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PHYS 265

Profs. Teuben and Clark

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Introduction

As you know, we have been working in the ATLAS detector recently to determine the mass of the Z^0-boson by examining the energy contained in the lepton pairs that it occasionally decays into. We have seen results recently that we believe may hold the key to calculating the invariant mass of the Z^0. The data we collected gives the transverse momentum of the emitted particles (p_T), as well as two angles (η and ϕ) which describe the angle made by the particle's motion relative to the proton beam. From these, we can determine the particle's momentum in a 3D coordinate system (p_x, p_y, p_z). Given that all energy is conserved in these interactions, we can calculate the total momentum of the two emitted leptons and get the mass M of the particle that they decayed from as:

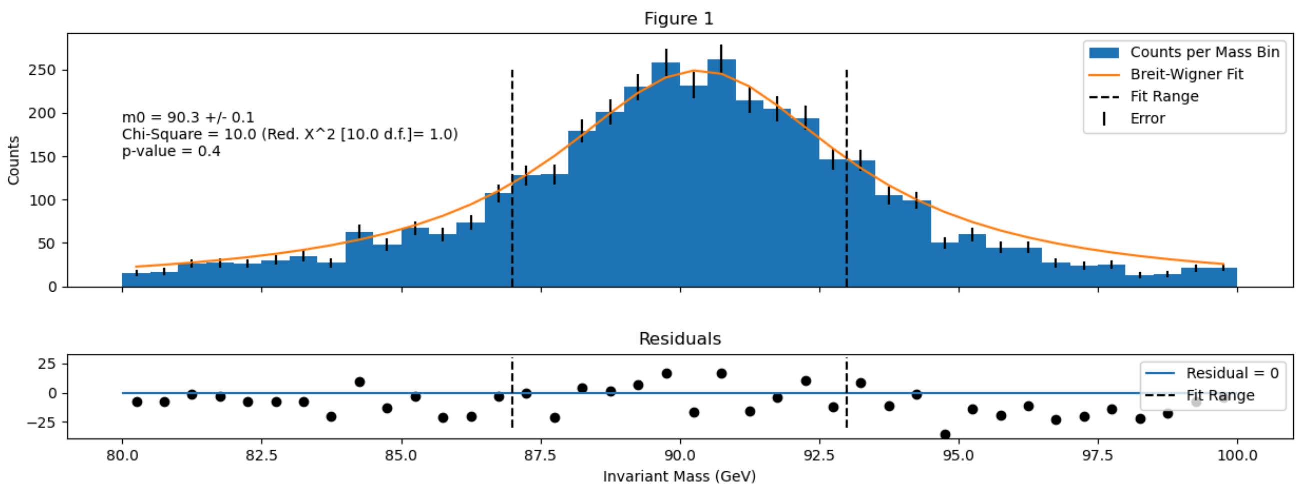
$$M = \sqrt{E^2 - ({p_x}^2 + {p_y}^2 + {p_z}^2)}$$

The Invariant Mass Distribution and Its Fit

After evaluating the above mass equation for all 5,000 lepton pairs we observed using Python, we compiled an array of calculated masses of 5,000 Z^0-bosons. With these, we created a 41-bin histogram and assessed an error on each bin count equal to the square root of the count in that bin. Our goal was to fit the Breit-Wigner model, a scattering theory method relating to the distribution of decays, to our data and determine the true mass of the Z^0 from that. The Breit-Wigner fit is modeled by the equation below:

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

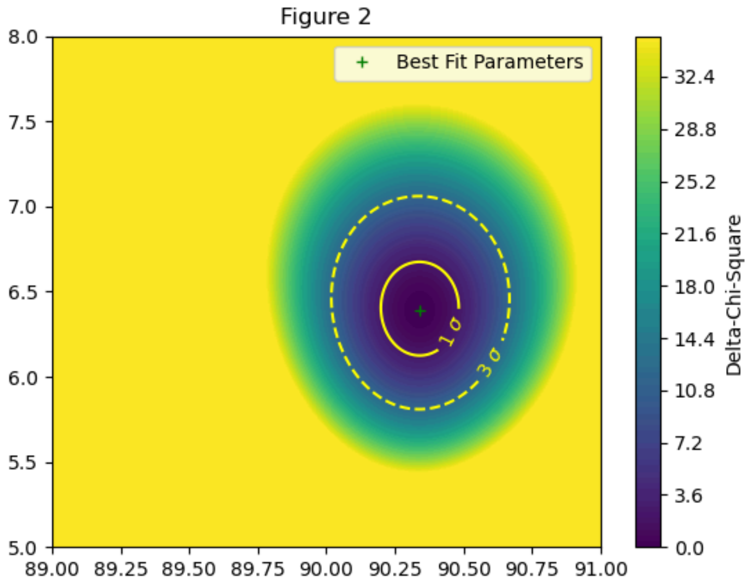
Using the scipy.optimize feature curve_fit, we fit the Breit-Wigner model to our data, adjusting m_0 and Γ (the true mass of Z^0 and a width parameter, respectively), and constrained the fit to only bin centers within the 87 to 93 GeV range. We then ran a chi-square test on the fit to determine its effectiveness. The graph below displays the data with error bars, the fit line, residuals from the fit values vs data values, and notes on the Chi-Square test results.



The fitting returned a mass of 90.3 GeV with an uncertainty of 0.1 GeV. The chi-square value is 10.0, which, with two degrees of freedom, gives a p-value of 0.4 - a satisfactory result indicating a good likelihood of our fitted values being accurate. For completeness, I'll mention that the fitted value for the width parameter Γ is 6.4 +/- 0.2 GeV.

2D Parameter Delta-Chi-Square Scan

To get an idea of how varying the two parameters adjusted in the curve_fit above (m_0 and Γ) would change the chi-square fit value, we ran a delta-chi-square analysis. We did this by selecting a range of values to evaluate both parameters over - [89, 91] for m_0 and [5, 8] for Γ - then calculating the chi-square value over a grid of 300x300 discrete points over those intervals. The minimum value in that meshgrid is then subtracted from all values in the meshgrid to attain the "delta" from the best possible chi-square at each point in the meshgrid - the delta-chi-square.



The delta-chi-square was clipped at 35 units to make the gradient more visible, and two lines were added to indicate the value for one standard deviation and three standard deviations, 2.30 and 11.83, respectively. To the left is the figure produced, with the parameters from curve_fit graphed.

Discussion and Future Work

As of 2024, the accepted value for the mass of the Z^0-boson from the Particle Data Group was 91.1880 +/- 0.0020 GeV/c^2 (note that our work normalised the value of c = 1). Our fitted value was 90.3 GeV with an error of 0.1, a bound that doesn't include the PDG value. The PDG value is nine standard deviations away from the fitted value, but considering the circumstances of the fit we ran, it isn't that far off the PDG value. In this process, we generalised 5,000 datapoints into only 41 bins, then selected only 12 of those to fit our curve to. We also approximated the error to be $\sqrt{n}$, ignoring the actual specifications of the ATLAS detector and systematic uncertainties we might encounter. In future experiments, we might be able to more accurately estimate the mass of the Z^0-boson by including more datapoints in our fit and examining the specifics of the ATLAS detector to be able to adjust our errors to more realistic values, taking into account the resolution of the detector, expected systemic uncertainties, and other factors.