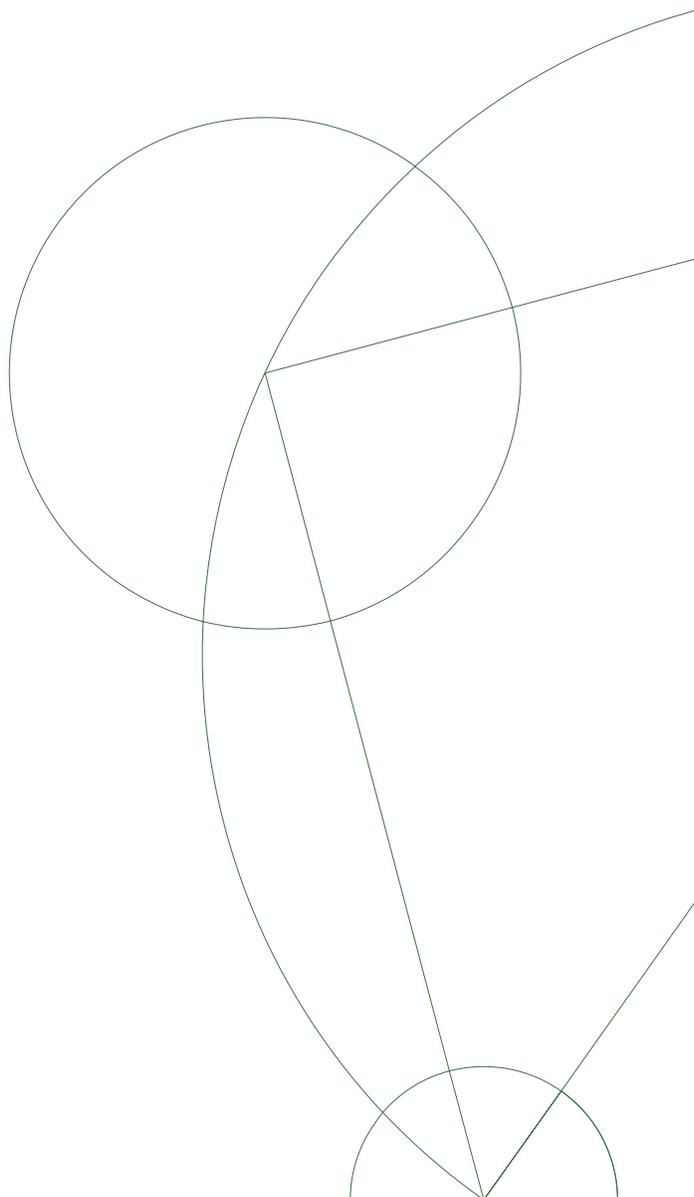Master's thesis

Measurement of the W-Boson Mass with the ATLAS Detector at LHC

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Abstract

This analysis is a first attempt at a W boson mass measurement at the LHC. The measurement is based on the $W \rightarrow \mu\nu$ events from 827 pb^{-1} proton collisions at 7 TeV collected with the ATLAS detector in the first half of 2011, when the pileup of other protons collisions in the same event were minimal. Using MC templates for various W-masses of the transverse muon momentum, high sensitivity to the W mass is obtained.

$Z \rightarrow \mu\mu$ events are used as calibration for the muon p_T scale, but the systematic uncertainties from other sources are still dominant compared to the muon p_T-scale and statistical uncertainty. The largest source of uncertainty is due to pileup events which degrades the resolution on missing transverse energy. This in turn biases the event selection and increases the amount of QCD background.

My final measurement of the W boson mass is $M_W = 80.510 \pm 0.032 \pm 0.060$ GeV.

Resume

Dette er et første forsøg påat måle W boson massen ved LHC. Målingen er baseret på $W \rightarrow \mu\nu$ begivenheder fra 827 pb^{-1} proton-kollisioner indsamlet ved 7 TeV med ATLAS detektoren i første halvdel af 2011, hvor pileup begivenheder fra andre proton-kollisioner i samme event var minimale. Ved at sammenligne MC skabeloner for muonens transverse impuls ved forskellige W-masser og sammenligne dem med data opnås høj sensitivitet til W-massen.

$Z \rightarrow \mu\mu$ begivenheder anvendes til kalibrering af muonens p_T skala, men systematiske fejl fra andre fejlkilder er stadig større, end dem fra muonens p_T skala og den statistiske fejl. Den største fejlkilde skyldes pileup begivenheder, som forringer målingen af manglende transvers energi. Dette medfører en bias i udvælgelsen af W begivenheder og forøger mængden af baggrund fra QCD begivenheder.

Min endelige måling af W-massen er $M_W = 80.510 \pm 0.032 \pm 0.060$ GeV.

Contents

1 Author's Preface

My Master Thesis is about a mass measurement of the W-boson with the ATLAS detector at LHC.

It is a $\frac{1}{10000}$ high precision measurement and at the Tevatron there was a 10-person group working around 10 years to get an accurate measurement of $m_W = 80.420 \pm 0.031 \text{GeV}$.[1] Neither ATLAS or CMS have published a result yet. Which means that it takes a lot of work to do the full analysis and it is impossible for at single person to get such an accurate measurement in just one year. What I can do instead is to get a less accurate measurement and investigate some of the systematic uncertainties, which I expect to dominate from the history of the measurement (see section 3). So the focus will primary be on the method because the result will be too difficult to get in good enough precision. I have chosen to focus on the $W \rightarrow \mu\nu$ channel and the mass measurement from the p_T-distribution of the muon. LHC will produce many more W's than any previous experiments. This makes me expect that the statistical uncertainty will be small and the systematics uncertainties to dominate, so I have chosen the channel with the expectation that this minimize the systematic uncertainties in the experiment. It is also possible to do the measurement using the electron channel and/or fit with the transverse mass instead of the transverse momentum of the lepton and all these analysis should in the end be combined[2].

The muon channel was chosen rather than the electron channel because the electron p_T-distribution is not gaussian due to bremsstrahlung and because the muon sample is cleaner than the electron sample.

The missing transverse energy measurement (E_T^{Miss}) is quite difficult and a study by itself. I want to minimize my dependence on that, and this makes me prefer the transverse momentum instead of the transverse mass. There still have to be a cut on E_T^{miss} in the analysis so it still depends on the E_T^{miss}, but m_T depends directly on E_T^{miss} because of its definition and p_T does not.

I chose this subject because it is a very hard measurement and demands a good understanding of statistics, it is unoccupied to some extent (maybe because it is a hard measurement) and because it is very important (see chapter 4.3)

All the prior experimental measured masses have been found at the home page of the particle data group [4] if I have not written otherwise.

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[1]This value is found at [8]

[2]Which is not trivial either because correlations have to be considered. I have discussed the decay channels in section 7.1

As normally in high energy particle physics I have used natural units unless other thing is mentioned. In these units the speed of light c and $\hbar$ is set to 1 which gives both the momentum, energy and mass in units of eV.

1.1 How to Read This Thesis

Unless the reader is a W-mass measurement expert, I highly recommend to read the first 3 pages in section 7 before reading the rest of the report to get an overview of the statistical method used to measure the W-mass.
It is an indirect measurement which makes it less intuitively compared to a direct one like a measurement of the Z-boson mass.

I have split my thesis into 3 parts. The first is a short overview of the Standard Model along with a motivation for the measurement. The second is a description of the detector and the third is my analysis. This part ends with an analysis of the systematic uncertainties that contributes to the measurement.

2 Introduction

The Large Hadron Collider (LHC) at CERN started to operate for the first time 8th September 2008. At 30th March 2010 were the first collisions with a center of mass energy, $\sqrt{s}$, with 7 TeV. Before it is possible to discover new physics at the experiments at the LHC the detectors have to be well understood, that means to know the output of the measurements, have the right trigger cuts on the events and be able to reproduce the results from what is already known from the theory, the Standard Model (SM).

This paper is about a measurement of the W-mass with the ATLAS detector. In the first months, W-events together with previous knowledge of its mass is used for calibration of the detector, mainly because it is an important tool for missing energy analysis. Later on the detector starts to get calibrated and the LHC will create more W's than any previous experiment have done. This makes it possible to get a smaller statistical uncertainty than the previous experiments and therefore a better mass measurement if the systematic uncertainties can be decreased to a reasonable size.

The W-mass is important because it can be calculated very accurately in theory and from higher order loop terms it is possible to do an indirect calculation of masses of other particles such as the missing piece of the standard model, the Higgs boson (see section 4.3). In the future when the Higgs particle has been found or excluded it can also be used to predict particles beyond the standard model (BSM).

There will be produced more Z-events than at previous hadron collider and in theory it has a lot in common with the W. This makes Z-events an excellent tool for calibration of the detector to get a better precision measurement of the W-mass.

To do a mass measurement of the W-boson the detector have to have a high-resolution measurement of photons, electrons and muons. The missing transverse energy, E_T^{Miss}, is an important calculation in W-analysis and this mass measurement relies heavily on other analysis and a good detector responds.

3 History of the W-mass

The first evidence of the weak interaction was found in 1930 via β-decays in nuclei where a neutron decays into a proton, an electron and an anti electron neutrino. Enrico Fermi described the 4 fermion interaction in 1933 as a contact interaction which is a force with no range. This was an old way to explain the weak force and from a measurement of the muon lifetime he then introduced the Fermi coupling constant G_F.

Around 1968 Abdus Salam, Sheldon Glashow and Steven Weinberg combined the electromagnetic force and the weak force to a common theory namely the electroweak theory. From their theory they predicted the W-boson and from the Fermi coupling constant they could also predict its mass. The W-boson should explain the β-decay, but their theory also predicted the Z-boson which had not been discovered yet. The experiment was in agreement with theory and this is said to be one of the biggest successes of the Standard Model.

Abdus Salam, Sheldon Glashow and Steven Weinberg got the Noble prize in 1979.

In 1983 the W and Z bosons were discovered at the Super Proton Synchrotron (SPS) at CERN. The discovery led to a Noble prize in 1984 to Simon van der Meer and Carlo Rubbia. Simon van der Meer invented the technique of stochastic cooling of particle beams and Carlo Rubbia led one of the experiments at SPS, UA1.

The W-mass can be calculated with high accuracy and it is one of the few Feynmann diagrams that has been calculated next to next to leading order (NNLO). The W-mass gave an indirect measurement of the top mass even before it was discovered by next to leading order calculation (NLO). When the top mass has been measured with high accuracy it can then be used to predict the mass of the missing piece of the Standard Model, the Higgs boson (see section 4.3).

The W-mass has been measured several time through history and its value along with its uncertainty can be seen in figure 1. [11, p222]
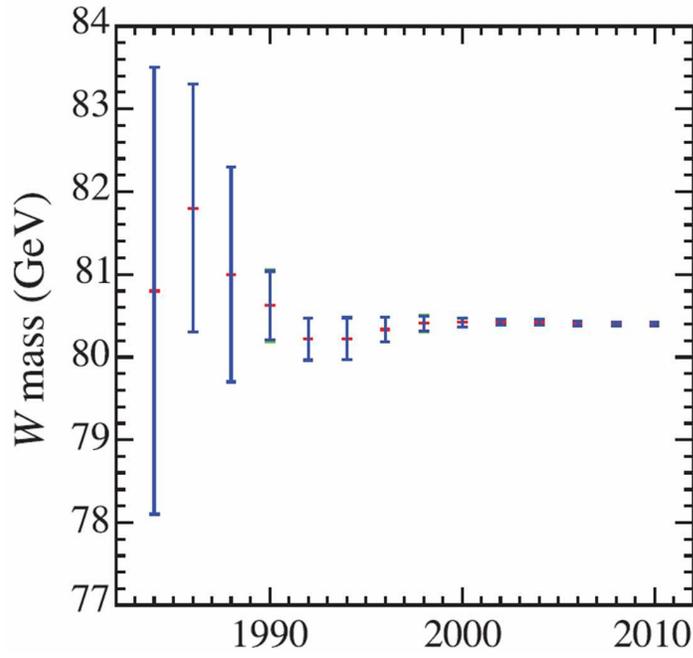
Figure 1: Measurements of M_W and its uncertainties through the history. The uncertainty decreases a lot as the statistics increases.
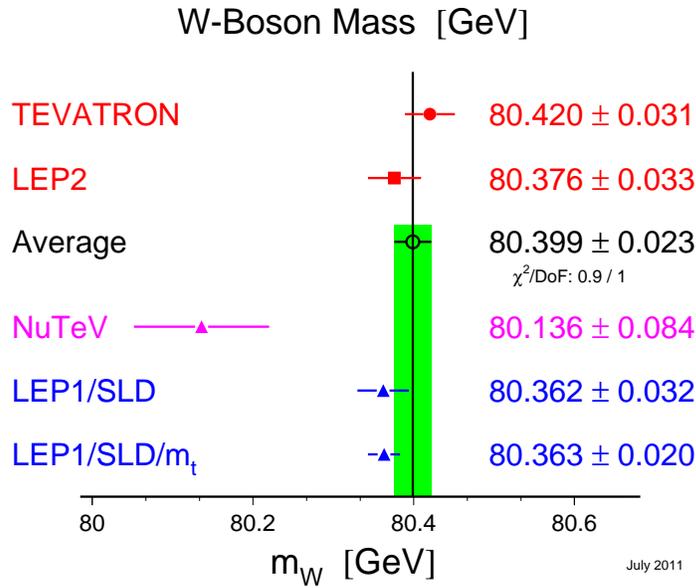

Figure 2: Measurements of M_W and its uncertainties from various experiments.

10

Part I

Theory

4 the Standard Model and its limitations

The standard model (SM) is the theory that describes how particles interacts and which particles exist. According to SM there are 6 quarks, 6 leptons and 3 forces which describes how the particles interact. There is also a Higgs field that gives the particles masses and this field gives rise to the so called Higgs particle which is the only particle left in SM that have not been discovered yet.

The forces in SM are the weak, the electromagnetic and the strong force. These forces are described by spin 1 bosons that are force carriers. The massless gluons, g, are the force carriers of the strong force, the massless photon, γ, is the force carrier of the electromagnetic force and the W^+, W^- and Z^0 are the force carriers of the weak force. The W's and Z are very heavy so they act at very short range compared to the electromagnetic force. The gluons couples to particles with color charge which is the quarks and gluons. Photons can couple to particles with electromagnetic charge and the heavy bosons (the W's and the Z) couples to particles with a weak hyper charge. This is basically all the fermions, but as the name suggests the weak force is weaker than the other two. The forces and their carriers can be seen at table 1.

	Acts On	Couples to	Carrier	Range	Coupling	Stable Systems	Induced Reaction
Weak Force	Fermions	Hyper-charge	$W^\pm$, Z^0	$< 10^{-17}$m	10^{-5}	None	β-decay
Electro-magnetism	Charged Particles	Electric Charge	γ	$F \propto \frac{1}{r^2}$	$\frac{1}{137}$	Atoms, Molecules	Chemical Reactions
Strong Force	Quarks, Gluons	Colour Charge	gluons	10^{-15}m	~ 1	Hadrons, Nuclei	Nuclear Reactions

Table 1: Forces in the Standard Model and their carriers.

The quarks and leptons are the matter particles, they are related in 3 generations and are spin-$\frac{1}{2}$ fermions. Objects from our daily life are build of fermions from the first

generation (e^-, u and d). Except for the neutrinos the first generation fermions are the lightest and the heavier particles are less stable and will decay to the lighter ones. The up and the down quark are from the first generation and it is these quarks that are in protons and neutrons. The charm and strange quark are from the second generation and the top and bottom are from the third.

There are 2 up quarks and 1 down quark in the proton and there are 1 up quark and 2 down quarks in the neutron, but the mass of these light quarks are a few MeV and the mass of a proton is about 1 GeV so there is more in the proton than just these 3 quarks. The proton has a very complicated structure and is a study by itself. Knowledge of the proton is important for any analysis at the Large Hadron Collider (LHC) because it is a proton-proton collider. I will discuss this in section 4.4.

There are 6 leptons in SM. Most people have heard about the electron because electrons moves around the nuclei in atoms. The leptons and the quarks together are called fermions because they are spin-$\frac{1}{2}$ particles. All the fermions have anti particles. That means that it is possible to create anti down quarks, anti taus and so on. These antiparticles have the same mass as the non-anti particles, but they have opposite charge. The leptons also have a lepton number. These lepton numbers are conserved in every reaction. The electron and the electron neutrino have the electron number 1, the muon and muon neutrino have muon number 1 and the tau and tau neutrino have tau number 1. All the anti particles have opposite lepton numbers. This conservation leads to that if a muon is created from a decay for example then there also has to be created either an anti muon or an anti muon neutrino to conserve the muon number.

It is not possible to detect single isolated quarks directly. Like the electric charge in the electric force the strong force has another charge called color charge. Every quark has a color and a particle has to be color neutral to be isolated. The colored particles are combined by the strong force which is described in section 4.4.
All the leptons are color neutrals and can thereby move alone.

4.1 Weak Interaction

The force carriers in the weak interaction are the heavy W^-, W^+ and Z boson. The minus and the plus-sign indicates the W either has charge 1 or -1. The Z is neutral and its mass is know with very high accuracy from the LEP experiment and is $m_Z =$

91.1876 ± 0.0021GeV.[3]

The Z-boson have a lot in common with the W. It weights 10 GeV more and is neutral but other than that they are very similar because they both are force carriers for the weak interaction. Because the Z boson is neutral it can decay to a pair of electrons or muons and these leptons should be distributed the same way as the leptons from the leptonic W-decay except that it is possible to detect both leptons directly in the Z-decay. The leptonic W decay will contain a neutrino which goes strait through our detector. This makes it much easier to find Z's than W's and also easier to do accurate measurements via the lepton channel with the Z-boson.

LEP collided electrons and positrons (electron antiparticles) which made it very easy to create Z's and do a precision measurement of its mass. The W-mass was more difficult to measure partly because it cannot be produced single handed because of charge conservation and also because its leptonic decay channel includes a neutrino. This led to a mass measurement of 80.376 ± 0.033GeV [8]. Tevatron in USA have measured it to be 80.420 ± 0.031GeV which gives a combined measurement of $m_W = 80.399 \pm 0.023$GeV.

4.2 The Higgs Boson and Theories Beyond the Standard Model

The standard model has predicted a lot of measurements so far, for example the existence of the W and Z-bosons, the top quark and the tau neutrino. The mass of the top quark has also been predicted from indirect measurements using higher order loops from Quantum Field Theory (QFT) before it was discovered and the mass measured directly experimentally was in good agreement with the one predicted from SM. Even though SM have worked well so far it still has its limits. The neutrinos should be massless which is not in agreement with experiments. It also predicts the Higgs particle which has not been discovered yet.

A direct next to leading order (NLO) calculation of the Higgs mass also has some problems because each term in the calculation contribute extremely heavily to the mass, but with opposite sign. If the results should be consistent with the rest of the theory then each of the NLO terms should neglect each other with about 10^{32} digits. This is not very nice from a theoretical point of view and is called the Hierarchy problem. Luckily there are a lot theories beyond the standard model (BSM) that can fix this problem and at the same time give answers to some of the other questions that SM is not able to answer. So far we have not been able to detect any fundamental particles with spin 0 and the Higgs particle should have spin 0 so it behave different than the other bosons.

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[3]The Large Electron-Positron Collider (LEP) collided electrons and positrons in the 90's. It has a circumference of 27km and lies at CERN.

There is some other missing pieces of SM, one of them is that it does not include gravity. Gravity has been a well known force in physics for many years but it has not been possible to discover it at the particle level yet. According to most theories the force carrier of gravity is the graviton which is a boson with spin 2. So far it has only been possible to make upper limits of the strength of the force and the mass of the graviton.

It is well known that there exists dark matter in our universe, but SM does not have a candidate for a dark matter particle.

