The ATLAS discovery potential of hadronic $Z'$-Strahlung decays

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Abstract

One of the primary goals of the LHC is either detecting or excluding the Higgs particle. Although several alternative models exist, phenomenological implications have not been studied in depth. In the master’s thesis of Merlin Kole [1] the phenomenology of a fermiofobic $Z'$-model is studied. In this thesis the phenomenology of the model is further investigated to see whether the $Z'$ could be detected in the ATLAS detector at the LHC.

Focus is on the $Z'$-strahlung production process with the fully hadronic decay. A heavy $W$-boson radiates a $Z'$-boson, which decays into two $W$-bosons. All three $W$-bosons decay into quarks. Two reconstruction methods are used. In the first method pairs of two merged jets are matched to the $W$-bosons by requiring that the jet-constituents have an invariant mass around 80 GeV. In the second method two merged jets should result in the $W$-mass and four merged jets should result in the hypothetical $Z'$ mass.

Four different jet reconstruction algorithms and two different jet-substructure algorithms are evaluated. Using a jet-substructure analysis as Y-spliting or pruning can significantly improve the quality of the signal and reduce the background. The optimal combination of algorithms for this purpose is the C/A-algorithm in combination with pruning.

A full analysis of the $Z'$-signal and background samples of QCD di-jet events, $t\bar{t}$ events and events with two $W$-bosons is performed on Pythia 8 Monte Carlo data. The reconstruction of both signal and background is analyzed for two different reconstruction methods, two levels of luminosity ($10^{33}$ and $10^{34}$ $cm^{-2}s^{-1}$) and three different $Z'$-boson masses (300, 500 and 900 GeV).

Dedicated detector simulation software is developed in order to apply a variety of jet-reconstruction algorithms. The simulation is validated against the official Atlfast simulation package. The analysis of high-luminosity events ($10^{34}$ $cm^{-2}s^{-1}$) is repeated and compared with data on which no detector simulation is applied.
Acknowledgements

Blaise Pascal once wrote: “I would have written a shorter letter, but I did not have the time”. It may be obvious that the same excuse cannot be used for the length of this thesis. In the past one and a half year a lot has happened and I need to thank a lot of people for it. The first person who was the most involved in the realization of this thesis is Bob van Eijk. I need to thank him for the untiring reading he performed throughout the last year and the many help he offered during the process. Besides of his help in this thesis I would also like to thank him for creating the possibility for students from Twente to follow the particle physics track in Amsterdam and his support in getting me in the CERN summerschool. For the latter two subjects, the Nikhef institute and especially Els de Wolf also earn a lot of credits. I would like to thank the graduation committee for their willingness to perform this thankless task. It is definitely not a sinecure to read all the 119 pages of this thesis. My colleague students at Nikhef have been a great help, especially the many coffees and lunches I enjoyed with the people from the masterkamer were a nice variety to all the C++ code throughout the day. As it comes to the latter, Lars Beemster has been a neccessary assistant in programming and computer problems and helped me in endless occasions in which I really thought there was no solution. Merlin Kole was during the first year a great help in explaining me the physical details of everything around fermiofobic Z'-bosons, fermion delocalisation and vector-boson physics. It may be surprising that apart from writing a particle physics thesis I also have a life in which a lot of people facilitate the conditions that make it possible for me to spend more than a year on writing this thesis. I have lived for more than a year at my parents’ place now and for the most of this period they took care of all my dinner’s, cleaning the house, a lot of coffee and wine and this without requiring anything in return. The same goes for all the weeks I spent at the student’s house of my girlfriend. Special gratitude goes to her, for cheering me up at times I was fed up or completely bored from writing my thesis or perfectioning histograms. My friends at Mores who kept reminding me life should be a combination of remembering on the one hand that everything is “kødt !!!” and on the other hand that “het wel leuk moet blijven, voor ons!”. Of course a special word of thankfulness should go to all those people who keep reminding me that society will never benefit from either a Higgs or a Z’ discovery. It makes you putting things in the right perspective. “... let me give you some further advice: be careful, for writing books is endless, and much study wears you out.” Ecclesiastes 12:12
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Chapter 1

Introduction

The objective of this thesis is to explain whether or not the Z’ can be detected by the ATLAS detector at the LHC. In the first chapter an introduction into the Standard Model will be given. Theoretical techniques applied in Monte Carlo simulations of particle collisions at hadron colliders are discussed. Currently, the Higgs mechanism is the most widely accepted model to break symmetry. The Higgs mechanism is briefly explained. Experimental constraints on the Higgs mass are presented. The last section of this chapter focuses on the subject particle of this thesis: the Z’.

In the second chapter of this thesis, a description of the LHC and ATLAS are presented. At the end of the chapter a manual detector simulation that simulates jet detection is described and compared to the official Atlfast simulation package. The advantage of this manual package is the wider variety of jet reconstruction algorithms that can be used.

The objective of the third chapter is to give an overview of the available jet reconstruction algorithms and of how well each algorithm performs at reconstructing the Z’-Strahlung process.

In the fourth chapter Monte Carlo data is used to investigate the topology of Z’-Strahlung for three different Z’-masses. Two different reconstruction methods are investigated. The high luminosity case is studied. The $t\bar{t}$, QCD di-jet and the double W-boson backgrounds are used to model the background.

The fifth chapter discusses the difference between signal and background before and after the detector simulation.

Finally, results are summarized and conclusions are drawn. Recommendations for future studies are provided.

1.1 Standard Model

The Standard Model (SM) is the framework in which all discovered elementary particles are categorized. A remarkable aspect of the model is its predictive power. Since the papers of Weinberg, Glashow and Salam [2], [3], [4] several particle colliders in the USA, Europe and Japan collected data that confirm the theory. Although the model seems to predict all physics occurring at an energy scale up to the TeV scale, it is also commonly accepted that complementary models or Beyond the Standard Model (BSM) theories should be apparent at higher energies. A strong goal in physics is to prove that the electromagnetic, the weak and the strong force are manifestations of the same fundamental principle. How this unification should be modelled is still under investigation. The Standard Model can be visualised quite easily by putting the particles in diagrams and posing reasonably simple rules through which the particles are allowed to interact. The model has twenty-five free parameters of which most are already measured with high precision. There are still multiple
paramaters that have not been measured or need to be measured with higher precision, one of them being the Higgs mass. Below a short introduction into the Standard Codel will be given. A more detailed description, including the mathematics can be found in various textbooks [5], [6].

1.1.1 Particles & Interactions

In the Standard Model there are two categories of particles, of which one is again divided in two sub categories. There are fermions and bosons, the former are the building blocks of matter while the latter are responsible for the interactions between fermions. There are two “families” of elementary fermions, quarks and leptons. Quarks come in pairs, one with charge $-\frac{1}{3}$ and one with charge $\frac{2}{3}$. Both the particles have color, the property that defines whether a particle can interact through the strong force. Leptons come in pairs too, one particle has charge -1 and the other does not carry charge. The latter are called neutrinos and are of special interest because these particles only interact through the weak force and are therefore very difficult to detect. In both families there are three generations that consist of two elementary particles. The only difference between the particles in different generations is the mass. The properties of the quarks and leptons are summarized in tables 1.1 and 1.2 [7]. Except for the particles shown, there are also anti-particles. Anti-particles have exactly the same mass as there counterpart, but all quantum numbers are opposite to their original. Additionally, quarks come in three colors. In principle the three different colored quarks can be seen as three different particles.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Mass [MeV]</th>
<th>Charge</th>
<th>Lepton number</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Electron</td>
<td>0.511</td>
<td>-1</td>
<td>$L_e = 1$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>Electron neutrino</td>
<td>$\sim 0$</td>
<td>0</td>
<td>$L_e = 1$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Muon</td>
<td>105.658</td>
<td>-1</td>
<td>$L_\mu = 1$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>Muon neutrino</td>
<td>$\sim 0$</td>
<td>0</td>
<td>$L_\mu = 1$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Tau</td>
<td>1777</td>
<td>-1</td>
<td>$L_\tau = 1$</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>Tau neutrino</td>
<td>$\sim 0$</td>
<td>0</td>
<td>$L_\tau = 1$</td>
</tr>
</tbody>
</table>

Table 1.1: Standard Model properties of the three lepton generations.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Flavour</th>
<th>Mass [GeV]</th>
<th>Charge</th>
<th>Isospin</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>down</td>
<td>0.005-0.015</td>
<td>-1/3</td>
<td>$I_z = -1/2$</td>
</tr>
<tr>
<td>u</td>
<td>up</td>
<td>0.002-0.008</td>
<td>+2/3</td>
<td>$I_z = 1/2$</td>
</tr>
<tr>
<td>s</td>
<td>strange</td>
<td>0.1-0.3</td>
<td>-1/3</td>
<td>$S = -1$</td>
</tr>
<tr>
<td>c</td>
<td>charm</td>
<td>1.0-1.6</td>
<td>+2/3</td>
<td>$C = 1$</td>
</tr>
<tr>
<td>b</td>
<td>bottom</td>
<td>4.1-4.5</td>
<td>-1/3</td>
<td>$B = -1$</td>
</tr>
<tr>
<td>t</td>
<td>top</td>
<td>175</td>
<td>+2/3</td>
<td>$T = 1$</td>
</tr>
</tbody>
</table>

Table 1.2: Standard Model properties of the three quark generations.

All interactions between particles occur through the exchange of bosons. The forces that is exchanged by gluons is called the strong force. $W$- and $Z$-bosons couple to left handed helicity states, this force is called the weak force. The photon is the carrier of the electromagnetic force and couples to charge. An overview of these particles is given in table 1.3. Gluons are the bosons that carry the strong force and couple to color. Color is responsible for the
bonding between nuclei. Instead of having a scalar value as the electromagnetic charge, color has three parameters: red, green, and blueness. The fermions with color are the quarks. However, gluons have color themselves and Feynman diagrams with gluon three-point or four-point interactions also exist. An important breakthrough in particle physics was the theory of quark-confinement, which states that all stable particles should be color-neutral. To form a stable composite particle, a colored particle should always be bound with either a particle carrying its anti-color or with two particles that each carry a different color. For example, a blue particle could be bound with an anti-blue particle or together with a green and a red particle. These composite particles are called hadrons. If it consists of three quarks, it is a baryon, if it consists of two quarks it is a meson. The moment a quark is produced it will always directly go through a hadronization process as colored particles are extremely short-living. Gluons can only exist as virtual particles, a somewhat abstract concept that means that the particle only acts as mediator but however does not come to exist itself, or exists for an extremely short time.

The weak interactions were already studied at the beginning of the time when quantum mechanics was developed. Especially Enrico Fermi became famous for his pioneering work in the field of weak interactions. An important discovery however was done by C.S. Wu and L. Lederman when they performed experiments with polarized atoms in a magnetic field. Their discovery was that the electrons were far more often emitted in the opposite direction to the spin of the atoms than in the parallel direction. The conclusion of these experiments is that electrons emitted from beta-decay are left-handed. The distinction of nature between left and right was something that was far from expected as it was always assumed that nature is locally completely symmetric in reflections. From the conclusions of these experiments the theory of weak interactions was built. Whereas electromagnetism depends on charge, gravity on mass and gluons on color, the weak force is the force between left-handed particles. The particles that carry the force are the $W^\pm$ and Z bosons. “Handedness” is called helicity in physics and is defined as the projection of the spin of a particle on its momentum. The term “left-handed” is used to indicate the sign of the projection and is shown in figure 1.1.

![Figure 1.1: The difference between left-handed particles and right-handed particles. The helicity is the projection of the spin on the momentum of a particle.](image)

The Large Electron-Positron collider (LEP) was an important collider for precision measurements of the (electro-)weak force. The resonance peak of the Z-boson was measured very precisely. When a positron and an electron annihilate at an energy close to Z-mass the chances of producing a Z-boson are very high. The Z-boson then again decays to a new fermion pair of a particle and its anti-particle. With these measurements the branching ratio of the Z was measured and with that measurement the existence of a fourth generation was as good as excluded. The resonance peak of a W-boson is more difficult to produce with an electron-positron collider since the W-bosons are charged and an electron-positron pair is neutral. The physics of W-bosons are therefore to be measured more precise at the modern hadron colliders; the Tevatron and the LHC. W-boson studies are important for the field that is called CP-violation, but W-boson scattering is also one of the
reasons for the introduction of the electroweak spontaneous symmetry breaking, or what is better known as the Higgs-mechanism. As a last remark on the weak force it is interesting to consider the neutrino. Since it has no charge and no color, it can only couple through the weak interaction. Its anti-particle is just as interesting, as it cannot couple at all. One of the open discussions in particle physics is whether the anti-neutrino exists at all and as a parallel discussion, whether the neutrino might be its own anti-particle.

The electromagnetic force is the best imaginable of the three forces that are studied in experimental particle physics. It is significant both at the large size of stars and planets and at the small scale of quarks and leptons. The boson that carries the EM force is the photon, which is a massless particle and it is the only fundamental boson that is abundantly available in nature as a long-living particle. The formulation of Quantum Electro Dynamics (QED) was a breakthrough for Quantum Field Theory (QFT) and a Nobel Prize was granted to Feynman, Schwinger and Tomonaga for their contribution. It was also the first field in which the Feynman-formalism was applied, a formalism that is still at the basis of describing particle physics. The photon couples to everything that has charge.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Mass [GeV]</th>
<th>Charge</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>gluon</td>
<td>0</td>
<td>0</td>
<td>Strong</td>
</tr>
<tr>
<td>W±</td>
<td>W-boson</td>
<td>80.45</td>
<td>±1</td>
<td>Weak</td>
</tr>
<tr>
<td>Z</td>
<td>Z-boson</td>
<td>91.2</td>
<td>0</td>
<td>Weak</td>
</tr>
<tr>
<td>γ</td>
<td>photon</td>
<td>0</td>
<td>0</td>
<td>Electromagnetic</td>
</tr>
</tbody>
</table>

Table 1.3: The bosons: force carriers in the Standard Model.

There is a fourth force that is very well measurable at the large scales of our universe, but difficult to put into a model and to measure at the small scale of particle colliders. This is the gravitational force. One of the things that can be deduced is that the force carrier should have zero mass, since the graviton has the ability of carrying long distance forces. A problem however is that zero mass particles should also be easy to produce. But until now the search for the graviton has not been successful. The unification of the descriptions of the gravitational force at the largest scale (general relativity) and on the smallest scale (quantum mechanics) has been proven to be very difficult and an explanation is beyond the scope of this thesis.

1.2 Theoretical description of particle collisions

The Standard Model describes the interactions between elementary particles. An important implication of the model is that these interactions can be described through “tree-level” diagrams. These are diagrams of which the cross sections can in principle be calculated analytically. Tree-level diagrams form typically the hardest interaction that occur in a collider event. In an experimental environment, especially at hadron colliders, there are many other processes that are of importance. The following topics will be discussed in this chapter:

- Perturbation theory.
- The compositeness of a proton (Proton Distribution Functions or PDFs).
- Higher order corrections (Initial and Final State Radiation).
• The hadronization of high energetic quarks and gluons into jets.
• Beam remnants and multiple parton-parton interaction.
• Pile-up effects at high luminosity.
• Simulating particle collisions with Pythia 8.

1.2.1 Perturbation Theory

The formalism through which interactions in particle physics are calculated is based on perturbation theory. This is a mathematical theory that is used to expand integrals into an infinite series of integrals that are each of a simpler form. Perturbation theory is only useful if the series it produces is strongly convergent. If such a series is convergent it has the property the first few terms are much more important than the higher order terms. For the electromagnetic and weak interactions the theory has been highly successful. Table 1.4 shows the order of magnitude of the coupling constant of each force. That the electromagnetic coupling constant is about 1/137 means that at every higher order, an additional factor 1/137 enters the calculation. The small coupling constant has the result that every second order term only contributes in the order of 1% to the final cross section and every third order term only contributes less than 0.01%.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Force</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_s$</td>
<td>strong</td>
<td>1</td>
</tr>
<tr>
<td>$\alpha_w$</td>
<td>weak</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$\alpha_{EM}$</td>
<td>Electromagnetic</td>
<td>$\frac{1}{137}$</td>
</tr>
</tbody>
</table>

Table 1.4: The running coupling energies at low scale.

A major problem in the formulation of the theory of strong interactions was the fact that the coupling constant is very close to one and perturbation techniques break down. A solution that was offered was quark confinement. One of the aspects of quark confinement is the idea of running coupling constants. The strength of each force depends on the energy scale at which it is manifested. The strong force cannot be calculated at low energies. Perturbationion theory breaks down because of the high coupling constant. At higher energies the strong coupling constant is much smaller again and from a certain scale, perturbation theory can be used again. For the weak and electromagnetic theories something different was discovered, the forces became more and more similar in interactions that were studied at higher energies. A theoretical confirmation of the suspicion that the two forces could indeed be manifestations of the same gauge group that was provided by Weinberg, Glashow and Salam [2], [3], [4]. The mathematical principle behind the electroweak theory is that the behaviour of the four relevant bosons is completely symmetric. One of the implications of the GWS-theory is that at the scale of a Grand Unification Theory (GUT) the running coupling constants should become equal as is shown in figure 1.2.

Feynman diagrams

One of the many contributions of Richard Feynman to physics is the visualization of interactions through diagrams. “Feynman diagrams” are a very convenient way of visualizing the mathematical formalism of perturbation theory that is explained above. Below, a few of the most basic strong, weak and electromagnetic interactions are displayed.
Figure 1.2: The colored lines show the running of the coupling constants and the point at which they should coincide.

(a) A strong interaction (b) A electromagnetic interaction (c) A weak interaction

Figure 1.3: The lowest order Feynman diagrams for the strong, electromagnetic and strong interactions.

These diagrams are characterised by two incoming fermions, an intermediate boson, and two outgoing quarks. Each of these lines represents a “propagator” and there are two vertices. Using these ingredients, Feynman diagrams can be transformed into a mathematical equation to calculate their “matrix element”. The matrix element represents the physical parameter of the cross section of the process. The cross section again represents the chance that a certain process occurs in nature. The first diagram represents quark scattering through a gluon in the s-channel. The other two diagrams represent fermion scattering through a photon and a Z-boson in the s-channel. A difference between the Z-boson and the photon is that neutrinos can interact through a Z-boson whereas this is not the case for a photon as neutrinos do not have charge.

The parts of a Feynman diagram that can actually be observed in an experiment are the incoming and outgoing particles. If one wants to determine the cross section of quark scattering, one should calculate the matrix elements of all above diagrams and also of all other diagrams in which there are two incoming quarks and two outgoing quarks. Two of those missing diagrams are for example the t-channels of figures 1.3 (b) and (c). A t-channel diagram is a diagram where the bosons are not represented by a horizontal line, but by a vertical line. Other diagrams are of a higher order and it is not necessary to calculate these. However, in the regime where $\alpha_s$ is close to one, higher order diagrams and loop diagrams should also be calculated to get a useful cross section.
1.2.2 Parton Density Functions

The reason that proton-proton collisions are more difficult to predict than electron-positron collision is that a proton is a composite particle. Which partons will interact cannot à priori be predicted. Fortunately the structure of the proton has been investigated by experiments in the HERA collider at DESY and in the Stanford Linear Accelerator. Because of these studies the distributions of valence quarks and sea-quarks and -gluons in the proton at different energies are well-understood. A PDF gives the density of a certain quark or of a gluon as a function of x and Q. x is here the fraction of the total proton energy and Q is the momentum transfer. A central formula in the computation of cross sections in proton-proton collisions is the following:

$$d\sigma(p(P_1) + p(P_2) \rightarrow Y + X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i_1,i_2} f_{i_1}(x_1) f_{i_2}(x_2) d\sigma(i_1(P_1) + i_2(P_2) \rightarrow Y) \quad (1.1)$$

The left hand side of equation 1.1 is the differential cross section of two colliding protons with momenta $P_1$ and $P_2$ ending up in a certain state $Y$ and all rest products $X$. The rehadronized beam remnants of the spectator quarks are included in $X$. The right hand side of the equation tells how this cross section can be computed. $f_{i_1}(x_1)$ is the parton distribution function of particle $i_1$ that can be a gluon or any quark and carries the fraction $x_1$ of the proton energy. The cross section can then be calculated as if the incoming beams were just these particles $i_1$ with momentum $x_1 P_1$ and be multiplied by the value of the PDFs. The inclusive cross section can be obtained by summing over all possible initial particles and integrating over the $x$ of both PDFs. To use this model the assumption must be done that the quarks in the proton act as free particles. This assumption is correct as long as the time scale of the interaction of the two incoming partons is much smaller than the time scale of the interactions between partons in the same proton. The conditions that are needed to fulfill this requirement are that the proton must have enough energy and the partons are under influence of time dilatation. And the second condition is that the time scale for the interaction is small and therefore the momentum transfer should be large.

Experimental difficulties are that in the center of mass frame of the protons the partons are not at rest. The center of mass frame of the partons has a velocity in respect of the mass frame of the protons. The latter coincides with the lab frame, as where the velocity in respect of the former is $\beta = \frac{x_1 - x_2}{x_1 + x_2}$. One of the consequence is that in the lab-frame the total $p_z$ is not zero and the missing energy can only be meaningfully be measured in the $x$ and $y$ directions. In measurements of processes with hard neutrinos in their final state this is an extra difficulty. The energy involved in the hard scattering is always smaller than the total centre of mass proton energy by a factor of $x_1 x_2$.

The PDFs for relatively small Q have been measured by electron-proton collisions in the sixties and seventies of the last century. The momentum transfer at the LHC will be orders of magnitude larger and therefore it is important to know the PDF as a function of Q. To calculate an explicit function is not possible, though two integro-differential equation, known as the Altarelli-Parisi equations are available. The first gives a relation for the quark densities and the second for the gluon densities.

$$\frac{df_q(x,Q^2)}{d\log(Q^2)} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} \left( f_q(y,Q^2)P_{qq} \left( \frac{x}{y} \right) + f_g(y,Q^2)P_{qg} \left( \frac{x}{y} \right) \right) \quad (1.2)$$

$$\frac{df_g(x,Q^2)}{d\log(Q^2)} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} \left( f_q(y,Q^2)P_{gq} \left( \frac{x}{y} \right) + f_g(y,Q^2)P_{gg} \left( \frac{x}{y} \right) \right) \quad (1.3)$$

Equations 1.2 and 1.3 give an implicit relation between the quark and gluon densities and the scale of the momentum transfer Q. The input to this equation are the fundamental interactions a gluon
and a quark can be part of. It can be said that the equation gives the probability that a scattered quark \( q_i \) with momentum fraction \( x \) originally was a quark with momentum fraction \( y \), but just before emitted a gluon with momentum fraction \( (y-x) \). Another possibility is that the scattered quark was created by gluon annihilation. All possibilities are described in figure 1.4. The splitting functions are calculated and given by equations 1.4, 1.5, 1.6 and 1.7. These functions represent the chance that a quark emits a gluon with a energy fraction \( z \) or a gluon annihilates in either two quarks or two gluons.

\[
P_{qq}(z) = \frac{1}{2} \left( z^2 + (1-z)^2 \right) \tag{1.4}
\]

\[
P_{gg}(z) = 6 \left( \frac{1-z}{z} + \frac{z}{1-z} + z(1-z) \right) \tag{1.5}
\]

\[
P_{qg}(z) = \frac{4}{3} \left( 1 - z \right)^2 \tag{1.6}
\]

\[
P_{qq}(z) = P_{qg}(1-z) \tag{1.7}
\]

\[
P_{qqg}(z) = \frac{2}{3} \left( 1 - z \right)^2 \tag{1.8}
\]

All the necessary ingredients to calculate the distribution functions for the quarks and gluons are available. The calculation of one proton-proton collision would however be an immense task to perform. Therefore there are theoretical groups that focus on the calculation on these functions together with experimental verification. The results of these calculations are coded as plug-in software that again is used by event generators. Two examples of PDFs at \( Q^2 = 10 \) and \( Q^2 = 10^4 \) are shown in figure 1.5, these PDFs were calculated in [8]. At low momentum transfer the influence of the valence quarks is still dominant in the higher x-regions. The difference between sea-quarks and valence quarks is hardly observable at \( Q^2 = 10^4 \). Another important difference between PDFs at low and high \( Q^2 \) is the influence of gluons in the low x-region. At higher momentum transfer, the gluon density increases. In the right graph in figure 1.5 the gluon density is even displayed as 10 % of the real density. The densities are also higher for the other particles at all \( x < 0.1 \). These facts are a big advantage for the cross sections at LHC in comparison to earlier hadron colliders (Tevatron, SppS)

1.2.3 Initial and Final State Radiation

In chapter 1 it was explained that the strength of perturbation theory is that usually only first order diagrams need to be considered to calculate the cross section of a certain process. This is especially the case for the process itself, though for the calculation of what happens to the incoming and
outgoing states it is important to include higher order diagrams. Leptonic initial and final states have a probability of emitting photons as Bremmstrahlung. Naively it can be estimated that the chance of emitting a photon is in the order of $\alpha_{em} \approx \frac{1}{137}$. As we shall see there are soft and collinear divergences that make the total cross section higher. For hadronic initial and final states the coupling constant is even around the order of 0.1 and the emittances of gluons is an effect that cannot be neglected. Except for a color factor and the stronger coupling, QCD diagrams can be calculated in the same way as QED diagrams. Examples of Feynman diagrams that belong to initial and final state radiation are shown in figure 1.6.

