Studies of the Phenomenology of $H^+ \rightarrow W^+Z$ events with ATLAS at LHC

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Abstract

The Higgs sector is the last part of the standard model of particle physics where we lack direct experimental results. Many extensions to the standard model describe an extended Higgs sector, often containing charged scalar bosons in addition to the standard model’s neutral Higgs boson. The $H^+WZ$ vertex can be used to distinguish between different non-standard Higgs sectors, and to measure the mass of the charged Higgs boson. In this report I will examine promising search channels at the LHC and look at its phenomenology using Monte Carlo simulations.
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Chapter 1

Theoretical Background

In this chapter, a short overview of the Standard Model of particle physics, its implications and possible extensions will be given. Extensive treatments of this can be found in e.g. [1, 2].

1.1 The Standard Model of Particle Physics

The Standard Model of particle physics (SM) is a set of quantum field theories that describe the properties and interactions of elementary particles. Interactions are modeled by the exchange of gauge bosons. The elementary particle content of the SM can be divided into fermions with half integer spin and bosons with integer spin. The fermions can be further divided into quarks (with color charge) and leptons (no color charge). Sorting the particles by mass, we find three “generations”, each containing two quarks, one charged lepton and one neutrino (uncharged lepton).

On the boson side, we have photons, $W^\pm$ and $Z^0$ bosons mediating the electroweak interactions and gluons mediating the strong interactions. Photons couple to all charged particles, $Z^0$ bosons to charged or left-handed particles (and charged or right-handed antiparticles). $W^\pm$ bosons couple to left-handed particles and right-handed anti-particles. They carry electrical charge and are the only gauge bosons that can mediate flavour changes.

Gluons couple to colour charge, i.e. to quarks and other gluons. Because the gluons themselves carry color charge, the strong force behaves almost paradoxically: It gets stronger the more the particles are separated, but is small for short distances/high energies. This leads to a phenomenon called “confinement”, which means that all macroscopically observed objects must be colour neutral. Hence, quarks and gluons can only exist in bound states, called hadrons, e.g. in a combination of quark/anti-quark (meson) or three quarks (baryon).

1.1.1 The Proton

As this work will deal with hadron collider physics, it is important to understand the structure of the protons that are used in the collisions.

Protons are composite particles, made up of a number of partons. The number and properties of the observed partons depends on the probe that is used to measure them, or rather on the momentum transferred between probe and proton. At low momentum transfers, the proton appears as an elementary particle: There is only one parton carrying the full proton momentum and energy.

At higher momentum transfers one can observe three valence quarks ($uud$) as well as gluons and quark-anti-quark pairs, the sea quarks. Each parton carries a fraction $x$ of the proton’s momentum.

3
and energy. The parton distribution functions, which have been measured over a wide range of momentum transfers, give the probability of finding a parton with a given momentum fraction $x$ of the protons’s momentum. Generally, it has been found that gluons dominate at low $x$, valence quarks at high $x$.

1.1.2 The Standard Model Lagrangian

The particles described above can be modeled using wave functions, arranged in spinors. They follow certain equations of motion, depending on the spin $1$. The interactions described above can be obtained by starting out with the observed fermion content and requiring a $U(1) \times SU(2) \times SU(3)$ gauge symmetry. The neutral gauge bosons from the $U(1) \times SU(2)$ symmetry mix to the observed (massless) photon and (massive) $Z^0$. Field equations can be obtained by the Euler-Lagrange formalism, i.e., using

$$\frac{\partial L}{\partial \phi_i} - \partial_{\mu} \left( \frac{\partial L}{\partial \left( \partial_{\mu} \phi_i \right)} \right) = 0$$

for all the fields $\phi_i$ the Lagrangian depends on. For electroweak interactions and for strong interactions at high energies, a perturbative approach (Feynman calculus) may be used instead to find observables like cross sections or decay rates. The “Feynman rules” needed for this can again be directly extracted from the Lagrangian; this will not be covered here but can be found in available literature, e.g. [1, 2, 4].

For hadronic interactions, e.g. the proton-proton collisions that will be treated here, the factorization theorem may be applied: It is possible to split up hadronic cross sections, e.g. the one giving the probability to produce a Higgs boson in a given proton-proton collision, into the “hard scattering” of quarks or gluons, modeled by a perturbative approach, and non-perturbative parts like the probability of finding a quark with a given momentum inside a proton, modeled by so-called parton distribution functions (pdf) which ultimately have to be extracted from data.

1.1.3 The Higgs Mechanism

However, while stipulation of gauge symmetry leads to a Lagrangian that describes the interactions well, it only predicts massless gauge bosons. Moreover, it cannot accommodate fermion masses either, even if they are inserted by hand. Since we can observe masses for almost all fermions and some gauge bosons, there must be another mechanism leading to massive particles. The most accepted way to explain particle masses is the Higgs mechanism, developed in 1964 [5, 6, 7]. It postulates a complex scalar doublet field $\phi$ with a potential

$$V = \mu \phi \phi - \lambda (\phi \phi)^2.$$  \hspace{1cm} (1.1)

If $\mu^2 < 0$, this potential has a local maximum at 0, but a (global) minimum at

$$v = |\langle \phi \rangle| = \sqrt{\frac{\mu}{2\lambda}},$$  \hspace{1cm} (1.2)

the so called vacuum expectation value (vev) $|\langle \phi \rangle|$. The vacuum state/ground state of the Higgs field is not the state $\phi = 0$, but some state with $|\phi| = v$. We are interested in small fluctuations

\footnotesize{\textsuperscript{1}e.g. the Dirac equation for a (hypothetical) free electron}
Figure 1.1: Left: Standard model Higgs production cross section for different production cross sections at a 14 TeV proton-proton collider, from [8]; right: Standard model Higgs branching ratios for different decay modes, from [8].

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<th>Vertex</th>
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<tr>
<td>$Hff$</td>
<td>$-\frac{igm_f}{2m_W}$</td>
</tr>
<tr>
<td>$HW^+W^-$</td>
<td>$igm_W g^{\mu\nu}$</td>
</tr>
<tr>
<td>$HHW^+W^-$</td>
<td>$\frac{1}{2}ig^2 m g_{\mu\nu}$</td>
</tr>
<tr>
<td>$HZZ$</td>
<td>$\frac{igm_Z^2}{\cos(\theta_W)} g^{\mu\nu}$</td>
</tr>
<tr>
<td>$HHZZ$</td>
<td>$\frac{ig^2}{2 \cos^2(\theta_W)} g_{\mu\nu}$</td>
</tr>
<tr>
<td>$HHH$</td>
<td>$-\frac{3igm_H^2}{2m_W}$</td>
</tr>
<tr>
<td>$HHHH$</td>
<td>$-\frac{3g^2m_H^2}{4m_W^2}$</td>
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Table 1.1: Vertex factors for the SM Higgs coupling to fermions and bosons. $g$ is the $SU(2)$ coupling constant, $\theta_W$ the Weinberg angle. Cf. [4].

of the field around this ground state, so it is useful to rewrite the Lagrangian using $\phi(x) = \langle \phi \rangle + h(x)$. The interactions between bosons/fermions and the Higgs field can then be split accordingly. Terms containing the space-time dependent $h(x)$ describe the behaviour of and the coupling of other particles to the Higgs boson, the terms containing the constant vacuum field give the desired mass terms. The “mass” of a particle is thus caused by the interactions with the vacuum Higgs field.

1.1.4 Phenomenology of the Higgs Boson

It is common to choose the ground state so that one of the two components of the doublet is 0. Rewriting the Lagrangian by expanding about the ground state then gives one massive and one massless scalar boson. The massless boson is a so called Goldstone-boson. It is not a physical particle and can indeed be removed by choosing a convenient gauge. We are left with one additional scalar, the Higgs boson, with a mass term and self interaction terms. Due to gauge invariance, the Higgs boson also couples to the massive gauge bosons. To obtain fermion masses, one has to add terms containing fermions and the higgs doublet to the Lagrangian. This means that the Higgs
boson has to couple to fermions, with a coupling strength proportional to the fermion’s mass. The predicted couplings are summarized in table I.1

Production at Hadron Collider Experiments

As the Higgs boson predominantly couples to heavy particles, the major production modes at hadron colliders involve heavy vector bosons or top quarks. At the LHC, the Higgs is expected to be predominantly produced by gluon fusion (via a top loop), vector boson fusion of $W^+W^-$ or $Z^0Z^0$, Higgs-Strahlung from an off-shell $W$ or $Z$, and in association with a $tt$ pair. The cross sections for these processes depend on the center of mass (cms) energy and the Higgs mass. The expected values for a proton-proton collider with a cms energy of 14 TeV, the design energy of the LHC, are shown in fig. I.1(a).

