

<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>9</sup> THE DEPARTMENT OF PHYSICS

<sup>10</sup> IN PARTIAL FULFILLMENT OF THE REQUIREMENTS  
<sup>11</sup> FOR THE DEGREE OF  
<sup>12</sup> DOCTOR OF PHILOSOPHY  
<sup>13</sup> IN THE SUBJECT OF  
<sup>14</sup> PHYSICS

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<sup>17</sup> MAY 2016

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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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# Acknowledgments

409 I have been a member of the Harvard ATLAS group for many years now, first as an undergraduate and  
 410 then as a graduate student. As a result, I have had the privilege of interacting with many amazing people  
 411 there over the years and have accumulated a large list of folks to thank.

412 First and foremost, I must thank the two people who have effectively been my academic parents since I  
 413 started in the Harvard group: João Guimarães da Costa and Melissa Franklin. Melissa Franklin and João  
 414 Guimarães da Costa. They have both been so important to both my academic and personal development  
 415 that I can't even put one before the other. João has been an excellent PhD advisor, showing me how to  
 416 look at the big picture and helping me navigate the sometimes complicated politics of ATLAS. He got me  
 417 started on my first projects with ATLAS as a young college sophomore before there was even beam in the  
 418 LHC (go cosmic ray muons!). He has also been a constant source of advice and support, even when we  
 419 have been on different continents. Melissa gave me my start in HEP as a summer student on CDF and  
 420 has been an unbelievable mentor throughout my time at Harvard. I still remember our weekly chalkboard  
 421 particle physics lessons after that first summer. She also graciously took me on as a co-advisee after João  
 422 moved on to his new position at IHEP. I am incredibly lucky to have had both of them as advisors.

423 Another mentor who was essential to my development as a graduate student is Paolo Giromini. His un-  
 424 canny knowledge and intuition about detectors is unmatched and I am very grateful to have had the chance  
 425 to work with him on the micromegas for the ATLAS New Small Wheel upgrade project. I owe essentially  
 426 all my practical knowledge about detectors (and building things in general) to him. I also appreciated his  
 427 unique sense of humor which made sometimes difficult tasks much easier to get through.

428 I am grateful to John Huth and Masahiro Morii for their helpful advice as the other professors in the  
 429 Harvard ATLAS group as well. I especially thank John for helping me get started on the micromegas  
 430 trigger project and being a great professor to TF particle physics for. Additionally I thank Howard Georgi  
 431 for serving as my third committee member and offering me feedback throughout my graduate career.

432 I also owe enormous thanks to Hugh Skottowe, the postdoc that I worked most closely with in my early  
433 years as a graduate student. He was always able to help me through complicated tasks in everything from  
434 writing code to understanding difficult physics concepts. I particularly enjoyed walking down to his office  
435 in Palfrey at random times and talking through whatever problem I was tackling on that day.

436 Alex Tuna, the second postdoc that I worked closely with at Harvard, deserves great thanks as well. He  
437 helped me push through to the end of my graduate career and offered great advice along the way.

438 Being at Harvard, I have seen an incredible array of graduate students graduate before me: Ben Smith,  
439 Verena Martinez Outschoorn, Srivas Prasad, Michael Kagan, Giovanni Zevi Della Porta, Laura Jeanty,  
440 Kevin Mercurio, William Spearman, and Andy Yen. I want to thank them all for showing me what a good  
441 physicist looks like and for patiently answering my questions and offering insightful advice about physics  
442 and life.

443 Getting through graduate school would not have been possible without the support and friendship of  
444 the other students in our group. Thanks to Emma Tolley for geeking out with me about cool comput-  
445 ing stuff, going to taste delicious beers with me, and helping start the Palfrey tradition of Taco Tuesdays.  
446 Thanks to Brian Clark for being a great friend and housing companion both in Kirkland House and in our  
447 tiny summer apartment in Geneva (and thanks to his partner Allison Goff for the same reasons!). Thanks  
448 to Siyuan Sun for giving me my first aikido lesson and always being there for great conversations, big and  
449 small. Tony (Baojia) Tong deserves special recognition for working with me on the  $4b$  analysis and putting  
450 up with my sometimes strange requests (and giving me rides to the Val Thoiry Migros so I wouldn't have  
451 to pay exorbitant Geneva grocery prices!). Stephen Chan is probably the only student in the group who  
452 both understands my references to the Sopranos and makes some of his own. To the younger graduate  
453 students - Karri Di Petrillo, Jennifer Roloff, Julia Gonski, and Ann Wang - I want to say thank you for  
454 making the group a fun and lively place to be and giving all of us energy that the older graduate students  
455 like myself can sometimes lack.

456 I'd like to thank Annie Wei and Gray Putnam, the two undergraduates I have worked with as a graduate  
457 student. Their unbelievable intuition and quickness in picking up difficult particle physics concepts is  
458 inspiring.

459 I would also like to thank all of the postdocs that I have interacted with in my time in the Harvard group:  
460 Kevin Black, Alberto Belloni (who would always ask me “Do you have it?”...I can now say that I do!),  
461 Shulamit Moed, Corrinne Mills, Geraldine Conti, David Lopez Mateos, Chris Rogan, Valerio Ippolito,  
462 and Stefano Zambito.

463 There are many people on ATLAS who have helped me get to this point as well. In the *WW* group, I  
464 have to thank Jonathan Long, Joana Machado Miguens, Ben Cerio, Philip Chang, Bonnie Chow, Richard  
465 Polifka, Heberth Torres, Tae Min Hong, and Jennifer Hsu for being wonderful colleagues and making the  
466 entire analysis run smoothly. In the *4b* group, I have to thank Qi Zeng, Tony Tong, Alex Tuna, Michael  
467 Kagan, Max Bellomo, John Alison, and Patrick Bryant.

468 Kirkland House was my home for the last three years of graduate school and was an wonderful envi-  
469 ronment and support system. I want to thank my fellow tutors, especially Brian Clark and Allison Goff  
470 (again), Zach Abel, Kelly Bodwin, Alex Lupsasca, John and Pam Park, Luke and Erin Walczewski, and  
471 Philip Gant for their friendship and support. I also want to thank Kate Drizos Cavell, Bob Butler, and the  
472 Faculty Deans Tom and Verena Conley.

473 There are still a few friends that haven’t been covered yet and deserve great thanks. Jake Connors and  
474 Meredith MacGregor have been absolutely wonderful friends and I thank them in particular for the many  
475 home-cooked meals and great conversations we’ve had in their apartment. Nihar Shah has been my friend  
476 and confidant since we were both wee freshmen in Harvard Yard. Gareth Kafka, though he sits on the  
477 “neutrino” side of Palfrey House, has made days there more fun and has also been an enthusiastic partici-  
478 pant in the Palfrey Taco Tuesdays.

479 Being at Harvard necessarily means having to navigate through bureaucracy at some point or another.  
480 I thank Lisa Cacciabuado, Carol Davis, Jacob Barandes, Korin Watras, and Angela Allen for always having  
481 open doors and being the most kind, helpful people in the Physics department.

482 I thank Venky Narayananuriti for putting on a great SPU course that I was proud to be a part of and  
483 TF for. I’d also like to thank Jim Waldo for offering me much advice about working in Computer Science  
484 and giving me a fun data project to be a part of in my free time.

485 I grew up in a very tight knit Serbian community on the south side of Chicago which helped make me

486 the person I am today. I would like to thank all of the people at St. Simeon Mirotochivi Serbian Orthodox  
487 Church who have always been sources of enthusiasm and support in my life.

488 I would not be here without the unconditional love and constant support and encouragement of my  
489 family. To my pokojni Deda Branko and Miloje, my pokojni Baba Milka, and my Baba Desa, I want to  
490 say thank you for instilling in me at an early age the love of curiosity and storytelling that I have carried  
491 throughout my life. To my sister Angelina, I want to say thank you for always loving me and being my  
492 partner in crime throughout our childhoods. To my parents, Miroljub and Nada, Tata and Mama, I really  
493 cannot express how grateful I am to you and how much I owe you. As I look back now I see how I am  
494 a combination of both of your best qualities. Every day I am in situations where I better understand the  
495 lessons you taught me and the sacrifices you made to make sure I got the best possible education. I love  
496 you all.

497 Finally, I have to thank my soul mate, the one person in my life who understands me more than anyone  
498 else, my fiancée Kelly Brock. You are my sounding board, my support system, my cheerleader (figuratively  
499 and literally!), my best friend, my role model, and my everything. I would not have gotten through grad-  
500 uate school without you and my life would not be the same without you. I cannot wait to start our new  
501 lives together as the married doctors, tackling whatever comes our way with the same zeal with which we  
502 tackled graduate school. I love you with all my heart and soul.

# 0

503

504

## Introduction

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

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

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

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

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

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

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

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

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

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

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

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

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

594

## Part I

595

# Theoretical and Experimental Background

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

Richard Morris

# 1

596

597

## The Physics of the Higgs Boson

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

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

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

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

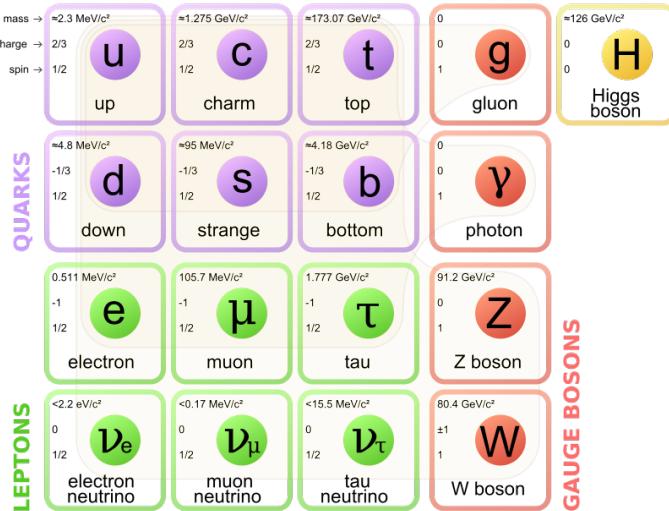


Figure 1.1: The particles of the Standard Model and their properties [6].

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

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

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

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

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

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

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

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

643 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>644</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>645</sup> where  $v = \sqrt{\mu^2/\lambda}$ . Because this is the location of the minimum, it corresponds to the vacuum expecta-  
<sup>646</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>647</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>648</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>649</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>650</sup> and  $g'$  are the corresponding coupling constants. The Pauli matrices are represented with  $\tau$ . With the  
<sup>651</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>652</sup>

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

<sup>653</sup>

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

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

657

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

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

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

660 The full Lagrangian of Higgs interactions can be written as

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

661 with

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

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

669 1.3 HIGGS BOSON PRODUCTION AND DECAY

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

673 1.3.1 HIGGS PRODUCTION

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

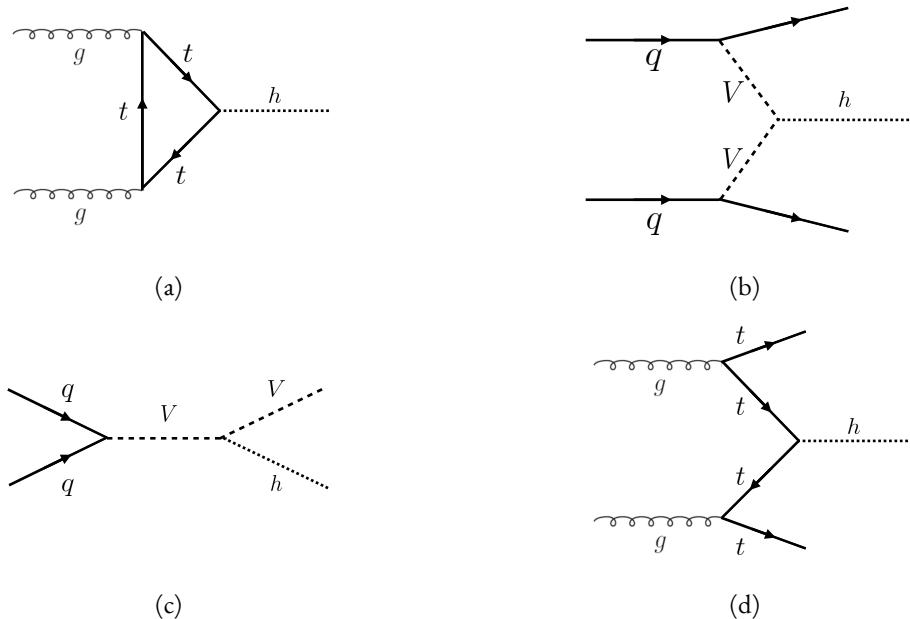


Figure 1.2: The four most common Higgs boson production modes at the LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c)  $W/Z + H$  production, (d)  $t\bar{t}H$  production

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

682 momentum of the incoming partons. The Higgs can also be produced in association with a  $W$  or  $Z$  boson.  
 683 The  $W/Z$  is produced normally and then radiates a Higgs<sup>2</sup>. Finally, the Higgs can be produced in associa-  
 684 tion with two top quarks. Each incoming gluon splits into a  $t\bar{t}$  pair, and one of the top pairs combines to  
 685 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

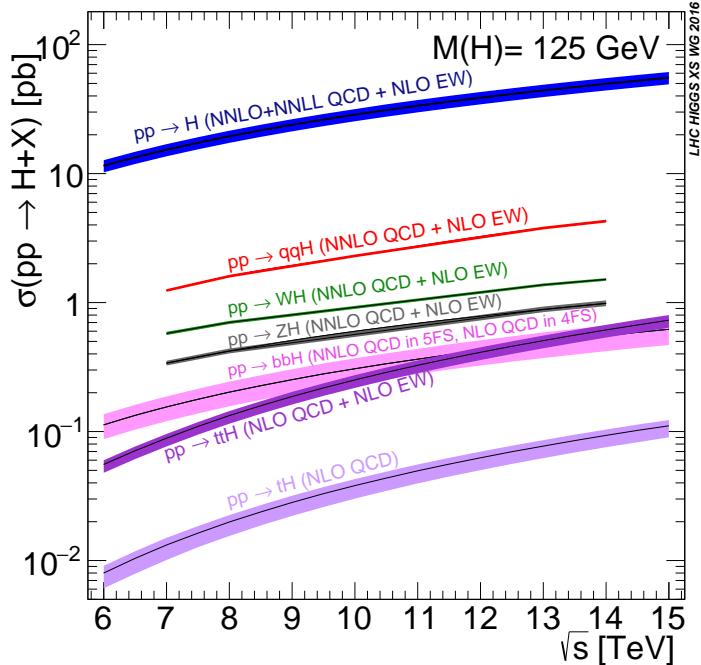


Figure 1.3: Higgs production cross sections as a function of center of mass energy ( $\sqrt{s}$ ) at a  $pp$  collider [18].

686  
 687 largest cross section, while VBF is the second largest at approximately a factor of 10 smaller. The figure also  
 688 includes the less commonly studied  $b\bar{b}H$  and  $tH$  modes. While the  $b\bar{b}H$  mode has a larger cross section  
 689 than  $t\bar{t}H$ , it also has larger backgrounds and is thus less sensitive. The  $tH$  mode is not as sensitive as  $t\bar{t}H$   
 690 due to its lower cross section. At  $\sqrt{s} = 8$  TeV, ggF production of a 125 GeV Higgs has a cross section  
 691 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  
 692 boson fusion cross sections have been computed to next-to-next-to-leading order (NNLO) in the QCD  
 693 couplings and next-to-leading order in the electroweak couplings [19–26]. The gluon fusion cross section  
 694 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”.

695 the main Higgs production modes at this center of mass energy, as well as their uncertainties from varying  
 696 the QCD renormalization and factorization scales and PDFs, are summarized in table 1.1 for a 125 GeV  
 697 Higgs. The relative uncertainty of the gluon fusion mode is larger than the relative uncertainty in the  
 698 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].

### 699 1.3.2 HIGGS BRANCHING RATIOS

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

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

702 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  
 703  $m_H$  is the mass of the Higgs. Note that the width scales with the square of the fermion mass. (This also  
 704 assumes that the Higgs mass is large enough to decay with both the fermions on shell.)

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

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

707 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  
 708 where  $m_H \geq 2m_Z$ ), the equation is divided by 2 to account for identical particles in the final state, and  
 709  $x_W$  is replaced with  $x_Z = 4M_Z^2/m_H^2$ . This is shown in equation 1.16 [5].

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

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

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

712 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  
 713 the  $W$  or  $Z$  width.  $\Gamma_0$  is the squared matrix element, which is given in equation 1.18 [28].

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

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

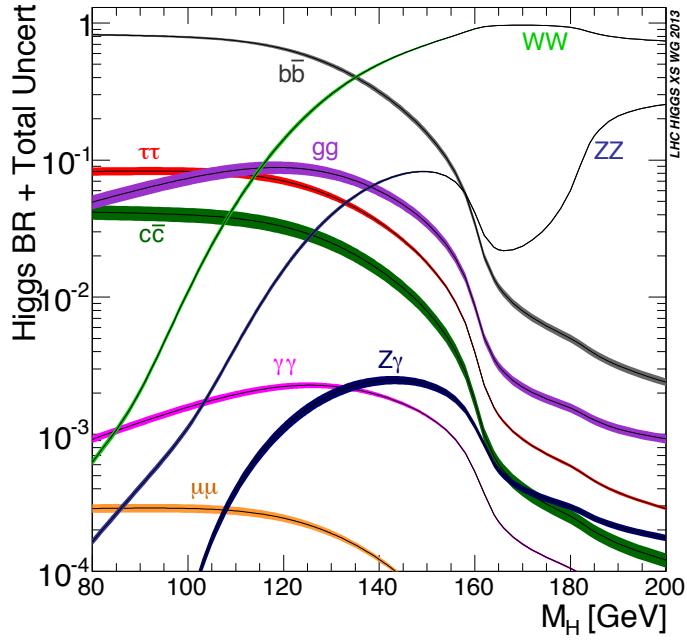


Figure 1.4: Higgs boson branching ratios as a function of  $m_H$  [18].

725 the theoretical branching ratios for a Higgs with a mass of 125 GeV. Note that there is a Higgs branching  
 726 ratio to  $\gamma\gamma$  even though photons are massless. This decay happens through a loop, which suppresses the  
 727 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].

728 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.

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

#### 734 1.4 HIGGS PAIR PRODUCTION IN THE STANDARD MODEL

735 The Standard Model also allows for processes that produce two Higgs bosons in the final state, known  
 736 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

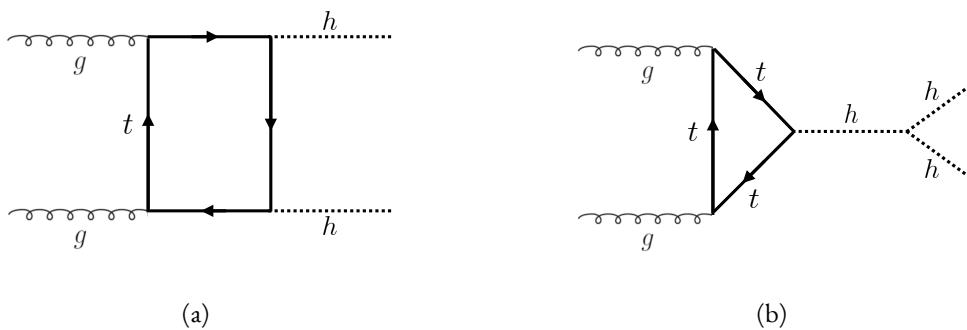


Figure 1.5: The two leading diagrams for Standard Model di-Higgs production at the LHC: (a) box diagram, (b) Higgs self coupling.

737  
 738 cross section for di-Higgs production at the LHC. Nevertheless, Higgs pair production is quite interesting

<sup>739</sup> to study because it gives direct access to the  $\lambda$  parameter of the Higgs potential, also known as the Higgs  
<sup>740</sup> self coupling. The diagram in figure 1.5(b) is sensitive to this coupling through the triple Higgs vertex.

<sup>741</sup> One can substitute the gluon fusion production of diagram 1.5(b) with any of the other production  
<sup>742</sup> modes previously discussed. These other modes do not suffer from interference with the box diagram in  
<sup>743</sup> figure 1.5(a) due to the presence of additional particles in the final state. They still have a lower cross section  
<sup>744</sup> than the gluon fusion mode, however. The cross sections for di-Higgs production in the different modes,  
<sup>745</sup> as well as their uncertainties, are shown in table 1.4 [29]. These are shown for  $\sqrt{s} = 14$  TeV as this is the  
<sup>746</sup> 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  $\alpha_S$ .

<sup>747</sup>

## <sup>748</sup> 1.5 HIGGS PAIR PRODUCTION IN THEORIES BEYOND THE STANDARD MODEL

<sup>749</sup> The Higgs pair production cross section in the Standard Model is rather small, and datasets on the scale of  
<sup>750</sup> the full  $3000 \text{ fb}^{-1}$  expected from the High Luminosity LHC will be required to obtain sensitive measure-  
<sup>751</sup> ments of the Higgs self-coupling [29]. However, the discovery of the Higgs also gives particle physicists  
<sup>752</sup> a new tool that can be exploited in the search for new physics beyond the Standard Model. In particular,  
<sup>753</sup> Higgs pair production is a promising channel in the search for new physics. The cross section for di-Higgs  
<sup>754</sup> production can be altered through both resonant and non-resonant production of Higgs pairs. In non-  
<sup>755</sup> resonant production, di-Higgs production vertices can arise from the presence of a new strong sector and  
<sup>756</sup> additional colored particles [30–32]. Figure 1.6 shows examples of the types of vertices that can arise. In  
<sup>757</sup> the resonant case, new heavy particle can decay to Higgs pairs. Such new particles can include heavy Higgs

758 bosons arising in two Higgs doublet models (2HDM) or Higgs portal models as well as heavy gravitons in  
 759 Randall-Sundrum theories [30, 33–39]. Figure 1.7 shows a generic diagram for a heavy resonance decaying  
 760 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

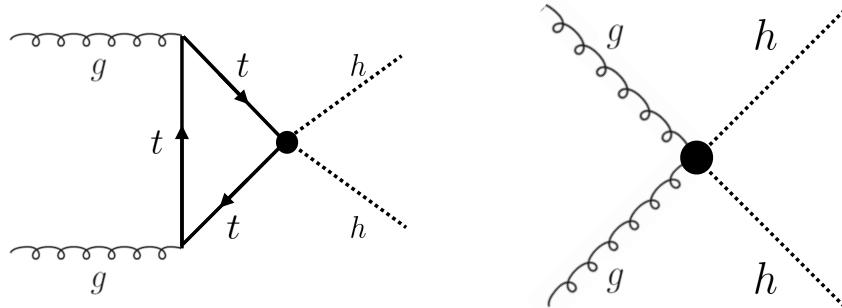


Figure 1.6: Diagrams with new vertices for non-resonant Higgs pair production arising in composite Higgs models.

761  
 762 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.

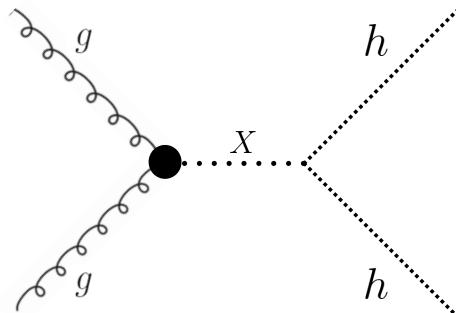


Figure 1.7: Generic Feynman diagram for resonant Higgs pair production in BSM theories.

763

### 764 1.5.1 RANDALL-SUNDRUM GRAVITONS

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

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

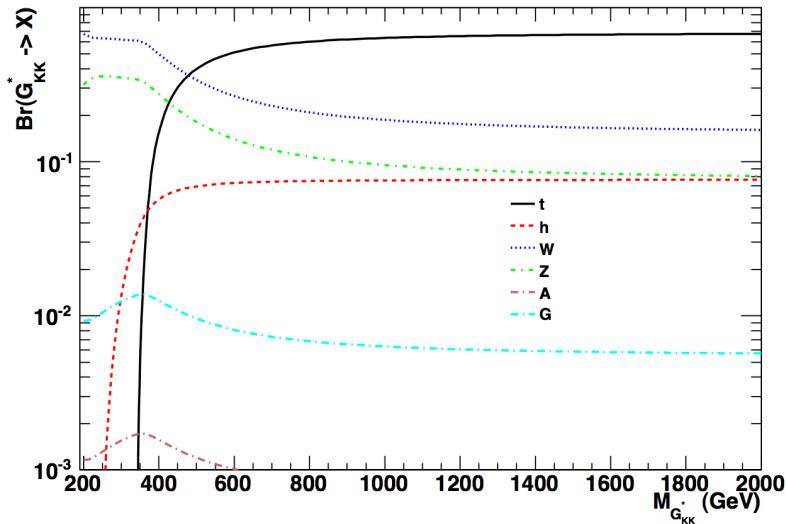


Figure 1.8: Branching ratios for a spin-2 Randall-Sundrum graviton as a function of mass computed in MadGraph with the CP3-Origins implementation [34, 40, 41].

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

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

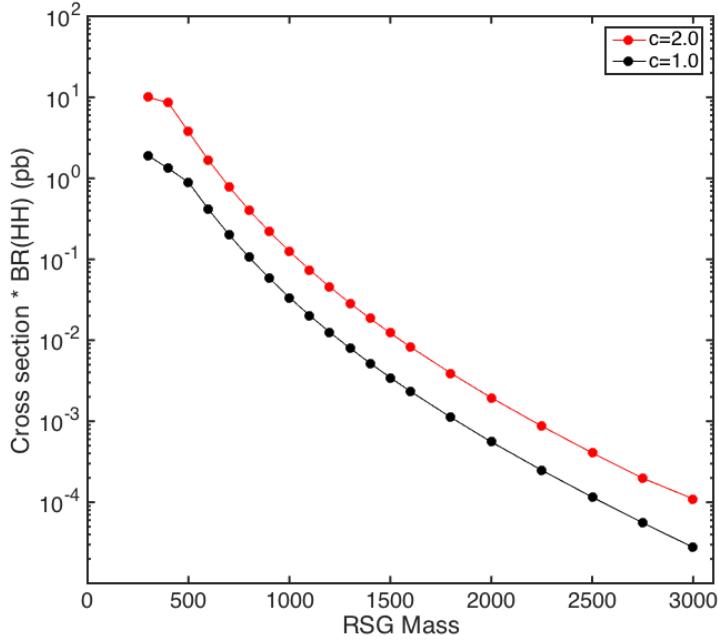


Figure 1.9:  $\sigma \times \text{BR}(HH)$  for Randall-Sundrum gravitons as a function of mass computed in MadGraph with the CP3-Origins implementation [34, 40, 41].

784      $c = 1.0$ , the width starts at 8.365 GeV for a mass of 300 GeV and increases to 187.2 GeV at a mass of  
 785     3 TeV. Similarly, with  $c = 2.0$ , the width starts at 33.46 GeV for  $m_G = 300$  GeV and increases to  
 786     748.8 GeV at a mass of 3 TeV.

### 787     1.5.2    TWO HIGGS DOUBLET MODELS

788     In Two Higgs Doublet Models (2HDM), a second complex scalar doublet is added to the Standard Model [36–  
 789     38]. In this case, all four degrees of freedom in the second doublet correspond to new particles, meaning  
 790     that there are five total scalars from the two Higgs doublets -  $h$  (light CP-even Higgs),  $H$  (heavy CP-even  
 791     Higgs),  $A$  (heavy CP-odd Higgs), and  $H^\pm$  (charged Higgs). The model is parameterized by two main pa-  
 792     rameters. The first,  $\tan \beta \equiv \frac{v_2}{v_1}$ , is the ratio of the vacuum expectation values of the two Higgs doublets  
 793     (where  $v_1$  corresponds to the  $v$  in the SM Higgs model described above). The second parameter is  $\alpha$ , a mix-  
 794     ing angle between the heavy and light Higgs fields. Models are also often parameterized with  $\cos(\beta - \alpha)$   
 795     rather than  $\alpha$  directly. The limit where  $\cos(\beta - \alpha) = 0$  is called the alignment limit, and in this limit the

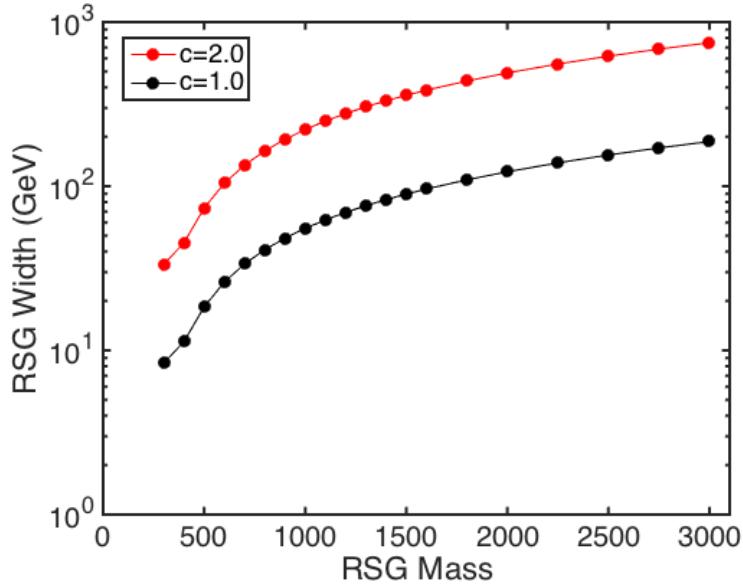


Figure 1.10: Randall-Sundrum graviton width as a function of mass computed in MadGraph with the CP3-Origins implementation [34, 40, 41]

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

797 2HDM models are usually separated into two main types - Type I and Type II. In Type I models, the  
 798 charged fermions only couple to the second Higgs doublet, leading to a fermiophobic light Higgs. In  
 799 Type II models, up-type quarks couple to the first doublet while down-type quarks couple to the second  
 800 doublet. One specific realization of a Type II 2HDM is the Minimal Supersymmetric Standard Model  
 801 (MSSM).

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

807 **1.6 CONCLUSION**

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

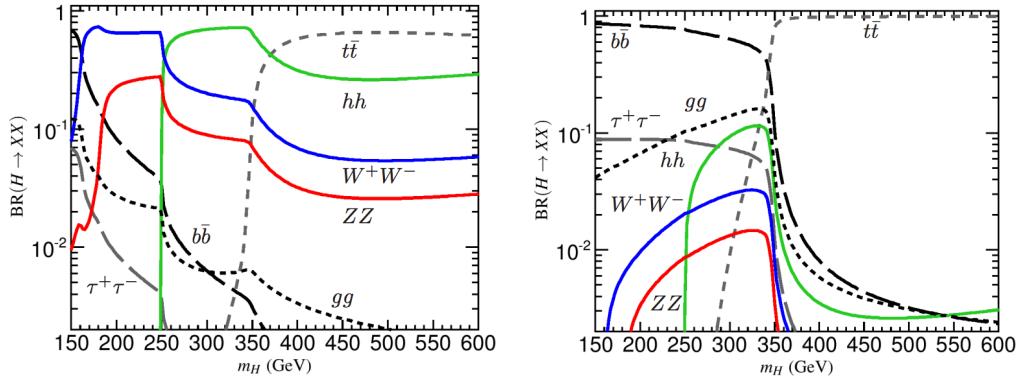


Figure 1.II: Branching ratios for heavy Higgs  $H$  in Type I (left) and Type II (right) 2HDM models with  $\tan \beta = 1.5$  and  $\cos(\beta - \alpha) = 0.1$ (0.01) for Type I (Type II) [38].

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

814

815

816

## The ATLAS detector and the Large Hadron Collider

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

827 2.1 THE LARGE HADRON COLLIDER

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

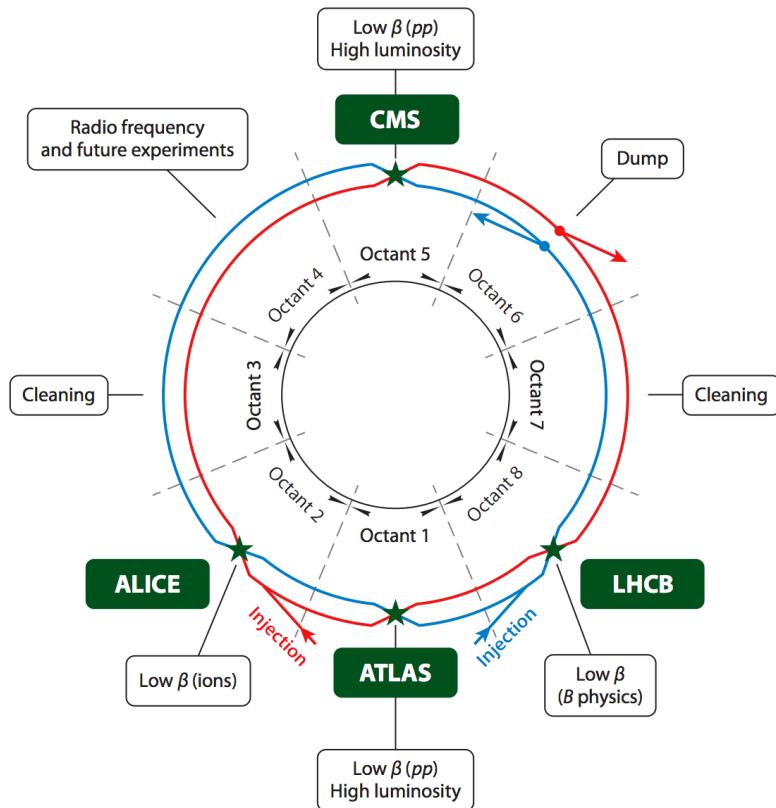


Figure 2.1: A schematic view of the LHC ring [47]. Four main experiments are located at interaction points along the ring. ATLAS and CMS are general purpose experiments, while ALICE is dedicated to heavy ion collisions and LHCb is dedicated to studying  $B$  physics.

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

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

839 **2.1.1 INSTANTANEOUS LUMINOSITY**

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

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

846 The LHC collides protons in bunches, and in the above equation  $N_b$  is the number of protons per bunch  
 847 while  $n_b$  is the number of bunches per beam. Nominally, the LHC can hold up to 2808 proton bunches.  
 848  $f_{\text{rev}}$  is the revolution frequency.  $\epsilon_n$  is the normalized transverse beam emittance, a measurement of the  
 849 average spread of the particles in position-momentum space which has the dimension of length.  $\beta^*$  is the  
 850 value of the  $\beta$  function for the beam at the interaction point. It relates the emittance to the Gaussian  
 851 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  
 852 are colliding at an angle at the IP.

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

855

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

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

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

863 **2.1.2 EVOLUTION OF MACHINE CONDITIONS**

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

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

Table 2.1: Evolution of LHC machine conditions [49, 50].

868 **2.2 THE ATLAS DETECTOR**

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

873 **2.2.1 COORDINATE SYSTEM**

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



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

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

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

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

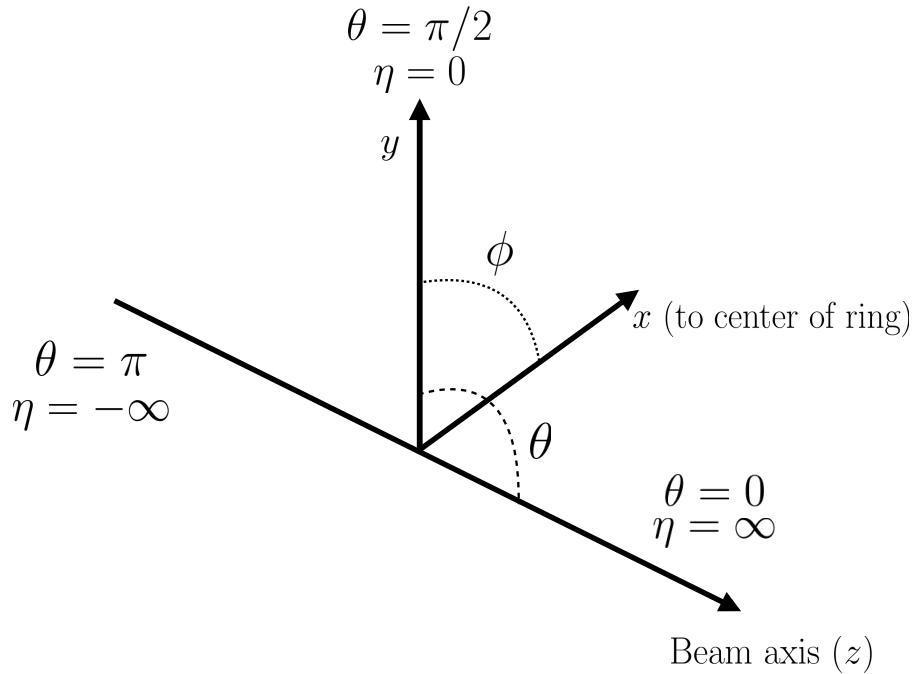


Figure 2.3: The ATLAS coordinate system. The  $z$  direction corresponds to the beam axis, while  $x$  and  $y$  define the transverse plane.  $\theta$  is the angle relative to the beam axis and  $\phi$  is the azimuthal angle.  $\eta$ , the pseudorapidity, approaches infinity at small angles relative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

886    2.2.2    INNER DETECTOR

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

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



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

## 895 PIXEL DETECTOR

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

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

907 **INSERTABLE B-LAYER**

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

913 **SEMICONDUCTOR TRACKER (SCT)**

914 The semiconductor tracker (SCT) consists of silicon microstrips and comprises the next four layers of  
915 the ID. This sub-detector has 6.4 cm long sensors that are daisy-chained into strips with a strip pitch of  
916 80  $\mu\text{m}$  [43]. Some of the strips have a small stereo angle to allow for measurement of both angular coor-  
917 dinates. In total there are 6.3 million readout channels. The intrinsic accuracies are 17  $\mu\text{m}$  in  $R\text{-}\phi$  and  
918 580  $\mu\text{m}$  in  $z$  (or  $R$  in the endcap).

919 **TRANSITION RADIATION TRACKER (TRT)**

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

927 **2.2.3 CALORIMETERS**

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

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

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

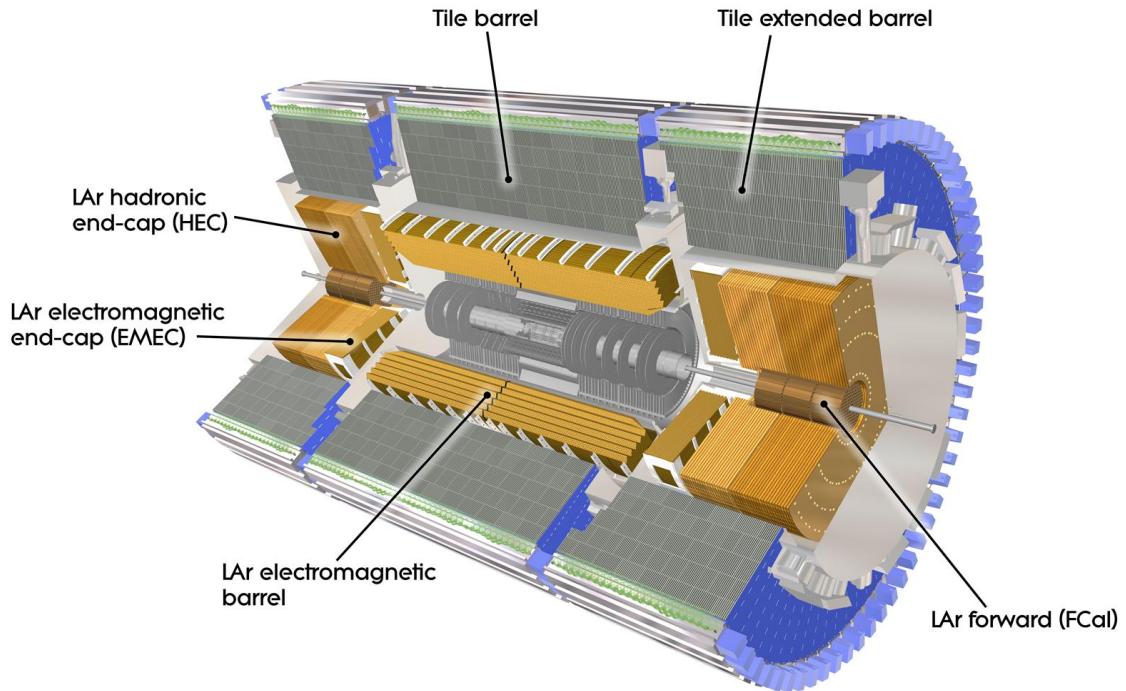


Figure 2.5: Layout of the ATLAS calorimeter system [43].

#### 936 ELECTROMAGNETIC CALORIMETER

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

942 In order to provide good containment the calorimeter depth must be optimized. Typically, for elec-  
943 tromagnetic calorimeters the depth is measured in radiation lengths. In general, the intensity of a particle  
944 beam attenuates exponentially in distance with an attenuation constant equal to the radiation length. That  
945 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.  
946 The ATLAS EM calorimeter is designed to have  $> 22$  radiation lengths in the barrel and  $> 24$  in the  
947 endcap [43].

948 **HADRONIC CALORIMETERS**

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

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

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

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

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

966 2.2.4 MUON SPECTROMETER

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

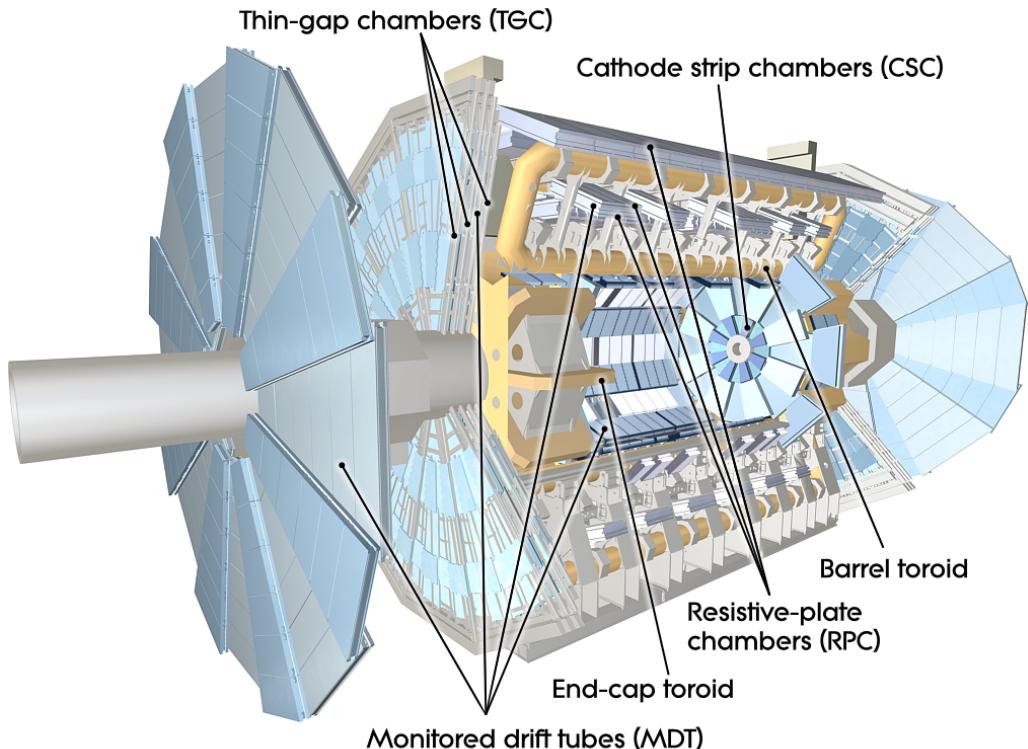


Figure 2.6: Layout of the ATLAS muon system [43].

