# PHYS 265 Lab Report 3

May 6, 2025 ■ Erika Falco

## I. Introduction

The $Z^0$ boson is one of the most important particles in modern physics. As a neutral carrier of the weak force, it plays an integral role in facilitating the nuclear interactions that govern our universe. In CERN's Large Hadron Collider (LHC), proton-proton interactions produce these $Z^0$ bosons, which decay rapidly into lepton pairs due to their instability. Energy is conserved during this process, with the energy stored in the mass of the $Z^0$ boson being transferred to the lepton pair. This allows physicists to reconstruct the boson's invariant mass by analyzing lepton momentum and energy: the total energy of each lepton pair must add up to at least the mass of the associated $Z^0$ boson. Our group is working directly with the A Toroidal LHC Apparatus (ATLAS) experiment at CERN to investigate and verify the mass of the $Z^0$ boson via this reconstruction method.

ATLAS measures the total energy, transverse momentum, pseudorapidity, and azimuthal angle of the leptons produced in the LHC. This report analyzes 5,000 double lepton events from the 2020 ATLAS data set, calculating the energy of each event and reconstructing the invariant mass of the original particle. This mass distribution is fitted and analyzed taking the peak of the distribution as an indication of the $Z^0$ boson's true invariant mass. This analysis strives to measure the mass of the $Z^0$ boson, ultimately comparing it to the currently accepted value from the Particle Data Group.

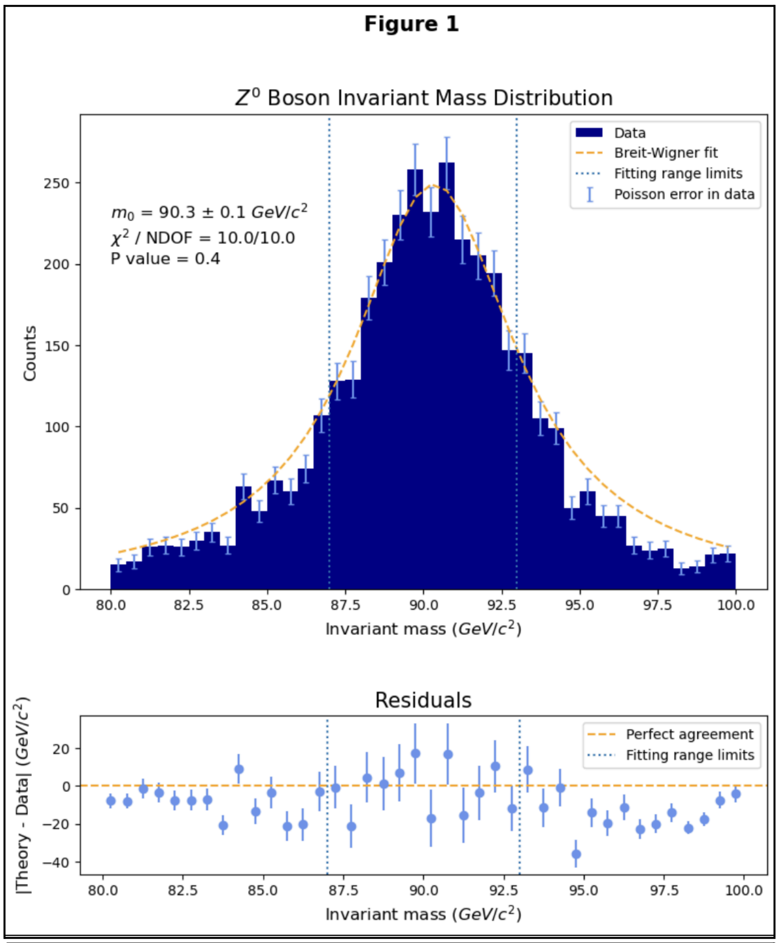


**Figure 1: Distribution of reconstructed invariant masses of the $Z^0$ boson, fitted to the normalized Breit-Wigner function.**

