Lab 3 Atlas Data Analysis

Kanjonavo Sabud
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Introduction

The Z^0 boson occupies a central place in the Standard Model as the neutral mediator of the weak interaction, one of the four fundamental forces that govern particle behavior. Unlike the massless photon, the Z^0 carries a nonzero mass, making its precise determination critical for testing electroweak theory. The A Toroidal LHC ApparatuS (ATLAS) experiment at CERN's Large Hadron Collider (LHC) is uniquely equipped to perform this measurement: by colliding protons, ATLAS produces Z^0 bosons which decay almost instantaneously into pairs of charged leptons.

Because energy and momentum are conserved in the decay $Z^0 \to \ell^+\ell^-$, the invariant mass of the lepton pair directly reflects the mass of the parent boson. In this analysis, we use a sample of 5000 dilepton events drawn from the 2020 ATLAS open dataset. For each event, we reconstruct the four-momentum of the two leptons—using their transverse momentum, pseudorapidity, and azimuthal angle—and compute the particles' invariant masses.

By histogramming these invariant masses between 80 and 100 GeV and fitting the resulting distribution with a normalized Breit–Wigner function in the region 87–93 GeV, we extract the best-fit values of the Z^0 mass m_0 and its experimental width Γ. To quantify the joint uncertainty and correlation of these two parameters, we then perform a two-dimensional χ^2 scan. Together, these techniques allow us to measure the Z^0 resonance and compare our findings to world-average values, illustrating both the power and the limitations of a straightforward resonance fit.

The Invariant Mass Distribution

The 2020 ATLAS open dataset contained three values for each lepton particle which fully determine the momentum of that particle:pT (transverse momentum), η (pseudorapidity), and ϕ (azimuthal angle). Using these values and the assumption that the speed of light c is set equal to 1 we are able to calculator the momentums of each lepton using the following equation (1).

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

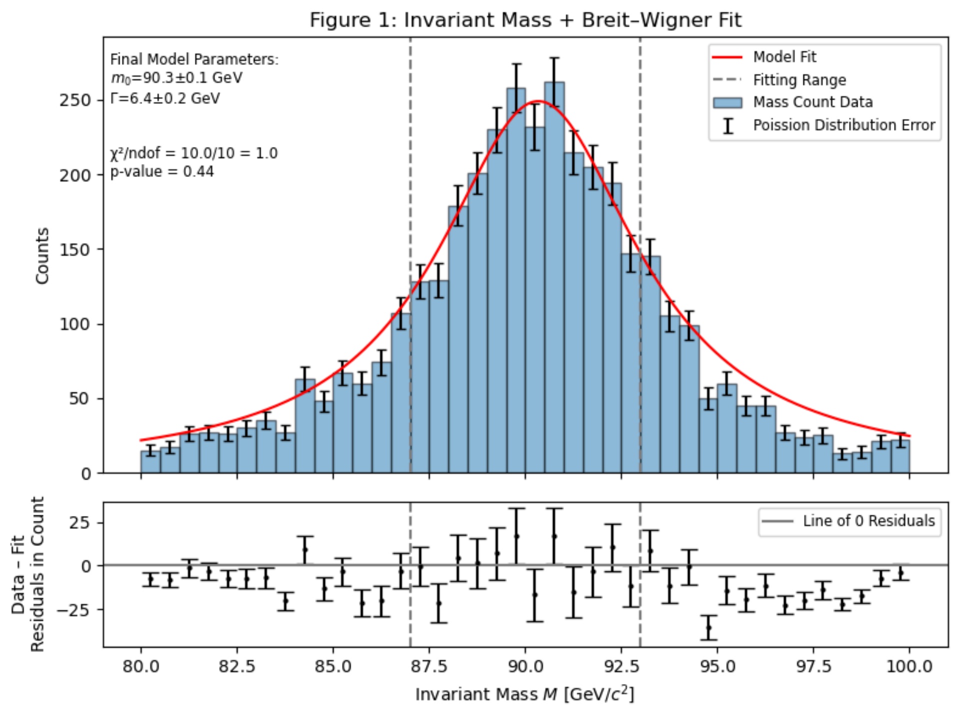
The total momentum and energy (E - given as part of the dataset) of the dilepton pair is calculated simply by summing up the components. Then the difference between the Energy and Moments of the dilepton pair is the particles invariant mass calculated using the following equation (2):

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

Therefore, by following this process we are able to calculate the invariant mass of the main particle from the lepton pair characteristics. The next steps were then to calculate the true mass of the Z boson. This was done using a mass distribution fit using the Breit Wigner function. The distribution of decays D as different masses m, using the scattering theory, can be shown to follow the Breit Wigner function peak. This distribution depends on the true Z^0 boson mass m_0 and a width parameter Γ. Therefore, by curve fitting using the Breit Wigner distribution on our distribution of invariant masses, we will be able to get the most optimal values of m_0 and width Gamma. The Briet Wigner function is given by the following equation (3) where m is the test mass, m_0 is the true mass of the Z^0 boson, and Γ is the width parameter (experimental in our case) :

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

This will complete our goal as the value m_0 or the true Z^0 boson mass is what we are searching for. Some technical notices: we normalized our distribution by half the number of datapoints so it D = 2500 * D. Additionally, to make uniform grading possible we only curve fitted on the lepton pairs whose invariant masses were between 87 and 93 GeV (fitting region) but the model results were shown for the entire range of invariant masses (80 - 100 GeV). For the actual numerical minimization we use SciPy's `curve_fit` function from the optimize module. We pass our bin-centers and counts, along with the array of errors σ, and set absolute_sigma=True so that `curve_fit` treats our supplied uncertainties as exact. The routine returns the best-fit parameter vector (m_0, Γ) and the covariance matrix V where we obtain one-sigma error from by taking the square roots of the diagonal elements of V.