4.3   Motivation

Even though the SM has predicted a lot of measurements so far, the Higgs boson has not been discovered yet. It has not been detected directly, but via NLO calculation it is possible to do an indirect measurement of the Higgs mass by calculating higher order loop diagrams for the W boson mass as seen in [6]. If the W did not couple to other particles it would have a mass of $M_W = 78.4 \pm 0.9$ GeV[4], but the presence of other particles and the fact that the W couples to them changes its mass. The contribution from each loop calculation depends on the mass of the particles inside the loop and the most important loop corrections can be seen in figure 3.
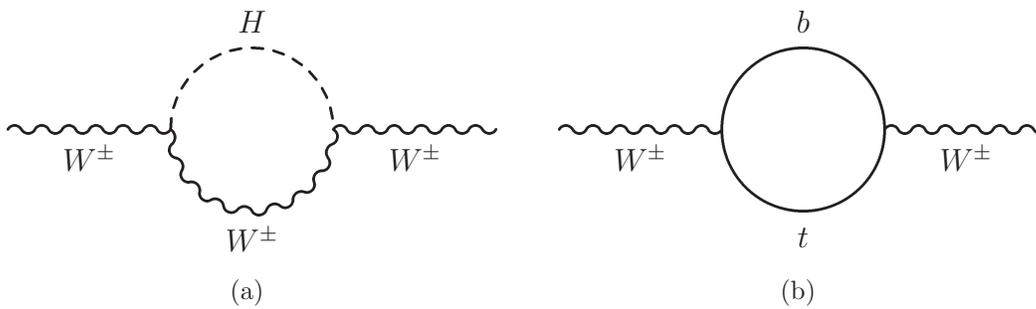

(a)   (b)

Figure 3: Higher order loop diagrams for virtual W decays that contribute to the W mass. These are the most dominated contributions according to the SM. Figure 3a has a loop with a Higgs and a W and figure 3b has a loop with a pair of heavy quarks. I case of a W^+ the b quark is antiparticle and in case of a W^{-1} the t-quark is an antiparticle. I could also have looked at the contribution from leptonic loops (for example a tau and a tau neutrino in the loop) and loops from lighter quarks, but these contribution to the M_W is negligible compared to these loops because of their lower masses.

The two loops contribute differently to the calculation of the W mass. A higher top mass gives a higher W mass and a higher Higgs mass gives a smaller W mass.
As explained before the Z mass is known very accurately, the same is the Weinberg angle θ_W and the fine structure constant α. A variation of the W mass is inspired by [6, p. 143].

$$M_W^2 = M_Z^2 \cos \theta_W \left(1 + \delta_t + \delta_H\right) \tag{1}$$

This variation, δ, can then be explained by either a variation of the top mass or at the

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[4]This value is found in [11, p223], but this is an old value

Higgs mass.

$$\delta_t \sim \left[3\alpha_W \left(\frac{m_t}{M_W} \right)^2 \right] / 16\pi \qquad (2)$$

$$\delta_H = - \left[11\alpha_W \tan \theta_W{}^2 / 24\pi \right] \ln \left(\frac{M_H}{M_W} \right) \qquad (3)$$

which leads to

$$M_W^2 = M_Z^2 \cos \theta_W \left(1 + \left[3\alpha_W \left(\frac{m_t}{M_W} \right)^2 \right] / 16\pi - \left[11\alpha_W \tan \theta_W{}^2 / 24\pi \right] \ln \left(\frac{M_H}{M_W} \right) \right) \qquad (4)$$

From these equation it can be shown that an uncertainty of the top mass at $\sim 5\text{GeV}$ corresponds to an uncertainty of the M_W at 22MeV according to [6].
Right now the top mass is measured to be $m_t = 172.9 \pm 0.6 \pm 0.9\text{GeV}$ so the uncertainty of M_W, σ_{MW}, contribute much more to the Higgs mass uncertainty than the top quark. A plot of the Higgs mass dependence of the W-mass and the top-mass can be seen in figure 4a. Also from the figure it can easy be seen that the uncertainty of the W-mass right now have the biggest impact on the uncertainty of the Higgs mass. This makes an improve measurement of M_W very important.

Before the top quark was discovered[5] this very same way was used to predict its mass. M_W only depends logarithmic on m_H, so m_H could be neglected when m_t should be calculated. But now when the error on M_W and m_t is so small, the very same method can be used to predict the Higgs mass.
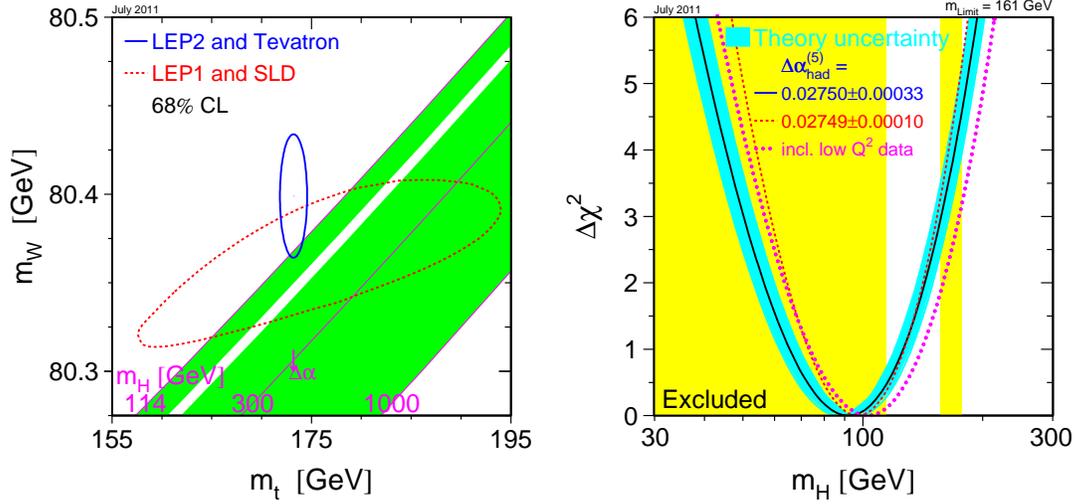
It is worth to note that the LEP experiments have excluded a Higgs mass of less than 114.4GeV with 95% confidence, but according to figure 4b the standard model would prefer a Higgs mass of 95^{+31}_{-24}GeV.[6]
In the standard model it is the Higgs mechanism that gives the particles masses. The Higgs mechanism gives rise to the Higgs particle, so the Higgs particle should exist according to the standard model, and if it does not exist then it is important for SM and BSM theories to figure out how the heavy bosons got their masses. Another thing about the mass measurement of the W-boson is that it can be used as calibration of the detector and maybe even an investigation of the parton distribution functions (PDF).

The W-mass is so far measured to be 80.399 ± 0.023 GeV. This means that for the

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[5]The top quark was discovered in the 90s at the Tevatron
[6]the theoretical calculated Higgs mass can be found at gfitter [9]

(a) Constraints of the Higgs mass based on the measurements of M_W and m_t from previous experiments.

(b) χ^2-curve as a function of the Higgs mass derived from high Q^2 precision electroweak measurements. The yellow region is excluded from previous experiments.

Figure 4: Constrains on the Higgs mass from previous experiments and indirect measurements.

ATLAS experiment to improve this value significantly it has to get a very accurate measurement with just a few MeV uncertainty. As mentioned there was more than 10 people that worked on this measurement for more than 10 years at the Tevatron to get an accurate measurement. This indicates that it is an extremely difficult task and it is by no means possible for a single person to make such a accurate measurement in just one year, but if several people worked together and the detector and and the theoretical uncertainties are understood well enough then it should be possible to make the measurement that accurate according to [1].

4.4 The Parton Distribution Function

Protons collides at LHC so beside the investigation of the properties of W's and Z's there also have to be focused on the protons because it is these particles that will create those bosons at CERN. As explained in chapter 4 the protons are not elementary particles, they consist of two up quarks and a down quark which are called the valence quarks. The mass of the proton is 938 MeV and the quark masses are only a few MeV so there is more in the proton than just the valence quarks. Most of the energy in the proton comes from kinetic energy that binds the valence quarks together.

The valence quarks are combined by gluons and in a short period of time a gluon can split into two quarks[7]. These quarks is then often referenced to as sea quarks. So when two protons collide at the LHC it is not just quarks that collides, but also gluons and antiquarks.

The structure of the proton changes when the energy scale changes. At very low energy scale the proton can be considered as a single particle, but as the energyscale increases the proton gets more detailed. At low energy the valence quarks dominates, but as the energy increases the gluons and sea quarks has to be taken into account. Figure 5 illustrates the difference of the proton when the energy scale changes.

In an electron collider it is easy to find the momentum of the colliding particles because the electrons are elementary particle but this is different at a proton collider. With the high collision energy at the LHC it is more like throwing bags of particles against each other and it is not possible to determine which particles in proton 1 that hit particles in proton 2. To solve this problem an approximation is made and it is assumed that it is only one particle from each proton that hit each other. So the proton is treated as it consists of several particles, called partons, where each parton carry a fraction of the momentum of
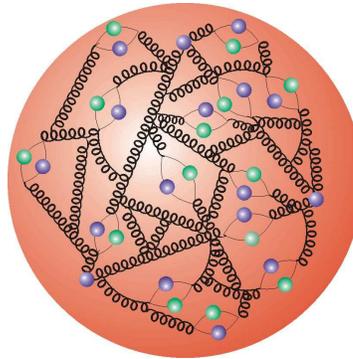

Figure 5: The proton structure changes when the energy scale changes. For high energies gluons and sea quarks have to be taken into account besides the three valence quarks. This figure illustrates it and is found at the homepage for DESY [5].

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[7]These 2 quarks should be a quark and an antiquark with the same flavor.

the proton. So the momentum fraction, x, is defined to be

$$x = \frac{\vec{p}_{parton}}{\vec{p}_{proton}} \tag{5}$$

where $\vec{p}_{parton}$ is the momentum of the parton and $\vec{p}_{proton}$ is the momentum of the proton. $f_i(x)$ is defined to be the probability distribution to find parton i with momentum fraction x. The valence quarks acts differently compared to the gluons and the sea quarks, and therefor these partons should have different probability distribution. This model is called the parton model and it turns out so far to in agreement with experiments. The invariant mass of the produced particle is then given by

$$M^2_{INV} = x_a x_b E^2_{CM} \tag{6}$$

where E_{CM} is the center of mass energy in the proton-proton collision, x_a is the momentum fraction of parton a and x_b is the momentum fraction of parton b.[8]

The probability distributions are very important for the theoretical calculations of the different cross sections, but the measured value is actually $xf(x)$ and this is called the parton distribution function (PDF). An important thing to notice is that the probability to produce particle X depends on the energy of the two partons because of equation 6. It is for example more likely to produce a W-boson if the invariant mass of the two partons is close to the invariant mass of the W-boson.

To calculate the probability to produce a particle X at a hadron collider would then be the probability to get parton a from the first proton times the probability to get parton b of proton 2 (this particle X could for example be a W, a Z or a Higgs). This value is multiplied with to probability for these two partons to produce particle X so the final result is a convolution of the partonic cross section with the PDFs and it can be seen in the equation

$$\sigma_X = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 f_a\left(x_1, \mu_F^2\right) f_b\left(x_2, \mu_F^2\right) \cdot \hat{\sigma}_{ab \to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S\left(\mu_R^2\right), \alpha\left(\mu_R^2\right), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right) \tag{7}$$

where x_1 and x_2 is the momentum fraction that parton 1 and 2 carry from the total momentum of the proton. μ_F, μ_R and Q^2 are scale factors. α and α_S are running coupling constants.

[8]Equation 6 is also important when the collision energy of a hadron collider is compared with the collision energy of a lepton collider.

μ_F is called the factorial scale factor which is a scale factor that describe the proton model. For one value of μ_F the proton will just be the three valence quarks and as the value increases there will be more gluons and sea quarks.

μ_R is a renormalisation factor that comes from renormalisation in quantum field theory and it deals with higher order corrections. α is the running coupling constant of the weak interaction.

The quarks are able to emit gluons and α_S is a coupling for those interactions.

The scale factors have to be separated into μ_F and μ_R in equation 7 to separate the parton function with the cross section.
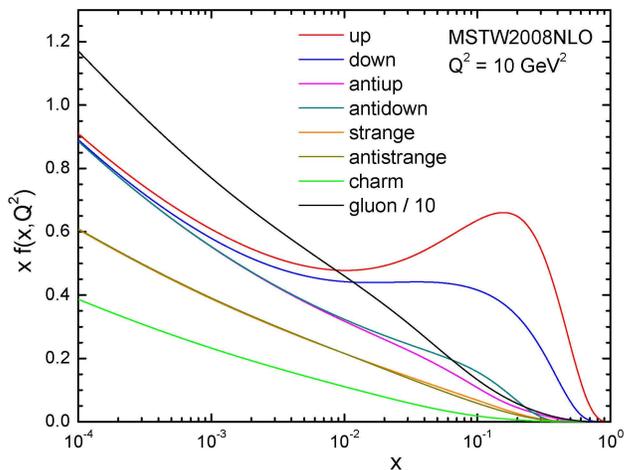

Figure 6: The parton distribution function. x is the momentum fraction that the parton carry from the total momentum of the proton. $f(x)$ is the probability that the parton has momentum x.

As explained in section 2, Z-events will be used for calibration in the analysis. If Z-events should be used as calibration then it first have to be noted that they behave like W's. There will be produced more W's than Z's. At the Tevatron the production of W^+ and W^- is symmetric because it is a proton-antiproton collider[9]. This means that the ratio of produced W's and Z's from a valence quark and a sea quark and produced

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[9]They have opposite $\eta - distribution$, but are otherwise equal distributed. There exist theories proposing that the W^+ differs from the W^- in other things than the sign, but this is beyond the scope of this thesis.

W's and Z's from only sea quarks should be the same and be distributed equally. This is different at the LHC. There will be produced more W^+'s than W^-'s because there are two valence up quarks and only one valence down quark in the proton and the antiquarks will always be sea quarks. So the relative amount of W^+'s produced from valence quarks is greater than the relative amount of Z's produced from valence quarks which can be a systematic uncertainty in an analysis.
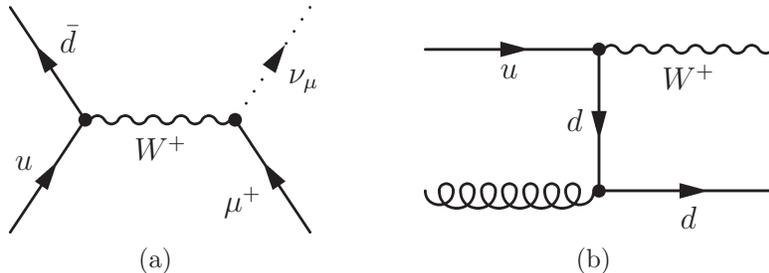

Figure 7: Examples to produce W's at a proton-proton collider. A quark and an antiquark makes a W^+ in figure 7a and a W plus jet event is in figure 7b. The W will decay before it reaches the detector.

The partons that are capable to produce a W or a Z-boson are $q\bar{q}$ or qg. If the $q\bar{q}$ pair have the right charge and invariant mass it is possible for the quarks to produce one of the massive bosons. If a valence quark will create one of the bosons it will properly be $u\bar{d}$ that creates a W^+, $d\bar{u}$ that creates a W^- or a Z-boson that is created by a $u\bar{u}$ or a $d\bar{d}$[10].

So even though the relative amount of W^+'s produced from valence quarks is greater than the relative amount of Z's produced from valence quarks the opposite holds true for W^-, and the overall ratio of W's produced from valence quarks will be as those from Z's.

It is very important to have a good estimation of the momentum fraction for each parton in a precision measurement and the W-mass measurement is not an exception. The momentum fraction distribution of the different partons is described with high accuracy for energies lower than the LHC. This is mainly because of the HERA experiment at

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[10]Quarks from the first generation prefer to interact with other quarks from the first generation according to Cabibbo-Kobayashi-Maskawa. The same argument also holds true from quarks mixing, but the probability for the interaction should be multiplied by the corresponding parameter from the CKM- matrix.

Figure 8: Examples to produce Z's at a proton-proton collider. A quark and an antiquark makes a Z in figure 8a and a Z plus jet event is in figure 8b. The Z will decay before it reaches the detector.

DESY where they collided protons and electrons. This type of collider is very good to determine the parton structure because the electron is an elementary particle. In figure 6 the momentum distribution of the different partons is plotted. Gluons have a low momentum compared to the other particles and it can be seen that the valence quarks have a different PDF than the sea quarks.

5   Kinematics

A particle is said to be short living if it decays before it hits the detector. The invariant mass of such a particle which decay into two particles is found by using 4-momentum invariance. This gives the equation:

$$M = \sqrt{(E_1 + E_2)^2 - (\bar{p}_1 + \bar{p}_2)^2} = \sqrt{m_1^2 + m_2^2 + 2E_1 E_2 \left(1 - \beta_1 \beta_2 \cos\theta\right)} \tag{8}$$

where E_i is the energy and m_i is the mass of outgoing particle i, $\beta = \frac{|v|}{c}$, where v is the velocity and θ is the angle between the outgoing particles.
For massless outgoing particles equation 8 will be

$$M = \sqrt{2p_1 p_2 \left(1 - \cos\theta\right)} \tag{9}$$

This can also be rewritten to

$$M = \sqrt{2p_{T1} p_{T2} \left(\cosh\left(\eta_1 - \eta_2\right) - \cos\left(\phi_1 - \phi_2\right)\right)} \tag{10}$$

where p_{Ti} is the transverse momentum of particle i, ϕ is the angle between the particle and the beamaxis called the azimuthal angle and η is the rapidity and defined to be

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \tag{11}$$

The two outgoing particles will be back to back in the rest frame of the decaying particle.

When one of the outgoing particles is invisible in the detector there have to be introduced some new variables. The transverse energy of a particle with energy E is

$$E_T = E \sin\theta \tag{12}$$

The transverse momentum is defined the same way and the transverse mass can be defined from these variables. The transverse mass of a particle which decays into two particles is given by

$$M_T^2 = (E_{T1} + E_{T2})^2 - (p_{T1} + p_{T2})^2 \tag{13}$$

When the decaying particles are massless then the transverse mass is given by

$$M_T = \sqrt{2p_T E_{Tmiss} \left(1 - \cos\left(\phi_{MET} - \phi_\mu\right)\right)} \tag{14}$$

The distribution of the transverse mass has an endpoint at the invariant mass $M_{Tmax} = M$. This happen when all the momentum of the two decaying particles is in the transverse plane which means that the decaying particles should have 0 momentum along

the beam axis. So the invariant mass is always bigger than or equal to the transverse mass, $M \geq M_T$ and it is only when the particles have no longitudinal momentum that $M_T = M$. So the maximum of M_T only dependence on M.

Because the outgoing particles have to be back to back in the decaying particle rest frame then from equation 14 the outgoing particles will go in opposite direction in the transverse plane ($\phi_{MET} - \phi_\mu = 0$) at the maximum for M_T. This is exactly were equation 14 will be the same as equation 10 ($\eta_i = 0$ because the longitudinal momentum was 0).

These kinematics holds true for both the Z and the W boson. Because the distributions from the decaying particles is the same, the Z boson can then be used as calibration for the W. The difference in the azimuthal angle does not change as the invariant mass change so it will be the p_T and E_T^{Miss} that will change. This makes it possible to use Z-events as calibration of the lepton momentum scale. If the transverse momentum of the outgoing leptons will be measured 1% too high then the invariant mass of the bosons will also be measured 1% too high. The transverse mass will also grown linear with the lepton p_T from equation 14.