Decay

The favoured decay modes of the Higgs strongly depend on its mass. Basically, the Higgs will predominantly decay into the heaviest decay mode that is kinematically allowed. For low masses (significantly lower than, say, 130 GeV), this will be $bb$ or $\tau^+\tau^-$, for higher masses $W^+W^-$, $Z^0Z^0$, or $tt$. Decays into pairs of photons or gluons is possible via loops. The expected branching ratios for a standard model Higgs boson are shown in fig. I.1(b).

![Figure 1.2: Likelihood ratio for the Higgs mass in a fit to the standard model [9], and mass ranges excluded by direct searches. The prefered value for the Higgs mass is $(94\pm29)\text{ GeV}$. This uncertainty refers to the fit uncertainty ($\Delta\chi^2 = 1$) and does not take the theory uncertainty (blue band) into account.](image)
1.1.5 Current Experimental Status

The Higgs field is an essential part of the Standard Model and its associated boson is the only elementary particle described by the standard model that has not been discovered yet. All its couplings and properties are fixed by the standard model except for its mass. There are, however, a number of direct and indirect constraints on the Higgs mass both from theory and experiments.

The Higgs mass influences other standard model parameters like the mass and width of the $W$ boson via loop corrections. A recent fit from [9], using precision measurements of several electroweak observables made at the Large Electron Positron Collider (LEP), the Stanford Linear Collider (SLC), and Tevatron puts the Higgs mass at $(94^{+29}_{-24})$ GeV, cf. fig. 1.2.

Through direct measurements at LEP, Tevatron, and the Large Hadron Collider (LHC), large regions of the standard model Higgs mass have been excluded at 95% CL or more [10, 11, 12, 13]. In particular, a standard model Higgs boson cannot be lighter than 115.5 GeV. The range $127 - 600$ GeV has also been excluded. The different experiments are sensitive to different mass ranges, but with large overlaps. Hence, a full combination (which is not available yet) might lead to slightly different exclusion regions.

CMS, ATLAS, and both Tevatron experiments see a slight excess of events that are compatible with a Higgs with a mass of $124$ GeV [13], $126$ GeV [12] and $115 - 135$ GeV [11], respectively. These results can be seen as a hint for a standard model Higgs boson in this mass range, but the statistic significance is not high enough to talk of a “discovery” of the Higgs boson. Further conclusions might be drawn once a full combination of results from the four experiments is available, or after more data has been taken and analyzed by the LHC experiments.

1.2 Extensions to the Standard Model Higgs Sector

While one Higgs doublet is sufficient to give mass to all particles in the standard model, there is no a priori reason why there should only be one such Higgs doublet. In fact, supersymmetry, a popular extension of the Standard Model, requires at least two scalar doublets in the Higgs sector. But a non-standard Higgs sector can exist independent of other extensions of the standard model. Additional scalar doublets or triplets will lead to the existence of additional charged (or even doubly charged) Higgs bosons. Most non-SM Higgs models predict deviations from the SM values of certain precision observables, which have not been observed so far. Hence, some regions of the parameter space of each extended Higgs sector have already been excluded. However, by choosing model parameters appropriately, it is usually possible to stay compliant with experimental results. On the other hand, no evidence for a non-SM Higgs sector (e.g. the detection of a non-SM Higgs boson) has been reported. A more detailed overview can be found in [4].

1.2.1 Two-Higgs-Doublet Models (2HDM)

The simplest way to extend the Higgs sector is to introduce an additional complex scalar doublet. This is needed e.g. in supersymmetry, where one needs one Higgs doublet coupling to the up-type quarks and leptons and another one coupling to the down-type quarks and leptons. After electronweak symmetry breaking, there are five Higgs bosons (in contrast to the Standard Model’s one Higgs boson), two of which are charged. The charged Higgs bosons are of interest here and will be treated in a little more detail. The neutral Higgs bosons mix to two scalar and one pseudoscalar.
eigenstate. In general, this will lead to flavour changing neutral currents, on which there are tight constraints from experiment. However, this can be avoided by specifying appropriate couplings of the fermions to the Higgs doublets. In context of the MSSM (minimal supersymmetric standard model), this is achieved automatically.

Two-Higgs-Doublet models can offer an interesting and challenging phenomenology in the Higgs sector. Especially the charged scalar bosons they predict offer new search channels, for example $t \rightarrow H^+ b$ decays. However, in these type of models, $H^+ W^− Z$ couplings always vanish at tree level \[^4\]. They might come in via loops (probably $tb$ or some supersymmetric particles), which means they will be suppressed compared to tree-level couplings. $H \rightarrow WZ$ decays might still be somewhat important in special kinematic regions. However, \[^14\] find that these decays are probably rare enough not to play an important role in the discovery of such a Higgs sector, hence they will not be treated in detail here.

1.2.2 Triplet Models

Instead of (or in addition to) a second scalar doublet one may extend the Standard Model Higgs sector by an additional real or complex scalar triplet. The kind of bosons one obtains depend on the hypercharge of the triplet. $Y = 2$ triplets will lead to doubly charged Higgs bosons. In models with only one Higgs triplet, the vacuum expectation value of the triplet is constrained by electroweak precision measurements, since a Higgs triplet would lead to deviations of the electroweak mass parameter $\rho = \frac{M_W}{M_Z \cos(\theta_W)}$ from unity. The vacuum expectation value of the triplet would have to be very small. Hence, the additional Higgs bosons would only couple very weakly to standard model particles and they would be hard to discover.

In models with one real and one complex triplet (and an arbitrary number of additional doublets and singlets), one can pose an additional symmetry (i.e. tune the vacuum expectation values of the two triplets) to fix $\rho = 1$ at tree level, like in the standard model. In this case, the vacuum expectation values of the triplets might be relatively large, so they could be produced in sufficient numbers to be discovered at a contemporary collider experiment.

1.3 Charged Higgs Phenomenology

In most 2HDM or Higgs triplet models, the charged Higgs couples to fermions, preferably to the heavier ones. The relative coupling strength of the Higgs to leptons and quarks depends on the model.

1.3.1 Production

Depending on its mass and the relevant coupling strengths, there are several ways to produce a charged Higgs boson at a proton collider. If the charged Higgs is lighter than the top quark, it can be produced via the decay $t \rightarrow H^+ b$. It can also be produced in association with a top quark or a weak boson or even with a neutral Higgs boson. Pairs of charged Higgs bosons may also be produced e.g. via a $Z^0$ boson or photon.
1.3.2 Decay

Again, the possible decay modes depend on the mass of the Higgs and the coupling strengths. If one assumes that the Yukawa couplings of the second Higgs doublet correspond to those of the first Higgs doublet, the charged Higgs would preferably decay into heavy fermions, i.e. $t \bar{b}$ (if kinematically allowed), $c \bar{s}$ and $\tau^+ \nu_\tau$. In this work, a different decay channel will be examined: The decay into two (real) vector bosons $H^+ \rightarrow W^+ Z$. This is kinematically allowed for $m_{H^+} > m_W + m_Z$. Its associated decay width depends on the (effective) coupling of the vertex $H^+ W^+ Z$, as discussed below.

1.4 The Vertex $H^+ W^+ Z$

In the following, I will develop a general description of the vertex $H^+ W^+ Z$, following [14]. Then I will specify the behavior in different physical models.

1.4.1 General Phenomenological Description

In general, the part of the Lagrangian describing the vertex will be of the form

$$i g m_W \cdot V_{\mu\nu} \cdot \epsilon_{W}^{\mu} (p_W, \lambda_W) \epsilon_{W}^{\nu} (p_Z, \lambda_Z),$$

where the $\epsilon$ are polarization vectors of the weak gauge bosons with momentum $p$ and helicity $\lambda$, and $V_{\mu\nu}$ is a stand-in for the (model-dependent) vertex factor. In the most general case, $V_{\mu\nu}$ can be written as

$$V_{\mu\nu} = F g_{\mu\nu} + \frac{G}{m_W^2} p_Z \mu p_W \nu + \frac{H}{m_W^2} \epsilon_{\mu\nu\rho\sigma} p_Z^\rho p_W^\sigma,$$

with form factors $F, G, H$ and the totally antisymmetric tensor $\epsilon$. This corresponds to an effective Lagrangian

$$\mathcal{L}_{\text{eff}} = f_{HWZ} \cdot H^\pm W^\pm Z^\mu + g_{HWZ} \cdot F_{\mu\nu}^W F_{\mu\nu}^W + h_{HWZ} \cdot \epsilon_{\mu\nu\rho\sigma} F_{\mu\nu}^W F_{\rho\sigma}^W$$

with coupling strengths $f_{HWZ}, g_{HWZ}, h_{HWZ}$ and field strength tensors $F_{W/Z}$. The (absolute and relative) strength of the couplings then depends on the physical model in question. On tree level, only the $F$ term can contribute. It turns out that it is always the dominant coupling. [14] calculate the approximate coupling strengths for different models including charged Higgs bosons.

