the barrel and endcap regions. The magnetic field  
1010    for bending of muons is provided by a system of three large air-core toroid magnets (from which ATLAS  
1011    derives its name.) These magnets provide 1.5 to 5.5 Tm of bending power at  $0 < |\eta| < 1.4$  and approx-  
1012    imately 1 to 7.5 Tm in the endcap region of  $1.6 < |\eta| < 2.7$ . The entire muon system covers the range  
1013     $0 < |\eta| < 2.7$ . Monitored drift tubes (MDTs) are used for tracking in the barrel and the two outer layers  
1014    of the endcap, while cathode strip chambers (CSCs) are used to provide tracking in the innermost endcap  
1015    wheel. In the barrel, resistive plate chambers (RPCs) are used as trigger chambers while thin gap chambers  
1016    (TGCs) are used in the endcap. Figure 2.6 shows the layout of the ATLAS muon system. The entire muon  
1017    system is designed with the specification of providing a 10% momentum resolution for a 1 TeV muon.

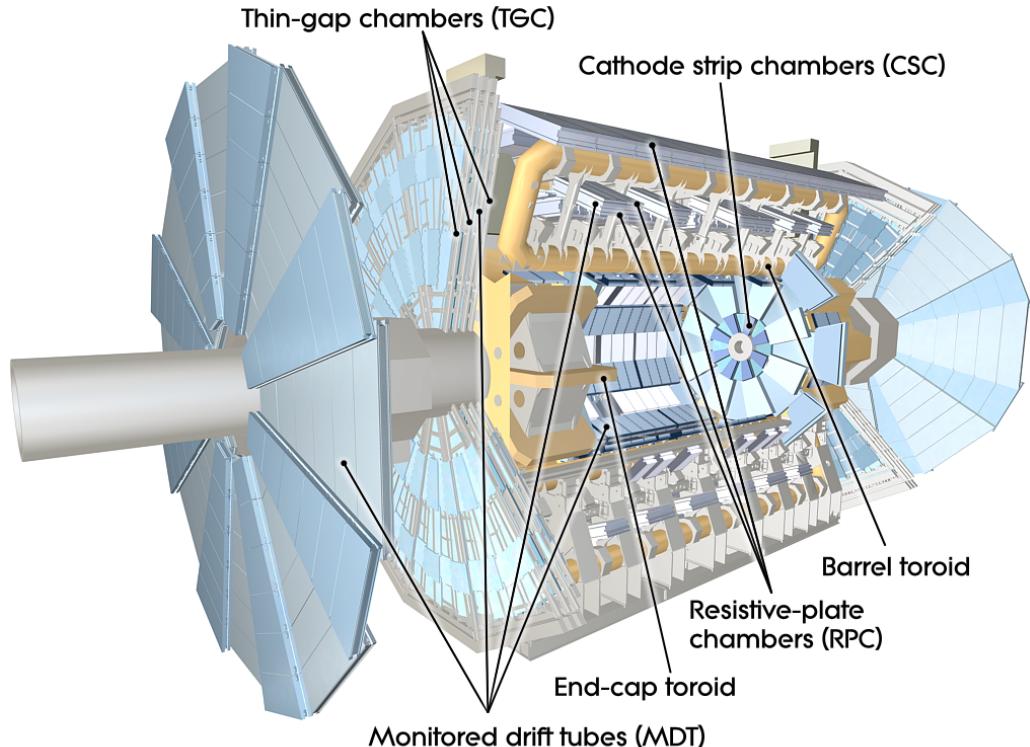


Figure 2.6: Layout of the ATLAS muon system [44].

1018 MONITORED DRIFT TUBES (MDTs)

1019 The monitored drift tubes (MDTs) are aluminum 3 cm diameter tubes filled with a 93/7 % mixture of  
1020 Argon and CO<sub>2</sub>, with trace amounts of water. As a charged particle traverses the tube, it ionizes the gas  
1021 and the ions drift to a wire at the center of the tube. The radial distance of traversal of the particle in the  
1022 tube is determined by the drift time of the electrons, allowing for fine position resolution. The tubes have  
1023 an average resolution of 80  $\mu\text{m}$  per tube and a maximum drift time of approximately 700 ns. The tubes  
1024 are oriented so that they give precision measurement in  $\eta$  and run along  $\phi$ . They cover  $|\eta| < 2.7$ , except  
1025 in the innermost layer of the endcap where they only go to  $|\eta| < 2.0$  [44].

1026 CATHODE STRIP CHAMBERS (CSCs)

1027 The cathode strip chambers cover a narrow window of the innermost endcap region at  $2.0 < |\eta| <$   
1028 2.7. In this region the background rates in the cavern are particularly high and the CSCs are designed to  
1029 handle these higher rates. The CSCs are multiwire proportional chambers with wires pointing in the radial  
1030 direction (away from the beam pipe). The wire serves as an anode and there are two types of segmented  
1031 cathode strip, one perpendicular to the wires which gives the precision measurement and one parallel which  
1032 provides the transverse coordinate. It has an 80/20% gas mixture of Argon and CO<sub>2</sub> [44].

1033 RESISTIVE PLATE CHAMBERS (RPCs)

1034 The resistive plate chambers (RPCs) are gaseous electrode-plate detectors covering the region  $|\eta| < 1.05$ .  
1035 They consist of two resistive plates separated by a distance of 2 mm. The gas mixture used is a 94.7/5/0.3%  
1036 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  
1037  $\phi$  measurement and thus provides measurement of the azimuthal coordinate in the barrel. The thin gas  
1038 gap allows for a quick response time which makes it ideal for use in the trigger. Signals in the RPC have  
1039 a width of approximately 5 ns. There are three layers of RPCs which are referred to as the three trigger  
1040 stations. They allow for programmable thresholds in both a low  $p_T$  and high  $p_T$  trigger. The coincidence  
1041 of hits in the innermost chambers allows for setting muon trigger thresholds between 6 and 9 GeV, while  
1042 the outermost layer allows the trigger to set trigger thresholds in the range of 9 to 40 GeV [44].

1043 THIN GAP CHAMBERS (TGCs)

1044 The thin gap chambers (TGCs) are multiwire proportional chambers where the wire to cathode distance  
1045 (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*-  
1046 pentane and use a high electric field to gain good time resolution. They serve two functions in the end-cap  
1047 system. First, they serve as the trigger chambers. Second, they also provide azimuthal coordinate measure-  
1048 ment. They sit on the inner and middle layers of the endcap. The outermost layer's azimuthal coordinate  
1049 is determined by extrapolation [44]. As with the RPCs, the TGCs also are capable of triggering with pro-  
1050 grammable thresholds in the same  $p_T$  range specified for the RPCs above.

1051 2.2.5 MAGNET SYSTEM

1052 As mentioned previously, there are two independent magnet systems in ATLAS. The first is a 2 T solenoid  
1053 field in the inner detector which provides bending in the azimuthal plane. The second is an approximately  
1054 0.5 T toroidal field in the muon system which provides bending in  $\eta$ . Figure 2.7 shows the predicted field  
1055 integral as a function of  $|\eta|$  [44].

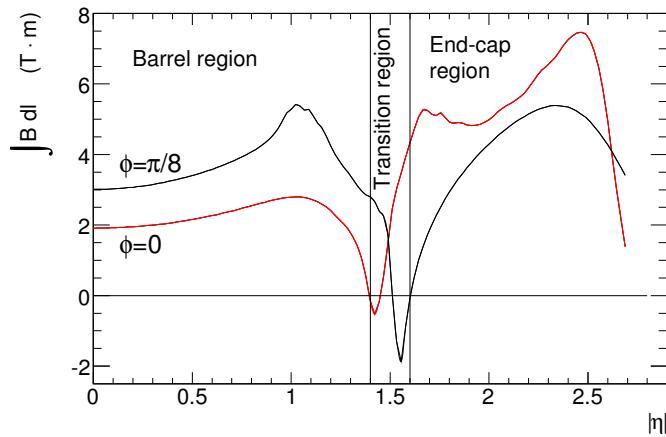


Figure 2.7: Predicted field integral as a function of  $|\eta|$  for the ATLAS magnet system [44].

1056    2.2.6    TRIGGER SYSTEM

1057    The ATLAS trigger system searches for signatures of muons, electrons, photons, hadronically decaying  $\tau$   
 1058    leptons, and jets in order to save these events for further analysis. The trigger system in ATLAS is designed  
 1059    to reduce the maximum LHC event rate of 40 MHz to a more reasonable rate that can be recorded. The  
 1060    trigger first consists of a fast, hardware based system called the Level-1 (L1) trigger. The L1 trigger consists  
 1061    of independent dedicated detector sub-components that can seed regions of interest (RoIs) for further  
 1062    analysis downstream. For muons, the RPCs and TGCs are used, while in the calorimeter coarsely grained  
 1063    sections of calorimeter cells called towers are used. Once regions of interest are seeded, a software based  
 1064    system called the High Level Trigger (HLT) is used to reconstruct objects and integrate information from  
 1065    different parts of the detector. In Run 1 of ATLAS, the HLT consisted of two separate stages: the level 2  
 1066    (L2) trigger and the event filter (EF).

1067    The maximum trigger rate that the L1 trigger can handle is 75 kHz. In the HLT, the rate of events  
 1068    written to disk is approximately 400 Hz. Figure 2.8 shows the trigger rates for different L1 triggers in 2012  
 1069    and 2015 for ATLAS [54].

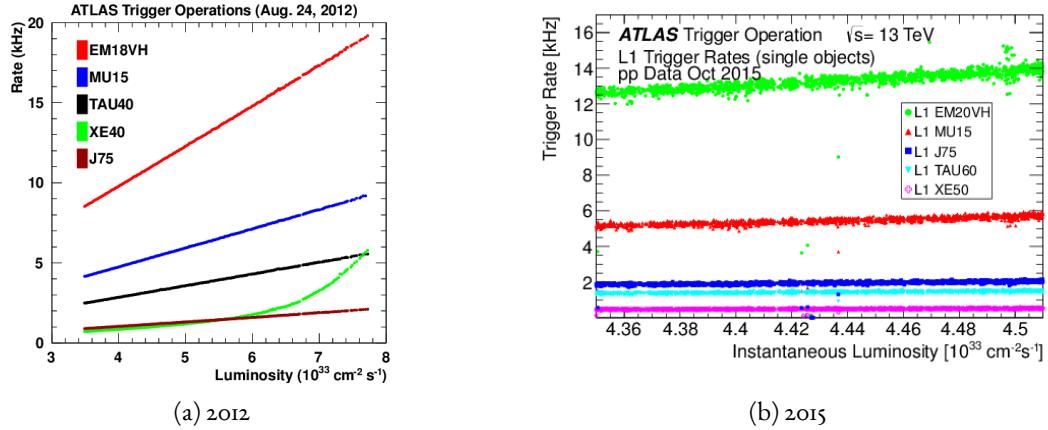


Figure 2.8: ATLAS trigger rates for Level-1 triggers as a function of instantaneous luminosity in 2012 and 2015 operation. These are single object triggers for electromagnetic clusters (EM), muons (MU), jets (J), missing energy (XE), and  $\tau$  leptons (TAU). The threshold of the trigger is given in the name in GeV [54].

1070 2.2.7 ATLAS DATASETS

1071 ATLAS has collected data at center of mass energies of 7, 8, and 13 TeV. Figure 2.9 shows the integrated  
1072 luminosity as a function of time for each of the three datasets. In the 2011 dataset with  $\sqrt{s} = 7$  TeV,  
1073 ATLAS recorded  $5.08 \text{ fb}^{-1}$ . Increased instantaneous luminosity in 2012 led to a larger dataset of  $21.3 \text{ fb}^{-1}$   
1074 recorded at  $\sqrt{s} = 8$  TeV. After Long Shutdown 1 (LS1) of the LHC and a restart in 2015, ATLAS  
1075 recorded  $3.9 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13$  TeV [55, 56]. The data recorded by ATLAS can only be used for  
1076 analysis if the required sub-detectors were in a stable state when the data was being taken. The fraction  
1077 of recorded ATLAS data that was labeled as being good for physics analysis was 90%, 95%, and 82% in  
1078 the 7, 8, and 13 TeV data respectively. Thus, the Run 1 results presented in this thesis use  $4.6 \text{ fb}^{-1}$  at  
1079  $\sqrt{s} = 7$  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.

1080 2.2.8 DETECTOR PERFORMANCE

1081 Table 2.2 summarizes the design requirements for each of the different sub-detectors. This table shows the  
1082 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 [44].

1083 2.3 THE ATLAS MUON NEW SMALL WHEEL UPGRADE

1084 As the LHC continues operation, it is scheduled to be upgraded in several phases to allow it to reach higher  
1085 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.

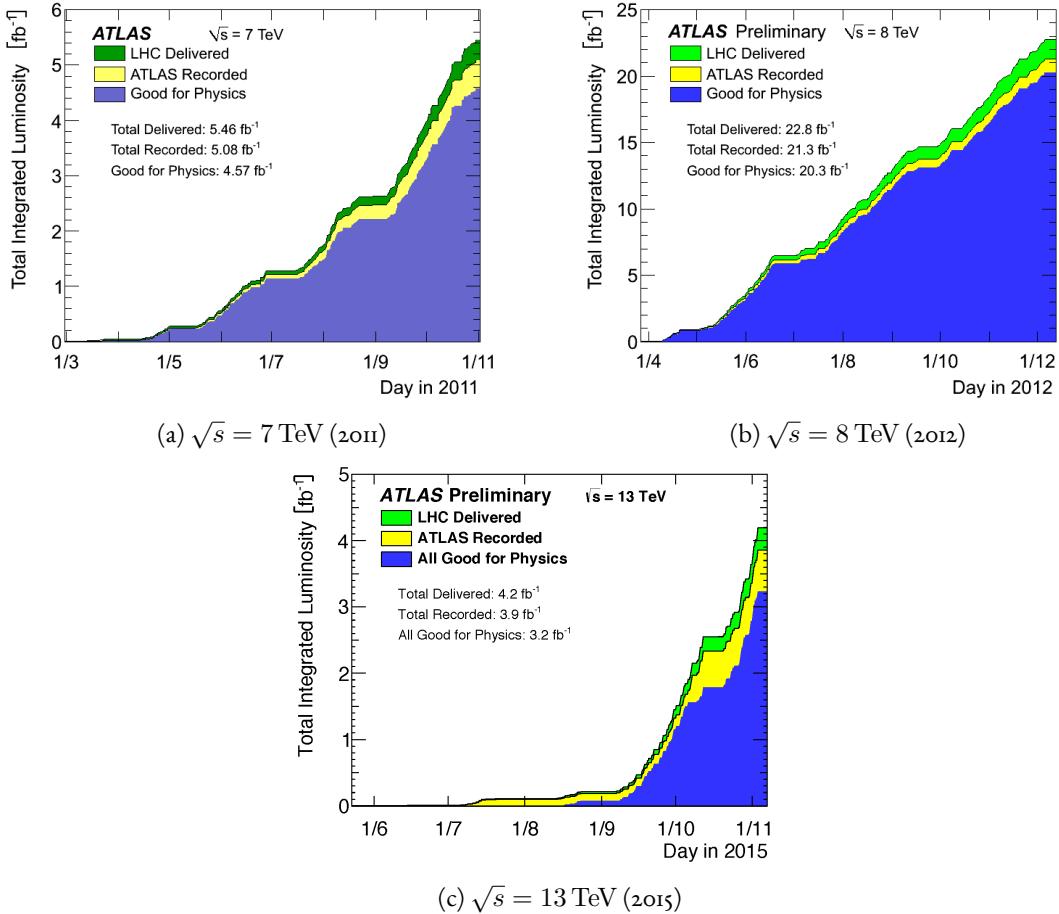


Figure 2.9: Instantaneous luminosity as a function of time for data recorded by ATLAS at different center of mass energies [55, 56].

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) [57]. 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.

1092 2.3.1 MOTIVATION

1093 The motivation of the NSW is two-fold. The first objective is to alleviate the decreased tracking efficiency  
1094 that comes in a high rate environment. As shown in figure 2.10, at the LHC design luminosity both the  
1095 efficiency of recording hits and reconstructing track segments in the MDTs decreases. While the MDTs  
1096 were designed to cope with the hit rates at the LHC design luminosity, the High Luminosity LHC will  
1097 exceed these design specifications and the MDTs will have to be replaced.

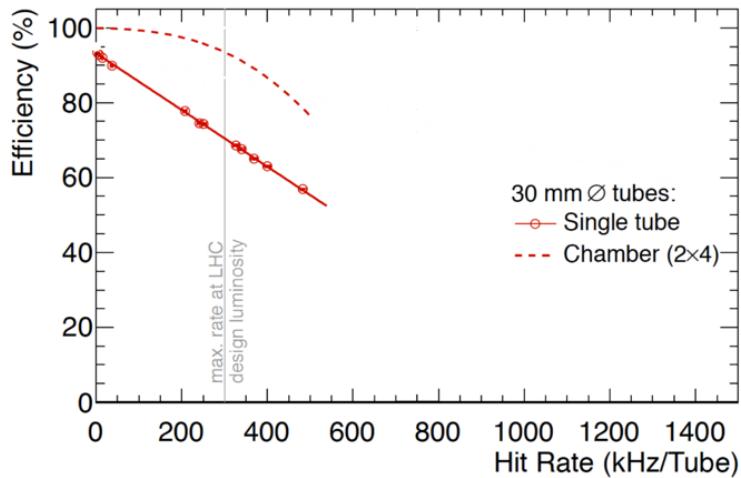


Figure 2.10: MDT tube hit (solid) and segment (dashed) efficiency as a function of hit rate per tube [57].

1098 The NSW will also work to alleviate the rate of fake triggers arising in the endcap. Figure 2.11 shows the  
1099 extrapolated trigger rates as a function of the  $p_T$  threshold with and without the NSW upgrade. As the  
1100 figure shows, the NSW upgrade will reduce the trigger rate considerably compared to the current endcap  
1101 trigger system. At a  $p_T$  threshold of 20 GeV, the level-1 trigger rate drops from 20 kHz to 7 kHz. This  
1102 reduction allows the  $p_T$  thresholds on muons to remain low, increasing the phase space of possible physics  
1103 studies and in particular maintaining good acceptance for Higgs physics.

1104 2.3.2 NSW DETECTOR TECHNOLOGIES

1105 The NSW will use two new detector technologies - micromesh gaseous structure detectors (micromegas)  
1106 and small-strip thin gap chambers (sTGCs) [57, 58]. The micromegas is more suited to tracking because

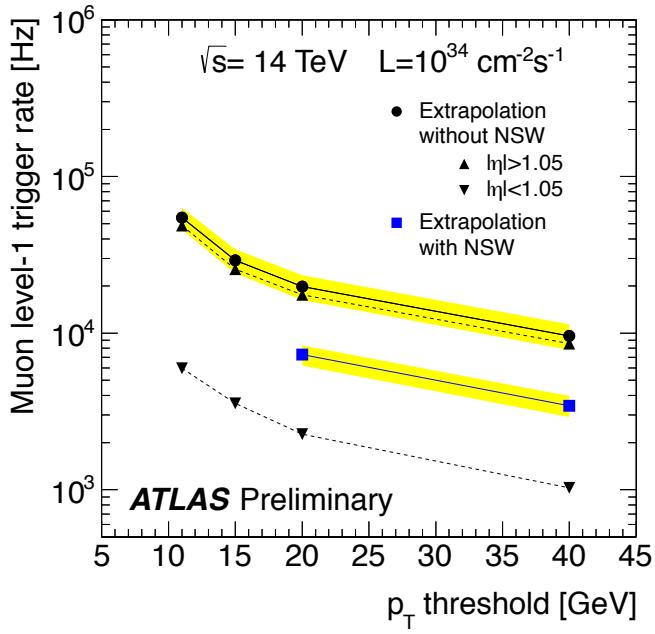


Figure 2.11: Trigger rate as a function of  $p_T$  threshold with and without the NSW upgrade [57].

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.

### 1111 MICROMEGAS

1112 Micromegas detectors operate using a thin metallic mesh that sits approximately  $100\ \mu\text{m}$  away from the  
 1113 readout electrodes to create the amplification region. Above this mesh, there is a drift region on the order  
 1114 of a few mm in length capped by a drift electrode. As a charged particle traverses the detector, it ionizes gas  
 1115 and the electrons drift down towards readout strips. The timing of the drift can be used to reconstruct the  
 1116 angle of traversal of the particle. This is illustrated in figure 2.12. The micromegas used in ATLAS will be  
 1117 resistive micromegas, where the readout electrodes are topped with resistive strips [59]. This alleviates the  
 1118 risk of sparking in the large area detectors that ATLAS will use.

1119 In ATLAS, the micromegas drift gap will be 5 mm and the amplification gap will be  $128\ \mu\text{m}$ . They are

1120 filled with the same gas mixture as the MDTs. They will be stacked in an octuplet in an XXUV-UVXX  
 1121 geometry, where X refers to nominal strips and U and V refer to stereo strips at an angle of  $\pm 1.5^\circ$ . This  
 1122 arrangement allows for measurement of the azimuthal coordinate and gives a large lever arm between the  
 1123 straight strips for triggering purposes. Figure 2.12 shows the geometry of a single micromegas detector as  
 1124 well as its operating principle [57].

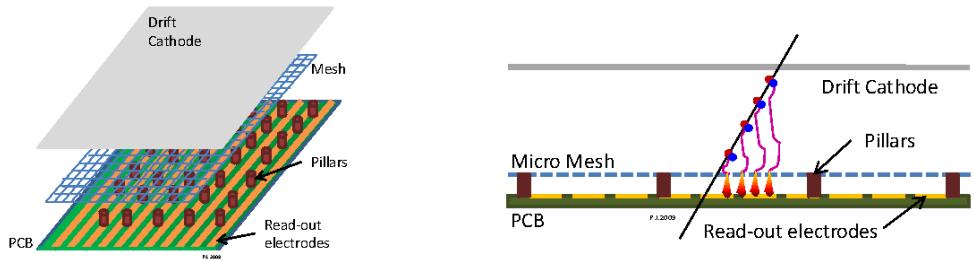


Figure 2.12: Illustrations of the geometry (left) and operating principle (right) of the micromegas detector [57].

## sTGCs

1125 sTGCs  
 1126 The sTGCs are similar to the TGCs currently in the ATLAS endcap muon system [44]. They consist  
 1127 of gold-plated tungsten wires (with a 1.8 mm pitch) between two cathode planes 1.4 mm away from the  
 1128 wire plane. One cathode plane consists of strips with a 3.2 mm pitch (much smaller pitch than the TGCs),  
 1129 while the other consists of coarser pads that are used for defining regions of interest in the sTGC trigger  
 1130 algorithm. Figure 2.13 shows the basic detector geometry.

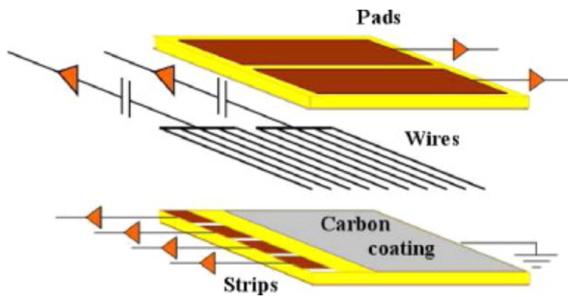


Figure 2.13: Geometry of the sTGC detector [57].

1131 2.3.3 PHYSICS IMPACT

1132 Maintaining low  $p_T$  thresholds for muons while still staying within the trigger rate budget at Level 1 for the  
1133 muon system (20 kHz) is crucial for physics analyses to be successful in high luminosity conditions. One  
1134 realm where the lepton trigger threshold is especially important is in Higgs physics. In the  $H \rightarrow WW^*$   
1135 analysis, one of the  $W$  bosons is off shell and tends to decay to soft leptons. In associated production of a  
1136 Higgs with a  $W$ , the lepton is also important because it provides the main handle which allows the event  
1137 to be triggered. Without the NSW, analyses would be required to either raise the muon  $p_T$  threshold or  
1138 only use muons triggered from the barrel muon system. Table 2.3 shows that both of these alternatives  
1139 significantly reduce the Higgs signal efficiency. With the NSW, the signal efficiency is largely maintained  
1140 and the triggers can remain unprescaled at lower  $p_T$  thresholds.

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

Table 2.3: Signal efficiencies for  $WH$  production with  $H \rightarrow b\bar{b}$  and  $H \rightarrow WW^* \rightarrow \mu\nu qq$  under different trigger configurations [57].

1141 2.4 OBJECT RECONSTRUCTION IN ATLAS

1142 ATLAS analyses first start by requiring the presence of certain reconstructed physics objects in the event.  
1143 This section will present a brief overview of the algorithms used to reconstruct electrons, muons, jets (in-  
1144 cluding  $b$ -jets), and missing energy<sup>2</sup>. The performance of physics object reconstruction and identification  
1145 will also be discussed as these are relevant to the analyses presented later. Figure 2.14 gives an overview of  
1146 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.

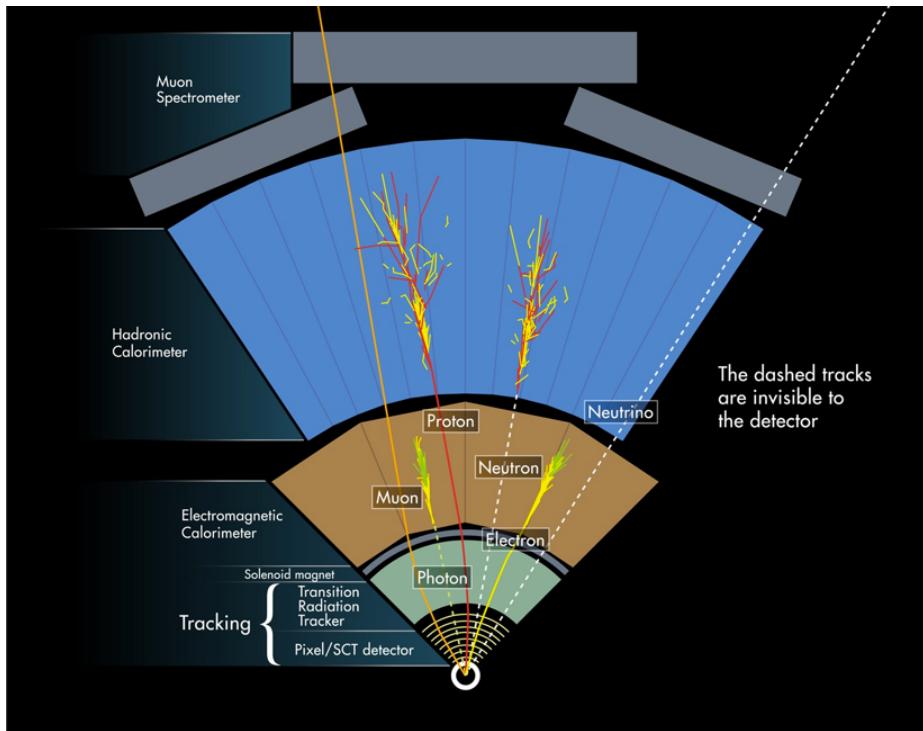


Figure 2.14: Illustration of particle interactions in ATLAS [60]

#### 1147 2.4.I ELECTRONS

1148 Electrons in ATLAS will leave tracks in the inner detector and energy deposits in the electromagnetic  
 1149 calorimeter. The algorithm for recognizing the signature of electrons proceeds in two steps: reconstruction  
 1150 and identification.

1151 In reconstruction, an electron candidate is formed by matching EM calorimeter deposits with ID tracks.  
 1152 The algorithm first chooses seed clusters in the EM calorimeter by using a sliding window algorithm that  
 1153 searches for towers with transverse energy larger than 2.5 GeV. In addition to seed clusters, track candi-  
 1154 dates must be identified in the ID. The algorithm selects seed tracks with  $p_T > 1$  GeV that do not fit well  
 1155 with a pion hypothesis. Once candidate tracks are selected, they are re-fit with a Gaussian Sum Filter (GSF)  
 1156 algorithm to estimate electron parameters [61]. Finally, an electron candidate is formed if at least one track  
 1157 matches to a seed cluster in the calorimeter. The full details of the reconstruction algorithm can be found  
 1158 in reference [62].

1159 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 [62]. 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 [62, 63]. The reconstruction efficiency is measured using both the  $Z$  and  $J/\psi$  with 8 TeV data.

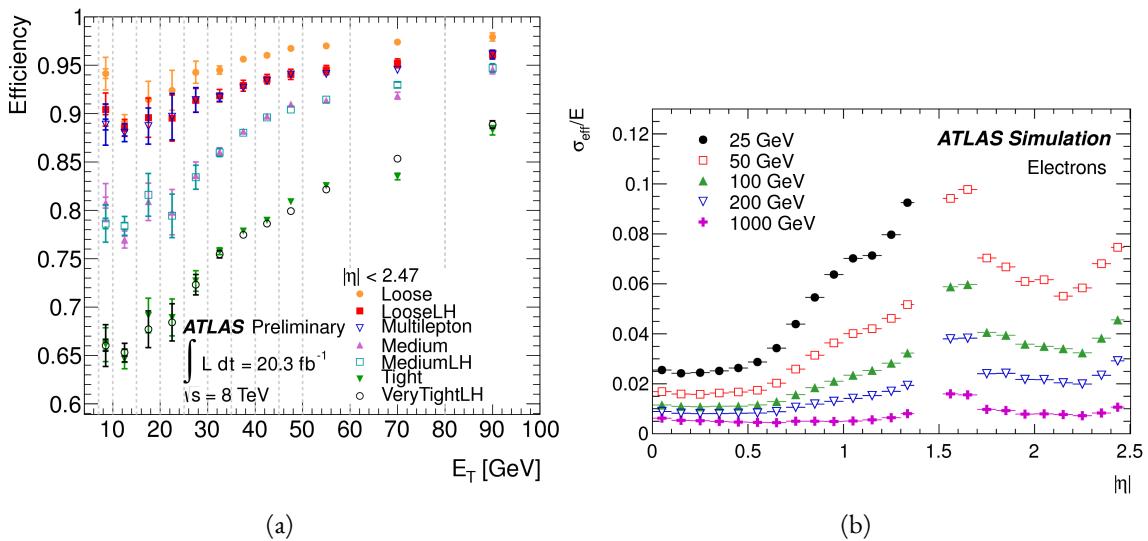


Figure 2.15: Electron performance: (a) reconstruction efficiency as a function of electron  $E_T$  [62] (b) energy resolution in simulation as a function of  $|\eta|$  for different energy electrons [63].

#### 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.

1174      The first step of reconstruction is to reconstruct local straight line tracks, called segments, in each muon  
1175      chamber. Segments are then fit to larger tracks that traverse the entire muon spectrometer. Such muon  
1176      tracks are referred to as “standalone” tracks (SA) as they only use information from the muon spectrometer.  
1177      The standalone tracks are then matched to tracks in the inner detector to form “combined” (CB) muons,  
1178      and both tracks are used to determine the momentum and direction of the muon. To improve acceptance,  
1179      segment-tagged and calorimeter-tagged muons are also reconstructed. In these cases, ID tracks are matched  
1180      to segments in the MS and calorimeter deposits consistent with a minimum ionizing particle, respectively.  
1181      The details of the reconstruction can be found in reference [64].

1182      As with electrons, once muon candidates are reconstructed they have identification criteria applied to  
1183      reduce background. These criteria include the  $\chi^2$  match between the ID and MS tracks, the number of  
1184      hits in the ID, overall ID and MS track fit quality, and additional variables. In Run 1, the muons used are  
1185      simply referred to as combined muons [64]. In Run 2, an improved reconstruction algorithm is used and  
1186      criteria ranging from “loose” to “tight” are defined (similar to what is done with electrons) [65]. Figure 2.16  
1187      shows the muon reconstruction efficiency (measured with the  $Z$  and  $J/\psi$ ) and invariant mass resolution  
1188      in  $\sqrt{s} = 8$  TeV data.

#### 1189      2.4.3 JETS

1190      When a quark or gluon is produced in collisions, it is not measured directly in ATLAS. Rather, due to  
1191      QCD effects, it produces a collimated spray of hadrons in the direction of the original parton, which is  
1192      known as a jet. Jets are reconstructed in ATLAS using energy deposits in the hadronic calorimeter. The  
1193      first step is build “topological clusters” out of energy deposits in calorimeter cells [66, 67]. This is done  
1194      using strategy where seed cells are chosen by picking cells whose energy measurements are four times the  
1195      amount of noise expected for that cell. Adjacent cells with at least  $2\sigma$  energy measurements are added to  
1196      the cluster, then a final layer of clusters with energy above  $0\sigma$  are added. Once calorimeter clusters are  
1197      formed, they are clustered further into jet candidates. The analyses presented in this thesis use the anti- $k_T$   
1198      jet clustering algorithm [68]. This algorithm defines a parameter  $R$  that appears in the denominator of  
1199      the clustering distance metric and defines the radial size of the jet in  $\eta$ - $\phi$  space.

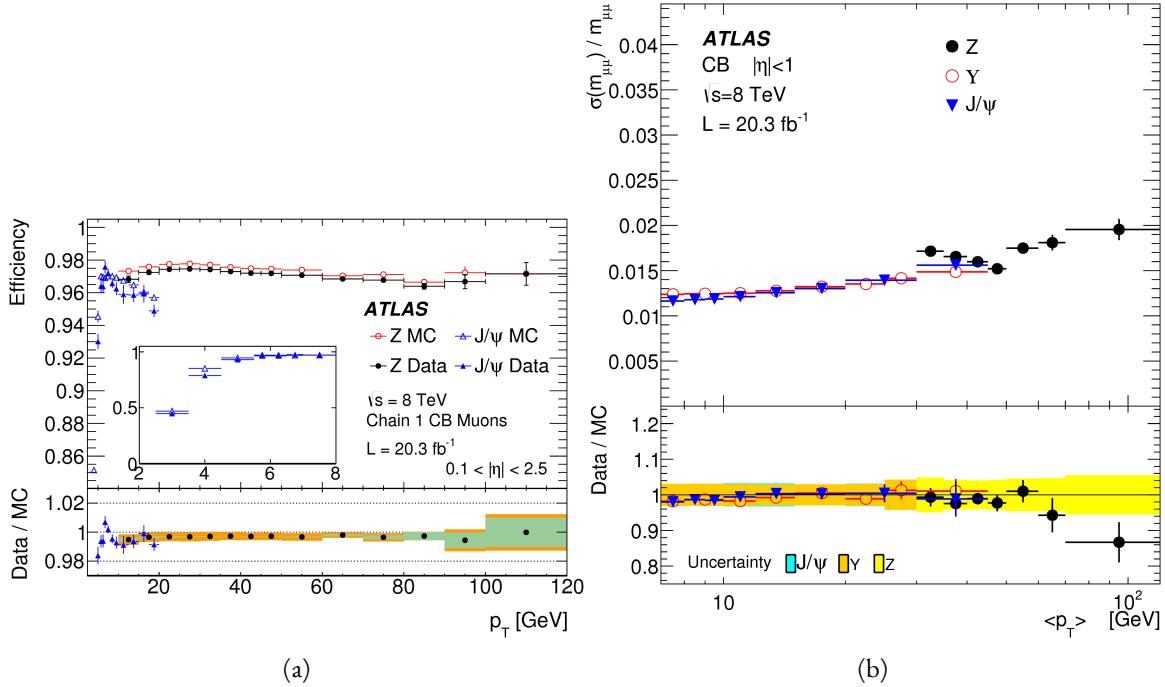


Figure 2.16: Muon performance in  $\sqrt{s} = 8$  TeV data: (a) reconstruction efficiency as a function of muon  $p_T$  (b) dimuon mass resolution as a function of average  $p_T$  [64].

1200     The energy response of the calorimeter must be properly characterized in order to reconstruct the true  
 1201     jet energy. Calorimeter clusters can be calibrated either with the EM calibration, where each cluster is as-  
 1202     sumed to have come from the energy deposit of an electron or photon, or the LCW calibration, where local  
 1203     cluster weights are computed to allow for local calibration of clusters as hadronic or electromagnetic. The  
 1204     details of the jet energy calibration are not discussed here and are presented in reference [69]. Figure 2.17  
 1205     shows the jet energy response after calibration in Monte Carlo as a function of the true  $p_T$  of the jet [69].

1206     Analyses often need to know how consistent a particular jet is with the primary vertex of the event in  
 1207     order to avoid contamination from pileup interactions. One measure of this consistency is known as the  
 1208     jet vertex fraction (JVF). The JVF is the ratio of tracks associated with a primary vertex to the total number  
 1209     of tracks inside a jet. Jets from the primary interaction in the event should have a large fraction of tracks  
 1210     consistent with the primary vertex and therefore have a large JVF value.

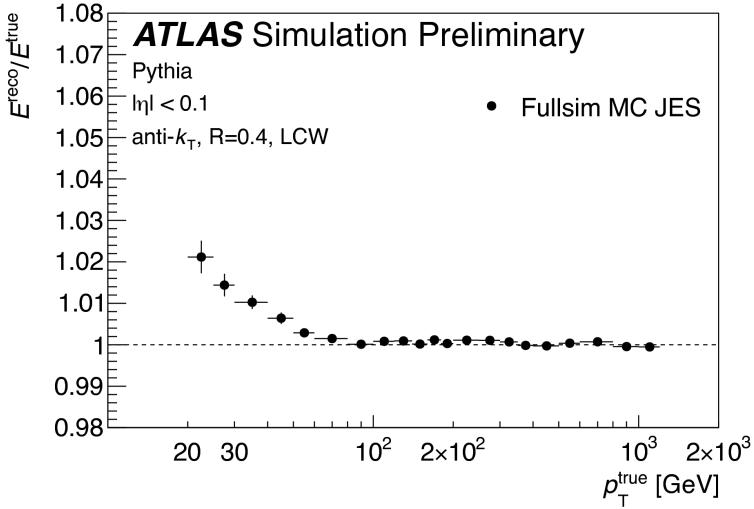


Figure 2.17: Jet energy response after calibration as a function of true  $p_T$  in simulation [69].

#### 2.4.4 $b$ -TAGGING

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

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

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

1225 flavor, charm, and bottom jets and then evaluate the likelihood of the jet coming from each of these types.

1226 The likelihood ratios are used as inputs to the multivariate algorithm.

1227 The next two algorithms used as input are referred to as the secondary vertex (SV) and JetFitter (JF)  
1228 algorithms. The SV algorithm uses tracks inside the jet to fit for vertices that are displaced from the pri-  
1229 mary vertex. The JF algorithm attempts to reconstruct the full flight path of the  $b$  by looking for multiple  
1230 displaced vertices along the same line (as  $B$  decays often result in subsequent charm meson decays).

1231 In Run 1, the multivariate  $b$ -tagging algorithm used a neural network and was referred to as MV1. The  
1232 details of this algorithm and its inputs are given in reference [70]. This algorithm is used for defining  
1233 a 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  
1234 inputs was simplified and a boosted decision tree with 24 input variables was used, referred to as MV2 [71].  
1235 The MV2 algorithm is a boosted decision tree incorporating twenty-four input variables constructed from  
1236 three lower level input algorithms described above. This algorithm is used for  $b$ -tagging in the  $X \rightarrow$   
1237  $HH \rightarrow b\bar{b}b\bar{b}$  search presented in Part 3. Figure 2.18 summarizes the inputs to MV2. Figure 2.19 shows the  
1238 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.