## II. Invariant Mass Distribution

The transverse momentum ($p_T$), pseudorapidity ($\eta$), and azimuthal angle about the beam ($\phi$) of each lepton involved in a double lepton event were used to calculate its momentum components, in accordance with the equations below:

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

The total x, y, and z components of the momentum of each lepton pair were calculated by summing each lepton's contribution, and the total energy E of each lepton pair was calculated as a sum of their individual energies. The invariant mass M of the associated $Z^0$ boson for each pair was then reconstructed using the total momentum and energy of the lepton pair via the invariant mass equation,

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

Reconstructed masses were organized into 41 bins ranging from 80 to 100 $GeV/c^2$. The data was approximated as a Poisson distribution, with a standard deviation of $\sqrt{N}$ taken as the error in the event counts N in each bin.

The resulting mass distribution was fitted with the Breit-Wigner function

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

which models the decay distribution D at a given reconstructed mass m, based on the $Z^0$ boson's true rest-mass $m_0$ and a width parameter $\Gamma$. This function, derived from scattering theory, models the expected reconstructed mass distribution from resultant lepton pairs for a boson of rest mass $m_0$. The fit was normalized in multiplying by a factor of 2,500, half the number of data points. The mass distribution was fitted to the Breit-Wigner function using the optimize.curve_fit function in the scipy Python library for masses ranging from < 87 to > 93 $GeV/c^2$. The function selected optimized fitting parameters of $m_0$ = 90.3 $\pm$ 0.1 $GeV/c^2$ and $\Gamma$ = 6.4 $\pm$ 0.2 $GeV/c^2$. A histogram of the mass distribution and Breit-Wigner fit with these best fit parameters are shown in Figure 1.

The fit was analyzed using a chi-squared test at bin centers for masses ranging from < 87 to > 93 $GeV/c^2$ and assuming 10 degrees of freedom, as 12 bin centers were analyzed and 2 fitting parameters were involved. This analysis yielded a chi-squared value of 10.0, a reduced chi squared of 1.0, and a p value of 0.4. This p value indicates an approximate 40% chance of obtaining the observed experimental results assuming the null hypothesis is true. The p value is within the acceptable range of 0.05 to 0.95, ultimately suggesting consistency between the fit and the data. The discrepancy between the theoretical and observed event counts for each bin midpoint were calculated and plotted as residuals in Figure 1, with error bars once again taken to be a Poisson standard deviation of $\sqrt{N}$.

**III. 2D Parameter Scan**

The optimized $m_0$ and $\Gamma$ parameters were selected to minimize the $\chi^2$ value when fitting the data to the Breit-Wigner function. To better understand the allowed flexibility in these parameters, a two-dimensional parameter scan was conducted. Chi-squared values were calculated for each possible pair of $m_0$ and $\Gamma$ parameters for $m_0$ ranging from 89.00 to 91.00 $GeV/c^2$ and $\Gamma$ ranging from 5.0 to 8.0 $GeV/c^2$. The differences between these values and the minimized $\chi^2$ of 10.0, denoted as $\Delta\chi^2$, were then calculated and plotted as a three dimensional color map as shown in Figure 2. $\Delta\chi^2$ values greater than 35