977 MONITORED DRIFT TUBES (MDTs)

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

985 CATHODE STRIP CHAMBERS (CSCs)

986 The cathode strip chambers cover a narrow window of the innermost endcap region at  $2.0 < |\eta| <$   
987 2.7. In this region the background rates in the cavern are particularly high and the CSCs are designed to  
988 handle these higher rates. The CSCs are multiwire proportional chambers with wires pointing in the radial  
989 direction (away from the beam pipe). The wire serves as an anode and there are two types of segmented  
990 cathode strip, one perpendicular to the wires which gives the precision measurement and one parallel which  
991 provides the transverse coordinate. It has an 80/20% gas mixture of Argon and CO<sub>2</sub> [43].

992 RESISTIVE PLATE CHAMBERS (RPCs)

993 The resistive plate chambers (RPCs) are gaseous electrode-plate detectors covering the region  $|\eta| < 1.05$ .  
994 They consist of two resistive plates separated by a distance of 2 mm. The gas mixture used is a 94.7/5/0.3%  
995 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  
996  $\phi$  measurement and thus provides measurement of the azimuthal coordinate in the barrel. The thin gas  
997 gap allows for a quick response time which makes it ideal for use in the trigger. Signals in the RPC have  
998 a width of approximately 5 ns. There are three layers of RPCs which are referred to as the three trigger  
999 stations. They allow for programmable thresholds in both a low  $p_T$  and high  $p_T$  trigger. The coincidence  
1000 of hits in the innermost chambers allows for setting muon trigger thresholds between 6 and 9 GeV, while  
1001 the outermost layer allows the trigger to set trigger thresholds in the range of 9 to 40 GeV [43].

1002 THIN GAP CHAMBERS (TGCs)

1003 The thin gap chambers (TGCs) are multiwire proportional chambers where the wire to cathode distance  
1004 (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*-  
1005 pentane and use a high electric field to gain good time resolution. They serve two functions in the end-cap  
1006 system. First, they serve as the trigger chambers. Second, they also provide azimuthal coordinate measure-  
1007 ment. They sit on the inner and middle layers of the endcap. The outermost layer's azimuthal coordinate  
1008 is determined by extrapolation [43]. As with the RPCs, the TGCs also are capable of triggering with pro-  
1009 grammable thresholds in the same  $p_T$  range specified for the RPCs above.

1010 2.2.5 MAGNET SYSTEM

1011 As mentioned previously, there are two independent magnet systems in ATLAS. The first is a 2 T solenoid  
1012 field in the inner detector which provides bending in the azimuthal plane. The second is an approximately  
1013 0.5 T toroidal field in the muon system which provides bending in  $\eta$ . Figure 2.7 shows the predicted field  
1014 integral as a function of  $|\eta|$  [43].

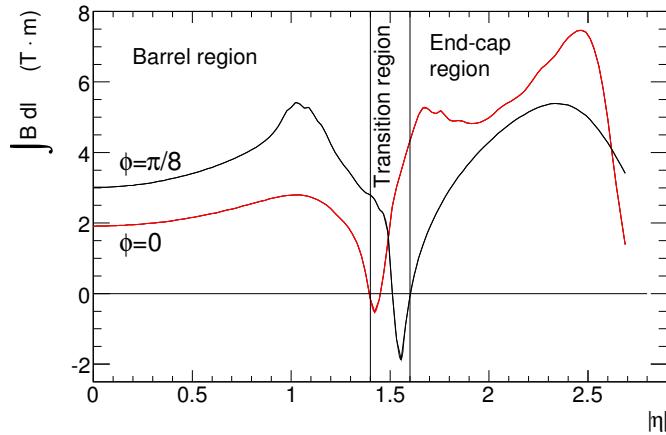


Figure 2.7: Predicted field integral as a function of  $|\eta|$  for the ATLAS magnet system [43].

1015    2.2.6    TRIGGER SYSTEM

1016    The ATLAS trigger system searches for signatures of muons, electrons, photons, hadronically decaying  $\tau$   
 1017    leptons, and jets in order to save these events for further analysis. The trigger system in ATLAS is designed  
 1018    to reduce the maximum LHC event rate of 40 MHz to a more reasonable rate that can be recorded. The  
 1019    trigger first consists of a fast, hardware based system called the Level-1 (L1) trigger. The L1 trigger consists  
 1020    of independent dedicated detector sub-components that can seed regions of interest (RoIs) for further  
 1021    analysis downstream. For muons, the RPCs and TGCs are used, while in the calorimeter coarsely grained  
 1022    sections of calorimeter cells called towers are used. Once regions of interest are seeded, a software based  
 1023    system called the High Level Trigger (HLT) is used to reconstruct objects and integrate information from  
 1024    different parts of the detector. In Run 1 of ATLAS, the HLT consisted of two separate stages: the level 2  
 1025    (L2) trigger and the event filter (EF).

1026    The maximum trigger rate that the L1 trigger can handle is 75 kHz. In the HLT, the rate of events  
 1027    written to disk is approximately 400 Hz. Figure 2.8 shows the trigger rates for different L1 triggers in 2012  
 1028    and 2015 for ATLAS [53].

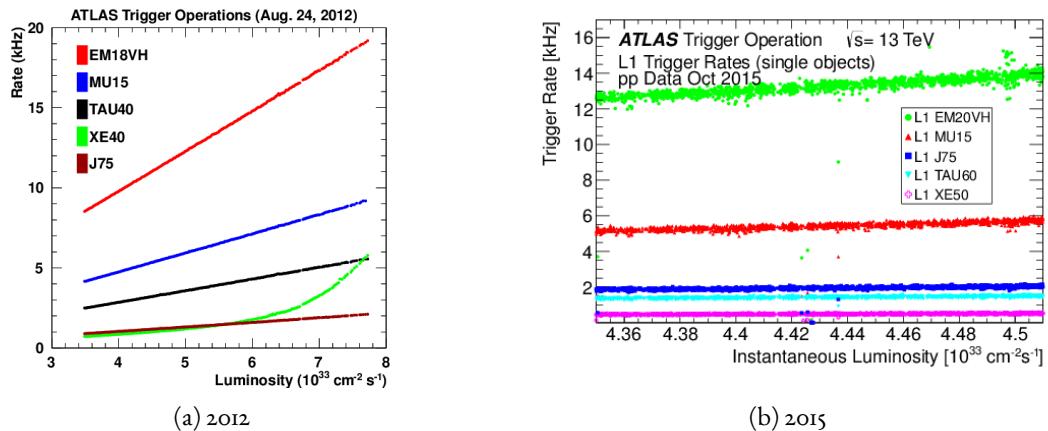


Figure 2.8: ATLAS trigger rates for Level-1 triggers as a function of instantaneous luminosity in 2012 and 2015 operation. These are single object triggers for electromagnetic clusters (EM), muons (MU), jets (J), missing energy (XE), and  $\tau$  leptons (TAU). The threshold of the trigger is given in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

1029    2.2.7    ATLAS DATASETS

1030    ATLAS has collected data at center of mass energies of 7, 8, and 13 TeV. Figure 2.9 shows the integrated  
1031    luminosity as a function of time for each of the three datasets. In the 2011 dataset with  $\sqrt{s} = 7$  TeV,  
1032    ATLAS recorded  $5.08 \text{ fb}^{-1}$ . Increased instantaneous luminosity in 2012 led to a larger dataset of  $21.3 \text{ fb}^{-1}$   
1033    recorded at  $\sqrt{s} = 8$  TeV. After Long Shutdown 1 (LS1) of the LHC and a restart in 2015, ATLAS  
1034    recorded  $3.9 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13$  TeV [54, 55]. The data recorded by ATLAS can only be used for  
1035    analysis if all detectors were in a stable state when the data was being taken. The fraction of recorded  
1036    ATLAS data that was labeled as being good for physics analysis was 90%, 95%, and 82% in the 7, 8, and  
1037    13 TeV data respectively. Thus, the Run 1 results presented in this thesis use  $4.6 \text{ fb}^{-1}$  at  $\sqrt{s} = 7$  TeV and  
1038     $20.3 \text{ fb}^{-1}$  at  $\sqrt{s} = 8$  TeV<sup>1</sup>. The Run 2 results use  $3.2 \text{ fb}^{-1}$  at  $\sqrt{s} = 13$  TeV.

1039    2.2.8    DETECTOR PERFORMANCE

1040    Table 2.2 summarizes the design requirements for each of the different sub-detectors. This table shows the  
1041    energy and momentum resolution of tracking, calorimetry, and muon measurements.

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

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

1042    2.3    THE ATLAS MUON NEW SMALL WHEEL UPGRADE

1043    As the LHC continues operation, it is scheduled to be upgraded in several phases to allow it to reach higher  
1044    instantaneous luminosities and thus collect larger datasets. These conditions will open new doors for study

---

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

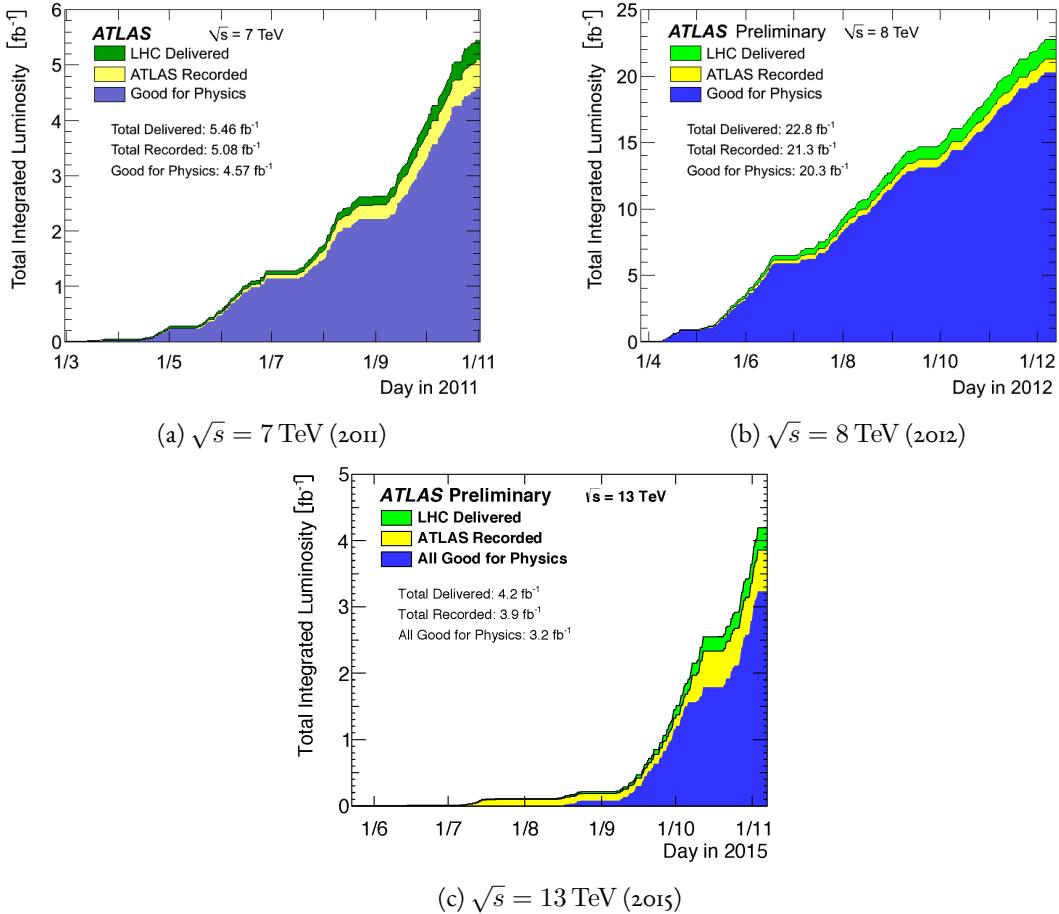


Figure 2.9: Instantaneous luminosity as a function of time for data recorded by ATLAS at different center of mass energies [54, 55].

of rare physics processes but will also present interesting challenges that must be faced. ATLAS will require new detector technologies to cope with the increased background rates in the cavern in these high luminosity conditions. One such upgrade, scheduled to be installed during Long Shutdown 2 (LS2) of the LHC in 2018, is the ATLAS Muon New Small Wheel (NSW) upgrade [56]. The NSW will replace the innermost end-cap wheel of the muon system with new technologies. This is the part of the muon detector closest to the beam line and thus experiences the highest rates of particle flux in the muon system.

1051    2.3.1 MOTIVATION

1052    The motivation of the NSW is two-fold. The first objective is to alleviate the decreased tracking efficiency  
1053    that comes in a high rate environment. As figure 2.10, at the LHC design luminosity both the efficiency of  
1054    recording hits and reconstructing track segments in the MDTs decreases.

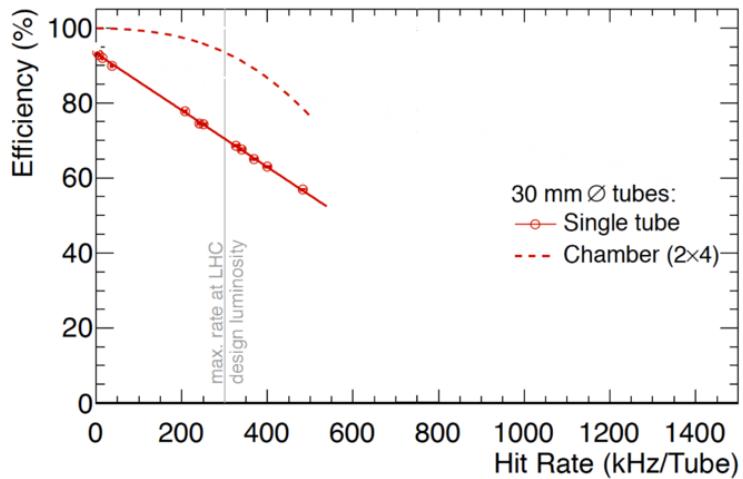


Figure 2.10: MDT tube hit (solid) and segment (dashed) efficiency as a function of hit rate per tube [56].

1055    The NSW will also work to alleviate the rate of fake triggers arising in the endcap. Figure 2.11 shows  
1056    the extrapolated trigger rates as a function of the  $p_T$  threshold with and without the NSW upgrade. As  
1057    the figure shows, the NSW upgrade will reduce the trigger rate by an order of magnitude compared to the  
1058    current endcap trigger system. This reduction allows the  $p_T$  thresholds on muons to remain low, increasing  
1059    the phase space of possible physics studies and in particular maintaining good acceptance for Higgs physics.

1060    2.3.2 NSW DETECTOR TECHNOLOGIES

1061    The NSW will use two new detector technologies - micromesh gaseous structure detectors (micromegas)  
1062    and small-strip thin gap chambers (sTGCs) [56, 57]. The micromegas is more suited to tracking because  
1063    of its good spatial resolution, while the sTGCs have better time resolution and are more suited for the  
1064    trigger. However, both systems are capable of providing tracking and trigger information. To maintain  
1065    full redundancy in cases of detector failure, both technologies will be used for tracking and trigger in the

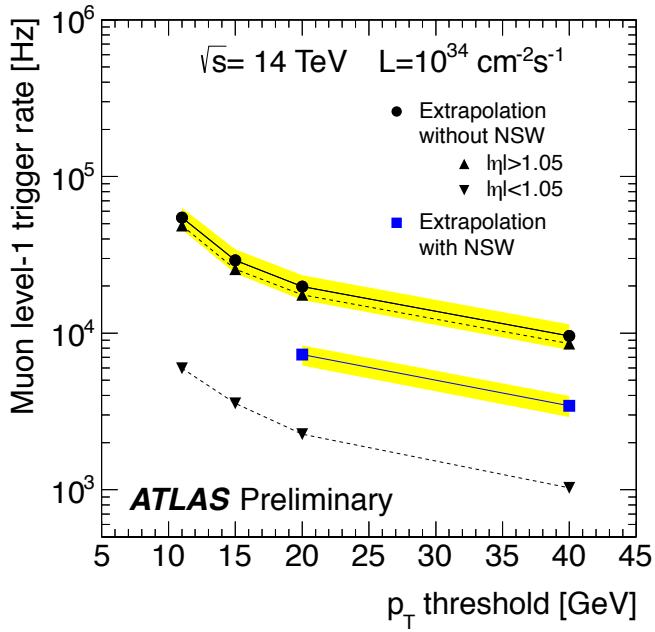


Figure 2.11: Trigger rate as a function of  $p_T$  threshold with and without the NSW upgrade [56].

1066 NSW.

1067 **MICROMEGAS**

1068 Micromegas detectors operate using a thin metallic mesh that sits approximately  $100\ \mu\text{m}$  away from the  
 1069 readout electrodes to create the amplification region. Above this mesh, there is a drift region on the order  
 1070 of a few mm in length capped by a drift electrode. As a charged particle traverses the detector, it ionizes gas  
 1071 and the electrons drift down towards readout strips. The timing of the drift can be used to reconstruct the  
 1072 angle of traversal of the particle. This is illustrated in figure 2.12. The micromegas used in ATLAS will be  
 1073 resistive micromegas, where the readout electrodes are topped with resistive strips [58]. This alleviates the  
 1074 risk of sparking in the large area detectors that ATLAS will use.

1075 In ATLAS, the micromegas drift gap will be 5 mm and the amplification gap will be  $128\ \mu\text{m}$ . They are  
 1076 filled with the same gas mixture as the MDTs. They will be stacked in an octuplet in an XXUV-UVXX  
 1077 geometry, where X refers to straight strips and U and V refer to stereo strips at an angle of  $\pm 1.5^\circ$ . This  
 1078 arrangement allows for measurement of the azimuthal coordinate and gives a large lever arm between the

1079 straight strips for triggering purposes. Figure 2.12 shows the geometry of a single micromegas detector as  
1080 well as its operating principle [56].

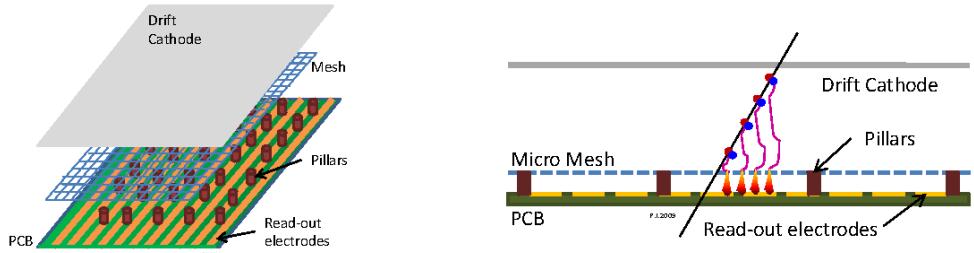


Figure 2.12: Illustrations of the geometry (left) and operating principle (right) of the micromegas detector [56].

## 1081 sTGCs

1082 The sTGCs are similar to the TGCs currently in the ATLAS endcap muon system [43]. They consist  
1083 of gold-plated tungsten wires (with a 1.8 mm pitch) between two cathode planes 1.4 mm away from the  
1084 wire plane. One cathode plane consists of strips with a 3.2 mm pitch (much smaller pitch than the TGCs),  
1085 while the other consists of coarser pads that are used for defining regions of interest in the sTGC trigger  
1086 algorithm. Figure 2.13 shows the basic detector geometry.

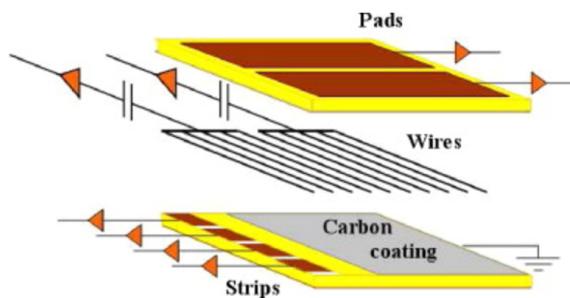


Figure 2.13: Geometry of the sTGC detector [56].

### 1087 2.3.3 PHYSICS IMPACT

1088 Maintaining low  $p_T$  thresholds for muons while still staying within the trigger rate budget at Level 1  
1089 (20 kHz) for the muon system is crucial for physics analyses to be successful in high luminosity condi-  
1090 tions. One realm where the lepton trigger threshold is especially important is in Higgs physics. In the

1091  $H \rightarrow WW^*$  analysis, one of the  $W$  bosons is off shell and tends to decay to soft leptons. In associated  
 1092 production of a Higgs with a  $W$ , the lepton is also important because it provides the main handle which  
 1093 allows the event to be triggered. Without the NSW, analyses would be required to either raise the muon  
 1094  $p_T$  threshold or only use muons triggered from the barrel muon system. Table 2.3 shows that both of these  
 1095 alternatives significantly reduce the Higgs signal efficiency. With the NSW, the signal efficiency is largely  
 1096 maintained and the triggers can remain unprescaled at lower  $p_T$  thresholds.

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

Table 2.3: Signal efficiencies for  $WH$  production with  $H \rightarrow b\bar{b}$  and  $H \rightarrow WW^* \rightarrow \mu\nu qq$  under different trigger configurations [56].

## 1097 2.4 OBJECT RECONSTRUCTION IN ATLAS

1098 ATLAS analyses first start by requiring the presence of certain reconstructed physics objects in the event.  
 1099 This section will present a brief overview of the algorithms used to reconstruct electrons, muons, jets (in-  
 1100 cluding  $b$ -jets), and missing energy<sup>2</sup>. The performance of physics object reconstruction and identification  
 1101 will also be discussed as these are relevant to the analyses presented later. Figure 2.14 gives an overview of  
 1102 the different sub-detectors that each type of particle will interact with in ATLAS.

### 1103 2.4.1 ELECTRONS

1104 Electrons in ATLAS will leave tracks in the inner detector and energy deposits in the electromagnetic  
 1105 calorimeter. The algorithm for recognizing the signature of electrons proceeds in two steps: reconstruction  
 1106 and identification.

1107 In reconstruction, an electron candidate is formed by matching EM calorimeter deposits with ID tracks.  
 1108 The algorithm first chooses seed clusters in the EM calorimeter by using a sliding window algorithm that

---

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

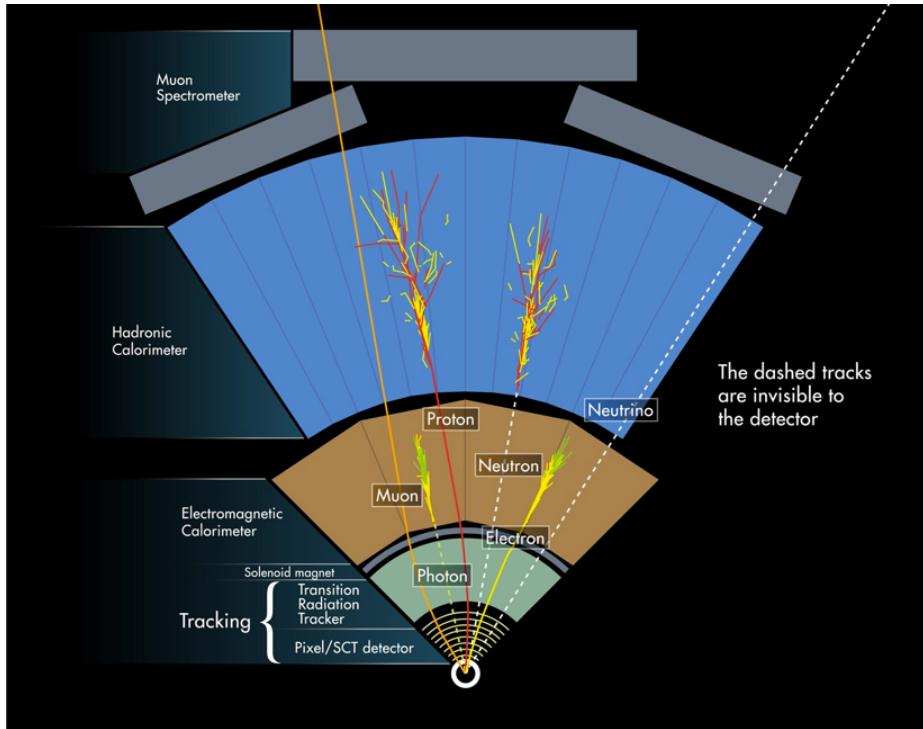


Figure 2.14: Illustration of particle interactions in ATLAS [59]

1109 searches for towers with transverse energy larger than 2.5 GeV. In addition to seed clusters, track candidates  
 1110 must be identified in the ID. The algorithm selects seed tracks with  $p_T > 1$  GeV that do not fit  
 1111 well with a pion hypothesis. Once candidate tracks are selected, they are re-fit with a Gaussian Sum Filter  
 1112 (GSF) algorithm to estimate electron parameters [60]. Finally, an electron candidate is formed if at least  
 1113 one track matches to a seed cluster in the calorimeter. The full details of the reconstruction algorithm can  
 1114 be found in reference [61].

1115 Once an electron candidate is present, identification criteria must be applied in order to reject fake elec-  
 1116 trons from background. Many different variables are used for this identification. They include informa-  
 1117 tion about the shower shape in the EM calorimeter and the amount of leakage into the hadronic calorime-  
 1118 ter, as well as information from the ID and in particular the TRT. There are both selection requirement  
 1119 based and likelihood-based criteria that range from “loose” to “very tight”. For details, see reference [61].

1120 Figure 2.15 shows the algorithm’s reconstruction efficiency for true electrons with different identification  
 1121 criteria as well as the electron energy resolution in simulation [61, 62]. The reconstruction efficiency is

1122 measured using both  $Z$  and  $J/\psi$  tag and probe techniques.

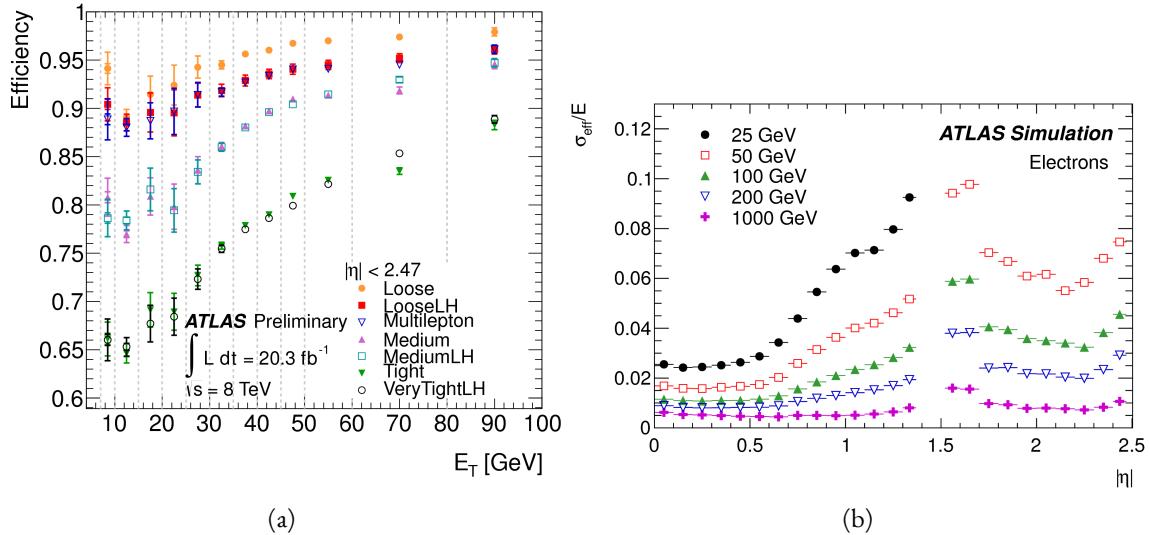


Figure 2.15: Electron performance: (a) reconstruction efficiency as a function of electron  $E_T$  [61] (b) energy resolution in simulation as a function of  $| \eta |$  for different energy electrons [62].

## 1123 2.4.2 MUONS

1124 The ATLAS detector is designed to stop most particles before they reach the muon spectrometer. Muons,  
1125 however, are minimum ionizing particles, meaning that they will not lose a significant amount of energy  
1126 through interactions with the detector and will thus pass through. Therefore, the muon reconstruction  
1127 works to match tracks in the muon spectrometer with tracks in the inner detector.

1128 The first step of reconstruction is to reconstruct local straight line tracks, called segments, in each muon  
1129 chamber. Segments are then fit to larger tracks that traverse the entire muon spectrometer. Such muon  
1130 tracks are referred to as “standalone” tracks (SA) as they only use information from the muon spectrometer.  
1131 The standalone tracks are then matched to tracks in the inner detector to form “combined” (CB) muons,  
1132 where the combined ID and MS fit are used to determine the momentum and direction of the muon. To  
1133 improve acceptance, segment-tagged and calorimeter-tagged muons are also reconstructed. In these cases,  
1134 ID tracks are matched to segments in the MS and calorimeter deposits consistent with a minimum ionizing  
1135 particle, respectively. The details of the reconstruction can be found in reference [63].

1136 As with electrons, once muon candidates are reconstructed they have identification criteria applied to  
 1137 reduce background. These criteria include the  $\chi^2$  match between the ID and MS tracks, the number of  
 1138 hits in the ID, overall ID and MS track fit quality, and additional variables [63]. The criteria range from  
 1139 “loose” to “tight” as with electrons. Figure 2.16 shows the muon reconstruction efficiency (measured with  
 1140  $Z$  and  $J/\psi$  tag and probe) and invariant mass resolution [63].

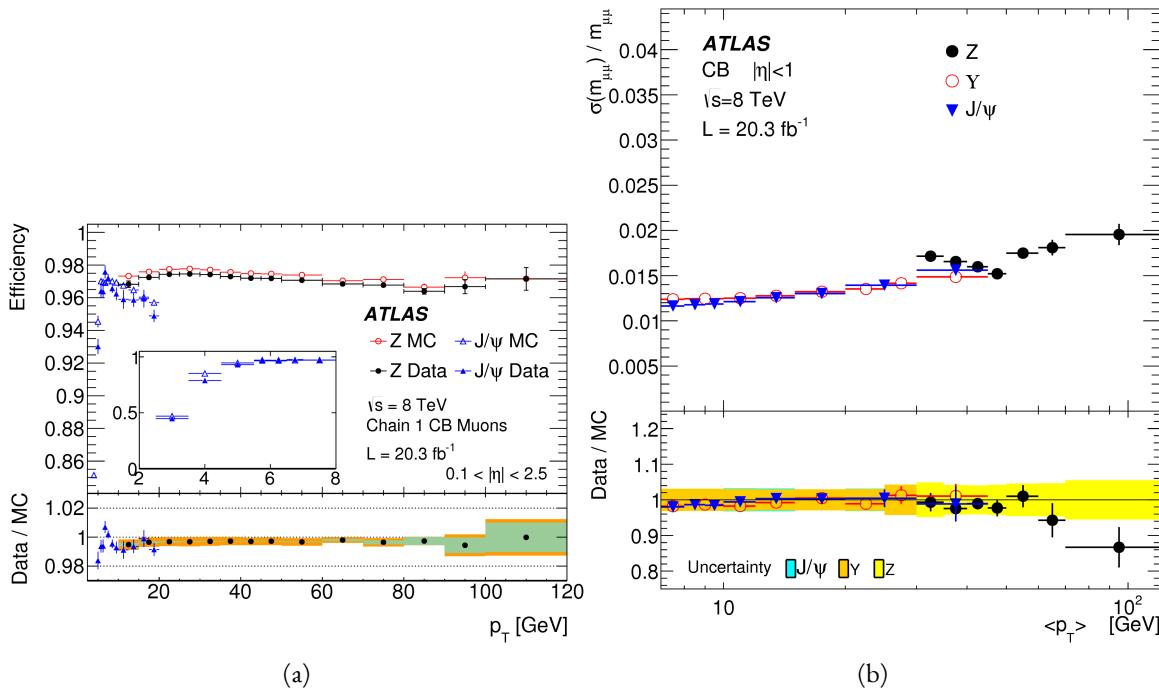


Figure 2.16: Muon performance: (a) reconstruction efficiency as a function of muon  $p_T$  (b) dimuon mass resolution as a function of average  $p_T$  [63].

### 1141 2.4.3 JETS

1142 When a quark or gluon is produced in collisions, it is not measured directly in ATLAS. Rather, due to  
 1143 QCD effects, it produces a collimated spray of hadrons in the direction of the original parton, which is  
 1144 known as a jet. Jets are reconstructed in ATLAS using energy deposits in the hadronic calorimeter. The  
 1145 first step is build “topological clusters” out of energy deposits in calorimeter cells [64, 65]. This is done  
 1146 using strategy where seed cells are chosen by picking cells whose energy measurements are four times the  
 1147 amount of noise expected for that cell. Adjacent cells with at least  $2\sigma$  energy measurements are added to  
 1148 the cluster, then a final layer of clusters with energy above  $0\sigma$  are added. Once calorimeter clusters are

1149 formed, they are clustered further into jet candidates using the anti- $k_T$  jet clustering algorithm [66]. This  
 1150 algorithm defines a parameter  $R$  that appears in the denominator of the clustering distance metric and  
 1151 defines the radial size of the jet in  $\eta\text{-}\phi$  space.

1152 The energy response of the calorimeter must be properly characterized in order to reconstruct the true  
 1153 jet energy. Calorimeter clusters can be calibrated either with the EM calibration, where each cluster is as-  
 1154 sumed to have come from the energy deposit of an electron or photon, or the LCW calibration, where local  
 1155 cluster weights are computed to allow for local calibration of clusters as hadronic or electromagnetic. The  
 1156 details of the jet energy calibration are not discussed here and are presented in reference [67]. Figure 2.17  
 1157 shows the jet energy response after calibration in Monte Carlo as a function of the true  $p_T$  of the jet [67].

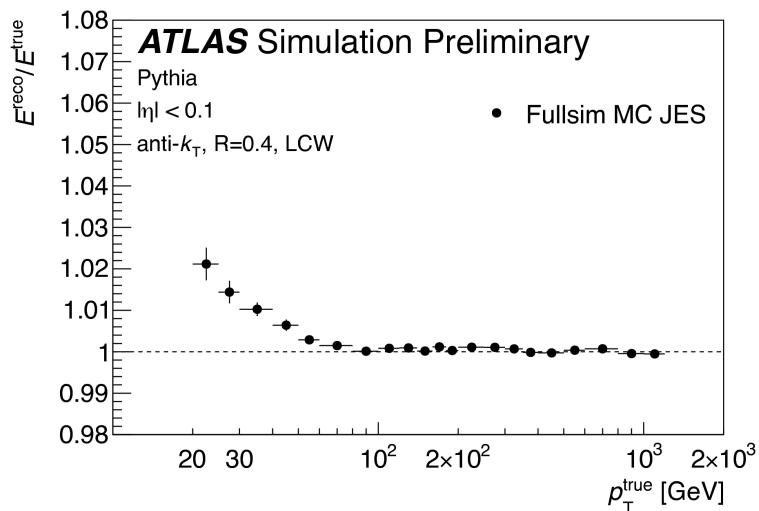


Figure 2.17: Jet energy response after calibration as a function of true  $p_T$  in simulation [67].

1158 Analyses often need to know how consistent a particular jet is with the primary vertex of the event in  
 1159 order to avoid contamination from pileup interactions. One measure of this consistency is known as the  
 1160 jet vertex fraction (JVF). The JVF is the ratio of tracks associated with a primary vertex to the total number  
 1161 of tracks inside a jet. Jets from the primary interaction in the event should have a large fraction of tracks  
 1162 consistent with the primary vertex and therefore have a large JVF value.

1163    2.4.4    *b*-TAGGING

1164    One important aspect of jet physics is the task of identifying the flavor of parton that produced the mea-  
1165    sured jet. While in general this is very difficult, jets from *b*-quarks offer an interesting case where such  
1166    identification is possible. *B* mesons have a lifetime on the order of  $10^{-12}$  seconds, which makes a  $c\tau$  on  
1167    the order of millimeters [6]. This type of displaced decay vertex can be identified in detectors like ATLAS  
1168    and allows *b*-jets to be distinguished from other flavors of jets<sup>3</sup>.

1169    ATLAS uses a multivariate machine learning algorithm to identify jets from *b*-quarks. The inputs to this  
1170    algorithm are determined from lower level reconstruction algorithms. There are three distinct algorithms  
1171    that reconstruct variables which are used as input to the multivariate technique.

1172    The first family of algorithms is referred to as IPxD (where the x can either be 2 or 3). These algorithms  
1173    use the transverse and longitudinal impact parameters  $d_0$  and  $z_0$  of the tracks inside a jet to determine  
1174    their consistency with the primary vertex. They two or three dimensional (hence the x) templates for light  
1175    flavor, charm, and bottom jets and then evaluate the likelihood of the jet coming from each of these types.  
1176    The likelihood ratios are used as inputs to the multivariate algorithm.

1177    The next two algorithms used as input are referred to as the secondary vertex (SV) and JetFitter (JF)  
1178    algorithms. The SV algorithm uses tracks inside the jet to fit for vertices that are displaced from the pri-  
1179    mary vertex. The JF algorithm attempts to reconstruct the full flight path of the *b* by looking for multiple  
1180    displaced vertices along the same line (as *B* decays often result in subsequent charm meson decays).

1181    In Run 1, the multivariate *b*-tagging algorithm used a neural network and was referred to as MV1.  
1182    The details of this algorithm and its inputs are given in reference [68]. In Run 2, the number of inputs  
1183    was simplified and a boosted decision tree with 24 input variables was used, referred to as MV2 [69]. The  
1184    MV2 algorithm is a boosted decision tree incorporating twenty-four input variables constructed from three  
1185    lower level input algorithms described above. Figure 2.18 summarizes the inputs to MV2. Figure 2.19 shows  
1186    the performance of each of these algorithms.

---

<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

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	# 1 track vertices
	Lxy	# 2 track vertices
	L3d	3D significance
	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.

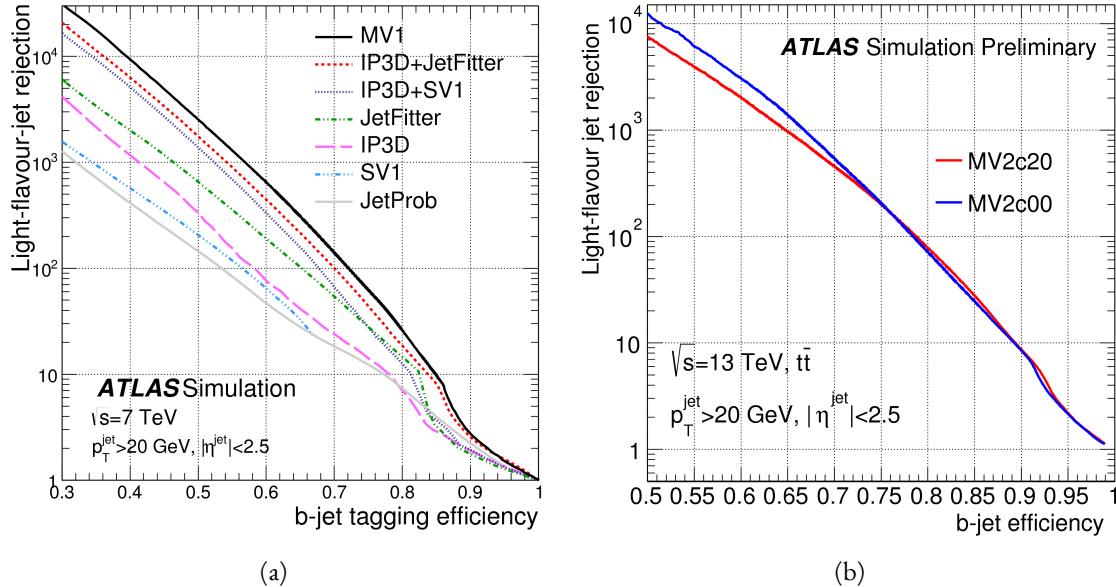


Figure 2.19: Light jet rejection ( $1/\text{efficiency}$ ) vs.  $b$ -jet efficiency for MV1 and its input algorithms (a) [68] and MV2 (b) [69] in simulated  $t\bar{t}$  events. The numbers in the algorithm names in (b) refer to the fraction of charm events used in the MV2 training.

#### 1187 2.4.5 MISSING TRANSVERSE ENERGY

1188 As noted in figure 2.14, neutrinos produced in ATLAS will pass through the detector without interacting.  
 1189 The only way of detecting the presence of weakly interacting particles like neutrinos (or BSM particles that

1190 are long-lived) is to use missing transverse momentum. The basic principle of missing transverse energy is  
 1191 to use the momentum balance of the incoming protons to infer the presence of missing particles. The net  
 1192 longitudinal momentum of the incoming partons that collide is not known (since each carries an unknown  
 1193 fraction of the proton's momentum). However, the protons (and thus incoming partons) have no net  
 1194 momentum in the plane transverse to the beam line (the  $x$ - $y$ ) plane. Therefore, if there are no undetected  
 1195 particles in the final state, the transverse momenta of all of the final state particles should balance. The  
 1196 magnitude of the imbalance in the transverse plane is known as missing transverse momentum ( $E_T^{\text{miss}}$ ).

1197 The basic calculation of missing transverse momentum from calorimeter cells is given in equation 2.4 [70].  
 1198

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

1199 The  $E_T^{\text{miss}}$  calculation is separated into different terms based on the objects that the calorimeter clusters  
 1200 are associated with. This way, each cell's contribution is calibrated appropriately according to the object.  
 1201 This separation of terms is shown in equation 2.5 [70].

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

1202 The CellOut term of the above equation corresponds to calorimeter cells with energy deposits that are  
 1203 not associated with other objects. The soft jets term comes from cells associated to jets with  $p_T$  between  
 1204 7 and 20 GeV, while the jets term comes from jets with  $p_T > 20$  GeV. Because muons do not deposit  
 1205 significant energy in the calorimeter, the muon momentum is used for the muon term [70]. The final  
 1206  $E_T^{\text{miss}}$  is calculated using equation 2.6.