Equation 8 is the definition that is used when the invariant mass of a shortlived particle is found. In a W or a Z decay that goes into leptons the mass of the leptons is much smaller than the invariant mass of the bosons, so nearly all the the energy will be the momentum of the leptons. m_1^2 and m_2^2 are neglectable and the energy distributions of lepton 1 and 2 will theoretically be the same if it is a neutrino, an electron or a muon. The neutrino masses are very close to zero and the muon mass is 105.66MeV. The W boson weight about 800 times more than the muon and the mass is added in quadrature so it is in fact neglectable even though this is a precision measurement.

In reality the p_T distributions will not be the same for the leptons because the particles will be detected differently or in the case of the neutrino only indirectly. But the difference will be because of the detector and not due to kinematics.

Part II
LHC and the ATLAS Detector

6   LHC

The Large Hadron Collider is a 27km long collider ring near Geneva. It lies about 100m underground and is designed to collide protons with a center of mass energy at $\sqrt{s} = 14$ TeV, which is 7 times more than any other particle collider. In 2010 and 2011 protons collide at 7 TeV and it is designed to have 1 billion collisions every second, but most of these collisions will just make inelastic proton-proton reactions. If all the data from just the ATLAS detector should be recorded, then it would fill $100,000$ CDs per second. This makes it impossible to save all the events so there has to be a trigger which decides which events that will be saved and which ones that will be thrown out.
There are 4 big detectors at the LHC. CMS, ATLAS, LHCb and ALICE. The CMS and ATLAS can be considered as the general purpose detectors. It is these two experiments that have been build with the intention to find the Higgs particle if it exist and otherwise be able to exclude it. These two experiments should also hopefully be able to discover new physics outside of the standard model.
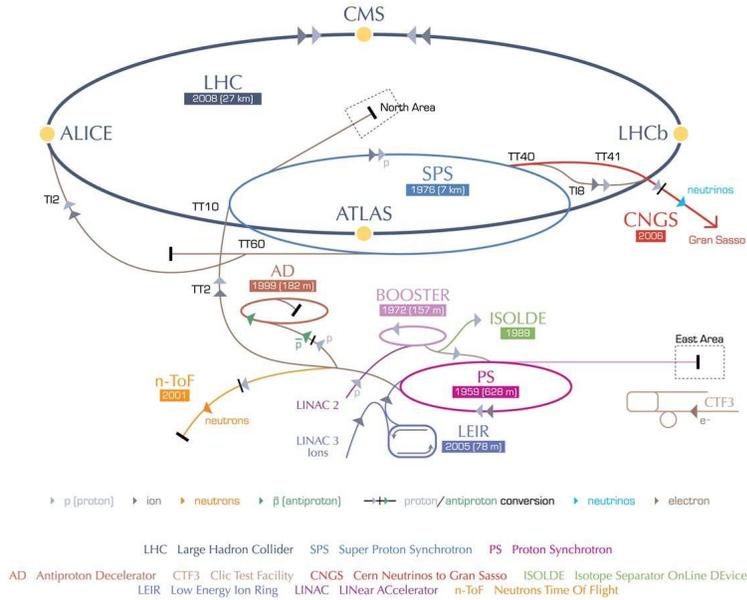
The LHCb was built with the main purpose to investigate the antisymmetry in quark antiquark that is observed in nature. It will do this by focusing on physics involving b-quarks and it is designed to detect these particles with high accuracy.

In November and December 2010 and 2011 lead ions collided at the LHC instead of protons at $\sqrt{s} = 2.76$TeV. These event were most important for the Alice experiment. When lead ions collide with such a high energy there are theories that predict that quark-gluon plasma will be created and the ALICE detector is build to find it if it exist and then analyse it. An understanding of the quark-gluon plasma will hopefully give a better understanding of what happened after the Big Bang.
In figure 9 the accelerator complex at CERN is showed. The protons are obtained after removing the electron from hydrogen atoms. Then they are injected into LINAC2[11] and after that they go to the PS booster and to the Proton Synchrotron (PS), followed by the Super Proton Synchrotron (SPS), before finally reaching the Large Hadron Collider (LHC). The protons are kept in approximately circular orbits by strong magnetic fields

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[11]a linear accelerator

Figure 9: CERN accelerator complex

from superconducting magnet. They move in both direction and only collide four places in the LHC. Each interaction is in the center of one of the four detectors.

The luminosity at the LHC is designed to be 10^{34}cm^{-2}s^{-1} and this makes it possible to detect more rare particles than ever before. Luminosity is proportional to the number of interaction per time and is the used term in high energy particle physics.
When the collision energy of protons increase the masses of the outgoing particles can be greater. The cross-section for different processes as a function of the center of mass energy can be seen in figure 10. It can be seen that for every femto barn in integrated luminosity it is expect to be around 10^8 W-bosons , but only 11% of these bosons will decay to a muon and a neutrino. There will be around 10^7 Z's.
A typical yearly run starts in March and ends in November. LHC is shut down during the winter because electricity is more expensive in this period. The 2010 and 2011 periods can be seen in figure 11. In 2010 the distribution looks exponential while it is more linear in 2011. This is because of a better understanding of the experiments doing the time and then the luminosity can increase.
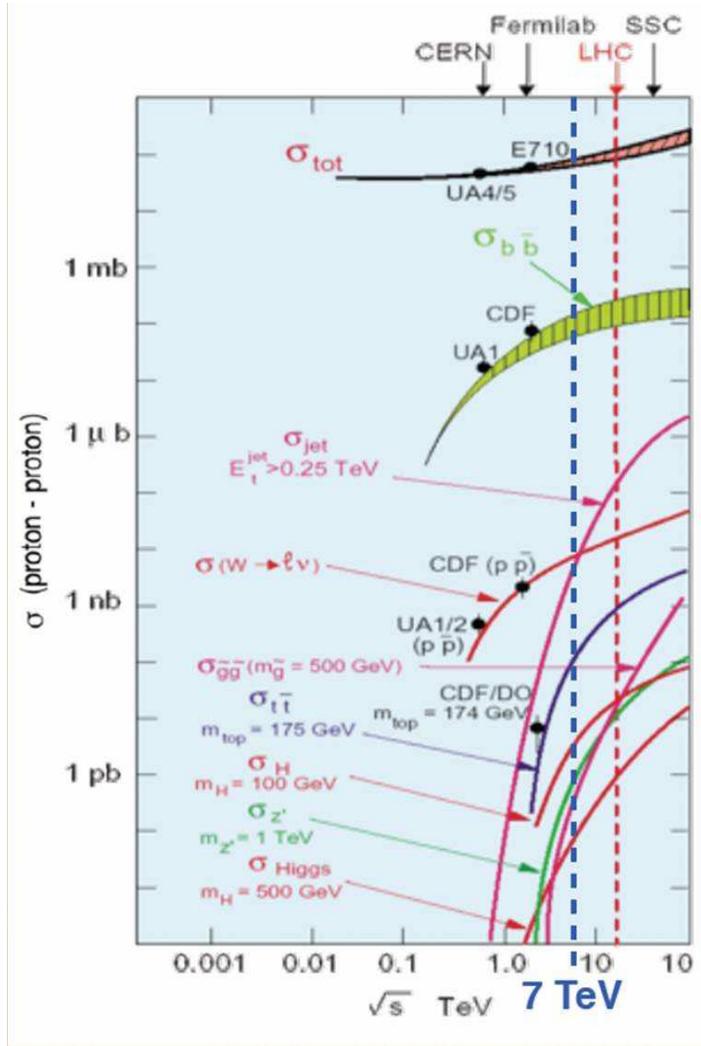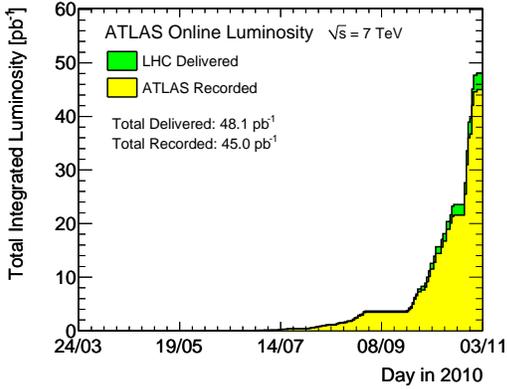
Figure 10: The cross section of different events as a function of the center of mass energy in proton-proton or proton antiproton collisions. 1.96TeV is marked for the center of mass energy at the Tevatron and 7 and 14TeV is marked for the LHC.

The protons comes in bunches. To improve the luminosity there can be added more protons in each bunch or the bunch spacing can be decreased. Bunch space is the space between each bunch of protons. It is designed to be 25ns which corresponds to $\sim$ 8m. This means that the detectors should be able to decide if an event should be saved in 25ns.

In the end of 2011 the bunch space was at 50ns and there are $1.1 \cdot 10^8$ particles in each

(a) Integrated luminosity in 2010. (b) Integrated luminosity in 2011.

Figure 11: Total integrated luminosity of ATLAS and the LHC as a function of time. The scale change as the luminosity increases.

bunch.

A typical run last $12 - 24$ hours and then the beam quality is so degraded, that it gets dumped.

The luminosity increases the first years for hadronic colliders and the LHC is no exception. The total integrated luminosity from 2010 can be seen in figure 11a and the distribution looks exponential. As the LHC is better understood the luminosity can increase. The integrated luminosity from 2011 is in figure 11b. This distribution is more linear but the luminosity is still increasing.

There are some times when no data is taken. In these periods there will be machine developments and updates which is not possible when to machine is running.

In my analysis I used data from period F, G and H. This is from 15th of May to 28th of June both in 2011 and it corresponds to $\sim 0.827 \text{fb}^{-1}$ in integrated luminosity. I will explain more on luminosity in section 6.4.

28

6.1 The ATLAS Detector

The ATLAS detector (A Toroidal LHC ApparatuS) is 44 metres long and 25 metres in diameter, weighing about 7,000 tonnes. This detector is a multicomponent detector with several layers of subdetectors and each of those subdetectors have a different focus. The layers are concentrated cylindrically around the interaction point. Closest to the beam point is the Inner Detector, then there is the Calorimeter and the outer part is the Muon Spectrometer. This can be seen in figure 12. I will go through each of the layers and explain what they can measure.

Each subdetector is a study by itself and is described in detail elsewhere. [3]

Figure 12: Cut-away view of the ATLAS Detector
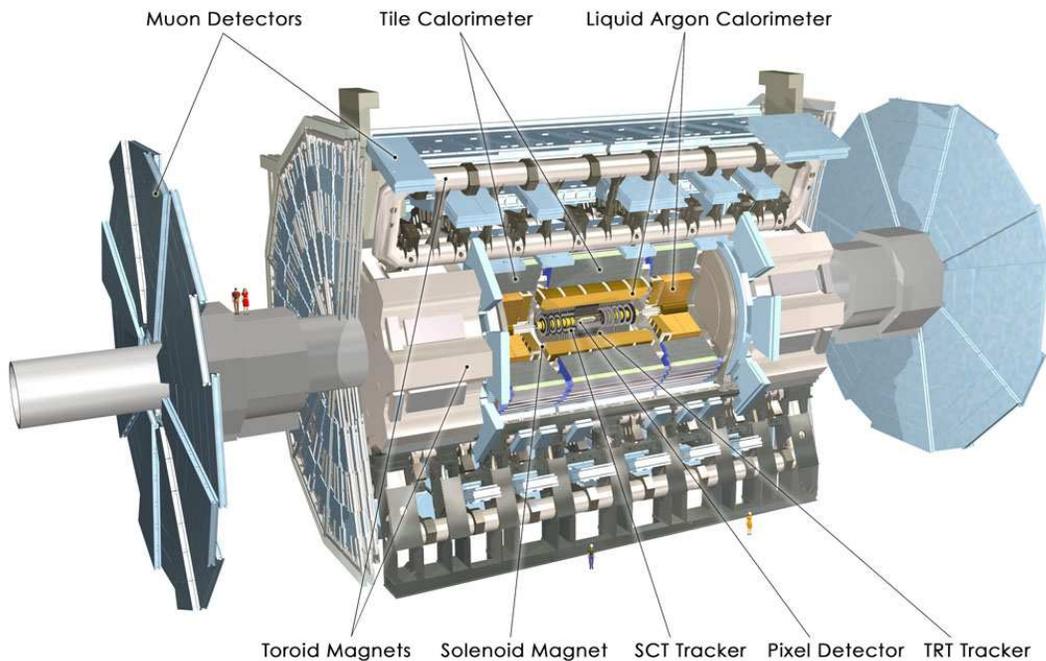
6.1.1 Inner Detector

The ATLAS Inner Detector consist of the pixel detector, the semi-conductor tracker (SCT) and the Transition Radiation Tracker (TRT). It is designed to provide a robust pattern recognition and be able to measure both the primary and the secondary vertex for charged tracks. It allows precision tracking of charged particles inside $|\eta| \approx 2.5$.

The innermost layer is the pixel detector. It is made of silicon and arranged in three layers both for the barrel and endcap. It is segmented in R, ϕ and z components. It has 288 modules and each module has 46080 readout channels. The next layer, the SCT, consist of four double-sided silicon strip layers. These strip layers is offset by a small angle to allow a measure of the z component. It is similar in construction and function to the pixels but differs by having long narrow strips rather than small pixels.

The pixel and the SCT together determines where the interaction occurred (the vertex position), the momentum of charged particles due to its curvature in the magnetic field and secondary vertices and impact parameter. This is very central in tagging of jets from b-quarks.

The last part is the transition radiation tracker (TRT), which are straw tubes that provide up to 36 additional R and ϕ measurement. The straws consist of 70% Xenon, 27% Carbon dioxide and 3% Oxygen. Carbon is used to stabilize the straws and it is Xenon that is used to make the measurement. When a particle crosses a straw, some of the Xenon atoms will ionize and create free electrons. These electrons will drift to the center of the straws because there is a wire with an electric potential in the center. The drift of these electrons creates an avalanche of electrons reaching the wire. This allows for a readout of the signal giving a drift time measurement, that gives a spatial resolution of 170μm per straw.

When an ultra-relativistic particle moves from one material to another material with a different dielectric constant as it does in the TRT the particle will radiate photons in the X-ray region. Xenon is very efficient to absorb those photons and it result in a massive ionisation and a large signal readout. Because of this the straws have two discriminators, one for normal hits and one for these so called high threshold hits. The ratio of high threshold hits to normal hits in the 36 straws makes a very useful variable to separate electrons from other particles for example pions. This makes the TRT a very useful to identify electrons.

This is an important detector part in the electron channel for the W-mass measurement.

6.1.2   Calorimeter

The ATLAS detector has two calorimeters which are sampling calorimeters. The calorimeters separate the inner detector from the muon spectrometer and measures the energy in the range $|\eta| < 4.9$ and is full ϕ-symmetric without azimuthal cracks .The system is able to measure the energies for both hadronic and electromagnetic particles.

The electromagnetic (EM) calorimeter is a liquid argon (LAr) calorimeter with inter-
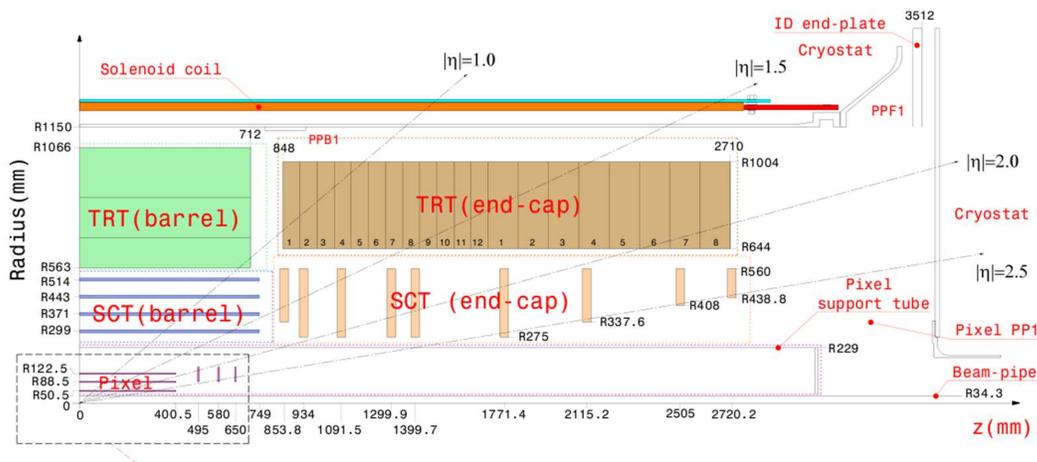
Figure 13: ATLAS Inner Detector. Closest to the interaction point is the Pixel detector, then the SCT and the TRT.

lacing layers of lead and stainless steel. It is divided into a barrel part for $|\eta| < 1.475$ and has two end-cap components for $1.375 < |\eta| < 3.2$, each of which is housed by there own cryostat for cooling.

It is suited for precision energy measurements of electrons and photons.

The hadronic scintillator-tile calorimeter is placed directly outside of the EM calorimeter envelope. Its barrel part covers $|\eta| < 1.0$ and have an extended part of $0.8 < |\eta| < 1.7$. It uses steel as the absorbing material and scintillating tiles as the active material.

The Forward Calorimeter (FCal) is integrated into the end-cap cryostats. It exist in an enviroment with high radiation and consist of 3 layers. The first is made of copper and optimized for electromagnetic measurement. The other two is made of tungsten. FCal covers a rapidity region of of 3.2 to 4.9

The calorimeter is hermetic so it can detect all the high energy particles in the standard model besides the neutrinos. Neutrinos will be detected indirectly in events with a single neutrino as missing transverse energy.

The calorimeter only covers a rapidity region $\eta \leq 4.9$ but particles with higher rapidity have low transverse energy.

6.1.3 Muon Spectrometer

The Muon Spectrometer can be seen in figure 14. It consists of Monitored Drift Tubes (MDT's) and Cathode Strip Chambers (CSC). The MDT is placed in three cylindrical layers around the beam axis at radii of approximately 5m, 7.5m and 10m. The MDT consist of several layers of aluminium tubes with argon based active gas and has a diameter of 29.970mm. Like the TRT straws it has a central wire with a magnetic potential, but the MDT's consist of Argon instead of Xenon, but it works the same way. When a particle hits the MDT some of the Argon atoms will be ionized and create free electrons. These electrons will drift towards the central wire because of its potential and there will be a signal readout.

Figure 14: ATLAS Muon Spectrometer. The first letter of the MDT naming scheme refers to barrel and end-cap chambers while the second refers to inner, middle and outer layer.

Around the muon spectrometer is large superconducting air-core toroid magnets (see section 6.1.4) which provide strong bending power and thereby reduce the effects of multiple scattering and optimise the momentum resolution in the process. The performance goal of the muon spectrometer is a stand-alone transverse momentum resolution of approximately 10% for 1TeV tracks and the MDT have an average resolution of $80\mu m$ per tube.

The MDT covers a rapidity range of $|\eta| < 2.7$, but at $2.0 < |\eta| < 2.7$ the inner most layer is replaced with Cathode Strip Chambers (CSC). There is a buildup of positive ions in these region because of a higher flux of particles.

There are also resistive plate chambers (RPC) at $|\eta| < 1.05$ and thin gap chambers (TGC) at $1.05 < |\eta| < 2.7$. These are used for triggering and measurement of the second coordinate of particles. The MDT's have a maximum drift time of 700ns. It is preferable to have first level trigger in the muon spectrometer and then the readout signal should be less than 25ns, because this is the designed bunchspacing at the LHC. The RPC and TGC are used as these first level triggers while the MDTs have better resolutions.

