Lab 3 – ATLAS Data Analysis

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I. Introduction

This report analyzes proton-proton collision data from A Toroidal LHC Apparatus (ATLAS) detector at CERN to determine the invariant mass of the Z^0 boson, a neutral mediator of the weak nuclear force. By reconstructing the invariant mass from decayed lepton pairs and fitting the resulting distribution with a normalized Breit-Wigner function, the rest mass of the Z^0 boson and decay "width" parameter are estimated. This analysis evaluates the fit quality through statistical measures and explores the confidence intervals of the parameters, offering any corrections and adjustments for future experiments.

II. Invariant Mass Distribution

Z^0 bosons are a product of proton-proton interactions and a neutral carrier of the weak force, one of the fundamental forces of nuclear interactions within the universe. To determine a fitted mass for the Z^0 boson, it is first important to determine how the mass of such an unstable particle can be found. As mentioned, Z^0 bosons are unstable and decay into charged lepton pairs (e.g., electron/positron, muon/anti-muon, tau/anti-tau). Since charge cannot be created or destroyed, these pairs must have the opposite or no charge, and since matter and energy cannot be created or destroyed as well, the decayed pairs' total energy will sum to the mass of the Z^0 boson. Therefore, measurements of double-lepton events made at CERN should have an energy peak at the mass of the Z^0.

The ATLAS detector can easily measure four different properties from products of proton-proton interactions. These include the total energy E, the transverse momentum p_T, or the momentum that the particle has transversely, the pseudorapidity η, which is the angle that the particle makes with the beamline of the LHC, and the azimuthal angle ϕ about the same beam. With this data, the invariant mass of the pair can be determined via Equation 1:

$$M = \sqrt{E^2 - \left(p_x^{\ 2} + p_y^{\ 2} + p_z^{\ 2}\right)} \tag{1}$$

Where E is the same total energy listed before (in GeV) while p_x, p_y, and p_z are the three momenta in the x, y, and z-directions. These momenta can be described via the following equations:

$$p_x = p_T cos(\phi), \quad p_y = p_T sin(\phi), \quad p_z = p_T sinh(\eta) \tag{2}$$

Given that there are two particles (leptons) within this data set, the momenta have to be summed such that:

$$p_{tot} = p_1 + p_2 \tag{3}$$

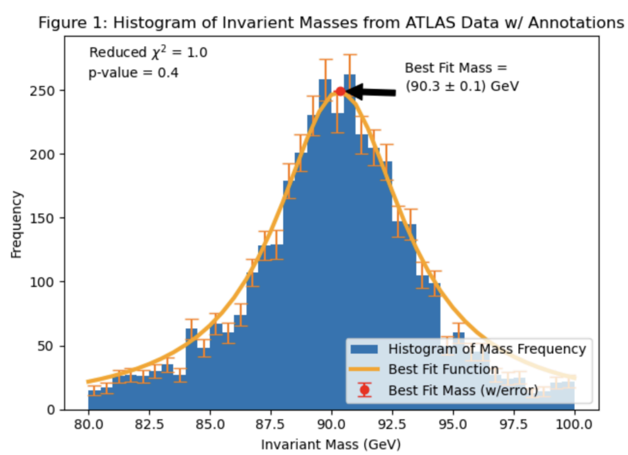
Where p_{tot} is the total four-momentum while p_1 and p_2 are the four momenta of the two resulting particles from the proton-proton interaction. This four-momentum is the vector of the energy and x/y/z momenta of the particle such that:

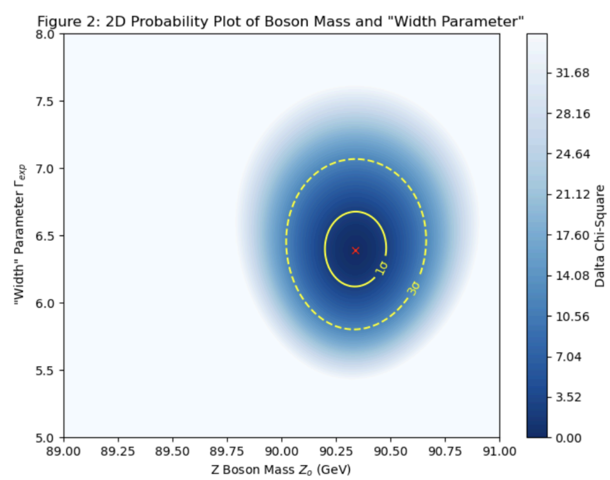
$$p = (E, p_x, p_y, p_z) \quad (4)$$

With these derivations, the frequency of invariant masses based on recent ATLAS data can be graphed as a histogram, binned from 80 to 100 GeV with 41 bins. However, such data must also align with theory for the result to be statistically significant. This distribution of decays D at a reconstructed mass m can be defined via the Breit-Wigner peak, where the distribution is dependent on the true rest mass of Z^0, m_0 and an experimental "width" parameter Γ_{exp}:

$$D(m; m_0, \Gamma_{exp}) = \frac{1}{\pi}\frac{\Gamma_{exp}/2}{(m-m_0)^2+(\Gamma_{exp}/2)^2} \quad (5)$$

To create a fit with this function, it must be fixed to half of the number of data points in the set (such that the fit is $2500 \times D$), and the function was fitted to where the bin centers were greater than 87 to less than 93 GeV. With these equations, the theoretical curve of the mass can be overlaid on the histogram of invariant mass, which reveals the true mass Z^0, as shown in Figure 1:





Within the historiographic data, the error of the bins can be equated to be the square root of the frequency within the bin, such that $\sigma = \sqrt{N}$. With this graph, the peak, or fitted mass Z^0, is (90.3 ± 0.1) GeV. Performing a χ^2 comparison between the fit and data, a χ^2 value of 10.0 was found, which, along with the 10 degrees of freedom (derived from the reduced number of data points for the fit, 12, minus the 2 fitting parameters of m and Γ), provides a p-value statistic of 0.4. With this statistic, it is determined that the data matches with the fit around 40% of the time, which is a reasonable agreement in this case. Therefore, it can be concluded, with reasonable confidence, that the fitted mass of a Z^0 boson is (90.3 ± 0.1) GeV.

III. 2D Parameter Scan

Throughout this fit, it is important to note that Z^0 via the Breit-Wigner equation cannot be determined independently; it is found in conjunction with Γ_{exp}. Therefore, it's important to visualize and demonstrate the probability of the variables jointly. This can be done via a contour graph, where the x and y axes are different Z^0 and Γ_{exp} values with differing colors representing a z-dimension: $\Delta\chi^2$. This difference in χ^2 is found by taking the χ^2 with different parameters and subtracting with the minimized χ^2 found through the best fit parameters. When graphed, as seen in Figure 2, an gradient of differing confidence in values can be displayed, with Figure 2 specifically showing the 1σ and 3σ contours. These contours display that within their area is a certain degree of confidence that the best fit is within itself, with 1σ and 3σ holding a 68.3% and 99.7% confidence respectively.

IV. Discussion and Future Work

With the collected ATLAS data and comparison to the Briet-Wigner curve of decay, a value for the rest mass of Z^0 boson and the "width" parameter Γ_{exp} was found. Throughout the calculations made during the following report, certain approximations and estimates were made to allow for the results made above. There is no consideration made for the lepton pairs to radiate energy which could artificially reduce the reconstructed mass and skew measurements made. No consideration was made for any systematic errors due to the calibration of the measuring device within the ATLAS detector. Another important complication that comes with the ATLAS detector as well; the resolution of the collider has a finite resolution which skews the proper distribution, which can be seen in the histogram versus the smoother curve of the Briet-Wigner shape. This comes with the fact that the mass derived from the Z^0 boson this data, (90.3 ± 0.1) GeV, which differs from new data by the PDG, which calculated a Z^0 boson mass of (91.2 ± 0.002) GeV. Although this data is not widely accepted, it does significantly differ from the found Z^0 boson mass, being a difference of 9σ. It is important to also note that while the p-statistic of the Z^0 boson was found to be reasonable at 0.4, a 40% agreement between the data and theory signifies that modifications are needed to better determine these values. Because of these variations and simplification, it is encouraged that further calculations are made to improve these differences in the future. With these future calculations, it is recommended that taking a larger set with a more refined resolution be done, along with fitting to a different distribution, such as a Gaussian, to better approximate the best fits. Future work should also strive to find a higher agreement between data and theory as well to determine if such adjustment produced favorable changes.