A search for the Higgs boson in the decay to $b$-quarks with the ATLAS detector

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Als ik wil
veeg ik de smeerkaas
van mijn bril
om ‘n Higgsveld te zien aan de horizon

Vrij naar Lucebert [2]
Abstract

The Higgs boson has been discovered in July 2012, but only decay channels to bosons were considered. In this Master’s thesis we search for the Higgs in a decay channel to fermions: we look for $b$-quarks from a 125 GeV Higgs. The data we use is obtained by the ATLAS detector in the period January-July 2012. We use muons, since these are easier to detect, to find the $b$-quarks from a Higgs boson that is produced in association with a $Z$-boson. The final state we search for consists of the two muons from the $Z$-boson and the two $b$-quarks from the Higgs boson; the three backgrounds we include in this thesis are $tt$, $Z$+jets and $ZZ$. We do a cut-based analysis, which leads to a mass distribution of the $b$-quarks. We were challenged with the Hadronic Calorimeter’s poor resolution and the large $Z$+jets background. A counting experiment gives us a significance of 1.4 $\sigma$ and an exclusion of 19 times the Higgs cross section. We conclude this analysis is not sensitive enough to discover or exclude the Higgs decay to $b$-quarks and we discuss options for further research. An additional chapter of this thesis describes a Monte Carlo study on the Higgs decay to $ZZ$ with a final state of two muons and two $b$-quarks.
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Introduction

Experimental Particle Physics is the study of elementary particles and their interactions. The experimental part includes the search for the particles that are predicted by theories in a controlled environment. This is a Master’s thesis in experimental Particle Physics, conducted at the Nikhef institute in Amsterdam.

The discovery of the Higgs particle at the 4th of July 2012, was a trajectory of almost fifty years and several technological developments. An example is that a little more than twenty years ago, CERN launched the first website in the World, the Nikhef had the third. The institute CERN is founded in 1954, the Netherlands joined from the beginning, and since then scientists from all over Europe shared their interest. Since the discovery of the Higgs particle was made public at the 4th of July 2012 and the research for this thesis has been conducted from March 2012-May 2013, this was a historical period to be part of the ATLAS group. The subject of this thesis is a search for the Higgs boson, in a decay channel that has not been discovered so far. New physics is looming on the horizon.

**Figure 1:** Two of the theoretical physicists who described the Higgs mechanism in the 1960’s: François Englert (left) and Peter Higgs. According to the Higgs mechanism the field is all around us, but we can only prove that indirectly when we build a sophisticated experiment.

**Thesis overview**

The structure of this thesis is as follows. An Abstract has given a short summary of the research we conducted. Then, in the first two chapters, we describe the information necessary to understand the rest of this thesis. Chapter 1 describes the theory of the Higgs boson and the Standard Model, we start with a listing of the particle’s properties and we continue with a more in-depth theoretical explanation. We look ahead at the channel we use to search for the Higgs: $ZH \rightarrow \mu^+\mu^-bb$ and calculate how many events we expect. In Chapter 2 we describe the experimental set-up, the accelerator LHC and the ATLAS detector. We also give an overview of the basics of data analysis.

From Chapter 3 onwards, we describe the research that has been conducted. Chapter 3 is an extended explanation of the choice for our channel, and includes an additional study on the channel $H \rightarrow ZZ \rightarrow \mu^+\mu^-bb$. Chapter 4 and 5 describe the search for the Higgs decay to $b$-quarks in the channel $ZH \rightarrow \mu^+\mu^-bb$, where we look at 8.2 fb$^{-1}$ of 2012 data. Chapter 4 explains the choices we make for the analysis and Chapter 5 describes the statistical calculations. The final chapter, Chapter 6, gives the conclusion and we discuss some options for further research.

In addition to the content of the chapters, this thesis contains two Appendices with the used data and the analysis’ Cutflows respectively. We round off this thesis with a Bibliography, a Summary in Dutch and Acknowledgements.
Chapter 1

The Higgs boson and the Standard Model

Nature’s smallest known constituents, are elementary particles. An example of an elementary particle is the electron, a negatively charged particle inside an atom. Another example is the photon, the light particle. This thesis describes a search for the Higgs boson in the decay channel to $b$-quarks; this first chapter provides the theoretical background to understand the properties of these particles.

The elementary particles and the interactions between them, are described by the Standard Model that came together in the 1960’s. We start this chapter with a summary of the Standard Model. The particles are listed and a short introduction of the ideas behind the Standard Model is given. The Standard Model is a quantum field theory, this will be explained thereafter. We will continue with a section on the Higgs mechanism. We describe the properties of the Higgs boson; its production and decay channels in the LHC, with a focus on the channel $ZH \rightarrow \mu^+\mu^-b\bar{b}$, the channel we use for this thesis. This chapter ends with shortcomings of the Standard Model and insights in future theories.

1.1 The particles of the Standard Model

The Standard Model describes elementary particles and the interactions between them. To understand the model, we need to summarise the particles first. This section aims to list all the particles, make an inventory of their properties and summarise everything (the goal of this section is to explain what is necessary to understand the information in Table 1.1 at Page 14). When we know what the World is made of, we will try to describe why this is the case, but first: the particles. There are matter particles and force particles. The spin of a particle, its internal angular momentum, tells us if we have a matter or a force particle: matter particles have half-integer spin and force particles integer spin. Matter particles make up matter, an example is the electron, and are fermions. Force particles are bosons.

1.1.1 Matter particles

There are several types of fermions, matter particles, distinguishable by their quantum numbers and mass. We start with the description of ‘ordinary matter’, or the first generation of fermions.

An atom has a heavy nucleus and a swarm of light electrons encircling it. The nucleus is not elementary, meaning we can break it into smaller particles: it consists of three fermions called quarks. The quarks are grouped together, confined, because as far as we know, an individual quark does not exist: it hadronises immediately. A group of quarks is called a hadron (the acronym LHC we will encounter later contains the word hadron: it stands for Large Hadron Collider). A proton has electrical charge $Q = +1$ and the neutron $Q = 0$. The three valence quarks of the proton are: two quarks with electrical charge $+\frac{2}{3}$, called up quarks, and one quark with electrical charge $-\frac{1}{3}$, a down quark. The neutron consists of two down quarks and one up quark.

The up and down quark are of the same order of mass, a few MeV. The electron, encircling the nucleus, is already an elementary particle, it does not consists of any smaller particles as the proton and neutron do. The charge is negative, $Q = -1$, for historical reasons (Ben Franklin defined it as such). Its mass is around 0.5 MeV. The electron is called a lepton and is often accompanied in an interaction by a
neutrino, an even lighter particle. The mass of the neutrino is less than a few eV and it has no electrical charge.

The four particles mentioned above make up ordinary matter: the up and down quark and the electron and its neutrino, in the notation \( u, d, e^- \) and \( \nu_e \). They form the first generation of the Standard Model.

**Colour**

Another quantum number, next to charge, is colour. The concept of colour has nothing to do with visible colour, the system just has the same symmetries of a colour palette. The colours used are those that make up white light: red, green and blue. Quarks are the only fermions with colour charge, every quark comes in these three colour states. If a particle has colour, it couples strongly. We will describe the strong interaction in the section about bosons.

**Anti particles**

If two particles have oppositely-signed electrical charge, they can annihilate. With the energy of the collision an electrically neutral particle is formed. The oppositely-signed charge of the particle we need for such an interaction, gives it the name ‘an anti particle’. An anti particle also has oppositely-signed spin and oppositely-signed colour. These quantum numbers add up if for example a quark and an anti quark are in a bound state: this state will have electrical charge and spin zero and is colour neutral. The anti particle of the electron, \( e^- \), is the positron, \( e^+ \). Quarks and neutrinos have a bar above it in the notation for the anti particle, thus \( \bar{u} \) and \( \bar{d} \) for the up quark, \( \bar{d} \) and \( \bar{d} \) for the down quark and \( \bar{\nu} \) and \( \bar{\nu} \) for the neutrino.

**Helicity**

We continue with helicity and left and right handedness. We need this to describe the weak force, in the section on bosons later on. The helicity operator is defined as \( h = \sigma \cdot \hat{p} \), with \( h \) helicity, \( \sigma \) the spin pauli matrices and \( \hat{p} \) momentum. The direction of the momentum \( \hat{p} \) is usually taken along the \( z \)-axis of the system, and with spinors \( \chi_s = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \) for spin up and \( \chi_s = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \) for spin down, this gives for a spin up particle a helicity of +1:

\[
\sigma \cdot \hat{p} \chi_s = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = +1 \chi_s.
\]

If a particle travels with the speed of light, left or right handedness is independent of its reference frame (in Formula 1.1, the sign of helicity depends on the direction of \( \hat{p} \)). Only mass-less particles travel with the speed of light, but we neglect the mass of the neutrinos in this section. It gives us the chance to say that, for a neutrino, having an helicity of \( \pm 1 \) is the same as being left- or right-handed.

In 1957 an experiment was done by Chien-Shiung Wu to look at the direction of the weak decay of Cobalt-60. She found that only left-handed neutrinos were detected. The anti neutrino is defined as the right-handed particle (the neutrino has no electrical charge, which was the earlier definition of the anti particle). Electrons, muons an tau leptons have a non-negligible mass, and their state consists of both left- and right-handed components. The weak force, described later, couples to left-handed particles. This happens in such a way that an electron is accompanied by an electron-neutrino. To have this symmetry already in the notation, we write them down as an isospin doublet: \( (e^-, \nu_e)_L \). The right-handed particles are a singlet, meaning that they have other symmetry requirements. We write them down as \( e_R \) (and a right-handed neutrino has not been detected so far). The quarks also form an isospin doublet for the left-handed particles and singlets for the right-handed ones: \( (u, d)_L, u_R \) and \( d_R \).

**Generations**

So far we described the four fermions that make up the first generation: \( u, d, e \) and \( \nu_e \). In special environments with high energies, there are more fermions than these four. Such an environment can be a star explosion, or a collision in an accelerator. The particles that pop up in such an environment, have the same quantum numbers as the particles we already encountered (e.g. spin, charge, etc.). The only differences are their mass and their names, the name of a fermion is called its flavour. For every fermion from the first generation, there are two heavier particles known, the one even more heavy than the other. The second generation is made up of a charm and a strange quark, \( c \) and \( s \), a muon \( \mu^- \) and a
muon neutrino $\nu_\mu$. The third generation consists of a top and a bottom quark $t$ and $b$, a tau lepton $\tau^-$ and a tau neutrino $\nu_\tau$.

### 1.1.2 Forces

Particles with an integer spin are called bosons. They have another role than fermions; bosons are the carriers of the fundamental forces. A boson carries or mediates force by interacting with itself or fermions. Such interactions are of a different strength, because of the strength of the coupling, a measure is the coupling constant. The coupling constant for the electromagnetic force, $\alpha$, with $4\pi\epsilon_0$ the permittivity factor, is:

$$\alpha = \frac{e^2}{(4\pi\epsilon_0)\hbar c} \approx \frac{1}{137}$$

(1.2)

The three fundamental forces in the Standard Model are the strong, the electromagnetic and the weak force. The Higgs particle is also a boson, it is mentioned shortly here, but there will be a whole extensive section about the Higgs mechanism later in this chapter.

#### Strong force

The particles carrying the strong force are called gluons, there are eight of them. The gluons couple to colour charge, so the quarks are the only particles interacting strongly. A gluon, in contrast to a quark, consists of two colours. A red-green gluon for example, can couple on one side to a red quark and on the other side to a green quark. The gluons also couple to themselves. The quarks are confined because the strong force keeps the nucleus together. This is a strong bond, the coupling constant of the strong force is $\alpha_s \approx 1$. The range of the strong force is limited to $10^{-15}$ m, not coincidentally the typical size of a nucleus, and at larger distances the quarks need to find new bonds (they do not exist un-confined).

#### Electromagnetic force

The electromagnetic force, classically described by the Maxwell equations, is carried by the photon. A photon is mass-less and travels with $3 \times 10^8$ m/s, the speed of light. The photon has spin 1 (because it is mass-less, it actually has an helicity of 1). Every particle that has nonzero charge, couples to the photon and is therefore sensitive to the electromagnetic force. This includes all fermions without the neutrinos, and the charged bosons of the weak force. The photon does not couple to itself, since the particle itself is not charged. The strength of the electromagnetic interaction is proportional to $\alpha \approx \frac{1}{137}$. The range of the electromagnetic force is infinite, $\alpha$ is the asymptotic value.

#### Weak force

The weak force is carried by three bosons: two $W$’s with electrical charge $\pm 1$, and the neutral $Z$. The $W^\pm$ have a mass of 80 GeV and the $Z$ has a mass of 91 GeV. Because the weak bosons are massive, the range of the force is limited (about $10^{-18}$ m) and their typical lifetime ($10^{-12}$ s) is longer than that from the gluon ($10^{-23}$ s) or the photon ($10^{-18}$ s). The $W^\pm$ and $Z$ couple to a property of particles that is called the third component of the weak isospin. The third component of the weak isospin is defined as $I_3 = \frac{1}{2} Y - Q$, where $Y$ stands for the weak hypercharge accounting for quark mixing and $Q$ is the electrical charge. This symmetry is discussed further in the next section; the following properties are obtained from it.

The weak force bosons couple to left-handed quarks and leptons and to themselves. For neutrinos, it is the only interaction they have. The charged $W$-bosons also couple to the photon. The strength of the weak force is proportional to about $\alpha_w \approx 10^{-6}$, making it a very weak force compared to the electromagnetic force. The electromagnetic and weak force were in the 1960’s combined as the electroweak force.

#### The Higgs boson

The Higgs boson\(^1\) couples in theory to all massive particles. The particle has spin zero and no charge, and has a mass around 125 GeV, as was discovered at July 4th 2012, during the research period of this

\(^1\)Leon Lederman, an American physicist, wrote a book about the Higgs particle named ‘the God particle’ [3]. Since then, the name caught on by the media, but it will not be used throughout this thesis.
Taking everything into account, the Standard Model counts 61 particles. Only the Higgs coupling to the weak bosons has been confirmed. Since the discovery has been so recent, more detailed properties of the Higgs are not known yet. We have discussed the elementary particles we know and their interactions. Before we can say we understand them, we need them to be part of the framework of modern physics. Only if everything is consistent, experiments and theory, we can formulate a physics law. The physics that was known before the Standard Model was written down, was threefold. At first there was classical physics, including Newton’s description of gravity and Maxwell’s formulas for electricity and magnetism. Einstein’s theory of relativity, published in 1905, was the beginning of modern physics. He described how a system behaves at high energies and velocities close the the speed of light. Quantum physics was formulated in the 1930’s, it describes how a system behaves at a small scale. The Standard Model describes how particles behave when they travel with a speed close to the speed of light (and light itself - photons), but also what happens in an interaction at a small scale. Therefore, the Standard Model is a combination of these theories: it is a quantum field theory, see Figure 1.1.

Gravity is not described by a quantum field theory. This is not a problem for this thesis: we neglect the effect of gravity because the gravitational force is negligible at the high-energy scales the experiment is working at. The inclusion of gravity would lead to a theory of everything (an example would be string theory), since all known particles and forces would be included. So far we do not know anything about this, because the energy at which the observables of the theory of everything would manifest itself is too high for us to build a controlled environment for (like an accelerator and a detector).

2There are 6 quark flavours and their anti particles, which all come in 3 colours, giving 36 quarks. For the leptons we have 6 and their anti particles, where the anti particles for the neutrinos are the right-handed ones (a discussion on whether neutrinos are massive or not can be found in for example [4]). We have 8 gluons, 1 photon, 3 weak bosons and so far one Higgs boson. Adding up gives 36 + 12 + 13 = 61. Because research is still going on, especially about the mass of the neutrinos and the amount of Higgs bosons, the number of particles is not set in stone yet.

### 1.1.3 Summary

Taking everything into account, the Standard Model counts 61 particles. Everything else is made up of these particles, and thus not elementary. The particles can be categorised according to spin, electrical charge, colour charge, hypercharge, mass and left and right handedness. A short summary of these is: spin says if a particle is a fermion or boson; the higher the generation, the more massive; coloured particles couple strongly, charged particles couple electromagnetically, particles with a nonzero third component of the weak isospin couple weakly and massive particles couple to the Higgs field. In Table 1.1 we summarise all the above mentioned properties.

### 1.1.4 Ideas behind the Standard Model

We have discussed the elementary particles we know and their interactions. Before we can say we understand them, we need them to be part of the framework of modern physics. Only if everything is consistent, experiments and theory, we can formulate a physics law. The physics that was known before the Standard Model was written down, was threefold. At first there was classical physics, including Newton’s description of gravity and Maxwell’s formulas for electricity and magnetism. Einstein’s theory of relativity, published in 1905, was the beginning of modern physics. He described how a system behaves at high energies and velocities close to the speed of light. Quantum physics was formulated in the 1930’s, it describes how a system behaves at a small scale. The Standard Model describes how particles behave when they travel with a speed close to the speed of light (and light itself - photons), but also what happens in an interaction at a small scale. Therefore, the Standard Model is a combination of these theories: it is a quantum field theory, see Figure 1.1.

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---

#### Table 1.1: The particles of the Standard Model and their properties

<table>
<thead>
<tr>
<th>Name</th>
<th>$S$</th>
<th>$Q$</th>
<th>$C$</th>
<th>$Y$</th>
<th>$I_3$</th>
<th>$M$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarks $(u,d)_L$, $(e,s)_L$, $(t,b)_L$</td>
<td>$(\frac{1}{2}, \frac{1}{2})$</td>
<td>$(\frac{2}{3}, -\frac{1}{3})$</td>
<td>yes</td>
<td>$\frac{1}{3}$</td>
<td>$(-\frac{1}{2}, \frac{1}{2})$</td>
<td>$(2.3, 4.8)$, $(1275, 95)$, $(173500, 4650)$</td>
</tr>
<tr>
<td>$\nu_R$, $\tau_R$, $\nu_R$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{2}{3}$</td>
<td>yes</td>
<td>$\frac{2}{3}$</td>
<td>$0$</td>
<td>$2.3$, $1275$, $173500$</td>
</tr>
<tr>
<td>$d_R$, $s_R$, $b_R$</td>
<td>$\frac{1}{2}$</td>
<td>$-\frac{1}{3}$</td>
<td>yes</td>
<td>$-\frac{2}{3}$</td>
<td>$0$</td>
<td>$4.8$, $95$, $4650$</td>
</tr>
<tr>
<td>Leptons $(e^-, \nu_e)<em>L$, $(\mu^-, \nu</em>{\mu})<em>L$, $(\tau^-, \nu</em>{\tau})_L$</td>
<td>$(\frac{1}{2}, \frac{1}{2})$</td>
<td>$(-1, 0)$</td>
<td>no</td>
<td>$-1$</td>
<td>$(\frac{1}{2}, -\frac{1}{2})$</td>
<td>$(0.5, &lt;10^{-3})$, $(106, &lt;10^{-3})$, $(1777, &lt;10^{-3})$</td>
</tr>
<tr>
<td>$e^-$, $\nu_R$, $\tau_R$</td>
<td>$\frac{1}{2}$</td>
<td>$-1$</td>
<td>no</td>
<td>$-2$</td>
<td>$0$</td>
<td>$0.5$, $106$, $1777$</td>
</tr>
<tr>
<td>Bosons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g$</td>
<td>$1$</td>
<td>$0$</td>
<td>yes</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$1$</td>
<td>$0$</td>
<td>no</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$W^\pm$ and $Z$</td>
<td>$1$</td>
<td>$\pm 1$ and $0$</td>
<td>no</td>
<td>$0$</td>
<td>$\mp 1$ and $0$</td>
<td>$80385$ and $91188$</td>
</tr>
<tr>
<td>$H$</td>
<td>$0$</td>
<td>$0$</td>
<td>no</td>
<td>$1$</td>
<td>$\frac{1}{2}$</td>
<td>$\approx 125000$</td>
</tr>
</tbody>
</table>
Figure 1.1: The combination of relativistic and quantum mechanics is called quantum field theory. Quantum field theory is relevant for systems with high energies and small scales.

Because the Standard Model is a quantum field theory, the distinction between a particle and a field is not obvious. In some situations we talk about a field, such as the electric field, and in some situations about a particle, such as the quark. The only thing we know is that the particle-manifestation of the field is the only observable we have. Another implication of using quantum field theory is that two particles with the same properties are indistinguishable, even if they are on the other side of the Earth, there is no difference. This idea is connected to the particles being a component of a quantum field theory, because in quantum field theory, the two particles are fluctuations of the same field so they must have the same properties.

In the next section we see how the particles and their interactions are incorporated in the quantum-field-theoretical formulation of the Standard Model. The calculations are time consuming, which led to Richard Feynman trying to find a new way to look at the interactions. He proposed to draw particle interactions in a schematic way: a line for a particle, a vertex for an interaction. This became known as a Feynman diagram, read from the left to the right in time. The Feynman diagram for muon decay, is shown as an example in Figure 1.2. A muon decays weakly to a muon neutrino, and the $W^-$-boson decays to an electron and an anti-electron neutrino.

Figure 1.2: A Feynman diagram of a muon decaying to a muon neutrino, an anti-electron neutrino and an electron via the weak force.

In every interaction are conserved quantities, such as energy, momentum, spin, charge, baryon number ($\pm \frac{1}{3}$ for every (anti) quark and 0 for the rest) and lepton number ($\pm 1$ for every (anti) lepton and zero for the rest). These conservation rules have its origin in the symmetries of the Standard Model. The reason we believe that some of the interactions are possible and others are not, is because we believe that nature has symmetries that account for conserved quantities. The symmetries of the Standard Model are described in the next section, and we need the Lagrangian formulation of the Standard Model to do this. In the above chapter, the properties of the particles are given and we summarised which interactions are possible. The following books can be used to find more information about particles and their interactions [5] [4].

1.2 Symmetries of the Standard Model

In the previous section we summarised the particles and explained that the Standard Model is a quantum field theory. The theory that describes the particles is directly linked to the symmetries of the the Standard Model; the symmetries are visible in the quantum-field-theoretical formulation of the model. In this section, we will see what the symmetries of the Standard Model are and how they give rise to the particles and their properties we stated in the previous section. A more thorough explanation of
quantum field theory can be found in the books [6] [7].

We will start with the Lagrangian formulation, because a Lagrangian contains all the information about a theory (also the symmetries). The Lagrangian we know from classical mechanics, is defined as \( \mathcal{L} = T - V \), the kinetic energy minus the potential energy. From the Lagrangian, via the principle of least action leading to the Euler-Lagrange equations, we can derive the equations of motion. The equations of motion are physics laws, an example is Newton’s law \( F = ma \). The behaviour of a system in time is described by a law; therefore we can use a law to make predictions about the future. These predictions can be verified or falsified by experiments, we will come back to the meaning of verifying and falsifying later in this thesis.

