Measuring Properties of the Higgs Boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4/$ channel with the ATLAS Detector at the LHC

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Abstract

This report summarizes the work performed for the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ analyses during the 2013 summer term. $H \rightarrow ZZ^{(*)} \rightarrow 4l$ is one of the most important channels for the search and measurement of properties of the Higgs Boson as the final decay state is fully reconstructable. As there are many background processes, a range of selection cuts are imposed on the events to improve the signal significance and over the term an analysis program was written which implemented all cuts. Furthermore, using simpler methods, many properties, such as mass, signal strength and spin/parity, were measured and were found to be consistent with the official results.

Introduction

The Standard Model (SM) is a set of equations penned down by physicists over the past decades, which describes the elementary particles of Nature and their interactions with each other. The SM includes three of the four known fundamental forces: namely electromagnetism, the weak force and the strong force. It describes and offers predictions for these phenomena over many energy regimes, making it an attractive physics theory. Concurrently with the theoretical developments, many different experiments were conducted to test its validity and, in the end, it has withstood the test of time. Currently, it is regarded as one of the most precise theories in existence, as many predictions of the SM have been confirmed to multiple decimal places by experiments.

However, despite the apparent success of the Standard Model, it is known that this model is not the ultimate theory that describes Nature. Some of the most obvious shortcomings of the theory include its many simplifying assumptions and its negligence of gravitational interactions between the fundamental particles. Furthermore, there are no viable candidates for Dark Matter and Dark Energy. While these are examples of the Standard Model's inability to describe certain parts of Nature, there are also several internal inconsistencies in the theory that lead to the above conclusion. To highlight a few, the WW scattering cross section blows up to infinity at energy scales of I TeV and above. Also, gauge symmetry, a fundamental part of the theory, requires an unphysical condition that all fundamental particles be massless. Overall, these problems in the Standard Model lead to the conclusions that the theory needs modifications for it to describe Nature more accurately [1].

There have been proposed modifications to the SM, in order to solve many of the issues described above. One such modification is the Higgs Mechanism [2]. This addition to the theory mainly deals with the problem of 'massless particles'. In the Higgs Mechanism, a new complex scalar field and an associated potential are introduced, with which all fundamental particles are allowed to interact. This coupling causes the particles to gain mass through a gauge invariant method, ensuring that all the required symmetry conditions are met. While this modification to the SM is considered to be simple and elegant, predictions from this theory need to be checked by experiments to see if Nature works in the proposed way.

One important prediction of the Higgs Mechanism is the existence of a new fundamental scalar boson, which is referred to as the Higgs boson. This boson arises from the self-coupling of the complex field and, thus, offers a direct probe for the proposed Higgs mechanism. As such, many high-energy experiments have devoted significant time and effort in trying to find evidence for this elusive particle. The LEP¹ collider at CERN in the 1990s excluded the existence of the Higgs boson with $m_H < 114.4$ GeV at 95% confidence level (CL) [3]. The next significant results came from the Tevatron Collider [4]. It excluded the Higgs Boson at 95% CL in the mass range of $100 < m_H < 103$ GeV and $147 < m_H < 180$ GeV and saw an approximate 3σ excess over the predicted background in the range $115 < m_H < 140$ GeV. Similarly, no other experiment had been able to give conclusive evidence for the Higgs Boson. However, now that the Large Hadron Collider (LHC) has starting running, and is probing much higher energy regimes, it is expected that the LHC will offer definite answers for the validity of the Higgs Mechanism. Hence, this report will focus on the study of the Higgs boson at LHC in the $H \rightarrow ZZ^{(*)} \rightarrow 4I$ channel.

¹Large Electron Positron

The Large Hadron Collider

The LHC is a two-ring superconducting hadron accelerator and collider, installed in the former LEP tunnel at CERN [5]. It is designed to accelerate two counter-rotating proton beams to a center-of-mass energy, $\sqrt{s} = 14$ TeV and collide the proton bunches every 25 ns. The LHC is also expected to yield a peak luminosity of 10^{34} cm⁻²s⁻¹, which will allow the 4 main experiments – ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment) and LHCb – to collect enough data to answer some of the most pressing questions about the SM.