1.4.2 Models with Doublets

In models containing one or more additional Higgs doublets, one will obtain a charged Higgs boson. However, those models can not contain a tree level $H^+ W^+ Z$ coupling. However, this vertex exists on the loop level and can be described by an effective Lagrangian as shown above. According to [14], the dominant contributions come from $tb$ and neutral Higgs bosons. In the case of a supersymmetric model, there can also be contributions from supersymmetric particles.

The effective couplings are fixed by the model and can in principle be calculated from loop diagrams. Of course, they depend on the parameters of the model, i.e. the masses and couplings of the loop particles. These parameters may be constrained by theory or experiment. [14] find that the $G$ and $H$ contributions can be neglected in the 2HDM case. They find $|F^{2HDM}|^2 \sim$
\(10^{-3} \left(10^{-4}, 10^{-5}\right)\) for \(\tan(\beta) = 0.3 \left(1.0, 3 - 10\right)\). Lower \(\tan(\beta)\) values are not considered because they would lead to a too large Yukawa coupling for the top quark. The \(tb\) loop dominates for most \(\tan(\beta)\) values. The bosonic loop only becomes important for \(3 \lesssim \tan(\beta) \lesssim 10\). For the MSSM model, they find that adding contributions from loops of supersymmetric particles does not significantly change the coupling.

### 1.4.3 Models with triplets

In models containing additional Higgs triplets, \(F\) will generally be non-zero at tree level, and hence contribute more than the loop-induced \(G\) and \(H\) terms. The details depend on the model, but generally \(F\) will be proportional to \(v' / v\), where \(v\) is the vacuum expectation value of the Higgs doublet and \(v'\) is the vev of the triplet (or a combination of the triplet vevs in case of more than one Higgs triplet).

In models with one Higgs triplet, \(v'\) is generally constrained to be quite small from precision measurements of the \(\rho\) parameter. For example, for the low energy effective field theory in the Littlest Higgs model \([4]\) predicts one complex Higgs triplet field. \([14]\) find (to leading order)

\[
F_{LLH} = \frac{4v'}{\cos \theta_W} \quad \text{and} \quad m_\Phi = \frac{2m_{h}\cdot f^2}{v^2 \cdot \left(1 - (4v'f/v^2)^2\right)}.
\]

Here, \(m_\Phi(= 115 \text{ GeV})\) refers to the mass of the triplet field, \(m_h\) is the SM Higgs mass, and \(f\) is the symmetry breaking scale. From electroweak precision measurements, one finds \(1 \lesssim v' \lesssim 4\) GeV for \(f = 2\) TeV. \([14]\) calculate the form factor \(F\) for two different reference points.

- \(f = 1\) TeV \(v' = 5\) GeV \(m_{Hpm} = 700\) GeV \(|F_{LLH}|^2 \simeq 0.0085\) and \(f = 2\) TeV \(v' = 4\) GeV \(m_{Hpm} = 1560\) GeV \(|F_{LLH}|^2 \simeq 0.0054\).

For models with additional real and complex triplet fields, one may impose additional symmetry \(v'_r = v'_c(= v')\) to set the \(\rho\) parameter to one at tree level\(^3\). This custodial symmetry avoids the constraints mentioned above. Here, the existence of exactly one real and one complex triplet (in addition to the Standard Model’s doublet field) is assumed. After electroweak symmetry breaking, the Higgs sector consists of a five-plet, a three-plet and two singlets under the custodial symmetry. If the three-plet and the five-plet do not mix, the five-plet does not couple to fermions. The singly charged five-plet Higgs, \(H^+_{5}\), couples to \(W\) and \(Z\) bosons. The relevant form factor is given by

\[
F_{\text{triplet}} = \frac{1}{\cos \theta_W} \cdot \sqrt{\frac{8v'^2}{v'^2 + 8v'^2}}.
\]

The ratio \(v'/v\) can be constrained experimentally, but the constraints depend on the mass of the three-plet Higgs. \([14]\) use \(\sqrt{8v'/v} = 0.5\) and \(m_{H_{5}} = 200\) GeV and find \(|F_{\text{triplet}}|^2 \simeq 0.26\). In an extended study \([15]\) they find \(|F_{\text{triplet}}|^2 = 0.26 - 0.97\). In the studies described later on, \(F = 1\) was used for simplicity.

Assuming no mixing between the three-plet and the five-plet, the \(H^+_{5}\) will not couple to fermions. The \(H^+_{5}W^-\gamma\) vertex is also zero at tree-level \([4]\). Hence, the charged five-plet Higgs may only decay into a \(WZ\) pair or a combination of scalar and/or massive vector bosons. In the context of

\(^3\)Here, \(v_r(\nu_c)\) refers to the vev of the real (complex) triplet, resp.
this work, it is assumed that the other Higgs bosons are substantially more massive than the weak
gauge bosons so that the other decays are kinematically suppressed. Hence they are not considered
here; neither is the possibility of the charged Higgs decaying into fermions via loops.

1.5 Monte Carlo Methods

Monte Carlo integration is a way of numerically evaluating integrals using sequences of pseudo-
random numbers. A similar method can also be used to obtain random number sequences following
a given distribution, starting from any other distribution.

1.5.1 Cross Section Calculation and Event Generation

Calculating observables like cross sections analytically is tricky due to the multi-dimensional inte-
grals that have to be solved. Additionally, one often encounters divergences that have to be treated
carefully. Due to this, monte carlo generators are often used to calculate (leading order or next-
to-leading order) differential cross sections. Given the geometry of the experiment, they are also
used to simulate collision events, including decays and even interaction of the decay products with
a detector.

Roughly, the event generation process works like this: First, phase space distributions for the de-
sired processes have to be calculated (this may be done externally, depending on the event gener-
ator). Then the event generator uses some random numbers to produce the 4-vectors describing
a possible collision event. Each event is weighted with some factors corresponding to the decay
probabilities, the phase space density and (for proton collisions) the momentum distribution of the
partons inside the proton (described by parton distribution functions). Divergences have to be taken
care of, usually by cutting away problematic phase space regions. These should be regions of phase
space that cannot be detected by experiments, e.g. radiation of very soft particles. The weights
should be normalized so that summing over all produced events gives the total cross section, or the
number of expected interactions for a given luminosity.

To make it easier to compare monte carlo simulations to data, there is often an additional step
called unweighting, in which certain events are dropped (randomly, with probability inversely pro-
portional to their weight). The events that are kept then all have the same weight. The kinematics
of the sample produced in this way should correspond to the “true” distribution.

1.5.2 Showering and Hadronization

Showering is a method that takes higher-order corrections to the produced processes into account by
producing (mostly collinear) gluons and quarks radiating from color-charged particles. This mim-
ics the processes which happen in reality, leading to the observation of “jets” of hadrons instead of
g single quarks.

Due to the so-called “confinement” property of QCD, only color singlets can be observed macro-
scopically. Hence, all quarks and antiquarks have to combine to colourless mesons and baryons.
This process cannot be described with perturbative calculations. Instead, one uses distributions
measured from experiments to simulate that part.
1.5.3 Detector Simulation

After passing through a showering and hadronization algorithm, the particles should have roughly the same kinematic properties as the ones produced in an actual experiment. However, the measuring apparatuses (detectors) used by the experiments are not (and cannot be) perfect. For example, they cannot provide full angular coverage. Moreover, the detection efficiency and resolution depend on the properties of the particle. Hence, detector simulations are often used to be able to compare simulations to actual data, or to study the feasibility of a given analysis. There are two kinds of detector simulations: Fast simulations only apply basic acceptance cuts and gaussian smearing or energies/momenta, according to expected resolutions. This can be done quite fast and does not require any proprietary information about the detector setup. Here, the pgs software \cite{16} was used for an approximate simulation of the ATLAS detector. Full detector simulations (e.g. with the GEANT \cite{17} package) follow the paths of charged particles through the hole detector, with a Monte Carlo approach to account for the statistical nature of decays and e.g. energy deposits in the material. They simulate the raw output of each detector channel, making it necessary to run a simulation of the detector readout/event reconstruction software. The full detector simulations take quite long to run (longer than event generation, showering etc.) and require proprietary software as the precise layout of the detector is not publically available.
Chapter 2

Experimental Overview

The work described in chapter 3 was done in a theory group, with no cooperation with any experimental collaboration. A crude simulation of the ATLAS detector was used to smear the simulation results in the hope of an eventual follow-up on this work as part of the ATLAS collaboration. In the following, a short introduction will provide the necessary basics of collider physics, especially the ATLAS detector.

