HINT OF THE STANDARD MODEL HIGGS
BOSON IN ITS DECAY TO $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

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Hint of the Standard Model Higgs
boson in its decay to $H \to ZZ^{(*)} \to 4\ell$

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The Standard Model (SM) Higgs boson may be searched for at the Large Hadron Collider (LHC) in various decay channels, the choice of which is determined by the signal rates and the signal-to-background ratios in various mass regions. This dissertation presents the search for the SM Higgs boson in the mass range from 110 to 600 GeV/c$^2$ in the golden channel $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$, where $\ell,\ell' = e, \mu$. It is one of the most promising experimental searches and is characterized by high signal-to-background ratios in the low-mass Higgs region where $m_H < 2m_Z$. In this low-mass region, one of the $Z$ bosons decays on-shell ensuring high efficiency (i.e., $H \to ZZ^{(*)}$). In the high-Higgs-mass region ($m_H > 2m_Z$), the channel performs well, with both $Z$ bosons decaying on-shell; this allows the search range to be extended to 600 GeV/c$^2$ (i.e., $H \to ZZ$). 4.8-4.9 fb$^{-1}$ of data at $\sqrt{s} = 7$ TeV collected by the ATLAS detector from the 2011 $pp$ collision run is used in the search that is presented. While a direct discovery of a Standard Model Higgs boson has not been made with the present analysis, exclusion limits are set on possible Higgs masses, and evidence points strongly to a low-mass Higgs near 125 GeV/c$^2$. 
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This dissertation is dedicated to my parents, brother, and best friend; their constant support and encouragement helped me stick through to the end.
Chapter 1
INTRODUCTION

By convention there is color,
By convention sweetness,
By convention bitterness,
But in reality there are atoms and space.

-Democritus (circa 400 B.C.)

One of the most important questions of modern physics is understanding where mass comes from. In ancient times, circa 460 B.C., a Greek philosopher by the name Democritus, essentially asked himself the following question: what happens if you break an object in half and then again? Just how many times could the object be broken before it could be broken no more? Democritus later thought that at the very end, there is a single, indivisible unit which he called ατοµoς (Gr. atomos) - the atom, which means “indivisible”.

Democritus’s atom was forgotten for many centuries. It was later discovered that all normal matter can be broken into components, which were made up of molecules - each made up of atoms. During the late 19th and early 20th centuries, physicists would discover that atoms were in fact divisible and made up of protons, electrons, and neutrons. Considering mass, we know that atoms vary in mass according to the number of protons, electrons, and neutrons inside. In other words: lower masses, less matter. Protons are heavier than electrons because they consist of up and down
quarks. Still, one must ask where does mass itself comes from? Why do some elementary particles weigh more than non-elementary particles? Just as important, why are some particles (i.e., photons) massless?

The Standard Model of particle physics is a theoretical framework that describes the fundamental interactions - electromagnetic, weak, and strong nuclear - which mediate the dynamics of all known elementary particles [1–3]. Unfortunately, the Standard Model is incomplete as it does not contain gravity nor explain particle masses. Its missing puzzle-piece is the Higgs boson. The Higgs boson comes from the proposed Higgs mechanism which in theory can give mass to all of the elementary particles in the Standard Model. The Higgs is an unstable particle, otherwise we would already have seen it today. The Higgs boson is the key to understanding the origin of particle mass and its discovery would be an incredible step for particle physics. It can decay into various final states that will be briefly discussed later.

This dissertation focuses on the search for a Standard Model Higgs boson decaying to two $Z$ bosons. This particular channel is commonly referred to as the “golden channel” on account of its clean signal; it is one of the most experimentally accessible channels for Higgs boson discovery.

The outline of this dissertation is as follows:

- Chapter 1 provides a brief introduction to the Standard Model.
- Chapter 2 presents an overview of the theoretical framework of the Higgs mechanism, which gives rise to the Higgs boson.
- Chapter 3 gives a short history of CERN and discusses physics experiments at the LHC.
- Chapter 4 describes the experimental setup of the ATLAS experiment at the LHC.
Chapter 5 presents the analysis used in searches for a Standard Model Higgs boson decaying to four leptons using the ATLAS experiment. Motivation for Higgs searches at ATLAS and an explanation of Higgs boson production at the LHC are also presented.

Chapter 6 presents the results of the baseline analysis in the form of mass distributions and exclusion limits at the 95% confidence level.

1.1. The Standard Model

The discoveries made in physics have resulted in remarkable insight into the fundamental structure of matter. Almost everything found in the Universe, e.g. normal matter, is made up from twelve fundamental particles and governed by four fundamental forces (or interactions). The effort of thousands of theoretical and experimental physicists has gone into understanding how these twelve particles interact with three of the four forces. The result of all our knowledge is encapsulated in the Standard Model of particle physics. The Standard Model was developed during the 1960s by Sheldon Glashow, Steven Weinberg, and Abdus Salam. It is also perhaps the best-tested and well-established physics theory verified by many experiments, which have resulted in many discoveries that provide explanations for a wide variety of phenomena.

1.1.1. Particles

Everything is made up of particles, including light, and all of the fundamental particles that we know of can be categorized into two types - leptons and quarks. The groups of leptons and quarks each contain six fundamental particles (twelve in total) which are grouped into three pairs called generations. All matter in the universe is made up of particles in the first generation which contains the lightest and
most stable particles. Matter made from particles belonging to the second and third
generations (heavier in mass and less stable) decay to the next most stable level. The
leptons are grouped into three pairs of charged leptons (electrons, muons, and taus)
and the corresponding neutral neutrinos are carrying the same flavor of the charged
lepton. Electrons, muons, and taus have mass, while their neutrino counterparts
have negligibly small mass. Quarks can also be paired into three generations: up and
down; charm and strange; top and bottom. The twelve fundamental particles of the
Standard Model are neatly summarized in Figure 1.1. 

Figure 1.1. The Standard Model of elementary particles: the twelve fundamental
fermions and four fundamental bosons.
1.1.2. Forces

The four fundamental forces recognized today are: the strong force, the weak force, the electromagnetic force, and the gravitational force. The effects of the first three are described by the exchange of force-carrying particles, which belong to another group named bosons (i.e., particles with integer spin). Quarks and leptons are particles with half-integer spin. Bosons, the carriers of the forces, are 8 gluons for strong interactions, \( W^\pm \) or \( Z \) bosons for weak interactions, and a \( \gamma \) (photon) for electromagnetic interactions. Gluons keep quarks together inside protons, neutrons and other particles and a residual strong force keeps protons and neutrons inside nuclei, which provides stability in the atomic nucleus. \( W \) and \( Z \) bosons mediate the weak force, making it possible for the sun to shine. The photon (\( \gamma \)) mediates the electromagnetic force; we use it everyday, while watching TV, using cellphones, playing computer games, and more.

The strong force, as its name implies, is the strongest and works at the subnuclear range. The weak force, despite its name, is not the weakest force (it is stronger than gravity) and it also works at subnuclear range. The electromagnetic force is many times stronger than gravity by a factor of about \( 10^{38} \) and works at an infinite range. The gravitational force is the weakest force, works at an infinite range and is perhaps the most commonly known force out of the four. Its special feature is that it is always attractive while, for instance electromagnetism can be also repulsive.

Particles exchange energy by exchanging bosons with each other and each fundamental force has its own corresponding particle. There are bosons that are not carriers for the fundamental forces, e.g., the B meson is composite and not fundamental. There are four fundamental known bosons right now, belonging to three forces (c.f. Figure 1.1). The fourth fundamental force is said to be mediated by the graviton which has yet to be discovered.
Although the Standard Model is currently the best description of particles and their interactions, not everything is explained. In particular, the most popular explanation for the mass of particles requires the existence of a theoretically defined, neutrally charged Higgs boson, a material component of the Higgs mechanism. The Higgs has not been seen so far and its existence is the key to understanding the origin of particle mass. This dissertation will describe the search for the Standard Model Higgs boson decaying to four leptons. The search is based on data collected by the ATLAS (A Toroidal LHC ApparatuS) experiment at the Large Hadron Collider (LHC) at CERN (the European Organization for Nuclear Research) in Geneva, Switzerland.
Chapter 2

THE HIGGS MECHANISM

The Higgs mechanism was developed in 1964 by Peter Higgs [5] and independently by Robert Brout and Francois Englert [6], and Gerald Guralnik, C. R. Hagen, and Tom Kibble [7], who worked out the results by the spring of 1963 [8]. Conceptually, the Higgs mechanism is a process that gives mass to all of the elementary particles; these particles gain mass by interacting with the Higgs field that permeates all space. A theoretical overview of the Higgs mechanism is presented in this chapter.

2.1. Spontaneous Symmetry Breaking

The way to generate the mass of a particle is done by spontaneous symmetry breaking. If we consider a simple Lagrangian consisting of only scalar particles, we have [9]

\[ L = \frac{1}{2} \left( \partial_{\mu} \phi \right)^2 - \left( \frac{1}{2} \mu^2 \phi^2 + \frac{1}{2} \lambda \phi^4 \right), \quad \text{where } \lambda > 0. \]  

(2.1)

The components of our Lagrangian are defined as follows:

- \( \mathcal{L} \) - the Lagrangian, a function that summarizes the dynamics of a system;
- \( T \) - the kinetic energy of a system;
- \( V \) - the potential energy of a system;
- \( \phi \) - a self-interacting field;
- \( \mu \) - the corresponding mass term for field \( \phi \);
- \( \lambda \) - the coupling factor;
Here, our Lagrangian is required to follow symmetry operations where $\phi$ is replaced by $-\phi$. In general, there are two possible solutions for the potential $V$, which is a function of $\phi$, as illustrated in Figure 2.1. The cases can be explained in the following way:

1. $\mu^2 > 0$ describes a scalar field with mass $\mu$. $\phi$ is a self-interacting field with coupling $\lambda$ (as shown by the $\phi^4$ term). The ground state vacuum expectation value here is $\phi = 0$; satisfying reflection symmetry.

2. $\mu^2 < 0$ describes a more interesting case. Here, the mass term has the wrong sign for $\phi$, since the relative sign between the kinetic and potential energy is now positive.

The potential has two minima which satisfy (2.1). The solutions to equation 2.1 are $\phi = 0$ and $\phi = \pm \sqrt{\mu^2/\lambda}$. $\phi = 0$ does not correspond to an energy minimum, so the two minima are:

$$\phi = \pm v, \text{ where } v = \sqrt{\mu^2/\lambda}. \quad (2.2)$$

Perturbative expansion about the minimum allow us to write $\phi$ in the following manner:

$$\phi(x) = v + \eta(x), \quad (2.3)$$

where $\eta(x)$ represents quantum fluctuations and the field has been translated to $\phi = +v$. $\phi = -v$ is easily achieved through reflection symmetry.

After substituting (2.3) into (2.1), we have a Lagrangian written as:

$$\mathcal{L} = \frac{1}{2} (\partial_{\mu} \eta)^2 - \lambda v^2 \eta^2 - \lambda v^3 \eta^3 - \frac{1}{4} \lambda \eta^4 + \text{const.} \quad (2.4)$$

Now the mass term of the field $\eta$ has a correct sign, so

$$m_\eta = \sqrt{2\lambda v^2} = \sqrt{-2\mu^2}, \text{ where } \lambda = -1. \quad (2.5)$$
Figure 2.1. Potential $V(\phi) = \frac{1}{2} \mu^2 \phi^2 + \frac{1}{4} \lambda \phi^4$ for $\mu^2 > 0$, and for $\mu^2 < 0$ where $\lambda > 0$ in both cases.

The higher order terms ($\eta^3$ and $\eta^4$) correspond to the self-interactions in $\eta$, similar to $\phi^4$ in (2.1). This new Lagrangian gives us an accurate picture of the physics for scalar particles. It now has a mass term because of the way it was generated, i.e. $\phi$ was expanded as a function of $\eta$ around the $\phi = +v$.

Spontaneous symmetry breaking corresponds to our choice in selecting the ground state $\phi = +v$. In physics, spontaneous symmetry breaking occurs when a system belonging to a particular symmetry group goes into a vacuum state that is not symmetric. Let us now look at the spontaneous breaking of a global gauge symmetry.

2.2. Spontaneous Symmetry Breaking of Global Gauge Symmetry

Our ultimate goal is to describe a Lagrangian for which the mass of gauge bosons can be generated. Repeating the above procedure for a complex scalar field $\phi = \frac{1}{\sqrt{2}} (\phi_1 + i\phi_2)$, which is invariant under the phase transformation $\phi \rightarrow e^{i\alpha} \phi$, the La-
The Lagrangian is:

\[ \mathcal{L} = (\partial_\mu \phi)^* \partial^\mu \phi - \mu^2 \phi^* \phi - \lambda (\phi^* \phi). \]  

(2.6)

By substituting the field \( \phi = \frac{1}{\sqrt{2}} (\phi_1 + i\phi_2) \) into (2.6), we obtain

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu \phi_1)^2 + \frac{1}{2} (\partial_\mu \phi_2)^2 - \frac{1}{2} \mu^2 (\phi_1^2 + \phi_2^2). \]  

(2.7)

After minimizing the potential, we can look at the cases \( \lambda > 0, \mu^2 < 0 \). The minima for \( v(\phi) \) exist in a plane \( \phi_1, \phi_2 \), with radius \( v \) (shown in Figure 2.2), such that

\[ v^2 = \phi_1^2 + \phi_2^2, \quad \text{where} \quad v^2 = -\frac{\mu^2}{\lambda^2}. \]  

(2.8)

Equation (2.8) translates \( \phi \) to a minimum energy position. For example, by setting \( \phi_1 = v \) and \( \phi_2 = 0 \), we may expand the Lagrangian about the vacuum in terms of the two fields \( \eta \) and \( \xi \).

\[ \phi(x) = \sqrt{\frac{1}{2}} [v + \eta(x) + i\xi(x)]. \]  

(2.9)

Substituting (2.9) into (2.6):

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu \xi)^2 + \frac{1}{2} (\partial_\mu \eta)^2 + \mu^2 \eta^2 + \text{const.} + \text{higher order terms in } \eta, \xi. \]  

(2.10)

The third term in this Lagrangian has the form of a mass term for \( \eta \) with a mass of \( m_\eta = \sqrt{-2\mu^2} \); this is similar to the scalar particle case. As for \( \xi \), there is no apparent mass term, but theory classifies it as a massless scalar-Goldstone boson. Goldstone bosons, also known as Nambu-Goldstone bosons [10–12], are bosons that appear in modes which exhibit spontaneous symmetry breaking.

### 2.3. The Higgs Mechanism

Now, we can look at the spontaneous breaking of local gauge symmetry. First, we must make the Lagrangian invariant under \( U(1) \) gauge transformations in \( \phi \). This
Figure 2.2. The potential $V(\phi)$ for a complex-scalar field, for $\mu^2 > 0$ and $\mu^2 < 0$, where $\lambda > 0$ in both cases.

is done by transforming $\phi \rightarrow e^{i\alpha(x)}\phi$ and replacing $\partial_\mu$ with a covariant derivative, $D_\mu = \partial_\mu - ieA_\mu$. The gauge field $A_\mu$ transforms as $A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu \alpha$. $A_\mu$ couples to the Dirac particle charge - $e$. Our Lagrangian can now be written as

$$L = \left( \partial_\mu + ieA_\mu \right) \phi^* \left( \partial_\mu + ieA_\mu \right) \phi - \mu^2 \phi^* \phi - \lambda (\phi^* \phi)^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}. \quad (2.11)$$

Looking again at the $\mu^2 < 0$ case and substituting (2.9) in (2.11):

$$L = \frac{1}{2} (\partial_\mu \xi)^2 + \frac{1}{2} (\partial_\mu \eta)^2 - v^2 \lambda \eta^2 + \frac{1}{2} e^2 v^2 A_\mu A^\mu - evA_\mu \partial_\mu \xi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ \text{interaction terms} , \text{ where } v = \pm \sqrt{\frac{\mu^2}{\lambda}} \quad (2.12)$$

We have a massless Goldstone boson $\xi$, a massive scalar $\eta$, and a massive vector $A_\mu$ with the following masses: $m_\xi = 0$, $m_\eta = \sqrt{2\lambda v^2}$, $m_A = ev$.

By having generated a mass for the gauge field, we still have a problem with the occurrence of a massless Goldstone boson. By simply giving mass to $A_\mu$, we have
raised the number of degrees of freedom from 2 to 3, requiring that we deduce that all the fields must not correspond to distinct particles.

Approximating $\phi$ to lowest order in $\xi$,

$$\phi = \sqrt{\frac{1}{2} [v + \eta + i\xi]} \approx \sqrt{\frac{1}{2} (v + \eta)} e^{i\xi/v}$$  \hspace{1cm} (2.13)

and substituting different fields $h, \theta, A_\mu$, where $h$ is real;

$$\phi \rightarrow \sqrt{\frac{1}{2} (v + h(x))} e^{i\theta(x)/v}$$

$$A_\mu \rightarrow A_\mu + \frac{1}{ev} \partial_\mu \theta$$  \hspace{1cm} (2.14)

Our Lagrangian has the following form:

$$\mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - \lambda v^2 h^2 + \frac{1}{2} e^2 v^2 A_\mu^2 - \lambda v h^3 - \frac{1}{4} \lambda h^4$$

$$+ \frac{1}{2} e^2 A_\mu^2 h^2 + ve^2 A_\mu^2 h - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$  \hspace{1cm} (2.15)

The Goldstone boson does not appear in the equation and the extra degree of freedom corresponds to the ability to make gauge transformations. The Lagrangian describes two interactive massive particles $A_\mu$ and $h$. $A_\mu$ is a vector gauge boson and $h$ is a massive scalar known as the Higgs particle. With this set of substitutions, the Goldstone boson now represents a longitudinal polarization for the massive gauge boson; this is known as the Higgs Mechanism.

### 2.4. The Higgs Field

From Quantum ElectroDynamics (QED), we know that electromagnetic amplitudes are calculated with the following interaction:

$$-ie j^em_\mu A^\mu = -ie (\bar{\psi} \gamma_\mu Q \psi) A^\mu \hspace{1cm} SU(1)_{em},$$  \hspace{1cm} (2.16)

$j^em_\mu$ is the transition current, $A^\mu$ - an electromagnetic field, $\psi$ - the amplitude of a scattering state, $\gamma_\mu$ - spin, $Q$ - the charge operator, and $e$ the charge.
In order to include weak processes in the formalism, we must replace (2.16) with an iso-triplet of weak current $J$ coupled to three vector bosons $W^\mu$.

$$-ig J_\mu \cdot W^\mu = -ig \bar{\chi}_L \gamma_\mu T \cdot W^\mu \chi_L \quad SU(2)_L, \tag{2.17}$$

and a weak hypercharge current couple to a four-vector $B^\mu$,

$$-ig' Y B^\mu = -ig' \bar{\psi} \gamma_\mu \frac{Y}{2} \psi B^\mu \quad U(1)_Y, \tag{2.18}$$

The operators $T$ and $Y$ are generators of $SU(2)$ and $U(1)_Y$ group of gauge transformations. Together, $SU(2) \times U(1)_Y$, the left and right hand components of $\psi$ are

$$\chi_L \rightarrow \chi'_L = e^{\alpha(x)T + i\beta(x)Y} \chi_L,$$

$$\psi_R \rightarrow \psi'_R = e^{i\beta(x)Y} \psi_R. \tag{2.19}$$

The electromagnetic interaction of (2.16) is embedded in both (2.17) and (2.18). The three groups satisfy $Q = T^3 + \frac{1}{2}$, such that $j^{em}_\mu = J^3_\mu + \frac{1}{2} j^Y_\mu$. This means that the two neutral currents $J^3_\mu$ and $j^Y_\mu$ combine to make the electromagnetic current. Therefore, $A_\mu$ and $Z_\mu$ are orthogonal combinations of the gauge fields $W^3_\mu$ and $B_\mu$, with a mixing angle $\theta_W$.