As an example the differential cross section of the left part of diagram 1.6 (a) is calculated in Appendix A.1. It is shown that the radiation of a photon or a quark is a generic process and the other diagrams can be deduced from diagram (a). The result of the calculation is the following:

$$\frac{d\sigma{}^{ISR}}{dz} \approx \frac{\alpha}{2\pi} \left[ \frac{1 + x^2}{1 - x} \right] \log \frac{Q}{m_e} dx \quad (1.9)$$

The equation tells the probability that an electron or quark that participates in a hard process already lost a fraction $z$ of its energy due to radiation into photons or gluons. The fact that factorization works is one of the prerequisites for what is called a parton-shower. The latter is how Monte Carlo event generators deal with initial and final state radiation. For every parton in the hard scattering a gluon/photon shower is developed. For ISR the gluon emittances are developed backwards (space-like) and for final state radiation forwards (time-like). This specific order is used because the hard scattering is still the central event but the initial and final states are further developed by using the splitting cross sections. The emitted particles can even split of their own gluons and photons and develop further showers. A method that works on a different basis is to calculate the matrix elements of all possible Next to-Leading Order (NLO) or Next-to-
Next-to-Leading Order (NNLO) diagrams in which these emitted ISR and FSR are included and generate events on basis of the calculated cross sections. The problem is that it is not even always possible to calculate all NLO and NNLO calculations of a certain process or at least they require a large human and computational effort. For the more important processes these calculations are nevertheless performed because parton showering has the disadvantage that for the higher $p_T$ emittances the splitting amplitudes are not properly calculated.

On an experimental level initial and final state radiation have several implications. Naturally, it cannot à priori be determined whether a photon or a jet originates from the hard scattering or from the parton shower. One of the struggles of the physics analysis of jets is that traditional cone-algorithms are sensitive to collinear radiations. Jet reconstruction algorithms will be explained in more detail in chapter 3, however it means that the reconstruction of a jet can be influenced greatly if a single quark emits a gluon collinearly. Another implication is the following. ISR is independent of the centre of mass energy of the hard scattering. If the corresponding particles are detected in the calorimeters, it can influence both the jet energies and the missing energy measurements. Due to ISR, the average jet energy therefore rises. Final state radiation can do the opposite because emitted gluons can escape from the jet surface. The measurement of $e^+e^-\gamma$ final states by CDF gives a clear demonstration of the explained facts 1.7. In the graph the scatter points that are displayed correlate to CDF events with final states $e^+e^-\gamma$. The y-axis gives the invariant mass of final state $e^+e^-\gamma$ and the x-axis the invariant mass of only the $e^+e^-$-pair. For most events the value on both the x-axis and y-axis is around 91 GeV, though there are events that are significantly heavier together with the photon (ISR) and there are events that are significantly lighter without the photon (FSR).

1.2.4 Fragmentation

Perturbation theory cannot be used at low energies in QCD and only colorless particles can be stable. A quark or a gluon produced in the hard scattering or the parton shower must therefore immediately undergo several other interactions to form hadrons and ultimately produce particle jets.
The same goes for other parts in the generation chain in which quarks and gluons are produced, for example in the beam remnants. In the seventies of the last century physicists have been investigating how to model these non-perturbative QCD-processes in the best way. One of the most successful models is the Lund string model \[9\]. In this model the interaction between colored particles were parametrized as strings with a string constant \(\kappa\). The complete model is extensive and has many parametrizations of which most were explained in \[9\]. In this section only the basis of the model is explained.

Because calculations at the level of Feynman diagrams are not useful to describe the formation of a hadron, a completely different approach is used. In theoretical physics there are non-perturbative QCD methods such as lattice QCD with which specific processes can still be calculated at low energy. Though these methods are not yet on a level that fast calculations for the hadronization of many quarks and gluons is possible. In the lund string model some basic assumptions are done. The first is that the QCD potential is linearly rising in \(r\) (the distance) for large \(r\). The potential can therefore be visualised as a string with a string constant \(\kappa\) that is spun between two quarks. The second is the parametrizations of how and when a string breaks into two pieces and two new end-points, a new \(q\bar{q}\) pair. Figure 1.8 shows an illustrative of two quarks evolving into a set of hadrons.

Two quarks generated in the hard scattering process move away from each other with a momentum that is too high to form a bound state. Though they do create a color/gluon field in between them in which more energy is stored as the quarks traverse farther away. When there is enough energy stored in the field to create a new \(q\bar{q}\) pair the string has a certain possibility to break. The quark pair should be produced at one point to preserve local flavour conservation and therefore the energy-momentum cannot be satisfied as there is new mass created and the field is still as strong as just before the creation of the quark pair. To solve this problem the quarks are allowed to tunnel.
with a probability proportional to:

$$\mathcal{P} \sim \exp \left( -\frac{\pi m_{\perp}^2}{\kappa} \right) = \exp \left( -\frac{\pi m_{\perp}^2}{\kappa} \right) \exp \left( -\frac{\pi p_{\perp}^2}{\kappa} \right) \quad (1.10)$$

The string constant has a value $\kappa \approx 1 \text{GeV}/\text{fm} = 0.2 \text{GeV}^2$. At the moment that a string breaks a new string is formed between the two left quarks and a new string is formed between the two right quarks. If the transverse mass of the pairs is still (much) larger than 1 GeV, there will be enough energy left in the strings to create a new quark-antiquark pairs and the procedure will be repeated. In figure 1.8 the final quark-pairs end up in a yo-yo state and are defined as hadrons. In the production of quarks, the probability of creating a specific flavor is $u:d:s:c = 1:1:0.3:10^{-10}$. This is a result from the mass hierarchy of the quarks. The meson that is produced depends on the spin states $L$ and $S$ as these these quantum numbers determine the multiplet from which a meson is picked. Once the meson is established, its parameters such as its mass and life time are obtained from the pdg database. The final step of the generator is the decay of the hadrons, which is not a complex task as the branchings are exactly those from the pdg.

In the procedure above, only mesons can be produced. There is also a formalism included in the model that generates the possibility of baryon production. The first possibility is that instead of a quark-pair production a pair of two quark-pairs are created. The second possibility is that instead of a single break-up of the string, the string breaks up at several pieces and multiple quark-pairs are produced. To model the probability of these phenomena to occur, several new parameters must be included. The complete description of the production “di-quarks” or the “popcorn model” is beyond the scope of this thesis. Also the calculation of how the momentum and energy gets divided at each string break up is not discussed here. The Pythia 6 manual can be recommended for further reading [10].

**1.2.5 Multiple parton interactions**

When two partons collide, the remains of the two protons also become unstable because of they lose their color neutrality. These beam remnants will therefore undergo a hadronization process that produces particles with a $p_T$ that can be high enough to cause activity in the inner detector. This
activity is part of what is usually called the “underlying event”. There is evidence that multiple partons have a role in the hard scattering process of a beam collision. To calculate the exact physics of Multiple Interactions (MI), one would need to use non-perturbative QCD calculations for many bound particles. To measure the effect experimentally is also difficult because the particles that come from MI cannot be separated in the detector from particle that come from ISR or beam remnants. According to T. Sjöstrand [10]: “In fact, in the full event generation process, probably no other area is as poorly understood as this one”. The fact that MI is indeed needed to compensate for a missing part of the underlying event can be seen in figure 1.9. The graph shows data from CDF for two-jet events. The two jets are almost opposite in φ direction and therefore the particles observed in the region transversal to the direction of these jets have a high correlation with the underlying event. The charged particles in the region transversal to the leading jet that are detected by the inner detector are plotted together with three different sets of simulated data by Pythia. There are two sets of data with different tunes, or different parameter settings, and one set of datapoints in which no MI is used at all. The clear observation can be done that the set of datapoints without the MI shows too little activity to model the underlying event properly.

![Figure 1.9: Charged particles in the region “transverse” to the leading jet in two-jet events in CDF together with simulated data for different Pythia tunes.](image)

Pythia models multiple interactions in two basic steps. The first is based on the assumption that the parton-parton interactions are independent and that therefore the amount of interactions can be calculated by using a poisson distribution. The second step is by using a model that accounts for the fact that not every proton collision is exactly head-on but that there is a difference in overlap of the collisions. At the end each parton-parton interaction is provided with its own ISR. The average number of parton-parton interactions is calculated by \( \sigma_{\text{hard}}(p_T,\text{min})/\sigma_{\text{nd}} \), where \( \sigma_{\text{nd}} \) is the elastic, non-diffractive cross section. This can be seen as a good approximation of the cross section that two protons collide. The fraction of hard scattering and elastic scattering is therefore the average amount of parton-parton interactions. Both cross sections can be calculated in perturbative QCD though a problem with the calculation hard scattering is that its cross section diverges for low \( p_T \). A cut-off is therefore done but the exact value is a sensitive and important tune in the model. At low \( p_T \) the amount of interactions in the low x-region of the PDFs rises.
steeply and the low-fraction regions in high $Q^2$-PDFs are not well understood. A justification to use a $p_{\perp \text{min}}$ cut-off is that the transverse wavelength of a gluon with small $p_\perp$ is large and the individual partons cannot be resolved individually. How the mechanism through which gluons do interact at low $p_\perp$ should be calculated in non-perturbative QCD, though here the assumption of a cut-off might be sufficient. The default cut-off in Pythia is:

$$p_{\perp \text{min}}(s) = (2.0 \text{ GeV}) \left( \frac{s}{1 \text{ TeV}} \right)^{0.08}$$  \hspace{1cm} (1.11)

Now in principle all ingredients are available to build a basic MI model. One of the difficulties is still what values for $x_\perp$, the perpendicular component of $x$, should be chosen. In Pythia an algorithm is used that corresponds to the one that is used to choose the splitting values in the parton shower. A difference is that an extra rescaling is done to compensate for the fact that the proton loses a considerable amount of energy after every hard scattering and the total energy used in the parton-parton interactions cannot be more than the total proton energy.

To model the overlap between two protons a parameter $b$ is introduced in the model, the shortest distance measured in the $x$-direction between the two cores. The average amount of parton-parton collisions should be proportional to how much matter has overlapped in the time the two protons crossed paths: $< \tilde{n} > = k\mathcal{O}(b)$. To calculate the overlap $\mathcal{O}$ another assumption is needed for the parton distribution in a proton $\rho(x,y,z)$. In Pythia several definitions for the matter distribution can be used. The overlap as a function of $b$ can be calculated as:

$$\mathcal{O}(b) \propto \int dt \int d^3x \rho(x,y,z)\rho(x+b,y,z+t)$$  \hspace{1cm} (1.12)

Assuming a poisson distribution, the chance of having a collision at a certain overlap is:

$$\mathcal{P}_{\text{int}}(b) = 1 - \exp(-<\tilde{n}>)$  \hspace{1cm} (1.13)

To exclude collisions with no hard scattering at all, $<\tilde{n}>$ should be divided by this probability:

$$<n>(b) = \frac{k\mathcal{O}(b)}{1-\exp(-k\mathcal{O}(b))}$$  \hspace{1cm} (1.14)

$<n>$ integrated over $b$ should be equal to $\sigma_{\text{hard}}/\sigma_{\text{nd}}$.

The provided explanation of how multiple interactions can be modeled is only a very short summary of the complete model that is implemented in Pythia. There were no analytical expressions offered for the cross sections and for example for the matter distribution of a proton. The colour flow has not even been touched and also the details of the computational implementation was not explained. Even though MI is a subject that leaves plenty space for improvement and better tuning, the implementation is nevertheless needed for a realistic simulation of the underlying event.

### 1.2.6 High luminosity

Starting at luminosities around $10^{33} \text{cm}^2\text{s}^{-1}$ the ATLAS Detector parts are not fast enough to separate tracks from different collisions. This is especially the case for the TRT and the calorimeters. The drift times of the freed electrons in these detection mechanisms are significantly larger than the average time that passes between two particles that pass through. Effectively the detector reacts as if it has a permanent offset and therefore jets, electrons and photons will be detected with a higher energy than they actually have. This effect is called pile-up and can be simulated in two ways. The first is to add energy to the detected jets, electrons and photons according to a certain distribution,
depending on the cone/area size of the jets and the luminosity. To do a more realistic simulation, additional particles can be added to the event list. These should correspond to the particles that cause the pile-up in real collisions. The name for this type of event is “minimum bias” and is defined to be the compositity of every type of event that does not cause a trigger. Because the cross section of minimum bias events is much higher than the cross section of a triggered event, the pile-up will always be caused by a certain amount of minimum bias events. How much events are included scales linearly with the luminosity and is calculated by the ATLAS Pile-up Performance group to have a mean of 23 minimum bias events for a luminosity of $10^{34}\text{cm}^2\text{s}^{-1}$. For $10^{33}\text{cm}^2\text{s}^{-1}$ there are about 2.3 pile-up events and so on. The distribution of how many events are added to the record is poissonian. Figure 1.10 shows some characteristics of minimum bias events. On average, the $p_T$ of the particles is low and are widely distributed of the $\eta$-range, though typically there are many particles produced. Because of the particles are distributed over the whole detector, it is not very useful to use cuts to reduce the background.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Pseudorapidity, transverse momentum and multiplicity of particles in minimum bias events (Pythia) after detector simulation.}
\end{figure}

\subsection{1.2.7 Monte Carlo simulation: Pythia [11]}

In the study of Merlin Kole Pythia 8 was used for the generation of $Z'$ particles and their decays. The pre-implemented $Z'$ was stripped of its fermion-interactions to model the fermiofobic $Z'$ and the necessary changes into Pythia were implemented. Pythia 8 is a particle generator written in C++. It calculates matrix elements for the hard interactions and uses a parton shower to calculate the initial and final state radiation. It already inhibits a comprehensive list of processes which it is able to simulate, though it able to use various interfaces to other programs. One popular interface is the Les Houches Accord (LHA) interface, which is able to read or write Les Houches Event Files (LHE). This is used to interface Pythia to comphep/calchep and also to interface Pythia 8 to
1.3 Symmetry breaking: Higgs

There are three forces active at the scale of energy in particle physics experiments. Each force has its own set of gauge bosons through which the force is describable in a completely symmetric way. It is already proven that two of these three forces, the weak and the electromagnetic, can actually be unified in the electroweak force. Currently theories in which the strong force is also incorporated in the unification are still under development. However, during the early development of the Standard Model and the underlying quantum field theory, various problems were already identified. Three important are listed below and explained afterwards:

- The unitarity violation of W-boson scattering
- The masses of the fermions
- The masses of the bosons

1.3.1 W-boson scattering

In processes where weak gauge bosons are scattered the answers to the calculation of the matrix elements get troubling. A common example is W-boson scattering: $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$. In figure 1.11 all possible diagrams for this scattering are drawn.

![Figure 1.11: Lowest order W-boson scattering diagrams.](image)

In the total cross section of the $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$ process there are terms containing the square of the energy and even terms with the energy to the power of four [12]. At a center of mass energy of 1.8 TeV the scattering would violate unitarity. In other words, the chances of the process occurring would get larger than one, which of course is logically impossible. Physicists were at an early stage aware of the fact that some additional sort of physics should exist. A large breakthrough in theoretical physics was the formulation of what is now known as the Higgs-model, where a fundamental scalar particle is added to the Standard Model. Since Higgs couples to everything with mass, two additional diagrams in the W-scattering come into play: fig 1.12

Calculations show that the interference with diagrams 1.12 cancel the second and fourth order energy terms in the diagrams in fig 1.11 up to a higher energy scale.

1.3.2 Masses of particles

The second and third problem can only be explained by using mathematics. The problem is that mass terms of fields, which are formed by the square of a wave function, are not allowed due
to the fact that these terms are not “gauge invariant”. Although the concept of mass is abstract, an idea of how it works can be explained by using an easy, but important, formula:

\[ E^2 = p^2 c^2 + m^2 c^4 \]  

(1.15)

This formula is actually a general form of Einstein’s famous \( E = mc^2 \) formula. It tells that the amount of kinetic energy depends both on the total energy and on the mass of a particle. So the weak gauge bosons will have a smaller speed than the light u and d quarks at the same energy, which is consistent with the classical idea of mass. It can be said that some particles seem to interact very heavily with what is called “the vacuum” and need more total energy to acquire the same kinetic energy as lighter particles. Massless particles seem to move through the vacuum without any problem. But for all particles with a mass it is evident that they do somehow interact with the vacuum and more important, that there is a non-zero vacuum. The idea of a vacuum was however quite difficult to implement in the Standard Model, since the normal quadratic potential which was always assumed does not provide for a non-zero vacuum value. The idea that the natural potential well could contain a fourth order term leads to what is now known as the Higgs particle. With the addition of a scalar particle to the Standard Model the symmetry gets “spontaneously broken”. An illustrative way to explain how the symmetry is broken, can be explained by using the “Mexican hat” potential as in figure 1.13.

Classically, it was always assumed that the potential of nature was purely quadratic and that the vacuum expectation value was at the origin. because the potential of a particle should be on a stable point, a point where the derivatives are zero. A purely quadratic potential can therefore not provide for a non-zero vacuum-expectation value. If a fourth order term is added the “Mexican
The "Mexican hat" potential comes into existence:

\[
\phi = \frac{1}{\sqrt{2}} (\phi_1 + i\phi_2) \\
V(x) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2
\tag{1.16}
\tag{1.17}
\]

The vacuum expectation value, or the position of the minimum of the potential, is shifted to the value

\[
\sqrt{\phi_1^2 + \phi_2^2} = \frac{-\mu^2}{\lambda} = v \tag{1.18}
\]

The reason that the mechanism is called "spontaneous" is that nature is forced away from its initial position to a more stable position. Though what the stable position precisely will be, cannot be determined deterministically. It can be compared to the bending of a needle by pushing it straight down on a table. When pushing hard enough it will bend, though it cannot be told on forehand in what direction the needle will bend. Because the vacuum acquires a non-zero value through spontaneous symmetry breaking, the mass of a particle can again be described in a fully symmetric theory. The question can be asked how the potential can be changed in a physical representative way. The remarkable discovery was done by three physicists in 1964 |13|, |14| that when a scalar particle is added to the lagrangian, the "Mexican hat" potential is created and that after excercizing some mathematics, both the fermions and the weak boson are allowed to be described as massive particles.

1.3.3 Higgs searches

Although theoretical limits on the Higgs mass were already determined in the seventies, the determination of the current limits ss mainly the contribution of experimental methods at the LEP and Tevatron colliders. Since 1964, experimental searches have been performed. After that the SppS did not find a Higgs signal, the LEP collider continued to perform precision measurements up to a centre of mass energies of 209 GeV. With LEP the Z-resonance was measured very precisely by letting electrons and positrons collide in photons, Z-bosons and in the highest energy regime into a WW-diboson pair. The dominant production process of Higgs particles should have been Higgs-Strahlung. A heavy off-shell Z-boson is produced that has enough invariant mass to radiate a Higgs boson. The centre of mass threshold for Higgs-Strahlung is: \(\sqrt{s} = M_Z + M_H\). The highest centre of mass energy reached was about 209 GeV and therefore it was derived with a 95% certainty level that the lower limit of the Higgs mass is 114.4 GeV. The Tevatron collaborations were able to do precision measurements of the W-boson mass. An upper limit of the Higgs mass can be derived from W-mass constraints by using the fast that the W mass is in small extent dependent on the Higgs mass through what are called "loop diagrams". The upper limit that is obtained by using the W-mass is called indirect and is determined to be 186 GeV with a 95% certainty level. On top of the upper limit, the region between 160 and 170 GeV is excluded by the Tevatron collider. The combined limits can be summarised in the next plot: |15|

1.4 Beyond the Standard Model: Z’

The subject of this thesis is the possible detection of an alternative to the Higgs particle. In this section it will be explained how a Z’ can be created through extra dimensions and how the Z’ can be an alternative to the Higgs particle. Kaluza and Klein demonstrated that when an extra dimension was imposed in QFT, a tower of excitations of existing particles can automatically be described.
The line of thought is that if an extra dimension should exist, it must be curled up. Curling can here be visualised as if it were a circle or a sphere and our visible dimensions would then be on the borders of these extra dimensions. One hypothesis says that our Standard Model particles are actually the lowest standing wave modes and that higher order modes could become visible at higher energies. In the Higgsless Z' theory new weak SU(2) groups are imposed. Of each weak gauge boson there are higher excitations that are denominated with one or more primes. Except for the Z, there would also be the Z', Z'', etc. The same goes for the W’s. To examine models that extend beyond the Standard Model on how they fit with the Standard Model, Peskin-Takeuchi parameters are designed. These parameters depend on higher order corrections such as loops. Every new BSM theory has its influence on these parameters. To examine the viability of such a new theory the parameters should be unchanged in the region where they are well-measured, though in the higher energy regions new theories have more freedom to deviate from default values of these parameters. By using the Peskin-Takeuchi parameters, Z' and W' bosons with strong couplings to fermions have already been excluded. In the higgsless sector of Z' theories, a fermiofobic Z' is theoretically well realisable through a theory that is called fermion delocalisation. [16]

The problems that are existent in the absence of a Higgs can also be solved by an extra Z resonance. This Z' has the same couplings as the Z, although its couplings to fermions is negligible. Diagram 1.15 shows how the Z' fits in the Standard Model, it is created by Merlin Kole ?? and it also provides a good summary of the Standard Model couplings.