2.1 Collider Physics and Detectors

Particle accelerators are an important tool for experimental particle physicists. They are used to accelerate beams of charged particles (usually electrons or protons as well as their anti-particles). These beams can be used for two different types of experiments: fixed target experiments and colliding beam experiments where two high-energy beams collide. The latter type of experiments needs more fine tuning to ensure that the beams collide at the right place. They are widely used as they allow for higher center-of-mass energies to be reached.

At the collision point, particles can scatter off each other, possibly producing other particles. These collisions usually happen inside a detector so that the reaction products can be detected and their properties (e.g. energy and momentum) can be measured. Most detectors that are in use today follow a layered design. The innermost layer (around the beam pipe) is used to track charged particles using, for example, wire chambers or silicon sensors. As the tracking system is usually surrounded by a magnetic field, the tracks can be used to determine the charge and momentum of the measured particles as well as the location of the interaction point. The tracking system is set up so that particles interact minimally with the detector and do not lose much energy.

The next layers form the calorimeter, which is designed so that most particles deposit all of their energy there. The energy deposited can be measured and the energy of the particle can be determined from that. Most calorimeters are split into two parts. The first one is the electromagnetic calorimeter, in which electrons, photons, and neutral pions (which quickly decay into photons) deposit most of their energy. Electrons emit bremsstrahlung (photons) when interacting with a nucleus, photons split into electron-positron pairs which radiate photons and so on. This process results in a shower of electrons and photons, growing exponentially, and stopping when the photons reach energies of $2 \cdot m_e$ or less and do not have enough energy for pair production. The remaining electrons and photons still deposit energy via bremsstrahlung, ionization and Compton scattering. The resulting radiation can be detected and amplified, e.g. using photo-multipliers.
Hadrons are heavier than electrons and take longer to deposit their energy via bremsstrahlung (neutral hadrons do not emit any bremsstrahlung at all, of course). They deposit most of their energy in the second part of the calorimeter, the hadronic calorimeter, where they form showers similar to the electrons. The shapes of the showers differ, though, because hadrons mainly interact strongly with the atomic nuclei. During those interactions, other hadrons such as pions, kaons or protons can be produced. Some of them (e.g. neutral pions) decay electromagnetically, causing small electromagnetic showers inside the hadronic shower. This makes hadronic calorimetry more difficult than electromagnetic calorimetry and is one cause of the uncertainties on jet energies.

Muons are heavier than electrons and do not interact strongly. Most muons produced at the LHC will have energies between 1 GeV and 1 TeV. They are so-called minimum ionizing particles, which means they deposit little energy in the calorimeters (up to a few GeV per muon). Muons are the only particles reaching and interacting with the outermost detector layers, the muon chambers, which are tracking chambers similar to those in the inner detector. If they are surrounded by a magnetic field, they can be used to measure muon momentum.

Neutrinos only interact weakly with matter. They leave no tracks in the inner detector and do not deposit any energy in the calorimeters. However, they can be detected indirectly: The magnitude of the vector sum of the transverse energies of all “visible” particles is defined as the missing transverse energy $E_T$. In hadron collisions, we do not know the initial state of the partons before the collision as we do not know their momentum fraction $x$. However, we can assume that their transverse momentum is negligibly small. If all particles in the final state are detected, the transverse energy should be balanced and the missing energy is zero (or close to zero, accounting for detector accuracy). If the missing energy is not zero, one knows that there was at least one an undetected particle, e.g. a neutrino, that caused this imbalance. As we do not know the longitudinal momentum of the partons in the initial state and we cannot measure the longitudinal momentum of the beam remnants in the final state, we can not use longitudinal missing energy. As the whole system may be boosted along the $z$-axis, projections to the transverse plane are often used as they are invariant under such boosts.

2.2 Important Physical Quantities

In this chapter, some physical quantities and coordinates that are often used in the description of high-energy particle physics experiments will be introduced.

2.2.1 Luminosity, Counting Rate and Cross Section

The luminosity $L$ describes the flux density of particles in the beam. For synchrotrons it is given by

$$L = \frac{n_B \cdot f \cdot n_1 \cdot n_2}{A} \quad (2.1)$$

where $f$ is synchrotron frequency, $n_B$ is the number of bunches per beam, $n_i$ is the number of particles per bunch in beam $i$ and $A$ is the effective bunch cross section at the interaction point $[19]$. However, determining the actual luminosity is not that trivial, especially for hadron colliders. In most cases, the luminosity is actually measured using eq. (2.2) and a process with a well known cross section. The integrated luminosity $L_{int} = \int L dt$ is just the luminosity integrated over a certain amount of time.

For each possible reaction, the cross section $\sigma(\sqrt{s})$ gives the probability of that reaction happening.
It can be calculated from Feynman rules and the available phase space. However, cross sections for QCD events like top quark pair production are difficult to calculate, leading to large uncertainties on the predicted cross sections.

Luminosity, cross section, and interaction rate $\frac{dP}{dt}$ (for a given process) are related by the formula

$$\frac{dP}{dt} = \sigma \cdot L.$$  \hspace{1cm} (2.2)

The counting rate $\frac{dN}{dt}$ is again related to the interaction rate by a factor $\epsilon_{\text{eff}}$, which depends on the acceptance of the detector as well as the efficiencies of the trigger, the reconstruction algorithms and the cuts used (see section 3.5.1).

2.2.2 Detector Coordinates

Because of the layout of the ATLAS detector, cylindrical coordinates are used to describe the positions and momenta of particles inside it [18]. The $z$-axis follows the beam direction, so the $x-y$ plane (transverse plane) is perpendicular to the beam. The origin is located at the center of the detector at the planned interaction point. The $x$-axis points to the center of the LHC ring, the $y$-axis points upward. The azimuthal angle $\varphi$ is measured in the transverse plane with respect to the $x$-axis, the polar angle $\theta$ is measured with respect to the $z$-axis. Instead of the polar angle, the pseudorapidity $\eta := -\ln \left( \tan \left( \frac{\theta}{2} \right) \right)$ is used. In the relativistic limit (i.e. for $m^2 \ll E^2$), this quantity is equal to the rapidity $y = \ln \left( \frac{E+p_z}{E-p_z} \right)$, which is invariant under Lorentz boosts along the $z$-axis apart from an additive constant. The distance $\Delta \eta$ between two objects is then Lorentz-invariant (for boosts along the $z$-axis).

The angular distance $\Delta R$ between two objects is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \varphi^2}$.

2.3 Experimental Setup

2.3.1 The LHC

The Large Hadron Collider (LHC) is a proton-proton collider that started operating in winter 2009. It currently operated at a center of mass energy of 7 TeV and is expected to eventually reach energies around 14 TeV at a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ [20]. The beam tunnel has a circumference of 27 km and was previously used for the Large Electron-Positron Collider (LEP). The four main experiments are ATLAS, CMS, LHCb and ALICE.

As it is the particle collider with the highest center of mass energy to date, the LHC focusses on searching for new physics, for example the predicted Higgs boson or hypothetical supersymmetric partners to known matter. There will also be precision measurements of the top quark properties, e.g. its production cross section. In addition to proton-proton collisions, lead ion collisions will be used to study the properties of quark-gluon plasma.

2.3.2 The ATLAS Experiment

The ATLAS (A Toroidal LHC Apparatus) detector is one of the two multipurpose detectors at LHC [18]. It is composed of an inner detector inside a 2 T solenoidal magnetic field, electromagnetic and hadronic calorimeters and muon chambers. Its design is shown in fig. 2.1). The inner detector consists of the pixel detector, the silicon strip detector (SCT) and the transition
radiation tracker (TRT). In the pixel detector, the approximately 80 million pixels are arranged in three barrel layers and six endcap disks. The closest barrel layer is only about 50 mm from the beam pipe. Following the pixel detector, the silicon strip detectors are arranged so that each track crosses eight strip layers. The TRT, made up of about 350,000 straw tubes, measures radiation that is produced when a charged particle crosses between two regions with different permittivities. This allows for the determination of the particle’s velocity. It can therefore be used to distinguish between e.g. electrons and charged pions.

The calorimeters can again be divided into barrel parts and endcap parts. The liquid argon electromagnetic calorimeter is followed by the hadronic calorimeters. In the endcap regions, the latter are made with liquid argon again, while in the barrel region the hadronic calorimeter is made from scintillating fiber tiles. ATLAS also has two liquid argon forward calorimeters. There are approximately 200,000 readout channels from all of the calorimeters.