The neutral current sector can be rewritten, after some work, as

$$-igJ^3_\mu W^3_\mu - ig' j^Y_\mu B^\mu = -i \left[ g \sin \theta_W J^3_\mu + g' \cos \theta_W \frac{j^Y_\mu}{2} \right] A^\mu$$

$$-i \left[ g \cos \theta_W J^3_\mu - g' \sin \theta_W \frac{j^Y_\mu}{2} \right] Z^\mu \tag{2.20}$$

$$= -iej^{em}_\mu A^\mu - \frac{ie}{\sin \theta_W \cos \theta_W} \left[ J^3_\mu - \sin^2 \theta_W j^{em}_\mu \right] Z^\mu,$$

with the electromagnetic interaction specified on the right. The weak neutral interaction is specified and fixed the couplings $g$ and $g'$ to $e$ and $\theta_W$,

$$e = g \sin \theta_W = g' \cos \theta_W. \tag{2.21}$$
We can reformulate the Higgs Mechanism from $U(1)$ to $SU(2) \times U(1)$ and retrieve a massless photon and massive bosons $W^\pm, Z^0$. We may first start by arranging four fields in an isospin doublet with weak hypercharge $Y = 1$.

\[
\phi = \begin{pmatrix}
\phi^+ \\
\phi^-
\end{pmatrix}, \quad \text{where} \quad \phi^+ \equiv (\phi_1 + i\phi_2)/\sqrt{2}, \\
\phi^- \equiv (\phi_3 + i\phi_4)/\sqrt{2}.
\]

(2.22)

This was the choice made by Weinberg in 1967. It is known as the Glashow-Weinberg-Salam model and completes the specification of the standard model of weak interactions. To generate gauge bosons, we use the usual Higgs potential $V(\phi)$ with the normal assumptions $\lambda > 0$ and $\mu^2 < 0$. The vacuum expectation value is $\phi_0$,

\[
\phi_0 \equiv \sqrt{\frac{1}{2}} \begin{pmatrix}
0 \\
v
\end{pmatrix}
\]

(2.23)

corresponding to $\phi_1 = \phi_2 = \phi_4$ and $\phi_3 = v$. Expanding the doublet, we have

\[
\phi(x) = \sqrt{\frac{1}{2}} \begin{pmatrix}
0 \\
v + h(x)
\end{pmatrix}
\]

(2.24)

Substituting $\phi_0$ into the appropriate Lagrangian, the relevant terms are

\[
\left| \left( -i g^2 \frac{\tau^7}{2} \cdot W_\mu - ig' B_\mu \right) \phi \right|^2 \\
= \frac{1}{8} \left| \begin{pmatrix}
gW^3_\mu + g' B_\mu \\
g (W^1_\mu + iW^2_\mu) - gW^3_\mu + g' B_\mu 
\end{pmatrix} \begin{pmatrix}
0 \\
v
\end{pmatrix} \right|^2 \\
= \frac{1}{8} v^2 g^2 \left( (W^1_\mu)^2 + (W^2_\mu)^2 \right) + \frac{1}{8} v^2 \left( g' B_\mu - gW^3_\mu \right) \left( g' B^\mu - gW^3_\mu \right) \\
= \left( \frac{1}{2} vg \right)^2 W^+ W^- + \frac{1}{8} v^2 (W^3_\mu, B_\mu) \begin{pmatrix}
g^2 & -gg' \\
-gg' & g'^2
\end{pmatrix} \begin{pmatrix}
W^3_\mu \\
B^\mu
\end{pmatrix}
\]

(2.25)

where $W^\pm = (W^1 \mp iW^2)/\sqrt{2}$. Comparing the first term to that of a charged boson $M_W^2 W^+ W^-$,

\[
M_W = \frac{1}{2} vg.
\]

(2.26)
The remaining term is off-diagonal in the $W^2_\mu$ and $B_\mu$ basis:

$$\frac{1}{8}v^2 \left[ g^2 \left( W^3_\mu \right)^2 - 2gg'W^3_\mu B^\mu + g'^2B^2_\mu \right] = \frac{1}{8}v^2 \left[ gW^3_\mu - g'B^\mu \right]^2$$

$$+ 0 \left[ g'W^3_\mu + gB^\mu \right]^2$$

(2.27)

Referring back to (2.17), one of the eigenvalues of the $2 \times 2$ matrix is zero and is included in (2.27) for completion. The physical fields $Z_\mu$ and $A_\mu$ diagonalize the mass matrix in (2.25) so (2.26) is identified with the appropriate mass terms $\frac{1}{2}M^2_ZZ^\mu_\mu + \frac{1}{2}M^2_AA^\mu_\mu$. After normalizing the fields, we are left with

$$A_\mu = \frac{g'W^3_\mu + gB^\mu}{\sqrt{g^2 + g'^2}} \quad \text{with } M_A = 0$$

(2.28)

$$Z_\mu = \frac{g'W^3_\mu - gB^\mu}{\sqrt{g^2 + g'^2}} \quad \text{with } M_Z = \frac{1}{2}v\sqrt{g^2 + g'^2}.$$  

(2.29)

Following (2.21), we get

$$\frac{g}{g'} = \tan \theta_W, \text{ where } \theta_W \text{ is the Weinberg angle.}$$  

(2.30)

Allowing for us to rewrite (2.28) and (2.29) as

$$A_\mu = \cos \theta_W B^\mu + \sin \theta_W W^3_\mu,$$

$$Z_\mu = -\sin \theta_W B^\mu + \cos \theta_W W^3_\mu,$$

(2.31)

and after combining (2.26) and (2.28), we have

$$\frac{M_W}{M_Z} = \cos \theta_W.$$  

(2.32)

This relation comes out of the fact that there is a mixing between the $W^3_\mu$ and $B_\mu$ fields. The mass eigenstates are now a massless photon and a massive $Z_\mu$ field with $M_Z > M_W$. To summarize the standard Weinberg-Salam model, the final and
The complete Lagrangian is:

\[ \mathcal{L} = -\frac{1}{4} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \]

\[ + L^\gamma \mu \left( i \partial_\mu - g_1 \frac{1}{2} \tau \cdot W_\mu - g' \frac{1}{2} B_\mu \right) L \]

\[ + \bar{R}^\gamma \mu \left( i \partial_\mu - g' \frac{1}{2} B_\mu \right) R \]

\[ + \left| \left( i \partial_\mu - g_1 \frac{1}{2} \tau \cdot W_\mu - g' \frac{1}{2} B_\mu \right) \phi \right|^2 - V(\phi) \]

\[ - \left( G_1 \bar{L} \phi R + G_2 \bar{L} \phi C R + \text{hermitian conjugate} \right) . \]

(2.33)

Here, \( L \) denotes a left-handed fermion (lepton or quark) doublet, \( R \) denotes a right-handed fermion singlet, \( G \) denotes the weak coupling constant.
Chapter 3
CERN AND THE LARGE HADRON COLLIDER

An overview of the particle physics laboratory – CERN – and its main particle accelerator – the LHC – is presented in this chapter.

3.1. CERN

The European Council for Nuclear Research (French: Conseil Européen pour la Recherche Nucléaire (CERN)) was founded as a provisional body in 1952 with the mandate of establishing a world-class fundamental physics research organization in Europe. At the time, physics research primarily focused on understanding what was inside of an atom, hence the use of the word “nuclear.” In 1954, the organization was born and the council was dissolved. The new organization was given the title European Organization for Nuclear Research while retaining the acronym, CERN. CERN’s main function is to provide the particle accelerators and related infrastructures needed for high-energy physics research. The laboratory, which is located near Geneva, Switzerland, employs approximately 2,400 full-time employees and services some 8,000 scientists and engineers representing more than 600 universities and research institutions and more than 110 nationalities [13]. Figure 3.1 indicates the location of the variety of experiments at CERN.

3.2. LHC

The Large Hadron Collider (LHC) is a circular particle accelerator used by physicists to study the smallest known particles. It has a circumference of 27 km and is
located about 100 m beneath the ground. The LHC currently circulates two beams of either protons or lead ions – traveling in opposite directions inside the accelerator, gaining energy with every lap. In 2011, each beam achieved an energy of 3.5 TeV\(^1\) before colliding; for 2012, the beams are expected reach an energy of 4 TeV before colliding. The LHC is currently the home of seven particle physics experiments (of which, the first four are illustrated in Figure 3.1):

\(^{1}\)In physics, the electron volt (eV) is a unit of energy equal to approximately \(1.602 \times 10^{19}\) joule (J). The prefix T is the common SI prefix “tera”, i.e., trillion - \(10^{12}\).
- A Toroidal LHC ApparatuS (ATLAS) [14]:
  
  – The ATLAS experiment, one of two general-purpose detectors at the LHC, is described in Chapter 4.

- Compact Muon Solenoid (CMS) [15]:
  
  – The CMS experiment is one of two general-purpose detectors at the LHC. It is complementary to ATLAS in its hardware design and physics goals, e.g. Higgs physics, supersymmetry, and heavy ion collisions.

- Large Hadron Collider beauty (LHCb) [16]:
  
  – The LHCb experiment specializes in studying the decay of B-mesons (b(eauty) and anti-b quarks). In proton-proton collisions, B mesons and their associated decay products stay close to the beam pipeline, and this is reflected in the design of the detector.

- A Large Ion Collision Experiment (ALICE) [17]:
  
  – The ALICE experiment is designed to study heavy ion collisions of lead nuclei. The collisions studied by this experiment are taken near the end of year, during which time the LHC accelerates each nucleon at a centre of mass energy of 2.76 TeV. The main goal of ALICE is to study the properties of quark-gluon plasma. Quark-gluon plasma occurs in conditions of high temperature and energy density, for which quarks and gluons are no longer bound inside a hadron.

- TOTal Elastic and diffractive cross section Measurement (TOTEM) [18]:
  
  – The TOTEM experiment is designed with forward physics in mind (near the beam pipeline) and to precisely measure the total proton-proton interaction cross section as well as study elastic scattering and diffractive
processes. TOTEM is a small detector, split in three parts (two telescopes based on gas electron multiplier technology and Roman pots - designed to intercept particles that are very close to the beam pipeline) which are located on each side of CMS.

- Large Hadron Collider forward (LHCf) [19]:
  
  – The LHCf experiment is also designed with forward physics in mind and is the smallest detector at the LHC (measuring a mere 30 cm in width). It is designed to measure the energy and number of $\pi^0$ (neutral pions) produced by the collider as well as compare data from the LHC with various shower models to hopefully explain the origin of ultra-high-energy cosmic rays.

- Monopole and Exotics Detector At the LHC (MoEDAL) [20]:
  
  – The MoEDAL experiment is the newest experiment on the LHC, sanctioned in May 2010 and deployed January 2011. The MoEDAL experiment aims to search for the magnetic monopole and other highly ionizing stable massive particles at the LHC. It is situated at the interaction point for LHCb.

With increasing collision energies and unprecedented, large delivered luminosities\(^2\) (further explained in Section 4.11), physicists working on experiments at the LHC can continue testing fundamental concepts in the Standard Model as well as explore new and exciting physics.

\(^2\)Luminosity is the number of particles per unit area per unit time times the opacity of the target, usually units cm\(^{-2}\)s\(^{-1}\) or b\(^{-1}\) s\(^{-1}\), where b is the unit barn. The integrated luminosity is the integral of the luminosity with respect to time.
Chapter 4

ATLAS

In this chapter, the ATLAS experiment is described, followed by an overview of: event simulation and reconstruction, lepton reconstruction, and luminosity.

4.1. General Description

The design of the ATLAS detector [21] (Figure 4.1) allows physicists to study and search for a wide range of physics phenomena at the LHC including Higgs boson, supersymmetry, extra dimensions, magnetic monopoles, and heavy ion collisions.

Figure 4.1. The ATLAS Experiment.
The experimental hardware can be separated into four sets of systems. The inner tracking detector provides tracking up to a pseudorapidity$^{1}$ of 2.5, a calorimeter system with $|\eta|$ coverage up to 4.9, and a muon spectrometer, which provides $|\eta|$ coverage up to 2.7. In addition to these sub-detectors, there is the magnet system which consists of a large solenoid and toroid magnet to provide muon tracking and identification and an extensive systems of readout electronics and computers provide a trigger and on-detector preliminary signal processing. ATLAS is currently the largest and most complex detector ever built and also houses the largest superconducting magnet ever built$^{22}$. It is 44 m long, 25 m wide and 25 m high and weighs approximately 7,000 tonnes. An extensive and detailed description of the ATLAS detector can be found in References$^{23, 24}$.

4.2. Coordinate System

ATLAS uses a right-handed coordinate system with the x-axis pointing to the center of the LHC ring, the z-axis follows the beam direction, and the y-axis points upwards (illustrated in Figure 4.2). The azimuthal angle $\phi$ corresponds to the angle between the x-axis and the y-axis. The polar angle $\theta$ is measured from the x-axis and z axis. Pseudorapidity, $\eta$, is parameterization of the polar angle and is defined as $\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$. The transverse energy, $E_T$, (or momentum, $p_T$) is defined as the energy (or momentum) perpendicular to the z-axis.

---

$^1$Pseudorapidity is defined as $\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$, where $\theta$ is the polar angle, measured from the beam pipe (the z-axis of the experimental coordinate system).
4.3. Particle Identification

The design of the ATLAS detector allows it to “see” particles; illustrated in Figure 4.2. Muons are weakly interacting charged particles that will pass through the entire detector, leaving tracks in the inner tracking detector and muon spectrometer and small energy deposits in the electromagnetic and hadronic calorimeters. Photons and electrons are electromagnetically interacting particles that will pass through inner tracking detector and will deposit their energy in the electromagnetic calorimeter; only electrons will leave tracks. Protons and neutrons will deposit most of their energy in the hadronic calorimeter, yet only protons will leave tracks in the inner tracking detector and small amounts of energy electromagnetic calorimeter. Lastly,
neutrinos are invisible to the detector, but are represented by missing energy\textsuperscript{2}.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{atlas_detector.png}
\caption{Particle identification with the ATLAS experiment.}
\end{figure}

\textsuperscript{2}Missing energy refers to the energy of particles that are not detected but can be calculated from the conservation laws of energy and momentum.
4.4. Magnet Systems

The ATLAS detector uses two large superconducting magnet systems. Under the influence of a magnetic field, charged particle trajectories bend in such a way that their momenta can be measured. Bending is due to the Lorentz force (proportional to velocity). The amount of curvature a particle’s trajectory undergoes in a magnetic field is directly related to its momentum. Particles produced with velocities near the speed of light\(^3\) (i.e., with high-momenta) curve very little while the low-momenta particles have a high curvature trajectory.

The solenoidal magnet surrounding the ID generates a 2 T (Tesla) magnetic field, which allows highly energetic particles up to 1 TeV to curve enough for their momentum to be determined. The shape of the magnetic field is nearly uniform in axial direction and its strength has been mapped allowing for precise measurements.

The second magnet system is comprised of superconducting air-core toroids situated outside and around the calorimeters and in the middle of the muon spectrometer. There are eight coils 26 m long, 19.5 m in diameter with an inner bore of 9.4 m situated symmetrically along the longitudinal axis of the detector and store \(\sim 1.6 \text{ GJ}\) of energy. Additionally, there are two end-cap magnets, 5.6 m in length with an inner bore of 1.26 m situated on the outside of each barrel of the calorimeter.

\(^3\)In its original design, protons would travel with an energy of 7 TeV, which corresponds to a speed of 99.9999991\(\%\)c, where c, the speed of light, is 299,792,458 m/s.

\(^4\)1 gigajoule (GJ) of energy will keep a 60-watt lightbulb continuously lit for 6 months. It will also melt 1 ton of steel!
4.5. Inner Detector

The Inner Detector (ID) of ATLAS is designed to provide measurements of charged particle trajectories with high momentum resolution and vertex (an intersection of multiple tracks) measurement in high-multiplicity track environments. It is composed of three sub-detectors, shown in Figure 4.4. Starting from the interaction point inside the LHC beam pipe, a track has to pass through:

- The Silicon Pixel (Pixel) detector – mainly used for accurate vertex measurement [25].
- The Semi-Conductor Tracker (SCT) – provides precise measurement of particle momenta [26].
- The Transition Radiation Tracker (TRT) – uses fractions of energy deposition along the x-axis, i.e. dE/dx, to ease pattern recognition; used in electron identification [27].

Figure 4.4. The Inner Detector of the ATLAS Experiment.
4.6. Calorimetry

High precision, high sensitivity, and high granularity calorimeters provide precise measurement of electrons and photons characterized by electromagnetic interactions in the ATLAS detector. The calorimeters are used to measure precisely the energy absorption and conversion of a particle’s energy into an electromagnetic shower. The ATLAS Liquid Argon (LAr) calorimeter (the main calorimeter used for electrons and muons in $H \to ZZ^{(*)} \to 4\ell$ studies) measures the energy of charged and neutral particles. It is illustrated in Figure 4.5. It consists of an electromagnetic barrel (EMB) calorimeter - which incorporates a presampler (PS) - an electromagnetic end-cap calorimeter (EMEC), hadronic end-cap calorimeter (HEC) and forward calorimeter (FCal). Information on the Tile hadronic Calorimeter and Zero Degree Calorimeter can be read here [28] and [29], respectively.

Figure 4.5. The Liquid Argon and Tile Calorimeters of the ATLAS Experiment.
4.6.1. Electromagnetic Calorimeter

The LAr electromagnetic calorimeter uses liquid argon as an active medium and lead as the absorber. It is highly segmented, both in \( \eta \), the azimuthal angle \( \phi \) (the angle between the x-axis and y-axis), and in depth and provides about 220,000 readout channels. The accordion-shape geometry allows full azimuthal coverage with no cracks and coverage in \(|\eta|\) up to 3.2. This unique geometry provides a signal sampling rate that is independent of the particle incident angle. The choice of LAr as the active medium was based on the need for radiation hardness and for its fast and uniform response. There are 3 layers in the EMB calorimeter after the presampler, shown in Figure 4.6. The first layer is very finely segmented in order to provide excellent position resolution, which is necessary for good invariant mass resolution of electromagnetic final states, as well as \( \gamma - \pi^0 \) separation. A similar accordion-shape geometry was used for the EMEC. It consists of two concentric wheels: an outer wheel which provides coverage up to \(|\eta| < 2.5\) with three longitudinal samplings and the inner wheel which provides two samplings out to \(|\eta| < 3.2\). An end-cap presampler provides coverage for \(|\eta| < 1.8\).
4.6.2. Hadronic Calorimeter

In the HEC, the absorber is copper. Each HEC is composed of two wheels with 32 wedge-shaped modules and has four layers arranged in a more conventional parallel-plate structure. Overall, the coverage provided by the HEC is $1.5 < |\eta| < 3.2$. An illustration of the HEC is shown in Figure 4.7.
4.6.3. Forward Calorimeter

The FCal, situated inside the HEC, provides coverage for $3.1 < \eta < 4.9$ and consists of three disk-shaped modules, with copper absorber for one electromagnetic layer and tungsten for two hadronic layers. An illustration of the FCal is shown in Figure 4.7.