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

1207 Figure 2.20 shows the resolution of the components of the  $E_T^{\text{miss}}$  with different pileup suppression tech-  
 1208 niques [71].

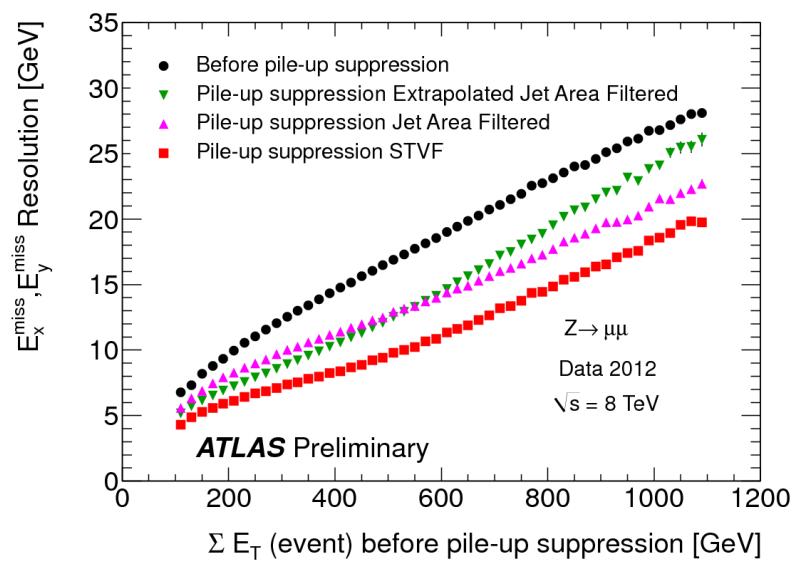


Figure 2.20: Resolution of  $E_T^{\text{miss}}$  components as a function of  $\sum E_T$  before pileup suppression with different pileup techniques [71].

## Part II

1209

Observation and measurement of Higgs

1210

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

1211

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

1212

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

Wernher von Braun

# 3

1213

## 1214 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ Analysis Strategy

### 1215 3.1 INTRODUCTION

1216 This chapter presents an overview of the strategy for searching for a Higgs boson in the  $H \rightarrow WW^* \rightarrow$   
1217  $\ell\nu\ell\nu$  decay topology. Its purpose is to define in broad terms how the search and measurement are under-  
1218 taken, before going into details on the specific sub-categories within the larger analysis. First, the properties  
1219 of the Higgs signal are discussed and the associated backgrounds are presented. Next, the observables used  
1220 to enhance the signal to background ratio are defined. Finally, the parameters of interest in the search  
1221 and measurement will be shown, along with a brief overview of the statistical treatment of the final Higgs  
1222 candidates.

1223 Following this chapter, three different results from the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel are shown.  
1224 Chapter 4 presents a search for Higgs boson production in gluon fusion mode and the role of the  $H \rightarrow WW^*$   
1225 channel in its discovery. Chapter 5 shows the search and first evidence in ATLAS for the Vector Boson Fu-  
1226 sion (VBF) production mode of the Higgs. Finally, chapter 6 shows the combined Run 1  $H \rightarrow WW^*$

1227 results for the measurement of the Higgs cross section and relative coupling strengths to other SM parti-  
1228 cles.

### 1229 3.2 THE $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ SIGNAL IN ATLAS

1230 The signal studied in this and subsequent chapters is the Higgs boson in the  $WW^*$  final state, where each  
1231  $W$  boson subsequently decays into a charged lepton and a neutrino. In the simplest decay path, the final  
1232 state consists of two neutrinos and two charged leptons, each of which can be either an electron or a muon.  
1233 If a  $W$  decays to a  $\tau$  lepton, only leptonic decays of the  $\tau$  are considered. The  $\tau$  lepton produce additional  
1234 neutrinos in the final state but still yield two charged leptons (where each lepton is an electron or muon).  
1235 Neutrinos are not detected in ATLAS, so the final state ultimately consists of two reconstructed leptons  
1236 and missing transverse momentum (denoted as  $E_T^{\text{miss}}$ ). Final states where both of the charged leptons are  
1237 electrons or muons are referred to as the “same flavor” ( $ee/\mu\mu$ ) final states, while those with one electron  
1238 and one muon are referred to as “different flavor” ( $e\mu$  or  $\mu e$ ).

1239 There can be additional jets produced in association with the Higgs boson. As described in detail in  
1240 Chapter 1, if the Higgs is produced via vector boson fusion production, there will be two additional forward  
1241 jets in the event. In gluon fusion, one or more jets can be produced through initial state radiation from  
1242 the incoming gluons. Because of the varying background composition as a function of jet multiplicity,  
1243 each bin in this variable has its own dedicated requirements applied in the search and measurement. The  
1244  $n_j = 0$  and  $n_j = 1$  bins are dedicated to gluon fusion production, while the  $n_j \geq 2$  bin has separate  
1245 dedicated searches for ggF and VBF production.

1246 Figure 3.1 shows the relative branching fractions for the  $H \rightarrow WW^*$  process, calculated from the Par-  
1247 ticle Data Group values for the  $W$  and  $\tau$  branching ratios [6]. The largest branching ratio corresponds  
1248 to both  $W$  bosons decaying to quark pairs at 45.44%. The second largest ratio is for one  $W$  decaying lep-  
1249 tonically and the other decaying to quarks, a branching ratio of 34.18%. In all cases,  $\ell$  denotes either an  
1250 electron or muon, and the leptonic branching ratios of the  $\tau$  are included. For example, the  $\ell\nu qq$  final  
1251 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  
1252 decays to an electron or muon via  $\tau \rightarrow \nu_\tau \ell \nu_\ell$ . Final states with a  $\tau_h$  refer to hadronic decays of the  $\tau$ . The

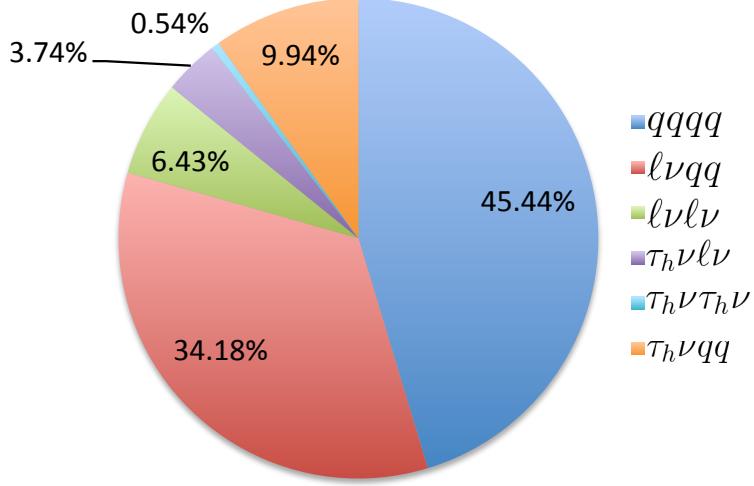


Figure 3.1: Branching ratios for a  $WW$  system.  $q$  refers to quarks.  $\ell$  can be either an electron or muon, and the leptonic branching ratios of the  $\tau$  are included. For example, the  $\ell\nu qq$  final state includes one  $W$  decaying to  $e\nu$ ,  $\mu\nu$ , or  $\tau\nu$ .  $\tau_h$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

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

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

### 3.3 BACKGROUND PROCESSES

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

#### 3.3.1 STANDARD MODEL WW PRODUCTION

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

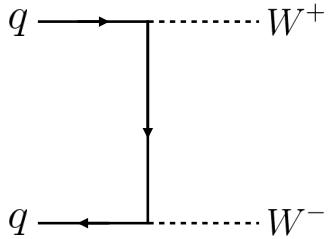


Figure 3.2: Feynman diagram for Standard Model  $WW$  production

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

### 3.3.2 TOP QUARK PRODUCTION

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

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

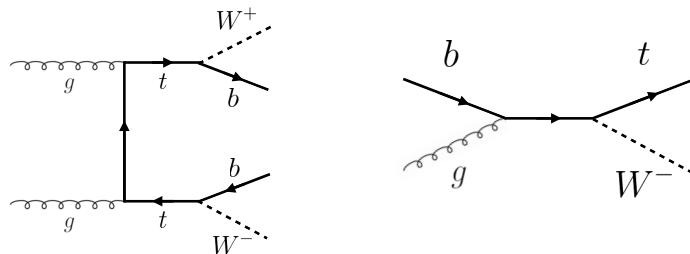


Figure 3.3: Feynman diagrams for top pair production (left) and  $Wt$  production (right)

1276 3.3.3  $W$ +JETS BACKGROUND

1277 Single  $W$  boson production in association with jets is a unique background to Higgs production. The  
1278 other backgrounds considered thus far have all included two prompt leptons, each decaying from a  $W$   
1279 boson, in the final state. In  $W$ +jets production, however, only one reconstructed lepton originates from  
1280 a  $W$ . The second reconstructed lepton is either an algorithmic “fake” or the result of non-prompt decays.  
1281 In the first case, the lepton is a jet misidentified as a lepton by either the electron or muon reconstruction  
1282 algorithms. In the second case, the lepton may be a real lepton but coming from semi-leptonic decays of  
1283 particles inside the shower of the jet. This background can be reduced by requiring that the reconstructed  
1284 lepton have little activity in the surrounding region of the calorimeter (also known as an “isolation”). Fig-  
1285 ure 3.4 shows the Feynman diagram for  $W$ +jets production.

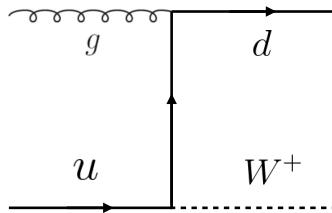


Figure 3.4: An example Feynman diagram of  $W$ +jets production

1286 3.3.4  $Z/\gamma^*$ +JETS BACKGROUND

1287 Production of a  $Z$  boson or virtual photon (also known as Drell-Yan and denoted with  $Z/\gamma^*$ ) in associa-  
1288 tion with jets is also a background to Higgs production. The  $Z$  boson decays to two leptons of the same  
1289 flavor. When the  $Z/\gamma^*$  decays directly to electrons or muons, the background enters the same flavor final  
1290 state. When the  $Z$  decays to two  $\tau$  leptons the background can enter the different flavor final state as well.  
1291 Figure 3.5 shows the production of a  $Z$  in association with one jet. Because there are no neutrinos in this  
1292 final state, variables like  $E_T^{\text{miss}}$  can be used to reduce the background<sup>i</sup>.

---

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

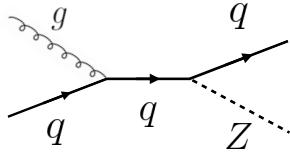


Figure 3.5: An example Feynman diagram of  $Z$ +jets production

### 1293 3.3.5 SUBDOMINANT BACKGROUNDS

1294 There are additional processes which contribute to the background composition. These backgrounds are  
 1295 subdominant and contribute less to the total background estimate than those discussed previously. The  
 1296 first process is referred to as  $VV$  or “Other diboson” processes and includes multiple Standard Model  
 1297 diboson processes, including  $WZ$ ,  $ZZ$ ,  $W\gamma$ ,  $W\gamma^*$ , and  $Z\gamma$  production. Additionally, there is a back-  
 1298 ground contribution from QCD multijet production. While the cross section for this process is large, its  
 1299 contribution to the  $WW^*$  final state is small because two jets must be misidentified as leptons.

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

### 1300 3.4 SHARED SIGNAL REGION SELECTION REQUIREMENTS

1301 As presented in section 3.2, there are many different combinations of physics objects that can define a  
 1302  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  final state. The multiplicity of jets and the flavor combinations of the leptons

1303 both lead to many potential signal regions. Additionally, signal regions can be optimized separately to be  
 1304 sensitive to the distinct production modes of the Higgs. Gluon fusion, vector boson fusion, and associated  
 1305 production of a Higgs all lead to unique final state topologies. Figure 3.6 delineates the different signal  
 1306 regions used in the gluon fusion and vector boson fusion  $H \rightarrow WW^*$  analyses. While there are different  
 1307 optimizations possible in each signal region, there are also some commonly shared selections that will be  
 1308 described here.

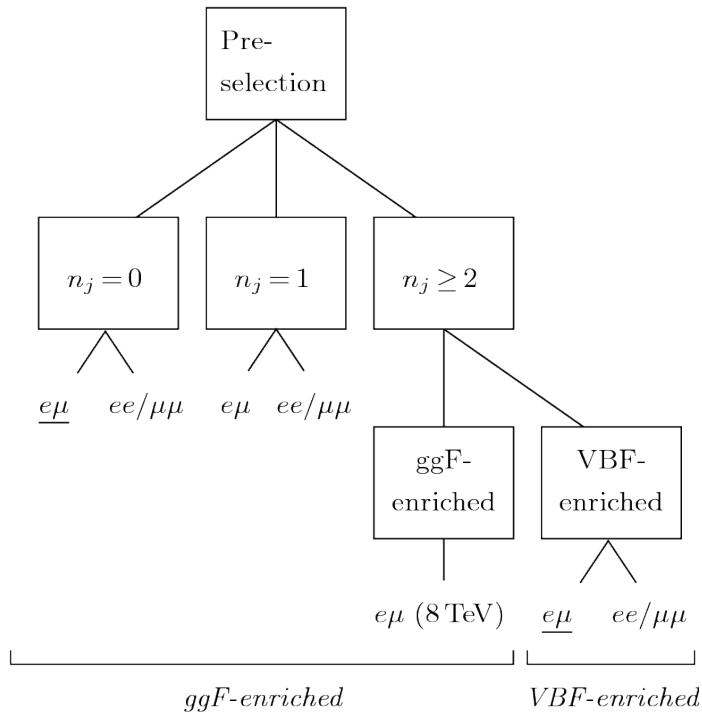


Figure 3.6: An illustration of the unique analysis signal regions [72]. The most sensitive regions for both gluon fusion and vector boson fusion production are underlined.

#### 1309 3.4.1 EVENT PRE-SELECTION

1310 Before being sorted into the distinct signal regions, basic requirements are applied to the reconstructed  
 1311 objects in the event to select Higgs-like event candidates. First, two oppositely charged leptons are required.  
 1312 Once the leptons are selected, the last requirement for event pre-selection is the presence of neutrinos. As  
 1313 neutrinos cannot be detected directly in ATLAS,  $E_T^{\text{miss}}$  can be used as a proxy for the combined neutrino  
 1314 momentum in the transverse plane.

1315 In general, it is expected that the signal should have a harder  $E_T^{\text{miss}}$  spectrum than backgrounds, espe-  
 1316 cially if these backgrounds do not contain neutrinos in the final state. When using  $E_T^{\text{miss}}$ , it is possible  
 1317 mis-measurements of objects in the detector can lead to imbalances in the transverse plane. When such a  
 1318 mis-measurement occurs, the  $E_T^{\text{miss}}$  vector in the transverse plane will often point in the same direction as  
 1319 the mis-measured object. Therefore, a new variable,  $E_{T,\text{rel}}^{\text{miss}}$ , is used in the pre-selection.  $E_{T,\text{rel}}^{\text{miss}}$  is defined  
 1320 in equation 3.1.

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

1321 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  
 1322 away from this object. Otherwise, the normal  $E_T^{\text{miss}}$  vector is used. Figure 3.7 shows a graphical illustration  
 of this concept.

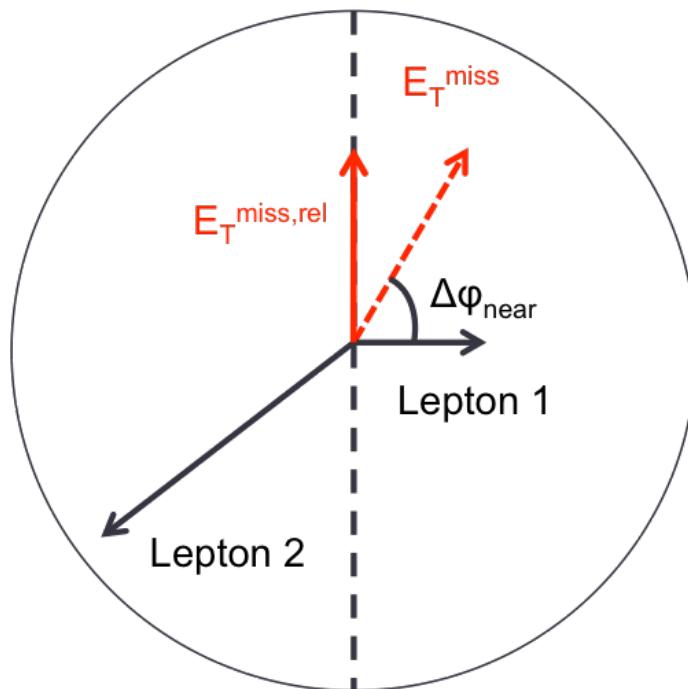


Figure 3.7: A graphical illustration of the  $E_{T,\text{rel}}^{\text{miss}}$  calculation

1323  
 1324 Once the lepton and  $E_T^{\text{miss}}$  pre-selections are made, the analysis is divided into different regions accord-  
 1325 ing to jet multiplicity.

1326 3.4.2 JET MULTIPLICITY

1327 Jet multiplicity, denoted as  $n_j$ , is used to sub-divide the analysis into distinct signal regions. By creating  
 1328 separate signal regions, each bin in jet multiplicity becomes sensitive to different modes of Higgs produc-  
 1329 tion and different backgrounds.

1330 For example, the  $n_j \geq 2$  region is more sensitive to VBF production because of the two high momen-  
 1331 tum jets produced at matrix element level. For gluon fusion production to enter this bin, two initial state  
 1332 radiation jets must be emitted.

1333 Figure 3.8 shows the jet multiplicity in both the different flavor and same flavor regions after the pre-  
 1334 selection. It also shows the background composition in the bins of  $n_b$ . A few trends from this distribution  
 1335 are worth noting. The first is that the Drell-Yan background dominates in the same flavor channels for  
 1336  $n_j \leq 1$ . Second, the top background becomes a clear contributor to the total background for  $n_j \geq$   
 1337 1. Lastly, the SM WW production dominates in the  $n_j = 0$  bin, as it is an irreducible background to  
 1338  $H \rightarrow WW^*$  production. Because of these distinct features, each jet multiplicity bin is treated separately.

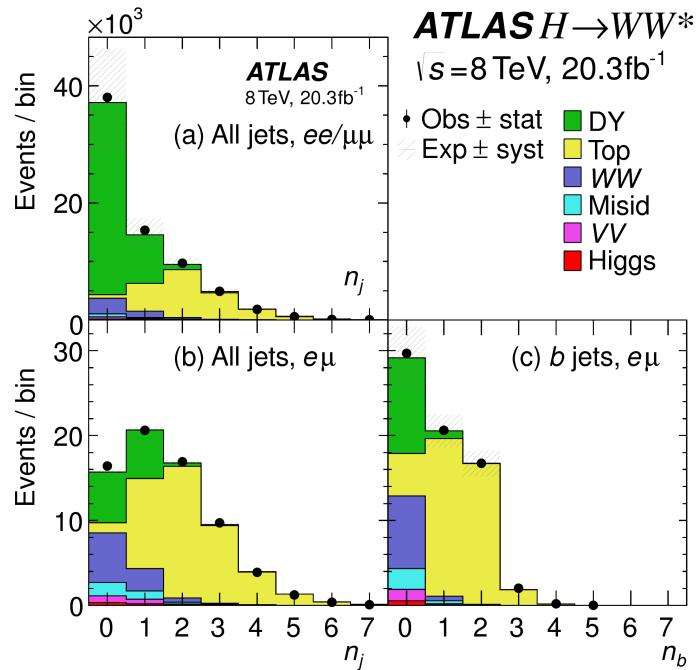


Figure 3.8: Predicted backgrounds (compared with data) as a function of  $n_j$  (a and b) and  $n_b$  (c) after pre-selection requirements

1339 3.5 BACKGROUND REDUCTION IN SAME-FLAVOR FINAL STATES

1340 As described in section 3.4.2, the background composition of the same flavor final states is different from  
1341 that of the different flavor states. In particular, Drell Yan processes play a much larger role because the  
1342  $Z/\gamma^*$  decays to same flavor leptons. Because real neutrinos are absent in the  $Z/\gamma^*$  decays to  $ee$  and  $\mu\mu$ , a  
1343 requirement on  $E_T^{\text{miss}}$  should largely reduce the background. However, as this section will demonstrate,  
1344 with increasing pileup conditions the resolution of the calorimeter-based  $E_T^{\text{miss}}$  degrades greatly. There-  
1345 fore, two new variables for  $Z/\gamma^*$  background reduction are constructed and described in this section.

1346 3.5.1 PILEUP AND  $E_T^{\text{miss}}$  RESOLUTION

1347 Secondary interactions of protons in the colliding bunches of the LHC (known as pileup interactions,  
1348 described in detail in Chapter 2) deposit energy into the ATLAS calorimeter in addition to the energy that  
1349 comes from the hard scatter process of interest. The calculation of  $E_T^{\text{miss}}$  is fundamentally Poissonian.  
1350 Summing up all of the energy deposits in individual calorimeter cells or clusters is similar to a counting  
1351 experiment. The error on a mean of  $N$  in a Poisson distribution is  $\sqrt{N}$ , so the energy resolution scales  
1352 as  $\sqrt{E}$ . As more energy is deposited in the calorimeter, the  $E_T^{\text{miss}}$  resolution degrades, meaning that the  
1353  $E_T^{\text{miss}}$  resolution is particularly sensitive to LHC instantaneous luminosity conditions.

1354 Figure 3.9 shows an event display of a  $Z/\gamma^* + \text{jets}$  event candidate with the twenty-five reconstructed  
1355 primary vertices. This display illustrates that while the interaction of interest only has tracks coming from  
1356 the hardest primary vertex, all of the secondary interactions deposit energy in the calorimeter as well.

1357 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-  
1358 trinos) as a function of the number of the average number of interactions. Under 2011 LHC conditions,  
1359 this RMS was approximately 9 GeV, while under 2012 running conditions the resolution worsened to 12  
1360 GeV. The increase in pileup dilutes the  $E_T^{\text{miss}}$  variable’s ability to reduce the  $Z/\gamma^*$  background.

1361 3.5.2 TRACK-BASED DEFINITIONS OF MISSING TRANSVERSE MOMENTUM

1362 Because the increasing number of secondary proton-proton interactions degrades calorimeter-based  $E_T^{\text{miss}}$   
1363 resolution, a new variable using only contributions from the primary interaction vertex is necessary to

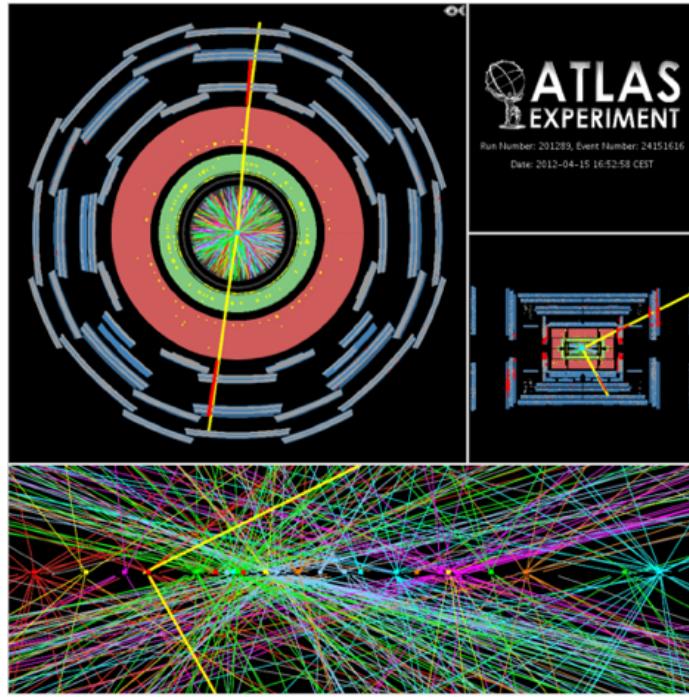


Figure 3.9: An event display of a  $Z/\gamma^*$  + jets event illustrating the effect of pileup interactions

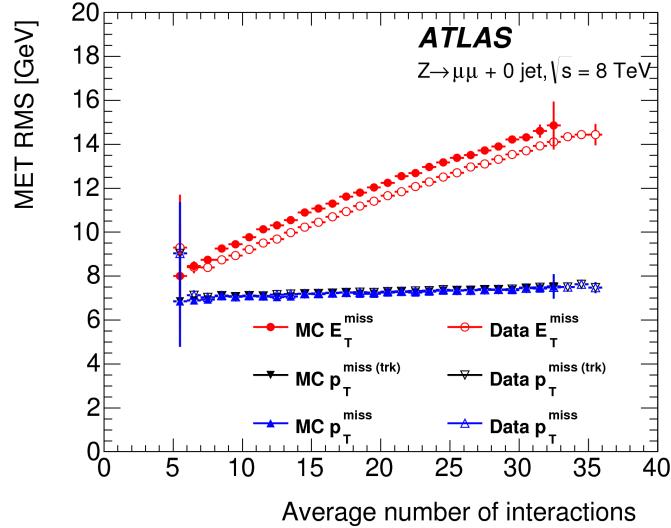


Figure 3.10: The RMS of different missing transverse momentum definitions as a function of the average number of interactions per bunch crossing

<sup>1364</sup> further reduce the  $Z/\gamma^*$  background. While it is not possible to associate calorimeter energy deposits  
<sup>1365</sup> with a particular vertex, individual charged particle tracks in the Inner Detector are associated to unique  
<sup>1366</sup> vertices. Thus, two track-based definitions of missing transverse momentum , using only tracks coming

1367 from the primary vertex in the event, are used in the analysis. The simplest variable,  $p_T^{\text{miss}(\text{trk})}$ , is the  
 1368 vectorial sum of the  $p_T$  of all of the tracks from the primary vertex and the selected leptons (excluding the  
 1369 tracks associated with the selected leptons to avoid double counting). Equation 3.2 defines  $p_T^{\text{miss}(\text{trk})}$ .

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

1370 To further improve the resolution on the missing transverse momentum, the variable  $p_T^{\text{miss}}$  is used as de-  
 1371 fined in equation 3.3. For selected leptons and jets, the nominal  $p_T$  measurements are used. Tracks are used  
 1372 to estimate the soft component of the missing transverse momentum instead of calorimeter measurements.

1373

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

1374 Figure 3.10 illustrates that these two new variables accomplish their intended purpose. The resolution as a  
 1375 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  
 1376 for  $E_T^{\text{miss}}$ . Figure 3.11a shows the difference between the true and reconstructed values of missing transverse  
 1377 momentum using both the track-based  $p_T^{\text{miss}}$  and calorimeter based  $E_T^{\text{miss}}$ . The RMS of the distribution  
 1378 improves by 3.5 GeV when using  $p_T^{\text{miss}}$ .

### 1379 3.5.3 DISTINGUISHING $Z/\gamma^*$ +JETS AND $H \rightarrow WW^*$ TOPOLOGIES

1380 In addition to measuring missing transverse momentum, another variable can be constructed to exploit  
 1381 kinematic and topological differences between the  $Z/\gamma^*$  background and  $H \rightarrow WW^*$  signal. Because  
 1382 there are no real neutrinos in the final state (in the case of  $Z/\gamma^* \rightarrow ee, \mu\mu$  decays), the dilepton system will  
 1383 be balanced with the jets produced in the hard scatter. A new variable,  $f_{\text{recoil}}$ , is constructed to estimate  
 1384 the balance between the dilepton system and recoiling jets and is defined in equation 3.4. The transverse  
 1385 plane is divided into four sections, or quadrants, with one quadrant centered on the dilepton vector. The  
 1386 numerator of  $f_{\text{recoil}}$  is the magnitude of the vectorial sum of the  $p_T$  of jets in the quadrant opposite the  
 1387 dilepton system, weighted by each jet's Jet Vertex Fraction (JVF, described in chapter 2). The denominator

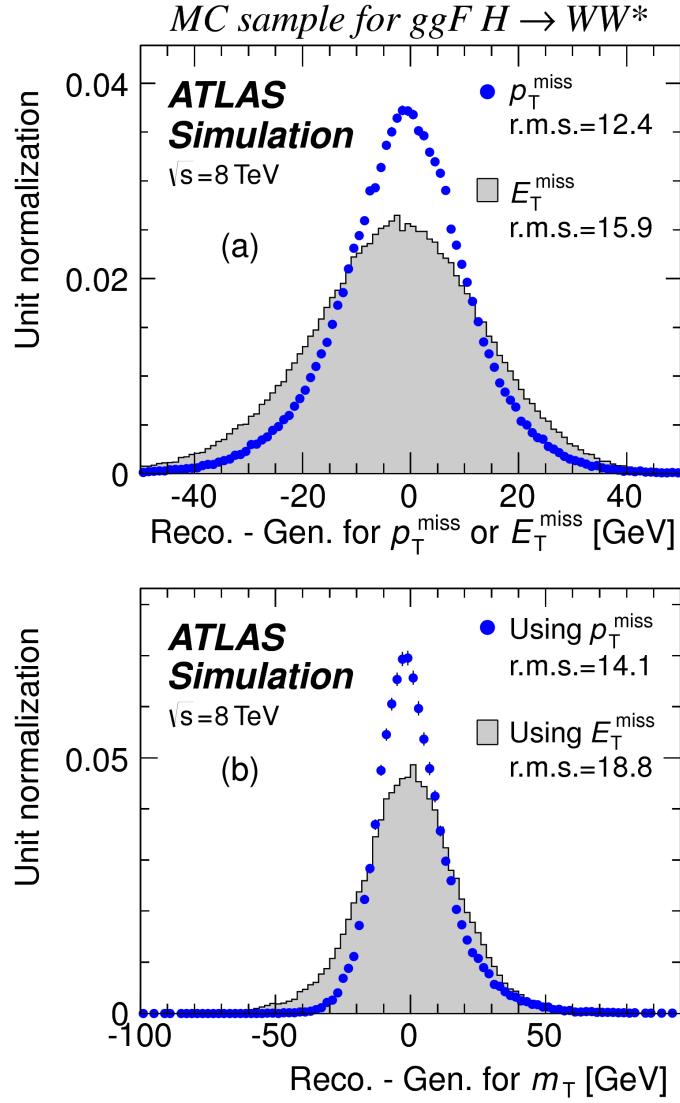


Figure 3.11: The difference between the true and reconstructed values of the missing transverse momentum (a) and  $m_T$  (b) in a gluon fusion signal sample

is the magnitude of the dilepton  $p_T$ .

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

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

1391 tend to be more balanced between the dilepton system and recoiling jets, while the processes containing  
 1392 real neutrinos are less balanced in the transverse plane. Thus, a requirement on  $f_{\text{recoil}}$  will reduce the  $Z/\gamma^*$   
 1393 + jets background while maintaining a good signal efficiency.

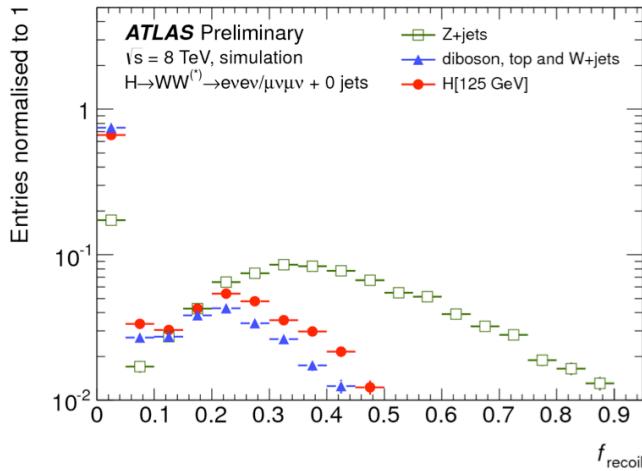


Figure 3.12: Comparison of  $f_{\text{recoil}}$  distributions for  $Z/\gamma^* + \text{jets}$ ,  $H \rightarrow WW^*$ , and other backgrounds with real neutrinos.

### 1394 3.5.4 OPTIMIZING BACKGROUND REDUCTION SELECTION REQUIREMENTS

1395 The requirements on  $p_T^{\text{miss}(\text{trk})}$  and  $f_{\text{recoil}}$  used to reduce the  $Z + \text{jets}$  background must be optimized to  
 1396 maximize expected signal significance in the same flavor channels. Figure 3.13 shows an optimization of  
 1397 the combination of the two requirements in the gluon fusion zero jet bin. Each bin shows the expected  
 1398 signal significance if the  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  is required to be greater than the left edge of the bin and the  $f_{\text{recoil}}$  is  
 1399 required to be less than the top edge of the bin. The figure shows that the best signal significance comes  
 1400 from requiring low values of  $f_{\text{recoil}}$  ( $< 0.05$ ) and  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  values greater than 45 GeV.

## 1401 3.6 PARAMETERS OF INTEREST AND STATISTICAL TREATMENT

1402 As with any search or measurement, there are particular parameters of the Higgs that the  $H \rightarrow WW^*$   
 1403 analysis is interested in measuring. In this case, the parameters of interest are the mass of the Higgs boson  
 1404 and its production cross section. Because the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  process does not have a closed final

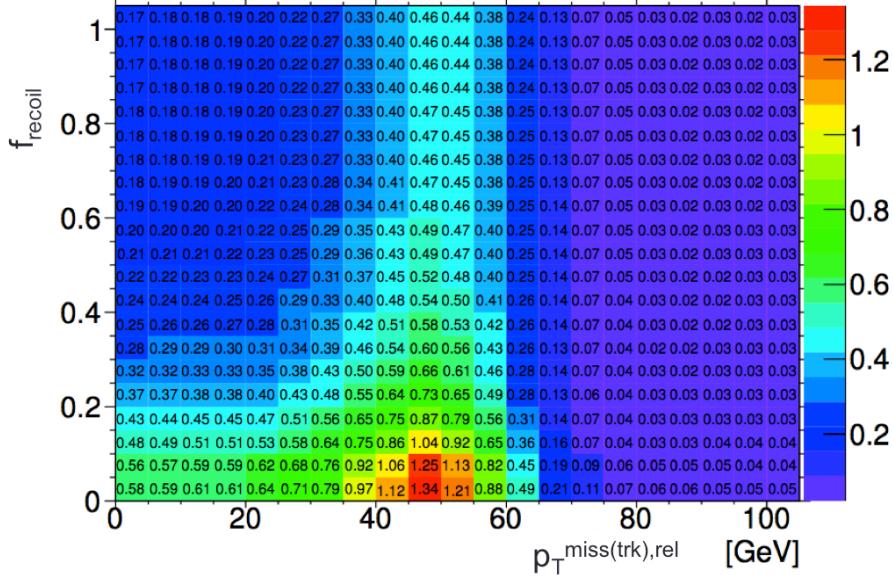


Figure 3.13: Signal significance as a function of required value for  $f_{\text{recoil}}$  and  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  in the ggF  $H \rightarrow WW^*$  with  $n_j = 0$

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

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

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

### 3.6.1 TRANSVERSE MASS

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

1415 information from the transverse plane. The transverse mass is defined in equation 3.6.

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

1416 Here the  $E_T^{\ell\ell}$  and  $\vec{p}_T^{\ell\ell}$  are the transverse energy and momentum of the dilepton system, while  $p_T^{\text{miss}}$  is a  
1417 proxy for the transverse momentum of the di-neutrino system. The track-based  $p_T^{\text{miss}}$  is used in the  $m_T$   
1418 rather than the calorimeter based  $E_T^{\text{miss}}$  because it has a better resolution on the true transverse mass.  
1419 Figure 3.11b shows the improvement in the RMS of the difference between the true and reconstructed  
1420 transverse mass in a ggF signal sample. The RMS improves by 4.7 GeV using  $p_T^{\text{miss}}$  in the  $m_T$  calculation.

1421 **3.6.2 STATISTICAL TREATMENT<sup>2</sup>**

1422 **LIKELIHOOD FUNCTION**

1423 The statistical analysis of final event candidates is framed as a hypothesis test, where the null hypothesis is  
1424 background-only (no Standard Model Higgs). The first step in the analysis is to form a likelihood function  
1425 for the data. In its simplest form, this likelihood is the probability of observing the number of events seen  
1426 in the final signal region given knowledge of the signal strength. Because observation of events is funda-  
1427 mentally a Poisson counting experiment, this simple likelihood can be expressed as a Poisson probability of  
1428 observing  $N$  events given a total number of predicted signal and background events. This basic likelihood  
1429 is shown in equation 3.7.

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

1430 Here,  $P$  is the Poisson probability density function,  $N$  is the total number of observed events,  $\mu$  is the  
1431 signal strength,  $S$  is the predicted number of signal events, and  $B$  is the predicted number of background  
1432 events.

1433 In particle physics, certain background estimates are commonly normalized in so-called “control” re-  
1434 gions and those predictions are scaled by the same normalization factor in the signal region. This leads to a  
1435 slightly more complicated likelihood, which is a function of both the signal strength and the background

---

<sup>2</sup>Many thanks to Aaron Armbruster, whose thesis [73] inspired parts of this section.

1436 normalization. This is shown in equation 3.8.

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

1437 Here,  $\theta$  serves as a “nuisance parameter”, or a parameter that is not of primary interest but still enters the  
1438 likelihood. The second Poisson term enforces that the background normalization be consistent with the  
1439 number of observed events in data in the control region,  $N_{\text{CR}}$ .

1440 So far, these two formulations of likelihoods have assumed a single signal region and do not take into  
1441 account any shape information of potential discriminating variables. The  $H \rightarrow WW^*$  analysis is divided  
1442 into many different categories, the counting experiment described above can be performed in each individ-  
1443 ual category. As mentioned in section 3.6.1, the transverse mass is used as the primary discriminating vari-  
1444 able in many of the  $H \rightarrow WW^*$  sub-analyses. The same counting experiment can be performed in each  
1445 bin of the  $m_T$  distribution to incorporate some shape information. Thus, the total likelihood becomes a  
1446 product over signal regions and bins of the  $m_T$  distribution. Finally, there are usually many backgrounds  
1447 that are normalized in control regions. The new formulation of the likelihood takes this into account by  
1448 including a product over control regions in the second Poisson term. All of these modifications are shown  
1449 in equation 3.9.

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

1450 The final step to obtain the full likelihood used in the analysis is to add nuisance parameters for the  
1451 systematic uncertainties. In cases where the uncertainty does not affect the shape of  $m_T$  bin-by-bin, each  
1452 systematic uncertainty  $\epsilon$  is allowed to affect the expected event yields through a linear response function  
1453 of the nuisance parameter, namely  $\nu(\theta) = (1 + \epsilon)\theta$ . If instead the uncertainty does affect the shape, the  
1454 effect is instead parameterized by  $\nu_b(\theta) = 1 + \epsilon_b\theta$ . The value of the nuisance parameters for the systematic  
1455 uncertainty are constrained with a Gaussian term that is added to the likelihood as well. This is of the form  
1456  $g(\delta|\theta) = e^{-(\delta-\theta)^2/2}/\sqrt{2\pi}$ , where  $\delta$  is the central value and  $\theta$  is a nuisance parameter. Finally, a last term is  
1457 added to account for the statistical uncertainty in the Monte Carlo samples used, which adds an additional

<sup>1458</sup> poisson term. The full likelihood used in the final statistical analysis is defined in equation 3.10.

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

<sup>1459</sup> The fourth term of the equation quantifies the uncertainty due to finite Monte Carlo sample size. Here,  
<sup>1460</sup>  $\xi$  represents the central value of the background prediction,  $\theta$  is the associated nuisance parameter,  $\zeta =$   
<sup>1461</sup>  $(B/\delta B)^2$ , where  $\delta B$  is the statistical uncertainty of  $B$ .

<sup>1462</sup> The best fit value of the signal strength  $\mu$  is determined by finding the values of  $\mu$  and  $\boldsymbol{\theta}$  that maximize  
<sup>1463</sup> the likelihood, while setting  $\delta = 0$  and  $\xi = \zeta$ . Once the likelihood is defined, a test statistic must be built  
<sup>1464</sup> for use in hypothesis testing.

#### <sup>1465</sup> TEST STATISTIC

<sup>1466</sup> To distinguish whether the data match a background only or background and signal hypothesis, a test  
<sup>1467</sup> statistic must be used. The  $H \rightarrow WW^*$  analysis uses the profile likelihood technique [74]. The first step  
<sup>1468</sup> in formulating this test statistic is to define the profile likelihood ratio, shown in equation 3.11.

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

<sup>1469</sup> Here  $\hat{\theta}_\mu$  is the value of  $\theta$  that maximizes the likelihood for the choice of  $\mu$  being tested. Additionally,  $\hat{\theta}$   
<sup>1470</sup> and  $\hat{\mu}$  represent the values of  $\theta$  and  $\mu$  that gives the overall maximum value of the likelihood.

<sup>1471</sup> Once this is defined, a test statistic  $q_\mu$  is constructed. This is shown in equation 3.12.

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

1472 A higher value of  $q_\mu$  indicates that the data are more incompatible with the hypothesized value of  $\mu$ , and  
1473  $q_0$  then corresponds to the value of the test statistic for the background only hypothesis. A  $p_0$  value is  
1474 then defined to quantify the compatibility between the data and the null hypothesis. The  $p_0$  value is the  
1475 probability of obtaining a value of  $q_0$  larger than the observed value, and this is shown in equation 3.13.

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

1476 Here  $f(q_\mu)$  is the probability distribution function of the test statistic. Finally, the  $p_0$  value can be con-  
1477 verted into a signal significance, using the formula in equation 3.14, or the one-sided tail of the Gaussian  
1478 distribution.

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

1479 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

1480

## 1481 The discovery of the Higgs boson and the role 1482 of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel

### 1483 4.1 INTRODUCTION

1484 This chapter presents the results of the search for the Higgs boson in  $4.8 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 7 \text{ TeV}$   
1485 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  $H \rightarrow WW^* \rightarrow$   
1486  $\ell\nu\ell\nu$ ,  $H \rightarrow \gamma\gamma$ , and  $H \rightarrow ZZ \rightarrow 4\ell$  channels are shown. These results at  $8 \text{ TeV}$  are combined  
1487 with the results of searches at  $\sqrt{s} = 7 \text{ TeV}$  in the same channels along with  $H \rightarrow \tau\tau$  production and  
1488 associated production searches for  $H \rightarrow b\bar{b}$ . The results of this combination are a  $5.9\sigma$  detection of a  
1489 new particle consistent with a Higgs boson produced via gluon fusion. Rather than going into detail for  
1490 all of the different Higgs decay searches, this chapter will discuss the three most sensitive channels and in  
1491 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

1492 are shown for completeness. The results not discussed here can be found in the ATLAS Higgs discovery  
1493 publication [1].