6.1.4 Magnet System

The Magnet System of the ATLAS detector consist of one solenoid and three toroids superconducting magnets which creates a magnetic field across the whole apparatus.
The Solenoid Magnet System: The solenoids is aligned along the beam axis and provides a 2T axial magnetic field for the inner detector. It is places so it surrounds the inner detector and will make the charge particles bend according to their momentum and charge. This makes it possible to get a measurement of the charged particles momentum in the inner detector from the positions, because a charge particle with high momentum will bend less than a particle with a smaller momentum.
The Toroid Magnet System: There is a toroid magnet at the barrel and two at the end-cap. These produce a toroidal magnetic field of approximately 0.5T to 1T at the muon spectrometer. This is lower than the one at the inner detector but it covers a larger region which makes it possible to make a precision measurement anyway. The magnet system gives a momentum measurement for charged particles in its regions.

6.2 Particle Interaction and Muon Reconstruction

The charged particles will bend at the inner detector because of the magnets. This makes it easy to separate charged particles from the neutral ones and also easy to get the electric sign from the direction the charged particle bends.

The different particles leaves different signals in the detector. Figure 15 gives a simplified way to illustrate this. Photons and electrons gets to the EM calorimeter where they will cascade and make an electromagnetic shower. The photons are neutral and will not

be bended in the inner detector.

Neutrons and protons will get to the hadronic calorimeter where they will make hadronic showers. These two can again be separated in the inner detector.

Figure 15: Particle reconstruction in the ATLAS detector. Particles leave signals in different parts of the detector and can be identified from this.

The muons behaves like electrons except that they are ~ 200 times heavier. Even though they behave like electrons this mass increment makes them not interact with much and they are able to travel all the way to the muon spectrometer. They will also make a signal in the inner detector and at the energy range the muons have from a W or a Z-event the best energy resolution measurement will be from a combined measurement from the inner detector and the muon spectrometer. This can be seen in figure 16.

Unfortunately the simplification in figure 15 is not in total agreement with reality. It gives a good indication of how the particles will be identified, but unfortunately there

(a) Central region (b) End-cap

Figure 16: Muon resolution as a function of transverse energy. It is expected that the muon p_T will have a peak at 40GeV if they decayed from a W and at 45GeV if they decayed from a Z.

is some misidentification of the particles. Particles with high momentum are able to get to the muon spectrometer some times and pions can ionise several straws in the TRT so they can be detected as electrons.

So if a particle in data looks like a muon it is not surely a muon. There is a good indication that it could be a muon, but it is not surely a muon. This means that when I simulate MC events that look like $W \to \mu\nu$ and $Z \to \mu\mu$ in data, I will also have to generate background events in MC that will be detected as $W \to \mu\nu$ or $Z \to \mu\mu$ events.

6.3 Data Acquisition and Trigger

In figure 11 is the integrated luminosity plotted as a function of time. As it can be seen from the plots there are many more events per second in the end of 2011 than there were in the run periods in 2010. Because of this there have to be different trigger cuts for each period. At the early times of LHC all events with an identified lepton candidate was saved, but that is not possible to do anymore because there are many more interactions and there will be that many more lepton candidates.

The p_T distribution of outgoing particles in proton collisions goes roughly as an exponentially decreasing function. An indication for new physics is events with high p_T, so p_T is a good variable for triggers and when the luminosity goes up in each data block then the p_T cuts will also go up.

Triggers are studies by themselves because there is limited bandwidth and disk space and at the same time all the interesting events should be kept for analysis. There would be too much data stored if every event should be saved, to make up for that there will be new triggers for each data period, but also in a single cycle and even doing a single run. The number of collisions decreases during a run and at some point there are so few protons left that it does not make any sense to keep running. The beam will get dumped and a new run will be prepared.

It takes some time before data is available for analysis. There can be problems with a subdetector, triggers or other stuff that makes a run not good for analysis. So after each data period there is a good run list (GRL) that lists all the good runs in the period. A GRL should be used to give a better comparison of different analysis within the same topics.

In order to try to minimize any systematic uncertainties caused by the selection of data periods and runs I have chosen to use the same data runs for both the Z and the W analysis along with a GRL. If there is a problem in the period then it will be in both the Z and the W sample and if the error contributes linearly to the p_T^μ-distribution then it will cancel out.

The official non-scaled trigger in the data periods I used for single muon selection is EF_ mu18. All the muons should be detected with a p_T greater than 18 GeV in the muon trigger (the RPC and TGC) before the event will go to the second trigger level. The RPC and TGC is not able to measure the muon p_T with as good resolution as the

MDT so it is possible that an event with a muon with $p_T = 18.1$ GeV will not be stored because the muon p_T was measured too low in RPC and TGC. In my analysis I should use a trigger that is at least EF_ mu18 and for technical reasons I end up using EF_ mu20. As long as it is the same for all the data periods and MC and equal or greater that the hardest non-scaled trigger then it is acceptable.

6.4 Luminosity

The integrated luminosity is not very important in a W-mass measurement analysis. What is important is the number of W's and Z-events in the analysis, because it is preferable to have enough events to minimize statistical uncertainties. The number of W-events is given by $n_W = \sigma_W \cdot L$ where σ_W is the W-cross-section and L is the integrated luminosity. Even tough the luminosity is not that important for the analysis it is still a good measurement to have in any analysis and it is not a trivial measurement to do.

I used data from run period F, G and H with a GRL. This is from 15th of May to 28th of June in 2011 and run number 182013 to 184169. The official way to do the luminosity calculation is to use a luminosity calculator. This is a technical and time consuming tool. Normally the GRL document is included in the analysis, and when the GRL file is included then the program will only include events from the GRL. To use the luminosity calculator the GRL should be used with the corresponding trigger that match the analysis. The run numbers should be added to the luminosity calculator and it will end up given a 3% uncertainty of the value.

The luminosity calculation gave 826.83pb^{-1} for both the EF_ mu18 and EF_ mu20 triggers.

As a cross check I scaled my W and Z sample in MC to match data. Given the W and Z cross section I got an integrated luminosity around 840pb^{-1} which is clearly acceptable.

The problem with just scale after the amount of W's and Z's in MC is that it does not take the cross section or the acceptance into account. It could be that the luminosity in MC is the right one, but that it is either the cross section, the acceptance or both of them that deviates.

This uncertainty on the cross section made me scale the MC events by hand with a scale factor which I will come back to in section 6.6.1.

6.5 Missing Energy

As explained in section 4 the neutrino will not be detected directly in the detector so its energy and direction can only be found indirectly. The neutrino will go straight through the detector, but from momentum and energy conservation there will be some missing energy in the direction where the neutrino passed. In an event with only 1 neutrino the energy of the neutrino will be the missing energy of the detector. [12]

The ATLAS is cylindrical and for obvious reasons there is no detection of particles along the beam axis. It is unknown how many particles and how much energy there is at the beam axis. This means that there will always be missing energy along the z-axis and due to that it is not possible to measure the z-component of the neutrino momentum. The rapidity, η, depends on p_z so that variable is not possible to get for the neutrino neither.

What can be measured instead is the transverse momentum p_T. Right before a collision the sum of transverse momentum of the particles will be 0 and this should be the same after the collision. This gives that in an event with only one neutrino, the transverse momentum of all the other particles is measured and the transverse momentum of the neutrino will then be equal to the missing transverse momentum in the event. The kinematics of the neutrino has a much higher uncertainty than other leptons because the neutrinos have to be measured indirectly. If the kinematics of a single jet is measured with a low accuracy then it will contribute to the accuracy of the neutrino.

There is also pileup that contributes to the uncertainty of the missing energy and all these uncertainties will in the end be combined to the uncertainty of the missing transverse energy, E_T^{Miss}. In fact pileup may turn out to be the biggest challenge for a high precision measurement.

E_T^{miss} is a study by itself but W-analysis depends on the measurement. All the sub-detectors will measure the energy that is allocated in each layer and direction. There will also be an estimate of the energy of particles that goes through all the subdetectors and the measurement from all the subdetectors will be collected to give a final E_T^{miss}-measurement.

The uncertainty of the missing energy depends on the sum of all E_T-measurement in the detector as it can be seen in figure 15. The uncertainty increases as $\sum E_T$ increases. This means that because $\sum E_T$ increases when the luminosity increases the uncertainty of the missing energy will also increase.

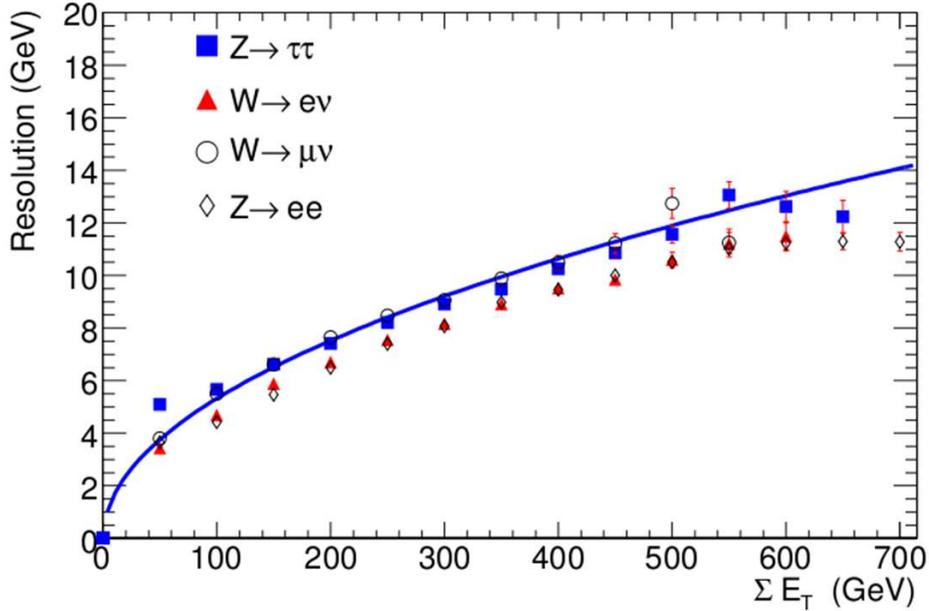[12]This is only if all the other particles is detected.

Figure 17: Resolution of the two components (x, y) of the E_T^{MISS}-vector as a function of $\sum E_T$ in the ATLAS detector.

The uncertainty on E_T^{miss} changes from each run period because the luminosity will change. The number of pileup events increases when the luminosity increases and this will also affect the E_T^{miss}. So because the W-mass value depends on the E_T^{miss}-variable, the W-mass analysis will be a bit different for each run period. It is not guaranteed that the E_T^{miss}-scale is the the same for each run period.

The strategy for me will then be to choose one or more run periods which have enough W- and Z-events to somewhat neglect the statistical uncertainty and then analyse the data. There will be produced so many W's and Z's at the LHC that the statistical uncertainty will be suppressed so it is preferred to only run at few run periods to minimize the systematic uncertainty than run on all the data.

6.6   MC Simulation

Monte Carlo (MC) simulation is an important part of experimental high energy physics. It can be split up to an event simulator and a detector simulator. The event simulator simulates collisions event and detector simulators simulates how the events will be detected. In the end of the day MC should look like the possible outcome of the real data. They are very useful tools to test whether the detector is well understood and to discover new physics. Before it is possible to discover new physics beyond the standard model the standard model should be rediscovered and the detector should be well known.

The different experiments at the LHC can use the same event simulation and there exists more than one. The most famous event simulator in Scandinavia is Pythia because it is created by physicists from Lund. The event simulators used at LHC experiments try not just to simulate how a proton-proton interaction is but also initial-state showers and final-state showers. Event Simulation is a study by itself in Phenomenology, but in my thesis I will just use it as a tool in my analysis.

The detector simulator uses GEANT4 for a full simulation of the ATLAS detector. It includes a precise description of the geometry of ATLAS, that means the position, dimension and material of all parts of the subdetectors. If a channel in a subdetector is dead then this should also be turned off in the detector simulator. A detector simulator gets input from Pythia, Herwig or another event generator. This makes it possible to study the different shower algorithms and the parton distribution functions to name a few of the subjects. The detector simulator should work for both the eV-scale as well as at TeV-scale. This is a very time consuming step in the MC simulation.

One of the advantages of MC simulation is that they have the truth particles in the sample. The particles will not always be detected and sometimes they will even be misidentified. MC samples are very useful tools in analysis about the detector efficiency and it is possible to compare the data with MC-samples that only includes the standard model to discover new physics. If there is a lot of events in the data after cuts have been made and none in the SM MC-events then this is a good indication that there is something new besides SM, but it is not always as simple as that.

It is just an indication because in reality MC is not the same as the data. A part of the detector simulation could have some missing parts, maybe a detector part in data does not function optimally and maybe the parton distribution function is not well enough understood at high energy.

Normally in analysis the MC events have been downloaded and not produced from the beginning. It is too time consuming to run first Pythia and then GEANT4 and if a mistake has been made the events have to be simulated from the beginning to make up for it. It could be due to inefficiency in a small part of a subdetector and if that is the case then it can in some situations ruin the whole analysis.

What should be done is to download the signal event in the analysis, which in my case is the $W \to \mu\nu$-events and $Z \to \mu\mu$. The amount of MC-events should correspond to the number of events that is expected from data, but there can also be produced more or less of these events. To make up for it there is a weight factor that weights the MC so the number of W's will be the same as in data. If there are twice as many events in MC then all the events should be weighted with a half so the MC events can be compared with data but also with each other.

There also have to be produced background events and then the weight factor makes it easier to compared the background events with the signal events.

This scaling of events is especially useful in analysis with only a few data events but with a very good prediction of how the events should look like in MC. Then the statistical uncertainty will only be in data.

The way to implement the number of events in MC is to add the integrated luminosity from data because the cross section of events is already implemented in MC. The weight factor will then be calculated easily and that is how the different MC samples is put together.

I have also used MC samples for background events. The ones I used were the $W \to \tau\nu$ and $Z \to \tau\tau$. I used the skim with no filter for all the MC samples except the $W \to \tau\nu$ where I used the 1 lepton skim. I also had access to $W \to \mu\nu$ and $Z \to \mu\mu$ at 1 lepton skim but there were less events in those samples and after my cuts it did not end up deviate significant from the no filter skim so I ended up using the no filter skim.[13]

6.6.1 More on luminosity and MC scaling

When data and MC is compared there is not the same amount of events even after the amount of MC events is scaled with respect to the luminosity. The luminosity, the cross section and the efficiency has an uncertainty but fortunately the analysis does not

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[13]I want to mention the how each sample got skimmed because there were troubles with the $W \to \tau\nu$-background (I will come back to it in section 9.0.2)

depend on the amount of events predicted in MC as long as MC has the right scale between signal and each background sample.

In my analysis I have chosen to scale MC-events so it is the same amount of events as data in the fit range I do the χ^2-test. The scale was not more than a couple of percent off, but it did not change any results in the analysis.

Part III

Analysis

7 Short Introduction to full Analysis

A measurement of the W-mass is not like the Z-mass. For the Z-mass there is a significant mass peak and nearly no background, but for the W there is the neutrino, which escapes the detector and therefore only can be detected indirectly. This makes it impossible to get the z-component of the neutrino, and so there will not be a mass peak like the Z-events. Thus other methods have to be used.

The way to get the W-mass is to consider variables sensitive to M_W and to generate MC-samples with different W-mass and find out which MC-sample is in best agreement with the data. Making such an array of templates is called the "template method". This is a problematic way to do a precision measurement, because there is no guarantee that MC will look like data and any small unknown difference can ruin the result.

The variables to compare is the transverse mass of the W boson, M_T, and the transverse momentum, p_T, of the muon from the decaying W, because these variables are correlated with the W-mass.[14]

With this method it is really important to have a good understanding of the detector and have a well tuned MC. To check this, Z-events is used because $Z \rightarrow \mu\mu$ is a very clean channel and it has a lot in common with the $W \rightarrow \mu\nu$ (see section 5).

An obvious example of an uncertainty is the muon momentum scale, which could very likely be different in data and MC. Luckily, there is enough Z-events that it is possible to use muons from these events for calibration[15]. The Z-mass is well known with high precision from LEP-experiments and the muon momentum scale can be found from there. The momentum deviation in the detector will be linear in energy, so if the momentum is measured 0.1% too low for Z's then it should also be 0.1% too low for W's[16].

The measured W-mass can be expressed as:

$$M_W^{Data} = M_W^{Truth} \cdot \frac{TS_W}{TS_Z} \tag{15}$$

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[14]In theory the missing transverse energy could also be used, but the uncertainty of the measurement is too high to use in reality.

[15]This has also been done at Tevatron but with a lot fewer Z's [2]

[16]I will come back to this linearity in section 5

where M_W^{Truth} is the generated value in the MC-events. This was chosen to be the measured value from previous experiments which is $M_W^{Truth} = 80.399 \pm 0.023 \text{GeV}$.
TS_Z is the template scale factor, TS, from the Z-analysis and TS_W is the template scale factor from the W-analysis. TS_Z and TS_W are the values that shift the templates in the W and the Z analysis to best match the distributions in data.

W-events are generated in Monte Carlo for different W-masses. W-events from data are then compared with each of the sampled W-mass from MC, and a χ^2-test for the muon p_T-distributions has been made to compare the data with MC.
I have illustrated this in figure 18. Two MC-templates have been made for $M_W = 79.0$ GeV and $M_W = 82.0$ GeV, where p_T^μ have been plotted for $W \rightarrow \mu\nu$. The maximum for $M_W = 82.0$ GeV is higher than the one for $M_W = 79.0$ GeV and the idea is that the distribution from data should be between these two.
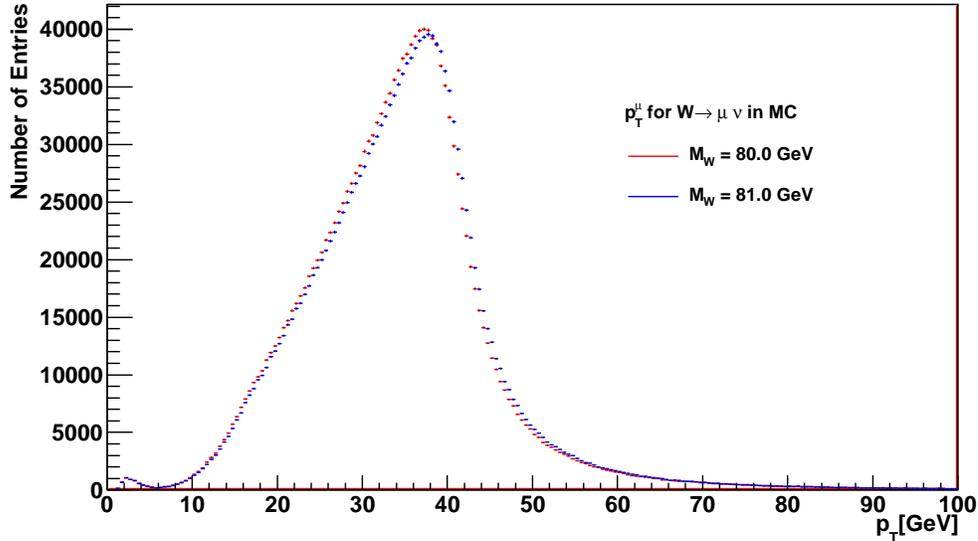

Figure 18: p_T^μ-distribution for two MC templates. One with a W-mass of 80.0GeV and another with a W-mass of 81.0GeV. The p_T^μ-distribution from W-events in data will be between these two distributions.