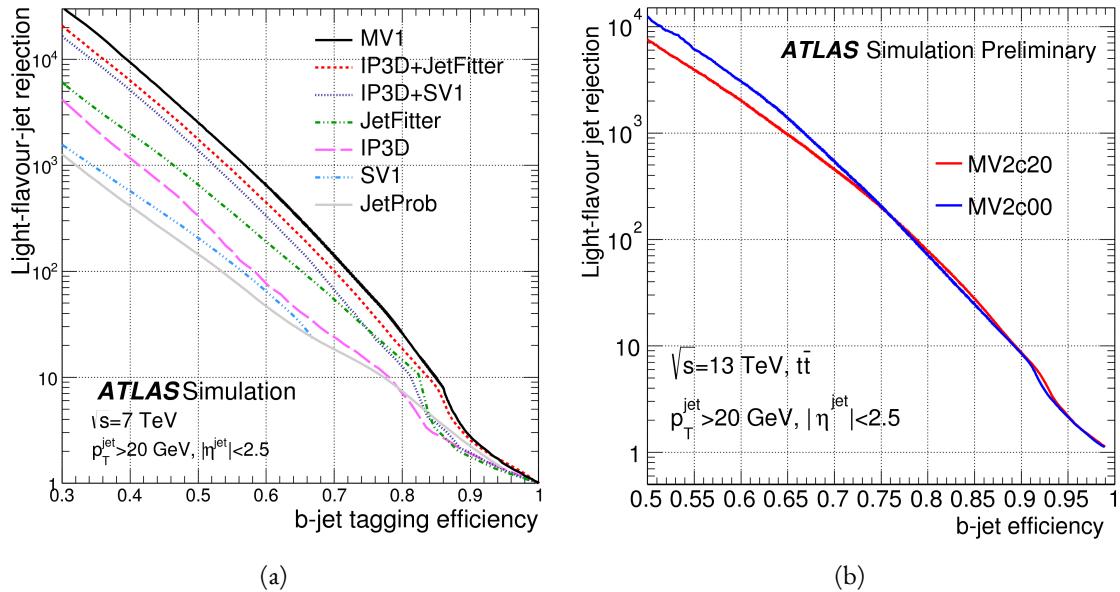


Figure 2.19: Light jet rejection ( $1/\text{efficiency}$ ) vs.  $b$ -jet efficiency for MV1 and its input algorithms (a) [70] and MV2 (b) [71] in simulated  $t\bar{t}$  events. The numbers in the algorithm names in (b) refer to the fraction of charm events used in the MV2 training.

## 1239 2.4.5 MISSING TRANSVERSE ENERGY

1240 As noted in figure 2.14, neutrinos produced in ATLAS will pass through the detector without interacting.  
 1241 The only way of detecting the presence of weakly interacting particles like neutrinos (or BSM particles  
 1242 that are long-lived) is to use missing transverse momentum. The basic principle of missing transverse en-  
 1243 ergy is to use the momentum balance of the incoming protons to infer the presence of missing particles.  
 1244 The net longitudinal momentum of the incoming partons that collide is not known (since each carries  
 1245 an unknown fraction of the proton's momentum). However, the protons (and thus incoming partons)  
 1246 have essentially no net momentum in the plane transverse to the beam line (the  $x$ - $y$  plane). Therefore, if  
 1247 there are no undetected particles in the final state, the transverse momenta of all of the final state particles  
 1248 should balance. The magnitude of the imbalance in the transverse plane is known as missing transverse  
 1249 momentum ( $E_T^{\text{miss}}$ ).

1250 The basic calculation of missing transverse momentum from calorimeter cells is given in equation 2.4 [72].

1251

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

1252 The  $E_T^{\text{miss}}$  calculation is separated into different terms based on the objects that the calorimeter clusters  
 1253 are associated with. This way, each cell's contribution is calibrated appropriately according to the object.  
 1254 This separation of terms used to define the  $E_T^{\text{miss}}$  in Run 1 is shown in equation 2.5 [72].

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

1255 The CellOut term of the above equation corresponds to calorimeter cells with energy deposits that are  
 1256 not associated with other objects. The soft jets term comes from cells associated to jets with  $p_T$  between  
 1257 7 and 20 GeV, while the jets term comes from jets with  $p_T > 20$  GeV. Because muons do not deposit  
 1258 significant energy in the calorimeter, the muon momentum (after correction for the energy deposited in  
 1259 the calorimeter for non-isolated muons) is used for the muon term [72]. The final  $E_T^{\text{miss}}$  is calculated using  
 1260 equation 2.6.

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

1261 Figure 2.20 shows the resolution of the components of the  $E_T^{\text{miss}}$  with different pileup suppression tech-  
 1262 niques [73].

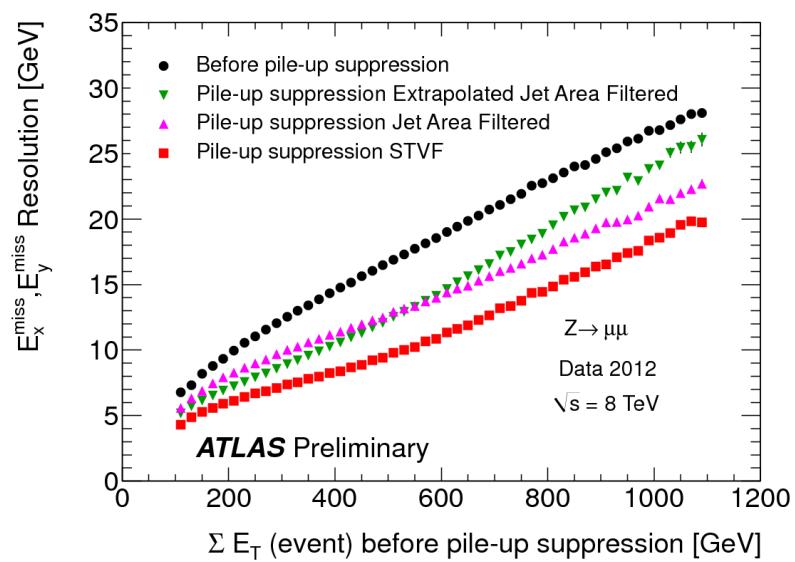


Figure 2.20: Resolution of  $E_T^{\text{miss}}$  components as a function of  $\sum E_T$  before pileup suppression with different pileup techniques [73].

1263

## Part II

1264

Observation and measurement of Higgs

1265

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

1266

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

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

Wernher von Braun

# 3

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

### 1269 3.1 INTRODUCTION

1270 This chapter presents an overview of the strategy for searching for a Higgs boson in the  $H \rightarrow WW^* \rightarrow$   
1271  $\ell\nu\ell\nu$  decay topology. Its purpose is to define in broad terms how the search and measurement are under-  
1272 taken, discussing common aspects of the analysis before going into the details of individual sub-categories.  
1273 First, the properties of the Higgs signal are discussed and the associated backgrounds are presented. Next,  
1274 the observables used to enhance the signal to background ratio are defined. Finally, the parameters of in-  
1275 terest in the search and measurement will be shown, along with a brief overview of the statistical treatment  
1276 of the final Higgs candidates.

1277 Following this chapter, three different results from the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel are shown.  
1278 Chapter 4 presents the discovery and subsequent measurement of Higgs boson production in gluon fusion  
1279 mode and the role of the  $H \rightarrow WW^*$  channel. Chapter 5 shows the search and first evidence in ATLAS  
1280 for the Vector Boson Fusion (VBF) production mode of the Higgs. Finally, chapter 6 shows the combined

1281 Run 1  $H \rightarrow WW^*$  results for the measurement of the Higgs cross section and relative coupling strengths  
1282 to other SM particles.

1283 3.2 THE  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  SIGNAL IN ATLAS

1284 The signal studied in this and subsequent chapters is the Higgs boson in the  $WW^*$  final state, where each  
1285  $W$  boson subsequently decays into a charged lepton and a neutrino. In the simplest decay path, the final  
1286 state consists of two neutrinos and two charged leptons, each of which can be either an electron or a muon.  
1287 If a  $W$  decays to a  $\tau$  lepton, only leptonic decays of the  $\tau$  are considered. The  $\tau$  leptons produce additional  
1288 neutrinos in the final state but still yield two charged leptons (where each lepton is an electron or muon).  
1289 Neutrinos are not detected in ATLAS, so the final state ultimately consists of two reconstructed leptons  
1290 and missing transverse momentum. Final states where both of the charged leptons are electrons or muons  
1291 are referred to as the “same flavor” ( $ee/\mu\mu$ ) final states, while those with one electron and one muon are  
1292 referred to as “different flavor” ( $e\mu$  or  $\mu e$ ).

1293 There can be additional jets produced in association with the Higgs boson. As described in detail in  
1294 Chapter 1, if the Higgs is produced via vector boson fusion production, there will be two additional forward  
1295 jets in the event. In gluon fusion, one or more jets can be produced through initial state radiation from  
1296 the incoming gluons. Because of the varying background composition as a function of jet multiplicity,  
1297 each bin in this variable has its own dedicated requirements applied in the search and measurement. The  
1298  $n_j = 0$  and  $n_j = 1$  bins are dedicated to gluon fusion production, while the  $n_j \geq 2$  bin has separate  
1299 dedicated searches for ggF and VBF production.

1300 Figure 3.1 shows the relative branching fractions for the  $H \rightarrow WW^*$  process, calculated from the Par-  
1301 ticle Data Group values for the  $W$  and  $\tau$  branching ratios [6]. The largest branching ratio corresponds  
1302 to both  $W$  bosons decaying to quark pairs at 45.44%. The second largest ratio is for one  $W$  decaying lep-  
1303 tonically and the other decaying to quarks, a branching ratio of 34.18%. In all cases,  $\ell$  denotes either an  
1304 electron or muon, and the leptonic branching ratios of the  $\tau$  are included. For example, the  $\ell\nu qq$  final  
1305 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  
1306 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  $\tau$ .

1307 branching ratio of the  $\ell\nu\ell\nu$  final state is 6.43%.

1308 While the  $\ell\nu\ell\nu$  final state is not a large fraction of the branching ratio, there are significant advantages  
1309 to using this channel in an analysis. First, both the  $qqqq$  and  $\ell\nu qq$  channels suffer from a large QCD  
1310 multijet background, which is often difficult to model. Second, events in the the  $\ell\nu\ell\nu$  channel in data can  
1311 be triggered more efficiently due to the presence of two leptons.

1312 Figure 3.2 delineates the different signal regions used in the gluon fusion and vector boson fusion anal-  
1313 yses of  $H \rightarrow WW^*$ . Signal regions are defined using jet multiplicity and the flavor combination of the  
1314 final state leptons.

### 1315 3.3 BACKGROUND PROCESSES

1316 Many processes from the Standard Model can also produce a final state with two leptons and missing  
1317 transverse momentum. This section describes the dominant backgrounds to Higgs production and further  
1318 explains how they can be reduced. Table 3.1 summarizes the different background processes.

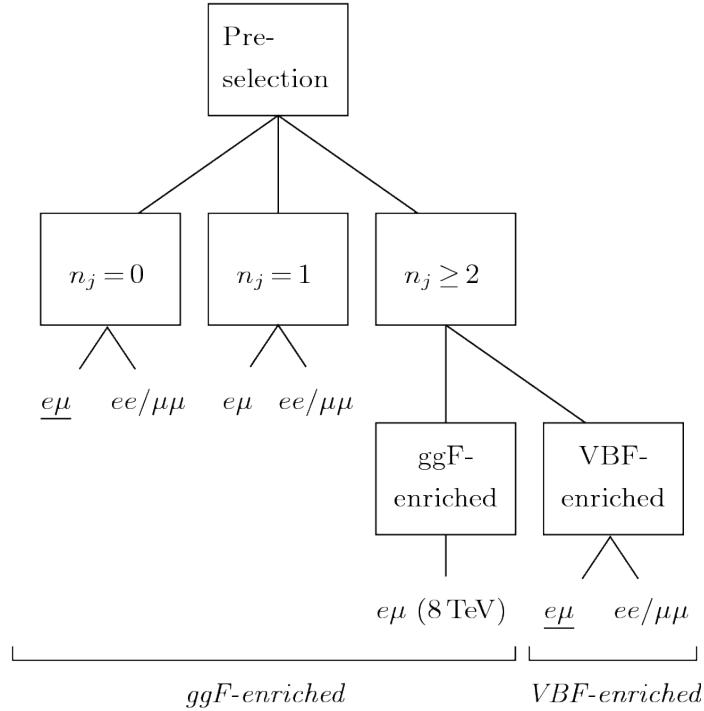


Figure 3.2: An illustration of the unique analysis signal regions [74]. The most sensitive regions for both gluon fusion and vector boson fusion production are underlined.

1319 3.3.1 STANDARD MODEL WW PRODUCTION

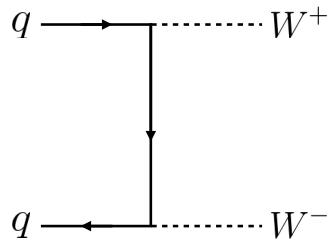


Figure 3.3: Feynman diagram for Standard Model WW production

1320 Non-resonant Standard Model diboson production, as shown in figure 3.3, is an irreducible background  
1321 to Higgs boson production in the WW final state. It produces the same exact final state objects, namely  
1322 leptonically decaying W bosons. There are no additional objects in the final state that allow for back-  
1323 ground reduction. Therefore the analysis solely relies on the correlations between the leptons to reduce  
1324 this background.

1325    3.3.2    TOP QUARK PRODUCTION

1326    Top quark production can mimic the Higgs in the  $WW^*$  final state as well. Top quarks can be produced  
1327    either in pairs ( $t\bar{t}$  production) or singly ( $s$ -channel,  $t$ -channel, or associated production  $Wt$ ). The domi-  
1328    nant top background are  $t\bar{t}$  and  $Wt$  production.

1329    Because top quarks decay via  $t \rightarrow Wb$ , top pair production can produce a final state with two  $W$  bosons  
1330    that then decay leptonically. In  $Wt$  production, there are two real  $W$  bosons produced, as with  $t\bar{t}$ . In  
1331    both cases, there is at least one  $b$ -jet in the final state. By vetoing on the presence of  $b$ -jets, these top quark  
1332    backgrounds can be reduced. Figure 3.4 shows the Feynman diagrams for  $t\bar{t}$  and  $Wt$  production.

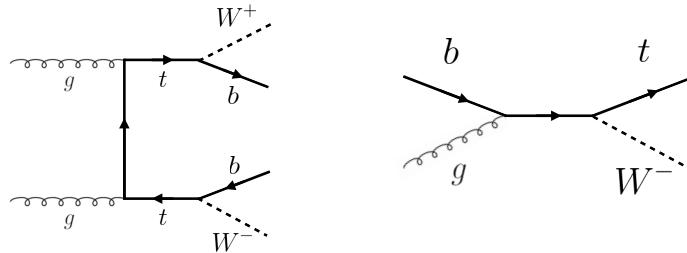


Figure 3.4: Feynman diagrams for top pair production (left) and  $Wt$  production (right)

1333    3.3.3     $W$ +JETS BACKGROUND

1334    Single  $W$  boson production in association with jets is a unique background to Higgs production. The  
1335    other backgrounds considered thus far have all included two prompt leptons, each decaying from a  $W$   
1336    boson, in the final state. In  $W$ +jets production, however, only one reconstructed lepton originates from  
1337    a  $W$ . The second reconstructed lepton is either an algorithmic “fake” or the result of non-prompt decays.  
1338    In the first case, the lepton is a jet misidentified as a lepton by either the electron or muon reconstruction  
1339    algorithms. In the second case, the lepton may be a real lepton but coming from semi-leptonic decays of  
1340    particles inside the shower of the jet. This background can be reduced by requiring that the reconstructed  
1341    lepton have little activity in the surrounding region of the calorimeter (also known as an “isolation”). Fig-  
1342    ure 3.5 shows the Feynman diagram for  $W$ +jets production.

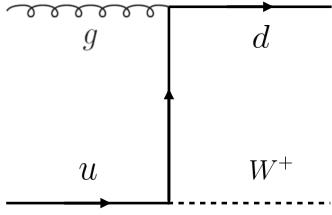


Figure 3.5: An example Feynman diagram of  $W$ +jets production

#### 1343 3.3.4 $Z/\gamma^*$ +JETS BACKGROUND

1344 Production of a  $Z$  boson or virtual photon (also known as Drell-Yan and denoted with  $Z/\gamma^*$ ) in associa-  
1345 tion with jets is also a background to Higgs production. The  $Z$  boson decays to two leptons of the same  
1346 flavor. However, the background is present in both the same flavor and different flavor samples. When the  
1347  $Z/\gamma^*$  decays directly to electrons or muons, the background enters the same flavor final state sample, and  
1348 when it decays to two  $\tau$  leptons the background can enter the different flavor sample as well. Figure 3.6  
1349 shows the production of a  $Z$  in association with one jet. Because there are no neutrinos in this final state,  
1350 variables like  $E_T^{\text{miss}}$  can be used to reduce the background<sup>1</sup>.

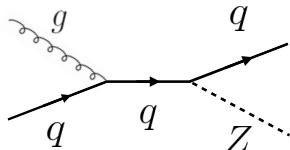


Figure 3.6: An example Feynman diagram of  $Z$ +jets production

#### 1351 3.3.5 SUBDOMINANT BACKGROUNDS

1352 There are additional processes which contribute to the background composition. These backgrounds are  
1353 subdominant and contribute less to the total background estimate than those discussed previously. The

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<sup>1</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.

1354 first process is referred to as  $VV$  or “Other diboson” processes and includes multiple Standard Model  
 1355 diboson processes, including  $WZ$ ,  $ZZ$ ,  $W\gamma$ ,  $W\gamma^*$ , and  $Z\gamma$  production. Additionally, there is a back-  
 1356 ground contribution from QCD multijet production. While the cross section for this process is large, its  
 1357 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	$t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu b\ell\nu\bar{b}$	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” $E_T^{\text{miss}}$
	$Z/\gamma^* \rightarrow \tau\tau \rightarrow \ell\nu\nu\ell\nu\nu$	Real leptons and neutrinos
Other dibosons	$ZZ \rightarrow \ell\ell\nu\nu$	Real leptons and neutrinos
	$W\gamma^*, WZ \rightarrow \ell\nu\ell\ell, ZZ \rightarrow \ell\ell\ell\ell$	Unreconstructed leptons
	$W\gamma, Z\gamma$	$\gamma$ 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

### 1358 3.4 SHARED SIGNAL REGION SELECTION REQUIREMENTS

1359 As presented in section 3.2, there are many different combinations of physics objects that can define a  
 1360  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  final state. The multiplicity of jets and the flavor combinations of the leptons  
 1361 both lead to many potential signal regions. Additionally, signal regions can be optimized separately to be  
 1362 sensitive to the distinct production modes of the Higgs. Gluon fusion, vector boson fusion, and associated  
 1363 production of a Higgs all lead to unique final state topologies. While there are different optimizations  
 1364 possible in each signal region, there are also some commonly shared selections that will be described here.

#### 1365 3.4.1 EVENT PRE-SELECTION

1366 Before being sorted into the distinct signal regions, basic requirements are applied to the reconstructed  
 1367 objects in the event to select Higgs-like event candidates. First, two oppositely charged leptons are required.  
 1368 Once the leptons are selected, the last requirement for event pre-selection is the presence of neutrinos.  
 1369  $E_T^{\text{miss}}$  is used as a proxy for the combined neutrino momentum in the transverse plane.

1370 In general, the signal tends to have higher values of  $E_T^{\text{miss}}$  than backgrounds, especially if these back-  
 1371 grounds do not contain neutrinos in the final state. It is possible mis-measurements of objects in the detec-  
 1372 tor can lead to imbalances in the transverse plane. When such a mis-measurement occurs, the  $E_T^{\text{miss}}$  vector  
 1373 in the transverse plane will often point in the same direction as the mis-measured object. Therefore, a new  
 1374 variable,  $E_{T,\text{rel}}^{\text{miss}}$ , is used in the pre-selection.  $E_{T,\text{rel}}^{\text{miss}}$  is defined in equation 3.1.

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

1375 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  
 1376 away from this object. Otherwise, the normal  $E_T^{\text{miss}}$  vector is used. Figure 3.7 shows a graphical illustration  
 1377 of this concept.

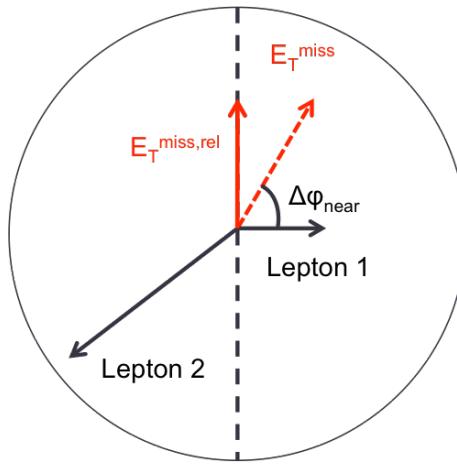


Figure 3.7: A graphical illustration of the  $E_{T,\text{rel}}^{\text{miss}}$  calculation.

1378 Once the lepton and  $E_T^{\text{miss}}$  pre-selections are made, the analysis is divided into different regions accord-  
 1379 ing to jet multiplicity.

#### 1380 3.4.2 JET MULTIPLICITY

1381 Jet multiplicity, denoted as  $n_j$ , is used to sub-divide the analysis into distinct signal regions. By creating  
 1382 separate signal regions, each bin in jet multiplicity becomes sensitive to different modes of Higgs produc-  
 1383 tion and different backgrounds. For example, the  $n_j \geq 2$  region is more sensitive to VBF production

1384 because of the two high momentum jets produced at matrix element level. For gluon fusion production  
1385 to enter this bin, two initial state radiation jets must be emitted.

1386 Figure 3.8 shows the jet multiplicity in both the different flavor and same flavor regions after the pre-  
1387 selection. It also shows the background composition in the bins of the number of  $b$ -tagged jets,  $n_b$ . A  
1388 few trends from this distribution are worth noting. The first is that the Drell-Yan background dominates  
1389 in the same flavor channels for  $n_j \leq 1$ . Second, the top background becomes a clear contributor to the  
1390 total background for  $n_j \geq 1$ . Lastly, the SM WW production dominates in the  $n_j = 0$  bin, as it is an  
1391 irreducible background to  $H \rightarrow WW^*$  production. Because of these distinct features, each jet multiplicity  
1392 bin is treated separately.

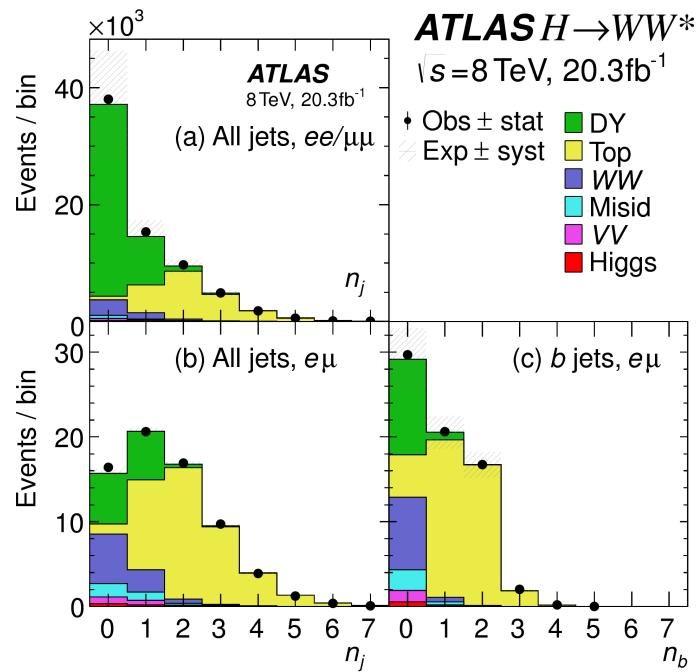


Figure 3.8: Predicted backgrounds (compared with data) as a function of the number of jets,  $n_j$  (a and b), and the number of  $b$ -tagged jets,  $n_b$  (c), after pre-selection requirements. Panel a shows  $n_j$  in the same flavor sample, while panels b and c show the  $n_j$  and  $n_b$  distributions in the different flavor sample.

1393 3.5 BACKGROUND REDUCTION IN SAME-FLAVOR FINAL STATES

1394 As described in section 3.4.2, the background composition of the same flavor final states is different from  
1395 that of the different flavor states. In particular, Drell Yan processes play a much larger role because the

1396  $Z/\gamma^*$  decays to same flavor leptons. Because real neutrinos are absent in the  $Z/\gamma^*$  decays to  $ee$  and  $\mu\mu$ , a  
1397 requirement on  $E_T^{\text{miss}}$  should largely reduce the background. However, as this section will demonstrate,  
1398 with increasing pileup conditions the resolution of the calorimeter-based  $E_T^{\text{miss}}$  degrades greatly. There-  
1399 fore, two new variables for  $Z/\gamma^*$  background reduction are constructed and described in this section.

1400 **3.5.1 PILEUP AND  $E_T^{\text{miss}}$  RESOLUTION**

1401 Secondary interactions of protons in the colliding bunches of the LHC (known as pileup interactions,  
1402 described in detail in Chapter 2) deposit energy into the ATLAS calorimeter in addition to the energy that  
1403 comes from the hard scatter process of interest. The calculation of  $E_T^{\text{miss}}$  is fundamentally like a Poisson  
1404 process - summing up all of the energy deposits in individual calorimeter cells or clusters is similar to a  
1405 counting experiment. The error on a mean of  $N$  in a Poisson distribution is  $\sqrt{N}$ , so the energy resolution  
1406 scales as  $\sqrt{E}$ . As more energy is deposited in the calorimeter, the  $E_T^{\text{miss}}$  resolution degrades, meaning that  
1407 the  $E_T^{\text{miss}}$  resolution is particularly sensitive to LHC instantaneous luminosity conditions.

1408 Figure 3.9 shows an event display of a  $Z/\gamma^* + \text{jets}$  event candidate with the twenty-five reconstructed  
1409 primary vertices. This display illustrates that while the interaction of interest only has tracks coming from  
1410 the hardest primary vertex, all of the secondary interactions deposit energy in the calorimeter as well.

1411 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-  
1412 trinos) as a function of the number of the average number of interactions. Under 2011 LHC conditions,  
1413 this RMS was approximately 9 GeV, while under 2012 running conditions the resolution worsened to 12  
1414 GeV. The increase in pileup dilutes the ability of the  $E_T^{\text{miss}}$  variable to reduce the  $Z/\gamma^*$  background.

1415 **3.5.2 TRACK-BASED DEFINITIONS OF MISSING TRANSVERSE MOMENTUM**

1416 Because the increasing number of secondary proton-proton interactions degrades calorimeter-based  $E_T^{\text{miss}}$   
1417 resolution, a new variable using only contributions from the primary interaction vertex is necessary to  
1418 further reduce the  $Z/\gamma^*$  background. While it is not possible to associate calorimeter energy deposits  
1419 with a particular vertex, individual charged particle tracks in the Inner Detector are associated to unique  
1420 vertices. Thus, two track-based definitions of missing transverse momentum, using only tracks coming

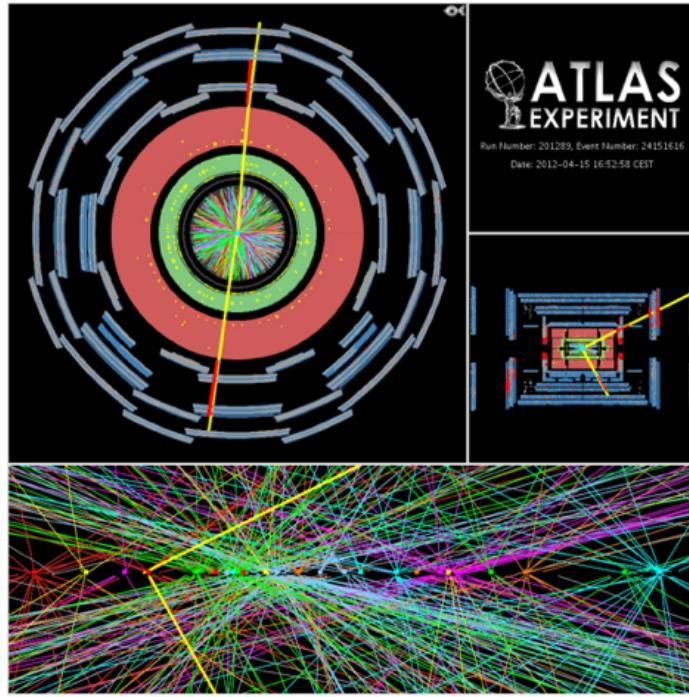


Figure 3.9: An event display of a  $Z/\gamma^* + \text{jets}$  event illustrating the effect of pileup interactions

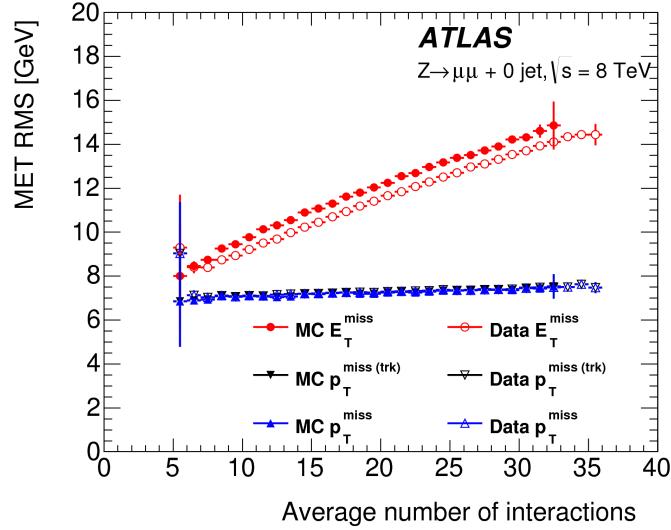


Figure 3.10: The RMS of different missing transverse momentum definitions as a function of the average number of interactions per bunch crossing

from the primary vertex in the event, are used in the analysis. These variables are not intended to substitute  $E_T^{\text{miss}}$ , as they only account for charged particles and do not measure neutrals. However, the track-based variables serve as a confirmation that any measured momentum imbalance is coming from real particles

<sup>1424</sup> and not detector effects. The simplest variable,  $p_T^{\text{miss}(\text{trk})}$ , is the vectorial sum of the  $p_T$  of all of the tracks  
<sup>1425</sup> from the primary vertex and the selected leptons (excluding the tracks associated with the selected leptons  
<sup>1426</sup> to avoid double counting). Equation 3.2 defines  $p_T^{\text{miss}(\text{trk})}$ .

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

<sup>1427</sup> To further improve the resolution on the missing transverse momentum, the variable  $p_T^{\text{miss}}$  is used as de-  
<sup>1428</sup> fined in equation 3.3. For selected leptons and jets, the nominal  $p_T$  measurements are used, as the calorime-  
<sup>1429</sup> ter information improves the  $p_T$  resolution of the objects by taking into account the presence of neutral  
<sup>1430</sup> particles in showers. The soft component of the missing transverse momentum, which is more suscep-  
<sup>1431</sup> tible to spurious contributions from pileup interactions, is estimated using tracks instead of calorimeter  
<sup>1432</sup> measurements.

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

<sup>1433</sup> Figure 3.10 illustrates that these two new variables accomplish their intended purpose. The resolution as a  
<sup>1434</sup> 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  
 for  $E_T^{\text{miss}}$ . Figure 3.11 shows the difference between the true and reconstructed values of missing transverse

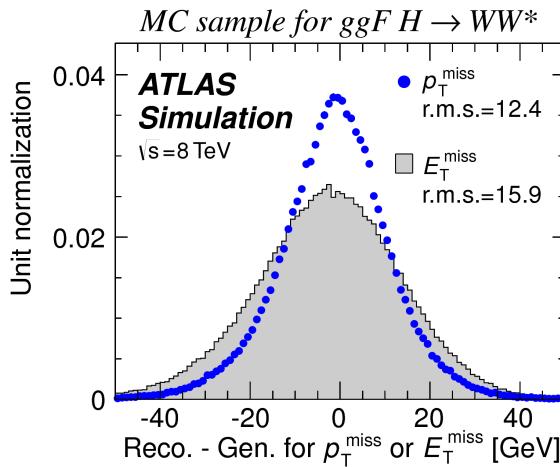


Figure 3.11: The difference between the true and reconstructed values of the missing transverse momentum in a gluon fusion signal sample using both track-based ( $p_T^{\text{miss}}$ ) and calorimeter-based  $E_T^{\text{miss}}$  definitions.

<sup>1435</sup>

<sup>1436</sup> momentum using both the track-based  $p_T^{\text{miss}}$  and calorimeter based  $E_T^{\text{miss}}$ . The RMS of the distribution  
<sup>1437</sup> improves by 3.5 GeV when using  $p_T^{\text{miss}}$ .

### <sup>1438</sup> 3.5.3 DISTINGUISHING $Z/\gamma^*$ + JETS AND $H \rightarrow WW^*$ TOPOLOGIES

<sup>1439</sup> In addition to measuring missing transverse momentum, another variable can be constructed to exploit  
<sup>1440</sup> kinematic and topological differences between the  $Z/\gamma^*$  background and  $H \rightarrow WW^*$  signal. Because  
<sup>1441</sup> there are no real neutrinos in the final state (in the case of  $Z/\gamma^* \rightarrow ee, \mu\mu$  decays), the dilepton system  
<sup>1442</sup> will be balanced with the jets produced in the hard scatter. A new variable,  $f_{\text{recoil}}$ , is constructed to es-  
<sup>1443</sup> timate the balance between the dilepton system and recoiling jets and is defined in equation 3.4. The  
<sup>1444</sup> transverse plane is divided into four sections, or quadrants, with one quadrant centered on the dilepton  
<sup>1445</sup> vector. The numerator of  $f_{\text{recoil}}$  is the magnitude of the vectorial sum of the  $p_T$  of jets in the quadrant  
<sup>1446</sup> opposite the dilepton system, weighted the Jet Vertex Fraction (JVF, described in chapter 2) of each jet.  
<sup>1447</sup> The denominator is the magnitude of the dilepton  $p_T$ .

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

<sup>1448</sup> Figure 3.12 shows a shape comparison of the  $f_{\text{recoil}}$  distribution in a simulated  $Z/\gamma^*$  + jets sample, a  
<sup>1449</sup>  $H \rightarrow WW^*$  signal sample, and other backgrounds that contain real neutrinos. The  $Z/\gamma^*$  + jets events  
<sup>1450</sup> tend to be more balanced between the dilepton system and recoiling jets, while the processes containing  
<sup>1451</sup> real neutrinos are less balanced in the transverse plane. Thus, a requirement on  $f_{\text{recoil}}$  will reduce the  $Z/\gamma^*$   
<sup>1452</sup> + jets background while maintaining a good signal efficiency.

### <sup>1453</sup> 3.5.4 OPTIMIZING BACKGROUND REDUCTION SELECTION REQUIREMENTS

<sup>1454</sup> The requirements on  $p_T^{\text{miss}(\text{trk})}$  and  $f_{\text{recoil}}$  used to reduce the Z+jets background must be optimized to  
<sup>1455</sup> maximize expected signal significance in the same flavor channels. Figure 3.13 shows an optimization of the  
<sup>1456</sup> combination of the two requirements in the gluon fusion zero jet bin. Each bin shows the expected signal  
<sup>1457</sup> significance if the  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  (the track-based version of  $E_{T,\text{rel}}^{\text{miss}}$ ) is required to be greater than the left edge  
<sup>1458</sup> of the bin and the  $f_{\text{recoil}}$  is required to be less than the top edge of the bin. The figure shows that the best

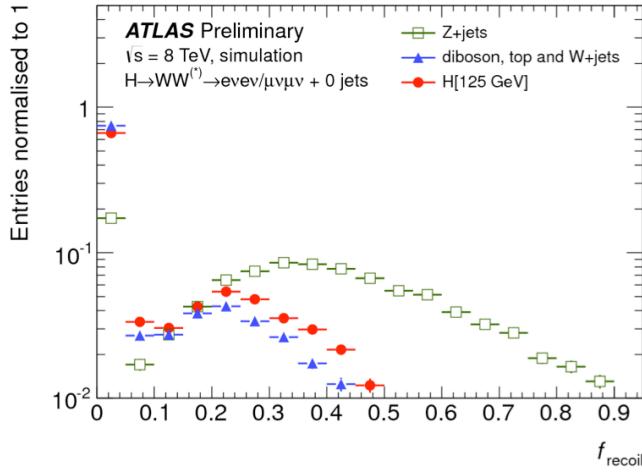


Figure 3.12: Comparison of  $f_{\text{recoil}}$  distributions for  $Z/\gamma^* + \text{jets}$ ,  $H \rightarrow WW^*$ , and other backgrounds with real neutrinos.

1459 signal significance comes from requiring low values of  $f_{\text{recoil}} (< 0.05)$  and  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  values greater than  
 1460 45 GeV.

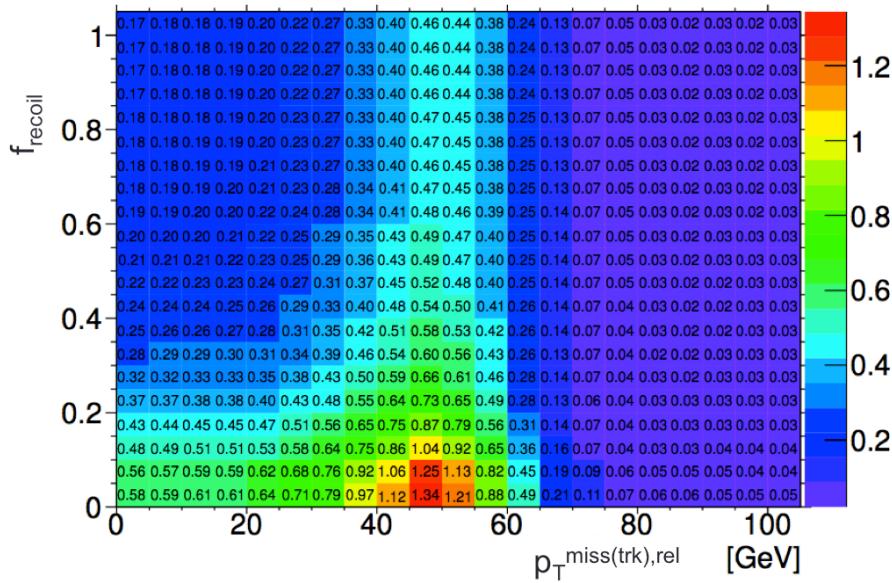


Figure 3.13: Signal significance as a function of required value for  $f_{\text{recoil}}$  and  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  in the ggF  $H \rightarrow WW^*$  with  $n_j = 0$

1461 3.6 PARAMETERS OF INTEREST AND STATISTICAL TREATMENT

1462 As with any search or measurement, there are particular parameters of the Higgs that the  $H \rightarrow WW^*$   
1463 analysis is interested in measuring. In this case, the parameters of interest are the mass of the Higgs boson  
1464 and its production cross section. In the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  final state, it is not possible to measure  
1465 the full invariant mass of the Higgs due to the presence of neutrinos. However, a proxy for the invariant  
1466 mass is defined using transverse plane information and detailed in section 3.6.1. The second parameter of  
1467 interest is the cross section  $\sigma$ , which in this analysis is measured relative to the theoretical prediction for a  
1468 Standard Model Higgs. This ratio,  $\mu$ , is defined in equation 3.5.

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

1469 All of the likelihoods used in the statistical analysis of the final signal region events are parameterized as a  
1470 function of  $\mu$ .  $\mu$  is a natural variable for hypothesis testing, as  $\mu = 0$  corresponds to a background only  
1471 hypothesis and  $\mu = 1$  corresponds exactly to a Standard Model Higgs.

1472 3.6.1 TRANSVERSE MASS

1473 The  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis cannot reconstruct the full invariant mass of the Higgs because of the  
1474 neutrinos in the final state. The transverse mass serves as a proxy for the full invariant mass by exploiting  
1475 information from the transverse plane. The transverse mass is defined in equation 3.6.