The divergence of the vector boson scattering is solved in the same way as it is solved for the Higgs boson, by the creation of two extra diagrams. Instead of a H, a Z' can be written in figure 1.12. It can be showed that scattering stays unitary up to a certain scale by these diagrams. The
scale up to which the diagrams are still unitary depends on the Z' mass, though extra Z'', Z''' etc. particles have the potential to keep the scattering unitary up to infinity. A comprehensive explanation is offered in [17]. The problem of the fact that mass terms are not gauge invariant in the Standard Model without Higgs, can be solved by imposing specific boundary conditions on the parameters of the extra dimensions. Symmetry breaking in Higgsless models is a theoretical subject that is covered in the paper [16] and will not be explained in this thesis.

The interesting topics to cover before elaborating how to discover a Z' particle are the results from phenomenological studies. Birkedal, Matchev and Perelstein [18] were the first to do a study on the feasibility of a discovery of the Z' and W' at the LHC and the ILC. They also included a discrimination study in which they pointed at the fact that with W' bosons a new scattering channel in the $WZ \rightarrow WZ$ would be present and therefore a new resonance that would not be available in the Higgs-scenario should appear. Merlin Kole [1] studied the phenomenology of the Z' boson in more detail in his thesis. Using sum rules he was able to formulate a relation between the mass of the Z' and the coupling between the Z' and the W-bosons. One important result is the relation between the Mass of the Z' and its coupling to the W-boson:

$$\frac{1}{3} \frac{M_Z^2}{M_{Z'}^2} = \frac{g_{WWZ}^2}{g_{WWZ'}^2}$$

(1.19)
In the paper [17] it was recognized that the fraction $\frac{g_{WWZ}^2}{g_{WWZ}^2}$ should be smaller than 0.03 because of experimental constraints. The fraction of the couplings should also not be much smaller than 0.03 because otherwise the unitarity violation would occur at too low energies. These constraints force the mass of the $Z'$ to be between approximately 300 and 900 GeV.

As it was mentioned earlier that the $Z'$ interacts just like a heavy Z, except for the fact that it does not couple to fermions. The only vertex that is strong enough to participate in the production is the $Z'WW$ vertex and there are therefore only two production processes. One where a $Z'$ is radiated from a $W$ and one where two $W$-bosons fuse into a $Z'$ boson. The former has a larger cross section and has three $W$'s in its final state. “Z'-Strahlung” is therefore a promising channel to study at an detector. Though the cross section of vector boson fusion is smaller, its signature is promising because it has two forward jets and two $W$'s in its final state. The choice is made to restrict the analysis in this thesis to the Strahlung process.

An inevitable comparison is the one between the Higgs and a $Z'$. Two discriminating variables could be the cross section and the $p_T$ of the two bosons. The cross section of creating a $Z'$ with a mass of 300, 500 and 900 GeV is shown in figure 1.16 together with the cross section of creating a Higgs boson through the same process (Higgs-Strahlung). It is remarkable to see that the cross section of Z'-Strahlung is a factor of one hundred larger than that of Higgs-Strahlung. On the right side of figure 1.17 the $p_T$ distribution is shown for the three mass values of 300, 500 and 900 GeV for both the Higgs and the Z'-boson. This figure shows that for all masses the $Z'$ $p_T$ is significant larger than that of a Higgs boson with a similar mass. This can be useful when kinematical cuts are applied to isolate the $Z'$ and it can also be useful to determine whether a newly discovered resonance is more likely to be a Higgs- or Z'-boson.

![Figure 1.16](image)

Figure 1.16: *A comparison of the absolute cross section of the Z'-Strahlung (circles) and the Higgs-Strahlung (squares) processes. The fact that Z'-Strahlung has an absolute cross section that is about a hundred times larger, is a promising prospect for its discovery.*
Figure 1.17: The $p_T$ distribution of the Higgs (left) and $Z'$ (right) bosons as a function of their mass. In green $M = 300$ GeV, in red $M = 500$ GeV and in blue, $M = 900$ GeV. Both the average $p_T$ and the cross section of the $Z'$ are significantly larger than those of the Higgs boson.
Chapter 2

LHC & ATLAS

In this chapter the most important aspects of the LHC will be discussed and the geometry and functioning of the ATLAS detector is presented in greater detail. In a third section a brief overview of the software packages that are closely related to ATLAS is presented. The fast simulation package of ATLAS is introduced. In order to facilitate the application of a wide range of jet reconstruction algorithms, an alternative fast detector simulation package has been developed.

2.1 The Large Hadron Collider

The Large Hadron collider is at the moment the largest and strongest particle collider in the world. It is a proton-proton collider with an aimed maximal center of collision energy of 14 TeV and a design luminosity of $1.10^{34} cm^{-2}s^{-1}$. The design luminosity will only be reached after the testing at lower luminosities of $1.10^{27} - 5.10^{33} cm^{-2}s^{-1}$. The schedule is currently that the high luminosity phase of the project will only be reached after a one-year break in 2012 to do necessary maintenance and upgrades to reach the highest designed energy of 14 TeV. The ultimate luminosity will possibly increased to $1.10^{35} cm^{-2}s^{-1}$ in the last stage of the project that would be named super LHC. The energy is an important parameter of a collider as it determines the range of physical processes that is possible to study. The LHC will be the first collider that has a center of mass energy well above the so called TeV-scale. Somewhere on the scale of the LHC energies a certain form of spontaneous symmetry breaking must occur, a central topic in this thesis. The luminosity is as a parameter of a particle collider that is at least as important as the the energy, it is a measurement of the amount of collisions per second. Since the background of many theories that are to be tested will be some orders of magnitude larger than the processes itself, it is important to collect a large amount of data to do statistical correct statements. Except for the search of the Higgs particle the verification of other theories may be as important for our understanding of physics, and not unimportant, for the funding of future particle colliders. The most important class may be the "beyond the Standard Model" theories. These theories include multiple dimensions, supersymmetry and other less well-known theories as for example technicolor, which proposes a new fundamental strong force. A discovery of a particle beyond the boundaries of the Standard Model would be an impulse for physicists which has not occurred for quite a long time. It would probably open up a completely new class of particles and theories to discover and research. The collider has four main detectors, two general purpose detectors, CMS and ATLAS, a B-experiment, LHCb and a experiment that studies quark-gluon plasmas, ALICE. Next to these four there are Totem, which measures the total cross section and the elastic scattering of protons and there is LHCf, which studies astroparticle physics related topics.
2.2 The ATLAS detector

Considering ATLAS [19] to be an experiment on its own, it is with a cooperation of more than 2000 physicists one among the largest performed in the history of the world. The design of the detector started in the early nineties and since then a technical proposal (1995), a technical design report (1999) and a detector description (2008) have been completed. The information reported below is mainly extracted from the last paper.

The ATLAS detector can be divided in four different sections, three detector sections and its magnet system. These sections will be discussed below. After that the functioning of its triggering system will also be explained. ATLAS geometrically consists of three different detector parts. The inner detector tracks the charged particles. The calorimeters measure the energy and direction of all hadrons, electrons and photons. The most outer part are the muon spectrometers that are specifically designed to measure the energy and momentum of the muons. These are not stopped by the calorimeter because they are too heavy to be susceptible to the loss of energy due to bremsstrahlung. Apart from these three detector systems, it also has an internal magnet system through which the charged particles are bent and the particle momenta and masses can be measured. How the measurement works exactly will not be discussed in full detail, but description of the magnets will be offered. The last topic that will be discussed is the triggering system, which is important to cut back the enormous data flow that would be produced if all detector signals would be stored. On the other hand it also determines how much of the total signal will be lost if the used cuts are too tight.

An overview of the detector is given in figure 2.1. The detector is about 44 meters in length and the diameters is about 25 meters. It is the largest detector installed at the LHC. The central part of the detector is called the barrel and has its detector devices pointed perpendicular to the beam axis. On both sides of the barrel there also end-caps installed, which have their detector devices pointed perpendicular to the x-y plane. These end-caps ensure maximal coverage in the polar angular direction. To describe the geometry of the detector, a carthesian as well as an polar
coordinate system is used. The z-direction is in both systems the axis of the beam pipe, with z = 0 located at the interaction point. The x-axis is the horizontal one, with positive x in the direction of the centre of the LHC ring. The positive y-axis is the direction upwards. In the polar coordinate system, the \( \phi \) coordinate is the angle in the x-y plane, while the \( \theta \) angle is measured between the beam axis and the x-y plane, with \( \theta = 0 \) when pointing directly in the y-direction. Another quantity that is used as a way to measure the polar angle is the pseudorapidity. This is defined as:

\[
\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right) \tag{2.1}
\]

Since this number is almost always calculated by using the momenta of the measured particles, this can also be written as:

\[
\eta = 0.5 \ln \left( \frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \right) \tag{2.2}
\]

To measure distances in the polar-azimuthal space another quantity is used:

\[
\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \tag{2.3}
\]

In general it can be said that the detector fulfills the following requirements:

- Due to the high luminosity at the LHC, the detector is very fast as well as radiation hard (resistant).
- The coverage of the polar angle is as high as possible, while the coverage in the azimuthal angle is as good as optimal.
- The inner detector is as close to the interaction point as possible to maximize the possibility of flavour tagging and tau-tagging as well as to have a very high momentum resolution.
- The calorimeters are as good as possible to do refined measurements on electrons, photons and jets, as well as to maximize the missing energy resolution.
- It has a good muon identification system that unambiguously determines the muon charge of high-\( p_T \) muons
- The triggering system provides for a system that can also discriminate between background and signal at low \( p_T \).

In the table below a summary is given in advance of the required resolution of each individual detector component.

In the next sections, each individual component of the ATLAS detector will be discussed.

### 2.2.1 Inner Detector

The inner detector is the main tracking device of the ATLAS detector. It has three subdetectors, two high precision detectors, a pixel detector and a SemiConductor Tracker (SCT). The most outer layer is a Transition Radiation Tracker (TRT), which provides a high amount of particle track points. The total coverage of the inner detector is constrained by \( |\eta| < 2.5 \). This means that a good detection of charged particles and jets should at least demand that the detected particle should be in this region. An overview of the inner detector is given in figure 2.2.

For flavour tagging and the distinction of \( \tau \) particles a measurement very close to the vertex should be done. This is the task of the pixel detector, the most inner part of the inner detector.
The diameter is 50 cm, while its length is about 1.4 meter. In both the end cap part as the barrel part there are three layers. The closest layer in the barrel part is at a radial distance of 50.5 mm, followed by ladeyers at 88.5 mm and 122.5 mm. In total there are about 80 million read out channels, or individual pixels. A pixel has a size of 50 μm in the R–φ direction and 400 μm in the z direction, which determines the intrinsic resolution of the detector. The SCT is positioned just outside of the pixel detector. This is another precision detector and has four barrel layers and nine end cap disks at both side. The first layers start from about 25 cm from the interaction point, whereas Each silicon strip is about a strips and pixel positioned in a way that the resolution in z-direction is converted to the R-direction. The last part of the inner detector is the Transition Radiation Tracker. The precision of every module is somewhat lower than for the other detector parts, this is however compensated by the higher amount of measurement points that are done for every track, which is 36 for the most tracks. The TRT only provides information about the R – φ direction, since the straw strips have a length in the z-direction of 144 cm in the barrel and 37 cm in the end caps. The principle of the TRT is that it has various layers of materials with a slightly different diffraction index. When a charged particle traverses, it emits transition radiation and these photons are again measured. Because the amount of emitted photons is proportional to $\gamma = E/m$, the TRT is an excellent instrument to distinguish between electrons, pions and photons. This can be done with a 90% efficiency at energies higher than 1 GeV. Figure 2.3 gives a good overview of the coverage and the geometry of each detector in the inner detector.

The tracks in the inner detector are bent by the solenoid magnet of ATLAS, which again is important for the determination of the momentum of the particles. This solenoid is constructed
to fit right in the barrel toroid, shown in figure 2.7. Since a solenoid only has a magnetic field inside of the cylinder, it is fit very well to serve the inner detector while not disturbing the fields of the toroids. It is important to precisely know the magnetic field in the detector. Though it is technically not possible to produce a completely homogeneous field, it is possible to measure the deformation to the smallest detail. This is also done for the fields in the ATLAS detector. A result for the field in the inner detector is summarised in figure 2.4

![Figure 2.4: The magnetic field in the inner detector in the z-direction and R-direction. Each line represents a different radial distance from R=0.](image)

### 2.2.2 Calorimeters

The calorimeters are placed radially just behind the inner detector. First the electromagnetic and after that the hadronic. Both cover a large range in the polar angle, since it is important to measure the missing energy coming from neutrinos and hypothetic other weakly interacting particles as precisely as possible. The electromagnetic calorimeter has a barrel and two end cap parts at each side. The hadronic calorimeter has a tile calorimeter in the barrel region with an extended section on top of the end caps and a end cap calorimeter. also has two extended barrel parts around the end caps. In the most forward region, $3.1 < \eta < 4.9$, the calorimeter is fit to absorb and measure the energy and direction of electrons and photons as hadronic particles. This
The geometrical arrangement is summarised in figure 2.5

Figure 2.5: A geometrical overview of the ATLAS calorimeters.

The calorimeters are responsible for the energy measurements of all particles transversing the ATLAS detector except for muons and neutrinos. Important aspects are the measurement jets and the missing $E_T$. For the former, a high granularity in the calorimeters is needed and for the latter a large coverage in $\eta$ is required. Calorimeters are usually divided in two sections, one for the electromagnetic measurements and another part that is specialized in stopping hadronically interacting particles. The EM calorimeter stops photons and electrons, while it also adds tracks for charged hadrons. Processes through which photons and electrons lose their energy are mainly pair-production for photons and Bremsstrahlung for electrons. Due to the heavy mass of muons, they do not lose enough energy in the EM calorimeter and transverse through both the EM and the hadronic calorimeters without losing much energy. Hadronic calorimeters stop hadrons through nuclear interactions. These have smaller cross section than the ionizing interaction in EM calorimeters and therefore hadronic calorimeters are typically a few times larger. A general build-up structure for both types is the use of passive and active material. The passive material is dense and has a high stopping power. Its function is to initiate a shower that extends into the active material when a particle traverses it. The active material then measures the signal from the shower which is usually proportional to the energy of the detected particle.

Both types of calorimeters have an increased granularity in the $|\eta| < 2.5$ for the extrapolation of the inner detector tracks coming from photons and electrons. The other parts of the calorimeter have a granularity that is high enough to measure the parameters of jets and missing energy with a high enough precision. The electromagnetic calorimeter has a barrel part that covers the region $|\eta| < 1.475$ and two end caps that cover the region $1.375 < |\eta| < 3.2$. The passive material that is used to stop the energetic particles is lead while the active material through which the freed electrons are measured is liquid argon (LAr). It also uses a presampler in the region $|\eta| < 1.8$ to compensate for the energy loss of electrons and photons, this is comprised of a small strip of LAr. The total thickness of the EM calorimeter is more than twenty-two radiation lengths in the barrel and more than 24 radiation lengths in the end caps. As an electron loses a factor $1/e$ of its energy after one radiation length, the deposited energy of the particles should be around $1 - (1/e)^{22} \times 100\% = 99.99999997\%$. A complete overview is provided in table 2.2.2

The barrel and the extended barrel part of the hadronic calorimeter uses steel as its passive material and scintillating plates for the active layers. The tile calorimeter part, including the extended parts above the end caps cover the region $|\eta| < 1.7$. An overview of the granularity can
Table 2.2: An overview of the η coverage and granularity of the Electromagnetic calorimeter.

<table>
<thead>
<tr>
<th>Calorimeter Part</th>
<th>η coverage</th>
<th>Granularity (Δη × Δφ)</th>
<th>η coverage</th>
<th>Granularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presampler</td>
<td>&lt;</td>
<td>η</td>
<td>&lt; 1.52</td>
<td>0.025 × 0.1</td>
</tr>
<tr>
<td>1st layer</td>
<td></td>
<td>η</td>
<td>&lt; 1.40</td>
<td>0.025/8 × 0.1</td>
</tr>
<tr>
<td></td>
<td>1.40 &lt;</td>
<td>η</td>
<td>&lt; 1.475</td>
<td>0.025 × 0.025</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5 &lt;</td>
<td>η</td>
<td>&lt; 1.8</td>
<td>0.025/8 × 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0 &lt;</td>
<td>η</td>
<td>&lt; 2.4</td>
<td>0.025/4 × 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd layer</td>
<td></td>
<td>η</td>
<td>&lt; 1.40</td>
<td>0.025 × 0.025</td>
</tr>
<tr>
<td></td>
<td>1.40 &lt;</td>
<td>η</td>
<td>&lt; 1.475</td>
<td>0.075 × 0.025</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5 &lt;</td>
<td>η</td>
<td>&lt; 3.2</td>
<td>0.1 × 0.1</td>
</tr>
</tbody>
</table>

Table 2.3: An overview of the η coverage and granularity of the Hadronic Tile Calorimeter.

<table>
<thead>
<tr>
<th>Calorimeter part</th>
<th>η coverage</th>
<th>Granularity (Δη × Δφ)</th>
<th>η coverage</th>
<th>Granularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>First two layers</td>
<td></td>
<td>η</td>
<td>&lt; 1.0</td>
<td>0.1 × 0.1</td>
</tr>
<tr>
<td>3rd layer</td>
<td></td>
<td>η</td>
<td>&lt; 1.0</td>
<td>0.2 × 0.1</td>
</tr>
</tbody>
</table>

Table 2.4: An overview of the η coverage and granularity of the Hadronic End Cap Calorimeter.

be found in table 2.2.2

The hadronic end cap calorimeter uses copper as its passive material and LAr for the sampling. It covers the region 1.5 < |η| < 3.2. The most inner calorimeters in the end caps cover the region 3.1 < |η| < 4.9. This forward region has the strongest radiation due to the radiation constantly coming from the beam remnants and initial state radiation. To make the FCal radiation-hard enough the two outer layers of this calorimeter are manufactured from the expensive tungsten, the most inner layer is still made out of copper for the electromagnetic showering. How the layers of the FCal are structured precisely and what their granularity is can be found in table 2.2.2

2.2.3 Muon Spectrometers

Although for the purpose of this thesis the detection of muons is not as important as the inner detector and the calorimeter, for the completeness the muons spectrometers will be discussed in this

<table>
<thead>
<tr>
<th>LAr Hadronic End-Cap (HEC)</th>
<th>η coverage</th>
<th>Granularity (Δη × Δφ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5</td>
<td>η</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>η</td>
</tr>
</tbody>
</table>

Table 2.4: An overview of the η coverage and granularity of the Hadronic End Cap Calorimeter.
section. Since muons are too heavy to lose their energy through Bremmstrahlung in the calorimeters and only lose a few GeV at maximum due to ionizing effects they are the only particles, except for neutrinos, that pass through the calorimeters. For this reason a third layer of detector systems is usually installed in particle detectors to measure the parameters of muons more precisely. An overview of the positioning of the different detection and triggering systems is provided in figure 2.6. There are four different detector systems, two have triggering as their main purpose while the other two are for the actual measurements of the tracks. The muon momentum is measured by using information of the measured tracks and the magnetic field. This field is produced by three large toroids, one large barrel toroid and two somewhat smaller end cap magnets, both are showed in figure 2.7.

The barrel toroid is mainly responsible for the field between $0 < |\eta| < 1.4$ while the the end cap toroids each determine one side of the region $1.6 < |\eta| < 2.7$. The missing region between $|\eta| = 1.4$ and $|\eta| = 1.6$ is called the transition region. The field here is determined by a combination of two magnets. The resulting field integral for a certain muon track on the whole region is shown in figure 2.8.

### Table 2.5: An overview of the $\eta$ coverage and granularity of the Forward Calorimeter.

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\eta$ coverage</th>
<th>Granularity ($\Delta x \times \Delta y$ (cm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM</td>
<td>$3.15 \eta &lt; 4.30$</td>
<td>$3.0 \times 2.6$</td>
</tr>
<tr>
<td></td>
<td>$3.10 \eta &lt; 3.15$</td>
<td>$\sim$ 4 times finer</td>
</tr>
<tr>
<td></td>
<td>$4.30 \eta &lt; 4.83$</td>
<td></td>
</tr>
<tr>
<td>1st hadronic</td>
<td>$3.24 \eta &lt; 4.50$</td>
<td>$3.3 \times 4.2$</td>
</tr>
<tr>
<td></td>
<td>$3.20 \eta &lt; 3.24$</td>
<td>$\sim$ 4 times finer</td>
</tr>
<tr>
<td></td>
<td>$4.50 \eta &lt; 4.81$</td>
<td></td>
</tr>
<tr>
<td>2nd hadronic</td>
<td>$3.32 \eta &lt; 4.60$</td>
<td>$5.4 \times 4.7$</td>
</tr>
<tr>
<td></td>
<td>$3.29 \eta &lt; 3.32$</td>
<td>$\sim$ 4 times finer</td>
</tr>
<tr>
<td></td>
<td>$4.60 \eta &lt; 4.75$</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.6:** A geometrical overview of the muon spectrometers.
The requirements for the precision of muon measurements are demanding in the ATLAS detector for various reasons. There are three different aspects that determine how precise a momentum measurement can be done, the determination of the field, the intrinsic precision of the muon chambers and the measurement of the relative positions of the muon chambers. To fulfill to the requirement of the magnetic field, more than 1800 hall sensors are installed in the muon chambers to correct for small fluctuations in the field.

The four types of muon chambers are "Monitored Drift Tubes" (MDTs), Cathode Strip Chambers (CSCs), which are both tracking chambers, Thin Gap Chambers (TGCs) and Resistive Plate Chambers (RPCs), which are both triggering chambers. The MDTs are constructed from long tubes with a very thin wire, held at a voltage of 3080 V. These tubes are mounted in a box in layers of three or four tubes. The precision measurements are done by using the information of the drift time, which again can be derived from the measured pulse width and height. The maximum drift time can be 700 ns, which is far above the interaction rate and therefore also above the requirements for triggering. The tubes are called "monitored" because the system has an internal optical system that keeps track of transformations to the order of a few micro meters. For the tracking in the forward directions, the MDTs are again too slow and Cathode Strip Chambers are used. These are multiwire proportional chambers which have drift times that are much smaller than those of the MDTs. The precision is comparable to that of the MDTs and another advantage is the ability of
good track distinction if more than one muon traverses the chambers.

Because the MDTs and the CSCs have drift times that can extend to several hundred nanoseconds there are separate chambers installed to do the triggering. These triggering chambers have several requirements and functions:

- Capable of measuring the muon $p_T$, on the whole range of $\eta$.
- Have access to the bunch crossing information.
- Provide rough tracking information for the higher level triggers.
- A good noise/background reduction.
- Provide an extra tracking point for the precision chambers.

In the barrel RPCs are used. These chambers do not use wires and are therefore easier to produce. These plates are suited well enough to fulfil the requirements in the barrel region. Transverse momentum is easier to measure, the magnetic field is more homogeneous and the rates are lower. The requirements are harder to fulfil in the end cap parts. Since the momenta of the particles are much higher here compared to the $p_T$, while the magnetic field is not proportionally larger, it is harder to get the same resolution as in the barrel. For these reasons a different technique was used in the end caps (TGCs) and there is an additional, fourth, layer installed for the triggering. TGCs function in the same way as multiwire proportional chambers, the wires are positioned very close to each other and the voltage between anodes and cathodes is relative high, which results in drift times that are smaller than 25 ns in 99% of all cases.

