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David Hall

Discovery and Measurement of the Higgs Boson in the *WW* Decay Channel

Doctoral Thesis accepted by
the University of Oxford, UK

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By believing passionately in something
that still does not exist, we create it.
The nonexistent is whatever we have not
sufficiently desired.

Nikos Kazantzakis

Supervisor's Foreword

The Large Hadron Collider was built with the primary goal of determining the mechanism for electroweak symmetry breaking. The leading theory, the Brout–Englert–Higgs mechanism, predicted the presence of a new scalar particle known as the Higgs boson, with couplings to other particles determined by their masses. The mass of the Higgs boson itself was unknown, but was indirectly constrained to a narrow range by other precision measurements. By the time the first beam circulated in 2008, large teams of researchers on the ATLAS and CMS experiments were preparing for the search, with data from the Tevatron collider in the United States steadily reducing the allowed Higgs boson mass range.

Less than two weeks after the first LHC beam, a faulty connection short-circuited a section of superconducting magnets, ripping them from their cement base. This incident delayed first collisions by more than a year, and to protect the LHC the centre of mass energy was cut by half. The Higgs boson production rates were thus reduced and it seemed a Higgs boson discovery would take years to achieve. However, the collider performed exceptionally well in 2011 and 2012, producing data faster than anticipated. On July 4, 2012, the ATLAS and CMS experiments announced the discovery of a new boson, with considerably less data than pre-collision predictions.

The ATLAS publication describing the discovery included three Higgs boson decay channels: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ and $H \rightarrow WW$. The strongest evidence for a new boson came from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ channels, for which the observed rates were somewhat higher than expected, whereas the rate in the $H \rightarrow WW$ decay channel was somewhat lower than expected. After the discovery, the LHC more than doubled the data set, and the rates in the three channels became more compatible with expectation. In early 2013, ATLAS published these rate measurements, as well as measurements demonstrating that the discovered boson was most likely a spin-0 particle—a crucial requirement for a Higgs boson.

In order to improve the precision of these measurements and that of the Higgs boson mass, ATLAS dedicated the following year to upgrading its analyses. The $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ channels provided the most precise measurement of the

Higgs boson mass, while the $H \rightarrow WW$ channel gave the most precise determination of the production rate. In each channel, the signal significance was above the threshold for discovery. In addition, evidence for the predicted $H \rightarrow \tau\tau$ decay was achieved.

David Hall's thesis presents the final ATLAS measurement of the $H \rightarrow WW$ decay in gluon-fusion production using the 2011 and 2012 data sets, taking the reader through the process of discovery and measurement. A precursor to the observation of the $H \rightarrow WW$ decay was the measurement of the dominant background of non-resonant WW production. This measurement shared many of the features of the $H \rightarrow WW$ measurement; one important feature was the removal or separation of events with one or more jets. A zero-jet requirement effectively eliminated the large top-quark background, but it introduced an uncertainty on the efficiency of this jet veto. David was responsible for a data-based correction to reduce this uncertainty, and for evaluating the residual uncertainty. The details of the procedure, and of the full 2011 WW cross section measurement, are provided in his thesis.

In the $H \rightarrow WW$ measurement events are separated by jet multiplicity, as events with one jet contribute significantly to the sensitivity. In the analysis, one must determine the theoretical uncertainty on the migration of events between jet bins. A covariance matrix can be constructed to describe the normalisation and migration uncertainties, and different procedures for their evaluation make different assumptions about this matrix. David studied these issues in detail and evaluated the uncertainties associated with a method that had not been previously used by the experiments, but which accommodated the highest precision calculations and thus led to a reduction in the uncertainty associated with jet binning. His thesis details this method and provides a comparison of covariance matrices for different uncertainty estimation procedures.

A final notable aspect of the thesis is the clear and detailed description of the backgrounds to the $H \rightarrow WW$ search and measurement. The dominant non-resonant WW background is normalised to data using a control region; Monte Carlo simulation is then used to model the signal region, with corresponding theoretical uncertainties. David worked directly on evaluating these uncertainties and describes them in detail. A smaller background is a W boson produced in association with an off-shell photon that splits into a pair of leptons. When only one of these leptons is reconstructed, it can mimic the leptonic decay of a W boson and serve as a background to the signal process. David performed extensive studies to ensure this process was accurately simulated, and details are given in his thesis.