From this procedure we find the fitted mass of the Z^0 boson to be 90.3 +/- 0.09 GeV and Γ to be 6.4 +/- 0.1 GeV. Using these parameters, we obtained results from the model across the span of 80 - 100 GeV. Figure 1 shows the results, including our model fit, final chosen m_0 and Γ parameters, and other statistical characteristics of our fit (χ^2, degrees of freedom and the p value). The error bars were calculated as the Poisson distribution error as the √N where N is the count of observations in that bin.

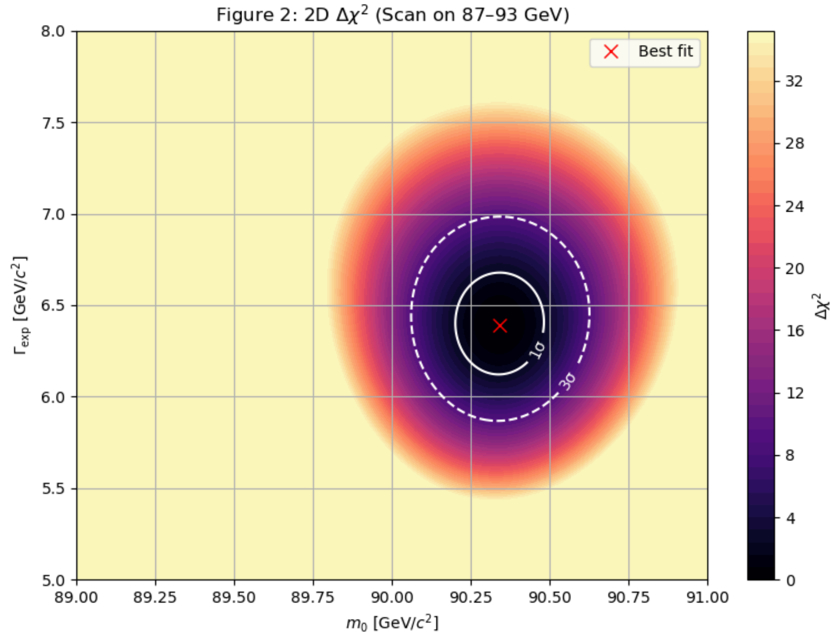
Statistical analysis

With 12 bins and two fitted parameters, we have DOF = 12 - 2 = 10; obtaining χ^2 = 9.9 gives a reduced χ^2 of approximately 0.99 and a p-value of 0.4. A reduced χ^2 near 1 indicates that our input uncertainties (σ = √N) correctly describe the data scatter, and the p-value of 0.4 means there's a 40 % probability of seeing a χ^2 this large (or larger) purely by chance—comfortably above any threshold for concern. The usual range of accepted p values is between 0.05 and 0.99 making a 0.4 p value indicative of a very good fit between the model and the observed data. This great fit can also be seen in the residual plot where each difference is at least one measure of uncertainty away from the 0 difference line.

2D Parameter Scan

In the last section we analyzed the performance of the Briet Wigner function with the best fitting parameters found only. This, however, failed to show how the two parameters Z^0 boson mass and width Γ may be correlated. To understand their joint behaviour we computed the resulting χ^2 statistic across the meshgrid of m_0 going from 89 to 91 and Γ going from 5 to 8 with 300 points on each dimension. At each of these points, the χ^2 value of the model evaluated across the fitting region is calculated and the change in χ^2 value is calculated by subtracting the global minimum χ^2 value from the current calculated χ^2 value. Then by plotting the change in χ^2 value as a filled contour plot over the m_0, Γ plane, we are able to get a better understanding of the goodness of our fit as well as the relationship between the two parameters. As we only have 2 fitting parameters 1σ and 3σ were found to be 2.30, 9.21 respectively. Then we placed our previously found best parameters m_0 = 90.3 and Γ = 6.4 on the plot which, expectedly, aligns perfectly with the lowest change in χ^2 region in the contour plot as can be seen in Figure 2.

Figure 2: 2D $\Delta\chi^2$ (Scan on 87–93 GeV)



Discussion and Future Work

Our one-dimensional Breit–Wigner fit yielded mass of the Z^0 boson to be 90.3 +/- 0.09 GeV, and Γ to be 6.4 +/- 0.1 GeV. Statistical analysis shows χ^2/N Degrees of Freedom to be approximately equal to 1 and p value = 0.4. While statistically self-consistent, these values diverge substantially from the 2024 PDG averages where the mass of the Z boson was calculated to be 91.1880 ±0.0020 GeV. The difference is over 9 times the uncertainties and is therefore very significant. Several assumptions in our procedure may explain this offset. First we assumed that the ATLAS dataset contained no errors which can be a far fetched idea as any real experiment has inherent technical and/or equipmental errors associated with them. Second, our choice of uniform 0.5 GeV bins and Poisson-only uncertainties ignores potential bin-to-bin correlations from detector acceptance and resolution effects. Finally, we considered only statistical errors; calibration, and lepton-identification errors for example, each contribute additional systematic uncertainty at the percent level or higher. Therefore to improve our measurement, we could measure more data on lepton pair characteristics. The additional data should at that point allow us to increase the resolution of our bins (maybe go from 0.5 to 0.1 GeV bins). We also need some measure of the systematic error which is happening at the background of the ATLAS system. By incorporating those uncertainties in addition to or in place of the simpler Poisson uncertainty we would be able to lower our overall uncertainty and strive for the ideal per million uncertainty. Our Breit–Wigner model may also be too less dynamic inherently so changing to something far more sophisticated such as Monte Carlo may be essential to reaching the high precision and accuracy required for calculating the mass of the Z^0 boson using the ATLAS experimental setup.