Lab 3: ATLAS Data Analysis
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I. Introduction

As you all know, High energy particle collisions allow us a window into the fundamental building blocks of matter. Using the Large Hadron Collider at CERN, the ATLAS experiment records the by-products of proton-proton collisions with the Z^0 boson which is a neutral carrier of the weak force. The Z^0 boson decays instantly into pairs of lighter particles, most commonly two oppositely charged particles called leptons.

While the mass of the Z^0 boson is well established ($91.1880 \pm 0.0020\ GeV/c^2$), we wanted to reproduce the value. In this report we emphasized applying data analysis techniques like four momentum reconstruction and statistical fitting to reproduce the known mass peak for the Z^0boson using experimental data.

We analyzed 5000 dilepton events from the ATLAS data to reconstruct the invariant mass of the the Z^0 boson. Using the measured transverse momentum (p_t), pseudorapidity (η), azimuthal angle (ϕ), and energy (E) of each lepton given by each event, we were able to make an invariant mass distribution. With said distribution we were able to fit the central peak with a Breit-Wigner model. We then performed a 2D X^2 scan of the mass-width parameter space to visualise the correlations between the best-fit mass and width parameters, as well as the confidence region.

II. Invariant Mass Calculation and Breit-Wigner Fit

The data set provides the observables (p_t, η, ϕ ,E) mentioned above for each lepton.

Using these values we can compute the momentum components for each direction with the equations:

$$p_x = p_t \times cos(\phi),\ p_y = p_t \times sin(\phi),\ p_z = p_t \times sinh(\eta)$$

(1)

Using these directional components we were able to reconstruct the invariant mass of each lepton pair with the equation:

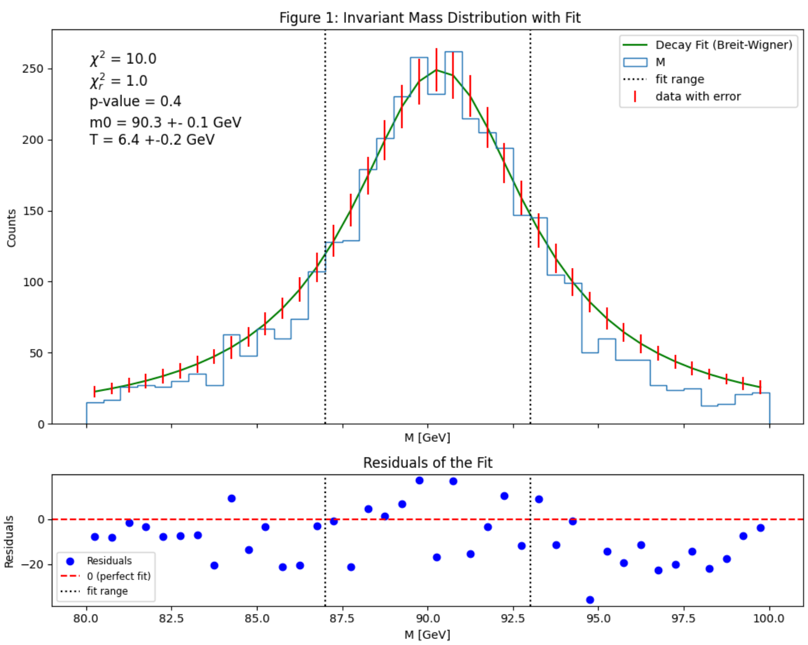
$$M = \sqrt{E^2 - (p_x^2 + p_y^2 + p_z^2)} \tag{2}$$

Now we generated a histogram of the invariant mass values with 41 bins ranging from 80 and 100 GeV. The uncertainty in this mass value was calculated $\sqrt{N}$ where N is the number of events in each bin.

To model the resonance structure in the invariant mass distribution, we fit the data using a Breit-Wigner function, which describes the probability distribution for an unstable particle's reconstructed mass:

$$D(m; m_0, \Gamma) = \frac{1}{\pi}\frac{\Gamma/2}{(m-m_0)^2+(\Gamma/2)^2} \tag{3}$$

Here, m_0 represents the resonance mass (expected to correspond to the Z^0 boson mass), and Γ is the width of the distribution. The peak of the function is supposed to be where $m = m_0$, but as you will see in Figure 1 below, the fit can be slightly shifted slightly due primarily to binning effects.