The χ^2-values for each W-mass-sample is then fitted with a parabola and the minimum is when MC is at best agreement with data. This minimum will then be the template

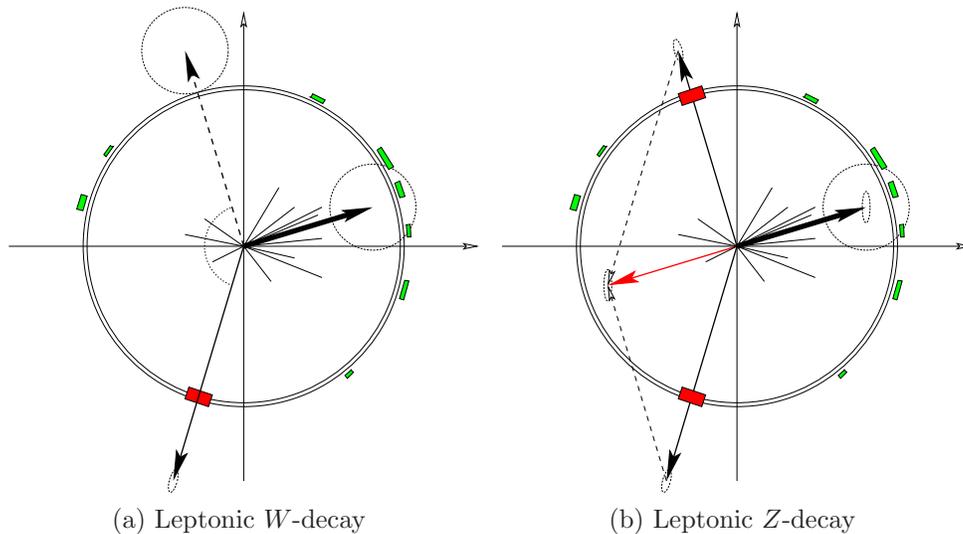(a) Leptonic W-decay   (b) Leptonic Z-decay

Figure 19: Illustration of leptonic boson decays. The red blocks illustrates hits in the detector that make the particle be treated as a lepton, which for example could be a hit in the muon detector. The green blocks are hits which looks hadronic. The thick arrow indicates the hadronic recoil.

scale factor TS_W.[17]

The same method is used to get TS_Z, but M_W^{Data} grows proportional to TS_W where TS_Z is inversely proportional. $M_W^{Truth} \cdot TS_W$ gives M_W^{Data} from only looking at W-events and TS_Z is then included to make up for systematic errors in the measurement of the muon momentum scale. Figure 18 is only made for signal events, but background events are also included in the distribution. The invariant mass of the boson increase linearly with the momentum of the lepton so the template scale factor will have the same value for a mass measurement.

In figure 19 is a simplification of W and a Z-event as it looks like in the detector. The thick arrow indicates the hadronic recoil which is an effective tool to do an E_T^{MISS}- analysis.[18]

This is the main points of the analysis. The important part of the analysis is to under-

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[17]I have discussed the template scale in section 7.1.1

[18]When a boson has a transverse energy then the hadrons have an equal amount of transverse energy as the boson, but in the opposite direction. This is called the hadronic recoil.

stand the systematic uncertainties because any small variation in the distributions will chance and possibly ruin the result. I will explain some of the systematic uncertainties in detail and some will just be mentioned how they effect the final result. To analyse the systematic uncertainties there have to be a good understanding of data, MC and the cuts that is used to find the events which contains a heavy boson.

7.1 The Decay Channel

In a mass measurement for an unstable particle one of the first thing to do is to choose a decay channel. The hadronic decay is excluded pretty fast because there is too much background from QCD events. The τ-channel is also excluded because the τ-lepton will decay before it hits the detector, it decays mostly hadronic but even when it decays leptonic it will be along with two neutrinos and with two additional neutrinos it becomes impossible to do a precision measurement in the MeV-scale. This ends with a decision between the electron and the muon channel. It is possible to do the measurement in any of these channels, but I have chosen to focus on the $W \rightarrow \mu\nu$ channel. Maarten Boonekamp and his group focus more on the electron channel so this analysis looked more unoccupied. The electron p_T-distribution is not gaussian due to bremsstrahlung and the muon signal should be cleaner from QCD events, but both channels should in the end be combined to give the final measurement.

A disadvantage of the muon channel is that it is more likely that a muon not will be detected. Most of the electrons will be identified. They can be misidentified but they will rarely not be detected at all. This leads to more background from Z-events but less from QCD-events because pions can be misidentified as electrons.

Both the transverse mass and the transverse momentum of the outgoing muon can be used for the analysis. This can be seen from section 5. Both have their advantages and disadvantages. M_T is more affected by E_T^{Miss} where the muon p_T is more affected by p_T^W. I have plotted the transverse mass of the W-MC-events in figure 20 and the transverse momentum of the muon in MC events in figure 21. These events are only signal events. E_T^{Miss} could in theory also be used for the analysis because it represent the transverse momentum of the neutrino but the uncertainty on this value is too high in reality to use.

In figure 20 M_T^W is plotted when $p_T^W = 0$, when $p_T^W \neq 0$ and when $p_T^W \neq 0$ after the detector resolution is taken into account. From the plot it is easy to see that M_T has its maximum and edge at $M_T = M$ just as expected. This value is called the Jacobian edge. It is still smeared because the W-mass has a width, but nonetheless it can be seen that the distribution depends on the W-mass.

In figure 21 the transverse momentum of the muons from the W-boson from MC is plotted. This variable should be compared with the transverse mass because it is those two that are best to use in the analysis to get M_W. In the W-rest frame both distributions looks the same except that the Jacobian edge of the p_T-distribution is at $p_T = \frac{1}{2}M_W$.
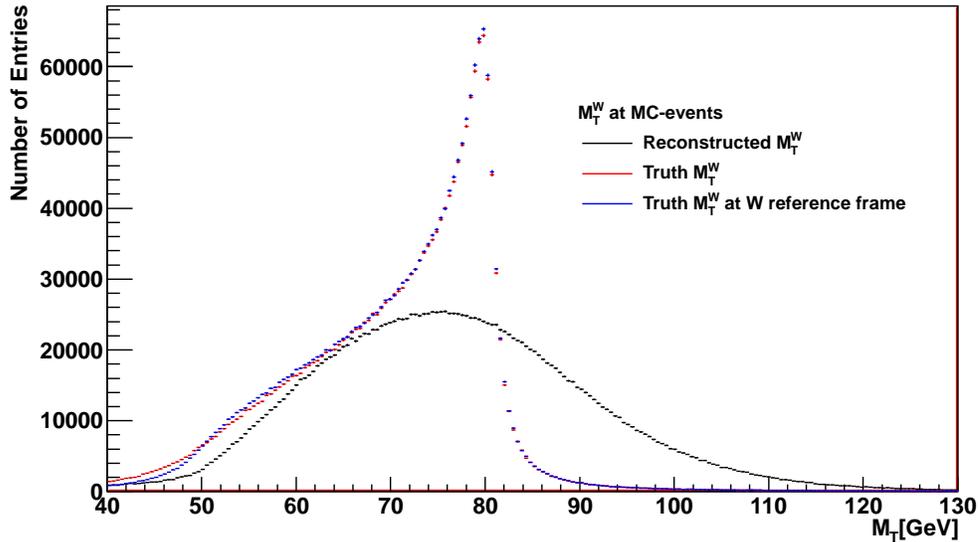
Figure 20: Transverse mass of the W-boson from MC.

Even though the Jacobian peak is smeared in the reconstructed events the x-value of the peak is still proportional to M_W in both distributions, but as expected both distributions are very depended on the energy scale which is why it is so important to use Z-events as calibration.

The difference between the two plots is when the detector resolution is taken into account. The p_T^μ does not change much but that is not the case for M_T^W. M_T^W depends directly on the missing energy (see equation 14) and that is a measurement with a high uncertainty (see section 6.5). p_T^μ also depends on E_T^{Miss} but not to first order. Instead p_T^μ is more dependent on transverse momentum of the boson and this leads to the change when p_T^μ is not in the W rest frame.

I expected that the uncertainty on the E_T^{Miss} measurement would have a larger impact than the uncertainty on p_T^W which made me choose p_T^μ as my variable for my template fit.

7.1.1 Production of MC Template

The optimal way to generate W and Z events in MC would be to simulate the bosons with different masses in the event generator and then do a full detector simulation with
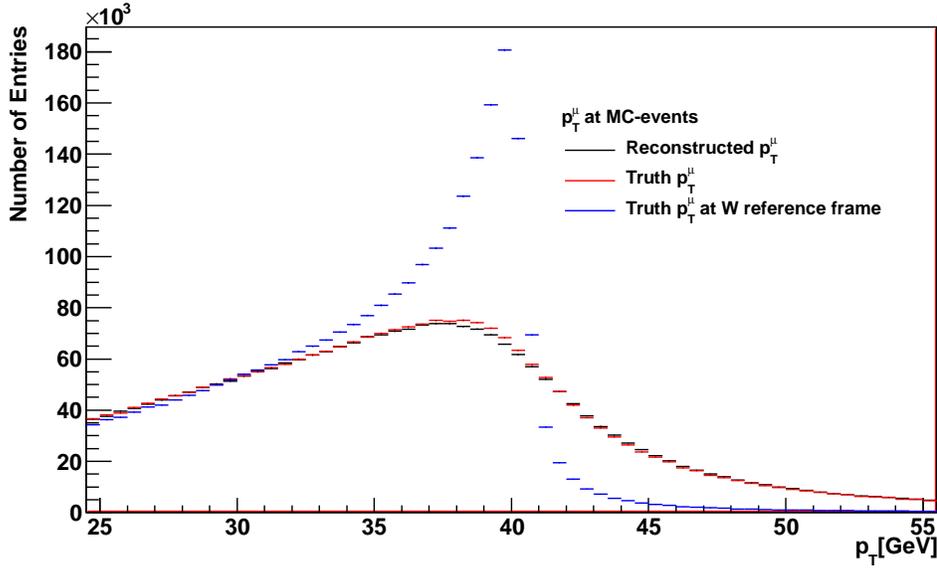
Figure 21: Transverse momentum of the muons from the W-boson from MC.

the muons decaying from the new bosons. But because GEANT4 is so time consuming it has not been possible. This is not that bad because the biggest change would be a change in the momentum (and thereby the transverse momentum) of the decaying leptons. So instead of vary the boson mass, the momentum of the muons have been multiplied by a scale factor instead.

From the original MC sample I have multiplied the transverse momentum of all the muons with a scale factor TS to make a single MC template. I used 0.99, 0.9925, 0.9950, 0.9975, 1.0, 1.0025, 1.0050, 1.0075 and 1.01 as my TS factors.[19] So I have multiplied p_T^μ with the 9 scale factors to get 9 MC templates. p_T^μ will increase linearly when M_W and M_Z increases so this gives templates for masses of $TS \cdot M_W$ and $TS \cdot M_Z$.

There is a good thing when the MC templates is generated this way. The templates comes from the exact same MC sample, so the statistical fluctuations will be the same and cancel out in any differences.

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[19]This section is about how to produce the MC templates. The choice for TS is described in section 10.2.

8 Trigger and Event Selection

The Atlas Experiment has a working group in the SM group which focuses on W- and Z-analysis. When a lot of people work on the same analysis and want to compare each individual subanalysis it is important that every person starts with the same datasamples, same trigger and same cuts, so this subgroup has made a baseline selection of events. This makes it a lot easier to compare each persons results so they can get the best possible measurement of for example the W mass. It also make it possible to understand how each source of systematic effects are affecting various measurements.
This should of cause be the foundation of every students analysis and it is mine as well. It is possible to deviate from these selections, but this needs to be justified in detail by showing that a different selection leads to a significant improvement of the final result.

Unfortunately the web page for the group and thereby the baselineselection is not updated regularly. Because of the trigger increment the muon p_T-cut has to be more than they recommend on the web page, but the baselinselection cuts can still be used as a foundation for my analysis.[20]

I have used a good run list data from periods F, G and H. This is the data I had available in the beginning of my study and as it can be seen in section 6.3 and 6.5 it is not a good idea to switch run periods or add new ones every time a new data set comes out. There is enough W's and Z's in this data set to do my analysis which did not make me want to add more periods.

These periods has a trigger on p_T^μ of 18 GeV. As explained in section 6.1.3 the detector part which is used for muon triggers is different than the detectorpart that measure the muon momentum. The p_T cut in the analysis has to be bigger than the trigger cuts. If that is not the case then there will be too few events with low momentum in data and this will lead to a W-mass that is measured too high. It is the RPC and the TGC that is used for the trigger, but it is the MDT that is used for the final muon momentum (along with the inner detector) because it has much better resolution. It is possible that the RPC and the TGC measure the muon p_T to less than 18GeV and the MDT would have measured it to more than 18, but if the event does not pass the trigger then the muon momentum will not be calculated in the MDT.

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[20]It is possible that there does not exist an update on the baselineselection at the moment and that the group is working on it.

The muon selection cuts I have used in my analysis are the following:

- Combined (detected as a muon in inner detector and muon detector)

- Minimum 1 hit in the Pixel detector and 6 hits in the SCT detector

- At least 1 hit in the TRT

- pseudorapidity $|\eta| < 2.4$

- Isolation criteria - p_T of a cone of size 0.2 divided by muon $p_T < 0.1$

In the $W \rightarrow \mu\nu$-channel I have the following cuts:

- $p_T > 25\text{GeV}$

- $\not{E}_T > 25\text{GeV}$

- $M_T > 40\text{GeV}$

For the $Z \rightarrow \mu\mu$-channel I have the following:

- Each muon should have $p_T > 25\text{GeV}$

- Two combined muons with opposite charge

- $66 < M_{\mu\mu} < 116$

The cuts are made in order to remove as much background as possible even though a lot of signal events will be lost in the way. At the LHC there should be enough events in order to make this possible.

The hit cuts were made in order to ensure a good track and remove cosmic background. The cuts were not directly in the baseline selection cuts and does not remove many events but I still had it in my analysis because they could not harm the analysis in any way so I did not want to remove them[21].

There is a pseudorapidity cut at $|\eta| < 2.4$ because muons are better detected within this region.

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[21] The cuts was good to have when I investigated how important each cut was. If I just somehow got a lot of muon candidates from background events when I excluded a cut then this cut would help me remove some of these candidates.

A cone is defined as $\Delta R^2 = \Delta\phi^2 + \Delta\eta^2$. There can be jets very close to the muon and this isolation criteria removes muon candidates with jets around or close to it. The isolation criteria is very important in the analysis. In $b\bar{b}$-events there will often be muon candidates because the b-quark will decay to a c-quark and a virtual W. This muon candidates will often be real muons, but I am not interested in these events because they do not come from a real W. There will be a lot of these QCD events, but this cut removes a lot of those events.

There could also be problems with the precision in the measurement of the muons kinematics when there is too much around the muon so it also optimize the muon resolution. There was a time when the isolation cut was at size 0.4 and the p_T of the cone divided by the muon p_T should be less than 0.2. I made the shift because I wanted my analysis to be in better agreement with the one used in the baseline selection. The old isolation cut had the same purpose as the new one.

It is not possible by a quick view to see a significant improvement with the change. It would take a deeper investigation to see the difference which I expect the W,Z physics working group[22] too already have done, so I ended up using their result.

The baseline selection had a p_T^μ-cut at 20 GeV for both the W and Z-events but I used 25 GeV to make up for my trigger cut at 20 GeV.

The p_T^μ range I use for my fit is significantly higher but there is a different in the W and Z definition when there is a 22 GeV muon, missing transverse energy and a high p_T muon with opposite charge if it should be considered as a W or a Z event. What I have hoped for is that it is the same in MC as it is in data and that it will not contribute to the mass measurement.

If there were more than two muons in an event that made it trough the cuts then I did not used them in my study. In an event with both a W and a Z event were both of them would decay to muons and the muons made it through the cuts then there could be some troubles with combining the right muons. I did not want this to happen so I just removed the events. This was not a problem because there was so few of these events.

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[22]The ATLAS Standard Model Working Group with focus on W and Z physics.

9 Analysis

The important thing in the measurement is to understand the data and the Monte Carlo events and see if they are in agreement. It should hopefully be easy after the cuts to separate signal events from background events and hopefully the MC events will look like the data.

The best place to start is with the Z-events because it is expected that the Z-sample is much cleaner than the W-sample because the neutrino will escape the detector.

A lot of parameters have to be investigated to see if MC is in agreement with the data and to see how the parameters effects the mass measurement. I have investigated some of these parameters in detail and some of them will I give an overview of how they should be handled and how it effects the mass measurement. The measurement requires high precision so the variables have to be well understood so MC should be comparable with data for all the important variables.

I will use the p_T^μ as the template fit parameter in Z-events even though the invariant mass fit could be used as well. If there for some reason should be a systematic uncertainty when going from M_{INV} to p_T^μ it will be neglected this way if it goes linear in energy because the uncertainty will be there for both the Z and the W analysis.

I will still use the invariant mass in Z-events in the beginning of the analysis to see if it makes sense to not include background events. In the end I will use it for comparison of the p_T^μ for the Z-events.

As explained in section 6.3 the data periods used for the analysis are period F, G and H. I have not used background events in the Z-analysis in MC because there were so few background events that it would not have changed much.

In the W-analysis the biggest contributions from background events is from $W \to \mu\nu$, $Z \to \mu\mu$ and $Z \to \tau\tau$ and I have used these in my study. The size of the QCD background is harder to estimate.

9.0.2 Comment on $W \to \tau\nu$ background

The events from $W \to \tau\nu$ did not behave the way it was expected. There was about twice as many background events in this channel than there were in the official plot at 33 pb^{-1}. This is less data events but the MC-channels should still be of the same fraction in my analysis than in these analysis, but that was unfortunately not the case.

I have about 10^6 events in MC witch gives a weight factor of 7.395. That is not optimal,

but I have spoken with Ingrid Daigaard from the τ-group of the Niels Bohr Institute and there is in fact something wrong with the scaling factor in MC in $W \to \tau\nu$. The papers about it have unfortunately not been publiced yet, but in the analysis there is a factor of 2 and at some points 2.5 of too many MC events.

This is not a τ-study and it is not possible to get a right scale factor from the article because their cuts are different than mine.

What I can do instead is to be aware of the problem in the $W \to \tau\nu$ MC events and try to minimize my dependence on these background events. This is possible by doing the fit procedure at a range with few background events from the $W \to \tau\nu$.

What I ended up with was to divide $W \to \tau\nu$ with a factor of 3. I compared p_T^μ in W-events from data and MC from 25.0GeV to 32.5GeV because this region is outside the range I fit and this range is also where $W \to \tau\nu$ is most dominant. With a factor of 3, $W \to \tau\nu$ has the same amount of events as $Z \to \mu\mu$ at 30.0GeV which is expected from previous studies and for more for 30.0GeV to 32.0GeV MC will look like data and it can be seen that QCD is missing as expected. This could have been done in a better way but the uncertainty on cross section for the different background events is not neglectable which made it very time consuming and also still not perfect to fit the scale of $W \to \tau\nu$. The uncertainty on luminosity is also important because it is not expected that MC has the same events as data for $p_T^\mu \in [25.0 \; 32.5]\,\mathrm{GeV}$ so $W \to \tau\nu$ could not just have been scaled so the amount of MC events was the same as the amount of data events.

This is not a $W \to \tau\nu$ study so to not spend more time on the $W \to \tau\nu$ scale I decided to divide the amount of events with a factor of 3.

9.1   Fit of Invariant Mass in Z-Events

The invariant mass of two muons is expected with the right cuts to have a clear clean peak around the Z-mass. I expected this in both data and MC. What is worth to note is if MC is distributed like data. The things to look for is if the momentum scale is right and the detector smearing is about the same for data and MC. The Z-mass and its width its known very precise from LEP, the mass could be used to set the muon p_T-scale and the Z-width to set the detector resolution.

The shape of the invariant mass of the Z-boson is expected to be a convolution of a Breit Wigner and a Gaussian. The Breit Wigner shape comes from the expected particle distribution when the heavy boson decays. This would also be the same if the

electron was used, but the detector responds from the muon will be gaussian where it is a crystal ball from the electrons.

It should be a convolution because it is each Breit Wigner-distributed event that should be multiplied by a gaussian and this ends up with a convolution.