Due to the initial start-up of the LHC, from 2010 to 2012, it was operated at below its design capabilities. In 2011, the center-of-mass energy of the beams was restricted to $\sqrt{s} = 7$ TeV and the LHC delivered 5.61 fb⁻¹ integrated luminosity, of which ATLAS recorded 5.25 fb⁻¹ [6]. In 2012, the energy of the beams was increased to $\sqrt{s} = 8$ TeV and, due to an increase in the instantaneous luminosity, the LHC delivered 23.3 fb⁻¹ of proton-proton (pp) collisions, of which ATLAS recorded 21.7 fb⁻¹[6]. Figure 1 shows the evolution of the cumulative luminosity of pp collisions that ATLAS recorded in the data taking

period.



Figure 1: The cumulative luminosity recorded by the ATLAS detector [6]

The ATLAS Detector

The ATLAS detector, along with CMS, is one of the two main general-purpose experiments at the LHC [7]. It has been designed to exploit the full physics potential of the LHC and, thus, is expected to answer many open questions in particle physics. One of its main goals is to find conclusive evidence for the existence or absence of the Higgs boson. Furthermore, ATLAS was designed to probe Beyond the SM (BSM) theories, such as Super-symmetry and Dark Matter, and perform precision measurements of known SM processes to find deviations from theoretical predictions.

The ATLAS detector is 44 m in length, 25 m in height and weights over 7000 tons [7]. It consists of 4 main detector subsystems: the Inner Detector (ID), the Electromagnetic Calorimeter (ECal), the Hadronic Calorimeter (HCal) and the Muon Spectrometer (MS). The ATLAS ID is designed to measure the tracks of charged particles and provide excellent momentum resolution for them. The ECal measures the energy of particles that interact predominantly through electromagnetic interactions, such electrons and photons. On the other hand, hadrons and mesons traverse the ECal relatively easily but are absorbed in the HCal, where their energy is measured. Lastly, muons are minimum ionizing particles and will escape the HCal. Hence, the MS provides measurements for the muons, which can be used to independently reconstruct them. Lastly, these detecting subsystems are immersed in a magnetic field of approximately 4 T created by the toroidal magnets and a field of 2 T created by the solenoid magnets. Figure 2 shows a picture of the ATLAS detector with all the detector subsystems labelled.



Figure 2: The ATLAS Detector [7]

The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction point. The z-axis is along the beam pipe, the x-axis points to the centre of the LHC ring and the y-axis is defined as pointing upwards. Polar coordinates (r, ϕ) are used in the transverse plane; ϕ being the azimuthal angle around the beam pipe. The pseudo-rapidity η is defined as $\eta = ln[tan(\theta/2)]$ where θ is the polar angle.

Higgs at the LHC

The SM Higgs theory predicts that when two proton bunches collide, there is a small cross section for the production of the Higgs Boson. At the LHC, there are four main production modes for this to happen, namely in decreasing order with respect to the predicted cross section: gluon-gluon fusion (ggF), Vector Boson Fusion (VBF), vector boson associated production (VH) and top quark associated production (tTH) [8]. Figure 3 shows the leading order Feynman diagram for the production modes and



Figure 3: Leading order Feynman diagrams of the Higgs production modes available at the LHC. Gluon-gluon fusion mode dominates, followed by Vector Boson Fusion; associated production with vector boson and top quarks. [6]

Figure 4 graphically outlines the relationship between the predicted cross sections and the mass of the Higgs Boson (m_H) at a center-of-mass energy of 7 TeV and 8 TeV. At $m_H = 125$ GeV, the ggF contribution at



Figure 4: Predicted Higgs boson cross section as a function of Higgs mass in pp collisions at a center of mass energy of 7 and 8 TeV [8]

19.27 pb is approximately 10 times greater than VBF at 1.578 pb and 100 times greater than the VH (0.704 pb) and tttt \overline{tH} (0.129 pb) production modes [8].

