

<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>8</sup> TO  
<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

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

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

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

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

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

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

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

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

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

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

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

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

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

467 Being at Harvard necessarily means having to navigate through bureaucracy at some point or another.  
468 I thank Lisa Cacciabuado, Carol Davis, and Jacob Barandes for always having open doors and being the  
469 most kind, helpful people in the Physics department.

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

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

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

476 I would not be here without the unconditional love and constant support and encouragement of my  
477 family. To my pokojni Deda Branko and Miloje, my pokojni Baba Milka, and my Baba Desa, I want to  
478 say thank you for instilling in me at an early age the love of curiosity and storytelling that I have carried  
479 throughout my life. To my sister Angelina, I want to say thank you for always loving me and being my  
480 partner in crime throughout our childhoods. To my parents, Miroljub and Nada, Tata and Mama, I really  
481 cannot express how grateful I am to you and how much I owe you. As I look back now I see how I am a  
482 combination of both of your best qualities and every day I am in situations where I understand more and  
483 more the lessons you made sure to teach me and the sacrifices you made to make sure I got the best possible  
484 education. I love you all.

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

# 0

491

492

## Introduction

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

503     One of the first priorities for the LHC when it began colliding proton beams in 2010 was the search for  
504     the Higgs boson. This search was initially tackled in three main channels:  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ^* \rightarrow 4\ell$ ,

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

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

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

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

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

536 After a two year shutdown, the LHC restarted in 2015 with a center of mass energy of  $\sqrt{s} = 13 \text{ TeV}$ .  
537 This increase improved the LHC’s ability to probe for physics beyond the Standard Model, and the Higgs  
538 sector remained one of the largest regions of unprobed phase space where such new physics could be dis-  
539 covered. Production of high mass resonances benefited most from the center of mass energy increase. In  
540 particular, the cross section for a generic gluon-initiated 2 TeV resonance increased tenfold with the in-  
541 crease from 8 to 13 TeV. Therefore, a natural next step in studies of the Higgs was a search for a new  
542 heavy resonance which decays into a pair of Higgs bosons. The final result shown in this dissertation is a  
543 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 by  
544 ATLAS at  $\sqrt{s} = 13 \text{ TeV}$ . This search has the unique advantage that it can both probe physics beyond  
545 the Standard Model and gain further understanding of the Standard Model through constraints on SM  
546 pair production of the Higgs.

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

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

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

573 Part 3 presents a search for Higgs pair production in the  $HH \rightarrow b\bar{b}b\bar{b}$  channel. Chapter 7 presents  
574 an overview of this search in the boosted regime, where the Higgs pairs are the result of the decay of a  
575 heavy resonance. Chapter 8 shows the combined results between the boosted regime and the resolved  
576 regime, which is sensitive to lower mass resonances and non-resonant Higgs pair production. Finally, Part  
577 4 presents a conclusion and brief outlook of future Higgs physics with ATLAS.

## Part I

### Theoretical and Experimental Background

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

Richard Morris

# 1

580

581

## The Physics of the Higgs Boson

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

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

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

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

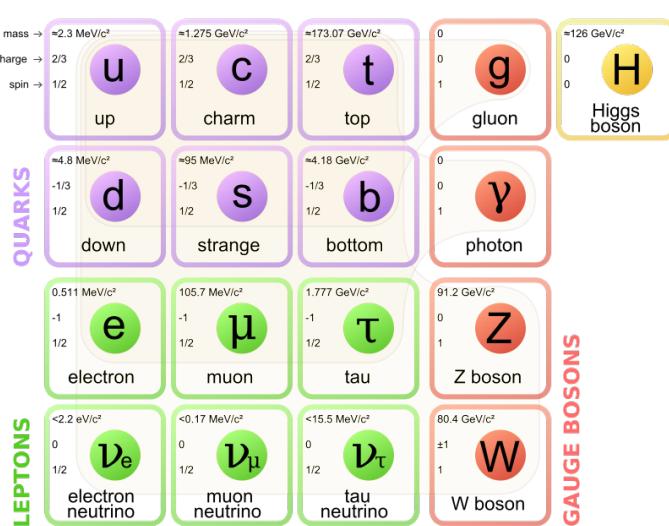


Figure 1.1: The particles of the Standard Model and their properties [6].

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

<sup>610</sup> the theory of quantum chromodynamics (which models the strong sector as a non-Abelian  $SU(3)$  gauge  
<sup>611</sup> group) to form the complete SM [13].

## <sup>612</sup> 1.2 ELECTROWEAK SYMMETRY BREAKING AND THE HIGGS

<sup>613</sup> In the Standard Model Lagrangian, it is difficult to include mass terms for the  $W$  and  $Z$  bosons without  
<sup>614</sup> breaking the fundamental gauge symmetry of the Lagrangian. A traditional mass term does not preserve  
<sup>615</sup> the  $SU(2) \times U(1)$  symmetry. Additionally, scattering of massive  $W$  and  $Z$  bosons violate unitarity and  
<sup>616</sup> these diagrams diverge at high energy scales. In the 1960s, Higgs, Brout, Englert, Guralnik, Kibble, and  
<sup>617</sup> Hagen developed a mechanism for spontaneous symmetry breaking via the addition of a complex scalar  
<sup>618</sup> doublet to the SM. Three of the four real degrees of freedom of this complex field would go to the lon-  
<sup>619</sup> gitudinal modes of the  $W^\pm$  and  $Z$ , thus allowing them to have mass [14–17]. The remaining degree of  
<sup>620</sup> freedom would manifest as an additional scalar, known now as the Higgs boson.

<sup>621</sup> The mechanism works by introducing a Lagrangian for the newly introduced field that still respects the  
<sup>622</sup> symmetry of the Standard Model inherently, but with a minimum at a non-zero vacuum expectation value  
<sup>623</sup> for the field. In this minimum of the potential, the electroweak symmetry is broken. Specifically, consider  
<sup>624</sup> a complex scalar doublet  $\Phi$  with four degrees of freedom, as shown in equation 1.1.

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

<sup>625</sup> The minimal potential of a self-interacting Higgs that still respects the SM symmetry is given in equa-  
<sup>626</sup> tion 1.2.

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

<sup>627</sup> If the  $\mu^2$  term of this potential is positive, then the potential has a minimum at  $\Phi = 0$  and the SM  
<sup>628</sup> symmetry is preserved. However, if instead  $\mu^2 < 0$ , then the minimum is at a finite value of  $\Phi$ , namely

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

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

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

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

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

632 where the covariant derivative is defined as

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

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

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

636

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

637

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

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

641

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

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

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

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

644 The full Lagrangian of Higgs interactions can be written as

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

645 with

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

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

### 655 1.3 HIGGS BOSON PRODUCTION AND DECAY

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

659    1.3.1    HIGGS PRODUCTION

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

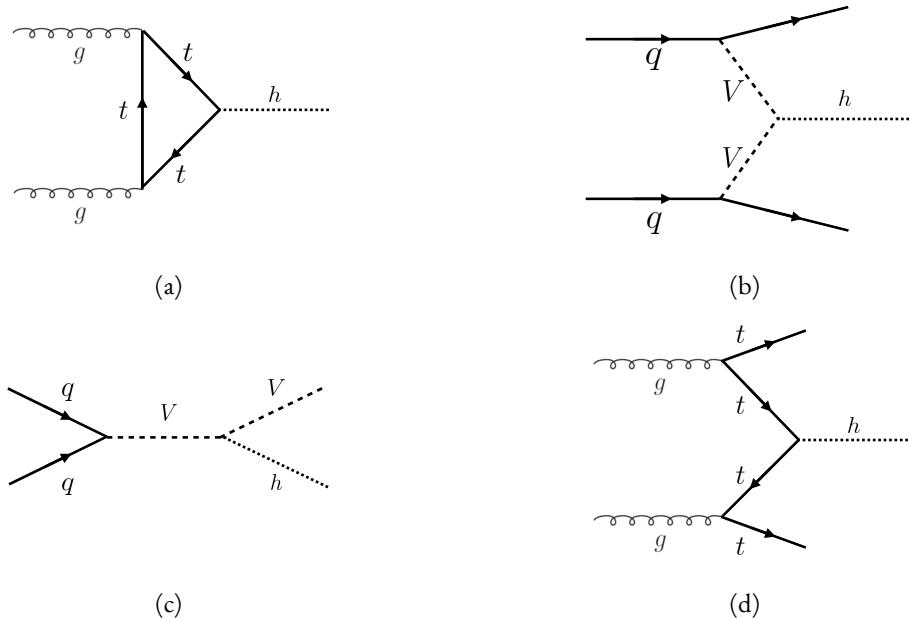


Figure 1.2: The four most common Higgs boson production modes at the LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c)  $W/Z + H$  production, (d)  $t\bar{t}H$  production

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

673 mass energy.

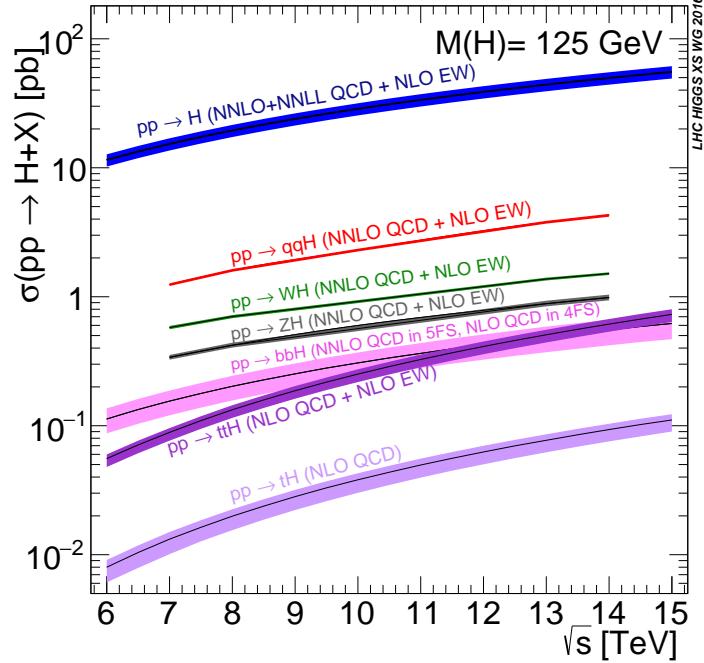


Figure 1.3: Higgs production cross sections as a function of center of mass energy ( $\sqrt{s}$ ) at a  $pp$  collider [18].

674 In figure 1.3, note that gluon fusion has the largest cross section, while VBF is the second largest at ap-  
 675 proximately a factor of 10 smaller. The figure also includes the less commonly studied  $b\bar{b}H$  and  $tH$  modes.  
 676 While the  $b\bar{b}H$  mode has a larger cross section than  $t\bar{t}H$ , it also has larger backgrounds and is thus less sensi-  
 677 tive. The  $tH$  mode is not as sensitive as  $t\bar{t}H$  due to its lower cross section. At  $\sqrt{s} = 8$  TeV, ggF production  
 678 of a 125 GeV Higgs has a cross section of 19.47 pb, while VBF has a cross section of 1.601 pb [18]. The  
 679 cross sections of all of the main Higgs production modes at this center of mass energy, as well as their un-  
 680 certainties from varying the renormalization and factorization scales and PDFs, are summarized in table 1.1  
 681 for a 125 GeV Higgs.

| Production mode      | $\sigma$ ( pb)         | QCD scale<br>uncert. (%) | PDF + $\alpha_s$<br>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].

### 682 1.3.2 HIGGS BRANCHING RATIOS

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

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

685 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  
 686  $m_H$  is the mass of the Higgs. Note that the width scales with the square of the fermion mass. (This also  
 687 assumes that the Higgs mass is large enough to decay with both the fermions on shell.)

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

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

690 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  
 691 where  $m_H \geq 2m_Z$ ), the equation is divided by 2 to account for identical particles in the final state, and  
 692  $x_W$  is replaced with  $x_Z = 4M_Z^2/m_H^2$ . This is shown in equation 1.16 [5].

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

<sup>693</sup> The more general formula for Higgs branching into  $WW$  or  $ZZ$ , taking into account the case where one  
<sup>694</sup> or both vector bosons is off-shell, is shown in equation 1.17 [19].

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

<sup>695</sup> Here,  $q_1^2$  and  $q_2^2$  are the invariant masses of the virtual gauge bosons,  $M_V$  is the  $W$  or  $Z$  mass, and  $\Gamma_V$  is  
<sup>696</sup> the  $W$  or  $Z$  width.  $\Gamma_0$  is the squared matrix element, which is given in equation 1.18 [19].

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

<sup>697</sup> The function  $\lambda$  is defined as  $\lambda(x, y, z) = (1 - x/z - y/z)^2 - 4xy/z^2$ . The integral in the general off-  
<sup>698</sup> shell boson case is much more difficult to interpret than the simpler on-shell branching ratios, but it can be  
<sup>699</sup> evaluated numerically. These formulas can also be visualized as a function of Higgs mass. Figure 1.4 shows  
the branching ratios as a function of the Higgs mass. There are a few interesting features to note in this

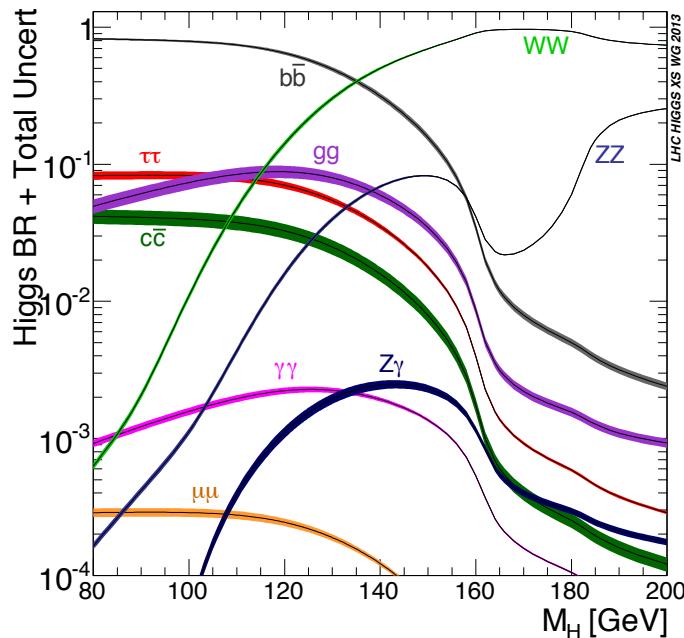


Figure 1.4: Higgs boson branching ratios as a function of  $m_H$  [18].

<sup>700</sup>  
<sup>701</sup> figure. First, note that at high Higgs masses, once on-shell production of both  $W$  and  $Z$  bosons is possible,

702 these two decays are the dominant ones due to the large masses of the  $W/Z$ . Also note that the branching  
 703 ratio to  $W$ s is twice that of  $Z$ s at these large masses due to the  $\delta_V$  symmetry factor noted previously. At  
 704 125 GeV, the Higgs is accessible through many different decay modes. The largest branching ratio is the  
 705 decay  $H \rightarrow b\bar{b}$  at 58.24% [18]. This branching is larger than the  $WW/ZZ$  decays because one of the two  
 706 bosons must be produced off-shell for  $m_H = 125$  GeV. The second largest branching ratio is to  $WW^*$  at  
 707 21.37 % (before taking into account the branching ratios of the  $W$ ). Table 1.2 summarizes the branching  
 708 ratios for a 125 GeV Higgs. Note that there is in fact a Higgs branching ratio to  $\gamma\gamma$  even though photons  
 709 are massless. This decay happens through a loop (the largest contributions to the loop are top and  $W$ )  
 710 which suppresses the branching ratio.

| Decay          | Branching ratio (%) | Relative uncertainty (%) |
|----------------|---------------------|--------------------------|
| $b\bar{b}$     | 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            |
| $c\bar{c}$     | 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: 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].

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

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

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

## 717 I.4 HIGGS PAIR PRODUCTION IN THE STANDARD MODEL

<sup>718</sup> The Standard Model also allows for processes that produce two Higgs bosons in the final state, known  
<sup>719</sup> 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

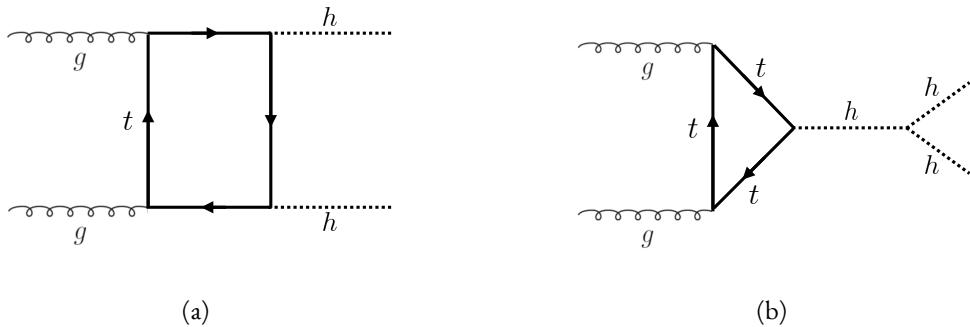


Figure 1.5: The two leading diagrams for Standard Model di-Higgs production at the LHC: (a) box diagram, (b) Higgs self coupling

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

One can substitute the gluon fusion production of diagram 1.5(b) with any of the other production modes previously discussed. These other modes do not suffer from interference with the box diagram in figure 1.5(a) due to the presence of additional particles in the final state. They still have a lower cross section than the gluon fusion mode, however. The cross sections for di-Higgs production in the different modes,

728 as well as their uncertainties, are shown in table 1.4 [20]. These are shown for  $\sqrt{s} = 14$  TeV as the higher  
729 center of mass energy is more sensitive to this process. Note that the scale of cross section quoted is now  
in fb rather than pb.

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

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

730

## 731 1.5 HIGGS PAIR PRODUCTION IN THEORIES BEYOND THE STANDARD MODEL

732 The Standard Model Higgs pair production cross section is rather small, and datasets on the scale of  
733 the full lifetime of the LHC will be required to obtain sensitive measurements of the Higgs self-coupling.  
734 However, the discovery of the Higgs also gives particle physicists a new tool that can be exploited in the  
735 search for new physics beyond the Standard Model. In particular, Higgs pair production is a promising  
736 channel in the search for new physics. The cross section for di-Higgs production can be altered through  
737 both resonant and non-resonant production of Higgs pairs. In non-resonant production, di-Higgs pro-  
738 duction vertices can arise from the presence of a new strong sector and additional colored particles [21–23].  
739 Figure 1.6 shows examples of the types of vertices that can arise. In the resonant case, new heavy particle  
740 can decay to Higgs pairs. Such new particles can include heavy Higgs bosons arising in two Higgs doublet  
741 models (2HDM) or Higgs portal models as well as heavy gravitons in Randall-Sundrum theories [21, 24–  
742 30]. Figure 1.7 shows a generic diagram for a heavy resonance decaying to two Higgs bosons. In the 2HDM,  
743  $X$  corresponds to the heavy CP-even scalar  $H$ . In the Randall-Sundrum model,  $X$  corresponds to a heavy  
744 spin-2 graviton  $G$ . The next sections provide more detail on the phenomenology of resonant Higgs pro-  
745 duction in Randall-Sundrum and 2HDM models, as these models will later be tested in a dedicated search  
746 for resonant production of boosted Higgs pairs.

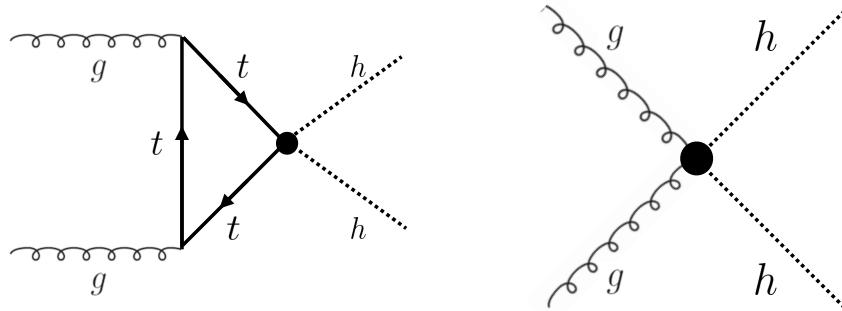


Figure 1.6: Diagrams with new vertices for non-resonant Higgs pair production arising in composite Higgs models

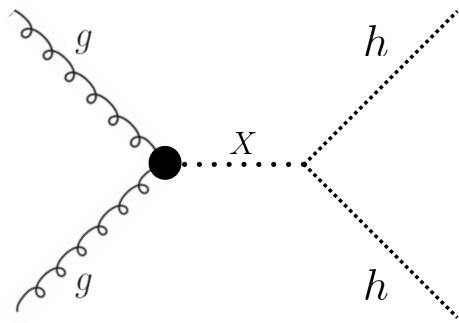


Figure 1.7: Generic Feynman diagram for resonant Higgs pair production in BSM theories

### 747 1.5.1 RANDALL-SUNDRUM GRAVITONS

748 The Randall-Sundrum model is a proposed solution to the hierarchy problem that posits a five-dimensional  
 749 warped spacetime that contains two branes: one where the force of gravity is very strong and a second brane  
 750 at the TeV scale corresponding to the known Standard Model sector [24]. In the theory, the branes are  
 751 weakly coupled and the graviton probability function drops exponentially going from the gravity brane  
 752 to the SM brane, rendering gravity weak on the SM brane. The experimental consequence of this theory  
 753 is a tower of widely spaced (in mass) Kaluza-Klein graviton resonances. In theories where the fermions  
 754 are localized to the SM brane, production of gravitons from fermion pairs is suppressed and the primary  
 755 mode of production is gluon fusion [25]. These gravitons have a substantial branching fraction to Higgs  
 756 pairs, ranging from 6.43% for gravitons with a mass of 500 GeV to 7.66% at 3 TeV. Figure 1.8 shows the  
 757 branching ratios of the spin-2 Randall Sundrum graviton (RSG) as a function of its mass. The predomi-

758 nant decays are to  $t\bar{t}$  above the mass threshold for that channel.

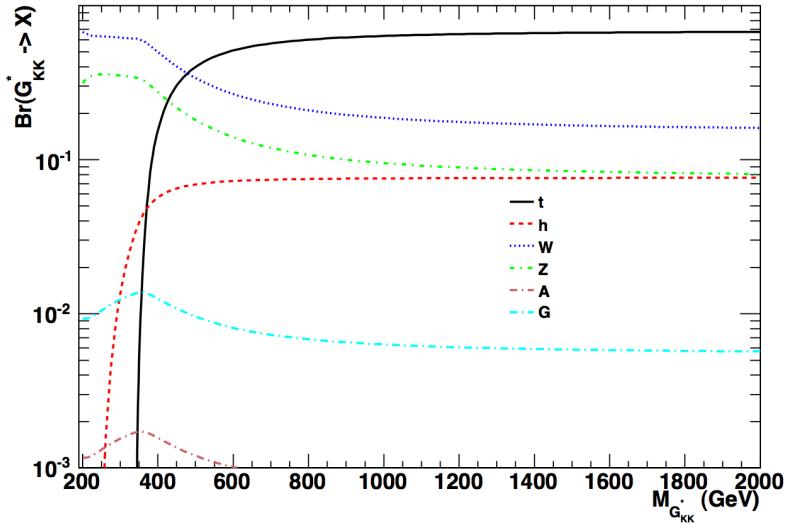


Figure 1.8: Branching ratios for a spin-2 Randall-Sundrum graviton as a function of mass computed in MadGraph with the CP3-Origins implementation [25, 31]

759 These models have two free parameters - the mass of the graviton and a curvature parameter  $k$ . Typically,  
 760 rather than  $k$ , the theory is parameterized using  $c \equiv k/\bar{M}_{\text{Pl}}$ , where  $\bar{M}_{\text{Pl}}$  is the reduced Planck mass. The  
 761 cross section for production of the RSG decreases as a function of mass and is strongly dependent on the  
 762 gluon PDF. The increase in center of mass energy from 8 to 13 TeV in LHC Run 2 greatly increases the  
 763 cross section at higher mass. Figure 1.9 shows the cross section as a function of graviton mass at  $\sqrt{s} =$   
 764 13 TeV for RSG models with  $c = 1.0$  and  $c = 2.0$ .

765 Another interesting feature of the theory is that the width of the graviton increases with both  $c$  and  $m_G$ .  
 766 Figure 1.10 shows the graviton width for both  $c = 1.0$  and  $c = 2.0$  as a function of mass. In  $c = 1.0$ ,  
 767 the width starts at 8.365 GeV for a mass of 300 GeV and increases to 187.2 GeV at a mass of 3 TeV.  
 768 Similarly, with  $c = 2.0$ , the width starts at 33.46 GeV for  $m_G = 300$  GeV and increases to 748.8 GeV  
 769 at a mass of 3 TeV.

### 770 1.5.2 TWO HIGGS DOUBLET MODELS

771 In Two Higgs Doublet Models (2HDM), a second complex scalar doublet is added to SM [27–29]. In  
 772 this case, all four degrees of freedom in the second doublet correspond to new particles, meaning that there

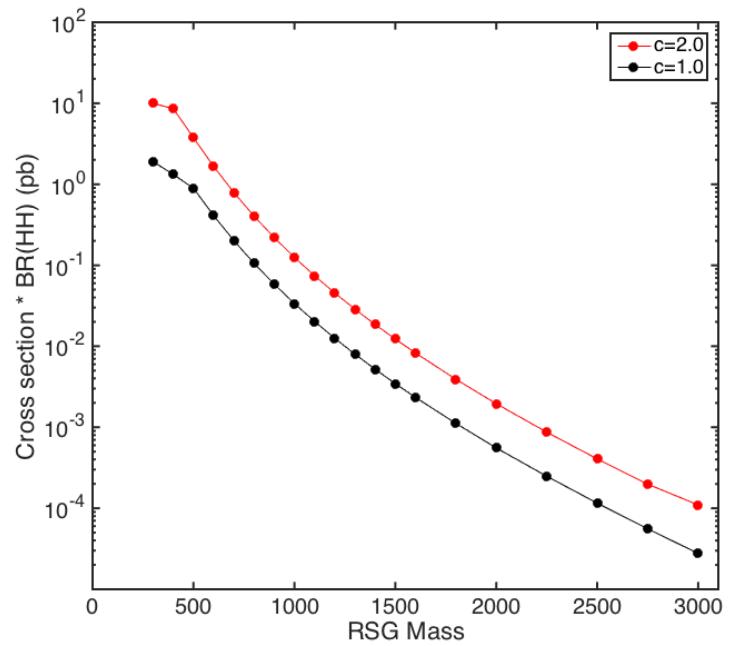


Figure 1.9:  $\sigma \times \text{BR}(HH)$  for RSG as a function of mass computed in MadGraph with the CP3-Origins implementation [25, 31]

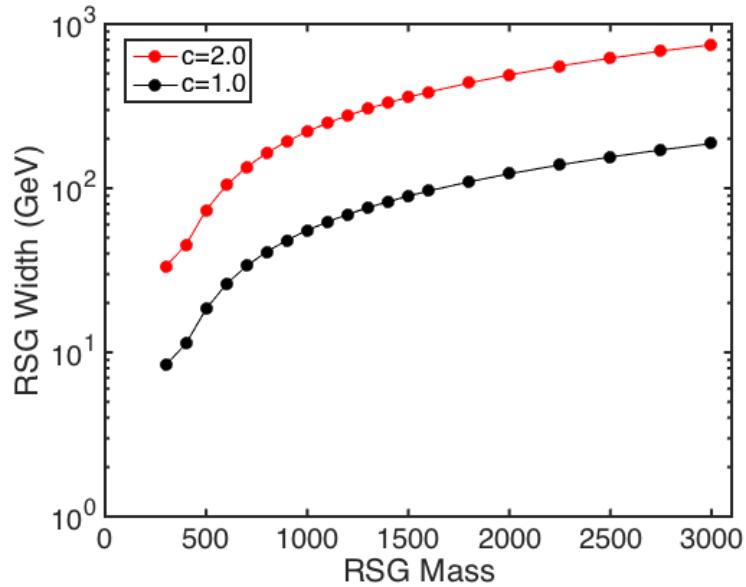


Figure 1.10: RSG width as a function of mass computed in MadGraph with the CP3-Origins implementation [25, 31]

773 are five total scalars from the two Higgs doublets -  $h$  (light CP-even Higgs),  $H$  (heavy CP-even Higgs),  $A$   
 774 (heavy CP-odd Higgs), and  $H^\pm$  (charged Higgs). The model is parameterized by two main parameters.  
 775 The first,  $\tan \beta \equiv \frac{v_2}{v_1}$ , is the ratio of the vacuum expectation values of the two Higgs doublets (where  $v_1$   
 776 corresponds to the  $v$  in the SM Higgs model described above). The second parameter is  $\alpha$ , a mixing angle  
 777 between the heavy and light Higgs fields. Models are also often parameterized with  $\cos(\beta - \alpha)$  rather  
 778 than  $\alpha$  directly. The limit where  $\cos(\beta - \alpha) = 0$  is called the alignment limit, and it is in this limit that  
 779 the light Higgs  $h$  has the same couplings as a Standard Model Higgs.

780 2HDM models are usually separated into two main types - Type I and Type II. In Type I models, the  
 781 charged fermions only couple to the second Higgs doublet, leading to a fermiophobic light Higgs. In  
 782 Type II models, up-type quarks couple to the first doublet while down-type quarks couple to the second  
 783 doublet. One specific realization of a Type II 2HDM is the Minimal Supersymmetric Standard Model  
 784 (MSSM).

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

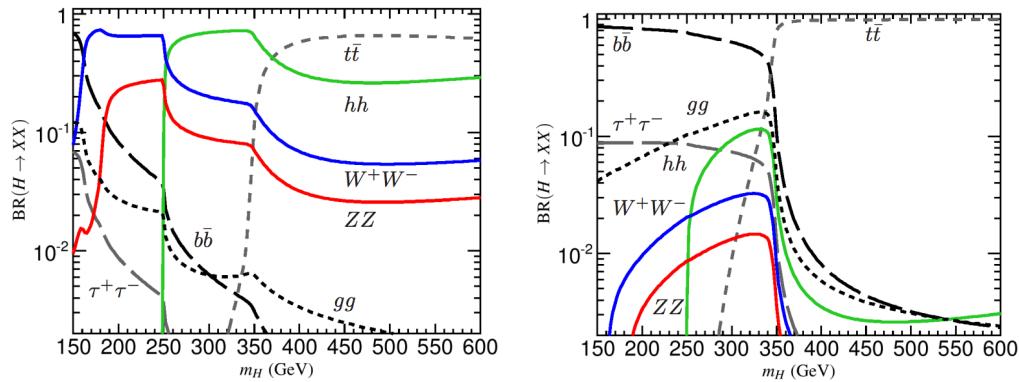


Figure 1.II: Branching ratios for heavy Higgs  $H$  in Type I (left) and Type II (right) 2HDM models with  $\tan \beta = 1.5$  and  $\cos(\beta - \alpha) = 0.1$  (Type I) ( $0.01$  Type II). [29]

790 1.6 CONCLUSION

791 Studying the Higgs sector is essential for understanding the details of how mass arises in the Standard  
792 Model and how the electroweak symmetry is broken. The discovery of the Higgs boson also opens the  
793 door for its use as a tool to search for new physics, and Higgs pair production is an ideal candidate for  
794 this study. Even if no BSM physics is found in Higgs pair production, searches for Higgs pairs will put  
795 constraints on the Higgs self coupling and thus further knowledge of the Standard Model and the details  
796 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

797

798

## The ATLAS detector and the Large Hadron 799 Collider

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

810    2.1 THE LARGE HADRON COLLIDER

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

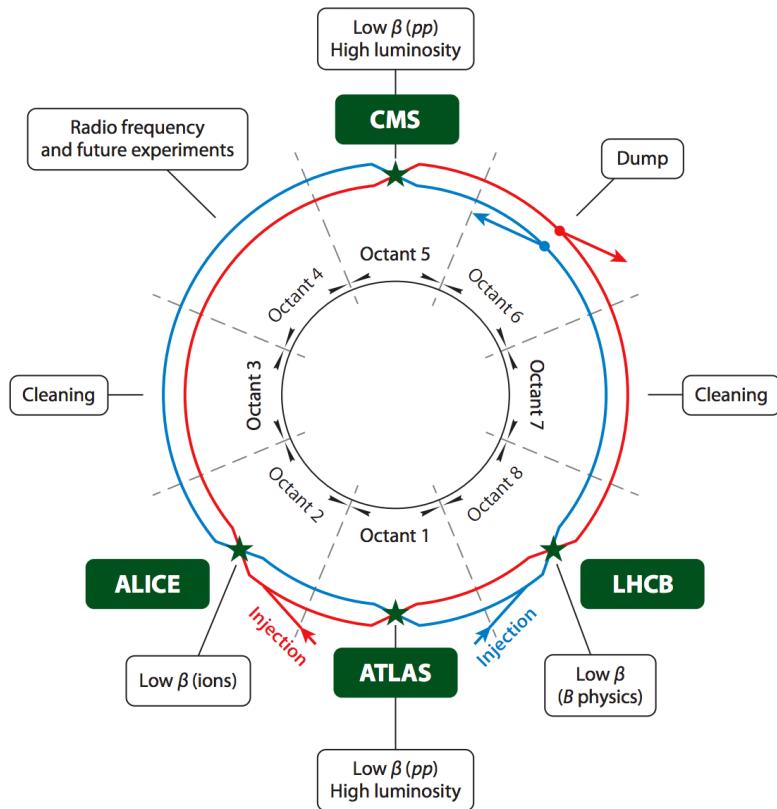


Figure 2.1: A schematic view of the LHC ring [37]

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

821 helium.

822 2.1.1 INSTANTANEOUS LUMINOSITY

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

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

829 The LHC collides protons in bunches, and in the above equation  $N_b$  is the number of protons per bunch  
830 while  $n_b$  is the number of bunches per beam. Nominally, the LHC can hold up to 2808 proton bunches.  
831  $f_{\text{rev}}$  is the revolution frequency.  $\epsilon_n$  is the normalized transverse beam emittance, a measurement of the  
832 average spread of the particles position-momentum space which has the dimension of length.  $\beta^*$  is the  
833 value of the *beta* function for the beam at the interaction point. It relates the emittance to the Gaussian  
834 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  
835 are colliding at an angle at the IP.

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

838

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

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

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

846 **2.1.2 EVOLUTION OF MACHINE CONDITIONS**

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

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

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

851 **2.2 THE ATLAS DETECTOR**

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

856 **2.2.1 COORDINATE SYSTEM**

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



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

860 to the beam axis is referred to as  $\theta$ . Rather than using  $\theta$  directly as a coordinate, the experiment often uses  
 861 the pseudorapidity  $\eta$ .  $\eta$  is defined in equation 2.3.

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

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

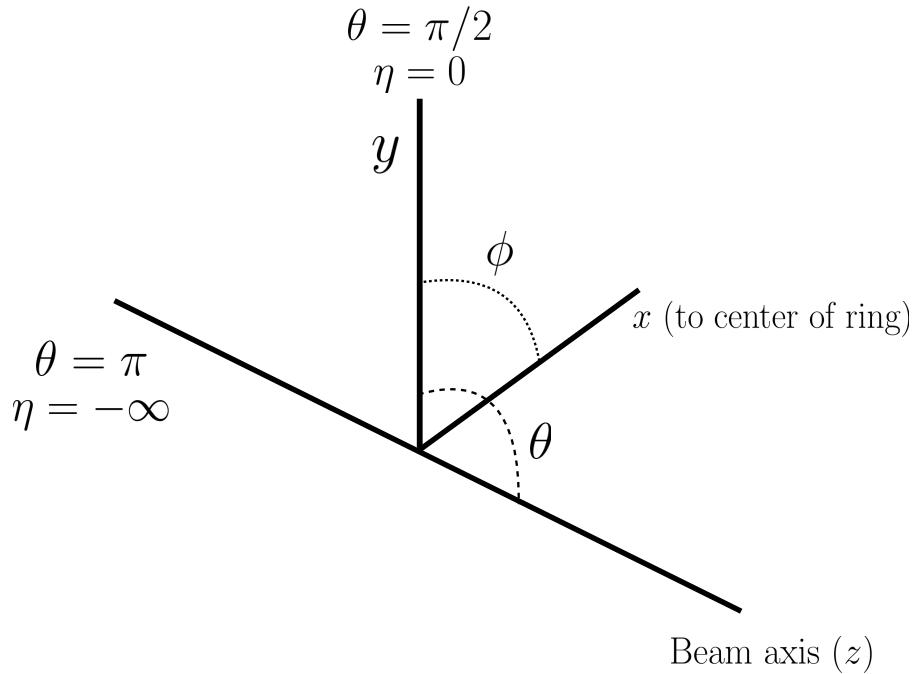


Figure 2.3: The ATLAS coordinate system

869    2.2.2 INNER DETECTOR

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

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

878    PIXEL DETECTOR

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



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

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

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

#### 891 INSERTABLE B-LAYER

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

894 high luminosity HL-LHC. Additionally it improves tracking position resolution which in turn improves  
895 the vertexing and  $b$ -tagging capabilities in ATLAS. The detector sits directly on a new beam pipe, only  
896 33.25 mm away from the collision points in the azimuthal plane.

897 **SEMICONDUCTOR TRACKER (SCT)**

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

903 **TRANSITION RADIATION TRACKER (TRT)**

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

912 **2.2.3 CALORIMETERS**

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

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

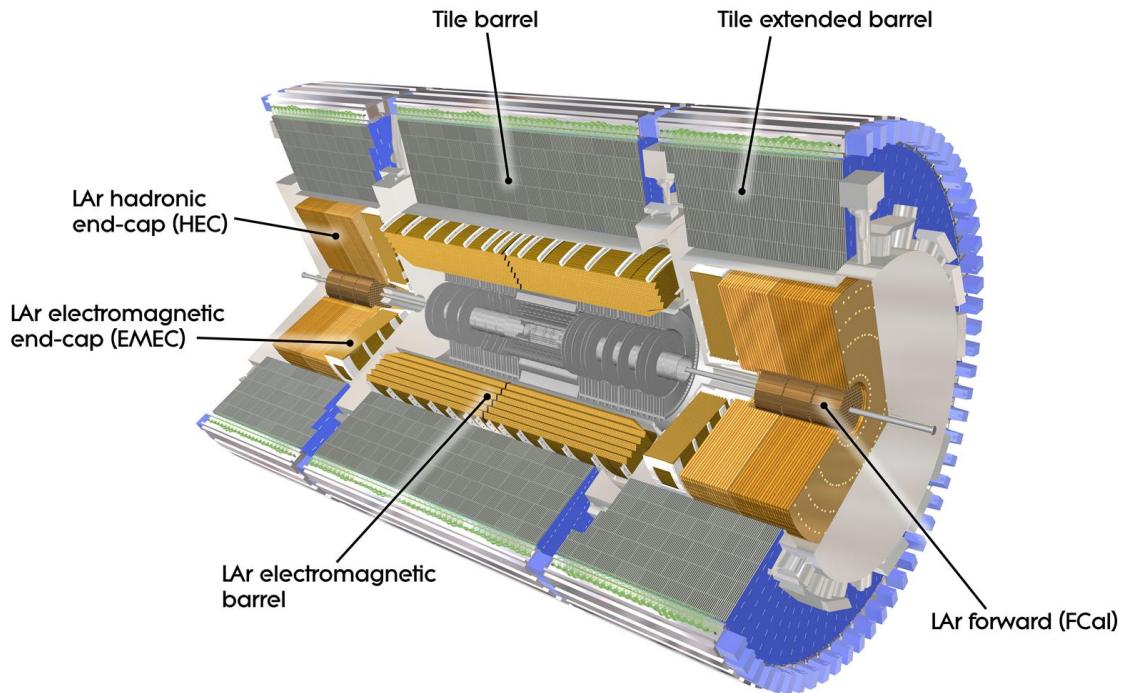


Figure 2.5: Layout of the ATLAS calorimeter system [33]

921 ELECTROMAGNETIC CALORIMETER

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

927 In order to provide good containment the calorimeter depth must be optimized. Typically, for elec-  
928 tromagnetic calorimeters the depth is measured in radiation lengths. In general, the intensity of a par-  
929 ticle beam attenuates exponentially in distance with a constant equal to the radiation length. That 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.  
The ATLAS EM calorimeter is designed to have  $> 22$  radiation lengths in the barrel and  $> 24$  in the endcap [33].

### 933 HADRONIC CALORIMETERS

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

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

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

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

947 The hadronic equivalent of radiation length is called the interaction length and is denoted as  $\lambda$ . In the  
948 barrel, the hadronic calorimeter depth is approximately  $9.7\lambda$ , while in the endcap is  $10\lambda$ . The outer  
949 supports contribute an additional  $1.3\lambda$ . This is been shown to be sufficient to limit punch-through of  
950 showers to the muon system [33].

#### 951 2.2.4 MUON SPECTROMETER

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

955 derives its name.) These magnets provide 1.5 to 5.5 Tm of bending power at  $0 < |\eta| < 1.4$  and approx-  
 956 imately 1 to 7.5 Tm in the endcap region of  $1.6 < |\eta| < 2.7$ . The entire muon system covers the range  
 957  $0 < |\eta| < 2.7$ . Monitored drift tubes (MDTs) are used for tracking in the barrel and the two outer layers  
 958 of the endcap, while cathode strip chambers (CSCs) are used to provide tracking in the innermost endcap  
 959 wheel. In the barrel, resistive plate chambers (RPCs) are used as trigger chambers while thin gap chambers  
 960 (TGCs) are used in the endcap. Figure 2.6 shows the layout of the ATLAS muon system. The entire muon  
 961 system is designed with the specification of providing a 10% momentum resolution for a 1 TeV muon.