2.2.4 Triggering

Level 1 trigger

Since the LHC provides forty million bunch crossings per second, with at least as much interactions, it is not practical nor possible to store all events for offline storage. The goal is to reduce the 40 MHz to about 200 Hz, a reduction factor of 200,000. Decisions should be made about whicht events will be left out and which events will pass all the trigger levels. The difficulty is that using a triggering system is inherent to throwing away interesting data or biasing the data that will be stored. An effective approach that is also used by ATLAS is to develop a general triggering system that can be adjusted easily. There are three levels, each using different input for the criteria that are used to trigger. What these criteria will be is however not predefined and can be configured through the so-called trigger menus. The first two are online triggering systems, while the third is an offline system. The level 1 (L1) trigger is completely hardware-based and makes decisions based on calorimeter and muon triggering information. It determines whether there are electron/photon, muon, tau and jet candidates. It can also trigger on the total energy or missing $E_T$. If a trigger condition is satisfied, a signal is given to the data acquisition system to read out the data, and the necessary information is passed on to the L2 trigger and the detector front-ends. Since data collection takes more time than there is time between a bunch crossing (25 ns), for various detector components that are used by the trigger, triggering decisions cannot be done with the same speed as the bunch crossings. A pipeline is used to enable the possibility of a L1 latency, which is allowed to be 2.5 $\mu$s at maximum. The maximum trigger rate of the L1 trigger is defined by the speed on which the DAQ functions, 75 kHz during the first stage.
**Level 2 trigger**

The second level trigger is the first of the two high level triggers (HLT), which are both software based. Unlike the L1 trigger, the L2 uses the full granularity of the muon triggers and calorimeters in the Region of Interest (RoI) that is defined by the L1 trigger. The main purpose of the L2 trigger is to check the parameters on which the L1 trigger made its decisions, but with more complete information and with more refined algorithms. It for example evaluates the shower shapes and the track-clusters in in the calorimeter with full granularity. Secondary RoI can also be accessed to evaluate the importance of lower $p_T$ objects or in some special cases the full detector information can already be accessed. The L2 trigger should reduce the trigger rate to about 3.5 kHz, processing one event takes in the order of tens of milliseconds. A large cluster of computers is used to process the events parallel. If the L2 trigger is passed, the event is "built" and after the building process the event can be handled by normal ATLAS analysis procedures, which is done by the Event filter (EF).

**Event filter**

Since the next step after the L2 trigger is the "event builder", the event filter (EF) uses the full detector information to completely assess the events. The EF makes use of the regular offline algorithms, built in the ATLAS framework Athena to make decisions both on whether to store the event and also how to tag the event. It can be tagged as an electron, muon, jet, photon, missing $E_T$ & $\tau$ or B-physics event. It can also have two or more tags, in which case it is also written to more data files. The output of the event filter should be around 200 Hz, the maximum that the ATLAS offline system can handle. The processing of one event takes the time in the order of seconds. Therefore, a large network of computers is dedicated to doing the EF tasks.

**Trigger menus**

To control the triggering and tune or fine-tune the trigger conditions in later stages of the collider, a system of trigger menus is used. A trigger menu is a list of trigger conditions that can be set with an easy-interpretable syntax that can be set up for the L1 and HLT separately. Although the trigger conditions at higher energies are not determined yet, there are proposals for luminosities of $10^{31}$, $10^{32}$ and $10^{33}$ cm$^{-2}$s$^{-1}$. The chance is large that not much will be changed in these proposed menus except for the pre-scaling. This means that the thresholds may change and there may be additional requirements for the triggers. Leptons may be required to be isolated or certain triggers are only performed in combination with other particles. Except for the primary triggers of which the purpose is to do physics analysis, there are also secondary and supporting triggers that have the purpose of collecting data for the testing of certain aspects of the triggers, or calibrating the detector. The interesting trigger menu for the hadronic $Z'$-Strahlung process is the jet-menu. It is listed in list 2.2.4, the proposed trigger menu for a luminosity of $10^{33}cm^{-2}s^{-1}$. The first number is the amount of particles, ones are omitted. The second character denotes the type of particle, this is straightforward except for a photon that is denoted by a g for gamma and met stands for missing $E_T$. The third character is again a number and gives the threshold in GeV. An extra i denotes the fact that isolation is required for a trigger, this means no other particles should be detected in a cone of $\Delta R = 0.2$. The trigger menus for $10^{34}cm^{-2}s^{-1}$ are not yet proposed, although the expectation is that these menus are similar, but have higher thresholds.
<table>
<thead>
<tr>
<th>Triggername</th>
<th>Expected rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e22i</td>
<td>40</td>
</tr>
<tr>
<td>2e12i</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>g55i</td>
<td>25</td>
</tr>
<tr>
<td>2g17i</td>
<td>2</td>
</tr>
<tr>
<td>mu20i</td>
<td>40</td>
</tr>
<tr>
<td>2mu10</td>
<td>10</td>
</tr>
<tr>
<td>j370</td>
<td>10</td>
</tr>
<tr>
<td>4j90</td>
<td>10</td>
</tr>
<tr>
<td>j56+XE70</td>
<td>20</td>
</tr>
<tr>
<td>tau35i+XE45</td>
<td>5</td>
</tr>
<tr>
<td>2mu6</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2.6: High level trigger menu at a luminosity of $10^{33}$ as denoted in the ATLAS detector report in 2008 [19].

2.3 Software

Since the subject of this thesis is the simulation of $Z'$ events in the ATLAS detector, the used software is a critical instrument. Before analysis can be performed in root a long chain of generation, simulation and analysis software is used. Below follows a short introduction to each of those, starting at the beginning of the chain and ending at root, the final analysis program.

2.3.1 ROOT

ROOT [20] is a C++ histogramming package and is nowadays one of the most integral software packages used in the field of particle physics. One of the key concepts is a very convenient data storage system. It provides all statistical tools that are needed and a comprehensive list of multi-dimensional histograms and graphs can be produced.

2.3.2 Athena

Athena is the offline software framework of ATLAS. It has an internal data-format for events that enables the easy use of combinations of different monte-carlo generators and simulation packages within Athena. It provides:

- An interface with a large list of event generators.
- Different types of simulations of the detector and detector parts.
- Algorithms for the event filter.
- Event reconstruction.
- Event analysis.
2.3.3 ATLAS Modular Analysis

This program is mainly used to convert the Athena event format into a normal root format on which analysis can be performed. It provides functionality through which kinetic cuts and detector cuts can be applied to reduce the file formats as well as functionality to produce basic histograms of event parameters.

2.4 Simulation methodology

There are two officially validated detector simulation packages for the ATLAS detector. The first is the full detector simulation. In this package all detector parts and materials are implemented in GEANT. In GEANT an evaluation of the Bethe-Bloch is performed and the propagation of all primary and secondary particles is simulated as comprehensive as possible. The magnetic field, reflections, deflections and tunneling are all evaluated. To evaluate an event in the full simulation package takes in the order of twenty minutes on a fast computer, which is far too slow to study a sample of events that represent good distributions. The purpose of the full simulation is either to study specific details of a certain physical process, or either to study the functioning of a specific detector part. After the resolution functions of the different detector parts were measured these functions were used to build a faster detector simulation, Atlfast.

The fast simulation uses these parametrizations to return a limited set of information from the event. The missing energy, the (isolated) electrons, muons and photons and a list of jets with their flavour-tags are the most important containers. The jet reconstruction can be done by two different algorithms, a split-merge cone algorithm and a $k_T$-algorithm. Until this moment no implementation has been made of subjet analysis algorithms or the C/A algorithm. In chapter 3 it will be demonstrated that the C/A algorithm gives a significant better mass resolution than the $k_T$ algorithm when doing subjet analysis, a manual simulation has also been developed. In this chapter the first section gives a description of how the detection of jets is modelled in Atlfast. The last section provides a description of the manual simulation, together with a comparison of its performance to that of Atlfast.

2.4.1 Atlfast [21]

The main difference of Atlfast in respect of the full simulation is that only the resolutions of the particles that are interesting for physics analysis are used. Instead of simulating the pixel detector, the SCT and the TRT separately it is for example assumed that only particles with an energy larger than 500 MeV are detected and the magnetic field in the ID is simulated by a parametrized helix function in two regions in $|\eta|$. For every final particle in the event list only a few calculations have to be done, whereas in the full simulation every particle transverses meters of materials for which the bremsstrahlung, pair production and ionization processes are calculated separately. In the following it is explained how the detection of jets is modelled in Atlfast.

In Atlfast [21] there is no distinction made between the electromagnetic and hadronic calorimeters and the energy deposition is simulated by assuming that every particle loses all its energy in one cell, without an uncertainty in the energy measurement. The cells are divided in two $|\eta|$ regions. The central region extends to $|\eta| < 3.2$ and has a uniform granularity of $\eta \times \phi = 0.1 \times 0.1$. The forward region extends to $|\eta| < 5.0$ with a granularity of $\eta \times \phi = 0.2 \times 0.2$. All electrons, photons and hadrons deposit their energy in the same way. From the calorimeter cells, clusters are formed. Before the clusters are assigned to jets, it is checked whether they should be assigned to true electrons or true photons. If no electrons and photons were found in the in the event list
that are in the neighbourhood of the cluster, the cluster is assigned to a jet. If muons are in the area of the cluster, their four-vectors are added to the four-vectors of the jet. The jet energy is then smeared according to a normal distribution with the standard deviation computed with the following resolution functions:

\[
\frac{\sigma(E)}{E} = 3\% + \frac{50\%}{\sqrt{E}} \quad for \quad |\eta| < 3.2
\]

\[
\frac{\sigma(E)}{E} = 7\% + \frac{100\%}{\sqrt{E}} \quad for \quad 3.2 < |\eta| < 5.0
\]  

(2.4)  

(2.5)

At the end a jet calibration can be applied that corrects for the out-of-cone energy due to the magnetic fields. The function that is used for the calibration is a taylor-expansion of the measured response function that is obtained when comparing the Monte Carlo data to the simulated data.

### 2.4.2 Manual simulation

As it was mentioned before, an additional package was developed specially for the detection of jets. This manual simulation resembles Atlfast, but has the possibility of using every type of jet reconstruction algorithm instead of the limited choice of the \(k_T\) and the cone algorithms in Atlfast. Other aspects as muon, electron or photon simulation are not implemented. The simulation procedure consists of four steps:

1. The bending of charged particles in the magnetic field.
2. Detection of all particles in the calorimeters.
3. Jet reconstruction with the calorimeter cells as the input.
4. Smearing of the jets by using the Atlfast resolution function.

The formula that is used for the bending of the charged particles is copied from the Atlfast source, which uses:

\[
\phi_{def} = \frac{-150 \cdot B \cdot 3.0}{2p_T} \quad if \quad |\eta| < 1.4
\]

\[
\phi_{def} = \frac{-350 \cdot |\tan(\theta)| \cdot B \cdot 3.0}{2p_T} \quad if \quad 1.4 < |\eta| < 5.0
\]  

(2.6)  

(2.7)

The part where the calorimeters are simulated is also based on Atlfast as literally as possible. All particle are collected in cells of \(\eta \times \phi = 0.1 \times 0.1\) in the central region of \(|\eta| < 3.2\), and in cells of \(\eta \times \phi = 0.2 \times 0.2\) for the forward regions. Every particle deposits its energy completely in one cell, with no uncertainty in the detection.

The jet reconstruction is done by the fastjest package just as it was done in chapter 4. It is considered that every detected cluster should be assigned to a jet. This is a reasonable assumption as this simulation is only performed on data samples with full hadronic decay channels.

The jets are again smeared by the same functions that are used by Atlfast, written down in equation 2.4. In Atlfast an option to simulate higher luminosities is also included in the resolution functions. The assumption that is used is that pile-up effects do not influence the hard process of an event but only add a noise term to the calorimeter cells. This is a valid assumption for
luminosities up to the order of $10^{33} \text{cm}^{-2}\text{s}^{-1}$. At even higher luminosities “fake jets” can become a substantial influence in the analysis. These fake jets can only be simulated by adding a number of minimum bias events to the event list. For the highest LHC luminosity ($10^{34} \text{cm}^{-2}\text{s}^{-1}$) an average of 23 minimum bias events should be added.

Another difference between Atlfast and the manual simulation is that Atlfast uses Pythia 6 input Monte Carlo data by default in the Athena framework. The manual simulation is built in C++ and is for that reason particularly easy to use in combination with Pythia 8. The way the underlying event is modelled is different in the two versions.

### 2.4.3 Validation

Before the manual simulation will be used to analyze the $Z'$ reconstruction the simulation will be compared to the Atlfast simulation. A comparison is achieved by performing the $Z'$ reconstruction with the $k_T$ jet algorithm with $R = 1$ on data that is simulated by Atlfast and on data that is simulated by the manual simulation. The low-luminosity option of Atlfast is used because pile-up effects are simulated in different ways. To compare relevant representations of the output, histograms of the $p_T$ of the $Z'$ and the three W-bosons, the masses of all jets and the mass of the $Z'$ are produced. These histograms are produced for the two different simulations and are compared and divided to confirm that both simulations indeed produce the same output. The $p_T$-histograms for the Atlfast-simulation are plotted in figure 2.9, for the manual simulation in figure 2.10 and the histograms are divided in figure 2.11. The same is done for the histograms of the mass of all reconstructed jets and the mass of the $Z'$ in figures 2.12, 2.13 and 2.14. The $p_T$-distributions of both simulations are very similar, while the plots of the jet-mass and the $Z'$-mass show somewhat more differences. These differences can possibly explained by the different underlying events. The W- and $Z'$-resonances are sharper in the jet-mass distribution in Atlfast, while the reconstructed $Z'$-peak is somewhat broader in Atlfast. The mean value, the integral and the root-mean-square and even the peak height of the reconstructed $Z'$-peaks are almost equal. The question whether the manual simulation is sufficiently in line with Atlfast can be answered with a careful yes. The largest differences are that of the jet-mass distributions, though these differences do not result in differences in the $p_T$-distributions.
Figure 2.9: The $p_T$-distributions of the detected bosons in a $Z'$-Strahlung event, simulated by Atlfast. There are no pile-up effects and the jet-algorithm that is used is $k_T$ with $R = 1.0$. 
Figure 2.10: The $p_T$-distributions of the detected bosons in a $Z'$-Strahlung event, simulated by the manual detector simulation. There are no pile-up effects and the jet-algorithm that is used is $k_T$ with $R = 1.0$. 
Figure 2.11: The division of the $p_T$-distributions of the detected bosons in a $Z'$-Strahlung event simulated by Atlfast by the $p_T$-distributions simulated by the manual simulation. The only substantial deviations from 1 occur at the lowest and highest $p_T$ values and can be explained by differences in the underlying event and by statistical fluctuations.

Figure 2.12: The jet-mass and the $Z'$-mass distributions in a $Z'$-Strahlung event, simulated by Atlfast. There are no pile-up effects and the jet-algorithm that is used is $k_T$ with $R = 1.0$. 
Figure 2.13: The jet-mass and the Z'-mass distributions in a Z'-Strahlung event, simulated by the manual detector simulation. There are no pile-up effects and the jet-algorithm that is used is $k_T$ with $R = 1.0$.

Figure 2.14: The jet-mass distributions and the Z'-mass simulated by Atlfast, divided by the same distributions simulated by the manual simulation. The plots show that the mass-distributions of the two simulations are a bit more different than the $p_T$ distributions. The jet-mass distributions are especially different at the two important places: the W- and the Z'-resonances. The Z'-resonance also shows deviations from 1, though at the peak value, the deviation is only small.
Chapter 3

Jets

3.1 Introduction to jet reconstruction

Jet reconstruction is a fundamental aspect of the analysis of particle collider events. Jets are formed when a gluon or quark with sufficient energy/momentum to initiate a hadronization process is produced. Although the principles of jet reconstruction are the same in electron-positron colliders and hadron colliders, at the latter the analysis of jets is significantly more difficult since underlying event effects such as beam remnants and multiple parton interactions usually produce more particles than just the partons from the hard scattering and their decay and hadronization products. These particles can produce fake jets or background jets.

One of the problems of background jets is that they may overlap with the signal jets and it is therefore not always clear which particles to assign to which jets. Another problem is that they form a serious background to the process under investigation. To discriminate between background and signal, it is important to have a solid jet reconstruction algorithm and to know how this algorithm behaves for different types of events.

In large, there are two types of algorithms, cone and sequential recombination algorithms. The first defines a jet based on the particles that are included in a cone of size R (see eq. 2.3 pointing in a certain direction. In a general sequential recombination jet algorithm each particle is considered as a protojet. These protojets are recombined based on the distance in a defined metric. Once the minimum distance is smaller than a preset R-parameter the protojets are promoted to real jets.

In the following section the two types will be discussed; [22] is used a reference paper.

3.2 Cone algorithms

Cone algorithms especially are popular at hadron colliders where the multiplicity of particles in a single event is in the order of a few hundred at tevatron up to a few thousand at high luminosity LHC events, which make sequential recombination algorithms slow. A general cone algorithm uses a certain direction in the azimuthal angle and the pseudorapidity as a seed and around its seed direction all particles, or calorimeter towers, within a cone of $\Delta R$ are included in the jet. The jet direction is used as a new seed and this procedure is iterated until the jet definition converges and a stable jet is formed. An important property of such a stable cone is that its four-vector coincides with the four-vector of the addition of all its constituents. When the first jet is formed a new seed is used to repeat the same procedure.

Issues with these algorithms involve questions like what should be taken as a seed, what should be done with the overlap between jets and whether the jet definitions would change if the soft
or collinear radiation of partons would be slightly different (are the algorithms infrared safe and collinear safe?). The two main classes of algorithms are discussed below.

### 3.2.1 Progressive removal

In the class of progressive removal algorithms, the hardest particle is used as a seed. When a stable cone is found, its constituents are removed from the list of particles to ensure that these cannot overlap in the cone of the next jet. A disadvantage of the progressive removal approach is that it is collinear unsafe. If the hardest particle would have been split in two particles with almost the same direction but with each of the new particles having only half the $p_T$ of the original, most probably another particle will become the hardest and therefore the first seed. The new seed probably has a different direction and therefore the new stable cone will be different. The final set of jets therefore depends to a certain extent on how the parton shower evolves, while a requirements of a jet-algorithm is that it is independent of FSR.

### 3.2.2 Split-merge

In the split-merge approach first a (large) set of stable cones in the set of particles are identified according to a seed definition. After the iterations have converged, the cones are re-evaluated beginning at the one with the largest $p_T$. If there is no overlap, it is promoted to a jet. If it has an overlap with another cone that is larger than a fraction ‘f’ of the second cone, the two cones are merged to one cone. If the overlap is smaller than f, the cones are split according to some defined principle. This procedure is repeated and every time first the cone in the list with the largest $p_T$ is compared with the cone with the second largest $p_T$ and else the third largest, etc.

Split-merge algorithms do not suffer from collinear unsafety. If there is an overlap between cones with somewhere in the total area two collinear particles, these particle will either contribute both to one of the cones or both to the overlap area. Because of their collinearity it will however never happen that each of the particles contributes to a different area. It does suffer however from infrared unsafety. What this means is best illustrated by using an example of the hadronic decay of electroweak bosons. When one of the partons emits a soft gluon in the direction that lies between the two partons, a new stable cone with large overlap of both other cones comes to exist. If the overlap of the gluon cone with the two parton cones is large enough, the three cones will be merged into one large cone.

### 3.2.3 Seedless algorithms

The infrared and collinear (IRC) unsafeties are regarded as not just an academic problem but as a serious problem in the interpretation of the analyses with these jet algorithms. One of the problems is that higher than leading order calculations are rendered unuseful by the problem and these calculations are important when investigating ISR and FSR effects. But even more serious is the experimental aspect of it, as it is eloquently stated in [23]: “...it makes no sense for the structure of multi-hundred GeV jets to change radically just because hadronisation, the underlying event or pileup threw a 1 GeV particle in between them.”

An alternative that is still used is the midpoint fix for the split-merge algorithm. In midpoint algorithms, cones in the direction just between of two stable cones are also evaluated. In the case where only two hard partons have a possible overlap, the midpoint fix offers a solution. Though with more than two partons, midpoint algorithms become infrared unsafe again. A full solution of the problem can only be offered if literally all possible stable cones can be evaluated. The problem here is the procedure to evaluate a cone algorithm for all possible particles as seeds has a complexity
of $N^2N$, which means it would take approximately $10^{17}$ years to perform the algorithm on a 100 particle event. In 2007 a solution was found by [23]. The main idea was that to find all stable cones it is not necessary to evaluate all combinations of particles, but only those that are connected on a circle with radius $R$. achieved to reduce the complexity to $N^2\ln N$. The jet-algorithm was named SISConE, or Seedless Infrared Safe Cone algorithm.

3.3 Sequential recombination algorithms

As explained in the introductory part the class sequential recombination (SR) algorithms defines jets by evaluating one particle recombination at a time. Whether a recombination is made between particle $i$ and $j$ depends on two parameters, the distance between two protojets (or single particles) $\rho_{ij}$ and the beam distance $\rho_i$. In a set of measured particles it adds the four-vectors of two the two protojets that are nearest according to the defined metric and combines these to make a new protojet. It repeats this procedure until the smallest distance of a protojet with a second is larger than the beam distance and promotes the protojet to a jet. SR algorithms are generally IRC safe.

SR algorithms are mostly popular at electron-positron and electron-proton colliders because here the particle multiplicity is low enough for their high complexity. Recently, multiple publications were published that presented methods with which these algorithms become more attractive. Fastjet, a new algorithm, greatly increases the speed of clustering methods. A “perfect cone” algorithm, anti-$k_T$, [24] was developed with various attractive properties. The name refers to the fact that the metric of the algorithm resembles the inverse metric of the $k_T$ algorithm. It clusters jets around hard particles and while doing so the shape of the “passive area” resembles a circle in $\phi - \eta$ space very well. The passive area of a jet defines the area in which soft particle would still be incorporated in the jet. For the already existent Cambridge-Aachen algorithm and the $k_T$-algorithm two jet-substructure algorithms were developed, Y-splitting [25] and Pruning [26]. Sub-structure techniques might prove quite useful in the light of the subject of this thesis and are discussed in the next section after the three most used SR algorithms are discussed.

3.3.1 Cambridge-Aachen algorithm [27]

The Cambridge-Aachen (C/A) algorithm is based on geometrical parameters. The metric is the following:

$$\rho_{ij} = \frac{\Delta R^2}{R^2}$$

$$\rho_i = 1$$

\(\Delta R\) is the spherical distance between two outgoing particles as it is also defined in chapter 2: \(\Delta R^2 = \Delta \eta^2 + \Delta \phi^2\). $R$ in equation 3.2 can be compared to the cone size as defined in cone algorithms and is the free parameter of the algorithm, it defines the maximum distance two protojets can have to be recombined.

The C/A algorithm is interesting when using jet substructure analyses since it only makes decisions based on the angle between particles or protojets and therefore does not “pre-select” a certain jet-structure.

3.3.2 Inclusive $k_t$ algorithm

Except for the geometrical information (directions) of the particles, the $k_t$ algorithm [28] also makes use of the hardness ($p_T$ or $k_T$) of the jet constituents. By the multiplication of the minimum of
the two $k_t$s in the metric, the algorithm tends to cluster particles with small transverse momentum in jets. The metric and the beam distance are the following:

$$\rho_{ij} = \min (k_{ti}, k_{tj}) \frac{\Delta R^2_{ij}}{R^2}$$

$$\rho_i = k_{ti}$$

The “inclusive” in the name comes from the incorporation of the factor $\frac{1}{R^2}$ in the metric. The extra factor results in the fact that protojets with an angular distance more than R will not be merged and the possibility comes to exist that single particle can be defined as jets. The problem that arbitrarily soft particles will individually be promoted to jets can be solved by incorporating a minimum $p_T$ of the final jet.