For the rest of this section we use the Lagrangian density (and call it Lagrangian), which is the Lagrangian integrated over space. In quantum field theory, there is a similar Lagrangian to the classical system, which uses fields \( \phi \) and their derivatives \( \partial_\mu \phi \). We use the space-time-fourvector notation here: \( x = (t, \mathbf{x}) \) and \( \partial_\mu = (\partial_t, \nabla) \). An example of a Lagrangian for a free relativistic scalar field is the Klein-Gordon Lagrangian:

\[
\mathcal{L} = \mathcal{L}_{\text{kinetic}} - \mathcal{L}_{\text{potential}} = \frac{1}{2} (\partial_\mu \phi)^2 - \frac{1}{2} M^2 \phi^2. \tag{1.3}
\]

The first term with the derivative of the field is the kinetic term, and the second term is the potential term, which is quadratic in \( \phi \) depends on a constant \( M \) - this will later become a mass term.

From a symmetry of the Lagrangian a conserved current can be derived (proved in Noether’s theorem). Two global symmetries of the Standard Model are translation invariance and Lorentz invariance. Translation invariance means that if you shift \( \phi(x) \) to \( \phi(x + a) \), where \( x \) is the space-time four vector \( x = (t, \mathbf{x}) \), the Lagrangian obtains an extra term for the conserved current. Since this term is a constant for the Euler-Lagrange equations, we do not see it back in the laws of physics. The conserved current of translation invariance causes conservation of energy and momentum in a system (or an interaction). Lorentz invariance comes back for example in the fourvector notation; space and time are on the same footing.

### 1.2.1 Local-gauge invariance in QED

Before we continue with the symmetries of the Standard Model, we take a look at quantum electrodynamics (QED), the quantum-field-theoretical description of the electromagnetic force. A symmetry is local if the system is invariant under a transformation from which the angle or phase, \( \Lambda \), depends on the point in space-time, \( x \), of the field \( \phi(x) \):

\[
\phi(x) \rightarrow \phi'(x) = e^{ie\Lambda(x)} \phi(x), \tag{1.4}
\]

This local symmetry can be imposed on the Lagrangian and is known as phase or gauge invariance. The Lagrangian we use describes a complex scalar field:

\[
\mathcal{L} = \mathcal{L}_{\text{kinetic}} - \mathcal{L}_{\text{potential}} = (\partial_\mu \phi)^\dagger \partial_\mu \phi - V(\phi). \tag{1.5}
\]

The derivative of the field needs to be shifted as well to keep the symmetry: \( \partial_\mu \) is replaced by the covariant derivative:

\[
D_\mu = \partial_\mu + ieA_\mu(x). \tag{1.6}
\]

This is called minimal substitution. In this example, the field \( A_\mu \) is the photon field, from which the Maxwell equations that describe electricity and magnetism can be derived. The field \( A_\mu(x) \) transforms as

\[
A_\mu(x) \rightarrow A'_\mu(x) = A_\mu(x) - \partial_\mu \Lambda(x), \tag{1.7}
\]

where \( \Lambda(x) \) is again the angle or phase of the local gauge transformation. The QED Lagrangian for a complex scalar field is given by:

\[
\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\phi). \tag{1.8}
\]

Here \( F^{\mu\nu} = \partial_\mu A^\nu - \partial_\nu A^\mu \), making the term \( -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \) the kinetic term for the photon field. The potential term is given by \( V(\phi) \). What happened is that by imposing the local gauge symmetry on the Lagrangian, we obtained a field which is mediated by the photon. The properties of the electromagnetic interaction are described by this field, so from a symmetry we obtained a particle and its properties - which was the intention of this section. We go back to the Standard Model.
1.2.2 Group-theoretical formulation of the symmetries of the Standard Model

The systematic study of symmetries in Mathematics, is Group theory. Since the symmetries of the Standard Model are also described by Group theory, we use it here. A group is an abstract concept: it can consist of numbers, but also of matrices or other mathematical structures. Group elements can also be transformations: such as the rotations and translations we encountered before. The elements of the group have the restriction that there must be an identity element, every element must have an inverse element, and the elements are associative. If the elements of the group are not known, they can be provided by the generator that we usually do know. The commutation relations between the generators contain the structure of the group. The structure of the group contains the symmetries we are looking for to give rise to the particles. For the groups we use for the Standard Model, ‘continuous Lie-groups’, the group elements are obtained by taking the exponent of the infinitesimal generator. A thorough description of group theory for physicists is given in [8].

The groups that describe the symmetries of the Standard Model are:

\[
\text{Standard Model} = SU(3)_C \times SU(2)_L \times U(1)_Y. \tag{1.9}
\]

The strong force has an \( SU(3)_C \) symmetry, where the \( C \) stands for colour. The \( U(n) \)-group is the collection of unitary \( n \times n \)-matrices, \( U^{-1} = U^\dagger \) for if \( U \) is a group element, and the \( S \) stands for special, if the determinant of the matrices is 1. The carriers for the strong force are gluons, there are \( 2^3 = 8 \) colour configurations possible, leading to eight gluons, as we saw earlier. The group \( SU(3)_C \) has eight generators, and this is not a coincidence: it makes the group a proper mathematical description of the symmetry of the strong force.

The groups \( SU(2)_L \times U(1)_Y \) are used for the electroweak sector, \( Y \) is the weak hypercharge and \( L \) the left handedness (see Table 1.1 to see the symmetries for the particles). The local gauge invariance we saw for QED can be extended to include the weak force. We obtain a Lagrangian for a local gauge invariant \( SU(2)_L \times U(1)_Y \) symmetry with the following covariant derivative (we can compare it to Formula 1.6):

\[
D_\mu = \partial_\mu + ig \frac{1}{2} \tau \cdot W_\mu + ig'YB_\mu. \tag{1.10}
\]

What we see here are fields, constants and generators of the fields. The three fields \( W_\mu \) and one field \( B_\mu \) are thus accompanied by the constants \( g \) and \( g' \), the matrices \( \tau \) (generators of \( SU(2)_L \) and the same as the spin pauli matrices \( \sigma \) - spin has a \( SU(2) \) symmetry with generators \( \sigma \)) and the weak hypercharge \( Y \) (the generator of \( U(1)_Y \)). If the fields \( W_\mu \) and \( B_\mu \) are rotated properly, they mix and \( W^1 \) and \( W^2 \) form the fields that are carried by the charged gauge bosons \( W^+ \) and \( W^- \); the mixing of \( W^3 \) and \( B \) gives the fields for the \( Z \) and the photon. The electroweak Lagrangian is given by:

\[
\mathcal{L} = (D^\mu \varphi)(D_\mu \varphi) - \frac{1}{4} W_{\mu\nu}W^{\mu\nu} - \frac{1}{4} B_{\mu\nu}B^{\mu\nu} - V(\varphi). \tag{1.11}
\]

So, from the symmetry \( SU(2)_L \times U(1)_Y \) we obtain the fields for the gluons, the weak bosons and the photons. These are the force carriers of the Standard Model. The fields of the fermions, the matter particles, are obtained in a similar way.

We started this section with the Klein-Gordon Lagrangian, Formula 1.3, that contained a mass term \(-\frac{1}{2}M^2\varphi^2\). We know the weak bosons are massive, this has been experimentally verified (and fermions are massive as well). Adding a mass term violates the local gauge symmetry: a local gauge transformation of the mass term changes the term, which would change the equations of motion. Luckily, there is a loophole: spontaneous symmetry breaking, which introduces masses for the particles, without breaking the local gauge invariance. This is the Higgs mechanism.

1.3 The Higgs mechanism

The Higgs mechanism explains the mass of the fermions and bosons of the weak force, by including the Higgs field and its carrier the Higgs particle in the theory. This section describes the Higgs potential and the mechanism to give mass to the particles.

\[^3\text{Associative means } a \cdot (b \cdot c) = (a \cdot b) \cdot c \text{ for the group elements } a, b \text{ and } c.\]

\[^4\text{An example of commutation relations are } [x, p] = ih \text{ in quantum mechanics. The square brackets mean } [A, B] = AB - BA \text{ and in Group theory the commutation relations are the algebra of the group.} \]
1.3.1 The Mexican-hat potential

The Higgs mechanism works via spontaneous symmetry breaking. Note that the Higgs mechanism is often referred to as electroweak-symmetry breaking, because it gives mass to the weak gauge bosons. To describe spontaneous symmetry breaking, we best start with a Lagrangian. We look at the electroweak Lagrangian, which is defined as such that it obeys the symmetry $U(1)_Y \times SU(2)_L$ we encountered before, Formula 1.11. We have not discussed the potential term much, but we will do that now. We choose a potential that depends on the field, and contains two constants $\mu$ and $\lambda$:

$$V(\varphi) = \mu^2 \varphi^\dagger \varphi + \lambda (\varphi^\dagger \varphi)^2.$$  \hfill (1.12)

The scalar part of the Lagrangian, with the covariant derivative $D_\mu$ from minimal substitution (Formula 1.10), is:

$$\mathcal{L} = (D^\mu \varphi)^\dagger D_\mu \varphi - \mu^2 \varphi^\dagger \varphi - \lambda (\varphi^\dagger \varphi)^2.$$  \hfill (1.13)

The field we use in this Lagrangian is a local gauge invariant complex scalar field. For reasons that become clear later in this section, we need to find the ground state or the vacuum value of this field. The complex field $\varphi$ can be written down as a isospin doublet which obeys the $U(1)_Y \times SU(2)_L$ symmetry:

$$\varphi = \frac{1}{\sqrt{2}} \left( \varphi_1 + i \varphi_2 \right) \left( \varphi_3 + i \varphi_4 \right).$$ \hfill (1.14)

We find the vacuum by setting $\varphi_1 = \varphi_2 = \varphi_4 = 0$ and $\varphi_3 = v$:

$$\varphi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}.$$ \hfill (1.15)

The constant $v$ depends on $\mu$ and $\lambda$ and gives a new vacuum for $\mu^2 < 0$: the vacuum is shifted to $+v$ or $-v$, with $v = \sqrt{-\frac{\mu^2}{\lambda}}$. If we would not have shifted the vacuum, we would have obtained a negative mass and we do not know how to interpret that. The potential term gets the shape of a Mexican hat for $\mu^2 < 0$, in Figure 1.3 we see this shape on the right. On the left of Figure 1.3 we see the potential for $\mu^2 > 0$, which describes a scalar field with mass $\mu$ and the vacuum at 0, without spontaneous symmetry breaking.

![Figure 1.3: Potential of the Higgs field for different definitions of the vacuum. On the left the potential without spontaneous symmetry breaking. On the right the Mexican-hat potential for $\mu^2 < 0$.](image)

We expand $\varphi$ around the vacuum value to $v + h$, where $h$ is a perturbation around the vacuum at $v$ and we get it when we use the unitary gauge. We obtain the following vacuum:

$$\varphi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}.$$ \hfill (1.16)

To see what the effect is of this re-definition of the vacuum, we use Formula 1.16 for $\varphi$ in the covariant derivative of Formula 1.10. This results in an equation from which we can see the mass of the gauge bosons explicitly. We see that the $W$ bosons are equally heavy: $m_W = \frac{1}{2} v g$. The $Z$-boson obtains a mass of $m_Z = \frac{1}{2} \sqrt{g^2 + g'^2}$ and the photon is mass-less (the photon propagates the field $A_\mu$).

$$(D^\mu \varphi)^\dagger D_\mu \varphi = \frac{1}{8} v^2 (g^2 (W^{+2} + W^{-2}) + (g^2 + g'^2) Z_\mu^2 + 0 \cdot A_\mu^2).$$ \hfill (1.17)
We obtain 3 massive scalars, the gauge bosons of the weak force, 1 mass-less scalar, the photon, and have 1 degree of freedom of the field \( \varphi \) left, that goes into the mass term of another boson. This is the Higgs, the quantum of the field \( h \) of Formula 1.16. This comes out exactly as we wanted, because of the demand that the field and the vacuum, the formulas 1.14 and 1.15, have to obey the electro-weak symmetry \( U(1)_Y \times SU(2)_L \).

With the Higgs mechanism, we also generate a mass term for the fermions. We obtain a mass term for the electron which is \( m_e = \frac{\lambda_e}{2} \), where we see that we have the free parameter \( \lambda_e \) (\( v \) has been obtained experimentally). The actual masses of the electron and the other leptons that we gave in the beginning of this chapter, are obtained experimentally. An example of that we have a free parameter is that the electron is really light compared to the \( W \)-boson, but the theory cannot explain why this is.

For the quarks we need to make a distinction between up-type (u, c and t) and down-type quarks (d, s and b). The up-type quarks have a vacuum at:

\[
\varphi_0^{\text{up}} = -\frac{1}{\sqrt{2}} \begin{pmatrix} v + h \\ 0 \end{pmatrix},
\]

and the fermion field obtains a mass term \( \lambda_u \bar{u}_L u_R \) in the Lagrangian (without the higher-order corrections and the hermitian conjugate part). The \( L \) and \( R \) are the left and right handedness, which must be included because the weak forces only couples to left-handed helicity states. For the down-type quarks we get a vacuum at

\[
\varphi_0^{\text{down}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix},
\]

like we had before, and a mass term \( \lambda_d \bar{d}_L d_R \). From the mass terms we obtain the mass for the quarks:

\[
m_u = \frac{1}{\sqrt{2}} \lambda_u v, \quad m_d = \frac{1}{\sqrt{2}} \lambda_d v,
\]

The actual mass of the quarks depends again on a free parameter in the theory, \( \lambda \), just as is was for the leptons, and we do not know why some of the quarks are heavier than others. The different generations of left-handed quarks can interact with each other via the weak force, the amount of mixing between the quarks is described by the CKM mixing matrix. An extensive explanation of the mixing between quarks and its consequence \( CP \)-violation (the violation of the symmetry charge-parity), can be found in [7]5.

The symmetry is said to be spontaneous or hidden, because the symmetry of the vacuum is broken (the expectation value of the vacuum does not vanish) but the symmetry of the field and the Lagrangian is not. This causes the local gauge symmetry still to be intact, and the Standard Model is still renormalisable (proved by 't Hooft in 1971).

So, we keep the local gauge symmetry, but the offer is that the vacuum has a non-zero expectation value. What this means, is essentially that there is no vacuum anymore - if everything is gone, there is still always a Higgs field. That we have not noticed anything about this field before, is because the observable of the field, the Higgs boson, only becomes visible at high energies in a controlled environment. On the other hand we know now the mass of the particles is also an observable of the Higgs mechanism, and we could say we already found an observable of the Higgs mechanism before, without realising it.

But, without a discovery of the Higgs boson, we were not able to say anything about the underlying mechanism.

### 1.3.2 The properties of the Higgs boson

The Higgs boson is the quantum of the field \( h \), explained above. The Higgs couples to all massive particles, namely all fermions and the bosons of the weak force, \( W^\pm \) and \( Z \), and itself. The Higgs is a scalar particle, which means it has spin zero. The mass of the Higgs boson comes from the quadratic term in the Lagrangian and leads to \( m_H = \sqrt{2\lambda v^2} \). The mass of the Higgs boson is not predictable from theory, because we do not know \( \lambda \) (\( v \) has been measured before), so it needs to be obtained experimentally. One of the experiments dedicated to the Higgs search is the LHC and its detectors. The 4th of July 2012 a particle was discovered in these detectors that was compatible with the Higgs boson, at a mass of \( \approx 125 \) GeV. This Higgs-like particle will be investigated further the coming years, to find our the properties in more details. An example of one of these properties, is that the decay of the Higgs to all massive particles needs to be confirmed to accept the theory. The decay to fermions was not part of the discovery

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5In Chapter 2 we introduce the experiments at the LHC. One of those, LHCh, is specifically designed to investigate \( CP \)-violation.
of 2012. This thesis presents a search for one of these: the decay of the Higgs particle to \( b \)-quarks. At the end of this chapter, in Section 1.5, we will give a prediction of what theories we can think of when the Higgs decay to fermions would be excluded.

1.4 Higgs couplings in the LHC

The data used for the analysis in this thesis is obtained by the ATLAS detector. The technical details of the ATLAS detector and the LHC, the accelerator that provides protons that are used for the collision, will be given in Chapter 2. The ATLAS detector is designed to find new physics, including the Higgs mechanism. This thesis is about the search for the decay of the Higgs particle to \( b \)-quarks. The choice for this channel will be motivated in Chapter 3. This section will give the production and decay channels for the Higgs particle in the ATLAS detector. After that we will calculate how many Higgs events we expect in 2012 for the channel \( ZH \rightarrow \mu^+\mu^-bb \).

1.4.1 Higgs production

The Higgs boson couples to particles with mass, as explained in the previous section. The mass of the Higgs is high, around 125 GeV, which means the production of the Higgs via leptons or light quarks has a small phase space. The LHC collides protons, which consist of quarks and gluons. From these only the quarks can couple to the Higgs, not the gluons, because the Higgs is colourless and the gluons mass-less. A possibility to still make a Higgs via gluons is drawn in figure 1.4, gluon-gluon fusion, where a top quark loop is included (top quarks have mass and colour, so they couple to both Higgs and gluons).

The second most occurring production channel for the Higgs boson in the LHC is vector-boson fusion, where two quarks radiate two \( W \)’s or \( Z \)’s and annihilate to form a Higgs. A third production mechanism will be relevant for this thesis: the associated production with a weak boson, see figure 1.5. A \( W \) or \( Z \) is produced from the fusion of a quark and anti quark and subsequently the Higgs radiates of this \( W \)- or \( Z \)-boson. The last production mechanism we will mention here is the associated top-quark channel: a Higgs is produced in gluon-gluon fusion, but the two top quarks do not form a closed loop so they are still there in the final signal.

Cross section

A quantity for how often the Higgs is produced via the above-explained channels, is the cross section. With the cross section of a complete channel, we can calculate how many events we expect in a collision (we will do this at the end of this section). The number of events depends on the specifications of the beam of particles that is accelerated and the beam area, combined into one measure as luminosity with dimensions of area\(^{-1}\). The cross section has therefore dimensions of area, often we use barns \( (1 \text{ barn} = 10^{-24} \text{ cm}^2) \). The intrinsic cross section depends on the probability amplitude \( W_{fi} \), the phase space \( \Phi \) and a factor for the Parton Distribution Functions (PDF’s):

\[
\sigma = W_{fi} \times \Phi \times \text{PDF’s}.
\] (1.21)
Figure 1.5: The associated production of a Higgs with a $Z$. The $Z$ is produced from the collision of a quark and an anti quark (a sea quark) and radiates the Higgs.

We need to calculate the probability amplitude $W_{f_i}$ for the transition from the initial to the final state of the Feynman diagram in question. This is done with the Feynman rules, as described in the previous section, and gives us a measure for how often an interaction occurs, based on the type of interaction and the particles involved. The probability amplitude accounts for the physics part of the cross section, namely, the dynamics of the fundamental particles.

We continue with the phase space $\Phi$, a Lorentz invariant factor that looks at the kinematic information: the bigger the phase space, the more available energy states for the final particles.

The last term we need for the calculation of the cross section is the factor for the PDF’s, the Parton Distribution Functions. A collision in the LHC is caused by accelerated protons, from which we know the constituents, the partons. But, since the quarks are confined and the rest of the proton consists of gluons, the only way to know which particle interacts precisely is by modelling the distribution of the partons in a function: the PDF’s. The PDF’s depend on the com energy of the collision: the likelihood of interacting with another particle than the usual $uud$-quarks in the proton, is higher for higher collision energies. A quark that is not reachable in a lower-energy regime, is called a sea quark. For a quark-anti quark collision in the creation of $ZH$, figure 1.5, a sea quark is involved, making the cross section lower than if we would have had a proton-anti proton collider.

The calculation of a cross section is usually done for only the first order (or leading order, LO) Feynman diagram, with the least amount of vertices. If higher order is taken into account, the terms next-to-leading order (NLO) or next-to-next-to-leading order (NNLO) are used.

The production cross section is calculated in this case by the theory group in ATLAS. Figure 1.6 shows the cross section for the production channels gluon-gluon fusion ($pp \rightarrow H$), vector-boson fusion ($pp \rightarrow qqH$) and the associated production with a $W$, a $Z$ and top quarks respectively.

Figure 1.6: The production cross section for several Higgs-production channels, at the centre-of-mass energy of 8 TeV. In this thesis we will search for a Higgs that is produced in the associated channel $pp \rightarrow ZH$, the second one from below.

The cross section in the figure is calculated for the com energy of 8 TeV, at which data was taken
in 2012. The cross section varies with the mass of the Higgs boson, which is on the $x$-axis. The cross section is used later on in the simulation (see Chapter 2) because when a particle is detected, the only way to find out where it came from is to compare it with the simulation. That vector-boson fusion has a lower cross section than gluon-gluon fusion does not mean it is less used; we cannot distinguish the two processes in the final signature, so it needs to be included in the simulation. The associated channels have a different final signature, so these are distinguishable. To find out the exact properties of the Higgs, we need to check all the channels, including the associated ones, regardless of their lower cross section for a 125 GeV Higgs.

1.4.2 Higgs decay

The decay of the Higgs is possible to all quarks, all leptons, and $W$ and $Z$. For a Standard-Model Higgs, the total spin and charge of the decay products needs to be zero. Figure 1.7 is an example of the Higgs decaying to two neutral $Z$ bosons.

![Figure 1.7: The decay of a Higgs boson to two Z bosons. One of them decays to $b$-quarks and the other one to muons. In Chapter 3 we will have a closer look at the properties of this decay channel.](image)

For a decay to be kinematically allowed, the invariant mass of the particle that decays needs to be equal or higher than the invariant mass of the decay products. So, the Higgs decay to two $Z$-bosons is only kinematically allowed if the Higgs is heavier than 182 GeV ($m_Z = 91$ GeV). Since the Higgs particle is discovered at a mass of around 125 GeV, we have a problem with this decay channel. The same is the case for the Higgs decay to top quarks ($m_t = 174$ GeV) and $W$'s ($m_W = 80$ GeV). In the discovery paper of the Higgs [9], the decay to $W$’s has been included, indicating that the decay is possible. If the invariant mass of a particle is lower than its rest mass in a collision, it violates conservation of energy. The most commonly used name for such a particle is ‘off shell’, with the symbol $Z^*$ instead of $Z$, because its mass is not on the mass-shell it is supposed to be in special relativity, $p^2 \neq m^2$. A particle which has the expected invariant mass is called on shell.

The decay to a photon final state is possible, but needs a loop of particles with mass and electrical charge to couple to both the Higgs and the photon (such as quarks, $e$, $\mu$, $\tau$ and the $W$). For the decay to a gluon final state we need a loop of massive particles that have colour charge (these are quarks), as is seen before in the gluon-gluon fusion production process.