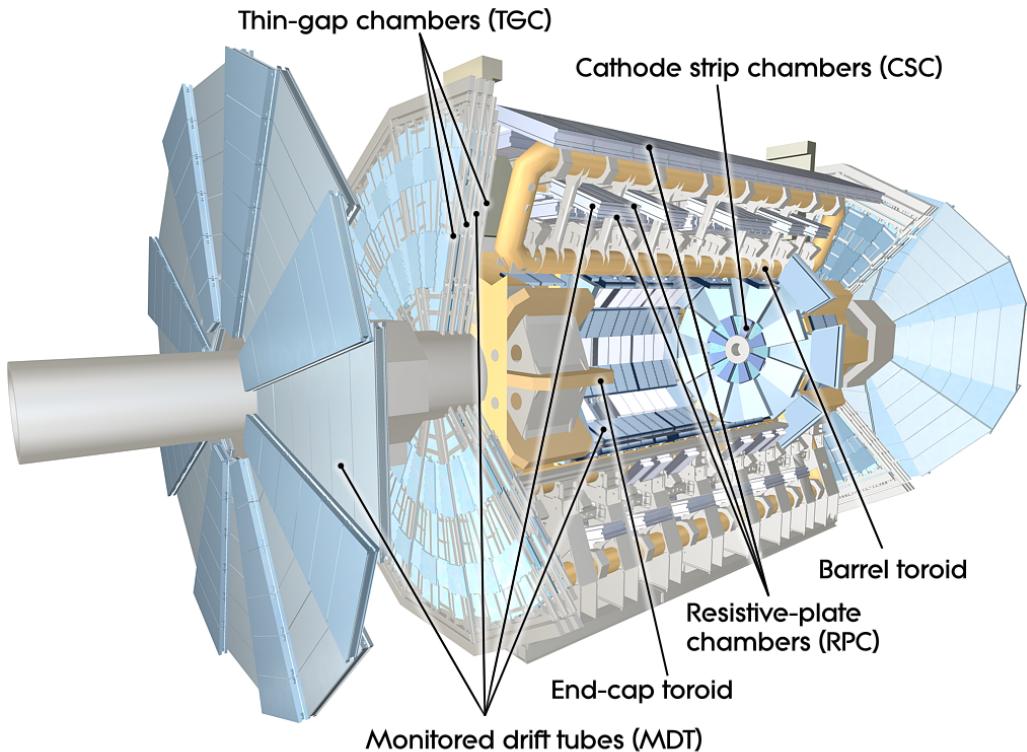


Figure 2.6: Layout of the ATLAS muon system [33]

## 962 MONITORED DRIFT TUBES (MDTs)

963 The monitored drift tubes (MDTs) are aluminum 3cm diameter tubes filled with a 93/7 % mixture of  
 964 Argon and CO<sub>2</sub>, with trace amounts of water. As a charged particle traverses the tube, it ionizes the gas  
 965 and the ions drift to a wire at the center of the tube. The radial distance of traversal of the particle in the

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

970 **CATHODE STRIP CHAMBERS (CSCs)**

971 The cathode strip chambers cover a narrow window of the innermost endcap region at  $2.0 < |\eta| <$   
972 2.7. In this region the background rates in the cavern are particularly high and the CSCs are designed to  
973 handle these higher rates. The CSCs are multiwire proportional chambers with wires pointing in the radial  
974 direction (away from the beam pipe). The wire serves as an anode and there are two types of segmented  
975 cathode strip, one perpendicular to the wires which gives the precision measurement and one parallel which  
976 provides the transverse coordinate. It has an 80/20 gas mixture of Argon and CO<sub>2</sub> [33].

977 **RESISTIVE PLATE CHAMBERS (RPCs)**

978 The resistive plate chambers (RPCs) are gaseous electrode-plate detectors covering the region  $|\eta| <$   
979 1.05. They consist of two resistive plates separated by a distance of 2 mm. The gas mixture used is a  
980 94.7/5/0.3% 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  
981 for both  $\eta$  and  $\phi$  measurement and thus provides measurement of the azimuthal coordinate in the barrel  
982 that the MDTs do not. The thin gas gap allows for a quick response time which makes it ideal for use in the  
983 trigger. There are three layers of RPCs which are referred to as the three trigger stations. They allow for  
984 both a low  $p_T$  and high  $p_T$  trigger. The coincidence of hits in the innermost chambers allows for triggering  
985 of muons between 6 and 9 GeV, while the outermost layer allows the trigger to select high momentum  
986 tracks in the range of 9 to 35 GeV [33].

987 **THIN GAP CHAMBERS (TGCs)**

988 The thin gap chambers (TGCs) are multiwire proportional chambers where the wire to cathode dis-  
989 tance (1.4mm) is smaller than the wire-to-wire distance (1.8 mm). They contain a gas mixture of CO<sub>2</sub>  
990 and *n*-pentane and use a high electric field to gain good time resolution. They serve two functions in the

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

#### 994 2.2.5 MAGNET SYSTEM

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

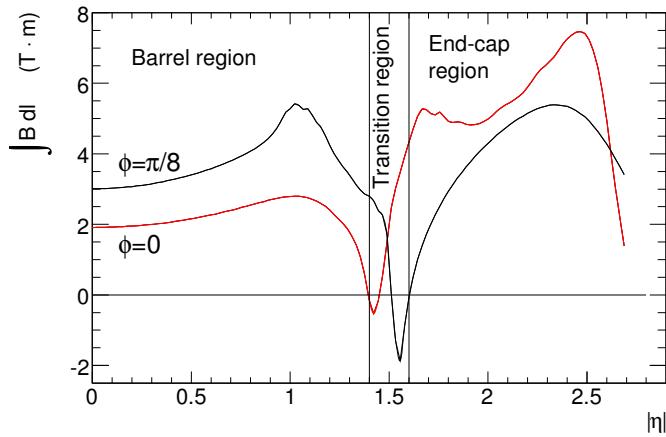


Figure 2.7: Predicted field integral as a function of  $|\eta|$  for the ATLAS magnet system [33]

#### 999 2.2.6 TRIGGER SYSTEM

1000 The ATLAS trigger system searches for signatures of muons, electrons, photons, hadronically decaying  
 1001  $\tau$  leptons, and jets in order to save these events for further analysis. The trigger system in ATLAS is de-  
 1002 signed to reduce the maximum LHC event rate of 40 MHz to a more reasonable rate that can be recorded.  
 1003 The trigger first consists of a fast, hardware based system called the Level-1 (L1) trigger. The L1 trigger  
 1004 consists of independent dedicated detector sub-components that can seed regions of interest (RoIs) for  
 1005 further analysis downstream. For muons, the RPCs and TGCs are used, while in the calorimeter coarsely  
 1006 grained sections of calorimeter cells called towers are used. Once regions of interest are seeded, a software

1007 based system called the High Level Trigger (HLT) is used to reconstruct objects and integrate information  
 1008 from different parts of the detector. In Run 1 of ATLAS, the HLT consisted of two separate stages: the  
 1009 level 2 (L2) trigger and the event filter (EF).

1010 The maximum trigger rate that the L1 trigger can handle is 75 kHz. In the HLT, the rate of events  
 1011 written to disk is approximately 200 Hz. Figure 2.8 shows the trigger rates for different L1 triggers in 2012  
 1012 and 2015 for ATLAS [43].

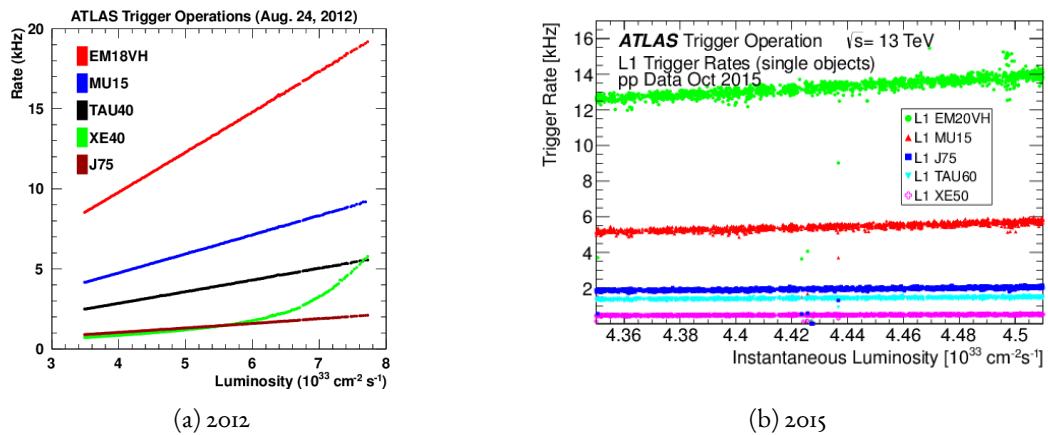


Figure 2.8: ATLAS trigger rates for Level-1 triggers as a function of instantaneous luminosity in 2012 and 2015 operation. These are single object triggers for electromagnetic clusters (EM), muons (MU), jets (J), missing energy (XE), and  $\tau$  leptons (TAU). The threshold of the trigger is given in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

### 1013 2.2.7 ATLAS DATASETS

1014 ATLAS has collected data at center of mass energies of 7, 8, and 13 TeV. Figure 2.9 shows the integrated  
 1015 luminosity as a function of time for each of the three collected datasets. At  $\sqrt{s} = 7$  TeV, ATLAS recorded  
 1016  $5.08 \text{ fb}^{-1}$ . Increased instantaneous luminosity in 2012 led to a larger dataset of  $21.3 \text{ fb}^{-1}$  recorded at  
 1017  $\sqrt{s} = 8$  TeV. After Long Shutdown 1 (LS1) of the LHC and a restart in 2015, ATLAS recorded  $3.9 \text{ fb}^{-1}$   
 1018 of data at  $\sqrt{s} = 13$  TeV. [44, 45]

### 1019 2.2.8 DETECTOR PERFORMANCE

1020 Table 2.2 summarizes the design requirements for each of the different sub-detectors. This table shows  
 1021 the energy and momentum resolution of each tracking, calorimetry, and muon measurements.

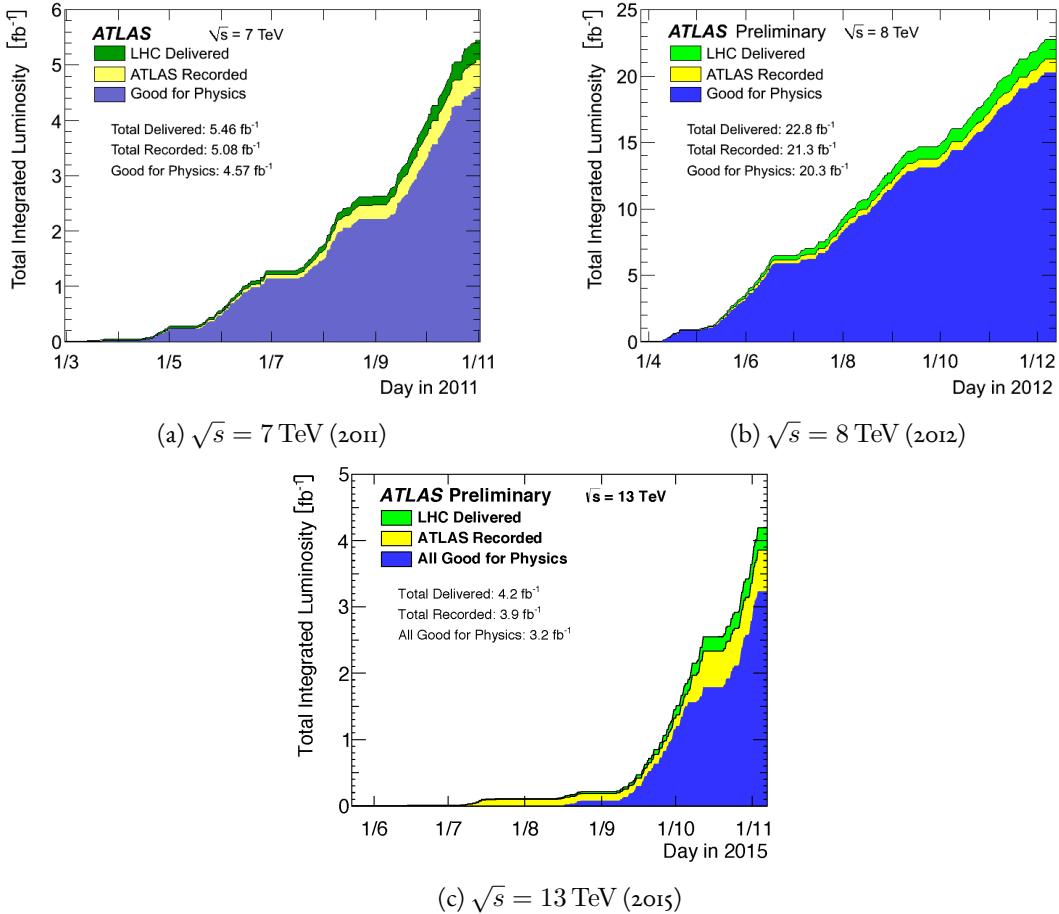


Figure 2.9: Instantaneous luminosity as a function of time for data recorded by ATLAS at different center of mass energies [44, 45]

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

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

## 2.3 THE ATLAS MUON NEW SMALL WHEEL UPGRADE

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

1025 for study of rare physics processes but will also present interesting challenges that must be faced. ATLAS  
 1026 will require new detector technologies to cope with the increased background rates in the cavern in these  
 1027 high luminosity conditions. One such upgrade, scheduled to be installed during Long Shutdown 2 (LS2)  
 1028 of the LHC in 2018, is the ATLAS Muon New Small Wheel (NSW) upgrade [46]. The NSW will replace  
 1029 the innermost end-cap wheel of the muon system with new technologies, as this is the part of the muon  
 1030 detector closest to the beam and thus suffers from the highest rates.

### 1031 2.3.1 MOTIVATION

1032 The motivation of the NSW is two-fold. First, the objective is to alleviate the decreased tracking ef-  
 1033 ficiency that comes in a high rate environment. As figure 2.10, at the LHC design luminosity both the  
 1034 efficiency of recording hits and reconstructing track segments in the MDTs decreases at the LHC design  
 1035 luminosity.

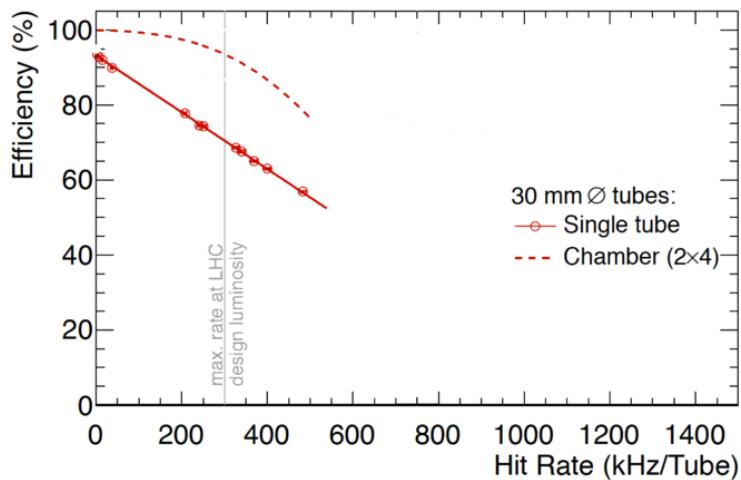


Figure 2.10: MDT tube hit (solid) and segment (dashed) efficiency as a function of hit rate per tube [46]

1036 Second, the NSW will work to alleviate the rate of fake triggers arising in the endcap. Figure 2.11 shows  
 1037 the extrapolated trigger rates as a function of the  $p_T$  threshold with and without the NSW upgrade. As  
 1038 the figure shows, the NSW upgrade will reduce the trigger rate by an order of magnitude compared to the  
 1039 current endcap trigger system.

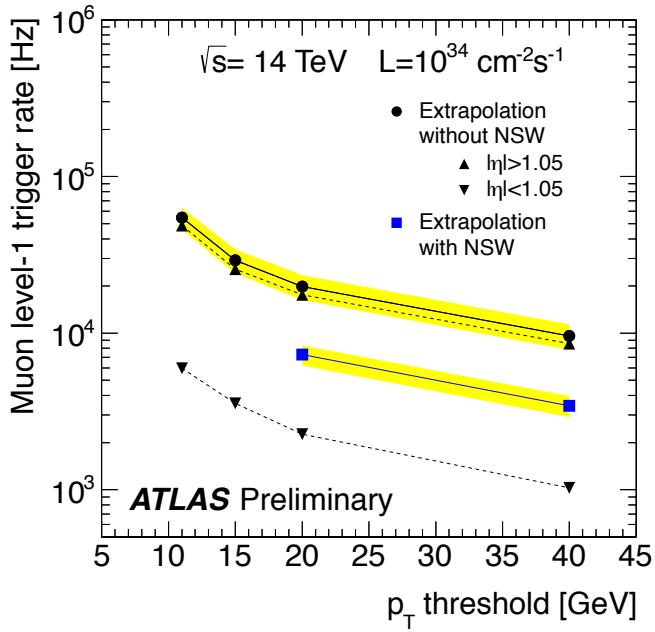


Figure 2.11: Trigger rate as a function of  $p_T$  threshold with and without the NSW upgrade [46]

### 1040 2.3.2 NSW DETECTOR TECHNOLOGIES

1041 The NSW will use two new detector technologies - micromesh gaseous structure detectors (micromegas)  
 1042 and small-strip thin gap chambers (sTGCs) [46, 47]. Unlike the previous detectors, both of these detector  
 1043 technologies can be used for tracking or trigger. However, the micromegas is more suited to tracking be-  
 1044 cause of its good spatial resolution, while the sTGCs have better time resolution and are more suited for  
 1045 the trigger. To maintain a fully redundant system, both technologies are used for both purposes.

### 1046 MICROMEGAS

1047 Micromegas detectors operate using a thin metallic mesh that sits approximately  $100 \mu\text{m}$  away from the  
 1048 readout electrodes to create the amplification region. Above this mesh, there is a drift region on the order  
 1049 of a few mm in length capped by a drift electrode. As a charged particle traverses the detector, it ionizes gas  
 1050 and the electrons drift down towards readout strips. The timing of the drift can be used to reconstruct the  
 1051 angle of traversal of the particle. This is illustrated in figure 2.12. The micromegas used in ATLAS will be  
 1052 resistive micromegas, where the readout electrodes are topped with resistive strips [48]. This alleviates the

1053 risk of sparking in the large area detectors that ATLAS will use.

1054 In ATLAS, the micromegas drift gap will be 5 mm and the amplification gap will be  $128 \mu\text{m}$ . They are  
1055 filled with the same gas mixture as the MDTs. They will be stacked in an octuplet in an XXUV-UVXX  
1056 geometry, where X refers to straight strips and U and V refer to stereo strips at an angle of  $\pm 1.5^\circ$ . This  
1057 arrangement allows for measurement of the azimuthal coordinate and gives a large lever arm between the  
1058 straight strips for triggering purposes. Figure 2.12 shows the geometry of a single micromegas detector as  
1059 well as its operating principle [46].

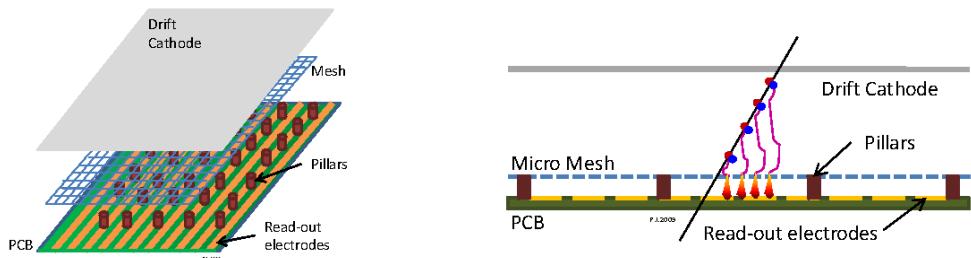


Figure 2.12: Illustrations of the geometry (left) and operating principle (right) of the micromegas detector [46]

1060 sTGCs

1061 The sTGCs are similar to the TGCs already described. They consist of gold-plated tungsten wires with a  
1062 1.8 mm pitch between two cathode planes 1.4 mm away from the wire plane. One cathode plane consists  
1063 of strips with a 3.2 mm pitch (much smaller pitch than the TGCs), while the other consists of coarser  
1064 pads that are used for defining regions of interest in the sTGC trigger algorithm. Figure 2.13 shows the  
1065 basic detector geometry.

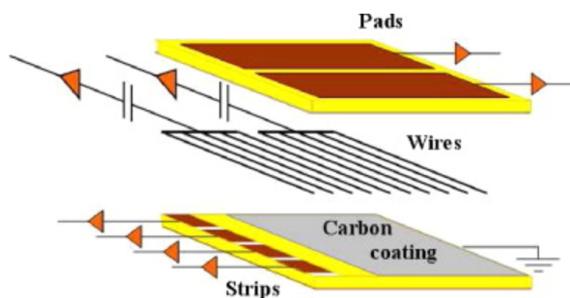


Figure 2.13: Geometry of the sTGC detector [46]

1066 2.3.3 PHYSICS IMPACT

1067 Maintaining low  $p_T$  thresholds for muons while still staying within the trigger rate budget at Level 1  
1068 (20 kHz) for the muon system is crucial for physics analyses to be successful in high luminosity condi-  
1069 tions. One realm where the lepton trigger threshold is especially important is in Higgs physics. In the  
1070  $H \rightarrow WW^*$  analysis, one of the  $W$  bosons is off shell and tends to decay to soft leptons. In associated  
1071 production of a Higgs with a  $W$ , the lepton is also important because the lepton provides the main han-  
1072 dle which allows the event to be triggered. Table 2.3 shows the impact of increasing the trigger thresholds  
1073 on these analyses. It shows that either raising the threshold or using only the barrel both have significant  
1074 impacts on the signal efficiency. With the NSW, the signal efficiency is largely maintained and the triggers  
1075 can be unprescaled.

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

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

1076 2.4 OBJECT RECONSTRUCTION IN ATLAS

1077 ATLAS analyses first start by requiring the presence of certain reconstructed physics objects in the event.  
1078 This section will present a brief overview of the algorithms used to reconstruct electrons, muons, jets (in-  
1079 cluding  $b$ -jets), and missing energy<sup>1</sup>. The performance of object reconstruction and measurement will also  
1080 be discussed as these are relevant to the analyses presented later. Figure 2.14 gives an overview of the differ-  
1081 ent sub-detectors that each type of particle will interact with in ATLAS.

---

<sup>1</sup>Reconstruction algorithms for other objects, such as photons and  $\tau$  leptons, are not detailed here as these objects are not used in the presented studies.

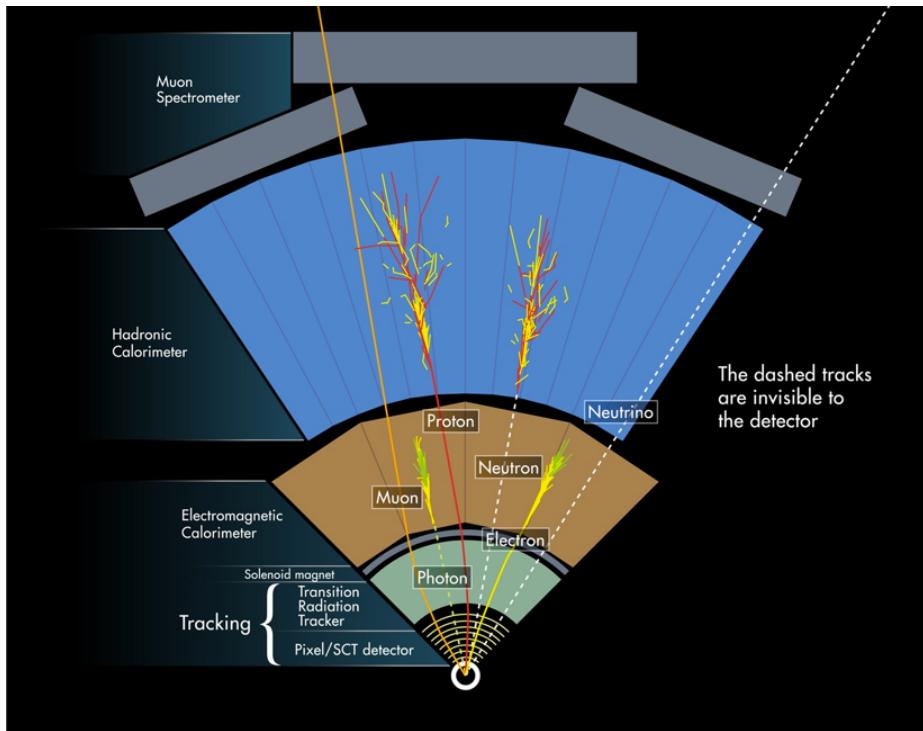


Figure 2.14: Illustration of particle interactions in ATLAS [49]

#### 1082 2.4.I ELECTRONS

1083 Electrons in ATLAS will leave tracks in the inner detector and energy deposits in the electromagnetic  
 1084 calorimeter. The algorithm for recognizing the signature of electrons proceeds in two steps: reconstruction  
 1085 and identification.

1086 In reconstruction, an electron candidate is formed by matching EM calorimeter deposits with ID tracks.  
 1087 The algorithm first chooses seed clusters in the EM calorimeter by using a sliding window algorithm that  
 1088 searches for towers with transverse energy larger than 2.5 GeV. In addition to seed clusters, track candi-  
 1089 dates must be identified in the ID. The algorithm selects seed tracks with  $p_T > 1$  GeV that do not fit well  
 1090 with a pion hypothesis. Once candidate tracks are selected, they are re-fit with a Gaussian Sum Filter (GSF)  
 1091 algorithm to estimate electron parameters [50]. Finally, an electron candidate is formed if at least one track  
 1092 matches to a seed cluster in the calorimeter. The full details of the reconstruction algorithm can be found  
 1093 in reference [51].

1094 Once an electron candidate is present, identification criteria must be applied in order to reject fake elec-

1095 trons from background. Many different variables are used for this identification, most of them related to  
 1096 the shower shape in the EM calorimeter and the amount of leakage into the hadronic calorimeter, as well  
 1097 as information from the ID and in particular the TRT. There are both cut-based and likelihood-based  
 1098 criteria that range from “loose” to “very tight”. For details, see reference [51].

1099 Figure 2.15 shows the algorithm’s reconstruction efficiency of true electrons for different identification  
 1100 criteria as well as the electron energy resolution in simulation [51, 52]. The reconstruction efficiency is  
 1101 measured using both  $Z$  and  $J/\psi$  tag and probe techniques.

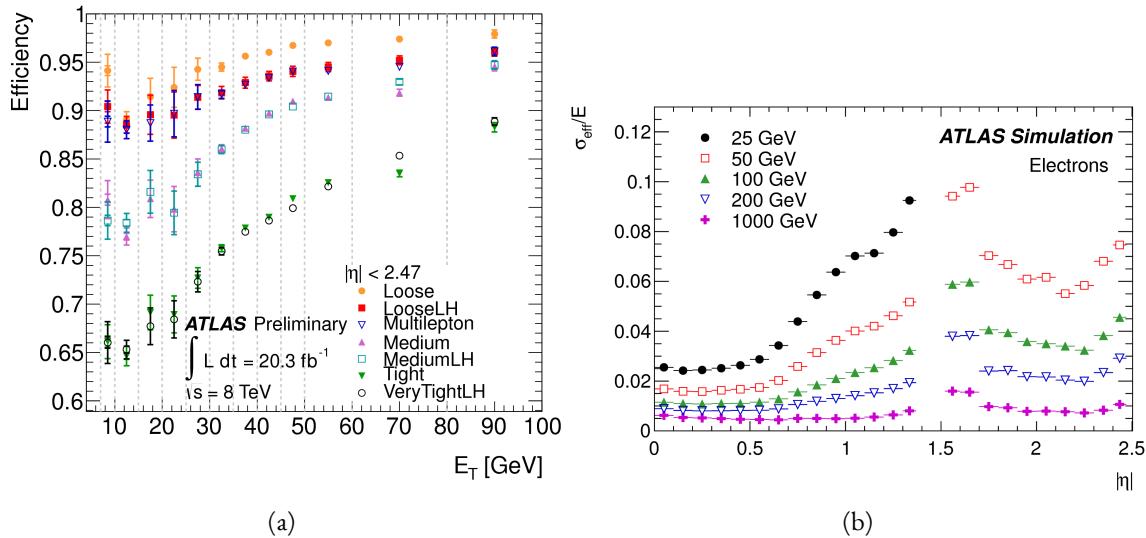


Figure 2.15: Electron performance: (a) reconstruction efficiency as a function of electron  $E_T$  [51] (b) energy resolution in simulation as a function of  $|\eta|$  for different energy electrons [52]

#### 1102 2.4.2 MUONS

1103 The ATLAS detector is designed to stop most particles before they reach the muon spectrometer. Muons,  
 1104 however, are minimum ionizing particles, meaning that they will not lose a significant amount of energy  
 1105 through interactions with the detector and will thus pass through. Therefore, the muon reconstruction  
 1106 works to match tracks in the muon spectrometer with tracks in the inner detector.

1107 The first step of reconstruction is to reconstruct local straight line tracks, called segments, in each muon  
 1108 chamber. Segments are then fit to larger tracks that traverse the entire muon spectrometer. Such muon  
 1109 tracks are referred to as “standalone” tracks (SA) as they only use information from the muon spectrometer.

1110 The standalone tracks are then matched to tracks in the inner detector to form “combined” (CB) muons,  
 1111 where the combined ID and MS fit are used to determine the momentum and direction of the muon. To  
 1112 improve acceptance, segment-tagged and calorimeter-tagged muons are also reconstructed. In these cases,  
 1113 ID tracks are matched to segments in the MS and calorimeter deposits consistent with a minimum ionizing  
 1114 particle, respectively. The details of the reconstruction can be found in reference [53].

1115 As with electrons, once muon candidates are reconstructed they have identification criteria applied to  
 1116 reduce background. These criteria include the  $\chi^2$  match between the ID and MS tracks, the number of  
 1117 hits in the ID, overall ID and MS track fit quality, and additional variables [53]. The criteria range from  
 1118 “loose” to “tight” as with electrons.

1119 Figure 2.16 shows the muon reconstruction efficiency (measured with  $Z$  and  $J/\psi$  tag and probe) and  
 1120 invariant mass resolution [53].

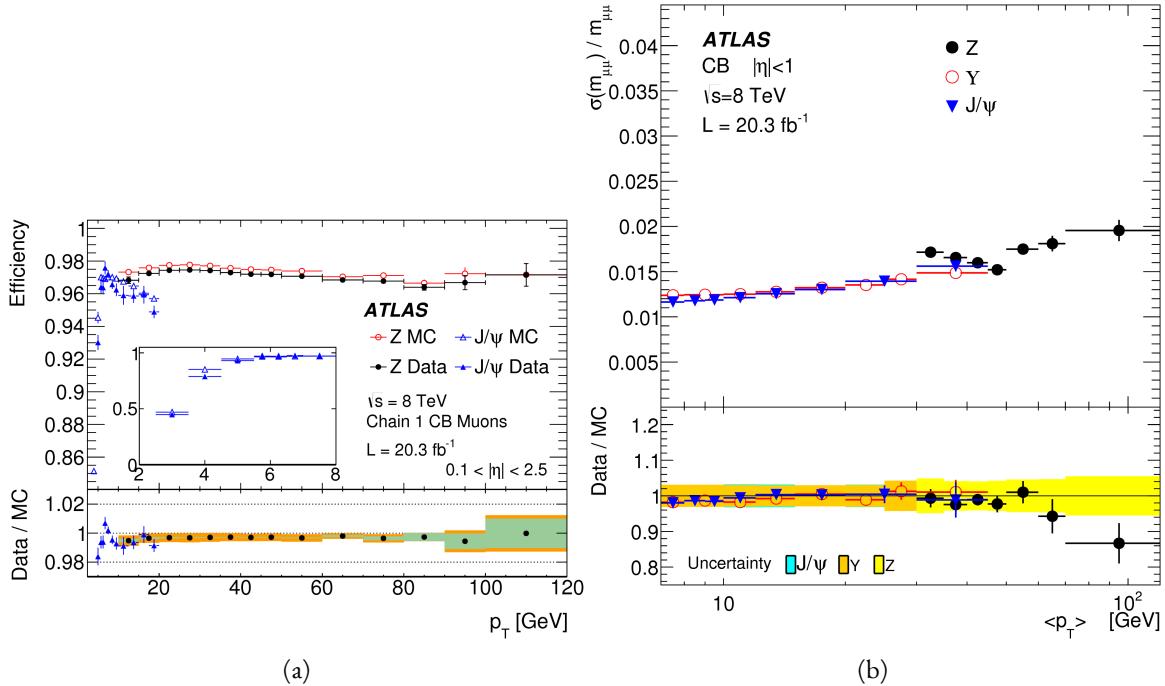


Figure 2.16: Muon performance: (a) reconstruction efficiency as a function of muon  $p_T$  (b) dimuon mass resolution as a function of average  $p_T$  [53]

1121 2.4.3 JETS

1122 When a quark or gluon is produced in collisions, it is not measured directly in ATLAS. Rather, due to  
1123 QCD effects, it produces a collimated spray of hadrons in the direction of the original parton, which is  
1124 known as a jet. Jets are reconstructed in ATLAS using energy deposits in the hadronic calorimeter. The  
1125 first step is build “topological clusters” out of energy deposits in calorimeter cells [54, 55]. This is done  
1126 using strategy where seed cells are chosen by picking cells whose energy measurements are four times the  
1127 amount of noise expected for that cell. Adjacent cells with at least  $2\sigma$  energy measurements are added to  
1128 the cluster, then a final layer of clusters with energy above  $0\sigma$  are added. Once calorimeter clusters are  
1129 formed, they are clustered further into jet candidates using the anti- $k_T$  jet clustering algorithm [56]. This  
1130 algorithm uses a parameter  $R$  that appears in the denominator of the clustering distance metric and defines  
1131 the radial size of the jet in  $\eta$ - $\phi$  space.

1132 The energy response of the calorimeter must be properly characterized in order to reconstruct jet energy.  
1133 Calorimeter clusters can be calibrated either with the EM calibration, where each cluster is assumed to have  
1134 come from the energy deposit of an electron or photon, or the LCW calibration, where local cluster weights  
1135 are computed to allow for local calibration of clusters as hadronic or electromagnetic. The details of the  
1136 jet energy calibration are not detailed here and are discussed in reference [57].

1137 Figure 2.17 shows the jet energy response after calibration in Monte Carlo as a function of the true  $p_T$   
1138 of the jet [57].

1139 2.4.4  $b$ -TAGGING

1140 One important aspect of jet physics is the task of identifying the flavor of parton that produced the  
1141 measured jet. While in general this is very difficult, jets from  $b$ -quarks offer an interesting case where such  
1142 identification is possible.  $B$  mesons have a lifetime on the order of  $10^{-12}$  seconds, which makes a  $c\tau$  on  
1143 the order of millimeters [6]. This type of displaced decay vertex can be identified in detectors like ATLAS  
1144 and allows  $b$ -jets to be distinguished from other flavors of jets<sup>2</sup>.

---

<sup>2</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

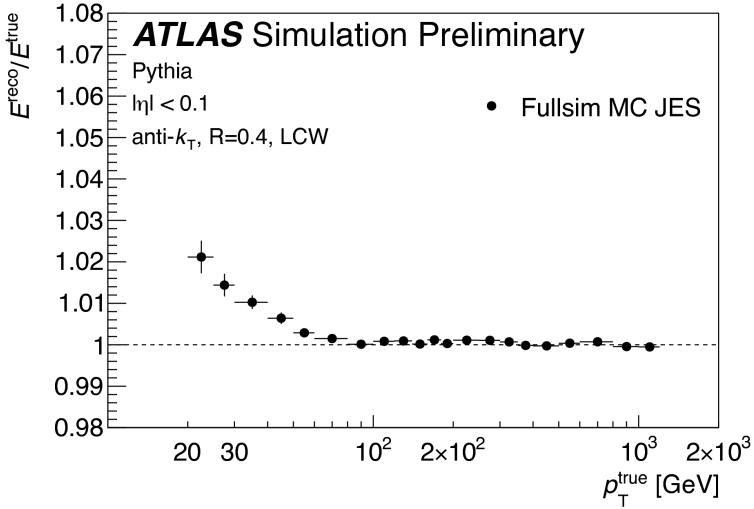


Figure 2.17: Jet energy response after calibration as a function of true  $p_T$  in simulation [57]

1145     ATLAS uses a multivariate machine learning algorithm to identify jets from  $b$ -quarks. The inputs to this  
 1146     algorithm are determined from lower level reconstruction algorithms. There are three distinct algorithms  
 1147     that reconstruct variables which are used as input to the multivariate technique.

1148     The first family is referred to as IPxD (where the x can either be 2 or 3). These algorithms use the trans-  
 1149     verse and longitudinal impact parameters  $d_0$  and  $z_0$  of the tracks inside a jet to determine their consistency  
 1150     with the primary vertex. They two or three dimensional (hence the x) templates for light flavor, charm,  
 1151     and bottom jets and then evaluate the likelihood of the jet coming from each of these types. The likelihood  
 1152     ratios are used as inputs to the multivariate algorithm.

1153     The next two algorithms used as input are referred to as the secondary vertex (SV) and JetFitter (JF)  
 1154     algorithms. The SV algorithm uses tracks inside the jet to fit for vertices that are displaced from the pri-  
 1155     mary vertex. The JF algorithm attempts to reconstruct the full flight path of the  $b$  by looking for multiple  
 1156     displaced vertices along the same line (as  $B$  decays often result in subsequent  $c$  decays).

1157     In Run 1, the multivariate  $b$ -tagging algorithm used a neural network and was referred to as MV1.  
 1158     The details of this algorithm and its inputs are given in reference [58]. In Run 2, the number of inputs  
 1159     was simplified and a boosted decision tree with 24 input variables was used, referred to as MV2 [59]. The  
 1160     MV2 algorithm is a boosted decision tree incorporating twenty-four input variables constructed from three

1161 lower level input algorithms described above. Figure 2.18 summarizes the inputs to MV2. Figure 2.19 shows  
1162 the performance of each of these algorithms.

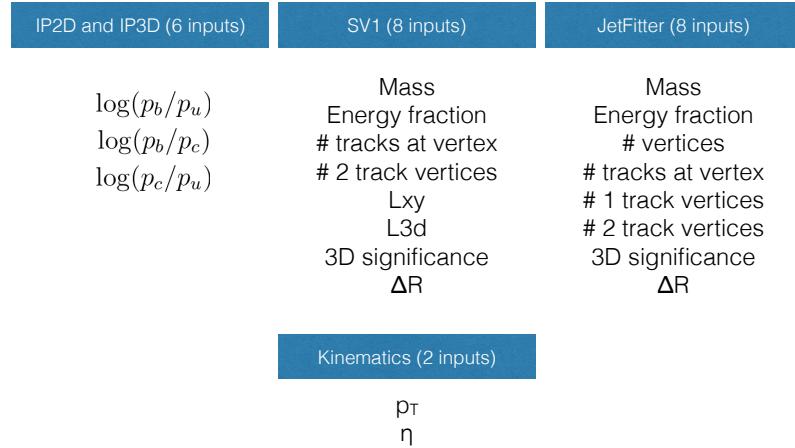


Figure 2.18: Summary of the inputs to the MV2  $b$ -tagging algorithm

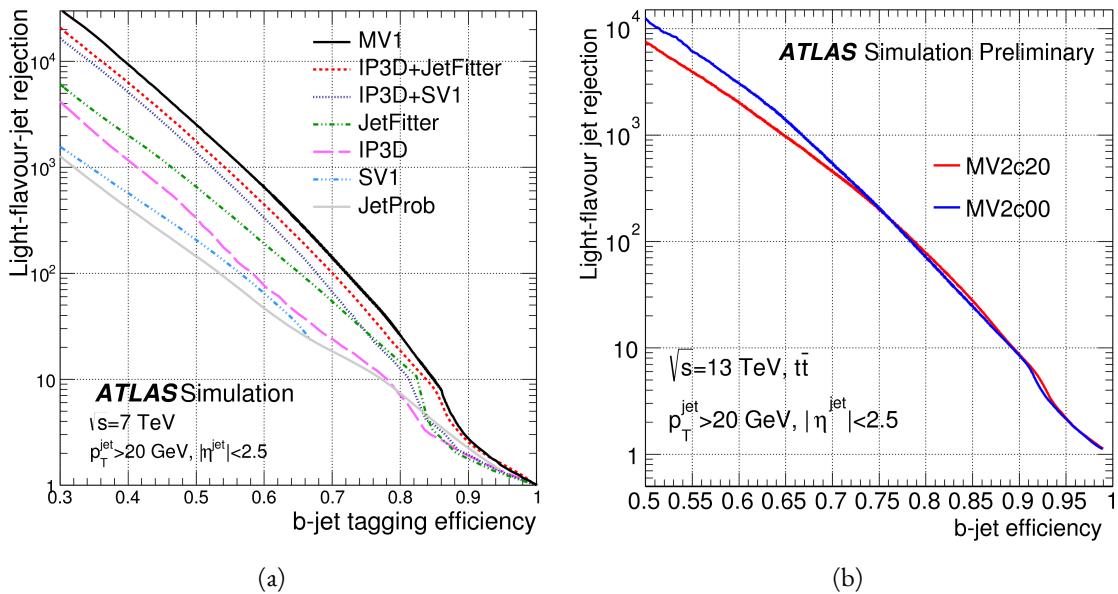


Figure 2.19: Light jet rejection (1/efficiency) vs.  $b$ -jet efficiency for MV1 and its input algorithms (a) [58] and MV2 (b) [59] in simulated  $t\bar{t}$  events. The numbers in the algorithm names in (b) refer to the fraction of charm events used in the MV2 training.

1163    2.4.5 MISSING TRANSVERSE ENERGY

1164    As noted in figure 2.14, neutrinos produced in ATLAS will pass through the detector without interact-  
1165    ing. The only way of detecting the presence of particles like neutrinos (or BSM particles that are long-lived)  
1166    is to use missing transverse momentum. The basic principle of missing transverse energy is to use the mo-  
1167    mentum balance of the incoming protons to infer the presence of missing particles. The net longitudinal  
1168    momentum of the incoming partons that collide is not known (since each carries an unknown fraction of  
1169    the proton's momentum). However, the protons (and thus incoming partons) have no net momentum  
1170    in the plane transverse to the beam line (the  $x$ - $y$ ) plane. Therefore, if there are no un-measured particles  
1171    in the final state, the transverse momenta of all of the final state particles should balance. The magnitude  
1172    of this imbalance is known as missing transverse momentum ( $E_T^{\text{miss}}$ ).

1173    The basic calculation of missing transverse momentum from calorimeter cells is given in equation 2.4 [60].

1174

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

1175    The  $E_T^{\text{miss}}$  calculation is separated into different terms based on the objects that the calorimeter clusters  
1176    are associated with. This way, each cell's contribution is calibrated appropriately according to the object.  
1177    This separation of terms is shown in equation 2.5 [60].

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

1178    The CellOut term of the above equation corresponds to calorimeter cells with energy deposits that are  
1179    not associated with other objects. The soft jets term comes from cells associated to jets with  $p_T$  between  
1180    7 and 20 GeV, while the jets term comes from jets with  $p_T > 20$  GeV. Because muons do not deposit  
1181    significant energy in the calorimeter, the muon momentum is used for the muon term [60]. The final  
1182     $E_T^{\text{miss}}$  is calculated using equation 2.6.

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

1183 Figure 2.20 shows the resolution of the components of the  $E_T^{\text{miss}}$  under different pileup suppression techniques [61].

