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# Studying the $Z$ Boson with the ATLAS Detector at the LHC

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# Abstract

This experiment was conducted in the scope of the advanced lab course in physics at the Heidelberg University.
The goal was making oneself familiar with data analysis tools that are common in the field of particle physics. Therefore data from the ATLAS experiment at CERN (Geneva) was used to calculate the invariant mass of the $Z$ boson, one of the three bosons responsible for the weak interaction.
The experiment was conducted in the week of the $8^{\text{th}}$ april, 2019.


# Contents

# 1 Introduction

The main goal of the lab course is to analyze data from the ATLAS experiment and to calculate the invariant mass of the $Z$ Boson.

## 1.1 The Standard Model of Particle Physics

The Standard Model of Particle Physics (fig. 1) is the summarization of the known structure of matter. It implies, that matter is composed of the twelve elementary fermions with spin $\frac{1}{2}$, which are the quarks and leptons. Each of these particles has a corresponding anti-particles, which are equal, except that they have opposite charge.

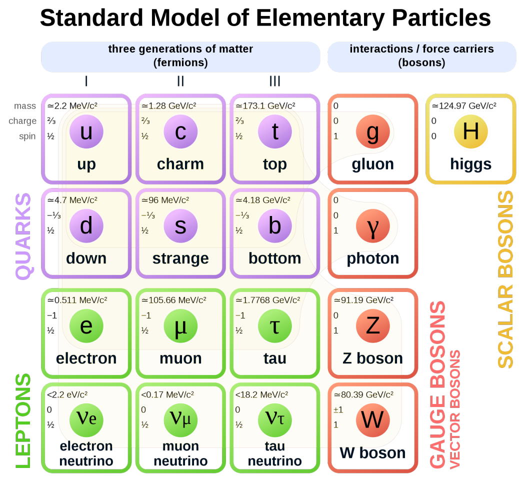



**Figure 1:** standard model of particle physics

There are three different interactions which are mediated by bosons carrying spin 1. The weak force exchange particles are the massiv $Z$ and $W^{\pm}$ bosons, the massless photons for the electromagnetic force and eight massless gluons are mediating the strong force. In this experiment the $Z$ Boson is especially important. Its properties are shown in table 1:

| Charge | Mass [MeV] | $\Gamma$[GeV] |
|---|---|---|
| 0 | $91.1876 \pm 0.0021$ | $2.4952 \pm 0.0023$ |

**Table 1:** Properties of the $Z$ Boson

## 1.2 Drell-Yan Process

A $Z$ Boson can be created during the so called "Drell-Yan" Process (fig. 2).

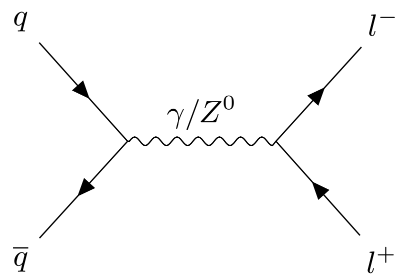



**Figure 2:** Drell-Yan process

This process happens predominatly in proton-proton collisions. When a quark and an anti-quark collide either a virtual photon $\gamma^*$ or a $Z$ Boson can be produced. The $\gamma^*$ or the $Z$ can then split into a lepton and its anti-particle partner like electron-positron or muon and anti-muon. The sum of the lepton and anti-particle partner momenta will then add up to the former boson momentum. A peak around 90 GeV will be observed corresponding to the $Z$ boson.

## 1.3 ATLAS Detector

### 1.3.1 Components

The Detector consists of three main components: inner detector, calorimeters and the muon spectrometer. They are onion-like constructed. The inner detector, the innermost layer, is mainly used to reconstruct the trajectories of electrically charged particles and to determine their momentum. With three aswell onion-like ordered tracking detectors, the pixel detector, the semi-conductor tracker and the transition radiation tracker, the inner detector can measure charged particles in a range of $|\eta| < 2.5$ and a $p_T > 400$ MeV.

The electromagnetic and the hadronic calorimeter allow to reconstruct the shower shapes of the showers from electromagnetically and strongly interacting particles. They are designed to contain the whole shower and cover a range up to $|\eta| < 4.9$. A precise energy measurement is possible.
The outermost layer is the muon spectrometer. Muons would espace the ATLAS detector without it and can now be tracked.