4.6.4. Calibration Runs

The translation of the electrical signals for the detector into the energy deposited by a particle requires several constants. Calibration runs are used by the Liquid Argon (LAr) Calorimeter to calculate constants for the signal amplitude (in MeV),
timing and quality factor [24, 30]. These constants are used in energy calibration and correction. They are monitored regularly and updated when necessary, between ATLAS runs. These constants are made from the reconstruction and analysis of three types of calibration runs:

- Pedestal Runs
  - Pedestal runs provide: pedestal information from the average, noise from the RMS, and noise autocorrection from timing correlation of samples. The run collects data from the detector when no input signal is given.

- Ramp Runs:
  - During a ramp run, different input current signals (DAC\textsuperscript{5}) are injected. The gain slope of these currents are extracted from a fit of the DAC versus ADC\textsuperscript{6} curve and used in energy reconstruction.

- Delay Runs:
  - For a delay run, a single injected calibration pulse is shifted by steps of 1.04 ns to reconstruct the pulse shape.

Calibration runs for the LAr calorimeter were taken using the LAr Shifter Panel, described in Appendix A. Monitoring of the temperature of crates is done with the use of the LAr Crates Panel, described in Appendix B. These two panels were developed by the author as contributions to experiment and detector.

\textsuperscript{5}Digital-to-analog converter.
\textsuperscript{6}Analog-to-digital converter.
4.7. Muon Spectrometer

For the high quality measurement of muons, ATLAS employs the use of three large air-core superconducting toroids, tracking chambers (for precise momentum resolution), and an efficient trigger system (based on wire chambers). Figure 4.8 illustrates the entire Muon Spectrometer (MS), which spans the entirety of the detector.

Figure 4.8. The Muon System of the ATLAS Experiment.
4.7.1. Resistive Plate Chambers

Resistive Plate Chambers (RPCs) are used in the barrel and consist of two gas volumes, Bakelite plates, and four planes of read-out strips. Two layers of chambers are installed in the middle station and provide triggering for the low-\(p_T\) threshold. A third layer is installed on the outer chamber station and is used (along with the other two layers) for high-\(p_T\) threshold triggering.

4.7.2. Thin Gap Chamber

The Thin Gap Chambers (TGCs) are Multi-Wire Proportional Chambers (MWPC) that operate in a saturated mode and provide L1 trigger information for muon triggers. Cathodes in the chamber are coated with graphite and external pickup strips provide the coordinate axis in each sensor-wire. The gas mixture in each chamber is 55% CO\(_2\) and 45% \(n\)-pentane\(^7\). There are three multi-layers of chambers located in the middle tracking station. Additional TGCs make up a part of the inner station and are used to increase tracking ability.

4.7.3. Muon Drift Tubes

The Muon Drift Tubes (MDTs) serve the purpose of precisely measuring muon momenta in almost all of the spectrometer. The MDTs are made up of aluminum tubes, varying in length from 0.9 m to 6.2 m, with a 3 cm diameter. Tubes are arranged in two multi-layers of three or four layers of tubes. The gas mixture in each tube is Ar-CO\(_2\) in a 93%-7% mixture, operated at 3 bar pressure with a gas gain of \(2 \times 10^4\). These conditions allow for the MDT to sustain high rates without aging. The \(n\)-pentane or normal pentane has the molecular formula C\(_5\)H\(_{12}\); it is used as a quencher in order to operate the chambers in a saturated mode, thus allowing for strong signals and high signal-to-noise ratios.
spatial resolution of a position measurement provided by a single tube is 100 µm and the resolution provided by a multi-layer is ∼50 µm.

4.7.4. Cathode Strip Chamber

The Cathode Strip Chambers (CSCs) are designed to provide high granularity in the inner station of the end-cap. A MWPC with strip readout is used in the CSC, where the sensing wire has a pitch of 2.54 mm and the readout strip has a pitch of 5.08 mm. The track resolution provided in the bending plane is 60 µm. 32 MWPCs are used in the CSC.

4.8. Trigger and Data Acquisition

The amount of data delivered by the LHC is very large and exceeds the recording capability by several orders of magnitude. In order to determine which events should be recorded, ATLAS has developed a complex trigger system. The bunch crossing (i.e., collision) frequency at the LHC is 20-40 MHz, depending on the bunch spacing. Selecting and storing event information at this speed presents quite challenge, necessitating an efficient trigger system. The designed recording ability of ATLAS is 300 Hz (six orders of magnitude smaller than the output from the LHC), but the trigger has been able to surpass this and achieve 350 Hz. There are three sets of ATLAS triggers used in the online event selection: Level 1 (L1), Level 2 (L2), and Event Filter (EF). An illustration of the online event selection chain is illustrated in Figure 4.9; more detailed information can be found in Reference [31].

4.8.1. Level 1 Trigger

The term “online” refers to the time in which the data is being collected. Its counterpart, offline, refers to the time after which the data has been collected and (re)processed.
The L1 trigger is hardware-based and selects events using energy thresholds of electrons, photons, muons, jets, missing energy, and other information coming from the calorimeters and muon detector. It receives the up-to 40 MHz bunch crossing rate from the LHC and must make a decision to keep or disregard the event within 2.5 $\mu$s; it reduces the incoming rate to $\sim$65 kHz.

4.8.2. Level 2 Trigger

The L2 trigger is software-based, processing only sub-regions (also known as regions of interest) of the detector that have been seeded by the L1 trigger. The decision time for this particular trigger is on the order of 10 ms and reduces the incoming rate to $\sim$5 kHz. Events that pass this stage of the decision process are partially reconstructed by an “Event Builder” and sent to the next level trigger.

4.8.3. Event Filter

The EF trigger is the last step in the online event selection, reducing the incoming rate from $\sim$5 kHz to $\sim$350 Hz. It is software-based and uses quasi-offline reconstruction algorithms for its decisions. The output of these event filters are the triggers typically used by physicists as a means to select events that are useful for their specific analyses. Thus, only events fulfilling specific criteria are recorded.
Figure 4.9. A simple overview of the Trigger system in the ATLAS Experiment.

4.9. Event Simulation, Reconstruction, and ATLAS Software

A general method of searching for new physics phenomena is to compare data with a simulation of known processes and looking for deviations. To make such comparisons precise, all known process are simulated using their best theoretical description available. The resulting final state particles in such simulations are then traced through the detector to generated simulated detector response. The resulting data are fed back to the event reconstruction program. In this way, any known detector effects is reproduced in simulation.
4.9.1. Monte Carlo

Monte Carlo (MC) methods (or experiments) are often used to simulate physical phenomena and/or mathematical systems. They are based on algorithms, which can be trivially simple or extremely complex, taking up many hundreds of thousands of lines of code. In particle physics, the underlying theoretical models for physics processes/phenomenal is crucial in defining analyses, developing ways to interpret the measurements of particle-properties, and developing ways to infer the existence of new physics. MC is based on the latest and most up-to-date models of physics from various experiments and can even be tuned to match what is seen in newer data at an experiment.

At the ATLAS experiment, the MC event simulation and reconstruction chain is based on a number of steps: Event Generation, Simulation, Digitization, and Reconstruction. The majority of this chain is done within the official ATLAS software infrastructure – ATHENA.

4.9.1.1. Event Generation

Event generation is the first step in the production chain. As perturbative methods are only applicable to fundamental constituents of theory (e.g. quarks and gluons), parton⁹-level events are the first thing generated in pp collision MC. Event generators are based on fundamental physical concepts and the ability to isolate independent phases of an overall collision (otherwise known as factorization). A pp collision can be factorized into a parton collision weighted by a number of parton distribution functions (PDFs). These PDFs are dependent on the fraction of momentum carried by each parton relative to its parent hadron. From a technical standpoint, an event

⁹The parton model was proposed by Richard Feynman in 1969 to analyze high-energy hadron collisions. The term partons refer to either real or virtual quarks or gluons.
generator is a computer program that models the physics processes that occur in collisions at high-energy physics experiments. The result of running an event generator is a list of particles (created, decay products, etc.), their momenta, their properties, and their origin.

4.9.1.2. Simulation

After the particles have been produced in the generation step, the next step is to determine how they interact with the detector. This step is crucial as it calculates the interaction of particles with the material and the energy deposition in each component of the detector. GEANT4 (Geometry and Tracking) is a toolkit developed to simulate the passage of particles through matter. It is commonly used in high-energy physics, but is used in other disciplines such as medical physics and space science. In order to use GEANT4, a detector model must be loaded into the simulation; this model is based on precision surveys and schematics of the ATLAS detector. In short, given a generated particle, GEANT4 will simulate how a particle travels through the detector, the detector response, signal gains, energy loss in dead regions, and so on.

4.9.1.3. Digitization

The digitization process is the easiest process describe conceptually – it is simply the step in which the analog information produced by simulation is converted into digital information formatted as it would have been measured in the detector.

4.9.1.4. Reconstruction

\footnote{Some sources prefer to use the abbreviation Geant over GEANT. In this vein, some sources prefer to define GEANT as Generation and Tracking, which is dependent on the age of the source, but is still acceptable.}
Conceptually, the reconstruction step is also simple, and arguably the most involved. Each of the detector signals produced in the simulation step is reconstructed via complex algorithms to produce particles (electrons, muons, photons, taus, etc.) with an established energy, momenta, position in $\theta$ and $\phi$, vertex, impact parameter, and more. During this step, MC and data are saved into the following file formats:

- Event Summary Data (ESD) – which has the most complete information on tracks, hits in the detector, and more. It is also the largest (in file size) format; accessible by the ATLAS software framework - ATHENA.

- Analysis Object Data (AOD) – a slimmer version of the ESD format, has less information, making it unsuitable for analyses in which standard particles are not used. This format is accessible by ATHENA and by the software analysis package ROOT.

- N-tuples – the most commonly used format that is slimmed to only contain what is needed in particle physics analyses. Users have the option of creating their own N-tuples from ESDs or AODs or using official N-tuples. In some cases, extra information is added or recalculations are added to minimize algorithms needed in the analysis. This is the smallest file format and can be reduced even more by stripping more information from the file. In general, file-size reduction is critical because ATLAS produces several Petabytes of data per year.

4.9.2. ATHENA

ATHENA can best be defined as a control framework implemented by the Gaudi architecture [33]. ATHENA provides common services like transient data storage, database access/usage, message streams, etc. for ATLAS all software.
4.9.3. **ROOT**

ROOT is the most commonly used tool used for data analysis on ATLAS and other particle physics experiments\[34]. It provides an object-oriented framework combined with a built-in C++ interpreter and other tools to handle various aspects of analyzing data sets (both small and large). The system was designed with parallelization\[11\] in mind, making it ideal in the constantly evolving technical environment of particle physics.

4.10. **Lepton Reconstruction in ATLAS**

Lepton reconstruction and identification in the ATLAS detector is important to most of the physics analyses; it is particularly important in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ searches where emphasis is placed on high reconstruction efficiency and on the identification purity while maintaining significantly high background\[12\] rejection rates. Efficiency refers to the ability to successfully reconstruct lepton candidates. On the other hand, purity (no fakes\[13\]) refers to the probability that a reconstructed lepton candidate is in fact a lepton.

4.10.1. **Electron Identification and Reconstruction**

An electron is a charged particle that leaves a reconstructed track in the tracking detector and deposits all of its energy in the electromagnetic calorimeter \[35\]. A particle is considered an electron if it meets the following basic selection criteria:

\[11\] The ability to run a program on multiple clusters of workstations or multi-core machines to reduce overall run-time.

\[12\] Background refers to objects, which exhibit leptonic signatures, while not being leptons themselves, e.g. jets.

\[13\] A fake is a reconstructed lepton candidate that has lepton-like characteristics, but is in fact not a lepton, i.e., pions as compared to electrons.
- The energy deposit in the Electromagnetic Calorimeter (EM) was identified as electron-like and had a matching track pointing to the corresponding region of the calorimeter. Track quality is based on the number of Pixel hits, SCT hits, and the impact parameter.

- Depending on the electromagnetic shower shape and the quality of the matching track, electrons were divided into inclusive qualities: \textit{Loose++}, \textit{Medium++} or \textit{Tight++}.

Electron quality essentially describes the purity and efficiency of reconstructing an actual electron. \textit{Tight++} represents the highest purity but lowest efficiency of the candidates selected and \textit{Loose++} corresponds to lower purity, but high efficiency. These qualities are available for electrons in the central tracking region, $|\eta| < 2.5$, and are based on what is known as the isEM variable (Appendix C), which consists of many shower shape, track and cluster-track matching requirements.

Electrons identified as \textit{Loose++} have requirements placed on: shower shape variables in the first and second calorimeter layer, hadronic leakage variables, track quality, and $\Delta\eta$ between the extrapolated track and the cluster. The \textit{Medium++} identification quality requires an additional b-layer\footnote{The b-layer is the innermost part of the Pixel detector; it is used to optimize the impact parameter resolution and is very important for b-jet tagging.} hit (if the module is not dead) and adds a cut on the impact parameter of the matched track and TRT high threshold hits ratio. The \textit{Tight++} quality has additional requirements on the ratio of energy measured in the calorimeter to the momentum measured in the inner tracking detector - $E/p$\footnote{The $E/p$ ratio is used to reject electrons with a large amount of bremsstrahlung radiation, which are less efficiently reconstructed.}. stricter cuts on $\Delta\phi$ between the extrapolated track and the cluster, the number of
TRT hits\textsuperscript{16} and for potential overlap with reconstructed photon conversions.

4.10.1.1. Bremsstrahlung and GSF Electrons

Bremsstrahlung comes from the German words \textit{bremsen} “to brake” and \textit{Strahlung} “radiation”, i.e., “braking radiation”. In this context, it is electromagnetic radiation produced by the deceleration of an electron when deflected by another charged particle (like another electron) or as it stops in matter. Electrons in ATLAS, typically lose 20% - 50% of their energy by the time they have passed the inner tracker \cite{31}. In order to correct for this phenomenon, ATLAS implemented an electron reconstruction algorithm using Gaussian-sum filters (GSF) \cite{36,38}. Energy loss is modeled in this algorithm by a weighted sum of Gaussians, which produces a probability density function describing the track parameters.

4.10.2. STAtistical COmbination (STACO) Muon Reconstruction and Identification

Muons are weakly interacting charged particles that can penetrate large amounts of material. In ATLAS, muons are the only particles that can pass though the electromagnetic and hadronic calorimeters and leave tracks both in the inner detector and in the outer muon chamber system. Thus, muon tracks are reconstructed in two segment areas of the detector: one is in the solenoidal and one in the toroidal magnetic field. In addition, muon leaves a characteristic narrow track in the calorimeter because they do not generate electromagnetic or hadronic showers. Muon reconstruction is based on the combined information from the calorimeters, muon spectrometer (MS), and inner tracking detector (ID) \cite{39,41}. They are categorized as follows:

\textsuperscript{16}The TRT offers substantial discriminating power between electrons and charged hadrons via the detection of X-rays produced by transition radiation. The number of hits in the TRT is used as a discriminant.
- Standalone muons – muons identified by tracks reconstructed in the MS alone.

- Combined muons – muons that are identified by using a fitted combination of ID and MS tracks.

- Segment-tagged muons – muons identified by matching an ID track of sufficiently high momentum with a reconstructed track segment located in the MS; they recover muons in poorly covered regions and at low transverse momenta.

- Calorimeter tagged muons – muons that are identified using the calorimeter, these are highly effective in efficiency recovery in the region near $|\eta| \approx 0$.

4.10.2.1. Reconstruction Chain

Muon reconstruction is fundamentally different than electron reconstruction. In place of a set of basic builder algorithms, muons uses a set of chains. The STACO muon chain contains the muons found by three different algorithms:

- Muonboy, which starts from the hit information in the MS and produces standalone segments and track; standalone tracks are extrapolated to the vertex.

- STACO, statistically combines an ID track with a MS track, producing combined muons.

- Mutag identifies muons by associating an ID track with Muonboy segments. Only ID tracks not combined in the STACO algorithm and segments not belonging to a MS track already combined in the STACO algorithm are used in this identification; producing segment-tagged muons.
4.10.2.2. **STACO Algorithm**

The algorithm is designed to combine ID tracks with MS tracks; the combination results in Combined track parameters obtained by statistically averaging the ID and MS track parameters. The combination of these two independent measurements is done by means of their covariance matrices.

More information on the performance of muons and chains used in muon reconstruction and identification can be found in References [39–41]. Detailed information on the STACO algorithm can be found in [31, 42, 43].

4.11. **Luminosity**

The ATLAS detector has been fully operational since 2008, starting with cosmic ray data taking and commissioning. The acquisition of proton-proton (pp) collision data began November 2009 at $\sqrt{s} = 900$ GeV. In March 2010, after the year-end-winter-shutdown, the LHC resumed delivering collisions, but at higher energies – $\sqrt{s} = 7$ TeV. Initially, pp collisions in 2010 were characterized by rather low luminosity i.e., low interaction rate. The events obtained during that period were used to calibrate the detector and to commission the reconstruction software. By mid-April 2011 the luminosity delivery increased, leading up to an average of 10 pp collisions per bunch crossing. The total integrated luminosity recorded by ATLAS in 2010 and 2011 can be seen in Figures 4.10(a) and 4.10(b) respectively. Reference [44] contains a detailed description of the detectors in ATLAS used to determine the total integrated luminosity.
Figure 4.10. Total integrated luminosity recorded by ATLAS in 2010 (a) in pb$^{-1}$ and 2011 (b) in fb$^{-1}$.

The number of proton-proton interactions is related to the integrated luminosity by

$$N_{\text{events}} \approx \mathcal{L} = \int L \cdot \sigma dt$$

where $\sigma$ is the cross section for the $pp$ interaction at the collision energy and is equal to $\sim 100$ mb at 7 TeV. That means that the integrated luminosity of 5.25 fb$^{-1}$ corresponds to $5.25 \times 10^{14}$ $pp$ interactions. That means $\sim 1.84 \times 10^8$ events were selected and recorded for further analysis.
Chapter 5
ANALYSIS

In this chapter, an overview of the analysis for a Standard Model Higgs boson decaying to a pair of Z bosons decaying to four leptons – \( H \rightarrow ZZ(\ast)\rightarrow 4\ell \) – is presented. Also presented is an introduction to Standard Model Higgs production at the LHC, description of the data and Monte Carlo used in the analysis, event selection, background estimation, and an overview of systematics uncertainties accounted for in the analysis. Naturalized units are used henceforth, where \( c = 1 \), unifying the units of mass, momentum, and energy to eV.

5.1. Introduction

The search for the Standard Model Higgs boson \([15][17]\) is a main goal of the LHC program. Direct searches at the CERN LEP \( e^+e^- \) collider led to a lower limit on the Higgs boson mass, \( m_H \), of 114.4 GeV at the 95% confidence level (CL) \([48]\). Searches at the Fermilab Tevatron \( p\bar{p} \) collider, which ended in 2011, have excluded the mass region \( 158 \text{ GeV} < m_H < 173 \text{ GeV} \) at the 95% CL \([19]\).

The Standard Model Higgs boson may be searched for at the LHC in various decay channels, the choice of which is given by the signal rates and the signal-to-background ratio in various mass regions. This dissertation presents a study on the search for the Standard Model Higgs boson in the mass range from 110 to 600 GeV in the channel \( H \rightarrow ZZ(\ast) \rightarrow \ell^+\ell^-\ell'^+\ell'^- \), where \( \ell, \ell' = e, \mu \). It is one of the most promising experimental searches and is characterized by high signal-to-background ratios in the low mass Higgs region where \( m_H < 2m_Z \) \((2m_Z \approx 180 \text{ GeV})\). In this low mass region,
one of the $Z$ bosons decays on-shell and can be clearly identified as a narrow $Z$ peak in the $\ell^+\ell^-$ invariant mass distribution, thus ensuring high data selection efficiency, i.e., $H \rightarrow ZZ^*$, where $Z^*$ denotes a virtual $Z$ boson. For the high-mass Higgs region ($m_H > 2m_Z$), both $Z$ bosons decay on-shell, thus allowing the search range to be extended to about 600 GeV (i.e., $H \rightarrow ZZ$). The search for higher mass Higgs is hampered by the increasing width of the boson (see Figure 5.4(b)) that becomes comparable to its mass and therefore inaccessible experimentally. Properties of the Standard Model Higgs boson, such as production cross section and decay branching ratio are detailed in References [50, 51].