Measuring the Higgs boson in the WW decay channel presents many challenges, which are apparent as one reads David's thesis. The solutions to these challenges represent an impressive body of work from many people over many years. Collecting them into a thesis with many unique insights, David provides a clear exposition of the final word on the ATLAS $H \rightarrow WW$ measurement in the discovery data set.

Oxford
March 2015

Dr. Chris Hays

Abstract

In the Standard Model of particle physics, the non-zero masses of the W and Z bosons and the fermions are generated through interactions with the Higgs field, excitations of which correspond to Higgs bosons. Thus, the experimental discovery of the Higgs boson is of prime importance to physics, and would confirm our understanding of fundamental mass generation.

This thesis describes a search for the $gg \to H \to WW \to \ell\nu\ell\nu$ process of Higgs boson production and decay. It uses the LHC Run I dataset of pp collisions recorded by the ATLAS detector, which corresponds to an integrated luminosity of 4.5 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV. An excess of events is observed with a significance of 4.8 standard deviations, which is consistent with Higgs boson production. The significance is extended to 6.1 standard deviations when the vector boson fusion production process is included. The measured signal strength is $1.11^{+0.23}_{-0.21}$ at $m_H = 125$ GeV. A cross section measurement of WW production, a major background to this search, is also presented using the $\sqrt{s} = 7$ TeV dataset only.

Preface

As a D.Phil. research topic, the $H \rightarrow WW$ analysis has proven to be a baptism of fire. It is the most complicated of the three "discovery channels",[1] as it involves a variety of physics objects and requires a good understanding of many difficult backgrounds. As such, the analysis took huge effort from a large number of individuals. My role focussed on theoretical aspects of the signal and background modelling, and these parts shall be emphasised. I contributed to multiple iterations of the analysis [1–8], though the version presented here is unpublished at the time of writing [9]. I also co-authored the third Yellow Report produced by the LHC Higgs Cross Section Working Group [10].

When I began the degree in October 2010, there was no direct evidence for a Higgs boson. This thesis is written from a personal perspective and motivates a low mass search by electroweak fits, when in fact this aspect was motivated later by observations of a resonance in the $\gamma\gamma$ and ZZ channels.[2] Also, an advanced search strategy is described, though the discovery of $H \rightarrow WW$ was actually a gradual process with multiple iterations of blinding, optimising and unblinding the analysis. As more data were recorded and the analysis was enhanced, the results improved.

Early on, I gained relevant insight by performing multiple WW cross section measurements [12–15]. My main contribution was a jet veto correction factor applied to the WW signal, which reduces the dominant uncertainty in the analysis. This measurement shall be described when considering the WW background to the $H \rightarrow WW$ search.

To qualify for authorship within the ATLAS collaboration, I performed Run Control shifts. I also worked within the Versatile Link project [16] to investigate radiation-hardened optical components for the HL-LHC. As this research does not easily relate to the Higgs boson, it is excluded from this thesis. However, I have published articles on the radiation tolerance of optical fibres [17] and their connectors [18].

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[1] The $\gamma\gamma$, ZZ and WW decay channels quickly gave sensitivity to the Higgs boson ultimately discovered.

[2] Dedicated high mass searches for $H \rightarrow WW$ have also been performed [11].

Overview

This thesis describes the search, discovery and measurement of the Higgs boson using proton–proton collision data recorded by the ATLAS experiment at CERN. This is accomplished by searching for collisions where a Higgs boson is produced and subsequently decays to two W bosons, each of which decay to an electron or muon and a neutrino (i.e. $H \rightarrow WW \rightarrow \ell\nu\ell\nu$). This search suffers from large experimental backgrounds, such as continuum WW production, which must be accurately modelled to yield sensitivity to the Higgs boson.

First, the theoretical motivation for the Higgs boson is presented in Chap. 1. Then, Chap. 2 outlines some important concepts related to making precise predictions within the Standard Model, which shall be referred to throughout the thesis. The experimental setup of the LHC and the ATLAS detector are described in Chap. 3.