### 1.3.2 Geometry of the detector

In figure 3 one can see a drawing of the cross section of the ATLAS detector, which has a rotational symmetry around the $z$-axis. A good understanding of the detector is necessary to compute the $Z$ bosons mass later on. One introduces the so called pseudo rapidity $\eta$:

$$\eta = -\log \tan\left(\frac{\theta}{2}\right) \tag{1}$$

The components of the momentum of a given particle are:

$$p_x = p_T \cos\phi \tag{2}$$
$$p_y = p_T \sin\phi \tag{3}$$

where $p_T$ is the transversal momentum. By using the $eta$ definition one can derive $p_z$ in the following way:

$$p_z = p_t \cot\theta \tag{4}$$
$$\text{use: } \cot\left(2\arctan \mathrm{e}^{-x}\right) = \sinh x \tag{5}$$
$$\Rightarrow p_z = p_T \sinh\eta. \tag{6}$$

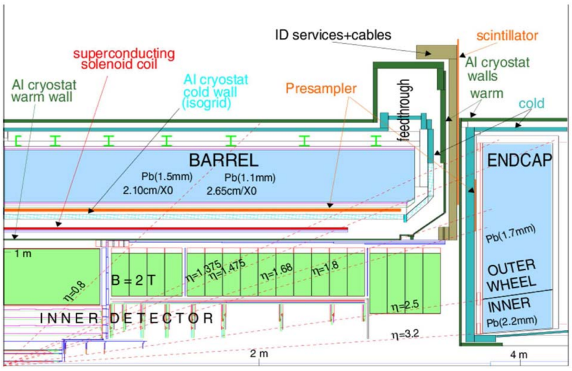



**Figure 3:** Cross section of the detector

## 1.4 Distributions

For the experiment the following distributions are important.
Gaussian distribution:

$$f_{\mathrm{G}}(E) = \frac{\mathcal{N}}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(E-\mu)^2}{2\sigma^2}\right) \tag{7}$$

Breit-Wigner Distribution:

$$f_{\mathrm{BW}} = \frac{\mathcal{N}k}{(E^2 - M^2)^2 + M^2\Gamma^2}, \tag{8}$$

with $k = \frac{M\Gamma\gamma\sqrt{8}}{\pi\sqrt{M^2+\gamma}}$ and $\gamma = M\sqrt{M^2+\Gamma^2}$. $\Gamma$ is the decay width.
One also needs a third distributions which is the convolution of the Gauss and the Breit-Wigner Distribution in order to account for the uncertainties caused the detector. The Breit-Wigner describes the physical decay process. However it does not consider the energy uncertainties which can be recognized by the gaussian distribution. A convolution of two functions $(f * g)$ is defined as:

$$(f * g)(x) = \int f(y)g(x-y)\mathrm{d}y \tag{9}$$

## 1.5 Efficiency

The efficiency of the measurements plays a crucial role. At the ATLAS detector it consists of for components:

$$\varepsilon_{\text{tot}} = \varepsilon_{\text{recon}} \times \varepsilon_{\text{id}} \times \varepsilon_{\text{trig}} \times \varepsilon_{\text{add}} \tag{10}$$

The focus on this experiment lies on the identification efficiency. One can get an estimate for $\varepsilon_{\text{id}}$ by using the so called tag and probe method. One searches for one event where two electrons are involved. Now strict conditions are applied on one of the electrons, the *tag* electron, and on the other one, the *probe* electron, weaker conditions are applied. Let $N_tp$ be the number of events where both tag and probe fulfill their conditions and $N_t$ be the number of events where only the tag electron passes the requirements, then the efficiency is given by:

$$\varepsilon_{\text{id}} = \frac{N_tp(p_T)}{N_t(p_T)}. \tag{11}$$

# 2 Experimental procedure

## 2.1 Getting familiar with the data

Before starting with the computation of the mass of the $Z$ bosons one has to make oneself familiar with the provided data of the ATLAS detector and the data analysis library ROOT. The given data was preselected; one only has data from events where a primary vertex was found and at least one lepton has a minimal transverse momentum of $p_T = 25$ GeV.