5.1.1. Standard Model Higgs Production at the LHC

There are four main modes of Standard Model Higgs production at the LHC (see Figure 5.1), gluon-gluon fusion, vector-boson fusion, the associated production of a Standard Model Higgs with an additional $W^\pm$ boson or $Z$ boson, and the associated production of a Standard Model Higgs with a top pair ($t\bar{t}$). Only the first three production mechanisms are currently studied in the $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$ analysis.

5.1.1.1. Gluon-gluon fusion (ggF): $gg \rightarrow H$:

Gluon-gluon fusion is the main production mechanism (nearly 87%) for the Standard Model Higgs boson at the LHC and is the most common production studied in searches for Higgs (including $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$). It is one of the most important production mechanisms for Higgs boson searches and studies for Higgs masses between 100 GeV and 1 TeV. The Feynman diagram$^1$ for the gluon-gluon fusion process is illustrated in Figure 5.2(a).

$^1$A picture that jointly represents a particle’s physics process and mathematical expressions needed in quantum field theory. They were introduced by Richard Feynman in 1948.
Figure 5.1. Standard Model Higgs boson production cross sections at $\sqrt{s} = 7$ TeV. From top to bottom, the lines represent gluon-gluon fusion, vector-boson fusion and associated production with $W$, $Z$, and $t\bar{t}$.

5.1.1.2. Vector-boson fusion (VBF): $q\bar{q} \rightarrow q\bar{q} + H$:

Vector-boson fusion (see Figure 5.2(b)) is another production of a Standard Model Higgs boson (second-most dominant) with two hard jets\(^2\) in the forward and background regions of the detector. Vector-boson fusion is an important production mechanism for Standard Model Higgs searches and in the determination of Higgs and boson couplings.

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\(^2\)A jet is a collection of particles that is made during gluon-quark interactions in a $pp$ collision.
5.1.1.3. Associated production with $W^\pm / Z$ Bosons ($WH/ZH$): $q\bar{q} \rightarrow W^\pm + H$ and $q\bar{q} \rightarrow Z + H$:

The associated production of a Standard Model Higgs boson with other particles as Higgs-strahlung$^3$. The production of a $W$ boson or $Z$ boson in association with a Higgs boson (see Figure 5.2(c)) is the result of quark-antiquark interactions. Like $ggF$ and VBF, it is used in Standard Model Higgs searches.

5.1.1.4. Associated production with a top pair: $gg, q\bar{q} \rightarrow t\bar{t} + H$:

Higgs-strahlung off top quarks plays a role for light Higgs masses, the measurement of its production rate can provide relevant information on the top-Higgs Yukawa coupling. The expected production of a Standard Model Higgs with an associated top pair is low at the LHC, on the order of 1%, and is not currently studied in the $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$ analysis.

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$^3$German: Strahlung, meaning “radiation”.
5.1.2. Higgs Mass Width

The mass of the Higgs boson determines which final states are available to it. The Higgs boson couples to mass, which means that it will decay to the heaviest kinematically available objects. This means that for a given Higgs mass, certain final states are easier to search for given the availability of more events. The rates - branching ratios (BR) - for which a Standard Model Higgs bosons decays to either bosons or quarks is illustrated in Figure 5.3. The total production rate which is the cross section times the branching ratio, i.e., the rate at which a $pp$ collision produces a Standard Model Higgs boson that decays to two $Z$ bosons, where each $Z$ decays leptonically (i.e., $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$), is illustrated in Figure 5.4(a).

(a) SM Higgs boson decay branching ratios for $90 \text{ GeV} < m_H < 200 \text{ GeV}$. (b) SM Higgs boson decay branching ratios for $90 \text{ GeV} < m_H < 1,000 \text{ GeV}$.

Figure 5.3. Standard Model Higgs boson decay branching ratios.

The Higgs boson has a mass dependent width\(^4\) (illustrated in Figure 5.4(b)) that suffers from off-shell Higgs boson production and quantum chromodynamics/electric...

\(^4\)The decay width or resonance width refers to the width of a particle’s invariant mass distribution.
troweak interference effects at higher masses. These interference effects include:

- The interference from $Z/\gamma$ is not calculated; this is necessary for internal conversions.

- The rates for $pp \to H \to WW/ZZ$ v. $pp \to WW/ZZ$ is either missing or roughly approximated as the interference terms need calculations that are correlated to experimental cuts.

Thus it fundamentally makes sense to only look for lower Higgs masses, $m_H < 600$ GeV. This is directly reflected in Higgs searches at the LHC, where searches are performed between 100 GeV and 600 GeV.

(a) Standard Model Higgs boson production cross section times branching ratio at $\sqrt{s} = 7$ TeV, inclusive (solid line) and VBF (dashed line) $H \to \tau\tau$.

(b) SM Higgs boson total width.

Figure 5.4. Standard Model Higgs boson production times branching ratios and total width.
This channel has a signature of four leptons whose invariant mass is consistent with the theorized Higgs boson mass. Four distinct final states, $\mu\mu\mu\mu$ (4$\mu$), $ee\mu\mu$ (2$e$2$\mu$), $\mu\mu ee$ (2$\mu$2$e$), and $eeee$ (4$e$), are selected. Unless otherwise indicated, the 2$e$2$\mu$ and 2$\mu$2$e$ final states will be referred to as 2$e$2$\mu$.

The latest results from ATLAS in this channel are presented in the summary – Chapter 6.

5.2. Data and Monte Carlo samples

5.2.1. Data Samples

In 2011, the total luminosity of $pp$ collisions recorded by the ATLAS detector at $\sqrt{s} = 7$ TeV – that is also useful in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analyses – corresponds to an average integrated luminosity of 4.8 fb$^{-1}$ [44]. The data are subjected to a multiple quality requirements (encompassed in the GoodRunList Section 5.4.1) ensuring that all sub-systems (e.g. MS, ID, LAr Calorimeter, etc.) in the ATLAS detector are working within nominal expectations. The requirements necessary for the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analysis are summarized in Appendix B of Reference [52]. The integrated luminosities for each of the final states are summarized in Table 5.1. A detailed breakdown of the total integrated luminosity per period is given in Table 5.2.

5.2.2. Signal Monte Carlo Samples and Cross-sections

The $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ signal is modeled in the range 110 to 600 GeV using the POWHEG Monte Carlo event generator [53, 54], which calculates the gluon-gluon and vector-boson fusion production mechanisms of the Higgs boson with matrix elements up to next-to-leading order (NLO). POWHEG is interfaced to PYTHIA [55] for showering
Table 5.1. The total integrated luminosities available for each of the final states in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analyses.

<table>
<thead>
<tr>
<th>Final State</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>4.81 fb$^{-1}$</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>4.81 fb$^{-1}$</td>
</tr>
<tr>
<td>$4e$</td>
<td>4.91 fb$^{-1}$</td>
</tr>
</tbody>
</table>

Table 5.2. Integrated Luminosity for Data 2011 (in pb$^{-1}$) collected in different periods (B-M) of 2011. A data period is a group of runs that correspond to stable detector conditions.

<table>
<thead>
<tr>
<th>Period</th>
<th>B</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>$4\mu$</td>
<td>11.7</td>
<td>166.8</td>
<td>48.7</td>
<td>142.6</td>
<td>537.5</td>
<td>259.5</td>
<td>386.2</td>
<td>226.5</td>
<td>600.1</td>
<td>1401.9</td>
<td>1025.6</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>11.7</td>
<td>166.7</td>
<td>48.8</td>
<td>142.6</td>
<td>537.5</td>
<td>259.5</td>
<td>386.2</td>
<td>226.5</td>
<td>600.1</td>
<td>1401.9</td>
<td>1025.6</td>
<td>4807</td>
</tr>
<tr>
<td>$4e$</td>
<td>14.6</td>
<td>167.6</td>
<td>48.8</td>
<td>142.6</td>
<td>539.7</td>
<td>262.2</td>
<td>393.8</td>
<td>228.0</td>
<td>610.0</td>
<td>1457.8</td>
<td>1046.8</td>
<td>4910</td>
</tr>
</tbody>
</table>

and hadronization, which in turn is interfaced to PHOTOS [56] for QED\(^5\) radiative corrections in the final-state and to TAULOLA [57] for the simulation of $\tau$ decays.

The cross sections for Higgs boson production, the corresponding branching fractions, as well as their uncertainties, are listed in Reference [50]. These cross sections correspond to next-to-next-to-leading order (NNLO) in QCD\(^6\) for gluon-gluon fusion (ggF) [58-63] and vector-boson fusion (VBF) [64]. In addition, QCD soft-gluon resummations up to next-to-next-to-leading log (NNLL) are available for the gluon fusion process [65], while the NLO electroweak (EW) corrections are applied to both

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\(^5\)Quantum Electrodynamics.

\(^6\)Quantum Chromodynamics.
the gluon-gluon fusion \[66, 67\] and vector-boson fusion \[68, 69\].

The Higgs boson decay branching ratio to the four-lepton final state is predicted by PROPHECY4F \[70, 71\], including the complete NLO QCD+EW corrections with all interference and leading two-loop heavy Higgs boson corrections to the four-fermion width.

The cross-section times the branching ratio values used in the following are listed in the second column of Table 5.3 and have been obtained as \(\sigma(ggF + VBF) \times \text{BR}(H \rightarrow 4\ell)\), \(\ell = e, \mu\) from Reference \[50\]. A short summary of the generators used for Monte Carlo simulation of signal and background processes is presented in Table 5.4.

From studies performed for EPS-HEP\[7\]-2011 \[72\], the signal efficiency between POWHEG and PYTHIA generators was found to be in agreement within a few % for both gluon-gluon and vector-boson fusion production mechanisms. An additional 2% uncertainty is added to the signal selection efficiency due to the modeling of the signal kinematics. This is evaluated by comparing signal samples generated with PYTHIA and the default POWHEG samples.

A full list of signal Monte Carlo samples is available in Appendix \[D\].

5.2.3. Background Monte Carlo Samples and Cross-sections

The cross sections of the most commonly used background samples used in \(H \rightarrow ZZ(\ast)\rightarrow 4\ell\) analyses are presented in Table 5.5; a full list of Monte Carlo samples is available in Appendix \[D\]. Detailed information on generation of background Monte Carlo is presented in Reference \[52\]. A short summary of the generators used for background processes is presented in Table 5.4. ALPGEN and JIMMY correspond to specialized event generators for multiple parton processes.

Table 5.3. Higgs boson production cross-sections for both gluon-gluon and vector-boson fusion processes in $pp$ collisions at $\sqrt{s} = 7$ TeV. The cross-sections include the branching ratio of $H \rightarrow 4\ell$, $\ell = e, \mu$.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$\sigma \cdot \text{BR}(H \rightarrow 4\ell)$ (fb)</th>
<th>$m_H$ (GeV)</th>
<th>$\sigma \cdot \text{BR}(H \rightarrow 4\ell)$ (fb)</th>
<th>$m_H$ (GeV)</th>
<th>$\sigma \cdot \text{BR}(H \rightarrow 4\ell)$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>1.37</td>
<td>220</td>
<td>6.16</td>
<td>420</td>
<td>2.24</td>
</tr>
<tr>
<td>130</td>
<td>2.87</td>
<td>240</td>
<td>5.35</td>
<td>440</td>
<td>1.89</td>
</tr>
<tr>
<td>140</td>
<td>4.23</td>
<td>260</td>
<td>4.68</td>
<td>460</td>
<td>1.59</td>
</tr>
<tr>
<td>150</td>
<td>4.38</td>
<td>280</td>
<td>4.16</td>
<td>480</td>
<td>1.33</td>
</tr>
<tr>
<td>160</td>
<td>1.90</td>
<td>300</td>
<td>3.75</td>
<td>500</td>
<td>1.11</td>
</tr>
<tr>
<td>165</td>
<td>0.93</td>
<td>320</td>
<td>3.49</td>
<td>520</td>
<td>0.94</td>
</tr>
<tr>
<td>170</td>
<td>0.92</td>
<td>340</td>
<td>3.40</td>
<td>540</td>
<td>0.79</td>
</tr>
<tr>
<td>180</td>
<td>2.04</td>
<td>360</td>
<td>3.42</td>
<td>560</td>
<td>0.66</td>
</tr>
<tr>
<td>190</td>
<td>6.22</td>
<td>380</td>
<td>3.08</td>
<td>580</td>
<td>0.56</td>
</tr>
<tr>
<td>200</td>
<td>6.77</td>
<td>400</td>
<td>2.66</td>
<td>600</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Table 5.4. Monte Carlo programs used for modeling signal and background processes and their corresponding cross-sections.

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>$\sigma \times \text{BR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg, qq \rightarrow H$</td>
<td>POWHEG</td>
<td>See Table 5.3</td>
</tr>
<tr>
<td>$Z/\gamma* \rightarrow \ell \ell$</td>
<td>ALPGEN, PYTHIA</td>
<td></td>
</tr>
<tr>
<td>$m_{\ell \ell} &gt; 60$ GeV</td>
<td></td>
<td>0.989 nb [73, 74]</td>
</tr>
<tr>
<td>$Z/\gamma*bb \rightarrow \ell \ell bb$</td>
<td>ALPGEN</td>
<td>12.4 pb</td>
</tr>
<tr>
<td>$m_{\ell \ell} &gt; 30$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$qq, gg \rightarrow ZZ$</td>
<td>MCFM</td>
<td>14.4 pb [75, 76]</td>
</tr>
<tr>
<td>$m_Z &gt; 12$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>MC@NLO</td>
<td>164.6 pb [77]</td>
</tr>
</tbody>
</table>
Table 5.5. Background sample run number, names, and their cross-sections.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Sample Name</th>
<th>Cross-Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>107650</td>
<td>Alpgen+Jimmy Zee + 0 partons</td>
<td>827375</td>
</tr>
<tr>
<td>107651</td>
<td>Alpgen+Jimmy Zee + 1 partons</td>
<td>166625</td>
</tr>
<tr>
<td>107652</td>
<td>Alpgen+Jimmy Zee + 2 partons</td>
<td>50375</td>
</tr>
<tr>
<td>107653</td>
<td>Alpgen+Jimmy Zee + 3 partons</td>
<td>14000</td>
</tr>
<tr>
<td>107654</td>
<td>Alpgen+Jimmy Zee + 4 partons</td>
<td>3375</td>
</tr>
<tr>
<td>107655</td>
<td>Alpgen+Jimmy Zee + 5 partons</td>
<td>1000</td>
</tr>
<tr>
<td>107656</td>
<td>Alpgen+Jimmy Zmumu + 0 partons</td>
<td>822125</td>
</tr>
<tr>
<td>107657</td>
<td>Alpgen+Jimmy Zmumu + 1 partons</td>
<td>166000</td>
</tr>
<tr>
<td>107658</td>
<td>Alpgen+Jimmy Zmumu + 2 partons</td>
<td>49500</td>
</tr>
<tr>
<td>107659</td>
<td>Alpgen+Jimmy Zmumu + 3 partons</td>
<td>13875</td>
</tr>
<tr>
<td>107660</td>
<td>Alpgen+Jimmy Zmumu + 4 partons</td>
<td>3500</td>
</tr>
<tr>
<td>107661</td>
<td>Alpgen+Jimmy Zmumu + 5 partons</td>
<td>1000</td>
</tr>
<tr>
<td>107662</td>
<td>Alpgen+Jimmy Ztautau + 0 partons</td>
<td>828125</td>
</tr>
<tr>
<td>107663</td>
<td>Alpgen+Jimmy Ztautau + 1 partons</td>
<td>167375</td>
</tr>
<tr>
<td>107664</td>
<td>Alpgen+Jimmy Ztautau + 2 partons</td>
<td>50375</td>
</tr>
<tr>
<td>107665</td>
<td>Alpgen+Jimmy Ztautau + 3 partons</td>
<td>13875</td>
</tr>
<tr>
<td>107666</td>
<td>Alpgen+Jimmy Ztautau + 4 partons</td>
<td>3500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Sample Name</th>
<th>Cross-Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>116960</td>
<td>Zbb, $\rightarrow$ ee (l$&gt;$30 GeV) + 0 parton</td>
<td>20.701</td>
</tr>
<tr>
<td>116961</td>
<td>Zbb, $\rightarrow$ ee (l$&gt;$30 GeV) + 1 parton</td>
<td>18.809</td>
</tr>
<tr>
<td>116962</td>
<td>Zbb, $\rightarrow$ ee (l$&gt;$30 GeV) + 2 parton</td>
<td>10.505</td>
</tr>
<tr>
<td>116963</td>
<td>Zbb, $\rightarrow$ ee (l$&gt;$30 GeV) + 3 parton</td>
<td>7.30463</td>
</tr>
<tr>
<td>116964</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 0 parton</td>
<td>21.516</td>
</tr>
<tr>
<td>116965</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 1 parton</td>
<td>19.6674</td>
</tr>
<tr>
<td>116966</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 2 parton</td>
<td>10.516</td>
</tr>
<tr>
<td>116967</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 3 parton</td>
<td>7.93834</td>
</tr>
<tr>
<td>116968</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 4 parton</td>
<td>7.93834</td>
</tr>
<tr>
<td>116950</td>
<td>Zbb, $\rightarrow$ ee (l$&gt;$30 GeV) + 0 parton 3l filter, veto on $m_{d}$ 60/12 GeV</td>
<td>756.32x1.4</td>
</tr>
<tr>
<td>116951</td>
<td>Zbb, $\rightarrow$ ee (l$&gt;$30 GeV) + 1 parton 3l filter, veto on $m_{d}$ 60/12 GeV</td>
<td>432.25x1.4</td>
</tr>
<tr>
<td>116952</td>
<td>Zbb, $\rightarrow$ ee (l$&gt;$30 GeV) + 2 parton 3l filter, veto on $m_{d}$ 60/12 GeV</td>
<td>176x1.4</td>
</tr>
<tr>
<td>116953</td>
<td>Zbb, $\rightarrow$ ee (l$&gt;$30 GeV) + 3 parton 3l filter, veto on $m_{d}$ 60/12 GeV</td>
<td>96.75x1.4</td>
</tr>
<tr>
<td>116955</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 0 parton 3l filter, veto on $m_{d}$ 60/12 GeV</td>
<td>730.24x1.4</td>
</tr>
<tr>
<td>116956</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 1 parton 3l filter, veto on $m_{d}$ 60/12 GeV</td>
<td>432.25x1.4</td>
</tr>
<tr>
<td>116957</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 2 parton 3l filter, veto on $m_{d}$ 60/12 GeV</td>
<td>179.3x1.4</td>
</tr>
<tr>
<td>116958</td>
<td>Zbb, $\rightarrow$ mumu (l$&gt;$30 GeV) + 3 parton 3l filter, veto on $m_{d}$ 60/12 GeV</td>
<td>92.3962x1.4</td>
</tr>
<tr>
<td>105200</td>
<td>ttbar (at least 1lepton filter)</td>
<td>91550.6</td>
</tr>
<tr>
<td>109345</td>
<td>ttbar (with Mll$&gt;$60 GeV filter)</td>
<td>12707.2</td>
</tr>
<tr>
<td>109346</td>
<td>ttbar (with Mll$&gt;$60 GeV filter and Mll$&gt;$12 GeV)</td>
<td>515.2</td>
</tr>
<tr>
<td>109292</td>
<td>ZZ$\rightarrow$4l 3LepFilter</td>
<td>91.54</td>
</tr>
</tbody>
</table>
5.3. Backgrounds at the LHC

At the LHC, all of the Standard Model Higgs background processes have cross-sections that are many orders of magnitude higher than typical Higgs boson cross-sections (see Figure 5.5). Background comes from processes other than Higgs production and decays that results in the same final state of 4 leptons. We distinguish between reducible backgrounds due to misidentification, e.g. pions as electrons due to accidental similarities, and the irreducible background where allowed physics processes lead to 4 leptons in the final state. The irreducible background for $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ process is the $pp \rightarrow ZZ^{(*)} \rightarrow 4\ell$ continuum. There are two other important and reducible background processes: $Zb\bar{b} \rightarrow 4\ell + X$ and $tt \rightarrow 4\ell + X$ with two leptons coming from the semi-leptonic decays of two $b$-quarks. For $m_H < 2m_Z$, contributions from $Z +$jets and $tt$ processes, where the additional leptons come from semi-leptonic decays of heavy flavor or light jets misidentified as leptons, are important. The majority of events in these backgrounds can be rejected by requiring that the invariant mass of at least one lepton pair is compatible with the $Z$ mass and that all of the leptons are isolated and coming from the interaction vertex. Other potential backgrounds considered in this paper are $WZ$, QCD, and $Z \rightarrow ee$.