### 3.3.3 Anti-$k_t$ algorithm

Instead of clustering jets with low transverse momenta, the opposite is also possible. The idea of the anti-$k_T$ algorithm [24] is a relatively new idea. Instead of starting the clustering with lower momentum particles, it combines one high-momentum particle with clusters of softer particles in its neighbourhood:

$$\rho_{ij} = \min \left(\frac{1}{k_{ti}}, \frac{1}{k_{tj}}\right) \frac{\Delta R^2_{ij}}{R^2}$$

$$\rho_i = \frac{1}{k_{ti}}$$

One of the remarkable aspects of this algorithm is that the passive jet area is both very constant and very nicely shaped in $\phi - \eta$ space. Two benefits of the well-shaped area are that it is easier to predict how the jet area changes under influence of background particles and it is less susceptible to a phenomenon that is called “back reaction”. In short, back reaction is the effect that the wrong signal particles get incorporated in a jet due to the influence of background particles. Figure 3.1 shows the jet shapes of the four discussed algorithms. The anti-$k_T$ algorithm even has a more circular shape in $\phi - \eta$ space than the SISCone algorithm. The other SR algorithms have deformed areas.

### 3.4 Substructure in jets

Sequential recombination algorithms have become more interesting lately because of the increase in approaches in jet-substructure analysis. The jet-substructure investigations are especially interesting when trying to reconstruct boosted heavy particles such as weak bosons or top-quarks at the LHC. The decay products of these particles will be heavily collimated and therefore it will be difficult to catch these in individual cones. To get an idea of the numbers, it is useful to consider that the decay products of a W-boson have approximately an angle of $R \sim 1$. However, the two W’s coming from the Z’ are heavily boosted because of the large mass drop. The decrease of the angle of the decay products is related to $\frac{p_T}{m_W}$ where again the increase $p_T$ is related to the mass of the Z’ boson and which can be estimated by $\frac{p_T}{m_W}$ · $m_{Z'}$, if it is assumed that the Z’ decays isotropically. If the Z’-boson would have a mass of 500 GeV, an estimation of the average $\Delta R$ of two partons coming from a W-boson is about $1/\sqrt{\frac{500}{80.4}} \sim 0.4$. Figure 3.2 shows how the angular distributions are for the W’s and the partons. The upper left plot in 3.2 shows the differential cross section as a function of the transverse momentum of the Z’ partice, which is the same as for the third W boson.
Figure 3.1: An illustration of the passive jet areas in $\phi - \eta$ space for four different jet reconstruction algorithms. In the top left corner the passive area of the $k_T$-algorithm is shown, in the top right the area of C/A, in the bottom left the area of SISCone and in the bottom right the area of the anti-$k_T$.

The upper right plot shows the differential section of the two W’s that have decayed from the Z’ as a function of the transverse momentum. The other plots show how large the angular distance between the quarks from the same W is and how large the angular distance between the two W’s that come from the Z’ is. There are interesting facts that can be derived from figure 3.2.

- A large part of the quarks cannot be separated by small cones due to the fact that the quarks are too close.
- A large part of the W-bosons can be reconstructed in one jet if the cone/R size is large enough.
- A somewhat smaller part of the Z’-bosons can also be reconstructed in one jet with a large cone/R size.

Whatever the size of the cone is, there will always be events in which separate quarks will be reconstructed in separate jets. There will always be events in which hadronization products of two quarks, or even three or four quarks will be included in one cone. The latter effect can be very useful in the analysis of physics. Whether a jet with a large invariant mass comes from the decay products of a heavy particle can be studies by performing a substructure analysis. In the past years the substructure analysis of jets to reconstruct hadronically decaying heavy particles such as top-quarks, the Higgs boson or SUSY particles had a rapid development. These particle can in principle be reconstructed by using large jet cones or a large R-parameter. A disadvantage of using a large cone is that jets get more susceptible of particles from the usnderlying event and initial state radiation. In the following part two techniques to filter these QCD effect are explained.
Figure 3.2: Four plots that show the direction and the angular distance between the partons and the W's coming from the hard scattering simulated by Pythia8. The plot in the top left shows the $p_T$ distribution of the $Z'$ boson. The plot in the top right shows the $p_T$ distribution of the W-bosons that stem from the $Z'$. At the bottom left the $\Delta R$ distribution of the pair of quarks that stem from the same W-decay is shown. The last plot shows the $\Delta R$ distribution of the two W's that both stem from the $Z'$-decay.

3.4.1 Y-splitting

Y-splitting is a method that was first applied to SUSY and Higgs analyses in various articles. The studies reported in [29], [30] and [31] were all conducted using the $k_T$ algorithm while it was later recognized that a better mass resolution can be achieved by using the Cambridge/Aachen algorithm [32]. The idea is that when a jet originating from two decay products is reconstructed the last step will be the recombination of the the parton jets since the hadronization particles and QCD scattered particles will be closer to the partons than the partons are from each other. If after a potential W-jet is reconstructed the last step of the recombinations is undone, two protojets that approximately correspond to the two emitted partons of the W should be recovered. There are two conditions that can be used to check whether the two partons are recovered:

- A large decrease in invariant mass of the jets: $m_{j1} < \mu m_j$.
- The splitting should not be too asymmetric: $y = \frac{\min(p_{T1}^2, p_{T2}^2)}{m_j^2} \Delta_{j1,j2} > y_{cut}$; $j1$ is the heaviest subjet.

If one or both conditions is not fulfilled, the last recombination step of the heaviest subjet is made undone and the two conditions are again tested. This procedure is repeated until one either finds the two required subjets or one ends up with a heaviest jet that is outside the required mass window. If the two conditions are fulfilled, the procedure is wound up by further unclustering the jet until the angular distance between the particles is more than $R = \min(0.3, 0.5 R_{qq})$. The W can
be reconstructed by taking the three hardest protojets in the set, these should correspond to the two partons and the hardest gluon emission. The Y-splitting procedure was tested in [22], the result is shown in table 3.1. The Y-splitting procedure in combination with the C/A algorithm and with the $k_T$ algorithm was performed on a sample of HZ events and a background sample of Z+jets. In comparison the SISCone and the anti-$k_T$ algorithm were also used to reconstruct the same sample. The SISCone and anti-$k_T$ algorithms were not used with a Y-splitter because the SISCone is a cone algorithm on which the procedure cannot be applied. The anti-$k_T$ algorithm first recombines hard particles with softer ones. The algorithm does not tend to recombine the two partons in its last step but either much earlier or it does not recombine the two partons. Sub-structure analysis is likely to have less benefit when used with the anti-$k_T$ algorithm.

<table>
<thead>
<tr>
<th>Jet definition</th>
<th>$\sigma_S$(fb)</th>
<th>$\sigma_B$(fb)</th>
<th>$\sigma_S/\sqrt{\sigma_B}$(fb$^{0.5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A, R = 1.2</td>
<td>0.57</td>
<td>0.51</td>
<td>0.80</td>
</tr>
<tr>
<td>$k_T$, R = 1.0</td>
<td>0.19</td>
<td>0.74</td>
<td>0.22</td>
</tr>
<tr>
<td>SISCone, R = 0.8</td>
<td>0.49</td>
<td>1.33</td>
<td>0.42</td>
</tr>
<tr>
<td>anti-$k_T$, R = 0.8</td>
<td>0.22</td>
<td>1.06</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 3.1: Cross section for signal ($\sigma_S$) and the Z+jets background ($\sigma_B$ ) in the leptonic Z channel of HZ production at a 14 TeV LHC, for 200 < $p_T$ [GeV] < 600 and 110 < $m_J$[GeV] < 125, with perfect b-tagging; the C/A algorithm uses the procedure outlined in the text; the $k_T$ algorithm uses the first step of decomposition to identify two subjets with a cut on $y_{ij}$ as for C/A; SISCone and anti-$k_T$ do not use any subjet analysis, but each require two b-tags within the jet. In each case R has been chosen to give near optimal significance with that algorithm.

3.4.2 Pruning

While Y-splitting is a top-down procedure in which an original jet algorithm result is used to be further inspected, pruning [26] is a more bottom-up procedure. It makes use of the information that is gained from regular jet algorithm by selecting the interesting jets in a specific mass range. These jets are then reconstructed from the beginning but then with two additional conditions at every recombination $1,2 \rightarrow p$.

- $z < z_{cut}$, with $z = \frac{\min(p_T1,p_T2)}{p_Tp}$ and:

- $\Delta R_{j1,j2} > D_{cut}$

If both of these conditions are fulfilled, the softer jet is discarded. These conditions are grounded with arguments that come from QCD theory and can intuitively be understood. In section 1.2.3 it is explained that QCD effects are dominated by collinear and soft enhancements. Naively a cut would be expected on a maximum $z$ and a maximum $\Delta R$. Such cuts would also remove much FSR recombinations while these should be included. The goal of pruning is to reduce underlying event and pile-up effects as effective as possible to increase the mass resolution of the heavy resonance. The largest effects come from large $\Delta R$ combinations as the invariant mass is the highest for particles moving in opposite direction. Meanwhile, the last recombination of a heavy particle is often the recombination of the two parton-subjets and these also are expected to have a large $\Delta R$. The difference is that the parton-jets have comparable $p_T$ and $z$ is therefore not often much smaller than 0.5. The combination of putting a upper cut on $z$ and a lower cut on $\Delta R$ should therefore largely reduce the background effects in jets with large R-parameters. In a longer version
of their paper [33], S.D. Ellis, C.K. Vermillion and J.R. Walsh worked out elaborately why and how soft and collinear scattering can be distinguished from typical recombinations that occur at reconstruction of heavy particle decays. In the article, the algorithm was tested with the \( k_T \) and the C/A algorithms and a comparative study was performed with the jet \( p_T \) as a variable and for W and top reconstruction. One illustrative plot, that is shown in figure 3.4.2, is the multiplicity of recombinations as a function of \( z \) and \( R \) for QCD Jets with a \( p_T \) between 500 and 700 GeV. The left plot shows the recombinations in the C/A algorithm and the right plot shows the recombinations in the \( k_T \) algorithm. The metric of the latter is not independent of \( z \) and therefore there will be more recombinations with high \( z \) in the later stadium of the sequence. Especially the plot for the C/A algorithms shows that high-\( p_T \) QCD jets can effectively be reduced by using the proposed cuts. Typical values for the cuts are usually 0.1 when using pruning in combination with the C/A algorithm and 0.15 when using the \( k_T \)-algorithm. \( D_{cut} \) is typically chosen to be in the order of \( \frac{m_J}{p_T J} \), an argument for this value is that the angle between two partons that decayed from a heavy particle is proportional to \( 2 \frac{m_J}{p_T J} \).

Figure 3.3: Combined distribution in \( z \) and \( \Delta R_{12} \) for QCD jets, using the CA (left) and \( k_T \) (right) algorithms, for jets with \( p_T \) between 500 and 700 GeV with \( D = 1.0 \). Each bin represent a relative density, normalized to 1 for the largest bin.

Pruning was also compared to another substructure algorithm, the variable-R algorithm. The principle of this algorithm is that different cone algorithms are used. One with a large cone and then with decreasing cones to try to recover both the heavy particle in one cone and its decay products in smaller cones. The study showed that for the W reconstruction the C/A algorithm performs slightly better, especially for low \( p_T \) jets. Another important conclusion was that pruning never degrades the signal to background ratio and performs at least as good as variable-R algorithms and it is not useful to perform both algorithms on the same jets. A conclusion from the study is that pruning can be performed with a large \( R \) parameter.

### 3.5 Comparison of the Algorithms

It is not directly clear which algorithm is the best choice to reconstruct hadronic \( Z' \) events. The events are characterized by three high \( p_T \) W-bosons with. Each of these W’s can either be re-
constructed by catching the two parton jets in one jet cone/area definition, or by using smaller cones/area definitions and using the individual parton jets. Because of the high \( p_T \) of the W-bosons, the former method is probably more efficient because two parton jets will often have a large overlap. Larger jet areas are also more susceptible to the influence of underlying event particles and therefore are likely to have a smaller resolution. With substructure analysis the influence of QCD effects in the large jet areas (with a large \( R - \) parameter of the \( C/A \) and \( k_T \) algorithm can be reduced.

In this section the efficiency and the resolution of the SISCone, anti-\( k_T \), \( C/A \) and the \( k_T \) algorithms, with a small and a large area, will be tested by using a sample of purely hadronically decaying Z'-Strahlung events. The efficiency is defined as the percentage of events in which three W-bosons are reconstructed of which two have a combined invariant mass of 500 ± 10 GeV. The resolution is defined as the root mean square of the difference between the generated Z' mass and the reconstructed Z' mass.

3.5.1 Jet reconstruction in a clean environment

The first step is to produce the sample with only the hadronization and underlying event modeled as the beam remnants. Three different approaches are tested. The first is to use small jet areas with the purpose of reconstructing individual quarks. From these jets three W-bosons should be reconstructed and with two of those a Z' with a mass around five hundred GeV should be obtained. The complete algorithm can be written down as following:

- A loop is performed over all jets. If two jets have an invariant mass of 80.4 ± 5 GeV, their added four-vectors are regarded again as a W-jet.

- From the list of W-jets, two W's are subsequently tested to have a invariant mass of 500 ± 10 GeV. The combination that is closest to 500 GeV is regarded as the Z' particle.

- In the step above it is secured that two combined W's do not share the same jet in their reconstruction; there should also be at least 3 independent W's identified in every event.

  The second approach is applied on jet algorithms with R-parameters of 1.0 and only reconstructs events by using jets with a mass around the W-mass. The advantage of doing this might be that the background gets largely reduced. The algorithm for this approach is:

- If a jet has an invariant mass 80.4 ± 5 GeV it is defined as a W-jet.

- It is checked whether there are at least 3 W-jets identified.

- From the list of W-jets, two W's are subsequently tested to have a invariant mass of 500 ± 10 GeV. The combination that is closest to 500 GeV is regarded as the Z' particle.

The third approach is identical to the second, but with the difference that now only the \( C/A \) and \( k_T \) algorithms with Y-splitting and pruning are used.

The results are shown in three sets of four graphs that show the Z' resonance as reconstructed with small jets, large jets and large jets with subjet analysis 3.4,3.5 and 3.6. For the first two, the \( C/A \) algorithm, the \( k_T \) algorithm, the SISCone algorithm and the anti-\( k_T \) algorithm are used and for the third only for the \( C/A \) algorithm and the \( k_T \) algorithm. The efficiency and the resolution that are extracted from these graphs are also summarized in tables 3.5.1,3.5.1 and 3.4. The main conclusion is that reconstruction of the event with large jet areas is more efficient and has a higher
resolution in the scenario with no higher order corrections and no pile-up events. The reason that using small jets is inefficient for reconstructing Z’ events is because of the high $p_T$ of the W’s in the event. The reason that it has a good resolution is that there is a considerable amount of out-of-cone energy. Using subjet analysis does not increase the resolution in this scenario as there is not much QCD to filter from the jets.

Figure 3.4: The differential cross section for reconstructing the Z’ by using jet algorithms with R = 0.4 and requiring a corresponding quark (six jets). In the upper two graphs the C/A algorithm (left) and the $k_T$ algorithm (right) are used and in the lower graphs the SISCone (left) and the anti-$k_T$ (right) algorithms are used. It should be noted that the vertical scale is ten times smaller those of the graphs in figures 3.5 and 3.6. Both the resolution and the efficiency are worse than for the reconstruction with a larger R.

<table>
<thead>
<tr>
<th>Jet definition</th>
<th>Efficiency</th>
<th>Resolution (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A, R = 0.4</td>
<td>1.5 %</td>
<td>2.9</td>
</tr>
<tr>
<td>$k_T$, R = 0.4</td>
<td>1.6 %</td>
<td>2.9</td>
</tr>
<tr>
<td>SISCone, R = 0.4</td>
<td>0.74 %</td>
<td>2.9</td>
</tr>
<tr>
<td>anti-$k_T$, R = 0.4</td>
<td>1.5 %</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 3.2: The efficiency and resolution for reconstructing a Z’ by using small jet areas. The performance is worse than when using larger jet areas.

### 3.5.2 High luminosity reconstruction

In the previous section the default Pythia tune was used to create an underlying event as the background for the jets. In this section almost the same analysis will be performed but with a more
The differential cross section for reconstructing the $Z'$ by using three jets with invariant masses close to the $W$-mass. In the upper two graphs the C/A algorithm (left) and the $k_T$ algorithm (right) are used, while in the lower graphs these are SISCone (left) and anti-$k_T$ (right). All algorithms use $R = 1.0$. The C/A and the anti-$k_T$ algorithms show the highest peaks with the best resolution.

### Table 3.3

<table>
<thead>
<tr>
<th>Jet definition</th>
<th>Efficiency</th>
<th>Resolution (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A, $R = 1.0$</td>
<td>11.2 %</td>
<td>1.7</td>
</tr>
<tr>
<td>$k_T$, $R = 1.0$</td>
<td>10.2 %</td>
<td>1.9</td>
</tr>
<tr>
<td>SISCone, $R = 1.0$</td>
<td>9.1 %</td>
<td>1.9</td>
</tr>
<tr>
<td>anti-$k_T$, $R = 1.0$</td>
<td>9.6 %</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The efficiency and resolution for reconstructing a $Z'$ by using large jet areas to reconstruct complete $W$-bosons in one jet. The performance is considerably better than when only using jets to reconstruct the partons. The C/A algorithm performs the best of the four tested jet algorithms.

realistic background. Higher order corrections (parton showers) will be used as well as multiple parton interactions to model the underlying event and an average of five minimum bias events will be added to the event list to model a luminosity of about $2 \cdot 10^{33} cm^{-2} s^{-1}$. The only difference with the analysis that is used are the values for how the $W$- and $Z'$-bosons are defined. Because of the pile-up the reconstructed jets will have a larger energy and mass than the real bosons. For every jet algorithm this will be a different shift and therefore a different cut will be used for each different algorithm, depending on how it reconstructs $W$-bosons.

The resolution of the $W$-mass reconstruction can be measured by just plotting the invariant mass of all jets for the jets with a large area and plotting the mass of every combination of jets for
Figure 3.6: The differential cross section for reconstructing the Z' by using three jets with masses close to the W-mass and using subjet analysis. In the upper two graphs the C/A algorithm are combined with Y-splitting (left) and pruning (right). In the lower graphs the $k_T$ algorithm is combined with Y-splitting and (left) pruning (right) algorithms are used. All algorithms use $R = 1.0$. Only the combination of pruning and the C/A degrades the resolution of the peak. For the other algorithms the subjet analysis improves the resolution. The peak is also shifted somewhat to the left.

<table>
<thead>
<tr>
<th>Jet definition</th>
<th>Efficiency</th>
<th>Resolution (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A with Y-splitting, R = 1.0</td>
<td>8.8 %</td>
<td>2.3</td>
</tr>
<tr>
<td>C/A with pruning, R = 1.0</td>
<td>9.8 %</td>
<td>2.3</td>
</tr>
<tr>
<td>$k_T$ with Y-splitting, R = 1.0</td>
<td>9.4 %</td>
<td>2.3</td>
</tr>
<tr>
<td>$k_T$ with pruning, R = 1.0</td>
<td>10.5 %</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 3.4: The efficiency and resolution for reconstructing a Z' by using large jet areas together with subjet analysis to reconstruct complete W-bosons in one jet and filter QCD influences. The performance is in general somewhat degraded compared to the case in which no subjet analysis is performed. The reason for this is that only hadronization and the underlying event effects can be filtered out and relatively many vetos of the subjet analysis are signal recombinations.
larger area do show a clear W-resonance. The mean value of the peak is shifted with 15-30 GeV from the real W-mass value and the peaks have a broad width. Doing subjet analysis greatly increases the shape of the resonance. Y-splitting does not work well for the $k_T$-algorithm, though the other types of subjet analysis reduce the deviation from the real W-mass to 2-5 GeV and the width to only 10 GeV. The values that are shown in table 3.5.2.

![Graphs showing the invariant mass for every combination of two reconstructed jets for the C/A, $k_T$, SISCone and anti-$k_T$ algorithms (from upper left to bottom right) with small jet areas (R = 0.4). Note that the resonances of the W-boson are negligible, pointing at the high background.](image)

Figure 3.7: Four graphs showing the invariant mass for every combination of two reconstructed jets for the C/A, $k_T$, SISCone and anti-$k_T$ algorithms (from upper left to bottom right) with small jet areas (R = 0.4). Note that the resonances of the W-boson are negligible, pointing at the high background.

<table>
<thead>
<tr>
<th>Jet definition</th>
<th>W-peak mean</th>
<th>W-peak width (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A, R = 1.0</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>$k_T$, R = 1.0</td>
<td>110</td>
<td>30</td>
</tr>
<tr>
<td>SISCone, R = 1.0</td>
<td>95</td>
<td>15</td>
</tr>
<tr>
<td>anti-$k_T$, R = 1.0</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>C/A with Y-splitting, R = 1.0</td>
<td>85</td>
<td>10</td>
</tr>
<tr>
<td>C/A with Pruning, R = 1.0</td>
<td>82</td>
<td>10</td>
</tr>
<tr>
<td>$k_T$ with Y-splitting, R = 1.0</td>
<td>110</td>
<td>30</td>
</tr>
<tr>
<td>$k_T$ with pruning, R = 1.0</td>
<td>85</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.5: The mean values and the width of the W-peak in a Z' signal by using large jet areas with and without subjet analysis. The displayed values are also those that are used as the cuts for the W-bosons when reconstructing the Z'.
Figure 3.8: Four graphs showing the invariant mass of all reconstructed jets for the C/A, $k_T$, SISCone and anti-$k_T$ algorithms (from upper left to bottom right). The W-boson and $Z'$-boson resonances are clearly visible, though its peaks are shifted 15-30 GeV from the real W-mass value.
Figure 3.9: Four graphs showing the invariant mass of all reconstructed jets for the C/A and $k_T$ algorithms (upper and lower graphs), combined with Y-splitting and pruning (left and right graphs). Except for the combination of the $k_T$ algorithm with Y-splitting, the subjet analysis improves the resolution as well as the mean value of the resonances.
The full analysis is performed by using large jets with and without the substructure analysis. The results are presented in graphs 3.10 and 3.11 with corresponding tables 3.6 and 3.7.

When the reconstruction is done with large jet areas without subjet analysis, both the mean value of the Z'-mass and the resolution get approximately 30 GeV larger. The $k_T$ algorithm has a larger efficiency, but a degraded resolution and deviation from 500 GeV. The improved efficiency originates most probably from the pile-up background since after subjet analysis is performed, the efficiency is again on the same level as that of the C/A algorithm. The $k_T$ algorithm is especially vulnerable to pile-up events because it first recombines low-$p_T$ particles, after which the minimum bias influence cannot be distinguished anymore from higher $p_T$ signal particles. The other three algorithms perform about equally well and only show slight differences in their resolution and vulnerability to minimum bias influence.

Subjet analysis improves both the efficiency and resolution of the C/A and $k_T$ algorithms, except for the combination of Y-splitting and the $k_T$ algorithm. Especially pruning works surprisingly well. The deviation from the real mass is for the C/A algorithm improved with 23 GeV and for the $k_T$ algorithm even with 30 GeV. The combination of the C/A algorithm and pruning has with 3.9 GeV deviation from the real mass, the best reduction of the pile-up.