1494 **4.2 DATA AND SIMULATION SAMPLES**

1495 The data sample used for the following results was taken in 2011 and 2012 at center of mass energies of 7 and  
1496 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  
1497 in the gluon fusion and vector boson fusion modes is modeled with POWHEG for the hard scattering event  
1498 and PYTHIA for the showering and hadronization. Associated production of a Higgs with a vector boson  
1499 or top quarks is modeled via PYTHIA . Table 4.1 shows the Monte Carlo generators used for modeling the  
1500 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].

1501 **4.3  $H \rightarrow WW \rightarrow e\nu\mu\nu$  SEARCH**

1502 The  $H \rightarrow WW \rightarrow e\nu\mu\nu$  search is unique compared to the  $ZZ$  and  $\gamma\gamma$  channels. The Higgs mass  
1503 cannot be fully reconstructed due to the presence of neutrinos in the final state, so the transverse mass  $m_T$   
1504 is used as the final discriminating variable. This channel also has a wider variety of backgrounds compared  
1505 to other channels, as discussed in chapter 3. The same flavor final states are excluded from the 8 TeV dataset

1506 due to high pileup conditions<sup>1</sup>. These final states are later included in results with the full Run 1 dataset,  
1507 as discussed in chapters 5 and 6.

1508 **4.3.1 EVENT SELECTION**

1509 The analysis requires to opposite charge isolated leptons, with the leading (sub-leading) lepton required to  
1510 have  $p_T > 25(15)$  GeV. The events are separated into different signal regions depending on which flavor  
1511 of lepton is leading ( $e\mu$  for leading electron,  $\mu e$  for leading muon). Strict lepton quality cuts are applied  
1512 to the sample to reduce backgrounds from mis-reconstructed leptons.

1513 Jets are reconstructed with the anti- $k_T$  algorithm with a radius parameter  $R = 0.4$ . The jets are re-  
1514 quired to have  $p_T > 25$  GeV and  $|\eta| < 4.5$ , with jets in the tracking volume required to have a jet vertex  
1515 fraction of 0.5 and jets in the forward region required to have  $p_T > 30$  GeV. The analysis is separated  
1516 into three different signal regions based on jet multiplicity:  $n_j = 0, 1, \geq 2$ .

1517 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  
1518 requirement significantly reduces the QCD multijet and  $Z/\gamma^*$  + jets backgrounds. Figure 4.1 shows the  
1519 distribution of  $n_j$  in data and simulation after applying these “pre-selection” requirements.

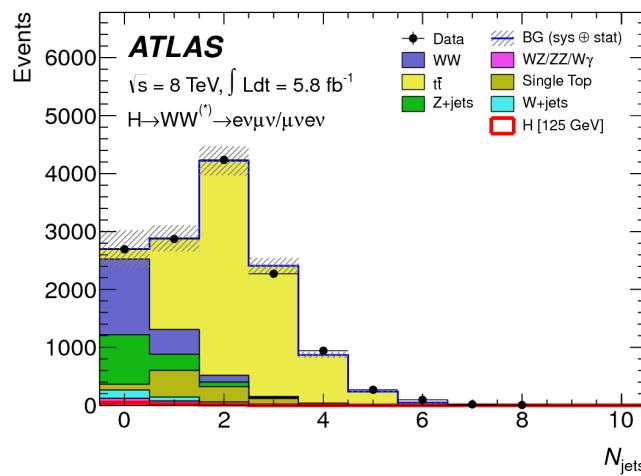


Figure 4.1: Jet multiplicity distribution in data and MC after applying lepton, jet, and  $E_{T,\text{rel}}^{\text{miss}}$  selections. The  $WW$  and top backgrounds have been normalized using control samples, and the hashed band indicates the total uncertainty on the prediction [1].

<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.

1520        Additional selections are applied to require the dilepton topology to correspond to that of a Standard  
1521        Model Higgs boson. The requirements are presented here - more detailed discussion on the motivation  
1522        for each requirement is saved for Chapter 5. In all of the jet multiplicity channels, the dilepton system  
1523        is required to have a small gap in azimuthal angle,  $\Delta\phi_{\ell\ell} < 1.8$ . Similarly, the dilepton invariant mass,  
1524         $m_{\ell\ell}$ , is required to be less than 50 GeV in the lower jet multiplicity channels and less than 80 GeV in the  
1525         $n_j \geq 2$  channel. In the  $n_j = 0$  channel, the magnitude of the dilepton  $p_T$ ,  $p_T^{\ell\ell}$ , is required to be greater  
1526        than 30 GeV.

1527        In the higher jet multiplicity channels ( $n_j \geq 1$ ), the top background is a larger fraction of the total  
1528        background and must be reduced more carefully. The total transverse momentum  $p_T^{\text{sum}}$  is thus required  
1529        to be less than 30 GeV. Additionally, the di- $\tau$  invariant mass  $m_{\tau\tau}$  (dilepton mass computed under the  
1530        assumption that the neutrinos from the  $\tau$  decay are emitted collinear to the charged leptons [75]) is used  
1531        to reject  $Z \rightarrow \tau\tau$  events by requiring  $|m_{\tau\tau} - m_Z| > 25$  GeV. These variables are also discussed in more  
1532        detail in Chapter 5.

1533        In the  $n_j \geq 2$  channel, requirements are made to isolate the VBF contribution to Higgs production.  
1534        The kinematics of the two leading jets are used to make these requirements. In particular, the event must  
1535        have  $\Delta y_{jj} > 3.8$  and  $m_{jj} > 500$  GeV, along with a veto on having any additional jets with rapidity  
1536        between the two leading jets.

#### 1537        4.3.2 BACKGROUND ESTIMATION

1538        The details of the background estimation techniques used in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis are  
1539        discussed in section 5.5. The dominant backgrounds are SM  $WW$  production and top (both pair and  
1540        single) production, and these backgrounds have their normalizations estimated from dedicated control  
1541        regions while their shapes are taken from simulation.

1542        The control sample for the Standard Model  $WW$  background is defined by making the same require-  
1543        ments as the signal region with the  $m_{\ell\ell}$  requirement inverted (now requiring  $m_{\ell\ell} > 80$  GeV) and remov-  
1544        ing the  $\Delta\phi_{\ell\ell}$  requirement. This creates a control sample that is 70% (40%) pure in the 0(1)-jet region. The  
1545        correction to the pure MC-based background estimate is quantified by defining a normalization factor  $\beta$

1546 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  
 1547 the  $WW$  normalization factors in the  $n_j = 0$  and  $n_j = 1$  bins (the  $n_j \geq 2$  estimate is taken directly  
 1548 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.

1549 The top background estimate is also computed separately in each jet multiplicity bin. In the  $n_j = 0$   
 1550 channel, the background is first normalized using data after pre-selection requirements with no selection  
 1551 on  $n_j$ . Then, a dedicated  $b$ -tagged control sample is used to evaluate the ratio of one-jet to two-jet events in  
 1552 data. The details of this technique are shown in reference [76]. In the  $n_j = 1$  and the  $n_j \geq 2$  regions, the  
 1553 top background is normalized in a control sample where the signal region selections are applied, but the  
 1554  $b$ -jet veto is reversed and the Higgs topology requirements on  $m_{\ell\ell}$  and  $\Delta\phi_{\ell\ell}$  are removed. The resulting  
 1555 normalization factors for these techniques are shown in table 4.2.

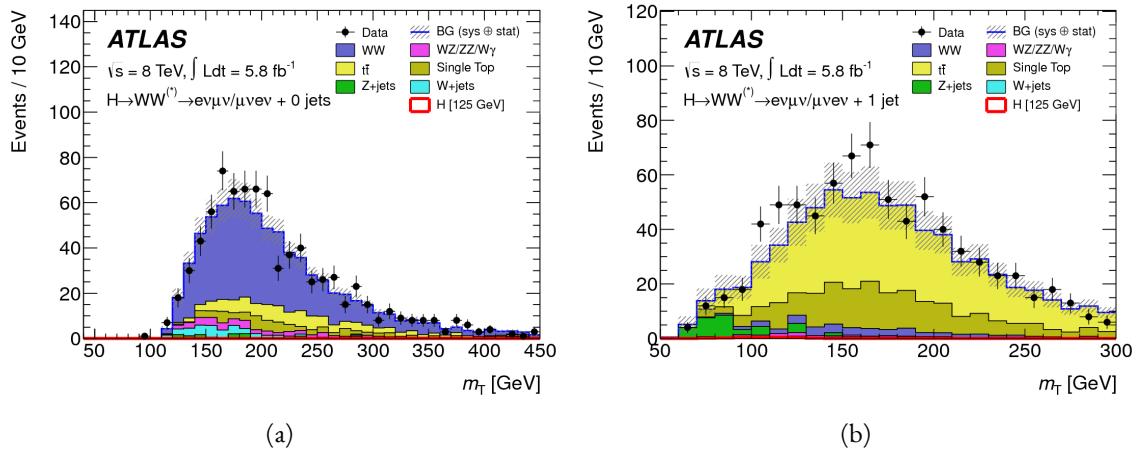


Figure 4.2: Comparison of  $m_T$  between data and simulation in the  $n_j = 0$   $WW$  (a) and  $n_j = 1$  top (b) control samples [1].

1556 The control samples which are used for background normalization can also be used to validate the mod-  
 1557eling of the  $m_T$  distribution for each background. Figure 4.2 shows the comparison between data and MC

1558 for the  $m_T$  distribution after correcting the normalization of the backgrounds in the  $WW$  and top control  
1559 regions. Good agreement between data and simulation is seen in both cases.

1560 The  $W + \text{jets}$  background estimate is taken entirely from data using a control sample with one well recon-  
1561 structed lepton and one anti-identified lepton. All other backgrounds are taken purely from simulation.

#### 1562 4.3.3 SYSTEMATIC UNCERTAINTIES

1563 The systematic uncertainties that have the largest impact on the analysis are the theoretical uncertainties  
1564 associated with the signal cross section. These are shared with the  $ZZ^*$  and  $\gamma\gamma$  channels. The uncertainties  
1565 resulting from variations of the QCD scale are  $+7\% / -8\%$  on the final signal yield. Those coming from  
1566 variations of the parton distribution function (PDF) used in the simulation add a  $\pm 8\%$  uncertainty on  
1567 the yield. The uncertainties on the branching ratios of the Higgs are  $\pm 5\%$ .

1568 The main experimental uncertainties come from variations of the jet energy scale (JES), jet energy reso-  
1569 lution, pile-up,  $E_T^{\text{miss}}$ ,  $b$ -tagging efficiency,  $W + \text{jets}$  background estimate, and integrated luminosity. For  
1570 more details, see reference [1].

#### 1571 4.3.4 RESULTS

1572 Table 4.3 shows the signal and background yields in the final signal region after normalizing the back-  
1573 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].

1574      Figure 4.3 shows the  $m_T$  distribution in the  $n_j \leq 1$  channels for 8 TeV data. (No events are observed  
 1575      in data in the  $n_j \geq 2$  channels in this dataset). The excess shown here relatively flat as a function of  
 1576      hypothesized Higgs mass. The combined 7 and 8 TeV data gives an excess with local significance of  $2.8\sigma$   
 1577      with an expected significance of  $2.3\sigma$ , corresponding to a  $\mu$  measurement of  $1.3 \pm 0.5$ .

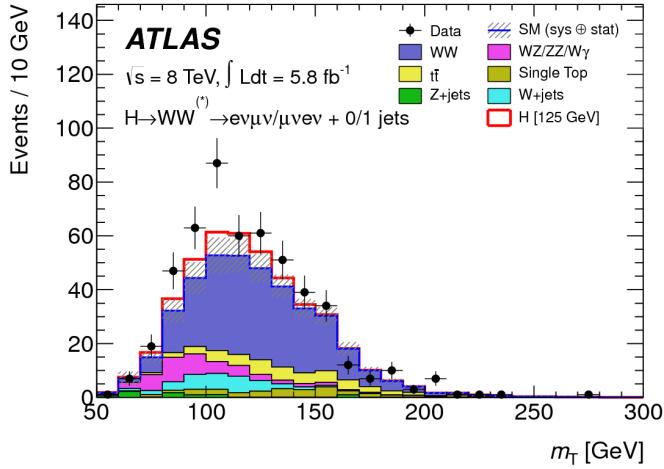


Figure 4.3:  $m_T$  distribution in the  $H \rightarrow WW \rightarrow e\nu\mu\nu$   $n_j \leq 1$  channels for 8 TeV data [1].

#### 1578    4.4    $H \rightarrow \gamma\gamma$ SEARCH

1579    The  $H \rightarrow \gamma\gamma$  search is a search for a peaked excess above the falling SM diphoton mass spectrum, with  
 1580     $m_{\gamma\gamma}$  as the ultimate discriminating variable. Events are selected by requiring two isolated photons, with  
 1581    the leading (sub-leading) photon required to have  $E_T > 40(30)$  GeV. In the 8 TeV data, the photons are  
 1582    required to pass identification criteria consistent with a photonic shower in the electromagnetic calorimeter  
 1583    and little leakage in the hadronic calorimeter.

1584    The main challenges for this analysis are accurate mass reconstruction and background estimation. In  
 1585    order to accurately reconstruct the invariant mass of the di-photon system, both the energy and direction  
 1586    of the photons must be measured well. Therefore, the identification of the primary vertex of the hard  
 1587    interaction is particularly important, and is done using a multivariate likelihood which combines informa-  
 1588    tion about the photon direction and vertex position. The background is modeled with a falling spectrum  
 1589    in  $m_{\gamma\gamma}$  that is parameterized by different functions depending on the category of the event.

1590 4.4.1 RESULTS

1591 The resulting diphoton mass spectrum is shown in figure 4.4. The best fit mass value in the  $\gamma\gamma$  channel  
 1592 alone in the combined 7 and 8 TeV data is 126.5 GeV. The local significance at this point is  $4.5\sigma$ , with  
 1593 an expected significance of  $2.5\sigma$ . Therefore, the measured signal strength  $\mu$  is  $1.8 \pm 0.5$  in this channel.

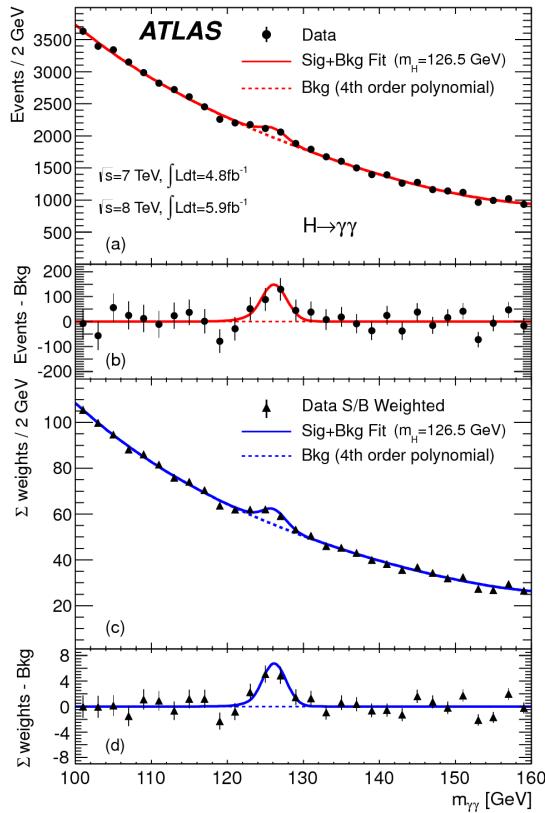


Figure 4.4: Diphoton mass spectrum in 7 and 8 TeV data. Panel a) shows the unweighted data distribution superimposed on the background fit, while panel c) shows the data where each event category is weighted by its signal to background ratio. Panels b) and d) show the respective distributions with background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

1594 4.5  $H \rightarrow ZZ \rightarrow 4\ell$  SEARCH

1595 The  $H \rightarrow ZZ \rightarrow 4\ell$  analysis searches for a Standard Model Higgs boson decaying to two  $Z$  bosons, each  
 1596 of which decays to a pair of same flavor, opposite charge isolated leptons. The ultimate discriminating  
 1597 variable is  $m_{4\ell}$ , or the invariant mass of the four selected leptons. The  $\ell$  denotes an  $e$  or  $\mu$  as with the  
 1598  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis.

1599     Four distinct signal regions are constructed depending on the flavors of the final state, additionally sep-  
 1600     arated by the flavor of the leading lepton pair. These are referred to as  $4e$ ,  $2e2\mu$ ,  $2\mu2e$ ,  $4\mu$ .

1601     The main backgrounds in the  $H \rightarrow ZZ \rightarrow 4\ell$  search are continuum  $ZZ^*$  production,  $Z + \text{jets}$  pro-  
 1602     duction, and  $t\bar{t}$ . The  $m_{4\ell}$  distribution for background is estimated from simulation. The normalization  
 1603     of the SM  $ZZ^*$  background is also taken from MC simulation, while the  $Z + \text{jets}$  and  $t\bar{t}$  normalizations are  
 1604     taken from data-driven methods.

1605     **4.5.1 RESULTS**

1606     Figure 4.5 shows the  $m_{4\ell}$  spectrum measured in the 7 and 8 TeV datasets. The total number of events  
 1607     observed in the window between 120 and 130 GeV is 13, with 6 events in the  $4\mu$  channel, 2 events in  
 1608     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  
 1609     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  
 1610     an expected significance of  $2.7\sigma$ .

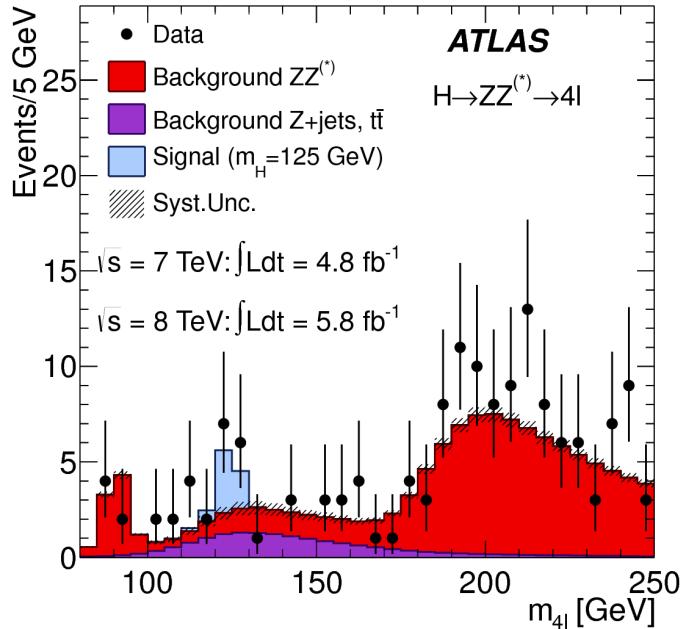


Figure 4.5: Four lepton invariant mass spectrum ( $m_{4\ell}$ ) in 7 and 8 TeV data compared to background estimate. A 125 GeV SM Higgs signal is shown in blue [1].

1611 4.6 COMBINED RESULTS

1612 The statistical interpretation of the combined results is undertaken as described in section 3.6.2, with a hy-  
1613 pothesis test based on a likelihood ratio parameterized by the Higgs signal strength  $\mu$ . The null hypothesis  
1614 corresponds to  $\mu = 0$ , while the SM Higgs corresponds to  $\mu = 1$ .

1615 Table 4.4 summarizes the properties of the individual channels as well as the significances of the excesses  
1616 seen. The most significant observed local excess comes from the  $\gamma\gamma$  channel. Figure 4.6 shows a com-  
1617 parison of the observed local  $p_0$  values as a function of hypothesized mass for the three different search  
1618 channels. Both the  $ZZ^*$  and  $\gamma\gamma$  channels have very peaked excesses, while the  $WW^*$  excess can be seen as  
1619 very broad because the  $m_T$  distribution does not provide detailed information about the true Higgs mass.  
1620 Figure 4.7 shows the combined exclusion limit,  $p_0$ , and signal strength. The highest local excess comes at  
1621 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].

1622 Figure 4.8 shows a comparison of the measured signal strengths between the different Higgs search  
1623 channels. All measured  $\mu$  are consistent with unity within their uncertainty, and the combined  $\mu$  mea-  
1624 surement is  $1.4 \pm 0.3$ .

1625 The likelihood can also be computed in a two-dimensional plane of  $m_H$  and  $\mu$ , and this is shown in  
1626 figure 4.9. The figure shows that while the  $\gamma\gamma$  and  $ZZ^*$  channels have very good mass resolution, the  
1627 excess in  $WW^*$  covers a broad mass range. The banana shape of the  $WW^*$  result is due to the fact that  
1628 the excess in this channel can either be explained by increasing the signal strength or by changing the mass  
1629 (and thus the cross section). The two parameters are correlated due to the lack of mass sensitivity in this  
1630 channel.

1631 Because multiple Higgs mass points are searched for, the local significance must be corrected for a look-

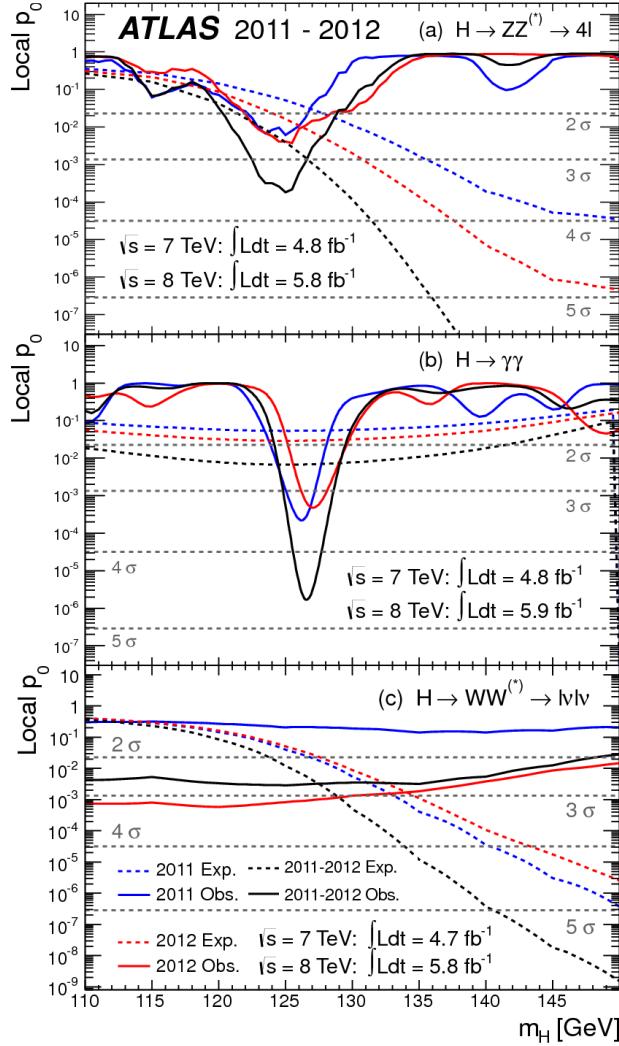


Figure 4.6: Local  $p_0$  distribution as a function of hypothesized Higgs mass for the  $H \rightarrow ZZ^* \rightarrow 4\ell$  (a),  $H \rightarrow \gamma\gamma$  (b), and  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  (c) channels. Dashed curves show expected results, while solid curves show observed.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

1632 elsewhere effect to compute a true global significance. The global significance for finding a Higgs anywhere  
1633 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  
1634 110 to 150 GeV.

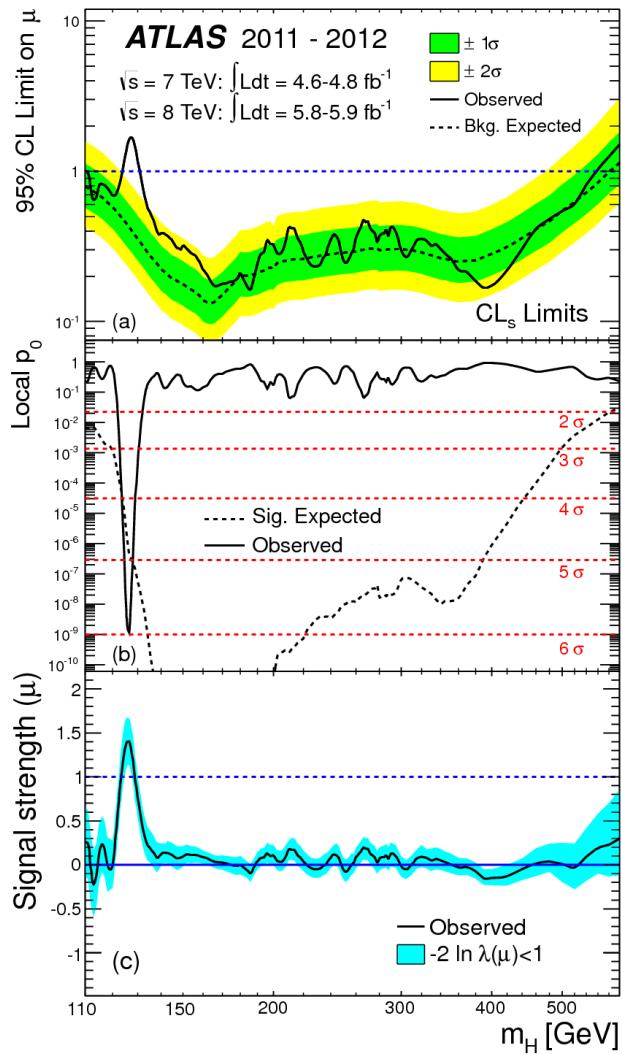


Figure 4.7: Combined 95% CL limits (a), local  $p_0$  values (b), and signal strength measurement (c) as a function of Higgs mass [1].

1635    4.7 CONCLUSION

1636    A search for the production of a Standard Model Higgs boson was conducted in  $4.8 \text{ fb}^{-1}$  collected at  
 1637     $\sqrt{s} = 7 \text{ TeV}$  and  $5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . A new particle consistent with the Higgs boson was observed,  
 1638    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  
 1639    observation of a particle consistent with the Higgs.

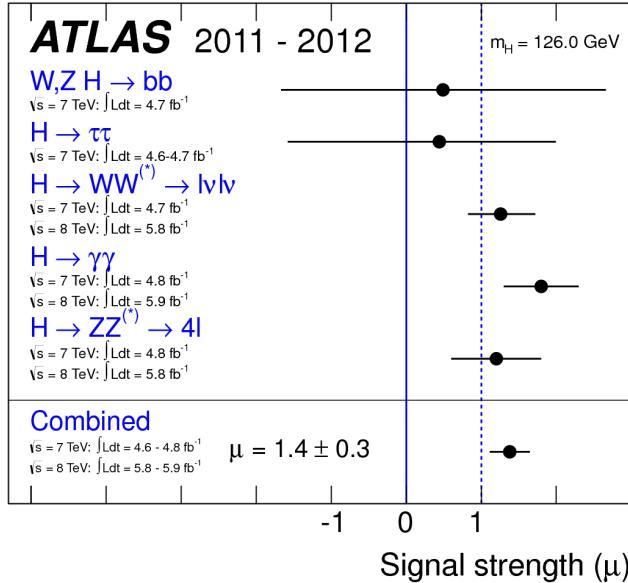


Figure 4.8: Comparison of measured signal strength  $\mu$  for a 126 GeV Higgs in the 7 and 8 TeV datasets [1].

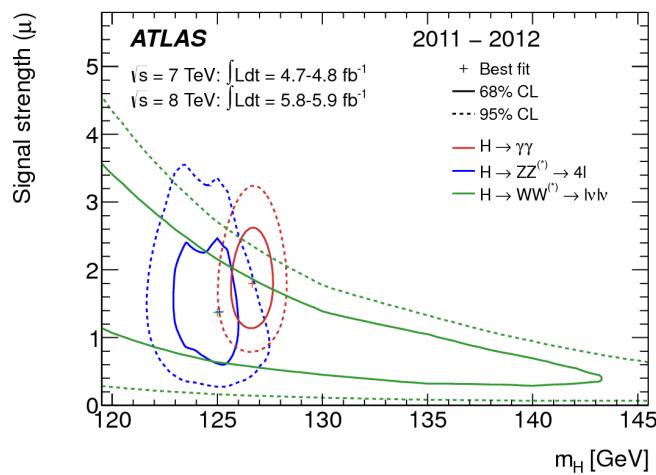


Figure 4.9: Two dimensional likelihood as a function of signal strength  $\mu$  and Higgs mass  $m_H$  [1].

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

Richard Feynman

# 5

1640

## 1641 Evidence for Vector Boson Fusion production

1642

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

1643

### 5.1 INTRODUCTION

1644 After the discovery of a particle consistent with the Higgs boson, the  $H \rightarrow WW^*$  analysis had two main  
1645 goals. The first goal was to increase the sensitivity of the analysis to fully confirm that the  $H \rightarrow WW^*$   
1646 process did indeed exist. The second goal was to characterize the particle as much as possible, including  
1647 searching for the lower cross-section production modes. This chapter presents a dedicated search for Vec-  
1648 tor Boson Fusion (VBF) production of a Higgs boson decaying via the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  mode. First,  
1649 the data and Monte Carlo samples are detailed, along with trigger and physics object selections. Then, the  
1650 details of the analysis are shown, including signal region definition, background estimation techniques,  
1651 and systematic uncertainties. Finally, the results of the analysis are presented. As will be shown, this anal-

ysis is the first and most sensitive evidence of the VBF production mode of the Higgs on ATLAS.

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

## 5.2 DATA AND SIMULATION SAMPLES

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

### 5.2.1 TRIGGERS

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

As discussed in Chapter 2, there are multiple levels in the ATLAS trigger system, and there are different  $p_T$  thresholds imposed for the leptons at each level. Additionally, some triggers have a loose selection on the isolation of the lepton (looser than that applied offline in the analysis object selection). Table 5.1 shows the  $p_T$  thresholds used for single lepton triggers, while table 5.2 shows the  $p_T$  thresholds coming from di-lepton triggers. The single lepton trigger efficiency for muons that pass the analysis object selection is 70% for muons in the barrel region ( $|\eta| < 1.05$ ) and 90% in the endcap region. The electron trigger

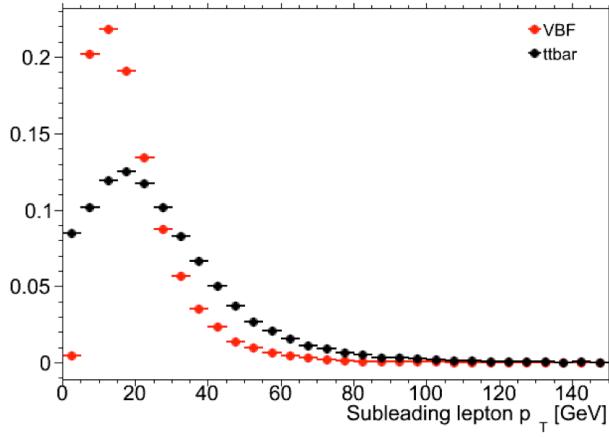


Figure 5.1: A comparison of the subleading lepton  $p_T$  spectrum between VBF  $H \rightarrow WW^*$  production and  $t\bar{t}$  background.

efficiency increases with electron  $p_T$  but the average is approximately 90%. These efficiencies are measured by combined performance and trigger signature groups [77, 78].

	Level-I 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-I 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-I.

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

1681 in the same table. The largest gain comes in the  $\mu\mu$  channel. Overall the trigger selection shows a good  
1682 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.

1683 5.2.2 MONTE CARLO SAMPLES

1684 Modeling of signal and background processes in the signal region, in particular for the  $m_T$  distribution,  
1685 is an important consideration for the final interpretation of the analysis. Therefore, careful consideration  
1686 must be paid to which Monte Carlo (MC) generators are used for specific processes. With the exception  
1687 of the  $W + \text{jet}$  and multijet backgrounds, the  $m_T$  shape used as the final discriminant is taken from simu-  
1688 lation<sup>1</sup>.

1689 Table 5.4 shows the MC generators used for the signal and background processes, as well as the cross  
1690 sections of each process. In order to include corrections up to next-to-leading order (NLO) in the QCD  
1691 coupling constant  $\alpha_s$ , the POWHEG [79] generator is often used. In some cases, only leading order gener-  
1692 ators like ACERMC [80] and GG2VV [81] are available for the process in question. If the process requires  
1693 good modeling for very high parton multiplicities, the SHERPA [82] and ALPGEN [83] generators are used  
1694 to provide merged calculations for five or fewer additional partons. These matrix element level calculations  
1695 must then be additionally matched to models of the underlying event, hadronization, and parton shower.  
1696 There are four generators used for this purpose: SHERPA, PYTHIA 6 [84], PYTHIA 8 [85], or HERWIG [86]  
1697 + JIMMY [87]. The simulation additionally requires an input parton distribution function (PDF). The  
1698 CT10 [88] PDFs are used for SHERPA and POWHEG simulated samples, while CTEQ6L1 [89] is used for  
1699 ALPGEN + HERWIG and ACERMC simulations. The Drell-Yan samples are reweighted to the MRST [90]

---

<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 [72].

1700 PDFs, as these are found to give the best agreement between data and simulation. The branching ratio  
 1701 for Higgs to  $WW^*$  and  $ZZ^*$  is computed with PROPHECY4f [91], while the width of all other decays is  
 1702 computed with HDECAY[92].

1703 Once the basic hard scattering process is simulated, it must be passed through a detector simulation  
1704 and additional pile-up events must be overlaid. The pile-up events are modeled with PYTHIA 8, and the  
1705 ATLAS detector is simulated with GEANT4 [93]. Because of the unique phase space of the  $H \rightarrow WW^*$   
1706 analysis, events are sometimes filtered at generator level to allow for more efficient generation of relevant  
1707 events. The efficiency of the trigger in MC simulation does not always match the measured efficiency in  
1708 data, so trigger scale factors are applied to correct the MC efficiency to the data. These are derived by the  
1709 combined performance groups [77, 78].

### 1710 5.3 OBJECT SELECTION

1711 In order to define the signal region, the analysis must first select the reconstructed physics objects to be  
1712 considered. The details of the object reconstruction algorithms are discussed in Chapter 2, while this sec-  
1713 tion gives specific selection requirements used in the  $H \rightarrow WW^*$  analysis. The first step in this process is  
1714 to select a primary vertex candidates. The event's primary vertex is the vertex with the largest sum of  $p_T^2$   
1715 for associated tracks and is required to have at least three tracks with  $p_T > 450$  MeV. Many of the object  
1716 selection cuts are then made relative to this chosen primary vertex.

#### 1717 5.3.1 MUONS

1718 The analysis uses combined muon candidates, where a track in the Inner Detector has been matched to a  
1719 standalone track in the Muon Spectrometer. The track parameters are combined statistically in the muon  
1720 reconstruction algorithm [63]. The muons are required to be within  $|\eta| < 2.5$  and have a  $p_T > 10$  GeV.  
1721 To reduce backgrounds coming from mis-reconstructed leptons, there are requirements on the impact  
1722 parameter of the muon relative to the primary vertex. The transverse impact parameter  $d_0$  is required to  
1723 be small relative to its estimated uncertainty, the exact cut value being  $d_0/\sigma_{d_0} < 3$ . The longitudinal  
1724 impact parameter  $z_0$  must satisfy  $|z_0 \sin \theta| < 1$  mm.

1725 As discussed previously, the muons must also be isolated. There are two types of lepton isolations that  
1726 are calculated: track-based and calorimeter-based. For muons, the track-based isolation is defined using the  
1727 scalar sum  $\sum p_T$  for tracks with  $p_T > 1$  GeV (excluding the muon's track) within a cone of  $\Delta R = 0.3$

1728 (0.4) for muon with  $p_T > 15 \text{ GeV}$  ( $10 < p_T < 15 \text{ GeV}$ ). The final isolation requirement is made my  
1729 requiring that this scalar sum be no more than a certain fraction of the muon's  $p_T$ . This requirement varies  
1730 with muon  $p_T$  and the exact requirements are defined in table 5.5.

1731 The calorimeter-based muon isolation is defined using the  $\sum E_T$  calculated from calorimeter cells with  
1732 the same cone size as the track-based isolation but excluding cells within  $\Delta R < 0.05$  around the muon.  
1733 This isolation is also defined as a requirement on the ratio of the sum to the muon  $p_T$  and varies with  
1734 muon  $p_T$ . The requirement values as a function of  $p_T$  are also given in table 5.5.

1735 The isolation requirements loosen as a function of  $p_T$  to allow for larger signal acceptance. At low  $p_T$ ,  
1736 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  $p_T$ .

### 1737 5.3.2 ELECTRONS

1738 Electrons are identified by matching reconstructed clusters in the electromagnetic calorimeter with tracks  
1739 in the inner detector. The electrons are identified using a likelihood based method [60, 61] which takes  
1740 into account the shower shapes in the calorimeter, the matching of tracks to clusters, and the amount of  
1741 transition radiation in the TRT. The electrons are required to have  $|\eta| < 2.47$ , and candidates in the  
1742 transition region between the barrel and endcap ( $1.37 < |\eta| < 1.52$ ) are excluded. As the muons, the  
1743 electrons are required to have transverse impact parameter significance  $< 3$ , while in the longitudinal  
1744 direction they must have  $|z_0 \sin \theta| < 0.4 \text{ mm}$ . Some electron requirements also vary with electron  $E_T$ ,  
1745 and these requirements are summarized in table 5.6.

1746 The isolation for electrons is defined similarly to the muons but with unique requirements on the ob-  
1747 jects included. The track-based isolation is constructed using tracks with  $p_T > 400 \text{ MeV}$  with cone sizes

1748 as defined for the muons. The calorimeter-based isolation also uses the same cone size as the muon, but  
 1749 here the cells within a  $0.125 \times 0.175$  area in  $\eta \times \phi$  around the electron cluster's barycenter are excluded.  
 1750 The other difference with respect to muons is that the denominator of the isolation ratio is the electron's  
 1751  $E_T$  rather than  $p_T$ . The isolation cuts very with electron  $E_T$  and are defined in table 5.6. The electron is  
 1752 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  $E_T$ .

### 1753 5.3.3 JETS

1754 Jets are clustered with the anti- $k_T$  reconstruction algorithm using a radius parameter of  $R = 0.4$ . They  
 1755 are required to have a jet vertex fraction (JVF) of at least 50%, meaning that half of the tracks associated with  
 1756 the jet originated from the primary vertex. Jets with no tracks associated (i.e. those outside the acceptance  
 1757 of the ID) do not have this requirement applied. Jets are required to have  $p_T > 25$  GeV if they are within  
 1758 the tracking acceptance ( $|\eta| < 2.4$ ). Jets with  $2.4 < |\eta| < 4.5$  are required to have  $p_T > 30$  GeV. This  
 1759 tighter requirement reduces jets from pileup in the region where JVF requirements cannot be applied. The  
 1760 two highest  $p_T$  jets in the event are referred to as the “VBF” jets and used to compute variables used in the  
 1761 analysis selection.

1762 Identification of  $b$ -jets is done using the MV1 algorithm and is limited to the acceptance of the ID  
 1763 ( $|\eta| < 2.5$ ) [68]. The operating point of MV1 that is used is 85% efficient for identifying true  $b$ -jets.  
 1764 This operating point has a 10.3% of mis-tagging a light quark jet as a  $b$ -jet. In order to improve the rejec-  
 1765 tion of  $b$ -jets, a lower threshold than the nominal  $p_T$  threshold described above is used. For the purposes  
 1766 of counting the number of  $b$ -jets, jets with  $p_T$  down to 20 GeV are used.

1767 5.3.4 OVERLAP REMOVAL

1768 There are some cases where reconstructed objects will overlap and one will have to be chosen (for example,  
1769 an electron and a jet in the calorimeter). First, the case of lepton overlap is dealt with. If an electron  
1770 candidate extends into the muon spectrometer, it is removed. If a muon and electron are within  $\Delta R < 0.1$   
1771 of each other, the electron is removed and the muon is kept. If two electron candidates overlap within the  
1772 same radius, then the higher  $E_T$  electron is kept. Next, the overlap between leptons and jets is considered.  
1773 If an electron and jet are within  $\Delta R < 0.3$  of one another, the electron is kept and the jet is removed.  
1774 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  
1775 result of a semileptonic decay inside the jet). Once the overlap removal is complete, the final set of objects  
1776 used in the analysis is defined.

1777 5.4 ANALYSIS SELECTION

1778 The VBF analysis uses two distinct selections. The first is a more standard selection, referred to as “cut-  
1779 based”, that applies requirements on the VBF variables and uses  $m_T$  as the final discriminating variable.  
1780 The second is a looser selection that uses an algorithm known as a Boosted Decision Tree (BDT). A BDT  
1781 is a multivariate technique that uses an ensemble of decision trees to split the phase space of input variables  
1782 into signal-like and background-like regions in order to provide separation power [94–96]. The output  
1783 score of a BDT trained to distinguish the VBF Higgs signal from background processes is used as the final  
1784 discriminating variable in order to take advantage of the detailed correlations between the VBF variables.  
1785 While the BDT-based analysis is ultimately more sensitive, the cut-based serves as an important component  
1786 of the analysis. First, the cut-based allows for confirming the modeling and validity of the variables used  
1787 as input to the BDT. Second, because this is the first use of such an MVA technique in the  $H \rightarrow WW^*$   
1788 analysis, the cut-based selection allows confirmation of the final BDT result with a more traditional anal-  
1789 ysis. The cut-based techniques are the focus of this chapter, but connections to the BDT result will be  
1790 illustrated when appropriate.

1791 One important note is that because this analysis is dedicated to the measurement of the VBF pro-  
1792 duction mode of the Higgs, events coming from gluon fusion production with the Higgs decaying via

1793    $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  are treated as background events. This will be seen throughout the background  
1794 predictions shown below.

1795   **5.4.1 COMMON PRE-SELECTION**

1796   Both the cut-based and BDT analyses have a common pre-selection that is applied before the signal region  
1797 requirements. The requirements on leptons are common to all  $n_j$  bins. The analysis requires two oppo-  
1798 sitely charged leptons, with the leading lepton required to have  $p_T > 22$  GeV while the subleading lepton  
1799 must have  $p_T > 10$  GeV. Next, to remove low mass  $Z/\gamma^*$  events, a requirement on the dilepton mass  
1800  $m_{\ell\ell} > 10$  (12) GeV is applied in the different (same) flavor channel. In the same flavor channels, there is  
1801 an additional veto placed on the region around the Z peak, requiring that  $|m_{\ell\ell} - m_Z| > 15$  GeV.