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

1476 Here the  $E_T^{\ell\ell}$  and  $p_T^{\ell\ell}$  are the transverse energy and momentum of the dilepton system, while  $p_T^{\text{miss}}$  is a  
1477 proxy for the transverse momentum of the di-neutrino system. The track-based  $p_T^{\text{miss}}$  is used in the  $m_T$   
1478 rather than the calorimeter based  $E_T^{\text{miss}}$  because it has a better resolution on the true transverse mass. Fig-  
1479 ure 3.14 shows the improvement in the RMS of the difference between the true and reconstructed trans-  
1480 verse mass in a ggF signal sample. The RMS improves by 4.7 GeV using  $p_T^{\text{miss}}$  in the  $m_T$  calculation.

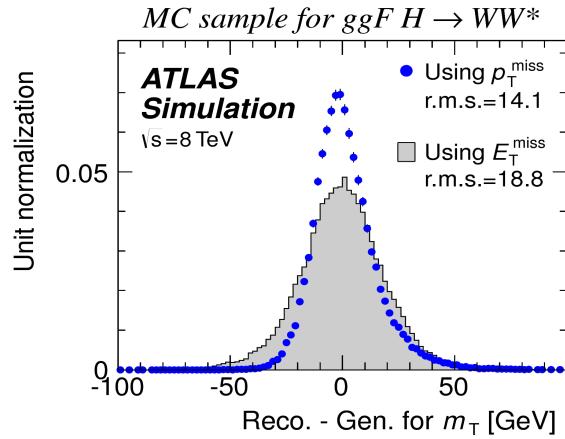


Figure 3.14: The difference between the true and reconstructed values of  $m_T$  in a gluon fusion signal sample using both track-based ( $p_T^{\text{miss}}$ ) and calorimeter-based  $E_T^{\text{miss}}$  definitions.

1481    3.6.2 STATISTICAL TREATMENT

1482    LIKELIHOOD FUNCTION

1483    The statistical analysis<sup>2</sup> of final event candidates is framed as a hypothesis test, where the null hypothesis is  
 1484    background-only (no Standard Model Higgs). The first step in the analysis is to form a likelihood function  
 1485    for the data. In its simplest form, this likelihood is the probability of observing the number of events seen  
 1486    in the final signal region given knowledge of the signal strength. Because observation of events is funda-  
 1487    mentally a Poisson counting experiment, this simple likelihood can be expressed as a Poisson probability of  
 1488    observing  $N$  events given a total number of predicted signal and background events. This basic likelihood  
 1489    is shown in equation 3.7.

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

1490    Here,  $P$  is the Poisson probability density function,  $N$  is the total number of observed events,  $\mu$  is the  
 1491    signal strength,  $S$  is the predicted number of signal events, and  $B$  is the predicted number of background  
 1492    events.

1493    Generally, in searches, certain background estimates are commonly normalized in so-called “control” re-  
 1494    gions and those predictions are scaled by the same normalization factor in the signal region. This method

---

<sup>2</sup>Many thanks to Aaron Armbruster, whose thesis [75] inspired parts of this section.

1495 allows for more precise background estimation by using data as a constraint, reducing the impact of theoretical  
1496 uncertainties on the background model. This leads to a slightly more complicated likelihood, which  
1497 is a function of both the signal strength and the background normalization. This is shown in equation 3.8.

1498

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

1499 Here,  $\theta$  serves as a “nuisance parameter”, or a parameter that is not of primary interest but still enters the  
1500 likelihood. The second Poisson term enforces that the background normalization be consistent with the  
1501 number of observed events in data in the control region,  $N_{\text{CR}}$ .

1502 So far, these two formulations of likelihoods have assumed a single signal region and do not take into  
1503 account any shape information of potential discriminating variables. The  $H \rightarrow WW^*$  analysis is divided  
1504 into many different categories, and the counting experiment described above can be performed in each  
1505 individual category. As mentioned in section 3.6.1, the transverse mass is used as the primary discriminating  
1506 variable in many of the  $H \rightarrow WW^*$  signal regions. The same counting experiment can be performed  
1507 in each bin of the  $m_T$  distribution to incorporate some shape information. Thus, the total likelihood  
1508 becomes a product over signal regions and bins of the  $m_T$  distribution. Finally, there are usually many  
1509 background sources that are normalized in control regions. The new formulation of the likelihood takes  
1510 this into account by including a product over control regions in the second Poisson term. All of these  
1511 modifications are shown in equation 3.9.

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

1512 Here, the variable  $i$  counts over the different signal regions,  $b$  counts over bins of  $m_T$ ,  $k$  counts over the  
1513 backgrounds, and  $l$  counts over the control regions.

1514 The final step to obtain the full likelihood used in the analysis is to add nuisance parameters for the  
1515 systematic uncertainties. In cases where the uncertainty does not affect the shape of  $m_T$  bin-by-bin, each  
1516 systematic uncertainty  $\epsilon$  is allowed to affect the expected event yields through a linear response function  
1517 of the nuisance parameter, namely  $\nu(\theta) = (1 + \epsilon)^{\theta}$ . If instead the uncertainty does affect the shape, the

1518 effect is instead parameterized by  $\nu_b(\theta) = 1 + \epsilon_b\theta$ . The value of the nuisance parameters for the systematic  
 1519 uncertainty are constrained with a Gaussian term that is added to the likelihood as well. This is of the form  
 1520  $g(\delta|\theta) = e^{-(\delta-\theta)^2/2}/\sqrt{2\pi}$ , where  $\delta$  is the central value and  $\theta$  is a nuisance parameter. Finally, a last term is  
 1521 added to account for the statistical uncertainty in the Monte Carlo samples used, which adds an additional  
 1522 poisson term. The full likelihood used in the final statistical analysis is defined in equation 3.10.

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

1523 Here,  $\boldsymbol{\theta}$  represents the full vector of nuisance parameters,  $r$  is an index for signal systematics,  $s$  is an index  
 1524 for background systematics, and  $t$  is an index for Monte Carlo samples. The fourth term of the equation  
 1525 quantifies the uncertainty due to finite Monte Carlo sample size. Here,  $\xi$  represents the central value of the  
 1526 background prediction,  $\theta$  is the associated nuisance parameter,  $\zeta = (B/\delta B)^2$ , where  $\delta B$  is the statistical  
 1527 uncertainty of  $B$ .

1528 The best fit value of the signal strength  $\mu$  is determined by finding the values of  $\mu$  and  $\boldsymbol{\theta}$  that maximize  
 1529 the likelihood, while setting  $\delta = 0$  and  $\xi = \zeta$ . Once the likelihood is defined, a test statistic must be built  
 1530 for use in hypothesis testing.

### 1531 TEST STATISTIC

1532 To distinguish whether the data match a background only or background and signal hypothesis, a test  
 1533 statistic must be used. The  $H \rightarrow WW^*$  analysis uses the profile likelihood technique [76]. The first step

1534 in formulating this test statistic is to define the profile likelihood ratio, shown in equation 3.11.

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

1535 Here  $\hat{\theta}_\mu$  is the value of  $\theta$  that maximizes the likelihood for the choice of  $\mu$  being tested. Additionally,  $\hat{\theta}$

1536 and  $\hat{\mu}$  represent the values of  $\theta$  and  $\mu$  that gives the overall maximum value of the likelihood.

1537 Once this is defined, a test statistic  $q_\mu$  is constructed. This is shown in equation 3.12.

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

1538 A higher value of  $q_\mu$  indicates that the data are more incompatible with the hypothesized value of  $\mu$ , and

1539  $q_0$  then corresponds to the value of the test statistic for the background only hypothesis. A  $p_0$  value is

1540 then defined to quantify the compatibility between the data and the null hypothesis. The  $p_0$  value is the

1541 probability of obtaining a value of  $q_0$  larger than the observed value, and this is shown in equation 3.13.

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

1542 Here  $f(q_\mu)$  is the probability distribution function of the test statistic. Finally, the  $p_0$  value can be con-

1543 verted into a signal significance, using the formula in equation 3.14, or the one-sided tail of the Gaussian

1544 distribution.

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

1545 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

1546

## 1547 The discovery of the Higgs boson and the role 1548 of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel

### 1549 4.1 INTRODUCTION

1550 This chapter presents the results of the search for the Higgs boson in  $4.8 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 7 \text{ TeV}$   
1551 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  $H \rightarrow WW^* \rightarrow$   
1552  $\ell\nu\ell\nu$ ,  $H \rightarrow \gamma\gamma$ , and  $H \rightarrow ZZ \rightarrow 4\ell$  channels are shown. These results at  $8 \text{ TeV}$  are combined  
1553 with the results of searches at  $\sqrt{s} = 7 \text{ TeV}$  in the same channels along with  $H \rightarrow \tau\tau$  production and  
1554 associated production searches for  $H \rightarrow b\bar{b}$ . The results of this combination are a  $5.9\sigma$  detection of a  
1555 new particle consistent with a Higgs boson produced via gluon fusion. Rather than going into detail for  
1556 all of the different Higgs decay searches, this chapter will discuss the three most sensitive channels and in  
1557 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

1558 are shown for completeness. The results not discussed here can be found in the ATLAS Higgs discovery  
1559 publication [1].

1560 **4.2 DATA AND SIMULATION SAMPLES**

1561 The data sample used for the following results was taken in 2011 and 2012 at center of mass energies of 7 and  
1562 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  
1563 in the gluon fusion and vector boson fusion modes is modeled with POWHEG for the hard scattering event  
1564 and PYTHIA for the showering and hadronization. Associated production of a Higgs with a vector boson  
1565 or top quarks is modeled via PYTHIA . Table 4.1 shows the Monte Carlo generators used for modeling the  
1566 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].

1567 **4.3  $H \rightarrow WW \rightarrow e\nu\mu\nu$  SEARCH**

1568 The  $H \rightarrow WW \rightarrow e\nu\mu\nu$  search is unique compared to the  $ZZ$  and  $\gamma\gamma$  channels. The Higgs mass  
1569 cannot be fully reconstructed due to the presence of neutrinos in the final state, so the transverse mass  $m_T$   
1570 is used as the final discriminating variable. This channel also has a wider variety of backgrounds compared  
1571 to other channels, as discussed in chapter 3. The same flavor final states are excluded from the 8 TeV dataset

1572 due to high pileup conditions<sup>1</sup>. These final states are later included in results with the full Run 1 dataset,  
1573 as discussed in chapters 5 and 6.

1574 **4.3.1 EVENT SELECTION**

1575 The analysis requires to opposite charge isolated leptons, with the leading (sub-leading) lepton required to  
1576 have  $p_T > 25(15)$  GeV. The events are separated into different signal regions depending on which flavor  
1577 of lepton is leading ( $e\mu$  for leading electron,  $\mu e$  for leading muon). Strict lepton quality cuts are applied  
1578 to the sample to reduce backgrounds from mis-reconstructed leptons.

1579 Jets are reconstructed with the anti- $k_T$  algorithm with a radius parameter  $R = 0.4$ . The jets are re-  
1580 quired to have  $p_T > 25$  GeV and  $|\eta| < 4.5$ , with jets in the tracking volume required to have a jet vertex  
1581 fraction of 0.5 and jets in the forward region required to have  $p_T > 30$  GeV. The analysis is separated  
1582 into three different signal regions based on jet multiplicity:  $n_j = 0, 1, \geq 2$ .

1583 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  
1584 requirement significantly reduces the QCD multijet and  $Z/\gamma^*$  + jets backgrounds. Figure 4.1 shows the  
1585 distribution of  $n_j$  in data and simulation after applying these “pre-selection” requirements.

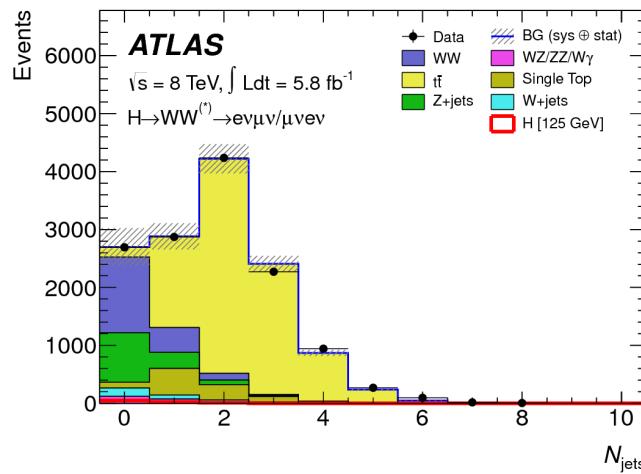


Figure 4.1: Jet multiplicity distribution in data and MC after applying lepton, jet, and  $E_{T,\text{rel}}^{\text{miss}}$  selections. The  $WW$  and top backgrounds have been normalized using control samples, and the hashed band indicates the total uncertainty on the prediction [1].

<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.

1586        Additional selections are applied to require the dilepton topology to correspond to that of a Standard  
1587        Model Higgs boson. The requirements are presented here - more detailed discussion on the motivation  
1588        for each requirement is saved for Chapter 5. In all of the jet multiplicity channels, the dilepton system  
1589        is required to have a small gap in azimuthal angle,  $\Delta\phi_{\ell\ell} < 1.8$ . Similarly, the dilepton invariant mass,  
1590         $m_{\ell\ell}$ , is required to be less than 50 GeV in the lower jet multiplicity channels and less than 80 GeV in the  
1591         $n_j \geq 2$  channel. In the  $n_j = 0$  channel, the magnitude of the dilepton  $p_T$ ,  $p_T^{\ell\ell}$ , is required to be greater  
1592        than 30 GeV.

1593        In the higher jet multiplicity channels ( $n_j \geq 1$ ), the top background is a larger fraction of the total  
1594        background and must be reduced more carefully. The total transverse momentum  $p_T^{\text{sum}}$  is thus required  
1595        to be less than 30 GeV. Additionally, the di- $\tau$  invariant mass  $m_{\tau\tau}$  (dilepton mass computed under the  
1596        assumption that the neutrinos from the  $\tau$  decay are emitted collinear to the charged leptons [77]) is used  
1597        to reject  $Z \rightarrow \tau\tau$  events by requiring  $|m_{\tau\tau} - m_Z| > 25$  GeV. These variables are also discussed in more  
1598        detail in Chapter 5.

1599        In the  $n_j \geq 2$  channel, requirements are made to isolate the VBF contribution to Higgs production.  
1600        The kinematics of the two leading jets are used to make these requirements. In particular, the event must  
1601        have  $\Delta y_{jj} > 3.8$  and  $m_{jj} > 500$  GeV, along with a veto on having any additional jets with rapidity  
1602        between the two leading jets.

#### 1603        4.3.2 BACKGROUND ESTIMATION

1604        The details of the background estimation techniques used in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis are  
1605        discussed in section 5.5. The dominant backgrounds are SM  $WW$  production and top (both pair and  
1606        single) production, and these backgrounds have their normalizations estimated from dedicated control  
1607        regions while their shapes are taken from simulation.

1608        The control sample for the Standard Model  $WW$  background is defined by making the same require-  
1609        ments as the signal region with the  $m_{\ell\ell}$  requirement inverted (now requiring  $m_{\ell\ell} > 80$  GeV) and remov-  
1610        ing the  $\Delta\phi_{\ell\ell}$  requirement. This creates a control sample that is 70% (40%) pure in the 0(1)-jet region. The  
1611        correction to the pure MC-based background estimate is quantified by defining a normalization factor  $\beta$

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 the  $WW$  normalization factors in the  $n_j = 0$  and  $n_j = 1$  bins (the  $n_j \geq 2$  estimate is taken directly 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.

The top background estimate is also computed separately in each jet multiplicity bin. In the  $n_j = 0$  channel, the background is first normalized using data after pre-selection requirements with no selection on  $n_j$ . Then, a dedicated  $b$ -tagged control sample is used to evaluate the ratio of one-jet to two-jet events in data. The details of this technique are shown in reference [78]. In the  $n_j = 1$  and the  $n_j \geq 2$  regions, the top background is normalized in a control sample where the signal region selections are applied, but the  $b$ -jet veto is reversed and the Higgs topology requirements on  $m_{\ell\ell}$  and  $\Delta\phi_{\ell\ell}$  are removed. The resulting normalization factors for these techniques are shown in table 4.2.

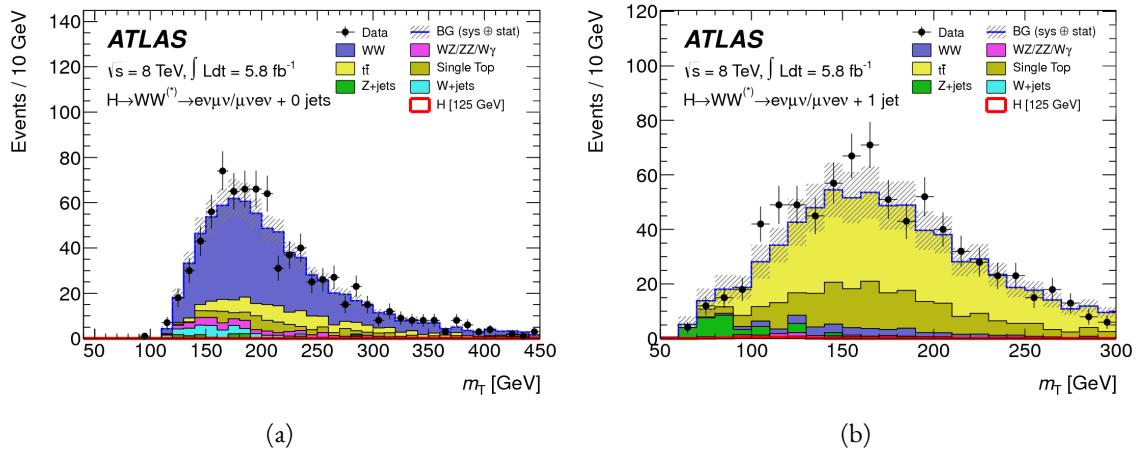


Figure 4.2: Comparison of  $m_T$  between data and simulation in the  $n_j = 0$   $WW$  (a) and  $n_j = 1$  top (b) control samples [1].

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

1624 for the  $m_T$  distribution after correcting the normalization of the backgrounds in the  $WW$  and top control  
1625 regions. Good agreement between data and simulation is seen in both cases.

1626 The  $W + \text{jets}$  background estimate is taken entirely from data using a control sample with one well recon-  
1627 structed lepton and one anti-identified lepton. All other backgrounds are taken purely from simulation.

#### 1628 4.3.3 SYSTEMATIC UNCERTAINTIES

1629 The systematic uncertainties that have the largest impact on the analysis are the theoretical uncertainties  
1630 associated with the signal cross section. These are shared with the  $ZZ^*$  and  $\gamma\gamma$  channels. The uncertainties  
1631 resulting from variations of the QCD scale are  $+7\% / -8\%$  on the final signal yield. Those coming from  
1632 variations of the parton distribution function (PDF) used in the simulation add a  $\pm 8\%$  uncertainty on  
1633 the yield. The uncertainties on the branching ratios of the Higgs are  $\pm 5\%$ .

1634 The main experimental uncertainties come from variations of the jet energy scale (JES), jet energy reso-  
1635 lution, pile-up,  $E_T^{\text{miss}}$ ,  $b$ -tagging efficiency,  $W + \text{jets}$  background estimate, and integrated luminosity. For  
1636 more details, see reference [1].

#### 1637 4.3.4 RESULTS

1638 Table 4.3 shows the signal and background yields in the final signal region after normalizing the back-  
1639 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].

1640      Figure 4.3 shows the  $m_T$  distribution in the  $n_j \leq 1$  channels for 8 TeV data. (No events are observed  
 1641      in data in the  $n_j \geq 2$  channels in this dataset). The excess shown here relatively flat as a function of  
 1642      hypothesized Higgs mass. The combined 7 and 8 TeV data gives an excess with local significance of  $2.8\sigma$   
 1643      with an expected significance of  $2.3\sigma$ , corresponding to a  $\mu$  measurement of  $1.3 \pm 0.5$ .

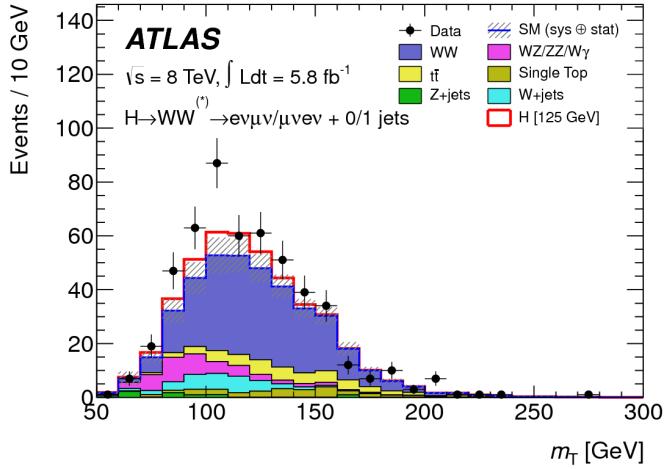


Figure 4.3:  $m_T$  distribution in the  $H \rightarrow WW \rightarrow e\nu\mu\nu$   $n_j \leq 1$  channels for 8 TeV data [1].

#### 1644    4.4    $H \rightarrow \gamma\gamma$ SEARCH

1645    The  $H \rightarrow \gamma\gamma$  search is a search for a peaked excess above the falling SM diphoton mass spectrum, with  
 1646     $m_{\gamma\gamma}$  as the ultimate discriminating variable. Events are selected by requiring two isolated photons, with  
 1647    the leading (sub-leading) photon required to have  $E_T > 40(30)$  GeV. In the 8 TeV data, the photons are  
 1648    required to pass identification criteria consistent with a photonic shower in the electromagnetic calorimeter  
 1649    and little leakage in the hadronic calorimeter.

1650    The main challenges for this analysis are accurate mass reconstruction and background estimation. In  
 1651    order to accurately reconstruct the invariant mass of the di-photon system, both the energy and direction  
 1652    of the photons must be measured well. Therefore, the identification of the primary vertex of the hard  
 1653    interaction is particularly important, and is done using a multivariate likelihood which combines informa-  
 1654    tion about the photon direction and vertex position. The background is modeled with a falling spectrum  
 1655    in  $m_{\gamma\gamma}$  that is parameterized by different functions depending on the category of the event.

1656 4.4.1 RESULTS

1657 The resulting diphoton mass spectrum is shown in figure 4.4. The best fit mass value in the  $\gamma\gamma$  channel  
 1658 alone in the combined 7 and 8 TeV data is 126.5 GeV. The local significance at this point is  $4.5\sigma$ , with  
 1659 an expected significance of  $2.5\sigma$ . Therefore, the measured signal strength  $\mu$  is  $1.8 \pm 0.5$  in this channel.

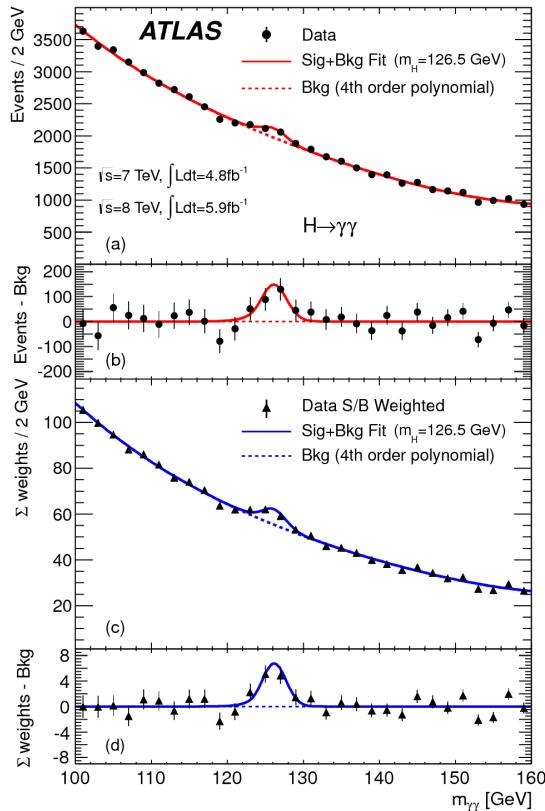


Figure 4.4: Diphoton mass spectrum in 7 and 8 TeV data. Panel a) shows the unweighted data distribution superimposed on the background fit, while panel c) shows the data where each event category is weighted by its signal to background ratio. Panels b) and d) show the respective distributions with background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

1660 4.5  $H \rightarrow ZZ \rightarrow 4\ell$  SEARCH

1661 The  $H \rightarrow ZZ \rightarrow 4\ell$  analysis searches for a Standard Model Higgs boson decaying to two  $Z$  bosons, each  
 1662 of which decays to a pair of same flavor, opposite charge isolated leptons. The ultimate discriminating  
 1663 variable is  $m_{4\ell}$ , or the invariant mass of the four selected leptons. The  $\ell$  denotes an  $e$  or  $\mu$  as with the  
 1664  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis.

1665     Four distinct signal regions are constructed depending on the flavors of the final state, additionally sep-  
 1666     arated by the flavor of the leading lepton pair. These are referred to as  $4e$ ,  $2e2\mu$ ,  $2\mu2e$ ,  $4\mu$ .

1667     The main backgrounds in the  $H \rightarrow ZZ \rightarrow 4\ell$  search are continuum  $ZZ^*$  production,  $Z + \text{jets}$  pro-  
 1668     duction, and  $t\bar{t}$ . The  $m_{4\ell}$  distribution for background is estimated from simulation. The normalization  
 1669     of the SM  $ZZ^*$  background is also taken from MC simulation, while the  $Z + \text{jets}$  and  $t\bar{t}$  normalizations are  
 1670     taken from data-driven methods.

#### 1671    4.5.1 RESULTS

1672     Figure 4.5 shows the  $m_{4\ell}$  spectrum measured in the 7 and 8 TeV datasets. The total number of events  
 1673     observed in the window between 120 and 130 GeV is 13, with 6 events in the  $4\mu$  channel, 2 events in  
 1674     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  
 1675     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  
 1676     an expected significance of  $2.7\sigma$ .

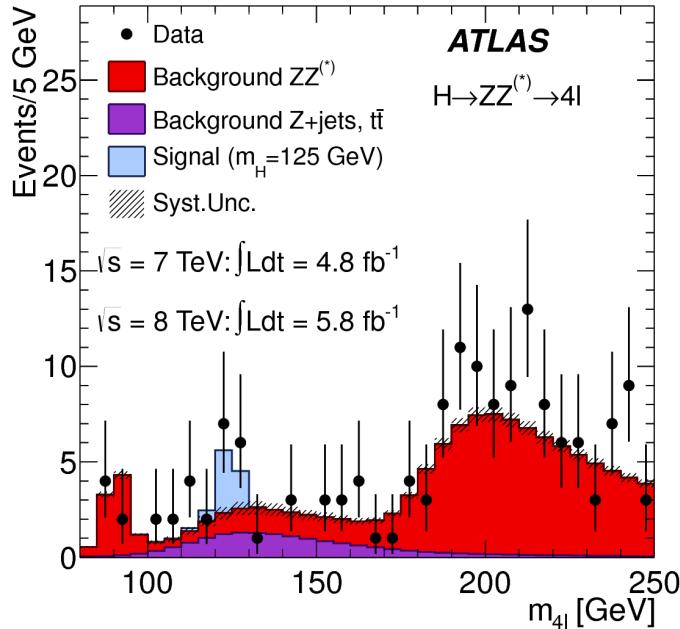


Figure 4.5: Four lepton invariant mass spectrum ( $m_{4\ell}$ ) in 7 and 8 TeV data compared to background estimate. A 125 GeV SM Higgs signal is shown in blue [1].

1677    4.6 COMBINED RESULTS

1678    The statistical interpretation of the combined results is undertaken as described in section 3.6.2, with a hy-  
1679    pothesis test based on a likelihood ratio parameterized by the Higgs signal strength  $\mu$ . The null hypothesis  
1680    corresponds to  $\mu = 0$ , while the SM Higgs corresponds to  $\mu = 1$ .

1681    Table 4.4 summarizes the properties of the individual channels as well as the significances of the excesses  
1682    seen. The most significant observed local excess comes from the  $\gamma\gamma$  channel. Figure 4.6 shows a com-  
1683    parison of the observed local  $p_0$  values as a function of hypothesized mass for the three different search  
1684    channels. Both the  $ZZ^*$  and  $\gamma\gamma$  channels have very peaked excesses, while the  $WW^*$  excess can be seen as  
1685    very broad because the  $m_T$  distribution does not provide detailed information about the true Higgs mass.  
1686    Figure 4.7 shows the combined exclusion limit,  $p_0$ , and signal strength. The highest local excess comes at  
1687    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].

1688    Figure 4.8 shows a comparison of the measured signal strengths between the different Higgs search  
1689    channels. All measured  $\mu$  are consistent with unity within their uncertainty, and the combined  $\mu$  mea-  
1690    surement is  $1.4 \pm 0.3$ .

1691    The likelihood can also be computed in a two-dimensional plane of  $m_H$  and  $\mu$ , and this is shown in  
1692    figure 4.9. The figure shows that while the  $\gamma\gamma$  and  $ZZ^*$  channels have very good mass resolution, the  
1693    excess in  $WW^*$  covers a broad mass range. The banana shape of the  $WW^*$  result is due to the fact that  
1694    the excess in this channel can either be explained by increasing the signal strength or by changing the mass  
1695    (and thus the cross section). The two parameters are correlated due to the lack of mass sensitivity in this  
1696    channel.

1697    Because multiple Higgs mass points are searched for, the local significance must be corrected for a look-

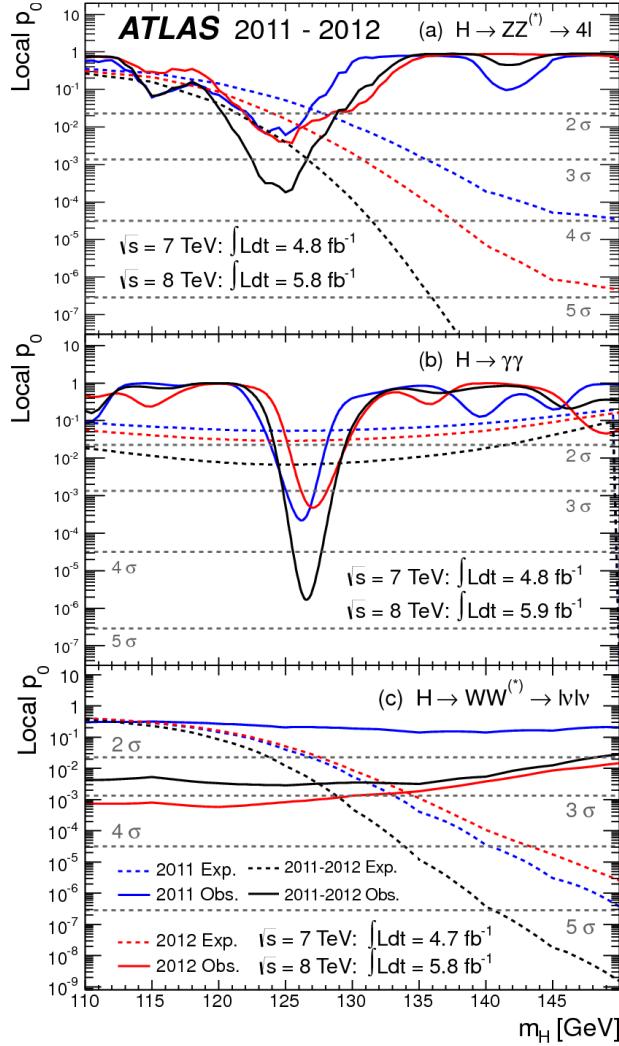


Figure 4.6: Local  $p_0$  distribution as a function of hypothesized Higgs mass for the  $H \rightarrow ZZ^* \rightarrow 4\ell$  (a),  $H \rightarrow \gamma\gamma$  (b), and  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  (c) channels. Dashed curves show expected results, while solid curves show observed.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

1698 elsewhere effect to compute a true global significance. The global significance for finding a Higgs anywhere  
 1699 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  
 1700 110 to 150 GeV.

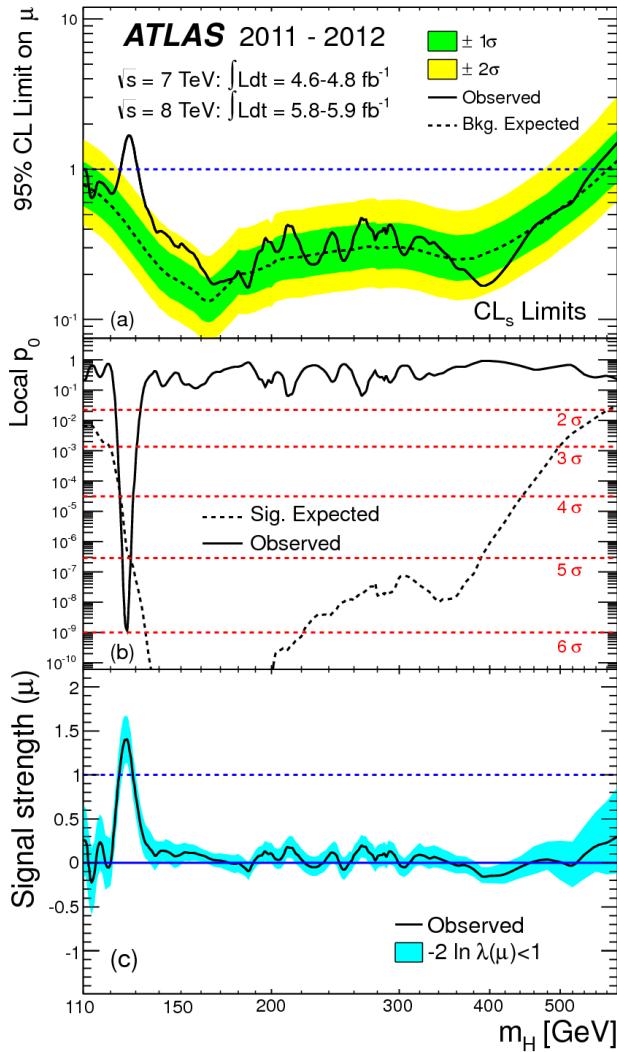


Figure 4.7: Combined 95% CL limits (a), local  $p_0$  values (b), and signal strength measurement (c) as a function of Higgs mass [1].

1701 **4.7 CONCLUSION**

1702 A search for the production of a Standard Model Higgs boson was conducted in  $4.8 \text{ fb}^{-1}$  collected at  
1703  $\sqrt{s} = 7 \text{ TeV}$  and  $5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . A new particle consistent with the Higgs boson was observed,  
1704 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  
1705 observation of a particle consistent with the Higgs.

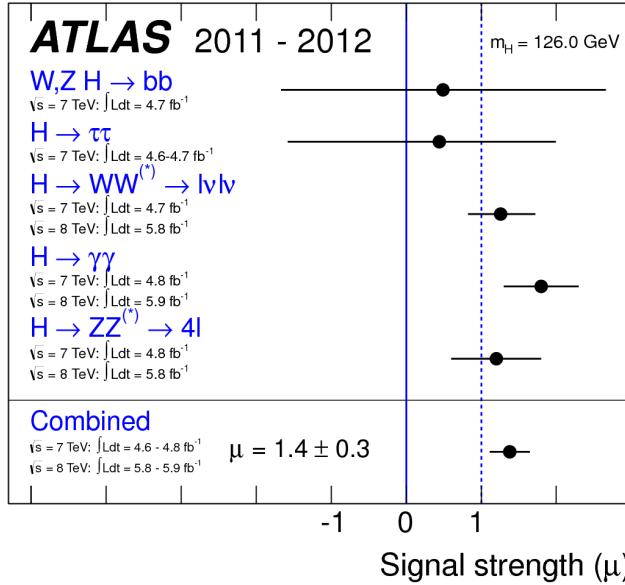


Figure 4.8: Comparison of measured signal strength  $\mu$  for a 126 GeV Higgs in the 7 and 8 TeV datasets [1].

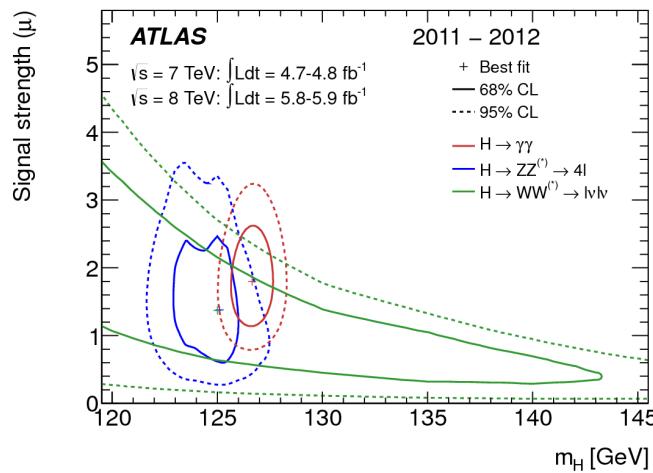


Figure 4.9: Two dimensional likelihood as a function of signal strength  $\mu$  and Higgs mass  $m_H$  [1].

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

Richard Feynman

# 5

1706

## 1707 Evidence for Vector Boson Fusion production

1708

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

### 1709 5.1 INTRODUCTION

1710 After the discovery of the Higgs boson, the  $H \rightarrow WW^*$  analysis had two main goals. The first goal was  
1711 to increase the sensitivity of the analysis to fully confirm that the  $H \rightarrow WW^*$  process did indeed exist.  
1712 The second goal was to characterize the particle as much as possible, including searching for the lower  
1713 cross-section production modes. This chapter presents a dedicated search for Vector Boson Fusion (VBF)  
1714 production of a Higgs boson decaying via the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  mode. First, the data and Monte  
1715 Carlo samples are detailed, along with trigger and physics object selections. Then, the details of the analysis  
1716 are shown, including signal region definition, background estimation techniques, and systematic uncer-  
1717 tainties. Finally, the results of the analysis are presented. As will be shown, this analysis is the first and

1718 most sensitive evidence for VBF production of the Higgs at the LHC.

1719 The VBF  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis defines two signal regions. The first is a more standard  
1720 selection, referred to as “cut-based”, that applies requirements on VBF topology variables and uses  $m_T$  as  
1721 the final discriminating variable. The second is a looser selection that uses an algorithm known as a Boosted  
1722 Decision Tree (BDT). A BDT is a multivariate technique that uses an ensemble of decision trees to split the  
1723 phase space of input variables into signal-like and background-like regions in order to provide separation  
1724 power [79–81]. The output score of a BDT trained to distinguish the VBF Higgs signal from background  
1725 processes is used as the final discriminating variable in the second signal region. While the BDT-based  
1726 signal region is ultimately more sensitive, the cut-based result is an important component of the analysis.  
1727 First, the cut-based analysis allows for confirming the modeling and validity of the variables used as input  
1728 to the BDT. Second, because this is the first use of a multivariate technique in the  $H \rightarrow WW^*$  analysis,  
1729 the cut-based selection allows confirmation of the final BDT result with a more traditional analysis. The  
1730 cut-based techniques are the focus of this chapter, but connections to the BDT result will be illustrated  
1731 when appropriate.

1732 One important note is that because this analysis is dedicated to the measurement of the VBF pro-  
1733 duction mode of the Higgs, events coming from gluon fusion production with the Higgs decaying via  
1734  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  are treated as background events. This will be seen throughout the background  
1735 predictions shown below.

## 1736 5.2 DATA AND SIMULATION SAMPLES

1737 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  $\sqrt{s} = 7 \text{ TeV}$ .  
1738 The details of the LHC and detector conditions during this period are given in Chapter 2. The trigger  
1739 selection defining the dataset is discussed in section 5.2.1. The simulation samples used for signal and back-  
1740 ground modeling are given in section 5.2.2.

1741 5.2.1 TRIGGERS

1742 The analysis uses a combination of single lepton and dilepton triggers to allow lowering of the  $p_T$  thresh-  
1743 olds and increased signal acceptance. The  $p_T$  threshold on the leptons is a particularly important con-  
1744 sideration for this signal. Because the  $W^*$  produced in the decay is off-shell, it tends to produce lower  
1745 momentum leptons. Thus, being able to lower the  $p_T$  threshold while still maintaining a low background  
1746 rate is critical. Figure 5.1 shows an example of the subleading lepton  $p_T$  for a VBF  $H \rightarrow WW^*$  signal com-  
1747 pared to the corresponding  $t\bar{t}$  background. Note that the lepton  $p_T$  spectrum is considerably softer in the  
1748 signal sample. The spectrum shown here is also similar in gluon fusion production of the Higgs as well.