![Figure 3.10: The differential cross section for reconstructing the Z' by using large jet areas. In the upper two graphs the C/A algorithm (left) and the $k_T$ algorithm (right) are used and in the lower graphs the SISCone (left) and the anti-$k_T$ (right) algorithms are used. All algorithms use R = 1.0. Though the cross section is not much different than in the case of a the low luminosity scenario, the resolution is worse. Another difference is that due to the pile-up events the peak is shifted 23-38 GeV to the right.](image-url)
Table 3.6: The efficiency and resolution for reconstructing a Z' by using large jet areas. From this table it can be seen that except for the $k_T$ algorithm, the performance is not much different. The C/A and the anti-$k_T$ algorithms have a somewhat better resolution, while the SISCone algorithm produces a peak that is closer to the real Z'-mass.

<table>
<thead>
<tr>
<th>Jet definition</th>
<th>Efficiency</th>
<th>Resolution (GeV)</th>
<th>Deviation Z’ mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A, $R = 1.0$</td>
<td>10.4%</td>
<td>22.2</td>
<td>27.0</td>
</tr>
<tr>
<td>$k_T$, $R = 1.0$</td>
<td>12.9%</td>
<td>27.8</td>
<td>38.8</td>
</tr>
<tr>
<td>SISCone, $R = 1.0$</td>
<td>10.8%</td>
<td>25.8</td>
<td>23.4</td>
</tr>
<tr>
<td>anti-$k_T$, $R = 1.0$</td>
<td>10.8%</td>
<td>22.3</td>
<td>29.7</td>
</tr>
</tbody>
</table>

Figure 3.11: The differential cross section of reconstructing the Z' by using three jets with masses in the neighbourhood of the W-mass and using subjet analysis. In the upper two graphs the C/A algorithm is combined with Y-splitting (left) and pruning (right). In the lower graphs the $k_T$ algorithm is combined with Y-splitting and (left) pruning (right) algorithms are used. All algorithms use $R = 1.0$. Only the combination of Y-splitting and the $k_T$ algorithm does not significantly improve the resolution or the influence from pile-up. For the other algorithms the subjet analysis improves the resolution, while the largest improvement is for the combination of the $k_T$ algorithm with Y-splitting.

3.5.3 Background

It is not only important how a jet algorithm reconstructs the signal, how the background is reconstructed is at least as important. A jet algorithm that scores high on its efficiency to reconstruct the signal may as well mis-reconstruct the background just as “efficient”. Because pruning showed promising results in reconstructing the signal and rejecting background influence from pile-up, both
Table 3.7: The efficiency, resolution and the deviation from the Z'-mass of reconstructing a Z' by using large jet areas together with subjet analysis. The efficiencies are somewhat lower because the background hits are filtered out. The resolution and especially the deviation from the real Z' mass is largely improved compared to the case in which no subjet analysis is performed. The combination of the $k_T$ algorithm with pruning performs the best.

the $k_T$ and the C/A algorithms together with pruning will be tested on the background processes as listed in table 3.5.3. Of every process a distribution of the Z-mass and the jet-mass for both the C/A and the $k_T$ algorithms is presented in the figures 3.12,3.13,3.14,3.15, 3.16 and 3.17. The reconstruction procedure is exactly equal to the procedure that is used for the Z'-signal. The background influence is estimated from the reconstructed Z'-mass distribution. For the C/A algorithm the signal is defined as the cross section of the hits in the bins between 494 and 514 GeV. For the $k_T$ algorithm the bounds 500 and 520 GeV are taken. At the end a summary of the background influence of every process for both algorithms and methods is listed in table 3.5.3.

Table 3.8: The cross sections of the signal and the used background processes. In all hard processes an additional phase space cut in the total invariant mass was applied of 400 GeV and only full hadronic decays are included.
Figure 3.12: The left plots show the differential cross section for mis-reconstructing QCD jets with a $p_T$ between 140 and 280 GeV at a luminosity of $2\times10^{33} s^{-1} cm^{-2}$ as a $Z'$. No kinematical cuts are used except for the definition of the W and the triggering cuts. The upper graph shows how the C/A in combination with pruning performs while the lower graph shows how the $k_T$ performs together with pruning. The right graphs show the differential cross sections for the mass of all reconstructed jets.
Figure 3.13: The left plots show the differential cross section for mis-reconstructing QCD jets with a $p_T$ between 280 and 560 GeV at a luminosity of $2 \times 10^3 s^{-1} cm^{-2}$ as a $Z'$. No kinematical cuts are used except for the definition of the W and the triggering cuts. The upper graph shows how the C/A in combination with pruning performs while the lower graph shows how the $k_T$ performs together with pruning. The right graphs show the differential cross sections for the mass of all reconstructed jets.
Figure 3.14: The left plots show the differential cross section for mis-reconstructing QCD jets with a $p_T$ between 560 and 1120 GeV at a luminosity of $2 \times 10^{33} s^{-1} cm^{-2}$ as a $Z'$. No kinematical cuts are used except for the definition of the W and the triggering cuts. The upper graph shows how the C/A in combination with pruning performs while the lower graph shows how the $k_T$ performs together with pruning. The right graphs show the differential cross sections for the mass of all reconstructed jets.
Figure 3.15: The left plots show the differential cross section for mis-reconstructing single W-events at a luminosity of $2 \cdot 10^{33} \text{s}^{-1} \text{cm}^{-2}$ as a $Z'$. No kinematical cuts are used except for the definition of the W and the triggering cuts. The upper graph shows how the C/A in combination with pruning performs while the lower graph shows how the $k_T$ performs together with pruning. The right graphs show the differential cross sections for the mass of all reconstructed jets. The process does not seem to be a considerable background.
Figure 3.16: The left plots show the differential cross section for mis-reconstructing double W-events with a $p_T$ between 0 and 100 GeV at a luminosity of $2 \times 10^{33} \text{s}^{-1} \text{cm}^{-2}$ as a $Z'$. No kinematical cuts are used except for the definition of the W and the triggering cuts. The upper graph shows how the C/A in combination with pruning performs while the lower graph shows how the $k_T$ algorithm together with pruning performs. The right graphs show the differential cross sections for the masses of all reconstructed jets.
Figure 3.17: The left plots show the differential cross section for mis-reconstructing double W-events at a luminosity of $2 \cdot 10^{33} \text{s}^{-1} \text{cm}^{-2}$ as a $Z'$. No kinematical cuts are used except for the definition of the W and the triggering cuts. The upper graph shows how the C/A in combination with pruning performs while the lower graph shows how the $k_T$ algorithm together with pruning performs. The right graphs show the differential cross sections for the mass of all reconstructed jets.
Table 3.9: The signal over background and signal over the square root of background of the background processes.

From Table 3.5.3 it can be seen that the largest background processes are QCD jets with a $p_T$ range between 140 and 560 GeV. If these background processes can be suppressed, the hadronic channel of $Z'$-strahlung will be a promising channel to resolve the $Z'$-resonance. Another important result is that the background hits of every background process are lower for the C/A algorithm in combination with pruning than for the $k_T$ algorithm with pruning. This means the resolution, the peak height, the deviation of the mean value of the peak from the real $Z'$-mass are better for the C/A algorithm and that the background is also lower for the C/A algorithm.

3.6 Summary & Conclusions

A broad collection of jet reconstruction has been studied with the purpose of determining which algorithm provides the best discovery potential for a $Z'$.

Jet algorithms can be divided into cone algorithms and sequential recombination algorithms. In the first, jets are defined by all particles that fall inside a cone with a defined radius starting at an initial seed. The initial direction of the cone is defined by the direction of an initial seed particle. The summation of all particles within the cone provides a new seed, from which an improved cone axis direction can be extracted. This procedure is iterated until a stable cone is found, which direction coincides with the direction of the vector summation of all particles in the cone. A problem of these algorithms is its infrared unsafety. The addition of a collinear or low-energetic splitting of a particle can result in a radical change of the jet directions and magnitudes. A solution was provided by introducing a method in which all particles are sequentially used as a seed (SISCone).

The sequential recombinations make use of a defined metric through which the distance between two particles can be calculated. The two closest particles are recombined into a protojet and this is iterated until there are no protojets that are closer than a certain maximum. The three most well-known algorithms are the Cambridge/Aachen (C/A) algorithm, the $k_T$-algorithm and the anti-$k_T$ algorithm. The metric of (C/A) is just $\Delta R$, of $k_T$ is $\min(k_T) \cdot \Delta R$ and of anti-$k_T$ it is $\min(\frac{1}{k_T}) \cdot \Delta R$. It can be said that the latter behaves very similar to cone-algorithms. Its passive area (the area in which a ultra-soft particle would still be included in the jets) is a perfect circle in $\eta$-$\phi$ space. A useful property of the C/A and $k_T$ algorithms are that the jets can be further analysed by applying subjet analysis to the results.

Two subjet algorithms are evaluated in this chapter. Undoing the last recombination to check whether the mass drop is large enough and whether the two subjets are pointing far enough from each other is called Y-splitting. The pruning algorithm is bottom-up. It discards all recombi-
nations in which the transverse momentum proportion of two protojets is too large and the angle between them is above a certain threshold.

Important properties of jet algorithms that are tested are:

- The efficiency with which the signal gets reconstructed.
- The resolution of the reconstructed signal.
- The amount of background that is picked up.
- The complexity of the algorithm, or how much CPU-power is needed for its application.

The last item of the list is not tested in this thesis, but this was already done in [22]. The result of the study is shown in figure 3.18. A remarkable fact is that the sequential algorithms are even faster than the relatively simple cone algorithms. This is only true if the sequential algorithms are performed by the Fastjet software [34] that applies Voronoi diagrams [35] to improve the speed. The diagram in figure 3.18 shows that is not necessary anymore to use a cone algorithm because of speed.

![Figure 3.18: Timings for the clustering of a simulated 50 GeV dijet event, to which increasing numbers of simulated minimum-bias events have been added (both simulated with Pythia). In dark colours one sees SISCone and the FastJet kt implementation (with automatic optimal choice been N n and N ln N strategies), while in grey one sees results for the KtJet implementation [56] of the the kt algorithm, the Midpoint cone (ICmp -SM) in CDFs implementation (with and without a 1 GeV cutoff on seeds) and the JetClu iterative cone (ICr -SM, with a 1 GeV seed threshold). All non-FastJet algorithms (except KtJet) have been accessed through FastJet plugins.](image)

To give a clear overview of the testing results with regards to the signal and background reconstruction in a low luminosity and a high luminosity scenario, all relevant parameters are summarized in tables 3.10 and 3.11 for the default algorithms and for the subjet algorithms. Only the most promising algorithms, the C/A and $k_T$ algorithms together with pruning, were applied on the background. The $k_T$ version has a background reconstruction of about 80% higher, a larger mass shift due to pile-up and a resolution that is worse than that of the C/A in combination with pruning. $k_T$ in combination with pruning does have a better reconstruction efficiency, although this is only
of order 20 %. From these measurements the conclusion can be drawn that: *The C/A algorithm combined with pruning is the most effective algorithm to reconstruct hadronic Z'-stralung events.*

In the next chapter the following topics will be studied:

- Kinematic cuts.
- Reconstruction at high (10^{34} cm^{-2}s^{-1}) luminosity.
- The discovery potential for Z'-bosons of different masses.

<table>
<thead>
<tr>
<th></th>
<th>SISCone</th>
<th>anti-(k_T)</th>
<th>C/A</th>
<th>(k_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No pile-up</strong></td>
<td>Efficiency (%)</td>
<td>9.1</td>
<td>9.6</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>Resolution (GeV)</td>
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<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>5 Minimum bias events</strong></td>
<td>Efficiency (%)</td>
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<td>10.8</td>
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<td></td>
<td>Resolution (GeV)</td>
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<td></td>
<td>Mass shift (GeV)</td>
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<td>29.7</td>
<td>27.0</td>
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</tbody>
</table>

Table 3.10: *A summary of the performance of the four default jet algorithms for Z' reconstruction. The analysis was performed for a Z'-mass of 500 GeV.*

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<tr>
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<th>C/A-Y</th>
<th>C/A-P</th>
<th>(k_T)-Y</th>
<th>(k_T)-P</th>
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<td><strong>No pile-up</strong></td>
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<td>9.8</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>Resolution (GeV)</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>5 Minimum bias events</strong></td>
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<tr>
<td></td>
<td>Resolution (GeV)</td>
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<td>16.9</td>
<td>27.8</td>
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<tr>
<td></td>
<td>Mass shift (GeV)</td>
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<td>3.9</td>
<td>37.9</td>
</tr>
<tr>
<td></td>
<td>Total background (\sigma) (pb)</td>
<td>-</td>
<td>1.17</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.11: *The performance of four combinations of subjet algorithms for Z' reconstruction. The analysis was performed for a Z'-mass of 500 GeV.*
Chapter 4

Z’ Topology

4.1 introduction

In the previous chapter an introductory study was performed to build a foundation for which jet algorithm should be used to detect a Z’ resonance. An approximation was made of the signal-to-background ratio based on Pythia 8 Monte Carlo data on which only the trigger cuts and the Z’ reconstruction algorithm was applied. The analysis of hadronic Z’-strahlung events should be extended with several aspects, to be:

- Applying kinematical cuts to improve the signal-to-background ratio.
- Testing a separate analysis procedure in which all decay products of the Z’ are caught in one jet.
- Analyzing the influence of the mass of the Z’.
- Doing the analysis on Monte Carlo samples with more added minimum bias events to test the influence of the highest luminosities.
- Performing a detector analysis on both the background and signal.

The first four topics will be covered in this chapter. The chapter is divided in two sections, one for the indirect measurement of the Z’ and one for the direct measurement of the Z’. In the first section the method in which the three W-bosons in the Z’-event are matched to three separate jets is evaluated. This method can be described as following:

- Three jets with each a mass of $82 \pm 10$ GeV should be reconstructed.
- The two jets with an invariant mass that is closest to the Z’ mass (variable if one does not know the mass on beforehand) are denoted as W1 and W2.
- If there are more than three jets with a W-boson mass detected, the one that is most opposite to the Z’-direction is denoted as W3.

In the second section, the method in which the Z’ is reconstructed directly from a single massive jet is discussed. This method can be described as:

- A massive jet with a mass around the searched-for Z’ mass should be detected.
• A second jet with its mass around the W-mass \( (82 \pm 10 \text{ GeV}) \) can be used to cut the background.

From here on the two methods will be referred to as the “direct” and the “indirect” method. In both chapters the influence of the mass of the \( Z' \) and high luminosity effects on the reconstruction procedure are discussed separately. In both sections the standard reconstruction is for a luminosity of \( 10^{33} \text{cm}^{-2}\text{s}^{-1} \).

In the section of the indirect method the kinematics of the \( Z' \) events and its background will be discussed in detail. It turns out that kinematical cuts in \( \eta \)-space are not useful for our purpose. The choice for using the \( p_T \) of the four bosons in a \( Z' \) event to cut away the background is grounded and it is explained how the optimal cuts are calculated. The \( Z' \)-mass resonances are calculated together with their background for three different masses with and without the addition of extra pile-up to simulate the highest luminosity. The resonances are reconstructed for different numbers of integrated luminosities to show the evolution in time. A conclusion of the section is that by using the indirect method a reconstruction of a \( Z' \) with a mass of 500 GeV or heavier should be possible, whereas a \( Z' \) with a mass significantly lower than 500 GeV will be more difficult.

In the third section about the direct method the choice for the kinematical cuts is briefly explained by showing the kinematics of the background and the signal. The resonances are again reconstructed for two different luminosities, for a \( Z' \) of 300 GeV and 500 GeV and also for different integrated luminosities. An important conclusion of this section is that a \( Z' \) can be reconstructed by the direct method for masses of 500 GeV or lighter.

### 4.2 Indirect measurement of the \( Z' \)

How the kinematical cuts should be applied in the reconstruction of \( Z' \) events should be based on the knowledge of the kinematics of both \( Z' \) events and its background. The differential cross section of in total eight variables will be tested:

- \( p_T \) of the reconstructed \( Z' \).
- \( \eta \) of the reconstructed \( Z' \).
- \( p_T \) of both of the reconstructed W’s coming from the \( Z' \).
- \( \eta \) of both of the reconstructed W’s coming from the \( Z' \).
- \( p_T \) of the reconstructed third W.
- \( \eta \) of the reconstructed third W.

In total there are eight kinematical variables on which cuts can be applied to improve the signal-to-background ratio. Assuming that only cuts with either an upper limit or a lower limit will be applied, the signal over the background and the signal over the root of the background can be written as a function of eight variables: \( \frac{S(x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8)}{\sqrt{B(x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8)}} \). To determine the optimal cuts is therefore a complex process. Especially if additional to the optimal ratio of the signal and the background also a lower bound on the number of signal hits is demanded. To start with, each of the distributions of the background and the signal for each of the kinematical variables can be plotted in one graph for every background process. The plots for the \( \eta \)-distributions are separated from the plots for the \( p_T \)-distributions. The \( \eta \)-distributions are shown in 4.6, 4.7, 4.8, 4.9, 4.10. The \( p_T \)-distributions are shown in 4.1, 4.2, 4.3, 4.4, 4.5.
Figure 4.1: The differential cross sections for the $\eta$ distributions of both the signal and the QCD background with a $p_T$ between 140 and 280 GeV for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. $W_1$, $W_2$ and $W_3$ refer to the the hardest $W$-boson coming from the decayed $Z'$ ($W_1$), the softest $W$-boson coming from the $Z'$ ($W_2$) and the $W$-boson from the $Z'$ was radiated ($W_3$). A conclusion is that cuts $\eta$ cannot be used to differentiate between signal and background.
Figure 4.2: The differential cross sections for the $\eta$ distributions of both the signal and the QCD background with a $p_T$ between 280 and 560 GeV for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the the hardest W-boson coming from the decayed Z' (W1), the softest W-boson coming from the Z' (W2) and the W-boson from the Z' was radiated (W3). A conclusion is that cuts $\eta$ cannot be used to differentiate between signal and background.
Figure 4.3: The differential cross sections for the $\eta$ distributions of both the signal and the QCD background with a $p_T$ between 560 and 1120 GeV for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the the hardest W-boson coming from the decayed Z' (W1), the softest W-boson coming from the Z' (W2) and the W-boson from the Z' was radiated (W3). A conclusion is that cuts $\eta$ cannot be used to differentiate between signal and background.
Figure 4.4: The differential cross sections for the $\eta$ distributions of both the signal and the ttbar background for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the the hardest W-boson coming from the decayed Z' (W1), the softest W-boson coming from the Z' (W2) and the W-boson from the Z' was radiated (W3). A conclusion is that cuts $\eta$ cannot be used to differentiate between signal and background.
Figure 4.5: The differential cross sections for the $\eta$ distributions of both the signal and the double-W background for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the hardest W-boson coming from the decayed Z' (W1), the softest W-boson coming from the Z' (W2) and the W-boson from the Z' was radiated (W3). A conclusion is that cuts $\eta$ cannot be used to differentiate between signal and background.
Figure 4.6: The differential cross sections for the $p_T$ distributions of both the signal and the QCD background with a $p_T$ between 140 and 280 GeV for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the the hardest W-boson coming from the decayed $Z'$ (W1), the softest W-boson coming from the $Z'$ (W2) and the W-boson from the $Z'$ was radiated (W3). QCD-background with a $p_T$ below 560 GeV can be eliminated by just using vetos for reconstructed bosons with a $p_T$ below a certain threshold.
Figure 4.7: The differential cross sections for the $p_T$ distributions of both the signal and the QCD background with a $p_T$ between 280 and 560 GeV for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the the hardest W-boson coming from the decayed Z' (W1), the softest W-boson coming from the Z' (W2) and the W-boson from the Z' was radiated (W3). QCD-background with a $p_T$ below 560 GeV can be eliminated by just using vetos for reconstructed bosons with a $p_T$ below a certain threshold.
Figure 4.8: The differential cross sections for the $p_T$ distributions of both the signal and the QCD background with a $p_T$ between 560 and 1120 GeV for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the the hardest W-boson coming from the decayed Z' (W1), the softest W-boson coming from the Z' (W2) and the W-boson from the Z' was radiated (W3). QCD-background with a $p_T$ that is higher than 560 GeV can strongly be reduced by just using vetos for reconstructed bosons with a $p_T$ below a certain threshold.
Figure 4.9: The differential cross sections for the $p_T$ distributions of both the signal and the QCD background with a $p_T$ between 140 and 280 GeV for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the the hardest W-boson coming from the decayed Z' (W1), the softest W-boson coming from the Z' (W2) and the W-boson from the Z' was radiated (W3). $t\bar{t}$-background can strongly be reduced by just using vetos for reconstructed bosons with a $p_T$ below a certain threshold.
Figure 4.10: The differential cross sections for the $p_T$ distributions of both the signal and the QCD background with a $p_T$ between 140 and 280 GeV for eight different kinematical variables. The signal is printed in red, while the background is printed in blue. W1, W2 and W3 refer to the hardest W-boson coming from the decayed Z' (W1), the softest W-boson coming from the Z' (W2) and the W-boson from the Z' was radiated (W3). double-W background can be eliminated by just using vetos for reconstructed bosons with a $p_T$ below a certain threshold.
From the signal/background graphs a number conclusions can be drawn:

1. A cut in the $p_T$ of the $Z'$ can eliminate all background processes except for the hardest QCD-jets.

2. Combined cuts in the $p_T$ of the two W’s can be effective in improving the signal-to-background ratio.

3. Because the difference in $p_T$ between the $Z'$ and its most opposite W is in general smaller for the background than for the signal, cuts on this variable may not prove to be very useful.

4. Cuts in the $\eta$-distributions of the bosons, especially of the $Z'$, may be used to slightly improve the signal-to-background ratio. It cannot be expected that these results will be dramatically differentiating though.

The next step in the process is to find the optimal cuts. The strategy to find these is to first focus on the four different $p_T$ cuts that can be used. Every variable will be tested for 20 values, which makes 160,000 calculations of the signal-to-background ratio. The following ranges will be used:

- Hardest W from the $Z'$: 200-1200 GeV.
- Softest W from the $Z'$: 67 % - 100 % of the Hardest W.
- Third W: 180-1180 GeV.
- $Z'$: 180-1180 GeV.
4.2.1 Removing the background

From these calculations an optimal combination of cuts can be picked, depending on what variables should be maximised. A logical choice is to maximise the ratio of the signal over the square-root of the background. This already gives a very promising result. With the cuts that are listed below, the ratio should already be 2.6 after a year of data-collection at a luminosity of $10^{33} \text{cm}^{-2}\text{s}^{-1}$. With these cuts about 10 signal events should have passed the cuts:

- Hardest W from the $Z'$: 200 GeV.
- Softest W from the $Z'$: 185 GeV.
- Third W: 980 GeV.
- $Z'$: 980 GeV.

There are many combinations possible through which decent ratios can be achieved. Figure 4.11 shows the optimal $\frac{S}{\sqrt{B}}$ that can be reached for the amount of minimal signal hits that is required to pass the cuts. It shows that even with relative loose cuts, in which more than half of the signal events still pass through, in a year a $\frac{S}{\sqrt{B}}$ ratio of more than 1.0 can be achieved.