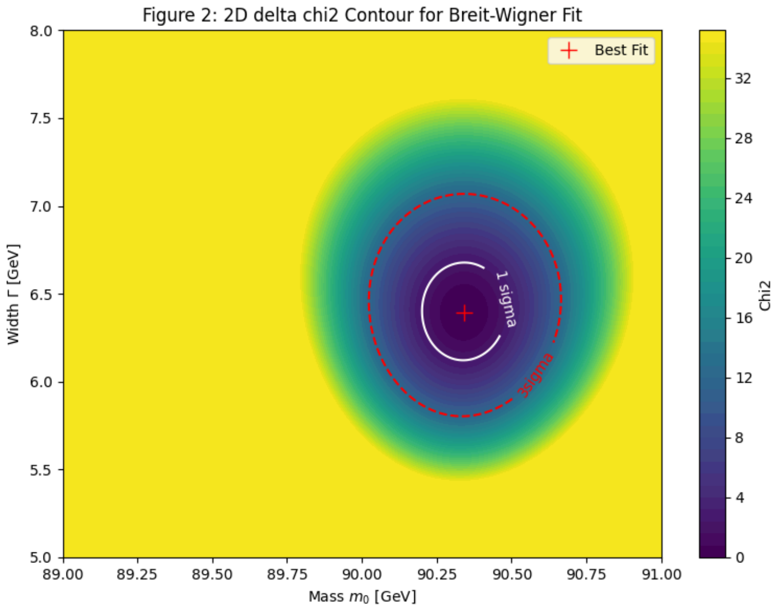
The fit is restricted to a mass range of 87-93 GeV and normalized for 2500 events. We then used pythons curve_fit function to get the best fit values for m_0 and Γ of 90.3 ± 0.1 GeV and 6.4 ± 0.2 respectively. With these fit variables we calculated a χ^2 of 10.0 with 10 degrees of freedom. A p-value of 0.4 indicates a reasonable fit between the data and the model.This is also shown by the graph of the residuals as there is no systematic structure over the selected region.

III. 2D X^2 Parameter Scan

After obtaining the best-fit values for m_0 and Γ we needed to see how the correlation between the fitted mass and the width affected the uncertainty. In order to investigate this we conducted a two-dimensional chi-square scan. To do this we evaluated χ^2 over a grid of (m_0, Γ) pairs ranging from 89-91 GeV and 5-8 GeV respectively to explore the dependence of the fit quality on both parameters.

For each point on the grid a Breit-Wigner function is generated using the specified values of (m_0, Γ) and subsequently compared to the data in the 87-93 GeV fit via χ^2 calculation. That χ^2 value is then used to compute the difference from the best χ^2 fit as shown by:

$$\Delta\chi^2 = \chi^2_{calc} - \chi^2_{min} \tag{4}$$



This value is then used to fill a contour plot with overlaid contours of 1σ and 3σ confidence intervals for a two-parameter fit which hold values of 2.3 and 11.8 respectively. For simplicity's sake, we clipped $\Delta\chi^2$ to be no larger than 35. This means that all values of $\Delta\chi^2$ that are larger than 35 are set equal to 35 to help prevent the color scale from being dominated by large $\Delta\chi^2$ values. The minimum value of $\Delta\chi^2$ is denoted in the figure above as a red cross.

IV. Discussion and Future Improvements

The measured mass of the Z^0 boson is 90.3 ± 0.1 GeV which, as shown by a p-value of 0.4 agrees reasonably well with the Particle Data Group accepted value of 91.2 ± 0.002 GeV. The difference likely arises from a combination of experimental and modeling limitations. Seeing as leptons can come from particles other than Z^0 bosons, it is possible that some of the events given in our data came from a different particle and in turn will add to a different mass. Also the Breit-Wigner model is fitted to binned data so there is a level of uncertainty that can come with the sorting. If the peak lies between bin centers the fitted mass can shift slightly affecting the statistical data. In this analysis, the binning was fixed at 41 bins between 80 and 100 GeV, following the lab guidelines, which does impose some quantization effects.

This analysis also assumes perfect energy resolution and neglects systematic uncertainties. If we want the analysis to be more realistic, the Breit-Wigner function should be used in tandem with a Gaussian function to help detect possible data smearing and account for it.

Systematic effects that are neglected are energy calibration errors, possible background contamination that could distort or even mimic our signal, interfering with the values we are identifying. Introducing a background model could help further isolate the extracted mass and width by helping eliminate the other processes that could interfere with the data.

It is also important to show that expanding the data sample or combining events from multiple lepton species like electrons or muons could further reduce statistical uncertainty in the data. With these refinements would yield a more accurate and precise determination of both the Z^0 boson's mass and decay width, and bring the analysis closer to methods used in professional collider physics.