Once the Higgs Boson has been produced in the collision, as seen from Figure 5, it can decay to many different particles. In the low Higgs mass range, $m_H < 130$ GeV, the $H \rightarrow b\bar{b}$ decay mode is dominant. Also in this mass range, the Higgs boson can decay to other particles with a large enough branching ratio to allow many different analyses to find a signature for the boson. As the mass of the boson is increased, the Higgs decay to the 2 vector bosons dominates and the branching ratio to other particles decreases quickly. However, $H \rightarrow t\bar{t}$ has a significant contribution when $m_H > 2m_{top}$.



Figure 5: Predicted branching ratio for the Higgs boson as a function of Higgs mass [8]

As such, ATLAS and CMS have been probing all the different decay modes to find evidence for the Higgs boson. In the summer of 2012, both experiments managed to confirm the existence of a new boson with an approximate mass of 125 GeV [9]. Using the full 4.6 fb⁻¹ of 2011 data and 5.8 fb⁻¹ of the 2012 dataset, it was also shown that the new particle had very similar properties to the proposed SM Higgs boson. The results presented at that time were mainly driven by the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow 4l$ decay channels, with $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ providing supporting evidence [8]. Now that more data has been collected and the full 2012 dataset is available, a more accurate measurement of the properties of the new boson is needed to conclusively answer if the newfound particle is the predicted SM Higgs boson or one of the other Higgs bosons predicted by BSM theories.

Search for the Higgs Boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4$ / Channel

One of the most important analysis channels for measuring the properties of the Higgs Boson is $H \rightarrow ZZ^{(*)} \rightarrow 4l^2$. While the branching ratio for this final state is approximately 1.25×10^{-4} , this channel is still referred to as 'The Golden Channel' for the search and study of the Higgs Boson. This is due to the fact that the final state is very clean and leptons have a clear detector signature, making them easily identifiable. This is coupled with the fact that there are no complex physics objects such as Missing Transverse Energy (MET) or jets, which are present in other decay channels such as $H \rightarrow WW^{(*)}$ and $H \rightarrow \tau\tau$. This simple final state allows the two Z bosons and subsequently the Higgs Boson to be fully reconstructed. Furthermore, unlike $H \rightarrow \gamma\gamma$ and $H \rightarrow b\bar{b}$, there are few expected backgrounds, allowing the contributions of the Higgs to be easily seen. Hence, many different properties of the boson can be easily tested, from which conclusions about the nature of the boson can be drawn.

Background

As the Higgs Boson has a predicted mean lifetime of 10^{-22} s [8], only the decay products of the boson can be seen in the ATLAS detector. Hence, for this analysis, only events where 4 or more leptons are produced in the collisions are selected. Leptons in this analysis only include muons and electrons. Taus decay too quickly to be seen in the detector, but particles coming from the leptonic decays of taus are not rejected. However, there are many other Standard Model processes that have the same final state, causing them to contribute to the backgrounds seen in this analysis.



Figure 6: Leading order Feynman diagrams of processes that contribute to the $H \rightarrow ZZ^{(*)} \rightarrow 4I$ analysis

The backgrounds are classified into two general categories, namely irreducible and reducible. The irreducible background consists of events in which two Z bosons or two virtual photons are produced. They subsequently decay leptonically, mimicking the same final decay state as the signal. As seen from the firstorder Feynman diagram in Figure 6, the only difference between the signal in Figure 6a, and the irreducible background in Figure 6b, is the intermediate Higgs Boson. This leads to the irreducible background having very similar event topologies and kinematic distributions as the signal. To estimate the contribution of this background in the final result, high statistics Monte Carlo (MC) samples were used which were normalized to predicted the theoretical cross section.

