ATLAS Data Analysis

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I. Introduction

Located at CERN, in Geneva, Switzerland, the Large Hadron Collider (LHC) is the largest particle accelerator built. In the LHC, particles are accelerated to near the speed of light and collide with another particle. Carrying high energies, the particles are broken down into new particles. LHC mainly works with proton-proton interactions. When colliding two protons, you can get a Z^0 and $W^{\pm}$ bosons. The proton is a carrier of electromagnetic force, while the bosons are carriers of weak force, so such a reaction is possible. However, looking at the Z^0 boson specifically, they are unstable and can decay into a lepton and their antiparticle pair, which includes electron/anti-electron (or positron), muon/anti-muon, and tau/ anti-tau. Following the fundamental conservation of matter and energy, taking the energy of the two leptons should ideally give the mass of the Z^0 boson. So by measuring the energies and momentums of the lepton pairs, one should get the mass of the Z^0 boson. These kinds of works are carried out by ATLAS (A Toroidal Lhc ApparatuS), one of the leading experiments at the LHC. ATLAS uses detectors to detect the lepton pairs coming out of the proton-proton interaction and measures the properties of the lepton pair. For this project, we will take the data collected from ATLAS detectors, and using the capabilities of Python, we can calculate invariant masses, visualize the invariant mass distribution, and use a model to find rest mass. It is imperative to know that each lepton has different mass, so there will be a scatter distribution. When fitting the variant mass distribution, we will be focusing the fit on the peak, as there should be the mass of Z^0 boson.

II. The Invariant Mass Distribution and Breit-Wigner Fit

To determine the invariant mass of the lepton and anti-lepton, the four momentums must be known. The four momentums are the energy and momentum in the three Cartesian coordinates (x, y, and z). In natural units (speed of light set to 1), the energy and momentum have units of energy, or for this case GeV. Thankfully the ATLAS detectors are able to measure the total energy of the lepton pair, but the same cannot be said for the momentum components. Since the momentum cannot be directly measured, the ATLAS detectors measure the transverse-momentum (p_T), the pseudorapidity (η), and the azimuthal angle (ϕ). Using those measurements, the momentum components can be calculated. The momentums are calculated as:

$$\begin{aligned} p_x &= p_T cos(\phi) \\ p_y &= p_T sin(\phi) \\ p_z &= p_T sinh(\eta) \end{aligned} \tag{1}$$

It is important to note that there are two particles, so the four momentums for each particle will need to be added together to get the total four momentum of the system. Afterward the invariant mass of the lepton pair can be calculated through the following equation:

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

Since there are many proton-proton interactions, each may lead to the Z^0 bosons decaying into one of the three lepton pairs, the invariant mass distribution will be scattered. The invariant mass distribution will be approximated as a Poisson count, so the uncertainty will be the square root of the number of counts in each bin. To find the rest mass of the Z^0 bosons from the distribution, one can use the Breit-Wigner fit. By looking at and fitting the peak, the rest mass of the Z^0 boson can be determined. The Breit-Wigner function is best described in the equation below:

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

Where m is the invariant mass, m_0 is the rest mass of the Z^0 boson, and Γ is the width parameter.

To begin the fitting, first begin by loading the ATLAS data containing transverse-momentum, the pseudorapidity, and the azimuthal angle of each lepton. Taking the data, calculate the four momentums and sum them. Using the four momentums, the invariant mass of the lepton pair can be calculated. To get a better sense of the invariant mass distribution, the masses are plotted as a histogram. Using Python 'curve_fit', fit the invariant mass distribution with the Breit-Wigner function. Since the idea is to fit a peak, a mask is used to limit the fit to around the peak of the distribution. So for this case, the fit was performed from masses of 87 to 93 GeV. Doing so, the best-fit rest mass of the Z^0 boson is $90.3 \pm 0.1\ GeV$. To verify whether the fit matches with the theory, a chi-squared test is performed. The chi-square is found by using the following equation:

$$\chi^2 = \sum \frac{(y_{data} - y_{theory})^2}{\sigma^2} \quad (4)$$

Using the equation above, I find the fit gave a chi-square value of 10.0. To truly get a better sense of whether the data and theory agree, we would need to calculate the p-value. To find the p-value, first determine the degrees of freedom. To get the degrees of freedom, take the difference between the number of data points and fitting parameters. Since the fit was performed over a certain range, I took the number of bin centers within that fitting range and subtract the number of fitting parameters, which is two in this case, giving 10 degrees of freedom. From there, I used the Python scipy.stats module to calculate the p-value. In the end, I got a p-value of 0.4, suggesting there is a significant probability for the data to fall outside the theory. While for the reduced chi-square, which is calculated as the chi-square divided by the degrees of freedom, I got 1.0, suggesting a good fit.