1802   There are also requirements on the amount of missing transverse momentum in the event. These are  
1803 only applied in the same flavor channels, as in the different flavor channels  $t\bar{t}$  is the dominant background  
1804 in  $n_j \geq 2$ . The BDT analysis requires  $p_T^{\text{miss}} > 40$  GeV and  $E_T^{\text{miss}} > 45$  GeV. The cut-based analysis  
1805 must select more tightly on these variables to have maximal sensitivity and thus requires  $p_T^{\text{miss}} > 50$  GeV  
1806 and  $E_T^{\text{miss}} > 55$  GeV.

1807   Finally, because this analysis is focused on VBF Higgs production, a requirement on the jet multiplicity  
1808 is placed, with  $n_j \geq 2$ . Additionally, the analysis requires that there are no jets identified as b-quarks in  
1809 the event, or  $n_b = 0$ .

1810   **5.4.2 CUT-BASED SELECTION**

1811   The cut-based selection places sequential requirements on variables reconstructed from the VBF jets in  
1812 order to increase the signal to background ratio.

1813   **GENERAL BACKGROUND REDUCTION**

1814   Top pair production is the primary background in the  $n_j \geq 2$  bin. Even though  $n_b = 0$  is required, an  
1815 additional variable is constructed to further suppress the top background. There is often additional QCD  
1816 radiation that accompanies the  $t\bar{t}$  system when it is produced. Therefore, a variable which tests for the

1817 presence of this additional radiation,  $p_T^{\text{sum}}$ , is constructed. It is defined in equation 5.1.

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

1818 After pre-selection, the cut-based analysis requires the event to have  $p_T^{\text{sum}} < 15 \text{ GeV}$  to further suppress  
1819  $t\bar{t}$  production.

1820 In the different flavor channels, a requirement is made to reduce the contamination from  $Z \rightarrow \tau\tau$   
1821 decays. The di- $\tau$  invariant mass,  $m_{\tau\tau}$ , is constructed by assuming that the neutrinos from the  $\tau$  decays  
1822 were collinear with the leptons [75]. The analysis requires that this mass satisfy  $m_{\tau\tau} < m_Z - 25 \text{ GeV}$  so  
1823 that it is not consistent with the mass of the  $Z$  boson.

1824 VBF TOPOLOGICAL CUTS

1825 The characteristic feature of VBF production of the Higgs is the presence of two additional forward jets  
1826 coming from the incoming partons which radiate the vector bosons that make the Higgs. These jets are  
1827 forward because the outgoing partons still carry the longitudinal momentum of the incoming partons.  
1828 Figure 5.2 shows the distribution of the  $\eta$  for the leading jet in a VBF event compared to a background top  
1829 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  
1830 central. Because the cross section for VBF production is an order of magnitude smaller than gluon fusion  
1831 production, these forward jets must be used in order to reduce background and achieve a good signal to  
1832 background ratio. The dedicated VBF search selection requirements are constructed to maximally exploit  
1833 the features of the unique VBF topology.

1834 Requirements on the VBF jets are collectively referred to as the “VBF topological cuts”. First, a require-  
1835 ment on the dijet invariant mass of the VBF jets,  $m_{jj}$ , is placed, requiring  $m_{jj} > 600 \text{ GeV}$ . Next, the  
1836 event is required to have a large gap in rapidity between the two VBF jets, or  $\Delta y_{jj} > 3.6$ . Both of these  
1837 are tight requirements on the presence of two forward, high  $p_T$  jets moving in opposite directions in the  
1838 longitudinal plane.

1839 Beyond requiring the presence of the two forward VBF jets, the analysis also vetoes on the presence of  
1840 any additional jets that fall between the two VBF jets. This requirement is referred to as the central jet

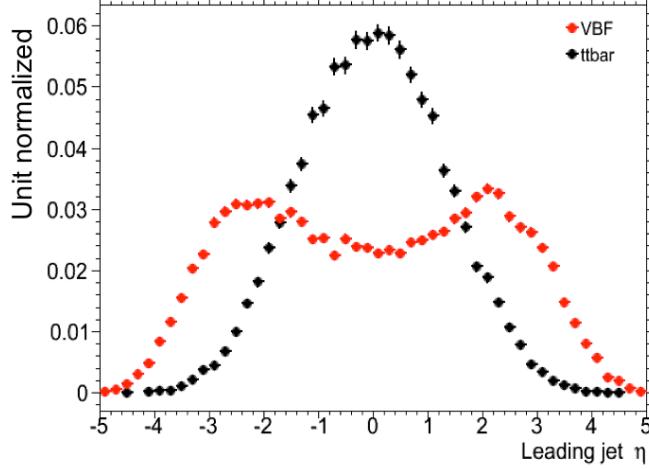


Figure 5.2: Leading jet  $\eta$  in VBF  $H \rightarrow WW^*$  (red) and  $t\bar{t}$  (black)

1841 veto, or CJV. Events are vetoed if they have a third jet with  $p_T > 20$  GeV whose rapidity is between the  
1842 region defined by the two VBF jets. This requirement can be expressed in terms of a variable called the jet  
1843 centrality, defined in equation 5.2.

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

1844 Here,  $\eta_{j1}$  and  $\eta_{j2}$  are the pseudorapidities of the leading and subleading jets, respectively, while  $\eta_{j3}$  is  
1845 the pseudorapidity of the extra jet in the event (if one exists). Intuitively,  $C_{j3}$  is zero when  $\eta_{j3}$  is directly  
1846 centered between the two jets and unity when  $\eta_{j3}$  is aligned with either of the VBF jets. Thus, the CJV  
1847 can be expressed as a requirement that  $C_{j3} > 1$ .

1848 The decay products of the Higgs tend to be central as well. Thus, the analysis also requires that both  
1849 leptons in the analysis fall within the rapidity gap defined by the jets. This cut is referred to as the outside  
1850 lepton veto, or OLV. Stated another way, leptons are required to have a centrality (defined analogously to  
1851 that of the third jet in equation 5.2) within the jet rapidity gap, or  $C_\ell < 1$  for both leptons.

1852 Figure 5.3a-c shows the  $m_{jj}$ ,  $\Delta y_{jj}$ , and  $C_{\ell 1}$  variables at the stage where all previous requirements in the  
1853 sequence have been made. The agreement between data and Monte Carlo is good, and the bottom panels

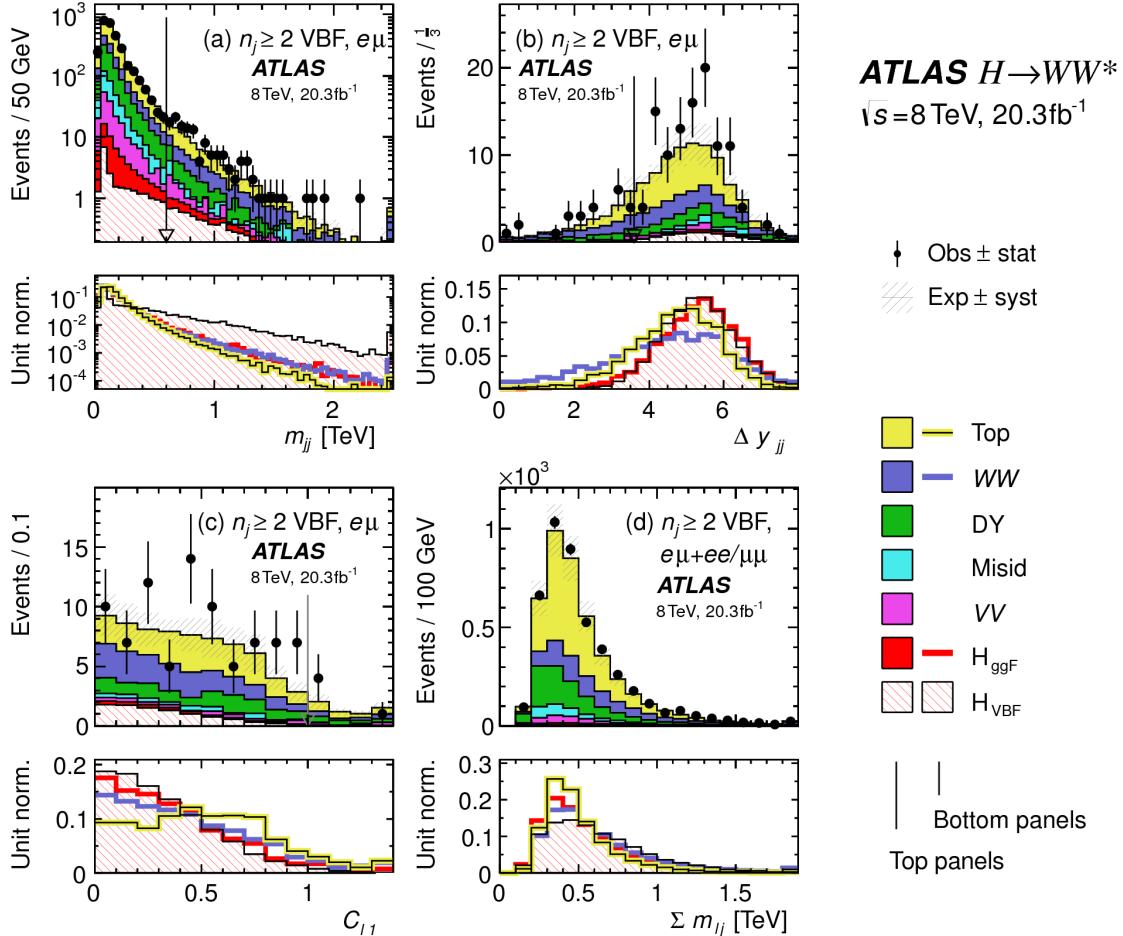


Figure 5.3: Distributions of (a)  $m_{jj}$ , (b)  $\Delta y_{jj}$ , (c)  $C_{\ell 1}$ , and (d)  $\Sigma m_{\ell j}$ , for the cut-based VBF analysis. The top panels compare simulation and data, while the bottom panels show normalized distributions for all background processes and signal for shape comparisons [72].

1854 show their power in discriminating the VBF signal from the background processes.

1855 The final signal region is also split into two bins of  $m_{jj}$ , with the first bin corresponding to  $600 \text{ GeV} <$   
 1856  $m_{jj} < 1 \text{ TeV}$  and the second bin corresponding to  $m_{jj} > 1 \text{ TeV}$ . The first bin has more events but also  
 1857 a larger contribution from background, while the second bin has a lower expected number of events but a  
 1858 1:1 signal to background ratio.

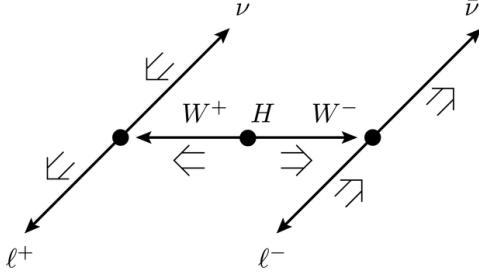


Figure 5.4: A cartoon of the WW final state. Momenta are represented with thin arrows, spins with thick arrows [72].

1859    HIGGS TOPOLOGICAL CUTS

1860    The final state leptons will exhibit unique correlations due to the fact that they arise from the decay of  
 1861    a spin zero resonance. In particular, the spins of the final state leptons and neutrinos must all cancel, as  
 1862    shown in figure 5.4. Because the neutrino has a left handed chirality and the anti-neutrino has a right  
 1863    handed chirality (in the massless neutrino approximation), the spin and momentum of the particles will  
 1864    be anti-aligned and aligned, respectively. In the transverse plane, the momenta of all four final state objects  
 1865    must cancel as well. With the constraint of having both the momenta and the spin alignments cancel, the  
 1866    final state kinematics strongly prefer having a small angle between the leptons in the transverse plane (low  
 1867     $\Delta\phi_{\ell\ell}$ ). This angular correlation will also lead to low values of the di-lepton invariant mass  $m_{\ell\ell}$ . These  
 1868    unique signal final state kinematic correlations are exploited to define the ultimate signal region.

1869    Two requirements on dilepton kinematics are made that are common with lower multiplicity jet bins  
 1870    as well. The angle between leptons in the transverse plane,  $\Delta\phi_{\ell\ell}$ , is required to be less than 1.8 radians.  
 1871    Additionally, the dilepton invariant mass,  $m_{\ell\ell}$ , is required to be less than 50 GeV.

1872    The cut-based analysis uses  $m_T$  as the final discriminating variable as in the ggF focused analysis. The  
 1873    optimal number of bins in  $m_T$  was found to be three bins, with the bin boundaries at 80 and 130 GeV.

1874    Table 5.7 shows a summary of the data and estimated signal and background yields from simulation  
 1875    as each requirement described above is made. The table shows how the overall signal to background ra-  
 1876    tio grows through the various selection requirements. Table 5.8 shows the background composition after  
 1877    each selection requirement, illustrating which backgrounds are reduced most by certain requirements. Fig-

<sup>1878</sup> ure 5.5 shows an ATLAS event display of a candidate event in the final signal region.

Selection	Summary					
	$\bar{N}_{\text{obs}}/\bar{N}_{\text{bkg}}$	$\bar{N}_{\text{obs}}$	$\bar{N}_{\text{bkg}}$	$\bar{N}_{\text{signal}}$		
				$N_{\text{ggF}}$	$N_{\text{VBF}}$	$N_{\text{VH}}$
$e\mu$ 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 [72].

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

Table 5.8: Background composition after each requirement in the  $n_j \geq 2$  VBF analysis in the 8 TeV cut-based analysis [72].

$H \rightarrow WW^* \rightarrow e\bar{\nu}\mu\nu$  candidate and two jets with VBF topology

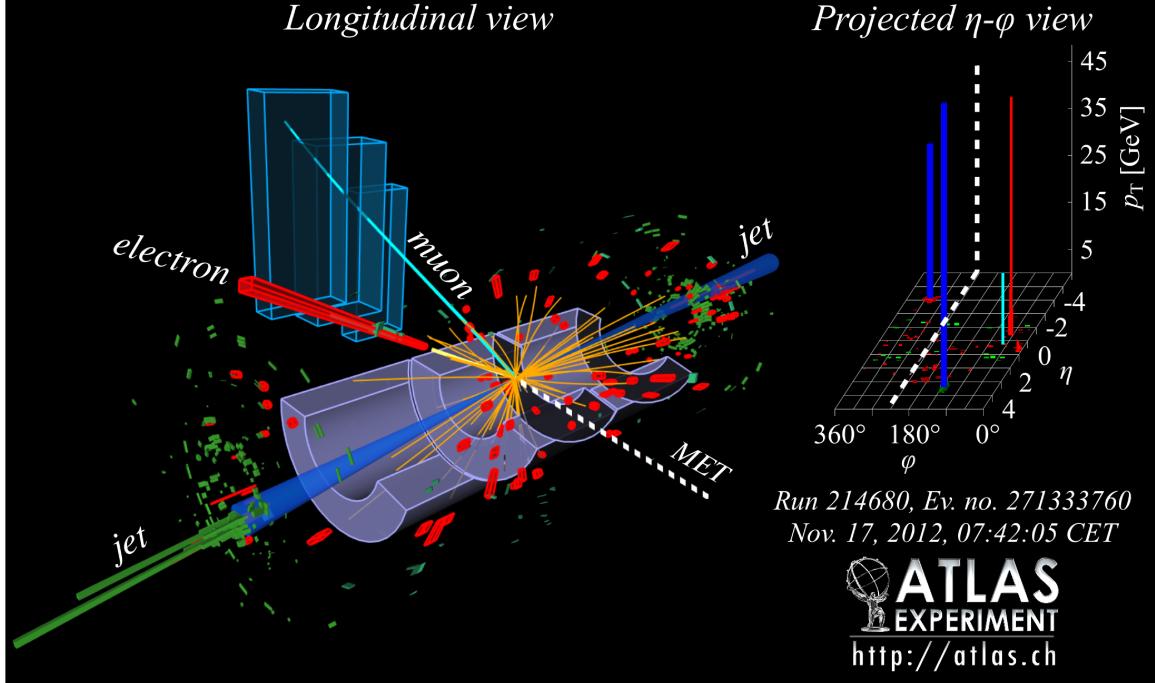


Figure 5.5: Event display of a VBF candidate event [72].

#### 1879 5.4.3 BDT-BASED SELECTION

1880 The boosted decision tree based analysis takes a different philosophy compared to the cut-based. Rather  
 1881 than making sequential requirements on many variables, the BDT analysis uses many of these variables  
 1882 as inputs to the BDT. The output BDT score ( $O_{\text{BDT}}$ ) is used as the final discriminant rather than  $m_T^2$ .  
 1883 The BDT is trained with the VBF  $H \rightarrow WW^*$  simulation as the signal samples and all other processes as  
 1884 background, including ggF  $H \rightarrow WW^*$  production. While the BDT based analysis is treated as a separate  
 1885 result, it has significant overlap with the cut-based selection.

#### 1886 PRE-TRAINING SELECTION AND BDT INPUTS

1887 Before training, the common pre-selection cuts described in section 5.4.1 are applied. Additionally, the  
 1888 central jet veto and outside lepton veto described in section 5.4.2 are applied. The BDT has eight input

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

variables, six of which are also variables that are used in the cut-based analysis. The six shared variables 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 the variables used to define the OLV in the cut-based analysis. The BDT uses as input the sum of lepton 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 the correlations between the jets and leptons in the event. It is the sum of the invariant masses of all four possible lepton-jet combinations.

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

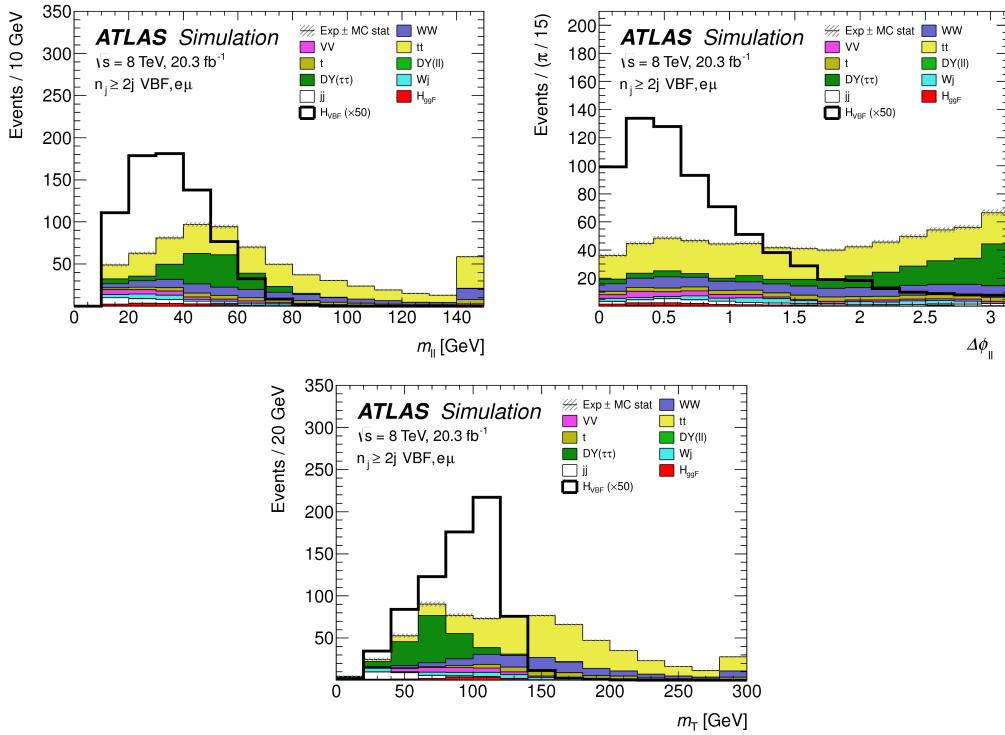


Figure 5.6: Distributions of  $m_{\ell\ell}$  (top left),  $\Delta\phi_{\ell\ell}$  (top right), and  $m_T$  (bottom), the Higgs topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [72].

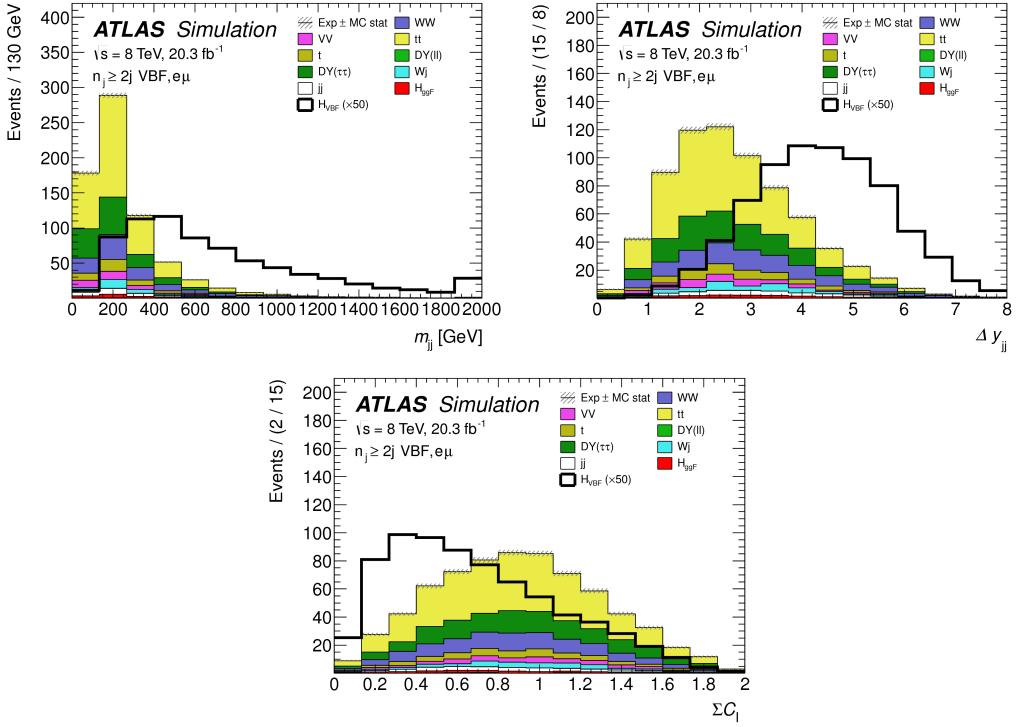


Figure 5.7: Distributions of  $m_{jj}$  (top left),  $\Delta y_{jj}$  (top right),  $\sum C_\ell$  (bottom), the VBF topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [72].

## 1900 5.5 BACKGROUND ESTIMATION

1901 This section describes the procedures used to estimate backgrounds for the VBF analysis in both the cut-  
 1902 based and BDT analyses.

### 1903 5.5.1 GENERAL STRATEGY

1904 Most of the backgrounds in the VBF Higgs analysis have shapes estimated from Monte Carlo simulation  
 1905 but normalizations derived from control regions in data. In essence, a normalization factor (denoted with  
 1906  $\beta$  or abbreviated as NF) is derived by scaling the MC yield in the control region to the corresponding yield  
 1907 in data. Once this factor is derived, it can be used to scale the MC estimate of the background in the signal

1908 region. This is illustrated in equation 5.3.

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

1909 Here,  $B$  is the MC yield prediction in the denoted region, while  $N$  is the observed number of events in  
1910 data in the denoted region.

1911 There is an alternative way of writing the same equation in terms of an extrapolation factor  $\alpha$  rather  
1912 than a normalization factor  $\beta$ . The overall calculation is exactly the same. However, when phrased in  
1913 this way, it shows how the uncertainty on the background estimation can be reduced. This is shown in  
1914 equation 5.4.

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

1915 Phrased this way, the equation shows that with enough events in the control region, a large theoretical  
1916 uncertainty on the overall background yield in the signal region can be replaced by a small statistical un-  
1917 certainty coming from the number of data events in the CR and a smaller theoretical uncertainty on the  
1918 extrapolation from the control region to the signal region.

### 1919 5.5.2 TOP BACKGROUND

1920 The normalization factor  $\beta_t$  for the top background in the VBF analysis is derived in a region required to  
1921 have one b-tagged jet, or  $n_b = 1$ . In the cut-based analysis, normalization factors are computed after every  
1922 selection requirement by making the same requirements in the CR. These NF are then applied to the  $t\bar{t}$  and  
1923 single top event yields in the SR. In the BDT analysis, a single normalization factor is computed for each  
1924 bin of  $O_{\text{BDT}}$  after applying the BDT pre-training cuts described previously. The computed normaliza-  
1925 tion factors are derived with all flavor combinations combined in order to decrease statistical uncertainty.  
1926 Additionally, in the BDT analysis, BDT bins 2 and 3 are merged for the same reason.

1927 Table 5.9 shows the evolution of the  $\beta_t$  through the cut-based selection. Table 5.10 shows the value of  
1928 the  $\beta_t$  in each bin of  $O_{\text{BDT}}$ . In all cases, the computed factors are relatively consistent with unity, with  
1929 the largest discrepancy coming in bin 1 of  $O_{\text{BDT}}$ . The normalization factors in the bins of  $O_{\text{BDT}}$  are also

<sup>1930</sup> consistent with those derived in the cut-based signal region, increasing confidence in the BDT estimation.

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

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

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

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

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

<sup>1931</sup>

<sup>1932</sup> consistent with the data. While these normalization factors can be computed and applied to the expected background yields listed in tables like table 5.8, the final normalization of the top background is profiled <sup>1933</sup> (meaning there is a dedicated Poisson constraint) and allowed to float in the final statistical fit. <sup>1934</sup>

### <sup>1935</sup> 5.5.3 $Z/\gamma^* \rightarrow \tau\tau$ BACKGROUND

<sup>1936</sup> In the different flavor channels, the  $Z/\gamma^* \rightarrow \tau\tau$  background is an important one. Di-tau production can <sup>1937</sup> produce an  $e\mu$  final state if each  $\tau$  lepton decays to a different flavor lepton.

<sup>1938</sup> In the BDT analysis, a single normalization factor for the background is derived. A control region <sup>1939</sup> is defined using the pre-training selection cuts, except requiring that  $|m_{\tau\tau} - m_Z| < 25 \text{ GeV}$  so that <sup>1940</sup> the region is enriched in  $Z/\gamma^* \rightarrow \tau\tau$  background. Additional requirements of  $m_{\ell\ell} < 80(75) \text{ GeV}$  <sup>1941</sup> in the different (same) flavor channel, as well as  $O_{\text{BDT}} > -0.48$  are applied to increase the purity of the

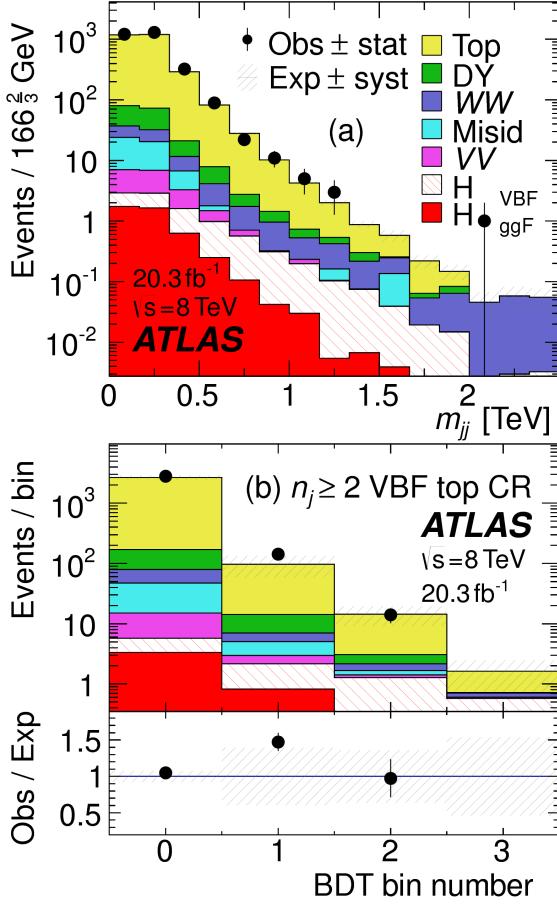


Figure 5.8: Distributions of  $m_{jj}$  (a) and  $O_{\text{BDT}}$  (b) in the VBF  $n_b = 1$  top CR [72].

region. The final  $\beta_{Z/\gamma^* \rightarrow \tau\tau}$  is calculated to be  $0.9 \pm 0.3$  (statistical uncertainty only). Because of the small contribution of this background in the BDT analysis and the large statistical uncertainty, no additional systematics are calculated. The final SR estimate is scaled by this  $\beta$  and not allowed to float in the fit.

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

1952 factors (CF) to the cut efficiencies of the VBF cuts are derived in a same flavor  $Z \rightarrow \ell\ell$  control region,  
 1953 which has significantly more statistics. The CF is simply the ratio of the cut efficiencies in data and MC  
 1954 derived in this region. In the end, the overall background estimate is given by equation 5.5.

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

1955 The hypothesis is that while the normalization correction must be derived in a dedicated region, the effi-  
 1956 ciency of the VBF topology requirements should not be sensitive to the type of  $Z/\gamma^*$  process and thus the  
 1957 higher number of events can be exploited to derive the CF. Figure 5.9 shows a shape comparison for the  
 1958  $m_{jj}$  variable in  $Z \rightarrow \tau\tau$  events in the signal region and  $Z \rightarrow \ell\ell$  events in the control region. The figure  
 1959 shows that the shapes are indeed comparable and thus any CF derived in the same flavor control region  
 1960 can reliably be applied in the signal region.

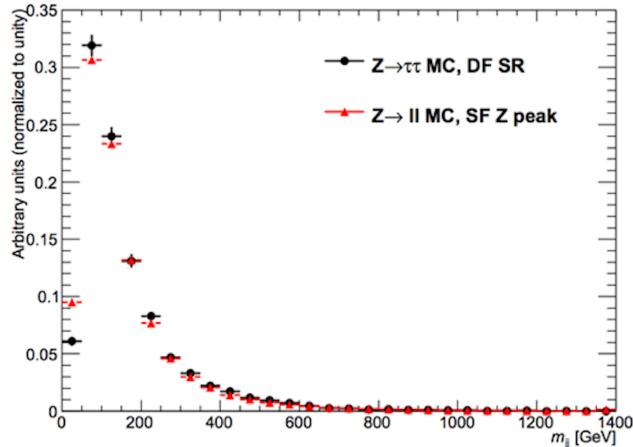


Figure 5.9: Comparison of  $m_{jj}$  shape in a same flavor  $Z \rightarrow \ell\ell$  control region and the VBF cut-based signal region.

1961 Table 5.11 shows the overall normalization factor  $\beta_{\tau\tau}$  and the efficiency correction factors for the various  
 1962 VBF topological cuts. In general, the statistical uncertainties on the cut efficiency corrections are quite  
 1963 good, and the MC tends to underestimate the efficiency of the VBF cuts for the  $Z/\gamma^* \rightarrow \tau\tau$  background.  
 1964 The overall normalization factor is also consistent with that calculated for the BDT analysis.

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

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

1965 5.5.4  $Z/\gamma^* \rightarrow \ell\ell$  BACKGROUND

1966 In the same flavor channels, the  $Z/\gamma^* \rightarrow \ell\ell$  background is dominant and thus must be estimated cor-  
 1967 rectly. In both the BDT and cut-based analyses, the background is estimated using the so-called “ABCD”  
 1968 method. The ABCD method creates four different regions by defining requirements on two variables.  
 1969 One of the regions (A) is the signal region, while the other regions are defined by inverting one of both of  
 1970 the requirements. in this case, the two variables used are  $m_{\ell\ell}$  and  $E_T^{\text{miss}}$ , because inverting either of the  
 1971 SR cuts on these variables will give regions rich in the  $Z/\gamma^* \rightarrow \ell\ell$  background. Figure 5.10 illustrates the  
 1972 definitions of each region.

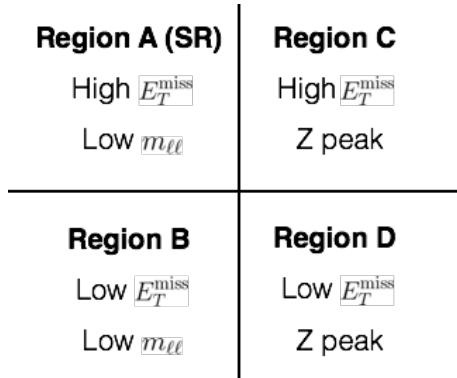


Figure 5.10: General illustration of the ABCD region definitions for  $Z/\gamma^* \rightarrow \ell\ell$  background estimation.

1973 In both of the cut-based and BDT analyses, the Z peak region is defined with  $|m_{\ell\ell} - m_Z| < 15 \text{ GeV}$ .  
 1974 In the cut-based analysis, low  $m_{\ell\ell}$  corresponds to  $m_{\ell\ell} < 50 \text{ GeV}$  (this defines the cut-based SR) while  
 1975 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

1976 the 55 GeV cut applied for the signal region definition. The BDT low  $E_T^{\text{miss}}$  region is between 25 and  
 1977 45 GeV, while the high  $E_T^{\text{miss}}$  region is  $E_T^{\text{miss}} > 45$  GeV.

1978 Once the regions are defined, the background in the signal region is estimated by extrapolating the  
 1979 estimate in region B to region A. This extrapolation is done by multiplying the number of events in region  
 1980 B by the ratio of the number of events in regions C and D. Effectively, the Z peak region is used to estimate  
 1981 the efficiency of the  $E_T^{\text{miss}}$  requirement in data, and then this efficiency is applied in the low  $m_{\ell\ell}$  region.  
 1982 An additional correction is also applied for the non-closure of the method in MC. This is summarized in  
 1983 equations 5.6 and 5.7.

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

1984

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

1985 Here, the  $N$  refer to data yields in each region with the non  $Z/\gamma^*$  backgrounds subtracted, while  $B$  refer  
 1986 to the  $Z/\gamma^*$  yields in MC in each region.

1987 A normalization factor  $\beta_{\ell\ell}$  is computed for each analysis as the ratio of the predicted data yield to the  
 1988 MC yield in the SR. The shape of the BDT distribution is taken from data region B, while the shape of  
 1989 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  
 1990 cut-based and BDT analyses from this method are summarized in table 5.12. They are quite consistent with  
 1991 one another within the statistical uncertainties. In the cut-based analysis, the same cut efficiency correction  
 1992 factors shown in table 5.11 are also applied (in product with the  $\beta_{\ell\ell}$ ) in the same flavor channels to the  $Z/\gamma^*$   
 1993 background.

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

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

1994    5.5.5     $WW$  AND OTHER DIBOSON BACKGROUNDS

1995    The Standard Model  $WW$  and other diboson backgrounds have both their shape and normalization taken  
 1996    from MC simulation. They are validated in dedicated control regions and found to agree with data well.

1997    As SM  $WW$  production is the largest of these backgrounds and is irreducible, validating the estimate  
 1998    is of particular importance. A validation region is constructed by requiring the pre-selection requirements  
 1999    on leptons and  $m_{\ell\ell}$ ,  $n_b = 0$ , and  $m_T > 100$  GeV. The  $m_{T2}$  variable [97] is an additional discriminant  
 2000    that will isolate the SM  $WW$  background, and a requirement of  $m_{T2} > 160$  GeV is placed to define  
 2001    the  $WW$  validation region. This requirement gives a 60% purity for the validation region. The derived  
 2002    normalization factor in the region is  $1.15 \pm 0.19$  and is thus consistent with unity. Figure 5.11 shows the  
 2003     $m_{T2}$  distribution and how it distinguishes the  $WW$  background.

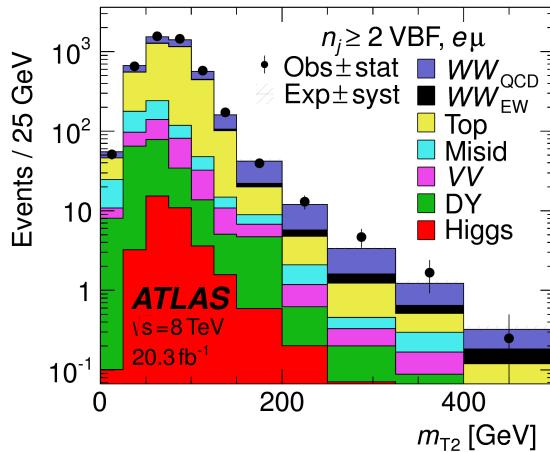


Figure 5.11: Distribution of  $m_{T2}$  in the  $WW$  validation region of the VBF analysis [72].

2004    5.5.6    HIGGS PRODUCTION VIA GLUON-GLUON FUSION

2005    Because this analysis is dedicated to measuring the VBF contribution to Higgs production, the compo-  
 2006    nent of Higgs production from gluon-gluon fusion is treated as a background. The shape is taken directly  
 2007    from simulation, using the generators described in table 5.4. In the final combined fit of all different signal  
 2008    regions, the normalization is controlled by either a combined signal strength parameter  $\mu$ , which controls  
 2009    the normalization of both ggF and VBF production, or a separate parameter  $\mu_{ggF}$  depending on the in-

2010 interpretation being presented in the final results.

2011 **5.5.7 BACKGROUNDS WITH MISIDENTIFIED LEPTONS**

2012 As discussed previously, the  $W$ +jets and QCD multijet backgrounds are derived with fully data-driven  
2013 methods. These backgrounds do not make a large contribution to the final VBF signal region but their  
2014 estimation methods are discussed briefly here.

2015  **$W$ +JETS BACKGROUND**

2016 The  $W$ +jets background enters the signal region by having one of the jets mis-reconstructed as a lepton.  
2017 The background is estimated by constructing a control sample with two leptons, where one lepton passes  
2018 the usual lepton quality requirements but the second lepton fails one of those requirements (also known  
2019 as the “anti-identified” lepton). This control region is rich in the  $W$ +jets contribution because if a second  
2020 lepton is reconstructed in a  $W$ +jets event it is likely to be poor quality. The purity of this  $W$ +jets control  
2021 sample is 85% to 90% depending on the exact configuration of leptons in the final state.

2022 The signal region estimate of  $W$ +jets is estimated by extrapolation from the control sample to the sig-  
2023 nal region using extrapolation factors derived in a  $Z$ +jets control sample in data. The extrapolation factor  
2024 is the ratio of the number of lepton candidates satisfying all quality criteria to the number of lepton can-  
2025 didates anti-identified. This ratio is measured in bins of  $p_T$  and  $\eta$ . Thus, the final signal region estimate  
2026 (binned as the extrapolation factor is binned) is simply the number of events in the anti-identified lepton  
2027 control sample multiplied by the extrapolation factor derived from the  $Z$ +jets control sample. Figure 5.12  
2028 shows the extrapolation factors derived for electrons and muons.

2029 **QCD MULTIJET BACKGROUND**

2030 The method for estimating the multijet background is very similar to the  $W$ +jets estimation method. The  
2031 control sample in this case has two anti-identified leptons but otherwise satisfies all signal region require-  
2032 ments. The extrapolation factor is estimated from a multijet sample and applied twice to the control sam-  
2033 ple.

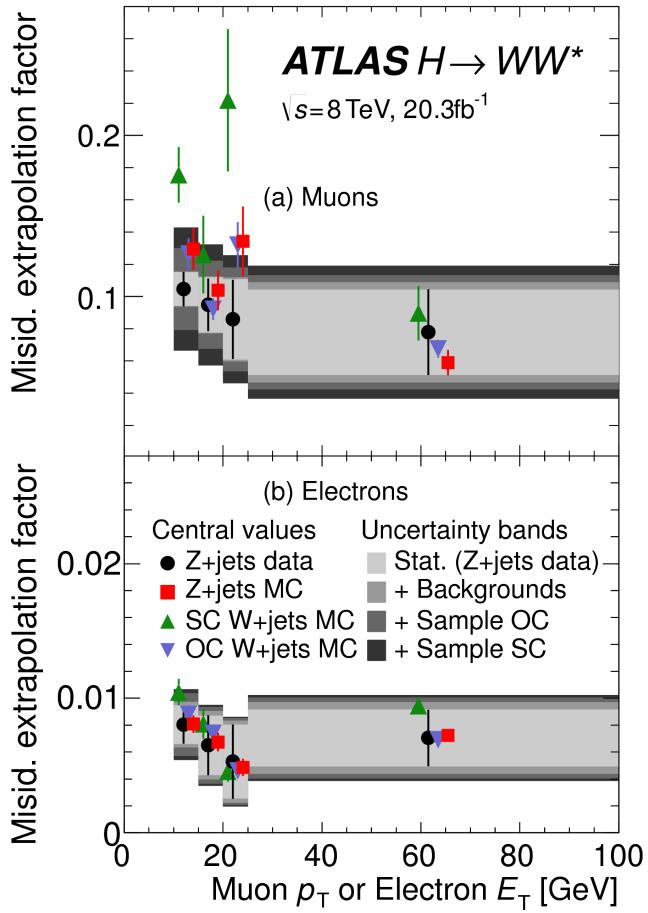


Figure 5.12: Extrapolation factors for the  $W+jets$  estimate derived for muons (a) and electrons (b) as a function of lepton  $p_T$  [72].

### 5.5.8 BACKGROUND COMPOSITION IN SIGNAL REGION

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

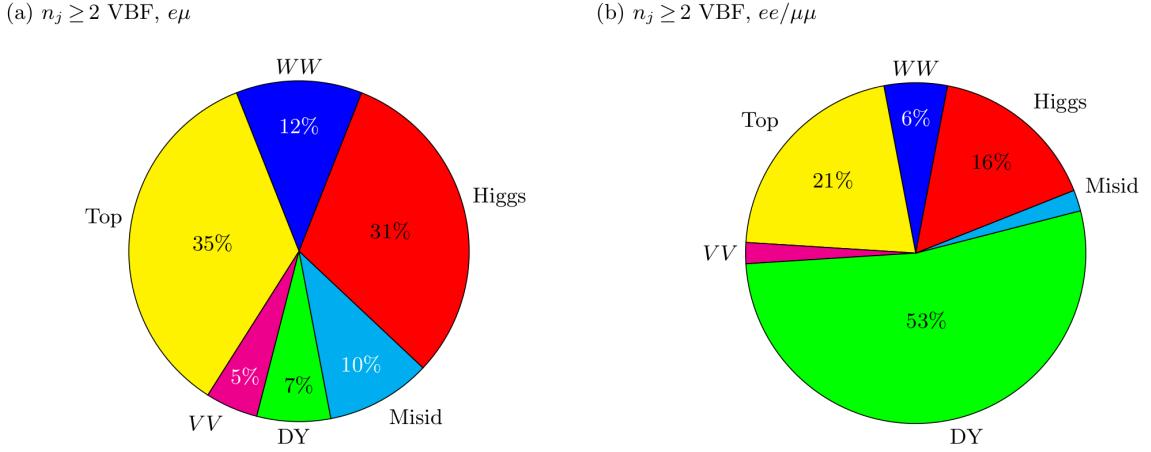


Figure 5.13: Background composition in final VBF signal region [72].

