# ATLAS Data Analysis: Report

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## 1 Introduction

Here at ATLAS (**A** **T**oroidal **L**hc **A**pparatu**S**), high-energy protons are smashed together with the purpose of analyzing the resulting byproducts, helping us understand the fundamental particles which make up the universe. One of the particles we are studying is the $Z^0$-boson, the neutral carrier of the weak force. About 10% of the time, it decays into a pair of charged leptons (electron/positron, muon/anti-muon, or tau/anti-tau). This is useful because, by measuring the energy of the resulting leptons, we are able to obtain an estimate of the mass of the $Z^0$ boson.

## 2 The Invariant Mass Distribution and its Fit

We reconstruct the original mass in the following manner. We measure four properties of the resulting leptons: the total energy $E$, the transverse-momentum $p_T$, the pseudorapidity $\eta$, (which describes the angle the particle makes with respect to the beamline), and the azimuthal angle $\phi$ about the beam. The momentum of the particle in each dimension is:

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

and the particle's invariant mass is:

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

To compute the total momentum of the two leptons, we simply sum their $E$, $p_x$, $p_y$, and $p_z$ values.

Obviously, when we take repeated measurements to reconstruct the mass of the original particle, we will end up with varying results each time. Thankfully, scattering theory tells us that the distribution of our reconstructed mass values follows a Breit-Wigner ("Cauchy-Lorentz") distribution:

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

where $\mathcal{D}$ is the probability density function for the given value of $m$, $m_0$ is the true rest-mass of the $Z^0$ boson, and $\Gamma$ is the width parameter (which controls the width of the distribution).

To fit the data we collected to this distribution, we first had to bin our values (otherwise, essentially all of our values would have a frequency of 1); here we used 40 bins of size 0.5 ranging from 80 to 100, meaning our x-values were the centers of the bins (80.25, 80.75, 81.25, etc.) and our y-values were the number of reconstructed mass values falling within 0.25GeV of our bin centers. We then had to scale the probability density function of the distribution to the number of values we obtained; here, we scaled the distribution by a factor of 2500. Figure 1 below shows our data overlayed with the best-fit Breit-Wigner distribution (fitted only to values between 87 and 93 GeV, marked by the dotted lines) and with the residuals underneath:

