PHYS265 Lab 03 Report

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Introduction

In this project, we dive into real data from the ATLAS experiment at CERN to study how Z^0 bosons decay into pairs of leptons. By working with variables like energy, momentum, and angles from these decay products, we calculate their invariant mass and look for a peak around the expected Z^0 mass. We then fit that distribution using a Breit-Wigner curve to estimate the Z^0 boson's mass and width, and check how well our results line up with the official PDG values. We finally scan the mass–width space to explore how sensitive our fit is and where the uncertainties lie.

The Invariant Mass Distribution and its Fit

To search for evidence of Z^0 boson decays, we began by analyzing 5000 ATLAS events, each containing two final-state leptons. For every lepton, we were given its transverse momentum (p_T), pseudorapidity (η), azimuthal angle (ϕ), and energy (E). Using these, we reconstructed each lepton's 3-momentum in Cartesian coordinates:

$px = p_T \times \cos(\phi)$ $\quad\quad$ $py = p_T \times \sin(\phi)$ $\quad\quad$ $pz = p_T \times \sinh(\eta)$

We then summed the four-momenta of each lepton pair and computed their invariant mass using the relativistic formula:

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

This calculation was repeated for all events. The resulting distribution of invariant masses was plotted as a histogram from 80 to 100 GeV, using 41 bins as specified. Poisson uncertainties (√N) were used for error bars.

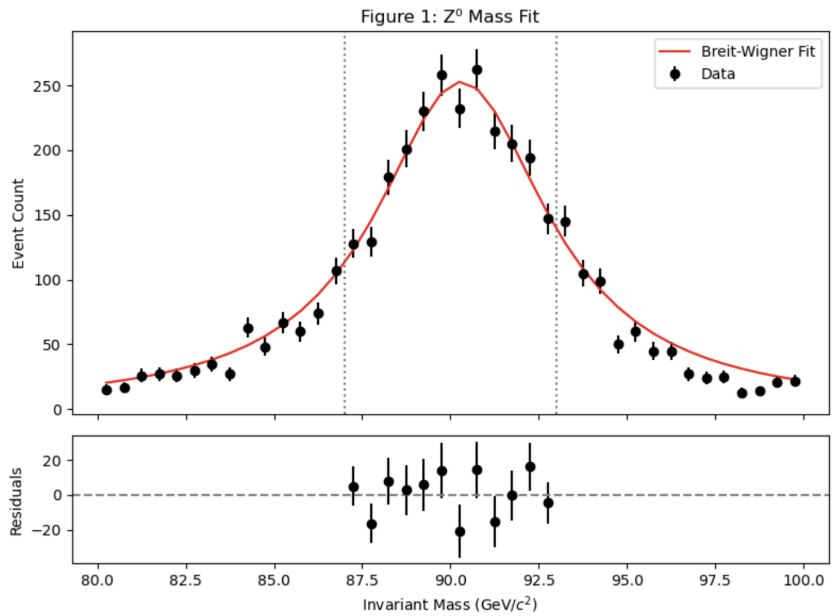
To extract the Z^0 parameters we fitted the region $87<m<93$ GeV$87<m<93$GeV with a Breit‑Wigner (Cauchy–Lorentz) shape

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

scaled to an overall normalisation of 2 500 events, as required. Non‑linear least squares with the bin‑by‑bin statistical uncertainties were used.

Quantity Value
Fitted Z^0 mass, m_0: 90.3 GeV
Uncertainty on m_0: ± 0.1 GeV
Chi-square: 8.8
Degrees of freedom: 9
p-value: 0.459

The fitted mass of the Z^0 boson is $m_0 = 90.3 \pm 0.1$ GeV, which is within 1.0% of the accepted PDG value (91.188 GeV). The associated chi-square of **8.8** for **9 degrees of freedom** yields a