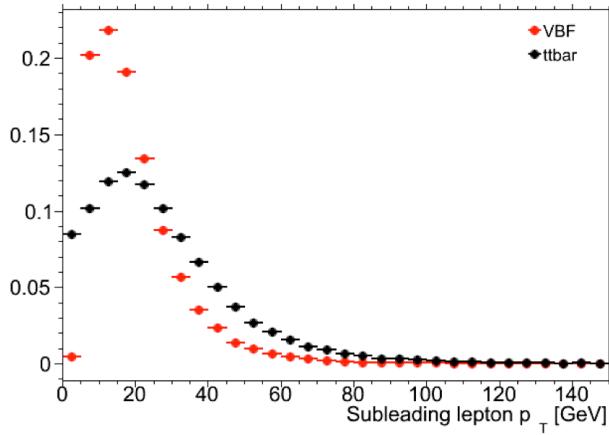


Figure 5.1: A comparison of the subleading lepton  $p_T$  spectrum between VBF  $H \rightarrow WW^*$  production and  $t\bar{t}$  background.

1749 As discussed in Chapter 2, there are multiple levels in the ATLAS trigger system, and there are different  
1750  $p_T$  thresholds imposed for the leptons at each level. Additionally, some triggers have a loose selection on  
1751 the isolation of the lepton (looser than that applied offline in the analysis object selection). Table 5.1 shows  
1752 the  $p_T$  thresholds used for single lepton triggers, while table 5.2 shows the  $p_T$  thresholds coming from  
1753 di-lepton triggers. The single lepton trigger efficiency for muons that pass the analysis object selection is  
1754 70% for muons in the barrel region ( $|\eta| < 1.05$ ) and 90% in the endcap region. The electron trigger  
1755 efficiency increases with electron  $p_T$  but the average is approximately 90%. These efficiencies are measured  
1756 by combined performance and trigger signature groups [82, 83].

	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.

1757        The combination of all listed triggers gives good efficiency for signal events. This efficiency is summa-  
 1758        rized in table 5.3. The relative improvement in efficiency by adding the dilepton triggers is also shown  
 1759        in the same table. The largest gain comes in the  $\mu\mu$  channel. Overall the trigger selection shows a good  
 1760        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.

### 1761        5.2.2 MONTE CARLO SAMPLES

1762        In both the gluon fusion and vector boson fusion focused analyses, modeling of signal and background  
 1763        processes in the signal region is an important consideration for the final interpretation of the analysis.  
 1764        Therefore, careful consideration must be paid to which Monte Carlo (MC) generators are used for specific

1765 processes. With the exception of the  $W + \text{jet}$  and multijet backgrounds, the  $m_T$  shape used as the final  
1766 discriminant is taken from simulation<sup>1</sup>.

1767 Table 5.4 shows the MC generators used for the signal and background processes, as well as the cross  
1768 sections of each process. In order to include corrections up to next-to-leading order (NLO) in the QCD  
1769 coupling constant  $\alpha_s$ , the `POWHEG` [84] generator is often used. In some cases, only leading order gener-  
1770 ators like `ACERMC` [85] and `GG2VV` [86] are available for the process in question. If the process requires  
1771 good modeling for very high parton multiplicities, the `SHERPA` [87] and `ALPGEN` [88] generators are used  
1772 to provide merged calculations for five or fewer additional partons. These matrix element level calculations  
1773 must then be additionally matched to models of the underlying event, hadronization, and parton shower.  
1774 There are four generators used for this purpose: `SHERPA`, `PYTHIA 6` [89], `PYTHIA 8` [90], or `HERWIG`  
1775 [91] + `JIMMY` [92]. The simulation additionally requires an input parton distribution function (PDF).  
1776 The `CT10` [93] PDFs are used for `SHERPA` and `POWHEG` simulated samples, while `CTEQ6L1` [94] is used  
1777 for `ALPGEN + HERWIG` and `ACERMC` simulations. The Drell-Yan samples are reweighted to the `MRST` [95]  
1778 PDFs, as these are found to give the best agreement between data and simulation. The branching ratio  
1779 for Higgs to  $WW^*$  and  $ZZ^*$  is computed with `PROPHECY4f` [96], while the width of all other decays is  
1780 computed with `HDECAY`[97].

1781 Once the basic hard scattering process is simulated, it must be passed through a detector simulation and  
1782 additional pile-up events must be overlaid. The pile-up events are modeled with `PYTHIA 8`, and the ATLAS  
1783 detector is simulated with `GEANT4` [98]. Because of the unique phase space of the  $H \rightarrow WW^*$  analysis,  
1784 events are sometimes filtered at generator level to allow for more efficient generation of relevant events.  
1785 The efficiency of the trigger in MC simulation does not always match the measured efficiency in data, so  
1786 trigger scale factors are applied to correct the MC efficiency to the data. The details of these corrections are  
1787 given in reference [82] for muons and reference [83] for electrons.

---

<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 [74]. The table lists the cross section for each process, taking into account the branching ratio for the process producing two leptons.

### 1788 5.3 OBJECT SELECTION

1789 In order to define the signal region, the analysis must first select the reconstructed physics objects to be  
1790 considered. The details of the object reconstruction algorithms were discussed in Chapter 2, while this

1791 section gives specific selection requirements used in the  $H \rightarrow WW^*$  analysis. The first step in this process  
1792 is to select a primary vertex candidates. The event's primary vertex is chosen to be the vertex with the largest  
1793 sum of  $p_T^2$  for its associated tracks. It is required to have at least three tracks with  $p_T > 450$  MeV. Many  
1794 of the object selection cuts are then made relative to this chosen primary vertex.

1795 **5.3.1 MUONS**

1796 The analysis uses combined muon candidates, where a track in the Inner Detector has been matched to a  
1797 standalone track in the Muon Spectrometer. The track parameters are combined statistically in the muon  
1798 reconstruction algorithm [64]. The muons are required to be within  $|\eta| < 2.5$  and have a  $p_T > 10$  GeV.  
1799 To reduce backgrounds coming from mis-reconstructed leptons, there are requirements on the impact  
1800 parameter of the muon relative to the primary vertex. The transverse impact parameter  $d_0$  is required to  
1801 be small relative to its estimated uncertainty, the exact cut value being  $d_0/\sigma_{d_0} < 3$ . The longitudinal  
1802 impact parameter  $z_0$  must satisfy  $|z_0 \sin \theta| < 1$  mm.

1803 As discussed previously, the muons must also be isolated. There are two types of lepton isolations  
1804 that are calculated: track-based and calorimeter-based. For muons, the track-based isolation is defined  
1805 using the scalar sum  $\sum p_T$  for tracks with  $p_T > 1$  GeV (excluding the muon track) within a cone of  
1806  $\Delta R = 0.3$  (0.4) around the track for muons with  $p_T > 15$  GeV ( $10 < p_T < 15$  GeV). The final  
1807 isolation requirement is made by requiring that this scalar sum be no more than a certain fraction of the  
1808 muon  $p_T$ . This requirement varies with muon  $p_T$  and the exact requirements are defined in table 5.5.

1809 The calorimeter-based muon isolation is defined using the  $\sum E_T$  calculated from calorimeter cells with  
1810 the same cone size as the track-based isolation but excluding cells within  $\Delta R < 0.05$  around the muon.  
1811 This isolation is also defined as a requirement on the ratio of the sum to the muon  $p_T$  and varies with  
1812 muon  $p_T$ . The requirement values as a function of  $p_T$  are also given in table 5.5.

1813 The isolation requirements loosen as a function of  $p_T$  to allow for larger signal acceptance. At low  $p_T$ ,  
1814 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  $p_T$ .

<sup>1815</sup> 5.3.2 ELECTRONS

<sup>1816</sup> Electrons are identified and reconstructed using the methods previously described in chapter 2. The elec-  
<sup>1817</sup> trons are required to have  $|\eta| < 2.47$ , and candidates in the transition region between the barrel and  
<sup>1818</sup> endcap ( $1.37 < |\eta| < 1.52$ ) are excluded. As the muons, the electrons are required to have transverse  
<sup>1819</sup> impact parameter significance  $< 3$ , while in the longitudinal direction they must have  $|z_0 \sin \theta| < 0.4$   
<sup>1820</sup> mm. Some electron requirements also vary with electron  $E_T$ , and these requirements are summarized in  
<sup>1821</sup> table 5.6.

<sup>1822</sup> The isolation for electrons is defined similarly to the muons but with unique requirements on the ob-  
<sup>1823</sup> jects included. The track-based isolation is constructed using tracks with  $p_T > 400$  MeV with cone sizes  
<sup>1824</sup> as defined for the muons. The calorimeter-based isolation also uses the same cone size as the muon, but  
<sup>1825</sup> here the cells within a  $0.125 \times 0.175$  area in  $\eta \times \phi$  around the electron cluster's barycenter are excluded.  
<sup>1826</sup> The other difference with respect to muons is that the denominator of the isolation ratio is the electron  
<sup>1827</sup>  $E_T$  rather than  $p_T$ . The isolation cuts vary with electron  $E_T$  and are defined in table 5.6. The electron is  
<sup>1828</sup> 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  $E_T$ .

1829 5.3.3 JETS

1830 Jets are clustered with the anti- $k_T$  reconstruction algorithm using a radius parameter of  $R = 0.4$ . They  
1831 are required to have a jet vertex fraction (JVF) of at least 50%, meaning that half of the tracks associated with  
1832 the jet originated from the primary vertex. Jets with no tracks associated (i.e. those outside the acceptance  
1833 of the ID) do not have this requirement applied. Jets are required to have  $p_T > 25$  GeV if they are within  
1834 the tracking acceptance ( $|\eta| < 2.4$ ). Jets with  $2.4 < |\eta| < 4.5$  are required to have  $p_T > 30$  GeV. This  
1835 tighter requirement reduces jets from pileup in the region where JVF requirements cannot be applied. The  
1836 two highest  $p_T$  jets in the event are referred to as the “VBF” jets and used to compute variables used in the  
1837 analysis selection.

1838 Identification of  $b$ -jets is done using the MV1 algorithm and is limited to the acceptance of the ID ( $|\eta| <$   
1839 2.5) [70]. The operating point of MV1 used is 85% efficient for identifying true  $b$ -jets. This operating  
1840 point has a 10.3% probability of mis-tagging a light quark jet as a  $b$ -jet. The analysis vetoes events that  
1841 contain  $b$ -tagged jets with  $p_T > 20$  GeV.

1842 5.3.4 OVERLAP REMOVAL

1843 There are some cases where reconstructed objects will overlap and one will have to be chosen (for example,  
1844 an electron and a jet in the calorimeter). First, the case of lepton overlap is dealt with. If an electron  
1845 candidate extends into the muon spectrometer, it is removed. If a muon and electron are within  $\Delta R < 0.1$   
1846 of each other, the electron is removed and the muon is kept. If two electron candidates overlap within the  
1847 same radius, then the higher  $E_T$  electron is kept. Next, the overlap between leptons and jets is considered.  
1848 If an electron and jet are within  $\Delta R < 0.3$  of one another, the electron is kept and the jet is removed.  
1849 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  
1850 result of a semileptonic decay inside the jet). Once the overlap removal is complete, the final set of objects  
1851 used in the analysis is defined.

1852    5.4 ANALYSIS SELECTION

1853    This section discusses the variables used to distinguish VBF production of the Higgs in the  $H \rightarrow WW^* \rightarrow$   
1854     $\ell\nu\ell\nu$  final state. First, pre-selection requirements are presented. Then, the definitions of analysis variables  
1855    and the cut-based signal region are shown. Finally, the BDT signal region is defined and the commonalities  
1856    between the two signal regions are discussed.

1857    5.4.1 PRE-SELECTION

1858    Both the cut-based and BDT analyses have a common pre-selection that is applied before the signal region  
1859    requirements. The requirements on leptons are common to all  $n_j$  bins. The analysis requires two oppo-  
1860    sitely charged leptons, with the leading lepton required to have  $p_T > 22$  GeV while the subleading lepton  
1861    must have  $p_T > 10$  GeV. Next, to remove low mass  $Z/\gamma^*$  events, a requirement on the dilepton mass  
1862     $m_{\ell\ell} > 10$  (12) GeV is applied in the different (same) flavor channel. In the same flavor channels, there is  
1863    an additional veto placed on the region around the Z peak, requiring that  $|m_{\ell\ell} - m_Z| > 15$  GeV.

1864    There are also requirements on the amount of missing transverse momentum in the event. These  
1865    are only applied in the same flavor channels, where  $Z/\gamma^* + \text{jets}$  production is one of the dominant back-  
1866    grounds. The BDT analysis requires  $p_T^{\text{miss}} > 40$  GeV and  $E_T^{\text{miss}} > 45$  GeV. The cut-based analysis  
1867    must select more tightly on these variables to have maximal sensitivity and thus requires  $p_T^{\text{miss}} > 50$  GeV  
1868    and  $E_T^{\text{miss}} > 55$  GeV. Figure 5.2 shows the distributions of both  $E_T^{\text{miss}}$  and  $p_T^{\text{miss}}$  compared between  
1869    data and simulation in the same flavor channels. Both variables are modeled fairly well in the bulk of the  
1870    distribution, with some mis-modeling arising in the tails. Additionally, it is interesting to note that the  
1871     $Z/\gamma^* \rightarrow \ell\ell$  backgrounds tends to have lower values of both variables compared to the VBF signal, as  
1872    expected.

1873    Finally, because this analysis is focused on VBF Higgs production, a requirement on the jet multiplicity  
1874    is placed, with  $n_j \geq 2$ . Additionally, the analysis requires that there are no jets identified as b-quarks in the  
1875    event, or  $n_b = 0$ . Figure 5.3 shows the jet multiplicity distributions in data and Monte Carlo simulation  
1876    for both  $n_j$  and  $n_b$ . The  $n_j$  variable is seen to be very well modeled for  $n_j \leq 7$ , with some discrepancies  
1877    appearing at very high jet multiplicities (where events are a small fraction of the total sample). Similarly,

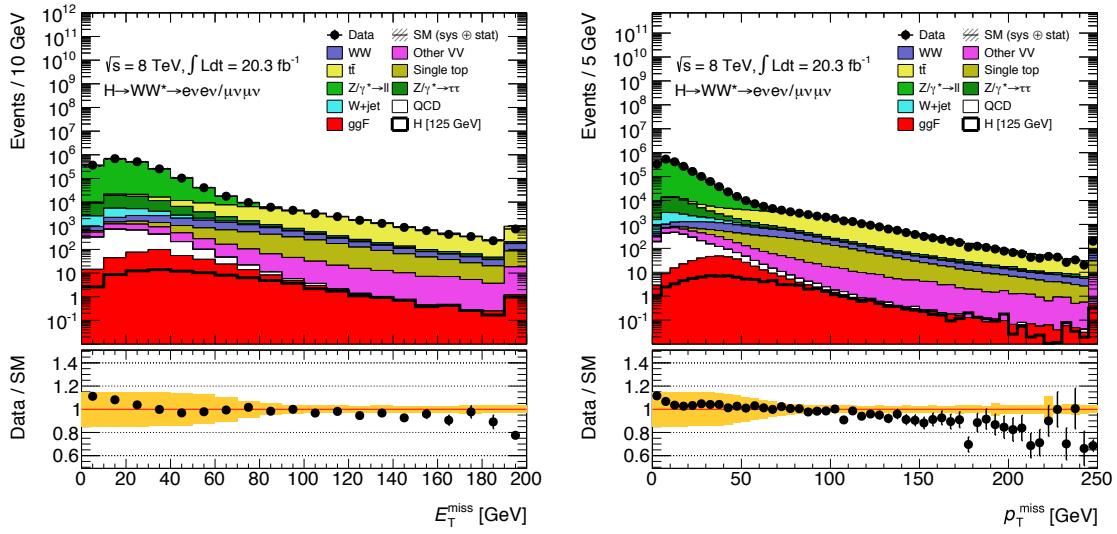


Figure 5.2: Comparisons between data and Monte Carlo simulation for the calorimeter-based  $E_T^{\text{miss}}$  (left) and the track-based  $p_T^{\text{miss}}$  (right) in the same flavor VBF  $H \rightarrow WW^*$  analysis channels. Both distributions are shown after the pre-selection cuts on  $m_{\ell\ell}$ . The bottom panel shows the ratio between the data and the number of events expected from combining the signal and background. The hashed and orange bands include both statistical and systematic uncertainties.

the  $n_b$  variable is modeled very well for  $n_b \leq 2$ , with some discrepancies at higher values.

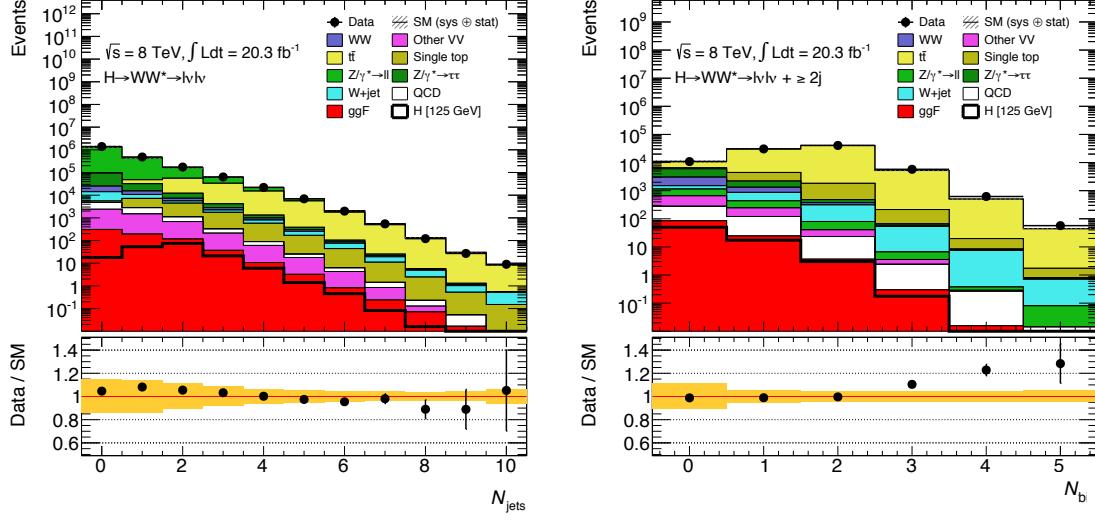


Figure 5.3: Comparisons between data and Monte Carlo simulation for the jet multiplicity  $n_j$  (left) and the number of  $b$ -tagged jets  $n_b$  (right) in the VBF  $H \rightarrow WW^*$  analysis.  $n_j$  is shown after the pre-selection cuts on  $m_{\ell\ell}$  and  $n_b$  is shown after the requirement that  $n_j \geq 2$ . The bottom panel shows the ratio between the data and the number of events expected from combining the signal and background. In the  $n_b$  distribution, the top background is normalized using the procedures described in section 5.5.2. The hashed and orange bands include both statistical and systematic uncertainties.

1879    5.4.2 ANALYSIS VARIABLE DEFINITIONS AND CUT-BASED SELECTION

1880    The cut-based selection places sequential requirements on variables reconstructed from the VBF jets in  
1881    order to increase the signal to background ratio. This section defines the variables that are used in the  
1882    cut-based selection and details the requirements that are placed on these variables.

1883    GENERAL BACKGROUND REDUCTION

1884    Top pair production is the primary background in the  $n_j \geq 2$  bin. Even though  $n_b = 0$  is required, an  
1885    additional variable is constructed to further suppress the top background. There is often additional QCD  
1886    radiation that accompanies the  $t\bar{t}$  system when it is produced. Therefore, a variable which tests for the  
1887    presence of this additional radiation,  $p_T^{\text{sum}}$ , is constructed. It is defined in equation 5.1.

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

1888    After pre-selection, the cut-based analysis requires the event to have  $p_T^{\text{sum}} < 15$  GeV to further suppress  
1889     $t\bar{t}$  production.

1890    In the different flavor channels, a requirement is made to reduce the contamination from  $Z \rightarrow \tau\tau$   
1891    decays. The di- $\tau$  invariant mass,  $m_{\tau\tau}$ , is constructed by assuming that the neutrinos from the  $\tau$  decays  
1892    were collinear with the leptons [77]. The analysis requires that this mass satisfy  $m_{\tau\tau} < m_Z - 25$  GeV so  
1893    that it is not consistent with the mass of the  $Z$  boson.

1894    VBF TOPOLOGICAL CUTS

1895    The characteristic feature of VBF production of the Higgs is the presence of two additional forward jets  
1896    coming from the incoming partons which radiate the vector bosons that make the Higgs. These jets are  
1897    forward because the outgoing partons still carry the longitudinal momentum of the incoming partons.  
1898    Figure 5.4 shows the distribution of the  $\eta$  for the leading jet in a VBF event compared to a background top  
1899    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  
1900    central. Because the cross section for VBF production is an order of magnitude smaller than gluon fusion

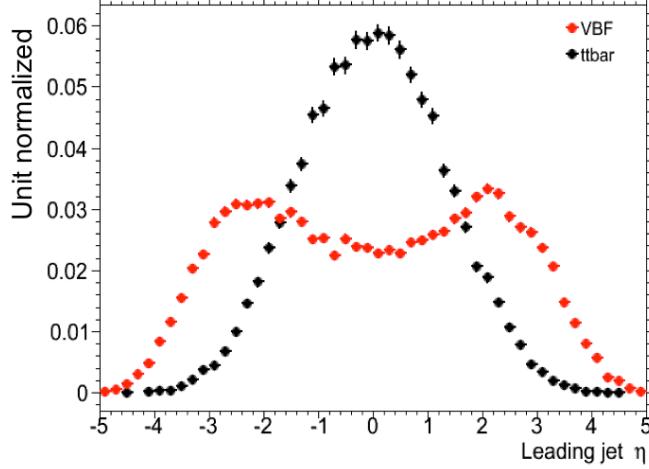


Figure 5.4: Leading jet  $\eta$  in VBF  $H \rightarrow WW^*$  (red) and  $t\bar{t}$  (black)

1901 production, these forward jets must be used in order to reduce background and achieve a good signal to  
 1902 background ratio. The dedicated VBF search selection requirements are constructed to maximally exploit  
 1903 the features of the unique VBF topology.

1904 Requirements on the VBF jets are collectively referred to as the “VBF topological cuts”. First, a require-  
 1905 ment on the dijet invariant mass of the VBF jets,  $m_{jj}$ , is placed, requiring  $m_{jj} > 600$  GeV. Next, the  
 1906 event is required to have a large gap in rapidity between the two VBF jets, or  $\Delta y_{jj} > 3.6$ . Both of these  
 1907 are tight requirements on the presence of two forward, high  $p_T$  jets moving in opposite directions in the  
 1908 longitudinal plane.

1909 Beyond requiring the presence of the two forward VBF jets, the analysis also vetoes on the presence of  
 1910 any additional jets that fall between the two VBF jets. This requirement is referred to as the central jet  
 1911 veto, or CJV. Events are vetoed if they have a third jet with  $p_T > 20$  GeV whose rapidity is between the  
 1912 region defined by the two VBF jets. This requirement can be expressed in terms of a variable called the jet  
 1913 centrality, defined in equation 5.2.

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

1914 Here,  $\eta_{j1}$  and  $\eta_{j2}$  are the pseudorapidities of the leading and subleading jets, respectively, while  $\eta_{j3}$  is  
1915 the pseudorapidity of the extra jet in the event (if one exists). Intuitively,  $C_{j3}$  is zero when  $\eta_{j3}$  is directly  
1916 centered between the two jets and unity when  $\eta_{j3}$  is aligned with either of the VBF jets. Thus, the CJV  
1917 can be expressed as a requirement that  $C_{j3} > 1$ .

1918 The decay products of the Higgs tend to be central as well. Thus, the analysis also requires that both  
1919 leptons in the analysis fall within the rapidity gap defined by the jets. This cut is referred to as the outside  
1920 lepton veto, or OLV. Stated another way, leptons are required to have a centrality (defined analogously to  
1921 that of the third jet in equation 5.2) within the jet rapidity gap, or  $C_\ell < 1$  for both leptons.

1922 Figure 5.5a-c shows the  $m_{jj}$ ,  $\Delta y_{jj}$ , and  $C_{\ell 1}$  variables at the stage where all previous requirements in the  
1923 sequence have been made. The agreement between data and Monte Carlo is good, and the bottom panels  
1924 show their power in discriminating the VBF signal from the background processes.

1925 The final signal region is also split into two bins of  $m_{jj}$ , with the first bin corresponding to  $600 \text{ GeV} <$   
1926  $m_{jj} < 1 \text{ TeV}$  and the second bin corresponding to  $m_{jj} > 1 \text{ TeV}$ . The first bin has more events but also  
1927 a larger contribution from background, while the second bin has a lower expected number of events but a  
1928 1:1 signal to background ratio.

## 1929 HIGGS TOPOLOGICAL CUTS

1930 The final state leptons will exhibit unique correlations due to the fact that they arise from the decay of a  
1931 spin zero resonance. These characteristics are present in  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  decays regardless of the  
1932 production mode being studies. In particular, the spins of the final state leptons and neutrinos must all  
1933 cancel, as shown in figure 5.6. Because the neutrino has a left handed chirality and the anti-neutrino has a  
1934 right handed chirality (in the massless neutrino approximation), the spin and momentum of the particles  
1935 will be anti-aligned and aligned, respectively. In the transverse plane, the momenta of all four final state  
1936 objects must cancel as well. With the constraint of having both the momenta and the spin alignments  
1937 cancel, the final state kinematics strongly prefer having a small angle between the leptons in the transverse  
1938 plane (low  $\Delta\phi_{\ell\ell}$ ). This angular correlation will also lead to low values of the di-lepton invariant mass  $m_{\ell\ell}$ .  
1939 These unique signal final state kinematic correlations are exploited to define the ultimate signal region.

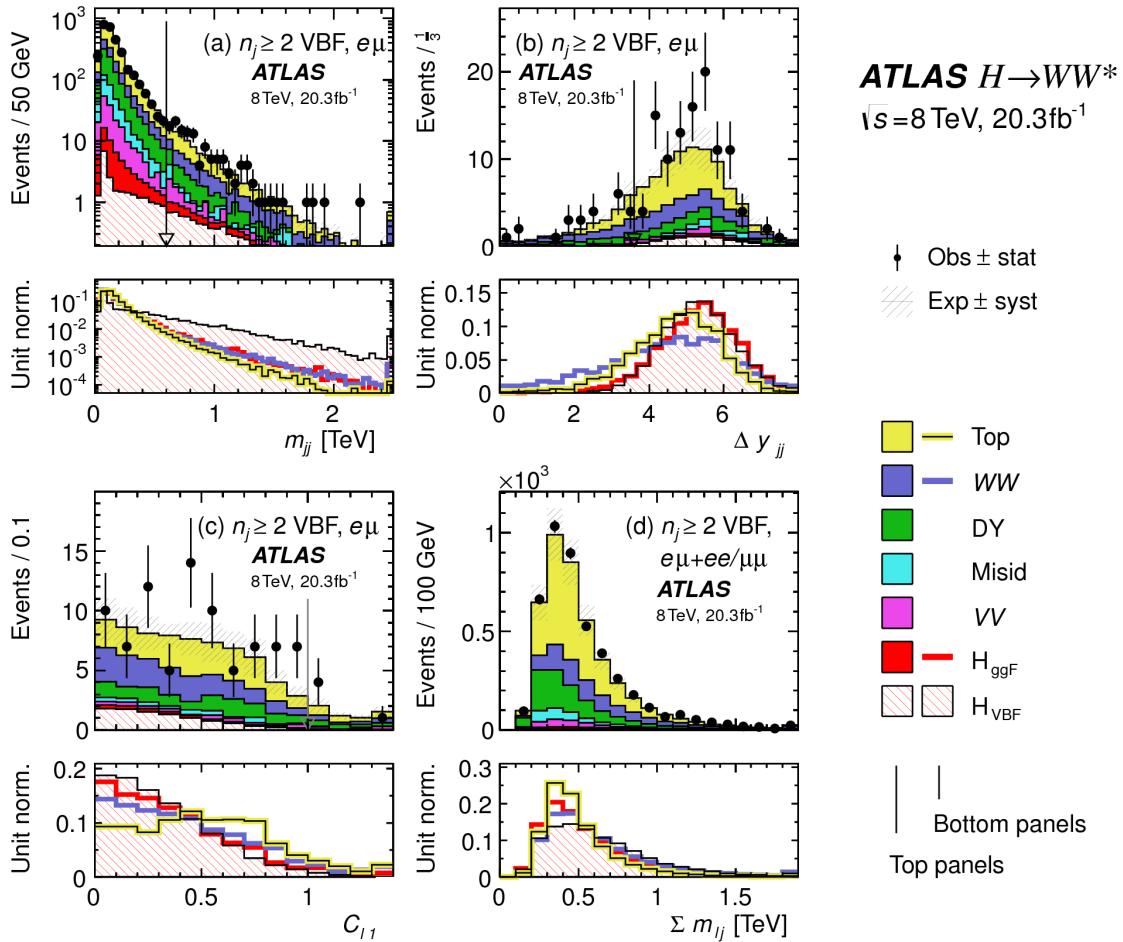


Figure 5.5: Distributions of (a)  $m_{jj}$ , (b)  $\Delta y_{jj}$ , (c)  $C_{ll}$ , and (d)  $\Sigma m_{ll}$ , for the cut-based VBF analysis. The top panels compare simulation and data, while the bottom panels show normalized distributions for all background processes and signal for shape comparisons [74].

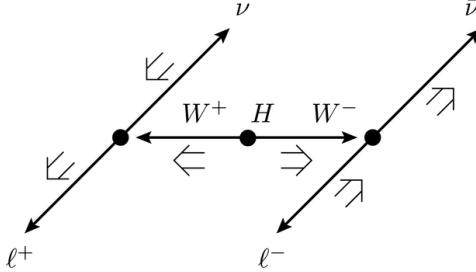


Figure 5.6: A cartoon of the WW final state. Momenta are represented with thin arrows, spins with thick arrows [74].

1940 Two requirements on dilepton kinematics are made that are common with lower multiplicity jet bins  
 1941 as well. The angle between leptons in the transverse plane,  $\Delta\phi_{\ell\ell}$ , is required to be less than 1.8 radians.  
 1942 Additionally, the dilepton invariant mass,  $m_{\ell\ell}$ , is required to be less than 50 GeV.

1943 The cut-based analysis uses  $m_T$  as the final discriminating variable as in the ggF focused analysis. The  
 1944 optimal number of bins in  $m_T$  was found to be three bins, with the bin boundaries at 80 and 130 GeV.  
 1945 Figure 5.7 shows the  $m_T$  distribution in the three bins used in the fit (also known as the “mapped”  $m_T$ )  
 1946 for both the  $600 < m_{jj} < 1000$  GeV bin and the  $m_{jj} \geq 1000$  GeV bin. As can be seen, both  $m_{jj}$   
 1947 bins offer discriminating power for the VBF Higgs, with the lower  $m_{jj}$  bin providing more events and the  
 1948 higher  $m_{jj}$  bin providing better signal to background ratio.

1949 Table 5.7 shows a summary of the data and estimated signal and background yields from simulation  
 1950 as each requirement described above is made. The table shows how the overall signal to background ra-  
 1951 tio grows through the various selection requirements. Table 5.8 shows the background composition after  
 1952 each selection requirement, illustrating which backgrounds are reduced most by certain requirements. Fig-  
 1953 ure 5.8 shows an ATLAS event display of a candidate event in the final signal region.

#### 1954 5.4.3 BDT-BASED SELECTION

1955 The boosted decision tree based analysis uses many of the variables defined in the cut-based selection as  
 1956 inputs to the BDT. The output BDT score ( $O_{\text{BDT}}$ ) is used as the final discriminant rather than  $m_T$ <sup>2</sup>.

---

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

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 [74].

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

Table 5.8: Background composition after each requirement in the  $n_j \geq 2$  VBF analysis in the 8 TeV cut-based analysis [74].

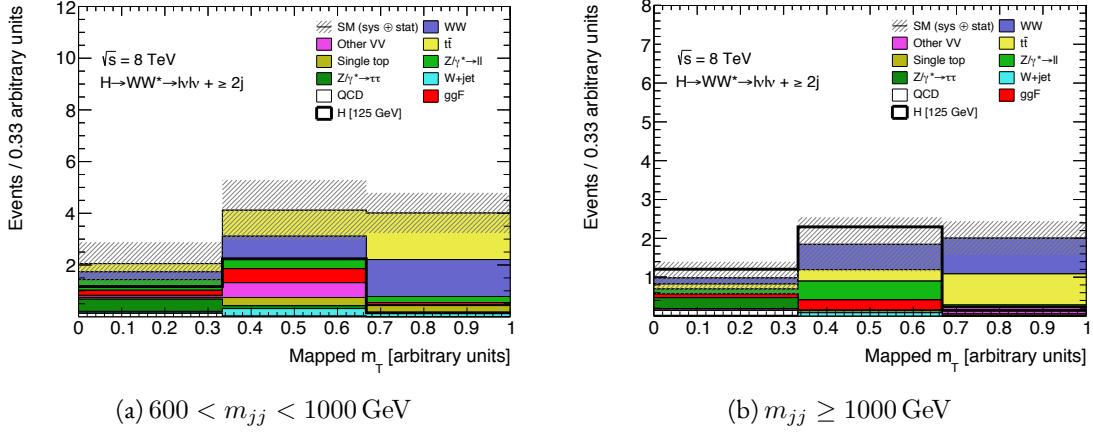


Figure 5.7:  $m_T$  distribution in simulation mapped to the three bins used in the final VBF cut-based analysis fit. The bin boundaries correspond 80 and 130 GeV. The solid black line corresponds to the VBF Higgs signal and is overlaid on the backgrounds to allow for shape comparison. Hashed bands include both statistical and systematic uncertainties.

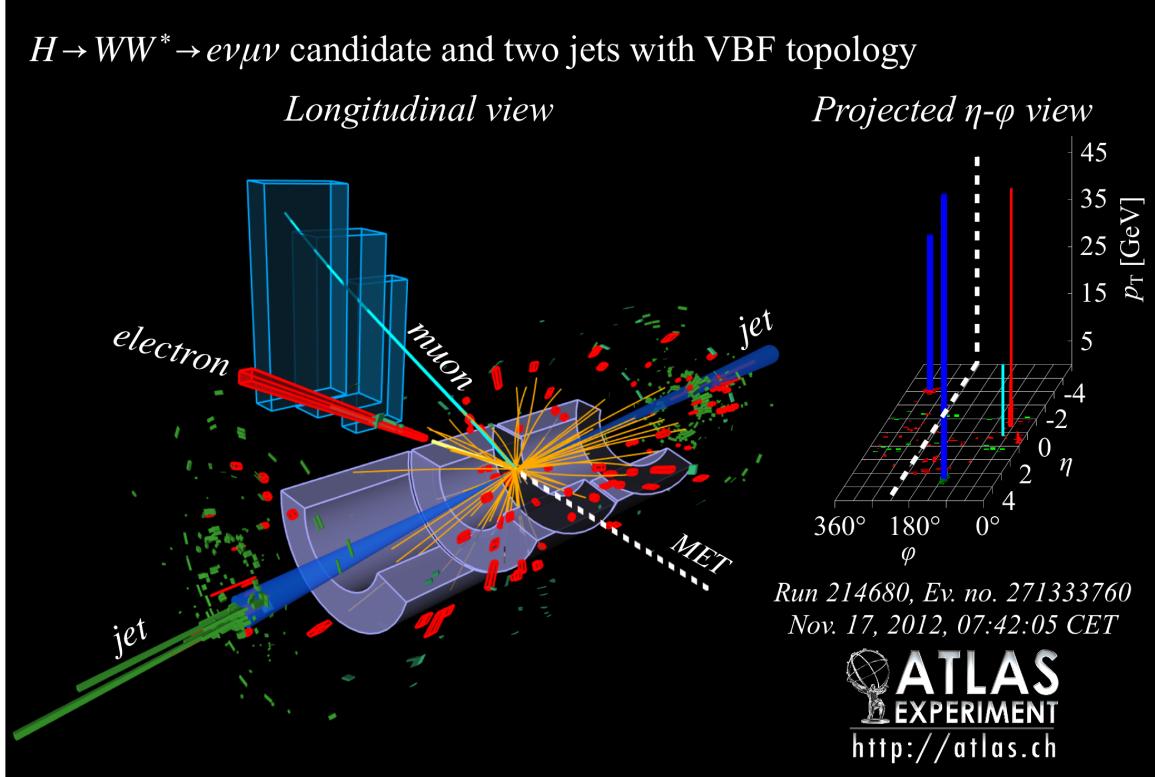


Figure 5.8: Event display of a VBF candidate event [74].

1957 The BDT is trained with the VBF  $H \rightarrow WW^*$  simulation as the signal samples and all other processes as  
 1958 background, including ggF  $H \rightarrow WW^*$  production. While the BDT based analysis is ultimately treated

1959 as a separate result, it has significant overlap with the cut-based selection.

## 1960 PRE-TRAINING SELECTION AND BDT INPUTS

1961 Before training, the common pre-selection cuts described in section 5.4.1 are applied. Additionally, the  
1962 central jet veto and outside lepton veto described in section 5.4.2 are applied. The BDT has eight input  
1963 variables, six of which are also variables that are used in the cut-based analysis. The six shared variables  
1964 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  
1965 the variables used to define the OLV in the cut-based analysis. The BDT uses as input the sum of lepton  
1966 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  
1967 the correlations between the jets and leptons in the event. It is the sum of the invariant masses of all four  
1968 possible lepton-jet combinations. Table 5.9 summarizes the cuts applied for the cut-based and analyses, as  
1969 well as which variables are used as input to the BDT.

1970 Figure 5.5d shows the agreement between data and simulation for the  $\Sigma m_{\ell j}$  variable, as well as showing  
1971 its discriminating power. Figure 5.9 shows the distributions of the Higgs topological variables that are  
1972 shared between the cut-based and BDT analyses. Figure 5.10 shows the distributions of the VBF topologi-  
1973 cal variables shared between the cut-based and BDT analyses. In both cases, the VBF yield has been scaled  
1974 by a factor of 50 to better show the shape difference compared to the backgrounds.

## 1975 5.5 BACKGROUND ESTIMATION

1976 This section describes the procedures used to estimate backgrounds for the VBF analysis in both the cut-  
1977 based and BDT analyses. First, the general strategy is presented. Then, specific procedures for each back-  
1978 ground in both signal regions are shown.

### 1979 5.5.1 GENERAL STRATEGY

1980 Most of the backgrounds in both the gluon fusion and VBF Higgs analyses have shapes estimated from  
1981 Monte Carlo simulation but normalizations derived from control regions in data. In essence, a normaliza-  
1982 tion factor (denoted with  $\beta$  or abbreviated as NF) is derived by scaling the MC yield in the control region

Category	Selection	Cut-based value	BDT-based value
Pre-selection	Leptons	2 oppositely charged	
	Leading lepton $p_T$	$> 22 \text{ GeV}$	
	Subleading lepton $p_T$	$> 10 \text{ GeV}$	
	$m_{\ell\ell}$	$> 10 (12) \text{ GeV for } e\mu/\mu e (ee/\mu\mu)$ $ m_{\ell\ell} - m_Z  > 15 \text{ GeV for } ee/\mu\mu$	
	$E_T^{\text{miss}}$ ( $ee/\mu\mu$ only)	$> 55 \text{ GeV}$	$> 45 \text{ GeV}$
	$p_T^{\text{miss}}$ ( $ee/\mu\mu$ only)	$> 50 \text{ GeV}$	$> 40 \text{ GeV}$
	$b$ -veto	$n_b = 0$	
Bkg. rejection	$p_T^{\text{sum}}$	$< 15 \text{ GeV}$	Input
VBF topology	$m_{jj}$	$> 600 \text{ GeV}$	Input
	$\Delta y_{jj}$	$> 3.6$	Input
	CJV and OLV	applied	
	$\sum C_\ell$	-	Input
	$\sum m_{\ell j}$	-	Input
Higgs topology	$m_{\ell\ell}$	$< 50 \text{ GeV}$	Input
	$\Delta\phi_{\ell\ell}$	$< 1.8$	Input
	$m_T$	Three bins with boundaries at 80 and 130 GeV	Input

Table 5.9: Summary of selections for the cut-based and BDT signal regions. “Input” denotes variables used as input to the BDT algorithm. Definitions and explanations of the variables can be found in sections 5.4.2 and 5.4.3.