### 2.1.1 Particle entrance

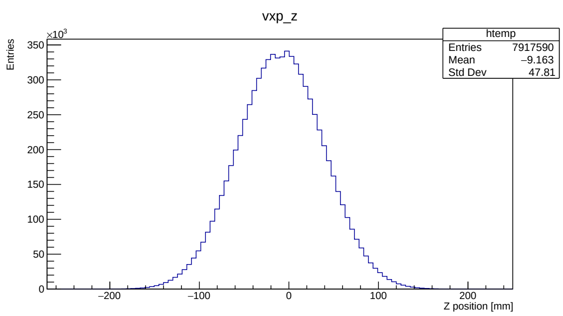



**Figure 4:** $z$-postion distribution, particle entrence in ATLAS detector

To check where the particle enter the detector, one can evaluate the given date for the vxp_z variable. The results are shown in fig. 4. The mean is shifted for $-9$ mm. This confirms, that the given data is from 2012 because collisions of bunches were not calibrated to the $0.0$ position back then [**atlasbeamspot**]. Left and right to the mean are two maxima, which can also be explained with the assumption above. A momentum change of $90$ degrees is impossible and most of the collisions take place at the place of the first intersection.

### 2.1.2 leptons per event

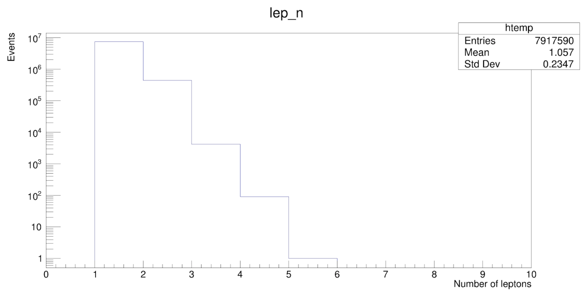
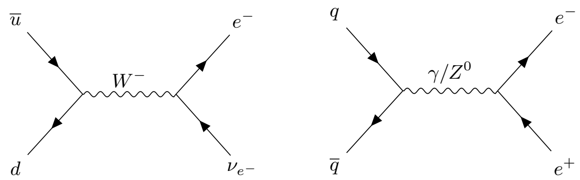



**Figure 5:** leptons recorded per event

To figure out, if one found a $Z$ decay, one analysis the *leptons per event* value of the data (fig. 5). Around the wanted two leptons, one gets many events with one and three leptons. For these events to happen, one needs a $W^{\pm}$ decay. Possible decays are shown in 6



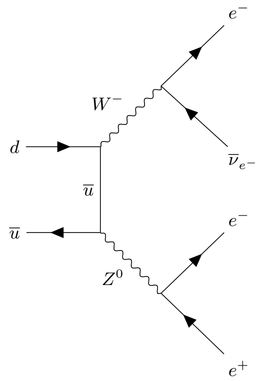



**Figure 6:** Feynman graphs for final states with one to three leptons

### 2.1.3 Data of the leptons

The stored data about the transverse momentum, the $\phi$ degree and the $\eta$ variable gives insight about the geometry and the data saving of the ATLAS experiment.

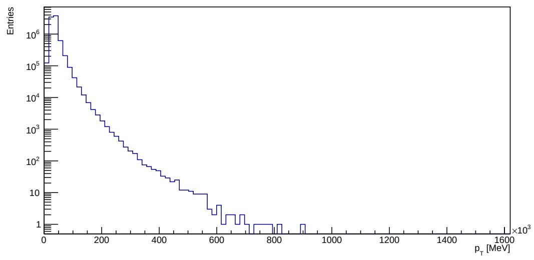
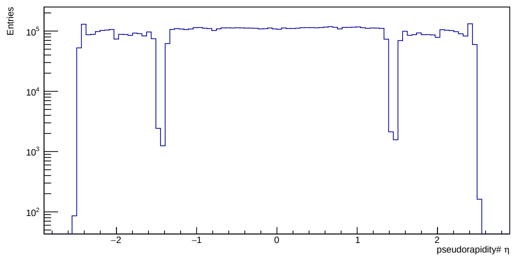



**Figure 7:** Distributions of $p_T$

One can identify a sharp rise at 25 GeV for the transverse momentum. At ATLAS only events with at least one lepton above this threshold will be stored.



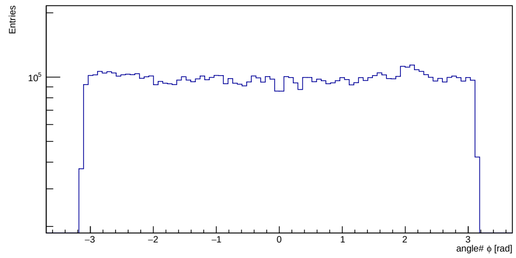




**Figure 8:** Distributions of $\eta$ and $\phi$

From the geometry one assumes an even distribution for the $\phi$ and $\eta$ values. It only applies for the first. The $\eta$ value has areas with a lack of data entries. This is a setback of the ATLAS geometry seen in fig. 3. Around $\eta = 1.8$, one misses the Barrel or the Endcap who are necessary for the event recognition.