The muon system is immersed in a toroidal magnetic field to be able to reconstruct the muon momentum. There are four different kinds of muon chambers: Monitored Drift Tubes (MDTs) and Resistive Plate Chambers (RPCs) in the barrel region, as well as Cathode Strip Chambers (CSCs) and Thin Gap Chambers (TGCs) in the endcap regions. The RPCs and TGCs have fast readout times and are mainly used for triggering (see below) while the MDTs and CSCs are used for precision tracking. The muon chambers are arranged so that each muon passes through several chambers,
allowing for the determination of the muon’s momentum and sign. Reading out the full ATLAS detector at each bunch crossing would lead to data rates that are too high to be able to save or analyse all of the data. Apart from that, most events are expected to be simple QCD scattering events. Interesting physics make up only a fraction of the observed reactions. Because of these two facts, a trigger system is needed. ATLAS employs a three level trigger system (L1, L2, and event filter). Its task is to reduce the recorded data rate to a manageable amount, preventing buffer overflows, and to filter out uninteresting events. The L1 triggers look for high-$p_T$ objects in certain regions of the detector, using muon chambers and calorimeter information. From their decisions, so-called Regions of Interest are identified which the L2 trigger systems investigate further. The event filters have access to information from all parts of the detectors. Their output rate is about $200\,\text{MHz}$, which is low enough to be written to tape for further offline analysis.
Chapter 3

Phenomenological Studies and Results

This chapter describes the results obtained during my work with the THEP group at Uppsala Universität, as part of my “Spezialisierungspraktikum” and “Forschungshauptpraktikum” (in preparation for my Master’s thesis).

3.1 Event Generation

For the generation of signal events, MadGraph/MadEvent [21, 22] was used together with pythia [23] (providing showering and hadronization) and pgs [16] (providing a fast detector simulation). The latter two programmes are called automatically from MadGraph depending on the configuration, with necessary parameters specified on run cards.

3.1.1 Signal Events

The purpose of this project was to study the \(HWZ\) vertex, which does not exist in the standard model or the most common extension, the MSSM, and other two-Higgs-doublet models, and hence is not implemented in any of the standard MC generators. To be able to generate events containing this vertex, it was added by hand into the existing 2HDM model file in MadGraph. As motivated in [1.4.1], a vertex with a purely scalar coupling was added to the relevant subroutine. The form factor \(F\) described above was set to unity so as to stay relatively model-independent. The cross sections can be manually rescaled according to the predictions of the specific models to be studied.

The \(H \rightarrow WZ\) decay channel was added to pythia via the pylha interface, which is automatically called from MadGraph. The branching rate for this decay was set to 1, since we were only interested in those decays. The branching rates for the leptonic/hadronic decays of the \(W\) and \(Z\) bosons were also set using the same interface, to obtain only the final states that we were interested in.

The width of the charged Higgs boson was initially set to a very low value (0.1 GeV). However, later on, the width of the charged Higgs was also calculated using MadGraph and studies were done involving off-shell Higgs bosons.
3.1.2 Production Chain

The first step in the event production is to let MadGraph generate the Feynman diagrams contributing to the process to be studied. This is done by specifying the initial and final state, and any intermediate particles if necessary. MadGraph finds all contributing tree diagrams (loop diagrams are not included). Once that is done, one can ask MadGraph to calculate cross section and generate events. We configured MadGraph to produce charged Higgs bosons (via $W/Z$ boson fusion and via associated production, see below). The produced events are then automatically fed into pythia, which handles the decays of the Higgs, W and Z as well as showering/hadronization of the quarks. It is possible to do the Higgs and even the $W/Z$ decays within MadGraph. However, this takes a lot of time to run due to the large number of final state particles, hence this was considered impractical. After pythia, pgs is called to provide a crude detector simulation. Hadrons are clustered into jets, the momenta of visible objects (electrons, muons, jets) are smeared. Objects outside of the detector acceptance are dropped and the rest are used to calculate the missing transverse energy.

After each stage in the production chain, the results are saved in the “lhe” format and also copied into ROOT trees, for easy analysis.

The masses of the Higgs bosons are not known and generally not predicted by theory. There are bounds from direct searches as well as theoretical predictions using loop contributions to variables measured in electroweak precision measurements. These bounds and predictions are of course highly model-dependent. Most seem to favor Higgs masses in the range of some 10 GeV to 1 TeV. As we want to study the decay of a charged Higgs boson into real $W$ and $Z$ bosons, only Higgs masses above the kinematic threshold of $m_W + m_Z \approx 172$ GeV were considered. All simulations were performed for seven different Higgs masses between 180 and 600 GeV. In the following, “low Higgs mass” will refer to Higgs masses just above the threshold, i.e. around 180 – 200 GeV.

3.2 Production Cross Section

There are several different production channels for the charged Higgs in a proton collider. To stay model-independent, we have focussed on production mechanisms that do not involve couplings of the charged Higgs to fermions or neutral Higgs bosons. To achieve this, all relevant couplings (eg. $H^+tb$) were set to zero. The production channels that were investigated further were associated production of $H^\pm$ and $W/Z$, and vector boson fusion (VBF). Pair production via $\gamma/Z$ was investigated briefly but does not contribute much.

3.2.1 Electroweak Pair Production

There are again several processes where a $H^+H^-$ pair is produced. The only ones that do not depend much on the particular model and the other Higgs masses/couplings are pair production via an $s$-channel photon or $Z$ boson (cf. fig. 3.1[a]). The coupling of $\gamma/Z$ to the charged Higgs is fixed, hence the cross section for this process only depends on the mass of the charged Higgs. The expected production cross section for the LHC running at 7 TeV can be seen in fig. 3.1[b]. Unsurprisingly it decreases for larger Higgs masses. But even for relatively small Higgs masses the cross section is so low (7.7 fb for $m_H = 180$ GeV) that looking for these events at the LHC (running at 7 GeV) will probably prove futile: For an integrated luminosity of 1 fb$^{-1}$ one would expect less than ten Higgs pairs to be produced that way.
3.2.2 Vector Boson Associated Production

In a theory containing the $WZH$ vertex, charged Higgs bosons may be produced in association with a $W$ ($Z$) boson via an $s$-channel off-shell $Z$ ($W$) boson (cf. fig. 3.2(a)). The cross section for this process then depends on the coupling constant associated with this vertex. In fig. 3.3 the cross section calculated with MadGraph as described in §3.1.1 is shown, with the model-dependent form factor set to 1. (In models where the vertex only comes in via loops, the cross section is thus much lower than shown here.)

Again, the cross section decreases quickly with the Higgs mass. The cross section for both processes ($W \to HZ$ and $Z \to HW$) are of the same order of magnitude. Even for low Higgs masses, the cross section is less than 100 fb for each process.
3.2.3 Vector Boson Fusion

There is another way to produce a single charged Higgs via the $HWZ$ vertex: Vector boson fusion (cf. fig. 3.2(b)). As in the case of neutral Higgs production, this process dominates over associated production with a vector boson (cf. fig. 3.3). Since both processes contain the $HWZ$ vertex exactly once, their cross sections have to be multiplied with the same model-dependent form factor, so their ratio is (at leading order) model-independent.

The cross section for the vector boson fusion process decreases less sharply with the Higgs mass than the associated production cross section does. For low Higgs masses, the cross section can reach several hundred fb, which means that this process could be observed at the LHC.

Vector boson fusion has a great advantage over most other production mechanisms: Since only colour singlets are exchanged between the two protons, there is no color connection between the beam remnants and hence we expect little hadronic activity in the central region (of course there will still be some due to hadronic decays, underlying event and multiple interactions).
### 3.3 Decay

<table>
<thead>
<tr>
<th>Process</th>
<th>Branching rate</th>
<th>Process</th>
<th>Branching rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W^+ \rightarrow e^+\nu_e )</td>
<td>(10.75 ± 0.13)%</td>
<td>( H^+ \rightarrow e^+e^-qq' )</td>
<td>(2.27 ± 0.01)%</td>
</tr>
<tr>
<td>( W^+ \rightarrow \mu^+\nu_\mu )</td>
<td>(10.57 ± 0.15)%</td>
<td>( H^+ \rightarrow \mu^+\mu^-qq' )</td>
<td>(2.27 ± 0.01)%</td>
</tr>
<tr>
<td>( W^+ \rightarrow qq' )</td>
<td>(67.60 ± 0.27)%</td>
<td>( H^+ \rightarrow e^+e^+\nu_e )</td>
<td>(0.362 ± 0.004)%</td>
</tr>
<tr>
<td>( Z^0 \rightarrow e^+e^- )</td>
<td>(3.363 ± 0.004)%</td>
<td>( H^+ \rightarrow e^+e^-\mu^+\nu_\mu )</td>
<td>(0.355 ± 0.005)%</td>
</tr>
<tr>
<td>( Z^0 \rightarrow \mu^+\mu^- )</td>
<td>(3.366 ± 0.007)%</td>
<td>( H^+ \rightarrow \mu^+\mu^-e^+\nu_e )</td>
<td>(0.362 ± 0.004)%</td>
</tr>
<tr>
<td>( Z^0 \rightarrow q\bar{q} )</td>
<td>(69.91 ± 0.006)%</td>
<td>( H^+ \rightarrow \mu^+\mu^-\mu^+\nu_\mu )</td>
<td>(0.356 ± 0.005)%</td>
</tr>
</tbody>
</table>

Table 3.1: \( W, Z, \) and charged \( H \) boson decays, assuming \( \text{BR}(H^+ \rightarrow W^+Z)=1 \), excluding \( \tau \). From [3].

