Lab 3: ATLAS Data Analysis

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PHYS265
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6 May 2025

I. Introduction

The purpose of this lab is to study the ATLAS experiment and the data it has collected at CERN in Geneva. At the Large Hadron Collider, beams of protons collide and break open protons (proton-proton interactions), which in turn causes fundamental particles to form, interact, and decay. One of these fundamental particles is the Z^0-boson, which decays into a pair of charged leptons about 10% of the time. Since the total energy stored within the leptons must at least equal the mass of the Z^0-boson, it is possible to measure the energy of all double-lepton events in the detector and use this data to show that there is an excess at the mass of the Z^0-boson.

II. The Invariant Mass Distribution and its Fit

There are four important properties that the ATLAS detector is able to measure from the proton-proton interactions, which include total energy E, transverse-momentum p_T, pseudorapidity η, and azimuthal angle ϕ about the beam. Transverse-momentum describes the momentum the particle has in the transverse direction. Pseudorapidity describes the angle the particle makes with respect to the beamline. These four values define the four momentum of a particle, represented by $p = (E, p_x, p_y, p_z)$, by these mathematical relationships:

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

The particle's invariant mass is calculated from the difference between the three-momentum and the energy:

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

Using data from the ATLAS detector, a histogram can be plotted to show the mass-distribution of the invariant mass for each lepton pair. This plot is shown in Figure 1 below, along with the Breit-Wigner fit. From scattering theory, the distribution of decays $\mathcal{D}$ at a reconstructed mass m follows a Breit-Wigner peak, which depends on the true rest-mass of the Z^0, m_0, and on a width parameter Γ:

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

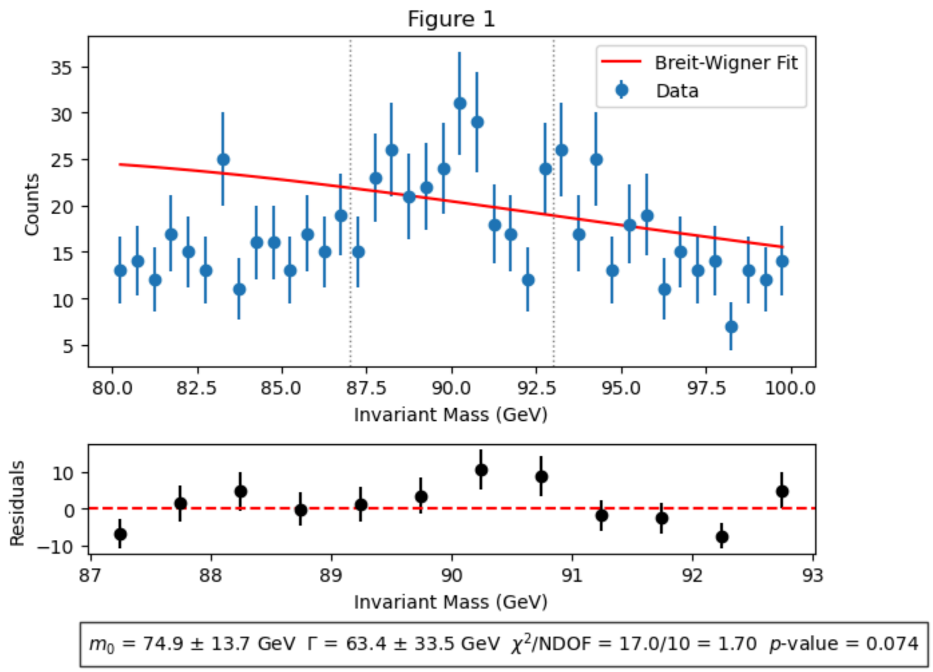

Figure 1: Histogram of lepton pair invariant masses with Breit-Wigner fit and residual plot.

The mass-distribution of lepton pair invariant masses and the Breit-Wigner fit were then used to calculate the chi-square, reduced chi-square, and p-value of the fit. Firstly, the fitted mass of the Z^0 was found to be 74.9 ± 13.7 GeV. The chi-square value was 17.0 and the number of degrees of freedom was 10.0, so the reduced chi-square value was 1.7. Finally, the p-value was found to be 0.074. Since the p-value is neither very small (less than 1 percent) nor very large (greater than 99 percent), it would be reasonable to assume that the model is a good fit for the data. Thus, the Breit-Wigner fit agrees with and is a good model for the mass-distribution data.

III. The 2D Parameter Scan

Since this is a 2-dimensional model, Z^0 and Γ_{exp} cannot be determined independently. Instead, it is possible to visualize the joint probability space. To do this, a 2D chi-square scan of the mass-width parameter space can be taken over many points. This means for each lepton pair, the Briet-Wigner model is used to calculate the chi-squared value, and the difference between this value and the global minimum value is used to create the contour plot in Figure 2 below.

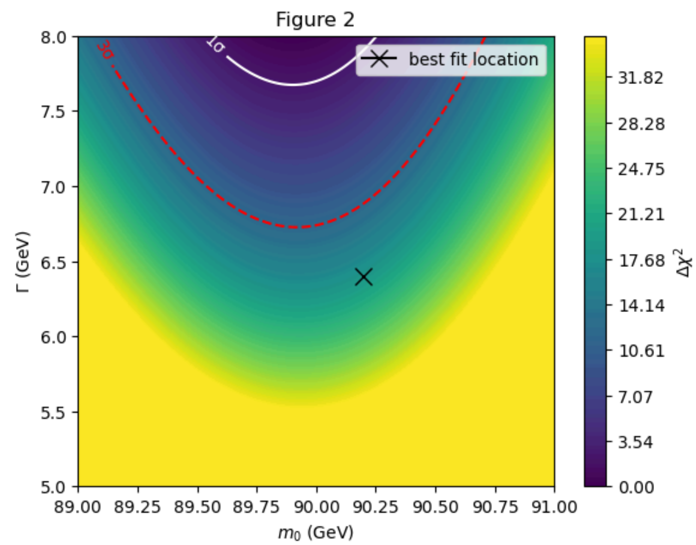

Figure 2: Contour plot of $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ with 1σ and 3σ confidence levels and a mark at the best fit location.

The difference between the chi-squared value for each lepton pair and the global minimum chi-squared value, $\Delta\chi^2$, shows the difference between each point and the "best" point, or the point where χ^2 is the least. In the plot, the best fit location is marked along with 1σ and 3σ confidence levels.

IV. Discussion and Future Work

In this lab, data from the ATLAS experiment was analyzed to determine the invariant mass-distribution of lepton pairs formed from the decay of Z^0-bosons. The analysis included finding a model for the data using the Breit-Wigner function and then performing a 2D chi-square scan to visualize the joint probability space of the data. This analysis found the fitted mass of the Z^0-boson to be 74.9 ± 13.7 GeV. The Particle Data Group reports this value as 91.1880 ± 0.0020 GeV/c^2, which is slightly higher than one sigma away from the analytical value.

When calculating the histogram, only Poisson uncertainties were assumed. The fit also assumes there are no systematic errors and that energy is measured perfectly regardless of the energy resolution of the ATLAS detector. The energy resolution of the detector does matter however, and a finite energy resolution would broaden the observed mass peak. In the future, this analysis could be redone to include the effects of the energy resolution of the detector. That could lead to a more accurate value for the fitted mass of the Z^0-boson.