## 2.2 Calculation of the invariant mass of the $Z$ boson

According to the structure of the ATLAS detector, one can calculate the invariant mass in the following way:

$$M_\mu = \sqrt{p_\mu p^\mu} = \sqrt{E_1 E_2 - \vec{p_1}\vec{p_2}} \tag{12}$$

An attempt to calculate it with the above given formula and the build-in function `TLorenz` in `ROOT` provided the exact same result. The calculated results will therefore be based on the `ROOT` method.
The first attempt to measure the mass was done by limiting the data to 2-lepton events. Further one ignored the events where $M_\mu^2 < 0$.

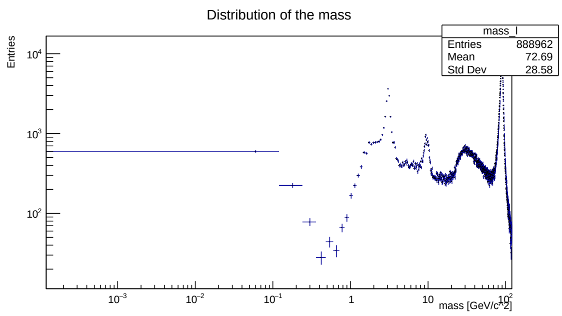


**Figure 9:** invariant Mass distribution of 2 lepton events

In 9, one can identify four peaks. The one on the right, at approximatly 91 GeV, is the subject of this investigation and the goal is to characterize it better in the course of this paper.
The two on the left are respectable by the virtue of the $J/\Psi$ and the $\Upsilon$ decay.

## 2.3 Selecting

The next step was to assert restictions to the dataset in order to ensure that a $Z$ decay was meassured. The restrictions that were used are:

1. **Weights**: Applies a weight to the events in the MC files, in contrast each event in real data counts as one event.
2. **Trigger**: events pass if the applied trigger identifies a $Z$ decay into an electron or muon pair.
3. **GRL**: The Good Run List only allows events where meaningful data for physical analysis is gatherd.
4. **Vertex**: Requires al least one well measured vertex per event.
5. **2 Leptons**: Restrict the data to 2 lepton events.
6. **PDGID**: A number is assigned to each particle through a track reconstruction in the detectors. $e$, $\mu$ and $\tau$ are respectivly identified with the integers 11, 13, and 15.
7. **Charge**: Checks if the leptons from the $Z$ decay have opposit charge.
8. $p_T$ **Cut**: Set an lower limit for the lepton energy to acknowledge the high $Z$ mass.
9. **Isolation**: Events pass if the observed leptons are well distinguishable from the background.
10. **Tight ID**: Lepton reconstruction algorithms allow to label leptons. Only ones labeled with "tight" will proceed.
11. **Z Mass**: With the known $Z$ mass, one can restrict the mass of the di-leptons to a range around it.

The impact of each of the restrictions can be seen in fig.10.

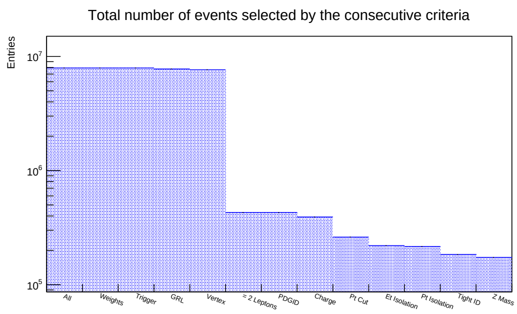



**Figure 10:** cutflow histogramm

The eventbased cuts (in fig.10 the first four columns) have close to no impact on the selection because the given raw data from ATLAS is preselected on event and physics object level. The most impact provides the 2 lepton Cut. As seen in 5, most of the events do not fulfill this criteria.

## 2.4 Comparing Data and Monte Carlo Simulation

One can now ask how well the meassured data matches with the theory. In order to do this one can perform Monte Carlo (MC) simulations and then compare with the data (fig. 11). Three MC simulations for the possible leptons after the $Z$ decay are analysed in the same way as in section 2.3 explained. One has to scale the results according to the luminosity of the ATLAS detector ($1fb^{-1}$). The comparison yields matching results.