In order to suppress contributions from backgrounds, we apply selection criteria on qualities describing lepton isolation for fakes\footnote{A fake is a reconstructed object that has electron or muon like characteristics, but is not either.} and on the impact impact parameter\footnote{The transverse impact parameter - $d_0$ - is the distance of closest approach to the of the track to the interaction (primary) vertex.} significance for leptons coming from $b$-decays. This second set of criteria selects electron (muon) candidates within 6 (3.5) $\sigma$ ($\sigma$ - standard deviation) from the point of event origin, thus eliminating those electrons that come from the decay of long-lived secondary particles like the $b$-quark. With negligible reducible backgrounds
for $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$, any event that is found becomes significant. This section will explain some of the procedures used in background studies to determine how well the background is understood as well as how much control is exerted in the use of various cuts.

5.3.1. Tools for Background Rejection

Since a discovery is always made with the smallest number of events, the goal of this analysis is to maximize the acceptance and maintain a high purity, which is different than the requirements of detector performance studies where purity is...
prioritized with higher importance. For low mass Higgs decays, $H \rightarrow ZZ^*$, the mass of the on-shell $Z$ boson is used as a powerful constraint.

5.3.1.1. $Z$ as a Constraint

Low mass Higgs bosons, e.g. $m_H = 130$ GeV, decaying to two $Z$ bosons can produce two off-shell or one on-shell $Z$ and one off-shell $Z^*$, as shown in Figure 5.6. If we choose one pair of leptons to be a real $Z$ - in other words, selecting a pair that is the most consistent with a $Z$ - we constrain ourselves to the case of one real $Z$ and one virtual $Z^*$.

![Figure 5.6](image-url)

Figure 5.6. Mass of $Z$ and $Z^*$ in the Higgs sample. $m_Z$ shown in black solid line (no fill), $m_{Z^*}$ also shown in solid black line (with fill). Histograms represent generation level, with the following selection criteria: final state electron and muon $p_T > 5.5$ GeV, $|\eta| < 2.7$, and $m_Z, m_{Z^*} > 12$ GeV in the event.

To ensure the purity of the signal, we search for events where one of the $Z$’s mass is on-shell. To find such events we request in the selection to pick up opposite signed lepton pairs with an invariant mass closest to the nominal on-shell $Z$ mass and require
it to be within $\pm 15$ GeV from the nominal $Z$ mass value of 91.1876 GeV \[4\].

5.3.1.2. Transverse Impact Parameter

Leptons from $t\bar{t}$ and $Zb\bar{b}$ backgrounds are most likely to originate from displaced vertices as the $b$ and $t$ and quarks have small, but non-zero lifetime. Partial rejection of these reducible backgrounds can be done with use of the transverse impact parameter criteria imposed on the tracks associated to the leptons. The impact parameter is the distance of closest approach of the track to the vertex. The impact parameter significance $|d_0|/\sigma(d_0)$ is defined as the transverse impact parameter $d_0$ of the lepton track with respect to the primary vertex, divided by its measurement error $\sigma(d_0)$. A cut requiring $|d_0|/\sigma(d_0) < 6$ (3.5) is applied on each of the electron (muon) tracks. These cuts are shown in Figure 5.7 for signal and for background. The impact parameter is calculated with respect to the event vertex fitted using a set of tracks reconstructed in the Inner Detector. This allows for removal of the spread on the broadened vertex position, which is 15 $\mu$m along each of the transverse $x$ and $y$ axes at the LHC.
Figure 5.7. Transverse impact parameter significance for pre-selected electrons (a) and muons (b) in Higgs ($m_H = 125$ GeV), $Z\bar{b}b$ and $t\bar{t}$ Monte Carlo. The vertical dashed line represents the value for which electrons (muons) are selected: $|d_0|/\sigma(d_0) < 6$ (3.5). Histograms are normalized to an area of 1 to compare shapes.

5.4. Event Selection

In this section, we describe the event, lepton, kinematic, and quadruplet selection used in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analysis. An overview of event selection requirements is summarized in Table 5.6.

5.4.1. GoodRunList

The very first step in the data selection criteria is use of the GoodRunList (GRL) package. The GRL package uses XML files produced by the combined performance and physics groups to determine which LumiBlocks in data runs have good detector performance. By applying separate GRLs to each of the final states, the integrated

\[^{10}\text{A luminosity block is a 1 or 2-minute block of data as recorded by ATLAS spanning several selected events.}\]
Table 5.6. Summary of the event selection requirements. The two lepton pairs are denoted as $m_{12}$ and $m_{34}$. The threshold values for $m_{34}$ are defined through linear interpolation of the values in Table 5.7.

<table>
<thead>
<tr>
<th>Event Preselection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrons:</strong>                      Loose++ quality GSF electrons with $E_T &gt; 7$ GeV and $</td>
</tr>
<tr>
<td><strong>Muons:</strong>                          Combined or segment-tagged muons with $p_T &gt; 7$ GeV and $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kinematic</strong></td>
</tr>
<tr>
<td>Require at least one quadruplet of leptons consisting of two pairs of same-flavor, opposite-charge leptons fulfilling the following requirements.</td>
</tr>
<tr>
<td>At least two leptons in the quadruplet with $p_T &gt; 20$ GeV.</td>
</tr>
<tr>
<td>Leading di-lepton pair mass requirement $</td>
</tr>
<tr>
<td>Sub-leading di-lepton pair mass requirement $m_{\text{threshold}} &lt; m_{34} &lt; 115$ GeV</td>
</tr>
<tr>
<td>$\Delta R(\ell, \ell') &gt; 0.10$ for all leptons in the quadruplet.</td>
</tr>
<tr>
<td><strong>Isolation</strong></td>
</tr>
<tr>
<td>Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_T/i / p_T &lt; 0.15$</td>
</tr>
<tr>
<td>Lepton calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/i / E_T &lt; 0.30$</td>
</tr>
<tr>
<td><strong>Impact</strong></td>
</tr>
<tr>
<td>Impact parameter significance cut applied to the 2 least energetic leptons of the quadruplet.</td>
</tr>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>For electrons: $</td>
</tr>
<tr>
<td>For muons: $</td>
</tr>
<tr>
<td>For $m_{4\ell} &gt; 190$ GeV no requirement is applied.</td>
</tr>
</tbody>
</table>

Table 5.7. Summary of mass thresholds applied to $m_{34}$ for reference values of $m_{4\ell}$. For other $m_{4\ell}$ values, the selection requirement is obtained via linear interpolation.

<table>
<thead>
<tr>
<th>$m_{4\ell}$ (GeV)</th>
<th>$\leq 120$</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>165</th>
<th>180</th>
<th>190</th>
<th>$\geq 200$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold (GeV)</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>
luminosity of the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analysis is maximized per final state.

5.4.2. LAr Error

As the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analysis heavily relies on the LAr calorimeter, an additional cut is placed on data to ensure that an event does not suffer from a noise burst or data corruption after bulk (re)processing, e.g. software or detector problems occurring during data collection [79].

5.4.3. Associated Tracks per Vertex

The next selection criterium used in the baseline analysis is that there is at least one reconstructed primary vertex with three associated tracks in each event. This requirement ensures that collision candidates are selected. During vertex finding/reconstruction, a beam spot constraint is applied, ensuring that the size of the beam spot is compatible with each primary vertex candidate.

5.4.4. Trigger

The next step involves selecting events based on the trigger decisions from the Event Filter. The lowest un-prescaled\footnote{The term prescaled and un-prescaled triggers refers to an additional cut on the event filter to reject additional events. This is done to reduce the triggering rates, ensuring that there is sufficient bandwidth to write event information to the sub-farms.} single-lepton or di-lepton $p_T$ triggers are used. A list of triggers used in data and Monte Carlo is located in Tables 5.8 and 5.9, respectively. The efficiency of these triggers on signal events, with respect to the offline selection, is nearly 100% as indicated in Tables 5.10 - 5.13. The evolution of triggers is based on increasing trigger rates (due to the substantial increase in luminosity delivery from the LHC); this means that as time progressed, trigger requirements at
the Event Filter (as described in Section 4.8) were tightened to reduce that rate of acceptance. Requirement changes primarily took the form of increased $p_T$ thresholds, tighter identification requirements, and near the end of 2011 – the addition of a veto on hadrons.

Table 5.8. Triggers used in the data. In each data-taking period, the OR of single- and di-lepton triggers is used to select each signature. Here, Loose++ electrons and combined or segment-tagged muons are used.

<table>
<thead>
<tr>
<th>Period</th>
<th>B-I</th>
<th>J</th>
<th>K</th>
<th>L-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>EF$\mu$18$_{MG}$</td>
<td>EF$\mu$18$_{MG}$medium</td>
<td>EF$\mu$18$_{MG}$medium</td>
<td>EF$\mu$18$_{MG}$medium</td>
</tr>
<tr>
<td>$4e$</td>
<td>EF$e$20$_{medium}$</td>
<td>EF$e$20$_{medium}$</td>
<td>EF$e$22$_{medium}$</td>
<td>EF$e$22vh$_{medium}$1</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$4\mu$ OR $4e$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.9. Triggers used in Monte Carlo samples. Here, Loose++ electrons and combined or segment-tagged muons are used.

<table>
<thead>
<tr>
<th>Period</th>
<th>B-I</th>
<th>J</th>
<th>K</th>
<th>L-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>EF$<em>{2\mu}$10$</em>{loose}$</td>
<td>EF$<em>{2\mu}$10$</em>{loose}$</td>
<td>EF$<em>{2\mu}$10$</em>{loose}$</td>
<td>EF$<em>{2\mu}$10$</em>{loose}$</td>
</tr>
<tr>
<td>$4e$</td>
<td>EF$<em>{2e}$12$</em>{medium}$</td>
<td>EF$<em>{2e}$12$</em>{medium}$</td>
<td>EF$<em>{2e}$12T$</em>{medium}$</td>
<td>EF$<em>{2e}$12Tvh$</em>{medium}$</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$4\mu$ OR $4e$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MC to match unprescaled trigger during data taking

<table>
<thead>
<tr>
<th>Period</th>
<th>B-I</th>
<th>J</th>
<th>K</th>
<th>L-M</th>
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<td>EF$<em>{\mu}$18$</em>{MG}$, EF$<em>{\mu}$18$</em>{MG}$medium OR EF$<em>{2\mu}$10$</em>{loose}$</td>
<td></td>
<td></td>
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<tr>
<td>$4e$</td>
<td>EF$<em>{e}$20$</em>{medium}$, EF$<em>{e}$22$</em>{medium}$, EF$<em>{e}$22$</em>{medium}$1 OR EF$<em>{2e}$12$</em>{medium}$, EF$<em>{2e}$12T$</em>{medium}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$4\mu$ OR $4e$</td>
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</table>
Table 5.10. Trigger efficiency as determined in Monte Carlo as a function of $m_H$ for gluon-gluon fusion signal samples.

<table>
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<th>Trigger:</th>
<th>w/ $4\mu$ w/o $4\mu$ Eff. ($%$)</th>
<th>w/ $2e2\mu$ w/o $2e2\mu$ Eff. ($%$)</th>
<th>w/ $4e$ w/o $4e$ Eff. ($%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H$</td>
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<td></td>
</tr>
<tr>
<td>110</td>
<td>260 275 94.545</td>
<td>306 313 97.764</td>
<td>92 92 100</td>
</tr>
<tr>
<td>115</td>
<td>631 654 96.483</td>
<td>775 790 98.101</td>
<td>237 238 99.58</td>
</tr>
<tr>
<td>120</td>
<td>951 975 97.538</td>
<td>1268 1286 98.6</td>
<td>427 429 99.534</td>
</tr>
<tr>
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<td>1283 1307 98.164</td>
<td>1685 1718 98.079</td>
<td>612 613 99.837</td>
</tr>
<tr>
<td>130</td>
<td>1597 1623 98.398</td>
<td>2037 2063 98.74</td>
<td>712 715 99.58</td>
</tr>
<tr>
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<td>1760 1786 98.544</td>
<td>2426 2449 99.061</td>
<td>829 830 99.88</td>
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<tr>
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<td>1892 1922 98.439</td>
<td>2711 2731 99.268</td>
<td>1045 1047 99.809</td>
</tr>
<tr>
<td>145</td>
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<td>1158 1161 99.742</td>
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<tr>
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<td>3522 3548 99.267</td>
<td>6560 6577 99.742</td>
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Table 5.11. Trigger efficiency as determined in Monte Carlo as a function of $m_H$ for vector-boson fusion signal samples.

<table>
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<tr>
<th>$m_H$</th>
<th>Trigger:</th>
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<th>w/o</th>
<th>Eff. (%)</th>
<th>w/</th>
<th>w/o</th>
<th>Eff. (%)</th>
<th>w/</th>
<th>w/o</th>
<th>Eff. (%)</th>
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<td>185</td>
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<td>68</td>
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<tr>
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<td>2e2$\mu$</td>
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<td>522</td>
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<td>152</td>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>682</td>
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<td>98.755</td>
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<td>315</td>
<td>100</td>
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<td>1150</td>
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<td>2097</td>
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Table 5.12. Trigger efficiency as determined in Monte Carlo as a function of $m_H$ for associated $WH$ production signal samples.

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<th>w/ $2e2\mu$</th>
<th>w/o $2e2\mu$</th>
<th>Eff. (%)</th>
<th>w/ $4e$</th>
<th>w/o $4e$</th>
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Associated $WH$ production.
Table 5.13. Trigger efficiency as determined in Monte Carlo as a function of $m_H$ for associated $ZH$ production signal samples.

<table>
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<tr>
<th>Trigger: $m_H$</th>
<th>w/ 4µ</th>
<th>w/o 4µ</th>
<th>Eff. (%)</th>
<th>w/ 2e2µ</th>
<th>w/o 2e2µ</th>
<th>Eff. (%)</th>
<th>w/ 4e</th>
<th>w/o 4e</th>
<th>Eff. (%)</th>
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<td>403</td>
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<td>2052</td>
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<td>971</td>
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<td>2322</td>
<td>99.828</td>
<td>1007</td>
<td>1009</td>
<td>99.802</td>
</tr>
</tbody>
</table>

Associated $ZH$ production.
5.4.5. Kinematics

Leptons in an event must satisfy certain kinematic selections (summarized in Table 5.6) that balances high signal reconstruction efficiency with good background rejection \cite{80, 86}. The choice of a minimum lepton $E_T$ or $p_T$ threshold at 7 GeV is made to ensure that the any scale factors, corrections, and associated systematic uncertainties are well-known. The choice of $\eta$ is based on the need for tracking. For electrons, tracking ends at $\eta = 2.5$, and to account for edge effects, this is reduced to $\eta = 2.47$. Muons on the other hand are defined to $\eta = 2.7$.

More specifically, the electrons and muons of an event must satisfy the following criteria:

- Electrons are required to:
  - To be reconstructed using Gaussian-sum filters to correct for bremsstrahlung.
    In addition, electron candidates must be reconstructed using a seed in the calorimeter or from a track in the inner detector combined with a seed in the calorimeter.
  - Satisfy minimal requirements on shower shape variables in the first and second calorimeter layer, hadronic leakage variables, track quality, and $\Delta \eta$ between the extrapolated track and the cluster. This is referred to as Loose++.
  - Have $E_T > 7$ GeV and $|\eta_{\text{cluster}}| < 2.47$; $\eta_{\text{cluster}}$ denotes the use of $\eta$ as measured in the in the calorimeter (not by the track).
  - Reject electrons that pass through the bad-quality clusters via use of the Object Quality Flag \cite{85}.
  - $z_0 < 10$ mm, the distance along the beam axis relative to the primary vertex.
- Muons are required to:
  
  - Fulfill combined/segment-tagged muon reconstruction requirements as outlined in Section 4.10.2.
  
  - Have $p_T > 7$ GeV and $|\eta| < 2.7$.
  
  - Satisfy associated ID track cuts [86].
  
  - Have $d_0 < 10$ mm, the distance relative to the primary vertex (used to reduce cosmic muons).
  
  - Have $z_0 < 10$ mm, the distance along the beam axis relative to the primary vertex.

In addition to these cuts, overlap removal cuts are applied to duplicate electrons (electrons sharing the same track, but reconstructed with different clusters) and electrons overlapping with muons within a cone $\Delta R \leq 0.1$, where $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$. Electrons are rejected when they overlap with other reconstructed electrons, i.e., sharing the same track, in which case the highest-$E_T$ electron is retained. Similarly, when an electron’s track overlaps with a muon’s, it is rejected.

5.4.6 Quadruplet Selection

After having pre-selected all of the electrons and muons in an event, there must be at least $4\mu$, $4e$, or $2e$ and $2\mu$ before continuing to the next step of the selection criteria; should their be less than $4\mu$, $4e$, or $2e$ and $2\mu$, the event is rejected. Candidate quadruplets (four-lepton objects) are selected from two oppositely charged, same-flavor di-lepton pairs in an event. In this initial stage, all possible quadruplets are reconstructed. The di-lepton pair with a mass\(^{12}\) $m_{12}$ of the quadruplet compatible with the nominal $Z$ boson mass\(^{13}\) (within $\pm 15$ GeV) is called the primary di-lepton

\(^{12}\)The indices 1 and 2 denote the first and second lepton in the quadruplet.

\(^{13}\)As a reminder, the nominal $Z$ mass is $m_Z = 91.1876$ GeV.
pair, while the second di-lepton pair of the quadruplet with a mass\textsuperscript{14} $m_{34}$ is the secondary pair.

To reduce the number of quadruplets per event, the following cuts are applied:

- Additional kinematic cuts – at least two of the leptons must have a $p_T$ or $E_T$ greater than 20 GeV.

- Quadruplets for which at least one or two of the reconstructed leptons do not match the the trigger requirements are rejected. E.g., a quadruplet in which EF$\_el_{EF}$e22\_medium was triggered in the event, yet the highest $E_T$ electron is less than 22 GeV.

- The primary di-lepton pair must have a mass $m_{12}$, that is within 15 GeV of the nominal $Z$ mass; this cut is commonly referred to as the $Z1$ mass cut.

