Lab 3: ATLAS Data Analysis

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I. Introduction

To measure the mass of the Z^0 boson using the ATLAS experiment data at CERN, I analyzed data consisting of 5,000 real ATLAS events containing lepton pairs from high-energy proton-proton collisions through the decay of the Z^0. For each of these events I measured the invariant mass of the lepton pairs by reconstructing their four-momenta from the transverse momentum, pseudorapidity, azimuthal angle, and energy provided. Then I plotted the invariant mass distribution by creating a histogram that focused on the mass region from 80-100 GeV/c^2. To acquire the mass of the Z^0 boson, I fit the histogram with a Breit-Wigner distribution considering the statistical uncertainties and fitting within the appropriate mass window. I analyzed the quality of the fit by calculating the chi-square, reduced chi-square, and p-value and extracted the best-fit mass and width and their uncertainties from the covariance matrix returned by numpy. Finally, I plotted the uncertainty and correlation of the mass and width parameters by creating a two-dimensional $\Delta\chi^2$ contour plot that shows the 1σ and 3σ confidence levels. Through these analyses, I can investigate how the experimental data at ATLAS allows us to learn about and determine the fundamental properties of the Z^0 boson, providing crucial insight into the Standard Model of particle physics.

II. The Invariant Mass Distribution

To measure the mass of the Z^0 boson, I analyzed data from lepton pairs in the ATLAS dataset. For each pair, I measured the invariant mass by determining the momentum components, then summing the four-momentum, and finally calculated the mass using the equation $M = \sqrt{E^2 - (p_x^2 + p_y^2 + p_z^2}$, where p_x, p_y, and p_z are the vector components of the momentum. Then I plotted a histogram of the invariant mass ranging from 80 to 100 GeV/c^2, using 41 bins, and displayed error bars on each bin ($\sigma = \sqrt{N}$, where N is the square root of the number of events in the bins which is returned by the first array element of the ax.hist function of matplotlib). To extract the Z^0 boson's mass and width, I used scipy.optimize.curve_fit to fit the data in the range of 87 to 93 GeV/c^2 using a Breit-Wigner distribution, which uses the equation $D(m; m_0, \Gamma) = \frac{1}{\pi}\frac{\frac{\Gamma}{2}}{(m-m_0)^2+(\frac{\Gamma}{2})^2}$, and fixing the normalization to half the number of data points in the set. The curve_fit function optimizes the fit parameters by minimizing the least-squares difference between the observed data and theoretical model. It returns both the best-fit values and the covariance matrix, which was used to estimate the uncertainties in the mass and width. The fit was performed only on data within this mass window, and I calculated the chi-square, reduced chi-square, and p-value to evaluate the quality of the fit. The fit determined the mass of the Z^0 to be

90.3 ± 0.1 GeV/c^2, the width $\mathbf{\Gamma}$ to be 6.4 ± 0.2 GeV, and chi-square was 10.0 for 10.0 degrees of freedom, which gave a reduced chi-square value of 1.0. The p-value resulting from this was 0.4, indicating that the probability of observing this data, assuming that the Breit-Wigner model is true, is about 40%, suggesting a good fit. Figure 1 shows the invariant mass histogram with error bars, the Breit-Wigner fit, and a residuals plot to visualize the agreement between data and theory.

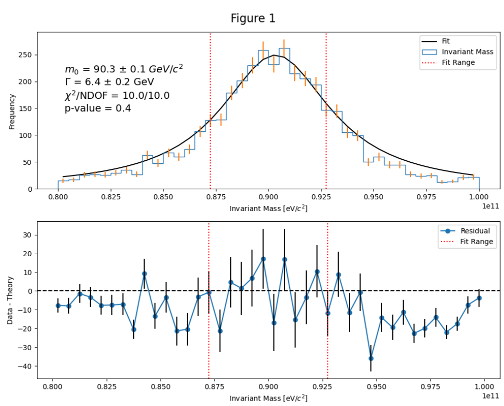

Figure 1: Figure showing two panels: the top panel shows invariant mass distribution of the data as a histogram with error bars, overlaid with the best-fit Breit-Wigner Function (black curve). The lower panel shows the residuals as a function of invariant mass. The fit was performed within the dashed lines as seen on both panels.