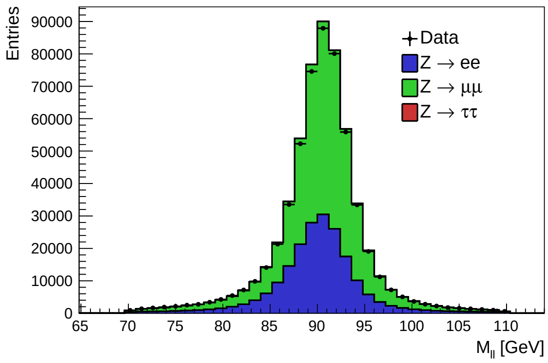



**Figure 11:** Comparison of meassured data and MC simulation

## 2.5 Fitting the $Z$ mass

12 underlines the assumption from section 1.5, the best fit is provided by the convolution of a gaussian and a Breit-Wigner distribution.

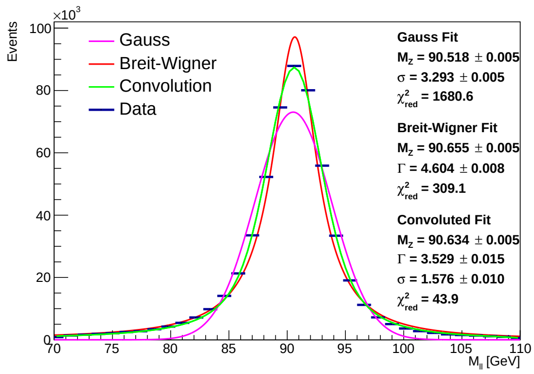



**Figure 12:** Comparison of meassured data and MC simulation

One can determine the mass of the $Z$ boson and the decay width to:

$$M_Z = (90.634 \pm 0.005)\ \text{GeV} \tag{13}$$
$$\Gamma = (3.529 \pm 0.015)\ \text{GeV} \tag{14}$$

A comparison of the results with the values (table 1) of the Particle Data Group yields differences of the order 1 GeV.

$$\Delta M_Z = (0.554 \pm 0.005)\ \text{GeV} \tag{15}$$
$$\Delta\Gamma = (1.034 \pm 0.015)\ \text{GeV} \tag{16}$$

## 2.6 Determining efficiencies

For determining the efficiency of the identification the tag and probe method (which was introduced earlier) is used. The efficiency was computed for the MC simulation and for the real data and can be seen in figure 13.

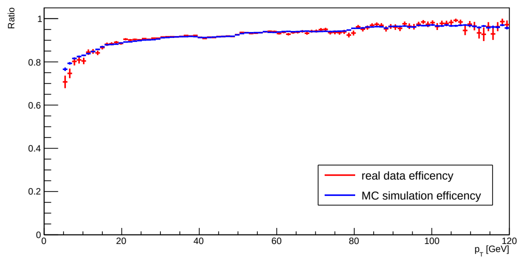



**Figure 13:** Comparison of the efficiencies of the MC simulation and the real data

One achieves an efficiency for this method of approximately $90 - 95\%$ over the whole momentum sprectrum, which is not influenced by the applied $p_T$ *Cut*.

# 3 Discussion

The diffrence between the calculated result and the litrature value of the $Z$ mass yields an underestimation of the involved errors. This is true, for the lab course one neglects all sorts of error, only the error according to the fit is recognised. Just from the volume of the data, one assumes that the stastical error is reduced to a minimum. The uncertainty scales with $\frac{1}{\sqrt{N}}$. For the provided data one concludes, that $\Delta_{stat.} \ll \Delta_{syst.}$. Various factors contribute to systematic errors. The variance of the convoluted fit ($\sigma = (1.576 \pm 0.010)$

GeV) provides a first estimate about the exent of the errors. One of the prominent errors is the energy resolution in the calorimeter, which gets improved since the start of the ATLAS experiment. Another major part, which influences the uncertainty, comes with the diffrent used triggers. Firstly, to record an event, triggers have to be passed which work with unknown efficiency. Later on, at the analysis of the data, one implements various filters (explained above). With more time the used thresholds could be optimized. As the diffrence of the values implies, a good understanding and recognition of the systematic uncertainties is necessary to improve the results.

Nevertheless, after one made oneself familiar with `ROOT` and the data, aswell with the Monte Carlo files, one was able to get insight into modern analysis in particle physics. The results ,even without extensiv error aknowledgment, verifies the used approach to identify the $Z$ boson mass.