As explained above, only decays of the charged Higgs into a \( W \) and a \( Z \) boson were considered. The decays can be further classified according to the decays of the weak bosons. Some factors should be considered when choosing decays channels for further studies:

- Hadronic decays of the weak bosons have a larger branching rate than leptonic decays (cf. tab. 3.1).
- Muons and to some degree electrons can be detected and reconstructed better and more precisely than jets.
- At least one lepton in the final state makes it easier to trigger on the desired events.
- In events with leptonically decaying \( W \) bosons, as well as events containing tauons, some information will be lost due to neutrinos carrying away momentum.

We have chosen to only use decay channels where the \( Z \) boson decays into electrons or muons. Both leptonic and hadronic decays of the \( W \) boson were considered. The resulting branching rates can be found in tab. 3.1.

### 3.4 Finite Width

In the simulations described above, MadGraph was asked to generate on-shell Higgs bosons. Their width was assumed to be negligibly small (1 MeV). However, it is possible to use MadGraph to calculate the partial width associated with a certain decay by asking for the cross section of a \( 1 \rightarrow 2 \)-process. If we assume that the charged Higgs only couples to the weak bosons, the partial width of the process \( H^+ \rightarrow W^+Z \) is equal to the total width of the Higgs. This partial width of course again depends on the coupling coefficient assigned to the vertex. This means that rescaling the cross section is unfortunately not the only thing one has to do when considering different models. This is only relevant for Higgs masses and coupling constants where the width is larger than the expected uncertainty in the mass measurements caused by detector effects (e.g. uncertainties in the energy measurements). If the width is smaller than that, its effects on e.g. the mass distribution and other kinematic observables will be negligible. However, the width of the Higgs boson also influences

\[1\] If we also consider non-zero couplings to e.g. fermions, the total width will be slightly larger, as we have to add the partial widths of the fermionic, while the partial width will not be affected.
Figure 3.4: Top: Predicted decay width in GeV of a charged Higgs boson of a given mass (green), compared to the partial width of a hypothetical heavy gauge boson decaying in the same manner ($W' \rightarrow WZ$) (red). Bottom: Predicted cross sections (times branching ratio) for the process $H^+ \rightarrow W^+Z \rightarrow qq'l'^{-l'^{-}}$. Red: Width fixed to 1 MeV. Green: Including the previously calculated width in MadGraph/pythia, all decays via pythia. Blue: Full matrix element calculated in MadGraph.
the total cross section close to the kinematic threshold. The predicted decay width assuming no other decay channels than $H \rightarrow WZ$ is shown in fig. 3.4(a). It can be seen that for masses larger than about 400 GeV the width is clearly large enough to be expected to influence mass measurements.

One can now include the previously calculated width as a fixed parameter in the MadGraph model and redo the cross section calculations. The results are compared to the previous calculations using a small width in fig. 3.4(b). The difference is negligibly small. One can also use MadGraph to calculate the full process, including all decays, with this width information. This will include off-shell $W$ and $Z$ bosons. The resulting cross sections can also be seen in fig. 3.4(b). There is a rather large deviation of more than 50% for small Higgs masses, but also for larger Higgs masses one can observe that the cross section obtained this way is about 20% smaller than the one quoted previously. This seems to indicate that simulating all decays in pythia is insufficient for our needs, which is a point of improvement for further studies.

3.5 Kinematic Properties, Event Selection Rules and Efficiencies

For each mass point and decay channel, a separate sample with 100,000 events was generated. Each had a positively charged Higgs boson, its decay products, and (simulated) detector information. In the following, “truth” will refer to the simulation results obtained from the pythia run, with all decays but before showering and hadronisation. “Measured” will refer to the results obtained after the detector simulation.

3.5.1 The Dilepton Channel

The results presented here were obtained using $\mu^+\mu^-+\text{jets}$ final states. As only a limited detector simulation was available, the results for electrons+jets are not expected to be drastically different. Events were selected using the following selection cuts:

- Exactly two muons, of opposite signs, with $p_T \geq 20$ GeV (“$\mu$ cut”).
- Dimuon mass between 60 and 100 GeV (“$Z$ mass cut”).
- At least two jets with $p_T \geq 15$ GeV, $|\eta| < 2.5$ (“jet cut”).

Each pair of such jets with $60 \text{ GeV} \leq m_{jj} \leq 95$ GeV was defined as a $W$ candidate; only events with at least one $W$ candidate were kept (“$W$ mass cut”). Each $W$ candidate combined with the $Z$ candidate gives a Higgs candidate, thus some events might have more than one Higgs candidate. In this case, histograms were filled once for each Higgs candidate. In a final cut, only events with exactly one Higgs candidate were kept. The cut acceptances (number of events passing this and every previous cut divided by total number of events) and cut efficiencies (number of events passing this cut divided by the number of events passing the previous cut) can be found in tables 3.2 and 3.3. The $p_T$ cuts used here were kept as loose as possible without getting to regions where object identification is unreliable.

3.6 Mass Measurements

We consider here a direct method of measuring the mass of the charged Higgs boson by simply combining the 4-momenta of the decay products to obtain the 4-momentum $p_H$ of the Higgs boson.
Table 3.2: Cut acceptances for different Higgs masses.

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\mu$ cut</th>
<th>$Z$ mass cut</th>
<th>jet cut</th>
<th>$W$ mass cut</th>
<th>=1 higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>0.456</td>
<td>0.430</td>
<td>0.386</td>
<td>0.247</td>
<td>0.150</td>
</tr>
<tr>
<td>200</td>
<td>0.492</td>
<td>0.458</td>
<td>0.414</td>
<td>0.264</td>
<td>0.163</td>
</tr>
<tr>
<td>250</td>
<td>0.553</td>
<td>0.511</td>
<td>0.467</td>
<td>0.303</td>
<td>0.198</td>
</tr>
<tr>
<td>300</td>
<td>0.587</td>
<td>0.542</td>
<td>0.499</td>
<td>0.330</td>
<td>0.224</td>
</tr>
<tr>
<td>400</td>
<td>0.631</td>
<td>0.580</td>
<td>0.536</td>
<td>0.366</td>
<td>0.257</td>
</tr>
<tr>
<td>500</td>
<td>0.656</td>
<td>0.604</td>
<td>0.550</td>
<td>0.357</td>
<td>0.260</td>
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<tr>
<td>600</td>
<td>0.680</td>
<td>0.626</td>
<td>0.552</td>
<td>0.298</td>
<td>0.219</td>
</tr>
</tbody>
</table>

Table 3.3: Cut efficiencies (cut flows) for different Higgs masses.

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\mu$ cut</th>
<th>$Z$ mass cut</th>
<th>jet cut</th>
<th>$W$ mass cut</th>
<th>=1 higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>0.456</td>
<td>0.942</td>
<td>0.897</td>
<td>0.641</td>
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<td>200</td>
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</tr>
<tr>
<td>250</td>
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<tr>
<td>300</td>
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<td>0.920</td>
<td>0.662</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>0.728</td>
</tr>
<tr>
<td>600</td>
<td>0.680</td>
<td>0.920</td>
<td>0.883</td>
<td>0.540</td>
<td>0.736</td>
</tr>
</tbody>
</table>

Its mass is then given by the relativistic mass energy relation, $m_H^2 = E_H^2 - \vec{p}_H^2$.

The dileptonic channel is best suited for this approach since it does not have any neutrinos in the final state. All the decay products can in principle be detected and their energy and momentum measured. In the trilepton channel, only three out of four final state particles can be detected. However, the neutrino’s transverse momentum can be determined from the energy balance in the detector (missing transverse energy $E_T$). Since the mass of the $W$ boson is known, the longitudinal momentum of the neutrino can then be determined up to a twofold ambiguity. However, this approach relies on a precise and accurate measurement of the missing energy, which is affected heavily by pileup/multiple interactions etc. However, the trilepton channel is expected to have less contributions from e.g. combinatorical background, hence making it an interesting channel for mass measurements, too.