The probability of the Higgs decaying into the several channels depends on the strength of the coupling, which depends for a large part on the mass of the decay products. We see this in the formulas for the decay rate. The decays that are interesting for this thesis are $H \to ZZ^*$ and $H \to bb$, so we will give the decay rate $\Gamma$ for these channels [10]:

$$\Gamma(H \to ZZ^*) = \frac{3m_Z^4}{32\pi^2v^4}m_H\delta'\mathcal{R}.$$  \hfill (1.22)

Here the $\delta'$-function depends on the weak-mixing angle (which describes the mixing from the $W_{\mu}$- and $B_{\mu}$-fields to the electroweak fields) and $\mathcal{R}$ depends on the mass of the $Z$ and Higgs. For the decay to $b$-quarks we get:

$$\Gamma(H \to bb) = \frac{3m_b^2}{8\pi v^2}m_H\sqrt{1 - \frac{4m_b^2}{m_H^2}}.$$  \hfill (1.23)

The fraction of the total decay rate for a certain channel is called the branching fraction: $\text{Br}(H \to bb) = \frac{\Gamma_{bb}}{\Gamma_{\text{tot}}}$. The branching fractions for the decay channels of the Higgs are calculated by the theory group in ATLAS, resulting in Figure 1.8. For a Higgs mass around 125 GeV, the decay to $bb$ is dominant, providing one of the first reasons towards the choice of subject for this thesis.
1.4.3 Calculation of number of expected Higgs events in the LHC

To calculate the number of expected Higgs events in the LHC $N$, for a certain mass of the Higgs and a certain cm energy of the collision, we need the luminosity $L$ and the cross section $\sigma$:

$$N = L \times \sigma. \quad (1.24)$$

Here $\sigma$ is the cross section for the whole process, which can be split up in production cross sections and branching fractions. These are shown above for several Higgs masses (Figure 1.6 for the production cross sections for $E_{\text{cm}} = 8$ TeV and Figure 1.8 for the branching fractions). The full formula for the number of events we expect for the a Higgs radiated of a $Z$ and decaying to $b$-quarks, where the $Z$ decays to muons, is:

$$N = L \times \sigma(pp \rightarrow ZH) \times Br(Z \rightarrow \mu^+\mu^-) \times Br(H \rightarrow b\bar{b}). \quad (1.25)$$

Luminosity is explained more thoroughly in chapter two. In chapter three a more detailed discussion will be given about the number of Higgs events we expect in the detector. Also the motivation for the subject of this thesis will be discussed further in chapter three. For now, we can give an idea of what to expect by calculating the number of events, for $E_{\text{cm}} = 8$ TeV, $m_H = 125$ GeV, $L = 5.8 \text{ fb}^{-1}$ (the obtained integrated luminosity by ATLAS from January until June 2012) for the channel $pp \rightarrow ZH \rightarrow \mu^+\mu^-b\bar{b}$; this gives 44 events.

1.4.4 Other processes in the LHC

Until now, we only have been discussing the production and decay of the Higgs particle. But, if two bunches of protons are collided with such high energies as the LHC’s, a large amount of processes take place that influence the prospects of finding the Higgs. These background processes have been modelled over the years, and experimentally verified. Thus, if we look at the data, we can subtract their distributions to influence the Higgs (more about data analysis is in chapter two). The main background processes for the channel $pp \rightarrow ZH \rightarrow \mu^+\mu^-b\bar{b}$ are $Z+\text{jets}$, $ZZ$ and $t\bar{t}$. In Chapter 4 we will give a detailed explanation of these channels. In $Z+\text{jets}$ a $Z$ is created by the fusion of a quark and an anti quark and decays to muons. Two jets are formed when a gluon radiates from the quarks. In the $ZZ$ channel two $Z$’s are created by quark fusion from which one decays to muons and the other one decays to $b$-quarks. The top-quark channel consists of a top and an anti top, that both decay in a $b$ and a $W$, from which the $W$’s decay in a muon and a neutrino. Since the signals of these processes are very similar to the $\mu^+\mu^-b\bar{b}$ signal of our channel, it is difficult to select the correct events. In the analysis of this thesis we will try to do this, and maybe we find a way to find the 44 events back. But, since for example for $ZZ$ we already expect more than 300 events in the same amount of data, this is going to be a challenge.

1.5 Beyond the Standard Model

The Standard Model has been very adequate in predicting the existence of particles since the 1960’s, with as highlights the discovery of the $W$ and $Z$ (1983), the top-quark (1995) and the Higgs (2012). But,
there is a lot of physics we do not understand yet, and we need to look further than the Standard Model. In this section we will give a short description of two models that are useful to investigate for the search of the Higgs decay to $b$-quarks: Supersymmetry and the fermiophobic model.

1.5.1 Supersymmetry

In the Standard Model, the electromagnetic and the weak force are combined into one framework, which endorses the idea of many physicists that there exists something as a theory of everything. Because the coupling constants of the three forces in the Standard Model depend on the probed energy scale and they seem to be approaching each other at high energies, the idea rose that there might be an energy scale where they come together. This unification of forces could mean the three forces have a similar origin, which would lead to a framework in which they are combined. If we want the theory of the Higgs mechanism to hold at this high energy scale, the renormalisation of the theory needs so much fine-tuning that it becomes difficult to believe the theory is correct. The problem that we do not have a reason for the Higgs mass to be low (where low means 125 GeV, which is low compared to the energy scale the forces would unite), is called the hierarchy problem.

A solution to the hierarchy problem is to impose another symmetry. This symmetry needs to cancel some of the positive and negative contributions to the vacuum energy, which are caused by respectively bosonic and fermionic fields. This is what is done in the Supersymmetry model, or Susy. All fermions have a Susy partner that is a boson and vice versa and these partners are heavier than the Standard-Model particles (if they would not be, we probably would have discovered them already). This would not only solve the hierarchy problem, but it also modifies the coupling constants. The running of the coupling constants, how they depend on the probed energy scale, changes in a way that the coupling constants of the three forces unite at $10^{16}$ GeV. In Figure 1.9 we see how the inverse coupling constants behave in Energy scale for the Standard Model and for Susy.

![Unification of the Coupling Constants in the SM and the minimal MSSM](image)

**Figure 1.9:** The running of the coupling constants $\alpha_i$, where $i = 1$ is the weak force, $i = 2$ the electromagnetic force and $i = 3$ the strong force. On the left the Standard Model, where only the weak and electromagnetic force are unified. On the right the Susy model, where all three forces are unified. The energy scale $Q$ for unification in Susy is $10^{16}$ GeV. Figure from [11].

A consequence of Susy, is that there are two Higgs doublets instead of the one singlet that we have now. Because of this, we get five Higgs bosons (three neutral and two charged). The properties of the lightest neutral Susy Higgs depend on the parameters of Susy and are not predicted by theory. If the properties were to be similar to the Standard Model Higgs we discovered in July 2012, we cannot conclude from the data we have now that we found one of the two. The ATLAS group is working on this problem by looking at the properties of the discovered particle in more detail, and by searching for other Susy particles. One of the properties is the branching fraction of the Higgs decay to $b$-quarks, the subject of this thesis. If we would discover this decay and could find this branching fraction, we could therefore exclude some of the Susy phase space. None of the Susy particles have been discovered so far.

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1.5.2 The fermiophobic model

The decay of the Higgs to fermions is not included in the discovery of the Higgs particle the 4th of July 2012; the three discovery channels were $H \rightarrow W^+W^-$, $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$, where the decay of the Higgs to photons needs a loop of $W$’s (or top-quarks, but then we do have a coupling to fermions). If the Higgs coupling to fermions would be excluded, a different Higgs model should be discussed. A model that we could look at is the fermiophobic model, where the Higgs does not couple to the fermions at all. The mass of the fermions should be generated in another way. A solution would be to have a partially fermiophobic model [12]. In this thesis we search for the Higgs decay to $b$-quarks, which means we aim to exclude the fermiophobic model. The branching fractions of the Higgs in the fermiophobic model are shown in figure 1.10.

![Branching Ratios and Cross Section Times Branching Fraction](Figure 1.10: The branching fraction (left) and the cross section times Branching fraction (right) for the fermiophobic decay of the Higgs. The dotted lines show the Standard Model (SM) that does include fermions.

In these plots is to be seen that the number of Higgs events ($N \propto \sigma \times Br$) for a Higgs with an invariant mass of 125 GeV, is lower than the Standard Model that includes fermions. This is mainly because the gluon-gluon-production process has a quark loop in it, so this is suppressed in the fermiophobic model and vector-boson-fusion becomes more prominent. The difference in the number of events gives us a measure to distinguish between the models, even without any knowledge of the decay to fermions. A paper by the ATLAS group based on 2011 data [13] has excluded the fermiophobic model with a 95% confidence level for the mass ranges 110-118 GeV and 119.5-121 GeV. A paper by the CMS group on 2011 data [14] reports that a fermiophobic Higgs boson is excluded at 95% confidence level in the mass range 110-194 GeV, and at 99% confidence level in the mass ranges 110-124.5 GeV, 127-147.5 GeV, and 155-180 GeV.

If the Higgs would be fermiophobic, we could also say something about Supersymmetry, that we discussed in the previous section. With a fermiophobic Higgs, the Minimal Supersymmetric Standard Model (MSSM) would be excluded, and we would have to consider a more complicated Supersymmetric model. More about this can be found in [15].
Chapter 2

The LHC, the ATLAS detector and data analysis

The search for the Higgs decay to $b$-quarks in this thesis is conducted with data from the ATLAS detector. In this chapter we describe the complete set-up that is used to obtain this data: the LHC accelerator and the ATLAS detector. At the end of this chapter, we will give an outlook on the basics of data analysis. With the information in this chapter and the previous one, we provide the necessary information to read the upcoming chapters, which describe the research that is done for this thesis.

2.1 The LHC

A Higgs particle is created in a collision of two highly-energetic particles. The collisions we are analysing in this thesis are those of two beams of protons that are accelerated up to a centre-of-mass energy of 8 TeV. The accelerator we use is the LHC, part of the accelerator complex in Figure 2.1 at the institute CERN in Geneva, Switzerland.

The LHC, Large Hadron Collider, is the ring with the largest radius of the complex, 27 kilometres in circumference. The tunnel in which the LHC is built exists longer than the LHC itself, because it is built for its predecessor, LEP, the Large Electron-Positron collider, that run from 1989 until 2000. The injection point for the proton beams into the LHC is close to Geneva, and the tunnel crosses the Swiss-French border to the furthest point where CMS (one of the detectors) is situated. The LHC is able to accelerate protons and heavy ions (heavy-ion physics is beyond the scope of this thesis). The building of the LHC was finished in 2008, when the first beams were circling around. Unfortunately, there was a technical defect that took a year to fix. In 2010, the accelerator was again ready for the beams, and in
March the first collisions were seen. From March 2010 until February 2013 the LHC provided beams for the experiments. The coming years there will be an upgrade of the accelerator and detectors, to achieve the design centre-of-mass energy of 14 TeV.

Protons are collected by ionising a hydrogen gas, and the first acceleration is done by a linear accelerator, LINAC2. After that the proton beams are accelerated by the BOOSTER, the PS and the SPS (see figure 2.1), before they are injected into the LHC - two beams go in opposite directions. When they are in the LHC, the protons are still gaining energy: they are injected with 0.45 TeV and collide with an energy of 7 TeV in one of the detectors (for the design centre-of-mass energy of the LHC of 14 TeV). The acceleration is done with radio frequency cavities and electric fields. The LHC is a synchrotron accelerator, in which the radius for all particles is the same because the beams are strongly focused. Protons are charged particles, so their path can be bend by magnets. In the LHC, there are 1232 dipole magnets of 8.3 Tesla installed to bend the proton beams and keep them in the ring. The bending of highly-energetic particles causes synchrotron radiation, making the protons loose energy.

The energy loss of particles depends on their mass, for the light electrons in LEP the loss was much higher, giving a reason to collide protons instead of electrons. The energy loss from synchrotron radiation would not happen in a linear collider, such as LINAC, but then we would also not have the possibility of doing multiple turns. Since we accelerate only protons and no anti protons, we need different magnets for the two beams going in opposite directions, but the trouble of making anti protons is bigger than the trouble of having two magnet systems. These arguments motivated the choice to build a proton-proton synchrotron accelerator.

The whole system is kept at a low temperature for superconductivity and a low density prevents energy loss from collisions with the gas. The protons come in bunches, clouds of about a hundred billion particles, a few centimetres long. To keep the bunches together there are quadrupole magnets installed, that keep the transverse width of a bunch at a few millimetres.

The usual quantity to describe the performance of an accelerator, is luminosity. Luminosity is the flux of the beam in cm$^{-2}$s$^{-1}$, and depends on how many protons there are accelerated, their velocity and how close together they are at the collision point. The definition of the luminosity in the LHC is the following [16]:

$$L = \frac{N_p n_b f_{\text{rev}} \gamma F}{A_{\text{eff}}}.$$  \hspace{1cm} (2.1)

Here we see in the nominator the number of particles per bunch, $N_p$, the number of bunches in a beam, $n_b$, the revolution frequency of the bunches in the LHC, $f_{\text{rev}}$, the relativistic factor for the bunches, $\gamma = 1/\sqrt{1-(\frac{v}{c})^2}$, and the term $F$, which accounts for a luminosity reduction depending on the angle the beams cross each other with. In the denominator we see $A_{\text{eff}}$, the effective area of the collision.

The luminosity can be raised by increasing the number of bunches or decreasing the collision area by focusing the beams. Between 2010 and 2012, the luminosity was raised to almost $8 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$. To have collisions we need a stable beam (the first stable beams in the LHC, in 2008, were worth a celebration). The period in which a beam is kept stable is called a run, that can last a few hours up to days. During a run, the protons loose energy and the luminosity goes down. In Figure 2.2 we see the peak luminosity per run.

![Figure 2.2: The luminosity (peak luminosity is the highest measured value for the luminosity in a run) by the LHC to the ATLAS detector per year.](image)

The design luminosity of the LHC is $10^{34} \text{cm}^{-2}\text{s}^{-1}$, the LHC is expected to reach this number after the upgrade. For the design luminosity, there will be 2808 bunches of protons circling around in the
LHC. With a nominal bunch spacing of 25 ns, the bunch-collision rate will be 40 MHz. The collision rate rises when the luminosity does, because the amount of protons at the area of the interaction point gets higher. When multiple collisions occur per crossing, the collision point the tracks in the detector originate from becomes harder to find. We need the collision point to determine which particle the tracks are the decay products of. The occurrence of multiple collision per bunch crossing is called pile-up. In Figure 2.3 we see the number of interactions per crossing.

![Figure 2.3](image-url)  
**Figure 2.3:** The number of interactions per bunch crossing in ATLAS per year, causing pile-up.

Finally, we show Figure 2.4, the luminosity integrated over time, with units inverse femtobarn, fb$^{-1}$. A barn is a measure of area, one barn is $10^{-24}$ cm$^2$. The integrated luminosity gives how much collision data is generated, and from it we can calculate how many events we expect for a certain process. In Chapter 1, Section 1.4.3, we calculated the number of events we expect for the channel $HZ \rightarrow \mu^+\mu^-bb$, for an integrated luminosity $L$ of 5.8 fb$^{-1}$: $N = L \times \sigma = 5.8 \times 7.66 = 44$. The plot in Figure 2.4 shows that the collaboration collected more data every year.

![Figure 2.4](image-url)  
**Figure 2.4:** The delivered or integrated luminosity by the LHC to the ATLAS detector per year.

### 2.2 The ATLAS detector

The design of the ATLAS detector was finished in 1999 [17]. This section starts with an overview of the detector design, continues with the coordinates that are used throughout the collaboration, and thereafter describes the detector layers and triggers in more details. This thesis is about $b$-quarks and muons, so we will give more attention to the signals of these particles.

The ATLAS detector is one of the four large experiments that detects particles collided by the LHC. There are two main reasons for building more experiments at one collider. One, they have different sub-detectors, shapes and sizes, and are specialised in detecting different kinds of particles. Two, the experiments can verify each others results. They are completely independent, for the technical as well as the computing methods. For example, the discovery of the Higgs particle would only be claimed if the
two general purpose detectors, ATLAS and CMS, both independently obtained a five sigma significance. The other two large detectors are LHCb, specialised in investigating charge-parity violation and ALICE, specialised in heavy-ion physics.

2.2.1 Overview

The ATLAS detector is a general purpose detector. This means the goal of the experiment is not to test a predefined theory, but to detect everything that comes out of a collision. A general purpose detector is designed to find new physics, whatever this may be.

The ATLAS detector consists of several layers, each designed to find a specific particle. The particles have different properties. The properties a detector can measure are its position, momentum, its charge and the ability to transverse a certain material. An example is given in Figure 2.5, where a positron enters from below and is bended by a magnetic field. It looses energy by the plate of lead in the middle, and afterwards has a smaller bending radius. From this, Anderson deduced in 1932 that the particle was positively charged and this was the first discovery of an anti particle.

Figure 2.5: Bubble-chamber picture of the discovery of the positron by Anderson in 1932. The positron enters from below and is bent by the Lorentz force, caused by a magnetic field going inwards into the paper. If it would have been an electron entering from below, the track would have been bended to the right instead of the left; if it would have been an electron entering from above, the bending radius would be smaller below the plate of lead.

The picture of the bubble-chamber tracks is one of the many photos that were taken and analysed one-by-one. In the ATLAS detector, the signals of the tracks are digitised and the data files are stored in computer storages around the World. In Figure 2.6 we see an impression of these tracks in the ATLAS detector. The different particles give a different signal in the detector layers, making them distinguishable in the analysis. The main layers we see are the tracking, the calorimeters and the muon chambers. The tracking detectors measure the momentum and the track of the charged particles: electrons, charged hadrons and muons. The calorimeters measure the deposited energy of the electrons, photons and hadrons. The calorimeters also detect a jet from tau-leptons, because the tau has such a short lifetime that it decays too close to the interaction point to detect. The muon chambers are specifically designed to detect the momentum and direction of the muons. The neutral and only weakly-interacting neutrino is an exception to the rest of the particles. Because it traverses all the detector material, the only way to know something about it is to calculate the energy that is missing after the collision (the total energy in a collision is conserved). Often the neutrino is referred to as missing energy, or $E_T$, missing transverse energy. To get a better overview of what a collision looks like, Figure 2.7 is added. This event display shows the remnants of the event $ZH \rightarrow \mu^+\mu^- b\bar{b}$, the subject of this thesis, after reconstruction. Two muons are seen in the muon chambers in the most outer layers of the detector, and two jets are reconstructed in the hadronic calorimeter. There are a lot of tracks surrounding the signal, that have been cut away by carefully chosen triggers and analysis cuts.

The total overview of the ATLAS detector is given in Figure 2.8. The detector is the largest of the LHC complex, $46 \times 25 \times 25$ m$^3$ (about the size of the Dam Palace in Amsterdam) and weighs 7000 tonnes. It is located close to Geneva, in Meyrin, Switzerland. The ATLAS collaboration in 2012 consists of about 3000 scientists from 38 countries. About 50 of those work at the Nikhef Institute in Amsterdam. The ATLAS group from the Nikhef Institute is connected to the University of Amsterdam, the Free University
and the Radboud University of Nijmegen.

Figure 2.6: An overview of the detector layers of ATLAS. If we start in the interaction point at the bottom of the figure, we first see the tracker, which measures the momentum and the track of charged particles, such as the muon, proton and electron. The calorimeters measure the energy; the electromagnetic calorimeter measures the energy of the photon and the electron, the hadronic calorimeter that of the proton and the neutron (and other bound quarks, such as the $b$-quarks). When the particles have deposited their energy in the calorimeters, their track stops. The muon spectrometer detects the momentum and track of the left-over particle, the muon. The neutrino escapes the detector all together.
Figure 2.7: An event display of \(ZH \rightarrow \mu^+\mu^- bb\) [18], the subject of this thesis. The input of the event display consists of real data that is analysed and compared with simulation. This Higgs event was recorded in September 2012. The cones are the jets from the \(b\)-quarks, that left their energy in the hadronic calorimeter. The thin tracks are the muons, that leave a signal in the most-outer part of the detector, the muon chambers. On the left we see the transverse plane around the interaction point (see Section 2.2.2 on coordinates).

Figure 2.8: The sectioned view of the ATLAS detector [17]. The interaction point is in the middle of the figure and the proton beams enter from the left and right. The different detector layers are pointed out. At the front we see some human-sized figures, to show the real size of the detector. The useful sections for this thesis are the Inner Detector, the Hadronic Calorimeters and the Muon Detectors.
2.2.2 Coordinates

For consistency, the whole ATLAS collaboration uses the same coordinate conventions. Next to the usual Cartesian coordinates, two frequently used coordinates in particle-physics experiments are the transverse momentum $p_T$ and the pseudorapidity $\eta$. In this section we explain these coordinates. In Figure 2.9 we see $p_T$ on the left and $\eta$ on the right.

Figure 2.9: The coordinates $p_T$ and $\eta$. On the left we see the transverse plane for which the coordinate $p_T = \sqrt{p_x^2 + p_y^2}$ is used for the momentum. On the right we see that the pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$ goes to infinity when it reaches the z-axis (the longitudinal direction).

The reference point we start from is the interaction point in the middle of the ATLAS detector. From the interaction point we define the coordinates $x$, $y$ and $z$ as follows. The beamline is the $z$-axis, the $x$-axis are defined as if the beamline were linear, with the positive $z$-axis pointing towards the left if you are standing in the middle of the LHC ring. Since the ATLAS detector is positioned on the south of the LHC ring, as we saw in the overview of the accelerator complex in Figure 2.1, the positive $z$-axis points eastwards. The positive $y$-axis goes upwards. The positive $x$-axis goes inwards, towards the middle of the LHC ring. This makes it a right-handed coordinate system. The transverse momentum $p_T$ is the momentum in the transverse plane at the collision point, defined as $p_T = \sqrt{p_x^2 + p_y^2}$.

In a collision with a high centre-of-mass energy such as we have in the LHC, the collision remnants scatter mostly in the transverse plane. The momentum in the direction of the beamline is therefore less important in the analysis, and for the momentum of the particles in the detector we use $p_T$.

To understand the pseudorapidity, we need to start with the familiar spherical coordinates, $r$, $\theta$ and $\varphi$, with a domain of $r \in [0, \infty]$, $\theta \in [0, \pi]$ and $\varphi \in [-\pi, \pi]$. The pseudorapidity $\eta$ is defined as $\eta = -\ln \tan \frac{\theta}{2}$ with a domain $\eta \in [-\infty, \infty]$. If $\eta = 0$ we are on the $y$-axis and if $\eta$ is infinity on the $z$-axis. The use of $\eta$ instead of $\theta$ is chosen in a lot of analyses. A Lorentz transformation along the $z$-axis of a particle’s direction, gives $\eta' = -\ln \tan \frac{\theta}{2} - \ln \gamma$. The factor $\gamma$, defined as $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$ with $\beta = \frac{\gamma v}{c}$, depends only on the velocity $v$ of the reference frame and not on the $\theta$ of the particle. The difference in $\eta$ between two particles is Lorentz invariant, because the term with $\gamma$ cancels. If two particles from the same collision are shifted to the centre-of-mass frame, which makes the analysis easier, their difference in $\eta$ remains intact. For more particles, or more events, this means the distribution of the $\eta$ of the particles maintains its shape.

With the coordinates $p_T$, $\eta$ and $\varphi$, we can fill an energy-momentum four vector of a highly-energetic particle: $p = (E, p) = (p_T \cosh \eta, p_T \cos \varphi, p_T \sin \varphi, p_T \sinh \eta)$. We use this for example to calculate the invariant mass of a $Z$-boson in the decay $Z \rightarrow \mu\mu$, the invariant mass is $m_Z^2 = p_1 \cdot p_2$, with $p_1$ and $p_2$ the energy-momentum four vectors of two muons.