## 2040 5.6 SYSTEMATIC UNCERTAINTIES

2041 There are two main types of systematic uncertainties that are assessed for the analysis. First, theoretical  
 2042 uncertainties associated with the signal and background yield estimates are discussed. Then, experimental  
 2043 uncertainties due to detector effects are shown. Normalization uncertainties refer to uncertainties that  
 2044 affect the cross section of the process in question in the signal region being probed. Shape uncertainties  
 2045 refer to systematic uncertainties that affect the shape of the final discriminating variable (either  $m_T$  or  
 2046  $O_{\text{BDT}}$ ).

### 2047 5.6.1 THEORETICAL UNCERTAINTIES

2048 There are four main components to theoretical uncertainties assigned to signal and background processes  
 2049 taken from Monte Carlo. Each one is a different source of variation in the overall acceptance for that  
 2050 process. The first involves variation of the QCD renormalization and factorization scales used in the cal-  
 2051 culation. In this case, the two scales are varied both independently and simultaneously by factors of two  
 2052 high or low. The resulting variation in normalization and shape for the process is taken as a systematic  
 2053 uncertainty (referred to as scale uncertainty). This uncertainty approximates the level of the correction  
 2054 to the cross section that would come from including the next order of the QCD calculation. Next, there  
 2055 is an uncertainty associated with the PDF set used in generating the events. The uncertainty eigenvec-

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

There are two additional uncertainties that are applied to the Higgs processes as well. First, there are uncertainties assigned to the Higgs total production cross section. Then, there are uncertainties assigned based on the fact that the analysis is done in exclusive jet bins and it is possible for signal events to migrate from one bin to the next depending on the presence or absence of jets. These are assigned using the Jet Veto Efficiency (JVE) procedure [18, 98] for ggF events and the Stewart-Tackmann (ST) method [99] for VBF production. Table 5.13 shows the total theory uncertainties on the backgrounds in the cut-based analysis. These are the sum in quadrature of the uncertainties from each of the variations described above.

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

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

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

2078 While the estimate for the same-flavor  $Z/\gamma^* \rightarrow \ell\ell$  background is data-driven, there is still a systematic  
 2079 uncertainty taken for the non-closure of the method in Monte Carlo. This is taken as the maximum of the  
 2080 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  
 2081 the cut-based analysis this non-closure uncertainty 23%, while for the BDT analysis it is 17%.

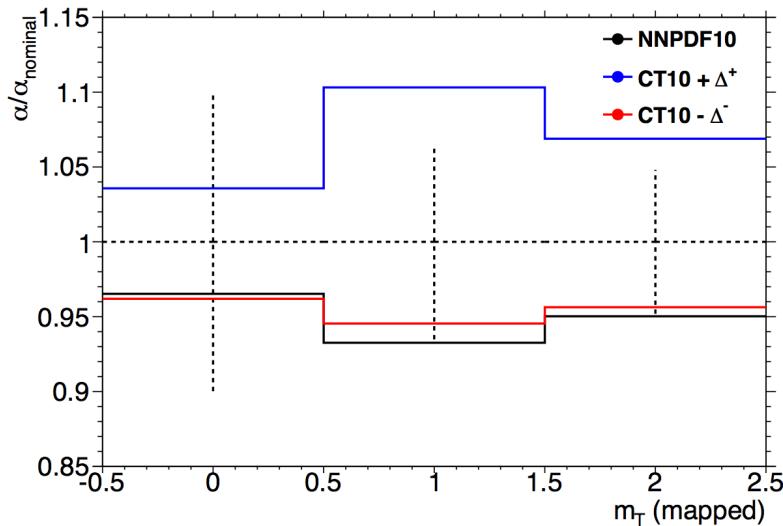


Figure 5.14: Variations in the top background extrapolation factor in the cut-based analysis due to PDF uncertainties. The uncertainties are shown in the three bins of  $m_T$  used in the final cut-based statistical fit. Variations from the eigenvector of the nominal PDF, CT10, as well as the result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

### 2082 5.6.2 EXPERIMENTAL UNCERTAINTIES

2083 In this analysis, the theoretical uncertainties are the most dominant after statistical, but there are some  
 2084 experimental uncertainties that make a contribution as well. The first is the uncertainty on the measured  
 2085 integrated luminosity, which affects backgrounds whose normalizations are taken from MC and is mea-  
 2086 sured to be 2.8% in the 8 TeV dataset [100]. The dominant sources of uncertainty overall are uncertain-  
 2087 ties on the jet energy scale and resolution and the  $b$ -tagging efficiency. Additional sources include lepton  
 2088 uncertainties on identification, resolution, and trigger efficiency, as well as uncertainties on the missing  
 2089 transverse momentum.

2090 The jet energy scale uncertainty is split into several independent components, including jet-flavor de-  
 2091 pendent calorimeter response uncertainties, uncertainties on modeling of pile-up interactions, uncertain-

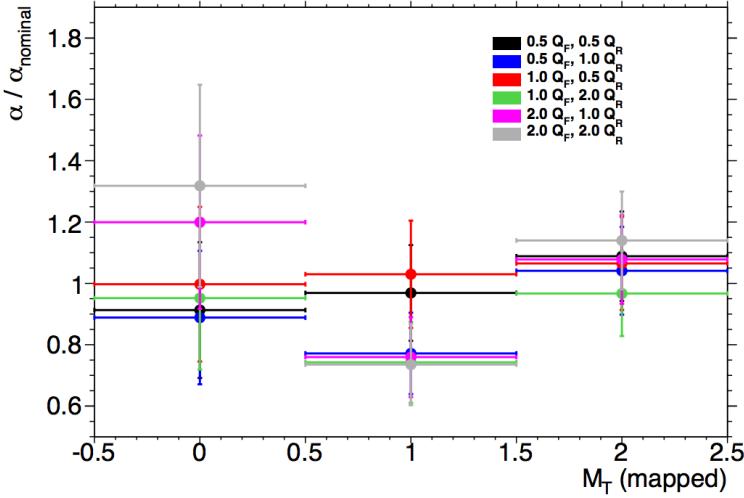


Figure 5.15: Variations in the top background extrapolation factor in the cut-based analysis due to QCD scale uncertainties. The uncertainties are shown in the three bins of  $m_T$  used in the final cut-based statistical fit.  $Q_F$  is the QCD factorization scale, while  $Q_R$  is the QCD renormalization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

ties on extrapolation from the central to forward detector regions, and MC non-closure [101]. The uncertainty on energy scale for jets used in this analysis ranges from 1% to 7% depending on the jet  $p_T$  and  $\eta$ . The jet energy resolution varies from 5% to 20%, with uncertainties ranging from 2% to 40% (the largest uncertainties occurring at the selection threshold).

The b-tagging efficiency is independently measured in data samples enriched in dileptonic decays of  $t\bar{t}$  events or in events where a muon is reconstructed in the vicinity of a jet [102, 103]. The efficiencies and their uncertainties are binned in  $p_T$  and decomposed into uncorrelated components using an eigenvector method [104]. Uncertainties on the efficiency range from 1% to 7.8%. The uncertainty on the rate of misidentification of  $c$ -jets as  $b$ -jets ranges from 6-14%, while the uncertainty on the rate of light jet mistagging ranges from 9-19% depending on  $p_T$  and  $\eta$ .

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

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

Table 5.14: Composition of the post-fit uncertainties (in %) on the total signal ( $N_{\text{sig}}$ ), total background ( $N_{\text{bkg}}$ ), and individual background yields in the VBF analysis [72].

## 2105 5.7 RESULTS

2106 While the combined results of all the  $H \rightarrow WW^*$  sub-analyses will be discussed in the next chapter, this  
 2107 section presents the results of the VBF specific analysis and interpretations. As table 5.7 shows, the final  
 2108 cut-based signal region contains 20 events in data with  $m_T < 150$  GeV, 14 coming from the  $e\mu$  channel  
 2109 and 6 coming from the  $ee + \mu\mu$  channel. The BDT analysis has many more candidates due to its looser  
 2110 selection, and the yields in each bin of  $O_{\text{BDT}}$  are shown in table 5.15.

2111 Figure 5.16(a) shows the final distribution of data candidates compared to the expected  $m_T$  distribution  
 2112 for signal and background. The data are very consistent with a VBF Higgs hypothesis. Figure 5.16(b) shows  
 2113 where the data candidates fall in the two-dimensional binning of  $m_T$  and  $m_{jj}$  used in the fit for the cut-  
 2114 based analysis. Figure 5.17 shows the distributions of  $O_{\text{BDT}}$  and  $m_T$  in the VBF BDT analysis. Again the  
 2115 data are quite consistent with a VBF Higgs hypothesis.

2116 Because the cut-based result is used as a validation for the BDT analysis and the two signal regions are  
 2117 not fully orthogonal, it is interesting to explore which events overlap between the two analyses. Of the  
 2118 twenty events in the cut-based signal region, only seven were not selected by the BDT analysis, while the  
 2119 other thirteen also enter the BDT signal region. Figure 5.18 shows where the different analysis candidates  
 2120 lie in the  $m_{jj}$ - $m_T$  plane. This shows clearly that the advantage of the BDT analysis is that it can extract  
 2121 signal candidates from the lower  $m_{jj}$  region due to its ability to recognize correlations with other variables.

(a) Before the BDT classification

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

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

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

Table 5.15: Event selection for the VBF BDT analysis. The event yields in (a) are shown after the pre-selection and the additional requirements applied before the BDT classification (see text). The event yields in (b) are given in bins in  $O_{\text{BDT}}$  after the classification [72].

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

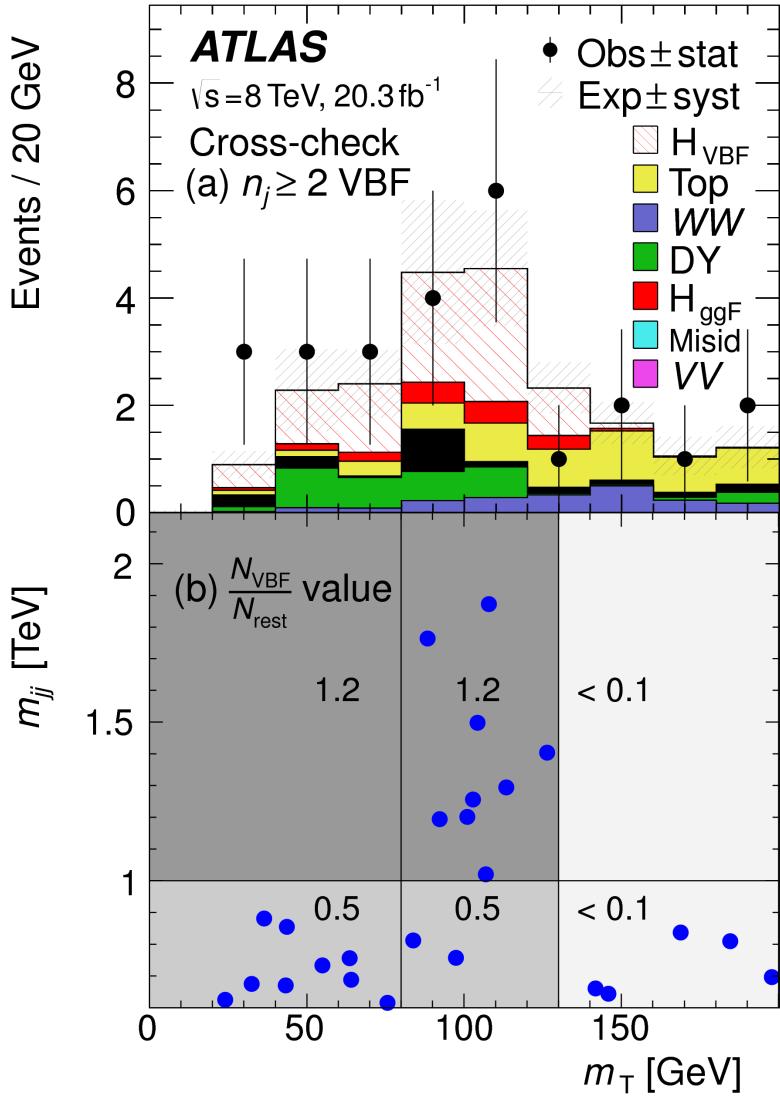


Figure 5.16: Post-fit distributions in the cut-based VBF analysis. Panel (a) shows the one-dimensional  $m_T$  distribution, while (b) shows the data candidates split into the bins of  $m_T$  and  $m_{jj}$  used in the final fit [72].

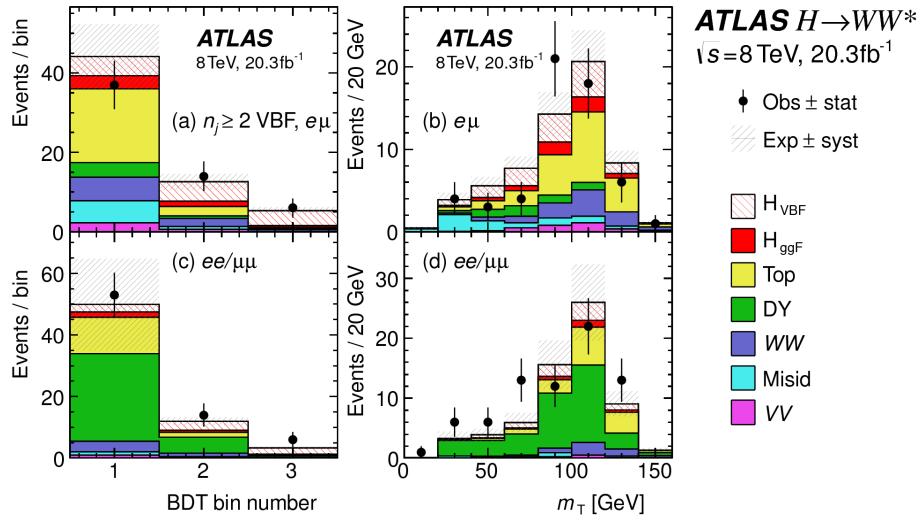


Figure 5.17: Postfit distributions in the BDT VBF analysis [72].

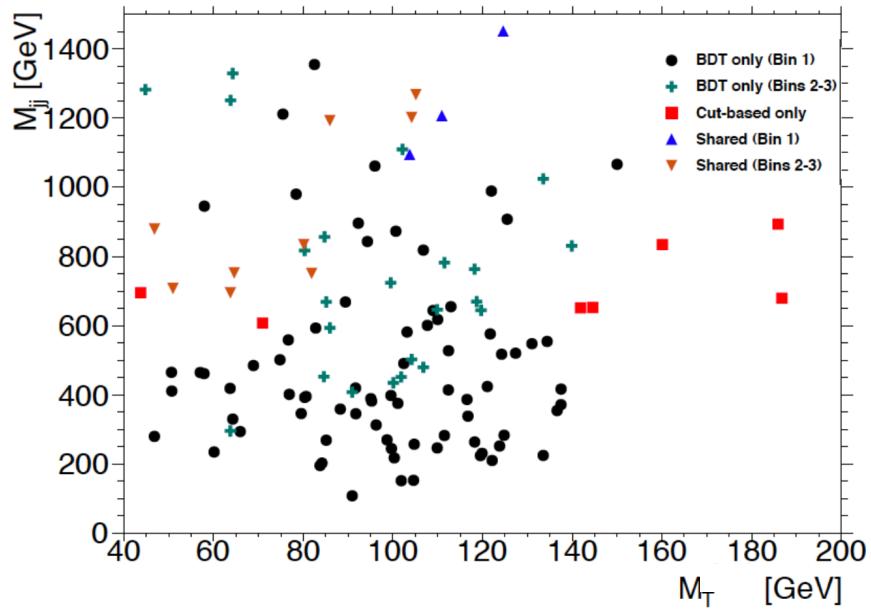


Figure 5.18: Overlap between cut-based and BDT VBF signal region candidates in the  $m_{jj}$ - $m_T$  plane.

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

Chuck Palahniuk

# 6

2131

2132

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

2133

## results

2134

### 6.1 INTRODUCTION

2135 In the final statistical analysis of  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ , the dedicated gluon-gluon fusion and vector  
2136 boson fusion sensitive signal regions are all combined into a single fit to determine the main parameters of  
2137 interest, the Higgs signal strength  $\mu$  and mass  $m_H$ . Therefore, while the specific requirements applied for  
2138 the VBF sensitive analysis are discussed in chapter 5, the final measurement of these parameters can only be  
2139 discussed in combination with the results of the ggF dedicated analysis. For example, because ggF Higgs  
2140 production is considered a background in the VBF analysis, the ggF dedicated signal regions can actually  
2141 constrain the normalization of this background in the VBF dedicated region.

2142 This chapter presents the combined interpretation of results in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis

2143 for gluon fusion and vector boson fusion Higgs production. First, the results of the dedicated gluon fu-  
 2144 sion search are presented. Then, a comparison of the individual production mode signal strengths ( $\mu_{\text{ggF}}$   
 2145 and  $\mu_{\text{VBF}}$ ) and a measurement of the combined signal strength ( $\mu$ ) are shown. Subsequently, the mea-  
 2146 sured values of the Higgs couplings to fermions and vector bosons is presented. Finally, the cross section  
 2147 measurement for ggF and VBF production are shown.

## 2148 6.2 RESULTS OF DEDICATION GLUON FUSION $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ ANALYSIS

2149 The details of the dedicated gluon fusion  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis are not discussed in this thesis  
 2150 and instead left to more comprehensive sources [72]. However, a brief summary of the results is essen-  
 2151 tial for describing the measurements of Higgs properties and interpreting the the dedicated VBF Higgs  
 2152 production search in a broader context. Additionally, the final Run 1 results on gluon fusion production  
 2153 make use of the dedicated variables for same flavor final states developed in section 3.5. The results in the  
 2154 same flavor final states will be shown here as well.

### 2155 6.2.1 RESULTS IN SAME FLAVOR ( $ee/\mu\mu$ ) FINAL STATES

2156 Final states of the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel where both leptons have the same flavor ( $ee/\mu\mu$ )  
 2157 were not included in the discovery result due to increased pileup conditions in the  $\sqrt{s} = 8$  TeV data.  
 2158 Dedicated techniques for background reduction in the same flavor final states were developed, as described  
 2159 in section 3.5. The results shown in this section are the first published results using the same flavor channels  
 2160 in the  $H \rightarrow WW^*$  analysis.

2161 Table 6.1 shows the background estimate, expected signal yield, and event count in data for the same  
 2162 flavor channels in the  $n_j \leq 1$  signal regions. The dedicated same flavor background reduction techniques  
 2163 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 [72].

2164     Figure 6.1 shows the final  $m_T$  distribution in data for the  $n_j \leq 1$  same flavor channels. The data is very  
 2165     consistent with the Higgs hypothesis and it can be seen that the same flavor channels are indeed sensitive  
 2166     to gluon fusion production of the Higgs.

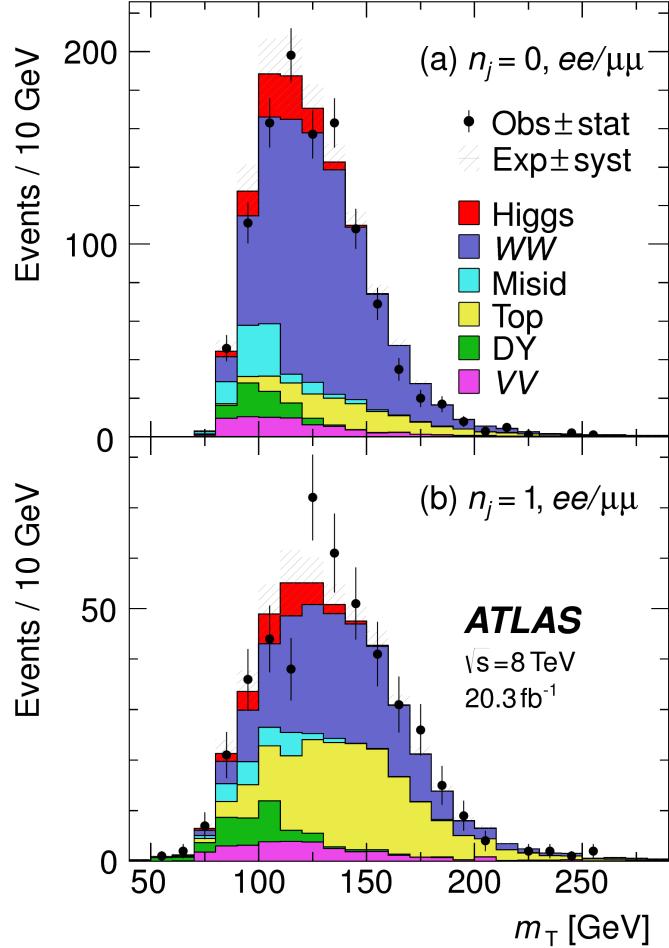


Figure 6.1: Post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions for the same flavor ( $ee/\mu\mu$ ) final states [72].

### 2167     6.2.2 COMBINED GLUON FUSION RESULTS

2168     Table 6.2 shows the individual signal regions that were input into the final statistical fit. The ggF dedicated  
 2169     bins use  $m_T$  as their discriminating variable and are separated into bins of  $p_T$  of the subleading lepton as  
 2170     well. The VBF dedicated bin uses the  $O_{BDT}$  distribution as its final discriminant.

2171     Table 6.3 shows the yields in the various signal regions in both data and expected signal and back-  
 2172     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 [72].

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 [72].

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

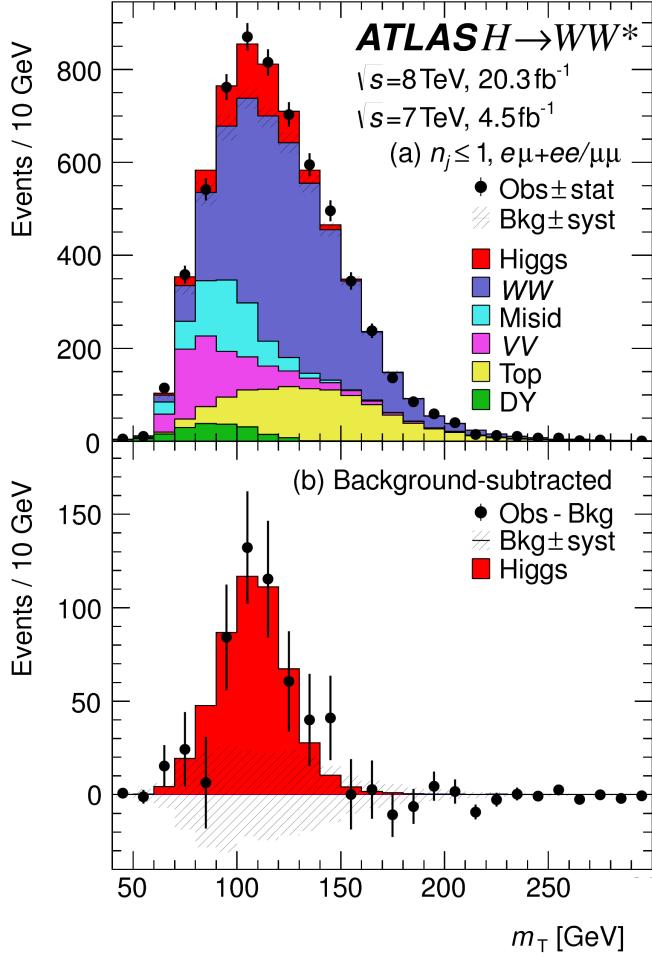


Figure 6.2: Post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions [72].

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.

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

2184 Figure 6.3 gives the best fit signal strength  $\hat{\mu}$  as a function of the hypothesized Higgs mass. The value at  
 2185 a mass of 125.36 GeV corresponds to the  $\mu$  quoted in equation 6.1. This value of the Higgs mass is used  
 2186 because it is the most precise mass measurement from ATLAS, a result of the combined  $\gamma\gamma$  and  $ZZ$  mass  
 2187 measurements [105].

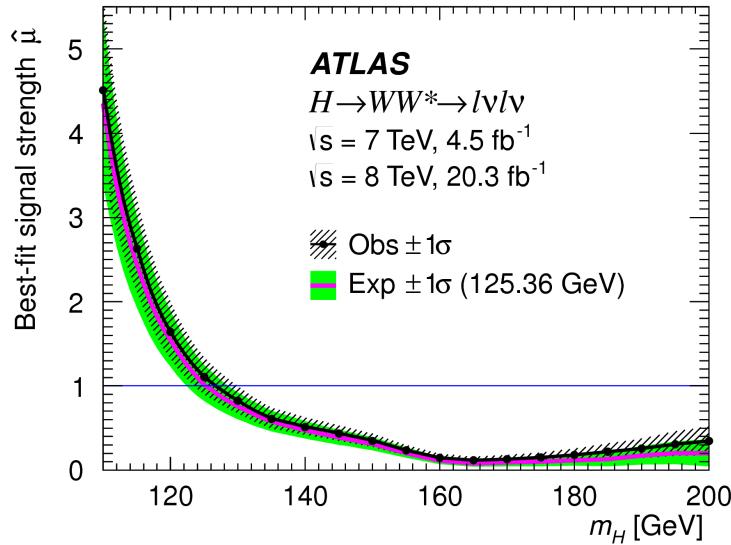


Figure 6.3: Best fit signal strength  $\hat{\mu}$  as a function of hypothesized  $m_H$  [72].

2188 As explained in chapter 3, a probability  $p_0$  can be computed using the test statistic  $q_0$  to quantify the  
 2189 probability that the background could fluctuate to produce an excess at least as large as the one observed  
 2190 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  
 2191  $m_H = 130$  GeV and corresponds to a significance of  $6.1\sigma$ . The curve is relatively flat and the significance  
 2192 is the same at 125.36 GeV within the quoted precision. The expected significance for a signal with strength  
 2193  $\mu = 1.0$  is  $5.8\sigma$ . This represents the first discovery level observation of Higgs production using only the  
 2194  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis.

2195 All the results presented so far in this section have been for the combined gluon fusion and VBF  
 2196 production modes. However, each signal strength can be calculated separately in the likelihood as well. There  
 2197 are two ways to do this. First, the likelihood can be parameterized in terms of a single parameter, the ratio  
 2198 of the VBF and gluon fusion signal strengths. With this method, the statistical significance of the VBF  
 2199 Higgs result can be evaluated. Figure 6.5 shows the likelihood as a function of the ratio  $\mu_{\text{VBF}}/\mu_{\text{ggF}}$ .

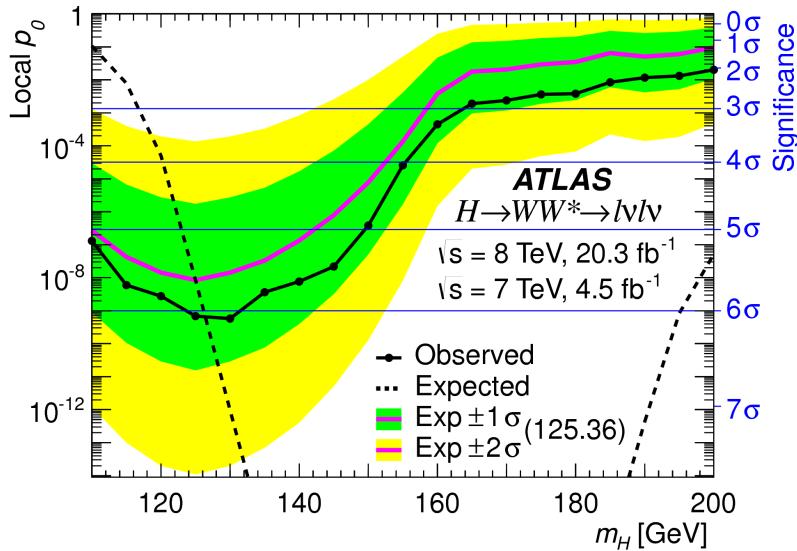


Figure 6.4: Local  $p_0$  as a function of  $m_H$  [72].

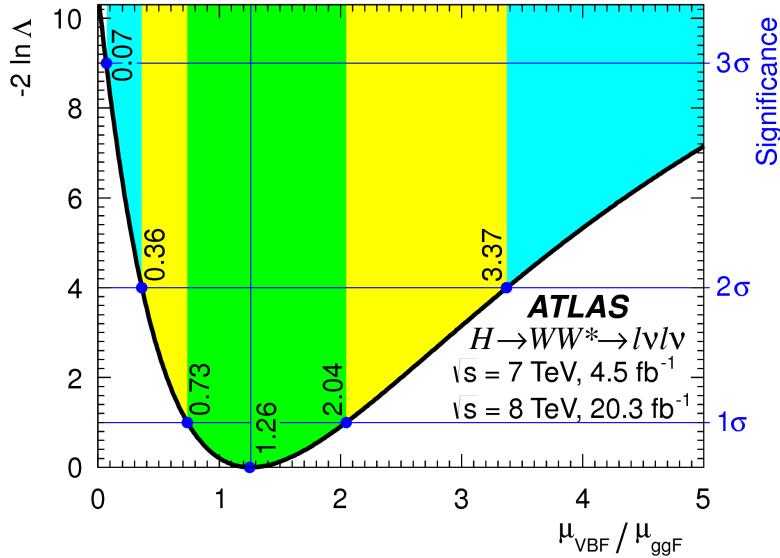


Figure 6.5: Likelihood as a function of  $\mu_{\text{VBF}} / \mu_{\text{ggF}}$  [72].

2200      The best fit value of the ratio of signal strengths is shown in equation 6.2. Within the quoted uncer-  
 2201      tainties, it is consistent with a ratio of unity.

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

2202 The null hypothesis for VBF production corresponds to a ratio of  $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ . The likelihood in  
 2203 figure 6.5 gives a significance of  $3.2\sigma$  at  $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ , as quoted in chapter 5.

2204 In addition to the ratio of signal strengths, each signal strength can be varied independently in the like-  
 2205 lihood as well. Figure 6.6 shows the two dimensional likelihood scan in the  $\mu_{\text{ggF}}-\mu_{\text{VBF}}$  plane. The best fit  
 2206 values of the two signal strengths are shown in equation 6.3. Both are consistent with unity within their  
 2207 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.)

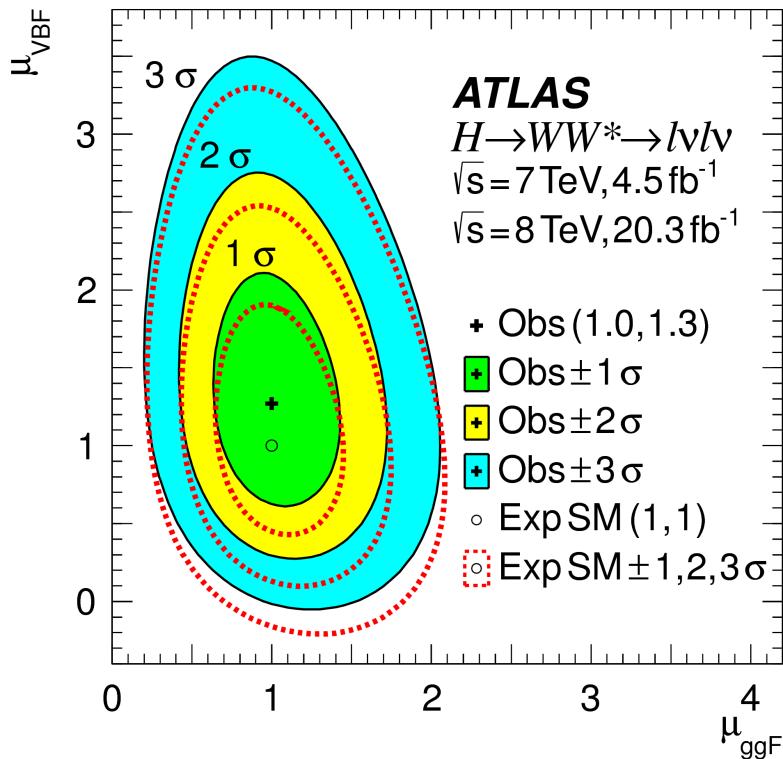


Figure 6.6: Two dimensional likelihood scan as a function of  $\mu_{\text{VBF}}$  and  $\mu_{\text{ggF}}$  [72].

2208 6.4 MEASUREMENT OF HIGGS COUPLINGS TO VECTOR BOSONS AND FERMIONS

2209 Similar to the parameterization of signal strength, the couplings of the Higgs to fermions and bosons can  
 2210 also be parameterized. The parameter of interest in this case is  $\kappa$ , or the ratio of the measured coupling to  
 2211 the Standard Model expectation. Both the fermion and boson couplings have these so-called scale factors,  
 2212  $\kappa_F$  for fermions and  $\kappa_V$  for bosons. Gluon fusion production is sensitive to the fermion couplings through  
 2213 the top quark loops in its production, while VBF production is sensitive to the vector boson couplings in  
 2214 its production. Both modes are sensitive to the vector boson couplings in their decays. The signal strengths  
 2215 will have dependence on the coupling scale factors as described in equation 6.4 [18].

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

2216 Figure 6.7 shows the two-dimensional likelihood scan of  $\kappa_F$  and  $\kappa_V$ . The best-fit values are given in equa-  
 2217 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.)

2218

2219 6.5 HIGGS PRODUCTION CROSS SECTION MEASUREMENT

2220 Another measurement that comes naturally from the signal strength measurements quoted earlier is the  
 2221 production cross section and 7 and 8 TeV for both gluon fusion and VBF production. The general equa-

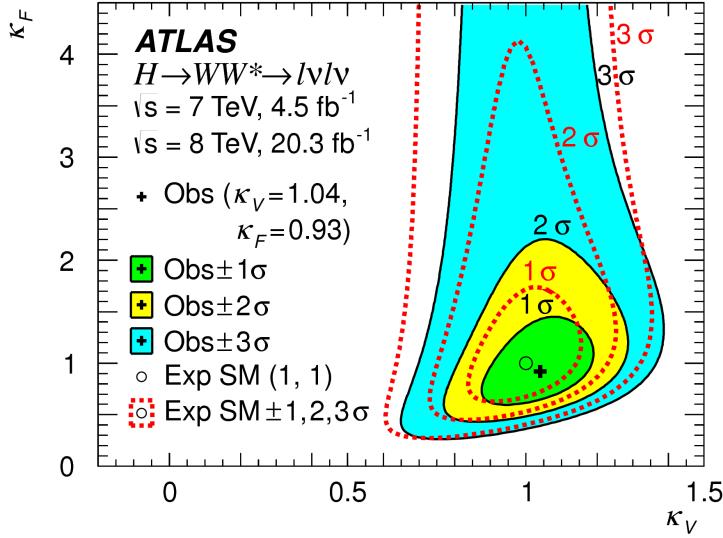


Figure 6.7: Likelihood scan as a function of  $\kappa_F$  and  $\kappa_V$ , the Higgs coupling scale factors [72].

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

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

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

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

(stat.) (syst.)

2228 The predicted cross section values (including the branching ratio of  $H \rightarrow WW^*$ ) for gluon fusion are  
2229  $3.3 \pm 0.4$  pb at 7 TeV and  $4.2 \pm 0.5$  pb at 8 TeV, consistent with the measured values within their uncer-  
2230 tainties. For vector boson fusion, the predicted cross section is  $0.35 \pm 0.02$  pb, again consistent with the  
2231 measured value.

2232 **6.6 CONCLUSION**

2233 The combined analysis of the gluon fusion and vector boson fusion processes in  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  in  
2234 the 7 and 8 TeV datasets has yielded the first discovery level significance for Higgs production in this decay  
2235 channel. Additionally, precise measurements of the couplings to vector bosons and fermions are given.  
2236 Finally, signal strengths and cross sections for each production mode are measured. Figure 6.8 shows the  
2237  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  measurements in comparison with other Higgs decay channels in ATLAS. The  
2238 measurement of signal strength from this channel remains the most sensitive in both the gluon fusion and  
2239 VBF production modes for the Run 1 dataset.

**ATLAS**

### Individual analysis

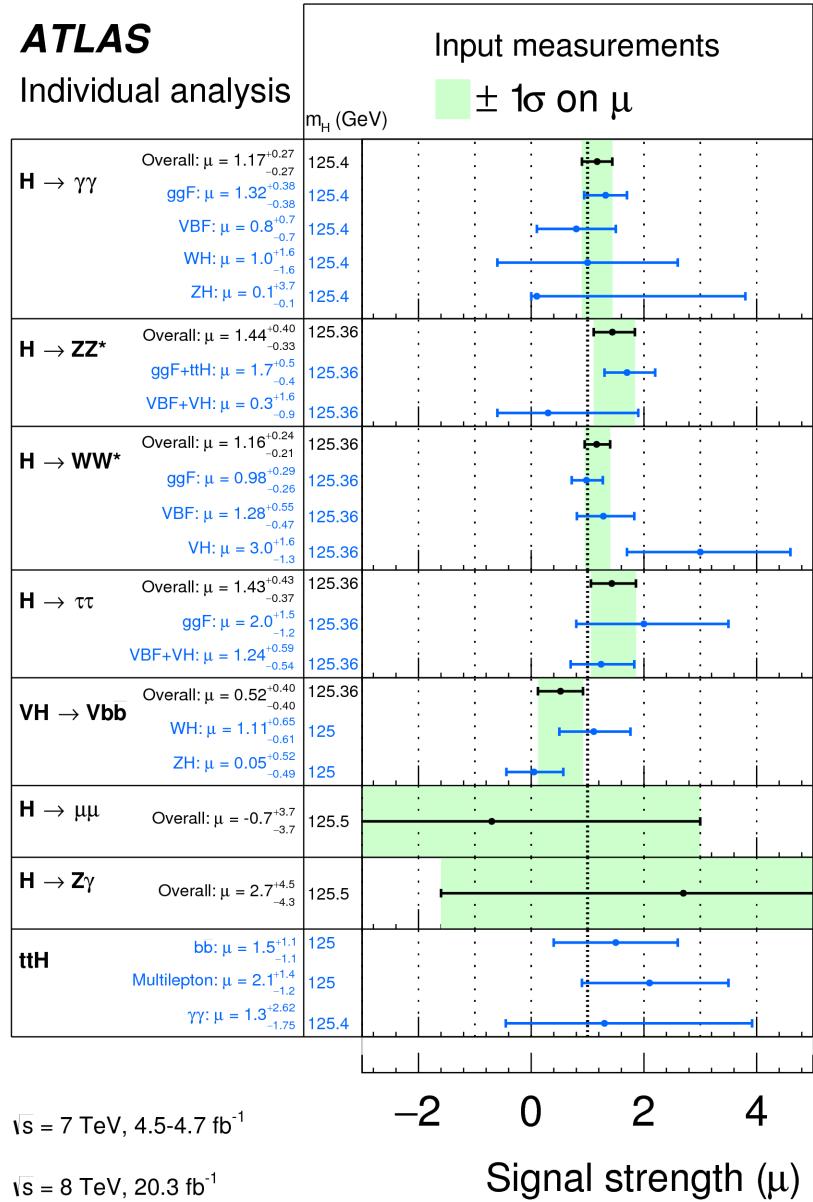


Figure 6.8: Comparison of signal strength measurements in different Higgs decay channels on ATLAS [106].

2240

## Part III

2241

Search for Higgs pair production in the

2242

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

2243

13 TeV

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

W. Eugene Smith

# 7

2244

## 2245 Search for Higgs pair production in boosted 2246 $b\bar{b}b\bar{b}$ final states

### 2247 7.1 INTRODUCTION

2248 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  
2249 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  
2250 final state in the regime where  $m_X$  is large ( $\gtrsim 1 \text{ TeV}$ ) and the Higgs bosons in the decay are significantly  
2251 boosted. A tailored selection for this boosted selection, using novel techniques in jet substructure and  $b$ -  
2252 tagging, is discussed. Then, the data-driven background estimate is presented. Finally, the results of the  
2253 search are shown. The signal models used as benchmarks are a spin-2 Randall Sundrum graviton (RSG)  
2254 and a narrow width spin zero resonance. These models are described in more detail in Chapter 1. Limits  
2255 on signal models are reserved for the next chapter where the results of this chapter are combined with the

2256 results of a separate selection dedicated to the lower  $m_X$  regime.

2257 **7.2 MOTIVATION**

2258 With the center of mass energy increase from  $\sqrt{s} = 8 \text{ TeV}$  to  $\sqrt{s} = 13 \text{ TeV}$ , the LHC and ATLAS are  
2259 able to probe new resonances at higher mass scales than previously accessible in Run 1. This is a powerful  
2260 motivator for searching for a new resonance in the early 13 TeV data. Figure 7.1 shows the ratios of parton  
2261 luminosities between 8 and 13 TeV for different resonance masses. For a resonance of  $M_X = 2 \text{ TeV}$ , the  
2262 cross section at  $\sqrt{s} = 13 \text{ TeV}$  is roughly a factor of 10 larger than at  $\sqrt{s} = 8 \text{ TeV}$ .

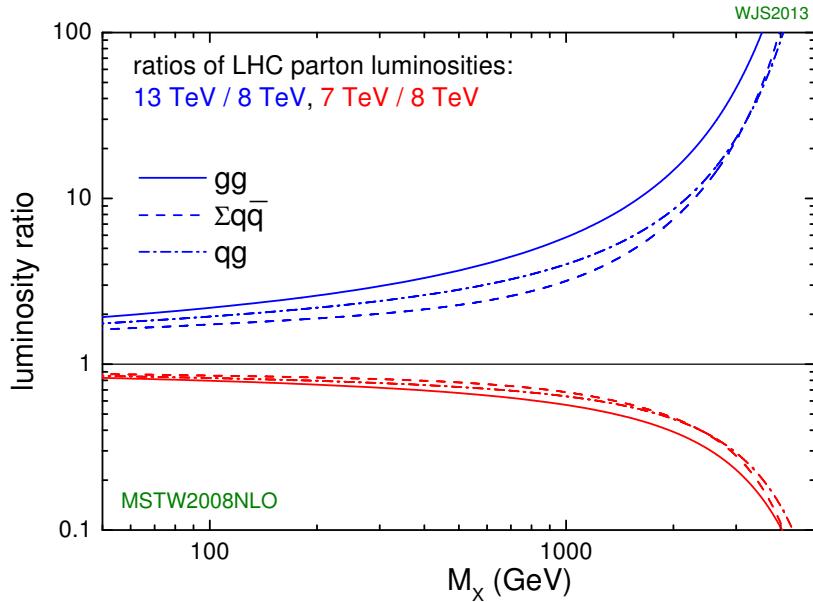


Figure 7.1: Parton luminosity ratios as a function of resonance mass  $M_X$  for 13/8 TeV and 7/8 TeV [107].