![Figure 4.11](image)

Figure 4.11: For every number of minimal signal events that is required to pass the cuts, the optimal $\frac{S}{\sqrt{B}}$ is plotted. It shows that even with relative loose cuts, a promising signal-to-background ratio can be achieved.

Figure 4.12 shows that additional cuts in the pseudorapidity will not significantly reduce the background in relation to the signal. When applying the most efficient $p_T$ cuts, the $\frac{S}{\sqrt{B}}$ after one year of data-taking is plotted for additional cuts in the four $\eta$ variables. Slight improvements could be achieved, though these cuts are also sensitive and could just as well decrease the signal more than the Monte Carlo simulations suggest.

Finally, it is interesting to know which processes are still a background after the kinematical cuts are applied. This is shown in figure 4.13. The figure shows that an integrated luminosity of 30 $fb^{-1}$ should be more than enough to exclude or confirm the existence of the hadronic decay channel of $Z'$-Strahlung.
Figure 4.12: For approximately one year of data-taking, the pseudorapidity distributions of the signal are divided by that of the background. It shows that additional cuts in the pseudorapidity will not significantly improve the signal-to-background ratio. The large values at $\eta = 3$ are the result of statistical fluctuations at the boundaries.

Figure 4.13: After the kinematical cuts are performed, an estimation of how the $Z'$ resonance would look after the LHC would have collected an integrated luminosity of 30, 60 and 150 inverse femtobarn. The signal hits are shown in red, the $t\bar{t}$ hits in green, the WW in blue and the QCD in yellow.
4.2.2 \(Z'\) mass influence

Up to this point, all calculations have been done together with the assumption that the \(Z'\) is 500 GeV. In reality, the only knowledge about the mass of the \(Z'\) is that it is most probable that it lies somewhere between 300 and 900 GeV. In this section, the analysis will be repeated for the most extreme cases: where the mass is 300 and 900 GeV. There are multiple things of influence on the question whether a \(Z'\) with higher or a lower mass is also detectable. The following aspects can be listed:

- The cross section of the process.
- The \(p_T\) of the \(Z'\).
- The angle between the decay products of the \(Z'\), which is dependent on the mass and the \(p_T\) of the \(Z'\) by: \(\sim \frac{m_{Z'}}{p_T}\).

The cross section and the distribution of the \(p_T\) of the \(Z'\) are shown in figures 1.16 and 1.17. The cross section of \(Z'\)-Strahlung with a \(Z'\)-mass of 300 GeV is about ten times larger than that of \(Z'\)-Strahlung with a \(Z'\)-mass of 900 GeV. The \(p_T\) distributions of the \(Z'\) are similar for different masses. The angle between the decay products of the \(Z'\) will therefore be larger for heavier \(Z'\)-bosons. The \(p_T\) of the W-bosons that originated from the \(Z'\) will on average have a higher \(p_T\) for \(Z'\)-bosons with a higher mass because of the Lorentz-boost coming from the mass-drop. The angle between the decay products of the two W-bosons will therefore again be smaller for \(Z'\)-bosons with a higher mass and therefore also be easier to detect. The hypothesis therefore is that for small \(Z'\)-masses, the direct detection will be a more efficient method, whereas for higher \(Z'\)-masses the indirect detection method will be more efficient. This hypothesis is grounded by figure 4.14, in which the jet-mass spectrum is plotted for hadronic \(Z'\)-Strahlung events with a \(Z'\)-mass of 300, 500 and 900 GeV. The figure shows that the cross section of reconstructing a jet with a mass around the \(Z'\)-mass is about ten times larger for a \(Z'\) of 300 GeV than for a \(Z'\) of 500 GeV. For a \(Z'\) of 900 GeV it is even negligible. The resonances at the W-mass are far less diverted. The resonance for the 300 GeV \(Z'\) is about 8 times larger than that of the 900 GeV \(Z'\).

To investigate whether high- and low-mass \(Z'\)-bosons can also be detected through the indirect method, the same analysis will be applied as it is done for a 500 GeV \(Z'\). The kinematical variables that will be used to cut the background are the \(p_T\) of the three W’s and the \(p_T\) of the \(Z'\). In figure 4.15 three distributions are shown transparently for a \(Z'\)-mass of 300 GeV (blue), 500 GeV (red) and 900 GeV (green). The distributions for the background remain the same as for the 500 GeV case.

Figure 4.15 shows that when using the same kinematical cuts for the case that the \(Z'\) would be 900 GeV as for the case that it would be 500 GeV works well, the result is shown in figure 4.16. A smaller percentage of the total number of signal events are cut away which can compensate for the smaller cross section. Though if the \(Z'\) would be 300 GeV, the proposed cuts are certainly too tight since the vast majority of the signal would also be cut away. Looser cuts could be chosen specially to search for a low-mass \(Z'\). The following cuts lead to \(\frac{S}{\sqrt{B}} \sim 1\) after 30 inverse femtobarn of LHC data:

- Minimum \(p_T\) of the hardest W that originated from the \(Z'\): 200 GeV
- Minimum \(p_T\) of the softest W that originated from the \(Z'\): 190 GeV
- Minimum \(p_T\) of the third W: 500 GeV
Figure 4.14: The jet mass-spectrum for $Z'$-Strahlung events with a $Z'$-mass of 300 GeV (blue), 500 GeV (red) and 900 GeV (green). The lower the mass of the $Z'$, the easier it is to detect the particle directly from jet reconstruction.

- Minimum $p_T$ of the $Z'$: 500 GeV

A visualization of how the resonances of a 300 GeV $Z'$ would look after a data-collection of 30, 60 and 150 inverse femtobarn is shown in figure 4.17. It shows that the indirect method is not that successful for low-mass $Z'$ reconstruction, because of its relative high background. Nonetheless, even through this reconstruction method, with adjusted cuts, an isolation of the resonance is still possible.
Figure 4.15: After the kinematical cuts are performed, an estimation of how the $Z'$ resonance would look after the LHC would have collected an integrated luminosity of 30, 60 and 150 inverse femtobarn. The signal hits are shown in red, the $t\bar{t}$ hits in green, the WW in blue and the QCD in yellow.

Figure 4.16: After the kinematical cuts are performed, an estimation of how the resonance of a $Z'$ with mass 900 GeV would look after the LHC would have collected an integrated luminosity of 30, 60 and 150 inverse femtobarn. The signal hits are shown in red, the background in blue. The collected signal hits for a $Z'$ of 900 GeV are almost as many as for a $Z'$ of 500 GeV when using the same method.
Figure 4.17: After the kinematical cuts are performed, an estimation of how the resonance of a $Z'$ with mass 300 GeV would look after the LHC would have collected an integrated luminosity of 30, 60 and 150 inverse femtobarn. The signal hits are shown in red, the background in blue. The hits were collected with looser cuts than the hits that were collected in figures 4.16 and 4.13. Although there are almost as many signal hits as when the $Z'$ has a higher mass, the background hits are also abundantly present.
4.2.3 High luminosity

As the luminosity increases, so does the pile-up in the calorimeters. The highest luminosity that will be reached at the LHC is $10^{34}\text{cm}^{-2}\text{s}^{-1}$. If the upgrade to the super LHC would become reality, a luminosity of even ten times higher would become possible. The latter scenario will not be discussed here. At a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$, the pile-up can be simulated by adding 23 minimum bias event to every hard scattering event. This can be on influence on multiple variables. The resolution of the signal will deteriorate and certain processes can become a (larger) background where they were not at lower luminosities. Also the mass of a jet coming directly from a W-boson is on average a few GeV heavier. At high luminosity a W-jet is defined as $85 \pm 10\text{ GeV}$.

In this section the same line of analysis will be used as above. In figures 4.18, 4.19 and 4.20 the $p_T$-distributions of the detected bosons are plotted for all the background processes together with the $p_T$ distributions of the detected bosons in the signal events. The QCD-process are plotted together in one figure. It shows that it becomes increasingly difficult at higher luminosities to isolate signal events by just using kinematical cuts.

![Figure 4.18](image)

Figure 4.18: In the four graphs the $p_T$ distributions for the kinematical variables of the QCD background samples and of the signal at a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ are plotted. The blue histogram is for QCD events with a total $p_T$ between 140 and 280 GeV, the green for events with a total $p_T$ between 280 and 560 GeV and the yellow for the events with a $p_T$ between 560 and 1120 GeV. The red histogram shows the distributions of the signal events. The figures show that an increased luminosity also increases the difficulty of separating the background and signal by using kinematical cuts.

Although it seems that a full isolation has become difficult, applying the same kinematical cuts that are used at lower luminosities is still sufficient. In figure 4.21 the $Z'$ resonance for a $Z'$ of 500
Figure 4.19: In the four graphs the $p_T$ distributions for the kinematical variables of the double-W background sample and of the signal at a luminosity of $10^{34} s^{-1} cm^{-2}$ are plotted. The blue histogram is for the double-W events and the red histogram shows the distributions of the signal events. For the double-W background, the higher luminosity does not create a difficulty.

GeV is shown after an integrated luminosity of 30, 60 and 300 inverse femtobarn. The background is only an extrapolation of the total background that passed the cuts after 30 inverse femtobarn and is most probably over-estimated. The resonances are not that clear as with the same integrated luminosity that is acquired at lower luminosity. The small degradation of the signal is compensated by the fact that data is acquired ten times faster. For example, 300 inverse femtobarn can be acquired in little more than a year. The deviation from the real $Z'$-mass is about 7 GeV.
Figure 4.20: In the four graphs the $p_T$ distributions for the kinematical variables of the $t\bar{t}$ background sample and of the signal at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ are plotted. The blue histogram is for the $t\bar{t}$ events and the red histogram shows the distributions of the signal events. The figure shows that the $t\bar{t}$ background becomes more difficult to discard by using kinematical cuts at higher luminosities.

Figure 4.21: In the three graphs the $Z'$ resonance is shown for 30, 60 and 300 inverse femtobarn for data that is acquired at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. Although the first two resonances are not as well shaped as with the data that is acquired at lower luminosity, the resonance peak grows much faster. The third graph resembles the data that is acquired after about a year of data-taking.
Different masses at high luminosity

To be complete, the indirect method at high luminosity will also be tested for \( Z' \)-masses of 300 and 900 GeV. The kinematical distributions are omitted, but it is interesting to check whether a \( Z' \) of 300 GeV can still be reconstructed using this method at high luminosity, whereas at lower luminosities it is already somewhat difficult. For a \( Z' \) of 900 GeV it is interesting to see what the deviation from the real mass is that the reconstructed \( Z' \) has. The results are shown in figures 4.22 and 4.23. The former shows how a \( Z' \) of 300 GeV would be reconstructed. The cuts that are used at lower luminosity for a low-mass \( Z' \) are also used here. It shows that even after a year of data-taking at the highest luminosity, a certain discovery would not be possible with this method. The second figure shows that a \( Z' \) of 900 GeV could be reconstructed without background influence. The reconstruction of the signal gets somewhat degraded because of the pile-up and it would take for about a year to see a clear resonance with a peak height of around 20 hits/GeV. The deviation from the real mass is again around 7 GeV.

Figure 4.22: The reconstructed mass of the signal (red) and background (blue) of a \( Z' \) of 300 that is reconstructed with the indirect method at a luminosity of \( 10^{34}\text{cm}^{-2}\text{s}^{-1} \) after 30, 60 and 300 inverse femtobarn data is collected. At none of the integrated luminosities, the signal can be clearly isolated from the background.
Figure 4.23: The reconstructed mass of the signal of a Z' of 900 that is reconstructed with the indirect method at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ after 30, 60 and 300 inverse femtobarn data is collected. A negligible number of background events that pass the kinematical cuts have a reconstructed Z'-mass in the neighbourhood of 900 GeV. To perform a good measurement of the Z'-mass, about a year of taking should take place.
4.3 Direct measurement of the Z’

Another method to reconstruct the Z’ resonance is to demand that a jet itself should have a mass of around the Z’ mass. Additionally it may be required that the third W-boson is reconstructed in a separate jet that should have a mass around 80 GeV. This method only reconstructs the events in which the $p_T$ of the Z’ is higher than 1000 GeV because at lower $p_T$ the two W’s are not collimated enough to be reconstructed in one jet. The trigger condition that can be used is for example two jets of 160 GeV that is in the proposed L33 trigger menu of ATLAS. The background of this method are hadronic $t\bar{t}$ events and the QCD jet events with a $p_T$ between 560 and 1120 GeV. In other background samples the cross section of reconstructing a jet with a mass of 500 GeV is negligible. Just as in section 4.2, first an overview of the kinematical variables of the two background samples and the signal is presented in figures 4.24 for the $t\bar{t}$ sample and in figure 4.25 for the QCD jets sample. The kinematical variables that are used to put cuts on are the $p_T$ and the pseudorapidity of both the Z’ and of the W-boson. The mass of the Z’ is also plotted.

As figures 4.24 and 4.25 show, the background samples (the blue histograms) have only limited events in which a W-boson is reconstructed. A first cut should be requiring the reconstruction of a jet with a mass around the W-mass. On top of that, in both the QCD and $t\bar{t}$ samples the $p_T$ of the reconstructed Z’ and the W are low in comparison to the $p_T$ of the bosons in the signal sample. After inspecting the significance of a series of cuts in the range of 1000-1400 GeV for the $p_T$ of
both boson, it can be concluded that cuts up to 1200 GeV do not decrease the signal significantly, while the background is reduced greatly. Using 1200 GeV for both the $p_T$ of the W- and Z'-bosons results in a mass spectrum that is shown in figure 4.26 for $30^{-1}, 60^{-1}$ and $150^{-1}$ fb. After $30^{-1}$ the $\frac{S}{\sqrt{B}}$ ratio is already higher than 5, where this is estimated to be in the order of 2.5 for the method in which first two W-bosons are reconstructed. Even at an integrated luminosity of 150 fb, the peak position deviates slightly from 500 GeV and its width is somewhat larger than in the indirect method.

Figure 4.25: From left to right, the pseudorapidity of the Z' and of the W, the $p_T$ of the Z' and of the W and the mass of the Z' are plotted for the signal (Z') and for the QCD background (blue) are plotted. The only restriction on the event selection is that the jet should have a mass around 500 GeV.
Figure 4.26: The expected number of hits of the signal (red), $t\bar{t}$ (blue) and the QCD (green) background after an integrated luminosity of 30, 60 and 150 inverse femtobarn and using the reconstruction method in which the reconstructed jet should correspond to the $Z'$ mass. Although the discriminability of this channel is higher than that for the channel in which first two $W$-bosons are reconstructed, the mass resolution is not as good.
4.3.1 Low $Z'$ mass

Just as in section 4.2.2, the direct reconstruction method will be tested for different masses in this section. In section 4.2.2 it was already noted that a $Z'$ with a higher mass should be easier reconstructable with the indirect method, whereas a $Z'$ with a lower mass should be easier reconstructable with the direct method. Figure 4.14 shows that a $Z'$ with a mass around 900 GeV will only return a minimal number of hits if a jet with a mass of 900 GeV is searched for. Therefore the direct method is only interesting to use if the mass of the $Z'$ is low and in this section the method is only applied on a $Z'$ with a mass of 300 GeV. Such a low-mass $Z'$ can be reconstructed with the indirect method at low luminosity, although a complete isolation is not possible even in the case of low luminosity. In the direct method there is probably also a higher background, though the signal can be reconstructed more efficiently than in the indirect method. Just as with 500 GeV, the kinematical variables that will be used to cut the background are the $p_T$ of the two reconstructed bosons. In this case not only the $t\bar{t}$ and the hardest QCD samples form a background, but also the double-boson and the QCD-dijet sample with a total $p_T$ between 280 and 560 GeV should be inspected. The $p_T$ distributions are plotted in 4.27, 4.28, 4.29 and 4.30.

Figure 4.27: The distributions of the $p_T$ of the reconstructed W and $Z'$ of the reconstructed $Z'$ for QCD events with a total $p_T$ between 280 and 560 GeV (blue) and the signal (red).

Figures 4.27 - 4.30 show that the cuts that are used for reconstructing a $Z'$ of 500 GeV by using the direct method should also sufficient for a $Z'$ of 300 GeV. In analogy to figure 4.26, figure 4.31 shows how a resonance at 300 GeV is reconstructed for different amounts of collected data. The difference with 4.17 is significant as in the direct method almost all background hits can be reduced by using kinematical cuts.
Figure 4.28: The distributions of the $p_T$ of the reconstructed W and Z' of the reconstructed Z' for QCD events with a total $p_T$ between 560 and 1120 GeV (blue) and the signal events (red).

Figure 4.29: The distributions of the $p_T$ of the reconstructed W and Z' of the reconstructed Z' for double-W events (blue) and the Z'-events (red).
Figure 4.30: The distributions of the $p_T$ of the reconstructed $W$ and $Z'$ of the reconstructed $Z'$ for $t\bar{t}$ events (blue) and the $Z'$-events (red).

Figure 4.31: The reconstructed $Z'$ resonance for a $Z'$ of 300 GeV that is reconstructed with the Direct method for three different amounts of collected data. The background hits are shown in blue. The difference with the indirect method is significant: almost all background is reduced, whereas the amount of signal hits is approximately the same.
4.3.2 High luminosity

The last step in this chapter is to check how the direct reconstruction method performs at a luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$. The reconstruction will directly be performed on all background and $Z'$ events with a $Z'$ of 300 and 500 GeV mass by using the kinematical cuts that are also used at lower luminosity. Figures 4.32 and 4.33 show that at both the masses of 300 and 500 GeV the signal can still be separated from the background, although the resolution gets degraded. Whereas the deviation from the real mass for the 300 GeV $Z'$ is again around 7 GeV, for the 500 GeV $Z'$ it is a few GeV higher. The peak width is for both the resonances somewhat smaller than 20 GeV. This is larger than can be achieved with lower luminosities, though for a 300 GeV $Z'$ the hits are collected much faster in time. For a 500 GeV $Z'$ the resonance that is visible at 30 inverse femtobarn at lower luminosity has a better signal over background ratio and a better resolution than a $Z'$ of 500 GeV that is reconstructed at high luminosity after 300 inverse femtobarn has been collected. The flow charts give an insight in how much the background is reduced and how efficient the $Z'$ gets reconstructed for different masses. The flow charts are also useful to gain insight in what the influence of a detector simulation is, which will be performed in the next chapter. After the flow charts are shown, three tables are presented in which an overview is provided of whether a certain reconstruction method can discriminate a $Z'$ of 300, 500 or 900 GeV and with which precision this can be done.

Figure 4.32: The reconstructed $Z'$ resonance for a $Z'$ of 300 GeV that is reconstructed with the direct method for three different amounts of collected data. The background hits are shown in blue.

Figure 4.33: The reconstructed $Z'$ resonance for a $Z'$ of 300 GeV that is reconstructed with the Direct method for three different amounts of collected data. The background hits are shown in blue. The difference with the indirect method is significant: almost all background is reduced, whereas the amount of signal hits is approximately the same.
4.4 Summary & Conclusions

To summarize the contents of this chapter, the same criteria as in chapter three are used. Flow charts of the reconstruction efficiency of the QCD and the $t\bar{t}$ background are provided in figures 4.34 and 4.35. Flow charts of the $Z'$ signal with a mass of 300, 500 and 900 GeV are provided in figure 4.36 and 4.37.

**Figure 4.34:** The efficiency flow chart of the different reconstruction steps of the $t\bar{t}$ background. Although only a very tiny fraction of the total amount of $t\bar{t}$ events pass the reconstruction criteria and the cuts, at the end the cross section of mis-reconstructed $Z'$-bosons is still larger than for the signal.

**Figure 4.35:** The efficiency flow chart of the different reconstruction steps of the $t\bar{t}$ background. Although only a very tiny fraction of the total amount of $t\bar{t}$ events pass the reconstruction criteria and the cuts, at the end the cross section of mis-reconstructed $Z'$-bosons is still larger than for the signal.

In table 5.2 it is noted for all combinations of luminosities and $Z'$ masses whether (a) the measurement of the $Z'$ can be done, (b) how large the deviation of the reconstructed $Z'$-mass is from the real $Z'$-mass and (c) how good the resolution is. The important conclusion that can be drawn is that for all $Z'$-masses a discovery is possible. For masses of 500 GeV and higher, the $Z'$ can be reconstructed by using the indirect method, as for masses lower than 500 GeV, the $Z'$ can be reconstructed by using the direct method. The deviation from the real $Z'$-mass mostly depends
Figure 4.36: The efficiency flow chart of the different reconstruction steps of a Z’ of 500 GeV. If the Z’ would have a mass of around 500 GeV, two reconstruction methods would be possible.

Figure 4.37: The efficiency flow charts of the different reconstruction steps of a Z’ of 300 GeV that is reconstructed with the direct method and for a Z’ of 900 GeV that is reconstructed with the indirect method.

On the luminosity, the indirect method performs slightly better. The resolution is about the same for all reconstruction methods and masses. If however a large background is present, the resolution also gets degraded.
### Table 4.1

<table>
<thead>
<tr>
<th></th>
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<th>Resolution (GeV)</th>
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<td>500</td>
<td>900</td>
</tr>
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<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Direct LL</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Direct HL</td>
<td>+</td>
<td>+/-</td>
<td>-</td>
</tr>
</tbody>
</table>

(a) Shows whether the resonance can be reconstructed. A ‘+’ means that the resonance will be very clear, a ‘-’ means that reconstruction is nearly impossible. A ‘+/-’ means that reconstruction of a resonance peak is possible but that it will be accompanied by considerable background.

(b) Shows how much the reconstructed Z’-mass deviates from the real Z’-mass for every method and Z’-mass.

(c) Shows the resolution that can be obtained for every combination of method and Z’-mass. The conclusion of the tables is that the Z’ can be reconstructed by hadronic Z’-Strahlung for every Z’-mass.
Chapter 5

Detector Simulation

5.1 Z’ detection

In chapter 4 the reconstruction of hadronic Z’-Strahlung events was analyzed. Two different methods are used. One in which the decay products of the Z’ are reconstructed directly into one jet, this happens most often when the Z’ has a very high \( p_T \) or the Z’ has a low mass. This method is called the “direct method”.

The other method is useful for events where the Z’ has a somewhat lower \( p_T \) or a higher mass. In the indirect method each of the three W-bosons in a Z’-Strahlung event are reconstructed in a single jet. The two methods are tested for different Z’-masses and for two different luminosities in chapter 4. In this chapter the influence of the detector will be studied. It is not the purpose of this chapter to repeat every step of the previous chapter, but a selection is made. Because events that are the most difficult to reconstruct, the most important and the most interesting events are those with the highest pile-up, only high-luminosity \( (L = 10^{34} cm^{-2}s^{-1}) \) events will be studied in this chapter. The indirect method will be used to study the reconstruction of a Z’ with a mass of 500 GeV and 900 GeV. The direct method will be used to reconstruct a Z’ with a mass of 300 GeV and 500 GeV. From the analysis in chapter 4 it became clear that the only realistic background processes are the QCD di-jet sample with the highest \( p_T \), i.e. 560-1120 GeV and the \( t\bar{t} \) sample. These samples are the only samples that are used to model the background in this chapter. The final objectives of this chapter are to establish whether detection and discrimination against the background is still possible after the detector simulation is applied. And if this is the case, what the detection resolutions and efficiencies of the two methods to reconstruct the Z’ are.

