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Lab 3 Report: ATLAS Data Analysis

I. Introduction

This report utilizes real data from the ATLAS detector at CERN's Large Hadron Collider in Geneva, Switzerland to measure the mass of the Z^0 boson, which is a neutral carrier of the *weak* force and is responsible for facilitating many nuclear interactions in the Universe. The Z^0 boson is unstable and quickly decays, sometimes into a pair of charged leptons (e.g., e^-e^+, $\mu^-\mu^+$, or $\tau^-\tau^+$). Using the leptons' energies and momenta, we can reconstruct the invariant mass and identify a peak that corresponds to the Z^0 mass. This analysis involves generating an invariant mass distribution histogram, fitting it with a Breit-Wigner function, and evaluating the accuracy of the fit using statistics. The correlation between the Z^0 mass m_0 and width Γ is then explored through a two-dimensional χ^2 scan. This experiment serves as an introduction to common data analysis techniques in experimental particle physics.

II. The Invariant Mass Distribution

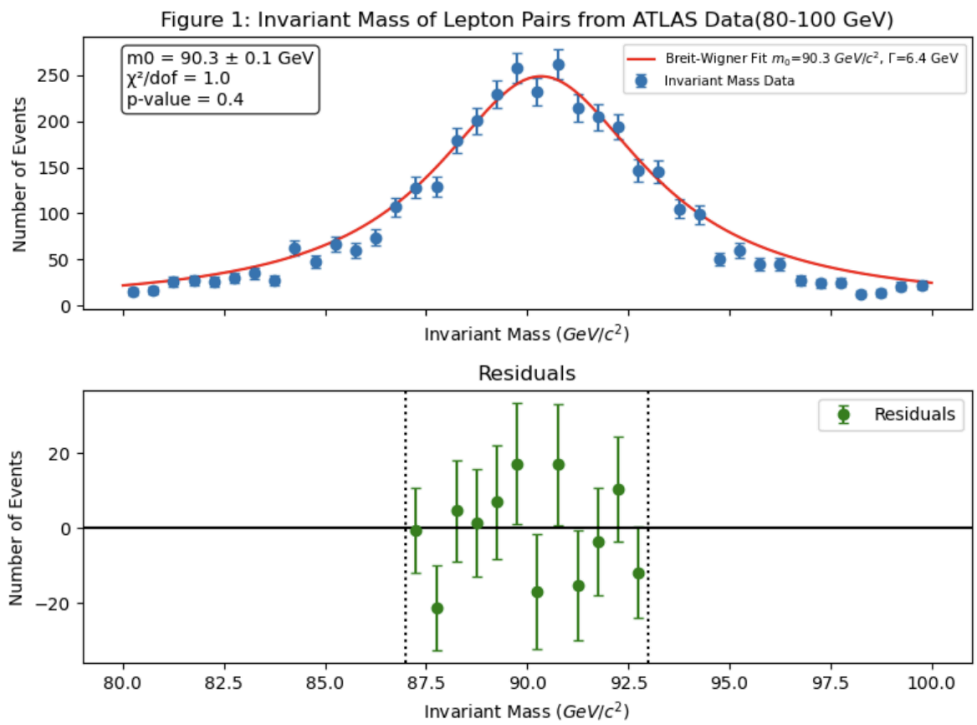
To begin the comparison, I first made a plot of just the data with error bars across bins ranging from 80 to 100 GeV. I then used the Breit-Wigner function,

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

where D is decays, m is the reconstructed mass, m_0 is the true rest-mass of Z^0, and Γ is a width parameter, to fit with my previously plotted mass-distribution, fixing the overall normalization to half the number of data points in the set. Afterwards, I calculated the residuals between the data and the fit by subtracting the Breit-Wigner values from the ATLAS data point values. Then, I calculated the errors of the residuals by fitting

$$\sigma = \sqrt{N} \quad (2)$$

into a mask ranging from 87 to 93 GeV and plotted the residuals and error bars in a sub-panel. For clarity, I added a horizontal line at y=0 to indicate what a perfect fit would look like, and I added two vertical dotted lines to denote the fitting range. The plot of the invariant mass of lepton pairs and the residuals can be viewed in Figure 1.



Based on the Breit-Wigner function, the best fitted mass of the Z^0 was 90.3 $\pm$ 0.1 GeV. To analyze the accuracy of the data's mass to the fitted mass of Z^0, I needed to calculate χ^2 and the p-value. χ^2 came out to be 10.0, the number of degrees of freedom was 10.0, and the p-value was calculated to be 0.4. Based on the p-value of 0.4, which is between the values of 0.05 and 0.95, we can conclude that the difference between the data and the fit is not statistically significant.