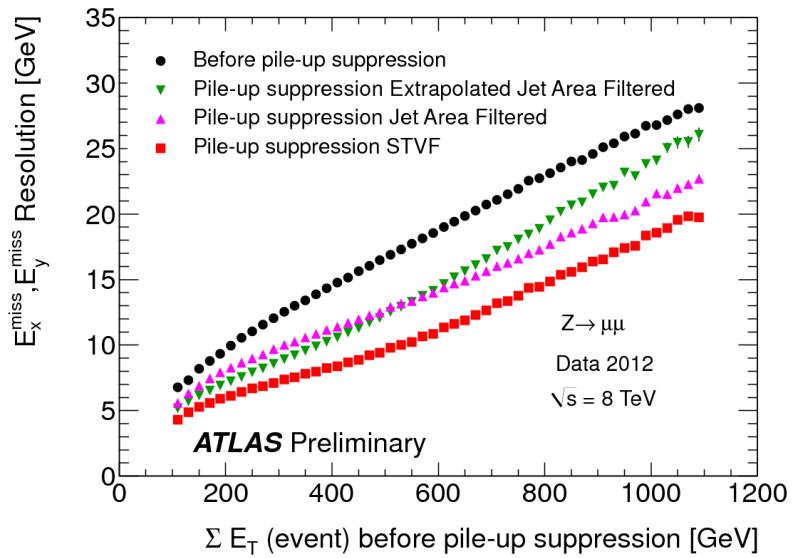


Figure 2.20: Resolution of  $E_T^{\text{miss}}$  components as a function of  $\sum E_T$  before pileup suppression with different pileup techniques [61]

1184

## Part II

1185

Observation and measurement of Higgs

1186

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

1187

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

1188

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

Wernher von Braun

# 3

1189

1190

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

### 1191 3.1 INTRODUCTION

1192 This chapter presents an overview of the strategy for searching for a Higgs boson in the  $H \rightarrow WW^* \rightarrow$   
1193  $\ell\nu\ell\nu$  decay topology. Its purpose is to define in broad terms how the search and measurement are under-  
1194 taken, before going into details on the specific sub-categories within the larger analysis. First, the properties  
1195 of the Higgs signal are discussed and the associated backgrounds are presented. Next, the observables used  
1196 to enhance the signal to background ratio are defined. Finally, the parameters of interest in the search  
1197 and measurement will be shown, along with a brief overview of the statistical treatment of the final Higgs  
1198 candidates.

1199 Following this chapter, the results of three different studies within the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel  
1200 are shown. Chapter 4 presents a search for Higgs boson production in gluon fusion mode and the role of  
1201 the  $H \rightarrow WW^*$  channel in its discovery. Chapter 5 shows the search and first evidence in ATLAS of the  
1202 Vector Boson Fusion (VBF) production mode of the Higgs. Finally, chapter 6 shows the combined Run

1203 1  $H \rightarrow WW^*$  results for the measurement of the Higgs cross section and relative coupling strengths to  
1204 other SM particles.

1205 3.2 THE  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  SIGNAL IN ATLAS

1206 The signal studied in this and subsequent chapters is the Higgs boson in the  $WW^*$  final state, where  
1207 each  $W$  boson subsequently decays into a charged lepton and a neutrino. In the simplest decay path, the  
1208 final state consists of two neutrinos and two charged leptons, each of which can be either an electron or a  
1209 muon. If a  $W$  decays to a  $\tau$  lepton, only leptonic decays of the  $\tau$  are considered. The  $\tau$  lepton produce  
1210 additional neutrinos in the final state but still yield two charged leptons (where each lepton is an electron or  
1211 muon). Neutrinos are not detected in ATLAS, so the final state ultimately consists of two reconstructed  
1212 leptons and missing transverse momentum (denoted as  $E_T^{\text{miss}}$ ). Final states where both of the charged  
1213 leptons are electrons or muons are referred to as the “same flavor” ( $ee/\mu\mu$ ) final states, while those with  
1214 one electron and one muon are referred to as “different flavor” ( $e\mu$  or  $\mu e$ ).

1215 There can be additional jets produced in association with the Higgs boson. As described in detail in  
1216 Chapter 1, if the Higgs is produced via vector boson fusion production, there will be two additional forward  
1217 jets in the event. In gluon fusion, one or more jets can be produced through initial state radiation from  
1218 the incoming gluons. Because of the varying background composition as a function of jet multiplicity,  
1219 each bin in this variable has its own dedicated requirements applied in the search and measurement. The  
1220  $n_j = 0$  and  $n_j = 1$  bins are dedicated to gluon fusion production, while the  $n_j \geq 2$  bin has separate  
1221 dedicated searches for ggF and VBF production.

1222 Figure 3.1 shows the relative branching fractions for the  $H \rightarrow WW^*$  process, calculated from the Par-  
1223 ticle Data Group values for the  $W$  and  $\tau$  branching ratios [6]. The largest branching ratio corresponds  
1224 to both  $W$  bosons decaying to quark pairs at 45.44%. The second largest ratio is for one  $W$  decaying lep-  
1225 tonically and the other decaying to quarks, a branching ratio of 34.18%. In all cases,  $\ell$  denotes either an  
1226 electron or muon, and the leptonic branching ratios of the  $\tau$  are included. For example, the  $\ell\nu qq$  final  
1227 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  
1228 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

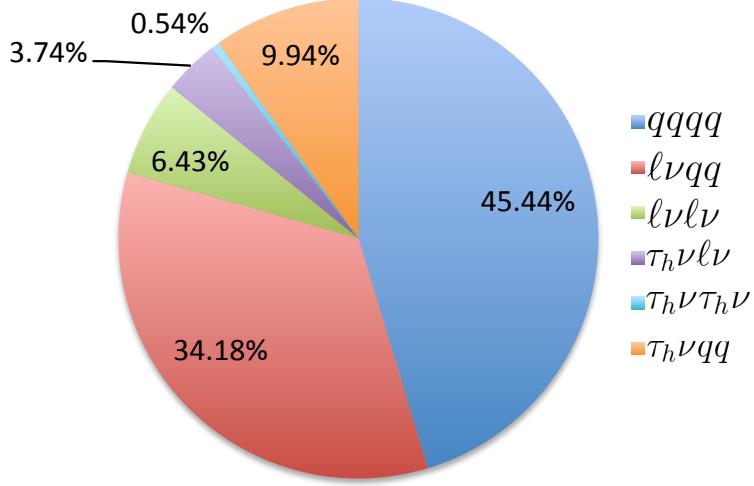


Figure 3.1: Branching ratios for a  $WW$  system.  $q$  refers to quarks.  $\ell$  can be either an electron or muon, and the leptonic branching ratios of the  $\tau$  are included. For example, the  $\ell\nu qq$  final state includes one  $W$  decaying to  $e\nu$ ,  $\mu\nu$ , or  $\tau\nu$ .  $\tau_h$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

<sup>1229</sup> branching ratio of the  $\ell\nu\ell\nu$  final state is 6.43%.

<sup>1230</sup> While the  $\ell\nu\ell\nu$  final state is not a large fraction of the branching ratio, there are significant advantages  
<sup>1231</sup> to using this channel in an analysis. First, both the  $qqqq$  and  $\ell\nu qq$  channels suffer from a large QCD  
<sup>1232</sup> multijet background, which is often difficult to model. Second, events in the the  $\ell\nu\ell\nu$  channel in data can  
<sup>1233</sup> be triggered more efficiently due to the presence of two leptons.

### <sup>1234</sup> 3.3 BACKGROUND PROCESSES

<sup>1235</sup> Many processes from the Standard Model can also produce a final state with two leptons and missing  
<sup>1236</sup> transverse momentum. This section describes the dominant backgrounds to Higgs production and further  
<sup>1237</sup> explains how they can be reduced. Table 3.1 summarizes the different background processes.

#### <sup>1238</sup> 3.3.1 STANDARD MODEL WW PRODUCTION

<sup>1239</sup> Non-resonant Standard Model diboson production, as shown in figure 3.2, is an irreducible background  
<sup>1240</sup> to Higgs boson production in the  $WW$  final state. It produces the same exact final state objects, namely

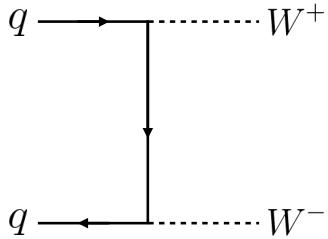


Figure 3.2: Feynman diagram for Standard Model  $WW$  production

1241 leptonically decaying  $W$  bosons. There are no additional objects in the final state that allow for back-  
1242 ground reduction. Therefore the analysis solely relies on the correlations between the leptons to reduce  
1243 this background.

1244 **3.3.2 TOP QUARK PRODUCTION**

1245 Top quark production can mimic the Higgs in the  $WW^*$  final state as well. Top quarks can be pro-  
1246 duced either in pairs ( $t\bar{t}$  production) or singly ( $s$ -channel,  $t$ -channel, or associated production  $Wt$ ). The  
1247 dominant top background are  $t\bar{t}$  and  $Wt$  production.

1248 Because top quarks decay via  $t \rightarrow Wb$ , top pair production can produce a final state with two  $W$  bosons  
1249 that then decay leptonically. In  $Wt$  production, there are two real  $W$  bosons produced, as with  $t\bar{t}$ . In  
1250 both cases, there is at least one  $b$ -jet in the final state. By vetoing on the presence of  $b$ -jets, these top quark  
1251 backgrounds can be reduced. Figure 3.3 shows the Feynman diagrams for  $t\bar{t}$  and  $Wt$  production.

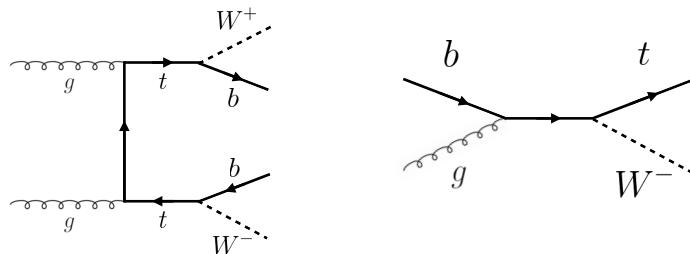


Figure 3.3: Feynman diagrams for top pair production (left) and  $Wt$  production (right)

1252    3.3.3     $W + \text{JETS BACKGROUND}$

1253    Single  $W$  boson production in association with jets is a unique background to Higgs production. The  
1254    other backgrounds considered thus far have all included two prompt leptons, each decaying from a  $W$   
1255    boson, in the final state. In  $W + \text{jets}$  production, however, only one reconstructed lepton originates from  
1256    a  $W$ . The second reconstructed lepton is either an algorithmic “fake” or the result of non-prompt decays.  
1257    In the first case, the lepton is a jet misidentified as a lepton by either the electron or muon reconstruction  
1258    algorithms. In the second case, the lepton may be a real lepton but coming from semi-leptonic decays of  
1259    particles inside the shower of the jet. This background can be reduced by requiring that the reconstructed  
1260    lepton have little activity in the surrounding region of the calorimeter (also known as an “isolation”). Fig-  
1261    ure 3.4 shows the Feynman diagram for  $W + \text{jets}$  production.

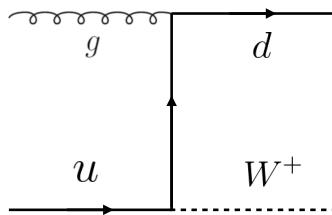


Figure 3.4: An example Feynman diagram of  $W + \text{jets}$  production

1262    3.3.4     $Z/\gamma^* + \text{JETS BACKGROUND}$

1263    Production of a  $Z$  boson or virtual photon (also known as Drell-Yan and denoted with  $Z/\gamma^*$ ) in as-  
1264    sociation with jets is also a background to Higgs production. The  $Z$  boson decays to two leptons of the  
1265    same flavor. When the  $Z/\gamma^*$  decays directly to electrons or muons, the background enters the same flavor  
1266    final state. When the  $Z$  decays to two  $\tau$  leptons the background can enter the different flavor final state as  
1267    well. Figure 3.5 shows the production of a  $Z$  in association with one jet. Because there are no neutrinos in  
1268    this final state, variables like  $E_T^{\text{miss}}$  can be used to reduce the background<sup>1</sup>.

---

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



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

### 1269 3.3.5 SUBDOMINANT BACKGROUNDS

1270 There are additional processes which contribute to the background composition. These backgrounds  
1271 are subdominant and contribute less to the total background estimate than those discussed previously.  
1272 The first process is referred to as  $VV$  or “Other diboson” processes and includes multiple Standard Model  
1273 diboson processes, including  $WZ$ ,  $ZZ$ ,  $W\gamma$ ,  $W\gamma^*$ , and  $Z\gamma$  production. Additionally, there is a back-  
1274 ground contribution from QCD multijet production. While the cross section for this process is large, its  
1275 contribution to the  $WW^*$  final state is small because two jets must be misidentified as leptons.

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

### 1276 3.4 SHARED SIGNAL REGION SELECTION REQUIREMENTS

1277 As presented in section 3.2, there are many different combinations of physics objects that can define a  
1278  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  final state. The multiplicity of jets and the flavor combinations of the leptons

1279 both lead to many potential signal regions. Additionally, signal regions can be optimized separately to be  
 1280 sensitive to the distinct production modes of the Higgs. Gluon fusion, vector boson fusion, and associated  
 1281 production of a Higgs all lead to unique final state topologies. Figure 3.6 delineates the different signal  
 1282 regions used in the gluon fusion and vector boson fusion  $H \rightarrow WW^*$  analyses. While there are different  
 1283 optimizations possible in each signal region, there are also some commonly shared selections that will be  
 1284 described here.

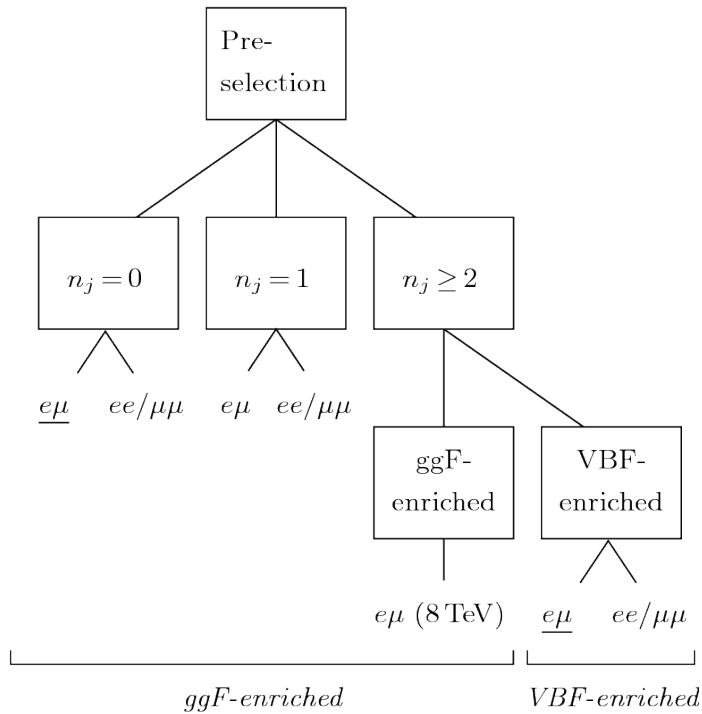


Figure 3.6: An illustration of the unique analysis signal regions [62]. The most sensitive regions for both gluon fusion and vector boson fusion production are underlined.

#### 1285 3.4.1 EVENT PRE-SELECTION

1286 Before being sorted into the distinct signal regions, basic requirements are applied to the reconstructed  
 1287 objects in the event to select Higgs-like event candidates. First, two oppositely charged leptons are required.  
 1288 Once the leptons are selected, the last requirement for event pre-selection is the presence of neutrinos. As  
 1289 neutrinos cannot be detected directly in ATLAS,  $E_T^{\text{miss}}$  can be used as a proxy for the combined neutrino  
 1290 momentum in the transverse plane.

1291 In general, it is expected that the signal should have a harder  $E_T^{\text{miss}}$  spectrum than backgrounds, espe-  
 1292 cially if these backgrounds do not contain neutrinos in the final state. When using  $E_T^{\text{miss}}$ , it is possible  
 1293 mis-measurements of objects in the detector can lead to imbalances in the transverse plane. When such a  
 1294 mis-measurement occurs, the  $E_T^{\text{miss}}$  vector in the transverse plane will often point in the same direction as  
 1295 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  
 1296 in equation 3.1.

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

1297 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  
 1298 away from this object. Otherwise, the normal  $E_T^{\text{miss}}$  vector is used. Figure 3.7 shows a graphical illustration  
 of this concept.

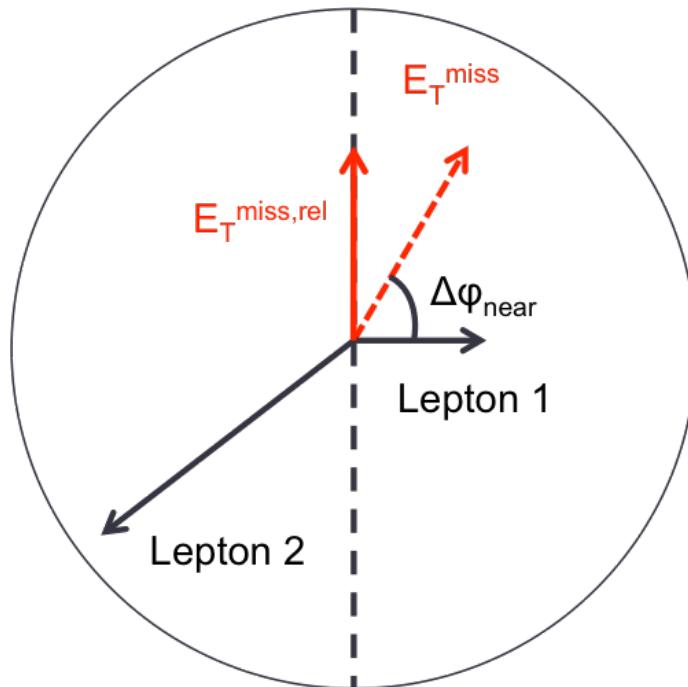


Figure 3.7: A graphical illustration of the  $E_{T,\text{rel}}^{\text{miss}}$  calculation

1299  
 1300 Once the lepton and  $E_T^{\text{miss}}$  pre-selections are made, the analysis is divided into different regions accord-  
 1301 ing to jet multiplicity.

1302    3.4.2 JET MULTIPLICITY

1303    Jet multiplicity, denoted as  $n_j$ , is used to sub-divide the analysis into distinct signal regions. By creating  
 1304    separate signal regions, each bin in jet multiplicity becomes sensitive to different modes of Higgs produc-  
 1305    tion and different backgrounds.

1306    For example, the  $n_j \geq 2$  region is more sensitive to VBF production because of the two high momen-  
 1307    tum jets produced at matrix element level. For gluon fusion production to enter this bin, two initial state  
 1308    radiation jets must be emitted.

1309    Figure 3.8 shows the jet multiplicity in both the different flavor and same flavor regions after the pre-  
 1310    selection. It also shows the background composition in the bins of  $n_b$ . A few trends from this distribution  
 1311    are worth noting. The first is that the Drell-Yan background dominates in the same flavor channels for  
 1312     $n_j \leq 1$ . Second, the top background becomes a clear contributor to the total background for  $n_j \geq$   
 1313    1. Lastly, the SM WW production dominates in the  $n_j = 0$  bin, as it is an irreducible background to  
 1314     $H \rightarrow WW^*$  production. Because of these distinct features, each jet multiplicity bin is treated separately.

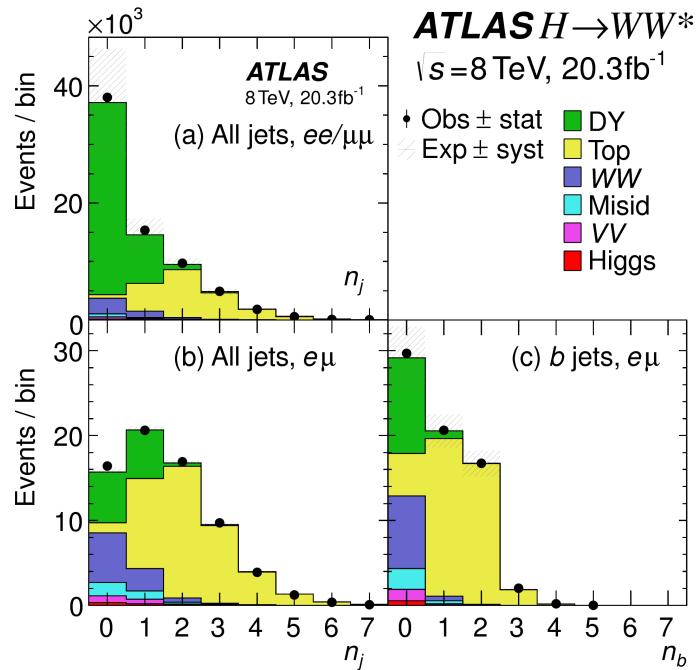


Figure 3.8: Predicted backgrounds (compared with data) as a function of  $n_j$  (a and b) and  $n_b$  (c) after pre-selection requirements

1315    **3.5 BACKGROUND REDUCTION IN SAME-FLAVOR FINAL STATES**

1316    As described in section 3.4.2, the background composition of the same flavor final states is different  
1317    from that of the different flavor states. In particular, Drell Yan processes play a much larger role because  
1318    the  $Z/\gamma^*$  decays to same flavor leptons. Because real neutrinos are absent in the  $Z/\gamma^*$  decays to  $ee$  and  $\mu\mu$ ,  
1319    a requirement on  $E_T^{\text{miss}}$  should largely reduce the background. However, as this section will demonstrate,  
1320    with increasing pileup conditions the resolution of the calorimeter-based  $E_T^{\text{miss}}$  degrades greatly. There-  
1321    fore, two new variables for  $Z/\gamma^*$  background reduction are constructed and described in this section.

1322    **3.5.1 PILEUP AND  $E_T^{\text{miss}}$  RESOLUTION**

1323    Secondary interactions of protons in the colliding bunches of the LHC (known as pileup interactions,  
1324    described in detail in Chapter 2) deposit energy into the ATLAS calorimeter in addition to the energy that  
1325    comes from the hard scatter process of interest. The calculation of  $E_T^{\text{miss}}$  is fundamentally Poissonian.  
1326    Summing up all of the energy deposits in individual calorimeter cells or clusters is similar to a counting  
1327    experiment. The error on a mean of  $N$  in a Poisson distribution is  $\sqrt{N}$ , so the energy resolution scales  
1328    as  $\sqrt{E}$ . As more energy is deposited in the calorimeter, the  $E_T^{\text{miss}}$  resolution degrades, meaning that the  
1329     $E_T^{\text{miss}}$  resolution is particularly sensitive to LHC instantaneous luminosity conditions.

1330    Figure 3.9 shows an event display of a  $Z/\gamma^* + \text{jets}$  event candidate with the twenty-five reconstructed  
1331    primary vertices. This display illustrates that while the interaction of interest only has tracks coming from  
1332    the hardest primary vertex, all of the secondary interactions deposit energy in the calorimeter as well.

1333    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-  
1334    trinos) as a function of the number of the average number of interactions. Under 2011 LHC conditions,  
1335    this RMS was approximately 9 GeV, while under 2012 running conditions the resolution worsened to 12  
1336    GeV. The increase in pileup dilutes the  $E_T^{\text{miss}}$  variable's ability to reduce the  $Z/\gamma^*$  background.

1337    **3.5.2 TRACK-BASED DEFINITIONS OF MISSING TRANSVERSE MOMENTUM**

1338    Because the increasing number of secondary proton-proton interactions degrades calorimeter-based  
1339     $E_T^{\text{miss}}$  resolution, a new variable using only contributions from the primary interaction vertex is necessary

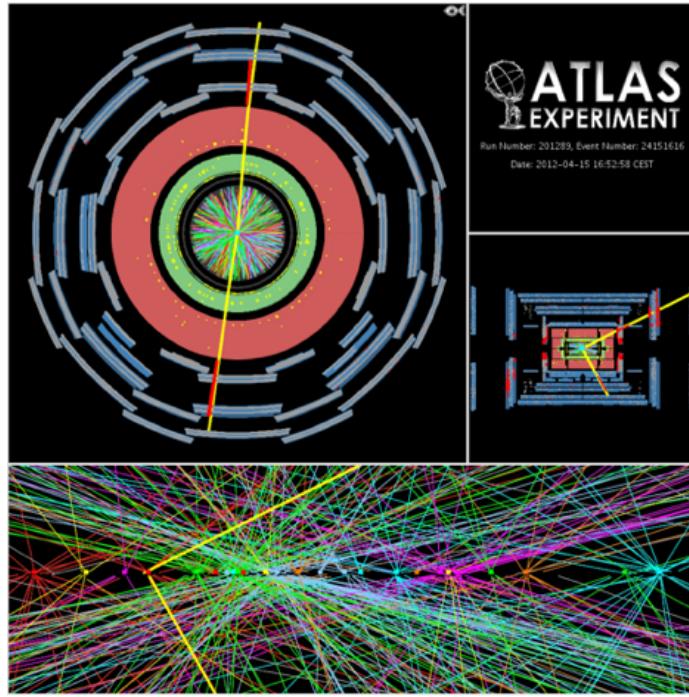


Figure 3.9: An event display of a  $Z/\gamma^*$  + jets event illustrating the effect of pileup interactions

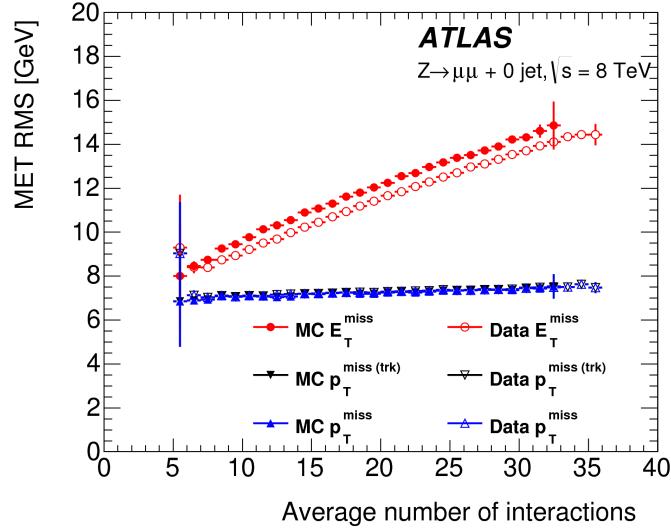


Figure 3.10: The RMS of different missing transverse momentum definitions as a function of the average number of interactions per bunch crossing

<sup>1340</sup> to further reduce the  $Z/\gamma^*$  background. While it is not possible to associate calorimeter energy deposits  
<sup>1341</sup> with a particular vertex, individual charged particle tracks in the Inner Detector are associated to unique  
<sup>1342</sup> vertices. Thus, two track-based definitions of missing transverse momentum , using only tracks coming

1343 from the primary vertex in the event, are used in the analysis. The simplest variable,  $p_T^{\text{miss}(\text{trk})}$ , is the vec-  
 1344 torial sum of the  $p_T$  of all of the tracks from the primary vertex and the selected leptons (excluding the  
 1345 tracks associated with the selected leptons to avoid double counting). Equation 3.2 defines  $p_T^{\text{miss}(\text{trk})}$ .

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

1346 To further improve the resolution on the missing transverse momentum, the variable  $p_T^{\text{miss}}$  is used as de-  
 1347 fined in equation 3.3. For selected leptons and jets, the nominal  $p_T$  measurements are used. Tracks are used  
 1348 to estimate the soft component of the missing transverse momentum instead of calorimeter measurements.

1349

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

1350 Figure 3.10 illustrates that these two new variables accomplish their intended purpose. The resolution as a  
 1351 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  
 1352 for  $E_T^{\text{miss}}$ . Figure 3.11a shows the difference between the true and reconstructed values of missing transverse  
 1353 momentum using both the track-based  $p_T^{\text{miss}}$  and calorimeter based  $E_T^{\text{miss}}$ . The RMS of the distribution  
 1354 improves by 3.5 GeV when using  $p_T^{\text{miss}}$ .

### 1355 3.5.3 DISTINGUISHING $Z/\gamma^*$ +JETS AND $H \rightarrow WW^*$ TOPOLOGIES

1356 In addition to measuring missing transverse momentum, another variable can be constructed to exploit  
 1357 kinematic and topological differences between the  $Z/\gamma^*$  background and  $H \rightarrow WW^*$  signal. Because  
 1358 there are no real neutrinos in the final state (in the case of  $Z/\gamma^* \rightarrow ee, \mu\mu$  decays), the dilepton system will  
 1359 be balanced with the jets produced in the hard scatter. A new variable,  $f_{\text{recoil}}$ , is constructed to estimate  
 1360 the balance between the dilepton system and recoiling jets and is defined in equation 3.4. The transverse  
 1361 plane is divided into four sections, or quadrants, with one quadrant centered on the dilepton vector. The  
 1362 numerator of  $f_{\text{recoil}}$  is the magnitude of the vectorial sum of the  $p_T$  of jets in the quadrant opposite the  
 1363 dilepton system, weighted by each jet's Jet Vertex Fraction (JVF, described in chapter 2). The denominator

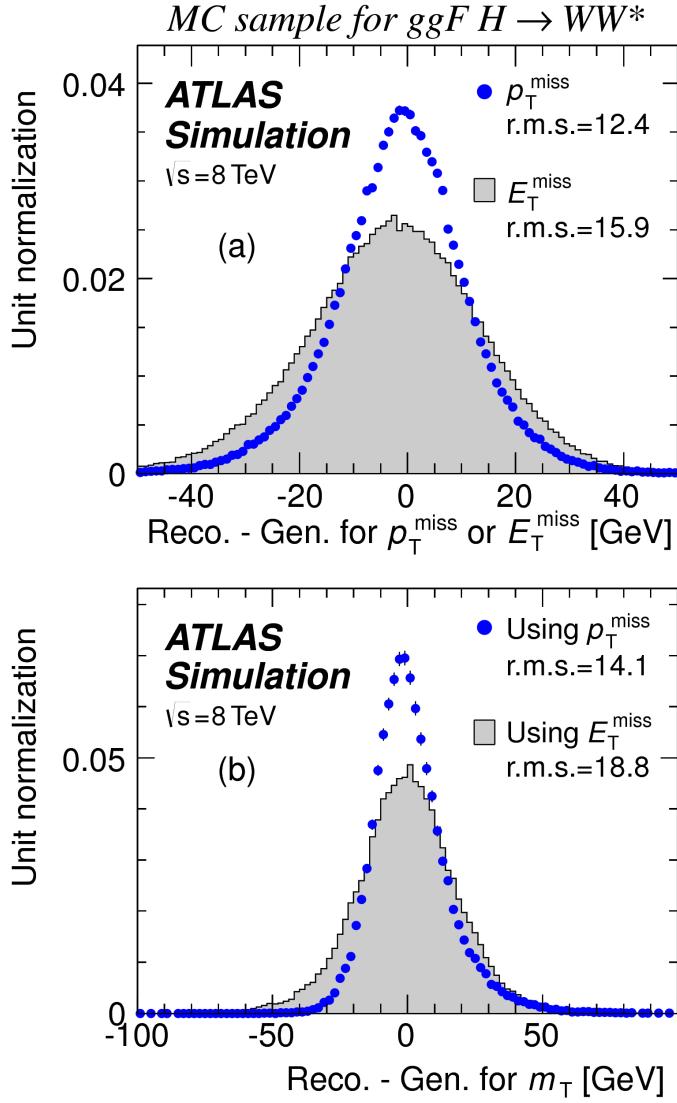


Figure 3.II: The difference between the true and reconstructed values of the missing transverse momentum (a) and  $m_T$  (b) in a gluon fusion signal sample

<sup>1364</sup> is the magnitude of the dilepton  $p_T$ .

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

<sup>1365</sup> Figure 3.12 shows a shape comparison of the  $f_{\text{recoil}}$  distribution in a simulated  $Z/\gamma^* + \text{jets}$  sample, a  
<sup>1366</sup>  $H \rightarrow WW^*$  signal sample, and other backgrounds that contain real neutrinos. The  $Z/\gamma^* + \text{jets}$  events

1367 tend to be more balanced between the dilepton system and recoiling jets, while the processes containing  
 1368 real neutrinos are less balanced in the transverse plane. Thus, a requirement on  $f_{\text{recoil}}$  will reduce the  $Z/\gamma^*$   
 1369 + jets background while maintaining a good signal efficiency.

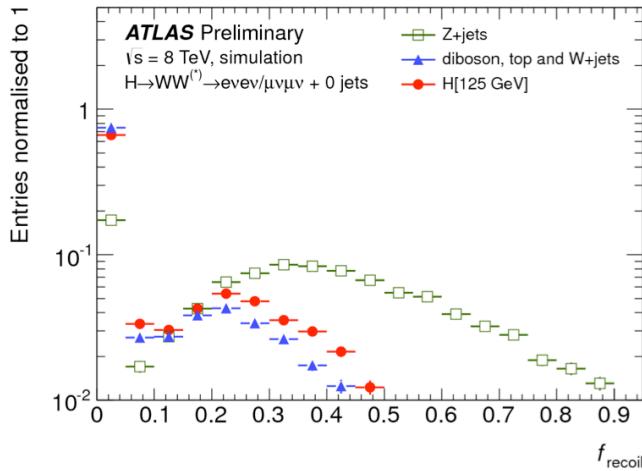


Figure 3.12: Comparison of  $f_{\text{recoil}}$  distributions for  $Z/\gamma^* + \text{jets}$ ,  $H \rightarrow WW^*$ , and other backgrounds with real neutrinos.

### 1370 3.5.4 OPTIMIZING BACKGROUND REDUCTION SELECTION REQUIREMENTS

1371 The requirements on  $p_T^{\text{miss}(\text{trk})}$  and  $f_{\text{recoil}}$  used to reduce the  $Z + \text{jets}$  background must be optimized  
 1372 to maximize expected signal significance in the same flavor channels. Figure 3.13 shows an optimization of  
 1373 the combination of the two requirements in the gluon fusion zero jet bin. Each bin shows the expected  
 1374 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  
 1375 required to be less than the top edge of the bin. The figure shows that the best signal significance comes  
 1376 from requiring low values of  $f_{\text{recoil}}$  ( $< 0.05$ ) and  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  values greater than 45 GeV.

## 1377 3.6 PARAMETERS OF INTEREST AND STATISTICAL TREATMENT

1378 As with any search or measurement, there are particular parameters of the Higgs that the  $H \rightarrow WW^*$   
 1379 analysis is interested in measuring. In this case, the parameters of interest are the mass of the Higgs boson  
 1380 and its production cross section. Because the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  process does not have a closed final

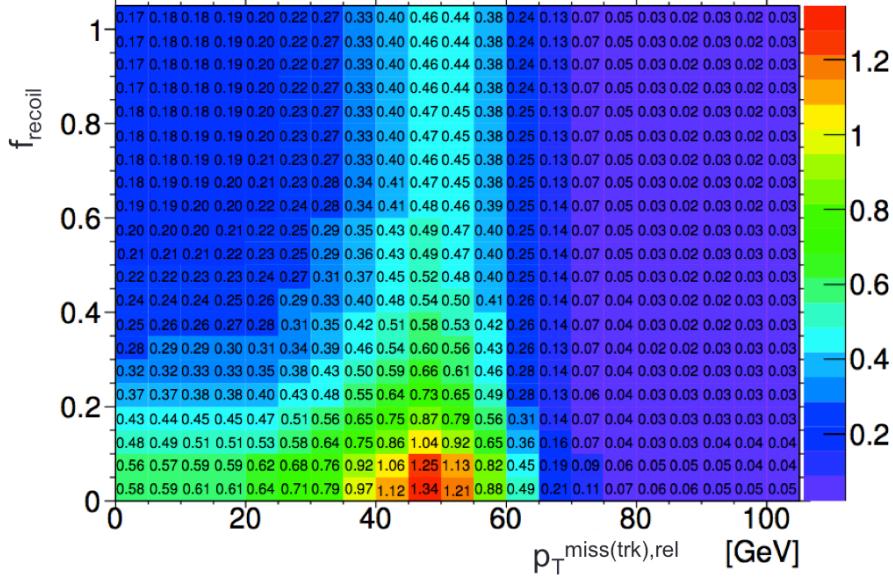


Figure 3.13: Signal significance as a function of required value for  $f_{\text{recoil}}$  and  $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$  in the ggF  $H \rightarrow WW^*$  with  $n_j = 0$

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

1391 exploiting information from the transverse plane. The transverse mass is defined in equation 3.6.

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

1392 Here the  $E_T^{\ell\ell}$  and  $p_T^{\ell\ell}$  are the transverse energy and momentum of the dilepton system, while  $p_T^{\text{miss}}$  is a  
1393 proxy for the transverse momentum of the di-neutrino system. The track-based  $p_T^{\text{miss}}$  is used in the  $m_T$   
1394 rather than the calorimeter based  $E_T^{\text{miss}}$  because it has a better resolution on the true transverse mass.  
1395 Figure 3.11b shows the improvement in the RMS of the difference between the true and reconstructed  
1396 transverse mass in a ggF signal sample. The RMS improves by 4.7 GeV using  $p_T^{\text{miss}}$  in the  $m_T$  calculation.

1397 **3.6.2 STATISTICAL TREATMENT<sup>2</sup>**

1398 **LIKELIHOOD FUNCTION**

1399 The statistical analysis of final event candidates is framed as a hypothesis test, where the null hypoth-  
1400 esis is background-only (no Standard Model Higgs). The first step in the analysis is to form a likelihood  
1401 function for the data. In its simplest form, this likelihood is the probability of observing the number of  
1402 events seen in the final signal region given knowledge of the signal strength. Because observation of events  
1403 is fundamentally a Poisson counting experiment, this simple likelihood can be expressed as a Poisson prob-  
1404 ability of observing  $N$  events given a total number of predicted signal and background events. This basic  
1405 likelihood is shown in equation 3.7.

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

1406 Here,  $P$  is the Poisson probability density function,  $N$  is the total number of observed events,  $\mu$  is the  
1407 signal strength,  $S$  is the predicted number of signal events, and  $B$  is the predicted number of background  
1408 events.

1409 In particle physics, certain background estimates are commonly normalized in so-called “control” re-  
1410 gions and those predictions are scaled by the same normalization factor in the signal region. This leads to a

---

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

<sub>1411</sub> slightly more complicated likelihood, which is a function of both the signal strength and the background  
<sub>1412</sub> normalization. This is shown in equation 3.8.

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

<sub>1413</sub> Here,  $\theta$  serves as a “nuisance parameter”, or a parameter that is not of primary interest but still enters the  
<sub>1414</sub> likelihood. The second Poisson term enforces that the background normalization be consistent with the  
<sub>1415</sub> number of observed events in data in the control region,  $N_{\text{CR}}$ .

<sub>1416</sub> So far, these two formulations of likelihoods have assumed a single signal region and do not take into  
<sub>1417</sub> account any shape information of potential discriminating variables. The  $H \rightarrow WW^*$  analysis is divided  
<sub>1418</sub> into many different categories, the counting experiment described above can be performed in each individ-  
<sub>1419</sub> ual category. As mentioned in section 3.6.1, the transverse mass is used as the primary discriminating vari-  
<sub>1420</sub> able in many of the  $H \rightarrow WW^*$  sub-analyses. The same counting experiment can be performed in each  
<sub>1421</sub> bin of the  $m_T$  distribution to incorporate some shape information. Thus, the total likelihood becomes a  
<sub>1422</sub> product over signal regions and bins of the  $m_T$  distribution. Finally, there are usually many backgrounds  
<sub>1423</sub> that are normalized in control regions. The new formulation of the likelihood takes this into account by  
<sub>1424</sub> including a product over control regions in the second Poisson term. All of these modifications are shown  
<sub>1425</sub> in equation 3.9.

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

<sub>1426</sub> The final step to obtain the full likelihood used in the analysis is to add nuisance parameters for the  
<sub>1427</sub> systematic uncertainties. In cases where the uncertainty does not affect the shape of  $m_T$  bin-by-bin, each  
<sub>1428</sub> systematic uncertainty  $\epsilon$  is allowed to affect the expected event yields through a linear response function  
<sub>1429</sub> of the nuisance parameter, namely  $\nu(\theta) = (1 + \epsilon)\theta$ . If instead the uncertainty does affect the shape, the  
<sub>1430</sub> effect is instead parameterized by  $\nu_b(\theta) = 1 + \epsilon_b\theta$ . The value of the nuisance parameters for the systematic  
<sub>1431</sub> uncertainty are constrained with a Gaussian term that is added to the likelihood as well. This is of the form  
<sub>1432</sub>  $g(\delta|\theta) = e^{-(\delta-\theta)^2/2}/\sqrt{2\pi}$ , where  $\delta$  is the central value and  $\theta$  is a nuisance parameter. Finally, a last term is

<sup>1433</sup> added to account for the statistical uncertainty in the Monte Carlo samples used, which adds an additional  
<sup>1434</sup> poisson term. The full likelihood used in the final statistical analysis is defined in equation 3.10.

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

<sup>1435</sup> The fourth term of the equation quantifies the uncertainty due to finite Monte Carlo sample size. Here,  
<sup>1436</sup>  $\xi$  represents the central value of the background prediction,  $\theta$  is the associated nuisance parameter,  $\zeta =$   
<sup>1437</sup>  $(B/\delta B)^2$ , where  $\delta B$  is the statistical uncertainty of  $B$ .

<sup>1438</sup> The best fit value of the signal strength  $\mu$  is determined by finding the values of  $\mu$  and  $\boldsymbol{\theta}$  that maximize  
<sup>1439</sup> the likelihood, while setting  $\delta = 0$  and  $\xi = \zeta$ . Once the likelihood is defined, a test statistic must be built  
<sup>1440</sup> for use in hypothesis testing.

#### <sup>1441</sup> TEST STATISTIC

<sup>1442</sup> To distinguish whether the data match a background only or background and signal hypothesis, a test  
<sup>1443</sup> statistic must be used. The  $H \rightarrow WW^*$  analysis uses the profile likelihood technique [64]. The first step  
<sup>1444</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>1445</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>1446</sup> and  $\hat{\mu}$  represent the values of  $\theta$  and  $\mu$  that gives the overall maximum value of the likelihood.

1447 Once this is defined, a test statistic  $q_\mu$  is constructed. This is shown in equation 3.12.

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

1448 A higher value of  $q_\mu$  indicates that the data are more incompatible with the hypothesized value of  $\mu$ , and  
1449  $q_0$  then corresponds to the value of the test statistic for the background only hypothesis. A  $p_0$  value is  
1450 then defined to quantify the compatibility between the data and the null hypothesis. The  $p_0$  value is the  
1451 probability of obtaining a value of  $q_0$  larger than the observed value, and this is shown in equation 3.13.

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

1452 Here  $f(q_\mu)$  is the probability distribution function of the test statistic. Finally, the  $p_0$  value can be con-  
1453 verted into a signal significance, using the formula in equation 3.14, or the one-sided tail of the Gaussian  
1454 distribution.

