# Lab 3: ATLAS Data Analysis

Zya Woodfork

## I. Introduction

The Large Hadron Collider at CERN, located in Geneva, Switzerland, collides beams of protons together. As members of the ATLAS (A Toroidal Lhc Apparatus) experiment, we study the byproducts of these collisions. One output is the $Z^0$ boson, which is of interest since it's the neutral carrier of the weak force and is responsible for many nuclear reactions in the universe. In order to measure this particle's mass, we must study what it decays into since it's very unstable. Ten percent of the time a $Z^0$ boson will decay into a pair of charged leptons, which could be an electron/anti-electron, muon/anti-muon, or tau/anti-tau pair. To conserve matter and energy, the total energy of the lepton pair must sum to at least the mass of the $Z^0$ boson, so we can study these values to get a good idea of what the mass of the $Z^0$ boson must be.

## II. The Invariant Mass Distribution

To calculate the mass of the $Z^0$ boson, I used the data of 5000 ATLAS events whose final states only contained two leptons. The invariant mass is given by the equation

$$M = \sqrt{E^2 - ({p_x}^2 + {p_y}^2 + {p_z}^2)} \quad \textbf{(1)}$$

where $E$ is the total energy of the lepton pair and $p_x$, $p_y$, and $p_z$ are defined as follows:

$$p_x = p_T\, cos(\phi)\,,\ p_y = p_T\, sin(\phi)\,,\ p_z = p_T\, sinh(\eta) \quad \textbf{(2)}$$

where $p_T$ is each lepton's transverse momentum, $\phi$ is the azimuthal angle about the proton beam, and $\eta$ is the angle the lepton makes with respect to the beamline. I calculated the momentum in each direction for each lepton separately and then added pairs together so that each pair had a $p_x$, $p_y$, and $p_z$ value. These values along with each pair's energy were plugged into Equation 1 to get a list of invariant mass values.

Next, I made a histogram to display how many of the 5000 events yielded each invariant mass value spanning from 80 to 100 GeV. Error bars were calculated by taking the square root of the number of events in each bin, or bar of the histogram. To fit this data, a Breit-Wigner fit was used. This fit models the relationship between the distribution of decays and the reconstructed mass and is defined as

$$D = \frac{1}{\pi}\frac{\Gamma/2}{(m-m_0)^2+(\Gamma/2)^2} \quad \textbf{(3)}$$

where $\Gamma$ is the width parameter, $m$ is the reconstructed mass, and $m_0$ is the true rest mass of the $Z^0$ boson. This fit was applied to the central portion of the graph since we know the peak of the fit will give us the best value of $m_0$ (Figure 1). Residuals were also calculated and plotted to see how close the theory was to the actual data. According to this fit, the best value for $m_0$ is $90.3 \pm 0.1$ GeV.