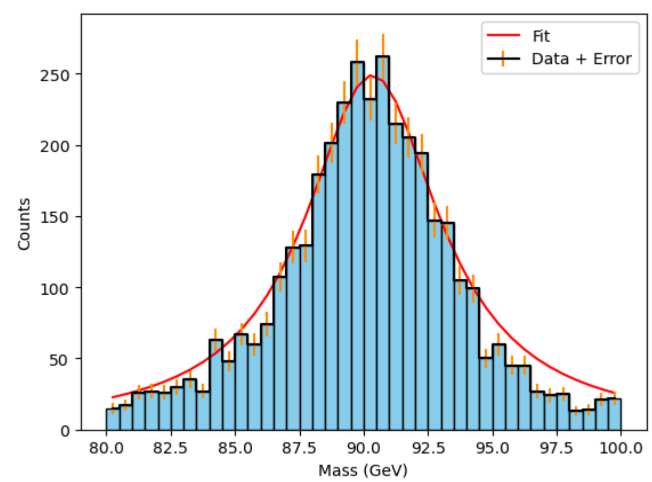

Figure 1: Histogram plot of the invariant mass distribution calculated from the ATLAS data with errorbars. In addition, the best-fit line is plotted in red.

III. 2D Parameter Scan

Based on the p-value, there is some disagreement between the data and theory, so we need to determine how well the best-fit values fit with the data. To this, I will perform the 2D chi-square scan on the rest mass of the Z^0 boson and width parameter. I first begin by initializing variables for testing the parameters. So the rest mass, I will be going from 89 to 91 GeV and 5 to 8 GeV for the width parameter with 300 steps for each. Next, utilizing the 'for' loop, a double for loop is created to recalculate the theory using the Breit-Wigner function and chi-square based on that theory value. The purpose of the double 'for' loop is to test the wide range of the fitted parameters and see how the chi-square changes. Taking the recalculated chi-square values, the delta chi-square is found by subtracting the chi-square values with the minimum chi-square value. Using matplotlib contour plot function, a 2D contour plot is created, plotting the fitting parameters on the x and y axes and the delta chi-square on the z-axis. In addition, 1σ and 3σ confidence levels are plotted, showing the uncertainties of the delta chi-square. The values of the confidence levels were found online.

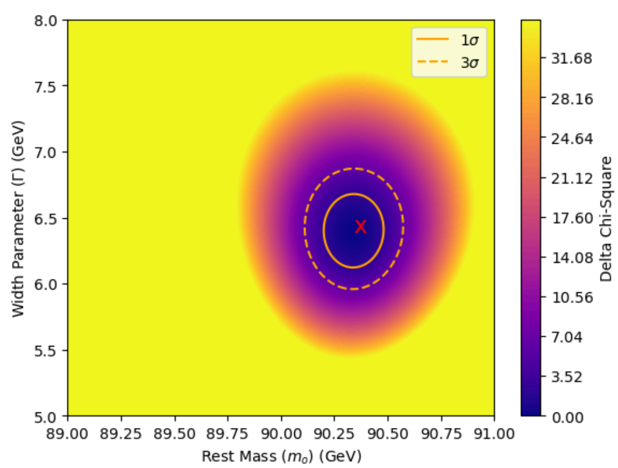

Figure 2: 2D contour plot of the delta chi-square calculated from the 2D chi-square scan. The best-fit parameter calculator from the 'curve_fit' is marked as the red X and σ levels are in orange.

IV. Discussion and Future Work

In the end, the best rest mass value of the Z^0 boson was found to be $90.3 \pm 0.1\ GeV$. Looking at the best-fit rest mass and comparing it to the accepted mass of $91.1880 \pm 0.0020\ GeV$, the value found through the fit does fit in the range of the accepted value. This can be explained through p-value because the p-value determines the probability of the data observed falling outside the fit. Since the p-value from the fit is 0.4, there is some disagreement, as some of the data have a ~40% chance of falling outside the fit. Then, there were approximations made when fitting the data. An approximation made in the calculations is that the invariant mass distribution was approximated as a Poisson counting experiment, so the errors were taken as the square root of the number of items per bin. By using this approach, the uncertainties are higher for the bins with more counts, creating a lack of systematic uncertainties. Another consideration is the resolution of the detectors at ATLAS. With many proton-proton interactions happening, the detectors could have been overloaded and possibly missed some leptons or only detected a portion of energy and transverse-momentum. A step that could be taken to improve the fit could be extending the fitting range. By increasing the number of data points within the fit, there would be more data points to observe and compare, possibly increasing the p-value as more data points could fall within the fit. Although the fit did not fall within the uncertainty range of the accepted mass of the Z^0 boson, the Breit-Wigner did prove to be a somewhat reasonable fit.