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

1455 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

1456

## 1457 The discovery of the Higgs boson and the role

1458

## of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel

1459

### 4.1 INTRODUCTION

1460

This chapter presents the results of the search for the Higgs boson in  $4.8 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 7 \text{ TeV}$

1461

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

1462

,  $H \rightarrow \gamma\gamma$ , and  $H \rightarrow ZZ \rightarrow 4\ell$  channels are combined with results of searches at  $\sqrt{s} = 7 \text{ TeV}$

1463

in the same search channels (as well as the  $H \rightarrow \tau\tau$  production and associated production searches for

1464

$H \rightarrow b\bar{b}$ ). The results of this combination are a  $5.9\sigma$  detection of a new particle consistent with a Higgs

1465

boson. Rather than going into detail for all of the different Higgs decay searches, this chapter will discuss

1466

the three most sensitive channels and in particular focus on  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ . While the focus is on

1467

$WW^*$ , some of the  $ZZ^*$  and  $\gamma\gamma$  results are shown for completeness. The results not discussed here can

1468 be found in the ATLAS Higgs discovery publication [1].

1469 **4.2 DATA AND SIMULATION SAMPLES**

1470 The data sample used for the following results was taken in 2011 and 2012 at center of mass energies  
1471 of 7 and 8 TeV, respectively, with  $4.8 \text{ fb}^{-1}$  collected at 7 TeV and  $5.8 \text{ fb}^{-1}$  collected at 8 TeV. Higgs  
1472 production in the gluon fusion and vector boson fusion modes is modeled with **POWHEG** for the hard  
1473 scattering event and **PYTHIA** for the showering and hadronization. Associated production of a Higgs with a  
1474 vector boson or top quarks is modeled via **PYTHIA**. Table 4.1 shows the Monte Carlo generators used for  
1475 modeling the signal and background processes relevant for the three analyses to be discussed.

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

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

1476 **4.3  $H \rightarrow WW \rightarrow e\nu\mu\nu$  SEARCH**

1477 The  $H \rightarrow WW \rightarrow e\nu\mu\nu$  search is unique compared to the  $ZZ$  and  $\gamma\gamma$  channels. The Higgs mass  
1478 cannot be fully reconstructed due to the presence of neutrinos in the final state, so the transverse mass  $m_T$   
1479 is used as the final discriminating variable. Compared to the other channels, there are more backgrounds  
1480 here as well, as discussed in chapter 3. The same flavor final states are excluded from the 8 TeV dataset due

<sup>1481</sup> to high pileup conditions<sup>1</sup>. These final states are later included in results with the full Run 1 dataset, as  
<sup>1482</sup> discussed in chapters 5 and 6.

<sup>1483</sup> **4.3.1 EVENT SELECTION**

<sup>1484</sup> The analysis requires two opposite charge isolated leptons, with the leading (sub-leading) lepton required  
<sup>1485</sup> to have  $p_T > 25(15)$  GeV. The events are separated into different signal regions depending on which  
<sup>1486</sup> flavor of lepton is leading ( $e\mu$  for leading electron,  $\mu e$  for leading muon). Strict lepton quality cuts are  
<sup>1487</sup> applied to the sample to reduce backgrounds from fake leptons.

<sup>1488</sup> Jets are reconstructed with the anti- $k_T$  algorithm with a radius parameter  $R = 0.4$ . The jets are re-  
<sup>1489</sup> quired to have  $p_T > 25$  GeV and  $|eta| < 4.5$ , with jets in the tracking volume required to have a jet  
<sup>1490</sup> vertex fraction of 0.5 and jets in the forward region required to have  $p_T > 30$  GeV. The analysis is sepa-  
<sup>1491</sup> rated into three different signal regions based on jet multiplicity:  $n_j = 0, 1, \geq 2$ .

<sup>1492</sup> 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  
<sup>1493</sup> requirement significantly reduces the QCD multijet and  $Z/\gamma^*$  + jets backgrounds. Figure 4.1 shows the  
<sup>1494</sup> distribution of  $n_j$  in data and simulation after applying these “pre-selection” requirements.

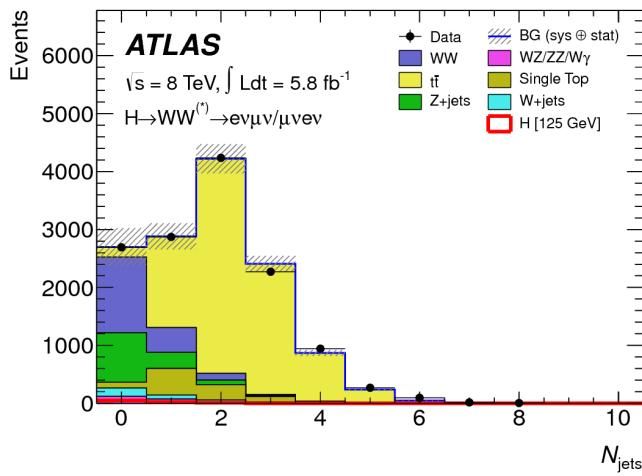


Figure 4.1: Jet multiplicity distribution in data and MC after applying lepton, jet, and  $E_{T,\text{rel}}^{\text{miss}}$  selections. The  $WW$  and top backgrounds have been normalized using control samples, and the hashed band indicates the total uncertainty on the prediction. [1]

<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 chapter 3

1495     Additional selections are applied to require the dilepton topology to correspond to that of a SM Higgs.  
1496     The requirements are presented here - more detailed discussion on the motivation for each requirement is  
1497     saved for Chapter 5. In all of the jet multiplicity channels, the dilepton system is required to have a small  
1498     gap in azimuthal angle,  $\Delta\phi_{\ell\ell} < 1.8$ . Similarly, the  $m_{\ell\ell}$  is required to be less than 50 GeV in the lower jet  
1499     multiplicity channels and less than 80 GeV in the  $n_j \geq 2$  channel. In the  $n_j = 0$  channel, the magnitude  
1500     of the dilepton  $p_T$ ,  $p_T^{\ell\ell}$ , is required to be greater than 30 GeV.

1501     In the higher jet multiplicity channels ( $n_j \geq 1$ ), the top background is a more important component  
1502     and must be reduced. The total transverse momentum  $p_T^{\text{sum}}$  is thus required to be less than 30 GeV. Ad-  
1503     ditionally, the di- $\tau$  invariant mass  $m_{\tau\tau}$  (dilepton mass computed under the assumption that the neutrinos  
1504     from the  $\tau$  decay are emitted collinear to the charged leptons) is used to reject  $Z \rightarrow \tau\tau$  events by requiring  
1505      $|m_{\tau\tau} - m_Z| > 25$  GeV. These variables are also discussed in more detail in Chapter 5.

1506     In the  $n_j \geq 2$  channel, requirements are made to isolate the VBF contribution to Higgs production.  
1507     The kinematics of the two leading jets are used to make these requirements. In particular, the event must  
1508     have  $\Delta y_{jj} > 3.8$  and  $m_{jj} > 500$  GeV, along with a veto on having any additional jets with rapidity  
1509     between the two leading jets.

#### 1510     4.3.2 BACKGROUND ESTIMATION

1511     The details of the background estimation techniques used in the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis are  
1512     discussed in section 5.5. As that section refers to a later iteration of the analysis, a general discussion is given  
1513     here for completeness. The dominant backgrounds are SM  $WW$  production and top (both pair and  
1514     single) production, and these backgrounds have their normalizations estimated from dedicated control  
1515     regions while their shapes are taken from simulation.

1516     The control sample for the Standard Model  $WW$  background is defined by making the same require-  
1517     ments as the signal region with the  $m_{\ell\ell}$  requirement inverted (now requiring  $m_{\ell\ell} > 80$  GeV) and remov-  
1518     ing the  $\Delta\phi_{\ell\ell}$  requirement. This creates a control sample that is 70% (40%) pure in the 0(1)-jet region. The  
1519     correction to the pure MC-based background estimate is quantified by defining a normalization factor  $\beta$   
1520     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

1521 the  $WW$  normalization factors in the  $n_j = 0$  and  $n_j = 1$  bins (the  $n_j \geq 2$  estimate is taken directly  
1522 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.

1523 The top background estimate is also computed separately in each jet multiplicity bin. In the  $n_j = 0$   
1524 channel, the background is first normalized using data after pre-selection requirements with no selection  
1525 on  $n_j$ . Then, a dedicated  $b$ -tagged control sample is used to evaluate the ratio of one-jet to two-jet events in  
1526 data. The details of this technique are shown in reference [65]. In the  $n_j = 1$  and the  $n_j \geq 2$  regions, the  
1527 top background is normalized in a control sample where the signal region selections are applied, but the  
1528  $b$ -jet veto is reversed and the Higgs topology requirements on  $m_{\ell\ell}$  and  $\Delta\phi_{\ell\ell}$  are removed. The resulting  
1529 normalization factors for these techniques are shown in table 4.2.

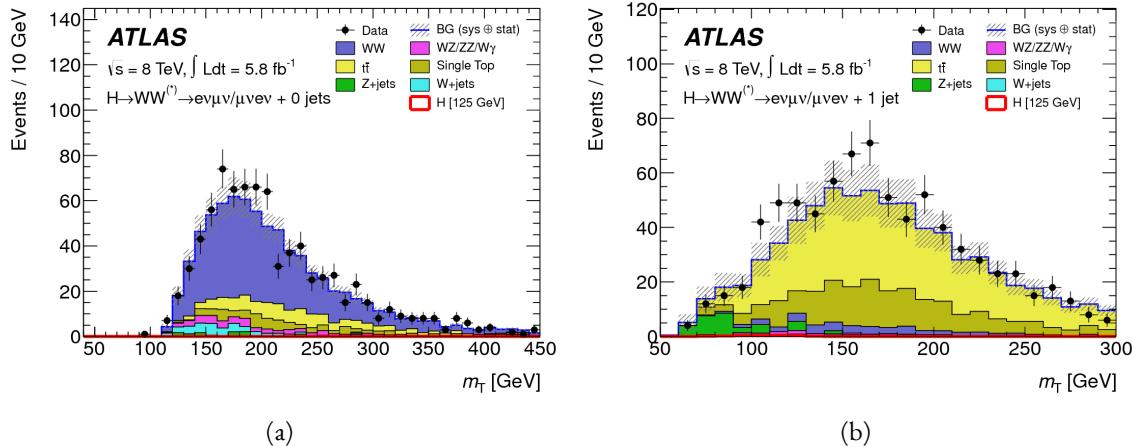


Figure 4.2: Comparison of  $m_T$  between data and simulation in the  $n_j = 0$   $WW$  (a) and  $n_j = 1$  top (b) control samples [1]

1530 The control samples which are used for background normalization can also be used to validate the mod-  
1531 eling of the  $m_T$  distribution for each background. Figure 4.2 shows the comparison between data and MC

1532 for the  $m_T$  distribution after correcting the normalization of the backgrounds in the  $WW$  and top control  
1533 regions. Good agreement between data and simulation is seen in both cases.

1534 The  $W + \text{jets}$  background estimate is taken entirely from data using a control sample with one well recon-  
1535 structed lepton and one anti-identified lepton. All other backgrounds are taken purely from simulation.

1536 **4.3.3 SYSTEMATIC UNCERTAINTIES**

1537 The systematic uncertainties that have the largest impact on the analysis are the theoretical uncertainties  
1538 associated with the signal cross section, and these are shared with the  $ZZ^*$  and  $\gamma\gamma$  channels. The uncer-  
1539 tainties resulting from variations of the QCD scale are  $+7\%/-8\%$  on the final singal yield. Those coming  
1540 from variations of the parton distribution function (PDF) used in the simulation add a  $\pm 8\%$  uncertainty  
1541 on the yield. The uncertainties on the branching ratios of the Higgs are  $\pm 5\%$ .

1542 The main experimental uncertainties come from variations of the jet energy scale (JES), jet energy reso-  
1543 lution, pile-up,  $E_T^{\text{miss}}$ ,  $b$ -tagging efficiency,  $W + \text{jets}$  background estimate, and integrated luminosity. For  
1544 more details, see reference [1].

1545 **4.3.4 RESULTS**

1546 Table 4.3 shows the signal and background yields in the final signal region after normalizing the back-  
1547 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]

1548      Figure 4.3 shows the  $m_T$  distribution in the  $n_j \leq 1$  channels for 8 TeV data. (No events are observed  
 1549      in data in the  $n_j \geq 2$  channels in this dataset). The excess shown here relatively flat as a function of  
 1550      hypothesized Higgs mass. The combined 7 and 8 TeV data gives an excess with local significance of  $2.8\sigma$   
 1551      with an expected significance of  $2.3\sigma$ , corresponding to a  $\mu$  measurement of  $1.3 \pm 0.5$ .

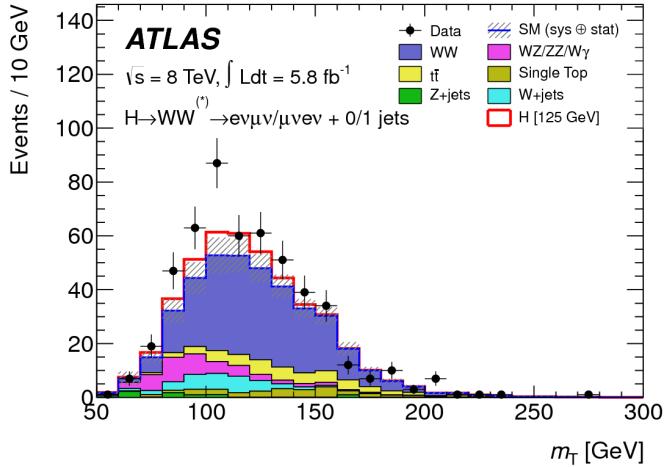


Figure 4.3:  $m_T$  distribution in the  $H \rightarrow WW \rightarrow e\nu\mu\nu$   $n_j \leq 1$  channels for 8 TeV data [1].

#### 1552    4.4    $H \rightarrow \gamma\gamma$ SEARCH

1553      The  $H \rightarrow \gamma\gamma$  search is in essence a search for a peaked excess above the falling SM diphoton mass  
 1554      spectrum, with  $m_{\gamma\gamma}$  as the ultimate discriminating variable. Events are selected by requiring two isolated  
 1555      photons, with the leading (sub-leading) photon required to have  $E_T > 40(30)$  GeV. In the 8 TeV data,  
 1556      the photons are required to pass cut-based identification criteria consistent with a photon in the electro-  
 1557      magnetic calorimeter and little leakage in the hadronic calorimeter.

1558      The main challenges for this analysis are accurate mass reconstruction and background estimation. In  
 1559      order to accurately reconstruct the invariant mass of the di-photon system, both the energy and direction  
 1560      of the photons must be measured well. Therefore, the identification of the primary vertex of the hard  
 1561      interaction is particularly important, and is done using a multivariate likelihood which combines informa-  
 1562      tion about the photon direction and vertex position. The background is modeled with a falling spectrum  
 1563      in  $m_{\gamma\gamma}$  that is parameterized by different functions depending on the category of the event.

1564 4.4.1 RESULTS

1565 The resulting diphoton mass spectrum is shown in figure 4.4. The best fit mass value in the  $\gamma\gamma$  channel  
 1566 alone in the combined 7 and 8 TeV data is 126.5 GeV. The local significance at this point is  $4.5\sigma$ , with  
 1567 an expected significance of  $2.5\sigma$ . Therefore, the measured signal strength  $\mu$  is  $1.8 \pm 0.5$  in this channel.

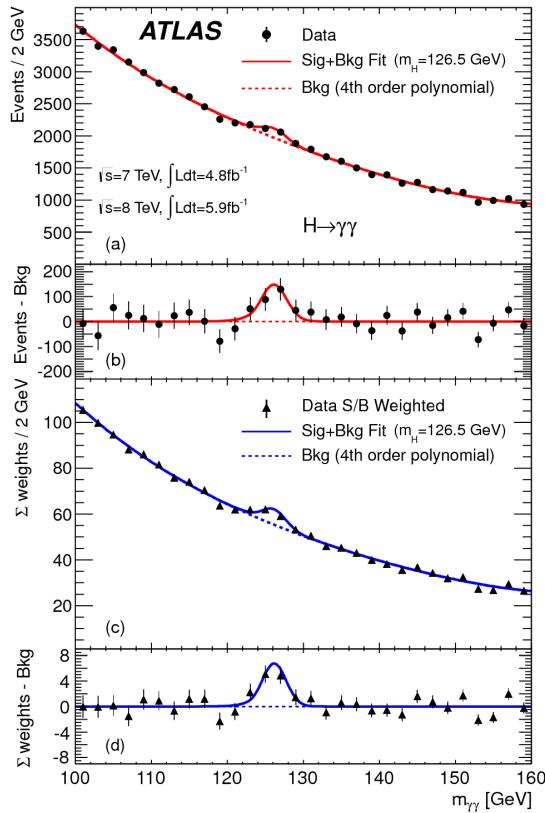


Figure 4.4: Diphoton mass spectrum in 7 and 8 TeV data. Panel a) shows the unweighted data distribution superimposed on the background fit, while panel c) shows the data where each event category is weighted by its signal to background ratio. Panels b) and d) show the respective distributions with background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

1568 4.5  $H \rightarrow ZZ \rightarrow 4\ell$  SEARCH

1569 The  $H \rightarrow ZZ \rightarrow 4\ell$  analysis searches for a Standard Model Higgs boson decaying to two  $Z$  bosons,  
 1570 each of which decays to a pair of same flavor, opposite charge isolated leptons. The ultimate discriminating  
 1571 variable is  $m_{4\ell}$ , or the invariant mass of the four selected leptons. The  $\ell$  denotes an  $e$  or  $\mu$  as with the  
 1572  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  analysis.

1573     Four distinct signal regions are constructed depending on the flavors of the final state, additionally sep-  
 1574     arated by the flavor of the leading lepton pair. These are referred to as  $4e$ ,  $2e2\mu$ ,  $2\mu2e$ ,  $4\mu$ .

1575     The main backgrounds in the  $H \rightarrow ZZ \rightarrow 4\ell$  search are continuum  $ZZ^*$  production,  $Z + \text{jets}$  pro-  
 1576     duction, and  $t\bar{t}$ . The  $m_{4\ell}$  distribution for background is estimated from simulation. The normalization  
 1577     of the SM  $ZZ^*$  background is also taken from MC simulation, while the  $Z + \text{jets}$  and  $t\bar{t}$  normalizations are  
 1578     taken from data-driven methods.

1579     **4.5.1 RESULTS**

1580     Figure 4.5 shows the  $m_{4\ell}$  spectrum measured in the 7 and 8 TeV datasets. The total number of events  
 1581     observed in the window between 120 and 130 GeV is 13, with 6 events in the  $4\mu$  channel, 2 events in  
 1582     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  
 1583     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  
 1584     an expected significance of  $2.7\sigma$ .

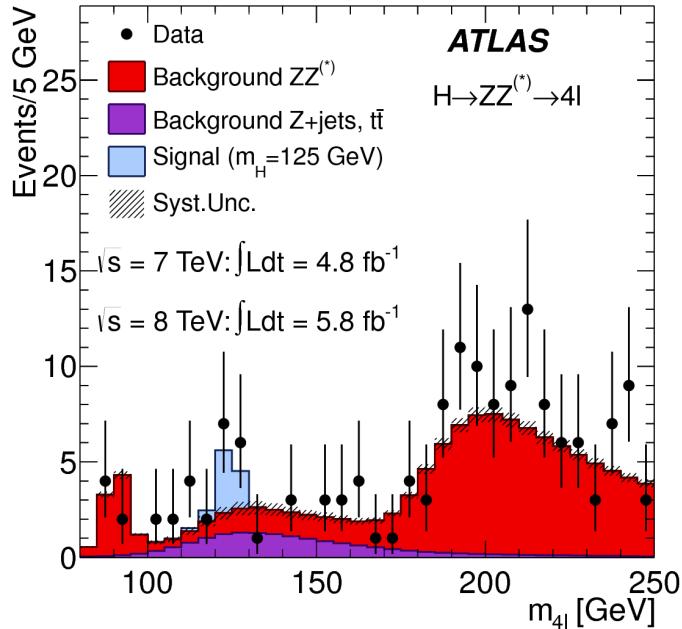


Figure 4.5: Four lepton invariant mass spectrum ( $m_{4\ell}$ ) in 7 and 8 TeV data compared to background estimate. A 125 GeV SM Higgs signal is shown in blue [1].

1585    4.6 COMBINED RESULTS

1586    The statistical interpretation of the combined results is undertaken as described in section 3.6.2, with a  
 1587    hypothesis test based on a likelihood ratio parameterized by the Higgs signal strength  $\mu$ . The null hypoth-  
 1588    esis corresponds to  $\mu = 0$ , while the SM Higgs corresponds to  $\mu = 1$ .

1589    Table 4.4 summarizes the properties of the individual channels as well as the significances of the excesses  
 1590    seen. The most significant observed local excess comes from the  $\gamma\gamma$  channel. Figure 4.6 shows a compari-  
 1591    son of the observed local  $p_0$  values as a function of hypothesized mass for the three different search chan-  
 1592    nels. Both the  $ZZ^*$  and  $\gamma\gamma$  channels have very peaked excesses, while the  $WW^*$  excess can be seen as very  
 1593    broad because the  $m_T$  distribution does not provide detailed information about the true Higgs mass.

| Channel                                     | Fit var.           | Observed $Z_l$ | Expected $Z_l$ | $\hat{\mu}$   |
|---|--------------------|----------------|----------------|---------------|
| $H \rightarrow ZZ^* \rightarrow 4\ell$      | $m_{4\ell}$        | 3.6            | 2.7            | $1.2 \pm 0.6$ |
| $H \rightarrow \gamma\gamma$                | $m_{\gamma\gamma}$ | 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].

1594    Figure 4.7 shows the combined exclusion limit,  $p_0$ , and signal strength. The highest local excess comes  
 1595    at a value of 126.5 GeV and corresponds to a  $6.0\sigma$  observed excess.

1596    Figure 4.8 shows a comparison of the measured signal strengths between the different Higgs search  
 1597    channels. All measured  $\mu$  are consistent with unity within their uncertainty, and the combined  $\mu$  mea-  
 1598    surement is  $1.4 \pm 0.3$ .

1599    The likelihood can also be computed in a two-dimensional plane of  $m_H$  and  $\mu$ , and this is shown in  
 1600    figure 4.9. The figure shows that while the  $\gamma\gamma$  and  $ZZ^*$  channels have very good mass resolution, the  
 1601    excess in  $WW^*$  covers a broad mass range. The banana shape of the  $WW^*$  result is due to the fact that  
 1602    the excess in this channel can either be explained by increasing the signal strength or by changing the mass  
 1603    (and thus the cross section). The two parameters are correlated due to the lack of mass sensitivity in this  
 1604    channel.

1605    Because multiple Higgs mass points are searched for, the local significance must be corrected for a look-

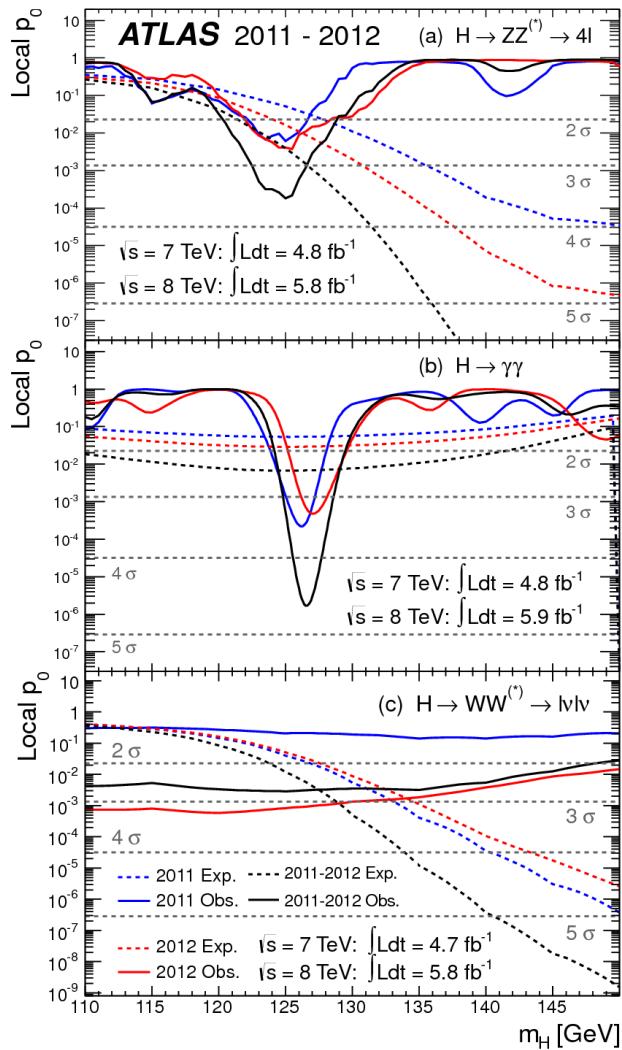


Figure 4.6: Local  $p_0$  distribution as a function of hypothesized Higgs mass for the  $H \rightarrow ZZ^* \rightarrow 4\ell$  (a),  $H \rightarrow \gamma\gamma$  (b), and  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  (c) channels. Dashed curves show expected results, while solid curves show observed.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

1606 elsewhere effect to compute a true global significance. The global significance for finding a Higgs anywhere  
 1607 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  
 1608 110 to 150 GeV.

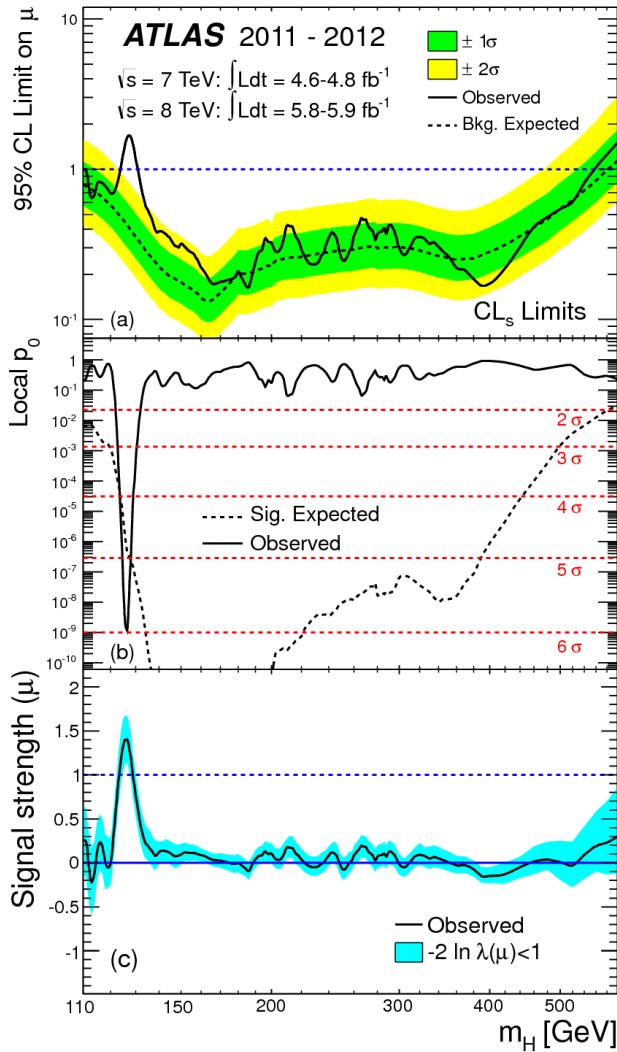


Figure 4.7: Combined 95% CL limits (a), local  $p_0$  values (b), and signal strength measurement (c) as a function of Higgs mass [1].

1609    4.7 CONCLUSION

1610    A search for the production of a Standard Model Higgs boson was conducted in  $4.8 \text{ fb}^{-1}$  collected at  
 1611     $\sqrt{s} = 7 \text{ TeV}$  and  $5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . A new particle consistent with the Higgs boson was observed,  
 1612    with a mass of 126.5 GeV and a global (local) significance of  $5.1(6.0)\sigma$ . This is the first discovery level  
 1613    observation of a particle consistent with the Higgs.

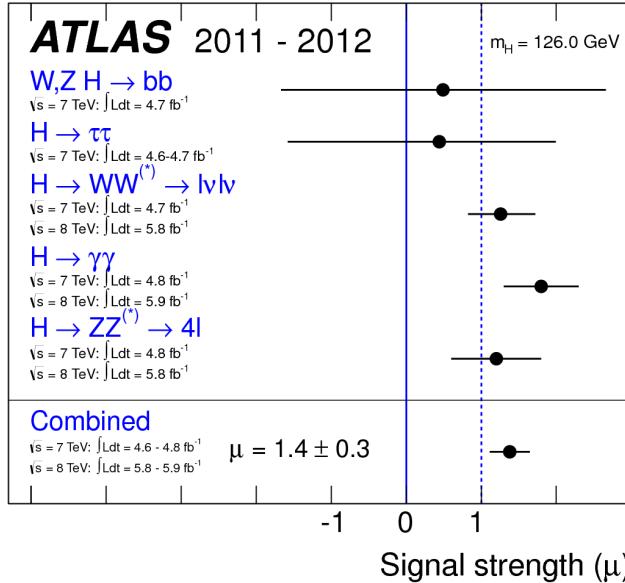


Figure 4.8: Comparison of measured signal strength  $\mu$  for a 126 GeV Higgs in the 7 and 8 TeV datasets [1].

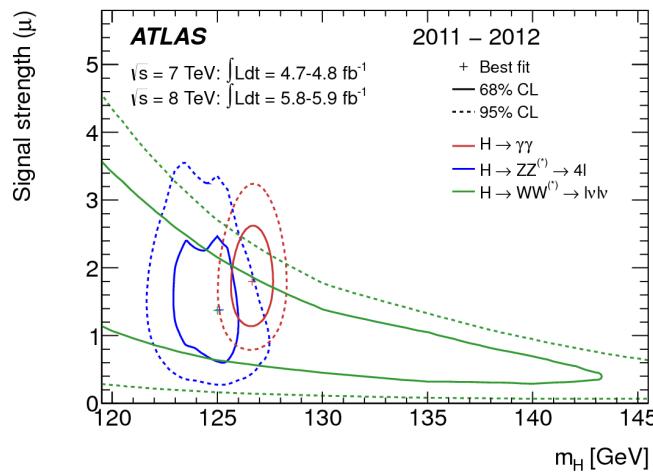


Figure 4.9: Two dimensional likelihood as a function of signal strength  $\mu$  and Higgs mass  $m_H$  [1].

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

Richard Feynman

# 5

1614

## 1615 Evidence for Vector Boson Fusion production

1616

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

### 1617 5.1 INTRODUCTION

1618 After the discovery of a particle consistent with the Higgs boson, the  $H \rightarrow WW^*$  analysis had two main  
1619 goals. The first goal was to increase the sensitivity of the analysis to fully confirm that the  $H \rightarrow WW^*$   
1620 process did indeed exist. The second goal was to characterize the particle as much as possible, including  
1621 searching for the lower cross-section production modes, in order to confirm that it was indeed a Higgs  
1622 boson. This chapter presents a dedicated search for Vector Boson Fusion (VBF) production of a Higgs  
1623 boson decaying via the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  mode. First, basics of the topology of VBF production  
1624 are presented. Then, the details of the analysis are shown, including signal region definition, background  
1625 estimation techniques, and systematic uncertainties. Finally, the results of the analysis are presented. As

1626 will be shown, this analysis is the first and most sensitive evidence of the VBF production mode of the  
1627 Higgs on ATLAS.

1628 In the VBF channel, there are both a selection requirement based signal region analysis (known as the  
1629 “cut-based”) and a multivariate analysis which uses a boosted decision tree (known as the BDT analysis).  
1630 The focus of this chapter will be on the cut-based signal region, as this is an important component of the  
1631 VBF analysis and in particular acts as strong validation for the final BDT result. Connections between the  
1632 cut-based and BDT analyses will be discussed where appropriate.

## 1633 5.2 DATA AND SIMULATION SAMPLES

1634 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  $\sqrt{s} = 7 \text{ TeV}$ .  
1635 The details of the LHC and detector conditions during this period are given in Chapter 2. The trigger  
1636 selection defining the dataset is discussed in section 5.2.1. The simulation samples used for signal and back-  
1637 ground modeling are given in section 5.2.2.

### 1638 5.2.1 TRIGGERS

1639 The analysis uses a combination of single lepton and dilepton triggers to allow lowering of the  $p_T$   
1640 thresholds and increased signal acceptance. The  $p_T$  threshold on the leptons is a particularly important  
1641 consideration for this signal. Because the second  $W$  produced in the decay can be off-shell, it tends to pro-  
1642 duce lower momentum leptons. Thus, being able to lower the  $p_T$  threshold while still maintaining a low  
1643 background rate is critical. Figure 5.1 shows an example of the subleading lepton  $p_T$  for a VBF  $H \rightarrow WW^*$   
1644 signal compared to the corresponding  $t\bar{t}$  background. Note that the lepton  $p_T$  spectrum is considerably  
1645 softer in the signal sample.

1646 As discussed in Chapter 2, there are multiple levels in the ATLAS trigger system, and there are different  
1647  $p_T$  thresholds imposed for the leptons at each level. Additionally, some triggers have a loose selection  
1648 on the isolation of the lepton (looser than that applied offline in the analysis object selection). Table 5.1  
1649 shows the thresholds used for single lepton triggers, while table 5.2 shows the thresholds coming from  
1650 di-lepton triggers. The single lepton trigger efficiency for muons that pass the analysis object selection is



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

1651 70% for muons in the barrel region ( $|\eta| < 1.05$ ) and 90% in the endcap region. The electron trigger  
 1652 efficiency increases with electron  $p_T$  but the average is approximately 90%. These efficiencies are measured  
 1653 by combined performance and trigger signature groups [66, 67].

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

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

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

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

1654 The combination of all triggers shown gives good efficiency for signal events. This efficiency is sum-  
 1655 marized in table 5.3. The relative improvement in efficiency by adding the dilepton triggers is also shown

1656 in the same table. The largest gain comes in the  $\mu\mu$  channel. Overall the trigger selection shows a good  
1657 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.

1658 5.2.2 MONTE CARLO SAMPLES

1659 Modeling of signal and background processes in the signal region, in particular for the  $m_T$  distribution,  
1660 is an important consideration for the final interpretation of the analysis. Therefore, careful consideration  
1661 must be paid to which Monte Carlo (MC) generators are used for specific processes. With the exception of  
1662 the  $W + \text{jet}$  and multijet backgrounds, the  $m_T$  shape used as the final discriminant is taken from simulation.  
1663 (Many backgrounds are normalized from data, as described in section 5.5).

1664 Table 5.4 shows the MC generators used for the signal and background processes, as well as their cross  
1665 sections. In order to include corrections up to next-to-leading order (NLO) in the QCD coupling constant  
1666  $\alpha_s$ , the POWHEG [68] generator is often used. In some cases, only leading order generators like ACERMC  
1667 [69] and GG2VV [70] are available for the process in question. If the process requires good modeling for  
1668 very high parton multiplicities, the SHERPA [71] and ALPGEN [72] generators are used to provide merged  
1669 calculations for five or fewer additional partons. These matrix element level calculations must then be  
1670 additionally matched to models of the underlying event, hadronization, and parton shower. There are  
1671 four possible generators for this: SHERPA, PYTHIA 6 [73], PYTHIA 8 [74], or HERWIG [75] + JIMMY [76].  
1672 The simulation additionally requires an input parton distribution function (PDF). The CTEQ [77] PDFs  
1673 are used for SHERPA and POWHEG simulated samples, while CTEQ6Li [78] is used for ALPGEN + HERWIG  
1674 and ACERMC simulations. The Drell-Yan samples are reweighted to the MRST [79] PDFs, as these are  
1675 found to give the best agreement between data and simulation.

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

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

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

1679 analysis, events are sometimes filtered at generator level to allow for more efficient generation of relevant  
1680 events. The efficiency of the trigger in MC simulation does not always match the measured efficiency in  
1681 data, so trigger scale factors are applied to correct the MC efficiency to the data. These are derived by the  
1682 combined performance groups [66, 67].

### 1683 5.3 OBJECT SELECTION

1684 In order to define the signal region, the analysis must first select the objects to be considered. The details  
1685 of the object reconstruction algorithms are discussed in Chapter 2, while this section gives specific selection  
1686 cuts used in the  $H \rightarrow WW^*$  analysis.

1687 The first step in this process is to select a primary vertex candidates. The event’s primary vertex is the  
1688 vertex with the largest sum of  $p_T^2$  for associated tracks and is required to have at least three tracks with  
1689  $p_T > 450$  MeV. Many of the object selection cuts are then made relative to this chosen primary vertex.

#### 1690 5.3.1 MUONS

1691 The analysis uses combined muon candidates, where a track in the Inner Detector has been matched to  
1692 a standalone track in the Muon Spectrometer. The track parameters are combined statistically in the muon  
1693 reconstruction algorithm [53]. The muons are required to be within  $|\eta| < 2.5$  and have a  $p_T > 10$  GeV.  
1694 To reduce backgrounds coming from mis-reconstructed leptons, there are requirements on the impact  
1695 parameter of the muon relative to the primary vertex. The transverse impact parameter  $d_0$  is required to  
1696 be small relative to its estimated uncertainty, the exact cut value being  $d_0/\sigma_{d_0} < 3$ . The longitudinal  
1697 impact parameter  $z_0$  must satisfy  $|z_0 \sin \theta| < 1$  mm.

1698 As discussed previously, the muons must also be isolated. There are two types of lepton isolations that  
1699 are calculated: track-based and calorimeter-based. For muons, the track-based isolation is defined using the  
1700 scalar sum  $\sum p_T$  for tracks with  $p_T > 1$  GeV (excluding the muon’s track) within a cone of  $\Delta R = 0.3$   
1701 (0.4) for muon with  $p_T > 15$  GeV ( $10 < p_T < 15$  GeV). The final isolation requirement is made my  
1702 requiring that this scalar sum be no more than a certain fraction of the muon’s  $p_T$ . This requirement varies  
1703 with muon  $p_T$  and the exact cuts are defined in table 5.5.

1704      The calorimeter-based muon isolation is defined using as a  $\sum E_T$  calculated from calorimeter cells us-  
 1705      ing the same cone size as the track-based isolation but excluding cells with  $\Delta R < 0.05$  around the muon.  
 1706      This requirement is also defined as a cut on the ratio of the sum to the muon  $p_T$  and varies with muon  $p_T$ .  
 1707      The cut values are also given in table 5.5.  
  
 1708      The isolation requirements loosen as a function of  $p_T$  to allow for larger signal acceptance. At low  $p_T$ ,  
 1709      the isolation is tightened to reduce the  $W + \text{jets}$  background which arises from a misidentified lepton.

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

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

### 1710    5.3.2 ELECTRONS

1711      Electrons are identified by matching reconstructed clusters in the electromagnetic calorimeter with tracks  
 1712      in the inner detector. The electrons are identified using a likelihood based method [50, 51] which takes into  
 1713      account the shower shapes in the calorimeter, the matching of tracks to clusters, and the amount of transi-  
 1714      tion radiation in the TRT. The electrons are required to have  $|\eta| < 2.47$ , and candidates in the transition  
 1715      region between the barrel and endcap ( $1.37 < |\eta| < 1.52$ ) are excluded. As the muons, the electrons  
 1716      are required to have transverse impact parameter significance  $< 3$ , while in the longitudinal direction  
 1717      they must have  $|z_0 \sin \theta| < 0.4$  mm. Some electron requirements also vary with electron  $E_T$ , and these  
 1718      requirements are summarized in table 5.6.

1719      The isolation for electrons are defined similarly to the muons but with unique cuts on the objects in-  
 1720      cluded. The track-based isolation is defined using tracks with  $p_T > 400$  MeV with cone sizes as defined  
 1721      previously. The calorimeter-based isolation also uses the same cone size as the muon, but here the cells  
 1722      within a  $0.125 \times 0.175$  area in  $\eta \times \phi$  around the electron cluster's barycenter are excluded. The other  
 1723      difference with respect to muons is that the denominator of the isolation ratio is the electron's  $E_T$  rather  
 1724      than  $p_T$ . The isolation cuts very with electron  $E_T$  and are defined in table 5.6.

1725 The electron is also required to not be consistent with a vertex coming from a photon conversion.

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

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

### 1726 5.3.3 JETS

1727 Jets are clustered with the anti- $k_T$  reconstruction algorithm using a radius parameter of  $R = 0.4$ . They  
1728 are required to have a jet vertex fraction (JVF) of at least 50%, meaning that half of the tracks associated with  
1729 the jet originated from the primary vertex. Jets with no tracks associated (i.e. those outside the acceptance  
1730 of the ID) do not have this requirement applied. Jets are required to have  $p_T > 25$  GeV if they are within  
1731 the tracking acceptance ( $|\eta| < 2.4$ ). Jets with  $2.4 < |\eta| < 4.5$  are required to have  $p_T > 30$  GeV.  
1732 This tighter requirement reduces jets from pileup in the region where JVF requirements cannot be applied.  
1733 The two highest  $p_T$  jets in the event are referred to as the “VBF” jets and used to compute various analysis  
1734 selections later.

1735 Identification of  $b$ -jets is done using the MV1 algorithm and is limited to the acceptance of the ID ( $|\eta| <$   
1736 2.5). The operating point of MV1 that is used is the one that is 85% efficient for identifying true  $b$ -jets. This  
1737 operating point has a 10.3% of mis-tagging a light quark jet as a  $b$ -jet. In order to improve the rejection of  $b$ -  
1738 jets, a lower threshold than the nominal  $p_T$  threshold described above is used. For the purposes of counting  
1739 the number of  $b$ -jets, jets with  $p_T$  down to 20 GeV are used.

### 1740 5.3.4 OVERLAP REMOVAL

1741 There are some cases where certain reconstructed objects will overlap and one will have to be chosen  
1742 (for example, an electron and a jet in the calorimeter). First, the case of lepton overlap is dealt with. If  
1743 an electron candidate extends into the muon spectrometer, it is removed. If a muon or electron have a  
1744  $\Delta R < 0.1$ , the electron is removed and the muon is kept. If two electron candidates overlap within the

1745 same radius, then the higher  $E_T$  electron is kept. Next, the overlap between leptons and jets is considered.  
1746 If an electron and jet are within  $\Delta R < 0.3$  of one another, the electron is kept and the jet is removed.  
1747 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  
1748 result of a semileptonic decay inside the jet).

1749 Once the overlap removal is complete, the final set of objects used in the analysis is defined.

#### 1750 5.4 ANALYSIS SELECTION

1751 The VBF analysis uses two distinct selections. The first is a more standard selection, referred to as “cut-  
1752 based”, that applies requirements on the VBF variables and uses  $m_T$  as the final discriminating variable.  
1753 The second is a looser selection that uses a Boosted Decision Tree (BDT) score as the final discriminator in  
1754 order to take advantage of the detailed correlations between the VBF variables. While the BDT analysis is  
1755 ultimately more sensitive, the cut-based serves as an important component of the analysis. First, the cut-  
1756 based allows for confirming the modeling and validity of many variables used as input to the BDT. Second,  
1757 because this is the first use of such an MVA technique in the  $H \rightarrow WW^*$  analysis, the cut-based selection  
1758 allows confirmation of the final BDT result with a more traditional analysis. The cut-based techniques are  
1759 the focus of this chapter, but connections to the BDT result will be illustrated when appropriate.

