Report on Z_0 Boson Measurements:

Rohan Panchwagh

I: Introduction

The purpose of this report is to detail physical properties of the Z^0 boson concluded from analyzing data from the ATLAS detector, as well as to explain the methods behind each calculation. It is prudent to give an overview of the theory behind the data analysis first, to elucidate the reasons for each calculation.

The ATLAS detector in CERN collides two proton beams together, generating many particle interactions/decays of interest. Of importance to this report is one particular mechanism, where a Z^0 boson (a force-carrying particle for the weak force) decays into a lepton-antilepton pair (leptons include particles such as electrons, muons, and tau particles). To determine characteristics of the Z^0 boson, one can investigate the properties of the ejected leptons to reconstruct features of the original boson. By measuring the momenta and energies of the ejected lepton-antilepton pair, and using both mass-energy and momentum conservation, one can determine the invariant mass of the Z^0 boson.

If the experiment is run many times, one can construct a table of the energies and momenta of the generated lepton-antilepton pair; after converting this data into the invariant mass of the Z^0 boson, the calculated masses can be complied into a histogram. The mass histogram should follow what is known as a Breit-Wigner distribution (a result derived from scattering theory); roughly speaking, this is a distribution which peaks at the true invariant mass of the Z^0 boson, and has a characteristic width associated with the lifetime of the particle before it decays (through the energy-time uncertainty principle). By fitting the B-W distribution to the data, one can determine the best-fit mass and width for the Z^0 boson.

II: The Invariant Mass Distribution

To determine the invariant mass energy of the Z^0 boson, we started by importing data from the ATLAS detector on several measured parameters of decay events; in particular, the transverse momentum p_T, the energy E, the azimuthal angle ϕ, and the pseudorapidity η (related to the angle between the particle and beamline) for each of the two ejected leptons for each event. We then used the equations detailed below:

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

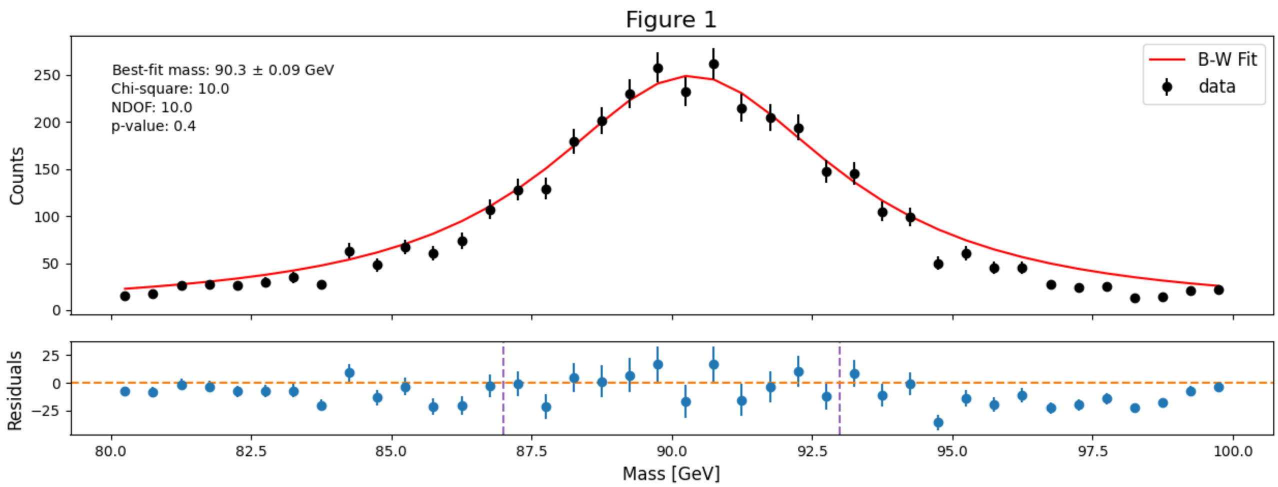
$$M = \sqrt{E^2 - (p_x^2 + p_y^2 + p_z^2)}$$

which allowed us to calculate M (the invariant mass) for a given event. After determining the invariant mass for each event, we created a histogram of the masses, with 41 bins between 80 and 100 GeV. We then took the bin centers (in units of mass) as our x data points, the counts (for each given bin) as our y data points, and the square root of the number of counts (in a given bin) as our error, giving us a distribution of data points we could use to fit the Breit-Wigner distribution.