I have fitted the distribution with a convolution of a Breit Wigner and a Gaussian along with an added exponential from expected background as seen in figure 22.
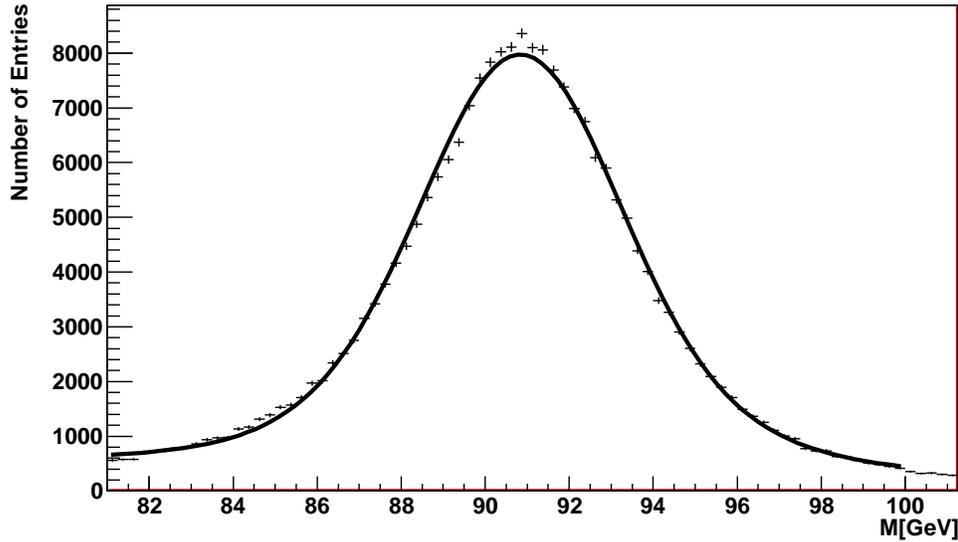

Figure 22: The invariant mass of two muons in data is fitted with a convolution of a Breit Wigner and a Gaussian plus an exponential function that is expected from the small background. The Breit Wigner shape comes from the expected particle distribution when the heavy boson decays and the gaussian is do to the detector responds.

The fit in figure 22 fits the data well in the fitting range which indicates that the original boson decay along with the detector response is well understood.

Unfortunately troubles arise when the fitting range increases. The fit is not in agreement with the distribution from the data at 82 to 85 GeV . This is not a problem if it is the same in MC. It just illustrates that it is not just a convolution of a Breit Wigner and a Gaussian but also something more. It would have surprised me if the data was so simple to fit because there are so many detector parts in the ATLAS detector and even though several small uncertainties would led to a gaussian distribution in the end (according to

the central limit theorem) it would still have surprised me if it was so simple to fit.
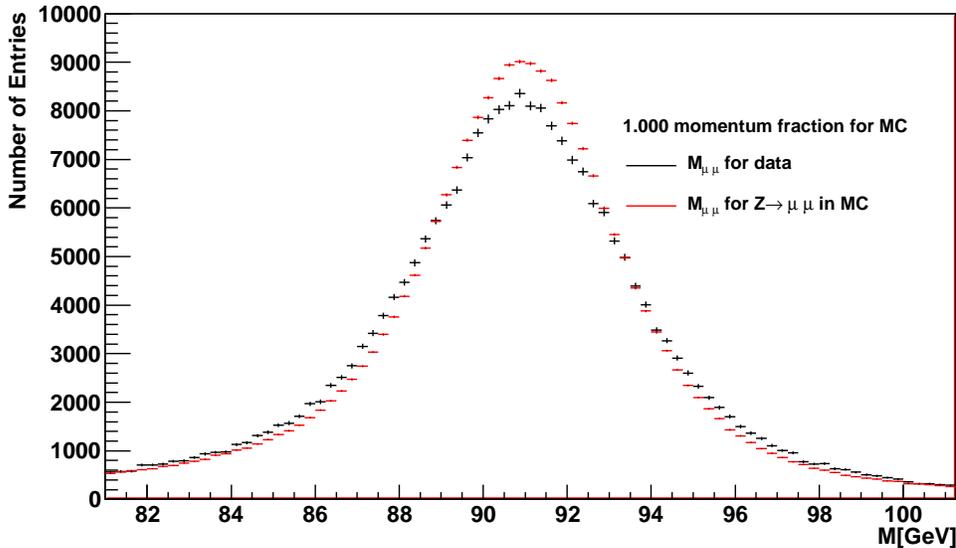

Figure 23: The invariant mass of two muons in data and MC. There is a clear peak at the Z-mass.

In figure 23 is the invariant mass of two muons with the cuts from section 8 in data and $Z \rightarrow \mu\mu$ MC events. Overall it looks like the data is in agreement with MC. There clearly is a Z-peak for both data and MC and background events looks neglectable compared to the clear amount of Z-events. However the detector is more smeared in data than it was expected from MC. This would make me expect p_T^μ to be more smeared in data as well.

9.2   Transverse Mass in W-Events

The W-sample was expected to be less clean than the Z-sample. In figure 24 the transverse mass of the W in the muon channel is plotted. In the W-sample there has to be included background events and these events have the same cuts as the signal events described in section 8. The black histogram is the data and the rest is MC. The pink is the background from $Z \rightarrow \tau\tau$-events, the difference between the pink and the blue histogram is $Z \rightarrow \mu\mu$, the inclusion of the green histogram is when background from $W \rightarrow \tau\nu$ is included and in the red histogram $W \rightarrow \mu\nu$ events are also included.

The background events have to be added to the MC signal events, otherwise the comparison would have been even worse but this is much easier to see in the p_T^μ distribution. I have used the same colors for all the plots from W-events.

There are not many events from $Z \to \tau\tau$ that looks like data. $Z \to \mu\mu$ have some more events like $W \to \tau\nu$.

MC does not look like data in this variable. E_T^{Miss} is so difficult to measure that this is obviously the first guess to the difference and this is in fact also the case. In figure 25 the missing energy of the data and MC is seen. The same colors is used as for M_T.
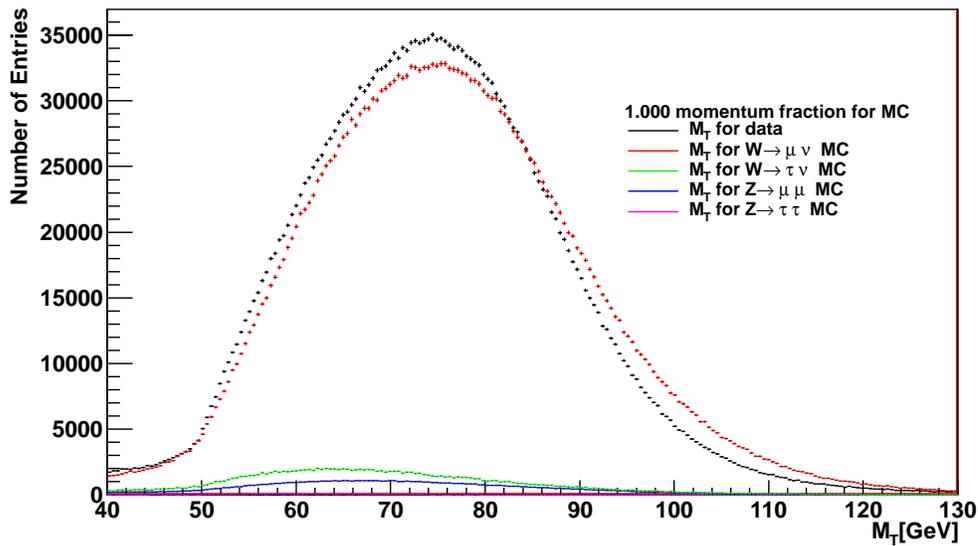

Figure 24: M_T^W in data an MC with background events. M_T^W depends on E_T^{Miss} so de distribution has poor resolution.

It is indeed the fact that the deviation is caused by E_T^{Miss}. As explained earlier, M_T could also have been used to get the template scale factor in the W-sample, TS_W, but when MC does not look like data it would not have made any sense. The result would be useless because the distributions from the data and MC are so far from each other. The uncertainty would be large and the result would be misleading because MC does not fit the data.
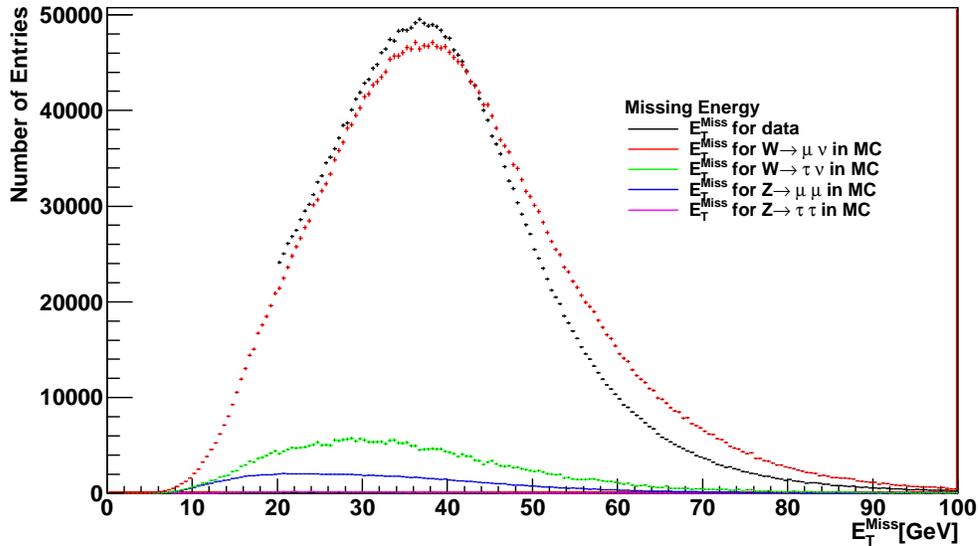
Figure 25: E_T^{Miss} of data and MC. The data still has a cut at $E_T^{Miss} = 20$GeV which is due to prior cuts, but the distribution will continue to grow from 20GeV to 0.

M_T depends on E_T^{Miss} to first order but p_T^μ does only depends on it to second order. It is still a problem that MC deviates so much from data in E_T^{Miss} and I have discussed this and how it effects the mass measurement in detail in section 11.1.

As M_{INV} is used as a check for p_T^μ in the Z-analysis, M_T could have been used as a check for p_T^μ in the W-analysis but because MC deviates so much from data this has not been possible. QCD events should have been included in MC but it cannot be seen directly where these events would be by subtracting MC from data.[23] It is expected that the events would contribute with low M_T but when MC is subtracted from data more events are needed at $M_T \sim 80$GeV.

It fortunately turns out that p_T^μ in MC looks much more like data so M_T will not be used as a crosscheck.

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[23]It is important to remember that MC have been scaled to fit the amount of events in data as explained in section 6.6.1. To include more background events the MC events have to be rescaled before the events are added and then scaled again.

10 p_T^μ-Distribution and Fitting the W-Mass

The full p_T distributions without any p_T-cuts can be seen in figure 26 for the W events. This plot is just for illustrative purpose because my definitions of a W event change when the p_T-cut gets removed, but the figure makes it possible to get an idea of the full p_T spectrum for the different background events and compare them with the signal. The trigger cut is also removed, but for obvious reasons it was not possible to remove them for data, but it should be clear that p_T^μ will increase from 22 GeV to 0 GeV if it was not because of the trigger.
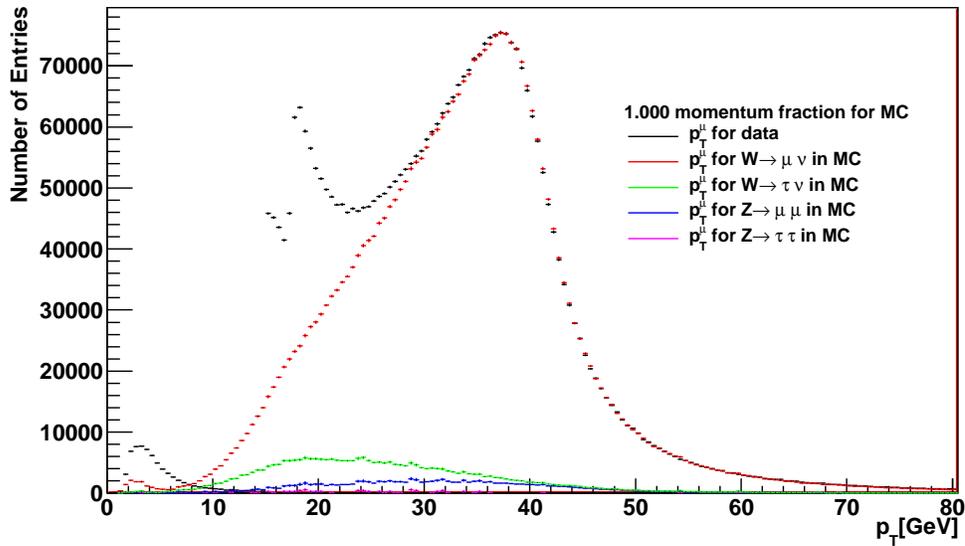

Figure 26: Muon p_T without any cuts on p_T^μ. The muontrigger has been removed from MC. The background from QCD events can be seen clearly for low p_T^μ.

The muon p_T-distribution for the $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ are very similar except for a scale factor as it was expected.

p_T-distribution of the muon for data and MC in Z-events can be seen in figure 27 and for W-events in figure 28. Before the template method can be applied the number of bins in each histograms has to be an appropriate value so it is neither too high or too low. This is strait forward but the momentum scale used in each template takes a bit more effort. In the beginning of the analysis it went from 0.97 to 1.03, but as the data

and MC became more familiar the range of the scaling could be narrowed down. In the end I ended up using $0.99, 0.9925, 0.9950, 0.9975, 1.0, 1.0025, 1.0050, 1.0075$ and 1.01. These values are found via try and error and seem to fit the data and MC. I have discussed this more with its uncertainty on 11.4.
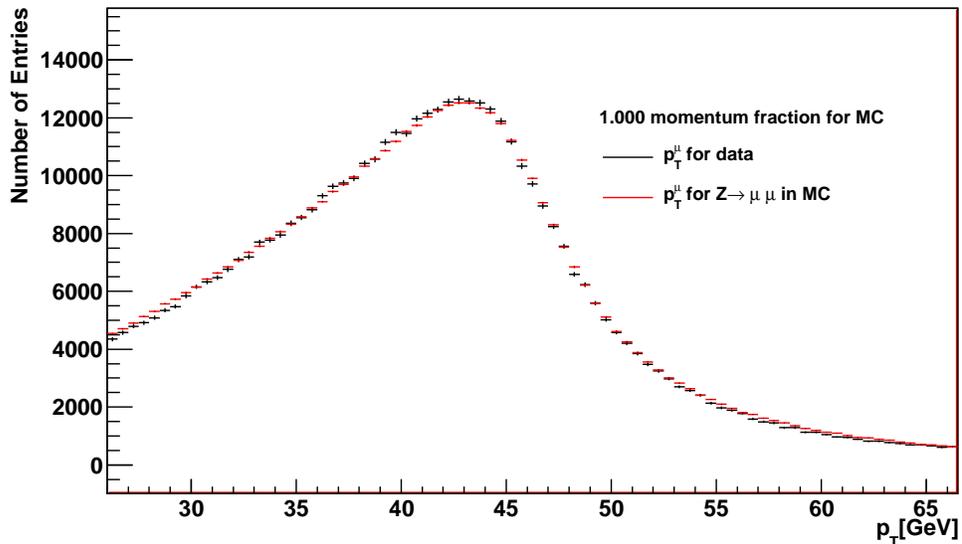

Figure 27: p_T^μ from $Z \to \mu\mu$.

I do not have QCD events in my analysis. It is easy to see that these events events is at 25 to 30 GeV. It is an exponential decreasing function that ends up to be neclectable around 30 GeV. However, at higher precision, this needs more investigation.

Before the χ^2-test between data and the MC templates can be used, an appropriate fitting range has to be chosen. I ended up using 32.5 GeV to 50.0 GeV for the W fit. To minimize systematic uncertainties from the Z-analysis these endpoint should be converted to match the kinematics of the Z-boson. As the transformation from M_{INV}-scale to p_T-scale is linear the p_T-values should be multiplied by $\frac{M_Z}{M_W}$ when the p_T endpoint is transformed from the W analysis to the Z analysis. This is what I did and I used the boson masses from pdg[4] to the transformation.
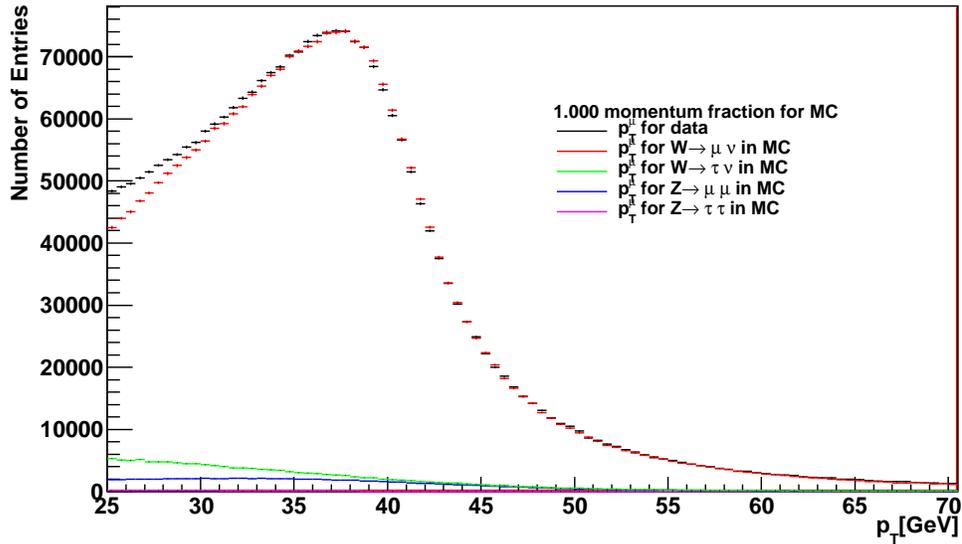
Figure 28: p_T^μ from $W \to \mu\nu$ along with background events.

10.1 Discussion of the Fit Range

The p_T^μ range that should be used for comparison between data and MC should include 40.2 GeV. This is the expected Jacobian edge before the detector smearing and p_T^{boson} is taken into account as this value is expected to be most sensitive to M_{INV}. The peak should be included for both the data and the MC templates but it can be done better. It is not just the peak but the whole spectrum that should be the same in a perfect world. In reality though it is not optimal to fit the whole spectrum.

For low values of p_T^μ there are all the background events and as explained in section 9.0.2 I got some scaling problems with the background. If just one of the background samples is scaled wrong then it would contribute to the mass. This is not unrealistic because the uncertainty on cross section and acceptance of the various events and the measurement should if possible be independent of these uncertainties. Figure 28 shows the background events are mostly significant for small values of p_T^μ so a fit from 25 GeV is not optimal.

As explained earlier I have not included QCD events which do not make me want to fit values for $p_T^\mu < 30$ GeV.

In the tail for high values of p_T^μ there is not many events in each bin. This makes

61

the χ^2-test less significant. If there for some reason should be significantly more events in data in the tail than MC then the peak of the best MC template would be moved to better match the data in this tail.[24] This is not the intention so the fit range should only include bins with a reasonably amount of events.

The tail of the p_T^μ-distribution could in theory also be used for the template fit by its own and exclude both the peak and low p_T^μ values. This is still correlated with the boson mass and would neglect the dependence of background events. This is fine, but then the measurement will depend too much on the detector resolution. If the detector resolution is too low in MC then the boson mass will be measured too high. Hopefully its contribution to M_W will be canceled out by the Z-analysis which makes it possible to have the end values of the fit to be asymmetric to the Jacobian peak.
It is still preferable to have a nearly symmetric fit range around the Jacobian peak because if there is a constant term for the detector resolution then it would not contribute to M_W. Unfortunately the uncertainty on the detector resolution is not symmetric a prior which means the fit range does not have to be symmetric either.