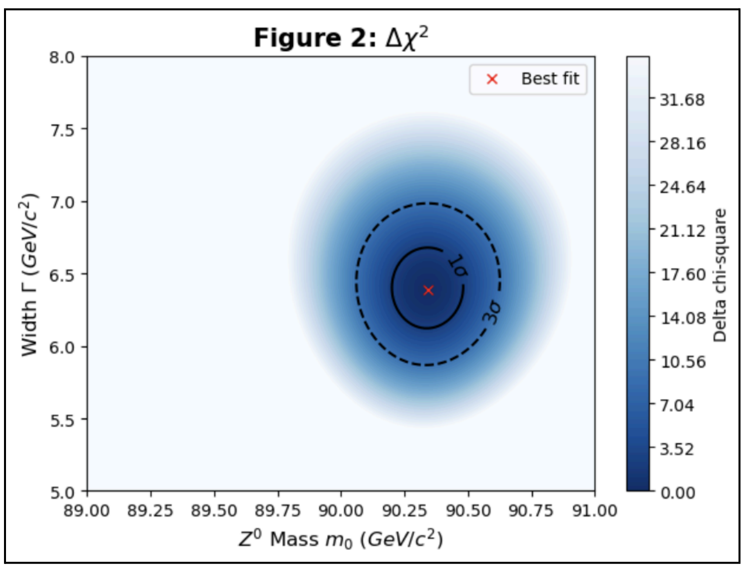


**Figure 2: Color map of the $\Delta\chi^2$ value corresponding to parameters $m_0$ and $\Gamma$ specified on the x and y axis. $1\sigma$ = 2.30, $3\sigma$ = 9.21.**

were neglected and plotted as a homogenous upper limit value of 35 to improve figure legibility in the relevant region.

Additionally, contours were plotted to indicate where $\Delta\chi^2$ would fall within one standard deviation $(1\sigma = 2.30)$ and three standard deviations $(3\sigma = 9.21)$ of the minimized best fit value of 10.0. These confidence levels are the accepted values for a fit involving N=2 fitting parameters. If the parameters' $\Delta\chi^2$ falls within the $1\sigma$ interval, that means that repeated experiments would have fitted $m_0$ and $\Gamma$ values fall within the enclosed range 68% of the time. Parameters within the $3\sigma$ range will occur approximately 99% of the time when the experiment is repeated. The optimized parameter values are within the $1\sigma$ region, indicating a good fit.

**IV. Discussion and Future Work**

This initial analysis of lepton pair data yielded an invariant mass distribution for the $Z^0$ boson that is consistent with a Breit-Wigner decay function with fitted mass $m_0$ = 90.3 $\pm$ 0.1 $GeV/c^2$ and fitted width $\Gamma$ = 6.4 $\pm$ 0.2 $GeV/c^2$. As of 2024, the Particle Data Group (PDG) reports the accepted value of $Z^0$ boson mass to be 91.1880 $\pm$ 0.0020 $GeV/c^2$. The difference between our fitted value and that reported by the Particle Data Group was computed and divided by the propagated uncertainty in that difference, yielding a value of 9.1. This means that our discrepancy is over 9 standard deviations away from zero, indicating a statistically significant disagreement between these two values.

This disagreement may be due to a number of assumptions and simplifications made in the process of data analysis. Our fitted $m_0$ value was calculated based on the peak of the mass distribution data. Purely experimental uncertainty would likely contribute to discrepancies in the width of this mass distribution but maintain the approximate location of this peak value. Our fitted $m_0$ value is over 9 standard deviations from the PDG reported value, indicating that the peak of the PDG mass distribution is shifted significantly from ours. This shift in the location of the mass distribution peak is likely due to some systematic uncertainty, as statistical uncertainties are unlikely to produce such a significant unidirectional shift in mass distribution. The most likely culprit for systematic uncertainty is in the calibration of the energy sensor within the ATLAS detector, and future work should aim to investigate and account for any calibration issues. This analysis also did not account for any uncertainties in the ATLAS data related to lepton momentum, energy, pseudorapidity, or azimuthal angle. Accounting for these additional sources of systematic and experimental uncertainty is essential to creating a more realistic model of invariant mass distribution, and an underestimation of uncertainty in boson mass could contribute to the discrepancy we see between our value and the accepted literature. Additionally, the Breit-Wigner fit was only performed for masses ranging from < 87 to > 93 $GeV/c^2$. This data was also only fitted into 41 bins, ranging from 80 to 100 $GeV/c^2$, limiting the precision of our mass estimate. Further analysis should investigate the influence of different binning and masking of the data set. Finally, in fitting the data to the Breit-Wigner function and assuming a Poisson distribution, the data was simplified in a way that may not fully reflect the physical processes occurring within the LHC. Future work should aim to build more sophisticated models of these phenomena to improve the accuracy of our mass distribution. It is essential that we investigate the sources of this inconsistency with the Particle Data Group's reported values, as this discrepancy is statistically significant. Future work may require additional data collection and analysis to further investigate this inconsistency with the 2024 reported value.