²'I' refers to lepton, which for the purpose of this report only includes electrons and/or muons

On the other hand, the irreducible background consists mainly of events where the Z boson is produced in association with quarks, which predominantly consist of $c\bar{c}$ and $b\bar{b}$, or $t\bar{t}$ pairs decaying semileptonically. In both cases, two leptons are created in the decay with at least two jets, which if mis-reconstructed as leptons, lead to the same final state. Figure 6c shows the leading order Feynman diagram of one of the contributing processes. Here, the Z boson decays into either electrons or muons, and the jets from the b quarks are misidentified as leptons, causing the event to fake the same final state as the signal. As the jets behave differently when compared to leptons, the event topologies and kinematic distributions of the irreducible backgrounds are different from that of the signal. The reducible backgrounds are estimated through multiple data driven methods with many cross checks to ensure an accurate determination of the contribution of the relevant processes to the signal selection.

Event Selection

As described in the previous section, due to background processes that have the same final state as the signal, simply requiring events with 4 leptons will make it very difficult to distinguish the contribution of the Higgs. Hence, further selection is required to reduce the background and improve the signal significance.

The data used for the analysis are chosen by using the single-lepton or di-lepton triggers. There are five overall triggers: the single and di-muon triggers select events that contain a muon above a given transverse momentum (p_T), which is in the 8 – 24 GeV range depending on the type of trigger and the period of data taking. Similarly, the single and di-electron triggers select events where the transverse energy (E_T) of the electron exceeds a certain threshold, which ranges from 20 – 25 GeV. Lastly, there is an electron-muon trigger, which has a lower threshold than the dedicated triggers; however, it requires leptons of each flavour to exceed the respective cut value [10]. Furthermore, for each event, it is also required that the ATLAS detector satisfy data quality cuts; thereby any event collected in a period where a part of the detector is not working as designed is vetoed.

Once the event has been selected, initial detector level cuts are imposed on the leptons. This is to ensure that the reconstructed objects are found in a region of the detector where the lepton can be detected and to reduce the number of fake leptons. Each electron (muon) must satisfy $E_T > 7$ GeV ($p_T > 6$ GeV), $|\eta| < 2.47(||\eta| < 2.7)$ and related identification cuts [10]. Also, to ensure that leptons come from the main interaction vertex in the events, the impact parameter for each lepton is required to be within 10 mm of the primary vertex. Lastly, to reduce cosmic ray muons, each muon must have a transverse impact parameter of less than 1 mm with respect to the primary vertex.

As there are many reconstruction algorithms, each optimized for certain regions of the detectors, overlaps between the muons (electrons) from different reconstruction algorithms are removed by choosing only one lepton if many particles share the same track or are close together in $\eta - \phi$ space. For example, for electrons, if multiple electrons are close together, the one with the highest cluster E_T is kept. Moreover, one of the reconstruction algorithms uses ECal data to reconstruct muons; thus, electrons can fake the signature of muons. Therefore, calorimeter-reconstructed muons that are close to electrons in $\eta - \phi$ space are also vetoed. Lastly, as stated in the previous section, jets may be reconstructed as electrons; therefore, electrons close to jets in $\eta - \phi$ space are vetoed [10].

Once the leptons are selected, two pairs of the same flavour opposite sign leptons (SFOS) are reconstructed, forming a quadruplet. As there are multiple ways in which leptons can be paired, the quadruplet where one of the pairs has a mass closest to the PDG mass for the Z boson is kept. This pair is referred to as the leading pair while the other is labelled as the sub-leading pair. If more than 4 leptons are present, multiple quadruplets are constructed; the one with the leading pair with the mass closest to the PDG Z boson mass is kept. Due to the nature of the Z boson decay, further kinematic and isolation cuts on the leptons are imposed. It is required that the 3 highest p_T leptons must satisfy: $p_{T1} > 20$ GeV, $p_{T2} > 15$ GeV and $p_{T3} > 10$ GeV and for each same (opposite) flavour lepton pair, it is required that $\Delta R > 0.10(0.20)^3$. To veto leptons coming from J/ψ decays, events are rejected if any same flavour lepton pair has an invariant mass of less than 5 GeV. Lastly, it is also required that at least one lepton in the quadruplet has triggered the relevant data trigger [10].