1760 One important note is that because this analysis is dedicated to the measurement of the VBF pro-  
1761 duction mode of the Higgs, events coming from gluon fusion production with the Higgs decaying via  
1762  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  are treated as background events. This will be seen throughout the various predic-  
1763 tions shown.

##### 1764 5.4.1 COMMON PRE-SELECTION

1765 Both the cut-based and BDT analyses have a common pre-selection that is applied before the main signal  
1766 region requirements. The requirements on leptons are common to all  $n_j$  bins. The analysis requires two  
1767 oppositely charged leptons, with the leading lepton required to have  $p_T > 22$  GeV while the subleading  
1768 lepton must have  $p_T > 10$  GeV. Next, to remove low mass  $Z/\gamma^*$  events, a cut on the dilepton mass  
1769  $m_{\ell\ell} > 10$  (12) GeV is applied in the different (same) flavor channel. In the same flavor channels, there is

1770 an additional veto placed on the region around the Z peak, requiring that  $|m_{\ell\ell} - m_Z| > 15$  GeV.

1771 There are also requirements on the amount of missing transverse momentum in the event. These are  
1772 only applied in the same flavor channels, as in the different flavor channels  $t\bar{t}$  is the dominant background  
1773 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  
1774 must select more tightly on these variables to have maximal sensitivity and thus requires  $p_T^{\text{miss}} > 50$  GeV  
1775 and  $E_T^{\text{miss}} > 55$  GeV.

1776 Finally, because this analysis is focused on VBF, a requirement on the jet multiplicity is placed, with  
1777  $n_j \geq 2$ . Additionally, the analysis requires that there are no jets identified as b-quarks in the event, or  
1778  $n_b = 0$ .

#### 1779 5.4.2 CUT-BASED SELECTION

1780 The cut-based selection places sequential requirements on variables reconstructed from the VBF jets in  
1781 order to increase the signal to background ratio.

#### 1782 GENERAL BACKGROUND REDUCTION

1783 Top pair production is the primary background in the  $n_j \geq 2$  bin. Even though  $n_b = 0$  is required, an  
1784 additional variable is constructed to further suppress the top background. There is often additional QCD  
1785 radiation that accompanies the  $t\bar{t}$  system when it is produced. Therefore, a variable which tests for the  
1786 presence of this additional radiation,  $p_T^{\text{sum}}$ , is constructed. It is defined in equation 5.1.

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

1787 The first cut after pre-selection in the cut-based analysis requires  $p_T^{\text{sum}} < 15$  GeV to further suppress  $t\bar{t}$   
1788 production.

1789 In the different flavor channels, a cut is made to reduce the contamination from  $Z \rightarrow \tau\tau$  decays.  
1790 The di- $\tau$  invariant mass,  $m_{\tau\tau}$ , is constructed by assuming that the neutrinos from the  $\tau$  decays were  
1791 collinear with the leptons [81]. The analysis requires that this mass not be consistent with a  $Z$  by requiring  
1792  $m_{\tau\tau} < m_Z - 25$  GeV.

1793 VBF TOPOLOGICAL CUTS

1794 The characteristic feature of VBF production of the Higgs is the presence of two additional forward  
1795 jets coming from the incoming partons which radiate the vector bosons that make the Higgs. These jets  
1796 are forward because the outgoing partons still carry the longitudinal momentum of the incoming partons.  
1797 Figure 5.2 shows the distribution of the  $\eta$  for the leading jet in a VBF event compared to a background top  
1798 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  
1799 central.

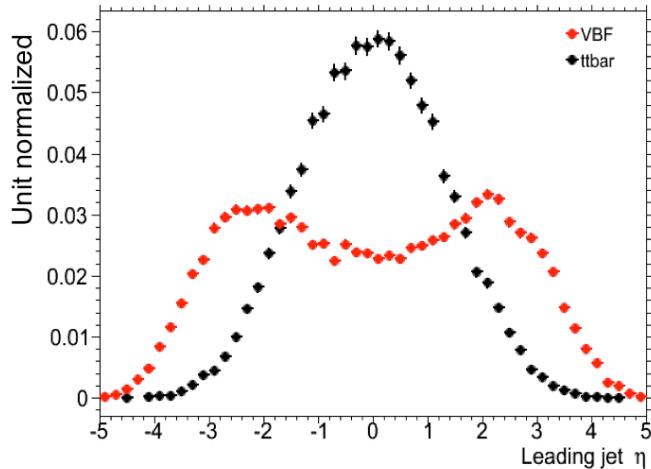


Figure 5.2: Leading jet  $\eta$  in VBF  $H \rightarrow WW^*$  (red) and  $t\bar{t}$  (black)

1800 Because the cross section for VBF production is an order of magnitude smaller than gluon fusion pro-  
1801 duction, these forward jets must be used in order to better reduce background and achieve a good signal to  
1802 background ratio. The dedicated VBF search selection requirements are constructed to maximally exploit  
1803 the features of the unique VBF topology.

1804 Requirements on the VBF jets are collectively referred to as the “VBF topological cuts”. First, a require-  
1805 ment on the dijet invariant mass of the VBF jets,  $m_{jj}$ , is placed, requiring  $m_{jj} > 600$  GeV. Next, the  
1806 event is required to have a large gap in rapidity between the two VBF jets, or  $\Delta y_{jj} > 3.6$ . Both of these  
1807 cuts put tight requirements on the presence of two forward, high  $p_T$  jets moving in opposite directions in

1808 the longitudinal plane.

1809 Beyond requiring the presence of the two forward VBF jets, the analysis also vetoes on the presence  
1810 of any additional jets that fall between the two VBF jets. This cut is referred to as the central jet veto, or  
1811 CJV. Any events with a third jet with  $p_T > 20$  GeV whose rapidity is between the region defined by the  
1812 two VBF jets are vetoed. This can be expressed in terms of a variable called the jet centrality, defined in  
1813 equation 5.2.

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

1814 Here,  $\eta_{j1}$  and  $\eta_{j2}$  are the pseudorapidities of the leading and subleading jets, respectively, while  $\eta_{j3}$  is  
1815 the pseudorapidity of the extra jet in the event (if one exists). Intuitively,  $C_{j3}$  is zero when  $\eta_{j3}$  is directly  
1816 centered between the two jets and unity when  $\eta_{j3}$  is aligned with either of the VBF jets. Thus, the CJV  
1817 can be expressed as a requirement that  $C_{j3} > 1$ .

1818 The decay products of the Higgs tend to be central as well. Thus, the analysis also requires that both  
1819 leptons in the analysis fall within the rapidity gap defined by the jets. This cut is referred to as the outside  
1820 lepton veto, or OLV. A quantitative way to define the cut is to require that the centrality of each lepton  
1821 (defined analogously to that of the third jet in equation 5.2) correspond to the lepton being within the jet  
1822 rapidity gap, or  $C_\ell < 1$  for both leptons.

1823 Figure 5.3a-c shows the  $m_{jj}$ ,  $\Delta y_{jj}$ , and  $C_{\ell 1}$  variables at the stage where all previous cuts in the sequence  
1824 have been made. The agreement between data and Monte Carlo is good, and the bottom panels show their  
1825 power in discriminating the VBF signal from the background processes.

1826 The final signal region is also split into two bins of  $m_{jj}$ , with the first bin corresponding to  $600 \text{ GeV} <$   
1827  $m_{jj} < 1 \text{ TeV}$  and the second bin corresponding to  $m_{jj} > 1 \text{ TeV}$ . The first bin has more statistics but  
1828 also a larger contribution from background, while the second bin has lower statistics but a 1:1 signal to  
1829 background ratio.

### 1830 HIGGS TOPOLOGICAL CUTS

1831 The final state leptons will exhibit unique correlations due to the fact that they are arising from the  
1832 decay of a spin zero resonance. In particular, the spins of the final state leptons and neutrinos must all

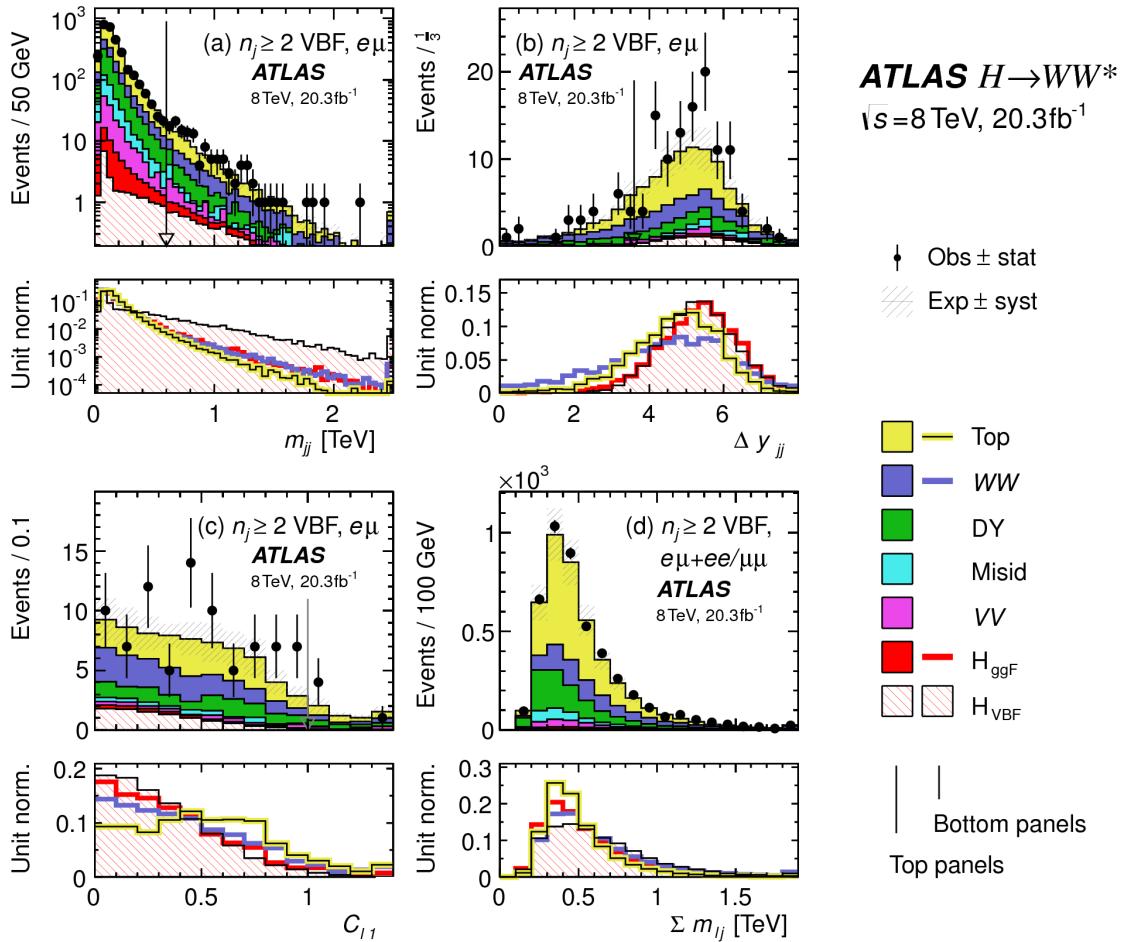


Figure 5.3: Distributions of (a)  $m_{jj}$ , (b)  $\Delta y_{jj}$ , (c)  $C_{\ell 1}$ , and (d)  $\Sigma m_{\ell j}$ , for the VBF analysis. The top panels compare simulation and data, while the bottom panels show normalized distributions for all background processes and signal [62].

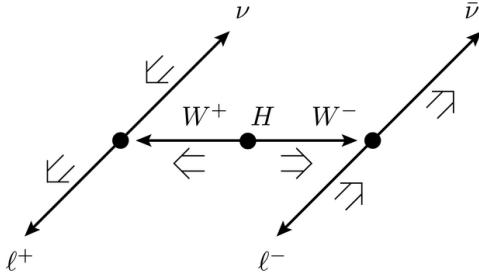


Figure 5.4: A cartoon of the WW final state. Momenta are represented with thin arrows, spins with thick arrows.  
[62]

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

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

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

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

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

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

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

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

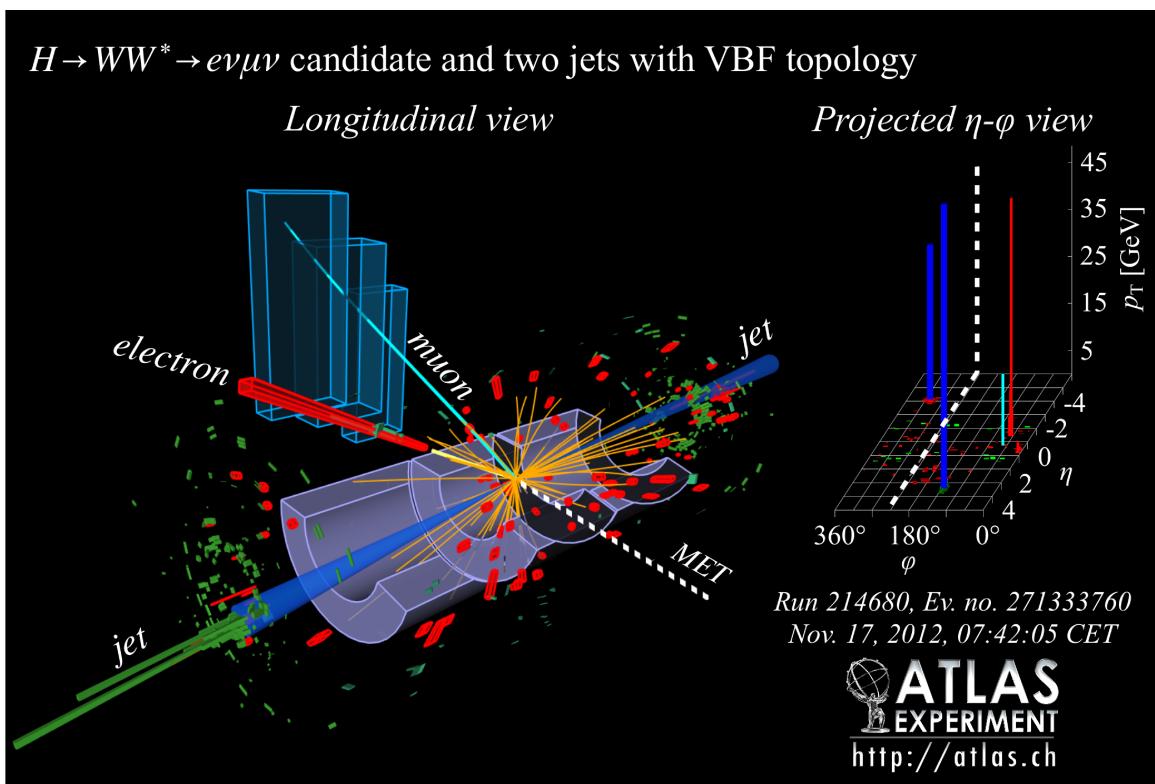


Figure 5.5: Event display of a VBF candidate event [62].

### 1851 5.4.3 BDT-BASED SELECTION

1852 The boosted decision tree based analysis takes a different philosophy compared to the cut-based. Rather  
 1853 than cutting sequentially on many variables, the BDT analysis uses many of these variables as inputs to  
 1854 the BDT and the output BDT score ( $O_{\text{BDT}}$ ) as the final discriminant. The BDT is trained with the  
 1855 VBF  $H \rightarrow WW^*$  simulation as the signal samples and all other processes as background, including ggF  
 1856  $H \rightarrow WW^*$  production. While the BDT based analysis is treated as a separate result, it has significant  
 1857 overlap with the cut-based selection.

### 1858 PRE-TRAINING SELECTION AND BDT INPUTS

1859 Before training, the common pre-selection cuts described in section 5.4.1 are applied. Additionally, the  
 1860 central jet veto and outside lepton veto described in section 5.4.2 are applied. The BDT has eight input  
 1861 variables, six of which are also variables that are used in the cut-based analysis. The six shared variables

1862 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  
 1863 the variables used to do the OLV in the cut-based analysis. The BDT uses as input the sum of lepton  
 1864 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  
 1865 the correlations between the jets and leptons in the event. It is the sum of the invariant masses of all four  
 1866 possible lepton-jet combinations.

1867 Figure 5.3d shows the agreement between data and simulation for the  $\Sigma m_{\ell j}$  variable, as well as showing  
 1868 its discriminating power. Figure 5.6 shows the distributions of the Higgs topological variables that are  
 1869 shared between the cut-based and BDT analyses. Figure 5.7 shows the distributions of the VBF topological  
 1870 variables shared between the cut-based and BDT analyses. In both cases, the VBF yield has been scaled by  
 1871 a factor of 50 to better show the shape difference compared to the backgrounds.

1872 Table ?? summarizes the cuts applied for the cut-based and analyses, as well as which variables are used  
 1873 as input to the BDT.

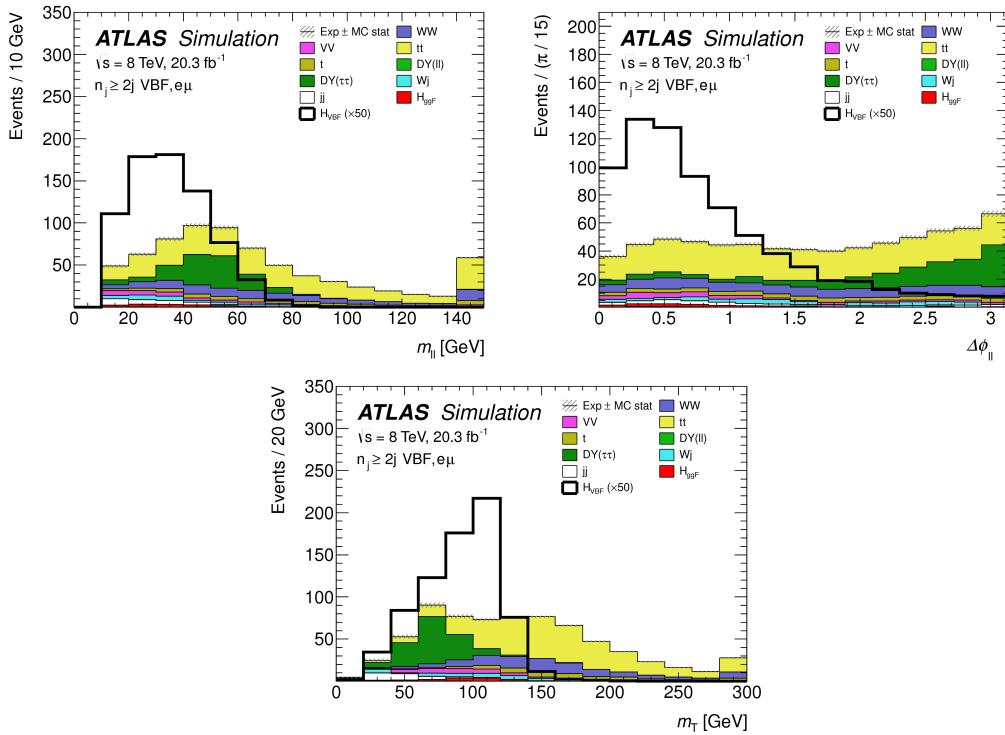


Figure 5.6: Distributions of  $m_{\ell\ell}$  (top left),  $\Delta\phi_{\ell\ell}$  (top right), and  $m_T$  (bottom), Higgs topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection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

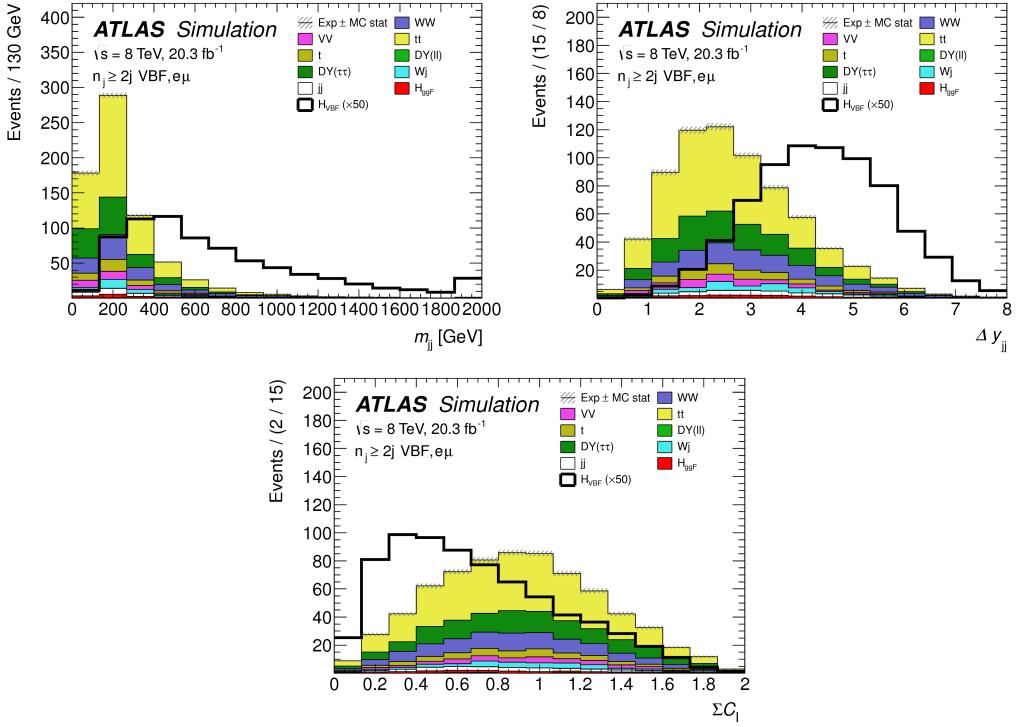


Figure 5.7: Distributions of  $m_{jj}$  (top left),  $\Delta y_{jj}$  (top right),  $\sum C_\ell$  (bottom), VBF topology variables used in the selection requirements of the cut-based signal region and as inputs to the BDT result. These are plotted after all of the BDT pre-training selection cuts [62].

## 1874 5.5 BACKGROUND ESTIMATION

1875 This section describes the procedures used to estimate backgrounds for the VBF analysis in both the  
 1876 cut-based and BDT analyses.

### 1877 5.5.1 GENERAL STRATEGY

1878 Most of the backgrounds in the VBF analysis have shapes estimated from Monte Carlo simulation but  
 1879 normalizations derived from control regions in data. In essence, a normalization factor (denoted with  $\beta$   
 1880 or abbreviated as NF) is derived by scaling the MC yield in the control region to the corresponding yield  
 1881 in data. Once this factor is derived, it can be used to scale the MC estimate of the background in the signal

1882 region. This is illustrated in equation 5.3.

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

1883 Here,  $B$  denotes the MC yield prediction in the denoted region, while  $N$  denotes the observed number of  
1884 events in data in the denoted region.

1885 Another way of writing the same equation, in terms of an extrapolation factor  $\alpha$  rather than a normal-  
1886 ization factor  $\beta$ . The overall calculation is exactly the same. However, when phrased in this way, it shows  
1887 how the uncertainty on the background estimation can be reduced. This is shown in equation 5.4.

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

1888 Phrased this way, the equation shows that with enough statistics in the control region, a large theoretical  
1889 uncertainty on the overall background yield in the signal region can be replaced by a small statistical un-  
1890 certainty coming from the number of data events in the CR and a smaller theoretical uncertainty on the  
1891 extrapolation from the control region to the signal region.

### 1892 5.5.2 TOP BACKGROUND

1893 The normalization factor  $\beta_t$  for the top background in the VBF analysis is derived in a region required  
1894 to have one b-tagged jet, or  $n_b = 1$ . In the cut-based analysis, normalization factors are computed at every  
1895 stage of the cutflow by applying the appropriate cuts in the CR. These NF are then applied to the  $t\bar{t}$  and  
1896 single top event yields in the SR. In the BDT analysis, a single normalization factor is computed for each  
1897 bin of  $O_{\text{BDT}}$  after applying the BDT pre-training cuts described previously. The computed normaliza-  
1898 tion factors are derived with all flavor combinations combined in order to decrease statistical uncertainty.  
1899 Additionally, in the BDT analysis, BDT bins 2 and 3 are merged for the same reason.

1900 Table 5.9 shows the evolution of the  $\beta_t$  through the cut-based selection. Table 5.10 shows the value of  
1901 the  $\beta_t$  in each bin of  $O_{\text{BDT}}$ . In all cases, the computed factors are relatively consistent with unity, with  
1902 the largest discrepancy coming in bin 1 of  $O_{\text{BDT}}$ . The normalization factors in the bins of  $O_{\text{BDT}}$  are also

1903 consistent with those derived in teh cut-based sisgnal region, increasing confidence in the BDT estimation.

| 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.

| $O_{\text{BDT}}$ | $\beta_t$       |
|------------------|-----------------|
| Bin0             | $1.09 \pm 0.02$ |
| Bin1             | $1.58 \pm 0.15$ |
| Bin2             | $0.95 \pm 0.31$ |
| Bin3             | $0.95 \pm 0.31$ |

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

1904 Figure 5.8 shows the  $m_{jj}$  and  $O_{\text{BDT}}$  distributions in the top control region. Overall the modeling looks  
1905 consistent with the data.

1906 While these normalization factors can be computed and applied to the expected background yields listed  
1907 in tables like table ??, in the end the normalization of the top background is profiled (meaning there is a  
1908 dedicated Poisson constraint) and allowed to float in the final statistical fit.

### 1909 5.5.3 $Z/\gamma^* \rightarrow \tau\tau$ BACKGROUND

1910 In the different flavor channels, the  $Z/\gamma^* \rightarrow \tau\tau$  background is an important one. Di-tau production  
1911 can produce an  $e\mu$  final state if each  $\tau$  lepton decays to a different flavor lepton.

1912 In the BDT analysis, a single normalization factor for the background is derived. A control region  
1913 is defined using the pre-training selection cuts, except requiring that  $|m_{\tau\tau} - m_Z| < 25 \text{ GeV}$  so that  
1914 the region is enriched in  $Z/\gamma^* \rightarrow \tau\tau$  background. Additional requirements of  $m_{\ell\ell} < 80(75) \text{ GeV}$

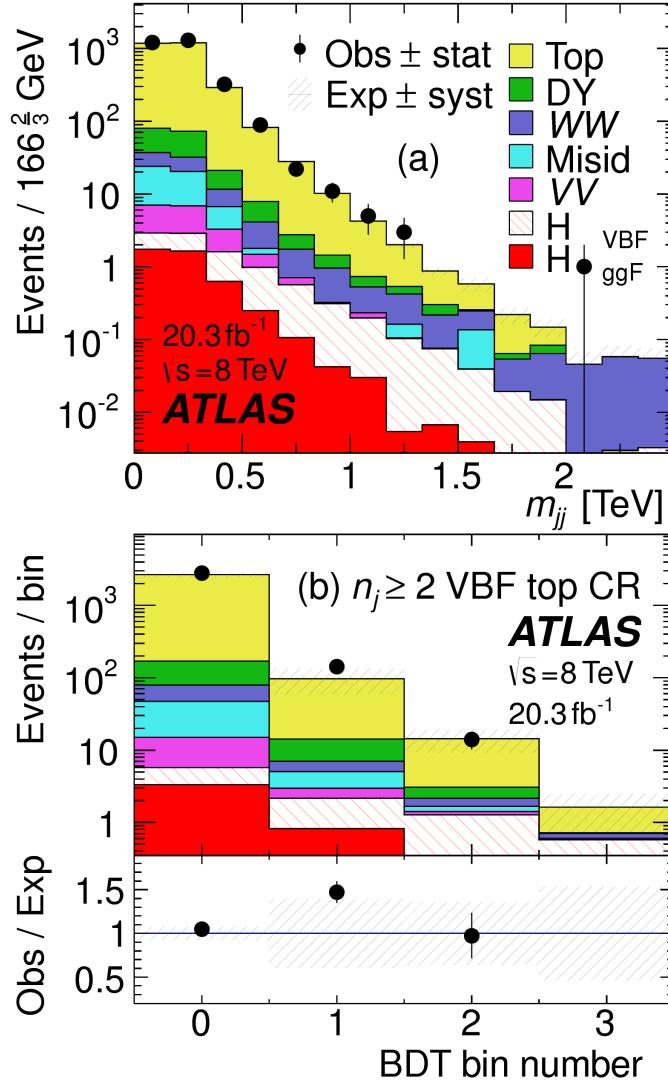


Figure 5.8: Distributions of  $m_{jj}$  (a) and  $O_{\text{BDT}}$  (b) in the VBF  $n_b = 1$  top CR [62].

in the different (same) flavor channel, as well as  $O_{\text{BDT}} > -0.48$  are applied to increase the purity of the region. The final  $\beta_{Z/\gamma^* \rightarrow \tau\tau}$  is calculated to be  $0.9 \pm 0.3$  (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 region is defined including all SR cuts up to the  $Z/\gamma^* \rightarrow \tau\tau$  veto, which is instead made into a Z mass peak requirement as for the BDT region. The  $m_{\ell\ell}$  cut from

1922 the BDT region is included as well. The cut-based approach aims to correct the normalization of the  
 1923  $Z/\gamma^* \rightarrow \tau\tau$  background in two ways. First, an overall normalization factor is computed from the control  
 1924 region. However, the VBF topological cuts are not included in this region, and applying them as is done in  
 1925 the top CR is not feasible due to limited statistics. So, instead, correction factors (CF) to the cut efficiencies  
 1926 of the VBF cuts are derived in a same flavor  $Z \rightarrow \ell\ell$  control region, which has significantly more statistics.  
 1927 The CF is simply the ratio of the cut efficiencies in data and MC derived in this region. In the end, the  
 1928 overall background estimate is given by equation 5.5.

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

1929 The hypothesis is that while the normalization correction must be derived in a dedicated region, the ef-  
 1930 ficiency of the VBF cuts should not be sensitive to the type of  $Z/\gamma^*$  process and thus the larger control  
 1931 region can be exploited to derive the CF. Figure 5.9 shows a shape comparison for the  $m_{jj}$  variable in  
 1932  $Z \rightarrow \tau\tau$  events in the signal region and  $Z \rightarrow \ell\ell$  events in the control region. The figure shows that the  
 1933 shapes are indeed comparable and thus any CF derived in the same flavor control region can reliably be  
 1934 applied in the signal region.

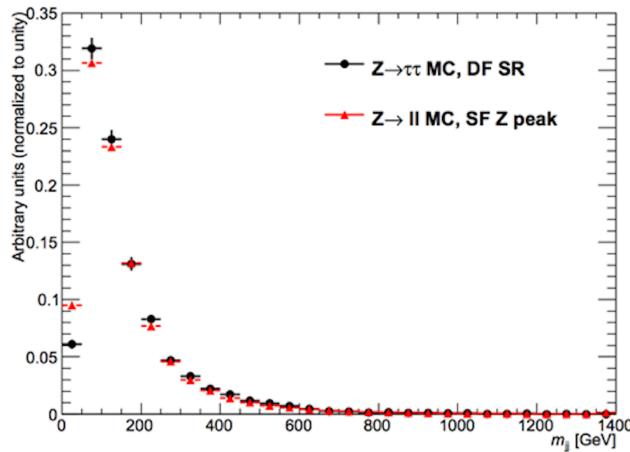


Figure 5.9: Comparison of  $m_{jj}$  shape in a same flavor  $Z \rightarrow \ell\ell$  control region and the VBF cut-based signal region.

1935 Table 5.11 shows the overall normalization factor  $\beta_{\tau\tau}$  and the efficiency correction factors for the various  
 1936 VBF topological cuts. In general, the statistical uncertainties on the cut efficiency corrections are quite

<sup>1937</sup> good, and the MC tends to underestimate the efficiency of the VBF cuts for the  $Z/\gamma^* \rightarrow \tau\tau$  background.  
<sup>1938</sup> 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.

<sup>1939</sup> 5.5.4  $Z/\gamma^* \rightarrow \ell\ell$  BACKGROUND

<sup>1940</sup> In the same flavor channels, the  $Z/\gamma^* \rightarrow \ell\ell$  background is dominant and thus must be estimated cor-  
<sup>1941</sup> rectly. In both the BDT and cut-based analyses, the background is estimated using the so-called “ABCD”  
<sup>1942</sup> method. The ABCD method creates four different regions by defining cuts on two variables. One of the  
<sup>1943</sup> regions (A) is the signal region, while the other regions are defined by inverting one of both of the cuts.  
<sup>1944</sup> in this case, the two variables used are  $m_{\ell\ell}$  and  $E_T^{\text{miss}}$ , because inverting either of the SR cuts on these  
<sup>1945</sup> variables will give regions rich in the  $Z/\gamma^* \rightarrow \ell\ell$  background. Figure 5.10 illustrates the general strategy  
<sup>1946</sup> for each region.

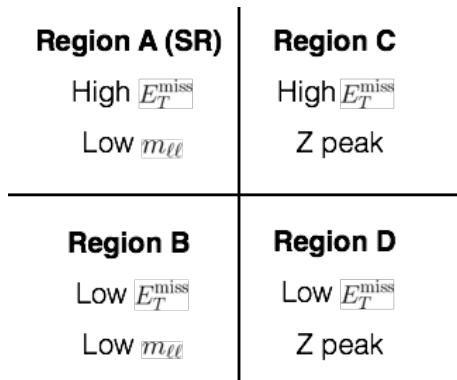


Figure 5.10: General illustration of the ABCD region definitions for  $Z/\gamma^* \rightarrow \ell\ell$  background estimation.

<sup>1947</sup> In both of the cut-based and BDT analyses, the Z peak region is defined with  $|m_{\ell\ell} - m_Z| < 15 \text{ GeV}$ .

1948 In the cut-based analysis, low  $m_{\ell\ell}$  corresponds to  $m_{\ell\ell} < 50$  GeV (this defines the cut-based SR) while  
 1949 in the BDT it is  $m_{\ell\ell} < 75$  GeV. In the cut-based, high and low  $E_T^{\text{miss}}$  are defined as opposite ends of  
 1950 the 55 GeV cut applied for the signal region definition. The BDT low  $E_T^{\text{miss}}$  region is between 25 and  
 1951 45 GeV, while the high  $E_T^{\text{miss}}$  region is  $E_T^{\text{miss}} > 45$  GeV.

1952 Once the regions are defined, the final signal region background estimate is done by taking the estimate  
 1953 in region B and extrapolating it to the signal region (A) by multiplying it by the ratio of regions C and  
 1954 D. Effectively, the  $Z$  peak region is used to estimate the efficiency of the  $E_T^{\text{miss}}$  cut in data, and then this  
 1955 efficiency is applied in the low  $m_{\ell\ell}$  region. An additional correction is also applied for the non-closure of  
 1956 the method in MC. This is summarized in equations 5.6 and 5.7.

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

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

1957 Here, the  $N$  refer to data yields in each region with the non  $Z/\gamma^*$  backgrounds subtracted, while  $B$   
 1958 refer to the  $Z/\gamma^*$  yields in MC in each region.

1959 A normalization factor  $\beta_{\ell\ell}$  is computed for each analysis as the ratio of the predicted data yield to the  
 1960 MC yield in the SR. The shape of the BDT distribution is taken from data region B, while the shape of  
 1961 the  $m_T$  distribution in the cut-based analysis is taken from  $Z/\gamma^*$  MC in the SR. The values of the  $\beta_{\ell\ell}$  in  
 1962 the cut-based and BDT analyses from this method are summarized in table 5.12. They are quite consistent  
 1963 with one another within the statistical uncertainties. In the cut-based analysis, the same cut efficiency  
 1964 correction factors shown in table 5.11 are also applied (in product with the  $\beta_{\ell\ell}$ ) in the same flavor channels  
 1965 to this background, as they were derived in the  $Z$  peak region.

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

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

1966    5.5.5     $WW$  AND OTHER DIBOSON BACKGROUNDS

1967    The  $WW$  and other diboson backgrounds have both their shape and normalization taken from MC  
 1968    simulation. They are validated in dedicated control regions and found to agree with data well.

1969    As  $WW$  is the largest of these backgrounds and is irreducible, validating the estimate is of particular  
 1970    importance. The validation region is constructed by requiring the pre-selection cuts on leptons and  $m_{\ell\ell}$ ,  
 1971     $n_b = 0$ , and  $m_T > 100$  GeV. The  $m_{T2}$  variable [82] is an additional discriminant that will isolate  
 1972    the  $WW$  background, and a requirement of  $m_{T2} > 160$  GeV is placed to define the  $WW$  validation  
 1973    region. This cut gives a 60% purity for the validation region. The derived normalization factor in the  
 1974    region is  $1.15 \pm 0.19$  and is thus consistent with unity. Figure 5.11 shows the  $m_{T2}$  distribution and how it  
 1975    distinguishes the  $WW$  background.

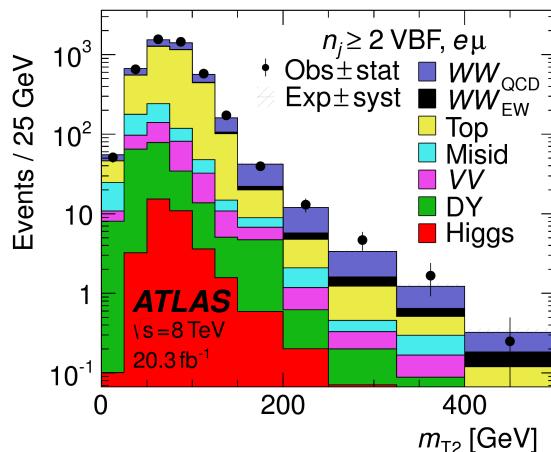


Figure 5.11: Distribution of  $m_{T2}$  in the  $WW$  validation region of the VBF analysis [62].

1976    5.5.6    HIGGS PRODUCTION VIA GLUON-GLUON FUSION

1977    Because this analysis is dedicated to measuring the VBF contribution to Higgs production, the compo-  
 1978    nent of Higgs production from gluon-gluon fusion is treated as a background. The shape is taken directly  
 1979    from simulation, using the generators described in table 5.4. In the final combined fit of all different signal  
 1980    regions, the normalization is controlled by either a combined signal strength parameter  $\mu$ , which controls  
 1981    the normalization of both ggF and VBF production, or a separate parameter  $\mu_{ggF}$  depending on the in-

1982 terpretation being presented in the final results.

### 1983 5.5.7 BACKGROUNDS WITH MISIDENTIFIED LEPTONS

1984 As discussed previously, the  $W + \text{jets}$  and QCD multijet backgrounds are derived with fully data-driven  
1985 methods. These backgrounds do not make a large contribution to the final VBF signal region but their  
1986 estimation methods are discussed briefly here.

#### 1987 $W + \text{jets}$ BACKGROUND

1988 The  $W + \text{jets}$  background enters the signal region by having one of the jets mis-reconstructed as a lep-  
1989 ton. The background is estimated by constructing a control sample with two leptons, where one lepton  
1990 passes the usual lepton quality cuts but the second lepton fails one of those cuts (also known as the “anti-  
1991 identified” lepton). This control region is rich in the  $W + \text{jets}$  contribution because if a second lepton is  
1992 reconstructed in a  $W + \text{jets}$  event it is likely to be poor quality. The purity of this  $W + \text{jets}$  control sample is  
1993 85% to 90% depending on the exact configuration of leptons in the final state.

1994 The signal region estimate of  $W + \text{jets}$  is estimated by extrapolation from the control sample to the sig-  
1995 nal region using extrapolation factors derived in a  $Z + \text{jets}$  control sample in data. The extrapolation factor  
1996 is the ratio of the number of lepton candidates satisfying all quality criteria to the number of lepton can-  
1997 didates anti-identified. This ratio is measured in bins of  $p_T$  and  $\eta$ . Thus, the final signal region estimate  
1998 (binned as the extrapolation factor is binned) is simply the number of events in the anti-identified lepton  
1999 control sample multiplied by the extrapolation factor derived from the  $Z + \text{jets}$  control sample. Figure 5.12  
2000 shows the extrapolation factors derived for electrons and muons.

#### 2001 QCD MULTIJET BACKGROUND

2002 The method for estimating the multijet background is very similar to the  $W + \text{jets}$  estimation method.  
2003 The control sample in this case has two anti-identified leptons but otherwise satisfies all signal region re-  
2004 quirements. The extrapolation factor is estimated from a multijet sample and applied twice to the control  
2005 sample.

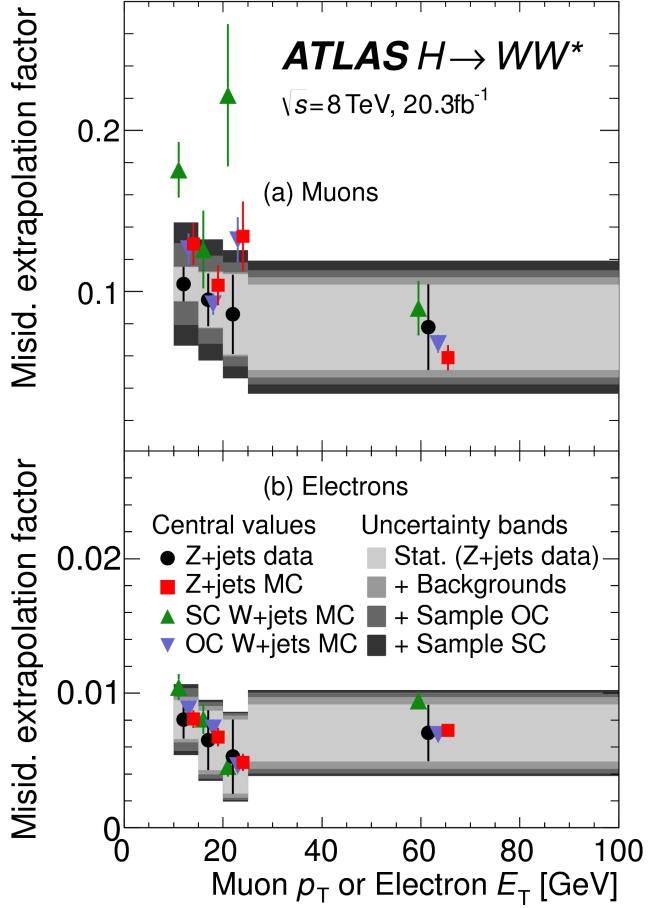


Figure 5.12: Extrapolation factors for the  $W+jets$  estimate derived for muons (a) and electrons (b) as a function of lepton  $p_T$  [62].

