Lab 3: ATLAS Data Analysis

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I. Introduction

Understanding our physical world is best done through carefully studying the sub-atomic particles that make it up. The goal of this project is to better understand the Z^0 boson, a byproduct of high energy proton collisions, by exploring this particle's mass distribution. ATLAS, a detector at the CERN particle accelerator, gathers data on the two leptons a Z^0 boson decays into, which can then be used to reconstruct the rest mass the original particle by understanding the relationship between the lepton pair's energy and varying momentums to the rest mass of the Z^0 boson. Using the distribution of the detected particles' invariant masses, we can fit a model using least squares to find the rest mass of the Z^0 boson. In this report, we will discuss the process by which this model was made and how the best fitting parameters were determined.

II. The Invariant Mass Distribution

When a high energy proton-proton interaction occurs, many fundamental particles are produced, one of them being the Z^0 boson which is the neutral carrier of the weak force. This boson is unstable and decays. About 10% of the time, it decays into a pair of charged leptons. Knowing a pair's total energy and momenta in the x, y, and z directions allows us to construct the original particle's invariant mass using Equation 1 and its sub-equations.

$$M = \sqrt{E^2 - (p_x^{\,2} + p_y^{\,2} + p_z^{\,2})} \qquad [1]$$

$$p_x = p_T cos(\phi) \qquad [1a]$$

$$p_y = p_T sin(\phi) \qquad [1b]$$

$$p_z = p_T sinh(\eta) \qquad [1c]$$

Where E is the total energy, p_T is the transverse-momentum, ϕ is the azimuthal angle about the beam, and η, the pseudorapidity, describes the angle the particle travels with respect to the beam's path. Equations 1a, 1b, and 1c are all for a single particle detection (i.e. each individual lepton). Values found for lepton pairs must be summed to reconstruct the original boson.

Using data collected from ATLAS and the equations above, we computed the hypothetical mass of a Z^0 boson that decayed into a lepton pair for five-thousand different decays. These particles can be described by the Breit-Wigner peak, a theoretical model used to find the true mass of a particle, where the rest mass of the boson is the x-location of the peak of this model. The Breit-Wigner model is shown in Equation 2,

$$D(m; m_0, \Gamma) = \frac{1}{\pi}\frac{\Gamma/2}{(m-m_0)^2+(\Gamma/2)^2} \qquad [2]$$

where Γ is the width parameter, m is the calculated mass, and m0 is the true rest-mass.

For the purpose of our experiment, we practiced fitting the Breit-Wigner function to a specific section of our mass-distribution data, ranging from 87-93 GeV with 40 bins, as about 50% of the data falls within this range. Where this model peaks is where the best fit for the mass can be found. We then calculated the residuals to determine the quality of our fit. Figure 1 shows a histogram of the invariant mass distribution and a plot of the residuals. We can apply a Poisson count experiment to this distribution, attributing the error on each bin to be described by $\sigma = \sqrt{N}$, where N is the number of counts in each bin.

From this fit, we were able to determine the fitted mass of the Z^0 boson to be 90.3 ± 0.1 GeV. We determined the number of degrees of freedom to be 10, as we are assessing twelve data points in our range and have two fitting parameters. We assessed the quality of the fit by determining the chi-square and p-value. We found each of those values to be 10.0 and 0.4, respectively. The p-value states that there is a 40% chance of finding a chi-square of 10.0 or higher, assuming the model and uncertainties are correct. We anticipate that the chi-square and the number of degrees of freedom should have similar values as we expect the deviation of the data to be about 1σ away from the model. σ is in the denominator of the chi-square calculation, making the value of each chi-square term normalized and typically about one (assuming a decent model). When summing each term to find the chi-square we should find the total to be about the number of degrees of freedom, meaning our model is in agreement with the data.