- The secondary di-lepton pair must have a mass $m_{34}$ which is always less than 115 GeV. Additional cuts are placed on the lower bound of this cut, which are defined as a function of $m_{4\ell}$ and obtained via interpolation of the mass points shown in Table 5.7. These mass cuts are commonly referred to as the $Z2$ mass cut.

- The four leptons in each quadruplets are required to be well separated in $\eta$ and $\phi$.

\textbf{5.4.6.1. Single Quadruplet Selection}

It is possible to have more than one quadruplet in an event as a result of combinatorics. The selection of one quadruplet in an event is then done by selecting quadruplets for which $m_{12}$ is the closest to nominal $Z$ mass. To ensure we have one and only one quadruplet, we then choose the quadruplet containing the most

\textsuperscript{14}The indices 3 and 4 denote the third and fourth lepton in a quadruplet.
energetic secondary di-lepton pair (determined by most massive $m_{34}$). It is worth noting that by having interpolated the mass cuts used on the secondary di-lepton pair, a unique mass spectrum for each background regardless of the hypothesized Higgs mass is produced.

5.4.6.2. Tracking and Calorimeter Isolation

After a single quadruplet has been chosen, three final cuts are applied, two of which correspond to normalized isolation cuts. The normalized track isolation discriminant is defined as the sum of the transverse momenta of tracks, $\Sigma p_T$, in a cone of $\Delta R < 0.20$ around the lepton, divided by the lepton $p_T$. Each lepton is required to have a normalized track isolation smaller than 15%.

The normalized calorimetric isolation discriminant is defined as the sum of the calorimeter cells, $\Sigma E_T$, inside an isolation $\Delta R < 0.20$ around the lepton, divided by the lepton $E_T$. Each lepton is required to have a normalized calorimetric isolation smaller than 30%.

5.4.6.3. Impact Parameter Significance

The impact parameter significance, $|d_0|/\sigma(d_0)$, is required to be less than 3.5 for muons and 6 for electrons if and only if the reconstructed invariant mass of all four leptons, $m_{4\ell}$ is less than 190 GeV. The electron impact parameter significance is affected by bremsstrahlung and, as a result, is much broader. The performance of the isolation and impact parameter criteria has been studied using $Z \rightarrow \ell\ell$ and $b, c \rightarrow \mu$ events and the efficiency of the criteria in the Monte Carlo was found to be in close agreement with that observed in the data.
5.4.7. Higgs Mass Resolution

The Higgs mass resolution is obtained from statistical fits of an unbinned maximum likelihood of a gaussian model to the $4\ell$ invariant mass distribution [52]. The theoretical width of hypothetical Standard Model Higgs masses in various final states are listed in Tables 28 and 29 of Reference [50].

5.5. Selection efficiency for the Higgs signal

By applying the previously described selection criteria to the signal samples of Higgs decays to $ZZ^{(*)}$ for different masses, one can calculate the total analysis efficiency to reconstruct the final state. Table 5.14 shows the total analysis efficiency with respect to the generated $4\ell$ events with fiducial cuts on the generated events, i.e., the efficiency is based on the acceptance region of the detector as compared to the analysis and without, i.e., selected events are compared to all generated $H \rightarrow 4\ell$ events. These efficiencies are calculated for selected Higgs masses for $4\mu$, $2e2\mu$, and $4e$ final states. Figure 5.8 presents the total efficiency of selection criteria as a function of hypothetical Higgs masses. The discontinuity of the efficiency curve for $m_H < 180$ GeV after the $Z2$ cut in Figure 5.8(b) is due to the threshold mass cuts on $m_{34}$, which are represented in Table 5.7

5.6. Background Estimation Methods

This section summarizes the data-driven background estimation techniques used in different control regions in the data. A more detailed explanation is available in Reference [52]. In general, the main backgrounds that affect the $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$ process are the irreducible $pp \rightarrow ZZ^{(*)}\rightarrow 4\ell$ continuum and the reducible $Z +$ jets, $Zb\bar{b} \rightarrow 4\ell + X$, and $t\bar{t} \rightarrow 4\ell + X$ processes, $X$ denotes the additional leptons. We use kinematical control regions defined by invariant mass and transverse momenta vari-
<table>
<thead>
<tr>
<th>$m_H$ GeV</th>
<th>With fiducial cuts</th>
<th>No fiducial cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4µ</td>
<td>2e2µ</td>
</tr>
<tr>
<td>110</td>
<td>10.5</td>
<td>6.12</td>
</tr>
<tr>
<td>115</td>
<td>23.4</td>
<td>14.7</td>
</tr>
<tr>
<td>120</td>
<td>32.2</td>
<td>21.5</td>
</tr>
<tr>
<td>125</td>
<td>39.5</td>
<td>25.9</td>
</tr>
<tr>
<td>130</td>
<td>44.5</td>
<td>29.9</td>
</tr>
<tr>
<td>135</td>
<td>47.4</td>
<td>33.1</td>
</tr>
<tr>
<td>140</td>
<td>49.0</td>
<td>35.3</td>
</tr>
<tr>
<td>145</td>
<td>52.4</td>
<td>36.4</td>
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<td>54.0</td>
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<td>180</td>
<td>70.2</td>
<td>54.1</td>
</tr>
<tr>
<td>200</td>
<td>71.8</td>
<td>58.0</td>
</tr>
<tr>
<td>260</td>
<td>69.7</td>
<td>59.1</td>
</tr>
<tr>
<td>360</td>
<td>70.0</td>
<td>61.0</td>
</tr>
<tr>
<td>460</td>
<td>69.5</td>
<td>63.2</td>
</tr>
<tr>
<td>600</td>
<td>68.9</td>
<td>64.1</td>
</tr>
</tbody>
</table>

Table 5.14. Efficiency of reconstructing the Higgs signal after the selection criteria summarized in Table 5.6 with and without fiducial cuts. The Monte Carlo is weighted to match the pileup conditions measured in data. For the columns with fiducial cuts applied, the following criteria were applied: final state electron and muon $p_T > 5.5$ GeV, $|\eta| < 2.7$, and $m_{Z}, m_{Z^*} > 12$ GeV in the event.
Figure 5.8. The efficiencies in each plot correspond to ggF+VBF+WH+ZH (see Figure 5.1) and they are normalized to the truth cuts mentioned in Table 5.14. The results in (a) occur after the Z1 mass cut, (b) after the Z2 mass cut. Figures (c) occur after track isolation and (d) after calorimeter isolation. Results in Figure (e) occur after impact parameter significance and (f) is after ΔR.
ables, where the signal is not expected and then extrapolate the signal-like shape into the search region of the data. This technique avoids systematic problems with theoretical uncertainties of background modeling and uses the same detector performance as signal data.

The first control region aims at constraining a possible residual contribution from QCD multi-jet production. Then a $t\bar{t}$ control region is constructed using $e^{\pm}\mu^{\pm}$ consistent with the $Z$ mass and requiring the presence of additional leptons in the event. The observed events are then compared to the $t\bar{t}$ expectation from MC. Finally, the estimation of the most important reducible background $Z+XX$, where each $X$ denotes one additional leptons.

5.6.1. $Z+XX$

$Z$ plus additional leptons ($Z$+jets, $Zb\bar{b}\rightarrow 4l+X$) is the most important reducible background for a low-mass Higgs ($m_H<2m_Z$) where a sub-leading (secondary) muon pair is the four-lepton final state of the $ZQQ$ production process\textsuperscript{15} In the case of electrons, the most significant contributions come from jets faking electrons and photon conversions.

Data-driven background estimation for the $Z$ plus heavy quark and $Z$ plus light jets backgrounds is done by selecting appropriate control regions where no signal is expected. Background contributions are extrapolated to the signal region and used to cross-check Monte Carlo simulation.

\textsuperscript{15}Q denotes heavy-flavor jets originating from $b$ and $c$ quarks
5.6.2. $t\bar{t}$

A control region for $t\bar{t}$ is constructed by selecting events with an $e^{\mp}\mu^{\pm}$ di-lepton pair with an invariant mass consistent with an on-shell Z within 15 GeV and two additional opposite-sign same-flavor leptons. The four leptons must satisfy the selection criteria mentioned in Section 5.4.5 while the $p_T$ requirement for the $e\mu$ pair is 20 GeV and 7 GeV for the additional leptons. Track isolation requirements are applied to the leptons of the $e\mu$ pair.

The contribution of other electroweak processes is negligible. Possible contributions from QCD events are estimated using a control region constructed with the same selection as above with the exception of same-sign $e\mu$ di-lepton pairs, further discussed in Reference [52].

5.6.3. QCD

By simple requirement of four isolated leptons with low impact parameter significance in the final state, possible contributions from QCD multi-jet production is minimal.

The control region is constructed by selecting events where the primary di-lepton is formed by same sign leptons and that fulfill all of the other selection criteria for the analysis. From Monte Carlo, the ratio of same-sign to opposite-sign QCD events is expected to be on the order of 50%. One should also include the expected number of events from other processes like $ZZ$, $Z$+jets and $t\bar{t}$, especially for the electrons where the charge mis-identification rate is non-negligible.

The event yields in the QCD control region are summarized in Table 11 of Reference [52] where the Monte Carlo includes contributions from $ZZ$, $Z$+jets and $t\bar{t}$. All QCD events in the leading di-lepton mass window are rejected after requiring track isolation on the leading ($p_T$) leptons.
5.7. Systematic Uncertainties

In this section, the sources of magnitudes of various systematic uncertainties are discussed for the $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$ analysis. More details can be found in Reference [52].

5.7.1. Luminosity

An overall normalization uncertainty of 3.9% is applied to the luminosity of Monte Carlo samples for which normalization was not obtained from the data.

5.7.2. Cross-sections of Higgs boson production

The Higgs boson production cross-sections have been studied extensively by the LHC Higgs cross-section theory working group and the results are compiled in Reference [50]. The theoretical uncertainties on the cross-sections have been estimated to be between $15 - 20\%$ for $gg \rightarrow H$, $5\%$ for $q\bar{q} \rightarrow q\bar{q}H$, $3.5\%$ for $q\bar{q} \rightarrow W/ZH$, all of which are used in Higgs production; their uncertainties are applied to the signal samples for all mass points.

The $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$ analysis follows the LHC Higgs combination recommendation and splits the uncertainty for the PDF+$\alpha_s$ and QCD scale as shown in Table 5.15. Studies [50, 87] have indicated that the effects related to off-shell Higgs boson production and interference with with other Standard Model processes at higher masses ($m_H > 400$ GeV). A conservative estimate on the possible size of effects was included as a signal normalization systematic uncertainty following a parameterization as a function of $m_H : 150\% \times (m_H[^{[TeV]}])^3$, for $m_H \geq 300$ GeV.

5.7.3. Cross-sections of background processes
Table 5.15. PDF and scale uncertainties. Higgs mass dependent values are available at Reference [88].

<table>
<thead>
<tr>
<th>Group</th>
<th>Nuisance</th>
<th>Comments</th>
<th>Typical Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDFs+${\alpha_s}$</td>
<td>$gg$</td>
<td>$gg \to H$, $t\bar{t}H$, $gg \to VV$</td>
<td>8%</td>
</tr>
<tr>
<td>(cross sections)</td>
<td>$q\bar{q}$</td>
<td>VBF $H$, VH, VV@NLO</td>
<td>4%</td>
</tr>
<tr>
<td>Higher-order uncertainties</td>
<td>$ggH$</td>
<td>Total inclusive $gg \to H$</td>
<td>+12%</td>
</tr>
<tr>
<td>on cross sections</td>
<td>$qqH$</td>
<td>VBF $H$</td>
<td>-7%</td>
</tr>
<tr>
<td></td>
<td>$VH$</td>
<td>associate $VH$</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>$VV$</td>
<td>$WW$, $WZ$, and $ZZ$ up to NLO</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>$ggVV$</td>
<td>$gg \to WW$ and $gg \to ZZ$</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$</td>
<td>$t\bar{t}$</td>
<td>+3%</td>
</tr>
</tbody>
</table>

A normalization error of 15% is assigned to the ZZ contribution, which accounts for the theoretical uncertainties in the cross-section calculation and the uncertainty due to the use of the $gg \to ZZ$ correction. Uncertainties of 45% and 40% are assigned on the normalization of the $Z+\text{light-flavor-jets}$ and $Zb\bar{b}$ samples, respectively, to account for the uncertainty on their data-driven estimation (statistical uncertainty in the control sample and the MC-based extrapolation to the signal region. The theoretical uncertainties on the $t\bar{t}$ cross-section, approximately 10%, are included with the PDFs correlated. The additional uncertainty in the $t\bar{t}$ selection efficiency, estimated to be 10%, is negligible in comparison with the errors on the larger backgrounds.

5.7.4. Lepton Reconstruction and Identification

In this subsection, the results of calculating systematic uncertainties based on various scale factors associated with the energy/momentum resolution, reconstruction and identification efficiency, and energy scale uncertainty are presented. A detailed
procedure for calculating systematic uncertainties is available at Reference [89]; more information on the scale factors and associated uncertainties are available at the following References: [81, 82, 86].

The systematic uncertainty on the energy (for electrons) or momentum resolution (for muons) is calculated by first shifting the energy/momenta of an electron/muon by a scale factor (derived from data-Monte Carlo agreement) prior to selecting events; then by observing the effect of this scale factor on the number of events in the final state, i.e., events that survive all of the selection criteria, and the shift in the mean of the invariant $4\ell$ mass distribution. The shifting procedure, often referred to as “smearing”, is done for a nominal scaling value (e.g., $\alpha$) and scaling value $\pm 1 \sigma$ (e.g. $\alpha + \sigma$, $\alpha - \sigma$). For electrons, this procedure is done three times ($\alpha$, $\alpha + \sigma$, $\alpha - \sigma$) as the energy is only measured in the calorimeter. The smearing procedure for muons is a little different, where momenta is measured in the muon spectrometer and the inner detector. There is a single nominal scale factor for both components of the detector and two different standard deviations to apply, i.e., one standard deviation based on the muon spectrometer, the other on the inner tracking detector.

The systematic uncertainty on reconstruction and identification efficiency is calculated by an additional scale factor (derived from data-Monte Carlo agreement) applied to each lepton in the final state. These uncertainties are related to the ability to reconstruct lepton candidates as well as identify given certain requirements on their quality.

5.7.4.1. Electron Reconstruction and Identification

The electron energy scale uncertainty is found to be less than 1% in most of the $\eta$ region of interest, while the energy resolution uncertainty is estimated to vary between 0.1% and 0.4%. The effect of the energy resolution in the final state is on average a
few per mil, see Figure 5.10, 5.11 and 5.12.

The reconstruction and identification efficiency uncertainty (summarized in Table 5.19) is on average 6% in the $E_T$ region relevant for electrons from $Z \rightarrow ee$ decays. Systematic uncertainties in all final states are given in Table 5.16 for the signal, and in Table 5.18 and Figure 5.9 for the $ZZ \rightarrow 4\ell$ background.

5.7.4.2. Muon Reconstruction and Identification

The muon momentum scale uncertainty is generally found to be less than 1%, see Table 5.17 while the uncertainty in the momentum resolution is negligible and less than 1%. The effect of momentum resolution uncertainty for the muon spectrometer (MS) and inner tracking Detector (ID) is of the order of a few per mil (see Figure 5.10 and 5.11).

Finally, the uncertainty on the identification efficiency of muons (summarized in Table 5.19) is estimated to be between 0.16% and 0.22% for the phase space of interest. The muon final state systematic uncertainties are given in Table 5.16 for the signal and Table 5.18 and Figure 5.9 for the $ZZ \rightarrow 4\ell$ background.

5.7.5. Trigger

Due to the presence of multiple high-$p_T$ leptons in the final state, the trigger efficiency is very close to 100% as presented in Tables 5.10 - 5.13. The corresponding uncertainties are calculated by checking the number of events that pass all the selection criteria with and without the trigger requirement; the uncertainties are found to be negligible.
Table 5.16. Systematic uncertainty on the signal yield, determined by electron and muon reconstruction efficiency uncertainty; in percent.

<table>
<thead>
<tr>
<th>( m_H ) GeV</th>
<th>Electron Uncertainties</th>
<th>Muon Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( H \rightarrow 4\mu )</td>
<td>( H \rightarrow 2e2\mu )</td>
</tr>
<tr>
<td>110</td>
<td>-1.673</td>
<td>13.618</td>
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<tr>
<td>115</td>
<td>-1.769</td>
<td>13.254</td>
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<tr>
<td>120</td>
<td>-1.810</td>
<td>12.237</td>
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<tr>
<td>125</td>
<td>-1.791</td>
<td>11.296</td>
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<tr>
<td>130</td>
<td>-1.891</td>
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<td>135</td>
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<td>8.401</td>
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<tr>
<td>140</td>
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<td>7.564</td>
</tr>
<tr>
<td>145</td>
<td>-2.067</td>
<td>6.493</td>
</tr>
<tr>
<td>150</td>
<td>-2.034</td>
<td>5.789</td>
</tr>
<tr>
<td>180</td>
<td>-2.017</td>
<td>2.833</td>
</tr>
<tr>
<td>200</td>
<td>-1.996</td>
<td>2.683</td>
</tr>
<tr>
<td>260</td>
<td>-1.953</td>
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<td>360</td>
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<td>2.123</td>
</tr>
<tr>
<td>460</td>
<td>-1.695</td>
<td>1.953</td>
</tr>
<tr>
<td>600</td>
<td>-1.554</td>
<td>1.893</td>
</tr>
</tbody>
</table>

Table 5.17. Effect of using fixed and non-fixed energy scales for muons when smearing the \( p_T \) measured in the MS for several gluon-gluon fusion samples.

<table>
<thead>
<tr>
<th>( m_H ) GeV</th>
<th>Number of Events Fixed Energy Scale</th>
<th>Number of Events Non-Fixed Energy Scale</th>
<th>Difference in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>269</td>
<td>264</td>
<td>-1.86</td>
</tr>
<tr>
<td>130</td>
<td>1543</td>
<td>1535</td>
<td>-0.52</td>
</tr>
<tr>
<td>200</td>
<td>3276</td>
<td>3274</td>
<td>-0.06</td>
</tr>
<tr>
<td>360</td>
<td>2769</td>
<td>2757</td>
<td>-0.43</td>
</tr>
</tbody>
</table>
Figure 5.9. Systematic uncertainties due to reconstruction and identification in percent for the $ZZ \rightarrow 4\ell$ background per 10 GeV for masses 100 - 250 GeV, per 25 GeV for masses 250 - 500 GeV and per 50 GeV for masses higher than 500 GeV.
Figure 5.10. The $m_\Delta$ distributions shown are obtained by varying the resolution of the ID or MS momenta of each by 1 $\sigma$ for the Higgs mass $m_H = 150$ GeV. Systematic uncertainties are obtained by comparing the number of events passing all the selection criteria before and after smearing. They are less than 1% and considered negligible.
Figure 5.11. The $m_{4\ell}$ distributions shown are obtained by varying the resolution of the ID or MS momenta of each by 1 $\sigma$ for the Higgs mass $m_H = 200$ GeV. Systematic uncertainties are obtained by comparing the number of events passing all the selection criteria before and after smearing. They are less than 1% and considered negligible.
Figure 5.12. $m_4l$ obtained varying the resolution by 1 $\sigma$ for the electrons in the case of (a) $m_H = 150$ GeV and (b) $m_H = 200$ GeV. Systematic uncertainties are obtained by comparing the number of events passing all the selection criteria before and after smearing. They range between 0.1% and 0.4% and considered negligible.
Table 5.18. Systematic uncertainty yield on the $ZZ \rightarrow 4\ell$ background; determined by electron and muon reconstruction efficiency uncertainty; in percent.