As the mass of the newly found particle is approximately 125 GeV, kinematic constraints ensure that in the Higgs decay to 2 Z's, one Z boson is mostly on-shell while the other is always an off-shell particle. As such, the mass of the leading pair (m_{12}) is required to lie between 50 GeV and 106 GeV and the mass of the sub-leading pair (m_{34}) is required to be within the range $m_{min} < m_{34} < 115$ GeV, where m_{min} is 12 GeV if the mass of the quadruplet (m_{4l}) is less than 140 GeV. It then rises linearly to 50 GeV at $m_{4l} = 190$ GeV [10].

To limit the contribution of the reducible background, further cuts based on impact parameter significance and track and calorimeter isolation requirements are imposed [10]. For example, the track isolation cut is based on the sum of p_T of leptons in a cone of $\Delta R = 0.2$ divided by the E_T of the particle being tested, and it is required to be less than 0.15. Figure 7 shows the distribution of this discriminant for the signal and the background processes. It can be clearly seen that leptons coming from the signal and irreducible background are relatively isolated. Calorimeter isolation is based on similar principles and compares the isolation of the energy deposits of particles in the calorimeter. For the impact parameter selection criteria, leptons



Figure 7: Distribution of the Track Isolation Discriminant for the signal and background processes

coming from heavy quark decay have a displaced reconstructed vertex due to the small but finite lifetime of heavy quarks. Hence this cut, which is the ratio of the distance of the displaced vertex from the primary vertex and its associated error, reduces the contribution of background due to the semileptonic decay of quarks.

As charged particles bend in the magnetic field that permeates the ATLAS detector, leptons may emit a photon through the bremsstrahlung process, which is referred to as the Final State Radiation (FSR) [11]. FSR for electrons is taken into account by the reconstruction process [10], however, for muons it is manually added in the analysis. For all muon leading pairs with an invariant mass of $66 < m_{12} < 89$ GeV, the photon which is closest to the muon [10] and has the highest cluster E_T is added to the calculation of the invariant mass; provided that the new mass satisfies: $m_{12+\gamma} < 100$ GeV. Lastly, the mass resolution for the 4 leptons is improved by applying a Z-mass constraint to the leading pair if $m_{4l} < 190$ GeV and to both pairs for higher masses [10]. The Z-line shape and di-lepton mass uncertainty are taken into account by the Z-mass

$$^{3}\Delta R = \sqrt{\Delta \eta^{2} + \Delta \phi^{2}}$$

Selection Cut	Signal $(m_H = 125 \text{ GeV})$	Irreducible Background	Reducible Background	Signal Significance
Total	94.7	2281	379420	0.153
Trigger	52.3	2148	213289	0.113
4 Lepton	7.94	260	1667	0.181
SFOS	7.85	258	1116	0.212
Kinematics	7.45	225	898	0.222
Trigger Match	7.45	225	897	0.222
ZI Mass	7.24	206	690	0.241
Z2 Mass	6.60	142	376	0.289
ΔR and J/ ψ veto	6.47	140	282	0.314
Track Isolation	6.05	135	7.49	0.504
Calo Isolation	5.91	3	3.90	0.504
Impact Parameter	5.81	130	0.86	0.505

Table I: Number of normalized weighted events passing each cut for 4μ channel

constraint, reducing the difference between the reconstructed mass and true mass of the 4 leptons.

Over this summer, a C++/ROOT analysis program was written which implemented all of the above event selection cuts, along with the smearing and reweighting for the Monte Carlo (MC) samples. This allowed the production of skimmed mini-ntuples, which are being used by the group working on the Higgs to 4 leptons decay for further studies. In addition, the cutflow analysis program was used to test and validate new recommendations from different performance groups, such as e/gamma and Muon combined.

Expected Signal Significance

To understand the impact of each cut on the event selection, the numbers of events passing each criterion were counted for different processes using the MC generated samples. Table I lists the normalized events for the $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ decay sub-channel after the detector level cuts, such as lepton selection and where removal of overlapping leptons have been imposed. The signal significance is computed using Equation I, which is the probability of observing the event count, given the expected background [12]. It is expressed as the number of standard deviations for a Gaussian probability density function:

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

where s is the number of signal events and b is the number of background events. In Table 1, both the irreducible and reducible background event counts are used to compute the expected background.