Focus then moves to the data analysis itself. Chapter 4 offers an overview of the entire $H \rightarrow WW$ analysis, detailing the selection of Higgs boson signal events and the rejection of backgrounds. Following this, signal modelling is described in Chap. 5, WW background modelling is described in Chap. 6 (including a dedicated cross section measurement), and the modelling of other backgrounds is described in Chap. 7. The experimental results are presented and discussed in Chap. 8. Finally, in Chaps. 9 and 10, we draw conclusions from the results of this analysis and of others conducted simultaneously at the LHC, and consider the outlook of Higgs physics.

References

1. ATLAS Collaboration, Search for the Standard Model Higgs boson in the $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ decay mode with 4.7 fb^{-1} of ATLAS data at $\sqrt{s} = 7$ TeV, ATLAS-CONF-2012-012 (2012)
2. ATLAS Collaboration, Search for the Standard Model Higgs boson in the $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ decay mode using Multivariate Techniques with 4.7 fb^{-1} of ATLAS data at $\sqrt{s} = 7$ TeV, ATLAS-CONF-2012-060 (2012)
3. ATLAS Collaboration, Search for the Standard Model Higgs boson in the $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ decay mode with 4.7 fb^{-1} of ATLAS data at $\sqrt{s} = 7$ TeV, Phys. Lett. B **716**, 62 (2012), arXiv:1206.0756 [hep-ex]
4. ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B **716**, 1 (2012), arXiv:1207.7214 [hep-ex]
5. ATLAS Collaboration, Observation of an Excess of Events in the Search for the Standard Model Higgs Boson in the $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ Channel with the ATLAS Detector, ATLAS-CONF-2012-098 (2012)
6. ATLAS Collaboration, Update of the $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$ Analysis with 13 fb^{-1} of $\sqrt{s} = 8$ TeV Data Collected with the ATLAS Detector, ATLAS-CONF-2012-158 (2012)
7. ATLAS Collaboration, Measurements of the properties of the Higgs-like boson in the $WW^{(*)} \rightarrow \ell\nu\ell\nu$ decay channel with the ATLAS detector using 25 fb^{-1} of proton–proton collision data, ATLAS-CONF-2013-030 (2013)

8. ATLAS Collaboration, Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC, Phys. Lett. B **726**, 88 (2013), arXiv:1307.1427 [hep-ex]
9. ATLAS Collaboration, Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector, (2014) (in preparation for Phys. Rev. D.)
10. LHC Higgs Cross Section Working Group, Handbook of LHC Higgs Cross Sections: 3. Higgs Properties, CERN-2013-004 (2013), arXiv:1307.1347 [hep-ph]
11. ATLAS Collaboration, Search for a high-mass Higgs boson in the $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ decay channel with the ATLAS detector using 21 fb^{-1} of proton–proton collision data, ATLAS-CONF-2013-067 (2013)
12. ATLAS Collaboration, Measurement of the WW cross-section in $\sqrt{s} = 7$ TeV pp collisions with ATLAS, Phys. Rev. Lett. **107**, 041802 (2011), arXiv:1104.5225 [hep-ex]
13. ATLAS Collaboration, Measurement of the W^+W^- production cross section in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, ATLAS-CONF-2011-110 (2011)
14. ATLAS Collaboration, Measurement of the WW cross-section in $\sqrt{s} = 7$ TeV pp collisions with the ATLAS detector and limits on anomalous gauge couplings, Phys. Lett. B **712**, 289 (2012), arXiv:1203.6232 [hep-ex]
15. ATLAS Collaboration, Measurement of W^+W^- production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector and limits on anomalous WWZ and $WW\gamma$ couplings, Phys. Rev. D **87**, 112001 (2013), arXiv:1210.2979 [hep-ex]
16. F. Vasey et al., The Versatile Link common project: feasibility report, JINST 7, C01075 (2012)
17. D. Hall, B.T. Huffman, A. Weidberg, The radiation induced attenuation of optical fibres below −20 °C exposed to lifetime HL-LHC doses at a dose rate of 700 Gy(Si)/hr, JINST 7, C01047 (2012)
18. D.C. Hall, P. Hamilton, B.T. Huffman, P.K. Teng, A.R. Weidberg, The radiation tolerance of MTP and LC optical fibre connectors to 500 kGy(Si) of gamma radiation, JINST 7, P04014 (2012)

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