### 2006 5.5.8 BACKGROUND COMPOSITION IN FINAL SIGNAL REGION

2007 After all of these estimation procedures, the final signal region composition can be calculated. The esti-  
 2008 mated yields are all shown in table ???. Figure 5.13 shows the relative percentages of the different background  
 2009 for the different flavor and same flavor final states. In  $e\mu$ , the leading backgrounds are top backgrounds,  
 2010 ggF Higgs, and SM  $WW$  production. In  $ee/\mu\mu$ , the leading background is Drell-Yan, followed by top  
 2011 and ggF Higgs.

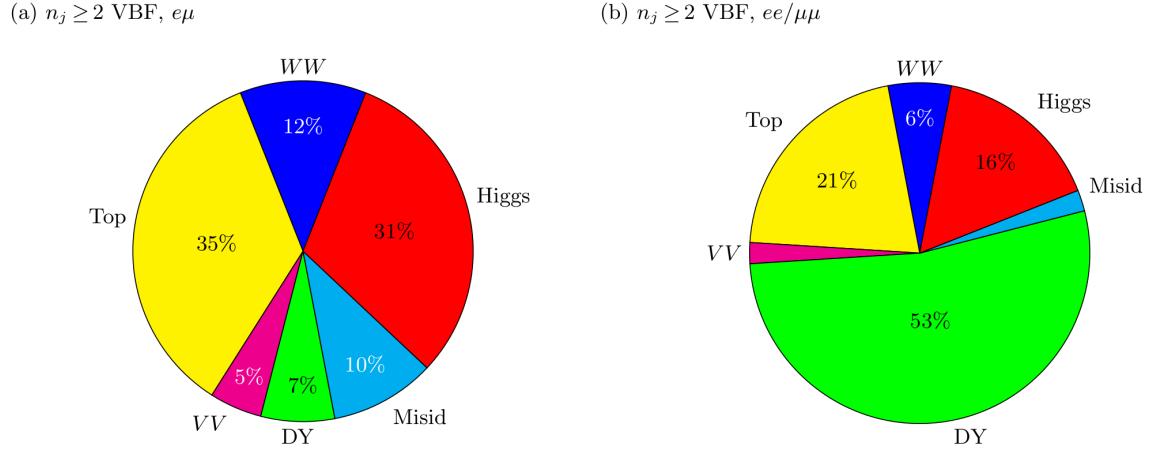


Figure 5.13: Background composition in final VBF signal region [62].

## 5.6 SYSTEMATIC UNCERTAINTIES

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

### 5.6.1 THEORETICAL UNCERTAINTIES

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

2028 envelope of maximal variation is taken as an uncertainty. Finally, there are two uncertainties associated with  
 2029 the choice of MC software (referred to as PDF uncertainty). An uncertainty associated with the generator  
 2030 chosen for the hard scattering process is evaluated by keeping the parton showering software constant but  
 2031 varying the matrix element generator and taking the maximal variation as an uncertainty (referred to as  
 2032 the generator uncertainty). The converse variation can also be done, where the matrix element generator  
 2033 remains constant and the generator used for the underlying event/parton shower modeling is varied (re-  
 2034 ferred to as the UE/PS uncertainty). In cases where the background is normalized in a control region, the  
 2035 systematic uncertainty arises from variations of the extrapolation factor  $\alpha$  between the CR and the SR,  
 2036 which can affect the normalization of the background in the SR.

2037 There are two additional uncertainties that are applied to the Higgs processes as well. First, there are  
 2038 uncertainties assigned to the Higgs total production cross section. Then, there are uncertainties assigned  
 2039 based on the fact that the analysis is done in exclusive jet bins and it is possible for signal events to migrate  
 2040 from one bin to the next depending on the presence or absence of jets. These are assigned using the Jet  
 2041 Veto Efficiency (JVE) procedure [18, 83] for ggF events and the Stewart-Tackmann (ST) method [84] for  
 2042 VBF production.

2043 Table 5.13 shows the total theory uncertainties on the backgrounds in the cut-based analysis. These are  
 2044 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.

2045 Figures 5.14 and 5.15 show the variations in the extrapolation factor from the PDF and QCD uncertain-  
 2046 ties on the top background estimate, binned in  $m_T$ , for the cut-based analysis. In both cases, there was  
 2047 no significant shape uncertainty but normalization uncertainties were assigned according to the maximal  
 2048 variation. These uncertainties enter into the 26% total uncertainty on top quoted in table 5.13

2049 While the estimate for the same-flavor  $Z/\gamma^* \rightarrow \ell\ell$  background is data-driven, there is still a systematic  
 2050 uncertainty taken for the non-closure of the method in Monte Carlo. This is taken as the maximum of the  
 2051 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  
 2052 the cut-based analysis this non-closure uncertainty 23%, while for the BDT analysis it is 17%.

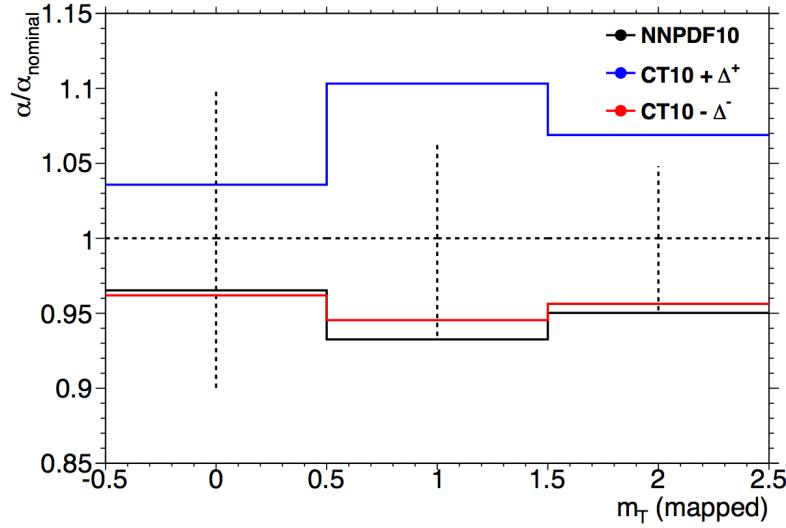


Figure 5.14: Variations in the top background extrapolation factor in the cut-based analysis due to PDF uncertainties, binned in  $m_T$ .

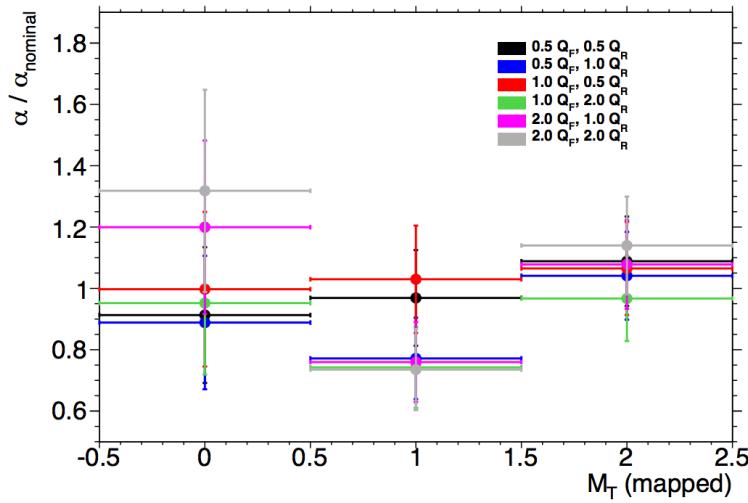


Figure 5.15: Variations in the top background extrapolation factor in the cut-based analysis due to QCD scale uncertainties, binned in  $m_T$ .

2053    5.6.2 EXPERIMENTAL UNCERTAINTIES

2054    In this analysis, the theoretical uncertainties end up being the most dominant, but there are some ex-  
2055    perimental uncertainties that make a contribution as well. The first is the uncertainty on the measured  
2056    integrated luminosity, which affects backgrounds whose normalization is taken from MC and is measured  
2057    to be 2.8% in the 8 TeV dataset [85]. The dominant sources of uncertainty overall are uncertainties on the  
2058    jet energy scale and resolution and the  $b$ -tagging efficiency. Additional sources include lepton uncertain-  
2059    ties on identification, resolution, and trigger efficiency, as well as uncertainties on the missing transverse  
2060    momentum .

2061    The jet energy scale uncertainty is split into several independent components, including jet-flavor de-  
2062    pendent calorimeter response uncertainties, uncertainties on modeling of pile-up interactions, uncertain-  
2063    ties on extrapolation from the central to forward detector regions, and MC non-closure [86]. The uncer-  
2064    tainty on energy scale for jets used in this analysis ranges from 1% to 7% depending on the jet  $p_T$  and  $\eta$ .  
2065    The jet energy resolution varies from 5% to 20%, with uncertainties ranging from 2% to 40% (the largest  
2066    uncertainties occurring at the selection threshold).

2067    The  $b$ -tagging efficiency is independently measured in data samples enriched in dileptonic decays of  $t\bar{t}$   
2068    events or in events where a muon is reconstructed in the vicinity of a jet [87, 88]. The efficiencies and  
2069    their uncertainties are binned in  $p_T$  and decomposed into uncorrelated components using an eigenvector  
2070    method [89]. Uncertainties on the efficiency range from 1% to 7.8%. The uncertainty on the rate of  
2071    misidentification of  $c$ -jets as  $b$ -jets ranges from 6-14%, while the uncertainty on the rate of light jet mis-  
2072    tagging ranges from 9-19% depending on  $p_T$  and  $\eta$ .

2073    The total experimental uncertainties on different signal and background components are summarized  
2074    in table 5.14. They are compared to the level of other statistical and systematic uncertainties as well. Overall,  
2075    the experimental uncertainties are sub-dominant compared to the statistical and theoretical uncertainties.

2076    5.7 RESULTS

2077    While the combined results of all the  $H \rightarrow WW^*$  sub-analyses will be discussed in the next chapter,  
2078    this section presents the results of the VBF specific analysis and interpretations. As table ?? shows, the final

| Sample                    | Total<br>error | Stat.<br>error | Expt.<br>syst. err. | Theo.<br>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 [62].

2079 cut-based signal region contains 20 events in data with  $m_T < 150$  GeV, 14 coming from the  $e\mu$  channel  
 2080 and 6 coming from the  $ee + \mu\mu$  channel. The BDT analysis has many more candidates due to its looser  
 2081 selection, and the yields in each bin of  $O_{\text{BDT}}$  are shown in table 5.15.

(a) Before the BDT classification

| Selection          | Summary                         |                  |                  |                     |                  |                 | Composition of $N_{\text{bkg}}$ |                      |          |       |          |          |          |                        |                              |                             |                            |
|--------------------|---------------------------------|------------------|------------------|---------------------|------------------|-----------------|---------------------------------|----------------------|----------|-------|----------|----------|----------|------------------------|------------------------------|-----------------------------|----------------------------|
|                    | $N_{\text{obs}}/N_{\text{bkg}}$ | $N_{\text{obs}}$ | $N_{\text{bkg}}$ | $N_{\text{signal}}$ |                  |                 | $N_{WW}^{\text{QCD}}$           | $N_{WW}^{\text{EW}}$ | $N_{tt}$ | $N_t$ | $N_{Wj}$ | $N_{jj}$ | $N_{VV}$ | $N_{\text{Drell-Yan}}$ | $N_{ee/\mu\mu}^{\text{QCD}}$ | $N_{\tau\tau}^{\text{QCD}}$ | $N_{\tau\tau}^{\text{EW}}$ |
|                    |                                 |                  |                  | $N_{\text{ggF}}$    | $N_{\text{VBF}}$ | $N_{\text{VH}}$ |                                 |                      |          |       |          |          |          |                        |                              |                             |                            |
| $e\mu$ 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 [62].

2082 Figure 5.16(a) shows the final distribution of data candidates compared to the expected  $m_T$  distribution  
 2083 for signal and background. The data are very consistent with a VBF Higgs hypothesis. Figure 5.16(b) shows

2084 where the data candidates fall in the two-dimensional binning of  $m_T$  and  $m_{jj}$  used in the fit for the cut-  
 2085 based analysis.

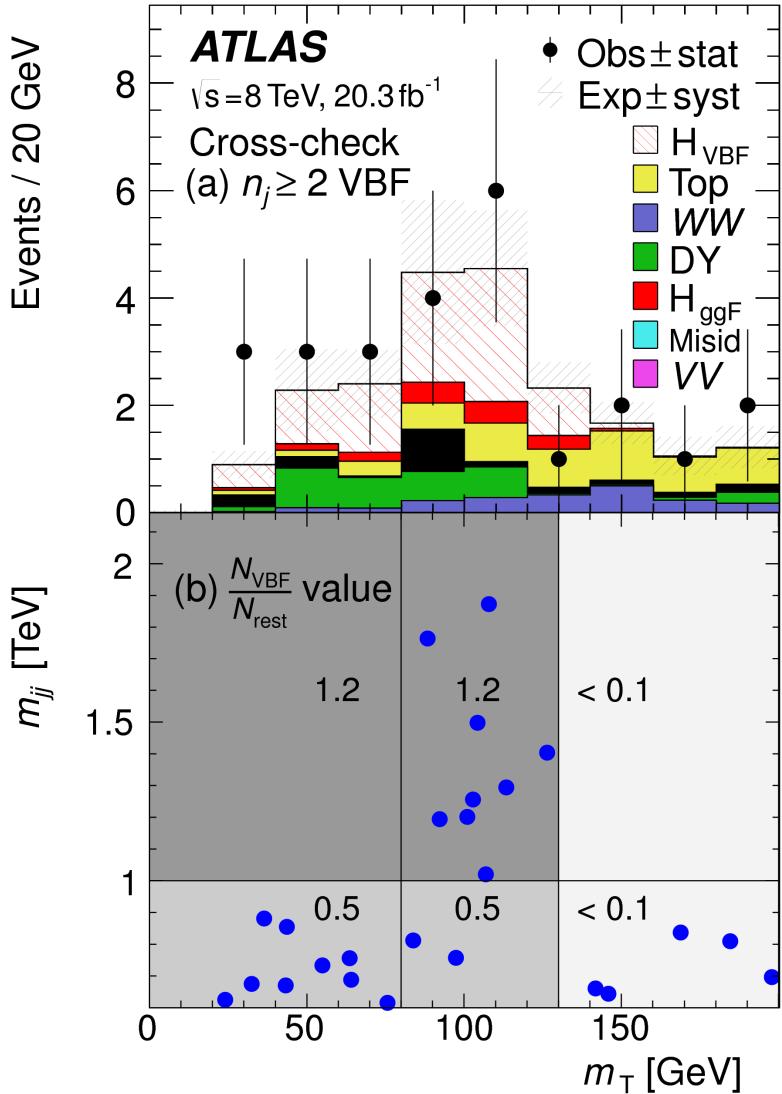


Figure 5.16: Post-fit distributions in the cut-based VBF analysis. Panel (a) shows the one-dimensional  $m_T$  distribution, while (b) shows the data candidates split into the bins of  $m_T$  and  $m_{jj}$  used in the final fit [62].

2086 Figure 5.17 shows the distributions of  $O_{\text{BDT}}$  and  $m_T$  in the VBF BDT analysis. Again the data are quite  
 2087 consistent with a VBF Higgs hypothesis.

2088 Because the cut-based result is used as a validation for the BDT analysis and the two signal regions are  
 2089 not fully orthogonal, it is interesting to explore which events overlap between the two analyses. Of the

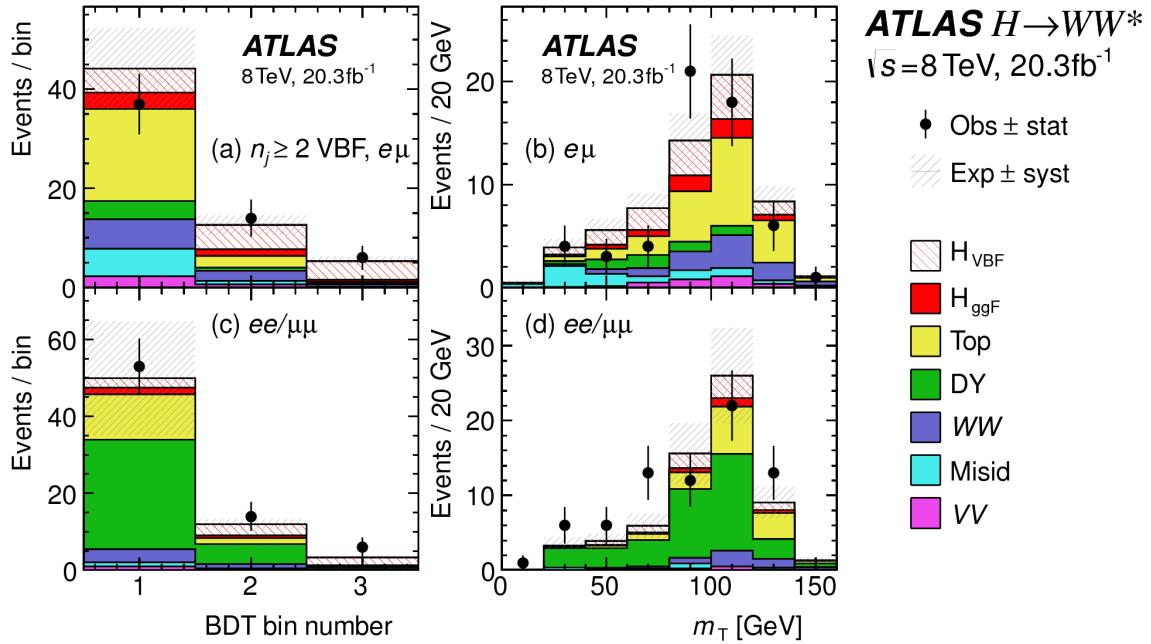


Figure 5.17: Postfit distributions in the BDT VBF analysis [62].

2090 twenty events in the cut-based signal region, only seven were not selected by the BDT analysis, while the  
 2091 other thirteen also enter the BDT signal region. Figure 5.18 shows where the different analysis candidates  
 2092 lie in the  $m_{jj}$ - $m_T$  plane. This shows clearly that the advantage of the BDT analysis is that it can extract  
 2093 signal candidates lower  $m_{jj}$  region due to its ability to recognize correlations with other variables.

2094 While the context of these results in the broader  $H \rightarrow WW^*$  statistical analysis will be presented in the  
 2095 next chapter, the statistical significance of the VBF Higgs result can be shown here. In the BDT analysis, the  
 2096 expected signal significance was  $2.7\sigma$ , while the observed significance was  $3.1\sigma$ . In the cut-based analysis,  
 2097 the expected significance was  $2.1\sigma$  and the observed significance was  $3.0\sigma$ . The compatibility between  
 2098 these two results can be evaluated by computing the probability of observing a larger difference in  $Z_0$  values  
 2099 than the one measured. Using toy Monte Carlo with the ggF signal strength fixed to unity and considering  
 2100 only statistical uncertainties, this probability is computed to be 79%, indicating good agreement between  
 2101 the analyses. This result represents the first evidence of the vector boson fusion production of a Higgs  
 2102 boson.

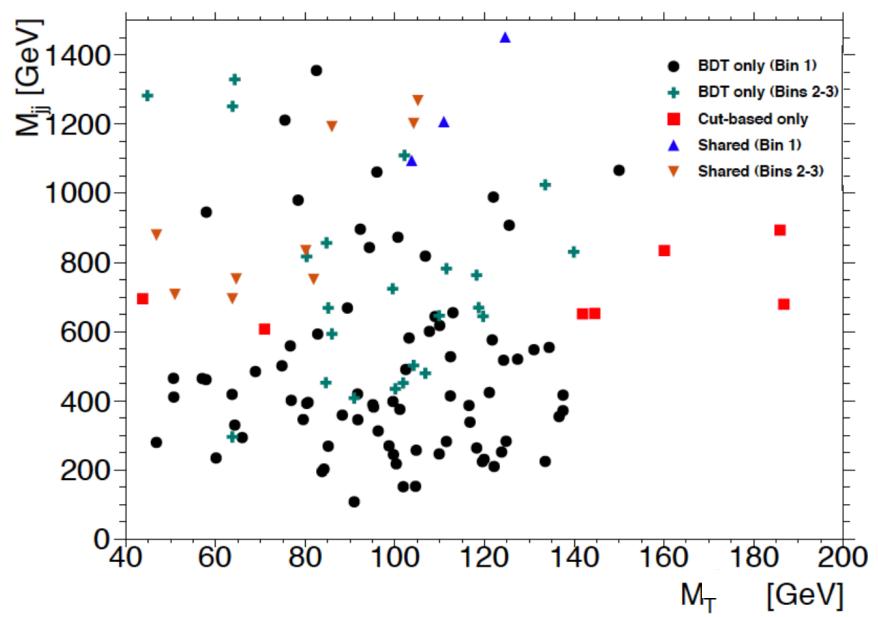


Figure 5.18: Overlap between cut-based and BDT VBF signal region candidates in the  $m_{jj}$ - $m_T$  plane.

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

Chuck Palahniuk

# 6

2103

2104

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

2105

## results

2106

### 6.1 INTRODUCTION

2107

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

2114

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

| SR category $i$  |                        |                        |                                | Fit var.           |                  |
|------------------|------------------------|------------------------|--------------------------------|--------------------|------------------|
| $n_j$ , flavor   | $\otimes m_{\ell\ell}$ | $\otimes p_T^{\ell 2}$ | $\otimes \ell_2$               |                    |                  |
| $n_j = 0$        | $e\mu$                 | $\otimes [10, 30, 55]$ | $\otimes [10, 15, 20, \infty]$ | $\otimes [e, \mu]$ | $m_T$            |
|                  | $ee/\mu\mu$            | $\otimes [12, 55]$     | $\otimes [10, \infty]$         |                    | $m_T$            |
|                  |                        |                        |                                |                    |                  |
| $n_j = 1$        | $e\mu$                 | $\otimes [10, 30, 55]$ | $\otimes [10, 15, 20, \infty]$ | $\otimes [e, \mu]$ | $m_T$            |
|                  | $ee/\mu\mu$            | $\otimes [12, 55]$     | $\otimes [10, \infty]$         |                    | $m_T$            |
|                  |                        |                        |                                |                    |                  |
| $n_j \geq 2$ ggF | $e\mu$                 | $\otimes [10, 55]$     | $\otimes [10, \infty]$         |                    | $m_T$            |
|                  |                        |                        |                                |                    |                  |
| $n_j \geq 2$ VBF | $e\mu$                 | $\otimes [10, 50]$     | $\otimes [10, \infty]$         |                    | $O_{\text{BDT}}$ |
|                  | $ee/\mu\mu$            | $\otimes [12, 50]$     | $\otimes [10, \infty]$         |                    | $O_{\text{BDT}}$ |
|                  |                        |                        |                                |                    |                  |

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

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

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

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

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

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

2129 grounds. The yields for signal and background are all scaled according to the final normalizations cal-  
2130 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             | $1470 \pm 40$    | $102 \pm 26$     | $17 \pm 5$       |
| $n_j \geq 2, \text{ggF } e\mu$ | 1017             | $960 \pm 40$     | $37 \pm 11$      | $13 \pm 1.4$     |
| $n_j \geq 2, \text{VBF}$       | 130              | $99 \pm 9$       | $7.7 \pm 2.6$    | $21 \pm 3$       |

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

2131 Figure 6.1 shows the final post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions. The data are very consistent with the hypothesis of ggF Higgs production. These yields are used as input, along with the VBF results

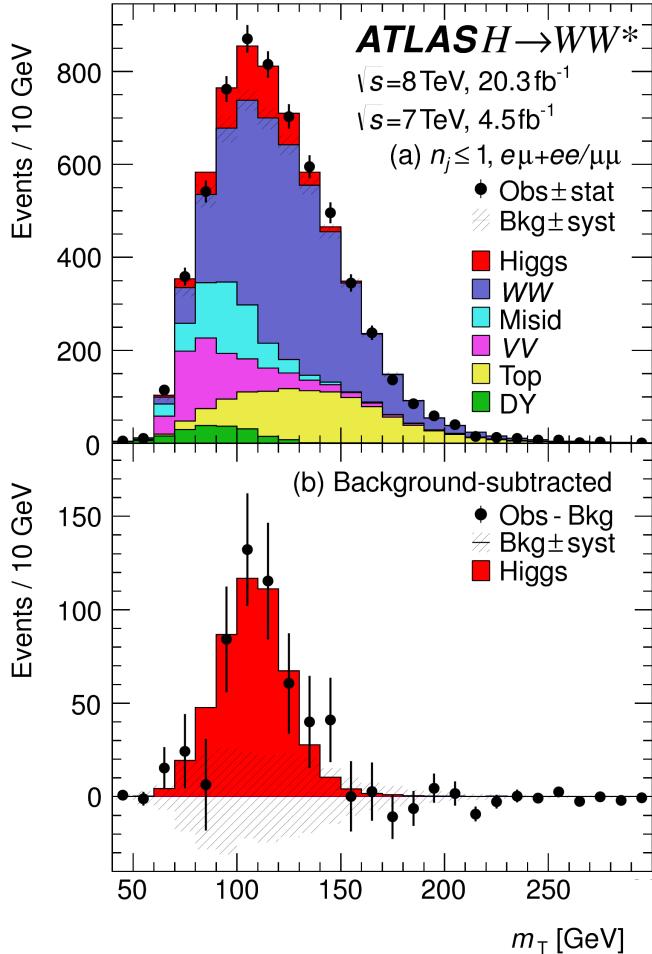


Figure 6.1: Post-fit  $m_T$  distribution in the  $n_j \leq 1$  regions [62].

2132

2133 in chapter 5, for the physical interpretation of results presented in subsequent sections.

2134 **6.3 SIGNAL STRENGTH MEASUREMENTS IN ggF AND VBF PRODUCTION**

2135 When all of the signal regions are combined in the fit, there can be a combined measurement of the  
 2136 signal strength as well as the individual ggF and VBF signal strengths. The combined signal strength is the  
 2137 ratio of the sum of the gluon fusion and VBF cross sections to the theory prediction, or a signal strength  
 2138 for the total Higgs production cross section that this analysis is sensitive to. The final measured combined  
 2139 signal strength  $\mu$  is measured shown in equation 6.1.

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

2140 Figure 6.2 gives the best fit signal strength  $\hat{\mu}$  as a function of the hypothesized Higgs mass. The value  
 2141 at 125.36 GeV corresponds to the  $\mu$  quoted in equation 6.1. This value of the Higgs mass is used because it  
 2142 is the most precise mass measurement from ATLAS, a result of the combined  $\gamma\gamma$  and  $ZZ$  mass measure-  
 2143 ments [90].

2144 As explained in chapter 3, a probability  $p_0$  can be computed using the test statistic  $q_0$  to quantify the  
 2145 probability that the background could fluctuate to produce an excess at least as large as the one observed  
 2146 in the data. The local  $p_0$  value is shown in figure 6.3 as a function of  $m_H$ . The minimum  $p_0$  value is at  
 2147  $m_H = 130$  GeV and corresponds to a significance of  $6.1\sigma$ . The curve is relatively flat and the significance  
 2148 is the same at 125.36 GeV within the quoted precision. The expected significance for a signal with strength  
 2149  $\mu = 1.0$  is  $5.8\sigma$ . This represents the first discovery level significance measurement in the  $H \rightarrow WW^* \rightarrow$   
 2150  $\ell\nu\ell\nu$  analysis.

2151 All the results presented so far in this section have been for the combined gluon fusion and VBF pro-  
 2152 duction modes. However, each signal strength can be calculated separately in the likelihood as well. There  
 2153 are two ways to do this. First, the likelihood can be parameterized in terms of a single parameter, the ratio

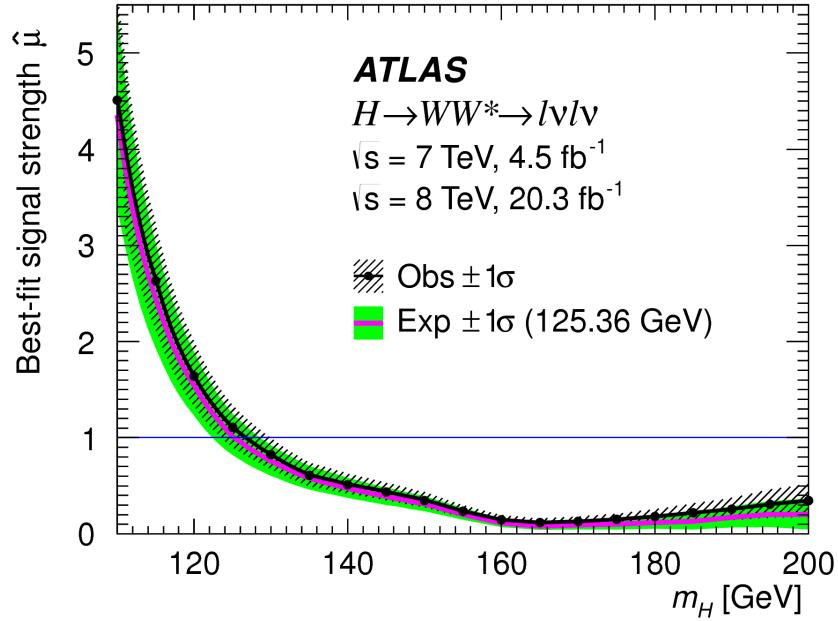


Figure 6.2: Best fit signal strength  $\hat{\mu}$  as a function of hypothesized  $m_H$  [62].

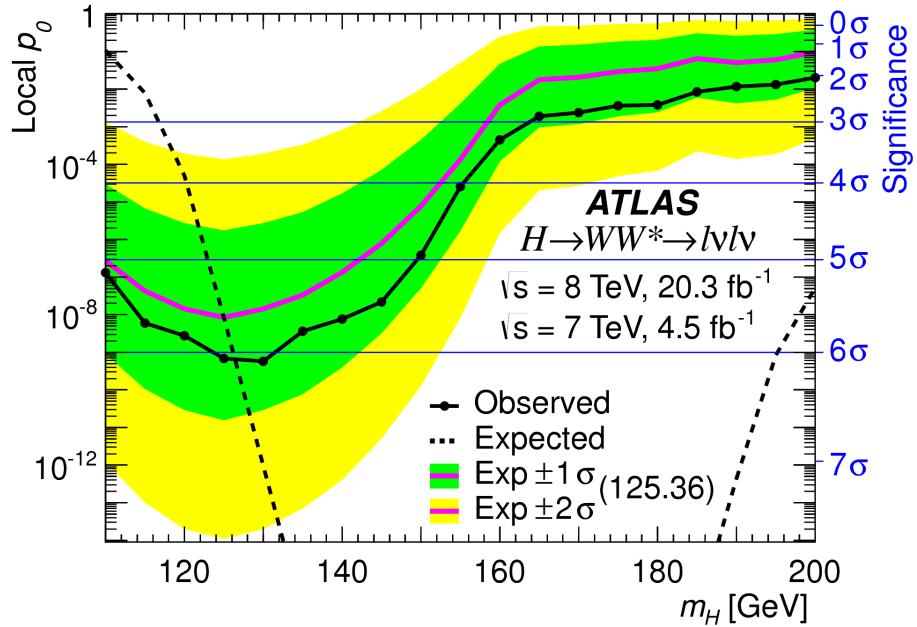


Figure 6.3: Local  $p_0$  as a function of  $m_H$  [62].

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

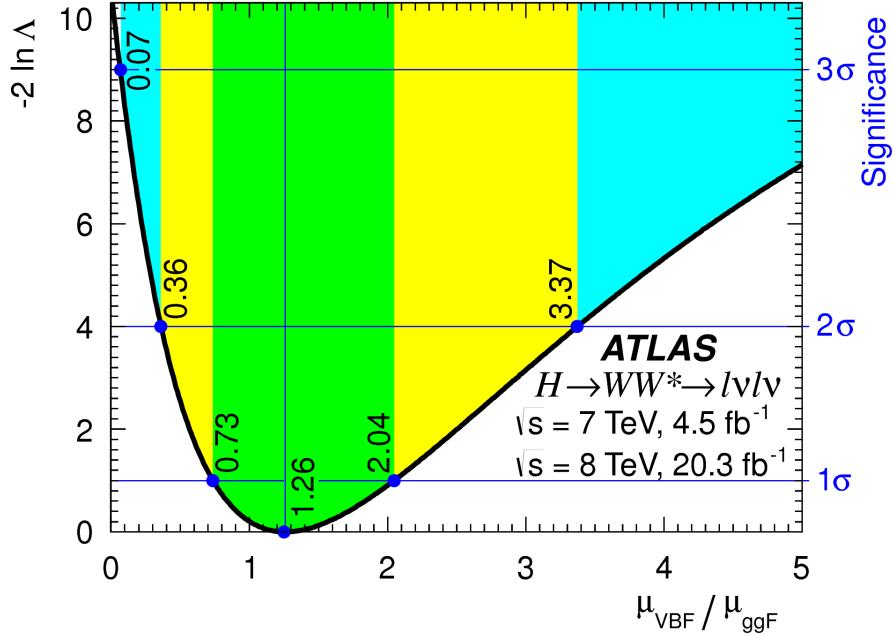


Figure 6.4: Likelihood as a function of  $\mu_{\text{VBF}} / \mu_{\text{ggF}}$  [62].

2156     The best fit value of the ratio of signal strengths is shown in equation 6.2. Within the quoted uncer-  
 2157     tainties, it is consistent with a ratio of unity.

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

2158     The null hypothesis for VBF production corresponds to a ratio of  $\mu_{\text{VBF}} / \mu_{\text{ggF}} = 0$ . The likelihood in  
 2159     figure 6.4 gives a significance of  $3.2\sigma$  at  $\mu_{\text{VBF}} / \mu_{\text{ggF}} = 0$ , as quoted in chapter 5.

2160     In addition to the ratio of signal strengths, each signal strength can be varied independently in the like-  
 2161     lihood as well. Figure 6.5 shows the two dimensional likelihood scan in the  $\mu_{\text{ggF}}-\mu_{\text{VBF}}$  plane. The best fit  
 2162     values of the two signal strengths are shown in equation 6.3. Both are consistent with unity within their  
 2163     uncertainties.

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

(stat.) (syst.)

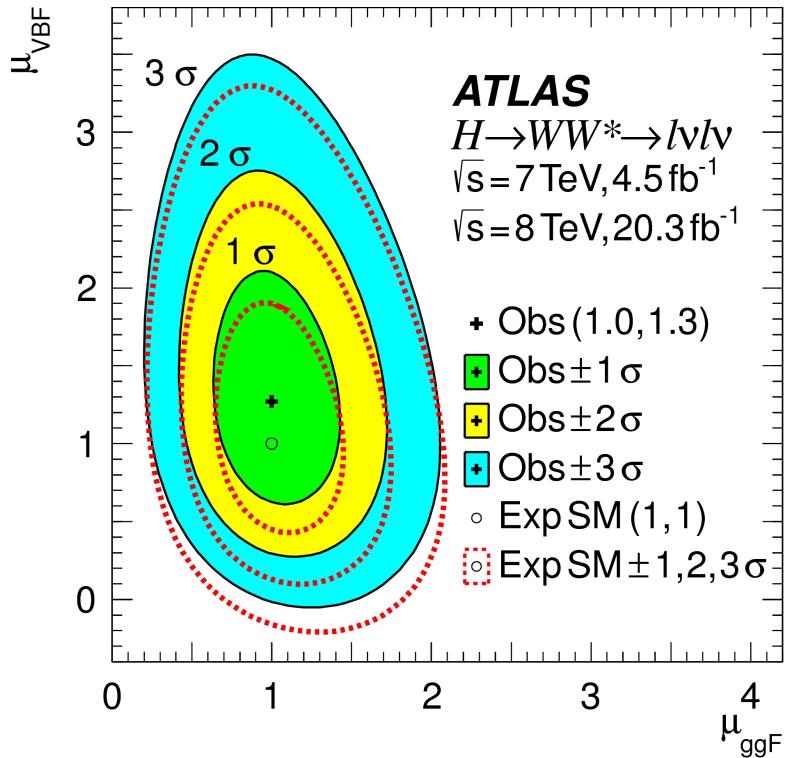


Figure 6.5: Likelihood scan as a function of  $\mu_{\text{VBF}}$  and  $\mu_{\text{ggF}}$  [62].

#### 2164 6.4 MEASUREMENT OF HIGGS COUPLINGS TO VECTOR BOSONS AND FERMIONS

2165 Similar to the parameterization of signal strength, the couplings of the Higgs to fermions and bosons  
 2166 can also be parameterized. The parameter of interest in this case is  $\kappa$ , or the ratio of the measured coupling  
 2167 to the standard model expectation. Both the fermion and boson couplings have these so-called scale factors,  
 2168  $\kappa_F$  for fermions and  $\kappa_V$  for bosons. Gluon fusion production is sensitive to the fermion couplings through  
 2169 the top quark loops in its production, while VBF production is sensitive to the vector boson couplings in  
 2170 its production. Both modes are sensitive to the vector boson couplings in their decays. The signal strengths  
 2171 will have dependence on the coupling scale factors as described in equation 6.4 [18].

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

2172 Figure 6.6 shows the two-dimensional likelihood scan of  $\kappa_F$  and  $\kappa_V$ . The best-fit values are given in equa-  
 2173 tion 6.5. The best-fit values are consistent with unity within their uncertainties.

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

(stat.) (syst.)

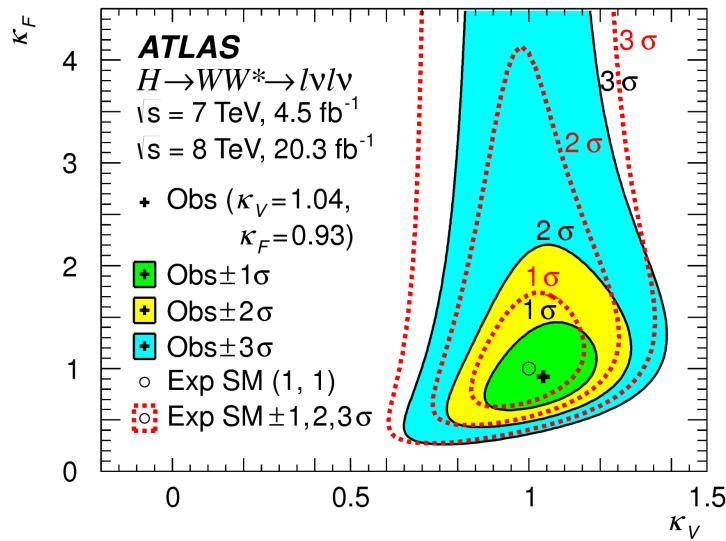


Figure 6.6: Likelihood scan as a function of  $\kappa_F$  and  $\kappa_V$  [62].

2174

## 2175 6.5 HIGGS PRODUCTION CROSS SECTION MEASUREMENT

2176 Another measurement that comes naturally from the signal strength numbers quoted earlier is the pro-  
 2177 duction cross section and 7 and 8 TeV for both gluon fusion and VBF production. The general equation  
 2178 for calculating the cross section is given in equation 6.6.

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

2179  $(N_{\text{sig}})_{\text{obs}}$  is the number of events observed in data.  $\mathcal{A}$  is the geometric and kinematic acceptance of the  
 2180 detector, while  $\mathcal{C}$  is the efficiency of the signal region selection for events that are reconstructed in the  
 2181 detector. The branching ratio of a  $WW$  system to leptons must also be divided out. The production  
 2182 cross section depends on the center of mass energy and the production mode desired (gluon fusion or  
 2183 VBF), and so three separate cross section measurements are quoted in equation 6.7.

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

(stat.) (syst.)

2184 The predicted cross section values for gluon fusion are  $3.3 \pm 0.4$  pb at 7 TeV and  $4.2 \pm 0.5$  pb at 8 TeV,  
 2185 consistent with the measured values within their uncertainties. For vector boson fusion, the predicted  
 2186 cross section is  $0.35 \pm 0.02$  pb, again consistent with the measured value.

## 2187 6.6 CONCLUSION

2188 The combined analysis of the gluon fusion and vector boson fusion processes in  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$   
 2189 in the 7 and 8 TeV datasets has yielded the first discovery level significance for Higgs production in this  
 2190 decay channel. Additionally, precise measurements of the couplings to vector bosons and fermions are  
 2191 given. Finally, signal strengths and cross sections for each production mode are measured. Figure 6.7 shows  
 2192 the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  measurements in comparison with other Higgs decay channels in ATLAS. The  
 2193 measurement of signal strength from this channel remains the most sensitive in both the gluon fusion and  
 2194 VBF production modes for the Run 1 dataset.

**ATLAS**

Individual analysis

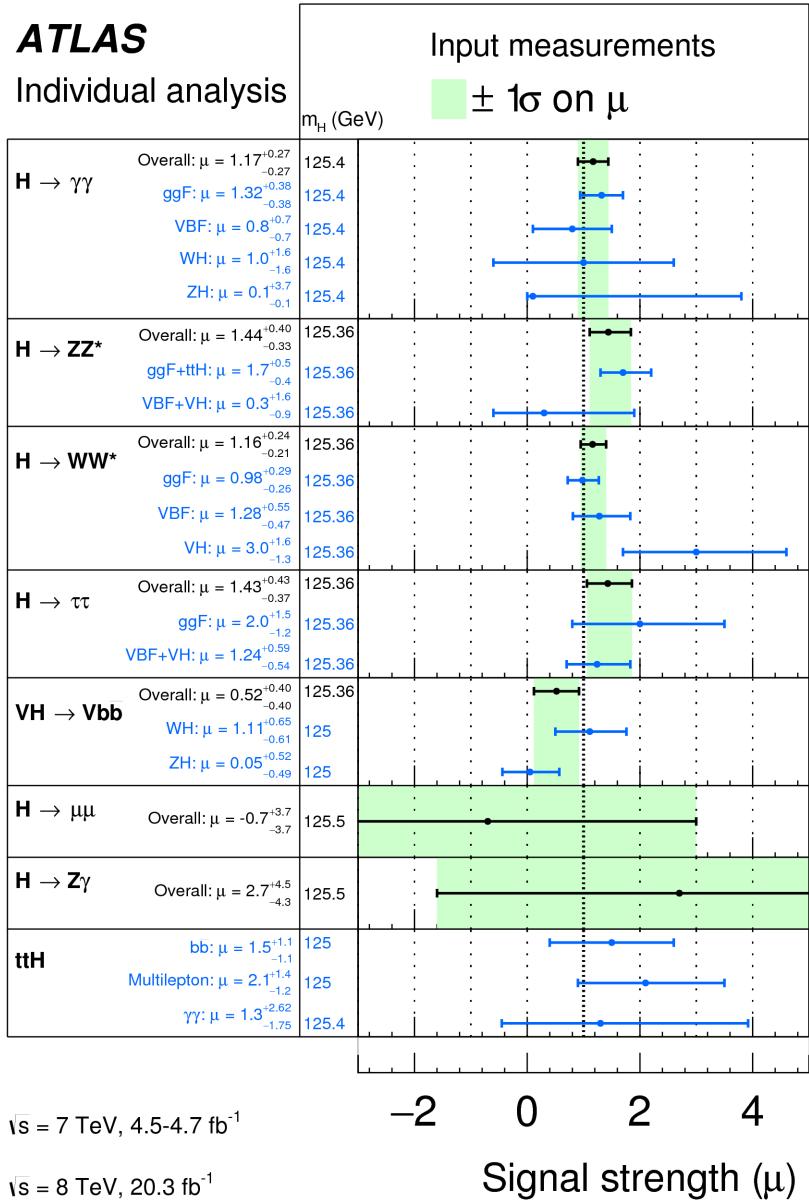


Figure 6.7: Comparison of signal strength measurements in different Higgs decay channels on ATLAS [91].

