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Lab 3: ATLAS Data Analysis

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I. Introduction

The ATLAS experiment at CERN in Geneva collides high energy protons in order to study the fundamental particles and forces. As a physicist working on the experiment, I am investigating the mass of the Z^0 boson, a neutral carrier of the weak force, discovered at CERN in 1983. The boson is unstable and decays into a pair of charged leptons around 10% of the time. Because of the conservation of charge and energy, the invariant mass of the laptop pairs has a clear peak at the mass of the Z^0 boson. This report presents a quantitative analysis of collision events using Python and its libraries such as NumPy, SciPy, and Matplotlib. We reconstruct the invariant mass of lepton pairs and fit the data to a Breit-Wigner distribution (which explains how the mass of unstable particles is distributed) to extract the mass and width of the Z^0 boson.

II. The Invariant Mass Distribution and its Fit

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

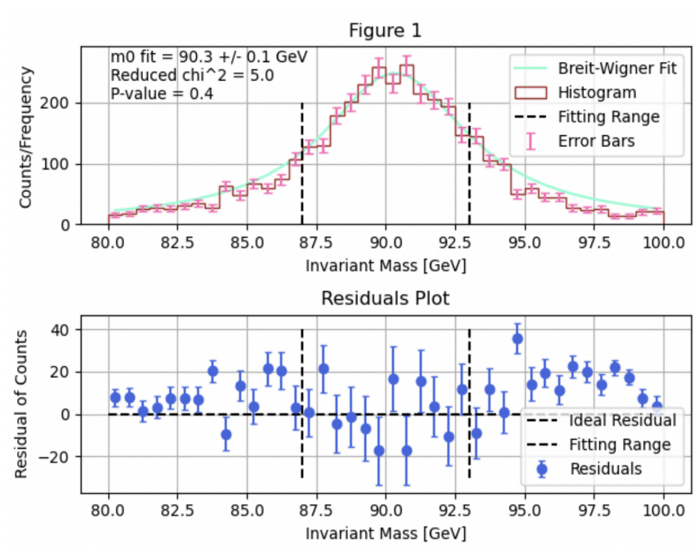
First, I extracted my ATLAS data for the four momentum of the particle with values for E and the momentum (p) in the x, y, and z directions. I defined the momentum of the particles in each direction according to the appropriate equations, which you may view above. Then, I added the particles' momentums in each direction so I could calculate the total momentum in each direction. I found the invariant mass (M) using those total momentums according to the displayed equation.

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

I turned it into a histogram with error bars, finding error by approximating it as a Poisson counting experiment. Then, using a scattering theory known as the Breit-Wigner

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

distribution (D), we can describe the invariant mass distribution. Recall, it is not uniform and can appear differently in experiments. Breit-Wigner allows us to view a peak in the invariant mass distribution which is determined to be at the mass of the Z^0 boson. In order to view the relationship between the data's distribution and the Breit-Wigner distribution, I added a Breit-Wigner fit line to my graph. You can also reference the fitting lines to see the range of data that was used to calculate the fit. Because only half of the data was used

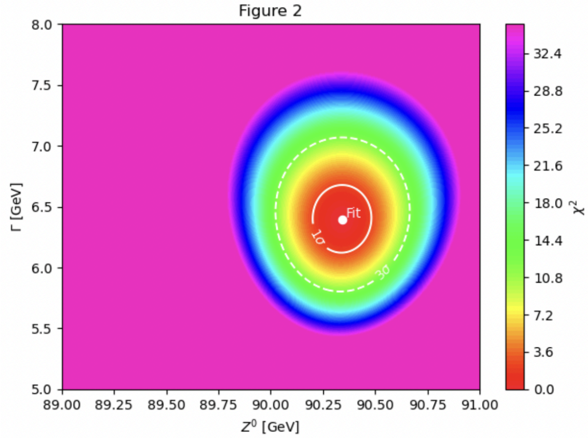


(from bin centers larger than 87 and smaller than 93 GeV), you can see that the fit is better within the fitting lines and worse as you deviate from the peak. The graph is included on the following page of this report with the label “Figure 1”. The residuals (difference between the actual value and that predicted by the model) are also included in the graph below. Following graphing, I calculated five numbers: the fitted mass of the Z^0 and fitted uncertainty, chi-squared, the degrees of freedom, and the p-value. Their respective values are 90.3 +/- 0.1 GeV, 10.0 and 5.0 reduced, 10, and 0.4. Furthermore, the calculated p-value of 0.4 means that there is a 40% probability that a chi-square value of ten or more would occur randomly. A p-value between 0.05 and 0.95 is statistically significant and so our p-value of 0.4 shows acceptable agreement between my data and the Breit-Wigner model.

III. The 2D Parameter Scan

For this section of my work, I first performed a 2D chi-square scan of the mass-width parameter space. Because this is a 2D fit, this is a joint probability space and as such, keep in mind that we are unable to find the Z^0, the boson’s mass, and Γ, its width, independently. Their best-fit values and uncertainties and interlinked. I scanned in masses from 89 to 91 GeV and widths from 5 to 8 with 300 bins along every dimension, creating a 300 by 300 grid where I evaluated chi-squared. At each grid point, I fitted the Breit-Wigner model to the current Z^0 and Γ values and then found chi-squared between the model and invariant mass histogram data. I made the delta chi-squared map by subtracting the minimum chi-squared value from the current one and then clipped it at 35 units. Figure 2 displays the values of Z^0, Γ, and chi-squared. I plotted constant contours of delta chi-squared on the 2D parameter space to show the statistical uncertainty. The delta chi-squared for each level depends on the number of fit parameters. Here, I had two: Z^0 and Γ. Delta chi-squared was taken from the chi-squared distribution with 2 degrees of freedom with the one sigma confidence level value being 2.30 and the three sigma confidence level being 11.83. The white solid line and dashed line are the one and three sigma confidence intervals (labelled). Also, there is a point in the center to show the best fit location (labelled). You can see that the chi-squared increases as you get farther from the best fit location.

Figure 2



IV. Discussion and Future Work

In this study, I analyzed ATLAS data to reconstruct the invariant mass of lepton pairs and fit the mass of the Z^0 boson using a Breit-Wigner distribution. I found the fitted mass and uncertainty of the Z^0 boson to be 90.3 +/- 0.1 GeV from the fit. In addition, I found a width of Γ = 6.7 GeV and reduced chi-squared of 5.0 with corresponding p-value of 0.4. The value of the Z^0 boson found by the Particle Data Group (PDG) was 91.2 GeV so my value is only 0.9 GeV lower. While the difference does exceed the reported uncertainty of 0.1 GeV, the agreement is still qualitatively reasonable when considering the possible sources of error. There were several simplifications and approximations made in my analysis that contribute to the discrepancy. For example, I did assume that the ATLAS detector had perfect energy resolution and neglected possible detector effects such as smearing or miscalibration. My model didn't account for systematic uncertainties like background contamination or luminosity normalization and I used a simple Breit-Wigner function without convolution with a detector resolution function. If I wanted to improve realism and accuracy in this study, I would incorporate detector resolution effects by combining models (Breit-Wigner and Gaussian) to simulate smearing. Additionally, I would estimate uncertainties in detector calibration, selection efficiencies, and background modeling. Plus, I could try to use a full likelihood-based fit instead of a least-squares approach. Using these techniques, I would be able to bring my measurement closer in line with the precision of the PDG's value.