2.2.3 The Inner Detector

The first step in finding out which particles came out of the collision, is to track their path and momentum. This happens in the Inner Detector (for charged particles). The high amount of tracks coming from the collision, calls for a high precision detector with a fine granularity. The first pattern of the track is recognised with a pixel detector. The pixels, made from silicon, give a signal to the read-out when a charged particle traverses the material and loses a small part of its energy. Because there are several
layers of pixels, the different signals or hits from a particle form a track. After the pixel detector follows a semi-conductor tracker, SCT, and after that comes a straw tube tracker or transition radiation tracker (TRT), that provides a large number of tracking points, improving the momentum measurement. Because there is a magnetic field applied to the Inner Detector, the charged particles have a bent track. This gives the momentum, because for a particle with a higher momentum, the track is less curved. The total inner tracker has a coverage of $|\eta| \leq 2.5$. The diameter is 2.1 m.

If a particle has a short lifetime, it decays in the Inner Detector. This causes a second vertex, in contrast to the first vertex from the proton-proton collision. An example of such a particle is the $b$-quark. Since free quarks do not exist, the $b$-quark track is made by a hadron, such as the particle $B^0$, which consist of an $d$- and a $b$-quark. The mean lifetime, $\tau$, of the $B^0$ is $\tau = 1.5 \times 10^{-12}$ s, leading to a track length (for a particle that travels with the speed of light $c$) of $c\tau = 0.45$ mm. A light quark would form a hadron that leaves a longer track (for example $K^0$ consists of $d\bar{s}$ and has a track length of $c\tau = 3.7$ m), so there would not be a secondary vertex in the Inner Detector. The $b$-quark decays at the second vertex into one of these lighter quarks and those will leave a signal in the hadronic calorimeter. The second vertex is detected by the first layer of the pixel detector, appropriately called the B-layer.

### 2.2.4 The calorimeters

A calorimeter absorbs the energy of a particle in several stages, until the particle’s track stops. This is done by several layers of lead or iron plates, in which the particle interacts, which gives a shower in the detector (we see the showers in the overview of the detector layers in figure 2.6). In between the plates is a material that detects the particles in the shower. The calorimeters in the ATLAS detector are surrounding the Inner Detector. There are different parts, each for different particles and with a different coverage. The detectors consist of a barrel and an endcap, where the endcap provides a higher $\eta$-coverage. The forward region, $3.1 < |\eta| < 4.9$, is covered by a separate liquid-argon calorimeter. Figure 2.10 shows an overview of the calorimeters.

![Figure 2.10: The calorimeters surround the Inner Detector. We see the tile calorimeters from the HCAL, the accordion calorimeters from the ECAL, the forward calorimeters with liquid argon (LAr) and the endcaps from the HCAL.](image)

The first layer is the electromagnetic calorimeter, the ECAL. This layer detects electrons and photons. The detector is a liquid-argon detector, where a charged particle leaves an ionised electron drifting to the anode. The particles lose energy by lead plates.

The second layer is the hadronic calorimeter, the HCAL. This layer detects showers from jets, caused by hadrons. The hadrons lose a very small amount of energy in the ECAL, but because the HCAL is heavier they will only be stopped there. The HCAL consists also of a liquid-argon calorimeter for the endcaps ($1.5 < |\eta| < 3.2$), but has an additional tile calorimeter ($|\eta| \leq 1.5$). The tile calorimeter uses the sampling method by alternating 3 mm thick scintillating tiles and iron plates. To reconstruct
a jet, a bunch of particles close together need to be found. The definition of the used jet area is
\[ dR = \sqrt{d\eta^2 + d\varphi^2}. \] Usually this is \( dR < 0.4 \). The large area makes it difficult to reconstruct the exact vertex where the quark hadronised. The relative error of the measurement is given by the resolution. The relative momentum resolution is defined as \( \frac{\sigma}{p_T} = \frac{N}{p_T} + \frac{S}{\sqrt{p_T}} + C \). The \( N \)-term is for the effective noise, independent of the jet \( p_T \), caused by electronics or pile-up, but is only significant for low energies. The \( S \)-term is for the stochastic error from the sampling fluctuations; for a large number the Poisson distribution becomes a Gaussian that goes with \( \sqrt{N} \propto \sqrt{p_T} \). The last term, with \( C \), is a constant term due to for example the loss of events in non-active material and depends on the jet \( p_T \). The design energy resolution (for highly-energetic particles, energy and momentum are about the same) of the HCAL is \( \frac{\sigma_E}{E} = 50\% / \sqrt{E} + 3\% \) with the energy \( E \) in GeV.

### 2.2.5 The muon spectrometer

The only particles left to detect are the muons. These are charged particles, and form a bent track in the detector. The muon loses a few GeV of its energy in the calorimeters, but it is the only particle that reaches the muon chambers. The muon is a minimum ionising particle [19], when it is relativistic it interacts less in the calorimeter materials than for example the electron. With the known strength of the magnetic field that is applied, the radius of the bent track gives away the momentum of the muon, just like in the Inner Detector. A track needs at least three hits in the chambers. The most used technique for the muon detector (in the Monitored Drift-Tube chambers or MDTs) is: The muon ionises an \( Ar-CO_2 \) gas mixture in a tube and the electrons drift towards a wire in the tube that gives a hit. The rest of the muon spectrometer consists of Cathode Strip Chambers (CSCs), Resistive Plate Chamber (RPCs) and Thin Gap Chambers (TGCs). The MDTs and CSCs are precision chambers that measure the position of the hit in 2D and 3D respectively. The RPCs and TGCs provide the trigger information for the barrel and the endcap when a muon enters the spectrometer. The design resolution of the momentum measurement (for \( p_T = 1 \) TeV) in the detector is \( \frac{\sigma_{p_T}}{p_T} = 10\% \) (the highly-energetic region is dominated by the constant term in the resolution formula).

In Table 2.1 a summary of the performance goals for the different detector layers is shown.

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Required resolution</th>
<th>( \eta ) coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>( \frac{\sigma_{p_T}}{p_T} = 0.05% ) ( p_T \leq 1% )</td>
<td>( \pm 2.5 )</td>
</tr>
<tr>
<td>EM calorimetry</td>
<td>( \frac{\sigma_{E}}{E} = 10% / \sqrt{E} + 0.7% )</td>
<td>( \pm 3.2 )</td>
</tr>
<tr>
<td>Hadronic calorimetry (jets)</td>
<td>( \frac{\sigma_{E}}{E} = 50% / \sqrt{E} + 3% ) ( \frac{\sigma_{E}}{E} = 100% / \sqrt{E} + 10% )</td>
<td>( 3.1 &lt; \eta &lt; 4.9 ) ( 3.1 &lt;</td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>( \frac{\sigma_{p_T}}{p_T} = 10% ) at ( p_T = 1 ) TeV</td>
<td>( \pm 2.7 ) ( \pm 2.4 )</td>
</tr>
</tbody>
</table>

Table 2.1: Resolution requirements for the energy (the calorimeters) and the \( p_T \) (for the tracking and muon spectrometer). The table also shows the \( \eta \)-coverage of the four detector layers. Table from [20].

### 2.2.6 Trigger systems

The detectors deliver a large amount of data, too large to store everything on computers. Therefore, we need to filter interesting events from the background. This is done by a trigger, the first level in ATLAS is a hardware trigger and the second and third level are software triggers.

The first level uses a low granularity and focuses mostly on high-\( p_T \) particles. For the design interaction rate of 1 GHz, the level-1 trigger reduces the input to 75 kHz. The second-level trigger uses a Region of Interest, RoI, where more detailed information about the particle can be obtained, in \( p_T \), \( \eta \) and \( \varphi \). By now, full-granularity data is used to make a trigger decision. The level-2 trigger reduces the rate to 1 kHz. The last step in triggering is the Event Filter, EF. The EF takes more time than the previous triggers, and can therefore work with more complicated algorithms. The EF also combines data from different parts of the detector for the object definitions of the particles. The trigger paths of the EF are named after these particles, for example EF2mu10 only keeps events with two muons that have an energy of more than 10 GeV. The final output of the trigger systems at design luminosity is 100 Hz. This is the raw data, ready to be analysed.
The computer storage needed for this data is still so large, that the ATLAS detector uses most of the Worldwide LHC Computing Grid. For the Grid 50.000 computers are distributed over 36 countries [21]. There is access to the EF data from every institute connected to ATLAS.

2.3 Overview of data analysis

A theory in physics can be used to make predictions of observables, like the decay properties of the Higgs boson. To test the theory, we need to compare the predictions with data from an experiment. The prediction from theory is simulated and the comparison of the simulation with detector data is the analysis. To draw a conclusion on whether to confirm or reject the theory, we need statistics. This section gives the necessary information and an overview of the analysis we will do in the Chapters 3 and 4 of this thesis. We will encounter statistics again in Chapter 5.

2.3.1 Simulated data

The simulated files we need for an analysis are the signal and the backgrounds. The simulation of an event is a process in several steps. The cross sections and branching fractions of a process are calculated, for example for the channel $pp \rightarrow ZH \rightarrow \mu^+\mu^-bb$, and these are used as the input for the simulation. An event signature depends on a lot of variables such as decay probabilities, which make it impossible to calculate exactly what happens. To predict what the signature we need to look for, we use series of random numbers for all the probability density functions of the variables. If we do that for a lot of events, we have a spectrum that we can use. This is called the Monte Carlo method. Monte Carlo generators in the ATLAS group are for example PowHeg, Pythia or Herwig [17]. The properties of the simulated particles we have now describe the physics of the event and they are called the true properties.

After the generation of the event, the behaviour of the detector is simulated. This is done in ATLAS by the program GEANT4 [17]. All the different layers of the detector are taken into account, from the geometry of the detector to hardware such as the positioning of a hole in the detector for the cables that take care of the read-out of the detector layers. Every particle behaves differently in the detector layers, as was described earlier in this chapter, and all these different properties need to be included in the reconstruction. The output of this process is digitised, leaving us with simulated data that is of a comparable format to the raw data coming from the Event-Filter trigger of the real detector. The reconstructed simulated properties of the particles are called the reco properties. We now have true information, which describes the physics, and reco information, which describes the behaviour in the detector.

If we have the data, we need to select the information we want to use. The goal of the selection is to keep the signal and throw out the background events, so we look for differences between the event properties. Every event has different properties, depending on what we want to investigate. The variables that are relevant for the analysis need to be extracted from the data, for example the distribution of the invariant mass, charge, $p_T$ or $\eta$ of a particle. The descriptions of the particles we need for the analysis are the object definitions, in which we for example say that a muon must have been detected in the Inner Detector as well as in the Muon chambers. After that we need to select on a final state, in our analysis we need two muons and two jets. The final state selection is called the event selection. In Chapter 4 we give the object definitions and the event selection for the channel $ZH \rightarrow \mu^+\mu^-bb$ with the backgrounds $tt$, $Z+$jets and $ZZ$.

2.3.2 Real data

The simulated data is compared with the real data from the detector. In figure 2.11 an example is shown how this is done. The simulated signal is a peak above the simulated background. In this plot, the real data peaks around the same mass as the signal, so this gives a hint that we discovered something.

Since the data in figure 2.11 does not exactly follow the signal plot (the signal is not within the error margins of the real data), we know we have to make the simulation better. To know how close the data and the signal distributions are, we calculate the probability that the data points are coming from a background event. If the probability the peak is a background fluctuation is $2.8 \times 10^{-7}$, we say we have discovered something, this number is known as a $5 \sigma$ significance. We can also exclude the existence of something new, when the data points follow exactly the distribution of the backgrounds and not the one of the signal. The latest particle discovered by the ATLAS detector is a Higgs-like particle with a mass around 125 GeV [9], this was on July 4th, 2012. In figure 2.12 we see the invariant mass distribution
of the Higgs decay to $Z$-bosons which subsequently decay to four muons. In this thesis we will search for the $ZH \rightarrow \mu^+\mu^-bb$ decay: we will make an event selection in order to discover the Higgs decay to $b$-quarks. The goal is to find a value for the probability that the real data is a background fluctuation in the invariant-mass region of $m_{bb} \approx 125$ GeV.

**Figure 2.12:** The invariant mass of the Higgs boson [9], as published on July 4th, 2012. The simulated signal and backgrounds are included, the data points are obtained by the ATLAS detector.
Chapter 3

A MC study of the final state $\mu^+ \mu^- b\bar{b}$ in Higgs searches

The subject of this thesis is a search for the Higgs boson in the associated channel $ZH \rightarrow \mu^+ \mu^- b\bar{b}$. The goal of this chapter is to give an extensive motivation for the choice of this channel.

The grass is always greener on the other side of the fence. After the investigation of another Higgs-decay, we will be more convinced of our choice for the associated channel. The associated channel, the subject of this thesis, contains the final state $\mu^+ \mu^- b\bar{b}$. This chapter describes a Monte Carlo study of $H \rightarrow ZZ^* \rightarrow \mu^+ \mu^- b\bar{b}$, a channel with the same final state. We chose to study this channel because it seems promising in the search for the Higgs boson. However, the results of the study described in this chapter contain two reasons to not continue working on this channel in the rest of this thesis. The study is done with 2011 Monte Carlo files and the content has been presented at the Nikhef ATLAS Workshop at June 20th, 2012. This chapter ends with a description of the channel that will be used as signal for the rest of this thesis ($ZH \rightarrow \mu^+ \mu^- b\bar{b}$).

3.1 The channel $H \rightarrow ZZ^* \rightarrow \mu^+ \mu^- b\bar{b}$ versus $H \rightarrow ZZ^* \rightarrow 4\mu$

In this section we will investigate the channel $H \rightarrow ZZ \rightarrow \mu^+ \mu^- b\bar{b}$, we see a Feynman diagram in figure 3.1. In the Feynman diagram we see that we have a final state of two muons and two $b$-quarks. The $b$-quarks hadronise into jets that are detected by the hadronic calorimeter of the ATLAS detector. The jets form an interesting study object, since the amount of particles in a jet is large, complicating the analysis, as was described in Section 2.2.4.

![Figure 3.1](image)

Figure 3.1: The Higgs is created by gluon-gluon fusion and decays into two $Z$-bosons, which subsequently decay into $b$-quarks and muons. In this chapter we will look at this channel.

Another property of the $\mu^+ \mu^- b\bar{b}$-final state, is that the branching fraction of $Z \rightarrow b\bar{b}$ is about 4.5 times higher than the branching fraction of $Z \rightarrow \mu^+ \mu^-$, which is also part of another channel that is used for Higgs searches: $H \rightarrow ZZ \rightarrow 4\mu$. In Table 3.1 we see the branching fractions of the $Z$-boson. The $Z$ decays to fermion-anti fermion combinations, because the $Z$ is neutral and couples weakly.
<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow q \bar{q}$</td>
<td>0.6991</td>
</tr>
<tr>
<td>$Z \rightarrow b \bar{b}$</td>
<td>0.1512</td>
</tr>
<tr>
<td>$Z \rightarrow \mu^+ \mu^-$</td>
<td>0.03366</td>
</tr>
<tr>
<td>$Z \rightarrow e^+ e^-$</td>
<td>0.03363</td>
</tr>
<tr>
<td>$Z \rightarrow \tau^+ \tau^-$</td>
<td>0.03370</td>
</tr>
<tr>
<td>$Z \rightarrow \nu^+ \nu^-$</td>
<td>0.2000</td>
</tr>
</tbody>
</table>

Table 3.1: Branching fractions of the $Z$-boson [19]. The branching fraction of $Z \rightarrow b \bar{b}$ is about 4.5 times higher than the one from $Z \rightarrow \mu^+ \mu^-$. 

For each process in the LHC, we can calculate the number of events we expect for a certain integrated luminosity. In Figure 3.2 we show the number of collision events we expect in the LHC for relevant channels for this chapter, where the number of events $N$ is defined as $L \times \sigma \times Br$; integrated luminosity $\times$ production cross section $\times$ branching fractions. We use the cross section for a centre-of-mass (com) energy of 7 TeV, because in this chapter we will use 2011 MC files. About 5 fb$^{-1}$ of data is obtained in 2011, so we use this number for the integrated luminosity. We see that the branching ratio of $Z \rightarrow b \bar{b}$ is about 4.5 times higher than the branching ratio of $Z \rightarrow \mu^+ \mu^-$ in Figure 3.2. The dip in the number of events at approximately 160 GeV is because the Higgs decay to $W$’s is dominant there.

![Figure 3.2](image-url)

Figure 3.2: Number of expected Higgs events in the LHC for an integrated luminosity of 5 fb$^{-1}$ in 2011. The vertical line is the Higgs mass of 126 GeV, which is approximately the mass of the Higgs-like particle discovered in July 2012. We see the channels $H \rightarrow ZZ \rightarrow \mu^+ \mu^- b \bar{b}$ and $H \rightarrow ZZ \rightarrow 4\mu$. The channel $ZH \rightarrow \mu^+ \mu^- b \bar{b}$ is added for comparison later in this chapter.

### 3.1.1 The challenges because of the off-shell $Z^*$

From the last section, summarised in Figure 3.2, we conclude we prefer the decay $H \rightarrow ZZ \rightarrow \mu^+ \mu^- b \bar{b}$ over $H \rightarrow ZZ \rightarrow 4\mu$. We will investigate this further by looking at the simulated data of $H \rightarrow ZZ \rightarrow \mu^+ \mu^- b \bar{b}$. We use the 2011 Monte Carlo (MC) simulation for a Higgs mass of 120 GeV, we use 30,000 events. In Appendix A we give more information on the used MC samples.

First, we look at the MC true information (before the detector reconstruction). The properties of the $Z$-bosons are obtained by adding the four vectors of two muons and two quarks. Because the Higgs mass of 120 GeV is lower than twice the $Z$ mass, we expect at least one of the $Z$’s to be off shell. The masses of the two $Z$-bosons are plotted in Figure 3.3, where we plotted the lightest and the heaviest $Z$ in an event separately. We did not make a distinction between the $Z$ from muons and the $Z$ from quarks.

From this plot we see that if a Higgs of 120 GeV decays to two $Z$-bosons, $m_Z = 91$ GeV, the mass is not equally distributed between the two; one is off shell and one is on shell. The probability for a particle to be at its mass shell is described in a Breit-Wigner distribution, which depends on the mass and the decay width of the particle. The distribution peaks at the mass of the particle, so the probability that
one of the $Z$’s is on shell is higher than if both $Z$’s were off shell. In the simulation, there is no preference for the off-shell $Z^*$ to decay to $b$-quarks or the other way around. Now we know we have one on-shell and one off-shell $Z$, we can look at the advantages and disadvantages when the off-shell $Z^*$ decays to either quarks or muons. We do this by taking into account the detector reconstruction.

**When $Z^*$ decays to $b\bar{b}$**

To find out what happens when the off-shell $Z^*$ decays to $b$-quarks, we look at the reconstructed muons and jets. For the reco muons we use the Muid reconstruction algorithm, demand two oppositely charged muons, a cut on $|\eta| < 2.5$ and the muon should be detected in the Inner Detector as well as in the Muon chambers (the cut is on ‘CombinedMuon’). We throw away muons from a $Z$ with $m_{\mu\mu} < 80$ GeV. For jets we use the AntiKt4TopoEM algorithm, we demand at least two jets, $p_T > 25$ GeV, $|\eta| < 2.5$ and badly reconstructed jets are removed (a cut on ‘BadLoose’). For the next plot we used this reco information to plot the reconstructed invariant mass of the on-shell $Z$-boson. The reconstructed objects, jets, muons, in this plot are linked to the true values: the reco particle is thrown out if it is further away from the true value than $dR = 0.5$, where $dR$ is the distance between two tracks, $dR = \sqrt{d\eta^2 + d\phi^2}$.

![Figure 3.4: The reconstructed invariant mass of the $Z$ bosons from muons and quarks for the on-shell $Z$.](image)

If we look at Figure 3.4, we see that the invariant-mass peak from the jets is broader than the one from the muons. We can blame this to the resolution of the HCAL, described in Section 2.2.4. From
the plot we see that it would be difficult to find the $Z$-decay to jets if the $Z$ were on-shell. For an analysis with real data it would be even harder, since we cannot link to the true values anymore. If we compare this plot to Figure 3.3, in which the off-shell $Z$ has a broader mass peak than the on-shell one, we conclude that the signal of the off-shell-$Z$ decay to jets does not look likely to yield results. We are left with the option that the off-shell $Z^*$ decays to muons. We will investigate this option in the next section.

**When $Z^*$ decays to $\mu^+\mu^-$**

The reasoning of the last section left us with an off-shell $Z^*$ decaying to muons, see the Feynman diagram in Figure 3.5.

![Feynman diagram](image)

**Figure 3.5:** The Feynman diagram for the decay $H \rightarrow Z^*Z \rightarrow \mu^+\mu^-\overline{b}b$, where the off-shell $Z^*$ decays to muons.

On the left in Figure 3.6 we see the $p_T$ of these muons, and we see two peaks. For the on-shell $Z$ we see a peak at approximately $p_{T,\mu} = 91/2 = 46$ GeV, because for relativistic muons, $E \approx |p|$, obeying $p_1 = -p_2$, we obtain $(2p_{T,\mu})^2 \approx M_Z^2$. For the off-shell $Z^*$ we see a peak at approximately $p_{T,\mu} = 29/2 = 15$ GeV. If we have such low $p_T$ particles, we get in trouble with the trigger possibilities. One of the lowest-$p_T$ trigger options we have for two muons, is EF2mu10. This trigger path only selects events with at least two muons that have a $p_T$ higher than 10 GeV. We count the number of events that is selected by this trigger, and see that 11% of the events is accepted. In Table 3.2 we see the number of selected events for EF2mu10 and two other low-$p_T$ triggers for comparison.

To get a closer look at the behaviour of the trigger, we plot the trigger efficiency per $p_T$. We use a $Z$+jets MC file, because it has higher statistics: 149,950 events. The triggered muons (the ones that are accepted by the trigger path) are linked to the reco muons by demanding them to be within the range $dR < 0.1$. For the reco muons we used again the Muid reconstruction algorithm, demand two oppositely charged muons, a cut on $|\eta| < 2.5$ and the cut on ‘CombinedMuon’. To calculate the trigger efficiency we divide the histogram of the $p_T$ of the reco muons that were within $dR < 0.1$ of the triggered muons, by the histogram of the $p_T$ of all reco muons. The trigger efficiency of EF2mu10 is shown on the right in Figure 3.6. From the plot, we see that the trigger efficiency rises with a higher $p_T$ until it reaches a plateau at 0.8. This shape is called the turn-on curve of the trigger. It does not go all the way up to one because the Level 1 trigger does not cover the region around $\eta = 0$ [23]. There are a few muons with a $p_T$ below 10 GeV because we demand at least two muons and not exactly two.