2263 Higgs pair production offers a vast array of unprobed regions of phase space where searches for BSM  
2264 physics can be made. Chapter 1 discusses some possibilities for both resonant and non-resonant enhance-  
2265 ment of the di-Higgs production cross section. Given the increased mass reach of the LHC in Run 2, it is  
2266 particularly important to focus on resonant searches at high  $m_X$ . When conducting a search in the  $HH$   
2267 final state, the different possible decay modes of each Higgs must be considered. Figure 7.2 shows the  
2268 branching ratio of the  $HH$  final state for different combinations of decays of each individual Higgs. As

<sup>2269</sup> 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  
<sup>2270</sup> largest at 33%.

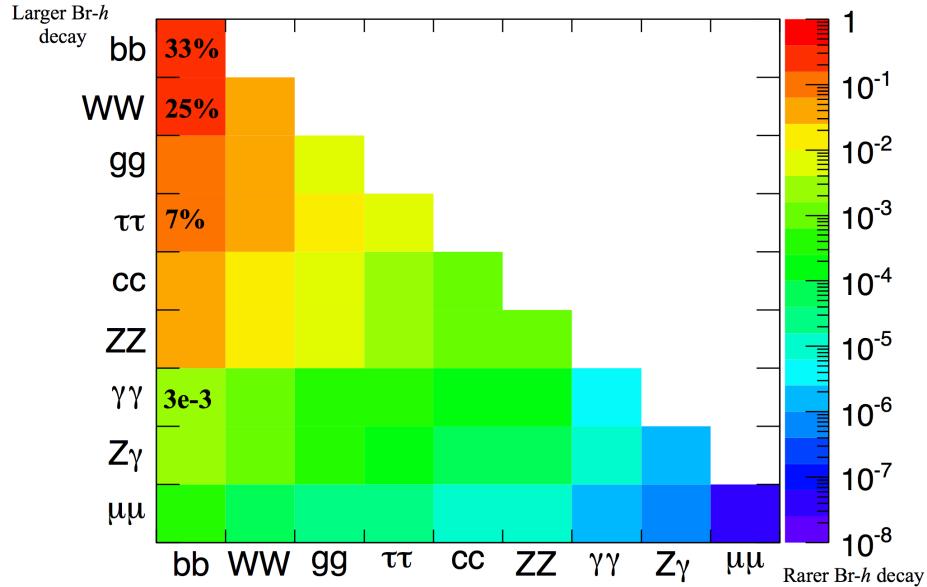


Figure 7.2: Summary of  $HH$  branching ratios [108].

<sup>2271</sup> At high  $m_X$ , the Higgs bosons resulting from the decay of a heavy resonance will have large  $p_T$ <sup>1</sup>. The  
<sup>2272</sup> angular separation between the decay products of the Higgs,  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ , is inversely  
<sup>2273</sup> proportional to the Higgs  $p_T$ , as shown in equation 7.1.

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

<sup>2274</sup> Figure 7.3 shows the minimum  $\Delta R$  between truth level  $B$  decay vertices in simulation samples for Randall-  
<sup>2275</sup> Sundrum gravitons of different masses. The figure shows that as the mass of the graviton increases, the  $\Delta R$   
<sup>2276</sup> distribution between the  $b$  quarks in the Higgs decay tends to shift to lower values. Because of this effect,  
<sup>2277</sup> 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  $m_X/2$ .

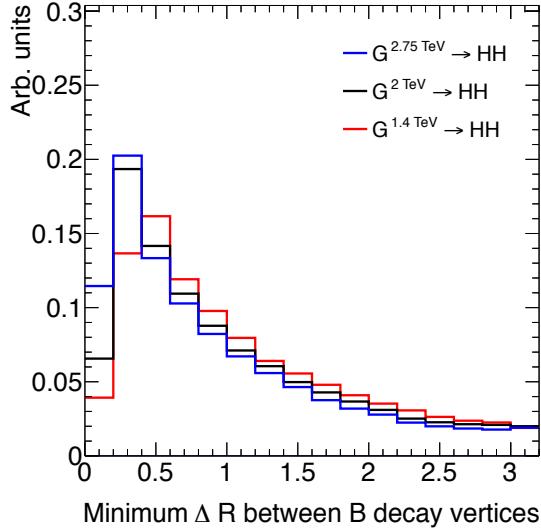


Figure 7.3: Minimum  $\Delta R$  between  $B$  decay vertices for different RSG masses in a  $G_{KK}^* \rightarrow HH \rightarrow 4b$  sample with  $c = 1$ .

2278    7.3 DATA AND SIMULATION SAMPLES

2279    7.3.1 SIGNAL MODELS

2280    While the resonance search is by its nature generic (as it is a simple search for a peak in the  $4b$  invariant mass  
 2281    spectrum), there are two signal models that the selection requirements have been optimized for. The first  
 2282    is Randall-Sundrum (RSG) model, where a tower of massive spin-2 Kaluza-Klein gravitons is predicted.  
 2283    The second is a heavy narrow scalar resonance, the so-called “heavy Higgs”. This type of resonance arises,  
 2284    for example, in the two Higgs doublet model (2HDM). More details about the physics of these models  
 2285    and their motivation is given in chapter 1.

2286    Signal graviton ( $G_{KK}^*$ ) events are generated at leading order (LO) with **MADGRAPH5 v2.2.2** [109]. The  
 2287    PDF set used is the **NNPDF2.3 LO** set [110]. For modeling parton shower and hadronization in jets, **PYTHIA**  
 2288    8.186 is used with the A14 tune [85, 111]. The free parameters in the RSG model are the graviton mass  
 2289    and the coupling constant  $c \equiv k/\bar{M}_{\text{Pl}}^2$ . Both the production cross section and width of the graviton are  
 2290    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  $8\pi$

2291 300 GeV and 3 TeV.

2292 The second signal sample is a heavy spin-0 resonance  $H$  with a fixed width of  $\Gamma_H = 1 \text{ GeV}$ . This  
2293 is generated with **MADGRAPH5** and uses the **CT10** PDF set [88]. The parton shower and hadronization  
2294 are handled by **HERWIG ++** with the **CTEQ6L1** PDF set and the **UEEE5** event tune [89, 112, 113]. Because  
2295 the width and branching ratios depend on 2HDM parameters, each mass point generated with this fixed  
2296 width corresponds to a different point in the 2HDM parameter phase space. Mass points are generated  
2297 between 300 GeV and 1 TeV as with the RSG signal samples.

2298 **7.3.2 BACKGROUND SAMPLES**

2299 While the dominant **QCD** multijet background is estimated with a fully data-driven method, the sub-  
2300 dominant backgrounds  $t\bar{t}$  and  $Z+\text{jets}$  are modeled with some input from simulation.

2301  $t\bar{t}$  events are simulated at next-to-leading order (NLO) with the **POWHEG-BOX** version 1 generator us-  
2302 ing the **CT10** PDF set [114]. The parton shower, hadronization, and underlying event are simulated with  
2303 **PYTHIA 6.428** with the **CTEQ6L1** PDF set [84]. The Perugia 2012 tune is used [115]. NNLO **QCD** correc-  
2304 tions to the cross sections are computed in **Top++ 2.0** [116]. The top quark mass is set to 172.5 GeV. The  
2305 shapes of distributions in  $t\bar{t}$  are taken from MC while the normalization is taken from data.

2306 Finally, the  $Z+\text{jets}$  background is simulated with **PYTHIA 8.186** and the **NNPDF2.3** LO PDF set. This  
2307 background is negligible compared to the others and is taken fully from MC.

2308 **7.3.3 DATA SAMPLE AND TRIGGER**

2309 This analysis is done on  $3.2 \text{ fb}^{-1}$  of data taken in 2015 at  $\sqrt{s} = 13 \text{ TeV}$ . The details of the machine  
2310 conditions during this time can be found in Chapter 2. Only data which was taken during stable beam  
2311 conditions with all detectors functioning is used. Events must pass a trigger which requires a single large  
2312 radius ( $R = 1.0$ ) jet with  $p_T > 360 \text{ GeV}$  to be reconstructed in the HLT. Figure 7.4 shows the trigger  
2313 efficiency for various trigger options as a function of graviton mass. Above  $m_{G_{KK}^*} > 1 \text{ TeV}$ , the single  
2314 large radius jet trigger is 99% efficient for events passing the signal selection.

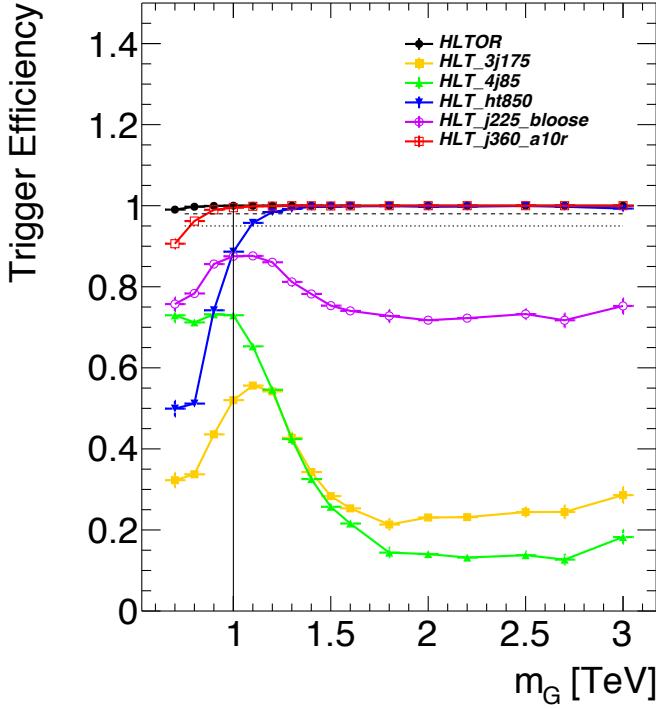


Figure 7.4: Trigger efficiency for events passing all signal region selections as a function of mass in  $G_{KK}^* \rightarrow HH \rightarrow 4b$  samples with  $c = 1$  [117]. In the trigger names, “j” refers to a jet or jets. “ht” refers to  $H_T$ , the scalar sum of transverse momenta in the event. “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.

2315    7.4    EVENT RECONSTRUCTION AND OBJECT SELECTION

2316    The boosted selection first begins by defining a unique set of objects that can be exploited to increase signal  
 2317    efficiency in the kinematic regime where the final state  $b$ -jets are very merged.

2318    7.4.1    LARGE RADIUS ( $R = 1.0$ ) JETS

2319    The first step towards reconstructing the final state is to define objects that can be used to measure the  
 2320    kinematics of the Higgs bosons. In the boosted selection anti- $k_T$  jets with a radius parameter of 1.0 are  
 2321    used. These jets are much larger in angular size than the typical  $R = 0.4$  jets and are intended to encompass  
 2322    all of the products of the Higgs decay<sup>3</sup>. The jets are built from clusters in the calorimeter calibrated with

---

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

local calibration weighting [67].

Because of the large extent of these jets, great care must be taken to remove potential contributions of calorimeter clusters from pile-up. This is done using a technique called jet trimming [118]. With trimming, the constituents of the large radius jet are re-clustered with a smaller radius using the  $k_T$  algorithm. Then, these so-called subjets are removed from the larger jet if  $p_T^{\text{subjett}} / p_T^{\text{jet}} < f_{\text{cut}}$ . In this analysis, the subjet radius is  $R = 0.2$  and  $f_{\text{cut}} = 0.05$ . Trimming has been shown to improve the mass resolution of large radius jets. Figure 7.5 shows the effect of trimming on the large radius jet mass ( $M_J$ ). Because the large radius jet fully contains the Higgs decay products, its invariant mass should correspond to the 125 GeV mass of the Higgs. The trimming algorithm brings the jet mass much closer to the expected Higgs mass and improves the mass resolution.

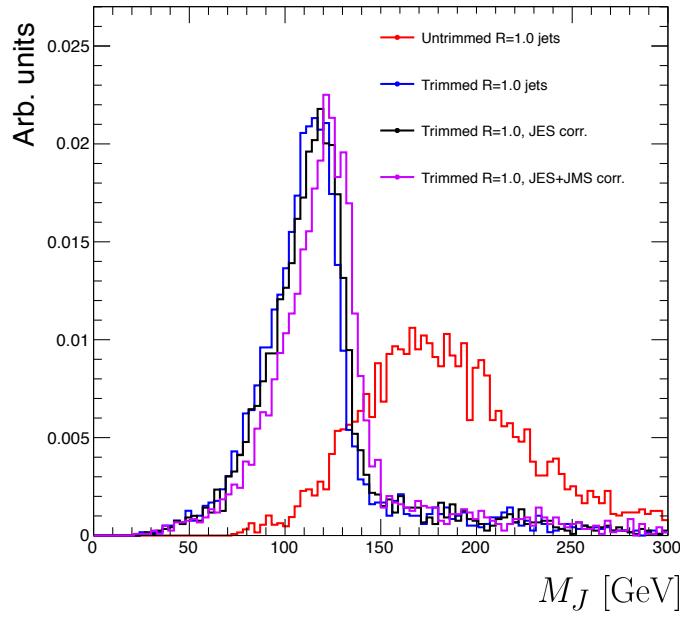


Figure 7.5: Comparison of untrimmed and trimmed jet masses for large radius jets in a RSG sample with  $m_{G_{\text{KK}}^*} = 1 \text{ TeV}$ . JES (JMS) refers to the standard jet energy (mass) scale calibration for ATLAS [67].

The large radius jets are required to satisfy  $250 < p_T < 1500 \text{ GeV}$ . They must also be within  $|\eta| < 2.0$  in order to ensure that the full jet is within the inner detector tracking volume. Finally, they are required to have  $M_J > 50 \text{ GeV}$ . The upper  $p_T$  cut and lower threshold on mass are applied to correspond to the kinematic range where uncertainties are available in ATLAS calibrations [119, 120].

2337 7.4.2 TRACK JETS AND  $b$ -TAGGING

2338 Because the  $b$ -jets from boosted Higgs decays are so close together (as illustrated in figure 7.3), narrow radius  
2339 jets are required to fully resolve both  $b$ -jets. The minimum radius feasible for jets based on calorimeter  
2340 deposits is determined by the calorimeter granularity. However, because  $b$ -tagging relies on information  
2341 from the inner detector, it is possible to define another type of jet that can have a smaller radius and better  
2342  $b$ -tagging resolution. These jets are called “track jets” [120, 121].

2343 Track jets are formed by applying the usual anti- $k_T$  clustering algorithm to tracks that are required to be  
2344 consistent with the primary vertex. After the jet axis has been determined using these tracks, a second step  
2345 of track association is also performed to add tracks that can be useful for  $b$ -tagging [121]. In this analysis,  
2346 the tracks are clustered with a radius parameter of  $R = 0.2$ . This radius has been shown to give good  
2347 performance in boosted Higgs tagging [120, 121]. Figure 7.6 shows a comparison among different track jet  
2348 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

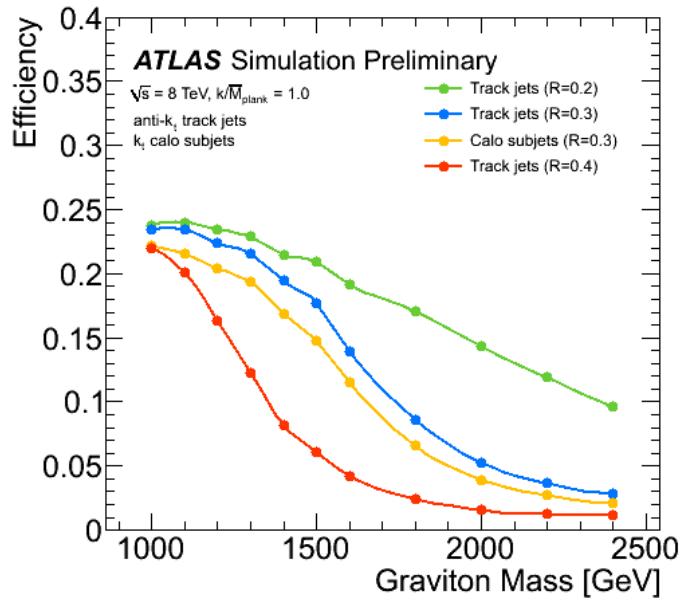


Figure 7.6: Efficiency of finding two  $b$ -jets from each Higgs in an RSG event using calorimeter jets with  $R = 0.3$  and track jet radii of  $R = [0.2, 0.3, 0.4]$  [121].

2349

2350 are required to have  $p_T > 10$  GeV and  $|\eta| < 2.5$ . They must also have at least two tracks.

2351 7.4.3 MUONS

2352 Muons are used in this study to correct the four-momenta of calorimeter jets by accounting for semi-  
2353 leptonic  $b$  decays. The muons used are combined ID and MS muons which must satisfy tight identification  
2354 requirements [63]. The muons must have  $p_T > 4 \text{ GeV}$  and  $|\eta| < 2.5$ . Table 7.1 summarizes the object  
2355 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

2356 7.5 EVENT SELECTION

2357 The first requirement in the boosted event selection is for  $\geq 2$  large radius jets satisfying the selections  
2358 outlined above. The two highest momentum large-R jets in the event are referred to as “Higgs candidates”.  
2359 The leading jet is required to have  $p_T > 350 \text{ GeV}$ .

2360 Track jets satisfying the object selections are matched to Higgs candidate jets via ghost association [122].  
2361 Each Higgs candidate must have at least 2 track jets associated with it. These basic requirements are illus-  
2362 trated graphically in figure 7.7.

2363 The QCD multijet background produces less central jets than high mass resonances, so there is an ad-  
2364 dditional requirement that the two Higgs candidates be close together in  $\eta$ . The large-R jets are required to  
2365 satisfy  $|\Delta\eta(JJ)| < 1.7$ .

2366 7.5.1 MASS REQUIREMENTS

2367 The final set of requirements ensures that the Higgs candidates are consistent with expected properties of  
2368 the 125.0 GeV Higgs. First, a variable ( $X_{hh}$ ) is defined to measure the consistency of both of the Higgs

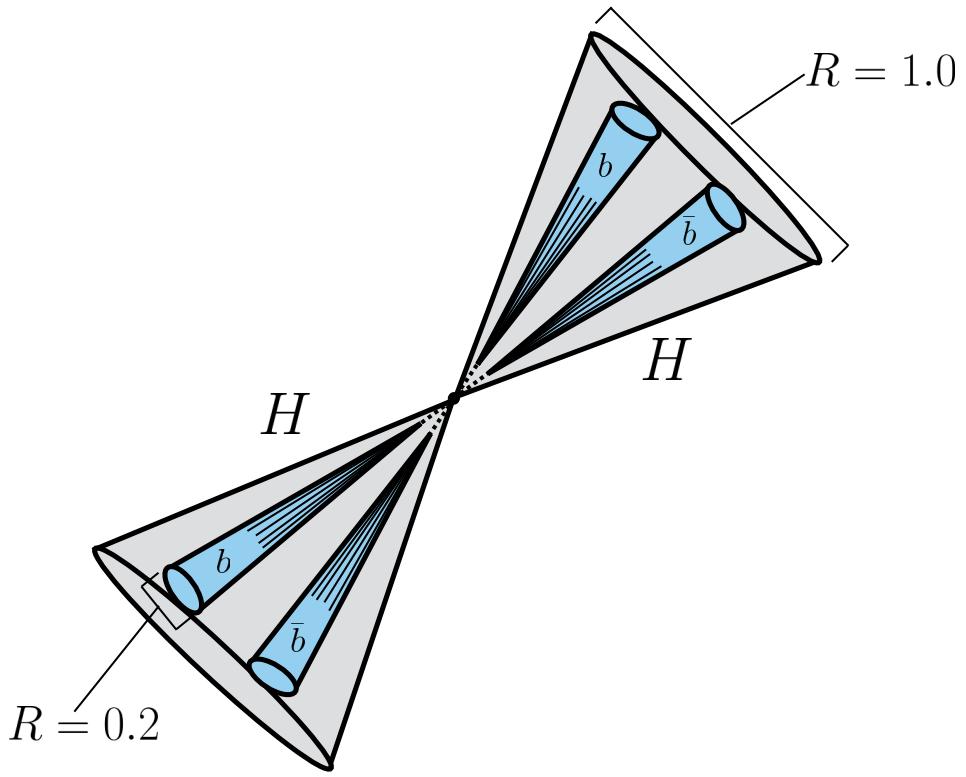


Figure 7.7: Illustration of the boosted selection requirements on Higgs candidates. Each large-radius calorimeter jet (Higgs candidate) must contain two track jets.

<sup>2369</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>2370</sup> The mass values in the  $X_{hh}$  formula are optimized to maximize signal efficiency. The sub-leading jet typ-  
<sup>2371</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>2372</sup> measurement of the consistency of the two Higgs candidate masses with the signal hypothesis. The de-  
<sup>2373</sup> nominators of each term ( $0.1 M$ ) give the uncertainty on the mass measurement for the large radius jets.  
<sup>2374</sup> Events are required to satisfy  $X_{hh} < 1.6$ .

<sup>2375</sup> Before making the requirement on  $X_{hh}$ , the masses of the Higgs candidates are corrected for semi-  
<sup>2376</sup> leptonic  $b$  decays using muons with the criteria outlined in the previous section. Any muons within a  
<sup>2377</sup>  $\Delta R < 0.2$  of a  $b$ -tagged track jet (as described in the next section) have their four-momenta added to the

2378 four-momentum of the Higgs candidate. This correction does not affect the pre-selection requirements  
 2379 but does affect the  $X_{hh}$  requirement and the final invariant mass discriminant.

2380 **7.5.2 b-TAGGING REQUIREMENTS**

2381 The last requirement applied is on the number of  $b$ -tagged track jets. There are two signal regions defined.  
 2382 The first requires exactly four  $b$ -tagged track jets, two in each Higgs candidate (known as the  $4b$  signal re-  
 2383 gion). At high resonance masses, this requirement is inefficient, so an additional signal region requiring  
 2384 only three  $b$ -tagged track jets is also defined (known as the  $3b$  signal region). While this has a larger back-  
 2385 ground it is also more efficient for high resonance masses. For both signal regions, the MV2c2o algorithm,  
 2386 where the training sample for the algorithm has 20% charm events is used. More details for this algorithm  
 2387 can be found in Chapter 2.

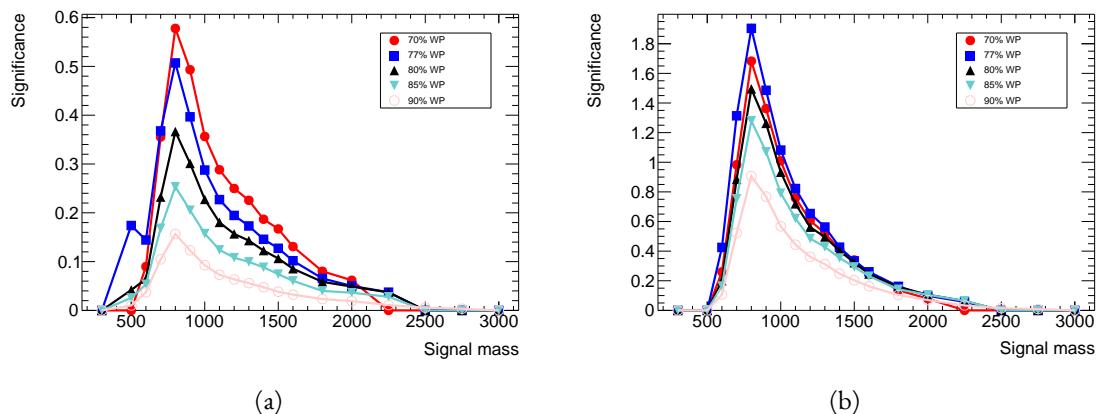


Figure 7.8: Estimated significance as a function of signal mass for RSG  $c = 1$  models in the  $3b$  (a) and  $4b$  (b)  
 regions for different  $b$ -tagging efficiency working points

2388 Once the algorithm is selected, an efficiency working point must also be chosen. This working point  
 2389 defines the efficiency with which true  $b$ -jets are tagged and also fixes the overall background rejection of the  
 2390 algorithm. Higher efficiency working points accept more true  $b$ -jets but also allow for more background.  
 2391 Five different working points (70%, 77%, 80%, 85%, 90%) are tested. With each working point, the  
 2392 full data driven background estimation method is run to quantify the amount of background that will be  
 2393 present in the final signal region. The significance is quantified using the median discovery significance for

2394 signal and background with Poisson errors, given in equation 7.3 [123].

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

2395 Here,  $s$  is the expected number of signal events and  $b$  is the expected number of background events. This  
 2396 formula is derived using Poisson statistics with errors on both the signal and background. It is used because  
 2397 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  
 2398 than  $b$ , this equation reduces to the more well known  $s/\sqrt{b}$ . Figure 7.8 shows the estimated significance as  
 2399 a function of signal mass in RSG  $c = 1$  models for the  $3b$  and  $4b$  signal regions. The 77% working point  
 2400 gives the best performance over a wide range of masses in the  $4b$  signal region. As this is the region which  
 2401 contributes the most to the total discovery significance, the 77% efficiency working point is chosen for the  
 2402 analysis.

### 2403 7.5.3 SELECTION EFFICIENCY

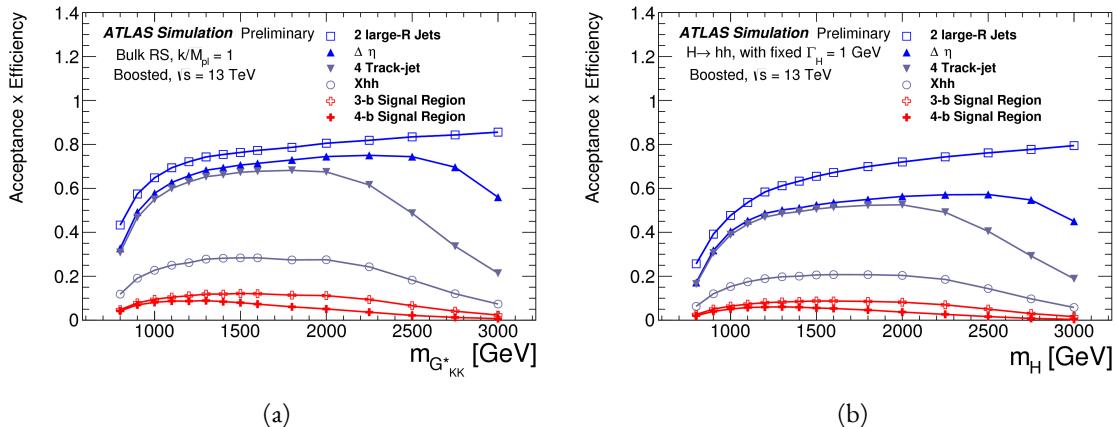


Figure 7.9: Acceptance  $\times$  efficiency as a function of mass for (a) RSG and (b) narrow heavy scalar signal models [124].

2404 Figure 7.9 shows the product of acceptance and efficiency as a function of mass for both the RSG and  
 2405 narrow heavy scalar resonance signal models. After  $m_X > 1$  TeV, the efficiency of the  $4b$  requirement  
 2406 begins to decline. After  $m_X > 2$  TeV, the efficiency of requiring two track jets in each Higgs candidate  
 2407 begins to decline as well. Both of these behaviors illustrate the difficulty of resolving the merged decay

2408 products at high mass. Figure 7.10 shows a more detailed comparison of the signal efficiency in the  $3b$  vs  
 2409  $4b$  signal regions for the RSG model. The efficiencies shown here are relative to all prior selection require-  
 2410 ments. It can be seen there that at high masses the  $3b$  signal region is more efficient for signal.

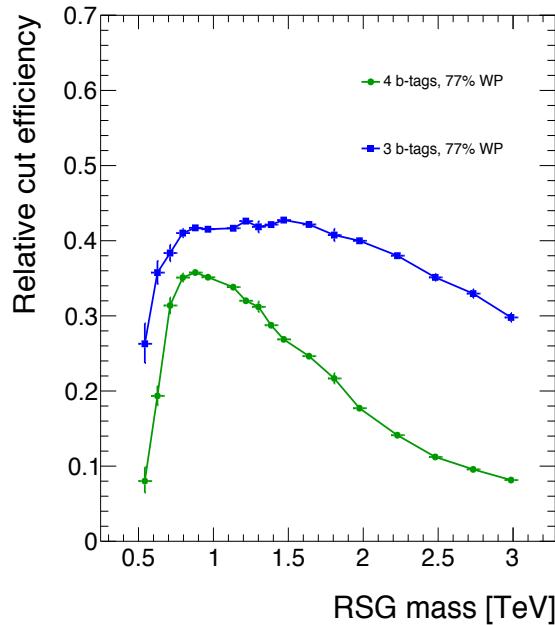


Figure 7.10: Efficiency of requiring 3 or 4  $b$ -tagged track jets vs. RSG mass. The efficiency quoted is relative to the previous selection requirements (rather than an absolute efficiency).

2411 To investigate the degradation of  $b$ -tagging efficiency at high  $p_T$ , the individual jet tagging efficiencies can  
 2412 be compared as a function of signal mass. This is shown in figure 7.11. The figure shows that the leading jet  
 2413 tagging efficiency in both calorimeter jets degrades heavily, while the sub-lead jet tagging efficiency remains  
 2414 relatively constant. More details on the cause of this degradation are shown in appendix A.

2415 The final discriminating variable used in the boosted analysis is  $M_{2J}$ , the invariant mass of the two  
 2416 Higgs candidates. In order to improve the mass resolution, the four-momenta of each Higgs candidate  
 2417 are scaled by  $m_h/M_J$ . The effect of this correction is small in the boosted analysis but is done for consis-  
 2418 tency with the resolved selection. Table 7.2 shows the effect of the selection requirements on signal and  
 2419 background simulations as well as data.

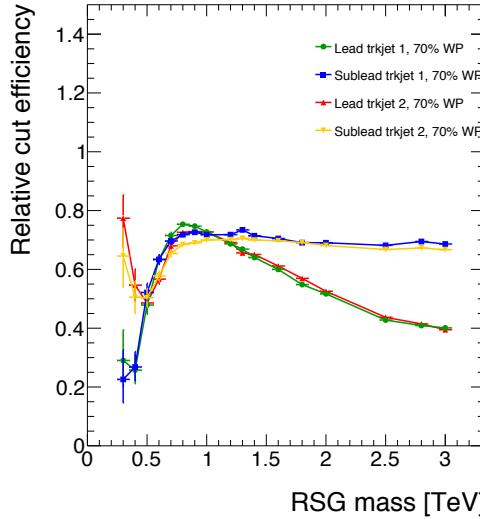


Figure 7.11: MV2c20  $b$ -tagging efficiency for each of the four track jets in the boosted  $4b$  selection as a function of RSG mass for  $c = 1$  models.

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 [125].

## 2420 7.6 DATA-DRIVEN BACKGROUND ESTIMATION

2421 The largest background to the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  final state is QCD multijet production, constitut-  
 2422 ing 80-90% of the total background. Because of the difficulties in modeling higher order QCD processes,  
 2423 this background is estimated with a fully data-driven method. The only other non-negligible background  
 2424 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

2425 background will be estimated, the normalization of the QCD and  $t\bar{t}$  backgrounds are simultaneously es-  
2426 timated.

2427 7.6.1 MASS REGION DEFINITIONS

2428 The first step in the data-driven background estimate is to define a sideband mass region where the back-  
2429 ground normalization can be derived. Additionally, a control region is defined where the background  
2430 estimate can be validated. The control (CR) and sideband (SB) regions are defined using a radial distance  
2431 in the two-dimensional large-R jet mass plane,  $R_{hh}$ , which is defined in equation 7.4.

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

2432 Events in the control region are required to fail the signal region  $X_{hh} < 1.6$  requirement and have  
2433  $R_{hh} < 35.8 \text{ GeV}$ . 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-

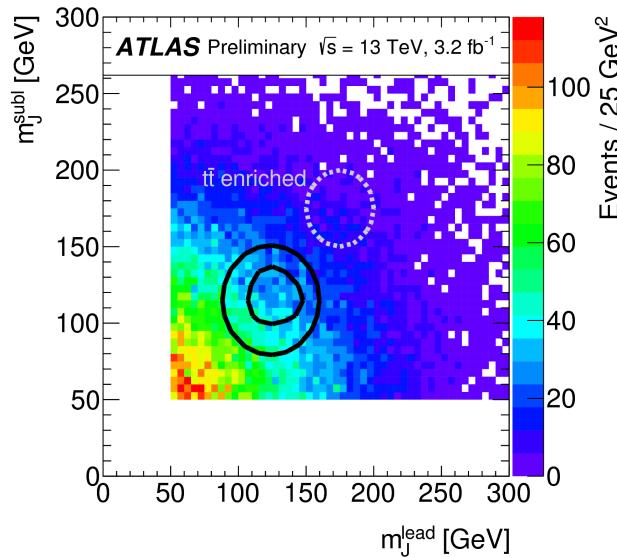


Figure 7.12:  $M_J^{\text{sublead}}$  vs.  $M_J^{\text{lead}}$  in a 2  $b$ -tag data sample. The signal region is defined by the inner black contour ( $X_{hh} < 1.6$ ) and the sideband region is defined by the outer contour ( $R_{hh} > 35.8 \text{ GeV}$ ). The region between the black contours is the control region. The mass region which is enriched in  $t\bar{t}$  background is also shown for illustration [[124](#)].

2434 marizes the mass region selections for the three different regions used in the analysis.  
2435

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.

2436 **7.6.2 BACKGROUND ESTIMATION**

2437 The method for estimating the background in this analysis is similar to the ABCD method presented in  
 2438 Chapter 5. In this case, the two handles used to define different regions for the estimate are the number  
 2439 of  $b$ -tagged track jets and the mass requirements. A region requiring exactly two  $b$ -tagged track jets in one  
 2440 large-R jet (referred to as the 2-tag or  $2b$  region) is defined for use in the background estimate. The number  
 2441 of expected background events in the  $3b$  and  $4b$  signal regions is then given by equation 7.5.

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

2442 In this equation,  $N_{\text{bkg}}^{3(4)-\text{tag}}$  is the expected number of background events in the  $3b$  or  $4b$  signal regions.  
 2443  $N_{\text{Multijet}}^{2-\text{tag}}$  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-  
 2444 dicted in the MC for the  $3b$  or  $4b$  signal region, and the variable is similarly defined for the  $Z+\text{jets}$  back-  
 2445 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  
 2446 region.  $\mu_{\text{Multijet}}$  is an extrapolation factor that is derived in the sideband region and used to estimate the  
 2447 ratio of 2-tag events to 3(4)-tag events in the signal region. It is defined in equation 7.6.

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

2448 The  $t\bar{t}$  scale factor ( $\beta_{t\bar{t}}$ ) and the QCD multijet extrapolation factor ( $\mu_{\text{Multijet}}$ ) are estimated together in  
 2449 a simultaneous fit in the sideband region. Then, the number of events in the 2-tag signal region is used,  
 2450 along with the  $t\bar{t}$  estimate in the  $3b$  and  $4b$  signal regions and  $\mu_{\text{Multijet}}$ , to estimate the total number  
 2451 of background events in the two final signal regions. The shape of the final discriminant  $M_{2J}$  is also

2452 taken from the 2-tag signal region where there are more events. This method is illustrated graphically in  
2453 figure 7.13. In the 3b region, the fit yields values of  $\mu_{\text{Multijet}} = 0.160 \pm 0.03$  and  $\beta_{t\bar{t}} = 1.02 \pm 0.09$ .

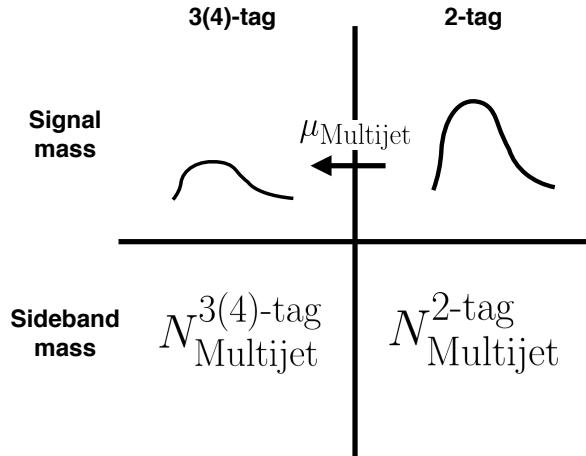


Figure 7.13: An illustration of the data-driven background estimation technique for the boosted analysis

2453

2454 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  
2455 quoted are statistical only. The larger uncertainties in the 4b values indicate the lower statistics available in  
2456 that region.

2457 Figure 7.14 shows the distributions of data and background estimates in the 3b and 4b sideband regions  
2458 after the background fit has been done. The normalizations are constrained from the fit to match that of  
2459 the data, but good modeling of the shape of the mass of the leading large-R jet is seen as well. The shapes  
2460 of the kinematic distributions for the  $t\bar{t}$  background in the 4b region are taken from the 3b region due to  
2461 the better MC statistics in that region.

### 2462 7.6.3 BACKGROUND SHAPE FIT

2463 As mentioned in the previous section, the background shape in the 3-tag and 4-tag signal regions is taken  
2464 from the 2-tag signal mass region. Due to the limited statistics available, the background shapes are addi-  
2465 tionally smoothed after being extrapolated to the 3-tag and 4-tag signal regions. Only the data in the range  
2466  $900 < M_{2J} < 2000$  GeV is included in the shape fit due to the limited statistics available above 2 TeV.  
2467 Both the  $t\bar{t}$  and QCD multijet background are independently fit with an exponential shape,  $y = e^{ax+b}$ .

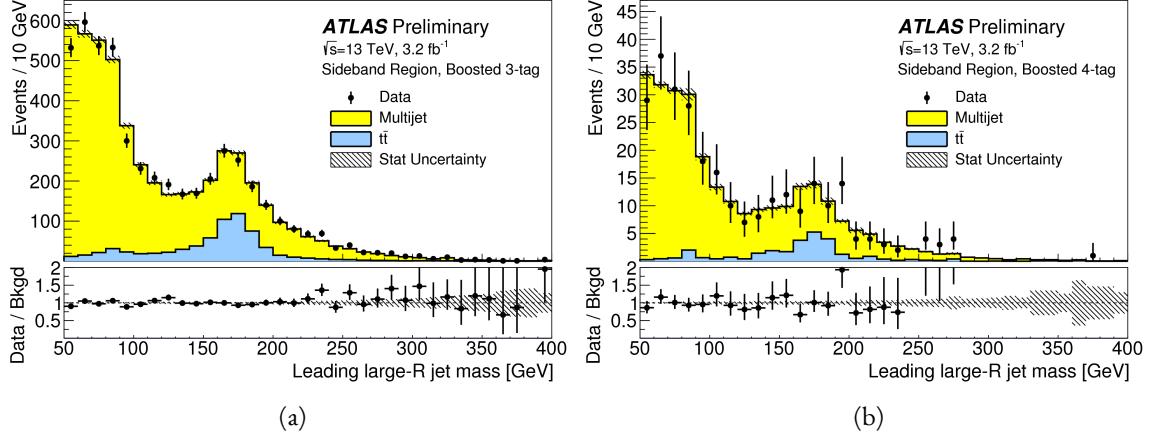


Figure 7.14: Leading large-R jet mass in the 3b (a) and 4b (b) sideband regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above. Because their normalizations are derived in the sideband region, the total background normalization is constrained by default to match the normalization of the data [124].

2468 Other shapes are considered and used for the systematic uncertainties. Table 7.4 shows the fit values for  
 2469 the parameters. Because both the 3b and 4b QCD shapes come from the 2-tag region, the slopes derived  
 2470 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 [125].

#### 2471 7.6.4 VALIDATION OF BACKGROUND ESTIMATE

2472 The background estimate can be validated by using the method to estimate the number of events in the  
 2473 control mass region rather than the signal mass region. Figure 7.15 shows the  $M_{2J}$  distribution in the 3b  
 2474 and 4b control regions, comparing data and background estimates. In both cases, both the background  
 2475 shape and normalization are consistent with the data, indicating good agreement. The ratio of data to the  
 2476 background estimates is also fit to a line in the figure to test for any shape difference. The slope of the  
 2477 line is within  $1\sigma$  (from the fit uncertainties) of flat, further indicating that the data is consistent with the  
 2478 background estimate in the control region.

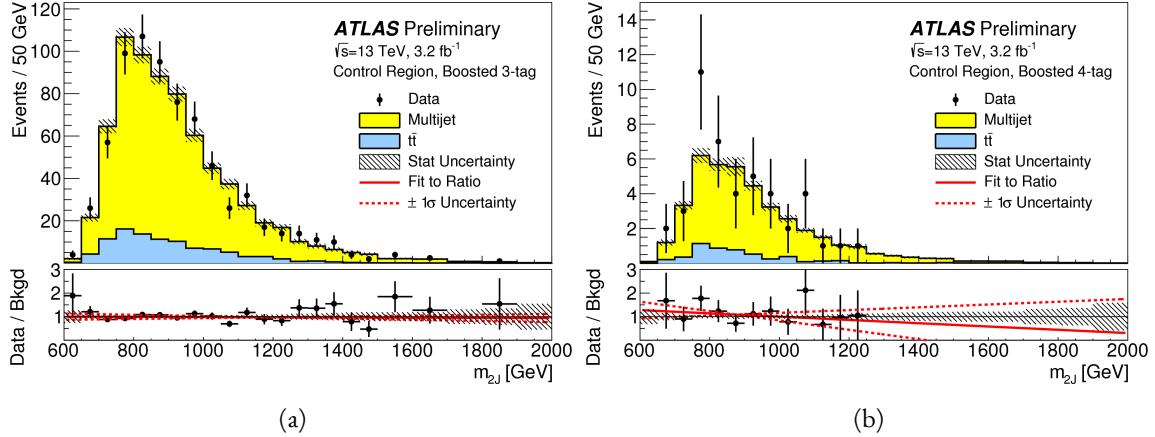


Figure 7.15: Di-jet invariant mass ( $M_{2J}$ ) in the 3b (a) and 4b (b) control regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above [124].

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 [124]. The uncertainties shown are statistical only.

2482 7.7 SYSTEMATIC UNCERTAINTIES

2483 The systematic uncertainties in this analysis can be divided into two broad categories. The first type is  
2484 uncertainties associated with the modeling of the signal processes. The second type of uncertainty is asso-  
2485 ciated with both the shape and normalization of the background prediction.

2486 7.7.1 SIGNAL MODELING UNCERTAINTIES

2487 The signal modeling uncertainty has three main components: theoretical uncertainty on the acceptance,  
2488 experimental uncertainties on the large-R jets, and experimental uncertainties on the track jets related to  
2489  $b$ -tagging. In this analysis the experimental uncertainties are the most significant.