2195

## Part III

2196

Search for Higgs pair production in the

2197

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

2198

13 TeV

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

W. Eugene Smith

# 7

2199

## 2200 Search for Higgs pair production in boosted 2201 $b\bar{b}b\bar{b}$ final states

### 2202 7.1 INTRODUCTION

2203 After the discovery of the Higgs boson in the ATLAS Run 1 dataset and the subsequent measurements  
2204 of its properties, the Higgs transformed into a potential tool in searches for physics beyond the Standard  
2205 Model. The pair production cross section of the Higgs can be enhanced through BSM physics. Studying  
2206 di-Higgs production also probes the Higgs self-coupling, shedding light on the structure of the Higgs po-  
2207 tential. This chapter presents a search for resonant production of a Higgs pair in the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$   
2208 final 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  
2209 this final state in the regime where  $m_X$  is large ( $\gtrsim 1 \text{ TeV}$ ) and the Higgs bosons in the decay are signifi-  
2210 cantly boosted. A tailored selection for this boosted selection, using novel techniques in jet substructure

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

## 7.2 MOTIVATION

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

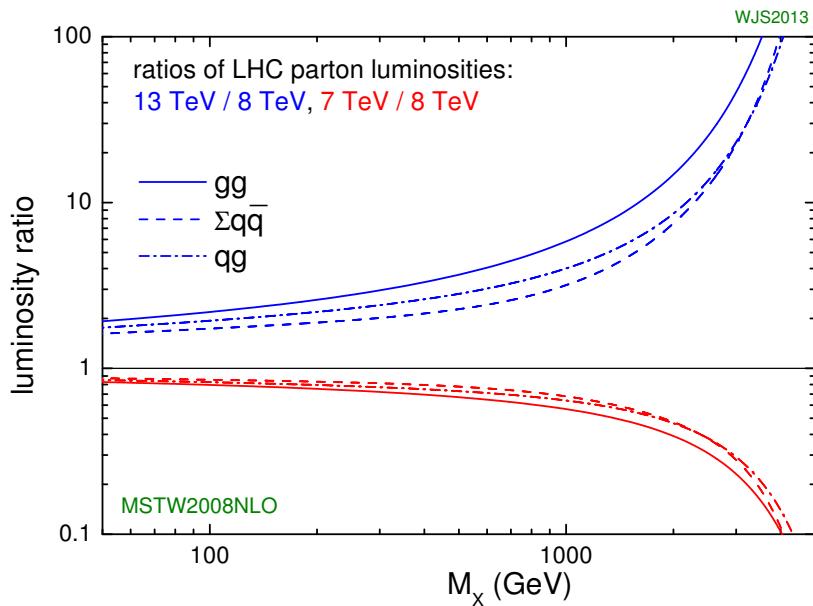


Figure 7.1: Parton luminosity ratios as a function of resonance mass  $M_X$  for 13/8 TeV and 7/8 TeV [92].

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

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

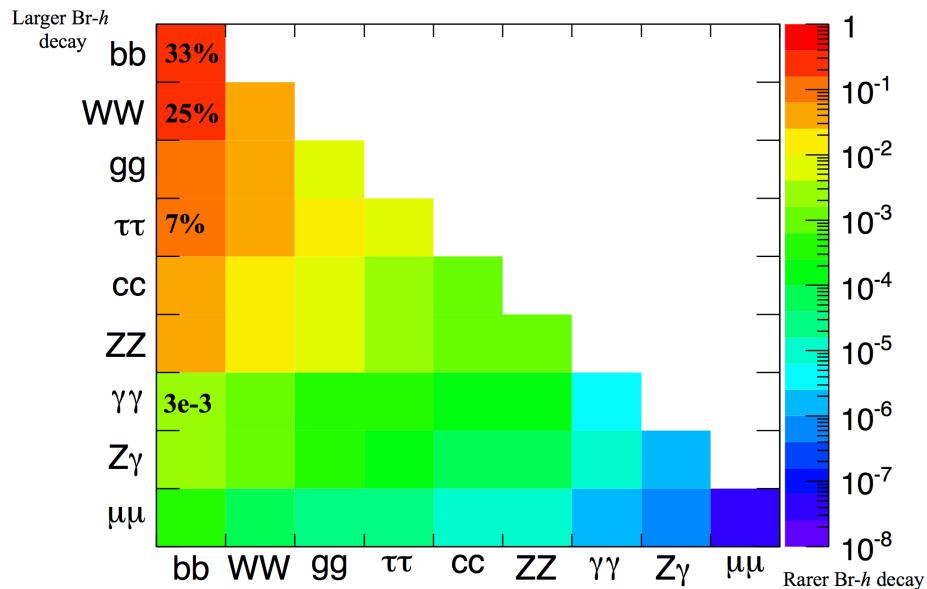


Figure 7.2: Summary of  $HH$  branching ratios [93].

At high  $m_X$ , the Higgs bosons resulting from the decay of a heavy resonance will have large  $p_T$ <sup>1</sup>. The  $\Delta R$  between the decay products of the Higgs is inversely proportional to the Higgs  $p_T$ , as shown in equation 7.1.

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

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

<sup>1</sup>In the limit that  $m_H \ell \ell m_X$ , the Higgs  $p_T$  is roughly  $m_X/2$ .

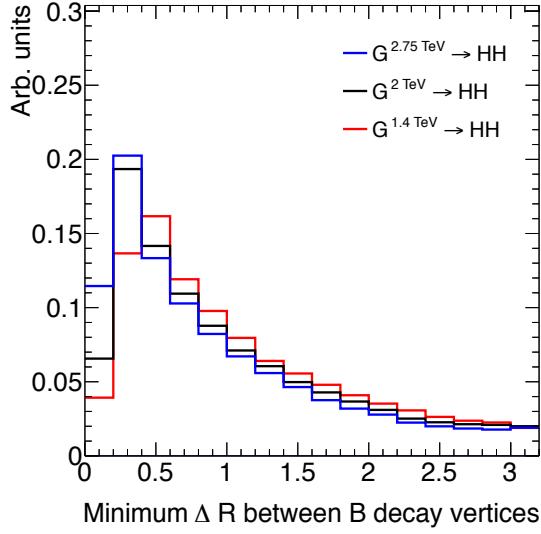


Figure 7.3: Minimum  $\Delta R$  between  $B$  decay vertices for different RSG masses in a  $G_{KK}^* \rightarrow HH \rightarrow 4b$  sample with  $c = 1$

2237 7.3 DATA AND SIMULATION SAMPLES

2238 7.3.1 SIGNAL MODELS

2239 While the resonance search is by its nature generic (as it is a simple search for a peak in the  $4b$  invariant  
 2240 mass spectrum), there are two signal models that the selection requirements have been optimized for.  
 2241 The first is Randall-Sundrum (RSG) model, where a tower of massive spin-2 Kaluza-Klein gravitons is  
 2242 predicted. The second is a heavy narrow spin-0 resonance, the so-called “heavy Higgs”. This type of res-  
 2243 onance arises, for example, in the two Higgs doublet model (2HDM). More details about the physics of  
 2244 these models and their motivation is given in chapter 1.

2245 Signal graviton ( $G_{KK}^*$ ) events are generated at leading order (LO) with **MADGRAPH5** v2.2.2 [94]. The  
 2246 PDF set used is the **NNPDF2.3** LO set [95]. For modeling parton shower and hadronization in jets, **PYTHIA**  
 2247 8.186 is used with the A14 tune [74, 96]. The free parameters in the RSG model are the graviton mass  
 2248 and the coupling constant  $c \equiv k/\bar{M}_{\text{Pl}}^2$ . Both the production cross section and width of the graviton are  
 2249 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  $8\pi$

2250 300 GeV and 3 TeV.

2251 The second signal sample is a heavy spin-0 resonance  $H$  with a fixed width of  $\Gamma_H = 1$  GeV. This  
2252 is generated with **MADGRAPH5** and uses the **CTEQ10** PDF set [77]. The parton shower and hadronization  
2253 are handled by **HERWIG ++** with the **CTEQ6L1** PDF set and the **UEEE5** event tune [78, 97, 98]. Because  
2254 the width and branching ratios depend on 2HDM parameters, each mass point generated with this fixed  
2255 width corresponds to a different point in the 2HDM parameter phase space. Mass points are generated  
2256 between 300 GeV and 1 TeV as with the RSG signal samples.

2257 **7.3.2 BACKGROUND SAMPLES**

2258 While the dominant **QCD** multijet background is estimated with a fully data-driven method, the sub-  
2259 dominant backgrounds  $t\bar{t}$  and  $Z$ +jets are modeled with some input from simulation.

2260  $t\bar{t}$  events are simulated at next-to-leading order (NLO) with the **POWHEG-BOX** version 1 generator us-  
2261 ing the **CTEQ10** PDF set [99]. The parton shower, hadronization, and underlying event are simulated with  
2262 **PYTHIA 6.428** with the **CTEQ6L1** PDF set [73]. The Perugia 2012 tune is used [100]. NNLO **QCD** cor-  
2263 rections to the cross sections are computed in **Top++ 2.0** [101]. The top quark mass is set to 172.5 GeV.  
2264 The shapes of distributions in  $t\bar{t}$  are taken from MC while the normalization is taken from data.

2265 Finally, the  $Z$ +jets background is simulated with **PYTHIA 8.186** and the **NNPDF2.3** LO PDF set. This  
2266 background is negligible compared to the others and is taken fully from MC.

2267 **7.3.3 DATA SAMPLE AND TRIGGER**

2268 This analysis is done on  $3.2 \text{ fb}^{-1}$  of data taken in 2015 at  $\sqrt{s} = 13$  TeV. The details of the machine  
2269 conditions during this time can be found in Chapter 2. Only data which was taken during stable beam con-  
2270 ditions with all detectors functioning is used. Events must pass a trigger which requires a single 360 GeV  
2271 large radius ( $R = 1.0$ ) jet to be reconstructed in the HLT. Figure 7.4 shows the trigger efficiency for vari-  
2272 ous trigger options as a function of graviton mass. Above  $m_G > 1$  TeV, the single large radius jet trigger  
2273 is 99% efficient for events passing the signal selection.

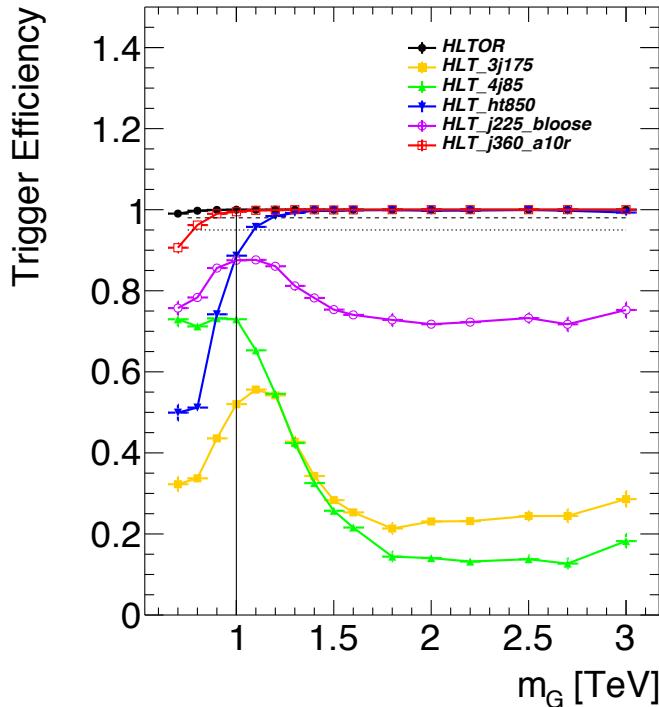


Figure 7.4: Trigger efficiency for events passing all signal region selections as a function of mass in  $G_{\text{KK}}^* \rightarrow HH \rightarrow 4b$  samples with  $c = 1$  [102]. In the trigger names, “j” refers to a jet or jets. “ht” refers to  $H_T$ , the scalar sum of transverse momenta in the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

2274    7.4    EVENT RECONSTRUCTION AND OBJECT SELECTION

2275    The boosted selection first begins by defining a unique set of objects that can be exploited to increase  
 2276    signal efficiency in the kinematic regime where the final state  $b$ -jets are very merged.

2277    7.4.1    LARGE RADIUS ( $R = 1.0$ ) JETS

2278    The first step towards reconstructing the final state is to define objects that can be used to measure the  
 2279    kinematics of the Higgs bosons. In the boosted selection anti- $k_T$  jets with a radius parameter of 1.0 are  
 2280    used. These jets are much larger in angular size than the typical  $R = 0.4$  jets and are intended to encompass  
 2281    both jets resulting from 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 [57].

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

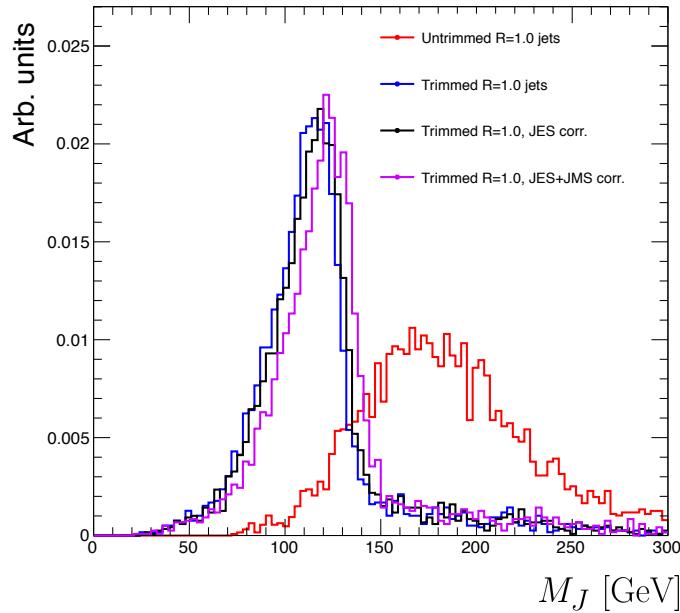


Figure 7.5: Comparison of untrimmed and trimmed jet masses for large radius jets in a RSG sample with  $m_{G_{KK}^*} = 1 \text{ TeV}$ . JES (JMS) refers to the standard jet energy (mass) scale calibration for ATLAS [57].

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

2296 7.4.2 TRACK JETS AND  $b$ -TAGGING

2297 Because the  $b$ -jets from boosted Higgs decays are so close together (as illustrated in figure 7.3), narrow ra-  
2298 dius jets are required to fully resolve both  $b$ -jets. The minimum radius feasible for jets based on calorimeter  
2299 deposits is determined by the calorimeter granularity. However, because  $b$ -tagging relies on information  
2300 from the inner detector, it is possible to define another type of jet that can have a smaller radius and better  
2301  $b$ -tagging resolution. These jets are called “track jets” [105, 106].

2302 Track jets are formed by applying the usual anti- $k_T$  clustering algorithm to tracks that are required to be  
2303 consistent with the primary vertex. After the jet axis has been determined using these tracks, a second step  
2304 of track association is also performed to add tracks that can be useful for  $b$ -tagging [106]. In this analysis,  
2305 the tracks are clustered with a radius parameter of  $R = 0.2$ . This radius has been shown to give good  
2306 performance in boosted Higgs tagging [105, 106]. Figure 7.6 shows a comparison among different track jet  
2307 radii of the efficiency for reconstructing two  $b$ -jets from each Higgs in a RSG sample as a function of mass.  
Track jets with radius of 0.2 give the best performance, especially at high mass. In this analysis, track jets

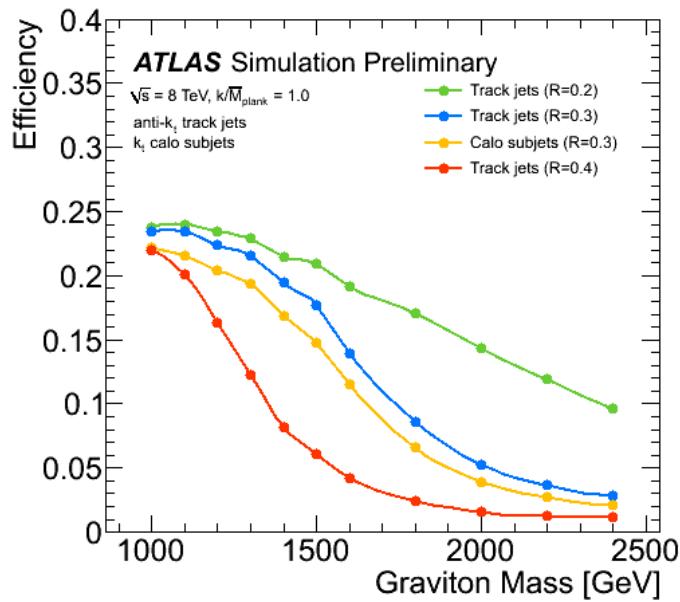


Figure 7.6: Efficiency of finding two  $b$ -jets from each Higgs in an RSG event using calorimeter jets with  $R = 0.3$  or  
2308 different track jet radii [106]

2309 are required to have  $p_T > 10$  GeV and  $|\eta| < 2.5$ . They must also have at least two tracks.

2310 7.4.3 MUONS

2311 Muons are used in this study to correct the four-momenta of calorimeter jets by accounting for semi-  
2312 leptonic  $b$  decays. The muons used are combined ID and MS muons which must satisfy tight identification  
2313 requirements [53]. The muons must have  $p_T > 4 \text{ GeV}$  and  $|\eta| < 2.5$ . Table 7.1 summarizes the object  
2314 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            | -   | $4 \text{ GeV}$                | $< 2.5$  | -                  |

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

2315 7.5 EVENT SELECTION

2316 The first requirement in the boosted selection is for  $\geq 2$  large radius jets satisfying the selections out-  
2317 lined above. The two highest momentum large-R jets in the event are referred to as “Higgs candidates”.  
2318 The leading jet is required to have  $p_T > 350 \text{ GeV}$ .

2319 Track jets satisfying the object selections are matched to Higgs candidate jets via ghost association [107].  
2320 Each Higgs candidate must have at least 2 track jets associated with it. These basic requirements are illus-  
2321 trated in figure 7.7.

2322 The QCD multijet background produces less central jets than high mass resonances, so there is an ad-  
2323 dditional requirement that the two Higgs candidates be close together in  $\eta$ . The large-R jets are required to  
2324 satisfy  $|\Delta\eta(JJ)| < 1.7$ .

2325 7.5.1 MASS REQUIREMENTS

2326 The final set of requirements ensures that the Higgs candidates are consistent with expected properties  
2327 of the 125.0 GeV Higgs. First, a variable ( $X_{hh}$ ) is defined to measure the consistency of both of the Higgs

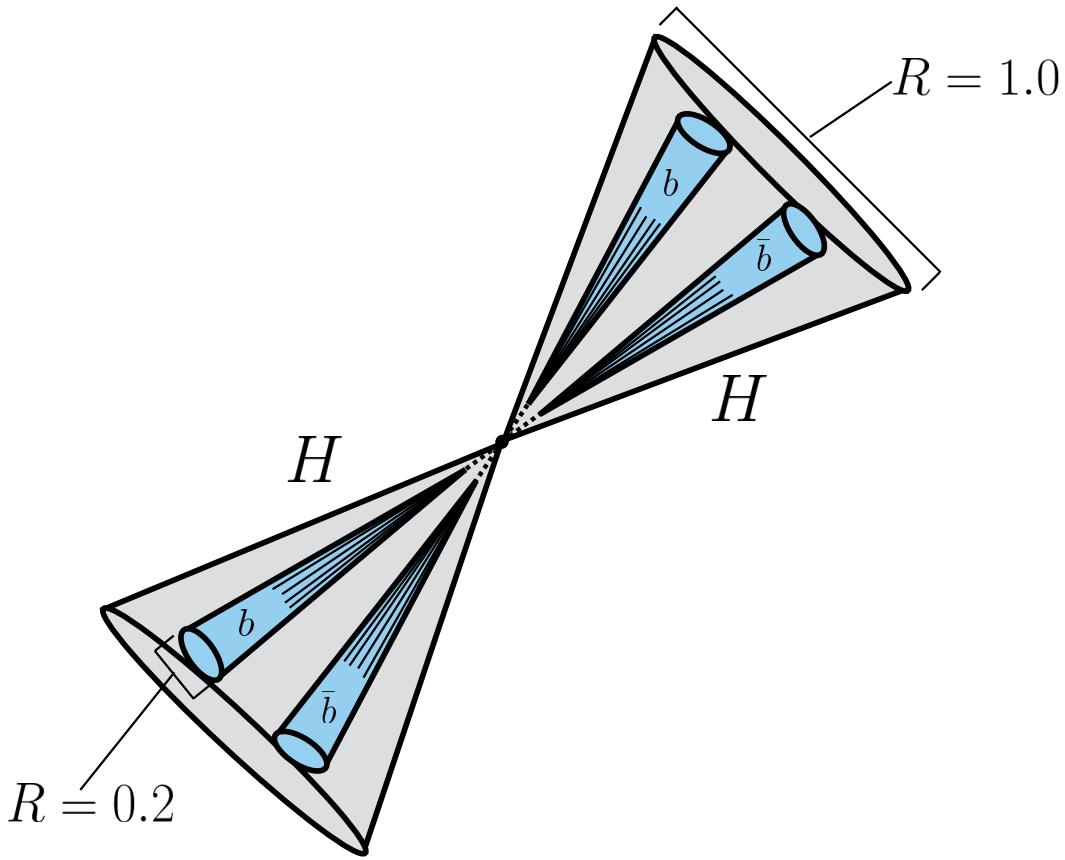


Figure 7.7: Illustration of the boosted selection requirements on Higgs candidates. Each large-radius calorimeter jet (Higgs candidate) must contain two track jets

<sup>2328</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>2329</sup> The mass values in the  $X_{hh}$  formula are optimized to maximize signal efficiency. The sub-leading jet  
<sup>2330</sup> typically has a lower mass due to semi-leptonic  $b$  decays and final state radiation.  $X_{hh}$  effectively acts as  
<sup>2331</sup> a  $\chi^2$  measurement of the consistency of the two Higgs candidate masses with the signal hypothesis. The  
<sup>2332</sup> denominators of each term ( $0.1M$ ) give the uncertainty on the mass measurement for the large radius jets.  
<sup>2333</sup> Events are required to satisfy  $X_{hh} < 1.6$ .

<sup>2334</sup> Before making the requirement on  $X_{hh}$ , the masses of the Higgs candidates are corrected for semi-

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

### 7.5.2 $b$ -TAGGING REQUIREMENTS

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

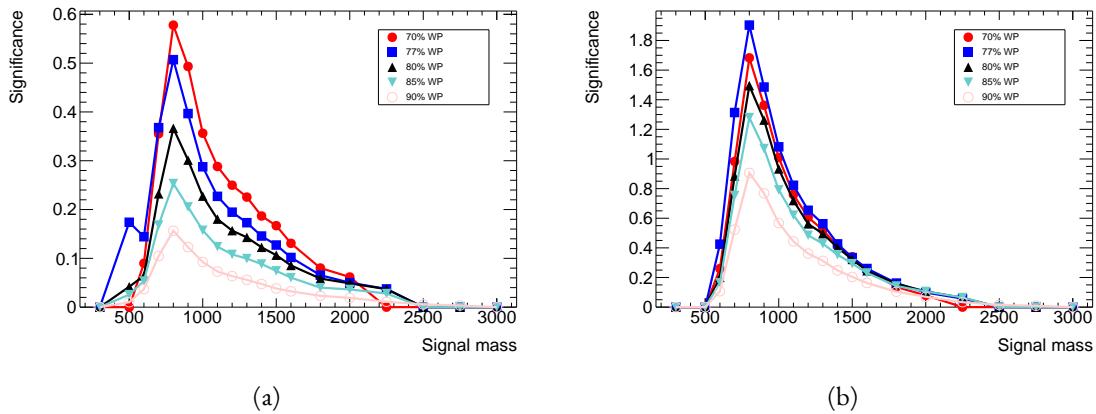


Figure 7.8: Estimated significance as a function of signal mass for RSG  $c = 1$  models in the  $3b$  (a) and  $4b$  (b) regions for different  $b$ -tagging efficiency working points

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

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

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

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

### 7.5.3 SELECTION EFFICIENCY

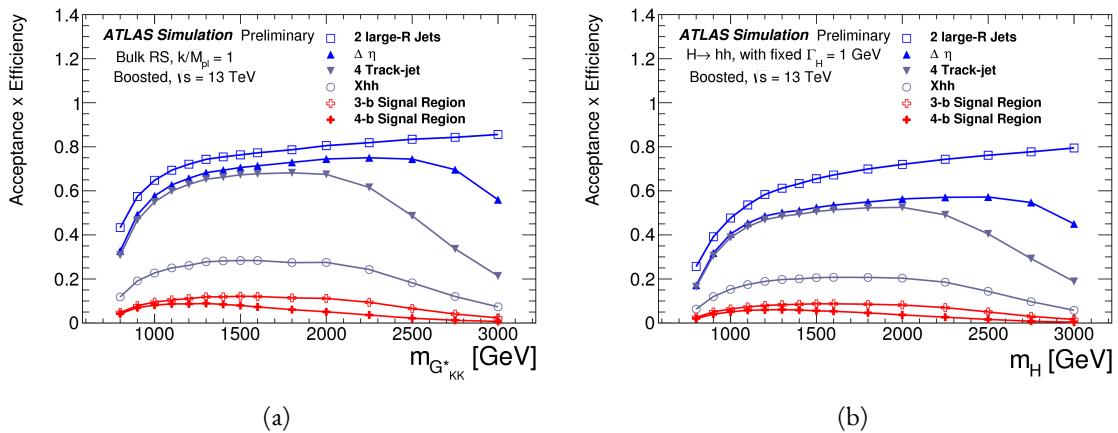


Figure 7.9: Acceptance  $\times$  efficiency as a function of mass for (a) RSG and (b) narrow heavy scalar signal models [109].

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

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

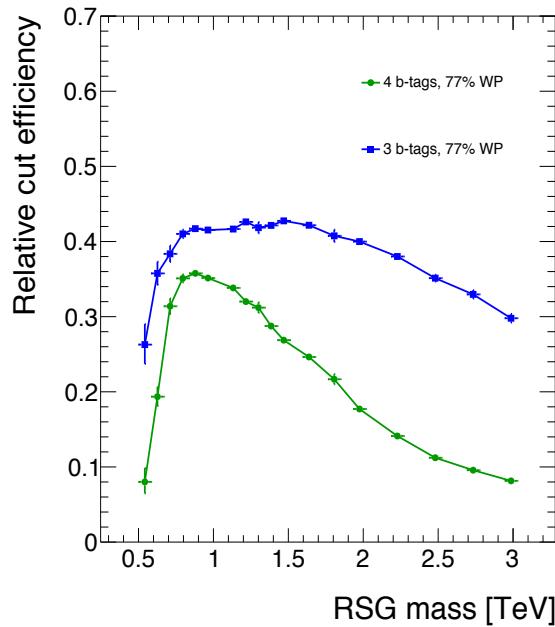


Figure 7.10: Efficiency of requiring 3 or 4  $b$ -tagged track jets vs. RSG mass. The efficiency quoted is relative to the previous selection requirements (rather than an absolute efficiency).

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

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

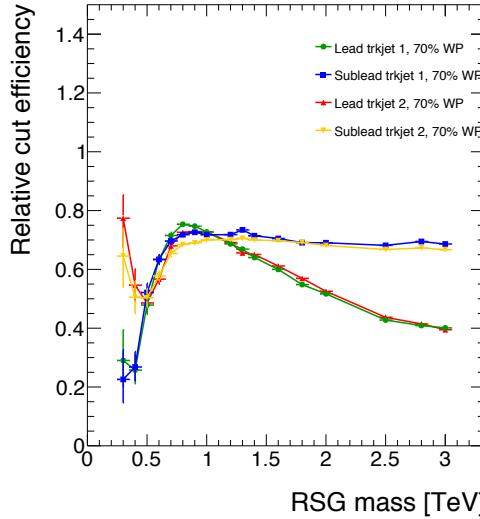


Figure 7.11: MV2c20  $b$ -tagging efficiency for each of the four track jets in the boosted  $4b$  selection as a function of RSG mass for  $c = 1$  models.

| Selection                                  | Data    | $m_{G_{KK}^*} = 1\text{TeV}$ | $m_{G_{KK}^*} = 2\text{TeV}$ | $t\bar{t}$ | $Z + \text{jets}$ |
|--|---------|------------------------------|------------------------------|------------|-------------------|
| $N(\text{fiducial large-R jets}) \geq 2$   | 2202396 | 23.3                         | 0.48                         | 32345.2    | 4255.7            |
| leading large-R jet $p_T > 350\text{ GeV}$ | 1873741 | 22.9                         | 0.48                         | 26511.7    | 3649.9            |
| Both large-R jet $m > 50\text{ GeV}$       | 1854625 | 21.2                         | 0.47                         | 24369.8    | 3575.8            |
| Both large-R jet $p_T < 1500\text{ GeV}$   | 1853601 | 21.2                         | 0.46                         | 24346.5    | 3572.9            |
| $ \Delta\eta(JJ)  < 1.7$                   | 1435273 | 20.8                         | 0.44                         | 20751.0    | 3265.8            |
| $\geq 2$ 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 [110].

## 2379 7.6 DATA-DRIVEN BACKGROUND ESTIMATION

2380 The largest background to this final state is QCD multijet production, constituting 80-90% of the total background. Because of the difficulties in modeling higher order QCD processes, this background is 2381 estimated with a fully data-driven method. The only other non-negligible background is  $t\bar{t}$ , constituting 2382 the other 10-20%<sup>4</sup>. Due to the presence of  $t\bar{t}$  in the sideband region where the QCD background will be 2383

---

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

2384 estimated, the normalization of the QCD and  $t\bar{t}$  backgrounds are simultaneously estimated.

2385 **7.6.1 MASS REGION DEFINITIONS**

2386 The first step in the data-driven background estimate is to define a sideband mass region where the  
2387 background normalization can be derived. Additionally, a control region is defined where the background  
2388 estimate can be validated. The control (CR) and sideband (SB) regions are defined using a radial distance  
2389 in the two-dimensional large-R jet mass plane,  $R_{hh}$ , which is defined in equation 7.4.

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

2390 Events in the sideband region are required to fail the signal region  $X_{hh} < 1.6$  requirement and have  
2391  $R_{hh} > 35.8 \text{ GeV}$ . The control region consists of those events which are not in the signal or sideband  
regions. Figure 7.12 shows the definition of the signal, control, and sideband mass regions. Table 7.3 sum-

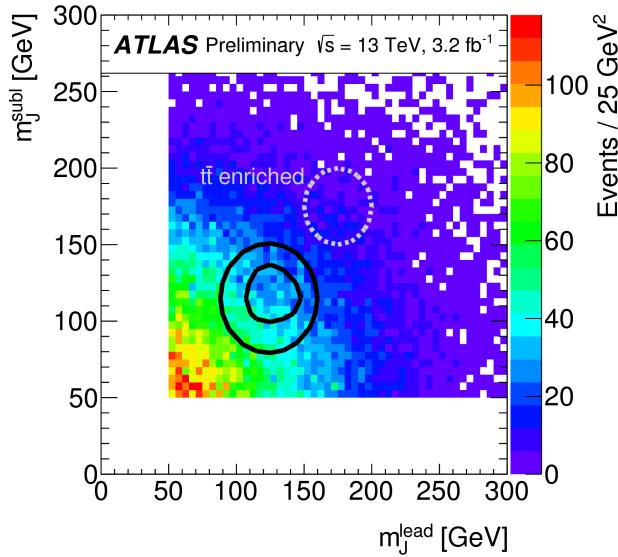


Figure 7.12:  $M_J^{\text{sublead}}$  vs.  $M_J^{\text{lead}}$  in a 2  $b$ -tag data sample. The signal region is defined by the inner black contour ( $X_{hh} < 1.6$ ) and the sideband region is defined by the outer contour ( $R_{hh} > 35.8 \text{ GeV}$ ). The region between the black contours is the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

2392

2393 summarizes the mass region selections for the three different regions used in the analysis.

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

Table 7.3: Mass region definitions used for background estimation

2394    7.6.2 BACKGROUND ESTIMATION

2395    The method for estimating the background in this analysis is similar to the ABCD method presented in  
 2396    Chapter 5. In this case, the two handles used to define different regions for the estimate are the number of  
 2397     $b$ -tagged track jets and the mass regions. A region requiring exactly two  $b$ -tagged track jets in one large-R  
 2398    jet (referred to as the 2-tag or  $2b$  region) is defined for use in the background estimate. The number of  
 2399    expected background events in the  $3b$  and  $4b$  signal regions is then given by equation 7.5.

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

2400    In this equation,  $N_{\text{bkg}}^{3(4)-\text{tag}}$  is the expected number of background events in the  $3b$  or  $4b$  signal regions.  
 2401     $N_{\text{Multijet}}^{2-\text{tag}}$  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-  
 2402    dicted in the MC for the  $3b$  or  $4b$  signal region, and the variable is similarly defined for the  $Z+\text{jets}$  back-  
 2403    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  
 2404    region.  $\mu_{\text{Multijet}}$  is an extrapolation factor that is derived in the sideband region and used to estimate the  
 2405    ratio of 2-tag events to 3(4)-tag events in the signal region. It is defined in equation 7.6.

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

2406    The  $t\bar{t}$  scale factor ( $\beta_{t\bar{t}}$ ) and the QCD multijet extrapolation factor ( $\mu_{\text{Multijet}}$ ) are estimated together in  
 2407    a simultaneous fit in the sideband region. Then, the number of events in the 2-tag signal region is used,  
 2408    along with the  $t\bar{t}$  estimate in the  $3b$  and  $4b$  signal regions and  $\mu_{\text{Multijet}}$ , to estimate the total number  
 2409    of background events in the two final signal regions. The shape of the final discriminant  $M_{2J}$  is also

<sup>2410</sup> taken from the 2-tag signal region where there are more statistics. This method is illustrated graphically in  
<sup>2411</sup> figure 7.13.

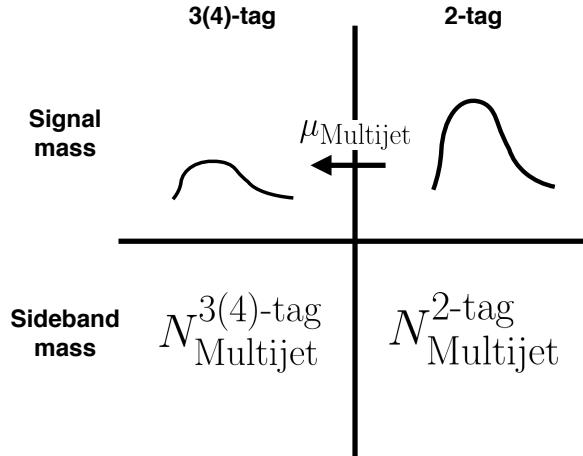


Figure 7.13: An illustration of the data-driven background estimation technique for the boosted analysis

<sup>2412</sup> In the  $3b$  region, the fit yields values of  $\mu_{\text{Multijet}} = 0.160 \pm 0.03$  and  $\beta_{t\bar{t}} = 1.02 \pm 0.09$ . In the  $4b$   
<sup>2413</sup> region, the fit gives  $\mu_{\text{Multijet}} = 0.0091 \pm 0.0007$  and  $\beta_{t\bar{t}} = 0.82 \pm 0.39$ . The uncertainties quoted are  
<sup>2414</sup> statistical only. The larger uncertainties in the  $4b$  values indicate the lower statistics available in that region.

<sup>2415</sup> Figure 7.14 shows the distributions of data and background estimates in the  $3b$  and  $4b$  sideband regions  
<sup>2416</sup> after the background fit has been done. The normalizations are constrained from the fit to match that of  
<sup>2417</sup> the data, but good modeling of the shape of the mass of the leading large-R jet is seen as well. The shapes  
<sup>2418</sup> of the kinematic distributions in the  $4b$  region are taken from the  $3b$  region due to the better MC statistics  
<sup>2419</sup> in that region.

### <sup>2420</sup> 7.6.3 BACKGROUND SHAPE FIT

<sup>2421</sup> As mentioned in the previous section, the background shape in the 3-tag and 4-tag signal regions is  
<sup>2422</sup> taken from the 2-tag signal mass region. Due to the limited statistics available, the background shapes are  
<sup>2423</sup> additionally smoothed after being extrapolated to the 3-tag and 4-tag signal regions. Only the data in the  
<sup>2424</sup> range  $900 < M_{2J} < 2000$  GeV is included in the fit due to the limited statistics available above 2 TeV.  
<sup>2425</sup> Both the  $t\bar{t}$  and QCD multijet background are independently fit with an exponential shape,  $y = e^{ax+b}$ .

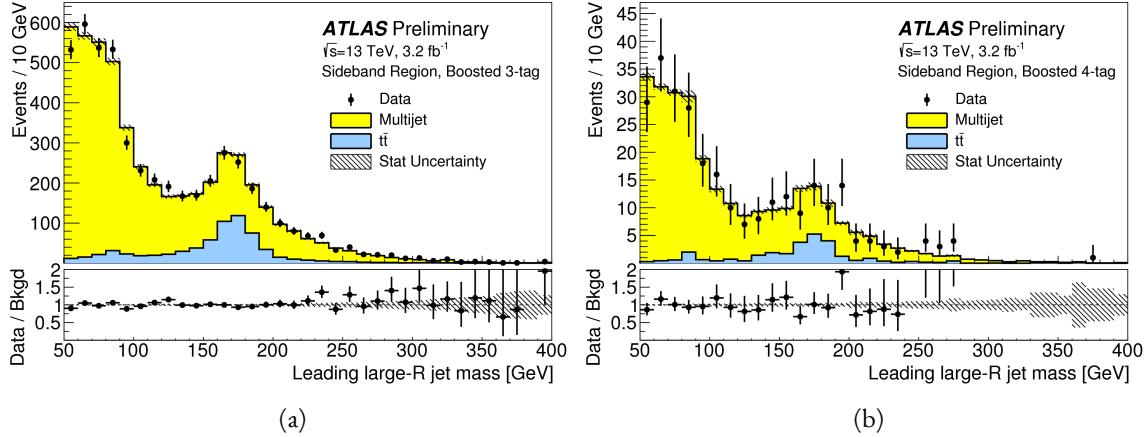


Figure 7.14: Leading large-R jet mass in the 3b (a) and 4b (b) sideband regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above. Because their normalizations are derived in the sideband region, the total background normalization is constrained by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

2426 Other shapes are considered and used for the systematic uncertainties. Table 7.4 shows the fit values for  
 2427 the parameters. Because both the 3b and 4b QCD shapes come from the 2-tag region, the slopes derived  
 2428 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 [109]

#### 2429 7.6.4 VALIDATION OF BACKGROUND ESTIMATE

2430 The background estimate can be validated by using the method to estimate the number of events in the  
 2431 control mass region rather than the signal mass region. Figure 7.15 shows the  $M_{2J}$  distribution in the 3b  
 2432 and 4b control regions, comparing data and background estimates. In both cases, both the background  
 2433 shape and normalization are consistent with the data, indicating good agreement. The ratio of data to the  
 2434 background estimates is also fit to a line in the figure to test for any shape difference. The slope of the  
 2435 line is within  $1\sigma$  (from the fit uncertainties) of flat, further indicating that the data is consistent with the  
 2436 background estimate in the control region.

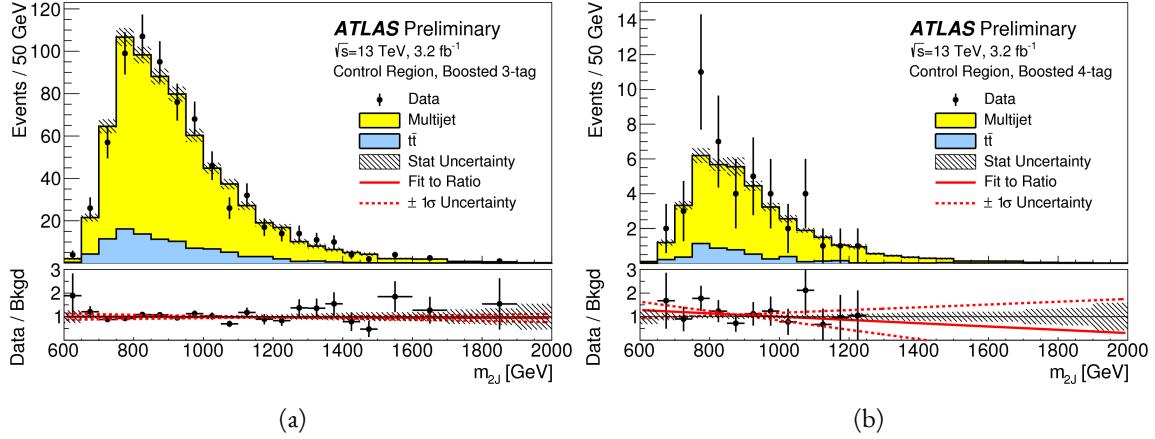


Figure 7.15: Di-jet invariant mass ( $M_{2J}$ ) in the 3b (a) and 4b (b) control regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above [109].

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

| Sample (3-tag) | Sideband Region | Control Region |
|----------------|-----------------|----------------|
| Multijet       | $4328 \pm 27$   | $607 \pm 10$   |
| $t\bar{t}$     | $683.5 \pm 8.1$ | $99.6 \pm 3.1$ |
| 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. The uncertainties shown are statistical only. [109]

2440 7.7 SYSTEMATIC UNCERTAINTIES

2441 The systematic uncertainties in this analysis can be divided into two broad categories. The first type  
2442 is uncertainties associated with the modeling of the signal processes. The second type of uncertainty is  
2443 associated with both the shape and normalization of the background prediction.

2444 7.7.1 SIGNAL MODELING UNCERTAINTIES

2445 The signal modeling uncertainty has three main components: theoretical uncertainty on the acceptance,  
2446 experimental uncertainties on the large-R jets, and experimental uncertainties on the track jets related to  
2447  $b$ -tagging. In this analysis the experimental uncertainties are the most significant.

2448 The first uncertainty on signal modeling is the theoretical uncertainty on the acceptance. As explained  
2449 in section 5.6.1, there are four components to this uncertainty. The first is related to missing higher order  
2450 terms from the matrix element calculations which is estimated by varying the QCD renormalization and  
2451 factorization scales. The second is uncertainty due to the PDF set used. The third is a generator uncer-  
2452 tainty which is estimated by modifying the generator used to model the underlying event and hadroniza-  
2453 tion. Finally, there is an uncertainty associated with the modeling of the initial state and final state radia-  
2454 tion (ISR/FSR). The total theoretical uncertainty on the signal yield is 3%, and this is dominated by the  
2455 ISR/FSR modeling.