It can be seen that the reducible background dominates the initial expected number of events. However, simply requiring at least 4 leptons in the event greatly reduces this background. The next few selection criteria reduce the overall background while keeping the expected signal events -- slowly increasing the signal significance. As mentioned in the previous section, the track isolation cut is specifically designed to decrease the reducible background and this effect is seen in the cutflow table. The calorimeter isolation and impact parameter significance cut have similar discriminating power, but after the track isolation, the reducible background is statistically limited.

Results

Once the 4 leptons candidates have been selected, the invariant mass of the quadruplet is calculated. Figure 8 plots the expected mass distribution of MC background and signal samples and the 7 TeV and 8 TeV data. Comparing only the background with the data, a clear excess is seen at around 125 GeV, which is consistent with the Higgs hypothesis. Table II presents the expected and observed number of events in a ± 5 GeV window around 125 GeV. Computing the significance of observing the data seen with the expected background, a 6.6 σ effect is seen at 124.3 GeV. This alone exceeds the 5 σ requirement; using just the $H \rightarrow ZZ^{(*)} \rightarrow 4I$ channel, discovery of a new particle can be claimed.



Figure 8: Invariant mass distribution of the 4 selected leptons

Mass Measurement

The mass of the Higgs Boson is one of the most important parameter in the SM Higgs mechanism as it is the only free quantity in the theory. Once the mass is fixed, the Higgs theory provides concrete predictions for other analyses to test. For the initial estimation of mass, a sum of 3 Gaussians functions was fitted to the data: one for the Z pole peak, one for the data excess and a last one for the flat irreducible and reducible background. Figure 9 shows the result of fitting the function to the data and using the mean of the Gaussian fitted to the excess, the mass of the new boson is found to be 124.4 ± 0.5 GeV. The error quoted in this measurement only includes the statistical uncertainty.

Channel	Signal $(m_H = 125$ GeV)	Irreducible Background	Reducible Background	Total Expected	Observed
4μ	6.8 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	9.6 ± 1.0	13
2µ2e	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	6.0 ± 0.8	5
2e2µ	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	6.6 ± 0.8	8
4e	2.6 ± 0.4	1.2 ± 0.1	1.11±0.28	4.9 ± 0.8	6
Total	15.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	27.1 ± 3.4	32

Table II: Number of expected and observed events in a ± 5 GeV range around 125 GeV for 2011 and 2012 data. [10]

For a better estimation of the mass, a ID unbinned likelihood fit is used [13]. The probability density functions (PDFs) describing the mass distributions are obtained from high statistics MC samples, thereby allowing various detector level effects to be taken into account. Signal shape, normalization and corresponding uncertainty are parameterized as a function of the Higgs mass and systematic uncertainties are accounted for by varying these three variables. For the final result, the profile likelihood is shown for the combined channel fit in Figure 10a and for each individual channel in Figure 10b [10]. By finding the minimum in the combined profile likelihood, the mass of the boson is found to be $123.4^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (sys) GeV [10].



Figure 9: Fitted invariant mass distribution

Signal Strength

Signal strength acts as a scale factor for the total

number of events predicted by the theory. Again for an initial measurement for this property, the sum of three Gaussians is fitted both to the data and to the weighted normalized MC sample. Taking the ratio of the overall normalization of the function fitted to the Higgs peak, the signal strength is found to be 1.6 ± 0.7 .

For a better estimation, a method similar to the likelihood fit, described in the previous section, is used. Instead of just varying the mass parameter, the overall normalization is also allowed to vary with respect to a scale factor. Figure 11 shows the likelihood contour obtained for the fit and the minimum is found to be at 124.3 GeV with signal strength of 1.5 ± 0.4 .