<sup>1983</sup> to the corresponding yield in data. Once this factor is derived, it can be used to scale the MC estimate of  
<sup>1984</sup> the background in the signal region. This is illustrated in equation 5.3.

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

<sup>1985</sup> Here,  $B$  is the MC yield prediction in the denoted region, while  $N$  is the observed number of events in  
<sup>1986</sup> data in the denoted region.

<sup>1987</sup> There is an alternative way of writing the same equation in terms of an extrapolation factor  $\alpha$  rather  
<sup>1988</sup> than a normalization factor  $\beta$ . The overall calculation is exactly the same. However, when phrased in  
<sup>1989</sup> this way, it shows how the uncertainty on the background estimation can be reduced. This is shown in

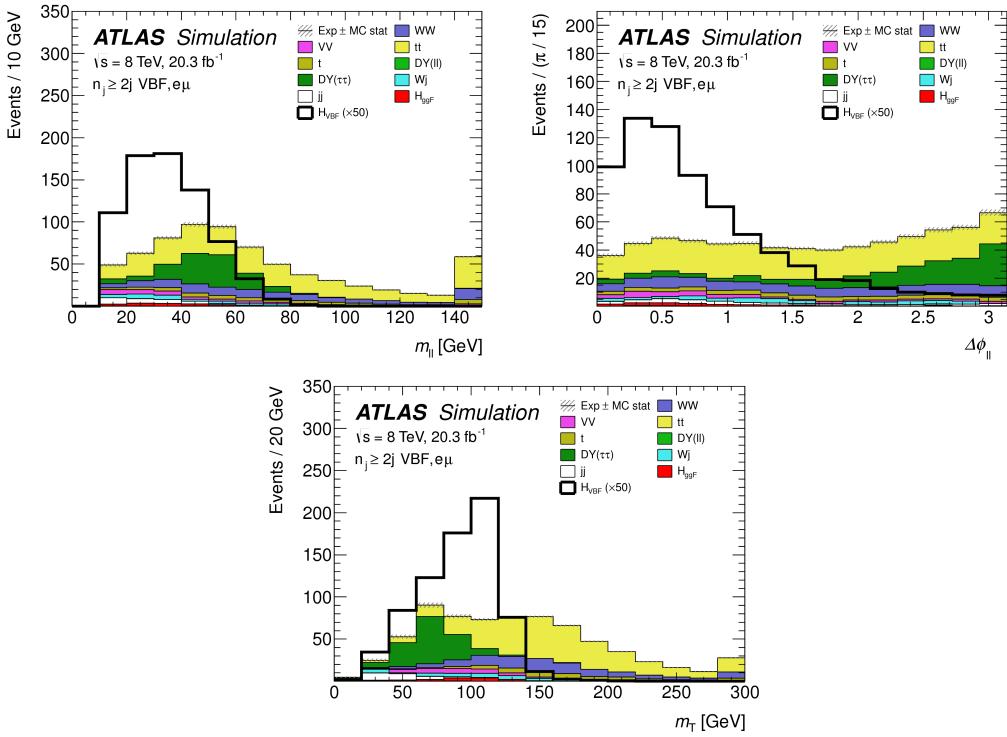


Figure 5.9: Higgs topology variables -  $m_{\ell\ell}$  (top left),  $\Delta\phi_{\ell\ell}$  (top right), and  $m_T$  (bottom) - used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [74]. The VBF Higgs signal cross section is multiplied by a factor of 50 to allow for shape comparisons.

1990 equation 5.4.

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

1991 Phrased this way, the equation shows that with enough events in the control region, a large theoretical  
 1992 uncertainty on the overall background yield in the signal region can be replaced by a small statistical un-  
 1993 certainty coming from the number of data events in the CR and a smaller theoretical uncertainty on the  
 1994 extrapolation from the control region to the signal region.

### 1995 5.5.2 TOP BACKGROUND

1996 The normalization factor  $\beta_t$  for the top background in the VBF analysis is derived in a region required to  
 1997 have one  $b$ -tagged jet, or  $n_b = 1$ . In the cut-based analysis, normalization factors are computed after every  
 1998 selection requirement by making the same requirements in the CR. These NF are then applied to the  $t\bar{t}$  and

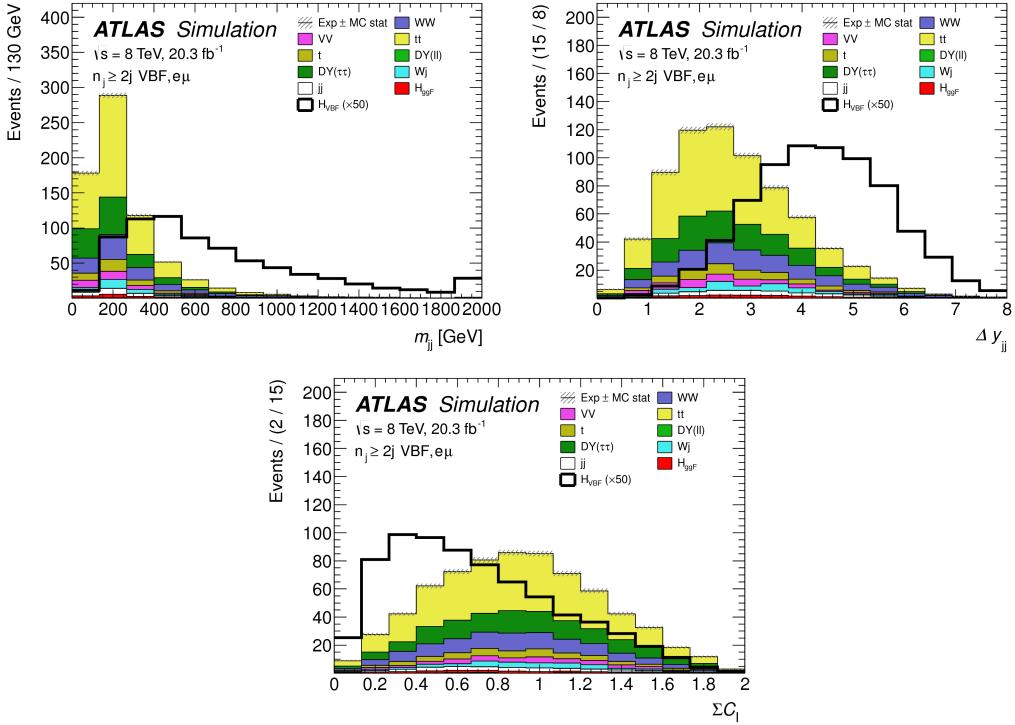


Figure 5.10: VBF topology variables -  $m_{jj}$  (top left),  $\Delta y_{jj}$  (top right),  $\sum C_\ell$  (bottom) - used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [74]. The VBF Higgs signal cross section is multiplied by a factor of 50 to allow for shape comparisons.

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 5.10 shows the evolution of the  $\beta_t$  through the cut-based selection. Table 5.11 shows the value of the  $\beta_t$  in each bin of  $O_{\text{BDT}}$ . The computed factors are almost all relatively consistent with unity, except for bin 1 of  $O_{\text{BDT}}$  which requires a larger correction. The normalization factors in bins 2 and 3 of  $O_{\text{BDT}}$  are also consistent with those derived in the cut-based signal region, increasing confidence in the BDT estimation. Figure 5.11 shows the  $m_{jj}$  and  $O_{\text{BDT}}$  distributions in the top control region. Overall the modeling looks 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

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 5.10: 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 5.11: Top normalization factors computed for each bin of  $O_{\text{BDT}}$ . Uncertainties are statistical only.

2010 (meaning there is a dedicated Poisson constraint) and allowed to float in the final statistical fit.

2011 5.5.3  $Z/\gamma^* \rightarrow \tau\tau$  BACKGROUND

2012 In the different flavor channels, the  $Z/\gamma^* \rightarrow \tau\tau$  background is an important one. Di-tau production can  
2013 produce an  $e\mu$  final state if each  $\tau$  lepton decays to a different flavor lepton.

2014 In the BDT analysis, a single normalization factor for the background is derived. A control region  
2015 is defined using the pre-training selection cuts, except requiring that  $|m_{\tau\tau} - m_Z| < 25 \text{ GeV}$  so that  
2016 the region is enriched in  $Z/\gamma^* \rightarrow \tau\tau$  background. Additional requirements of  $m_{\ell\ell} < 80(75) \text{ GeV}$   
2017 in the different (same) flavor channel, as well as  $O_{\text{BDT}} > -0.48$  are applied to increase the purity of the  
2018 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  
2019 contribution of this background in the BDT analysis and the large statistical uncertainty, no additional  
2020 systematics are calculated. The final SR estimate is scaled by this  $\beta$  and not allowed to float in the fit.

2021 The cut-based corrections are a bit more involved because they need to be applied selection by selection,  
2022 as well as in the final signal region for the fit. The control region is defined including all SR requirements

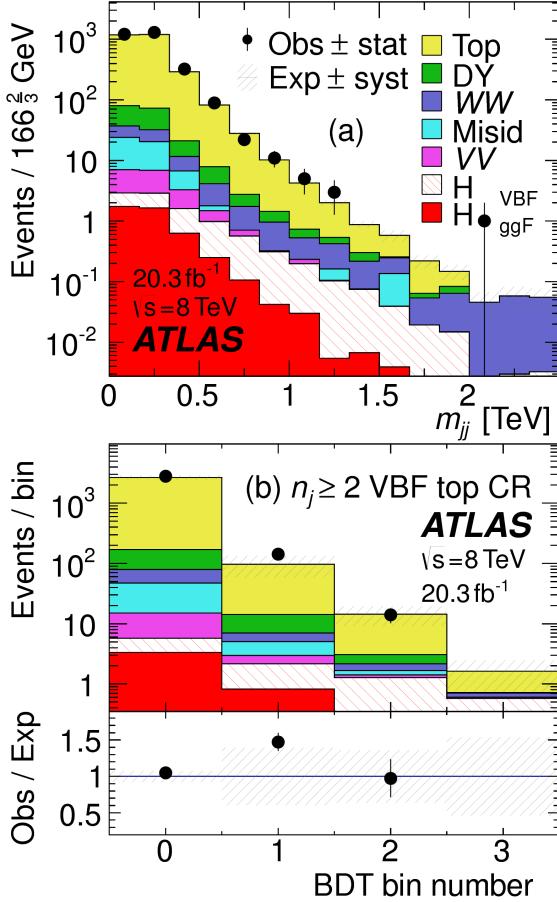


Figure 5.11: Distributions of  $m_{jj}$  (a) and  $O_{\text{BDT}}$  (b) in the VBF  $n_b = 1$  top CR [74].

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

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

2031 The hypothesis is that while the normalization correction must be derived in a dedicated region, the effi-  
 2032 ciency of the VBF topology requirements should not be sensitive to the type of  $Z/\gamma^*$  process and thus the  
 2033 higher number of events can be exploited to derive the CF. Figure 5.12 shows a shape comparison for the  
 2034  $m_{jj}$  variable in  $Z \rightarrow \tau\tau$  events in the signal region and  $Z \rightarrow \ell\ell$  events in the control region. The figure  
 2035 shows that the shapes are indeed comparable and thus any CF derived in the same flavor control region  
 2036 can reliably be applied in the signal region.

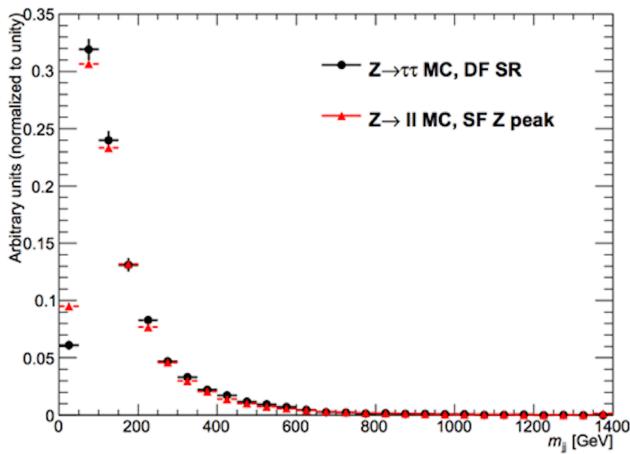


Figure 5.12: Comparison of  $m_{jj}$  shape in a same flavor  $Z \rightarrow \ell\ell$  control region and the VBF cut-based signal region.  
The MC samples used for these distributions are given in table 5.4.

2037 Table 5.12 shows the overall normalization factor  $\beta_{\tau\tau}$  and the efficiency correction factors for the various  
 2038 VBF topological cuts. In general, the statistical uncertainties on the cut efficiency corrections are quite  
 2039 good, and the MC tends to underestimate the efficiency of the VBF cuts for the  $Z/\gamma^* \rightarrow \tau\tau$  background.  
 2040 The overall normalization factor is also consistent with that calculated for the BDT analysis.

#### 2041 5.5.4 $Z/\gamma^* \rightarrow \ell\ell$ BACKGROUND

2042 In the same flavor channels, the  $Z/\gamma^* \rightarrow \ell\ell$  background is dominant and thus must be estimated cor-  
 2043 rectly. In both the BDT and cut-based analyses, the background is estimated using the so-called “ABCD”  
 2044 method. The ABCD method creates four different regions by defining requirements on two variables.  
 2045 One of the regions (A) is the signal region, while the other regions are defined by inverting one of both of  
 2046 the requirements. in this case, the two variables used are  $m_{\ell\ell}$  and  $E_T^{\text{miss}}$ , because inverting either of the

$\beta_{\tau\tau}$	$0.97 \pm 0.04$
Cut	Correction factors (CF)
$m_{jj} > 600 \text{ GeV}$	$1.09 \pm 0.01$
$\Delta y_{jj} > 3.6$	$1.14 \pm 0.02$
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 5.12:  $Z/\gamma^* \rightarrow \tau\tau$  correction factors for the VBF cut-based analysis. Uncertainties are statistical only.

2047 SR cuts on these variables will give regions rich in the  $Z/\gamma^* \rightarrow \ell\ell$  background. Figure 5.13 illustrates the  
 2048 definitions of each region.

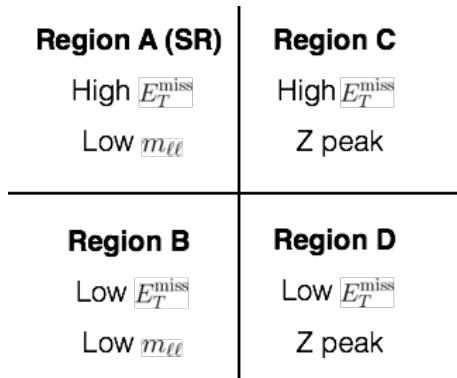


Figure 5.13: General illustration of the ABCD region definitions for  $Z/\gamma^* \rightarrow \ell\ell$  background estimation.

2049 In both of the cut-based and BDT analyses, the Z peak region is defined with  $|m_{\ell\ell} - m_Z| < 15 \text{ GeV}$ .  
 2050 In the cut-based analysis, low  $m_{\ell\ell}$  corresponds to  $m_{\ell\ell} < 50 \text{ GeV}$  (this defines the cut-based SR) while  
 2051 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  
 2052 the 55 GeV cut applied for the signal region definition. The BDT low  $E_T^{\text{miss}}$  region is between 25 and  
 2053 45 GeV, while the high  $E_T^{\text{miss}}$  region is  $E_T^{\text{miss}} > 45 \text{ GeV}$ .

2054 Once the regions are defined, the background in the signal region is estimated by extrapolating the  
 2055 estimate in region B to region A. This extrapolation is done by multiplying the number of events in region  
 2056 B by the ratio of the number of events in regions C and D. Effectively, the Z peak region is used to estimate  
 2057 the efficiency of the  $E_T^{\text{miss}}$  requirement in data, and then this efficiency is applied in the low  $m_{\ell\ell}$  region.  
 2058 The method assumes that the  $E_T^{\text{miss}}$  efficiency is uncorrelated with  $m_{\ell\ell}$ . The method can be applied in

2059 MC as a check on this assumption, and an additional correction,  $f_{\text{corr}}$ , is applied for the non-closure of  
 2060 the method in MC. This is summarized in equations 5.6 and 5.7.

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

2061

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

2062 Here, the  $N$  refer to data yields in each region with the non  $Z/\gamma^*$  backgrounds subtracted, while  $B$  refer  
 2063 to the  $Z/\gamma^*$  yields in MC in each region.

2064 A normalization factor  $\beta_{\ell\ell}$  is computed for each analysis as the ratio of the predicted data yield to the  
 2065 MC yield in the SR. The shape of the BDT distribution is taken from data region B, while the shape of  
 2066 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  
 2067 cut-based and BDT analyses from this method are summarized in table 5.13. They are quite consistent  
 2068 with one another within the statistical uncertainties. The value of  $f_{\text{corr}}$  is found to be  $0.77 \pm 0.13$ . In the  
 2069 cut-based analysis, the same cut efficiency correction factors shown in table 5.12 are also applied (in product  
 2070 with the  $\beta_{\ell\ell}$ ) to obtain the final estimate of the  $Z/\gamma^*$  background in the same flavor channels.

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

Table 5.13:  $Z/\gamma^* \rightarrow \ell\ell$  normalization factors for cut-based and BDT analyses. Uncertainties are statistical only.

2071 **5.5.5  $WW$  AND OTHER DIBOSON BACKGROUNDS**

2072 The Standard Model  $WW$  and other diboson backgrounds ( $WZ$ ,  $ZZ$ ,  $W\gamma$ ,  $W\gamma^*$ , and  $Z\gamma$ ) have both  
 2073 their shape and normalization taken from MC simulation as they are subdominant in the VBF analysis.  
 2074 They are validated in dedicated control regions and found to agree with data well.

2075 As SM  $WW$  production is the largest of these backgrounds and is irreducible, validating the estimate  
 2076 is of particular importance. A validation region is constructed by requiring the pre-selection requirements

2077 on leptons and  $m_{\ell\ell}, n_b = 0$ , and  $m_T > 100$  GeV. The  $m_{T2}$  variable is an additional discriminant that  
 2078 has been shown to have the ability to isolate the SM  $WW$  background [99]. It is calculated by scanning  
 2079 over all possible values of neutrino momentum for both  $W$  bosons and taking the minimum result. A  
 2080 requirement of  $m_{T2} > 160$  GeV is placed to define the  $WW$  validation region. This requirement gives a  
 2081 60% purity for the validation region. The derived normalization factor in this region is  $1.15 \pm 0.19$  and  
 2082 is thus consistent with unity. Figure 5.14 shows the  $m_{T2}$  distribution and how it distinguishes the  $WW$   
 2083 background.

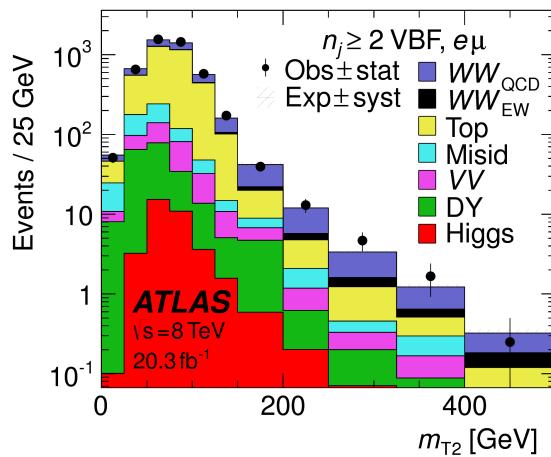


Figure 5.14: Distribution of  $m_{T2}$  in the  $WW$  validation region of the VBF analysis [74].

### 2084 5.5.6 HIGGS PRODUCTION VIA GLUON-GLUON FUSION

2085 Because this analysis is dedicated to measuring the VBF contribution to Higgs production, the component  
 2086 of Higgs production from gluon-gluon fusion is treated as a background. The shape is taken directly from  
 2087 simulation, using the generators described in table 5.4. In the final combined fit of all different Higgs  
 2088 signal regions, the normalization is controlled by either a combined signal strength parameter  $\mu$ , which  
 2089 controls the normalization of both ggF and VBF production, or a separate parameter  $\mu_{ggF}$  depending on  
 2090 the interpretation being presented in the final results.

2091 5.5.7 BACKGROUNDS WITH MISIDENTIFIED LEPTONS

2092 As discussed previously, the  $W+jets$  and QCD multijet backgrounds are derived with fully data-driven  
2093 methods. These backgrounds do not make a large contribution to the final VBF signal region but their es-  
2094 timation methods are discussed briefly here. Because both backgrounds involve at least one mis-identified  
2095 lepton, they are labeled as “misid” throughout this chapter.

2096  $W+jets$  BACKGROUND

2097 The  $W+jets$  background enters the signal region by having one of the jets mis-reconstructed as a lepton.  
2098 The background is estimated by constructing a control sample with two leptons, where one lepton passes  
2099 the usual lepton quality requirements but the second lepton fails one of those requirements (also known  
2100 as the “anti-identified” lepton). This control region is rich in the  $W+jets$  contribution because if a second  
2101 lepton is reconstructed in a  $W+jets$  event it is likely to be of poor quality. The purity of this  $W+jets$  control  
2102 sample is 85% to 90% depending on the exact configuration of leptons in the final state.

2103 The  $W+jets$  content of the signal region is estimated by extrapolation from the control sample to the  
2104 signal region using extrapolation factors derived in a  $Z+jets$  control sample in data. The assumption of  
2105 the method is that the probability of a jet being misidentified as a lepton does not change between  $W+jets$   
2106 and  $Z+jets$  samples, and systematic uncertainties are assigned for differences in sample composition. The  
2107 extrapolation factor is defined as the ratio of the number of lepton candidates satisfying all quality criteria  
2108 to the number of lepton candidates anti-identified. This ratio is measured in bins of  $p_T$  and  $\eta$ . Thus, the  
2109 final signal region estimate (binned as the extrapolation factor is binned) is simply the number of events in  
2110 the anti-identified lepton control sample multiplied by the extrapolation factor derived from the  $Z+jets$   
2111 control sample. Figure 5.15 shows the extrapolation factors derived for electrons and muons. The extrap-  
2112 olation factor can be seen in the figure to be an order of magnitude larger for muons than electrons, but  
2113 this does not indicate that jets have a larger probability to be mis-identified as a muon than an electron.  
2114 Values of the extrapolation factor are actually determined by the specific requirements used to define an  
2115 anti-identified lepton. The difference between the muon and electron extrapolation factors comes from  
2116 different definitions of the anti-identified lepton in each case.

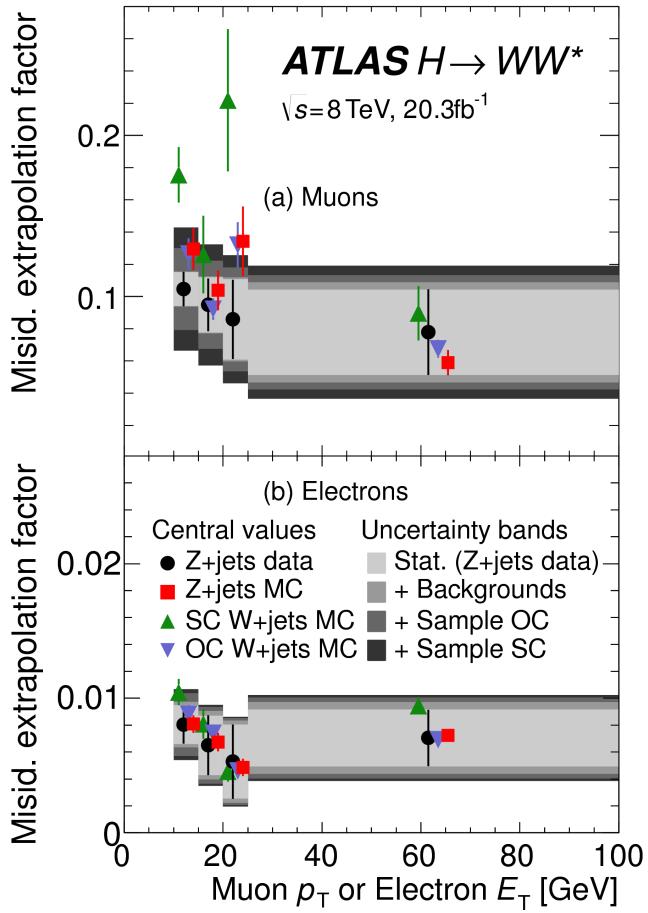


Figure 5.15: Extrapolation factors for the  $W$ +jets estimate derived for muons (a) and electrons (b) as a function of lepton  $p_T$  [74]. OC refers to the opposite charge  $W$ +jets MC sample, while SC refers to the same charge  $W$ +jets MC. The uncertainty bands have contributions from statistical uncertainty in the data and backgrounds to  $Z$ +jets that are subtracted from the data, as well as systematic uncertainties due to variations in the extrapolation factor between the three MC samples shown.

2117    QCD MULTIJET BACKGROUND

2118    The method for estimating the multijet background is very similar to the  $W$ +jets estimation method. The  
 2119    control sample in this case has two anti-identified leptons but otherwise satisfies all signal region require-  
 2120    ments. The extrapolation factor is estimated from a multijet sample and applied twice to the control sam-  
 2121    ple.

2122 5.5.8 BACKGROUND COMPOSITION IN SIGNAL REGION

2123 After all of these estimation procedures, the signal region background composition can be calculated. The  
2124 estimated yields are all shown in table 5.8. Figure 5.16 shows the relative percentages of the different back-  
2125 ground for the different flavor and same flavor final states. In  $e\mu$ , the leading backgrounds are top back-  
2126 grounds, ggF Higgs, and SM  $WW$  production. In  $ee/\mu\mu$ , the leading background is Drell-Yan, followed  
2127 by top and ggF Higgs.

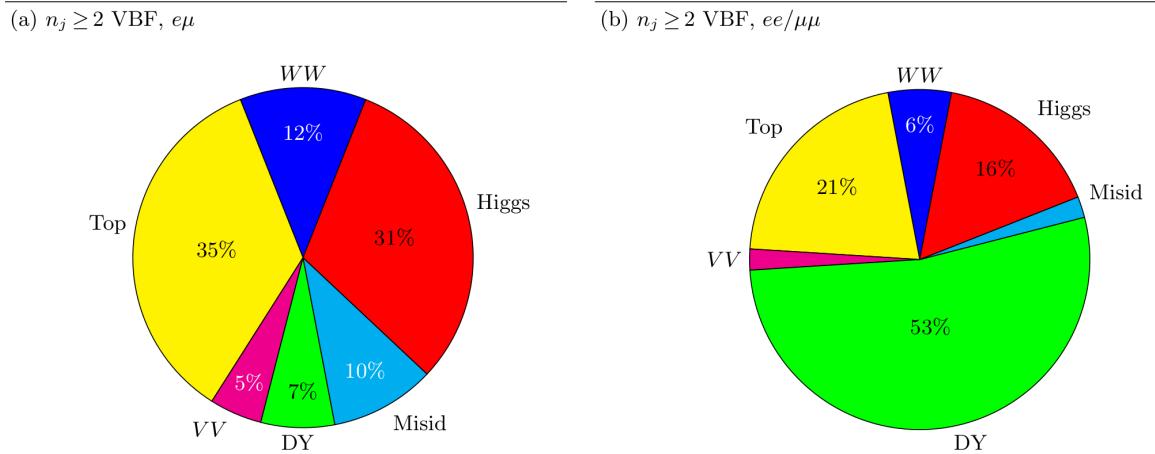


Figure 5.16: Background composition in final VBF signal region [74].

2128 5.6 SYSTEMATIC UNCERTAINTIES

2129 There are two main types of systematic uncertainties that are assessed for the analysis. First, theoretical  
2130 uncertainties associated with the signal and background yield estimates are discussed. Then, experimental  
2131 uncertainties due to detector effects are shown. Normalization uncertainties refer to uncertainties that  
2132 affect the cross section of the process in question in the signal region being probed. Shape uncertainties  
2133 refer to systematic uncertainties that affect the shape of the final discriminating variable (either  $m_T$  or  
2134  $O_{\text{BDT}}$ ).

2135    5.6.1 THEORETICAL UNCERTAINTIES

2136    There are four main components to theoretical uncertainties assigned to signal and background processes  
2137    taken from Monte Carlo. Each one is a different source of variation in the overall acceptance for that  
2138    process. The first involves variation of the QCD renormalization and factorization scales used in the cal-  
2139    culation. In this case, the two scales are varied both independently and simultaneously by factors of two  
2140    high or low. The resulting variation in normalization and shape for the process is taken as a systematic  
2141    uncertainty (referred to as scale uncertainty). This uncertainty approximates the level of the correction  
2142    to the cross section that would come from including the next order of the QCD calculation. Next, there  
2143    is an uncertainty associated with the PDF set used in generating the events. The uncertainty eigenvect-  
2144    tors for the given PDF set are inspected, and the envelope of maximal variation is taken as an uncertainty  
2145    (referred to as PDF uncertainty). Finally, there are two uncertainties associated with the choice of MC  
2146    software. An uncertainty associated with the generator chosen for the hard scattering process is evaluated  
2147    by keeping the parton showering software constant but varying the matrix element generator and taking  
2148    the maximal variation as an uncertainty (referred to as the generator uncertainty). The converse variation  
2149    can also be done, where the matrix element generator remains constant and the generator used for the un-  
2150    derlying event/parton shower modeling is varied (referred to as the UE/PS uncertainty). In cases where  
2151    the background is normalized in a control region, the systematic uncertainty arises from variations of the  
2152    extrapolation factor  $\alpha$  between the CR and the SR, which can affect the normalization of the background  
2153    in the SR.

2154    There are two additional uncertainties that are applied to the Higgs processes as well. First, there are  
2155    uncertainties assigned to the Higgs total production cross section. Then, there are uncertainties assigned  
2156    based on the fact that the analysis is done in exclusive jet bins and it is possible for signal events to migrate  
2157    from one bin to the next depending on the presence or absence of jets. These are assigned using the Jet Veto  
2158    Efficiency (JVE) procedure [18, 100] for ggF events and the Stewart-Tackmann (ST) method [101] for VBF  
2159    production. Table 5.14 shows the total theory uncertainties on the backgrounds in the cut-based analysis.  
2160    These are the sum in quadrature of the uncertainties from each of the variations described above.

2161    Figures 5.17 and 5.18 show the variations in the extrapolation factor from the PDF and QCD uncertain-

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

Table 5.14: Theoretical 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.

ties 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 5.14

While the estimate for the same-flavor  $Z/\gamma^* \rightarrow \ell\ell$  background is data-driven, there is still a systematic uncertainty taken for the non-closure of the method in Monte Carlo. This is taken as the maximum of the 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 the cut-based analysis this non-closure uncertainty 23%, while for the BDT analysis it is 17%.

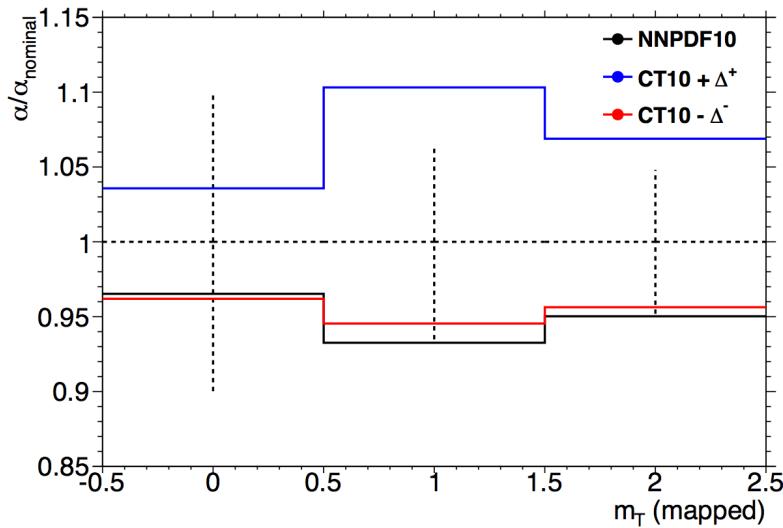


Figure 5.17: Variations in the top background extrapolation factor in the cut-based analysis due to PDF uncertainties. The uncertainties are shown in the three bins of  $m_T$  used in the final cut-based statistical fit. Variations from the eigenvector of the nominal PDF, CT10, as well as the result from an alternate PDF (NNPDF10), are compared.

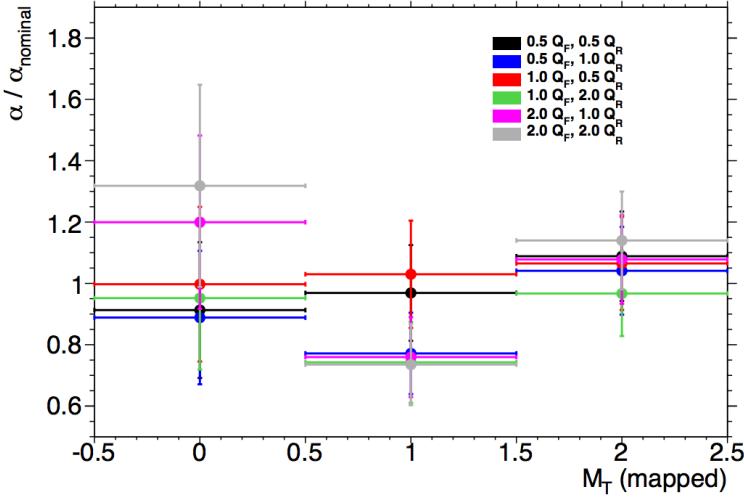


Figure 5.18: Variations in the top background extrapolation factor in the cut-based analysis due to QCD scale uncertainties. The uncertainties are shown in the three bins of  $m_T$  used in the final cut-based statistical fit.  $Q_F$  is the QCD factorization scale, while  $Q_R$  is the QCD renormalization scale.

### 2170 5.6.2 EXPERIMENTAL UNCERTAINTIES

2171 In this analysis, the theoretical uncertainties are the most dominant after statistical, but there are some  
 2172 experimental uncertainties that make a contribution as well. The first is the uncertainty on the measured  
 2173 integrated luminosity, which affects the signal estimate and backgrounds whose normalizations are taken  
 2174 from MC. It is measured to be 2.8% in the 8 TeV dataset [102]. The dominant sources of uncertainty over-  
 2175 all are uncertainties on the jet energy scale and resolution and the  $b$ -tagging efficiency. Additional sources  
 2176 include lepton uncertainties on identification, resolution, and trigger efficiency, as well as uncertainties on  
 2177 the missing transverse momentum.

2178 The jet energy scale uncertainty is split into several independent components, including jet-flavor de-  
 2179 pending calorimeter response uncertainties, uncertainties on modeling of pile-up interactions, uncertain-  
 2180 ties on extrapolation from the central to forward detector regions, and MC non-closure [103]. The uncer-  
 2181 tainty on energy scale for jets used in this analysis ranges from 1% to 7% depending on the jet  $p_T$  and  $\eta$ .  
 2182 The jet energy resolution varies from 5% to 20%, with uncertainties ranging from 2% to 40% (the largest  
 2183 uncertainties occurring at the selection threshold).

2184 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 [104, 105]. The efficiencies and their uncertainties are binned in  $p_T$  and decomposed into uncorrelated components using an eigenvector method [106]. Uncertainties on the efficiency range from 1% to 7.8%. The uncertainty on the rate of misidentification of  $c$ -jets as  $b$ -jets ranges from 6-14%, while the uncertainty on the rate of light jet mis-tagging ranges from 9-19% depending on  $p_T$  and  $\eta$ . These efficiency uncertainties are applied to each individual jet in the event.

Table 5.15 shows the effect of the experimental uncertainties on the VBF signal yield. The largest experimental uncertainty is the jet energy scale and resolution. Object uncertainties associated with  $p_T^{\text{miss}}$ , electrons, and muons also make a small contribution, as well as the uncertainty on the trigger efficiency.

Uncertainty source	Impact on signal yield (%)
Jet energy scale and resolution	5.4
Luminosity	2.8
$p_T^{\text{miss}}$ scale and resolution	1.2
Electron uncertainties	1.0
Muon uncertainties	0.9
Trigger efficiency	0.4

Table 5.15: Experimental systematic uncertainties (expressed as % of the estimated yield) for the VBF signal [74].

The total experimental uncertainties on different signal and background components are summarized in table 5.16. 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.

## 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 5.17. Most of the information about the VBF signal comes from bins 2 and 3 which have significantly better signal to background ratios than bin

Sample	Total uncert.	Stat. uncert.	Expt. uncert.	Theo. uncert.
$n_j \geq 2$ 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 5.16: 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 [74]. “Stat.” refers to statistical uncertainties, “Expt.” refers to experimental systematic uncertainties, and “Theo.” refers to theoretical systematic uncertainties.

- 2204 1. Additionally, the same-flavor channels contribute roughly the same sensitivity as the different flavor  
 2205 channels, highlighting the gain from adding these channels post-discovery with the techniques discussed  
 2206 in chapter 3.

(a) Before the BDT classification

Selection	Summary						Composition of $N_{\text{bkg}}$										
	$N_{\text{obs}}/N_{\text{bkg}}$	$N_{\text{obs}}$	$N_{\text{bkg}}$	$N_{\text{signal}}$			$N_{WW}^{\text{QCD}}$	$N_{WW}^{\text{EW}}$	$N_{t\bar{t}}$	$N_t$	$N_{Wj}$	$N_{jj}$	$N_{VV}$	$N_{\text{Drell-Yan}}$	$N_{ee/\mu\mu}^{\text{QCD}}$	$N_{\tau\tau}^{\text{QCD}}$	$N_{\tau\tau}^{\text{EW}}$
				$N_{ggF}$	$N_{VBF}$	$N_{\text{VH}}$											
$e\mu$ 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 5.17: 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 [74].