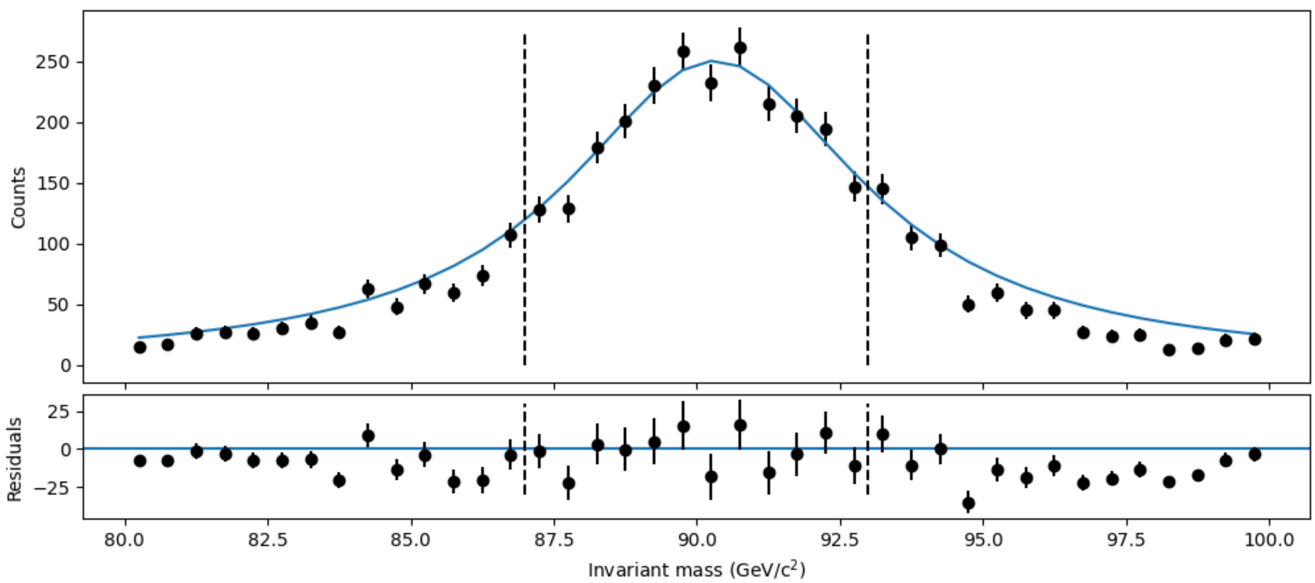


Figure 1: Breit-Wigner fit to histogram of invariant masses

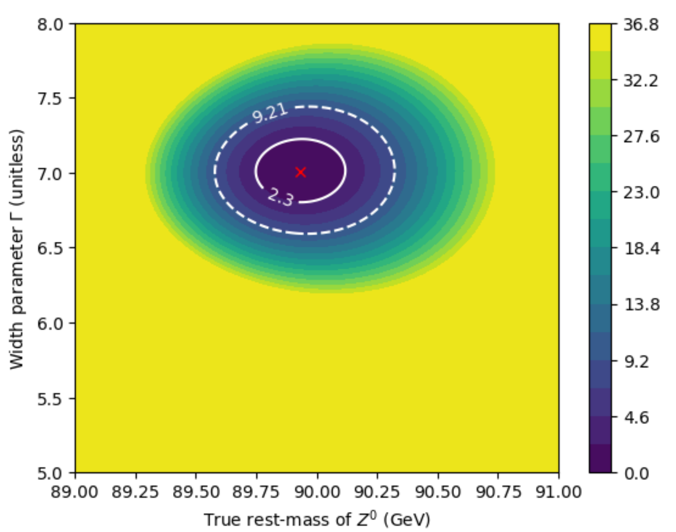
Approximating the counts of each bin as following a Poisson distribution, we estimate the uncertainty in our number of counts for each bin to be equal to the square root of the number of counts in that bin (shown in the figure by the error bars on each data point). With this uncertainty, we are able to perform a chi-squared test comparing our model to the data. Fitted just to the range from 87 GeV to 93 GeV, we obtain a chi-squared value of 10.1 with 10 degrees of freedom, giving us a p-value of 0.4, which is 8 times higher than the usual significance level of 0.05; this suggests that there is not a statistically significant disagreement between our model and the data. Of note is our best-fit value for the true rest-mass of the $Z^0$ boson, $m_0 = 90.3$ GeV, with an uncertainty of 0.1 GeV.

# 3 The 2D Parameter Scan

There is obviously some uncertainty in the values we obtained for $m_0$ and $\Gamma$, so we would like to determine a reasonable range of values within which the true values for these two parameters could fall given the results from our data. As both of these independent variables contribute to the goodness of our fit, we must perform a 2D chi-squared scan in the mass-width parameter space.

Assuming the uncertainty in our counts for each bin to be equal to the square root of the number of counts, we computed the increase in the chi-squared value (again, only for masses between 87 and 93 GeV) over our minimum chi-squared value (at the point of our best fit) for masses between 89 and 91 GeV and widths between 5 and 8, clipping our delta chi-squared values at a maximum of 35. Figure 2 shows a contour plot of delta chi-squared values (with

Figure 2: $\Delta\chi^2$ contour plot over mass-width parameter space



levels being multiples of 2.3) over this parameter space, with a cross marking the location of our best-fit parameters, and with the chi-squared values corresponding to 1 and 3 standard deviations from our best-fit chi-squared value ($\chi^2_{1\sigma} = 2.30,\ \chi^2_{3\sigma} = 9.21$) drawn with a solid white line and a dashed white line, respectively. To elaborate, based on our data, we are 68% confident that the true $m_0$ and $\Gamma$ fall within the solid ellipse, and we are 99.7% confident that the true $m_0$ and $\Gamma$ fall within the dashed ellipse.

# 4 Discussion and Future Work

The accepted value for the mass of the $Z^0$ boson from the 2024 edition of the Particle Data Group is $91.1880 \pm 0.002$ GeV. Our best-fit value for the mass of the $Z^0$ boson is $90.3196 \pm 0.095$ GeV. Qualitatively, this difference is almost ten times our uncertainty in our best-fit value for the true rest-mass, and it lies far outside even the $3\sigma$ parameter range in our contour plot. Quantitatively, combining the uncertainties and performing a chi-squared test on these two values gives a chi-squared value of 83.522 for only one degree of freedom, which gives us a p-value of essentially zero. In other words, our value and the latest accepted value from the PDG disagree in a statistically significant manner.

This implies a systematic error on our part, which could be due to many factors. For one, we only considered the interaction where the $Z^0$ boson decays into two charged leptons. However, as we mentioned at the beginning of our report, this interaction occurs only about 10% of the time. As such, it is far from unlikely that we performed our calculations on a skewed set of data points, which could explain the difference in our value for the true rest-mass. Additionally, our bin sizes were somewhat large compared to our number of observations; the largest bins had around 250 counts. Finally, we only fitted the Breit-Wigner distribution to a subset of our data points; looking at the sides of the residual plot, significantly more points fall under our best-fit line than fall above it outside of the range to which we fitted the distribution, implying that it is not a good fit outside of this range.

Future work could obtain a more accurate value for the true rest mass of the $Z^0$ boson by taking into account all of the possible interactions resulting from the decay of the $Z^0$ boson, to avoid fitting to a skewed subset of data; by reducing the bin size to obtain a finer approximation for our set of data points, which could lead to a better fit of the Breit-Wigner distribution to our data; and by fitting to all the reconstructed invariant mass values, rather than just a subset of them.