2456 There are uncertainties on the large-R jets in both the jet energy scale (JES) and jet energy resolution  
2457 (JER) as well as the jet mass scale (JMS) and jet mass resolution (JMR). These are evaluated using  $\sqrt{s} =$   
2458 8 TeV data from Run 1 of ATLAS and extrapolated to the Run 2 beam and detector conditions using  
2459 MC<sup>s</sup>. The details of these uncertainties can be found in reference [111].

2460 Uncertainties on the track jets are related to the  $b$ -tagging efficiency. The total uncertainty on the signal  
2461 yield due to  $b$ -tagging is evaluated by propagating variations of the  $b$ -tagging efficiency through the boosted  
2462 selection requirements. The uncertainties are calculated jet-by-jet and parameterized as a function of  $b$ -jet  
2463  $p_T$  and  $\eta$  [89]. For high  $p_T$   $b$ -jets (with  $p_T > 300$  GeV), the uncertainties are extrapolated using MC  
2464 simulation from the lower  $p_T$   $b$ -jets [112].

---

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

2465 Table 7.6 shows the systematic uncertainties on the signal normalization for models with  $m_{G_{\text{KK}}^*} =$   
2466 1.5 TeV and both  $c = 1$  and  $c = 2$  as well as a narrow width heavy scalar. The dominant uncertainty  
2467 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.

2468 7.7.2 BACKGROUND UNCERTAINTIES

2469 Uncertainties on the QCD multijet background normalization and shape are estimated using the con-  
2470 trol mass region. As shown previously, the background predictions in the control region match with the

2471 data yields within the statistical uncertainty in both the 3-tag and 4-tag control regions. As an additional  
2472 protection, the statistical uncertainty on the background prediction in the control region is assigned as a  
2473 systematic uncertainty on the normalization of the QCD background.

2474 Additional robustness tests are done by varying the definition of the control mass region and the  $b$ -  
2475 tagging requirements used to define the 2-tag sample. In all cases, the effect of the variations is found to be  
2476 within the statistical uncertainties on the background normalization in the control region.

2477 Shape uncertainties on the background are evaluated using two techniques. First, as shown in fig-  
2478 ure 7.15, the ratio between the data and background prediction is fit with a linear function. The uncer-  
2479 tainties on the slope of this fit are assigned as shape uncertainties. An additional uncertainty is assigned by  
2480 using alternate power law fit functions for the smoothing of the background shape. Table 7.7 shows the  
2481 alternate shapes used. The largest difference between the nominal fit function and the alternates, taking  
2482 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,  $x = M_{2J}/\sqrt{s}$ .

2483 The uncertainties on the  $t\bar{t}$  background are obtained by propagating the various experimental variations  
2484 (JES, JER, JMS, JMR,  $b$ -tagging) through the analysis selection requirements. Table 7.6 summarizes the  
2485 background uncertainties in the 3-tag and 4-tag regions.

2486    7.8    RESULTS

2487    Table 7.8 shows the observed yields in the 3-tag and 4-tag signal regions for the boosted analysis com-  
 2488    pared to the predicted number of background events. In the 3-tag region, 316 events are observed with  
 2489    a predicted background of  $285 \pm 19$ . In the 4-tag region, 20 events are observed with a predicted back-  
 2490    ground of  $14.6 \pm 2.4$ . Figure 7.16 shows the  $M_{2J}$  distribution in the 3-tag and 4-tag regions. There are  
 2491    some small excesses in the data, in particular in the 3-tag region around  $M_{2J} \approx 900$  GeV and in the region  
 2492    of  $1.6 < M_{2J} < 2.0$  TeV. The significance of these excesses will be evaluated in the next chapter in the  
 2493    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. [109]

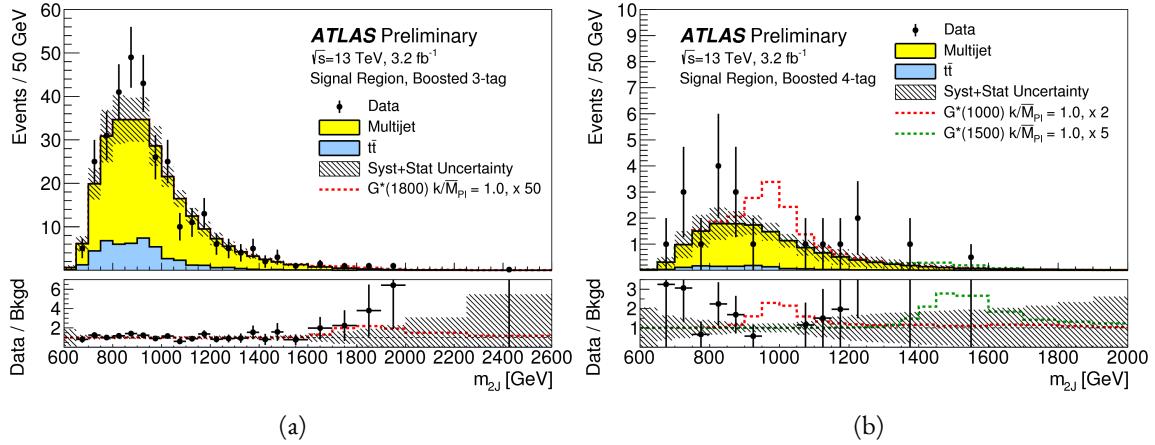


Figure 7.16: Di-jet invariant mass ( $M_{2J}$ ) in the 3b (a) and 4b (b) signal regions. The multijet and  $t\bar{t}$  backgrounds are estimated using the data-driven methods described above. In the 3b region, a graviton signal with  $m_{G_{KK}^*} = 1.8 \text{ TeV}$  and  $c = 1$  is overlaid, with the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

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

Frank Herbert

# 8

2494

2495

## Combined limits from boosted and resolved searches

2496

2497

### 8.1 INTRODUCTION

2498 In order to cover the full mass range of possible resonances decaying to di-Higgs final states, two distinct  
2499 tailored selections were produced. The resolved selection is more sensitive in the mass range of  $400 < m_X < 1100$  GeV while the boosted selection is more sensitive to masses in the range  $1100 < m_X <$   
2500  $3000$  GeV. Chapter 7 presents the details of the boosted selection and results. In setting limits on spin-2  
2501 Randall-Sundrum graviton (RSG) and narrow width heavy scalar ( $H$ ) models, the results of the boosted  
2502 selection are combined with the results of the resolved selection to cover the full mass range.  
2503

2504 This chapter presents limits on signal models resulting from the  $X \rightarrow HH \rightarrow b\bar{b}b\bar{b}$  search in both  
2505 the resolved and boosted selections. It first presents a brief overview of the resolved results that go into

2506 the limit setting. Then, an overview of the statistical methods used for the search and limit setting is given.  
 2507 Finally, limits on the RSG and heavy scalar models are presented.

2508 **8.2 RESOLVED RESULTS**

2509 The details of the resolved selection will not be presented here and can be found in reference [109]. In  
 2510 basic terms, the selection searches for four  $R = 0.4$  b-tagged calorimeter jets (where each pair of jets is  
 2511 one Higgs candidate). This is distinct from the boosted methodology which searches for merged decay  
 2512 products. The backgrounds to the resolved selection are the same as those presented in Chapter 7 for the  
 2513 boosted analysis.

2514 Table 8.1 shows the results for data yields and expected background in the resolved signal region. Fig-  
 2515 ure 8.1 shows the  $M_{2J}$  distribution in the resolved signal region. The total number of events is consistent  
 2516 with the prediction and no significant excess is seen. One event in the boosted 4-tag signal is shared with  
 2517 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 resolve selection 4-tag signal region compared to the predicted number of background events Errors correspond to the total uncertainties in the predicted event yields. The yields for a graviton with  $m_{G_{\text{KK}}^*} = 800 \text{ GeV}$  and  $c = 1$  are also shown. [109]

2518 **8.3 SEARCH TECHNIQUE AND RESULTS**

2519 The statistical technique used for the search in this analysis is the same as that used in the  $H \rightarrow WW^*$   
 2520 analysis presented in section 3.6.2. The test statistic  $q_0$  is used to define the  $p$ -values which measure the

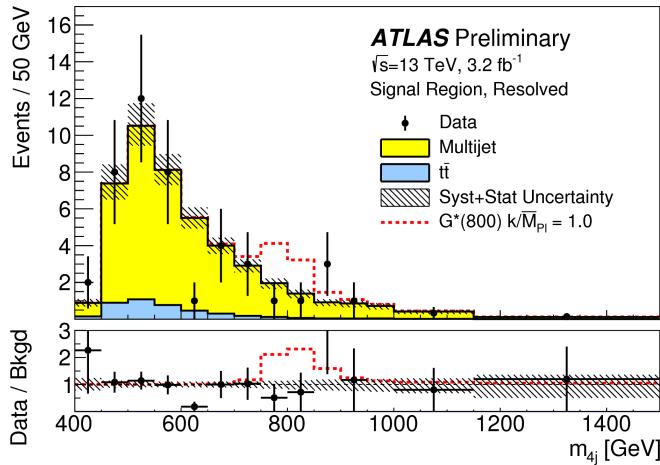


Figure 8.1: Di-jet invariant mass ( $M_{2J}$ ) in the resolved signal region. A graviton signal with  $m_{G_{KK}^*} = 800$  GeV and  $c = 1$  is overlaid. [109].

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

Local  $p_0$  values are computed to quantify the probability that the background could produce a fluctuation greater than or equal to the one observed in the data. In the resolved analysis, no significant excesses are observed. The largest discrepancy with respect to the background only hypothesis occurs near a resonance mass of 900 GeV and is found to be less than  $2\sigma$  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 [113]. The first step in setting the limits is to define a test statistic which will be used. For limit setting, the test statistic is shown

2536 in equation 8.1.

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

2537 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  
2538 best fit value of the nuisance parameters,  $\hat{\theta}$  is the best fit value of the nuisance parameters under the fixed  
2539  $\mu$  value, and  $L$  is the Poisson likelihood of the data (as described in section 3.6.2).

2540 The test statistic  $\tilde{q}_\mu$  is constructed to protect against two interesting corner cases when setting the upper  
2541 limit on the cross section. First, it protects against negative signal strengths  $\mu$  which are unphysical. Second,  
2542 it does not count excesses in the data larger than those expected by a signal strength  $\mu$  as evidence against  
2543 the  $\mu$  hypothesis.

2544 The  $CL_s$  statistic is constructed by taking a ratio of two probabilities.  $CL_{s+b}$  is the probability that the  
2545 signal+background hypothesis would produce a value of the test statistic that is less than or equal to the  
2546 observed value<sup>1</sup>.  $CL_b$  is the probability that the background only hypothesis will produce a value  
2547 of the test statistics less than or equal to the observed. The  $CL_s$  statistic is then the ratio  $CL_{s+b}/CL_b$ . A  
2548 95% upper limit on the cross section is set at the value of  $\mu$  that makes the  $CL_s$  statistic less than 5%.

2549 In practice, the limits are computed numerically within an asymptotic approximation for the distribu-  
2550 tion of the test statistic  $\tilde{q}_\mu$ . The details of this approximation can be found in reference [64].

2551 The resolved and boosted analyses are combined using a very simple procedure rather than a full statis-  
2552 tical combination. For each mass point tested, the limit which gives the most stringent constraint is used.  
2553 This means that for mass points below 1.1 TeV the resolved signal region is used, while at and above this  
2554 point the combination of the orthogonal 3b and 4b boosted signal regions is used.

#### 2555 8.4.2 LIMIT SETTING RESULTS

2556 Figure 8.2 shows the combined 95% upper bounds as a function of mass for three different models:  
2557  $G_{KK}^*$  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

2558        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  
2559        for masses in the range  $600 < m_{G_{\text{KK}}^*} < 3000$  GeV. For the RSG model with  $c = 2$ , cross sections limits  
2560        between 40 fb and 200 fb are set for the mass range of  $500 < m_{G_{\text{KK}}^*} < 3000$  GeV. Masses in the range  
2561        of  $475 < m_{G_{\text{KK}}^*} < 785$  GeV are excluded with  $c = 1$  (with an exclusion of the range 465 to 745 GeV  
2562        expected). Masses less than 980 GeV are excluded with  $c = 2$  (with an exclusion for masses less than  
2563        1 TeV expected).

2564        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  
2565        30 to 300 fb in the mass range of  $500 < m_H < 3000$  GeV. The resolved analysis can also set an upper  
2566        limit on the Standard Model di-Higgs production cross section discussed in chapter 3. The upper limit on  
2567         $\sigma(pp \rightarrow hh \rightarrow b\bar{b}b\bar{b})$  in the Standard Model is constrained to be less than 1.22 pb.

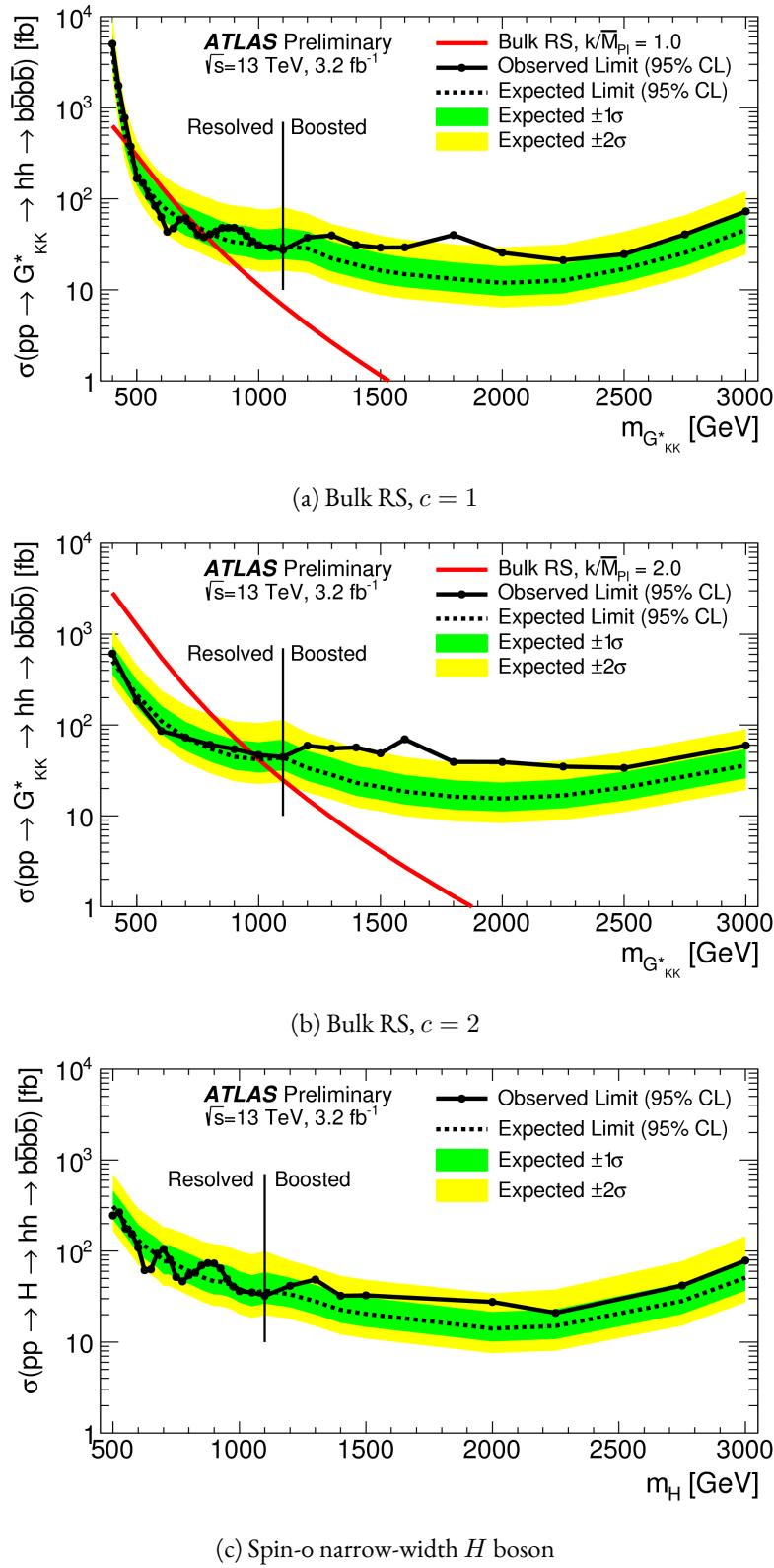


Figure 8.2: Expected and observed upper limit as a function of mass for  $G^*_{KK}$  in the RSG model with (a)  $c = 1$  and (b)  $c = 2$ , as well as (c)  $H$  with fixed  $\Gamma_H = 1$  GeV, at the 95% confidence level in the  $CL_s$  method. [109]

## Part IV

### Looking ahead

# 9

2570

## Conclusion

2571

2572 After being sought for many years at different collider experiments, the Higgs boson was discovered by  
2573 the ATLAS and CMS experiments in 2012, confirming the leading theory for the source of electroweak  
2574 symmetry breaking and filling in the last missing piece of the Standard Model. After its discovery, mea-  
2575 surements of the particle's detailed properties and searches for new particles decaying to Higgs final states  
2576 were both extremely important in constraining physics beyond the Standard Model. This dissertation  
2577 presented this evolution through two results: the observation and measurement of the Higgs boson in the  
2578  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  channel at  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV and a search for Higgs pair production  
2579 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  
2580 Hadron Collider.

2581 In the  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ , results from both the discovery of the Higgs boson and the full ATLAS  
2582 Run 1 dataset were presented. The Higgs boson was discovered with a  $6.1\sigma$  significance in a combination  
2583 of the  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ4\ell$ ,  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  with  $4.2\text{ fb}^{-1}$  at  $\sqrt{s} = 7$  TeV and  $5.2\text{ fb}^{-1}$  at

2584  $\sqrt{s} = 8$  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-  
2585covery level significance in the  $H \rightarrow WW^*$  channel alone and obtained the first evidence of vector boson  
2586fusion production in that channel. The combined signal strength is measured to be  $\mu = 1.09^{+0.23}_{-0.21}$ . The  
2587total observed significance of the  $H \rightarrow WW^*$  process is observed to be  $6.1\sigma$  (with  $5.8\sigma$  expected). Ad-  
2588vanced methods for background reduction and estimation, particularly in same-flavor lepton final states,  
2589are shown. The VBF signal strength is measured to be  $\mu_{\text{VBF}} = 1.27^{+0.53}_{-0.45}$  with an observed significance  
2590of  $3.2\sigma$  (with  $2.7\sigma$  expected).

2591 These results required many novel innovations. The increase of pileup interactions in the higher in-  
2592stantaneous luminosity LHC conditions of 2012 led to a degradation of missing transverse momentum  
2593resolution. As a result, the prominent  $Z/\gamma^* + \text{jets}$  background of the same flavor  $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$   
2594final states increased greatly. New variables, including a track-based missing transverse momentum and a  
2595measurement of the balance between the dilepton system and recoiling jets, allowed for significant reduc-  
2596tion of this background. In the VBF channel, selections were optimized to exploit the unique VBF final  
2597state topology. Incorporating these variables into a boosted decision tree technique allowed the analysis  
2598to exceed the  $3\sigma$  statistical significance threshold.

2599 After the end of Run 1, the results of Higgs measurements from ATLAS were combined with those  
2600from CMS to produce the most precise measurements of the Higgs boson so far [114]. Figure 9.1 shows the  
2601combination of ATLAS and CMS data for the Higgs signal strength in and coupling measurements. In the  
2602signal strength measurements of gluon fusion and vector boson fusion, the  $H \rightarrow WW^*$  channel provides  
2603the tightest constraints. Additionally, the Higgs coupling to  $W$  bosons is the most precisely measured with  
2604a relative uncertainty of 10%.

2605 With the discovery of the Higgs firmly established and its properties measured, a natural next step was  
2606to search for new physics with Higgs final states. At  $\sqrt{s} = 13$  TeV, a search for Higgs pair production  
2607in 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  
2608arising from high mass resonances was constructed. This signal region utilized large-radius calorimeter jets  
2609and  $b$ -tagging with small radius track jets to maximize the signal acceptance. No significant excesses were  
2610observed, and upper limits on cross sections are placed for spin-2 Randall Sundrum gravitons (RSG) and

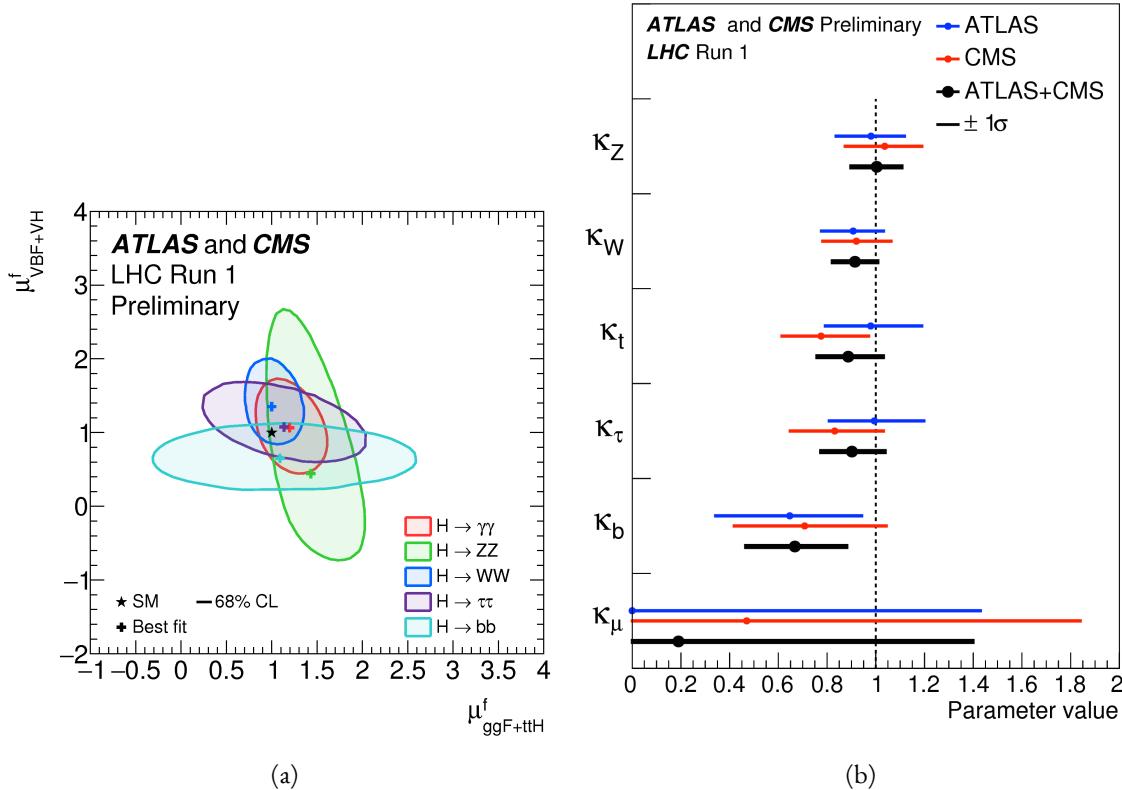


Figure 9.1: Combined ATLAS and CMS measurements in Run 1 for (a) Higgs signal strength in gluon fusion and VBF and (b) Higgs couplings normalized to their SM predictions

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

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

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

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

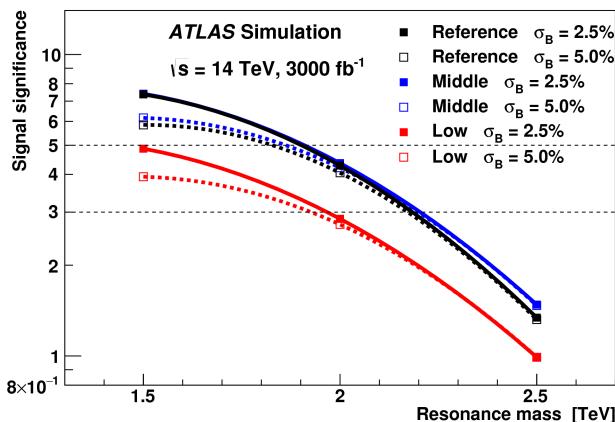


Figure 9.2: Discovery significance for RSG models at the HL-LHC in three different budget scenarios [ii6]. Systematic uncertainties on the background prediction ( $\sigma_B$ ) of 2.5% and 5.0% are both tested.

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

# A

2636

2637

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

2638 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  
2639 masses is the degradation of the *b*-tagging efficiency for high  $p_T$  jets. This appendix presents a study of the  
2640 underlying causes of this degradation.

### 2641 A.I CHANGES IN MV<sub>2</sub> SCORE AT HIGH $p_T$

2642 The degradation of *b*-tagging at high  $p_T$  was studied in particular in the context of RSG models at high  
2643 mass. Figure A.I shows the  $p_T$  of the leading track jet inside of the leading calorimeter jet in RSG events.  
2644 At high  $m_{G_{KK}^*}$ , the  $p_T$  spectrum of track jets is much harder than at lower masses due to the increased  
2645 Higgs  $p_T$ .

2646 Figure A.2 shows the MV<sub>2c2o</sub> algorithm score for the leading and subleading track jets inside of the  
2647 leading calorimeter jet. In both cases, it can be seen that at higher RSG masses the MV<sub>2</sub> score shifts towards  
2648 more background like (negative) values. Additionally, this effect is more pronounced in the leading track

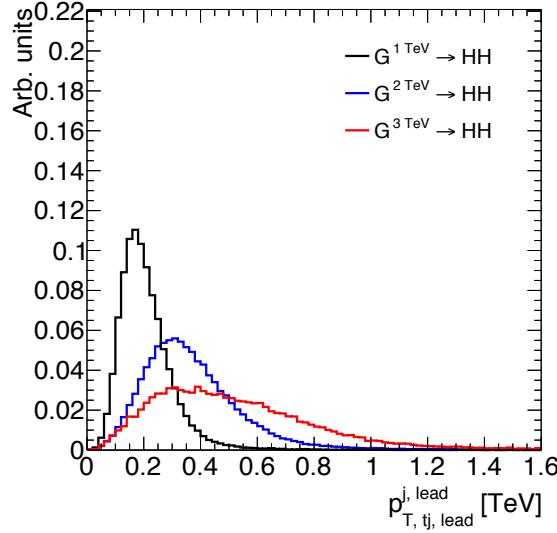


Figure A.1:  $p_T$  of the leading track jet in the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

2649 jet than the subleading.

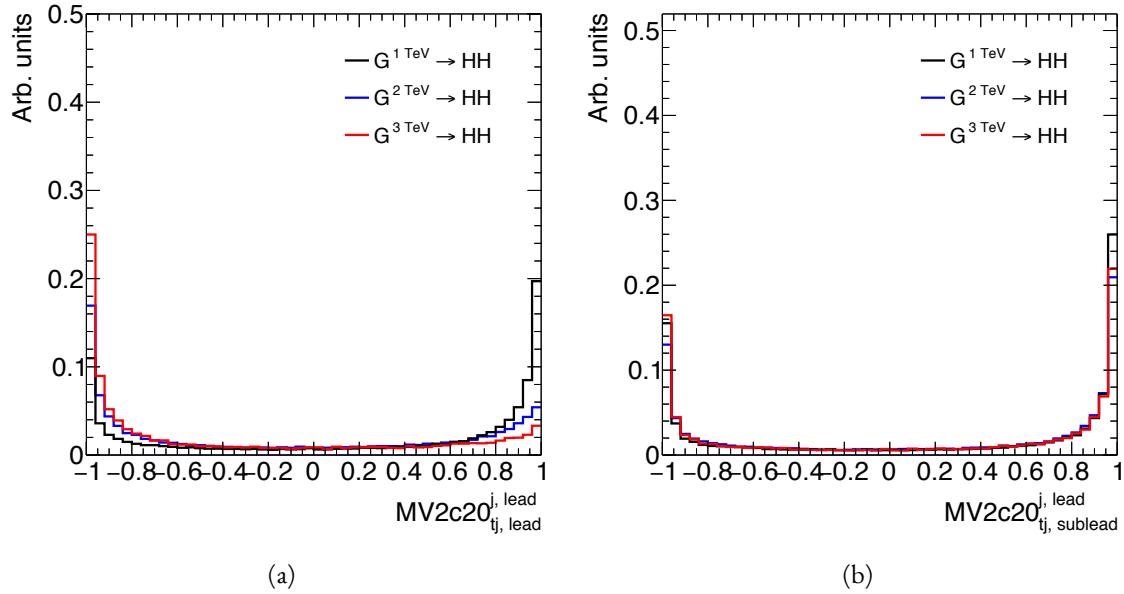


Figure A.2: MV2c20 score for the leading track jet (a) and subleading track jet (b) of the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

2650 To understand what is causing this change in the MV2c20 score, the same comparisons can be made for  
 2651 the input variables of MV2c20. The focus in these comparisons will be on the leading track jet as this is the  
 2652 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.

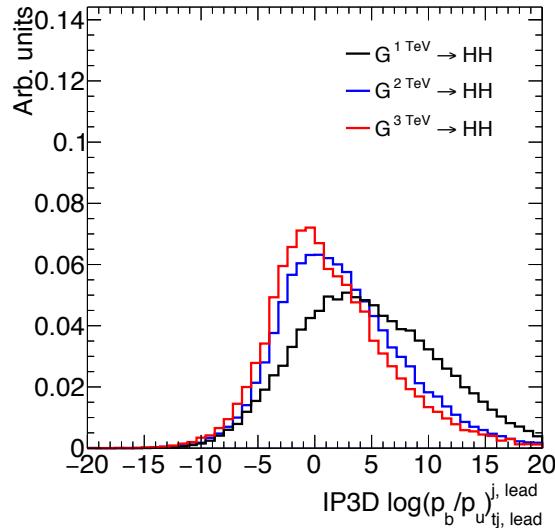


Figure A.3: IP<sub>3</sub>D log-likelihood ratio ( $\log(p_b/p_u)$ ) of the leading track jet in the leading calorimeter jet for different signal masses in RSG  $c = 1$  models

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>

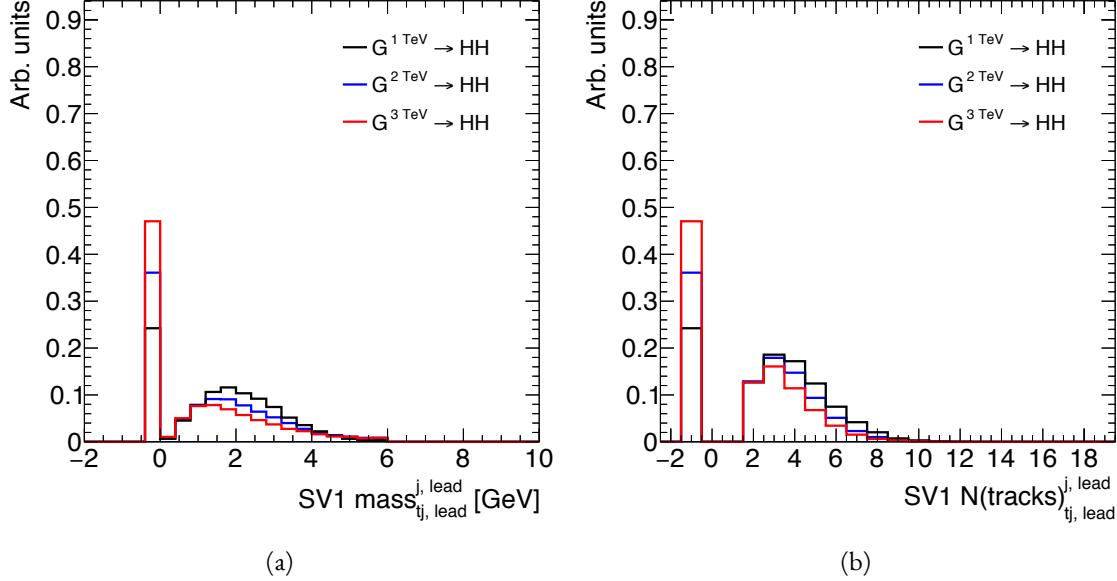


Figure A.4: Mass (a) and number of tracks (b) for the secondary vertices computed with the SV1 algorithm. When no secondary vertex is found, the quantities are assigned to default negative values.

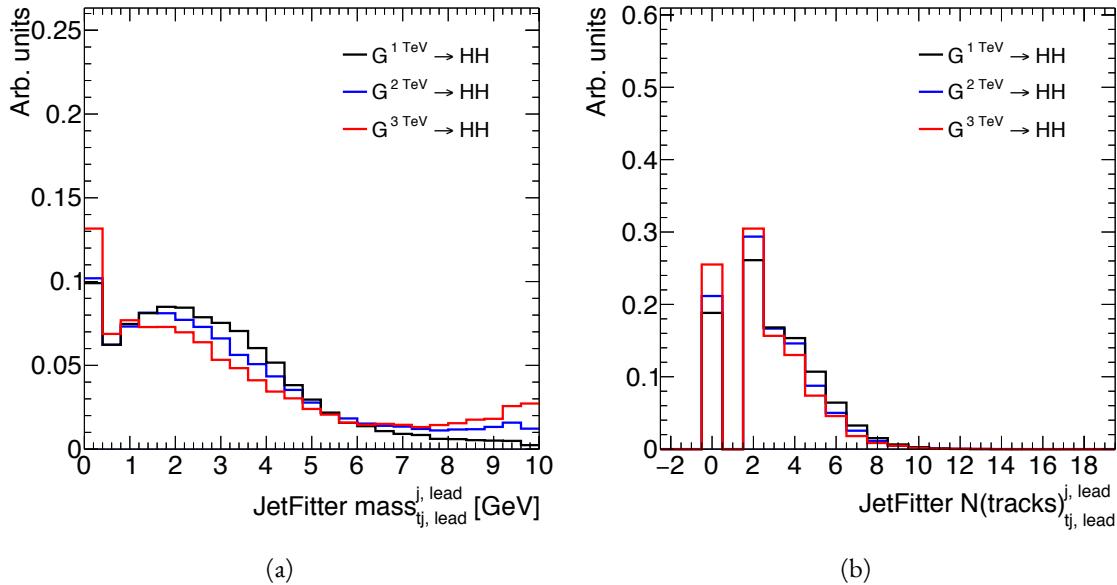


Figure A.5: Mass (a) and number of tracks (b) for vertices computed with the JetFitter algorithm. When no vertices are found, the quantities are assigned to default negative values.

2667 is not tuned for tagging multiple  $b$  quarks inside one jet, the tagging efficiency could degrade. Figure A.6  
 2668 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  $b^l$ . This figure suggests that the presence

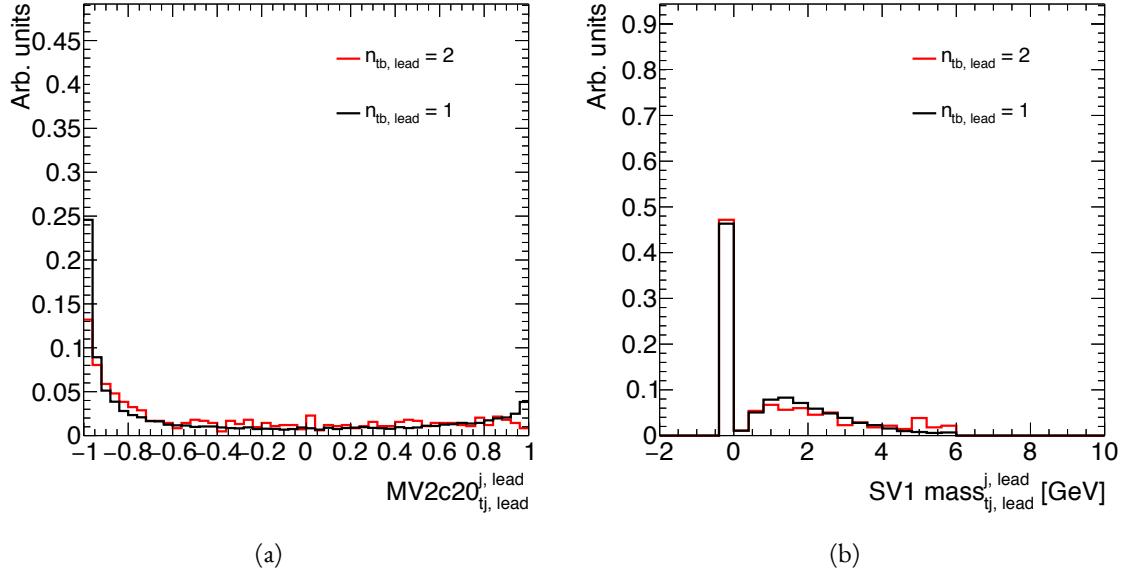


Figure A.6: MV<sub>2</sub>c20 score (a) and SV1 mass (b) for leading track jets with two truth  $b$  quarks ( $n_{tb, \text{lead}} = 2$ ) compared to those with only one truth  $b$  ( $n_{tb, \text{lead}} = 1$ ).

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  $p_T$ ,

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<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.

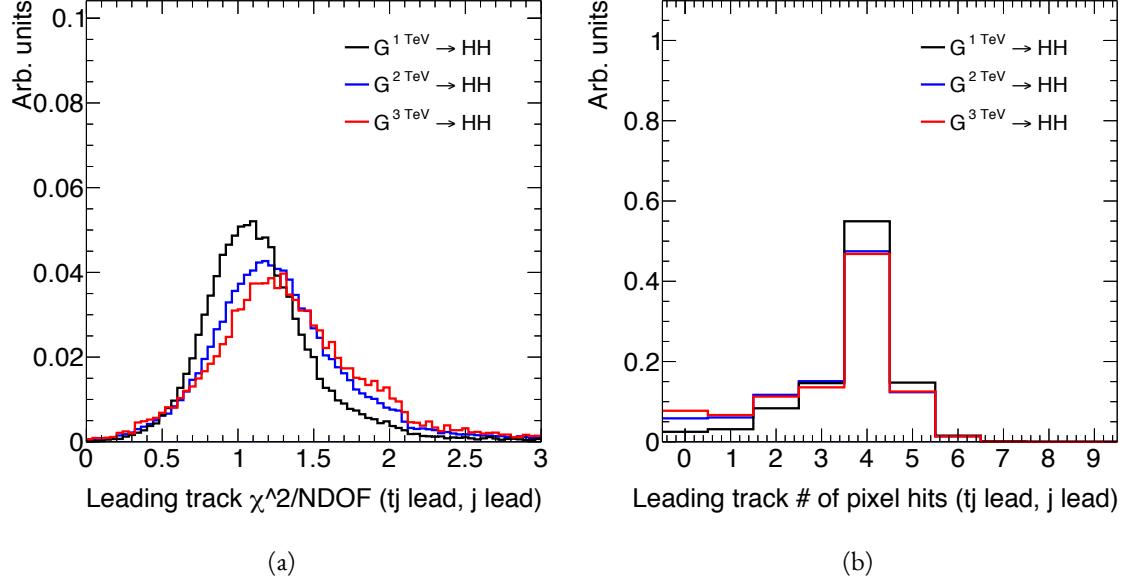


Figure A.7: Track fit  $\chi^2/\text{nDOF}$  (a) and number of pixel detector hits (b) for the leading track of the leading track jet in different mass RSG  $c = 1$  samples

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  $\text{MV}_{2\text{c}2\text{o}}$  score is shifted more significantly to background-like values. This seems to confirm the hypothesis that degrading track quality is responsible for the lowered  $b$ -tagging efficiency at high  $p_{\text{T}}$ .

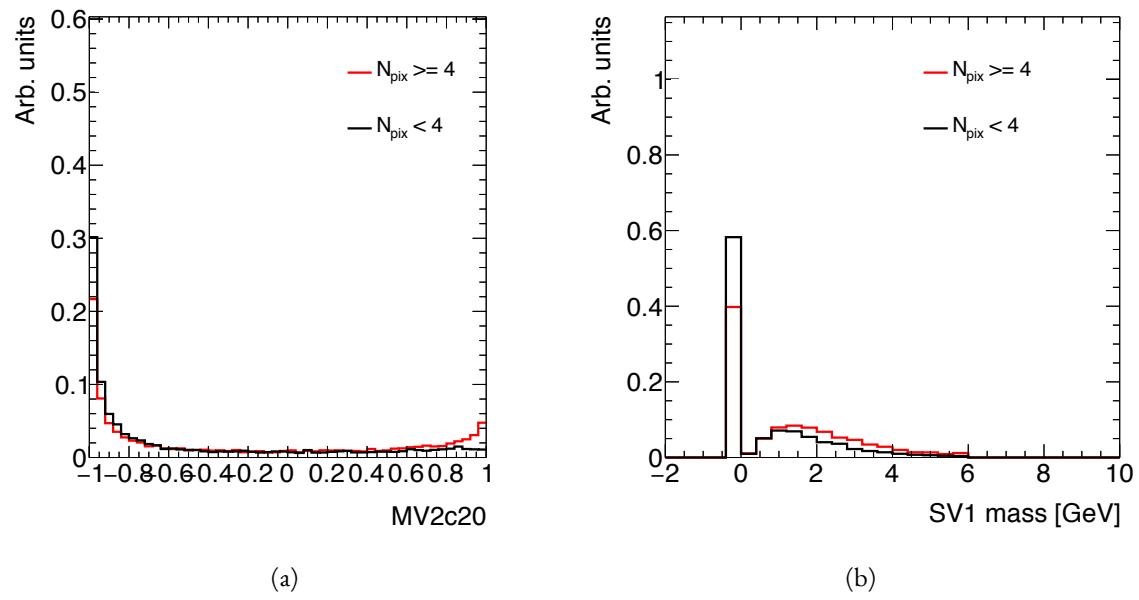


Figure A.8: MV<sub>2</sub>c<sub>20</sub> score (a) and SV1 mass (b) for leading track jets whose leading track jet has at least four pixel hits ( $N_{\text{pix}} \geq 4$ ) compared to those which do not ( $N_{\text{pix}} < 4$ ).

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**T**HIS THESIS WAS TYPESET using  $\text{\LaTeX}$ , originally developed by Leslie Lamport and based on Donald Knuth's  $\text{\TeX}$ . The body text is set in 11 point Egenolff-Berner Garamond, a revival of Claude Garamont's humanist typeface. The above illustration, *Science Experiment 02*, was created by Ben Schlitter and released under [CC BY-NC-ND 3.0](#). A template that can be used to format a PhD dissertation with this look & feel has been released under the permissive [AGPL](#) license, and can be found online at [github.com/asm-products/Dissertate](https://github.com/asm-products/Dissertate) or from its lead author, Jordan Suchow, at [suchow@post.harvard.edu](mailto:suchow@post.harvard.edu).