After a lot of changes I decided that 33GeV would be good for a low value. It was higher than 30GeV which was the absolute minimum because of QCD background but there still was a lot of other background events from 30GeV to 32GeV and I also got rid of these events. As explained in section 9.0.2 I got problems with the $W \to \tau\nu$ background and this would lower my dependence on these events. I wanted the upper limit to match my lower level cut to decrease the possible uncertainties from detector resolution which I would expect to be around 47GeV, but I was less certain about this value then the lower value before I looked at other analysis.

At [7] is the public result from CDF. They do a W-mass measurement by the template method as well but use M_T instead of p_T^μ. The fit range they use is 65GeV to 100GeV. These range should be transformed to match p_T^μ instead which is 32.5GeV to 50GeV. These values are very close to what I would have used if I did not saw their result and then I switch to 32.5GeV to 50GeV to match their analysis.

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[24]With the best MC template I mean the MC template witch has the lowest χ^2-value between data and MC. The scale factor for this template will be the minimum of figure 29.

10.2 χ^2 fit

With the choice of a fit range and the scale factor for the MC templates then the MC templates can be produced and a χ^2 test between data and each template have been made.
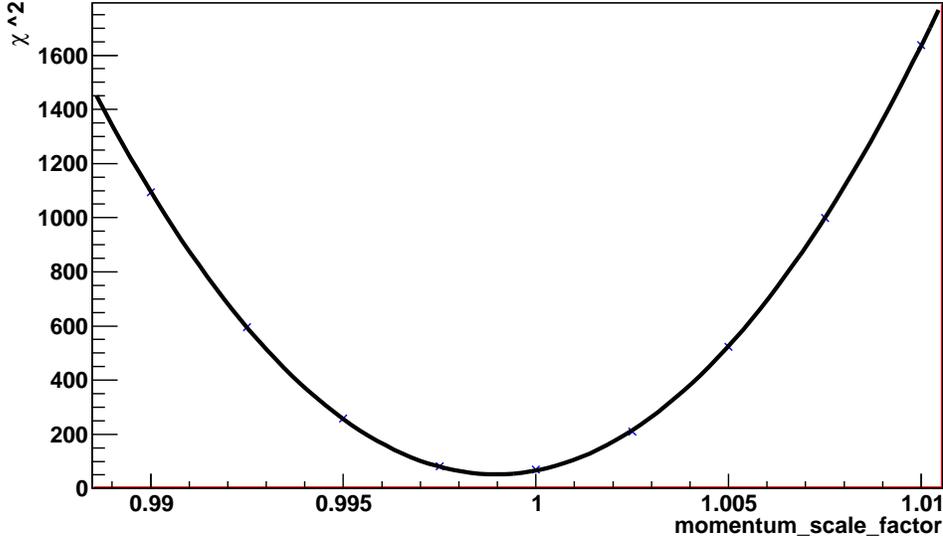

Figure 29: χ^2 from p_T^μ from W-events.

In figure 29 the χ^2-distribution for the W-sample is plotted when the data is compared by a χ^2-test with the MC-templates in the chosen fit range. As it can be seen in the figure the χ^2-values forms a parabola and the minimum of the parabola is found to get the template scale factor from the W-analysis $TS_W = 0.99896 \pm 0.00028$. The uncertainty is found by adding 1 to the minimum and check how far away the x-value is from the minimum.

The χ^2-distribution for the Z-sample is in figure 30. The template scale factor and the uncertainty from the Z-analysis is found the same way as for the W-analysis and is found to be $TS_Z = 0.99759 \pm 0.00042$.
This gave a combined scale of 1.00035 and my measurement of the W-mass is then

$$M_W^{Data} = M_W^{Truth} \cdot \frac{TS_W}{TS_Z} = 80.399\text{GeV} \cdot \frac{0.9989620}{0.9975878} = 80.510 \pm 0.032\text{GeV} \qquad (16)$$
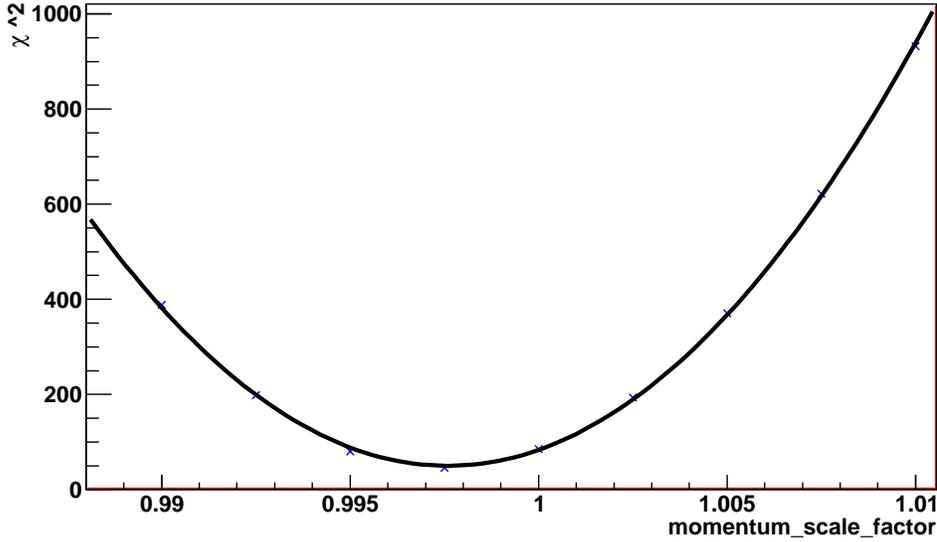
Figure 30: χ^2 from p_T^μ from Z-events.

The measured value is far off the one measured from the previous experiments. The statistical uncertainty is fairly low even though I only used a small fraction of the data collected from the ATLAS collaboration and the measured value is several standard deviation away from previous experiments. This is because that only statistical uncertainty has been taken into account so far.

If MC looks exact like the data then M_W^{Data} should not change significant when different p_T scales is used for the MC templates and neither should it be changed drastically when another fit range is used. That is unfortunately not the case and I have focused on some of the systematic uncertainties in section 11.

For the statistic uncertainty I have only used the uncertainty from the W-analysis and transformed the scale uncertainty directly to an uncertainty of the mass so that

$$\sigma_{MW} = \sigma_{TSW} \cdot M_W^{Truth} = 0.0002775 \cdot 80.399 \text{GeV} = 0.032 \text{GeV} \qquad (17)$$

Even though TS_Z is used to get M_W^{Data} from equation 15 it is not used for the statistical uncertainty but will be used as a systematic uncertainty. TS_Z is used to get the muon transverse momentum scale which is considered as a systematic uncertainty. This is an

indirect measurement of M_W and TS_Z contribute as much as TS_W to the result (but with opposite dependence) so it could be used as a statistical uncertainty, but I chosen to handle it as a systematic uncertainty.

10.2.1 M_{INV}-Distribution of the Muon from Z-events

From a fit of p_T^μ in the Z-analysis the template scale becomes $TS_Z = 0.99759 \pm 0.00042$. I also fitted $M_{\mu\mu}$ in the Z-analysis as a cross check. This gave me a template scale of $TS_Z = 0.997976 \pm 0.000076$. If I used $M_{\mu\mu}$ instead of p_T^μ the W-mass whould be measured to be $M_W^{Data} = 80.471 \pm 0.030$. The χ^2-distribution can be seen in figure 31. The minimum was at 1643, but was 49.9 for the χ^2-distribution when I fitted with p_T^μ.

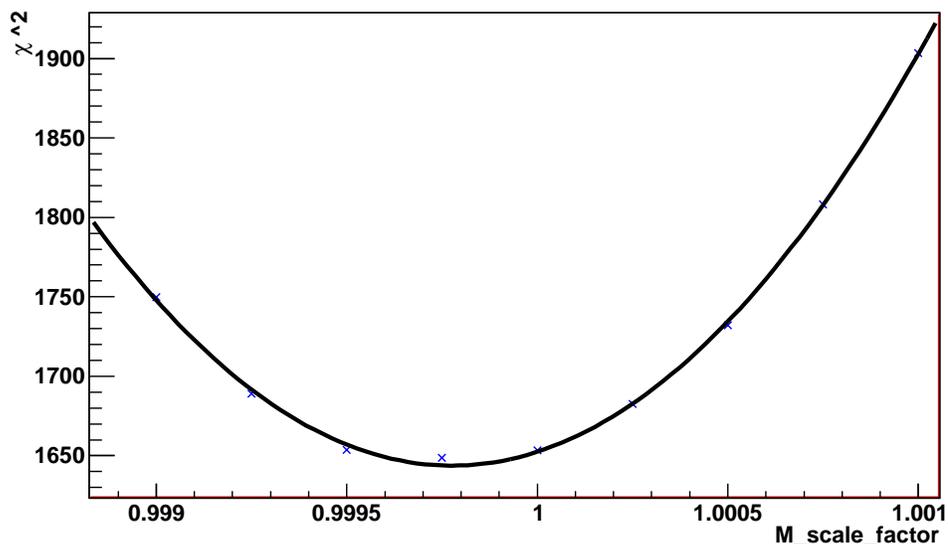Figure 31: χ^2 from $M_{\mu\mu}$ from Z-events.

11 Systematic Uncertainties

The main point of the W-mass measurement is to minimize the dependence on the systematic uncertainties because there will be enough events that the statistical uncertainties is small. So far I have measured the W-mass only with a statistical uncertainty. This section is about the systematic uncertainties that contribute to the overall uncertainty on the W-mass. I have looked at the different uncertainties one at a time and combined them all in section 11.8 by normal error propagation.

The best way to transform an uncertainty of a variable to an uncertainty of the W-mass is to insert the lower and upper limit of the standard deviation and see how it effects M_W^{Data}, but that is not possible for most of the variables. Sometimes it is not possible to change the variable directly like the uncertainty of the p_T^{boson} and sometimes it is not even possible to get an uncertainty of a variable directly like the choice of the fit range. Whatever I do in these cases there will not be a direct mathematical method to investigate how M_W^{Data} depends on this variable. No matter how this will be handled it can be discussed if it is the optimal way I have used and another person could even get a different result because he or she could use another method to get the uncertainty. But even if subjective estimations have to be used to get a contribution from a variable it is still better to get an estimation of how the variable effects M_W^{Data} than ignoring it.

11.1 Missing Energy

The 13th of December 2011 there was a public update of the Higgs analysis. There was a 3.0 standard deviation above the predicted amount of events from non-Higgs SM at a Higgs mass of 125GeV. The 3.0 standard deviation was a combined measurement from several Higgs decay channels for both the ATLAS experiment and CMS.
For a Higgs mass around 125GeV the second most efficient channel is the WW channel (the most efficiency is the $\gamma\gamma$-channel) but there was no update of the Higgs result in the WW-channel for the ATLAS experiment. The reason is caused by the E_T^{Miss} measurement because this channel also is very dependent on this measurement.

Even though I tried to minimize the dependence on the missing energy (I fit p_T^μ instead of M_T^W) there still have to be a cut on the variable. It is expected that E_T^{Miss} has a poor resolution as explained in section 6.5. This is fine if it just is the same in data and MC but as it can be seen in figure 25 this is not the case.

I have used a cut on E_T^{Miss} at 25 GeV, but I have made variations of the cut too see how M_W^{Data} change for different cuts. This is seen in table 2. There is not an uncertainty coupled directly to my E_T^{Miss}-cut. It is straitforward to change the E_T^{Miss}-cut and see how much M_W^{Data} has changed, but I want a value to represent the systematic uncertainty from E_T^{Miss} and this depends directly on how much I change my E_T^{Miss}-cut. I think a variation of more than 5 GeV is too much. With a cut of 20 GeV I will expect much background events from QCD and $W \to \tau\nu$ and for more than 30 GeV I will loose to much data events. If I variate E_T^{Miss} too little then I have downgraded my dependence on the variable and that whould be misleading because then it would seem like I have measured M_W better than what I actually have.

I decided to variate E_T^{Miss} with 3.0 GeV.

Cut on E_T^{Miss}	M_W^{Data}
22GeV	80.4704GeV
25GeV	80.5098GeV
28GeV	80.5522GeV

Table 2: A change of E_T^{Miss}-cut does also change M_W^{Data}

As described in section 6.5 the E_T^{Miss} is a by itself and an improvement of the E_T^{Miss} calculation is beyond the scope of this thesis. But the W-mass measurement depends heavily on that measurement and that is for all the channels.

It is possible that the E_T^{Miss} in MC11 is in a better comparison with the data than the used MC10, but when there is problems with other analysis that depends on the E_T^{Miss} calculation then I do not think the problems are solved yet and I do not think an official measurement of M_W is possible before the E_T^{Miss} problems is fixed.

The contribution to M_W from table 2 is:

$$\sigma_{MW} = \frac{|80.4704 - 80.5098| + |80.5522 - 80.5098|}{2} \text{GeV}$$
$$= \frac{0.0394 + 0.0524}{2} \text{GeV} = 0.0459 \text{GeV} \approx 0.046 \text{GeV}$$

11.2 QCD-background events

Unfortunately I did not include QCD events from MC. The cross section of QCD events is extremely high and it is not possible to generate QCD events and multiply the events

with the weight factor as it has been done with the other background events. The weight factor would be too high because of the high cross section and because it is not possible to get enough events to make up for it. Because of this another method have to be used when adding QCD events.

The traditional way to do it is to generate jets in specific p_T-ranges to decrease the cross section and add all the QCD events together in the end. This is very time consuming task and from intern notes and presentation I have seen that QCD events only should contribute for low p_T^μ and low M_T^W regions.[25] A lot of the QCD events are removed by the E_T^{Miss}-cut and the isolation criteria and when the fit range is above 33 GeV the contribution from QCD events should be small.

Even though QCD events did not contribute for $p_T^\mu > 30$ GeV for the old dataset it is not surely it will contribute with the same amount for my dataset. The amount of pileup events increases when luminosity increases and this will also increase the resolution on E_T^{Miss}. A more poor E_T^{Miss}-resolution will effect all the background events but mostly the QCD events because it has the highest cross section. I do not think it whould have contributed much to M_W^{Data} because of my choice of fit interval but it would still be interesting if I was able to include it in my analysis and check if it holds true. A general method to estimate this background could be to use the independency of E_T^{Miss} and the isolation cuts in an ABCD like method. However this only gives the overall estimation of the amount of QCD background and does not find its distribution.

11.3   Fit range

As explained in section 10.1 the choice of the fit range is not trivial. It is best too use as wide a range as possible, but if the minimum is too low then the result will depend too much on background and if it is too high there will be too few events in each bins. I used 32.5 GeV to 50.0 GeV for my fit range in the W sample to match the result from CDF. To vary the range I decided to subtract 5% to the minimum and add 5% to the maximum. I wanted to do it in percent so it still would match the Z analysis. This gave me: $M_W^{Data} = 80.5080 \pm 0.0310$.

This gave me the uncertainty:

$$\sigma_{MW} = |80.5098 - 80.5080|\,\text{GeV} = 0.0018\text{GeV}$$

In order to avoid additional uncertainty for detector resolution I chose the variation to be symmetric. The uncertainty is still surprisingly low and could be due to cancellation

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[25]It can also be seen in figure 34 and 35 for an integraded luminosity at $\mathcal{L} = 33$ pb^{-1}.

between two or more contributions. This illustrates how hard it is to control systematic uncertainties in the W-mass measurement. One can only see the impact on the W mass on not the underlying course of it. This is further examplified in the case of the boson p_T (see section 11.6).

11.4   Template variation at p_T scale

The template scale values I used was $0.99, 0.9925, 0.9950, 0.9975, 1.0, 1.0025, 1.0050, 1.0075$ and 1.01. These values was not chosen a priory but by try and error.
I chose to vary TS by only fit from 0.995 to 1.005. This gave a W mass: $M_W^{Data} = 80.5258 \pm 0.0321$ so the uncertainty becomes

$$\sigma_{MW} = |80.5098 - 80.5258| \, \text{GeV} = 0.0160 \text{GeV}$$

11.5 p_T scale from Z Analysis

The p_T^μ scale from the Z analysis is measured to be $TS_Z = 0.99759 \pm 0.00042$. As mentioned in section 10.2 the muon p_T-scale is treated as a systematic uncertainty and its contribution to M_W^{Data} is

$$\sigma_{MW} = \sigma_{TSZ} \cdot M_W^{Truth} = 0.0004162 \cdot 80.399 \text{GeV} = 0.03346 \text{GeV} \approx 0.0335 \text{GeV}$$

11.6   Boson p_T

The bosons does not have zero p_T. I have plotted p_T^W in figure 32 and P_T^Z in figure 33.

It is expected that p_T^Z can be reconstructed from MC. The truth p_T^Z value and the reconstructed does not differs much from each other. This made me expect the data-events would distribute like MC and they in fact do. This is different for p_T^W. p_T^W depends directly on E_T^{Miss} and because of the high uncertainty on E_T^{Miss} the uncertainty on p_T^W is also very high.
p_T^Z on the other hand could be fine. For kinematical reasons p_T^Z should behave like p_T^W (see section 5). The energy to produce the heavy bosons comes from the longitudenal momentum of the partons (in this case the quarks) so the transverse energy of these bosons should be independent if it is a W or a Z boson.[26] Because p_T^W has a poor resolution and because W's should behave like Z's then the p_T^Z-distribution can be used as the uncertainty for the uncertainty of the boson.

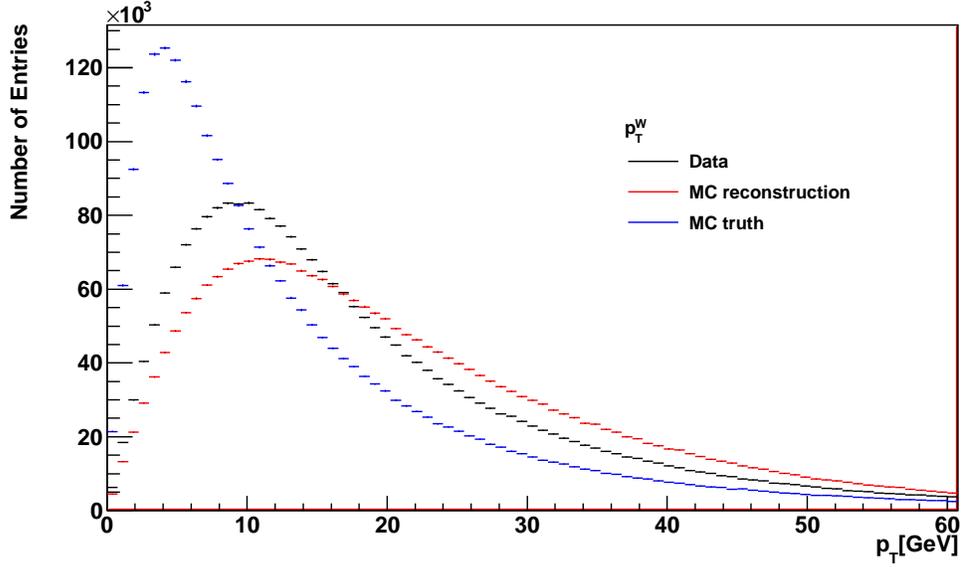[26] A least any difference would be small and known.

Figure 32: p_T^W for data and MC. The reconstructed distribution is very smeared because it depends directly on E_T^{Miss}.

Just like I did with p_T^μ I used the template method to find the template scale factor for which MC is in best agreement with data for p_T^Z. The χ^2-plot can be seen in appendix (figure 36) and the best template fit was for $TS_{boson} = 0.9600 \pm 0.0024$.

This made me want to rescale p_T^W with this TS_{boson}-factor and reboost the muon in MC along the new boosted W. This is possible to do in MC because it include the truth variables.