III. The 2D Parameter Scan

To visualize the joint probability space of the Z^0 boson mass and width, I performed a two-dimensional chi-square scan over the mass range of 89 to 91 GeV/c^2 and width range of 5 to 8 GeV, using 300 bins along each dimension. For each mass-width pair, I calculated the chi-square between the theoretical Breit-Wigner model and the data. Then I created a contour plot of $\Delta\chi^2 = \chi^2 - \chi^2_{min}$, clipping the $\Delta\chi^2$ at 35 units to improve the plot's visualization. The plot contains a colorbar labeled $\Delta\chi^2$, where the minimum value on the z-axis is zero. The best-fit location is marked with a cross as well. To indicate the confidence intervals, I drew the 1σ and 3σ confidence levels using a solid and dashed yellow lines, which corresponds to $\Delta\chi^2 = 2.30$, and 4.62 for two parameters. The axes are labeled mass and width in units of $\frac{eV}{c^2}$. This visualization can be seen in Figure 2. The two dimensional chi-square map was calculated using a double loop over the mass and width values. For each pair of mass and width I used the Breit-Wigner distribution that was used for the fit to generate the theoretical distribution and compared it to the data using a chi-square calculation. The result was then visualized using a filled contour plot with matplotlib's contourf and contour functions to display the contours of the chi-square values and the corresponding confidence levels.

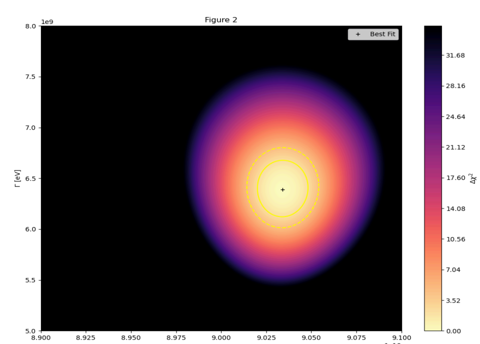

Figure 2: Contour plot of $\Delta\chi^2$ as a function of the resonance mass (m_0) and width ($\mathbf{\Gamma}$). The best-fit value is marked by a black "+". The

color scale indicates an increase in χ^2 relative to the minimum. The solid and dashed yellow lines represent the 1σ and 3σ confidence levels.

IV. Discussion and Future Work

These analyses measured the mass of the Z^0 boson using 5,000 ATLAS lepton pair events. The invariant mass distribution was fitted with a Breit-Wigner function, assuming only statistical uncertainties and neglecting detector effects or backgrounds. The measured Z^0 mass was 90.3 ± 0.1 GeV/c^2, which is approximately 0.9 GeV/c^2 less than the PDG value of PDG value of 91.1880 ± 0.0020 GeV/c^2. The measured width was $= 6.4 \pm 0.2$ GeV, which is significantly larger than the PDG value of 2.4955 ± 0.0023 GeV. This overestimate is likely due to not taking into account the ATLAS detector's energy resolution, systematic uncertainties, or possible background events. The confidence intervals for mass and width were visualized using a $\Delta\chi^2$contour plot. Including detector resolution in the fit would take into account the finite precision of the ATLAS detector when measuring lepton energies and momenta. This would reduce broadening of the invariant mass distribution, which would result in a Z^0 closer to the true value. Incorporating systematic uncertainties like calibration errors or variations in detector response would provide more accurate error estimates for the measured parameters, which reflects both statistical and experimental uncertainties. By modeling backgrounds from processes other than Z^0 decay would prevent non-signal events from impacting the fit, which would improve the accuracy of the extracted mass and width. Overall, these improvements would align the measurement more closely with accepted values, reduce bias and overestimation, and provide a more accurate check of the Standard Model of particle physics with ATLAS data.