![Graph](image)

**Figure 3.6:** On the left we see the $p_T$ of the reco muons. We see two peaks, one from the on-shell $Z$ at 45 GeV and one from the off-shell $Z^*$ at 15 GeV. On the right we see the turn-on curve for the trigger efficiency of EF2mu10 for muons in the $Z$+jets MC file.
Table 3.2: The trigger efficiency of three low $p_T$ muon triggers, EF2mu10, EFmu10 (triggers on one muon with a $p_T$ of more than 10 GeV) and EFmu18medium (triggers on one muon with a $p_T$ of more than 18 GeV). The MC file has 30,000 events.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Nr. of accepted events</th>
<th>Percentage accepted</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu10</td>
<td>9013</td>
<td>30%</td>
</tr>
<tr>
<td>2mu10</td>
<td>3328</td>
<td>11%</td>
</tr>
<tr>
<td>mu18medium</td>
<td>6356</td>
<td>21%</td>
</tr>
</tbody>
</table>

3.1.2 Conclusion

The assumption before we looked at the MC file of $H \rightarrow ZZ \rightarrow \mu^+\mu^-b\bar{b}$, was that we had a factor 4.5 advantage (from the branching fraction) on $H \rightarrow ZZ \rightarrow 4\mu$ for the number of expected events. In the MC analysis we encountered two problems for $H \rightarrow ZZ^* \rightarrow \mu^+\mu^-b\bar{b}$. The first problem was that the resolution for the off-shell $Z^*$ to decay to $b$-quarks was too low, so we demanded the off-shell $Z^*$ to go to muons. We lost a factor 2 on the number of events because of this. The second problem we encountered was a low efficiency when we had to trigger on low-$p_T$ muons, for the used trigger EF2mu10 we found an efficiency of 11%. Adding up makes us loose a factor $1/(0.5 \times 0.11)=18$ on the number of events, much higher than the factor 4.5 we gained from the branching fraction. The conclusion is that the channel $pp \rightarrow H \rightarrow ZZ \rightarrow \mu^+\mu^-b\bar{b}$ is not favoured over the 4$\mu$-signal anymore.

3.2 The channel $pp \rightarrow ZH \rightarrow \mu^+\mu^-b\bar{b}$

The subject of this thesis is the associated production of a Higgs with a $Z$, $pp \rightarrow ZH \rightarrow \mu^+\mu^-b\bar{b}$. A Feynman diagram of this channel is shown in figure 3.7, we see that the $Z$ is created from quark-anti quark fusion and it radiates the Higgs. The similarity with the previous channel we were discussing, $H \rightarrow ZZ \rightarrow \mu^+\mu^-b\bar{b}$, is the end signal with two muons and two jets. This makes the channel interesting for studies, because we can try to improve the analysis for the difficult-to-find jets, as was described earlier in this chapter. A difference between the channels, is the decay of the Higgs. In the previous sections we looked at $H \rightarrow ZZ$, a nice decay as such, but we concluded that we better use the 4$\mu$-channel if we would want to study it. Here we have the decay of the Higgs to $b\bar{b}$, which are fermions. If a fermiophobic model is considered, see Chapter 1, this channel would have to be excluded. This gives us a new reason to choose this channel for this thesis.

At a Higgs mass of approximately 126 GeV, the mass of the Higgs-like particle discovered in July 2012, the branching fraction of the Higgs decaying to $b$-quarks is the highest, as we see on the right of Figure 3.8. This makes it seem a promising channel for Higgs searches in the low-mass range. The problem lies in the difficulty to detect jets in a detector. There is a solution to this problem, namely, the associated production channel. Here the $H \rightarrow bb$ is associated to a $Z \rightarrow \mu^+\mu^-$ that gives a clear signal in the detector, the muons help us find the $H \rightarrow bb$ decay. The production cross section of the associated channel is lower than the gluon-gluon fusion channel, as we see on the left side of Figure 3.8.
So low even, that in the end we loose a large part of the benefits from the high branching fraction of the $H \rightarrow bb$. If we look again at Figure 3.2, we see the number of expected events around 126 GeV for the associated channel is almost the same as the $H \rightarrow ZZ$, which is not what we would expect from the branching fractions.

Figure 3.8: On the left the production cross section for the Higgs at a centre-of-mass energy of 7 TeV (2011). Gluon-gluon fusion ($pp \rightarrow H$) has a higher production cross section than the associated production ($pp \rightarrow ZH$). On the right the branching fractions for the Higgs, for a Higgs mass of approximately 126 GeV the probability of the decay to $bb$ is higher than the decay to $ZZ$.

From the final state of the two muons and two $b$-quarks, we can obtain the $Z$ and the $H$ by adding the four vectors. In Figure 3.9 we see the invariant mass of the $Z$ and the $H$, and we find the expected values for this Monte Carlo file: a $Z$ at 91 GeV and a $H$ at 125 GeV.

Figure 3.9: The invariant mass for the $Z$ (black, four vectors of the true muons added) and the $H$ (blue, four vectors of the true $b$-jets added) for the channel $HZ \rightarrow \mu^+\mu^-bb$.

One of the problems we encountered before in this chapter, when we calculated the trigger efficiency, was the low $p_T$ of the particles we needed. In the associated channel we find that the $p_T$ of the muons and jets is high enough to trigger on, in Figure 3.10 we see the distribution for the true muons and jets. The muons have a peak at half the $Z$-mass and the jets have a peak at half the Higgs mass.

In Chapter 4 we will look at further details of the properties of the associated channel, and we will also look at the reconstructed particles. To anticipate on the reco particles, we see the number of jets and muons per event in Figure 3.11. There are more than two jets and two muons per event, and in Chapter 4 we will describe the analysis in which we decide which ones we use for the reconstruction of the $Z$ and the Higgs.
Figure 3.10: The $p_T$ for the muons (black) and jets (blue) for the channel $ZH \rightarrow \mu^+ \mu^- b\bar{b}$.

Figure 3.11: The number of reco particles per event in the channel $HZ \rightarrow \mu^+ \mu^- b\bar{b}$. On the left muons, on the right jets.
3.2.1 The ZZ background

Before we continue to the next chapters of this thesis, we will discuss a property of ZZ background simulation. We need this background in Chapter 4, because there are also two muons and two b-jets in the final state. As we know from Chapter 1, the Z- and the γ-bosons originate from the weak mixing of the $B_{\mu}$- and $W_{\mu}$-fields in the Standard Model. They both couple to quarks and leptons, the photon electromagnetically and the Z weakly. The process of the ZZ background is $q\bar{q} \rightarrow ZZ \rightarrow \mu^{+}\mu^{-}b\bar{b}$, but it might as well be a $\gamma$ instead of a $Z$ in the process, because at first glance the decays are the same.

We look at the MC file of the ZZ background with 60,000 events. The propagators in this simulation are defined as Z's and not as γ's, and we will try to find out if this is true. We plot the invariant mass of the Z-bosons, by adding the four vectors of the decay products, and obtain figure 3.12. There is a peak at a bit more than two times the Z mass, for boosted particles, which we would expect from a ZZ-signal. But, there is also a peak at a lower mass, and some entries for $m_{ZZ}$ less than 50 GeV.

![Figure 3.12: The invariant mass obtained by adding the four vectors of the two MC true Z-bosons in the ZZ signal. We see three peaks, when we expected only one peak around 182 GeV.](image)

Maybe we can contribute these other peaks to a combination of $Z\gamma$ or $\gamma\gamma$. We look at this a bit further, and see if we can distinguish between the signals from a Z and those from a γ. The trick to do this is to look at the different branching fractions for the decay to up- and down-type quarks. These differ for the Z and the γ, we see on the left in figure 3.3. Here we have something we can test with the MC file. We place three cuts on the invariant mass as shown in the table on the right in Table 3.3, and calculate the decay rates in the same configuration. Indeed we see from the table that the couplings are the same as we calculated. We conclude that we have in this MC file not only Z bosons, but also the γ as propagator.

<table>
<thead>
<tr>
<th>Parent particle</th>
<th>$\frac{1}{2}(u\bar{u} + c\bar{c})$</th>
<th>$\frac{1}{4}(d\bar{d} + s\bar{s} + b\bar{b})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$</td>
<td>0.74</td>
<td>None</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>4</td>
<td>$M_{q\bar{q}} \leq 40$ GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$70$ GeV $\leq M_{q\bar{q}} \leq 110$ GeV</td>
</tr>
</tbody>
</table>

Table 3.3: On the left the difference between the branching fractions for decay to up- and down-type quarks for Z and γ. The branching fractions for the Z are from [19] and the γ couplings $\propto Q^2$. On the right we see the obtained values for the MC file of ZZ.

3.2.2 Status in July 2012

Now we know the channel that we are going to use for this thesis, we should see what research has been done so far. The 4th of July 2012 the discovery of a Higgs-like particle was claimed by ATLAS and CMS,
with an integrated luminosity of 5.8 fb$^{-1}$ of 8 TeV data obtained in 2012, combined with 4.8 fb$^{-1}$ of 7 TeV data from 2011. This was in the channels $H \to \gamma\gamma$, $H \to ZZ \to 4\mu$ and $H \to W^+W^- \to l^-\bar{v}l^+\nu$. The result was a significance of 6 $\sigma$, see figure 3.13, which is enough to claim the discovery of a particle. The decay $H \to bb$ has not been discovered yet, although some exclusion limits have been set by ATLAS [24]. In CMS also no discovery on $H \to bb$ has been reported [25].

**Figure 3.13:** The significance of the combined searches for the Higgs boson, result from July 2012 [9].

### 3.3 Conclusion

We started this chapter with an investigation of the channel $H \to ZZ^* \to \mu^+\mu^-bb$ by doing a short Monte Carlo study. A reason for studying this channel, is that we have the end signal $\mu^+\mu^-bb$ containing two $b$-jets. We know these are difficult to detect in ATLAS, making the channel investigate worthy. Furthermore, we were optimistic in showing the channel seemed promising for finding the Higgs, because of the factor 4.5 advantage on $H \to ZZ \to 4\mu$ for the number of expected events. In the MC study we did, we encountered two problems for a light Higgs of approximately 126 GeV: the energy resolution of the jets is too low for the off-shell $Z^*$ to decay to and the trigger efficiency of the muons is too low for the off-shell $Z^*$ to decay to. Because of these problems we would loose a factor 18, which is more than the factor 4.5 we gained. We concluded that we would not use this channel for the rest of this thesis, and presented a short outlook on an alternative channel, the associated channel $ZH \to \mu^+\mu^-bb$.

The first reason to choose this channel is that is has the same final state, but does not have the same problems, because the $Z$ is on-shell. The second reason to choose this channel is more theoretical; the discovery of the Higgs decay to fermions would exclude the fermiophobic model. The third reason we mention here to choose the associated channel, is that Higgs is found in the summer of 2012 in $H \to \gamma\gamma$, $H \to ZZ \to 4\mu$ and $H \to W^+W^- \to l^-\bar{v}l^+\nu$. The decay $H \to bb$ has not been discovered yet.

In view of the above three reasons, we choose to search for the Higgs boson in the associated channel $ZH \to \mu^+\mu^-bb$ in the rest of this thesis. There are several options to improve our chance of finding the Higgs in this channel. We could for example enhance the amount of events we have by letting the LHC run longer or with a higher centre-of-mass energy. We could also improve the detector, for example by upgrading the HCAL. These things are being done after 2013, when the LHC and the ATLAS detector are being upgraded. For this thesis, we will go another way and work with the 2012 data. We improve our chance of finding the Higgs in this channel, by improving the analysis.
Chapter 4

Data analysis

In the previous chapter we established the choice of our channel, now it is time for the analysis. In this chapter we will describe the analysis on the data of the channel $pp \rightarrowZH \rightarrow\mu^+\mu^-bb$. Throughout this chapter, this channel is meant when we write about ‘the signal’. We start with a review of the signal and calculate the cross section. We then give the object definitions of the muons and jets. Since neutrinos and electrons play a small role in this analysis, we will only give a short object definition of those. After this, we will have a closer look at the muons and $b$-jets, since these form the final state of our signal. We explain the differences between the true and reco particles by looking at the efficiency and the resolution. We will also spend a subsection on the $b$-tagging of the jets. When we have defined the objects, we will look at the differences between the signal and the backgrounds $t\overline{t}$, $Z+$jets and $ZZ$. When we know all the selection criteria from the object definitions and the signal-background comparison, we summarise the total event selection. After that, we look at the data from the ATLAS detector. Due to uncertainties in the simulations, we have to scale the Monte Carlo files to the data in Control Regions. The result of this chapter is a comparison of signal, backgrounds and ATLAS data. We will look at the $m_{bb}$ distribution to find the mass of the Higgs and we will count how many events we have left for each file after the event selection.

4.0.1 Signal

The simulated data we use for the signal are 2012 MC files for a 125 GeV Higgs, 90,000 events. More information on the used data in this chapter is given in Appendix A. The cross section, as explained in Chapter 1, is the production cross section times the branching fraction of the Higgs decay to $b$-quarks, times the branching fractions of the $Z$ to leptons added: cross section $= 0.3943 \times 0.577 \times (0.03366 + 0.03363 + 0.03370) = 0.02298$ pb. The weight factor for the file is calculated by the integrated luminosity, we take $8.2 \text{ fb}^{-1}$, multiplied by this cross section and divided by the number of events in the file: weight $= 8.2 \times 1000 \times 0.02298/90,000$. We will use this weight factor to compare the signal to the detector data later in this chapter. The Feynman diagram of the signal is drawn in Figure 4.1. We see the familiar final state we know from Chapter 3: two muons and two $b$-jets.

![Figure 4.1: A Feynman diagram of the signal: associated production of a Higgs with a $Z$. The $Z$ is produced from the collision of a quark and an anti quark (a sea quark) and radiates the Higgs. The Higgs decays to $b$-quarks and the $Z$ to muons.](image-url)
4.1 Object definitions

The objects we need for the analysis are muons, $b$-jets and neutrinos or missing $E_T$ and electrons. This section describes how these are selected in this analysis. We start with the definition of the muons and $b$-jets. The object selection for neutrinos or the missing $E_T$ and electrons concludes this section.

4.1.1 Muons

Muons are reconstructed with the Staco reconstruction algorithm, which combines the tracks from the Inner Detector with those from the muon chambers for a good $p_T$ reconstruction [17]. We select combined (a track in the Inner Detector and several segments of the muon chamber) or segment tagged muons (only one segment of the muon chamber is included). The Inner Detector has an $\eta$-range of 2.5, so we disregard muons with $|\eta| \geq 2.5$. To reduce hits from pile-up, we select muons that come from the interaction point, summarised as a cut on the impact parameters. We only select muons that have enough hits in the detector layers we want to use. Since the muons have a small track, the $p_T$ in a cone of $dR < 0.2$ should be less than 10% of the $p_T$ of the muon. The muons should be oppositely charged, and one of them is medium and the other one loose (these terms stand for medium or loose identification criteria [26]).

4.1.2 Jets

Jets are reconstructed with the algorithm AntiKt4TopoEM [27]. The radius of the jet is $R = 0.4$. We have an $\eta$ cut of 2.5, because the $b$-tagging happens in the inner detector, as was explained in Chapter 2. In the next Section we will calculate the $b$-tag efficiency. Badly reconstructed jets are removed by demanding jets not to be ’BadLoose’ [28]. To reduce pile-up we select jets with a vertex fraction of more than 0.5, which means that at least 50% of the tracks in a jet are associated with the primary vertex. If we find an electron within $dR < 0.4$, the jet is removed, because a particle coming from the interaction point reaches the ECAL first and after that the HCAL. If we would detect a jet together with an electron in the ECAL, chances are high the jet is a decay product of an earlier process and not the jet we are looking for.

4.1.3 Neutrinos or missing $E_T$

Since the neutrino couples only weakly, the ATLAS detector cannot measure it, as we explained in Chapter 2. The only way to know the particle was produced in a collision, is by calculating the missing transverse energy or missing $E_T$. The missing $E_T$ is calculated as follows. We take the sum of the $p_T$ from all the particles in the event, in the following order: electrons, photons, hadronically decaying tau-leptons, jets and muons [29]. Since the sum of the $p_T$ of the protons before the collision is zero, and momentum is conserved, we define the missing $E_T$ as the amount of $p_T$ that is left-over in the calculation to make it zero. The MET RefFinal reconstruction algorithm is used for the refined calibration, as the last step of the missing $E_T$ reconstruction.

4.1.4 Electrons

The electrons we use have $p_T > 20$ GeV, $|\eta| < 2.47$ and have the same $p_T$-cone cut as the muons.

4.2 A closer look at muons and $b$-jets

At the start of an analysis, we explain how the particles behave in the detector. The properties of the ATLAS detector are taken into account for the simulation of the reco information, as was explained in Chapter 2. In this section we will compare the reco information with the true information to show how the detector influences the particles’ signatures. The particles we look at in this section are muons and $b$-jets, since these are the final state of our signal. We will calculate the efficiency of the muons and jets as a function of their $p_T$ and $\eta$, and study the muon and jet resolution. The $p_T$-resolution is worse for jets than for muons and we will try to find out why. Because $b$-tagging is important in this analysis, we will explain this in more details and calculate the $b$-tag efficiency for different selection criteria.
4.2.1 Efficiency as a function of $p_T$ and $\eta$

If we would have a perfect detector, we would not lose any particles in the reconstruction and the efficiency of the detector reconstruction will be always be 1. This is not the case and we want to know why some particles are lost. In the plots below we show the dependence of the efficiency on $p_T$ and $\eta$, and we go back to the detector description of Chapter 2 to find out why there is a dependence. We need this information for the analysis later. We note that the cuts described above for the muons and jets are used for the final analysis, and not for the upcoming sections.

First we match the reco particles to the true particles by selecting those within a $dR$ range, where $dR = \sqrt{d\phi^2 + d\eta^2}$, which is used to give the distance between tracks of particles. In Figure 4.2 we see the $dR$-distribution between the reco jets and the one of the true jet. If a reco particle is matched, it is potentially a well reconstructed true particle. For most events we have more than two jets per event, as we see on the right side of Figure 4.2, and there are only two true jets. This means that for the reco distributions, we find in general more than two per event. We choose to do a cut at 0.4, to get rid of the reco jets that are not the result of the true particle. For the muons we do the same procedure and choose for a cut at 0.2.

![Figure 4.2: Jets: on the left the difference between the reco jets and one of the true jet in dR. On the right the number of jets per event.](image)

In Figure 4.3 we see the difference between the matched and not matched plots for muons, where $\eta$ is on the $x$-axis. We see we lose the muons at $|\eta| > 2.5$ and at $\eta = 0$, we will investigate this further.

![Figure 4.3: Muons: on the left the $\eta$ of the matched muons, on the right the not-matched ones. We see that the plots are mutually exclusive: if they were plotted together they would form the distribution of all muons.](image)

The efficiency is a quantity to find the number of true particles that we did not lose in the detector reconstruction. To get a better insight in the efficiency, we plot the efficiency versus the $p_T$ of the true muons, we calculate it as follows. If a reco particle is matched to a true particle, we store the true $p_T$. 

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This is divided by the true $p_T$ of all particles. In this way we get a number for the efficiency per $p_T$ bin:

$$\text{Efficiency} = \frac{p_T, \text{true-matched}}{p_T, \text{true}}.$$  \hfill (4.1)

This is also done for $\eta$-bins. In Figure 4.4 we see the efficiencies for the muons.

**Figure 4.4:** Muons: on the left the efficiency for the $p_T$, on the right the efficiency for $\eta$. These plots are for the muons. The $p_T$ of the true muons is shown in Figure 3.10 on Page 45.

If we look at the $p_T$ we see that low $p_T$ muons are less efficient reconstructed than higher $p_T$ muons. For $\eta$ we see that muons with a higher $\eta$ than 2.5 are not reconstructed. This is because the Staco muon-reconstruction algorithm reconstructs only muons that are detected in the inner detector as well as in the muon chambers, and the inner detector is limited to $|\eta| = 2.5$. The hole in the middle is because at $\eta = 0$, going upwards, there is a crack in the detector for the support structure and services of the detector layers.

In Figure 4.5 we see the efficiencies for the jets. For $\eta$ we see that the statistics get low for $|\eta| > 2.5$, but not the cut-off we saw for the muons.

**Figure 4.5:** Jets: on the left the efficiency for the $p_T$, on the right the efficiency for $\eta$. These plots are for the jets. The $p_T$ of the true jets is shown in Figure 3.10 on Page 45.

<table>
<thead>
<tr>
<th>Demands</th>
<th>Efficiency muons</th>
<th>Efficiency jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matched with one true particle</td>
<td>91.9%</td>
<td>85.2%</td>
</tr>
<tr>
<td>Matched with both true particles</td>
<td>80.2%</td>
<td>72.8%</td>
</tr>
</tbody>
</table>

**Table 4.1:** The efficiency for the muons and the jets. First we calculate the efficiency if the reco particle is matched to one of the true particles, then to both.

We calculate the total efficiency by checking how many events are left when we demand that at least one of the reco particles is matched to a true particle. This gives the numbers in Table 4.1. The numbers
show how good the reconstruction can become at its maximum, because the analysis can not be as good as the match with the true particles in the ntuple. We see that the efficiency for jets is lower than the one for muons, meaning that there are more events where none of the reco particles fulfil the match criteria.

4.2.2 Resolution

The resolution gives us a measure for the precision of the measurement. If a reco particle is matched, we can check how well the $p_T$ is reconstructed. The $p_T$ resolution gives the precision to which we can reconstruct a particle. The relative difference in the true and reco $p_T$ is given by the following formula:

$$\text{Relative difference true-reco} = \frac{p_{T,\text{true}} - p_{T,\text{reco-matched}}}{p_{T,\text{true}}}. \quad (4.2)$$

The resolution is defined as the standard deviation on the histogram of the difference true-reco:

$$\text{Resolution} = \sqrt{\frac{1}{N} \sum (x_i - \mu)^2}, \quad (4.3)$$

where $N$ is the number of entries, $x_i$ the data points (the difference true-reco per particle) and $\mu$ is the mean. We see the difference true-reco for muons and jets in Figure 4.6. The resolution as we defined it in Formula 4.3 is given by the value for RMS in the box (it says RMS instead of standard deviation for historical reasons). The muon resolution is approximately 6% and we see a narrow, symmetric peak. This is different for the jet resolution: we get a high resolution of approximately 25%. We see that the mean of the plot is shifted to the right. This complicates the analysis, as we will see later in this chapter.

To see if we can improve the resolution, we do a cut on $\eta$, $p_T$ and the $b$-tag variable, so we are left with reco jets that are more likely to be $b$-jets from our signal. A phenomenon that could be the cause of the shift of the centre of the plot, is the semileptonic decay of the $B$-hadrons to a muon and a lighter quark. The muon is not stopped by the calorimeters, continues to the muon spectrometer, and the energy of the muon is not taken into account in the calculation of the jet energy. We see the resolution plot with a cut on $\eta$, $p_T$, the $b$-tag variable and semileptonic (if a high-$p_T$ muon ($p_T > 20$ GeV) is close to the jet), in Figure 4.7. The resolution is reduced to 19%.