### 3.6.1 The Dilepton Channel

Higgs candidates were selected according to the criteria given in section 3.5.1 and the so called “4-object mass” was calculated as the mass of the sum of the four visible decay products:

$$M_{\mu\mu jj} := \sqrt{(p_{\mu^+} + p_{\mu^-} + p_{j_1} + p_{j_2})^2}. \quad (3.1)$$

Two methods of improving the Higgs mass resolution by taking into account our knowledge of the mass of the $W$ boson were tested. Both rely on the fact that the uncertainty of the jet energy scale is the dominant contribution to the mass resolution. In particular, the jet energy scale uncertainty
Figure 3.5: Reconstructed Higgs mass. Red: original 4-object mass. Blue: 4-object mass after applying the jet energy rescaling method. Green: Mass after applying the dijet mass subtraction method.

is expected to be larger than the width of the $W$ boson. In other words, we can assume that (for hadronically decaying $W$s) “most” of the deviation of the dijet mass from the known $W$ mass, and hence “most” of the deviation of the measured 4-object mass from the true (but unknown) Higgs mass, comes from a miss-measurement of the jet energy. We can therefore correct our measurements of the Higgs mass by constraining the dijet mass to the $W$ mass. However, the constraint is not unique since we have two jets with partially uncorrelated uncertainties contributing to the measurement. There are in principle continuously many ways to correct the jet energies that will result in the “correct” $W$ mass. Two methods that can be applied easily, without knowledge of the $\eta$- and $p_T$-dependence of the jet energy scale and with no additional computing time, were studied. It should be noted that, while not significantly biasing the signal, the correction methods presented here will probably bias the mass distribution due to background events (both combinatorical background and other processes with the same final state), as the dijet mass distribution is not expected to be symmetric about the $W$ mass.

The first method considered here is used by other analysis groups, e.g. [25]. The dijet mass is constrained to the known $W$ mass by rescaling both jet energies by a common factor $\frac{M_W}{M_{jj}}$, where $M_W = 80.4$ GeV is the $W$ mass and $M_{jj} := \sqrt{(p_{j1} + p_{j2})^2}$ is the originally measured mass of the dijet system. The “re-scaled” Higgs mass $M_{\text{scale}}$ is then calculated as before, but using the rescaled jet momenta. This method gives the most likely correction under the assumption that the relative energy uncertainty is the same for both jets.

In the second method, the measured 4-object mass is corrected by subtracting the measured dijet mass and adding the known $W$ mass: $M_{\text{sub}} := M_{\mu\mu jj} - M_{jj} + M_W$. This is only physically correct to first order.
Figure 3.6: Reconstructed Higgs masses for seven different simulated Higgs masses. Dashed lines: original mass before corrections. Solid lines: after applying dijet mass subtraction method.
In fig. 3.5, both the original 4-object mass distribution and the two corrected masses are plotted for a Higgs mass of 300 GeV, with a gaussian distribution fitted around the mass peak. All three distributions are well described by a gaussian function. Both corrections lead to a higher mass peak with a smaller standard deviation. In addition, the mean is moved closer to the nominal value. The subtraction method seems to perform slightly better than the scaling method, hence it is used in the following studies. However, studies with full detector simulation will be needed to make a definite claim that one of these methods works better than the other.

In fig. 3.6, the mass distributions for the seven studied Higgs masses can be seen. The original 4-object masses have dashed lines, the masses after applying the subtraction correction have solid lines. These distributions have been made using the 100000 events per mass point generated previously, and have not been rescaled according to the cross section. It can be seen that all masses except for $m_H = 180$ GeV feature a gaussian mass peak and some (negligible) amount of combinatorical background. For $m_H = 180$ GeV, the peak of the combinatorical background and the mass peak overlap, but one can still see a prominent Gaussian peak.
3.6.2 The Trilepton Channel

Mass measurements in the trilepton channels is tricky. A full reconstruction of the event kinematics is impossible due to the “missing energy” carried away by the neutrino. Still, these channels are expected to have less background and lower systematic uncertainties as the jet energy scale does not enter directly. Hence, mass measurements in this channel should be studied. The studies shown here were made in the $Z \rightarrow \mu\mu$, $W \rightarrow e\nu_e$ channel, but studies in other trileptonic channels are expected to show similar results.

Due to the neutrino in the final state, calculating the 4-object mass as in the analysis above is of course impossible. Hence, different variables related to the Higgs mass were studied:

Figure 3.7: Reconstructed transverse Higgs masses for seven different simulated Higgs masses.
Transverse mass

The transverse mass of an object is defined as

\[ m_T := \sqrt{E_T^2 - \mathbf{p}_T^2}, \]

where \( p_T := \sqrt{p_x^2 + p_y^2} \) is the transverse momentum and \( E_T \) is the transverse energy (i.e. the projection of the energy on the transverse plane, \( E_T := \cos(\theta) \cdot E \)). The transverse 4-object mass is then defined as above, only using transverse quantities. This is a very useful variable for final states containing one neutrino because it can be assumed that the transverse momentum of the neutrino is given by the “missing transverse energy” (the negative sum of all transverse energies of all detector objects), because events should be balanced in the transverse plane. The transverse mass is always smaller than the nominal mass. Due to the finite energy resolutions, one usually sees a steeply falling slope at the nominal mass of the parent particle.

In fig. 3.7, the reconstructed transverse mass distribution is plotted for the different simulated Higgs masses. As expected, there is a steep slope around the nominal mass and a visible peak before that. If the position of this slope can be measured accurately, it is easy to determine the Higgs mass.

Measuring the neutrino \( p_z \)

The transverse momentum of the neutrino can be determined from “missing energy” because we expect the event to be balanced on the transverse plane (due to momentum conservation). This argument cannot be used for the longitudinal part of the momentum of a neutrino in a hadron collider: We do not know the fraction of the proton’s longitudinal momentum carried by the partons that were involved in the “hard collision”. The proton remnants are too close to the beam pipe to be detected, leaving us unable to balance the event in the longitudinal direction. However, in the case of a \( W \) decaying into a charged lepton and a neutrino, there is an additional constraint that can be exploited: Neutrino and lepton must combine to an object with the (known) \( W \) mass. This can be expressed as

\[ M_W^2 = (E_l + E_{\nu})^2 - (\mathbf{p}_{T,l} + \mathbf{p}_{T,\nu})^2 - (p_{z,l} + p_{z,\nu})^2. \] (3.2)

If we assume that the transverse momentum of the neutrino is given by the missing transverse energy, the only unknown quantity left is \( p_{z,\nu} \), which we can solve for:

\[ p_{z,\nu} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \] (3.3)

where

\[ a = 4p_{z,l}^2 - 4E_l^2, \quad b = 4p_{z,l} \cdot (2\mathbf{p}_{T,l} \cdot \mathbf{p}_{T,\nu} + M_W^2), \quad \text{and} \quad c = (M_W^2 + 2\mathbf{p}_{T,l} \cdot \mathbf{p}_{T,\nu})^2 - 4E_l^2 p_{T,\nu}^2 \]

(and we set \( m_l = \sqrt{E_l^2 - \mathbf{p}_{T,l}^2 - p_{z,l}^2} \approx m_{\nu} = \sqrt{E_{\nu}^2 - \mathbf{p}_{T,\nu}^2 - p_{z,\nu}^2} \approx 0 \)).

There are in general two solutions for the neutrino momentum, and it is impossible to determine which is the “correct”, physical solution. For the following study, both solutions (if real) were kept and used to calculate the Higgs mass. If the solution turned out to be complex (due to missmeasured energies/momenta), the event was thrown out.

The reconstructed masses are plotted in fig. 3.8. It can be seen that the mass distributions peak at the nominal mass. However, due to the large uncertainties and combinatorical background, the peaks are quite broad. Additionally, especially for larger Higgs masses, there were large losses due to non-real solutions for \( p_{z,\nu} \). Further examination and use of full detector simulation is needed to determine if these losses will get bigger if the real detector resolution and pile-up effects are taken into account.
Figure 3.8: Reconstructed Higgs masses, using the neutrino $p_z$ from the $W$ mass constraint, for seven different simulated Higgs masses.
Neglecting the neutrino $p_z$

Since measuring the longitudinal momentum of the neutrino often leads to unphysical results (i.e. complex values), a third variable, $m_0$, was defined as the 4-object mass with the neutrino $p_z$ set to 0. This is of course unphysical but in principle it should not lead to large deviations from the nominal mass. In fig. 3.9 the resulting mass distributions are shown. They do not peak at the nominal masses, but at slightly larger values. The peaks are not Gaussian, but narrow peaks with wide tails. Due to the bias, it would be challenging to use this method for an actual mass measurement. However, the sharp peaks might make it useful for a cross section measurement because they should be easily seen above the background.
3.7 Angular correlations