Spin and Parity

As there are no know fundamental scalar bosons other than the predicted Higgs particle in nature, measuring the spin of newly found particle will provide important discriminating evidence. Furthermore, the SM Higgs mechanism predicts a positive parity for the boson, while predicted particles from other competing theories have different spin/parity combinations. The observables that are sensitive to the spin/parity of the



Figure 10: Combined and individual likelihood profile for the mass fit. The dashed lines are likelihood computed with mass scale systematics (MMS) applied [10]



Figure 11: Likelihood contours with and without mass scale systematics to estimate signal strength [10]

particles are the masses of the Z bosons, the production angle and 4 decay angles. The angular variables are illustrated in Figure 12 and are defined as follow [10]:

- θ_1 (θ_2) is the angle between the negative final state lepton and the direction of flight of Z1 (Z2) in the Z rest frame.
- ϕ is the angle between the decay planes of the four final state leptons expressed in the four lepton rest frame.
- ϕ_1 is the angle defined between the decay plane of the leading lepton pair and a plane defined by the vector of the Z1 in the 4 lepton rest frame and the direction of the parton following the positive z axis.
- θ^* is the production angle of the ZI defined in the 4 lepton rest frame.



Figure 12: Pictorial representation of the production and decay angles. [10]

For a spin 0 hypothesis, the cross-section does not depend on the production angle or ϕ_1 . However, all of these variables are needed to distinguish between other spin hypotheses. Figure 13 shows the expected and the observed distribution of 2 angular variables and the mass of the sub-leading Z boson for the 0⁺ spin parity hypothesis.

For the analysis, six spin parity combinations are tested, namely: 0^+ , 0^- , 1^+ , 1^- , 2^+ and 2^- . The spin I hypotheses are disfavoured due to the observation of the particle in $H \rightarrow \gamma \gamma$ decay mode. For the remaining four hypotheses, an initial test is done by comparing the expected and observed distributions for θ_1 , ϕ and m_{34} using a Kolmogorov–Smirnov test [14]. Table 3 summarizes the results and it can be seen that 0^- and 2^+ are disfavoured when compared to the 0^+ hypothesis. For the 0^+ and 2^- hypotheses, not enough data are present to conclusively discriminate between the two.

For a more accurate test, a Boosted Decision Tree (BDT) [15] is trained with the above-mentioned variables and a test discriminant is formed [10]. Moreover, another test based on the Matrix Element Likelihood ratio (MELA) [16], where the PDFs describing final state observables are created using MC samples, is also used. Both test statistics lead to a similar conclusion: 0^+ is strongly preferred over 0^- , 1^+ , 1^- and 2^+ . While it was expected to exclude 2^- in favour of 0^+ at 2.6 σ level with the amount of data collected, the observed data do not provide clear evidence in favour of either hypothesis [10].



(c) Distribution of the mass of sub leading pair

Figure 13: Distribution of 3 of the variables used to discriminate between different spin parity for the 0^+ hypothesis

Table III: Results of the KS test between the distribution observed for data and the expectation for a given spin hypothesis. 0^+ is favoured over 0^- and 2^+ . However, no significant conclusions can be drawn between 0^+ and 2^-

Hypothesis	0+	0-	2+	2-
m ₃₄	0.996	0.974	0.974	1.000
$\cos(\theta_1)$	1.000	1.000	1.000	1.000
ϕ	1.000	0.999	1.000	1.000
Combined	0.995	0.973	0.974	1.000



(a) Unsmoothed histogram

(b) Smoothed histogram

Figure 14: Comparison of the smoothed and unsmoothed histogram for the 4e channel. The x-axis is the invariant mass of the 4 leptons and the y-axis is the BDT output

Improvement to Mass Measurement

As stated in the previous section, one of the most important parameters in the SM Higgs mechanism is the mass of the Higgs boson, as it is the only free parameter in the theory. Once the mass is specified, all other properties such as the production cross-section and branching ratio are fixed in the SM. Since the Higgs is fully reconstructable in the 4 lepton decay channel, the mass can be measured very precisely, allowing for concrete predictions to be tested by other analyses.