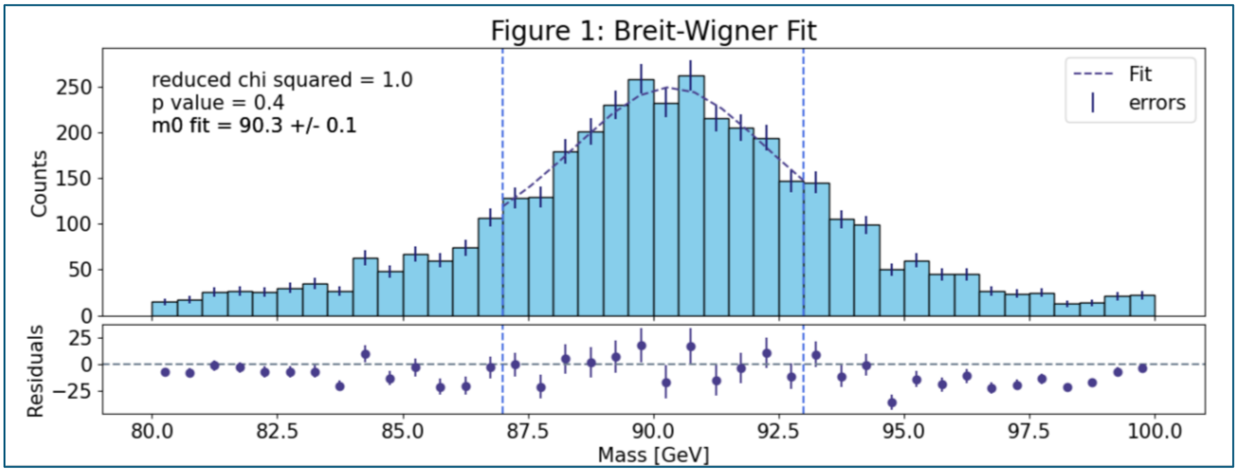


Figure 1: Top panel - Breit-Wigner model fit to the distribution of events over masses from 87 to 93 GeV
Bottom panel – residuals of data

I then calculated the chi-square value and compared it to the number of degrees of freedom to determine how well the theory fits the data. Chi-square rounds to 10.0 and the number of degrees of freedom for the central portion of data is also 10, so the theory found from the Breit-Wigner fit fits the data well. Using these values for chi-square and degrees of freedom, I then calculated the p-value of the data, which rounds to 0.4. This means there is a 40% chance of getting this same chi-square value or higher if we were to conduct the experiment again.

## III. The 2D Parameter Scan

The final way I verified that the best fit value of $m_0$ was actually the best was by creating a $\Delta\chi^2$ map of the data. This plot looks at every true width and rest mass combination within a defined range and calculates $\Delta\chi^2$ with Equation 4. Whichever true width/mass combination yields a $\Delta\chi^2$ value closets to zero is the best-fitting pair of values. Figure 2 shows that our calculated best fit values for true width and rest mass do in fact yield a $\Delta\chi^2$ of 0, and this point is indicated with the yellow X. The $1\sigma$ and $3\sigma$ confidence levels were also added for reference and were obtained from literature based on the number of degrees of freedom we have, which is 2.

$$\Delta\chi^2 = \chi^2 - {\chi^2}_{min} \qquad \textbf{(4)}$$

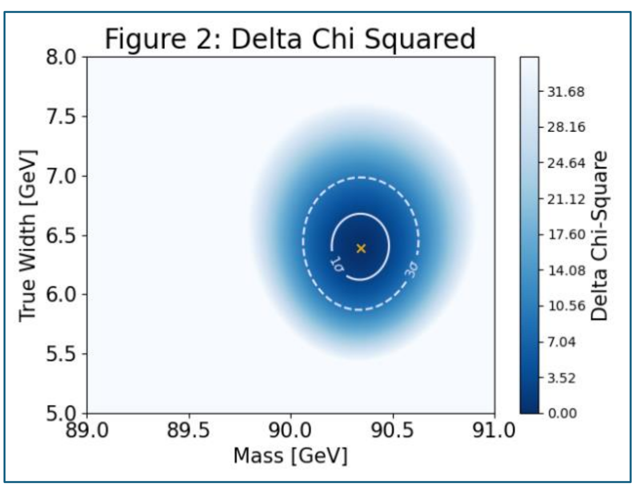


Figure 2: plot of 2D chi-square parameter scan with highlighted $1\sigma$ and $3\sigma$ contours.

## IV. Discussion and Future Work

This report has summarized the calculations made to determine the rest mass of the $Z^0$ boson. To restate, I calculated a $Z^0$ boson rest mass of $90.3 \pm 0.1$ GeV. As of 2024, the Particle Data Group reports that the rest mass of the $Z^0$ boson is 91.1880 $\pm$ 0.0020 GeV. The difference between these two values is about 0.8 GeV, and this accepted value is not within two sigma of my calculated value. The reason for these discrepancies is because my fit does not include any systematic uncertainties. If these were included, my calculated value would most likely have larger errors that would include the accepted value in its range. My value would also be more realistic if the energy resolution of the ATLAS detector were considered. In the future, we can calculate a more accurate $Z^0$ rest mass if we account for every uncertainty gained during the data collection and analysis process. In this way, we can be even more certain about the properties of the $Z^0$ boson and gain a better understanding of the weak force and mechanisms of the universe.