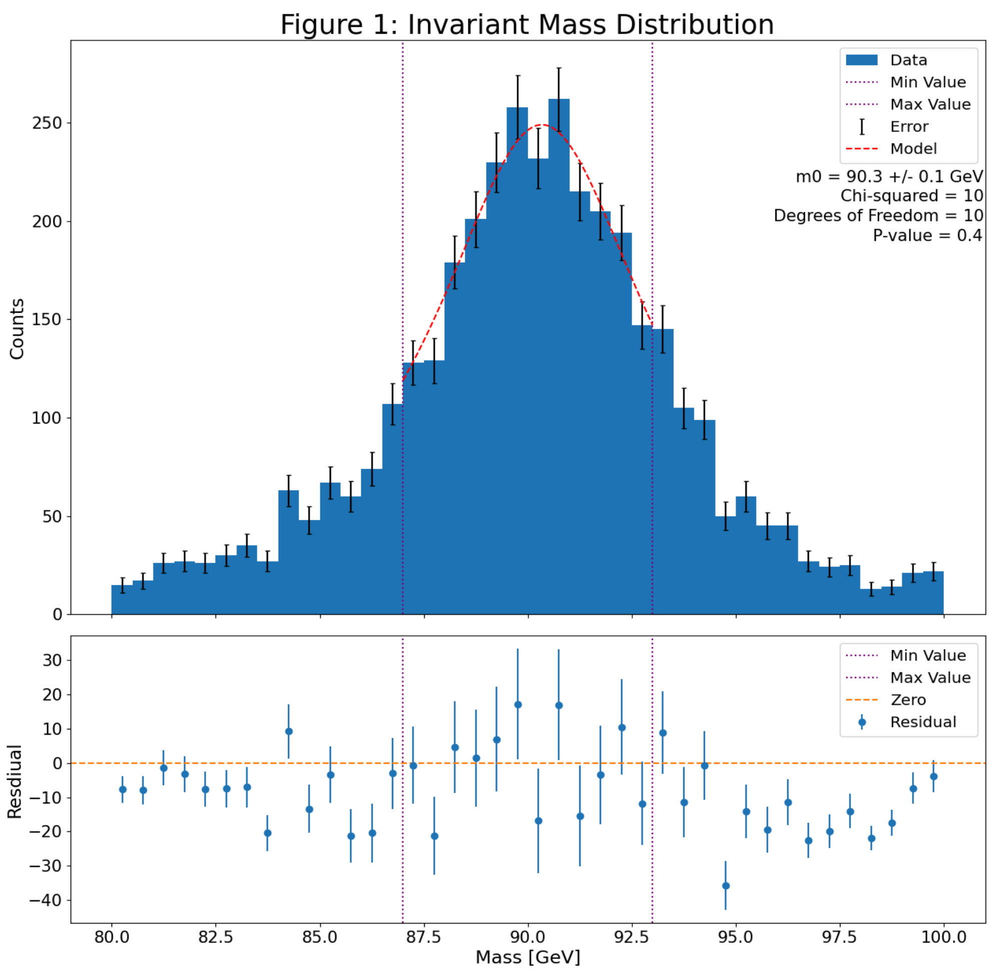

Figure 1: Histogram of the invariant mass distribution of the Z^0 boson and plot of the residuals of the data. The Breit-Wigner fit is also shown on the above plot. Vertical lines in both plots show the subsection of data we focused on. The horizontal line in the sub-panel indicates perfect agreement.

III. The 2D Parameter Scan

When computing higher dimensional fits, it can be helpful to visualize the chi-square for the fit in a three-dimensional space. To do this, we must consider a two-dimensional map of chi-square values produced for a range of parameter values. Throughout this process, we only considered a small sub-section of the data: the hypothetical masses from 89 -91 GeV and the width parameter from 5 to 8. We found these varying chi-squares by calculating a chi-square for each pair of parameters across our select range. We then found the delta chi-square, which was the difference between chi-square value for specific parameters and the minimum calculated chi-square across the entire map. This can be seen in Equation 3.

$$\Delta\chi^2 = \chi^2 - \chi^2_{min} \qquad [3]$$

To understand this better, a plot of the delta chi-squares was made as shown in Figure 2. The sections of deeper blue show a smaller delta chi-square closer to the minimum.

In the plot, the two yellow lines indicate different σ detections to test how confident we are in our fit. The dotted yellow line shows a 3σ confidence level, which represents a delta chi-square of 2.3, and the solid yellow line shows a 1σ confidence level, which shows a delta chi-square of 9.21. We picked these specific detections to annotate our delta chi-square plot with because we have two fitting parameters, and according to the literature, these are the delta chi-square associated with that situation.

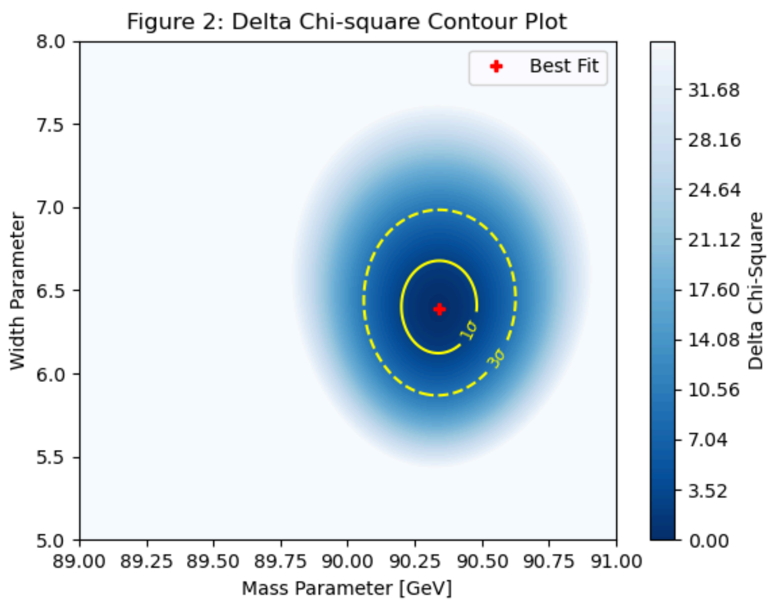

Figure 2: Contour plot of the delta chi-square for varying parameters of the model. The red cross indicates the best fit for the mass of the boson and the width parameter from our earlier calculations. The dotted and solid yellow lines represent a 3σ and 1σ region of confidence, respectively.

IV. Discussion and Future Work

As shown in this report, we found the mass of the Z^0 boson to be $90.3 \pm 0.1\, GeV$ using the Breit-Wigner model. According to the latest accepted value from the Particle Data Group, the mass of the Z^0 boson is $91.1880 \pm 0.0020 \frac{GeV}{c^2}$. The difference over the uncertainty in the difference between our calculated value and the true value is 9.1, meaning the value we found is 9σ away from the true value and is not consistent with the literature value. While completing this project, a few assumptions and simplifications were made, explaining the inconsistency between the true and calculated values. We assumed that all the data from ATLAS did not have any uncertainties and took those as exact values, making our uncertainties smaller. When considering the energy of the system, we assumed that after the collision but before the measurement was taken by ATLAS, there was no change in energy in the lepton pairs. We also only fitted about 50% of the data when fitting the chi-square. To improve this project in the future, we can gather more data from ATLAS, aiding us in attaining a better chi-square value and a more accurate fitted mass. We can also consider the uncertainties in the data from ATLAS to increase the validity of our own uncertainties. Lastly, to make these calculations more realistic in the future, we can consider the systematic uncertainties from ATLAS or the energy resolution of the detector.