<table>
<thead>
<tr>
<th>$m_{H}$ GeV</th>
<th>Electron Uncertainties</th>
<th>Muon Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H \rightarrow 4\mu$</td>
<td>$H \rightarrow 2e2\mu$</td>
</tr>
<tr>
<td>100.00 - 110.00</td>
<td>- 1.52 1.33 18.57</td>
<td>0.20 0.16 0.01</td>
</tr>
<tr>
<td>110.00 - 120.00</td>
<td>- 1.08 6.03 15.43</td>
<td>0.22 0.10 0.06</td>
</tr>
<tr>
<td>120.00 - 130.00</td>
<td>- 1.15 4.88 13.02</td>
<td>0.22 0.09 0.06</td>
</tr>
<tr>
<td>130.00 - 140.00</td>
<td>- 1.13 3.91 10.25</td>
<td>0.22 0.09 0.06</td>
</tr>
<tr>
<td>140.00 - 150.00</td>
<td>- 1.02 4.37 8.52</td>
<td>0.23 0.08 0.08</td>
</tr>
<tr>
<td>150.00 - 160.00</td>
<td>- 1.38 2.50 7.07</td>
<td>0.22 0.10 0.06</td>
</tr>
<tr>
<td>160.00 - 170.00</td>
<td>- 0.98 2.41 6.47</td>
<td>0.22 0.08 0.08</td>
</tr>
<tr>
<td>170.00 - 180.00</td>
<td>- 0.87 1.75 4.85</td>
<td>0.22 0.07 0.09</td>
</tr>
<tr>
<td>180.00 - 190.00</td>
<td>- 0.68 1.49 3.29</td>
<td>0.22 0.06 0.09</td>
</tr>
<tr>
<td>190.00 - 200.00</td>
<td>- 0.81 1.26 3.42</td>
<td>0.22 0.07 0.09</td>
</tr>
<tr>
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<td>0.22 0.07 0.09</td>
</tr>
<tr>
<td>210.00 - 220.00</td>
<td>- 0.91 1.35 3.45</td>
<td>0.22 0.07 0.09</td>
</tr>
<tr>
<td>220.00 - 230.00</td>
<td>- 0.90 1.33 3.77</td>
<td>0.22 0.07 0.09</td>
</tr>
<tr>
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<td>0.22 0.07 0.08</td>
</tr>
<tr>
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<td>0.22 0.07 0.09</td>
</tr>
<tr>
<td>250.00 - 275.00</td>
<td>- 0.99 1.53 3.93</td>
<td>0.22 0.07 0.08</td>
</tr>
<tr>
<td>275.00 - 300.00</td>
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<td>0.22 0.07 0.08</td>
</tr>
<tr>
<td>300.00 - 325.00</td>
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<td>0.22 0.07 0.08</td>
</tr>
<tr>
<td>325.00 - 350.00</td>
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<td>0.23 0.07 0.09</td>
</tr>
<tr>
<td>350.00 - 375.00</td>
<td>- 1.23 1.41 4.54</td>
<td>0.22 0.07 0.08</td>
</tr>
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<td>375.00 - 400.00</td>
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</tr>
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<td>0.22 0.07 0.09</td>
</tr>
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<td>0.22 0.08 0.08</td>
</tr>
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<td>0.23 0.08 0.08</td>
</tr>
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<td>0.22 0.07 0.08</td>
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<td>0.22 0.09 0.07</td>
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<td>0.23 0.07 0.08</td>
</tr>
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<td>0.22 0.06 0.09</td>
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<td>0.22 0.08 0.07</td>
</tr>
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<td>0.22 0.07 0.08</td>
</tr>
<tr>
<td>750.00 - 800.00</td>
<td>- 2.50 1.02 3.75</td>
<td>0.24 0.13 0.04</td>
</tr>
</tbody>
</table>
Table 5.19. Systematic uncertainty on the signal yield, determined by electron and muon reconstruction efficiency, energy scale and resolution uncertainty; in percent for $m_H = 110$ GeV.

<table>
<thead>
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<th>Channel</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
<th>$2\mu2e$</th>
<th>$4e$</th>
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<td>±3.9</td>
<td>±3.9</td>
<td>±3.9</td>
<td>±3.9</td>
</tr>
<tr>
<td>$e/\gamma$ efficiency</td>
<td>-</td>
<td>±1.6</td>
<td>±8.0</td>
<td>±8.2</td>
</tr>
<tr>
<td>$e/\gamma$ energy scale</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$e/\gamma$ resolution</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\mu$ efficiency</td>
<td>±0.22</td>
<td>±0.16</td>
<td>±0.16</td>
<td>-</td>
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</tr>
<tr>
<td>$\mu$ resolution</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>
5.8. Beyond the Baseline Analysis

There are many ways to build upon the baseline analysis to improve signal acceptance. This topic is constantly pursued within the Higgs working group; higher efficiencies mean less data are needed to make a discovery. Studies designed and developed to improve the overall acceptance of the 4\ell final state, the worst performing final state in the $H \to ZZ^{(*)}\to 4\ell$ channel, are briefly discussed in Appendix E.
Chapter 6
RESULTS

In this chapter, the results of applying the selection criteria as described in Section 5.4 to the data is presented. The data were collected in 2011 and correspond to an integrated luminosity of 4.8 fb$^{-1}$. Higgs exclusion limits at the 95% Confidence Level (CL) are also presented.

6.1. Data

In total, 71 candidate events are selected by this analysis in the data; a breakdown of the number of events per final-state is presented in Table 6.1. For the mass range 100 - 600 GeV, $62 \pm 9$ events are expected from the background processes. Event yields for the background contributions, multiple $m_H$ hypotheses, and data in the low ($m_{4\ell} < 180$ GeV) and high ($m_{4\ell} \geq 180$ GeV) mass regions are presented in Table 6.2.

Table 6.1. The total number of candidate events selected in each of the final states in $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$ analyses.

<table>
<thead>
<tr>
<th>Final State</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>4\mu</td>
<td>24</td>
</tr>
<tr>
<td>2e2\mu</td>
<td>30</td>
</tr>
<tr>
<td>4e</td>
<td>17</td>
</tr>
</tbody>
</table>
Table 6.2. The expected number of signal and background events, with their systematic uncertainty, separated into “Low-mass” \( (m_{4\ell} < 180 \text{ GeV}) \) and “High-mass” \( (m_{4\ell} \geq 180 \text{ GeV}) \) regions. The observed numbers of events are also presented.

<table>
<thead>
<tr>
<th>Int. Luminosity</th>
<th>( \mu\mu\mu )</th>
<th>( e\mu\mu )</th>
<th>( eee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.81 fb(^{-1})</td>
<td>Low-mass</td>
<td>High-mass</td>
<td>Low-mass</td>
</tr>
<tr>
<td>4.81 fb(^{-1})</td>
<td>Low-mass</td>
<td>High-mass</td>
<td>Low-mass</td>
</tr>
<tr>
<td>4.91 fb(^{-1})</td>
<td>Low-mass</td>
<td>High-mass</td>
<td>Low-mass</td>
</tr>
</tbody>
</table>

- \( Z\ell\ell \): 2.1±0.3 16.3±2.4 2.8±0.6 25.2±3.8 1.2±0.3 10.4±1.5
- \( Z \): 0±0. 0±0. 1.0±0.5 0.18±0.08 1.3±0.6 0.21±0.09
- \( Zbb \): 0.14±0.06 0.02±0.01 0.21±0.08 0.04±0.01 0.17±0.07 0.03±0.01
- \( tt \): 0.02±0.01 0.01±0.01 0.04±0.01 0.02±0.01 0.01±0.01 0.01±0.01
- \( Z, Zbb, \) and \( tt \): 0.16±0.06 0.02±0.01 1.4±0.5 0.17±0.08 1.6±0.7 0.18±0.08

Total Background: 2.2±0.3 16.3±2.4 4.3±0.8 25.4±3.8 2.8±0.8 10.6±1.5

<table>
<thead>
<tr>
<th>Data</th>
<th>3</th>
<th>21</th>
<th>3</th>
<th>27</th>
<th>2</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>14.1^{+2.7}_{-2.1}</td>
<td>1.154^{+0.032}_{-0.027}</td>
<td>0.501 ± 0.020</td>
<td>0.278 ± 0.014</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>10.5^{+2.9}_{-1.6}</td>
<td>0.962^{+0.028}_{-0.021}</td>
<td>0.300 ± 0.012</td>
<td>0.171 ± 0.009</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>5.2^{+0.9}_{-0.8}</td>
<td>0.637^{+0.022}_{-0.015}</td>
<td>0.103 ± 0.005</td>
<td>0.061 ± 0.004</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>2.0 ± 0.3</td>
<td>0.162^{+0.010}_{-0.005}</td>
<td>–</td>
<td>–</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>0.33 ± 0.06</td>
<td>0.058^{+0.002}_{-0.005}</td>
<td>–</td>
<td>–</td>
<td>1.23</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.1. Invariant mass distributions of the lepton pairs in the control sample defined by a $Z$ boson candidate and an additional same-flavor lepton pair. The sample is divided according to the flavor of the additional lepton pair. In (a) the $m_{12}$ and in (b) the $m_{34}$ distributions are presented for $Z(\rightarrow \mu^+\mu^-/e^+e^-) + \mu\mu$ events. In (c) the $m_{12}$ and in (d) the $m_{34}$ distributions are presented for $Z(\rightarrow \mu^+\mu^-/e^+e^-) + ee$ events. The kinematic selections of the analysis are applied. Isolation requirements are applied to the first lepton pair only.
Figure 6.1 represents the mass distributions of the primary and secondary di-lepton pairs belonging to the control regions as described in Section 5.6. These control regions directly reflect on the ability to select regions for which we expect background only, i.e., no signal. In general, one can see that the agreement between the data and Monte Carlo is good, implying that we understand our contributions from the background.

In Figure 6.2, the $\eta$ and $E_t/p_T$ distributions of the leptons passing all of the selection criteria are shown. The invariant mass distributions for the primary and secondary di-lepton pairs are shown in Figure 6.3. In both of these figures, the data is shown with the expected contributions from background-only. One can see that the agreement between the data and background is not good, implying that a background-only model is insufficient to explain our observations in the data.

Finally, the invariant mass distributions of four-lepton events passing the selection criteria along with background expectations and hypothetical Standard Model Higgs masses at $m_H = 125$ GeV, $m_H = 150$ GeV, and $m_H = 190$ GeV are presented in Figure 6.4. A further breakdown of these events into their $4\mu$, $2e2\mu/2\mu2e$, and $4e$ final states is presented in Figure 6.5. One can see that there are significant fluctuations in the signal and background expectations.
Figure 6.2. (b) $\eta$ and (a) $p_T$ distribution for the leptons of the 71 candidates surviving the selection criteria. The data (dots) is compared to the expectations from the dominant $ZZ^{(*)}$ process and the sum of $t\bar{t}$, $Zb\bar{b}$ and $Z+$light jets processes. Error bars represent 68.3% central confidence intervals.

Figure 6.3. Invariant mass distributions (a) $m_{12}$ and (b) $m_{34}$ for the selected candidates. The data (dots) are compared to the background expectations. Error bars represent 68.3% central confidence intervals.
Figure 6.4. Invariant mass distributions (a) $m_{12}$, (b) $m_{34}$ for the selected candidates. All plots show comparisons with background expectation from the dominant $ZZ^*$ and the sum of $t\bar{t}$, $Z\bar{b}b$ and $Z$+jets processes. Error bars respect 68.3% central confidence intervals.

Figure 6.5. $m_{4\ell}$ distribution of the selected candidates for the different sub-channels of the analysis, compared to the background expectation: (a) $4\mu$, (b) $2\mu 2e/2e 2\mu$, (c) $4e$. Error bars represent 68.3% central confidence intervals. The signal expectation for several $m_H$ hypotheses is also shown.
6.2. Exclusion Limits

Upper limits have been derived for the Standard Model Higgs boson production cross section at the 95% Confidence Level (CL); using the $CL_s$ modified frequentist formalism \cite{90} with the profile likelihood test statistic \cite{91} and calculated using RooStat \cite{92}. The test statistic is evaluated with a maximum likelihood fit of signal and background models to data. Figure \ref{fig:6.6} shows the 95% Confidence Level, which is the ratio of the observed to expected number of events for a given Higgs mass, i.e., observations in data to the expectations for background. This ratio equal to one describes a perfect agreement with background-only. The ratio smaller than one describes regions where the Higgs region is excluded. This ratio greater than one describes regions for which the Higgs has not been excluded. The expected and observed exclusions as a function of $m_H$ and Table \ref{tab:6.3} and Table \ref{tab:6.4} summarize the numerical values for selected $m_H$ points. The Standard Model Higgs boson is excluded at 95% CL in the ranges $134 - 156$ GeV, $182 - 233$ GeV, $256 - 265$ GeV and $268 - 415$ GeV.

Table 6.3. Median expected and observed 95% CL upper limits using asymptotics on the Higgs boson production cross section for several Higgs boson masses, divided by the expected Standard Model Higgs boson cross section.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>5.05</td>
<td>4.71</td>
</tr>
<tr>
<td>130</td>
<td>1.56</td>
<td>1.73</td>
</tr>
<tr>
<td>150</td>
<td>0.68</td>
<td>0.83</td>
</tr>
<tr>
<td>200</td>
<td>0.59</td>
<td>0.67</td>
</tr>
<tr>
<td>300</td>
<td>0.79</td>
<td>0.52</td>
</tr>
<tr>
<td>400</td>
<td>1.02</td>
<td>0.72</td>
</tr>
<tr>
<td>600</td>
<td>5.07</td>
<td>8.44</td>
</tr>
</tbody>
</table>
Another way of looking at these data is to assume the existence of a background only. The $p$-value is defined as the probability of upward fluctuations in the background to be as high as or higher than the excesses observed in data in a background-only model. The consistency of the observed results with the background-only hypothesis expressed as $p$-values for the full $m_H$ mass range of the analysis is shown in Figure 6.7. The most significant upward deviations from the background-only hypothesis and corresponding $p_0$ in the presence of a Higgs boson for $m_H = 125$ GeV, 244 GeV, and 500 GeV are shown in Table 6.5.

The quoted values do not account for the so-called look-elsewhere effect, which takes into account the fact that we are looking for deviations in large numbers of bins.
Table 6.4. Median expected and observed 95% CL upper limit using toys on the Standard Model Higgs boson production cross section, in multiples of the Standard Model rate, as a function of the Higgs boson mass in GeV, obtained with $CL_s$.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>5.32</td>
<td>5.40</td>
</tr>
<tr>
<td>130</td>
<td>1.66</td>
<td>1.89</td>
</tr>
<tr>
<td>150</td>
<td>0.72</td>
<td>0.85</td>
</tr>
<tr>
<td>200</td>
<td>0.59</td>
<td>0.68</td>
</tr>
<tr>
<td>300</td>
<td>0.85</td>
<td>0.55</td>
</tr>
<tr>
<td>400</td>
<td>1.00</td>
<td>0.77</td>
</tr>
<tr>
<td>600</td>
<td>5.29</td>
<td>8.55</td>
</tr>
</tbody>
</table>

and in many final states thus increasing the probability of observing fluctuations. In other words, the look-elsewhere effect addresses the probability that such an excess (or a larger one) can appear anywhere in the search range as a result of an upward fluctuation of the background. When considering the complete mass range of this search, using the method of Reference [93], the global $p_0$-value for each of the three excesses becomes of order 50%. Thus, once the look-elsewhere effect is considered, none of the observed local excesses are significant.

6.3. Summary

A study of Standard Model Higgs boson in the golden decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ based on 4.8 fb$^{-1}$ of data recorded by the ATLAS detector at $\sqrt{s} = 7$ TeV during the 2011 run has been presented. The Standard Model Higgs boson is excluded at 95% CL in the mass ranges $134 - 156$ GeV, $182 - 233$ GeV, $256 - 265$ GeV and $268 - 415$ GeV. The largest significances for the background-only hypothesis are
Table 6.5. $p$-values for the most significant upwards deviations in a background-only hypothesis and in the presence of a Higgs boson for $m_H = 125$ GeV, 244 GeV, and 500 GeV.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>Background-only Hypothesis</th>
<th>Presence of Standard Model Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 GeV</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>244 GeV</td>
<td>2.2</td>
<td>3.0</td>
</tr>
<tr>
<td>500 GeV</td>
<td>2.1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

observed at $m_H = 125$ GeV, 244 GeV, and 500 GeV with corresponding local significances of $2.1 \sigma$, $2.2 \sigma$ and $2.1 \sigma$, where $\sigma$ is the standard deviation. The most interesting of which is the significance near 125 GeV.

When the results of the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analysis are combined with the results of other search channels at ATLAS, the combined local significance for a Standard Model Higgs boson with $m_H = 125$ GeV increases to $3.6 \sigma$ [94]. The consistency of $p$-values for the three channels ($H \rightarrow \gamma\gamma$, $H \rightarrow WW^{(*)} \rightarrow \ell^+\nu\ell^-\bar{\nu}$, and $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell'^+\ell'^-$) contributing to the area near 125 GeV is shown in Figure 6.8.

In a subsequent publication by the competing LHC experiment CMS in February 2012, a combined local significance of $3.1 \sigma$ has been observed for the background-only hypothesis for masses near 124 GeV [95]. Finally, during the Rencontres de Moriond conference in March 2012, the Tevatron experiments CDF and D0 announced the observation of an enhancement of $2.2 \sigma$ significance in the region between 115 GeV and 135 GeV, also for the background-only hypothesis [96]. Figure 6.9 shows the $p$-values for the CMS and Tevatron experiments in the region near 125 GeV.
Figure 6.7. The consistency of the observed results with the background-only hypothesis expressed as p-values is shown in the full mass range of the analysis. The dashed line shows the median expected significance in the hypothesis of a Standard Model Higgs boson production. The two horizontal dashed lines indicate the p-values corresponding to local significances of 2 σ and 3 σ, using toy Monte Carlo pseudo-experiments and using the asymptotic approximation.

Before the start of data taking period, the LHC experiments decided that due to the large number of the final states that will be studied, the claim of a discovery of the Higgs boson will require a significance of 5 σ. We are not there yet.

A Standard Model Higgs boson has yet to be discovered experimentally; but there is an incredibly strong hint for a Standard Model Higgs near 125 GeV, corroborated by the latest results from ATLAS, CMS, and the Tevatron [94–96]. The LHC is preparing to deliver beams at $\sqrt{s} = 8$ TeV and has announced a goal of delivering additional integrated luminosity of $\sim 7$ fb$^{-1}$ by the end of June 20, 2012, at which time, more will be said about the existence of Standard Model Higgs boson during the summer conferences. By the end of $pp$ collision data-taking in late October, the LHC hopes to have delivered 15-20 fb$^{-1}$ of integrated luminosity.
Figure 6.8. The consistency of the observed results with the background-only hypothesis for the three strongest channels and the combination in the low mass region. The dashed curves show the median expected significance in the hypothesis of a Standard Model Higgs boson production signal, which is about equal for all three of these channels near 125 GeV.

Figure 6.9. $p$-values for the background-only hypothesis near 125 GeV at the CMS (a) and Tevatron (b) experiments.
A.1. Shifter Panel Overview

The LAr Shifter Panel was developed and maintained in Java beginning in summer of 2008. Like the LAr Crate Panel (Appendix B), this control panel was developed in Java for use within the Trigger and Data AcQuisition T/DAQ software infrastructure. It is used by the shifters sitting at the LAr subsystem desk in the ATLAS control room to control calibration runs that are periodically needed to determine calibration constants. These calibration constants are used in energy calibration and correction. Initial work on this panel was dedicated to removing a number of bugs that affected the functionality and efficiency of the panel. Afterward, the algorithms that control calibration-run-taking were optimized, the user interface was aesthetically enhanced, and scripts to reformat the output files produced by each calibration run were developed. The interface can be seen in Figure A.1.