**Figure 4.6:** On the left the difference true-reco for muons, on the right for jets. The resolution is the RMS of this plot, we see it in the box. The plots have the same $x$-axis range, to display the difference between the muons and jets.
Figure 4.7: Jets: the difference true-reco with a cut on $p_T \leq 20$ GeV, $|\eta| \geq 2.5$, $b$-tag variable $w \leq 0.795$ and sl-decays (semileptonic decays: true muon with $p_T > 20$ GeV within $dR < 0.4$ of the true jet). The resolution is the RMS on this plot.
4.2.3 Tagging of \(b\)-jets

To find out if we have a \(b\)-jet or another jet, we can use a \(b\)-tagging algorithm. In Chapter 2, in the section on the Inner Detector, we explained the difference between \(b\)-jets and light jets. As we will see later in this chapter, \(b\)-tagging is an important tool to reduce the main background in the analysis (\(Z+\)jets). In this section we calculate the efficiency of the \(b\)-tagging-algorithm MV1 [30]. To find a \(b\)-jet, we look for a secondary vertex in the Inner Detector, as we explained in Chapter 2. This is given by the impact parameter, defined as such that it gives a higher value for jets that decay in front of the primary vertex, in the direction of the jet. So if jets are not coming from the interaction point, we say they decayed at the secondary vertex. The MV1-algorithm is a combination of two \(b\)-tagging-algorithms that use the impact-parameter significance of the jet and one algorithm that looks at the \(b\)-jet topology.

In an analysis we do a cut on the \(b\)-tag variable \(w\), which is the parameter of the MV1 algorithm. To find the efficiency we start with matching the reco jets to the true jets. We use \(dR < 0.3\). We have the matched and not-matched plots from the reco jets that are matched to one of the true \(b\)-quark, and those that are not matched.

We plot the \(b\)-tag variable \(w\) on the \(x\)-axis, from 0 to 1, if \(w\) is closer to 1 the jet is more likely to be a \(b\)-jet, and obtain the plots in Figure 4.8.

![Figure 4.8](image_url)

Figure 4.8: The \(b\)-tag variable for the matched jets on the left and for the not-matched jets on the right. If a jet is not matched to a \(b\)-quark, it does not mean that it is matched to anything else. It is the left-over category. In Figure 4.2 we do this differently.

Now we can calculate the efficiency of a cut at \(w \leq 0.05, 0.1, 0.15, ... , 0.95\), where a jet is called ‘tagged’ if it survives the cut:

\[
\text{\(b\)-tag efficiency} = \frac{\text{number of reco jets, matched and tagged}}{\text{number of reco jets, matched}}.
\]

The \(b\)-tag efficiency gives the part of the jets that are correctly \(b\)-tagged. If we would for example do a cut at \(w \leq 0.5\) and we look at the matched plot in Figure 4.8, we see the majority of the jets being kept. We also still have a peak close to 0, on the left plot, which gives the amount of jets that are matched to a true jet, but incorrectly not \(b\)-tagged, they lower the efficiency. We can also check how many jets are incorrectly tagged, by looking at the not-matched plot. We see the majority is not tagged for a cut at \(w \leq 0.5\), but there is a peak close to 1 that gives an uncertainty on our result. We need to take into account the light jets that are rejected when we want to see how well our \(b\)-tagging-algorithm works. We define the light-jet rejection as follows:

\[
\text{light-jet rejection} = \frac{1}{\left(\frac{\text{number of reco jets, not matched and tagged}}{\text{number of reco jets, not matched}}\right)}.
\]

The plot we can make of this is the \(b\)-tag efficiency versus the light-jet rejection, where there is a data point for every cut on \(w\) in Figure 4.9. The \(b\)-tag efficiency goes up for a cut on a lower value of \(w\), but the light-jet rejection goes down (the cut on \(w \leq 0.95\) is the most-left entry in the plot and the cut on \(w \leq 0.05\) is the most-right entry).

To check our procedure, we compare the signal to the \(t\bar{t}\)-file (specifics in Section 4.3.1). This gives a higher light-jet rejection, as we see in Figure 4.10. The reason for this is that the \(t\bar{t}\)-file contains more...
c-jets (6% and the signal 3%). Because c-jets are heavier than u-, d- or s-jets, they look more like a b-jet and are more likely to be wrongly tagged as one. We want to investigate this further and look for c-, τ-, u-, d- and s-jets in the true information for the signal and tt. If one of the reco jets is not matched to a b-quark, we check if it is matched to a c-quark. If the jet is not match to b- or c-jets, we check if it is matched to a τ-jet, and in the end we check if the jet is matched to the light jets (uds). The cut that is used within the ATLAS group for the b-tag variable with the MV1 algorithm is at $w \leq 0.795$, so we use this number also here. For this cut we obtain for the b-tag efficiency and the light-jet rejection the numbers in Table 4.2. We obtain a b-tag efficiency of almost 70%, and we will use this cut for the analysis.

![Figure 4.9](image-url)  
**Figure 4.9:** The b-tag efficiency versus the light-jet rejection for the signal. The cuts are $p_T > 20$ GeV, $|\eta| < 2.5$.

![Figure 4.10](image-url)  
**Figure 4.10:** The b-tag efficiency versus the light-jet rejection for tt. The cuts are $p_T > 20$ GeV, $|\eta| < 2.5$.

<table>
<thead>
<tr>
<th>File</th>
<th>b-tag efficiency</th>
<th>c-jet rejection</th>
<th>τ-jet rejection</th>
<th>u/d/s-jet rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>0.65</td>
<td>7.68</td>
<td>15.92</td>
<td>167.21</td>
</tr>
<tr>
<td>tt</td>
<td>0.67</td>
<td>5.25</td>
<td>14.88</td>
<td>146.47</td>
</tr>
</tbody>
</table>

**Table 4.2:** The b-tag efficiency and light-jet rejection for a cut at $w \leq 0.795$. 

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4.3 Backgrounds

In Chapter 2 we described the main idea of data analysis. We simulate the $ZH$-signal and its backgrounds and use those to design a selection procedure that saves most of the signal and cuts away most of the background. In this section we describe the different backgrounds and how we can discriminate between the signal and them. The backgrounds we describe here are not all the processes that happen in the detector, there are many more in a proton-proton collision. It is however not necessary to take processes into account that are completely different from our signal, because we know they will not pass our selection criteria anyway. In this section we describe three signals that are created in a proton-proton collision and have a similar final state as our signal: two muons and two $b$-quarks. The channels we look at are $t\bar{t}$, $Z+$jets and $ZZ$. All the cuts we do in this analysis and their effect on the different backgrounds are summarised in the cutflows in Appendix B.

4.3.1 Background $t\bar{t}$

The first background we discuss is the $t\bar{t}$ background, in Figure 4.11 we see a Feynman diagram. The channel consists of a $t\bar{t}$-pair, created in a quark-anti quark collision. A top quark decays weakly to a $W$ and a $b$-quark. If the $W$ decays to a muon and a muon neutrino, we see a final state of two $b$-quarks, two muons and two neutrinos. The top quark MC file we use has 249,999 events, the cross section is 129.267 pb.

![Figure 4.11: The $t\bar{t}$ background. We see a final state of two muons, two $b$-quarks and two muon neutrinos.](image)

What we know from this channel is that the decay $t \rightarrow W^+b$ has a branching fraction of 0.91 [19]; almost all of the top quark decays are into $b$-quarks, and we see that the $b$-quarks are just as prominent as the $b$-quarks in our $ZH$-signal. If we compare the $t\bar{t}$ to the signal file, we see that the cuts for jets have a similar effect and we can not use them to discriminate between the files. We investigate the other particles: first we plot the amount of missing $E_T$ in the event in Figure 4.12. We conclude that the reconstructed missing $E_T$ for most events is higher for the $t\bar{t}$ final state than for the signal, as we expected from the neutrinos being present. The difference indicates that we can disregard events with a lot of missing $E_T$, in order to get rid of the $t\bar{t}$ events. Since we expect a small signal, we try to keep a lot of the signal events and disregard not too much: we do a loose cut of $E_T \leq 60$ GeV. We see a blue line at this point in Figure 4.12. With this cut, 54.2% of the events are not selected in the $t\bar{t}$ background file and 14.6% of the events in the signal file.

If we look at the Feynman diagram of Figure 4.11 again, we see that we have two muons, like the signal, but they are not the decay products of the $Z$. We know the $Z$-mass is 91 GeV, and a cut on the invariant mass of the two muons would select muons coming from a $Z$ and not the muons from the top quark decay. The $m_{\mu\mu}$ distribution is shown in Figure 4.13, where we show the true values because they give the information on the properties of the channel before the detector reconstruction. We calculate the effect of a cut on $m_{\mu\mu}$ by dividing the number of reco $Z$’s that are not selected, by the total number of reco $Z$’s. No other cuts are done when we do this calculation, because this would influence the effect of the one cut we need. We find that a cut on the invariant mass of the muons of $83 < m_{\mu\mu} < 99$ GeV, disregards 98.3% of the reco $Z$’s in $t\bar{t}$ in comparison to 68.1% of the signal. That the muons are not the product of a $Z$ we also see in the $p_T$ distribution in Figure 4.14. Again we calculate the effect of this cut with the reco particles, we divide the amount of reco muons that are disregarded by the total amount of reco muons in the file. A cut on $p_T > 25$ GeV disregards 68.1% of the reco muons in $t\bar{t}$ and 52.1% of
the signal. Since the Figure 4.14 does not show a large discrepancy between signal and $t\bar{t}$ for the $p_T$ of the muons (there is some difference though, if we look at the Cutflows for the muons in Appendix B), we need to note here that the $p_T$ cut on the muons also serves to reduce the background from muons that are the decay products of showers in the ECAL and HCAL, the calorimeters from ATLAS, since the Muon chambers are the most outer layer of the ATLAS detector. Related to the $p_T$ are trigger cuts, where we select events that are kept after one of the following trigger paths: EF mu24i tight, EF mu36 tight or EF 2mu13 that respectively select on one muon with $p_T > 24$ GeV, $p_T > 36$ GeV or two muons with $p_T > 13$ GeV. For the trigger cut, 76.3% of $t\bar{t}$ events is disregarded and 69.2% of the signal.

In summary, the largest cuts to discriminate between the $t\bar{t}$ background and the signal, are the cuts on missing $E_T$ and on the $Z$-mass.

Figure 4.13: Invariant mass of the muons, four vectors added, for signal and $t\bar{t}$. We cut on $m_{\mu\mu}$ of less than 83 and more than 99 GeV, blue lines in the plot.
Figure 4.14: The $p_T$ distribution of the muons for the signal and $t\bar{t}$. We cut on $p_T < 25$ GeV, the blue line in the plot.
4.3.2 Background $Z$+jets

The next background we discuss is $Z$+jets, we see a Feynman diagram of the channel in Figure 4.15. The $Z$ is created in quark-anti quark fusion and decaying to muons, and additionally two $b$-jets are formed from a radiating gluon. The $Z$+jets background file we use has 230,000 events, the cross section is 65.759 pb.

![Feynman diagram of Z+jets](image)

**Figure 4.15:** The $Z$+jets background. We see a final state of two muons and two $b$-quarks.

The cuts we did to reduce the $t\bar{t}$ background are not useful here: we have no missing $E_T$ and the muons are coming from a $Z$. We have to look at the jets to come up with a relevant selection. The jets that are created in the $Z$+jets file are not coming from a massive particle such as the Higgs and the radiation of the light gluon happens more irregular than in our signal. We see this when we look at the number of jets in the $Z$+jets file, in Figure 4.16. We find a lot of events with one single jet (when a low $p_T$ jet is lost in the reconstruction) or zero jets. If we disregard events with zero or one jet, we disregard 0.4% of the signal and 19.7% of the $Z$+jets events. We see that this cut reduces a large part of the $Z$+jets background.

![Number of reco jets for signal and background](image)

**Figure 4.16:** The number of reco jets for the signal, the mean is 7.5 jets per event, and $Z$+jets, where the mean is 4.3 jets per event. We do not select events with less than two jets.

Further cuts on jets that show that we not have a $H \rightarrow b\bar{b}$ decay in our $Z$+jets data, are the cuts on $p_T$ and the $b$-tag cut. For a cut on $p_T < 20$ GeV we disregard 68.9% of the jets in $Z$+jets and 46.6% of the signal, the plot is in Figure 4.17. Another cut on the $p_T$ of the jets is that we want one of the jets to have a $p_T$ higher than 45 GeV. The cut on the $b$-tag variable $w > 0.795$ disregards 96.2% of the jets in $Z$+jets and 85.5% of the signal, showing that the jets in $Z$+jets are often light jets. The last cut on jets that shows a difference for $Z$+jets and the signal is a cut on the invariant mass of the jets of $80 < m_{bb} < 150$ GeV, a cut that gives an indication for the amount of events we expect close to the Higgs mass. We will not use this cut in the final analysis, but we use it here to establish the difference between the $Z$+jets data and the signal. In Figure 4.18 we see the invariant mass of the jets, the jets in the $Z$+jets background have a lower invariant mass. The muons have a peak at low mass due to the $\gamma$ in the simulation, just as the $ZZ$ has, described in Chapter 3. The cut disregards 82.0% of the $Z$+jets and
75.3% of the signal jets. This number is high for the signal because \( m_{t\bar{t}} \) is low, as we see in Figure 4.19. This is because the jets in the simulation that are not coming from the true particles are also shown since we did not make any specific selections on the reco jets (the only selection that is in there is that there should be at least two jets, otherwise we could not calculate \( m_{t\bar{t}} \)).

In summary we can say we can distinguish \( Z+jets \) from our signal with cuts on at least two, heavy b-jets.

**The \( dR_{b\bar{b}} \) cut per \( p_T^Z \)**

An additional cut we do to reduce the backgrounds \( t\bar{t} \) and \( Z+jets \), is based on a high-\( p_T \) final state. When the \( p_T \) of the Higgs becomes higher, we expect the b-quarks to be closer together since we have momentum conservation between the Higgs and the b-quarks after the decay. Indeed we find that the tracks of the b-jets are getting closer together, \( dR \) becomes smaller, for higher \( p_T \): \( dR_{b\bar{b}} \) has a mean of 2.6 for the signal, when we select only Z’s and H’s with a \( p_T \) higher than 100 GeV we find the mean has shifted to \( dR_{b\bar{b}} = 1.8 \). Since we have a good chance of finding the Z (or, in the case of \( t\bar{t} \), a Z-like system), we plot \( dR_{b\bar{b}} \) per \( p_T^Z \). In Figure 4.20 we see the \( p_T^Z \) on the x-axis for the signal, the \( t\bar{t} \) and the \( Z+jets \) background. From this plot we find that for high \( p_T \) we could reduce the \( t\bar{t} \) background. We
Figure 4.19: The invariant mass of the reco jets, so $m_{b\bar{b}}$ reco, for the signal. We see that $m_{b\bar{b}}$ is lower than in Figure 4.18, which shows the true $m_{b\bar{b}}$. Note that we did not select b-jets, so this is actually $m_{jj}$ for $j=\text{jet}$.

place the cut on $dR_{b\bar{b}} < 1.8$ for $150 \leq p_T^Z < 200$ GeV and $dR_{b\bar{b}} < 1.6$ for $p_T^Z \geq 200$ GeV, $dR_{b\bar{b}}$ for the signal goes down so the cut does as well. Note that for $p_T^Z \geq 200$ GeV we have very low statistics and the line in the plot fluctuates more. This cut disregards some of the $Z$+jets background, as we see in Figure 4.20, but $Z$+jets has the same shape as the signal, both of the lines go down.

Figure 4.20: The $dR_{b\bar{b}}$ per $p_T^Z$-bin of 10 GeV for the true jets. Signal, $t\bar{t}$ and $Z$+jets are shown.

Since the $p_T$ of the jets is lower for $Z$+jets, we look at low $p_T^Z$ to see if we can find more differences between signal and $Z$+jets in $m_{b\bar{b}}$. We see a plot for $p_T^Z < 100$ GeV in Figure 4.21. The jets have a wider distribution for $Z$+jets. We place a cut on the low side of the spectrum: on $dR_{b\bar{b}} < 0.7$ for $p_T^Z < 200$ GeV (a cut on $dR > 4$ has to be investigated, we did not use it in this analysis). A summary of the $dR_{b\bar{b}}$ cut per $p_T^Z$ is given in Table 4.3.

<table>
<thead>
<tr>
<th>$p_T$-bin [GeV]</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^Z &lt; 150$</td>
<td>$dR_{b\bar{b}} &gt; 0.7$</td>
</tr>
<tr>
<td>$150 \leq p_T^Z &lt; 200$</td>
<td>$0.7 \leq dR_{b\bar{b}} &lt; 1.8$</td>
</tr>
<tr>
<td>$p_T^Z \geq 200$</td>
<td>$dR_{b\bar{b}} &lt; 1.6$</td>
</tr>
</tbody>
</table>

Table 4.3: A summary of the $dR_{b\bar{b}}$ cut per $p_T^Z$-bin.
Figure 4.21: The $dR_{b\bar{b}}$ for true jets in events with $p_T^{Z\ell}\ <100$ GeV. A blue line indicates the cut at 0.7.
4.3.3 Background $ZZ$

The third background we consider is the $ZZ$ background, where two $Z$-bosons are created in quark-anti quark fusion. One of them decays to two muons, the other one to two $b$-jets. We see a Feynman diagram in figure 4.22. The $ZZ$ background file we use has 210,000 events, the cross section is $7.268 \text{ pb}$.

![Feynman diagram](image)

**Figure 4.22:** The $ZZ$ background. We see a final state of two muons and two $b$-quarks.

Unlike the $t\bar{t}$ and the $Z$+jets backgrounds, the $ZZ$ signal consists of two particles decaying in exactly the same way as the two particles in our signal, the $Z$ and the $H$. The $H$ is heavier than the $Z$, but not so much that it could not be a boosted $Z$. We do not know how to discriminate between these two signatures in the detector, and we call $ZZ$ an irreducible background. The only thing we can do is try to model the $ZZ$ decay as good as we can with a Monte Carlo analysis, and subtract this from the real data. To show that the $ZZ$ background is similar to our signal, we look at figure 4.23, that shows the invariant mass of the true jets for the $ZZ$ and our signal. We see the peaks are both inside the region that indicates where to search for a Higgs of 125 GeV.

![Graph](image)

**Figure 4.23:** The invariant mass of the jets for the signal and the $ZZ$ background. The blue lines at 80 and 150 GeV indicate the region to search for the signal of a 125 GeV Higgs, just as in Figure 4.18.

In the MC file of $ZZ$ we use, all decay products of the $Z$ are included, not only muons and $b$-quarks. This explains that the trigger cut we explained in the section on $t\bar{t}$ disregards 93.7% of the events in $ZZ$ and 69.2% of the signal, and the $b$-tag cut that disregards 94.6% of the jets in $ZZ$ and 85.1% of jets in the signal file. We also note that the $ZZ$-file is simulated as such that we have $\gamma$’s in there as well, as was explained in Chapter 3. We see this when we place a cut on the $p_T$ of the muons and we lose 73.3% of the muons in $ZZ$ and 52.1% of the muons in the signal. We also notice this in the cut on the invariant mass of the muons we used to reduce the $t\bar{t}$ background: 76.1% of the muons is not selected for $ZZ$ and 68.1% for signal.

In summary, $ZZ$ is an irreducible background, and we can only disregard the events in the Monte
Carlo file that have a Z that does not decay to muons or b-quarks. We take into account that for the ZZ background often a γ is included instead of a Z.

4.4 Summary of the event selection

The results are obtained with all the above described cuts, a summary of all the cuts in this analysis is shown in Figure 4.4.

There are cuts to obtain the objects we need, for example that the muons are combined and the jets have a vertex fraction of > 0.5. Other cuts are meant to reduce the backgrounds, such as the cut on missing $E_T$ and $m_{\mu\mu}$ that has to be at the Z-mass to reduce the $t\bar{t}$ background; the $b$-tag and the $p_T > 20$ GeV cut for the jets to reduce the $Z+$jets background. In Table 4.4, under events, we find some additional cuts when the muons and jets end their loop: they have to be OK, when they passed all the cuts, in order to be selected and if there are not exactly two of them left we disregard the event. In Appendix B we show the effect of the cuts in Cutflow plots for the signal, the backgrounds and the data, in Table 4.5 we show the final number of selected events.

**Table 4.4:** The selection of muons, jets and events. In Appendix B we see the cutflow, in Figure 4.5 the effect of all cuts.

<table>
<thead>
<tr>
<th>Muons</th>
<th>At least two muons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>Combined $</td>
</tr>
<tr>
<td></td>
<td>Impact parameter cuts</td>
</tr>
<tr>
<td></td>
<td>Sum $p_T / p_T$ 10%</td>
</tr>
<tr>
<td></td>
<td>Hits in the detector</td>
</tr>
<tr>
<td></td>
<td>One loose, one medium</td>
</tr>
<tr>
<td></td>
<td>Opposite charge</td>
</tr>
<tr>
<td></td>
<td>$83 \leq m_{\mu^+\mu^-} \leq 99$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jets</th>
<th>At least two jets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>MV1 weight for $b$-tagging $w &gt; 0.795$</td>
</tr>
<tr>
<td></td>
<td>BadLoose</td>
</tr>
<tr>
<td></td>
<td>Vertex fraction &gt; 0.5</td>
</tr>
<tr>
<td></td>
<td>No electrons within $dR &lt; 0.4$</td>
</tr>
<tr>
<td></td>
<td>At least one jet with $p_T \geq 45$ GeV</td>
</tr>
<tr>
<td></td>
<td>$dR_{b\bar{b}}$ per $p_T^Z$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Events</th>
<th>Muon triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Missing $E_T &lt; 60$ GeV</td>
</tr>
<tr>
<td></td>
<td>Muons OK</td>
</tr>
<tr>
<td></td>
<td>Exactly two muons left</td>
</tr>
<tr>
<td></td>
<td>Jets OK</td>
</tr>
<tr>
<td></td>
<td>Exactly two $b$-jets left</td>
</tr>
</tbody>
</table>

4.5 Results

To obtain the results we look at the real data obtained by the ATLAS detector. For this analysis we use 2012 data, with an integrated luminosity of 8.2 fb$^{-1}$. The data is obtained with a centre-of-mass energy of 8 TeV from January until July 2012. The pre-selection, on at least two muons and two jets with $p_T > 18$ GeV, left us with 716,445 events. In Figure 4.24 we see the $m_{b\bar{b}}$-distribution for the signal, after all the cuts. We see that the mean is not at 125 GeV, where we would have expected it to be for
Table 4.5: The effect of the cuts: how many events are left after selections for the signal, background and data. The efficiency $\epsilon$ gives the number of selected events divided by the number of initial events.