2490 The first uncertainty on signal modeling is the theoretical uncertainty on the acceptance. As explained  
2491 in section 5.6.1, there are four components to this uncertainty. The first is related to missing higher order  
2492 terms from the matrix element calculations which is estimated by varying the QCD renormalization and  
2493 factorization scales. The second is uncertainty due to the PDF set used. The third is a generator uncer-  
2494 tainty which is estimated by modifying the generator used to model the underlying event and hadroniza-  
2495 tion. Finally, there is an uncertainty associated with the modeling of the initial state and final state radia-  
2496 tion (ISR/FSR). The total theoretical uncertainty on the signal yield is 3%, and this is dominated by the  
2497 ISR/FSR modeling.

2498 There are uncertainties on the large-R jets in both the jet energy scale (JES) and jet energy resolution  
2499 (JER) as well as the jet mass scale (JMS) and jet mass resolution (JMR). These are evaluated using  $\sqrt{s} =$   
2500 8 TeV data from Run 1 of ATLAS and extrapolated to the Run 2 beam and detector conditions using  
2501 MC<sup>5</sup>. The details of these uncertainties can be found in reference [126].

2502 Uncertainties on the track jets are related to the  $b$ -tagging efficiency. The total uncertainty on the signal  
2503 yield due to  $b$ -tagging is evaluated by propagating variations of the  $b$ -tagging efficiency through the boosted  
2504 selection requirements. The uncertainties are calculated jet-by-jet and parameterized as a function of  $b$ -jet  
2505  $p_T$  and  $\eta$  [104]. For high  $p_T$   $b$ -jets (with  $p_T > 300$  GeV), the uncertainties are extrapolated using MC  
2506 simulation from the lower  $p_T$   $b$ -jets [127].

---

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

2507 Table 7.6 shows the systematic uncertainties on the signal normalization for models with  $m_{G_{\text{KK}}^*} =$   
 2508 1.5 TeV and both  $c = 1$  and  $c = 2$  as well as a narrow width heavy scalar. The dominant uncertainty  
 2509 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  $m_{G_{\text{KK}}^*} = 1.5$  TeV and both  $c = 1$  and  $c = 2$  as well as a narrow width heavy scalar.

2510 **7.7.2 BACKGROUND UNCERTAINTIES**

2511 Uncertainties on the QCD multijet background normalization and shape are estimated using the con-  
 2512 trol mass region. As shown previously, the background predictions in the control region match with the

2513 data yields within the statistical uncertainty in both the 3-tag and 4-tag control regions. As an additional  
 2514 protection, the statistical uncertainty on the background prediction in the control region is assigned as a  
 2515 systematic uncertainty on the normalization of the QCD background.

2516 Additional robustness tests are done by varying the definition of the control mass region and the  $b$ -  
 2517 tagging requirements used to define the 2-tag sample. In all cases, the effect of the variations is found to be  
 2518 within the statistical uncertainties on the background normalization in the control region.

2519 Shape uncertainties on the background are evaluated using two techniques. First, as shown in fig-  
 2520 ure 7.15, the ratio between the data and background prediction is fit with a linear function. The uncer-  
 2521 tainties on the slope of this fit are assigned as shape uncertainties. An additional uncertainty is assigned by  
 2522 using alternate power law fit functions for the smoothing of the background shape. Table 7.7 shows the  
 2523 alternate shapes used. The largest difference between the nominal fit function and the alternates, taking  
 2524 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,  $x = M_{2J}/\sqrt{s}$ .

2525 The uncertainties on the  $t\bar{t}$  background are obtained by propagating the various experimental variations  
 2526 (JES, JER, JMS, JMR,  $b$ -tagging) through the analysis selection requirements. Table 7.6 summarizes the  
 2527 background uncertainties in the 3-tag and 4-tag regions.

2528    7.8 RESULTS

2529    Table 7.8 shows the observed yields in the 3-tag and 4-tag signal regions for the boosted analysis compared  
 2530    to the predicted number of background events. In the 3-tag region, 316 events are observed with a pre-  
 2531    dicted background of  $285 \pm 19$ . In the 4-tag region, 20 events are observed with a predicted background  
 2532    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  
 2533    small excesses in the data, in particular in the 3-tag region around  $M_{2J} \approx 900$  GeV and in the region of  
 2534     $1.6 < M_{2J} < 2.0$  TeV. The significance of these excesses will be evaluated in the next chapter in the  
 2535    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 [124].

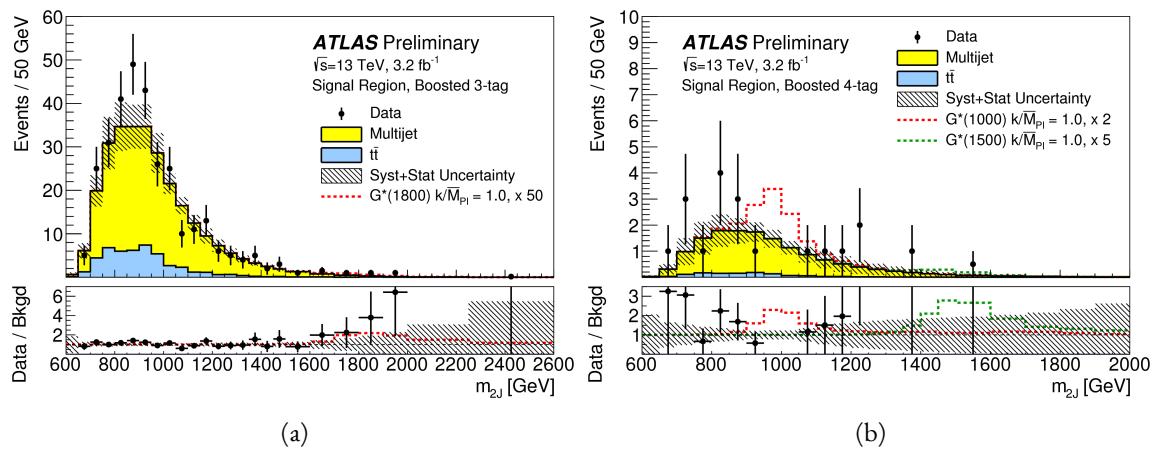


Figure 7.16: Di-jet invariant mass ( $M_{2J}$ ) in the  $3b$  (a) and  $4b$  (b) signal regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above. In the  $3b$  region, a graviton signal with  $m_{G_{KK}^*} = 1.8$  TeV and  $c = 1$  is overlaid, with 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 [124].

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

Frank Herbert

# 8

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2537

## Combined limits from boosted and resolved searches

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### 8.1 INTRODUCTION

2540 In order to cover the full mass range of possible resonances decaying to di-Higgs final states, two distinct  
2541 tailored selections were produced. The resolved selection is more sensitive in the mass range of  $400 < m_X <$   
2542  $1100 \text{ GeV}$  while the boosted selection is more sensitive to masses in the range  $1100 < m_X <$   
2543  $3000 \text{ GeV}$ . Chapter 7 presents the details of the boosted selection and results. In setting limits on spin-2  
2544 Randall-Sundrum graviton (RSG) and narrow width heavy scalar ( $H$ ) models, the results of the boosted  
2545 selection are combined with the results of the resolved selection to cover the full mass range.

2546 This chapter presents limits on signal models resulting from the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  search in both  
2547 the resolved and boosted selections. It first presents a brief overview of the resolved results that go into

2548 the limit setting. Then, an overview of the statistical methods used for the search and limit setting is given.  
 2549 Finally, limits on the RSG and heavy scalar models are presented.

2550 **8.2 RESOLVED RESULTS**

2551 The details of the resolved selection will not be presented here and can be found in reference [124]. In  
 2552 basic terms, the selection searches for four  $R = 0.4$  b-tagged calorimeter jets (where each pair of jets is  
 2553 one Higgs candidate). This is distinct from the boosted methodology which searches for merged decay  
 2554 products. The backgrounds to the resolved selection are the same as those presented in Chapter 7 for the  
 2555 boosted analysis.

2556 Table 8.1 shows the results for data yields and expected background in the resolved signal region. Fig-  
 2557 ure 8.1 shows the  $M_{2J}$  distribution in the resolved signal region. The total number of events is consistent  
 2558 with the prediction and no significant excess is seen. One event in the boosted 4-tag signal is shared with  
 2559 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 [124].

2560 **8.3 SEARCH TECHNIQUE AND RESULTS**

2561 The statistical technique used for the search in this analysis is the same as that used in the  $H \rightarrow WW^*$   
 2562 analysis presented in section 3.6.2. The test statistic  $q_0$  is used to define the  $p$ -values which measure the

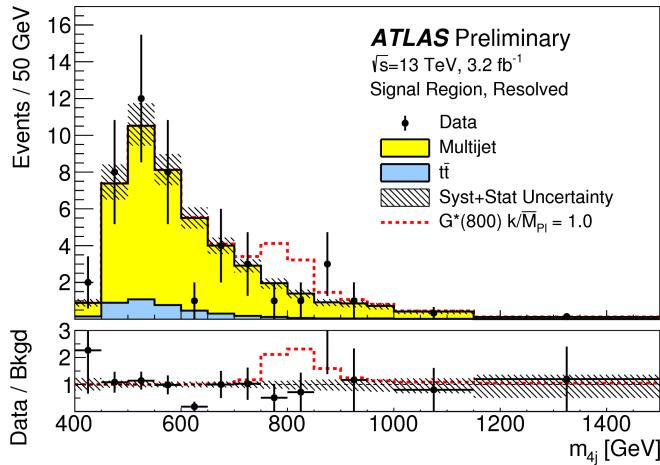


Figure 8.1: Di-jet invariant mass ( $M_{2J}$ ) in the resolved signal region. A graviton signal with  $m_{G_{KK}^*} = 800$  GeV and  $c = 1$  is overlaid. [124].

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 [128]. 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

2578 in equation 8.1.

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

2579 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  
2580 value of the nuisance parameters,  $\hat{\theta}$  is the best fit value of the nuisance parameters under the fixed  $\mu$  value,  
2581 and  $L$  is the Poisson likelihood of the data (as described in section 3.6.2).

2582 The test statistic  $\tilde{q}_\mu$  is constructed to protect against two interesting corner cases when setting the upper  
2583 limit on the cross section. First, it protects against negative signal strengths  $\mu$  which are unphysical. Second,  
2584 it does not count excesses in the data larger than those expected by a signal strength  $\mu$  as evidence against  
2585 the  $\mu$  hypothesis.

2586 The  $CL_s$  statistic is constructed by taking a ratio of two probabilities.  $CL_{s+b}$  is the probability that the  
2587 signal+background hypothesis would produce a value of the test statistic that is less than or equal to the  
2588 observed value<sup>1</sup>.  $CL_b$  is the probability that the background only hypothesis will produce a value  
2589 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%  
2590 upper limit on the cross section is set at the value of  $\mu$  that makes the  $CL_s$  statistic less than 5%. In practice,  
2591 the limits are computed numerically within an asymptotic approximation for the distribution of the test  
2592 statistic  $\tilde{q}_\mu$ . The details of this approximation can be found in reference [74].

2593 The resolved and boosted analyses are combined using a very simple procedure rather than a full statis-  
2594 tical combination. For each mass point tested, the limit which gives the most stringent constraint is used.  
2595 This means that for mass points below 1.1 TeV the resolved signal region is used, while at and above this  
2596 point the combination of the orthogonal 3b and 4b boosted signal regions is used.

#### 2597 8.4.2 LIMIT SETTING RESULTS

2598 Figure 8.2 shows the combined 95% upper bounds as a function of mass for three different models:  $G_{KK}^*$   
2599 with  $c = 1$ ,  $G_{KK}^*$  with  $c = 2$ , and a narrow heavy scalar  $H$ .

---

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

2600      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  
2601    for masses in the range  $600 < m_{G_{\text{KK}}^*} < 3000$  GeV. For the RSG model with  $c = 2$ , cross sections limits  
2602    between 40 fb and 200 fb are set for the mass range of  $500 < m_{G_{\text{KK}}^*} < 3000$  GeV. Masses in the range  
2603    of  $475 < m_{G_{\text{KK}}^*} < 785$  GeV are excluded with  $c = 1$  (with an exclusion of the range 465 to 745 GeV  
2604    expected). Masses less than 980 GeV are excluded with  $c = 2$  (with an exclusion for masses less than  
2605    1 TeV expected).

2606      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  
2607    30 to 300 fb in the mass range of  $500 < m_H < 3000$  GeV. The resolved analysis can also set an upper  
2608    limit on the Standard Model di-Higgs production cross section discussed in chapter 3. The upper limit on  
2609     $\sigma(pp \rightarrow hh \rightarrow b\bar{b}b\bar{b})$  in the Standard Model is constrained to be less than 1.22 pb.

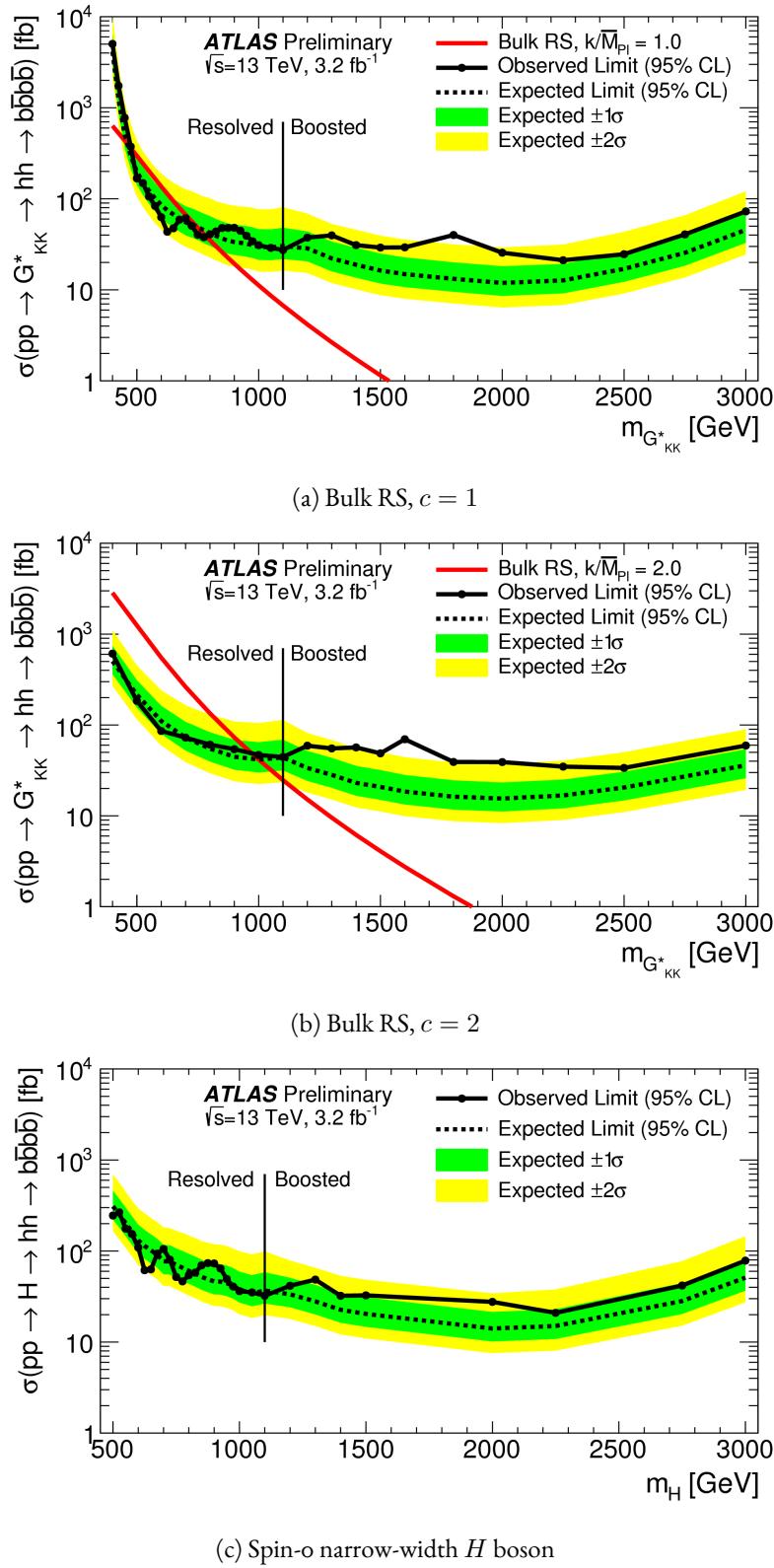


Figure 8.2: Expected and observed upper limit as a function of mass for  $G^*_{KK}$  in the RSG model with (a)  $c = 1$  and (b)  $c = 2$ , as well as (c)  $H$  with fixed  $\Gamma_H = 1$  GeV, at the 95% confidence level in the  $CL_s$  method [124].

2610

## Part IV

2611

## Looking ahead

# 9

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## Conclusion

2614 After being sought for many years at different collider experiments, the Higgs boson was discovered by  
2615 the ATLAS and CMS experiments in 2012, confirming the leading theory for the source of electroweak  
2616 symmetry breaking and filling in the last missing piece of the Standard Model. After its discovery, mea-  
2617 surements of the particle's detailed properties and searches for new particles decaying to Higgs final states  
2618 were both extremely important in constraining physics beyond the Standard Model. This dissertation  
2619 presented this evolution through two results: the observation and measurement of the Higgs boson in the  
2620  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel at  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV and a search for Higgs pair production  
2621 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  
2622 Hadron Collider.

2623 In the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ , results from both the discovery of the Higgs boson and the full ATLAS  
2624 Run 1 dataset were presented. The Higgs boson was discovered with a  $5.9\sigma$  significance in a combination  
2625 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

2626  $\sqrt{s} = 8$  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-  
2627covery level significance in the  $H \rightarrow WW^*$  channel alone and obtained the first evidence of vector boson  
2628 fusion production in that channel. The combined signal strength was measured to be  $\mu = 1.09^{+0.23}_{-0.21}$ . The  
2629 total observed significance of the  $H \rightarrow WW^*$  process was observed to be  $6.1\sigma$  (with  $5.8\sigma$  expected). Ad-  
2630vanced methods for background reduction and estimation, particularly in same-flavor lepton final states,  
2631 were shown. The VBF signal strength was measured to be  $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$  with an observed signifi-  
2632cance of  $3.2\sigma$  (with  $2.7\sigma$  expected).

2633 These results required many novel innovations. The increase of pileup interactions in the higher in-  
2634stantaneous luminosity LHC conditions of 2012 led to a degradation of missing transverse momentum  
2635resolution. As a result, the prominent  $Z/\gamma^* + \text{jets}$  background of the same flavor  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$   
2636final states increased greatly. New variables, including a track-based missing transverse momentum and a  
2637measurement of the balance between the dilepton system and recoiling jets, allowed for significant reduc-  
2638tion of this background. In the VBF channel, selections were optimized to exploit the unique VBF final  
2639state topology. Incorporating these variables into a boosted decision tree technique allowed the analysis  
2640to exceed the  $3\sigma$  statistical significance threshold.

2641 After the end of Run 1, the results of Higgs measurements from ATLAS were combined with those  
2642from CMS to produce the most precise measurements of the Higgs boson so far [129]. Figure 9.1 shows the  
2643combination of ATLAS and CMS data for the Higgs signal strength in and coupling measurements. In the  
2644signal strength measurements of gluon fusion and vector boson fusion, the  $H \rightarrow WW^*$  channel provides  
2645the tightest constraints. Additionally, the Higgs coupling to  $W$  bosons is the most precisely measured with  
2646a relative uncertainty of 10%.

2647 With the discovery of the Higgs firmly established and its properties measured, a natural next step was  
2648to search for new physics with Higgs final states. At  $\sqrt{s} = 13$  TeV, a search for Higgs pair production  
2649in 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  
2650arising from high mass resonances was constructed. This signal region utilized large-radius calorimeter jets  
2651and  $b$ -tagging with small radius track jets to maximize the signal acceptance. No significant excesses were  
2652observed, and upper limits on cross sections are placed for spin-2 Randall Sundrum gravitons (RSG) and

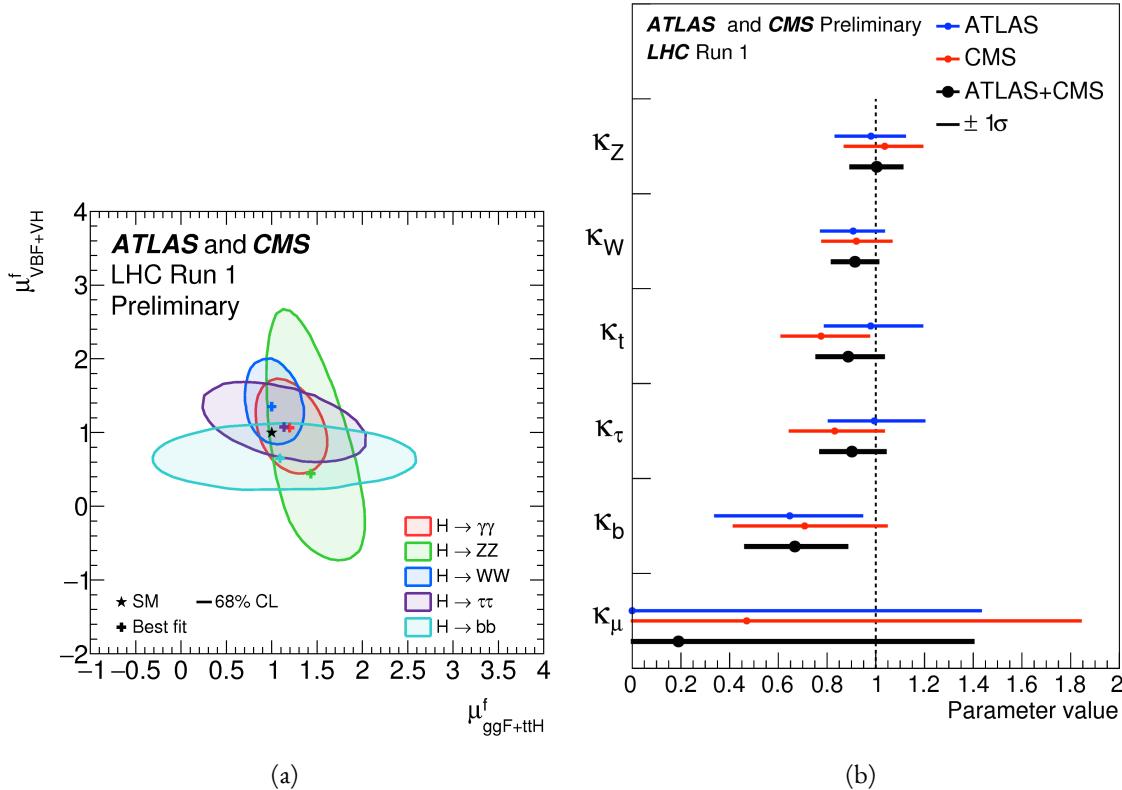


Figure 9.1: Combined ATLAS and CMS measurements in Run 1 for (a) Higgs signal strength in gluon fusion and VBF and (b) Higgs couplings normalized to their SM predictions

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  $3000 \text{ fb}^{-1}$  [130, 131]. This projection also assumes

2665 that theoretical uncertainties on the signal, which would be the largest contribution in the future dataset,  
 2666 remain as they are now. Improvements in the theoretical understanding of the Higgs signal would also  
 2667 reduce the signal strength uncertainty dramatically. Such precision results allow for measurements of the  
 2668 Higgs coupling to vector bosons precise to the few percent level, therefore giving much power to constrain  
 2669 or discover new physics.

2670 The prospects for detection of beyond the Standard Model resonant di-Higgs production at the HL-  
 2671 LHC are also quite promising. Figure 9.2 shows projections for the discovery significance of RSG signals at  
 2672 the HL-LHC in the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  search [131]. 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.

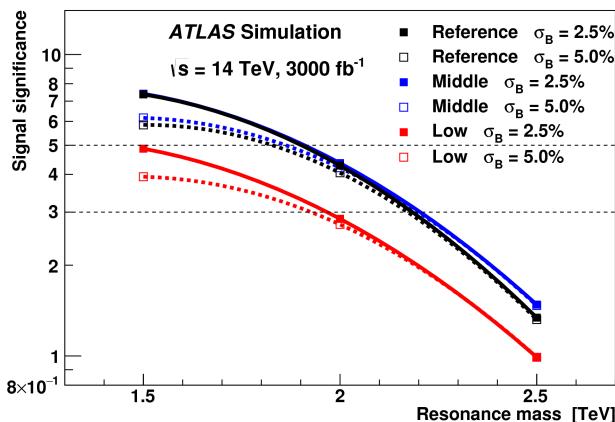


Figure 9.2: Discovery significance for RSG models at the HL-LHC in three different budget scenarios [131]. Systematic uncertainties on the background prediction ( $\sigma_B$ ) of 2.5% and 5.0% are both tested.

2673  
 2674 The Higgs will continue to be an incredibly powerful tool in the understanding of nature at the HL-  
 2675 LHC and beyond. Through both precision measurements and searches, the nature of electroweak symme-  
 2676 try breaking will be better understood and the potential for the discovery of physics beyond the Standard  
 2677 Model has never been greater.

# A

2678

2679

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

2680 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  
2681 masses is the degradation of the *b*-tagging efficiency for high  $p_T$  jets. This appendix presents a study of the  
2682 underlying causes of this degradation.

### 2683 A.I CHANGES IN MV<sub>2</sub> SCORE AT HIGH $p_T$

2684 The degradation of *b*-tagging at high  $p_T$  was studied in particular in the context of RSG models at high  
2685 mass. Figure A.I shows the  $p_T$  of the leading track jet inside of the leading calorimeter jet in RSG events.  
2686 At high  $m_{G_{KK}^*}$ , the  $p_T$  spectrum of track jets is much harder than at lower masses due to the increased  
2687 Higgs  $p_T$ .

2688 Figure A.2 shows the MV<sub>2c2o</sub> algorithm score for the leading and subleading track jets inside of the  
2689 leading calorimeter jet. In both cases, it can be seen that at higher RSG masses the MV<sub>2</sub> score shifts towards  
2690 more background like (negative) values. Additionally, this effect is more pronounced in the leading track

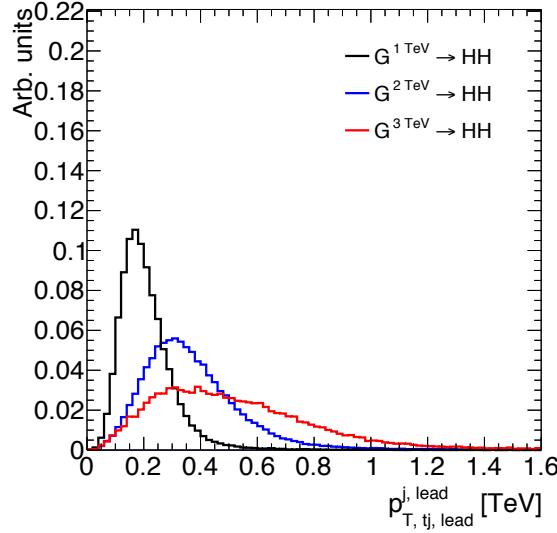


Figure A.1:  $p_T$  of the leading track jet in the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

2691 jet than the subleading.

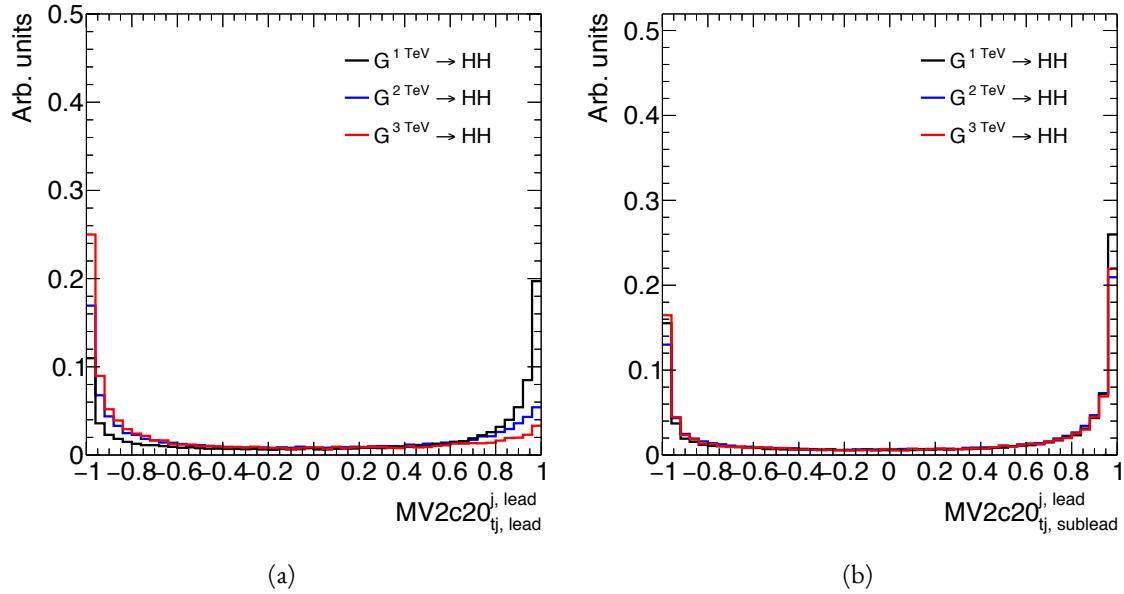


Figure A.2: MV2c20 score for the leading track jet (a) and subleading track jet (b) of the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

2692 To understand what is causing this change in the MV2c20 score, the same comparisons can be made for  
 2693 the input variables of MV2c20. The focus in these comparisons will be on the leading track jet as this is the  
 2694 one seen to have the largest difference in MV2 score. Figure A.3 shows the log likelihood ratio  $\log(p_b/p_u)$

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

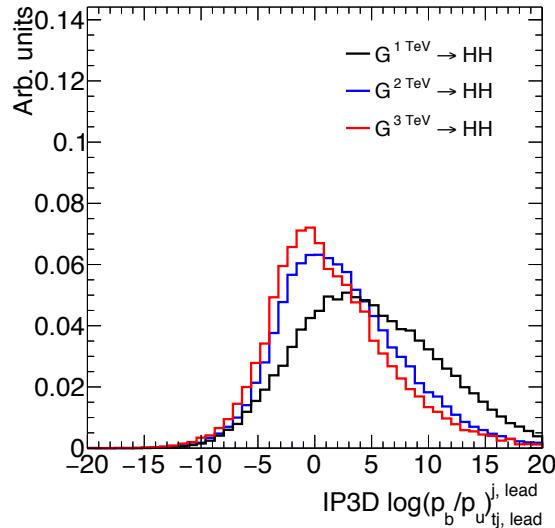


Figure A.3: IP<sub>3</sub>D log-likelihood ratio ( $\log(p_b/p_u)$ ) of the leading track jet in the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

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

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

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

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

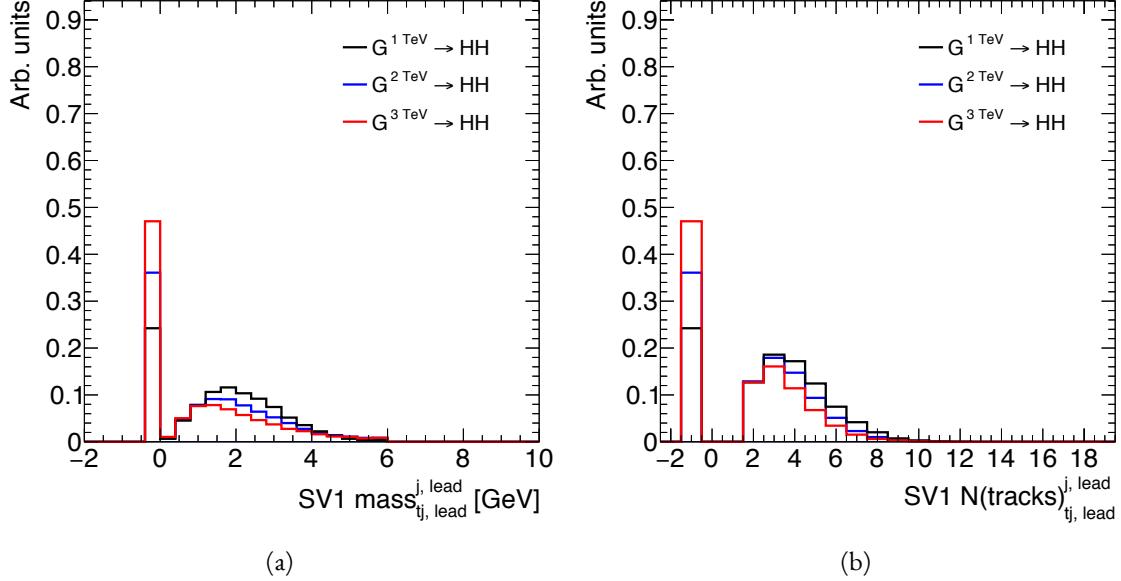


Figure A.4: Mass (a) and number of tracks (b) for the secondary vertices computed with the SV1 algorithm. When no secondary vertex is found, the quantities are assigned to default negative values.

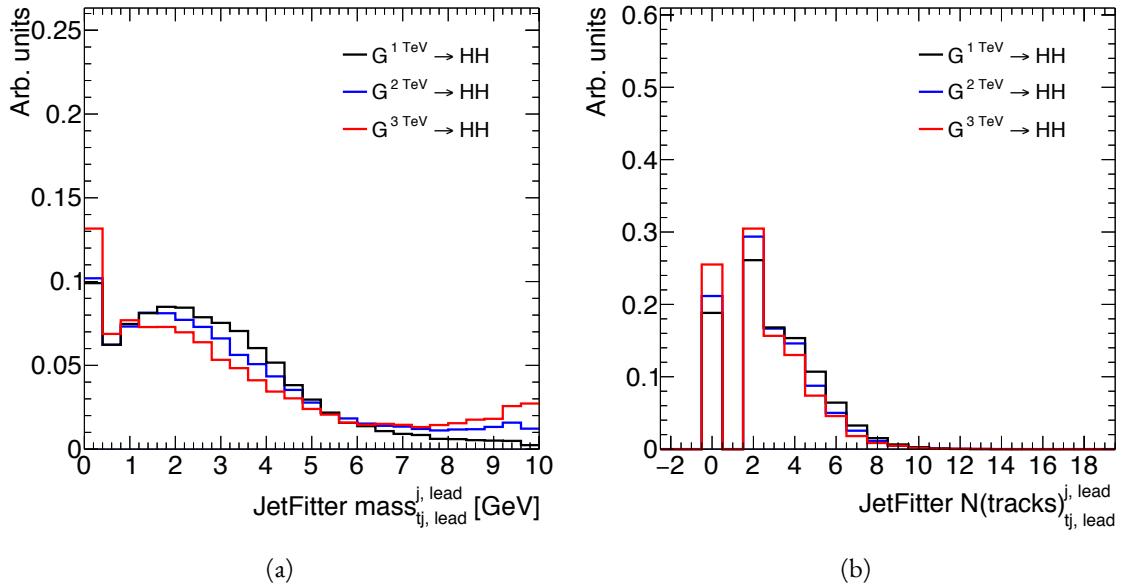


Figure A.5: Mass (a) and number of tracks (b) for vertices computed with the JetFitter algorithm. When no vertices are found, the quantities are assigned to default negative values.

tuned for tagging multiple  $b$  quarks inside one jet, the tagging efficiency could degrade. Figure A.6 shows MV<sub>2</sub> 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

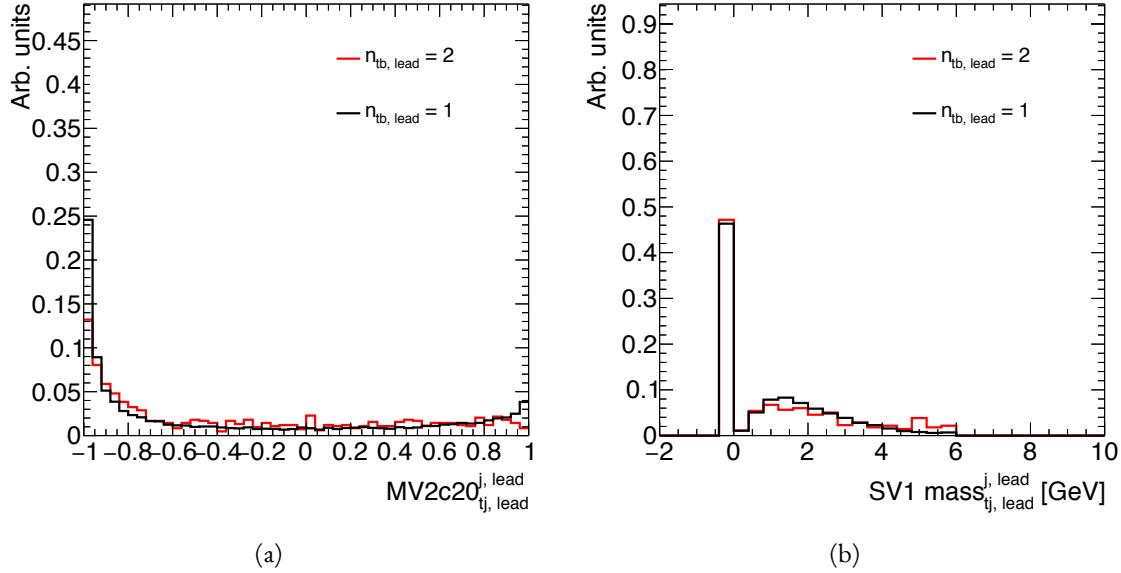


Figure A.6: MV<sub>2</sub>c20 score (a) and SV1 mass (b) for leading track jets with two truth  $b$  quarks ( $n_{tb, \text{lead}} = 2$ ) compared to those with only one truth  $b$  ( $n_{tb, \text{lead}} = 1$ ).

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.

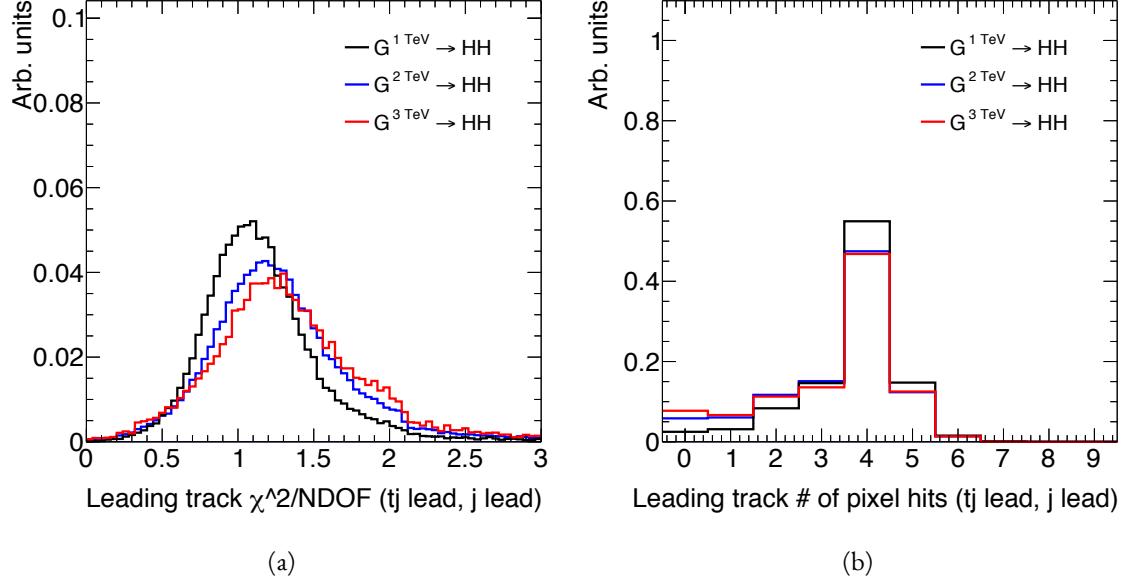


Figure A.7: Track fit  $\chi^2/\text{nDOF}$  (a) and number of pixel detector hits (b) for the leading track of the leading track jet in different mass RSG  $c = 1$  samples

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  $p_T$ .

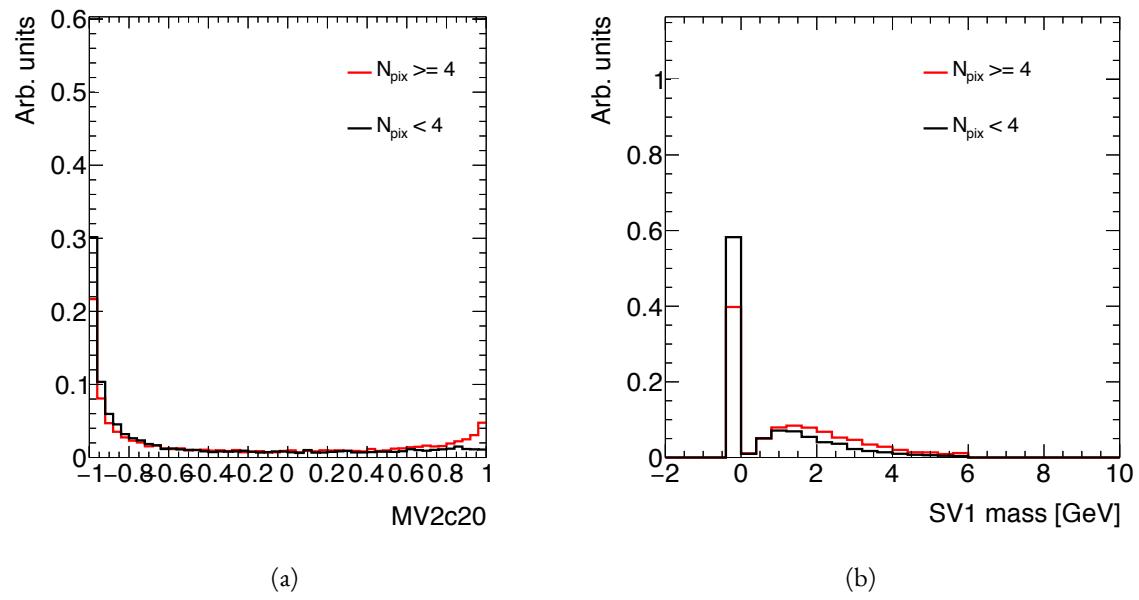


Figure A.8: MV<sub>2</sub>c<sub>20</sub> score (a) and SV<sub>1</sub> mass (b) for leading track jets whose leading track jet has at least four pixel hits ( $N_{\text{pix}} \geq 4$ ) compared to those which do not ( $N_{\text{pix}} < 4$ ).

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