Sophia Bender PHYS 265 5/6/2025

ATLAS Data Analysis Report

I. Introduction

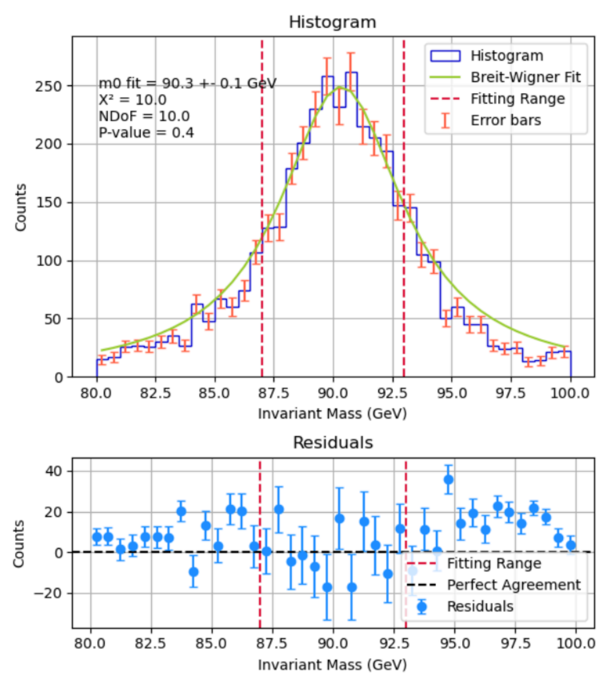
As a physicist working on the ATLAS experiment at CERN in Geneva, Switzerland, I've been investigating proton beam collisions, which causes protons to break open, resulting in interesting byproducts. One particular byproduct that is of focus is the Z^0-boson which is an unstable neutral carrier of the weak force responsible for facilitating many nuclear interactions in the Universe, and, in about 10% of cases, decays into charged lepton pairs ($\ell^+\ell^-$). By reconstructing these decay events, we determined the invariant mass of the Z^0 using properties of the leptons measured in the ATLAS detector. We found that the mass spectrum of these events exhibits a characteristic Breit-Wigner distribution, with a peak centered at the Z^0 mass. Using the Python coding language, we then fitted the resulting distribution to extract the mass and width parameters.

II. The Invariant Mass Distribution and its Fit

$$(1) \qquad p_x = p_T \cos(\phi), \quad p_y = p_T \sin(\phi), \quad p_z = p_T \sinh(\eta)$$

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

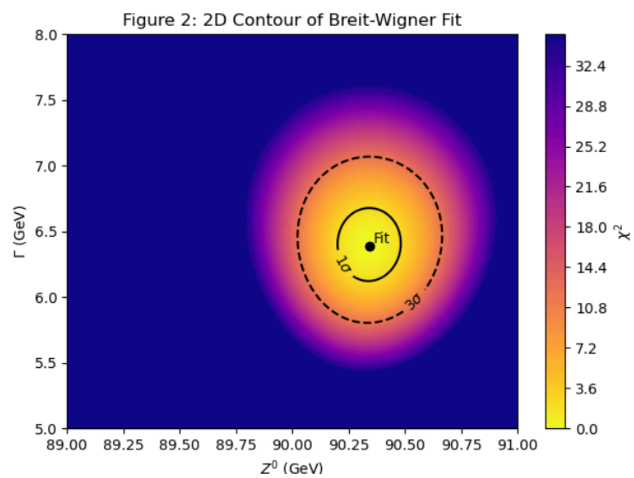
Figure 1: Histogram and Residual Plots of Invariant Mass Distribution



In the ATLAS detector, we measured four properties of particles that come out of the proton-proton interactions: Total energy E, transverse momentum p_T, pseudorapidity η, and azimuthal angle φ. Using these values, and equations (1) and (2), we calculated the invariant mass. Then, we input the data we collected into our code, and created a histogram from 80 to 100 GeV, using 41 bins. In order to do this, we used the np.linspace() function from the NumPy library in Python, creating a range from 80 to 100 with 41 intervals. We then plotted this histogram, and added error bars to the center of each bin, as you can see in Figure 1. Next, using scattering theory, we illustrated that the distribution of decays D at a reconstructed mass m follows a Breit-Wigner distribution. We coded a function of reconstructed mass, the true rest-mass of the Z^0, and the width parameter, that returns the decay distribution. We fit our mass distribution with the decay distribution. In our code, we created a mask to exclude the bin centers that were not between 87 GeV and 93 GeV, making uniform grading possible. The best fit of the mass of Z^0 we found was 90.3 GeV, with the uncertainty being 0.1 GeV. We added our fitted data to Figure 1, making sure to show the range of focus for our fit. We also calculated and plotted the residuals between the data and our fit, still displaying the fitting range, as well as where perfect agreement is. For a more quantitative measure of agreement, we conducted a chi-square analysis. Our chi-square value was 10.0, and the number of degrees of freedom was 10. From this, we calculated the p-value using the stats.distributions.chi2.sf() function from the SciPy library in Python, and our resulting p-value was 0.4. This indicates a good agreement, as the p-value falls between 0.05 and 0.95.

III. The 2D Parameter Scan

Our next task was to visualize a joint probability space between Z^0 and Γ_{exp} by performing a 2D chi-square scan of the mass-width parameter space. To do this, we created a colormap plot of the chi-square values of the Breit-Wigner fit for our data, using matplotlib's color mapping capabilities. We then included the 1σ and 3σ confidence levels, as well as where the best fit of Z^0 and Γ_{exp} is. As you can see in Figure 2, as you get further from the best fit point, the chi-square value increases, indicating that the agreement gets weaker.



IV. Discussion and Future Work

Our analysis successfully reconstructed the invariant mass distribution of Z^0 to $\ell^+\ell^-$ events, yielding a fitted mass of 90.3 ± 0.1 GeV, consistent with Standard Model predictions. The fit quality was strong, with a chi-square of 10.0, 10 degrees of freedom, and a p-value of 0.4, indicating good agreement between the model and data. Residuals showed no systematic deviation, supporting the validity of the fit. The 2D chi-square scan further revealed the correlation between the Z^0 mass and width parameters, with well-defined 1σ and 3σ confidence regions around the best-fit point. Future work could include analyzing a larger data set for improved precision, exploring other Z^0 decay channels, and investigating systematic uncertainties to better separate detector effects from the intrinsic properties of the Z^0 boson.