- 2207 Figure 5.19(a) shows the final distribution of data candidates compared to the expected  $m_T$  distribution

for signal and background in the cut-based signal region. The data are very consistent with a VBF Higgs hypothesis. Figure 5.19(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 5.20 shows the distributions of  $O_{\text{BDT}}$  and  $m_T$  in the

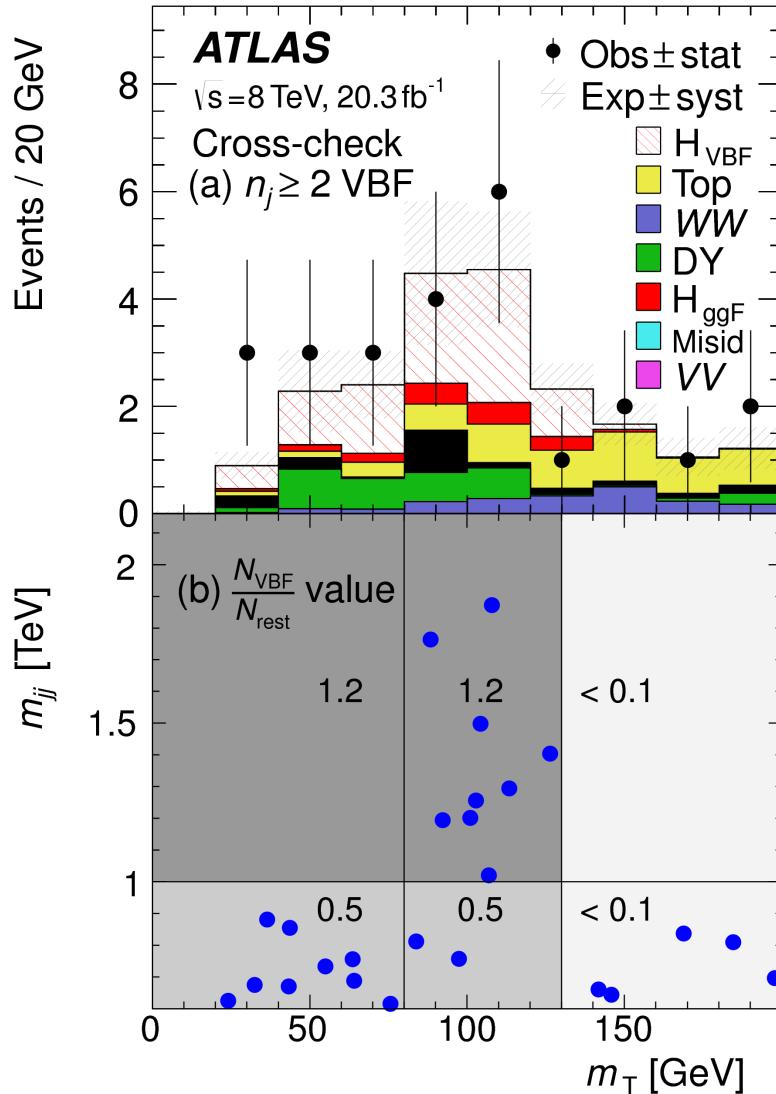


Figure 5.19: Post-fit distributions in the cut-based VBF analysis. Panel (a) shows the one-dimensional  $m_T$  distribution, while (b) shows the data candidates split into the bins of  $m_T$  and  $m_{jj}$  used in the final fit [74].

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

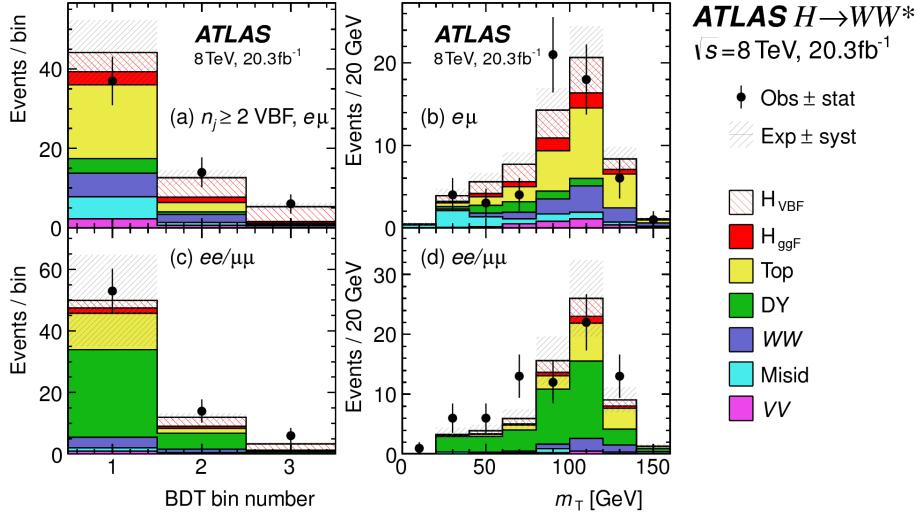


Figure 5.20: Postfit distributions in the BDT VBF analysis [74].

2214 twenty events in the cut-based signal region, only seven were not selected by the BDT analysis, while the  
 2215 other thirteen also enter the BDT signal region. Figure 5.21 shows where the different analysis candidates  
 2216 lie in the  $m_{jj}$ - $m_T$  plane. This shows clearly that the advantage of the BDT analysis is that it can extract  
 2217 signal candidates from the lower  $m_{jj}$  region due to its ability to recognize correlations with other variables.

2218 While the context of these results in the broader  $H \rightarrow WW^*$  statistical analysis will be presented in the  
 2219 next chapter, the statistical significance of the VBF Higgs result is shown here. In the BDT analysis, the  
 2220 expected signal significance was  $2.7\sigma$ , while the observed significance was  $3.1\sigma$ . In the cut-based analysis,  
 2221 the expected significance was  $2.1\sigma$  and the observed significance was  $3.0\sigma$ . The compatibility between  
 2222 these two results can be evaluated by computing the probability of observing a larger difference in  $Z_0$  values  
 2223 than the one measured. Using toy Monte Carlo with the ggF signal strength fixed to unity and considering  
 2224 only statistical uncertainties, this probability is computed to be 79%, indicating good agreement between  
 2225 the analyses. This result represents the first evidence of the vector boson fusion production of a Higgs  
 2226 boson.

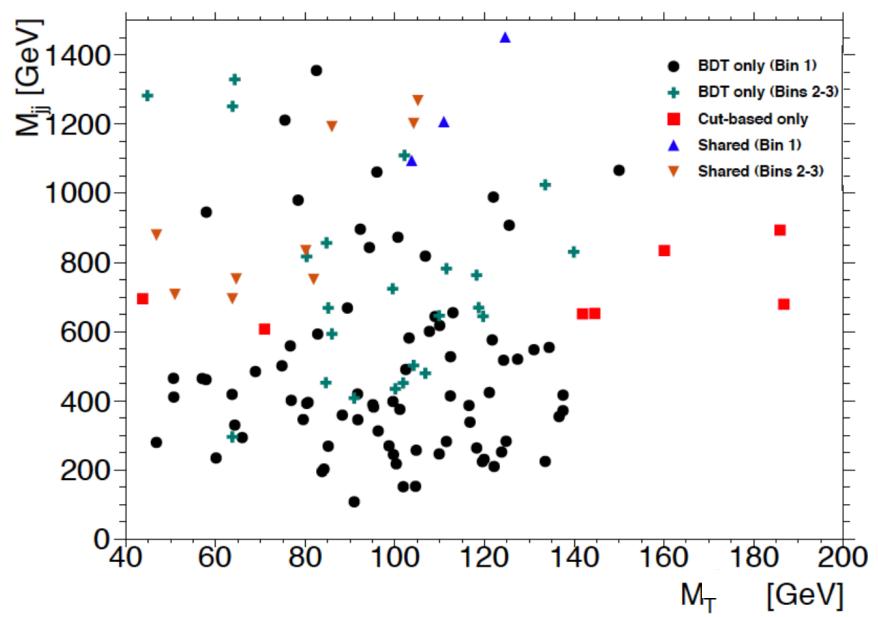


Figure 5.21: Overlap between cut-based and BDT VBF signal region candidates in the  $m_{jj}$ - $m_T$  plane.

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

Chuck Palahniuk

# 6

2227

2228

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

2229

## results

2230

### 6.1 INTRODUCTION

2231

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

2238

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

2239 for gluon fusion and vector boson fusion Higgs production. First, the results of the dedicated gluon fu-  
 2240 sion search are presented. Then, a comparison of the individual production mode signal strengths ( $\mu_{\text{ggF}}$   
 2241 and  $\mu_{\text{VBF}}$ ) and a measurement of the combined signal strength ( $\mu$ ) are shown. Subsequently, the mea-  
 2242 sured values of the Higgs couplings to fermions and vector bosons is presented. Finally, the cross section  
 2243 measurement for ggF and VBF production are shown.

## 2244 6.2 RESULTS OF DEDICATION GLUON FUSION $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ ANALYSIS

2245 The details of the dedicated gluon fusion  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis are not discussed in this thesis  
 2246 and instead left to more comprehensive sources [74]. However, a brief summary of the results is essen-  
 2247 tial for describing the measurements of Higgs properties and interpreting the the dedicated VBF Higgs  
 2248 production search in a broader context. Additionally, the final Run 1 results on gluon fusion production  
 2249 make use of the dedicated variables for same flavor final states developed in section 3.5. The results in the  
 2250 same flavor final states will be shown here as well.

### 2251 6.2.1 RESULTS IN SAME FLAVOR ( $ee/\mu\mu$ ) FINAL STATES

2252 Final states of the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel where both leptons have the same flavor ( $ee/\mu\mu$ )  
 2253 were not included in the discovery result due to increased pileup conditions in the  $\sqrt{s} = 8$  TeV data.  
 2254 Dedicated techniques for background reduction in the same flavor final states were developed, as described  
 2255 in section 3.5. The results shown in this section are the first published results using the same flavor channels  
 2256 in the  $H \rightarrow WW^*$  analysis.

2257 Table 6.1 shows the background estimate, expected signal yield, and event count in data for the same  
 2258 flavor channels in the  $n_j \leq 1$  signal regions. The dedicated same flavor background reduction techniques  
 2259 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 [74].

2260     Figure 6.1 shows the final  $m_T$  distribution in data for the  $n_j \leq 1$  same flavor channels. The data is very  
 2261     consistent with the Higgs hypothesis and it can be seen that the same flavor channels are indeed sensitive  
 2262     to gluon fusion production of the Higgs.

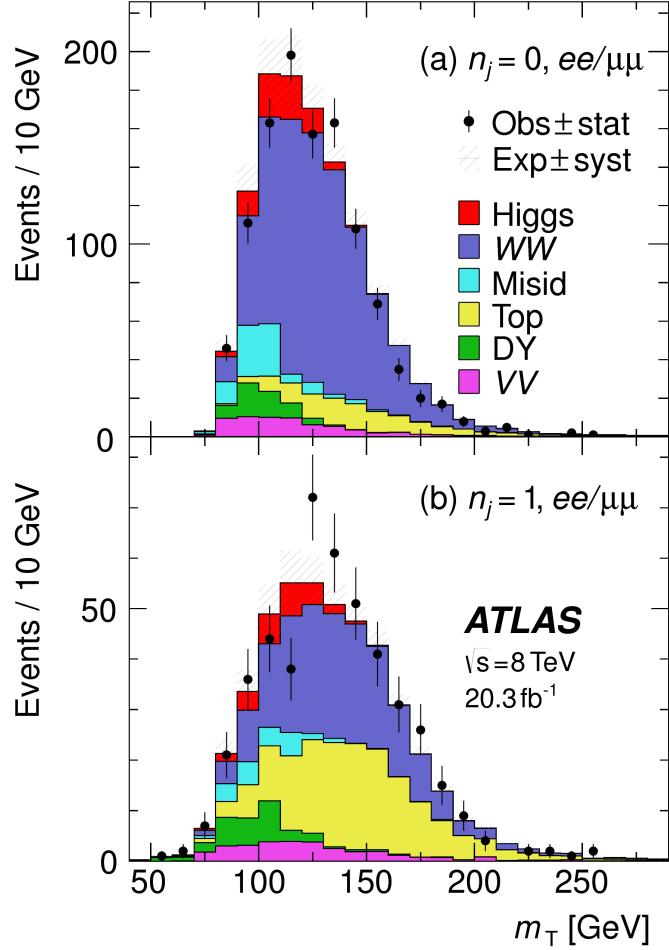


Figure 6.1: Post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions for the same flavor ( $ee/\mu\mu$ ) final states [74].

### 2263     6.2.2 COMBINED GLUON FUSION RESULTS

2264     Table 6.2 shows the individual signal regions that were input into the final statistical fit. The ggF dedicated  
 2265     bins use  $m_T$  as their discriminating variable and are separated into bins of  $p_T$  of the subleading lepton as  
 2266     well. The VBF dedicated bin uses the  $O_{BDT}$  distribution as its final discriminant.

2267     Table 6.3 shows the yields in the various signal regions in both data and expected signal and back-  
 2268     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 [74].

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 [74].

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

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

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

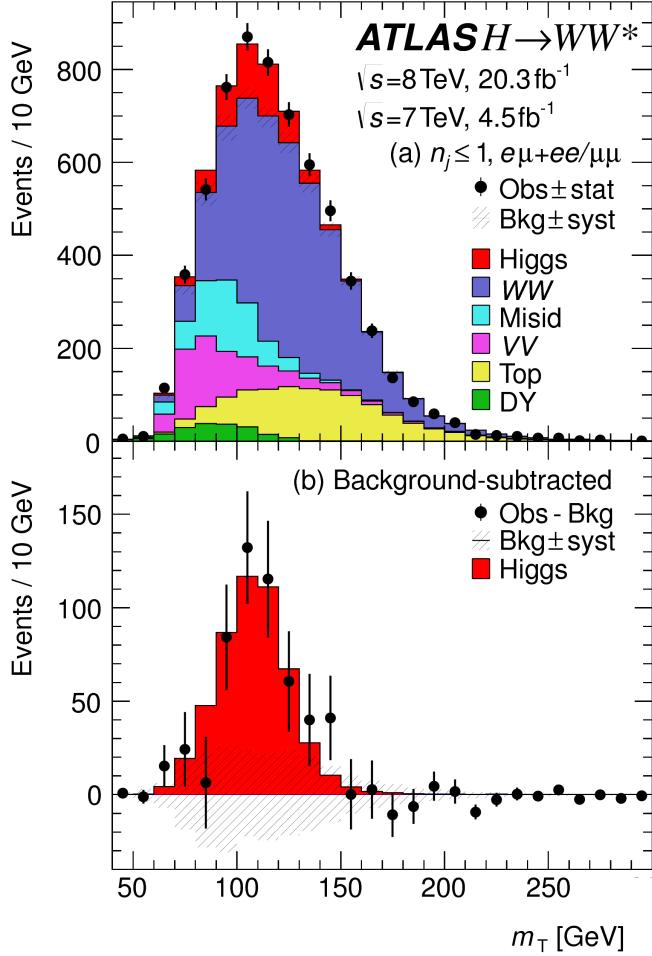


Figure 6.2: Post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions [74].

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.

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

2280 Figure 6.3 gives the best fit signal strength  $\hat{\mu}$  as a function of the hypothesized Higgs mass. The value at  
 2281 a mass of 125.36 GeV corresponds to the  $\mu$  quoted in equation 6.1. This value of the Higgs mass is used  
 2282 because it is the most precise mass measurement from ATLAS, a result of the combined  $\gamma\gamma$  and  $ZZ$  mass  
 2283 measurements [107].

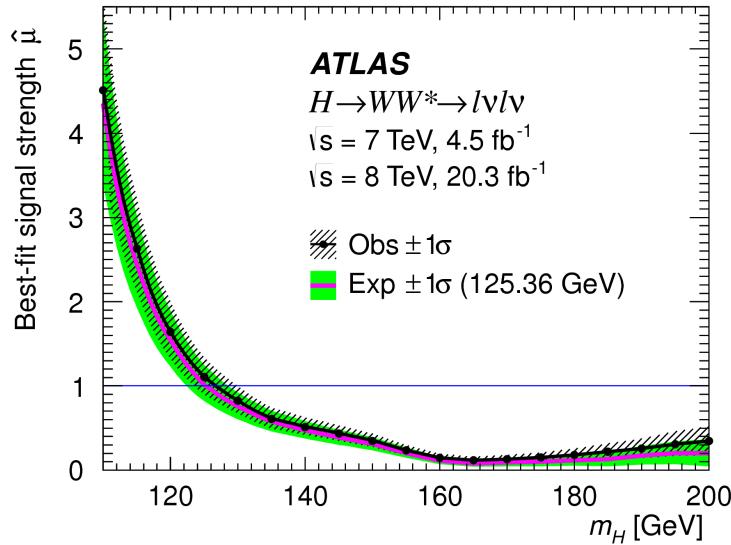


Figure 6.3: Best fit signal strength  $\hat{\mu}$  as a function of hypothesized  $m_H$  [74].

2284 As explained in chapter 3, a probability  $p_0$  can be computed using the test statistic  $q_0$  to quantify the  
 2285 probability that the background could fluctuate to produce an excess at least as large as the one observed  
 2286 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  
 2287  $m_H = 130$  GeV and corresponds to a significance of  $6.1\sigma$ . The curve is relatively flat and the significance  
 2288 is the same at 125.36 GeV within the quoted precision. The expected significance for a signal with strength  
 2289  $\mu = 1.0$  is  $5.8\sigma$ . This represents the first discovery level observation of Higgs production using only the  
 2290  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis.

2291 All the results presented so far in this section have been for the combined gluon fusion and VBF pro-  
 2292 duction modes. However, each signal strength can be calculated separately in the likelihood as well. There  
 2293 are two ways to do this. First, the likelihood can be parameterized in terms of a single parameter, the ratio  
 2294 of the VBF and gluon fusion signal strengths. With this method, the statistical significance of the VBF  
 2295 Higgs result can be evaluated. Figure 6.5 shows the likelihood as a function of the ratio  $\mu_{\text{VBF}}/\mu_{\text{ggF}}$ .

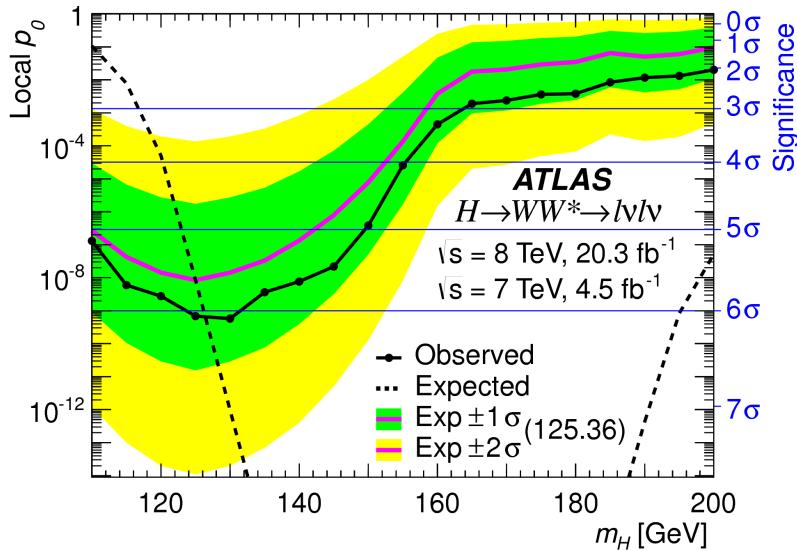


Figure 6.4: Local  $p_0$  as a function of  $m_H$  [74].

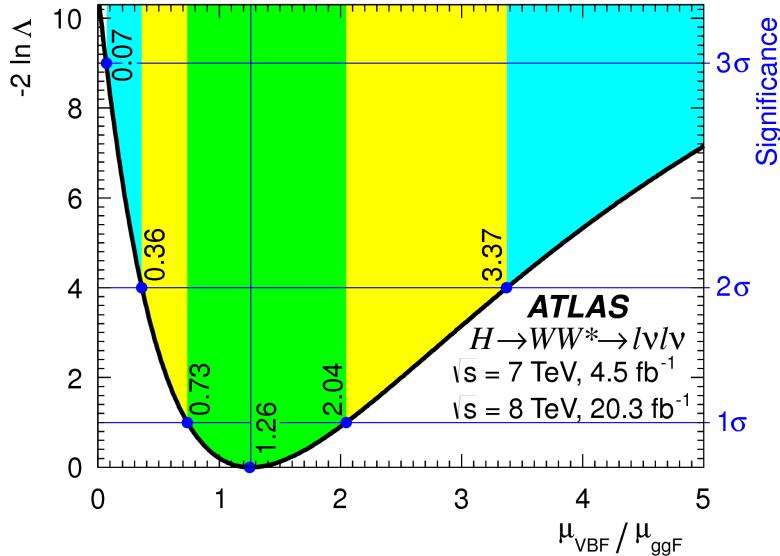


Figure 6.5: Likelihood as a function of  $\mu_{\text{VBF}} / \mu_{\text{ggF}}$  [74].

2296      The best fit value of the ratio of signal strengths is shown in equation 6.2. Within the quoted uncer-  
 2297      tainties, it is consistent with a ratio of unity.

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

2298 The null hypothesis for VBF production corresponds to a ratio of  $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ . The likelihood in  
 2299 figure 6.5 gives a significance of  $3.2\sigma$  at  $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ , as quoted in chapter 5.

2300 In addition to the ratio of signal strengths, each signal strength can be varied independently in the like-  
 2301 lihood as well. Figure 6.6 shows the two dimensional likelihood scan in the  $\mu_{\text{ggF}}-\mu_{\text{VBF}}$  plane. The best fit  
 2302 values of the two signal strengths are shown in equation 6.3. Both are consistent with unity within their  
 2303 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.)

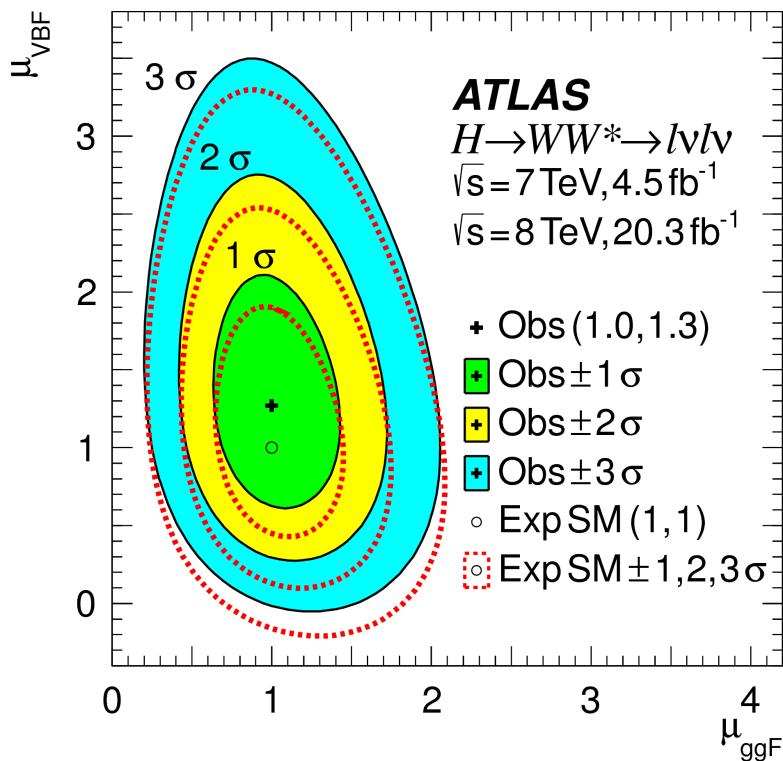


Figure 6.6: Two dimensional likelihood scan as a function of  $\mu_{\text{VBF}}$  and  $\mu_{\text{ggF}}$  [74].

2304 6.4 MEASUREMENT OF HIGGS COUPLINGS TO VECTOR BOSONS AND FERMIONS

2305 Similar to the parameterization of signal strength, the couplings of the Higgs to fermions and bosons can  
 2306 also be parameterized. The parameter of interest in this case is  $\kappa$ , or the ratio of the measured coupling to  
 2307 the Standard Model expectation. Both the fermion and boson couplings have these so-called scale factors,  
 2308  $\kappa_F$  for fermions and  $\kappa_V$  for bosons. Gluon fusion production is sensitive to the fermion couplings through  
 2309 the top quark loops in its production, while VBF production is sensitive to the vector boson couplings in  
 2310 its production. Both modes are sensitive to the vector boson couplings in their decays. The signal strengths  
 2311 will have dependence on the coupling scale factors as described in equation 6.4 [18].

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

2312 Figure 6.7 shows the two-dimensional likelihood scan of  $\kappa_F$  and  $\kappa_V$ . The best-fit values are given in equa-  
 2313 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.)

2314

2315 6.5 HIGGS PRODUCTION CROSS SECTION MEASUREMENT

2316 Another measurement that comes naturally from the signal strength measurements quoted earlier is the  
 2317 production cross section and 7 and 8 TeV for both gluon fusion and VBF production. The general equa-

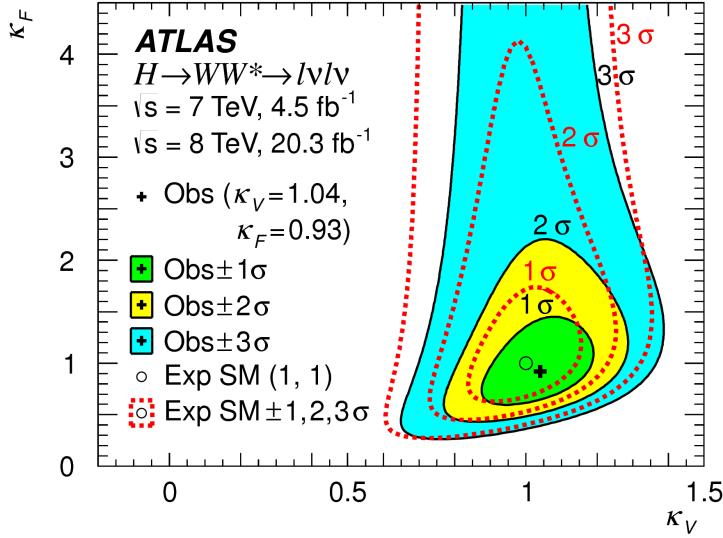


Figure 6.7: Likelihood scan as a function of  $\kappa_F$  and  $\kappa_V$ , the Higgs coupling scale factors [74].

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

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

$(N_{\text{sig}})_{\text{obs}}$  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.

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

(stat.) (syst.)

2324 The predicted cross section values (including the branching ratio of  $H \rightarrow WW^*$ ) for gluon fusion are  
2325  $3.3 \pm 0.4$  pb at 7 TeV and  $4.2 \pm 0.5$  pb at 8 TeV, consistent with the measured values within their uncer-  
2326 tainties. For vector boson fusion, the predicted cross section is  $0.35 \pm 0.02$  pb, again consistent with the  
2327 measured value.

2328 **6.6 CONCLUSION**

2329 The combined analysis of the gluon fusion and vector boson fusion processes in  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  in  
2330 the 7 and 8 TeV datasets has yielded the first discovery level significance for Higgs production in this decay  
2331 channel. Additionally, precise measurements of the couplings to vector bosons and fermions are given.  
2332 Finally, signal strengths and cross sections for each production mode are measured. Figure 6.8 shows the  
2333  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  measurements in comparison with other Higgs decay channels in ATLAS. The  
2334 measurement of signal strength from this channel remains the most sensitive in both the gluon fusion and  
2335 VBF production modes for the Run 1 dataset.

**ATLAS**

### Individual analysis

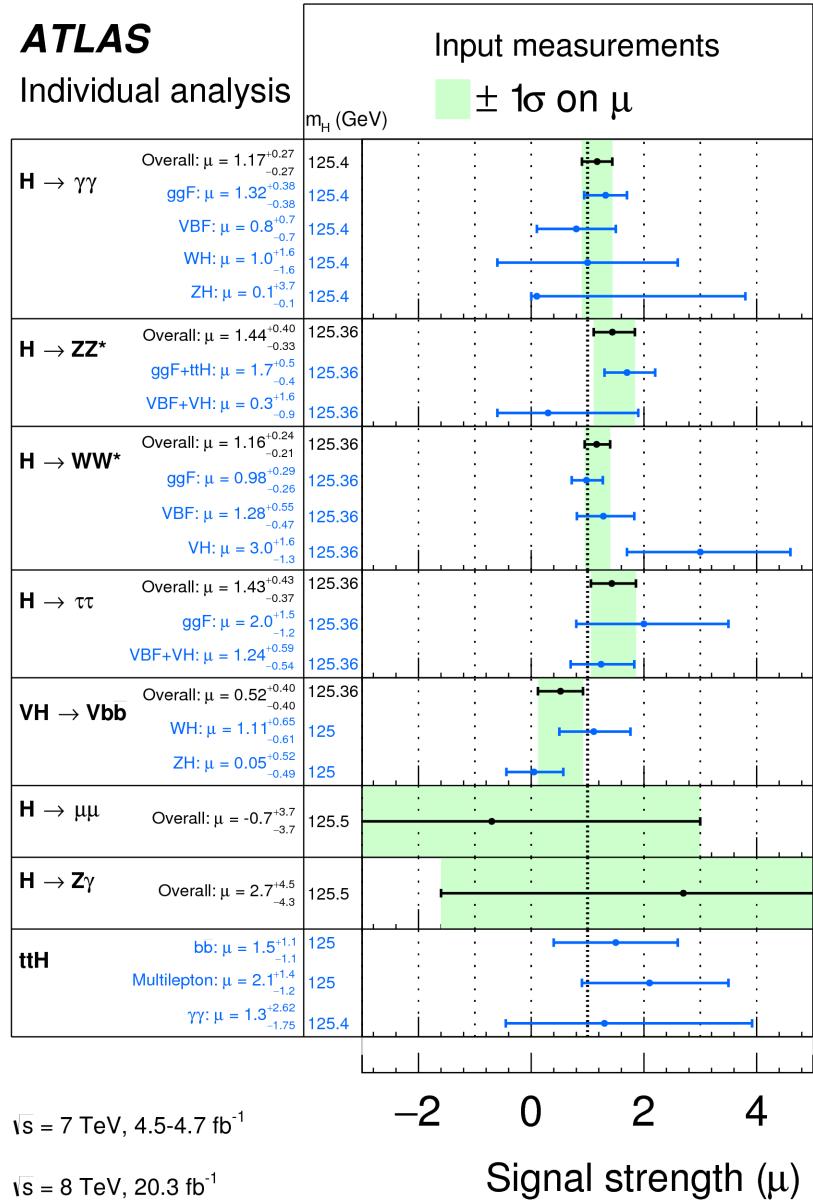


Figure 6.8: Comparison of signal strength measurements in different Higgs decay channels on ATLAS [io8].

2336

## Part III

2337

Search for Higgs pair production in the

2338

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

2339

13 TeV

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

W. Eugene Smith

# 7

2340

## 2341 Search for Higgs pair production in boosted 2342 $b\bar{b}b\bar{b}$ final states

### 2343 7.1 INTRODUCTION

2344 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  
2345 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  
2346 final state in the regime where  $m_X$  is large ( $\gtrsim 1 \text{ TeV}$ ) and the Higgs bosons in the decay are significantly  
2347 boosted. A tailored selection for this boosted selection, using novel techniques in jet substructure and  $b$ -  
2348 tagging, is discussed. Then, the data-driven background estimate is presented. Finally, the results of the  
2349 search are shown. The signal models used as benchmarks are a spin-2 Randall Sundrum graviton (RSG)  
2350 and a narrow width spin zero resonance. These models are described in more detail in Chapter 1. Limits  
2351 on signal models are reserved for the next chapter where the results of this chapter are combined with the

2352 results of a separate selection dedicated to the lower  $m_X$  regime.

2353 **7.2 MOTIVATION**

2354 With the center of mass energy increase from  $\sqrt{s} = 8 \text{ TeV}$  to  $\sqrt{s} = 13 \text{ TeV}$ , the LHC and ATLAS are  
2355 able to probe new resonances at higher mass scales than previously accessible in Run 1. This is a powerful  
2356 motivator for searching for a new resonance in the early 13 TeV data. Figure 7.1 shows the ratios of parton  
2357 luminosities between 8 and 13 TeV for different resonance masses. For a resonance of  $M_X = 2 \text{ TeV}$ , the  
2358 cross section at  $\sqrt{s} = 13 \text{ TeV}$  is roughly a factor of 10 larger than at  $\sqrt{s} = 8 \text{ TeV}$ .

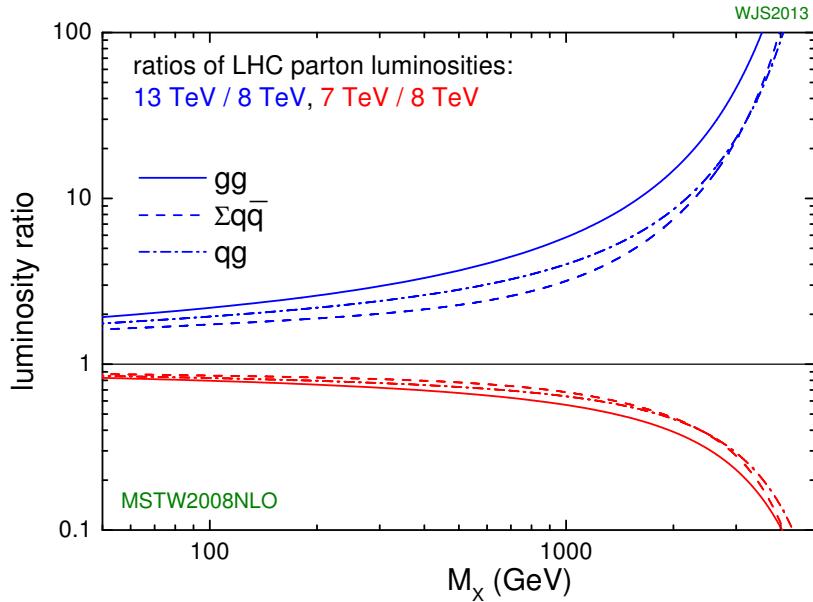


Figure 7.1: Parton luminosity ratios as a function of resonance mass  $M_X$  for 13/8 TeV and 7/8 TeV [109].

2359 Higgs pair production offers a vast array of unprobed regions of phase space where searches for BSM  
2360 physics can be made. Chapter 1 discusses some possibilities for both resonant and non-resonant enhance-  
2361 ment of the di-Higgs production cross section. Given the increased mass reach of the LHC in Run 2, it is  
2362 particularly important to focus on resonant searches at high  $m_X$ . When conducting a search in the  $HH$   
2363 final state, the different possible decay modes of each Higgs must be considered. Figure 7.2 shows the  
2364 branching ratio of the  $HH$  final state for different combinations of decays of each individual Higgs. As

2365 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  
2366 largest at 33%.

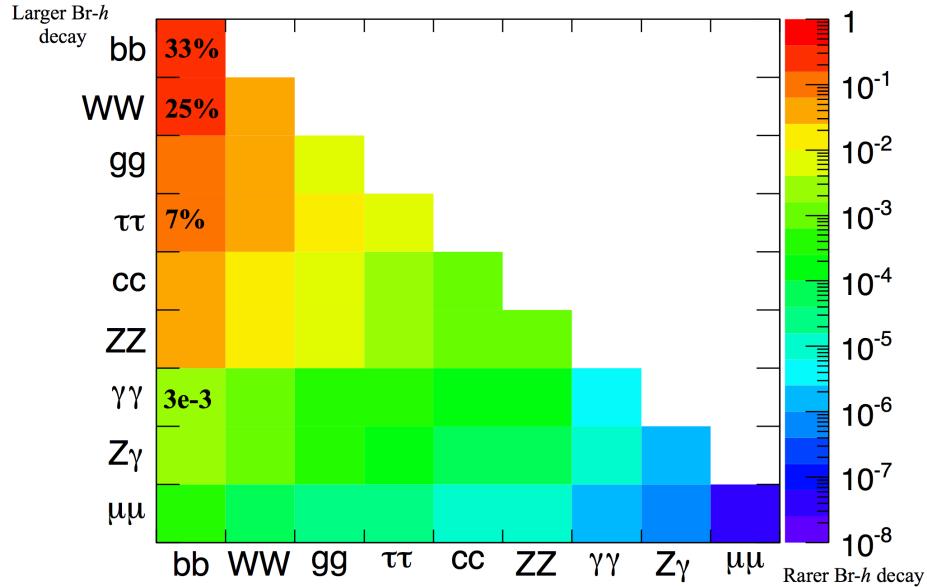


Figure 7.2: Summary of  $HH$  branching ratios [110].

2367 At high  $m_X$ , the Higgs bosons resulting from the decay of a heavy resonance will have large  $p_T$ <sup>1</sup>. The  
2368 angular separation between the decay products of the Higgs,  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ , is inversely  
2369 proportional to the Higgs  $p_T$ , as shown in equation 7.1.

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

2370 Figure 7.3 shows the minimum  $\Delta R$  between truth level  $B$  decay vertices in simulation samples for Randall-  
2371 Sundrum gravitons of different masses. The figure shows that as the mass of the graviton increases, the  $\Delta R$   
2372 distribution between the  $b$  quarks in the Higgs decay tends to shift to lower values. Because of this effect,  
2373 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  $m_X/2$ .

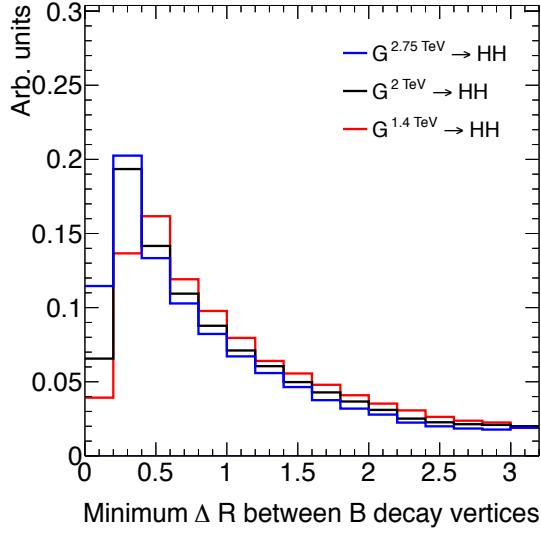


Figure 7.3: Minimum  $\Delta R$  between  $B$  decay vertices for different RSG masses in a  $G_{KK}^* \rightarrow HH \rightarrow 4b$  sample with  $c = 1$ .

2374    7.3 DATA AND SIMULATION SAMPLES

2375    7.3.1 SIGNAL MODELS

2376    While the resonance search is by its nature generic (as it is a simple search for a peak in the  $4b$  invariant mass  
 2377    spectrum), there are two signal models that the selection requirements have been optimized for. The first  
 2378    is Randall-Sundrum (RSG) model, where a tower of massive spin-2 Kaluza-Klein gravitons is predicted.  
 2379    The second is a heavy narrow scalar resonance, the so-called “heavy Higgs”. This type of resonance arises,  
 2380    for example, in the two Higgs doublet model (2HDM). More details about the physics of these models  
 2381    and their motivation is given in chapter 1.

2382    Signal graviton ( $G_{KK}^*$ ) events are generated at leading order (LO) with **MADGRAPH5 v2.2.2** [ii]. The  
 2383    PDF set used is the **NNPDF2.3 LO** set [ii]. For modeling parton shower and hadronization in jets, **PYTHIA**  
 2384    8.186 is used with the A14 tune [90, ii]. The free parameters in the RSG model are the graviton mass  
 2385    and the coupling constant  $c \equiv k/\bar{M}_{\text{Pl}}^2$ . Both the production cross section and width of the graviton are  
 2386    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  $8\pi$

2387 300 GeV and 3 TeV.

2388 The second signal sample is a heavy spin-0 resonance  $H$  with a fixed width of  $\Gamma_H = 1$  GeV. This  
2389 is generated with **MADGRAPH5** and uses the **CT10** PDF set [93]. The parton shower and hadronization  
2390 are handled by **HERWIG ++** with the **CTEQ6L1** PDF set and the **UEEE5** event tune [94, 114, 115]. Because  
2391 the width and branching ratios depend on 2HDM parameters, each mass point generated with this fixed  
2392 width corresponds to a different point in the 2HDM parameter phase space. Mass points are generated  
2393 between 300 GeV and 1 TeV as with the RSG signal samples.

### 2394 7.3.2 BACKGROUND SAMPLES

2395 While the dominant **QCD** multijet background is estimated with a fully data-driven method, the sub-  
2396 dominant backgrounds  $t\bar{t}$  and  $Z$ +jets are modeled with some input from simulation.

2397  $t\bar{t}$  events are simulated at next-to-leading order (NLO) with the **POWHEG-BOX** version 1 generator us-  
2398 ing the **CT10** PDF set [116]. The parton shower, hadronization, and underlying event are simulated with  
2399 **PYTHIA 6.428** with the **CTEQ6L1** PDF set [89]. The Perugia 2012 tune is used [117]. NNLO **QCD** correc-  
2400 tions to the cross sections are computed in **Top++ 2.0** [118]. The top quark mass is set to 172.5 GeV. The  
2401 shapes of distributions in  $t\bar{t}$  are taken from MC while the normalization is taken from data.