A calibration run injects fixed-value signals into the input of the readout electronics to check for deviations for the linearity, gain factors, pedestals, ramping, etc.; these runs are listed in 4.6.4.

The optimization of the algorithms used in the panel achieved gains of 33% in run-time efficiency. Prior to these changes, users would need to manually select the calibration runs needed as well as check various output files to check data integrity.
After the changes, were made, the most frequently taken calibration runs (called Daily and Weekly sets) are automated. Users only need to select which set (or run) is needed and monitor histograms to ensure excellent data quality. Before moving to the next calibration run, an external script is executed by the panel to check that the data taken suffered from no major errors (necessitating another run).

The algorithm is threaded to accommodate the (re)configure, running, shutdown commands needed by each calibration run (displayed in the bottom part of Figure A.1). These commands represent physical states of the LAr calorimeter. The (re)configure threads represent the time in which the information about the calibration run is retrieved from a database and loaded to the calibration boards in the LAr calorimeter. The running thread consists of the calibration run itself (Pedestal, Delay, or Ramp) and a data integrity check. The shutdown thread represents either a state in which the LAr calorimeter can safely change configurations within a specific type of calibration run or a state when the user shuts-down a partition of the LAr calorimeter after completing a set of calibration runs.
A variety of tasks performed by the LAr Shifter Panel are delegated to Bash shell scripts; most notably:

- the output file – lists all of the calibration runs taken along with information from the run and time stamps;

- data integrity – an external script is ran on the output ROOT ntuple to check the integrity of the data in each run as well as check for any errors.

More instructions on usage of the LAr Shifter Panel are available at References [97, 98].
Appendix B

Liquid Argon Crate Panel

B.1. Crate Panel Overview

The Liquid Argon (LAr) Crate Panel was designed and developed starting summer 2007. This monitoring panel was developed in Java for use within the Trigger and Data Acquisition (T/DAQ) software infrastructure. It is primarily used by shifters at the LAr subsystem desk in the ATLAS control room. It provides a fast and efficient way to control and monitor the temperatures of each front-end crate in the cryostats of the LAr Calorimeter. Users may monitor and or change the on and off status of any of the 122 LAr sections of the front-end crates with readout electronics. The panel has a simple interface, which allows the user to query the Relation Database for each available crate using the Data Access Library (DAL) package. After having done this, the user may select a partition of the detector (as shown in Figure B.1) allowing them to monitor the status of the crates in that location. The state of each crate as well as minimum and maximum temperatures are retrieved from Information Service and are displayed as they are updated. During special calibration runs or development modes there is a third Not Available state, which means that crates are not loaded in the current T/DAQ partition and will not be read out by DAQ.

An example of the panel when used in the Barrel partition during a run can be seen in Figure B.2. There are four partition buttons, 16 crate status windows, 32 temperature windows, 16 toggle on/off switches, a refresh button, a save button, and lastly two buttons that can change the state of all the crates in the current location.
Figure B.1. Crate locations in the Barrel – (a) and (b) and the in the End-Caps – (c) and (d).
Figure B.2. LAr Crates Panel displaying the status and temperatures of the crates on the C side of the Barrel partition.

The main algorithm, which is threaded, navigates through multiple tiers in the database looking for the crates and their states and retrieves all updated temperatures. The second algorithm associates the information with the correct components of the interface. The final algorithm handles the interface components and manages all of the users actions and the majority of the database output. More instructions on usage of the LAr Crates Panel are available at Reference [99].
Appendix C

Electron Identification

Electrons can be reconstructed by soft-e, e/γ, or forward electron builder algorithms, the Author variable, identifies which algorithm was used in reconstruction electrons:

- Central Electrons, |\eta| < 2.5:
  - Author 1: Electron candidates are reconstructed by the e/γ builder algorithm that starts from calorimeter seeds.
  - Author 2: Electron candidates are reconstructed with the track-based soft-e builder algorithm.
  - Author 3: An electron candidate is reconstructed by both the track-based and calorimeter-seeded algorithm.

- Forward Electrons, 2.5 < |\eta| < 5.0, where tracking is not available:
  - Author 8: Electrons are reconstructed by the forward-electron reconstruction algorithm.

C.1. Electron isEM

The electron isEM variable simply defines the quality of a reconstructed electron. Electrons meeting Loose requirements have higher reconstruction efficiencies and lower jet background rejection rates than Medium or Tight.
C.1.1. Central Electrons

The electron isEM variable for central electrons has 32 binary flags which act as cuts. They are defined as follows. Please note that bits 7, 14, and 23 have intentionally been left out as they are not defined, and have started from 0 as it would appear in code. More information about the isEM definitions can be found in the header file of the egammaEvent package [100].

0. ClusterEtaRange_Electron – Cluster \( \eta \) Range

1. ConversionMatch_Electron – Electron that matches to a photon, but is not necessarily conversion – the name is historical.

2. ClusterHadronicLeakage_Electron – Cluster leakage into the Hadronic calorimeter.

3. ClusterMiddleEnergy_Electron – Energy in 2\(^{nd}\) sampling (e.g. E277 > 0)

4. ClusterMiddleEratio37_Electron – Energy ratio in 2\(^{nd}\) sampling (e.g. E237/E277)

5. ClusterMiddleEratio33_Electron – Energy ratio in 2\(^{nd}\) sampling (e.g. E233/E237)

6. ClusterMiddleWidth_Electron – Width in the 2\(^{nd}\) sampling (e.g. Weta2)

8. ClusterStripsEratio_Electron – Fraction of energy found in 1\(^{st}\) sampling. (Not actually used for electrons).

9. ClusterStripsDeltaEMax2_Electron – Energy of 2\(^{nd}\) maximum in 1\(^{st}\) sampling \(\sim e2tst1/(1000+\text{const}_lumi*et)\).

10. ClusterStripsDeltaE_Electron – Difference between 2\(^{nd}\) maximum and 1\(^{st}\) minimum in strips (e2tst1-emins1).


13. ClusterStripsWeta1c_Electron – Shower width weighted by distance from the maximum one.

15. ClusterStripsDeltaE_Electron – Difference between 2nd maximum and 1st minimum in strips (e2tsts1-emins1)

16. TrackBlayer_Electron – B layer hit.

17. TrackPixel_Electron – Number of Pixel hits.

18. TrackSi_Electron – Number of Pixel and SCT hits.

19. TrackA0_Electron – Distance of closest approach.

20. TrackMatchEta_Electron – η difference between cluster and extrapolated track in the 1st sampling.

21. TrackMatchPhi_Electron – φ difference between cluster and extrapolated track in the 2nd sampling.


24. TrackTRThits_Electron – Number of TRT hits.

25. TrackTRTratio_Electron – Ratio of high to all TRT hits for isolated electrons.

26. TrackTRTratio90_Electron – Ratio of high to all TRT hits for non-isolated electrons.

27. TrackA0Tight_Electron – Distance of closest approach for tight selection.


C.1.2. Central Electron Qualities:

These 32 bits make up various electron qualities like Loose, Medium, and Tight.

- ElectronLoose - 0, 2, 3, 4, and 6.

- ElectronMedium - 0, 2, 3, 4, 6, 8, 9, 10, 11, 12, 13, 15, 17, 18, 19, and 20.
  Or ElectronLoose with the addition of bits 8-13 and 17-20.

- ElectronTight - 0, 1, 2, 3, 4, 6, 8, 9, 10, 11, 12, 13, 15, 17, 18, 19, 20, 21, 22, 24, 25, 27, and 28.
  Or ElectronMedium with the addition of bits 1, 21, 22, 24, 25, 27, and 28.

C.1.3. Forward Electrons

Since tracking is limited to $|\eta| < 2.5$, the forward electron reconstruction algorithm for electrons with $|\eta| > 2.5$ uses information from the calorimeters only, and the topological clusters for the shape of the energy deposits [101]. Preselection and identification is done in the same algorithm. The variables used to discriminate between electrons and hadrons are defined by moments if the energy distributions in individual cells of the electromagnetic cluster. This is done separately in two $\eta$ bins corresponding to different construction of the forward calorimeters: the Electromagnetic End-Cap (EMEC) Inner Wheel (IW) and the Forward Calorimeter (FCal). Thus, the calorimeter detector signal and reconstruction software algorithms allow
for electrons to be identified up to $|\eta| < 5.0$. In the region, $|\eta| > 2.5$ where there is no tracking, the electrons reconstructed does not identify the sign of the electrons.

The isEM variable for forward electrons works in the same way as central electrons, but the flags used are different [102].

1. **ENG_FRAC_MAX**: Fraction of the cluster energy that is deposited in the most energetic cell of the cluster.

2. **LONGITUDINAL**: Shower shape in the cluster’s longitudinal direction, based on the distance of each cell to the shower core.

3. **SECOND_LAMBDA**: Second moment in $\lambda$ - the distance of each cell to the cluster center along the shower axis.

4. **LATERAL**: Lateral moment of the shower taking into account the two most energetic cells (which constitutes the shower core).

5. **SECOND_R**: Second moment in $r$ - the radial distance of each cell to the shower axis.

6. **CENTER_LAMBDA**: $\lambda$ center - the distance of the shower center from the front of the calorimeter along the shower axis.

C.1.4. Forward Electron Qualities:

Forward electrons identified as Loose are made up of **SECOND_LAMBDA**, **SECOND_R**, and **CENTER_LAMBDA** and forward electrons identified as Tight are made from all six flags.
Appendix D
Monte Carlo Samples

D.1. Signal

This appendix lists the Monte Carlo samples (signal and background) used in the baseline $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analysis.

D.1.1. Gluon-gluon Fusion for $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

- mc11_7TeV_116611.PowHegPythia_ggH130_ZZ4lep.merge.NTUP_HSG2.
  e873.s1310.s1300.r2820.r2872.p768/
  e873.s1310.s1300.r2820.r2872.p768/
- mc11_7TeV_116621.PowHegPythia_VBFH130_ZZ4lep.merge.NTUP_HSG2.
  e893.s1310.s1300.r2820.r2872.p768/
  e893.s1310.s1300.r2820.r2872.p768/
  e873.s1310.s1300.r2820.r2872.p768/
  e873.s1310.s1300.r2820.r2872.p768/
- mc11_7TeV_116763.PowHegPythia_ggH120_ZZ4lep.merge.NTUP_HSG2.
  e873.s1310.s1300.r2820.r2872.p768/
- mc11_7TeV_116764.PowHegPythia_ggH125_ZZ4lep.merge.NTUP_HSG2.
  e873.s1310.s1300.r2820.r2872.p768/
  e873.s1310.s1300.r2820.r2872.p768/
D.1.2. Vector Boson Fusion for $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

mc11_7TeV.116766.PowHegPythia_ggH140_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116768.PowHegPythia_ggH150_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116769.PowHegPythia_ggH155_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116770.PowHegPythia_ggH160_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116771.PowHegPythia_ggH165_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116772.PowHegPythia_ggH170_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116774.PowHegPythia_ggH180_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116787.PowHegPythia_ggH360_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116792.PowHegPythia_ggH460_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116799.PowHegPythia_ggH600_ZZ4lep.merge.NTUP_HSG2.
e873.s1310_s1300_r2820_r2872_p768/

mc11_7TeV.125063.PowHegPythia_VBFH110_ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125064.PowHegPythia_VBFH115_ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
D.1.3. Associated Production – $WH$

mc11_7TeV.125065.PowHegPythia_VBFH120 ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125066.PowHegPythia_VBFH125 ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125067.PowHegPythia_VBFH135 ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125068.PowHegPythia_VBFH140 ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125069.PowHegPythia_VBFH145 ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125070.PowHegPythia_VBFH150 ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125076.PowHegPythia_VBFH180 ZZ4lep.merge.NTUP_HSG2.
e893.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125084.PowHegPythia_VBFH260 ZZ4lep.merge.NTUP_HSG2.
e920.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125089.PowHegPythia_VBFH360 ZZ4lep.merge.NTUP_HSG2.
e920.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125094.PowHegPythia_VBFH460 ZZ4lep.merge.NTUP_HSG2.
e920.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125101.PowHegPythia_VBFH600 ZZ4lep.merge.NTUP_HSG2.
e920.s1310_s1300_r2820_r2872_p768/
D.1.4. Associated production – $ZH$

mc11_7TeV.125425.PythiaZH110_ZZ4lep.merge.NTUP_HSG2.
   e825.s1310.s1300.r2820.r2872.p768/
mc11_7TeV.125426.PythiaZH115_ZZ4lep.merge.NTUP_HSG2.
   e825.s1310.s1300.r2820.r2872.p768/
mc11_7TeV.125427.PythiaZH120_ZZ4lep.merge.NTUP_HSG2.
   e825.s1310.s1300.r2820.r2872.p768/
mc11_7TeV.125428.PythiaZH125_ZZ4lep.merge.NTUP_HSG2.
   e825.s1310.s1300.r2820.r2872.p768/
mc11_7TeV.125429.PythiaZH130_ZZ4lep.merge.NTUP_HSG2.
   e825.s1310.s1300.r2820.r2872.p768/
D.2. Background

D.2.1. $t\bar{t}$

mc11_7TeV.125430.PythiaZH135_ZZ4lep.merge.NTUP_HSG2.
e825.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125431.PythiaZH140_ZZ4lep.merge.NTUP_HSG2.
e825.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125432.PythiaZH145_ZZ4lep.merge.NTUP_HSG2.
e825.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125433.PythiaZH150_ZZ4lep.merge.NTUP_HSG2.
e825.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125439.PythiaZH180_ZZ4lep.merge.NTUP_HSG2.
e825.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125443.PythiaZH200_ZZ4lep.merge.NTUP_HSG2.
e825.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.125448.PythiaZH260_ZZ4lep.merge.NTUP_HSG2.
e825.s1310_s1300_r2820_r2872_p768/

D.2.2. $WZ$

mc11_7TeV.105987.WZ_Herwig.merge.NTUP_HSG2.
e825.s1310_s1300_r2820_r2872_p768/
D.2.3. $Z$+jets

mc11\_7TeV\_107650. AlpgenJimmyZeeNp0\_pt20. merge\_NTUP\_HSG2.
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
   e835.s1299_s1300_r2820_r2872_p768/
e835.s1299_s1300_r2820_r2872_p768/
e835.s1299_s1300_r2820_r2872_p768/
e835.s1299_s1300_r2820_r2872_p768/

D.2.4. $ZZ \rightarrow 4\ell$

e825.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116600.gg2ZZ_JIMMY_ZZ4lep.merge.NTUP_HSG2.
e922.s1310_s1300_r2820_r2872_p768/

D.2.5. $Z \rightarrow b\bar{b}$

mc11_7TeV.109300.AlpgenJimmyZeebbNp0_nofilter.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.109305.AlpgenJimmyZmumubbNp0_nofilter.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116950.AlpgenHWfZeebbNp0_Veto4LepM_Pass3Lep.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116955.AlpgenHWfZmumubbNp0_Veto4LepM_Pass3Lep.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116960.AlpgenHWfZeebbNp0_4LepM.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116961.AlpgenHWfZeebbNp1_4LepM.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116962.AlpgenHWfZeebbNp2_4LepM.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116963.AlpgenHWfZeebbNp3_4LepM.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116965.AlpgenHWfZmumubbNp0_4LepM.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116966.AlpgenHWfZmumubbNp1_4LepM.merge.NTUP_HSG2.
e835.s1310_s1300_r2820_r2872_p768/
mc11_7TeV.116967.AlpgenHWfZmumubbNp2_4LepM.merge.NTUP_HSG2.e835.s1310.s1300.r2820.r2872.p768/
mc11_7TeV.116968.AlpgenHWfZmumubbNp3_4LepM.merge.NTUP_HSG2.e835.s1310.s1300.r2820.r2872.p768/
Appendix E

$H \rightarrow 4e$ Optimization

Since a discovery is always made with the smallest number of events achieving a $5\sigma$ global significance, much work has been done in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analyses to maximize the signal acceptance at a cost of purity. Currently, the poorest performing channel is the $H \rightarrow ZZ \rightarrow 4e$ channel as indicated in Table 5.14. This is due to the effects of a reconstruction and identification efficiency near $\sim80\%$, which has an overall effect of $(80\%)^4$ in the final $4e$ state.

For low mass Higgs decays, $H \rightarrow ZZ^*$, the mass of the on-shell Z is a powerful constraint. The following studies were made to check that whether by using such a constraint, the electron identification can be relaxed (addressed in $3M + 1R$ and $2L + 2M$ final-states) or whether the use of electrons in the forward region of the detector $2.5 < |\eta| < 5.0$, where there is no tracking, to increase signal acceptance at an acceptable signal-to-background ratio.

E.1. $3M + 1R$

The $3M + 1R^1$ analysis introduces a non-standard electron identification quality, Relaxed \cite{103}. Relaxed electrons were designed to address problematic areas and compliment the standard electron identification qualities provided by the ATLAS $e/\gamma$ working group. The problematic areas addressed are:

- recovering electrons passing through crack areas in the calorimeter or tracker;

- lost due to edge effects (where reconstruction efficiency drops);

\footnote{Here, $M$ refers to the usage of Medium quality electrons and $R$ refers to the Relaxed quality.}
- recover instances in which there is a bad track or cluster due to dead regions (e.g., dead optical link transmitters, front end boards, Pixels, etc.).

The $3M + 1R$ analysis proved to be successful, achieving a relative gains of $\sim 29\%$ in the signal (for $m_H = 130$ GeV) and $\sim 12\%$ for background contributions. More information regarding this study is addressed in Reference [103]. The analysis was not pursued in lieu of systematic uncertainty calculations and other complications with the $e/\gamma$ working group.

**E.2. 3M + 1F**

Current limitations on detector measurement precision and reconstruction software mean that electrons can be reconstructed and identified up to $|\eta| < 5.0$. Without tracking information, forward electrons do not have an associated charge, making the use of the $Z$ constraint crucial for controlling background contributions.

The $3M + 1F$ analysis proved to be unsuccessful for $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$ studies; a relative gain of $\sim 5\%$ was achieved in the signal ($m_H = 130$ GeV) and $\sim 8\%$ for background contributions. It was determined that the use of forward electrons in $4e$ final-states would better be suited for cross-section calculations in $ZZ \rightarrow 4\ell$. More information regarding this study can be found in References [72, 103].

**E.3. 2L + 2M**

$2L + 2M$ studies sought to further exploit the advantages of a $Z$ constraint by reducing the quality requirement of electrons making the primary di-lepton to Loose (as opposed to Medium) with additional requirements on the number of hits in the Pixel and SCT detector to reduce contributions from the background. The study proved successful, increasing the relative gain in the signal ($m_H = 130$ GeV) by $\sim 9\%$ and background by $\sim 6\%$. The study was not pursued as the $e/\gamma$ working group were
producing the ++ identification menu and in order to maintain similar efficiencies in
the $H \to ZZ^{(*)} \to 4\ell$ analysis, the requirement of 4 Medium electrons changed to 4
Loose ++ electrons.
REFERENCES


[94] Combined search for the Standard Model Higgs boson using up to 4.9 fb–1 of pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC. 2012.

[95] Serguei Chatrchyan et al. Combined results of searches for the standard model Higgs boson in $pp$ collisions at $\sqrt{s} = 7$ TeV. 2012.


[99] Ryan R. Rios. LAr Crate Panel. [https://twiki.cern.ch/twiki/bin/view/Main/LArCratesPanel](https://twiki.cern.ch/twiki/bin/view/Main/LArCratesPanel), March 2012.