The mass of the boson is measured by performing a one-dimensional unbinned likelihood fit to the invariant mass distribution. Probability density functions (PDFs), describing signal and background distributions, are reconstructed from the high statistics Monte Carlo samples. Furthermore, as the signal MC samples exist only for discrete Higgs mass, PDFs for intermediate mass points are created by 'morphing' between the simulated masses. Morphing generates the new PDFs by smoothly interpolating between the input PDFs, storing the changes in signal shape and overall normalization as a function of the Higgs mass. Uncertainties arising from different measurements are taken into account by distorting the signal shape and changing the overall normalization, and these are again parameterized as a function of the Higgs mass. Using this, the mass of the boson is measured to be $123.4^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (sys) GeV [10].

To improve this mass measurement, studies are being carried out to see the effects of introducing a Boosted Decision Tree (BDT) output based on the kinematics and angular distribution of the reconstructed quadruplet to the fit. This discriminant is added as a second dimension to the likelihood fit and is expected to increase the sensitivity to the signal and improve the mass errors.

Similar to the ID fit, 2D PDFs are needed to describe the distribution of the signal and background. These are obtained by smoothing 2D histograms and then using them to create continuous PDFs. As these are new procedures, each step in the process is validated by comparing the output to the original MC sample and ensuring that the overall smoothed shape matches the MC shape and only statistical fluctuations



Figure 15: Comparison of the morphed and smoothed PDF for 125 GeV Higgs Sample

are reduced. Figure 14 compares a smoothed histogram with the unsmoothed original histogram for the 4e channel. It can be seen that the overall distribution shape is the same and fluctuations, especially in low statistics bins, are reduced.

For the Higgs signal, PDFs for intermediate mass points are again obtained by morphing between the simulated mass points. To validate these 2D interpolations, a specific Higgs mass MC sample is removed from the morphing input, and the distribution for the morphed PDF at that mass is compared to the one obtained from the MC sample. For example, if the morphing is to be validated for the Higgs mass around 125 GeV, the 125 GeV MC sample is removed from the input and using the other samples, the morphed PDFs are created. Afterwards, the 125 GeV morphed-PDF is compared to the 125 GeV PDF obtained from MC. Figure 15 shows the result of the above procedure; the 2D PDFs are projected onto the mass and BDT axes. For the mass axis, the interpolation is extremely close to the MC shape, but for the BDT axis there are features in the MC sample that are smoothed by the morphing. However, it is expected that these will not greatly affect the measurement.

Summary

The Higgs mechanism is an important addition to the SM; however, experimental proof is required before the theory can be accepted as the SM Higgs Boson. $H \rightarrow ZZ^{(*)} \rightarrow 4l$ is one of the most important decay modes where the Higgs Boson can be seen and it is being studied in detail by the ATLAS Analysis group. As there are many background processes with the same final state, a range of selection cuts are imposed on the events to reduce the background while ensuring that signal is present. An analysis program was written over the summer that implemented these cuts and was used to produce the mini-ntuples for the analysis.

The mass of the Higgs is the only free parameter in the SM Higgs mechanism and previously it was measured by performing a ID likelihood fit. The mass of the new boson was measured to be $123.4^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (sys) GeV. Currently, studies are being undertaken to improve this fit by adding a BDT discriminant and performing a 2D fit. Over the summer, validations for the steps, such as smoothing and morphing, to create 2D PDFs were also carried out. No significant deviations in the smooth PDF shapes have been found up until now and further studies are being performed by using MC samples and toy experiments.

Other properties of the new boson were also measured. The signal strength was found to be 1.5 ± 0.4 , showing that the cross section and branching ratio of the boson are consistent with the rates predicted by the SM Higgs Mechanism. Also, the Higgs theory predicts 0^+ spin parity for the Higgs Boson. The data favour the 0^+ hypothesis over 0^- , 1^+ , 1^- and 2^+ . While it was expected to exclude 2^- in favour of 0^+ , the observed data does not provide clear evidence in favour of either hypothesis [10].

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