<table>
<thead>
<tr>
<th></th>
<th>Number of selected events</th>
<th>$\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG $t\bar{t}$</td>
<td>63</td>
<td>0.00025</td>
</tr>
<tr>
<td>BG $Z+jets$</td>
<td>259</td>
<td>0.00113</td>
</tr>
<tr>
<td>BG $ZZ$</td>
<td>75</td>
<td>0.00036</td>
</tr>
<tr>
<td>Signal</td>
<td>2713</td>
<td>0.03014</td>
</tr>
<tr>
<td>Data</td>
<td>635</td>
<td>0.00089</td>
</tr>
</tbody>
</table>

A 125 GeV Higgs MC sample, but at 106.7 GeV. The reason for this is the poor jet resolution: the $p_T$ we reconstruct is lower than the $p_T$ we expect from the true values. In the beginning of this chapter we calculated the resolution of the jets (Figure 4.6 at Page 53), and found that the resolution is shifted by 18%. We find that 18% of 125 GeV is 102.5 GeV, so we expect the mass of the signal to be shifted. For the rest of the analysis we decide to use the mean of the signal in the plot in Figure 4.24. To have a first idea of the results of this analysis, we look for the $Z$-boson. In the $Z+jets$ and the $ZZ$ background we expect a peak around 91 GeV, which we do not expect to be there in the $t\bar{t}$ background. We see a plot of the invariant mass of the muons in Figure 4.25. There is a clear peak at 91 GeV, in the simulation and in the data, as we expected. The simulations and the data do not match exactly, we will look at this in the next section.

![Graph](image)

**Figure 4.24:** The invariant mass of the $b$-jets for the signal Monte Carlo of 125 GeV. We see that the mean is 106.7 GeV and not the expected 125 GeV.
Figure 4.25: The invariant mass of the muons, stacked and weighted by cross section and luminosity. The signal is included, at the bottom, but too small to see here. There is no cut on the invariant mass of the muons around the Z-mass.
4.5.1 Scaling in Control Regions

Before we look at the signal region, which is the region where we expect the signal to be in the distribution of $m_{b\bar{b}}$, we check whether the backgrounds and the real data agree with each other. This is only possible in the Control Regions, where we have no signal. The common procedure is to look at the side bands of the $m_{b\bar{b}}$ plot, for higher and lower mass than the signal file has. In this case we do not have enough statistics in the side bands, so we look for other control regions.

The first Control Region we look at is to find the scale factor for the $t\bar{t}$ background. We invert the missing $E_T$ cut and the cut on $m_{\mu\mu}$ around 91 GeV. With these inverted cuts, we obtain a distribution of $m_{\mu\mu}$ in which we have mostly $t\bar{t}$ events. We see the distribution on the left of Figure 4.26 and find that the real data is lower than the simulated data. This happens when the Monte Carlo files are not scaled correctly, because the real data for example has less luminosity than we expected. We find the new scale factor for $t\bar{t}$ by looking at this plot, and obtain the distribution on the right of Figure 4.26, which is scaled by a factor 0.35. In Figure 4.27 we see the same Control Region, but then for the invariant mass of the $b$-jets.

![Figure 4.26](image1.png)  
**Figure 4.26:** The $t\bar{t}$ Control Region, with an inverted missing $E_T$ and inverted cut on $m_{\mu\mu}$ is approximately 91 GeV. On the right we see the distribution of $m_{\mu\mu}$ before scaling, on the right after a scale factor of 0.35 is applied.

![Figure 4.27](image2.png)  
**Figure 4.27:** The $t\bar{t}$ Control Region, with an inverted missing $E_T$ and inverted cut on $m_{\mu\mu}$ is approximately 91 GeV. On the right we see the distribution of $m_{b\bar{b}}$ before scaling, on the right after a scale factor of 0.35 is applied.

The biggest background we have is $Z+$jets. Because this backgrounds looks so much like the signal, we do not have a good Control Region. We use the $m_{\mu\mu}$ distribution we see on the left of Figure 4.28, where we used all the cuts from Figure 4.4 except the one on $m_{\mu\mu}$. We already applied the scale factor for $t\bar{t}$. We see a clear peak at the $Z$-mass of 91 GeV, as we expected from the signal, $Z+$jets and ZZ files. Because the biggest peak is from $Z+$jets, we use this distribution to scale the $Z+$jets background. After a scale factor of 0.8 is applied, we obtain the distribution on the right of Figure 4.28. We see that the scale factor helps for the region around 91 GeV, but the data starts to exceed the $Z+$jets MC sample at
masses between 60 and 80 GeV. Therefore we decide not to scale the $Z$+jets background any further. A reason for the discrepancy could be that in this thesis we only looked at backgrounds that were relevant for the signal region, not for the control regions. With other words, we predict that the lower tail of the $m_Z$-distribution in Figure 4.28 contains more processes. To find a good control region for $Z$+jets for example, maybe we could have looked at $Z$+light jets, but this would need further investigation.

Figure 4.28: The distribution of $m_{\mu^+\mu^-}$. We see a peak at the $Z$-mass of 91 GeV. On the left we have only applied the scale factor for $t\bar{t}$, on the right also the scale factor of $0.8$ for $Z$+jets.
4.5.2 The distribution of $m_{b\bar{b}}$

After the selection, the weighting to 8.2 fb$^{-1}$ and the cross sections and the applied scale factors for the backgrounds, we can continue to the final mass distribution of the $b$-jets. Table 4.6 shows how many events were cut in the analysis, and the weight/scale factor per file. This factor combines the weight factor for the cross section and the luminosity with the scale factor from the Control Regions and the number of events in the file. In Table 4.7 we see how many events we expect for the signal and the backgrounds. In Figure 4.29 we see how many events we expect for the signal and the backgrounds. In Figure 4.29 we see the $m_{b\bar{b}}$ distribution for the signal, $t\bar{t}$, Z+jets, ZZ and ATLAS data. In Figure 4.30 we see the same plot with the signal added for 20 times as much as we expect. The real data has passed exactly the same selection criteria, and the 8.2 fb$^{-1}$ of data is obtained by the ATLAS detector from April to June 2012.

In Figure 4.29 and Table 4.7 we see that we have a large background for low $m_{b\bar{b}}$. Since $t\bar{t}$ is scaled properly with the Control Region, and if we scale Z+jets lower we get a problem for higher $m_{b\bar{b}}$, maybe we have to scale the ZZ background as well. This gives a problem, since the ZZ background is irreducible: we do not have a Control Region. Another reason for a discrepancy between the Monte Carlo simulations and the real data can be because we have a small amount of Monte Carlo events left after all selections. This error we take into account in the next chapter, when we do the statistical calculations.

<table>
<thead>
<tr>
<th>File</th>
<th>Number of events</th>
<th>Number of selected events</th>
<th>Weight/scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG $t\bar{t}$</td>
<td>249,999</td>
<td>63</td>
<td>1.4840</td>
</tr>
<tr>
<td>BG Z+jets</td>
<td>230,000</td>
<td>259</td>
<td>1.8756</td>
</tr>
<tr>
<td>BG ZZ</td>
<td>210,000</td>
<td>75</td>
<td>0.2838</td>
</tr>
<tr>
<td>Signal</td>
<td>90,000</td>
<td>2713</td>
<td>0.0021</td>
</tr>
<tr>
<td>Data</td>
<td>716,445</td>
<td>635</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.6: Number of events per file. The weight/scale factor is calculated by multiplying the scale factor from the Control Regions, the integrated luminosity of the data, the cross section of the file and dividing by the number of events before selections.

<table>
<thead>
<tr>
<th>File</th>
<th>Total</th>
<th>0 ≤ $m_{b\bar{b}}$ &lt; 50.0</th>
<th>50.0 ≤ $m_{b\bar{b}}$ &lt; 100.0</th>
<th>100.0 ≤ $m_{b\bar{b}}$ &lt; 150.0</th>
<th>150.0 ≤ $m_{b\bar{b}}$ &lt; 200.0</th>
<th>200.0 ≤ $m_{b\bar{b}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG $t\bar{t}$</td>
<td>93.49</td>
<td>4.45</td>
<td>31.16</td>
<td>17.81</td>
<td>19.29</td>
<td>20.78</td>
</tr>
<tr>
<td>BG Z+jets</td>
<td>485.77</td>
<td>13.13</td>
<td>151.92</td>
<td>166.92</td>
<td>61.89</td>
<td>91.90</td>
</tr>
<tr>
<td>BG ZZ</td>
<td>21.28</td>
<td>0</td>
<td>19.01</td>
<td>1.42</td>
<td>0.28</td>
<td>0.57</td>
</tr>
<tr>
<td>Total BG</td>
<td>600.55</td>
<td>17.58</td>
<td>202.10</td>
<td>186.15</td>
<td>81.47</td>
<td>113.25</td>
</tr>
<tr>
<td>Signal</td>
<td>4.90</td>
<td>0.05</td>
<td>1.62</td>
<td>3.18</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Data</td>
<td>635</td>
<td>12</td>
<td>134</td>
<td>236</td>
<td>143</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 4.7: Number of selected events, weighted and scaled, per invariant mass bin of the $b$-jets of 50 GeV.
Figure 4.29: The invariant mass of the $b$-jets in GeV, for the signal and background Monte Carlo simulations and 8.2 fb$^{-1}$ of 2012 data. All Monte Carlo files are weighted and scaled. The bin size is 15 GeV. We see the signal events for $ZH \rightarrow \mu^+\mu^- b\bar{b}$ at the top in blue, with a mean of 107 GeV (for the $m_H = 125$ GeV signal Monte Carlo file we obtained a mean of 107 GeV, see text). The selections that have been done to obtain these results are summarised in Figure 4.4 on Page 65.

Figure 4.30: The same plot as Figure 4.29 with a dashed line added for $20 \times$ signal.
Chapter 5
Statistics

In this thesis we search for the Higgs decay to $b$-quarks, which has not been discovered yet and therefore qualifies as new physics. The theory was formed and an hypothesis formulated, an experiment was done and data was obtained and analysed. By now we reached the final part of this thesis: the interpretation of the results. Experimental science aims to verify or falsify hypotheses; in our case the goal was to either verify the existence of the Higgs decay to $b$-quarks or falsify the fermiophobic model (explained in Chapter 1: in the fermiophobic model, the Higgs decay to fermions is suppressed). In this chapter we go with the former, the positive approach, and try to discover the $H \rightarrow bb$-decay. We will do a counting experiment that uses Poisson statistics, find the optimal search window for a 125 GeV Higgs and incorporate the background uncertainty. We use a 125 GeV Higgs signal, because that is approximately the mass the Higgs is discovered at. This will give us the final result of this thesis: The probability that the background fluctuated to the number of observed events in the signal region. In addition we calculate what number we have to multiply the cross section of the Higgs with to exclude the Higgs decay to $b\bar{b}$.

5.1 From theory to experimental science

The subject of statistics, more information than we give in this chapter can be found in the book [31], provides a way to quantify the comparison between a theoretical model and measurements from an experiment. In Figure 5.1 we see a graphical explanation of this comparison.

![Diagram](image)

**Figure 5.1:** How we learn [32]; in this chapter we explain the last step, the comparison of the predictions with the measured quantities.

We see a theoretical model with parameters we want to verify or falsify, and physical quantities deduced from this model. These quantities, such as the mass of the Higgs particle, follow a distribution: they are likely to be around 125 GeV, because the theory predicts that the Higgs that decays to $b$-quarks has the same mass as the 125 GeV Higgs that was discovered in July 2012. For the mass and decay width of the particle, this is for example a Breit-Wigner distribution. We continue to obtain a prediction of the quantities from the Monte Carlo simulation: we obtain for example the $p_T$-distribution of the reco $b$-jets. This procedure is also done for the backgrounds. On the other hand we obtain the data from the
ATLAS detector, and have it undergo the same cuts as the simulated data. This gives us the measured quantities. The comparison of the predictions with the measured quantities, results in an update of our knowledge. The options we have in this last step for our goal (verifying the existence of the Higgs decay to $b$-quarks) are twofold: we either claim a discovery or we conclude that there is not enough information to claim a discovery. We could also exclude a Higgs decay to $b$-quarks, we have a discussion on this at the end of this chapter.

Whereas we introduced the ATLAS detector as a general-purpose detector in Chapter 2, designed to find new physics, the search for the Higgs particle was always a very clearly stated design goal of the LHC. The theory of the Higgs mechanism exists since 1964 and also in the LHC’s predecessor LEP scientists searched for the Higgs. As such, the ATLAS detector was tailor-made to discover the Higgs and the discovery of July 2012 was a matter of time. That the Higgs is discovered and not excluded, almost 50 years after the prediction, confirms the theory of the Standard Model and the paradigm we are in ever since the Standard Model is formulated. In Figure 5.1 we see on the left the box with Model Parameters and on the right the box with Experiment. In the light of this paragraph, we might want to draw an extra line between these two boxes. For further reading on the objectiveness of experiments we suggest [33].

5.2 Poisson statistics

The probability to obtain a certain value for a variable of the model, is given by a probability density function. The function has an expectation value or mean $\mu$ and a variance $\sigma^2$, which is the square of the standard deviation $\sigma$. An example is the probability density function $f(x; \mu, \sigma^2)$ for a random variable $x$, the Gaussian:

$$\text{Gaussian } f(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad (5.1)$$

which reduces to a standard Gaussian when we set $\mu$ to zero and $\sigma$ to one:

$$\text{Standard Gaussian } f(x; \mu = 0, \sigma^2 = 1) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2} \quad (5.2)$$

The values we obtained from our experiment, are numbers: the amount of background, signal and real data events in the signal region. For an experiment from which we do not know the amount of tries, only that it is large, and we expect a very small amount of successes, we use Poisson statistics. In our case the amount of collisions in the detector is very large, and we expect only a few Higgs particles (see Chapter 1: $N = L \times \sigma = 62$ events). The Poisson distribution $f(n; \nu)$ for a integer random variable $n$ and the parameter $\nu$ is the following:

$$\text{Poissonian } f(n; \nu) = \frac{\nu^n}{n!} e^{-\nu}. \quad (5.3)$$

The Poisson distribution has only one parameter, as opposed to the Gaussian, because the mean and the variance of this distribution are both $\nu$. This means that the standard deviation is the square-root of the mean: $\sigma = \sqrt{\nu}$. In Figure 5.2 we see the Poisson distribution for $\nu = 5, 10$ and 15. We see the distribution becomes more symmetric for higher $\nu$. If we want to know the probability to see $n_i$ events or more we have to integrate the Poisson distribution from $n_i$ to infinity. The result of the integration is the $p$-value:

$$\text{Poisson } p\text{-value}(n_i) = \int_{n_i}^{\infty} f(n; \nu)dn. \quad (5.4)$$

5.2.1 The optimal mass window

In Chapter 4 we described the signal and the background distributions. With this information we can define the signal region: the mass window that we will use for our search. We start with the distribution for $m_{b\bar{b}}$ of the signal, in Figure 4.24 at Page 66. The mean of this distribution is 106.7. From this mean we start looking at a bigger and bigger mass range in steps of 0.5 GeV, and for each mass range we calculate the $p$-value for $f(n_i = n_{\text{signal}} + n_{\text{background}}; \nu = n_{\text{background}})$. The number of signal and background events together give the number of events we expect in the real data. Therefore, the calculation of the $p$-value with these numbers gives the expected probability to measure $n_i$ or higher in an experiment for which we expected only background. The signal drops faster when we widen the mass window than
the background does, because the invariant-mass peak of the signal is smaller. We see that we find an optimal mass window in which we expect the lowest p-value. This mass window we will use for our search, we will give the result in Section 5.3.

### 5.2.2 Expected and observed significance

Now we know the p-value from the Poissonian, we know the probability \( n_i \) is a fluctuation of the number of background events \( \nu \). Since the commonly used Gaussian has a more familiar feel for most people, we convert this number to a significance, a certain amount of \( \sigma \), which is the standard deviation of the Gaussian. The familiarity of the significance comes back in the definition of a discovery: when we find a excess in the \( m_{\text{b\bar{b}}} \)-spectrum with a significance of more than 5 \( \sigma \), we claim the discovery of a particle. To obtain the significance, we look at a standard Gaussian which has the probability density function from Formula 5.2. If we would integrate this function from \( x_i \to \infty \), we would obtain a value between 0 and 1. When we insert the p-value we found with Formula 5.4, we can go the other way around and find the position of \( x_i \) on the x-axis of the Gaussian:

\[
\text{Gaussian p-value}(x_i) = \int_{x_i}^{\infty} f(x; \mu = 0, \sigma^2 = 1) dx.
\]  

The integral is the cumulative function of the Gaussian. Since we have a standard Gaussian, \( x_i \) gives the significance, the amount of \( \sigma \). With the significance we can give interpretations such as: a 5 \( \sigma \) significance means that we have a probability of \( 2.8 \times 10^{-7} \), or 1 in 3.6 million, that we observed the number of events we measured if we expected background only.

To summarise, we obtain an expected p-value from the Poissonian with mean \( \nu \) is the number of background events, and find the corresponding significance by taking the inverse of the cumulative function of the standard Gaussian for this p-value.

When we know this, we can look at the detector data. We calculate the p-value for a Poisson distribution with \( \nu = n_{\text{background}} \) and \( n_i = n_{\text{data}} \). The result is the observed p-value. From the observed p-value we calculate the observed significance with the cumulative function of the Gaussian like we did above.

### 5.3 Results

In this section we first calculate the optimal mass window and the expected and observed significance for the \( m_{\text{b\bar{b}}} \) distribution which was the result of Chapter 4. We then incorporate the background uncertainty to obtain the final result.
We vary the optimal mass window around the mean of the signal, which was 106.7, in steps of 0.5 GeV. In Figure 5.3 we see the expected significance per mass window. We find the optimal mass range with a width of 54.5 GeV, which leads to a signal region of 79.5 - 134.0 GeV.

![Figure 5.3](image)

**Figure 5.3:** The expected significance per mass window on the left (the significance is normalized). The optimal mass window has a width of 54.5 GeV. We see the optimal mass window 79.5-134 GeV indicated in the $m_{b\bar{b}}$ distribution on the right.

In the optimal mass window we find 214.6 background events, 4.2 signal events and 250 data events. We have to make integers of these numbers to use the Poisson distribution, these numbers are not integers anymore because they were weighted for their cross section, the integrated luminosity and the scale factor from the Control Regions.

We calculate the expected $p$-value and significance by adding for $n_i$ the number of background events with the number of signal events, and the observed $p$-value and observed significance by taking $n_i = 250$, the number of data events. In Table 5.1 we see the expected and observed $p$-value and significance for the optimal mass window. We see the number of observed events is higher than we expected, which means the observed $p$-value is lower and the observed significance is higher. The result of this section is that we observed a significance of 2.4 $\sigma$, which means the probability is $9.1 \times 10^{-3}$, or 1 in 110.7, that we observed a background fluctuation. In the next section we will look at the background’s uncertainties.

<table>
<thead>
<tr>
<th>$\nu$ (nr. of background events)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_i$</td>
<td>215</td>
<td>Data=250</td>
</tr>
<tr>
<td>Significance</td>
<td>0.38</td>
<td>0.009</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.29 $\sigma$</td>
<td>2.36 $\sigma$</td>
</tr>
</tbody>
</table>

**Table 5.1:** The $p$-values and significances for the signal region, observed and expected. No background uncertainty is taken into account yet.

### 5.3.1 The background uncertainty

After all the cuts, described in the Chapter 4, we are left with a small number of simulated background events. This gives an uncertainty on the number of events in the signal region. The number of selected events from the backgrounds, without any weight or scale factors, are given in Figure 5.2. If we add the numbers we get 157 background events. The uncertainty on the background is calculated by adding the uncertainties of the backgrounds quadratically (assuming uncorrelated uncertainties):

$$\sigma_{BG} = \sqrt{\sigma_H^2 + \sigma_{Z+jets}^2 + \sigma_{ZZ}^2}. \quad (5.6)$$

The weighted uncertainty for a background is calculated with the relative uncertainty (we ignore the uncertainties on the weight/scale factor):

$$\left(\frac{\sigma_{weighted}}{N_{weighted}}\right)^2 = \left(\frac{\sigma}{N}\right)^2, \quad (5.7)$$

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so since \( N_{\text{weighted}} = N \times w \), with \( w \) the weight/scale factor, we obtain \( \sigma_{\text{weighted}} = \sigma \times w \). The number of events is Poisson distributed, so \( \sigma = \sqrt{N} \). We obtain an uncertainty of 19.1 events, as we see in Table 5.2. This uncertainty of the background makes our result, the observed significance, less high, as we will explain below.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{File} & N & w & N_{\text{weighted}} & \sigma_{\text{weighted}} \\
\hline
\text{Background } t\bar{t} & 21 & 1.48 & 31.2 & 6.8 \\
\text{Background } Z+\text{jets} & 91 & 1.88 & 170.7 & 17.9 \\
\text{Background } ZZ & 45 & 0.28 & 12.8 & 1.9 \\
\hline
\text{Total} & 157 & & 214.6 & 19.1 \\
\hline
\end{array}
\]

Table 5.2: The number of selected events in the optimal mass range, the weight/scale factor \( w \) and the weighted number of events. The weighted uncertainties are calculated with \( \sigma_{\text{weighted}} = \sqrt{N \times w} \) and the total uncertainty on the background is calculated by Formula 5.6.

We find a background of 214.6 ± 19.1 events, and we have to put this into a Poissonian to obtain the \( p \)-value. We can do this by making toy-Poisson distributions. We do this 1000,000 times, and the mean \( \nu \) of the Poisson distributions is Gaussian distributed around a mean \( \mu = 214.6 \) and a standard deviation of 19.1. We use a Gaussian distribution because the mean is Gaussian distributed as a continuous random variable. We add the 1000,000 histograms to obtain the distribution of Figure 5.4. The RMS is the quadratically added uncertainty of the Poisson and the Gaussian: \( \text{RMS} = \sqrt{19.1^2 + 215^2} = 24 \). We see red and blue lines for the \( n_i \) from which we will calculate the expected (red) and observed (blue) \( p \)-value. This leads to higher \( p \)-values and a lower significances, exactly as we expected.

\[
\begin{array}{cc}
\text{Entries} & 1000000 \\
\text{Mean} & 214.6 \\
\text{RMS} & 24.09 \\
\end{array}
\]

Figure 5.4: The Poisson distribution from the toys on the left, on the right the Poisson distribution without background uncertainty is added. There is a red line at the amount of signal+background in the signal region \( n_i = 219 \), and a blue line for the amount of observed events in blue at \( n_i = 250 \). Note that we zoomed in a bit for the right plot.

The results are the expected and observed significances in the signal region, after taking into account the error on the background. We see these numbers in Table 5.3. The result is that we observed a significance of 1.4 \( \sigma \), which means that if we expect only background, we have a probability of 0.08 that we obtain the number of events we observed in the data or more.

\[
\begin{array}{ccc}
\text{Nr. of background events and error} & \text{Expected} & \text{Observed} \\
n_i & 215 \pm 19.1 & \text{Signal+background=219} & \text{Data=250} \\
p-value & 0.45 & 0.08 \\
\text{Significance} & 0.14 \sigma & 1.43 \sigma \\
\end{array}
\]

Table 5.3: The \( p \)-values and significances for the signal region 79.5-135 GeV, after the uncertainty on the background is taken into account.