2402 Finally, the  $Z$ +jets background is simulated with **PYTHIA 8.186** and the **NNPDF2.3** LO PDF set. This  
2403 background is negligible compared to the others and is taken fully from MC.

### 2404 7.3.3 DATA SAMPLE AND TRIGGER

2405 This analysis is done on  $3.2 \text{ fb}^{-1}$  of data taken in 2015 at  $\sqrt{s} = 13$  TeV. The details of the machine  
2406 conditions during this time can be found in Chapter 2. Only data which was taken during stable beam  
2407 conditions with all detectors functioning is used. Events must pass a trigger which requires a single large  
2408 radius ( $R = 1.0$ ) jet with  $p_T > 360$  GeV to be reconstructed in the HLT. Figure 7.4 shows the trigger  
2409 efficiency for various trigger options as a function of graviton mass. Above  $m_{G_{KK}^*} > 1$  TeV, the single  
2410 large radius jet trigger is 99% efficient for events passing the signal selection.

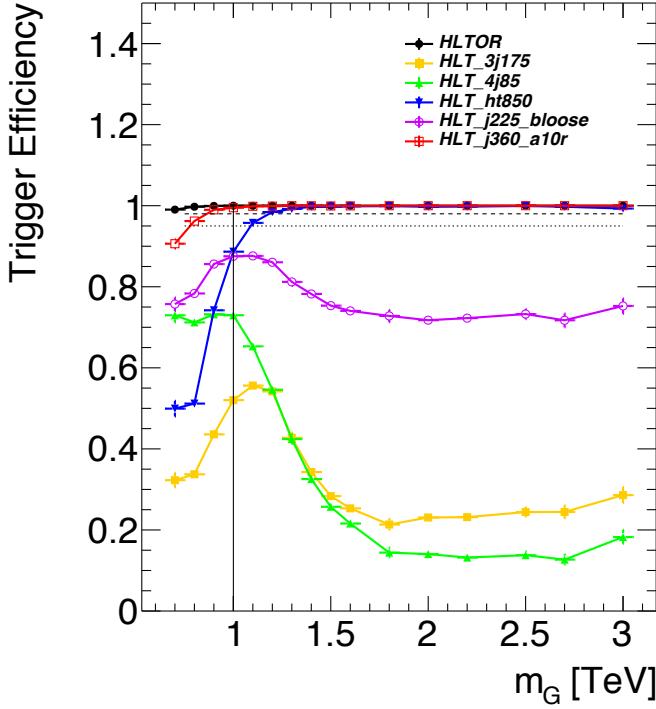


Figure 7.4: Trigger efficiency for events passing all signal region selections as a function of mass in  $G_{KK}^* \rightarrow HH \rightarrow 4b$  samples with  $c = 1$  [119]. In the trigger names, “j” refers to a jet or jets. “ht” refers to  $H_T$ , the scalar sum of transverse momenta in the event. “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.

## 2411 7.4 EVENT RECONSTRUCTION AND OBJECT SELECTION

2412 The boosted selection first begins by defining a unique set of objects that can be exploited to increase signal  
 2413 efficiency in the kinematic regime where the final state  $b$ -jets are very merged.

### 2414 7.4.1 LARGE RADIUS ( $R = 1.0$ ) JETS

2415 The first step towards reconstructing the final state is to define objects that can be used to measure the  
 2416 kinematics of the Higgs bosons. In the boosted selection anti- $k_T$  jets with a radius parameter of 1.0 are  
 2417 used. These jets are much larger in angular size than the typical  $R = 0.4$  jets and are intended to encompass  
 2418 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.

2419 local calibration weighting [69].

2420 Because of the large extent of these jets, great care must be taken to remove potential contributions of  
2421 calorimeter clusters from pile-up. This is done using a technique called jet trimming [120]. With trimming,  
2422 the constituents of the large radius jet are re-clustered with a smaller radius using the  $k_T$  algorithm. Then,  
2423 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  
2424 radius is  $R = 0.2$  and  $f_{\text{cut}} = 0.05$ . Trimming has been shown to improve the mass resolution of large  
2425 radius jets. Figure 7.5 shows the effect of trimming on the large radius jet mass ( $M_J$ ). Because the large  
2426 radius jet fully contains the Higgs decay products, its invariant mass should correspond to the 125 GeV  
2427 mass of the Higgs. The trimming algorithm brings the jet mass much closer to the expected Higgs mass  
2428 and improves the mass resolution.

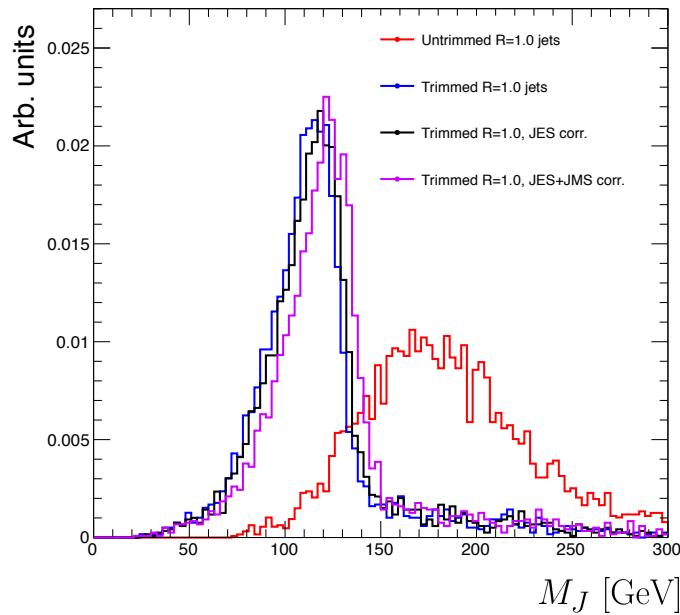


Figure 7.5: Comparison of untrimmed and trimmed jet masses for large radius jets in a RSG sample with  $m_{G_{\text{KK}}^*} = 1 \text{ TeV}$ . JES (JMS) refers to the standard jet energy (mass) scale calibration for ATLAS [69].

2429 The large radius jets are required to satisfy  $250 < p_T < 1500 \text{ GeV}$ . They must also be within  $|\eta| < 2.0$   
2430 in order to ensure that the full jet is within the inner detector tracking volume. Finally, they are required  
2431 to have  $M_J > 50 \text{ GeV}$ . The upper  $p_T$  cut and lower threshold on mass are applied to correspond to the  
2432 kinematic range where uncertainties are available in ATLAS calibrations [121, 122].

2433 7.4.2 TRACK JETS AND  $b$ -TAGGING

2434 Because the  $b$ -jets from boosted Higgs decays are so close together (as illustrated in figure 7.3), narrow radius  
2435 jets are required to fully resolve both  $b$ -jets. The minimum radius feasible for jets based on calorimeter  
2436 deposits is determined by the calorimeter granularity. However, because  $b$ -tagging relies on information  
2437 from the inner detector, it is possible to define another type of jet that can have a smaller radius and better  
2438  $b$ -tagging resolution. These jets are called “track jets” [122, 123].

2439 Track jets are formed by applying the usual anti- $k_T$  clustering algorithm to tracks that are required to be  
2440 consistent with the primary vertex. After the jet axis has been determined using these tracks, a second step  
2441 of track association is also performed to add tracks that can be useful for  $b$ -tagging [123]. In this analysis,  
2442 the tracks are clustered with a radius parameter of  $R = 0.2$ . This radius has been shown to give good  
2443 performance in boosted Higgs tagging [122, 123]. Figure 7.6 shows a comparison among different track jet  
2444 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

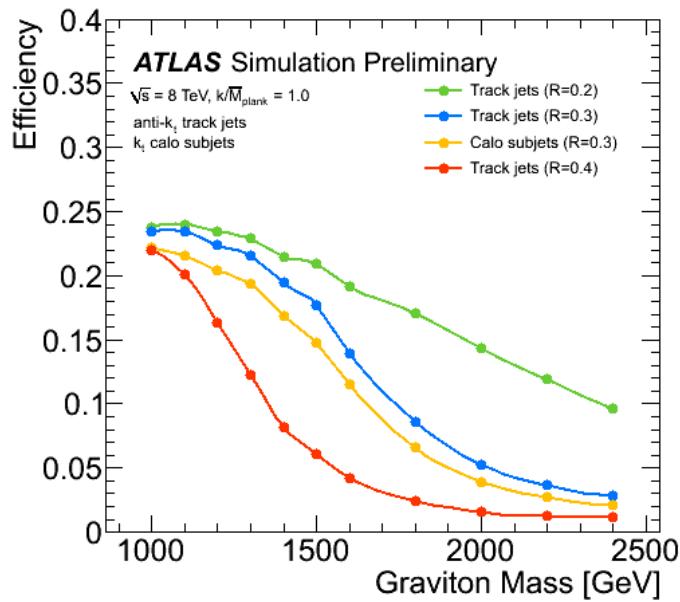


Figure 7.6: Efficiency of finding two  $b$ -jets from each Higgs in an RSG event using calorimeter jets with  $R = 0.3$  and track jet radii of  $R = [0.2, 0.3, 0.4]$  [123].

2445

2446 are required to have  $p_T > 10$  GeV and  $|\eta| < 2.5$ . They must also have at least two tracks.

2447 **7.4.3 MUONS**

2448 Muons are used in this study to correct the four-momenta of calorimeter jets by accounting for semi-  
2449 leptonic  $b$  decays. The muons used are combined ID and MS muons which must satisfy tight identification  
2450 requirements [65]. The muons must have  $p_T > 4 \text{ GeV}$  and  $|\eta| < 2.5$ . Table 7.1 summarizes the object  
2451 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

2452 **7.5 EVENT SELECTION**

2453 The first requirement in the boosted event selection is for  $\geq 2$  large radius jets satisfying the selections  
2454 outlined above. The two highest momentum large-R jets in the event are referred to as “Higgs candidates”.  
2455 The leading jet is required to have  $p_T > 350 \text{ GeV}$ .

2456 Track jets satisfying the object selections are matched to Higgs candidate jets via ghost association [124].  
2457 Each Higgs candidate must have at least 2 track jets associated with it. These basic requirements are illus-  
2458 trated graphically in figure 7.7.

2459 The QCD multijet background produces less central jets than high mass resonances, so there is an ad-  
2460 dditional requirement that the two Higgs candidates be close together in  $\eta$ . The large-R jets are required to  
2461 satisfy  $|\Delta\eta(JJ)| < 1.7$ .

2462 **7.5.1 MASS REQUIREMENTS**

2463 The final set of requirements ensures that the Higgs candidates are consistent with expected properties of  
2464 the 125.0 GeV Higgs. First, a variable ( $X_{hh}$ ) is defined to measure the consistency of both of the Higgs

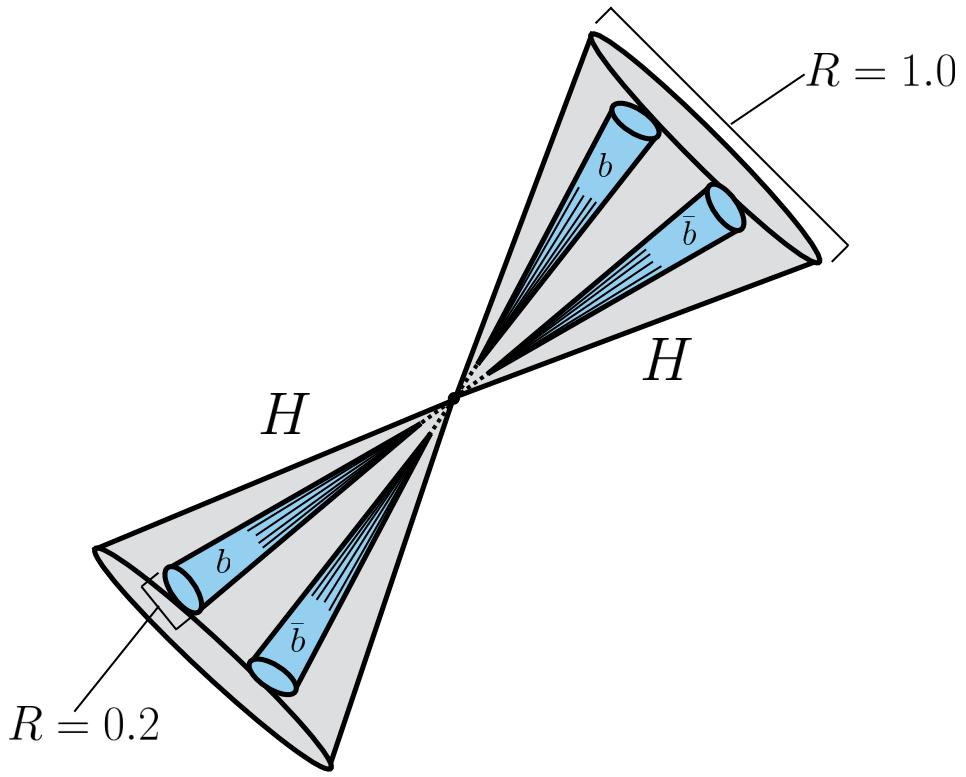


Figure 7.7: Illustration of the boosted selection requirements on Higgs candidates. Each large-radius calorimeter jet (Higgs candidate) must contain two track jets.

<sup>2465</sup> candidate jets with the SM Higgs mass. This is shown in equation 7.2.

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

<sup>2466</sup> The mass values in the  $X_{hh}$  formula are optimized to maximize signal efficiency. The sub-leading jet typ-  
<sup>2467</sup> ically has a lower mass due to semi-leptonic  $b$  decays and final state radiation.  $X_{hh}$  effectively acts as a  $\chi^2$   
<sup>2468</sup> measurement of the consistency of the two Higgs candidate masses with the signal hypothesis. The de-  
<sup>2469</sup> nominators of each term ( $0.1 M$ ) give the uncertainty on the mass measurement for the large radius jets.  
<sup>2470</sup> Events are required to satisfy  $X_{hh} < 1.6$ .

<sup>2471</sup> Before making the requirement on  $X_{hh}$ , the masses of the Higgs candidates are corrected for semi-  
<sup>2472</sup> leptonic  $b$  decays using muons with the criteria outlined in the previous section. Any muons within a  
<sup>2473</sup>  $\Delta R < 0.2$  of a  $b$ -tagged track jet (as described in the next section) have their four-momenta added to the

2474 four-momentum of the Higgs candidate. This correction does not affect the pre-selection requirements  
 2475 but does affect the  $X_{hh}$  requirement and the final invariant mass discriminant.

2476 **7.5.2 b-TAGGING REQUIREMENTS**

2477 The last requirement applied is on the number of  $b$ -tagged track jets. There are two signal regions defined.  
 2478 The first requires exactly four  $b$ -tagged track jets, two in each Higgs candidate (known as the  $4b$  signal re-  
 2479 gion). At high resonance masses, this requirement is inefficient, so an additional signal region requiring  
 2480 only three  $b$ -tagged track jets is also defined (known as the  $3b$  signal region). While this has a larger back-  
 2481 ground it is also more efficient for high resonance masses. For both signal regions, the MV2c2o algorithm,  
 2482 where the training sample for the algorithm has 20% charm events is used. More details for this algorithm  
 2483 can be found in Chapter 2.

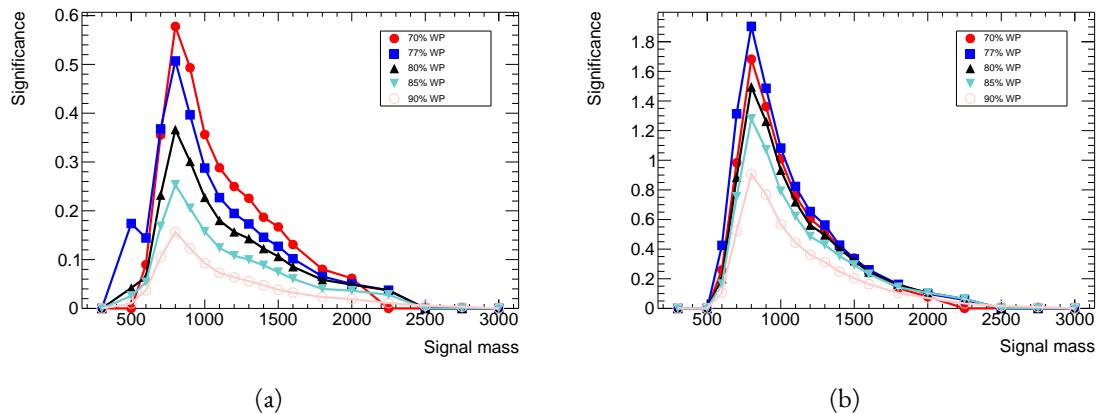


Figure 7.8: Estimated significance as a function of signal mass for RSG  $c = 1$  models in the  $3b$  (a) and  $4b$  (b) regions for different  $b$ -tagging efficiency working points

2484 Once the algorithm is selected, an efficiency working point must also be chosen. This working point  
 2485 defines the efficiency with which true  $b$ -jets are tagged and also fixes the overall background rejection of the  
 2486 algorithm. Higher efficiency working points accept more true  $b$ -jets but also allow for more background.  
 2487 Five different working points (70%, 77%, 80%, 85%, 90%) are tested. With each working point, the  
 2488 full data driven background estimation method is run to quantify the amount of background that will be  
 2489 present in the final signal region. The significance is quantified using the median discovery significance for

2490 signal and background with Poisson errors, given in equation 7.3 [125].

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

2491 Here,  $s$  is the expected number of signal events and  $b$  is the expected number of background events. This  
 2492 formula is derived using Poisson statistics with errors on both the signal and background. It is used because  
 2493 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  
 2494 than  $b$ , this equation reduces to the more well known  $s/\sqrt{b}$ . Figure 7.8 shows the estimated significance as  
 2495 a function of signal mass in RSG  $c = 1$  models for the  $3b$  and  $4b$  signal regions. The 77% working point  
 2496 gives the best performance over a wide range of masses in the  $4b$  signal region. As this is the region which  
 2497 contributes the most to the total discovery significance, the 77% efficiency working point is chosen for the  
 2498 analysis.

### 2499 7.5.3 SELECTION EFFICIENCY

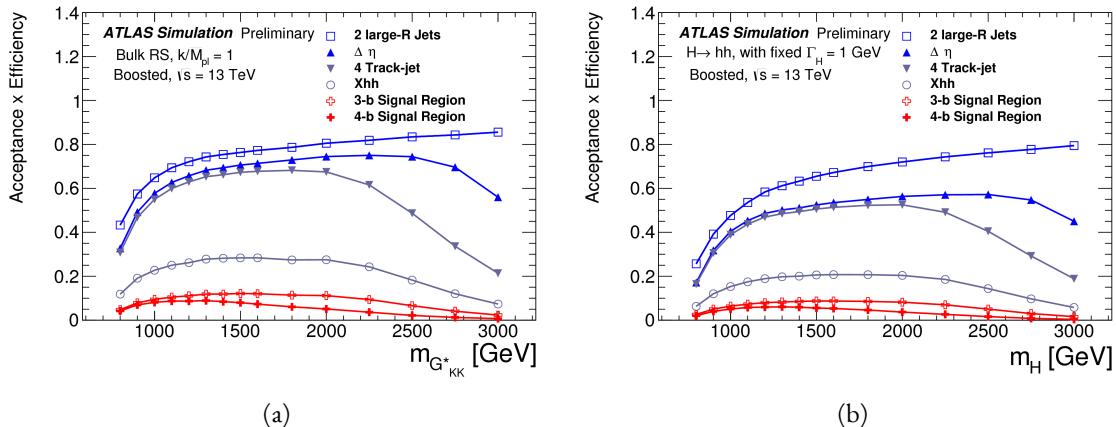


Figure 7.9: Acceptance  $\times$  efficiency as a function of mass for (a) RSG and (b) narrow heavy scalar signal models [126].

2500 Figure 7.9 shows the product of acceptance and efficiency as a function of mass for both the RSG and  
 2501 narrow heavy scalar resonance signal models. After  $m_X > 1$  TeV, the efficiency of the  $4b$  requirement  
 2502 begins to decline. After  $m_X > 2$  TeV, the efficiency of requiring two track jets in each Higgs candidate  
 2503 begins to decline as well. Both of these behaviors illustrate the difficulty of resolving the merged decay

2504 products at high mass. Figure 7.10 shows a more detailed comparison of the signal efficiency in the  $3b$  vs  
 2505  $4b$  signal regions for the RSG model. The efficiencies shown here are relative to all prior selection require-  
 2506 ments. It can be seen there that at high masses the  $3b$  signal region is more efficient for signal.

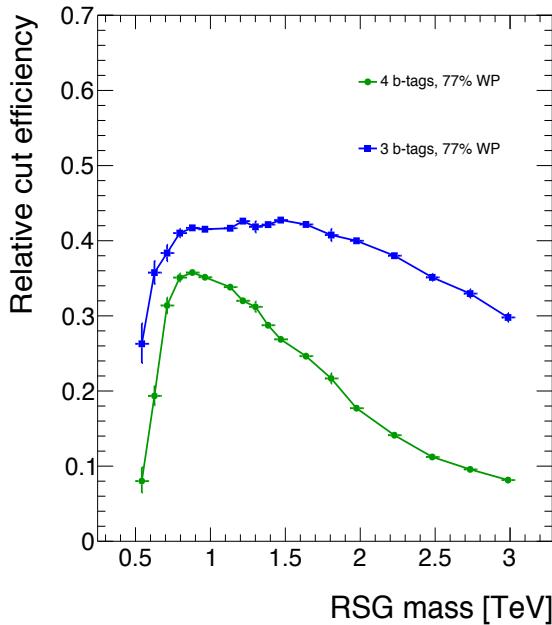


Figure 7.10: Efficiency of requiring 3 or 4  $b$ -tagged track jets vs. RSG mass. The efficiency quoted is relative to the previous selection requirements (rather than an absolute efficiency).

2507 To investigate the degradation of  $b$ -tagging efficiency at high  $p_T$ , the individual jet tagging efficiencies can  
 2508 be compared as a function of signal mass. This is shown in figure 7.11. The figure shows that the leading jet  
 2509 tagging efficiency in both calorimeter jets degrades heavily, while the sub-lead jet tagging efficiency remains  
 2510 relatively constant. More details on the cause of this degradation are shown in appendix A.

2511 The final discriminating variable used in the boosted analysis is  $M_{2J}$ , the invariant mass of the two  
 2512 Higgs candidates. In order to improve the mass resolution, the four-momenta of each Higgs candidate  
 2513 are scaled by  $m_h/M_J$ . The effect of this correction is small in the boosted analysis but is done for consis-  
 2514 tency with the resolved selection. Table 7.2 shows the effect of the selection requirements on signal and  
 2515 background simulations as well as data.

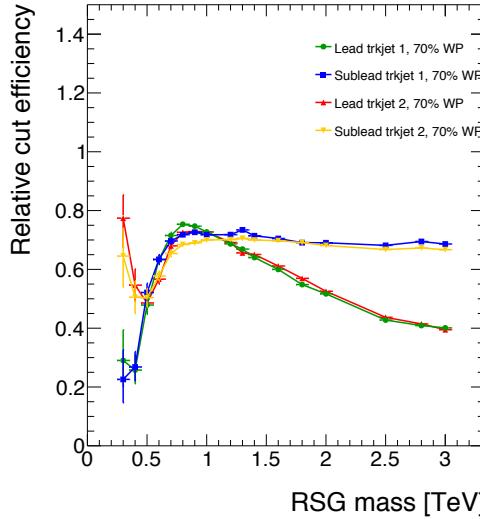


Figure 7.11: MV2c20  $b$ -tagging efficiency for each of the four track jets in the boosted  $4b$  selection as a function of RSG mass for  $c = 1$  models.

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 [127].

## 2516 7.6 DATA-DRIVEN BACKGROUND ESTIMATION

2517 The largest background to the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  final state is QCD multijet production, constitut-  
 2518 ing 80-90% of the total background. Because of the difficulties in modeling higher order QCD processes,  
 2519 this background is estimated with a fully data-driven method. The only other non-negligible background  
 2520 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

2521 background will be estimated, the normalization of the QCD and  $t\bar{t}$  backgrounds are simultaneously es-  
2522 timated.

2523 7.6.1 MASS REGION DEFINITIONS

2524 The first step in the data-driven background estimate is to define a sideband mass region where the back-  
2525 ground normalization can be derived. Additionally, a control region is defined where the background  
2526 estimate can be validated. The control (CR) and sideband (SB) regions are defined using a radial distance  
2527 in the two-dimensional large-R jet mass plane,  $R_{hh}$ , which is defined in equation 7.4.

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

2528 Events in the control region are required to fail the signal region  $X_{hh} < 1.6$  requirement and have  
2529  $R_{hh} < 35.8 \text{ GeV}$ . 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-

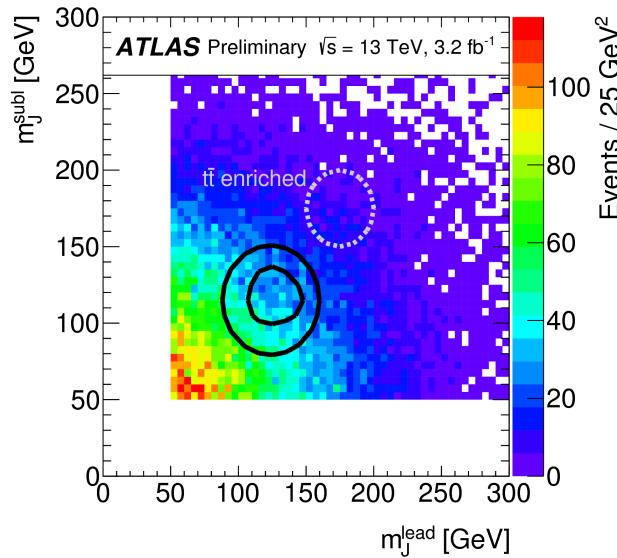


Figure 7.12:  $M_J^{\text{sublead}}$  vs.  $M_J^{\text{lead}}$  in a 2  $b$ -tag data sample. The signal region is defined by the inner black contour ( $X_{hh} < 1.6$ ) and the sideband region is defined by the outer contour ( $R_{hh} > 35.8 \text{ GeV}$ ). The region between the black contours is the control region. The mass region which is enriched in  $t\bar{t}$  background is also shown for illustration [[126](#)].

2530 marizes the mass region selections for the three different regions used in the analysis.

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

Table 7.3: Mass region definitions used for background estimation.

2532    7.6.2 BACKGROUND ESTIMATION

2533    The method for estimating the background in this analysis is similar to the ABCD method presented in  
 2534    Chapter 5. In this case, the two handles used to define different regions for the estimate are the number  
 2535    of  $b$ -tagged track jets and the mass requirements. A region requiring exactly two  $b$ -tagged track jets in one  
 2536    large-R jet (referred to as the 2-tag or  $2b$  region) is defined for use in the background estimate. The number  
 2537    of expected background events in the  $3b$  and  $4b$  signal regions is then given by equation 7.5.

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

2538    In this equation,  $N_{\text{bkg}}^{3(4)-\text{tag}}$  is the expected number of background events in the  $3b$  or  $4b$  signal regions.  
 2539     $N_{\text{Multijet}}^{2-\text{tag}}$  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-  
 2540    dicted in the MC for the  $3b$  or  $4b$  signal region, and the variable is similarly defined for the  $Z+\text{jets}$  back-  
 2541    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  
 2542    region.  $\mu_{\text{Multijet}}$  is an extrapolation factor that is derived in the sideband region and used to estimate the  
 2543    ratio of 2-tag events to 3(4)-tag events in the signal region. It is defined in equation 7.6.

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

2544    The  $t\bar{t}$  scale factor ( $\beta_{t\bar{t}}$ ) and the QCD multijet extrapolation factor ( $\mu_{\text{Multijet}}$ ) are estimated together in  
 2545    a simultaneous fit in the sideband region. Then, the number of events in the 2-tag signal region is used,  
 2546    along with the  $t\bar{t}$  estimate in the  $3b$  and  $4b$  signal regions and  $\mu_{\text{Multijet}}$ , to estimate the total number  
 2547    of background events in the two final signal regions. The shape of the final discriminant  $M_{2J}$  is also

2548 taken from the 2-tag signal region where there are more events. This method is illustrated graphically in  
2549 figure 7.13. In the  $3b$  region, the fit yields values of  $\mu_{\text{Multijet}} = 0.160 \pm 0.03$  and  $\beta_{t\bar{t}} = 1.02 \pm 0.09$ .

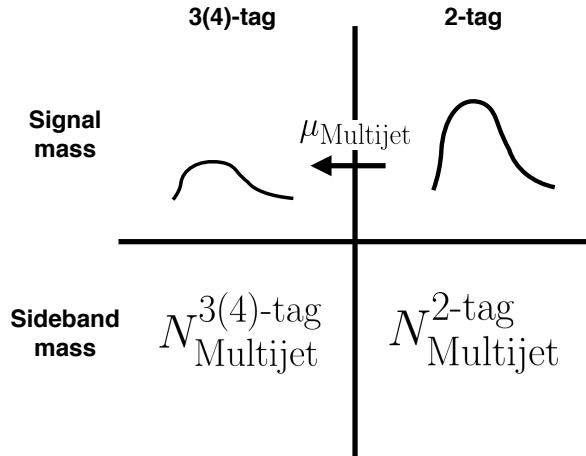


Figure 7.13: An illustration of the data-driven background estimation technique for the boosted analysis

2550 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  
2551 quoted are statistical only. The larger uncertainties in the  $4b$  values indicate the lower statistics available in  
2552 that region.

2553 Figure 7.14 shows the distributions of data and background estimates in the  $3b$  and  $4b$  sideband regions  
2554 after the background fit has been done. The normalizations are constrained from the fit to match that of  
2555 the data, but good modeling of the shape of the mass of the leading large-R jet is seen as well. The shapes  
2556 of the kinematic distributions for the  $t\bar{t}$  background in the  $4b$  region are taken from the  $3b$  region due to  
2557 the better MC statistics in that region.

### 2558 7.6.3 BACKGROUND SHAPE FIT

2559 As mentioned in the previous section, the background shape in the 3-tag and 4-tag signal regions is taken  
2560 from the 2-tag signal mass region. Due to the limited statistics available, the background shapes are addi-  
2561 tionally smoothed after being extrapolated to the 3-tag and 4-tag signal regions. Only the data in the range  
2562  $900 < M_{2J} < 2000$  GeV is included in the shape fit due to the limited statistics available above 2 TeV.  
2563 Both the  $t\bar{t}$  and QCD multijet background are independently fit with an exponential shape,  $y = e^{ax+b}$ .

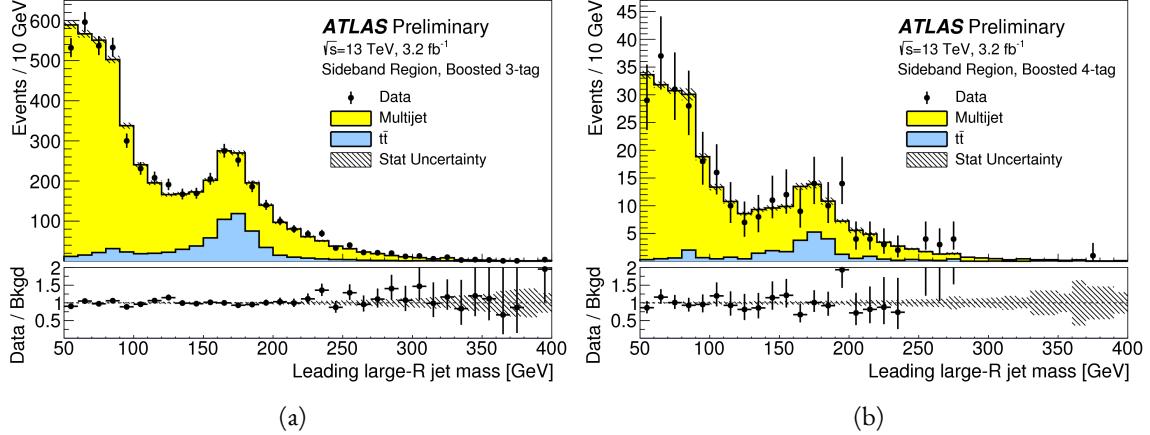


Figure 7.14: Leading large-R jet mass in the 3b (a) and 4b (b) sideband regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above. Because their normalizations are derived in the sideband region, the total background normalization is constrained by default to match the normalization of the data [126].

2564 Other shapes are considered and used for the systematic uncertainties. Table 7.4 shows the fit values for  
 2565 the parameters. Because both the 3b and 4b QCD shapes come from the 2-tag region, the slopes derived  
 2566 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 [127].

#### 2567 7.6.4 VALIDATION OF BACKGROUND ESTIMATE

2568 The background estimate can be validated by using the method to estimate the number of events in the  
 2569 control mass region rather than the signal mass region. Figure 7.15 shows the  $M_{2J}$  distribution in the 3b  
 2570 and 4b control regions, comparing data and background estimates. In both cases, both the background  
 2571 shape and normalization are consistent with the data, indicating good agreement. The ratio of data to the  
 2572 background estimates is also fit to a line in the figure to test for any shape difference. The slope of the  
 2573 line is within  $1\sigma$  (from the fit uncertainties) of flat, further indicating that the data is consistent with the  
 2574 background estimate in the control region.

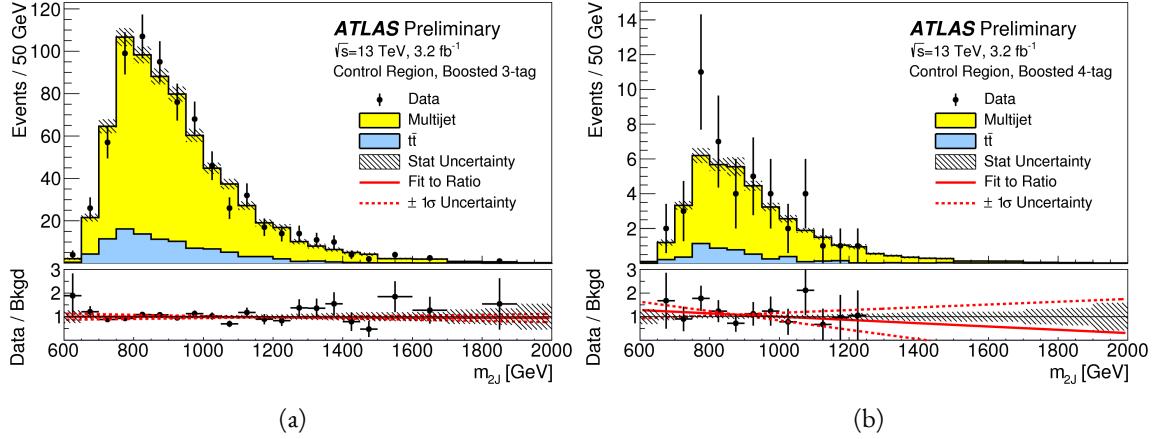


Figure 7.15: Di-jet invariant mass ( $M_{2J}$ ) in the 3b (a) and 4b (b) control regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above [126].

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 [126]. The uncertainties shown are statistical only.

2578 7.7 SYSTEMATIC UNCERTAINTIES

2579 The systematic uncertainties in this analysis can be divided into two broad categories. The first type is  
2580 uncertainties associated with the modeling of the signal processes. The second type of uncertainty is asso-  
2581 ciated with both the shape and normalization of the background prediction.

2582 7.7.1 SIGNAL MODELING UNCERTAINTIES

2583 The signal modeling uncertainty has three main components: theoretical uncertainty on the acceptance,  
2584 experimental uncertainties on the large-R jets, and experimental uncertainties on the track jets related to  
2585  $b$ -tagging. In this analysis the experimental uncertainties are the most significant.

2586 The first uncertainty on signal modeling is the theoretical uncertainty on the acceptance. As explained  
2587 in section 5.6.1, there are four components to this uncertainty. The first is related to missing higher order  
2588 terms from the matrix element calculations which is estimated by varying the QCD renormalization and  
2589 factorization scales. The second is uncertainty due to the PDF set used. The third is a generator uncer-  
2590 tainty which is estimated by modifying the generator used to model the underlying event and hadroniza-  
2591 tion. Finally, there is an uncertainty associated with the modeling of the initial state and final state radia-  
2592 tion (ISR/FSR). The total theoretical uncertainty on the signal yield is 3%, and this is dominated by the  
2593 ISR/FSR modeling.

2594 There are uncertainties on the large-R jets in both the jet energy scale (JES) and jet energy resolution  
2595 (JER) as well as the jet mass scale (JMS) and jet mass resolution (JMR). These are evaluated using  $\sqrt{s} =$   
2596 8 TeV data from Run 1 of ATLAS and extrapolated to the Run 2 beam and detector conditions using  
2597 MC<sup>5</sup>. The details of these uncertainties can be found in reference [128].

2598 Uncertainties on the track jets are related to the  $b$ -tagging efficiency. The total uncertainty on the signal  
2599 yield due to  $b$ -tagging is evaluated by propagating variations of the  $b$ -tagging efficiency through the boosted  
2600 selection requirements. The uncertainties are calculated jet-by-jet and parameterized as a function of  $b$ -jet  
2601  $p_T$  and  $\eta$  [106]. For high  $p_T$   $b$ -jets (with  $p_T > 300$  GeV), the uncertainties are extrapolated using MC  
2602 simulation from the lower  $p_T$   $b$ -jets [129].

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

2603 Table 7.6 shows the systematic uncertainties on the signal normalization for models with  $m_{G_{\text{KK}}^*} =$   
 2604  $1.5 \text{ TeV}$  and both  $c = 1$  and  $c = 2$  as well as a narrow width heavy scalar. The dominant uncertainty  
 2605 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.

2606 7.7.2 BACKGROUND UNCERTAINTIES

2607 Uncertainties on the QCD multijet background normalization and shape are estimated using the con-  
 2608 trol mass region. As shown previously, the background predictions in the control region match with the

2609 data yields within the statistical uncertainty in both the 3-tag and 4-tag control regions. As an additional  
 2610 protection, the statistical uncertainty on the background prediction in the control region is assigned as a  
 2611 systematic uncertainty on the normalization of the QCD background.

2612 Additional robustness tests are done by varying the definition of the control mass region and the  $b$ -  
 2613 tagging requirements used to define the 2-tag sample. In all cases, the effect of the variations is found to be  
 2614 within the statistical uncertainties on the background normalization in the control region.

2615 Shape uncertainties on the background are evaluated using two techniques. First, as shown in fig-  
 2616 ure 7.15, the ratio between the data and background prediction is fit with a linear function. The uncer-  
 2617 tainties on the slope of this fit are assigned as shape uncertainties. An additional uncertainty is assigned by  
 2618 using alternate power law fit functions for the smoothing of the background shape. Table 7.7 shows the  
 2619 alternate shapes used. The largest difference between the nominal fit function and the alternates, taking  
 2620 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,  $x = M_{2J}/\sqrt{s}$ .

2621 The uncertainties on the  $t\bar{t}$  background are obtained by propagating the various experimental variations  
 2622 (JES, JER, JMS, JMR,  $b$ -tagging) through the analysis selection requirements. Table 7.6 summarizes the  
 2623 background uncertainties in the 3-tag and 4-tag regions.

2624    7.8 RESULTS

2625    Table 7.8 shows the observed yields in the 3-tag and 4-tag signal regions for the boosted analysis compared  
 2626    to the predicted number of background events. In the 3-tag region, 316 events are observed with a pre-  
 2627    dicted background of  $285 \pm 19$ . In the 4-tag region, 20 events are observed with a predicted background  
 2628    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  
 2629    small excesses in the data, in particular in the 3-tag region around  $M_{2J} \approx 900$  GeV and in the region of  
 2630     $1.6 < M_{2J} < 2.0$  TeV. The significance of these excesses will be evaluated in the next chapter in the  
 2631    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 [126].