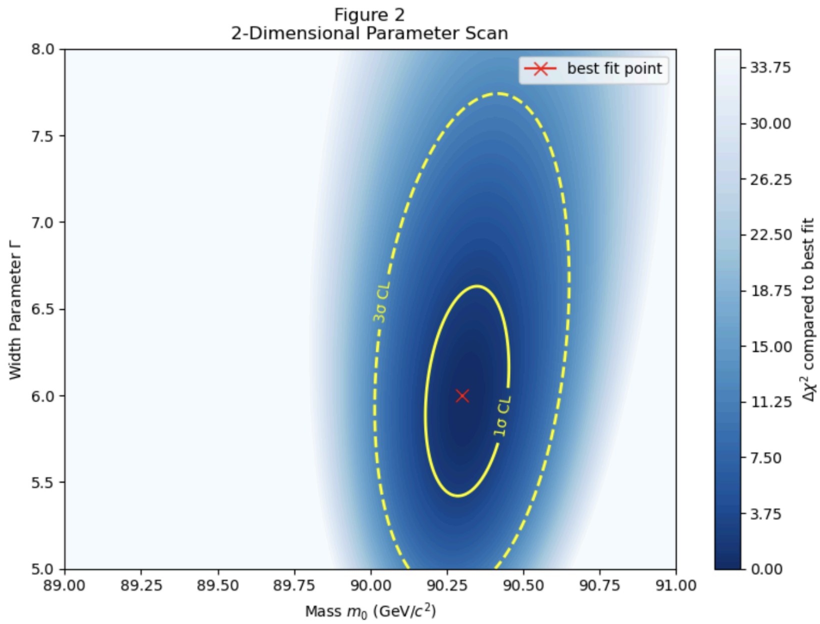
p-value of 0.459, indicating a statistically consistent fit. This means there is a **45.9% chance** of obtaining a chi-square this large or larger purely from statistical fluctuations, assuming the model is correct — a strong indication that the Breit-Wigner shape is appropriate for the observed resonance.

While no obvious deficiencies appear in the current model, a more refined analysis could incorporate known instrumental effects and background processes. Convolving the Breit-Wigner with a detector resolution function, adding a background component, and accounting for systematic uncertainties would allow for a more detailed and precise extraction of the Z^0 properties — especially useful in a higher-precision context.

2D Parameter Scan

Figure 2 (below) shows a 2D scan of the chi-square surface as a function of the Z^0 boson's mass and width. We generated this by evaluating the fit quality across a fine grid of parameter values—from 89 to 91 GeV in mass and 5 to 8 GeV in width, with 300 steps in each direction. At every grid point, we calculated the Breit-Wigner shape using the histogram bin centers, analytically solved for the best-fit amplitude, and computed the total chi-square. We then subtracted the global minimum to get a map of: $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ where lower values indicate better agreement with the data.

The result is a smooth $\Delta\chi^2$ surface that captures how sensitive the fit is to changes in mass and width. In Figure 2, the color scale represents increasing $\Delta\chi^2$, clipped at 35 to keep the plot readable. The red "×" marks the best-fit point from Section II. Two yellow contours show the 1σ and 3σ confidence levels—specifically, $\Delta\chi^2$ values of 2.30 and 11.83—which are the standard thresholds for a 2-parameter fit. These are drawn as solid and dashed lines, respectively, and labeled directly on the plot.



This visualization makes a few things clear. First, the contours are elongated, showing that there's some correlation between the mass and width—if you increase one slightly, you can compensate by adjusting the other without ruining the fit. Second, the tightness of the contours in the vertical direction confirms that the mass is well constrained (about ±0.1 GeV), while the width has more wiggle room (roughly 5.5–6.7 GeV at 1σ). Overall, the scan reinforces what we saw in the 1D fit: the model describes the data well, and the uncertainty in m0 is small and meaningful.

Discussion and Future Work

Our measured Z^0 mass of 90.3 +/- 0.1 GeV is reasonably close to the PDG value of 91.188 GeV, differing by about 1%. This small offset likely comes from simplifications in our model—we used a pure Breit-Wigner shape with no detector smearing or background subtraction. We also assumed only statistical uncertainties, ignoring possible systematics like energy calibration or bin migration.

We also treated all uncertainties as purely statistical, based on event counts in each bin, and did not account for any systematic sources such as detector calibration, acceptance variation, or bin migration. These assumptions make our uncertainty on m0 seem more precise than it likely is in reality.

Going forward, a more complete analysis would include Gaussian smearing to simulate detector resolution, a polynomial or exponential background term beneath the Z^0 peak, and estimates of systematic uncertainty. These additions would make the extracted mass more accurate and the quoted uncertainty more trustworthy.