The Breit-Wigner distribution is described by the following equation:

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

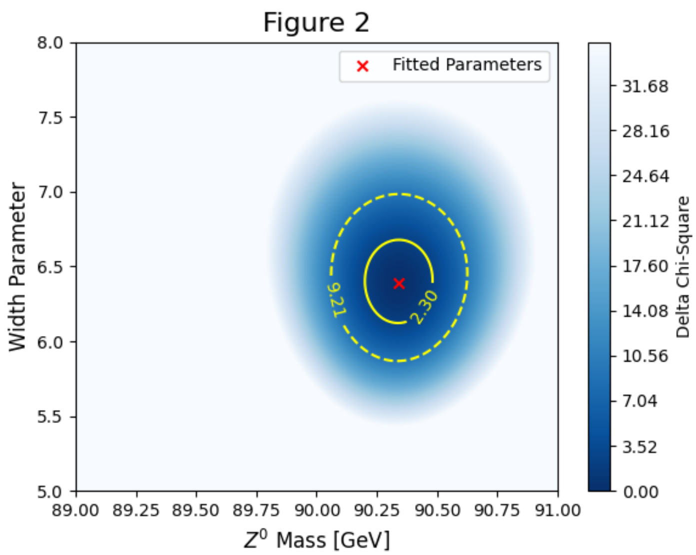
where m is the mass (a variable), and the parameters m_0 and Γ represent the true Z_0 rest mass and characteristic width, respectively. To fit our data to this distribution, we first multiplied the above distribution by 2500 (adjusting the normalization by half of the number of data points). We then masked the data points, only including points between 87 and 93 GeV. Finally, we used the curve_fit function in scipy to obtain the best-fit parameters. We then plotted the fitted distribution against the data (**Figure 1, upper**), as well as the residuals of the data (**Figure 1, lower**). The



points between the two vertical lines on the lower plot are the values over which the fit was performed, and the horizontal line gives the ideal residual values. Our fit gave us a Z^0 mass of 90.3 ± 0.09 GeV. To quantify the accuracy of the fit, we also determined the χ^2 value, number of degrees of freedom (NDOF), and the p-value of the fit, obtaining values of 10.0, 10.0, and 0.4 respectively. We obtained the χ^2 value by dividing the residual (for a given mass) by the error (at that mass), squaring the result, and then summing over all mass values. To determine the number of degrees of freedom, we subtracted the number of fitting parameters (2) from the number of data points used in the fit (12) to obtain 10. Our p-value indicates that our fitted result for the Z^0 mass is consistent with theory (being between 0.05 and 0.95); a p-value less than 0.05 indicates a disagreement between data and theory, while a p-value larger than 0.95 indicates that the theory fits the data *too* well, meaning that the error may have been overestimated. A result of 0.4 essentially means that if the experiment were repeated, there would be a 40% chance of obtaining a higher p-value (the ideal p-value is 0.5). Since our p-value is only 0.1 away from the ideal result, we can conclude that our fitted mass result is consistent with the data from the detector, and our fitted estimate for the uncertainty in the mass is also consistent with the data (if not slightly too low, since 0.4<0.5).

III: 2D Parameter Scan

To obtain the 1σ and 3σ intervals for the parameters of the data, we created a distribution of $\Delta\chi^2$ in parameter space. To do this, we first created a numpy meshgrid in parameter space, with m_0 linearly spaced from 89 to 91 GeV, and Γ from 5 to 8, both with 300 bins each. We then calculated chi-squared at each grid point, where the theory values (in the residual) corresponded with the B-W distribution specified by the parameter values at that point. We then took the minimum of the array of chi-squared values, allowing us to determine $\Delta\chi^2$ as $\chi^2(m_0, \Gamma) - \chi^2_{min}$. We plotted $\Delta\chi^2$ as a colormap, drawing contours at the values 2.3 and 9.21 (which correspond with the 1 and 3-sigma values of $\Delta\chi^2$ for a two-parameter fit, given in https://pdg.lbl.gov/2020/reviews/rpp2020-rev-statistics.pdf, Table 40.2). This plot is shown in **Figure 2**, with the red 'x' denoting the best-fit value for the parameters, the dotted line denoting the 3σ limit, and the solid line denoting the 1σ limit. As is expected, the best-fit values for the parameters coincide with the zero value in the $\Delta\chi^2$ distribution.



IV: Conclusions

In conclusion, our analysis of the ATLAS detector data found that the mass of the Z^0 boson is 90.3 ± 0.09 GeV, with a p-value of 0.4 for the fit indicating good agreement between the data and the fitted Z^0 mass value. The current PDG value for the mass of the Z^0 boson is 91.186 ± 0.0021 GeV, which is a difference of 0.886 eV from our analysis. These values do not lie within one standard deviation of each other, and thus, they don't agree. This is likely because the PDG analysis used 4.57 million events, whereas ours used only 5000, making theirs more accurate and bringing down their uncertainty to 0.23 of ours. Qualitatively, however, the values are relatively close to one another, and it is likely that by improving our analysis we would reach a value similar to theirs. In our analysis, we made assumptions to make calculations easier, in the future, these assumptions can be relaxed to give more accurate results. For example, our analysis did not include systematic detector uncertainties or bounds on the energy resolution of the ATLAS detector; including these may improve the fit of the model to the data (notably, our analysis found that the error was slightly underestimated, so including these sources of error may correct the error further). Additionally, we didn't account for other Z^0 decay methods, such as decay into neutrinos, quarks, or photons; repeating this analysis for other decay models may give us a more accurate value for the Z^0 mass. Finally, we chose a uniform binning method to generate our distribution of masses; in future studies, we could use a more sophisticated binning method (potentially by incorporating the error in the mass itself) and choose the bin sizes/distribution more wisely, which would have the effect of improving the experimental distribution, and potentially giving a better fit to the B-W distribution.