I rescaled the muons from $W \rightarrow \mu\nu$ to match a reconstructed W with a scaled p_T^W of $TS_{boson} = 0.9600$. Then I did the template method again for p_T^μ and end up with a minimum χ^2-value of 231.2 with 36 degrees of freedom where the old one had a minimum χ^2-value of 52.5. This shows p_T^μ in MC without a boost of the W is in better agreement with data than the boosted one, even though I found out p_T^{boson} in MC would look more like data if it got boosted. I do not have any explanation for this, but because MC was in better agreement with the data without the boosted W I chose to use MC as it is and not boost it.

The p_T^μ-distribution with a boostet W and the χ^2-plot can be seen in appendix in figure 37 and figure 38. I did boost the W-boson to get a measurement of how the boson
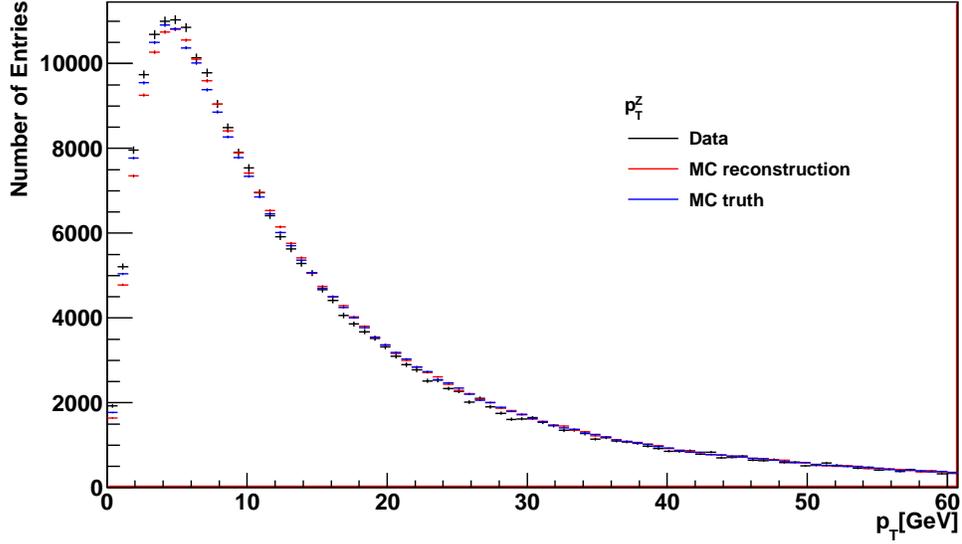
70

Figure 33: p_T^Z for data and MC. The reconstructed distribution is not as smeared as p_T^W in figure 32.

p_T effects M_W^{Data}. With a boosted W I got the template scale to be 1.00059 ± 0.00027 which gives a mass measurement $M_W = 80.6411$ GeV. The uncertainty of TS_{boson} was $\sigma_{TSboson} = 0.0024289$ so I varied the scale and the results can be seen in table 3.

A linear change in p_T^W leads to a linear change in p_T^μ which again leads to a linear change in M_W^{Data}. So even though I did not end up to boost p_T^W in the other parts of the analysis, M_W^{Data} should still change linear when I change p_T^W linear. So in the end the contribution

Boost on p_T^W	M_W
0.9600	80.641GeV
0.9624	80.633GeV
0.9575	80.649GeV
0.9842	80.562GeV
0.9357	80.721GeV

Table 3: I have variated p_T^{boson} and investigated how it changes M_W^{Data}.

from p_T^{boson} is found to be:

$$\sigma_{MW} = \frac{|80.6330 - 80.6411| + |80.6411 - 80.6486|}{2}\text{GeV}$$

$$= \frac{0.0119 + 0.0075}{2}\text{GeV} = 0.0097\text{GeV} \approx 0.010\text{GeV}$$

11.7 Other Uncertainties

There is other uncertainties that could contribute to M_W^{Data} that I did not focus on. There is a crossing angle when the protons collide that could contribute to the measurement if is not estimated in MC correct. The bosons does not in reality collide head on but has a small crossing angle. In most analysis this can be neglected but this is a precision measurement after all so it should be shown how much it effects the measurement. I did not do it but according to [10] it does not change the measurement significantly.

The isolation criteria could have been changed to match the old cut, but I did not expect the measurement would differ much by the choice of isolation cut and because the isolation cut I use match the one from the baseline selection I did not want to change it. But it could be an uncertainty that could contribute to M_W^{Data} and I did not include it in my analysis.

11.8 Propagation of Uncertainties

I have combined all the systematic uncertainties in my analysis in table 4. I got my total systematic uncertainty by adding all the systematic uncertainties together in quadrature and took the square root of that.

$$\sigma_{MW} = \sqrt{0.0459^2 + 0.03346^2 + 0.0018^2 + 0.0160^2 + 0.0097^2} = 0.05983 \qquad (18)$$

Systematic Uncertainties	Contribution to M_W^{Data}
E_T^{MISS}-Cut	0.0459
Z Calibration	0.0335
Fit Range for data and MC comparison	0.0018
Choice of range for TS fitting	0.0160
Uncertainty from p_T^{boson}	0.0097
Total Systematic Uncertainty	0.0598

Table 4: Combined systematic uncertainties in my analysis.

12   Conclusion and Outlook

I measured the W-mass by the template method for the p_T^μ-variable to be $M_W = 80.510 \pm 0.032 \pm 0.060$GeV. I used Z-events for calibration, my MC events are MC10 and data periods F, G and H.

The biggest impact on the analysis is due to the resolution on E_T^{Miss}. The amount of pileup events makes a significant contribution to the E_T^{Miss}-resolution and this has a big impact for the choice of data periods in the analysis. There was not much data in 2010 compared to 2011 but its amount of pileup events is also much less so this could be a tempting factor for the best data periods for the analysis. In the late of 2011 there was a lot of statistics but also a lot of pileup events. A change of run periods for the analysis could be useful for further analysis because of the change in the pileup events.

The MC events I use in my analysis is MC10 but during my studies an update to MC11 has been released. Further studies should update the MC sample to MC11.[27]

In my analysis I used the combined p_T-muon measurement from the inner detector and the muon spectrometer. As explained in section 6.1.4 it is a solenoid magnet field that surrounds the inner detector and toroid field that surrounds the muon spectrometer. Due to that it is possible the muon energy scale in the inner detector is more linear than the combined with the muon spectrometer. The muon spectrometer should still be used for trigger and identification but the p_T^μ-measurement should be done only by the inner detector. J/Ψ and Υ could also be used together with the Z for the determination of the muon momentum scale and its linearity and this should give a better precision of the measurement and decrease its uncertainty.

Later on M_W^{Data} should be a combined measurement for both the electron and the muon final state. Besides the p_T^{lepton} fit there should also be a fit for M_T^W but the M_T^W analysis becomes even worse when the amount of pileup increases because M_T^W depends more on E_T^{Miss}.

I did not include QCD in my analysis and if I had more time then this would be the next thing to do. However, this is very hard to do, as one can not rely on MC as

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[27]Like an update to every new data periods is not optimal (explained in section 8) it is not optimal either to update every time new MC version comes out. I got a problem with $W \rightarrow \tau\nu$ background by using MC10 and another problem could arrive with a change to MC11 which is why I did not make the swap in my analysis.

for the other backgrounds.

But even though I did not include QCD events I still manage to include systematic uncertainties and get a combined uncertainty of the W mass to be 68 MeV which is much better than I would have expected when I started and better than $\frac{1}{1000}$.

The W mass measurement is a difficult and complicated measurement. There is a lot of effects that contributes to the measurement. Two uncertainties can easely cancel each other out and when one of the effects is included then the result gets worse because the other uncertainty will dominate the measurement. Like when I included the effect from p_T^{boson}. This shows that there is more that needs to be understood.

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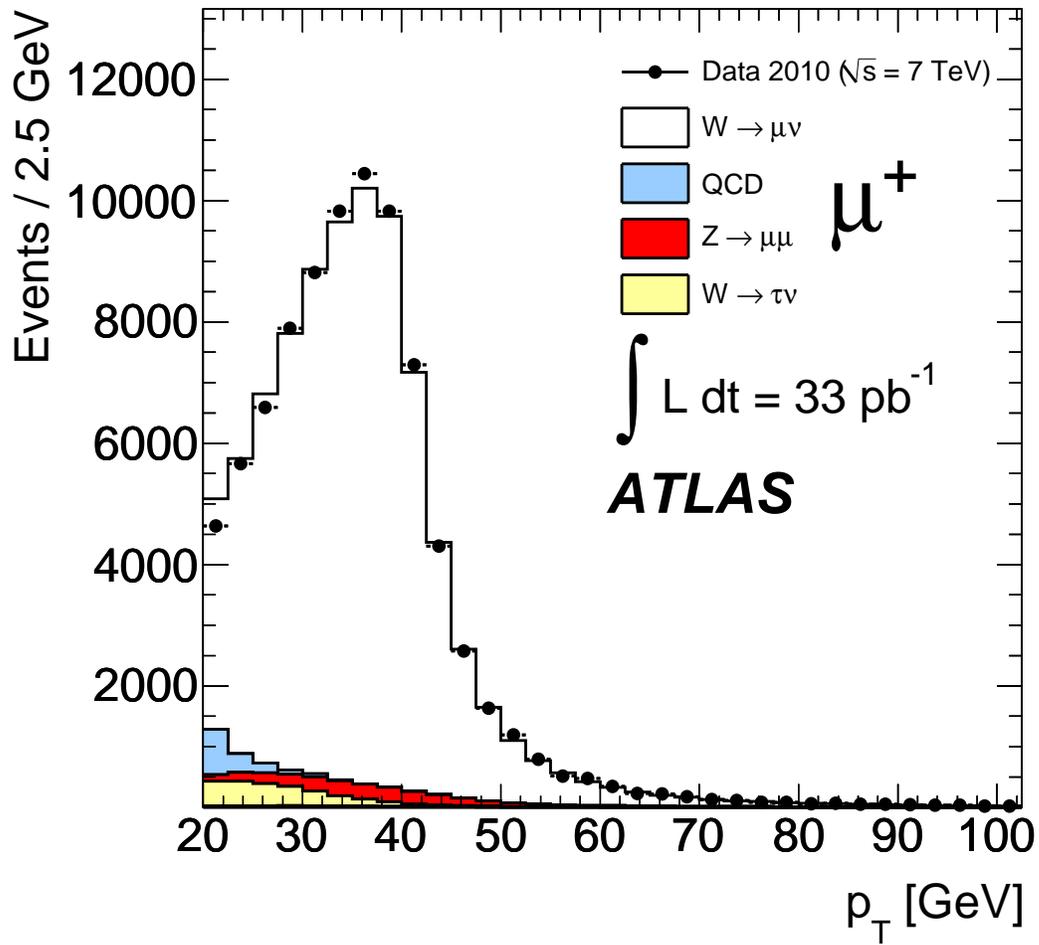
13 Appendix
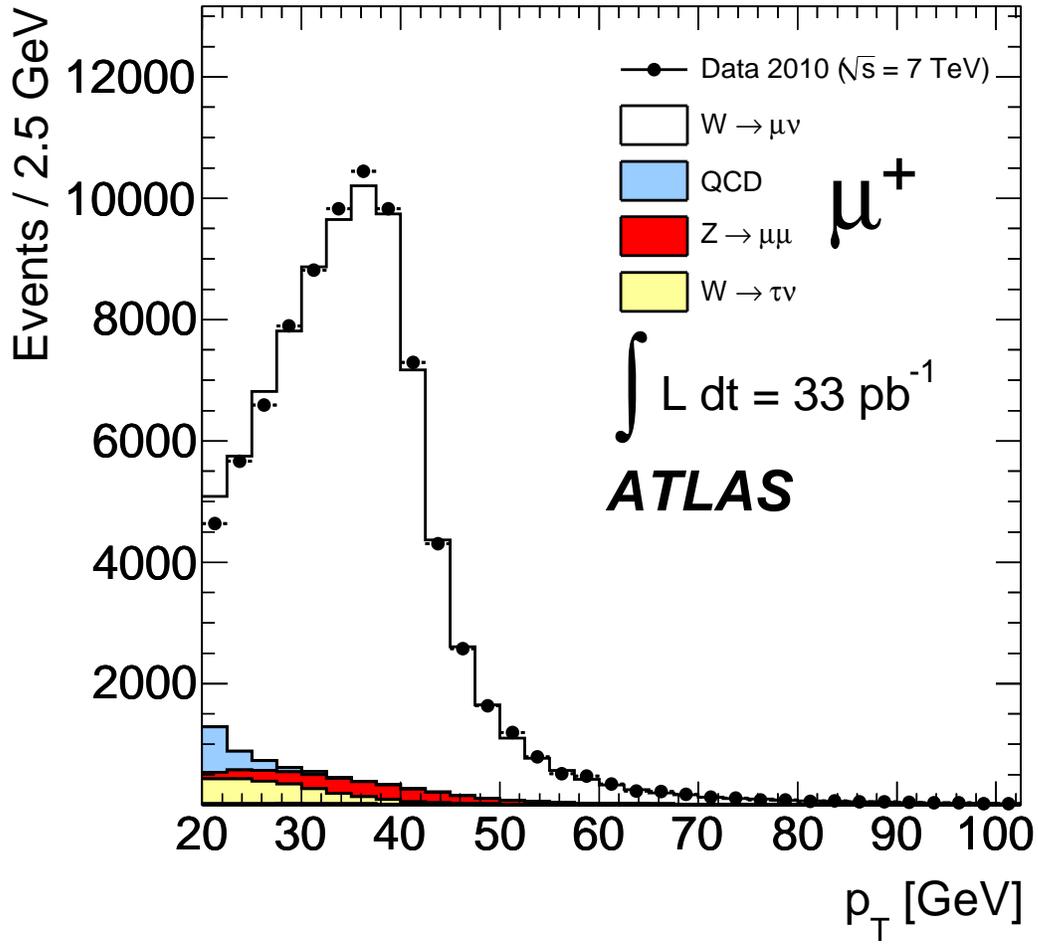

Figure 34: Official p_T^μ+-plot for W-events
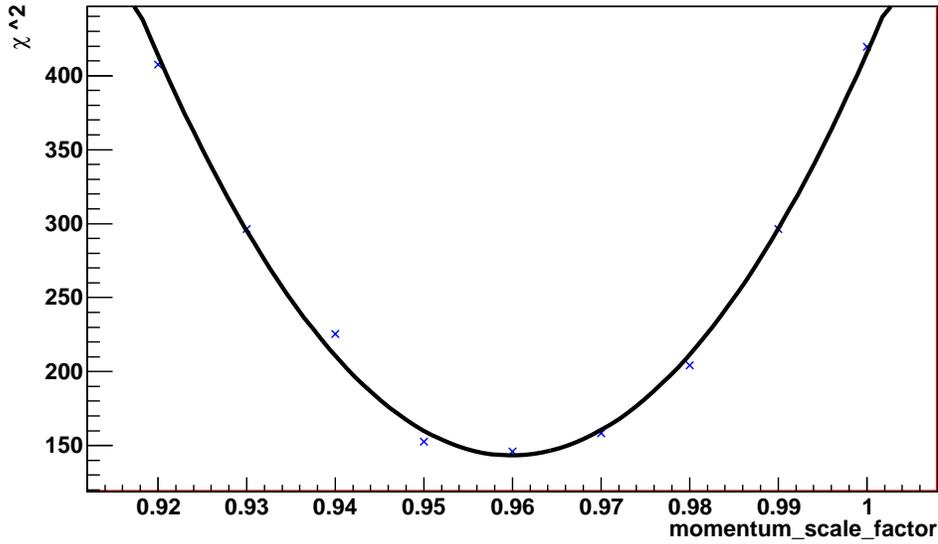
Figure 35: Official p_T^μ−-plot for W-events
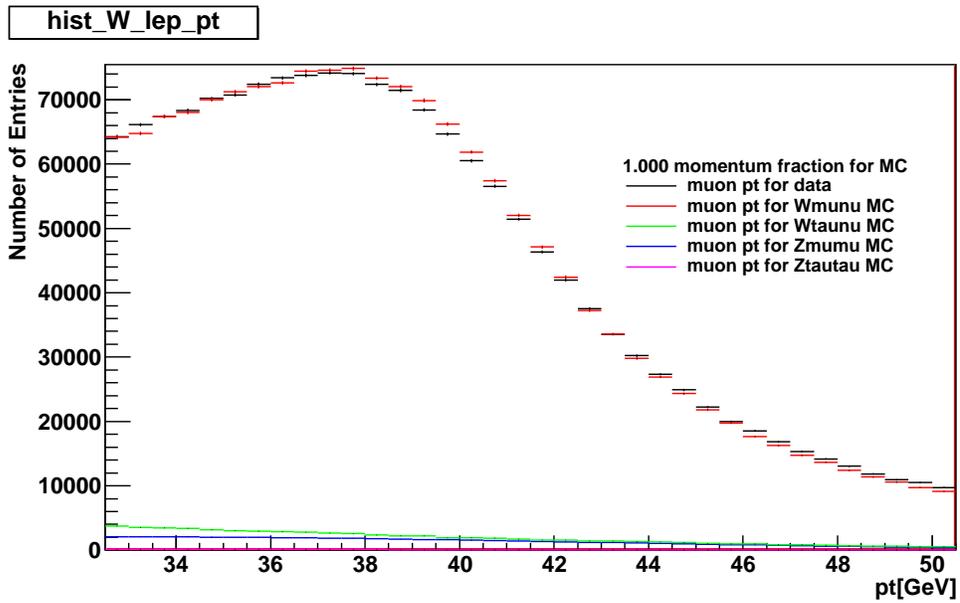
Figure 36: χ^2 for p_T^Z-templates

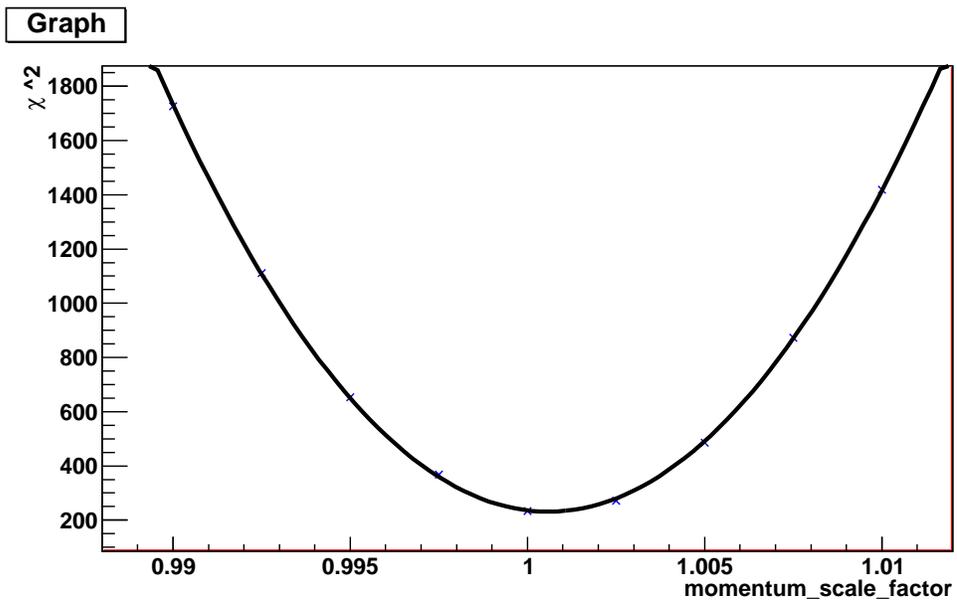Figure 37: p_T^μ in W-events with a p_T^W boost of 0.9599414

Figure 38: χ^2 for p_T^μ in W-events with a p_T^W boost of 0.9599414