If we could increase the luminosity, for example by letting the LHC run longer, we would obtain a higher difference in signal and background resulting in a higher \( \sigma \)-value. If we increase the luminosity...
100 times (we would have to let the LHC run for another 60 years at this centre-of-mass energy of 8 TeV, without any winter stops) we obtain an expected significance of $2.8 \sigma$. We will discuss this result in Chapter 6.

### 5.3.2 Exclusion limits

To calculate the exclusion limit, we draw a Poisson distribution with a mean $\nu = n_{\text{background}} + n_{\text{signal}}$. The expected exclusion $p$-value is calculated by integrating from 0 to $n_{\text{background}}$ and the observed by integrating from 0 to $n_{\text{data}}$. On the left of Figure 5.5 we see this distribution, with and without the background uncertainty taken into account. For the background uncertainty we include the uncertainty on the MC signal, but this is so small that we still obtain 19.1. Integrating from the left gives for the expected exclusion a $p$-value of 0.45 (without background uncertainty 0.39). The observed $p$-value is 0.91 (without background uncertainty 0.98).

To see if we can exclude a number of times the cross section of the Higgs, we enhance the signal while the background stays the same. After we multiply the signal with 19, see Figure 5.5 on the right, we obtain an observed exclusion $p$-value of 0.048, which is for the first time under 0.05. We have to calculate a new uncertainty, but we can still ignore the uncertainty on the signal (the uncertainty on the mean goes from 19.1 to 19.2, the $p$-value stays 0.048). A $p$-value of 0.05 corresponds to $2 \sigma$ which is the guideline for exclusion. We say we excluded 19 times the Higgs cross section with this analysis, which we estimated by enhancing the signal 19 times. In Chapter 4 we showed a plot of the $m_{b \bar{b}}$ distribution with the signal 20 times enhanced, so we can compare it to something like that (Figure 4.30).

![Figure 5.5: The Poisson distribution from the toys, on the left the Poisson distribution with background uncertainty is added. On the right we have 19 times cross section of the Higgs, note that we shifted the axis of the plot because the mean went from 219 to 294. There is a red line at the amount of background in the signal region $n_i = 215$, and a blue line for the amount of observed events in blue at $n_i = 250$.](image)

In this chapter we performed a counting experiment. We described how to find the optimal mass window for the search, from the $m_{b \bar{b}}$-distribution we obtained in Chapter 4. We looked at the background and its uncertainty and obtained $215\pm19.1$ events. Background and signal events together made 219 events, and in the ATLAS data we saw 250 events. The resulting significance was $0.14 \sigma$ expected and $1.43 \sigma$ observed. Enhancing the luminosity 100 times gives an expected significance of $2.8 \sigma$ and enhancing the signal 19 times gives an observed exclusion limit of 95%.
Chapter 6

Conclusion and discussion

In this thesis we did a search for the Higgs boson in the channel $ZH \rightarrow \mu^+\mu^-b\bar{b}$. The first two chapters served as an overview of the information that was needed to understand the rest of the thesis, they describe the theory and the experimental setup of this research. Chapters 3-6 described the thesis work. We presented an extended discussion on our channel choice, which included a Monte Carlo study on the $H \rightarrow ZZ$-decay in the final state $\mu^+\mu^-b\bar{b}$. We described the properties of the $H \rightarrow bb$-decay in the associated production channel, its backgrounds and the selection criteria for our analysis. From the statistical analysis in the previous chapter we conclude that, despite an excess in the 8.2 fb$^{-1}$ of 2012 data we analysed, we cannot claim a discovery of the $H \rightarrow bb$-decay. We obtained a significance of 1.4 $\sigma$, whereas a discovery is defined as a 5 $\sigma$ significance. The analysis is not very sensitive for a discovery, because even with 100 times the luminosity we expect only a small hint of 2.8 $\sigma$. As we could exclude 19 times the Higgs cross section, but not less, we also cannot claim that we exclude the decay.

The main reasons for not finding the Higgs boson in the decay to $b$-quarks are the poor jet resolution of the HCAL (the reason that we have to use the associated-production channel instead of gluon-gluon fusion) and the large $Z+\text{jets}$ background.

To improve this analysis in the future, we look at four improvements we could do on the sensitivity. Firstly we can improve the scaling of the backgrounds to the Control Regions with a fitting procedure for the scale factor. Secondly, we could include more, different, backgrounds than the three we considered. These backgrounds would be small, but since we have such a small signal it would be useful and they could also help with the scaling since the Control Regions might contain more of those other backgrounds ($Z+\text{light jets}$ would for example come in handy for a Control Region for the scaling of $Z+\text{jets}$). A third option to improve the background sensitivity is to use more MC files so we get a smaller background uncertainty. As a fourth improvement we can include the systematic uncertainties in this analysis to increase precision.

Since the signal is so small compared to the backgrounds, we expect the analysis needs larger improvements than the above mentioned to discover the Higgs decay to $b$-quarks. The LHC has been shut down after 8 TeV data taking, at 14 February 2013, for the upgrade. In this upgrade the centre-of-mass energy will increase to eventually 14 TeV, this will give us a higher production cross section for the Higgs, but also for the backgrounds. The luminosity will be higher, but also the pile-up. The detector will be improved, as well as the triggers and the electronics. After these upgrades we expect a higher precision for the measurements, and a lot more data.

Apart from the centre-of-mass energy improvement and the technical improvements, we could try to find new selection criteria to discriminate between the signal and the backgrounds. A cut that we did not to in this analysis is on the $p_T$ of the $Z$, which reduces the $t\bar{t}$-background (which is useful for the related channel $WH \rightarrow \mu\nu b \bar{b}$ for which we cannot discriminate on missing $E_T$). Furthermore, to reduce $Z+\text{jets}$, we could look at $dR$ between the tracks of the $Z$ and the $H$.

Suppose that we could improve the result with everything mentioned in this chapter, it is still a question mark whether we could soon discover or exclude the Higgs decay to $b$-quarks. If the luminosity is raised to 3000 fb$^{-1}$, we would obtain a significance of 5.4 $\sigma$ with this analysis. We could also wait for a more specifically designed collider to investigate Higgs properties, such as CLIC or the ILC [34]. We suspect it would take at least another 15 years before we have the definite answer.
Bibliography


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[22] G. Aad et al., “Measurement of the $W \rightarrow \ell \nu$ and $Z/\gamma^* \rightarrow \ell \ell$ production cross sections in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” JHEP, vol. 1012, p. 060, 2010.


[34] “ILC and CLIC Collaboration: www.linearcollider.org.”
Appendices

A: Used data

Real Data

The data we used for the analysis is taken with the ATLAS detector in 2012, at a centre-of-mass energy of 8 TeV. The time period in which the data was obtained is January-July 2012, in which 8.2 fb$^{-1}$ of data was taken. The pre-selection before the analysis starts is: two muons, two jets, for both muons and jets $p_T > 18$ GeV. After the pre-selection we have 716,445 events when we start our selection.

MC files

The MC files we used in this thesis are summarised in Table 6.1 for Chapter 3 and in Table 6.2 for Chapter 4.

<table>
<thead>
<tr>
<th>File</th>
<th>MC info</th>
<th>#Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ \rightarrow \mu^+\mu^-bb$</td>
<td>mc11 7TeV.116828.PowHegPythia ggH120 ZZllqq</td>
<td>30,000</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>mc11 7TeV.109305.AlpgenJimmyZmumubbNp0 nofilter</td>
<td>149,950</td>
</tr>
<tr>
<td>ZZ</td>
<td>mc11 7TeV.109294.Pythiazz 2l2q</td>
<td>60,000</td>
</tr>
</tbody>
</table>

Table 6.1: The 2011 MC files we used for Chapter 3.

<table>
<thead>
<tr>
<th>File</th>
<th>MC info</th>
<th>#Events</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>mc12 8TeV.161827.Pythia8 AU2CTEQ6L1 ZH125 llbb</td>
<td>90,000</td>
<td>0.02298</td>
</tr>
<tr>
<td>$tt$</td>
<td>mc12 8TeV.105200.McAtNloJimmy CT10 ttbar LeptonFilter</td>
<td>249,999</td>
<td>129.267</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>mc12 8TeV.128976.Sherpa CT10 ZmumuHeavyJets</td>
<td>230,000</td>
<td>65.759</td>
</tr>
<tr>
<td>ZZ</td>
<td>mc12 8TeV.161997.Herwig AUET2CTEQ6L1 ZZ NoLeptonFilter</td>
<td>210,000</td>
<td>7.268</td>
</tr>
</tbody>
</table>

Table 6.2: The 2012 MC files we used for Chapter 4.
B: Cutflows

This appendix gives the cutflows for muons, jets and number of events. We show the signal, the $t \bar{t}$ background, the $Z+$jets background, the $ZZ$ background and the real data.

Muons

The cuts for the muons are summarised in Figure 6.1.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Cutflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least two muons</td>
<td>0</td>
</tr>
<tr>
<td>$p_T &gt; 25$ GeV</td>
<td>1</td>
</tr>
<tr>
<td>$\eta &lt; 2.5$</td>
<td>2</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
</tr>
<tr>
<td>Impact parameter cuts</td>
<td>4</td>
</tr>
<tr>
<td>Sum pt over pt ten procent</td>
<td>5</td>
</tr>
<tr>
<td>hits in the detector layers</td>
<td>6</td>
</tr>
<tr>
<td>one loose one medium</td>
<td>7</td>
</tr>
<tr>
<td>opposite charge</td>
<td>8</td>
</tr>
<tr>
<td>$83 \leq m_{\mu^+\mu^-} \leq 99$ GeV</td>
<td>9</td>
</tr>
</tbody>
</table>

Figure 6.1: The cuts for the muons. After the cut we fill the Cutflow histogram at the position on the right side of the table.
Jets

The cuts for the jets are summarised in Figure 6.2.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Cutflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least two jets</td>
<td>0</td>
</tr>
<tr>
<td>$p_T &gt; 20$ GeV</td>
<td>1</td>
</tr>
<tr>
<td>$\eta &lt; 2.5$</td>
<td>2</td>
</tr>
<tr>
<td>MV1 weight for $b$-tagging $w &gt; 0.795$</td>
<td>3</td>
</tr>
<tr>
<td>BadLoose</td>
<td>4</td>
</tr>
<tr>
<td>Vertex fraction &gt; 0.5</td>
<td>5</td>
</tr>
<tr>
<td>No electrons within $dR &lt; 0.4$</td>
<td>6</td>
</tr>
<tr>
<td>At least one jet with $p_T \geq 45$ GeV</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 6.2: The cuts for the jets. After the cut we fill the Cutflow histogram at the position on the right side of the table.
Events

The cuts for the events are summarised in Figure 6.3.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Cutflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cuts</td>
<td>0</td>
</tr>
<tr>
<td>Trigger cuts</td>
<td>1</td>
</tr>
<tr>
<td>Missing $E_T &lt; 60$ GeV</td>
<td>2</td>
</tr>
<tr>
<td>Muons</td>
<td>3</td>
</tr>
<tr>
<td>No more than one $Z$</td>
<td>4</td>
</tr>
<tr>
<td>Jets</td>
<td>5</td>
</tr>
<tr>
<td>No more than one $H$</td>
<td>6</td>
</tr>
<tr>
<td>$80 \leq m_{bb} \leq 150$ GeV</td>
<td>7</td>
</tr>
</tbody>
</table>

**Figure 6.3:** The cuts for the events. After the cut we fill the Cutflow histogram at the position on the right side of the table.
‘Ik dènk... dat we ’t hebben.’, het is 4 juli 2012. Rolf Heuer, directeur van CERN, formuleert het voorzichtig. Het nieuws van de ontdekking van het Higgsdeeltje gaat de wereld over als de verklaring van hoe deeltjes massa krijgen.

In deze scriptie zoeken we het Higgsdeeltje. Officieel is het namelijk ontdekt, maar het deeltje heeft volgens de theorie van het Higgsmechanisme verschillende eigenschappen en die zijn nog niet allemaal bevestigd: reden voor de twijfel van Rolf Heuer. Eén van die eigenschappen is dat het Higgsdeeltje op verschillende manieren kan vervallen. Dit kan naar bosonen en naar fermionen zijn, respectievelijk deeltjes die krachten overbrengen en deeltjes die materie vormen. Tot nu toe is alleen het verval van het Higgsdeeltje naar bosonen bevestigd. In deze scriptie zoeken we het verval van het Higgsdeeltje naar een type fermion: het $b$-quark.

We gebruiken hiervoor de ATLAS detector van het instituut CERN in Genève, die is aangesloten op de LHC, de Large Hadron Collider. In Figuur 6.4 zien we een overzicht: links de tunnel van de LHC en rechts de ATLAS detector. Aan ATLAS werken 3000 onderzoekers aan vanuit de hele wereld, dat gebeurt via een computernetwerk ‘het Grid’. In Nederland werken er ongeveer 50 natuurkundigen aan van het Nikhef instituut, verbonden aan de Universiteit van Amsterdam, de Vrije Universiteit en de Radboud Universiteit Nijmegen.

We hebben het doel geformuleerd, het zoeken naar het Higgsdeeltje in het verval naar $b$-quarks, en we hebben bedacht dat we de data gaan verzamelen met de ATLAS detector. Nu kunnen we kijken naar de data analyse. Voor een analyse hebben we drie verschillende soorten data nodig: het gesimuleerde signaal, de gesimuleerde achtergrond en de data van de detector. De simulaties voorspellen op basis ...

---

Figure 6.4: Links zien we de LHC, die zich bevindt in een tunnel van 27 km, zo lang als de ring van Amsterdam. De tunnel overschrijdt de grens tussen Zwitserland en Frankrijk, de ATLAS detector bevindt zich in Genève. Rechts zien we de ATLAS detector, zo groot als het paleis op de Dam (vergelijk dit met de figuren van menselijk grootte op de voorgrond). In deze scriptie zoeken we muonen, die worden gemeten door de blauwe detectoren aan de buitenste laag van ATLAS. Verder zoeken we $b$-quarks, die vormen ‘hadrons’ in de detector en worden gemeten door de Hadronische Calorimeter (oranje in dit plaatje). Het woord hadron komt terug in de naam van de LHC: Large Hadron Collider. Dit komt omdat de protonen die worden versneld en die op elkaar botsen, ook onder de overkoepelende term hadron vallen. In het plaatje van ATLAS komen de protonen van links en rechts binnen en botsen precies in het midden op elkaar. Met deze energie wordt een deeltje gemaakt, zoals het Higgsdeeltje, dat meteen vervalt. De vervalsproducten, dit kunnen allerlei soorten deeltjes zijn, worden gemeten door de verschillende lagen van de detector.

We hebben het doel geformuleerd, het zoeken naar het Higgsdeeltje in het verval naar $b$-quarks, en we hebben bedacht dat we de data gaan verzamelen met de ATLAS detector. Nu kunnen we kijken naar de data analyse. Voor een analyse hebben we drie verschillende soorten data nodig: het gesimuleerde signaal, de gesimuleerde achtergrond en de data van de detector. De simulaties voorspellen op basis...
van de theorie en eerdere metingen hoe de deeltjes zich gedragen in de detector en ook hoe vaak een Higgsdeeltje wordt verwacht. De $b$-quarks geven een signaal dat lastig te meten is. Muonen, een soort elektrons, maar dan zwaarder, zijn gemakkelijker te meten. Daarom kiezen we er in deze scriptie voor om een Higgsdeeltje te zoeken dat samen met een $Z$-boson wordt gemaakt: het $Z$-boson vervalt naar twee muonen en de Higgs vervalt naar twee $b$-quarks, we selecteren de muonen en dan kijken we of er ook twee $b$-quarks waren. In Figuur 6.5 zien we welk gedeelte van de botsing in de detector terecht komt. Het middenstuk, waarin het Higgsdeeltje werd gemaakt en ook weer verviel, kunnen we niet zien.

In Figuur 6.6 zien we aan de linkerkant een schematisch plaatje van het signaal dat we zoeken. Dit signaal kunnen we simuleren, waardoor we toch een idee hebben wat er tijdens de botsing gebeurt. We zien een Higgsdeeltje dat kort bestaat en vervalt naar de $b$-quarks die we gaan meten. Aan de rechterkant van Figuur 6.6 zien we de grootste achtergrond of ruis voor ons vervalkanaal: $Z$+jets. Dit heet zo omdat de $b$-quarks jets vormen wanneer we ze meten in de detector. We zien dat er uit deze botsing ook twee muonen en twee $b$-quarks komen, maar dat er geen Higgsdeeltje heeft bestaan. Dit is de uitdaging van deze analyse, omdat we aan twee muonen en twee $b$-quarks dus niet direct kunnen zien of het signaal was of achtergrond.

![Figure 6.5: Twee protonen botsen op elkaar en achteraf meten we wat er uit de botsing kwam: twee muonen en twee $b$-quarks. Wat er in het midden gebeurde, kunnen we alleen simuleren. De tijd gaat van links naar rechts in dit figuur.](image)

![Figure 6.6: Het signaal, links, en de achtergrond, rechts. Links een botsing waarbij het Higgsdeeltje wordt gemaakt, rechts eentje waarbij dat niet zo is. Het Higgsdeeltje is aangegeven met de bolletjes. Het deeltje zelf kunnen we niet meten, we moeten het doen met de vervalsproducten. Hier zien we dat de achtergrond $Z$+jets rechts dezelfde eindtoestand heeft als het signaal links: twee muonen en twee $b$-quarks.](image)

In Figuur 6.7 wordt één van de manieren beschreven hoe we toch kunnen selecteren op signaal en hiermee de achtergrond kunnen verkleinen. We zien dat de $b$-quarks van de achtergrond een lagere impuls hebben dan de $b$-quarks van het signaal. In deze scriptie zoeken we naar zulke verschillen tussen signaal en achtergrond in de gesimuleerde data. De selectie-criteria worden gebruikt om elke botsing te bekijken. We houden een selectie van drie soorten botsingen over: signaal, achtergrond en ATLAS data. We zoeken de massa van het Higgsdeeltje en daarom vullen we een histogram met de verschillende massa’s die gevonden worden voor deze drie soorten. Aan de rechterkant van Figuur 6.8 zien we deze distributie, waarbij het signaal op de achtergrond is gestapeld. We zien dat het signaal erg klein is, omdat het Higgsdeeltje niet vaak wordt gemaakt bij een botsing in de LHC. We laten het signaal zien voordat het geschaald is, aan de linkerkant van Figuur 6.8. Uiteindelijk valt dit bijna helemaal weg als
Figure 6.7: Hier zien we een manier om het signaal van de achtergrond te kunnen onderscheiden: de verdeling van de impuls van de \( b \)-quarks in de simulatie. Voor het signaal (zwart) is de impuls gemiddeld hoger dan voor de achtergrond \( Z+jets \) (rood). Als we alle jets negeren die een lagere impuls dan 20 GeV (Giga-electronvolt) hebben, gooien we veel van de rode achtergrond weg en weinig van het zwarte signaal. In het figuur staat een blauwe lijn bij een impuls van 20 GeV.

de achtergrond wordt toegevoegd. Uit deze figuren kunnen we opmaken dat de achtergrond erg groot is en dat het lastig is om het Higgsverval naar \( b \)-quarks te vinden.

Figure 6.8: Als resultaat van deze scriptie laten we de massa van de Higgs zien. Links zien we de massa die de Higgs in het gesimuleerde signaal heeft, we zien een smalle piek in de distributie. Rechts zien we de drie soorten botsingen, zoals beschreven in de tekst: signaal (blauw), achtergrond (rood) en de ATLAS data (de punten met foutmarge). We zien hetzelfde signaal als links, maar nu op de achtergrond gestapeld en geschaald naar hoe vaak ze voorkomen. Omdat de achtergrond zo groot is, blijft er maar weinig van het signaal over. Dit bemoeilijkt de vergelijking met de ATLAS data.

Het aantal botsingen dat we verwachten, door te kijken naar de simulaties, kunnen we vergelijken met het aantal botsingen dat we meten in de detector. Hieruit kunnen we een conclusie trekken over hoe waarschijnlijk het is dat het Higgsverval naar \( b \)-quarks bestaat. We hebben meer botsingen in de detector gemeten dan we verwachten van de achtergrond. Als je meer meet dan je verwacht, kun je uitrekken hoe statistisch waarschijnlijk zo’n afwijking is. De kans dat we, als we dus alleen achtergrond verwachten, toch de hoeveelheid botsingen meten als we in dit onderzoek hebben gedaan, is ongeveer 8% (één op de 12,5). Voor een ontdekking, zo is dat gedefinieerd, moet deze kans om laag naar één op de 3,5 miljoen. We concluderen dat we met onze analyse geen ontdekking van het Higgsverval naar \( b \)-quarks kunnen claimen.

Omdat het onderzoek van deze scriptie gericht is op een verval dat nog niet aangetoond is, is het nieuwe natuurkunde. Misschien bestaat het wel helemaal niet, en kunnen we het verval van de Higgs naar \( b \)-quarks uitsluiten. We hebben uitgerekend dat we een signaal hebben uitgesloten dat 19 keer zo groot is als het signaal dat we verwachten van het Higgsdeeltje. Hier kunnen we dus ook geen uitsluitstel over geven. Dat het nieuwe natuurkunde is, zien we terug: ook wij kunnen er nog niets over zeggen. De twee belangrijkste redenen hiervoor zijn dat de \( b \)-quarks lastig te meten zijn in de detector en dat de
Z+jets achtergrond erg groot is. Om dit beter te begrijpen, hebben we in deze scriptie extra aandacht besteed aan hoe de deeltjes zich gedragen in de detector en wat we daarvan terug zien in de echte en de gesimuleerde data.

Naast de bovenstaande analyse, beschrijven we in deze scriptie een vergelijking tussen het vervalkanaal van de Higgs naar $b$-quarks met een ander kanaal dat ook twee muonen en twee $b$-quarks in de eindtoestand heeft ($H \rightarrow ZZ \rightarrow \mu^+ \mu^- bb$). De resultaten van deze vergelijking zijn gepresenteerd op de Workshop van de Nikhef ATLAS-groep op 20 juni 2012.

De analyse in deze scriptie kan op een paar manieren verbeterd worden. Het schalen van de achtergronden kan preciezer, door bijvoorbeeld naar meer verschillende achtergronden te kijken. Ook kunnen we meer gesimuleerde data gebruiken, zodat de onzekerheid daarop kleiner wordt. Verder zouden er andere selectie-criteria gezocht kunnen worden, zodat er misschien nog wat van de achtergrond weggeschoven kan worden.

Wanneer weten we of het Higgsverval naar $b$-quarks bestaat of niet? De LHC wordt de komende jaren verbeterd en het plan is dat er minstens 300 keer zoveel data verzameld gaat worden als dat er voor deze scriptie is gebruikt. Ook zijn er plannen om een nieuwe versneller te bouwen, een lineaire in plaats van een ronde, waardoor de eigenschappen van het Higgsdeeltje nog beter kunnen worden onderzocht. We denken dat het nog een jaar of 15 zal duren voordat er uitsluit is over het verval van het Higgsdeeltje naar $b$-quarks.
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