5.1.1 The indirect method

The strategy to reconstruct the Z’-resonances of a Z’ of 500 GeV and 900 are similar to the strategy that is used in 4. First the distributions of the pseudorapidity and the transverse momentum of the background samples will be compared to that of the signal. From these graphs, an estimation of the needed kinematical cuts is made and this estimation will be refined by testing a series of cuts on its \( \frac{S}{\sqrt{B}} \) ratio. By using the acquired cuts the reconstructed Z’ resonances are plotted together with an estimation of the background hits that pass the cuts. In the \( \eta \) and \( p_T \)-plots that are shown in figures 5.1, 5.2,5.3, and 5.4 the distributions for the 500 and 900 GeV Z’ are combined. The distributions of the 500 GeV Z’ are plotted in red, while the distributions for the 900 GeV Z’ are plotted in green.

The shape of the distributions of both the background and the signal have changed after the detector simulation was performed. The momentum plots can be compared to figures 4.18 and 4.20.
Figure 5.1: The pseudorapidity distribution of the four bosons in the QCD background (blue) at high luminosity are plotted together with the $Z'$ $\eta$ distributions with a mass of 500 GeV (red) and 900 GeV (green). Because of the high luminosity the pseudorapidity distributions are broad.

The observation that the tails are however still comparable in length could lead to the conclusion that using the same kinematical cuts as the ones that were used in chapter 4 will be adequate. Although that these cuts can indeed be used to discriminate the signal from the background, a larger part of the signal events are removed when the same cuts are applied after the detector simulation. A new set of cuts should therefore be applied. The following cuts provide a good combination of background removal and acceptance of the signal:

- $|\eta_{Z'}|,|\eta_{W_1}|,|\eta_{W_2}|,|\eta_{W_3}| < 3$.
- $Z'_{p_T} > 700$
- $W_{1_{p_T}} > 300$
- $W_{2_{p_T}} > 270$
- $W_{3_{p_T}} > 700$

The cuts in the pseudorapidity are applied because from low-luminosity simulations it is known that the vast majority of the bosons have a direction into the central direction of the detector. Bosons that are detected in the forward directions are therefore likely to come from fake jets. The cuts in $p_T$ are changed in a way that the cuts for the $Z'$ and the third $W$ are somewhat loosened,
Figure 5.2: The $p_T$ distributions of the four bosons in the QCD background (blue) at high luminosity are plotted together with the $Z'\eta$ distributions with a mass of 500 GeV (red) and 900 GeV (green). The tails of the distributions of the $Z'$-events are still longer than the tail of the QCD-background.

whereas the cuts for the two W’s coming from the $Z'$ are somewhat tightened. When these cuts are applied, the reconstructed resonance of a $Z'$ with a mass of 500 GeV would be clearly observable when there is around 150 inverse femtobarn of data collected. Measurements of the fine structure of the peak will only be visible after 600 inverse femtobarn of data is collected as can be seen in figure 5.5. At the highest LHC luminosity this amount of data could be reached after 20 months.

If the $Z'$ would have a mass of 900 GeV, it would be even more difficult to reproduce the reconstructed resonances and the resolution would also be worse. These facts can be derived from the plots in figure 5.6. If the $Z'$ would have this mass, the reconstructed $Z'$ resonance would only become visible after a few hundreds of inverse femtobarn is collected and a more precise measurement can only be done after about 1500 inverse femtobarn is collected.

It is remarkable that about ten times the amount of collected data is needed after a detector simulation is performed. This fact can be illustrated by dividing the $Z'$-resonances that are produced with the same amount of collected data and the same kinematical cuts, but where on one dataset the detector simulation is performed. The result is shown in figure 5.7. The figure clearly shows that the peak height of simulated events is in the order of ten times smaller and the peak is also broader.
Figure 5.3: The pseudorapidity distribution of the four bosons in the $t\bar{t}$ background (blue) at high luminosity are plotted together with the $Z'$ $\eta$ distributions with a mass of 500 GeV (red) and 900 GeV (green). Because of the high luminosity the pseudorapidity distributions are broad.
Figure 5.4: The $p_T$ distributions of the four bosons in the $t\bar{t}$ background (blue) at high luminosity are plotted together with the $Z'$ $\eta$ distributions with a mass of 500 GeV (red) and 900 GeV (green). Though it is tight, the tails of the distributions of the $Z'$-events are still longer than the tail of the $t\bar{t}$-background.

Figure 5.5: The plots show the number of hits that is expected to be seen after an inverse luminosity of 30, 150 and 600 inverse femtobarn is collected. The resonances are quite a bit broader after the detector effects have been simulated. The amount of data that is needed to produce a clear peak is also significantly higher.
Figure 5.6: The plots show the number of hits that is expected to be seen after an inverse luminosity of 30, 600 and 1500 inverse femtobarn is collected. The resonances are quite a bit broader after the detector effects have been simulated. The amount of data that is needed to produce a clear peak is also significantly higher.

Figure 5.7: For a $Z'$ of 500 GeV (left) and 900 GeV (right) the reconstructed resonances of a simulated set of events is divided by the resonance of events on which no detector simulation is performed. The plots show that the peaks of the resonances of the detector-simulated events have only 10% of the height of the monte carlo events. From the plots it can also be seen that the resonances of the simulated datasets are also broader.
5.1.2 The direct method

The direct method will be tested on whether it is capable of reconstructing and discriminating Z'-Strahlung events with Z'-bosons of 300 GeV and 500 GeV. The strategy will be the same as it was with the indirect method. First, the transverse momentum distributions will be plotted for the background and the signal, thereafter an optimal cut will be sought and the reconstructed Z'-mass distributions will be plotted together with the background hits.

The momentum distributions are plotted in figures 5.8 and 5.9. The plots already make it clear that the \( t\bar{t} \) background will be difficult to exclude. It is reasonable to try the cuts that are used in the analysis chapter: all events with a detected boson that has a \( p_T \) lower than 1200 GeV will be vetoed. These cuts exclude the QCD background, but a fraction of the \( t\bar{t} \) still pass these cuts. Figures 5.11 and 5.10 show the reconstructed signal and expected background for three different amounts of integrated luminosity. For three different integrated luminosities and Z’s of masses 500 and 300 GeV the expected mass hits of the background and signal are plotted in figures 5.10 and 5.11. For the Z'-bosons of both masses it is true that to claim a discovery, at least 300 inverse femtobarn is needed. The precision of the measurement will still be low at this integrated luminosity. For a precise measurement at least 1500 inverse femtobarn would be needed. This amount of data could be collected after five years of data-taking at the highest luminosity. To gain insight in the influence of the detector simulation it is useful to plot the division of the two mass-distributions of 1500 inverse femtobarn that are created before and after the detection simulation. These plots for Z'-bosons of 500 and 300 GeV are shown in figure 5.12

![Figure 5.8: The \( p_T \)-distributions of the reconstructed Z'-boson and the W-boson of the t\bar{t} background (blue) and for the signal events with a Z'-mass of 500 GeV (red) and 900 GeV (green). These distributions hint on the fact that t\bar{t} cannot be fully excluded by using cuts in \( p_T \).](image-url)
Figure 5.9: The $p_T$-distributions of the reconstructed $Z'$-boson and the W-boson of the $t\bar{t}$ background (blue) and for the signal events with a $Z'$-mass of 500 GeV (red) and 900 GeV (green). These distributions hint on the fact that $t\bar{t}$ cannot be fully excluded by using cuts in $p_T$.

Figure 5.10: Three plots of how the reconstructed $Z'$ resonance (red) and its background (blue) would look after 300, 600 and 1500 inverse femtobarn of data would have been collected with the LHC for a $Z'$ of 500 GeV that is reconstructed with the direct method. At least a few years of data-taking would be needed to construct a well-shaped resonance with this channel using this method.

Figure 5.11: Three plots of how the reconstructed $Z'$ resonance (red) and its background (blue) would look after 300, 600 and 1500 inverse femtobarn of data would have been collected with the LHC for a $Z'$ of 300 GeV that is reconstructed with the direct method. A $Z'$ with a mass of 300 GeV is somewhat easier to reconstruct with the direct method than a heavier $Z'$. Still a few years of data-taking would be needed to construct a well-shaped resonance.
Figure 5.12: The histograms of the expected signal hits after 1500 inverse femtobarn before and after simulation are divided to show the decline of the peak height in the reconstruction with the direct method. The decline is less than with the indirect method, though it still considerable.
5.2 Summary & Conclusions

The private simulation software is used to investigate whether it is possible to discriminate hadronic \( Z' \)-Strahlung events against the QCD and \( t\bar{t} \) background at the highest luminosity in ATLAS. This is done for \( Z' \)-bosons of 500 and 900 GeV with the indirect method and for \( Z' \)-bosons of 300 and 500 GeV with the direct method. The main conclusion is that for all the four combinations of \( Z' \)-masses and methods it is still possible to discriminate the signal against the background unless a considerable larger amount of data is needed to make the distinction. The resolution is also degraded. An overview of the reconstruction process can be provided by putting the efficiencies of the different steps in a flow chart. This is done for the \( t\bar{t} \) background in figure 5.13. The signal flow charts for \( Z' \)-bosons of 300, 500 and 900 GeV are shown in figures 5.14 and 5.15. Just as in chapter 4, a table of whether a \( Z' \)-boson with a certain mass can be reconstructed by either the direct or indirect method, a table with an overview of the resolutions and a table with an overview of the deviation of the original \( Z' \)-mass are presented after the flow charts are shown.

![Flow chart](image)

Figure 5.13: The efficiency flow chart of the different reconstruction steps of the \( t\bar{t} \) background. Although only a very tiny fraction of the total amount of \( t\bar{t} \) events pass the reconstruction criteria and the cuts, at the end the cross section of mis-reconstructed \( Z' \)-bosons is still larger than for the signal.
Figure 5.14: The efficiency flow chart of the different reconstruction steps of a $Z'$ of 500 GeV. If the $Z'$ would have a mass of around 500 GeV, two reconstruction methods would be possible.

Figure 5.15: The efficiency flow charts of the different reconstruction steps of a $Z'$ of 300 GeV that is reconstructed with the direct method and for a $Z'$ of 900 GeV that is reconstructed with the indirect method.
Various interesting facts can be extracted from the flow charts. One is that only less than 0.1% of the total events are used to reconstruct the Z' if it has a mass of 300 GeV. Although this efficiency is somewhat higher for Z'-bosons with higher masses, it is still only 1.1% for a Z' of 900 GeV. If these flow charts are compared to the charts in chapter 4 in figures 4.36 and 4.37, it can be concluded that the decline of the total reconstruction cross section due to the detector simulation is the for a Z' of 300 GeV (a factor 7), while the decline for a Z' of 900 GeV is the smallest (a factor 2). These decline numbers are not as large as figures 5.12 and 5.7 suggest. The reason for this is that except for the fact that less events are reconstructed, the events that are reconstructed also have a smaller precision and therefore the peak height is even smaller. That the resolution is considerably worse than without a detector simulation is also shown in table 5.2. In the first table it is summarized that reconstructing Z'-Strahlung events with the direct method can only be reconstructed together with a considerable number of background hits. The second table shows that the deviations of the reconstructed Z' masses from the original Z' mass are not larger than without a detector simulation. The resolutions that are shown in the third table are on the other hand much worse than without a detector simulation. Especially the resolutions of the direct method are large, in the order of 5 times larger than without a detector simulation.

<table>
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<td>Direct HL</td>
<td>+/+</td>
<td>+/+</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(a)</td>
<td>(b)</td>
<td>(c)</td>
</tr>
</tbody>
</table>

Table 5.1: A summary of whether methods can be applied to reconstruct a Z' for three different masses and how well they do. LL stands for Low Luminosity and HL for High Luminosity. (a) shows whether the resonance can be reconstructed. A ‘+’ means that the resonance will be very clear, a ‘-’ means that reconstruction is nearly impossible. A ‘+/-’ means that reconstruction of a resonance peak is possible but that it will be accompanied by considerable background. (b) shows how much the reconstructed Z'-mass deviates from the real Z'-mass for every method and Z'-mass. (c) shows the resolution that can be obtained for every combination of method and Z'-mass. The conclusion of the tables is that the Z' can be reconstructed by hadronic Z'-Strahlung for every Z'-mass.
Chapter 6

Conclusions & Outlook

6.1 Summary

The topic of this thesis is the question whether the $Z'$-boson proposed by Chivukula et al. [16] can be detected with the ATLAS detector. The production mechanism of the $Z'$ that is chosen for this purpose is the radiation of the $Z'$ from a W-boson and the decay channel is fully hadronic, i.e. the three W-bosons in the event decay hadronically. Dedicated detector simulation software is developed to study different jet-finders. The software is validated against the official simulation package Atlfast. An investigation is performed to determine which jet algorithm is optimal for this specific problem. The results of this study are written down in chapter 3. Two approaches are tested, the first is to match jets to partons and the second is to match jets to W-bosons. Matching jets to partons cannot be used to reconstruct a $Z'$-Strahlung event since the underlying event and the parton-shower produce too many jets that can be misinterpreted.

Matching jets to W-bosons is tested for eight different jet reconstruction algorithms. Four algorithms: C/A, $k_T$, anti-$k_T$ and SISCone are used and pruning and Y-splitting are used as substructure algorithms in combination with the C/A and $k_T$ algorithms. The objective of using substructure analysis is to reduce underlying event and pile-up effects to improve the resolution of the jets. The results are promising as both the efficiency as the resolution, and the deviation of the reconstructed $Z'$ mass can effectively be improved. Especially pruning performs very well. To draw a conclusion on which of the two jet-algorithms should be used in the full analysis, both the C/A and the $k_T$ algorithms are tested on a total of six background samples. These background samples consist of QCD di-jet events in three different $p_T$ bins, $t\bar{t}$, W-boson and WW events. As the C/A-algorithm in combination with pruning provides a better reconstruction of the signal as well as a better reduction of the background, this combination of algorithms is chosen for the full analysis.

In chapter 4 all aspects of the measurement of hadronically decaying $Z'$-Strahlung events are investigated for monte carlo samples without performing a detector simulation. The main question in each step is whether the signal can be separated from the background by using kinematical cuts. To reconstruct low-mass $Z'$-bosons an alternative method is proposed in which one jet is directly matched to the $Z'$-boson, while another jet in the event should be matched to the third W-boson. Both methods are tested on samples of events with three different $Z'$-masses, 300 GeV, 500 GeV and 900 GeV, and for the same background samples that are used in chapter 3. The two methods are tested for events with two different levels of pile-up. A number of minimum bias events are used corresponding to a luminosity of $10^{33} cm^{-2}s^{-1}$. After it is established how the events are reconstructed at that luminosity, more minimum bias events are added to the event list to simulate...
a pile-up that corresponds to the highest luminosity: \(10^{34} \text{cm}^{-2} \text{s}^{-1}\).

Finally the effect of the detector is investigated on both signal and background at the highest luminosity.

### 6.2 Conclusions

A first conclusion that can be drawn is that large jet areas to match jets to heavy particles such as the W-boson can be very useful. This is especially the case if substructure analysis is applied. The SISCone algorithm performs the best if no substructure analysis is performed. However, when reconstructing the Z'-resonance with the C/A algorithm with pruning, the peak height of the resonance is three times higher than with just the SISCone algorithm can be achieved and the shift in the deviation of the mean value of the resonance almost vanishes. Not only the reconstruction of the signal is far more efficient and effective, the reduction of the background is also much better as gluon-jets are suppressed. These results are at least remarkable.

Before the answer to the primary question in this thesis can be answered, several other questions need to be addressed. The most important are written down here and will be answered below:

- For what Z'-masses can matching jets to W-bosons be used?
- For what Z'-masses can matching jets to the Z'-boson be used?
- What is the influence of adding 23 minimum bias events to the event list?
- What is the influence of the detector simulation?

The opening angle of the decay products of a heavier particle should be larger to compensate for the mass drop. The two W-bosons that come from the Z' are therefore less collimated for higher Z'-masses and can easier be reconstructed separately. This effect has also been measured and the answer to the first question is that for a Z'-mass of 500 GeV and heavier the Z' can be reconstructed with the method in which the jets are matched to the W-bosons. For a Z' of about 500 GeV and lighter, the Z' can be reconstructed with the method in which the jets are directly matched to the Z'-boson since the two W-bosons from the Z' are more collimated for a lighter Z'.

The effect of adding extra minimum bias events to simulate the pile-up effects that occur at high luminosity usually results in higher jet-energies and higher masses. The pruning procedure is used to counteract these effects although it cannot be 100% efficient. The drop of the resolution and the increase of the mean value of the Z'-resonance due to the extra minimum-bias effects is in the order of a few GeV if no detector simulation is performed. The efficiency of reconstructing the events is degraded because of the extra minimum-bias events, though this effect is compensated by the fact that the data is collected much faster. An estimation is that from a luminosity \(10^{33}\) to \(10^{34} \text{cm}^{-2} \text{s}^{-1}\) the efficiency is halved, while the data is collected ten times faster.

The detector simulation has a rigorous influence on the reconstruction of both the background and the Z'-signal. The peak height of the Z'-resonance is reduced by a factor 5-10, depending on the Z'-mass and the method that is used to reconstruct the Z'. The resolution is also heavily degraded, the peak width (root mean square) is increased by a factor 5-10. Moreover, the kinematical cuts also have to be lowered for the indirect method because otherwise the efficiency would be that low that only a few hits per year would be expected. Because of the lower kinematical cuts, a larger number of background hits are expected to survive. The mean invariant mass is not affected by the detector simulation.
Since the indirect reconstruction method suffers less from background, a $Z'$-boson of 500 GeV and heavier can more easily be reconstructed than lighter $Z'$-bosons. Nonetheless, at around one hundred collected inverse femtobarn of data at $\sqrt{s} = 14\text{TeV}$ a discovery can be claimed with a certainty of about $1\sigma$ for all $Z'$-boson masses. A $5\sigma$ exclusion can be expected at around 600 inverse femtobarn for all $Z'$-masses. The resolution of a light $Z'$-boson will be worse than for heavier $Z'$-bosons though, as these can only be reconstructed by matching a jet directly to the $Z'$. And this method suffers from high backgrounds, as well as from the pile-up and detector effects. The main conclusions of this thesis is: Hadronic $Z'$-Strahlung events of every possible $Z'$-mass can be discriminated from the background in the ATLAS detector.

### 6.3 Recommendations

A first recommendation may be dedicated to the usage of jet algorithms. The development and application of substructure algorithms is a relatively new field due to improved calorimetry. Especially the combination of the C/A algorithm and pruning proves to be powerful. As the computational complexity can also be less than for cone algorithms, the reconstruction of a wide range of processes may benefit.

The results of this thesis form a basis for the experimental search for a $Z'$-boson. Only one $Z'$ production mechanism has been investigated in which the $Z'$ decays exclusively into hadrons. Especially the channel in which one W-boson decays leptonically could contribute greatly to its discovery potential as the branching fraction of this channel is comparable to that of the fully hadronic decay. It is difficult to predict how large the background of this channel will be and how good its resolution is. $t\bar{t}$ also has a channel with a single lepton and the background may still be large. The measurement precision of detecting hard electrons and muons is better than that of detecting jets, especially at high luminosity.

In the decay channels in which more than one W-boson decays leptonically, there are also two or more neutrinos. This means that the $Z'$-mass cannot be measured through these channels. These channels can still be interesting for the claim of the existence of the $Z'$.

The channel in which the $Z'$ is created through vector-boson fusion can especially be interesting when the $Z'$-boson has a large mass. The total cross section for the vector boson fusion production process is about three times smaller than the cross section of $Z'$-Strahlung at a $Z'$-mass of 400 GeV, though at a $Z'$-mass of 800 GeV the cross section becomes equal and for higher $Z'$-masses the vector boson fusion cross section is even higher. An interesting aspect of the vector boson fusion is that there are two hard jets pointing in almost opposite direction at high pseudorapidity. This could be a discriminating signature, although the fact that there are only two W-bosons to reconstruct makes the process more susceptible to background.

The analysis in this thesis uses 14 TeV as a centre of mass in the collider. As the LHC now functions at 7 TeV, an additional analysis should be performed to investigate what the best kinematical cuts are and what the expected number of reconstruction hits are of the signal and the background.
Appendix A

The Weisźäcker-Williams equation

Figure A.1: Four Feynman diagrams with initial and final state radiation.

If diagram A.1 (a) represents Bhabha scattering \((e^+e^- \to e^+e^-)\) together with a photon emission, it has one positron external line, one electron internal line, one external photon line, two photon vertices and a electron propagator. It is not necessary to include the rest of the diagram to compute the Weisźäcker-Williams equation. The feynman rules dictate that the matrix element in tensor notation is:

\[
M_{2 \to 3} = \bar{v}_B \gamma^\mu \frac{\delta(p_A - p_\gamma)}{-2p_A \cdot p_\gamma} \cdot (-ie\gamma^\alpha) u_A \epsilon^a_\alpha (p_\gamma) \times \ldots \tag{A.1}
\]

A is here the electron and B is the positron. The equation extend to the \(Z/\gamma\) propagator and the rest is written as \([\ldots]\). The electron propagator has already been simplified by asumming the ultra-relativistic limit and writing \((p_A - p_\gamma)^2 - m_e^2 = -2p_A \cdot p_\gamma\). In the new propagator term the divergences are more apparent. In the centre of mass frame of the electron, the momenta can be written as:

\[
p_A = (E, 0, 0, E); \quad p_\gamma = (zE, \vec{p}_\perp, \sqrt{z^2E^2 - \left|\vec{p}_\perp\right|^2}); \tag{A.2}
\]
$z$ is the fraction of energy emitted by the photon: $z = \frac{E_\gamma}{E}$. The dot product is:

$$p_A \cdot p_\gamma = z E^2 \left( 1 - \sqrt{1 - \frac{\left| p_\perp \right|^2}{z^2 E^2}} \right) \quad (A.3)$$

The inner product between the vectors of the electron and the photon is zero when either the transversal momentum of the photon is zero or when $z$ goes to zero, e.g. a "soft" photon is emitted. With the assumption that the $p_T$ of the photon in reference to the electron will indeed be small the electron and photon momentum can be related as:

$$p_\gamma z p_A \quad \text{and} \quad p_A - p_\gamma \approx (1 - z) p_A.$$  

In the second order taylor approximation for $\frac{p_\perp}{z} \to 0$, $p_A \cdot p_\gamma \approx \frac{p_\perp^2}{2z}$. And in the relativistic limit the electron propagator can be said to be on-shell and $p_A - p_\gamma$ can be replaced by the sum over the spins:

$$\sum_a \left| S^{h,a}(z) \right|^2 = \frac{2e^2 p_\perp^2}{z(1 - z)} \left[ \frac{1 + (1 - z)^2}{z} \right] \quad (A.5)$$

The factor between the brackets resembles equation 1.6. This is not a coincidence as the quark-gluon coupling is mathematically the same as the photon-electron coupling. To obtain the total cross section the phase space is incorporated and the differential cross section is integrated over the transverse momentum with the mass of the electron as a lower limit up to a scale $Q$ as a higher limit. The low limit arises as a compensation for the low-$p_T$ singularity and the upper limit should be there because a low-$p_T$ assumption was done. The following differential cross section is obtained:

$$\frac{d\sigma^{ISR}_{2\to2}}{dz} \approx \frac{\alpha}{2\pi} \left[ \frac{1 + x^2}{1 - x} \right] \log \frac{Q}{m_e} dx \quad (A.6)$$

Here $\alpha$ can either be the weak or the strong coupling constant. In the latter case a color factor should be added too.
Bibliography