There are several angular observables in the final state whose distributions depend on the spin of the parent particles. In our case, the Higgs is a scalar particle decaying into two massive vector bosons. The final state particles are all (nearly) massless fermions. Observation of a new heavy particle and its decay modes is not all that has to be done to claim the discovery of a Higgs boson. The measurement of its properties is also very important to distinguish a Higgs from other new physics phenomena. If e.g. evidence for a massive particle decaying into a $W$ and a $Z$ boson is indeed found, it will need to be shown that the parent particle is indeed the predicted charged Higgs. Part of that would be a measurement of the observed particle’s spin, e.g. by exploiting angular observables. Here, several angular correlations have been examined to see if they would be useful in distinguishing a scalar charged Higgs from e.g. a heavy (vector) $W'$. Since no spin information is read in by pythia, the setup used for the generation of the previously studied samples cannot be used for studies of the angular observables of interest. Hence, new samples were generated where the full $H \rightarrow WZ \rightarrow \mu\mu jj$ decay was simulated with MadGraph/MadEvent. However, MadGraph seemed to have trouble filling the whole phase space and only produced a few thousand events, even after several days of runtime. As a result, the Higgs samples suffer from low statistics. In addition, samples with the same final state, but with a heavy charged vector boson $W'$ instead of the Higgs boson, were generated, using the same mass points for the $W'$ as for the Higgs. For the following studies, the samples described above are used. In order to see if any of the angular observables can be used to distinguish a hypothetically observed Higgs from other exotic particles, samples with $W'$s with the same masses, decaying into $W$ and $Z$ bosons, were produced and studied. The observables studied here have been taken from [26], who studied $H \rightarrow ZZ$ in four-lepton final states.

3.7.1 Decay plane angle

The decay plane angle $\phi$ is defined as the angle between the decay plane of the $W$ boson and that of the $Z$ boson in the Higgs rest frame. [26] also fix the orientation of the angle using the charge of the leptons. That cannot be done here as the jet charge cannot be measured accurately. Hence, $\phi$ was always chosen from the interval $[0, \pi)$. According to [26], the decay plane angle is distributed according to

$$F(\phi) = 1 + \alpha \cdot \cos(\phi) + \beta \cdot \cos(2\phi). \tag{3.4}$$

For the case of $W'$, they calculate $\alpha \approx 0.017$ and $\beta = 0$. For the Higgs, $\alpha$ and $\beta$ depend on the Higgs mass. They are both positive and tend to 0 for larger Higgs masses. The measured decay plane angle distributions are plotted in fig. 3.10 for the Higgs and in fig. 3.11 for the $W'$, both on parton level and after the detector simulation. Due to the low statistics, it is almost impossible to make any definite statement about the distributions. It seems that the detector simulation noticeably changes their shapes. No further analysis was attempted for the Higgs case. The distributions for the $W'$ case were fitted according to eq. 3.4. The results have been plotted in fig. 3.12. It can be seen that they do not correspond to the expected values. The reason for that is unclear. It might point to an inconsistency in the configuration/use of MadGraph.
Figure 3.10: Decay plane angle for $m_H = 180, 200, 250, 300, 400, 500$ GeV (left to right, top to bottom). Thick lines: truth distribution, parton level (pythia). Thin lines: after pgs simulation.
Figure 3.11: Decay plane angle for $m_{W'} = 180, 200, 250, 300, 400, 500$ GeV (left to right, top to bottom). Thick lines: truth distribution, parton level (pythia). Thin lines: after pgs simulation.
Figure 3.12: $\alpha$ and $\beta$ parameters plotted against $m_{W'}$. (Left: truth distribution, parton level (pythia). Right: after pgs simulation.)
3.7.2 Angle between Z boson and muon

The angle $\theta$ is defined as the angle between the $Z$ boson (in the Higgs rest frame) and the $\mu^-$ in the $Z$ rest frame. The authors of [26] parametrise its distribution as

$$ G(\theta) = T \cdot (1 + \cos^2(\theta)) + L \cdot (\sin^2(\theta)). \quad (3.5) $$

Since the overall normalization is not important for this study, one defines the ratio

$$ R := \frac{L - T}{L + T}. \quad (3.6) $$

According to [26], $R = \frac{1}{3}$ for the $W'$ case. For the Higgs case, $R$ grows with $m_H$ and tends to 1 for large Higgs masses.

One can define a corresponding angle on the $W$ side as well. However, it is not possible to measure the charge of the jets well enough to discriminate between quark and anti-quark, so one would have to use the absolute value of the angle. Also, we expect a higher energy uncertainty on the $W$ side. Hence, only the $Z$ side was studied here.

In fig. 3.13, the $\cos(\theta)$ distribution for the Higgs case is plotted for different Higgs masses. Again we suffer from low statistics, but the shape looks more stable w.r.t. smearing than was the case for the $\phi$ distribution. Fits corresponding to eq. 3.5 were performed and the ratio $R$ was calculated for each Higgs mass. The resulting values of $R$ are plotted in fig. 3.15. The values on parton level are consistent with the ones after the detector simulation. $R$ is quite low (ca. 0.3) for low higgs masses and compatible with 1 for larger Higgs masses.

In fig. 3.14, the $\cos(\theta)$ distribution for the $W'$ case is plotted for different Higgs masses. Fits corresponding to eq. 3.5 were performed and the ratio $R$ was calculated for each $W'$ mass. The resulting values of $R$ are plotted in fig. 3.16. The values on parton level are similar to the ones after the detector simulation. For $m_{W'} = 200$ GeV there are larger deviations. For both cases, the overall shape does not confirm to the expectations. The shape is not flat, but definitely rising (at least for low $W'$ masses). In addition, the ratio tends to roughly .8 for large Higgs masses, not $\frac{1}{3}$ as predicted.

Lacking time for further studies, it was not possible to draw a final conclusion from these studies of two angular observables. In particular, the simulation of the spin correlations using MadGraph have to remain unverified. It is possible that they are not simulated correctly, or that MadGraph was not configured properly. Alternatively, the angular distributions might be different for the charged Higgs w.r.t. the neutral Higgs studied by [26], necessitating further studies and eventual measurements to verify the validity of this model. However, it is doubtful that a measurement of the spin correlations will even be possible in the near future as a large amount of observed events will be needed.
Figure 3.13: $\cos(\theta)$ distribution for $m_H = 180, 200, 250, 300, 400, 500$ GeV (left to right, top to bottom). Thick lines: truth distribution, parton level (pythia). Thin lines: after pgs simulation.
Figure 3.14: $\cos(\theta)$ distribution for $m_{W'}=180, 200, 250, 300, 400, 500$ GeV (left to right, top to bottom). Thick lines: truth distribution, parton level (pythia). Thin lines: after pgs simulation.
Figure 3.15: $R$ parameter plotted against $m_H$. (Top: truth distribution, parton level (pythia). Bottom: after pgs simulation.)
Figure 3.16: $R$ parameter plotted against $m_W$. (Top: truth distribution, parton level (pythia). Bottom: after pgs simulation.)
Chapter 4

Conclusion

In this work, a theoretical model has been introduced that predicts the existence of a charged Higgs boson which couples to the Standard Model $W$ and $Z$ bosons. The $HWZ$ vertex was added to the MadGraph event generator to enable the simulation of charged Higgs production and decays. The phenomenology of the charged Higgs in this model has been explored, in particular with a view towards a search at the Large Hadron Collider at CERN. Here, the role of the $HWZ$ vertex was examined both in the production and the decay of the charged Higgs.

The absolute production cross sections for the charged Higgs have been calculated for seven different Higgs masses, up to a model-dependent scale factor. The numbers show that one can expect to see the $H^\pm \rightarrow W^\pm Z$ decay at the LHC, if indeed a triplet model with a charged Higgs of a convenient mass is realized in nature. Preselection cuts to select such decays where the $Z$ decays into muons and $W$ decays hadronically.

The reconstruction of the Higgs mass and two methods to improve the mass reconstruction have been studied. It has been shown that in particular the dijet mass subtraction method is able to improve the mass reconstruction. Mass reconstruction in the trilepton channel (where both $W$ and $Z$ decay leptonically) has also been studied briefly.

Once the first signs of a charged Higgs have been seen, one would need to study its properties to ensure that the hypothetical particle is indeed a charged Higgs and not a different hypothetical particle like a heavy vector boson. Several angular distributions of the decay products of the Higgs boson have been studied and compared to the distributions seen in $W' \rightarrow WZ$ decays in the same final state. No final conclusions could be drawn here, possibly due to the problems with the simulation process.

In conclusion, it seems that the $lljj$ final states offer a good opportunity to search for $H^\pm \rightarrow W^\pm Z$ at the LHC, and to reconstruct the mass of the charged Higgs boson if signs of it are indeed found. However, more detailed studies with a realistic detector simulation, simulation of pile-up effects (several proton-proton interactions per bunch crossing), and studies of common backgrounds are needed before one can start a search for a charged Higgs in this channel.
Bibliography