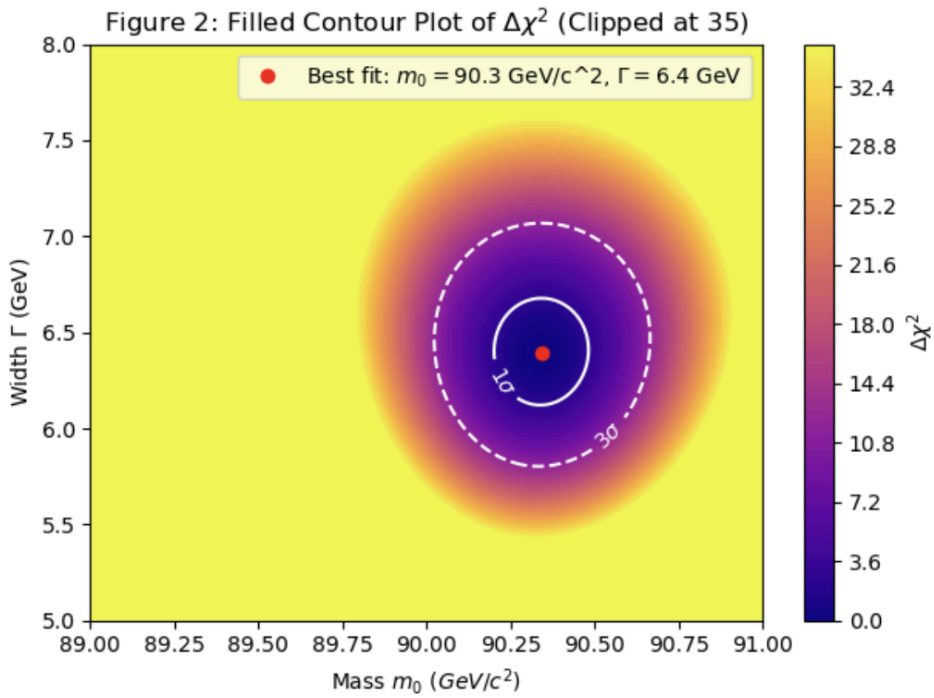
III. <u>The 2D Parameter Scan</u>

In order to visualize the joint probability space, it is necessary to create a filled contour plot. However, we must first perform a two-dimensional χ^2 scan of the mass-width parameter space by first setting up a grid of possible values for the two parameters: m_0 ranging from 89 to 91 GeV and Γ ranging from 5 to 8 GeV with 300 steps each, therefore creating a 300x300 grid of combinations. Then, I looped over every point on the grid and stored the χ^2 value in a two-dimensional array. I then found the minimum χ^2 value, which represents the best-fit parameters for m_0 and Γ. After, I computed the $\Delta\chi^2$:

$$\Delta\chi^2 = \chi^2 - \chi_{min}^2. \tag{3}$$

This shows how much each parameter combination deviates from the best-fit result. To make sure the plot is readable, I clipped the $\Delta\chi^2$ values to a maximum of 35. I created a filled contour plot of $\Delta\chi^2$ and plotted lines at the levels $\Delta\chi^2$ = 2.30 and $\Delta\chi^2$ = 11.83

because they correspond, respectively, to 68% (1σ) and 99.7% (3σ) confidence regions for two free parameters. Finally, I plotted a red point at the best fit for m_0 and Γ, as seen in Figure 2.



IV. Discussion and Future Work

In this analysis, I plotted the invariant mass of lepton pairs using ATLAS data and fitted the resulting mass distribution using a Breit-Wigner function. The best-fit mass of the Z^0 boson was found to be 90.3 $\pm$ 0.1 GeV/c^2, which is reasonably close to the Particle Data Group (PDG) value of 91.1880 $\pm$ 0.0020 GeV/c^2. Through consideration of the calculated p-value as well, we can assume that it is a statistically acceptable fit, showing that the Z^0 boson signal is present in the data. Several simplifications, however, were made in this analysis. For example, we neglected systematic uncertainties and assumed the ATLAS detector was perfect in its data collection, which is unrealistic. Furthermore, the Breit-Wigner function normalization was fixed, and only statistical uncertainties were considered when calculating the minimum χ^2. To enhance realism, future experiments should include uncertainties from detectors and systematic uncertainties in the fit, and the Breit-Wigner function should not be fixed. Overall, the analysis demonstrates the benefits of using invariant mass reconstruction and statistical fitting in order to identify the presence of particles.

Signed: Maria Nolan, 05/06/2025