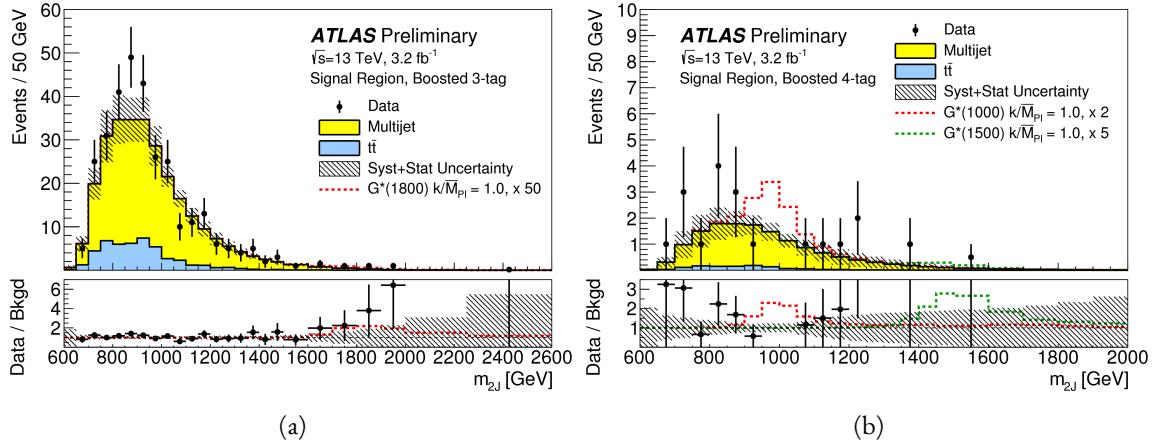


Figure 7.16: Di-jet invariant mass ( $M_{2J}$ ) in the  $3b$  (a) and  $4b$  (b) signal regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above. In the  $3b$  region, a graviton signal with  $m_{G_{KK}^*} = 1.8$  TeV and  $c = 1$  is overlaid, with 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 [126].

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

Frank Herbert

# 8

2632

2633

## Combined limits from boosted and resolved searches

2634

2635

### 8.1 INTRODUCTION

2636 In order to cover the full mass range of possible resonances decaying to di-Higgs final states, two distinct  
2637 tailored selections were produced. The resolved selection is more sensitive in the mass range of  $400 < m_X <$   
2638  $1100 \text{ GeV}$  while the boosted selection is more sensitive to masses in the range  $1100 < m_X <$   
2639  $3000 \text{ GeV}$ . Chapter 7 presents the details of the boosted selection and results. In setting limits on spin-2  
2640 Randall-Sundrum graviton (RSG) and narrow width heavy scalar ( $H$ ) models, the results of the boosted  
2641 selection are combined with the results of the resolved selection to cover the full mass range.

2642 This chapter presents limits on signal models resulting from the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  search in both  
2643 the resolved and boosted selections. It first presents a brief overview of the resolved results that go into

2644 the limit setting. Then, an overview of the statistical methods used for the search and limit setting is given.  
2645 Finally, limits on the RSG and heavy scalar models are presented.

2646 **8.2 RESOLVED RESULTS**

2647 The details of the resolved selection will not be presented here and can be found in reference [126]. In  
2648 basic terms, the selection searches for four  $R = 0.4$  b-tagged calorimeter jets (where each pair of jets is  
2649 one Higgs candidate). This is distinct from the boosted methodology which searches for merged decay  
2650 products. The backgrounds to the resolved selection are the same as those presented in Chapter 7 for the  
2651 boosted analysis.

2652 Table 8.1 shows the results for data yields and expected background in the resolved signal region. Fig-  
2653 ure 8.1 shows the  $M_{2J}$  distribution in the resolved signal region. The total number of events is consistent  
2654 with the prediction and no significant excess is seen. One event in the boosted 4-tag signal is shared with  
2655 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 [126].

2656 **8.3 SEARCH TECHNIQUE AND RESULTS**

2657 The statistical technique used for the search in this analysis is the same as that used in the  $H \rightarrow WW^*$   
2658 analysis presented in section 3.6.2. The test statistic  $q_0$  is used to define the  $p$ -values which measure the

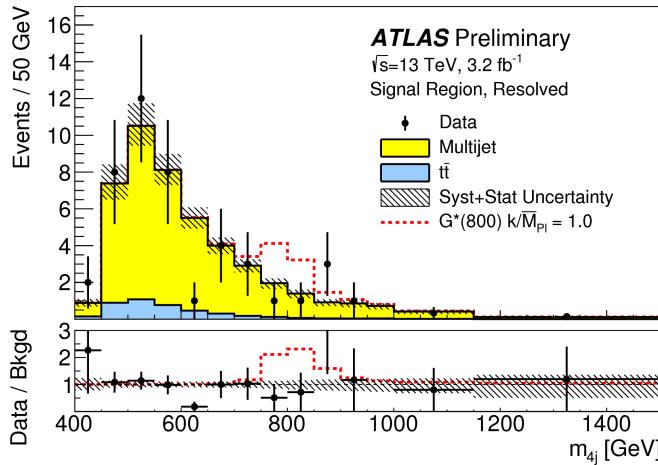


Figure 8.1: Di-jet invariant mass ( $M_{2J}$ ) in the resolved signal region. A graviton signal with  $m_{G_{KK}^*} = 800$  GeV and  $c = 1$  is overlaid. [126].

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 [130]. 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

2674 in equation 8.1.

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

2675 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  
2676 value of the nuisance parameters,  $\hat{\theta}$  is the best fit value of the nuisance parameters under the fixed  $\mu$  value,  
2677 and  $L$  is the Poisson likelihood of the data (as described in section 3.6.2).

2678 The test statistic  $\widetilde{q}_\mu$  is constructed to protect against two interesting corner cases when setting the upper  
2679 limit on the cross section. First, it protects against negative signal strengths  $\mu$  which are unphysical. Second,  
2680 it does not count excesses in the data larger than those expected by a signal strength  $\mu$  as evidence against  
2681 the  $\mu$  hypothesis.

2682 The  $CL_s$  statistic is constructed by taking a ratio of two probabilities.  $CL_{s+b}$  is the probability that the  
2683 signal+background hypothesis would produce a value of the test statistic that is less than or equal to the  
2684 observed value<sup>1</sup>.  $CL_b$  is the probability that the background only hypothesis will produce a value  
2685 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%  
2686 upper limit on the cross section is set at the value of  $\mu$  that makes the  $CL_s$  statistic less than 5%. In practice,  
2687 the limits are computed numerically within an asymptotic approximation for the distribution of the test  
2688 statistic  $\widetilde{q}_\mu$ . The details of this approximation can be found in reference [76].

2689 The resolved and boosted analyses are combined using a very simple procedure rather than a full statis-  
2690 tical combination. For each mass point tested, the limit which gives the most stringent constraint is used.  
2691 This means that for mass points below 1.1 TeV the resolved signal region is used, while at and above this  
2692 point the combination of the orthogonal 3b and 4b boosted signal regions is used.

#### 2693 8.4.2 LIMIT SETTING RESULTS

2694 Figure 8.2 shows the combined 95% upper bounds as a function of mass for three different models:  $G_{KK}^*$   
2695 with  $c = 1$ ,  $G_{KK}^*$  with  $c = 2$ , and a narrow heavy scalar  $H$ .

---

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

2696        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  
2697        for masses in the range  $600 < m_{G_{\text{KK}}^*} < 3000$  GeV. For the RSG model with  $c = 2$ , cross sections limits  
2698        between 40 fb and 200 fb are set for the mass range of  $500 < m_{G_{\text{KK}}^*} < 3000$  GeV. Masses in the range  
2699        of  $475 < m_{G_{\text{KK}}^*} < 785$  GeV are excluded with  $c = 1$  (with an exclusion of the range 465 to 745 GeV  
2700        expected). Masses less than 980 GeV are excluded with  $c = 2$  (with an exclusion for masses less than  
2701        1 TeV expected).

2702        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  
2703        30 to 300 fb in the mass range of  $500 < m_H < 3000$  GeV. The resolved analysis can also set an upper  
2704        limit on the Standard Model di-Higgs production cross section discussed in chapter 3. The upper limit on  
2705         $\sigma(pp \rightarrow hh \rightarrow b\bar{b}b\bar{b})$  in the Standard Model is constrained to be less than 1.22 pb.

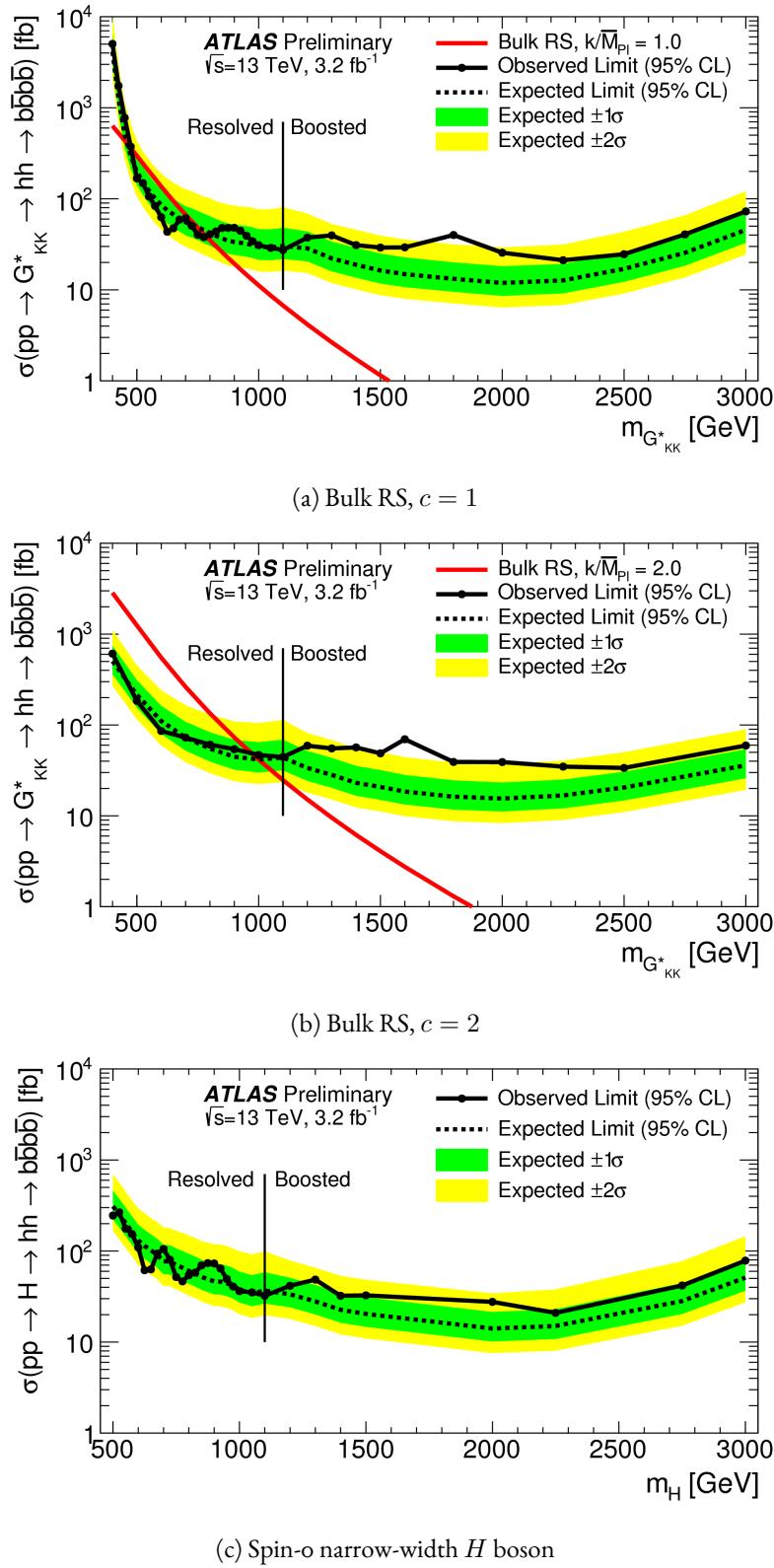


Figure 8.2: Expected and observed upper limit as a function of mass for  $G^*_{KK}$  in the RSG model with (a)  $c = 1$  and (b)  $c = 2$ , as well as (c)  $H$  with fixed  $\Gamma_H = 1$  GeV, at the 95% confidence level in the  $CL_s$  method [126].

2706

## Part IV

2707

## Looking ahead

# 9

2708

2709

## Conclusion

2710 After being sought for many years at different collider experiments, the Higgs boson was discovered by  
2711 the ATLAS and CMS experiments in 2012, confirming the leading theory for the source of electroweak  
2712 symmetry breaking and filling in the last missing piece of the Standard Model. After its discovery, mea-  
2713 surements of the particle's detailed properties and searches for new particles decaying to Higgs final states  
2714 were both extremely important in constraining physics beyond the Standard Model. This dissertation  
2715 presented this evolution through two results: the observation and measurement of the Higgs boson in the  
2716  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel at  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV and a search for Higgs pair production  
2717 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  
2718 Hadron Collider.

2719 In the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ , results from both the discovery of the Higgs boson and the full ATLAS  
2720 Run 1 dataset were presented. The Higgs boson was discovered with a  $5.9\sigma$  significance in a combination  
2721 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

2722     $\sqrt{s} = 8$  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-  
2723   covery level significance in the  $H \rightarrow WW^*$  channel alone and obtained the first evidence of vector boson  
2724   fusion production in that channel. The combined signal strength was measured to be  $\mu = 1.09^{+0.23}_{-0.21}$ . The  
2725   total observed significance of the  $H \rightarrow WW^*$  process was observed to be  $6.1\sigma$  (with  $5.8\sigma$  expected). Ad-  
2726   vanced methods for background reduction and estimation, particularly in same-flavor lepton final states,  
2727   were shown. The VBF signal strength was measured to be  $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$  with an observed signifi-  
2728   cance of  $3.2\sigma$  (with  $2.7\sigma$  expected).

2729    These results required many novel innovations. The increase of pileup interactions in the higher in-  
2730   stantaneous luminosity LHC conditions of 2012 led to a degradation of missing transverse momentum  
2731   resolution. As a result, the prominent  $Z/\gamma^* + \text{jets}$  background of the same flavor  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$   
2732   final states increased greatly. New variables, including a track-based missing transverse momentum and a  
2733   measurement of the balance between the dilepton system and recoiling jets, allowed for significant reduc-  
2734   tion of this background. In the VBF channel, selections were optimized to exploit the unique VBF final  
2735   state topology. Incorporating these variables into a boosted decision tree technique allowed the analysis  
2736   to exceed the  $3\sigma$  statistical significance threshold.

2737    After the end of Run 1, the results of Higgs measurements from ATLAS were combined with those  
2738   from CMS to produce the most precise measurements of the Higgs boson so far [131]. Figure 9.1 shows the  
2739   combination of ATLAS and CMS data for the Higgs signal strength in and coupling measurements. In the  
2740   signal strength measurements of gluon fusion and vector boson fusion, the  $H \rightarrow WW^*$  channel provides  
2741   the tightest constraints. Additionally, the Higgs coupling to  $W$  bosons is the most precisely measured with  
2742   a relative uncertainty of 10%.

2743    With the discovery of the Higgs firmly established and its properties measured, a natural next step was  
2744   to search for new physics with Higgs final states. At  $\sqrt{s} = 13$  TeV, a search for Higgs pair production  
2745   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  
2746   arising from high mass resonances was constructed. This signal region utilized large-radius calorimeter jets  
2747   and  $b$ -tagging with small radius track jets to maximize the signal acceptance. No significant excesses were  
2748   observed, and upper limits on cross sections are placed for spin-2 Randall Sundrum gravitons (RSG) and

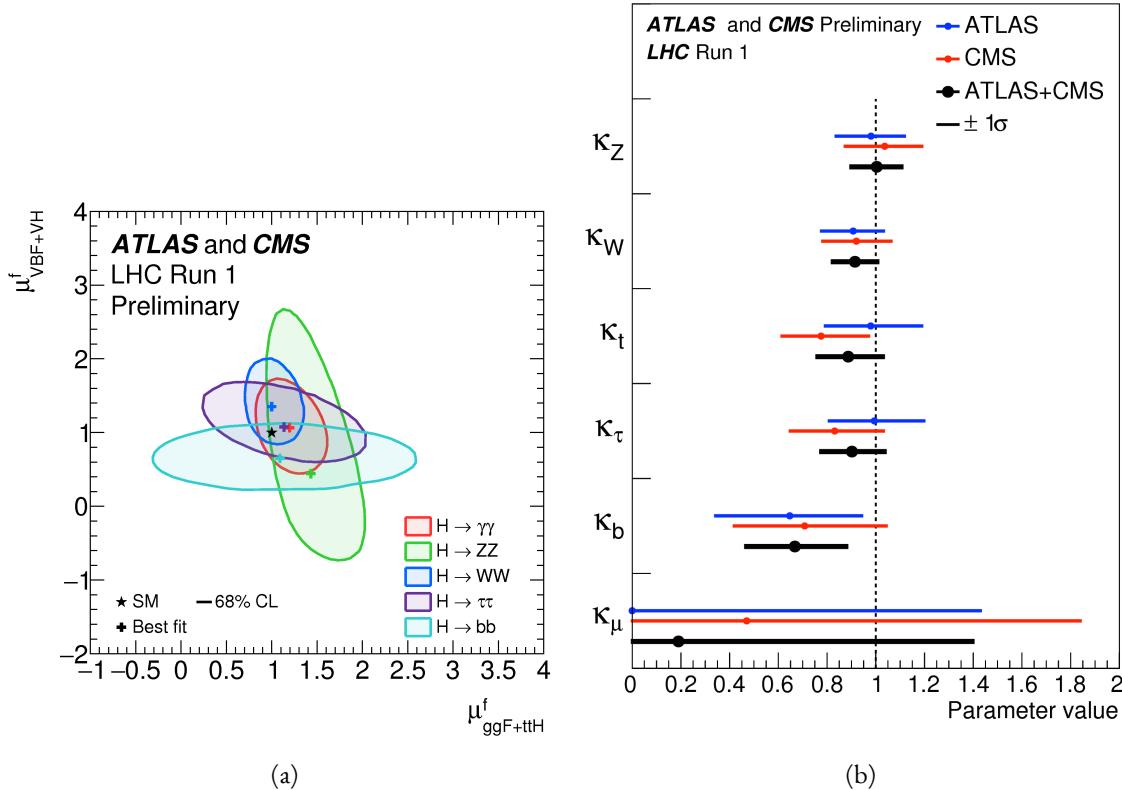


Figure 9.1: Combined ATLAS and CMS measurements in Run 1 for (a) Higgs signal strength in gluon fusion and VBF and (b) Higgs couplings normalized to their SM predictions

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  $3000 \text{ fb}^{-1}$  [132, 133]. This projection also assumes

2761 that theoretical uncertainties on the signal, which would be the largest contribution in the future dataset,  
 2762 remain as they are now. Improvements in the theoretical understanding of the Higgs signal would also  
 2763 reduce the signal strength uncertainty dramatically. Such precision results allow for measurements of the  
 2764 Higgs coupling to vector bosons precise to the few percent level, therefore giving much power to constrain  
 2765 or discover new physics.

2766 The prospects for detection of beyond the Standard Model resonant di-Higgs production at the HL-  
 2767 LHC are also quite promising. Figure 9.2 shows projections for the discovery significance of RSG signals at  
 2768 the HL-LHC in the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  search [133]. 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.

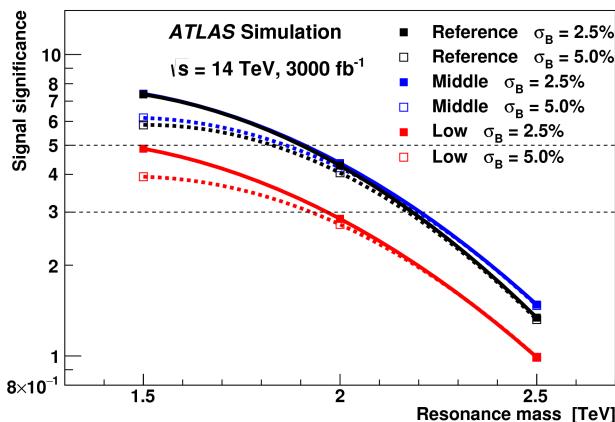


Figure 9.2: Discovery significance for RSG models at the HL-LHC in three different budget scenarios [133].  
 Systematic uncertainties on the background prediction ( $\sigma_B$ ) of 2.5% and 5.0% are both tested.

2769  
 2770 The Higgs will continue to be an incredibly powerful tool in the understanding of nature at the HL-  
 2771 LHC and beyond. Through both precision measurements and searches, the nature of electroweak symme-  
 2772 try breaking will be better understood and the potential for the discovery of physics beyond the Standard  
 2773 Model has never been greater.

# A

2774

2775

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

2776 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  
2777 masses is the degradation of the *b*-tagging efficiency for high  $p_T$  jets. This appendix presents a study of the  
2778 underlying causes of this degradation.

### 2779 A.I CHANGES IN MV<sub>2</sub> SCORE AT HIGH $p_T$

2780 The degradation of *b*-tagging at high  $p_T$  was studied in particular in the context of RSG models at high  
2781 mass. Figure A.i shows the  $p_T$  of the leading track jet inside of the leading calorimeter jet in RSG events.  
2782 At high  $m_{G_{KK}^*}$ , the  $p_T$  spectrum of track jets is much harder than at lower masses due to the increased  
2783 Higgs  $p_T$ .

2784 Figure A.2 shows the MV<sub>2c2o</sub> algorithm score for the leading and subleading track jets inside of the  
2785 leading calorimeter jet. In both cases, it can be seen that at higher RSG masses the MV<sub>2</sub> score shifts towards  
2786 more background like (negative) values. Additionally, this effect is more pronounced in the leading track

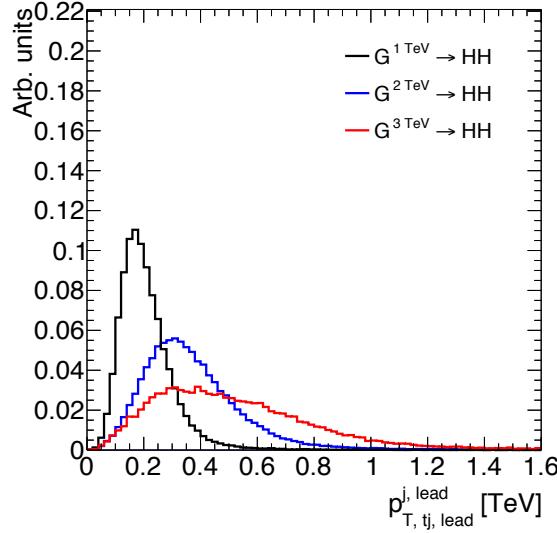


Figure A.1:  $p_T$  of the leading track jet in the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

<sup>2787</sup> jet than the subleading.

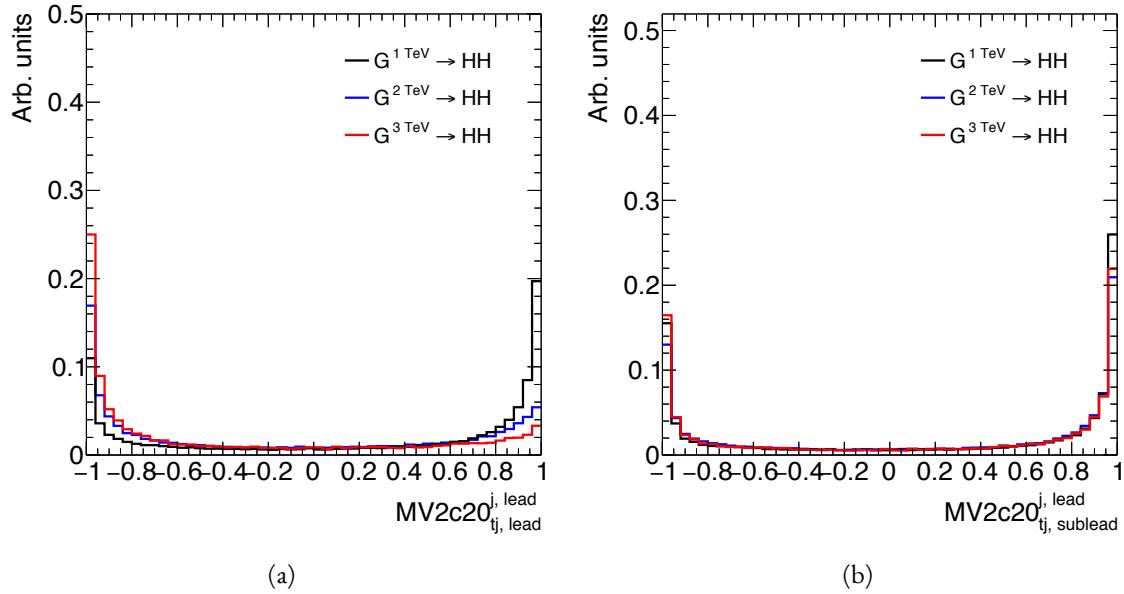


Figure A.2: MV2c20 score for the leading track jet (a) and subleading track jet (b) of the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

<sup>2788</sup> To understand what is causing this change in the MV2c20 score, the same comparisons can be made for  
<sup>2789</sup> the input variables of MV2c20. The focus in these comparisons will be on the leading track jet as this is the  
<sup>2790</sup> one seen to have the largest difference in MV2 score. Figure A.3 shows the log likelihood ratio  $\log(p_b/p_u)$

2791 from the IP<sub>3</sub>D (three dimensional impact parameter) algorithm. At higher masses, the IP<sub>3</sub>D likelihood  
 2792 ratio distribution does become more background-like.

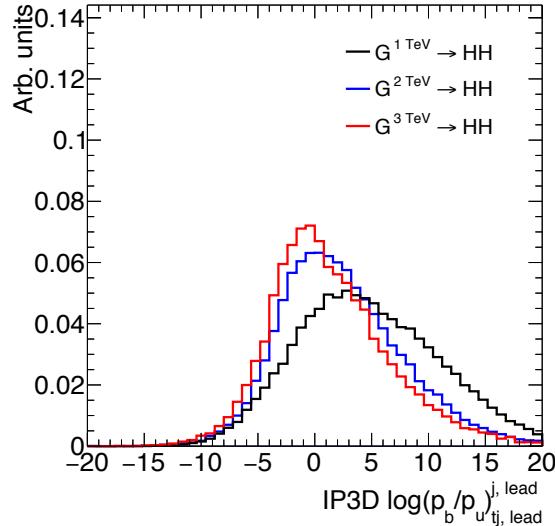


Figure A.3: IP<sub>3</sub>D log-likelihood ratio ( $\log(p_b/p_u)$ ) of the leading track jet in the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

2793 Figure A.4 shows the mass and number of tracks at the secondary vertex computed by the SV1 algorithm.  
 2794 When there is no secondary vertex found, the algorithm assigns a default negative value for these quantities.  
 2795 Both of these distributions show that there is a significantly larger fraction of jets where no secondary vertex  
 2796 is found in the high mass samples compared to the  $m_{G_{KK}^*} = 1$  TeV sample. The SV1 algorithm's inability  
 2797 to find a secondary vertex could be an important factor in the overall MV<sub>2</sub> score shift, as this eliminates  
 2798 eight of the input variables that would normally contribute information to the algorithm.

2799 Figure A.5 shows the same quantities for the JetFitter algorithm. In this case, there is also a change in  
 2800 the fraction of jets which have their secondary vertices successfully reconstructed, but this change is not as  
 2801 drastic as that seen in SV1. There is also an increase in the number of jets which have high values of mass.

## 2802 A.2 EFFECT OF MULTIPLE $b$ -QUARKS INSIDE ONE JET

2803 One hypothesis for why the efficiency of  $b$ -tagging the leading track jet degrades is that at high masses, the  
 2804  $b$  quarks get close enough together that both of them are inside of the leading track jet. Because MV<sub>2</sub> is not

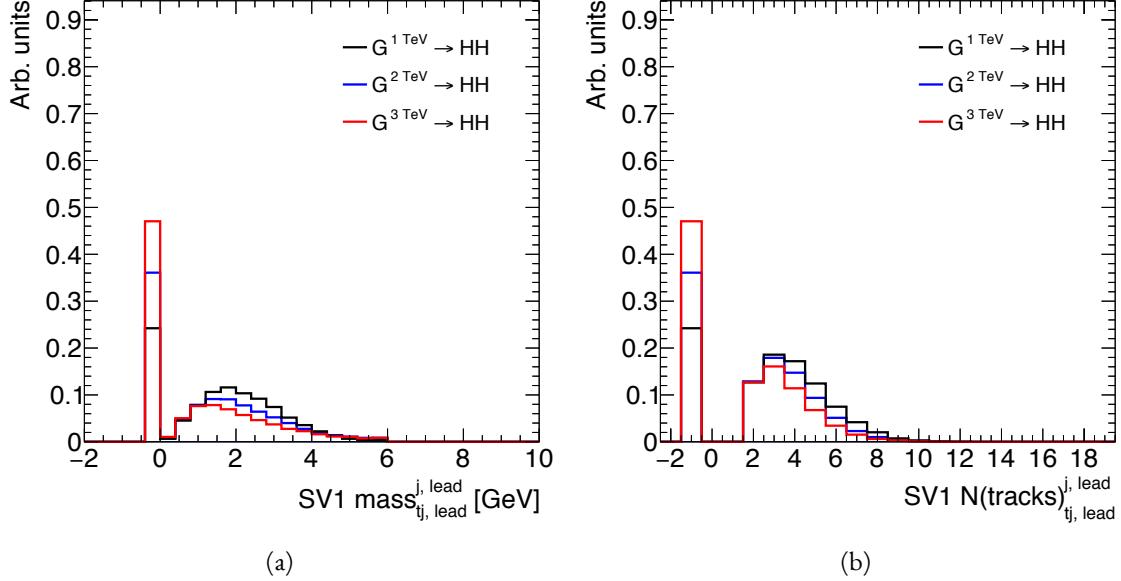


Figure A.4: Mass (a) and number of tracks (b) for the secondary vertices computed with the SV1 algorithm. When no secondary vertex is found, the quantities are assigned to default negative values.

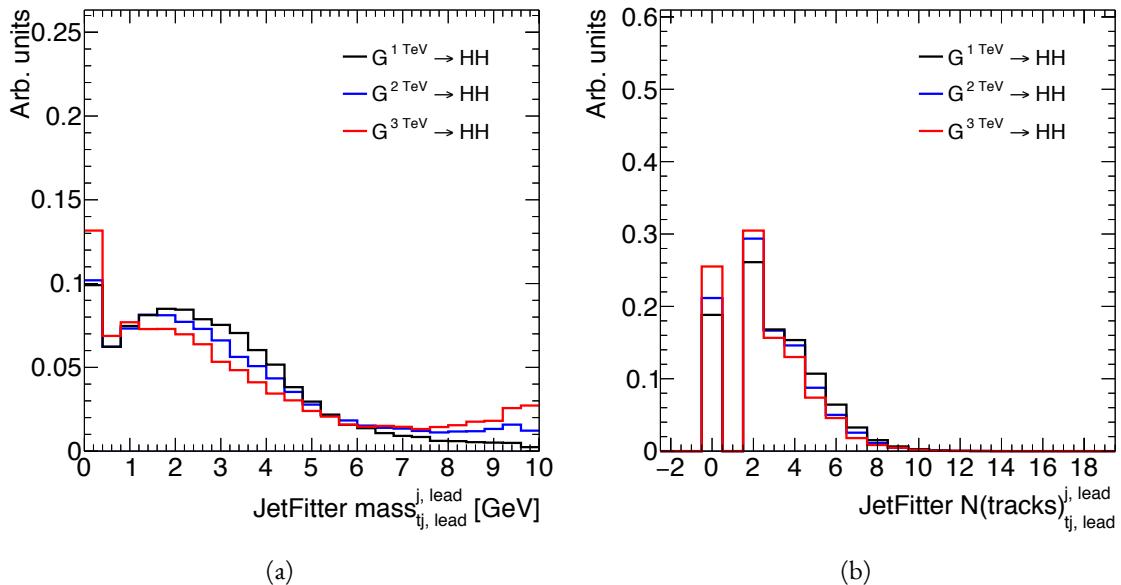


Figure A.5: Mass (a) and number of tracks (b) for vertices computed with the JetFitter algorithm. When no vertices are found, the quantities are assigned to default negative values.

2805 tuned for tagging multiple  $b$  quarks inside one jet, the tagging efficiency could degrade. Figure A.6 shows  
 2806 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

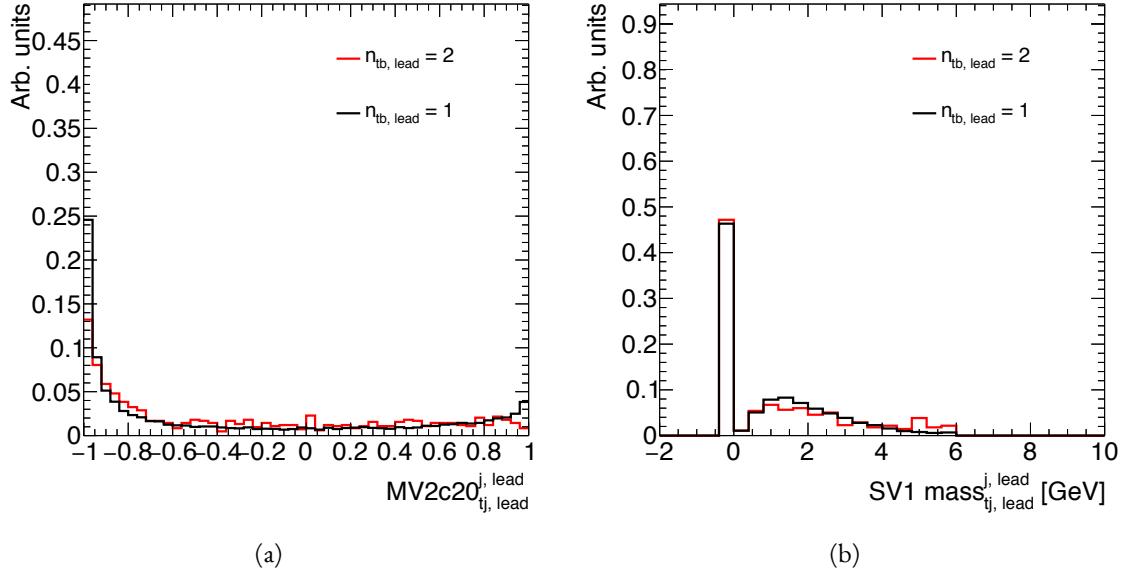


Figure A.6: MV<sub>2</sub>c20 score (a) and SV1 mass (b) for leading track jets with two truth  $b$  quarks ( $n_{tb,\text{lead}} = 2$ ) compared to those with only one truth  $b$  ( $n_{tb,\text{lead}} = 1$ ).

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.

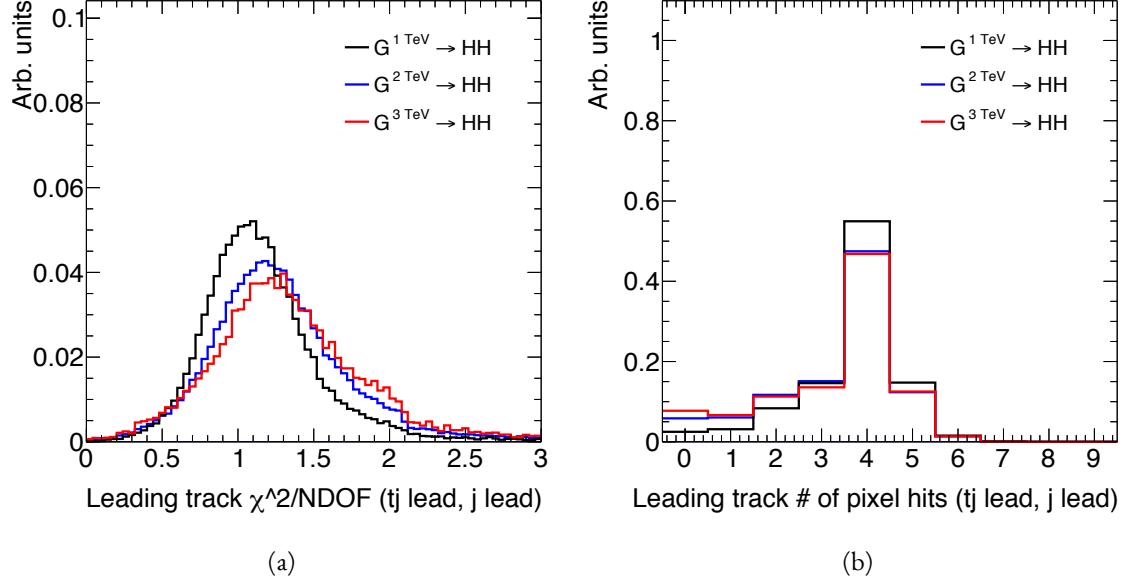


Figure A.7: Track fit  $\chi^2/\text{nDOF}$  (a) and number of pixel detector hits (b) for the leading track of the leading track jet in different mass RSG  $c = 1$  samples

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  $p_T$ .

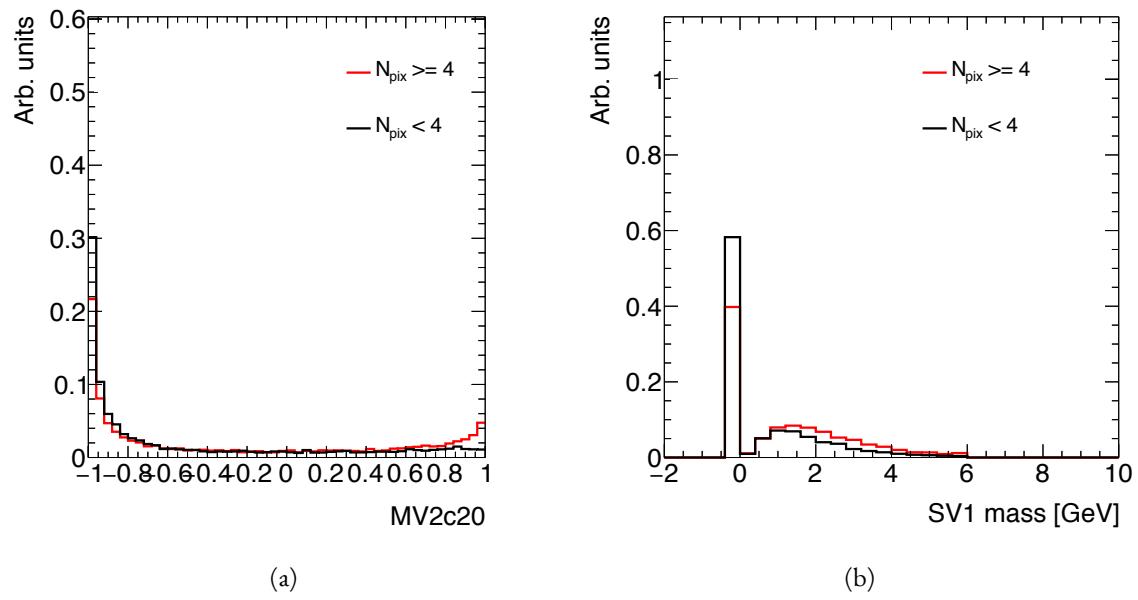


Figure A.8: MV<sub>2</sub>c<sub>20</sub> score (a) and SV<sub>1</sub> mass (b) for leading track jets whose leading track jet has at least four pixel hits ( $N_{\text{pix}} \geq 4$ ) compared to those which do not ( $N_{\text{pix}} < 4$ ).

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