ATLAS Data Analysis

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I Introduction

The ATLAS (A Toroidal Lhc Apparatus) experiment is an experiment taking place at CERN in Geneva. In this experiment high energy particles are smashed together and products of the collisions are studied. Specifically this report will cover data of proton-proton collisions. When these protons collide one product is sometimes the Z^0-boson. The Z^0-boson is the neutral carrier of the weak force, thus it is relevant to study it. About 10% of the time it decays into two charged leptons. These two pairs can be an electron and a positron, a muon and anti-muon, a tau and anti-tau, or two photons. Using 5000 data entries from ATLAS specifically selected where the "final state" has only the two leptons that we are interested in, we can analyze the data. The data contains the transverse momentum, the pseudorapidity (η) which describes the angle the particle makes from the beam line, the azimuthal angle (ϕ), and the energy. From this we can determine the invariant mass of all the lepton pairs, we can also fit the data and extract the true-rest mass of Z^0 and the "width" parameter related to the lifetime of a particle. We can compare these values and perform statistical tests such as chi square and find the p-value. Finally we can compare the true-rest mass values with accepted values. The data analysis was done using python code and utilizes different packages such as numpy, matplotlib, and scipy.

II The Invariant Mass Distribution and its Fit

Using the data from ATLAS the invariant mass can be calculated for each lepton pair using the equation $\sqrt{E^2 + (p_x^2 + p_y^2 + p_z^2)}$ where $p_x = p_t cos(\phi)$, $p_y = p_t sin(\phi)$, and $p_z = p_t sinh(\eta)$. The four momentum values (E, p_x, p_y, p_z) were calculated for each lepton, and then summed before being put in the invariant mass equation. A histogram of the invariant masses is then created. From that the uncertainties on each bin can be found since this can be approximated to follow a Poisson distribution where in this case the uncertainty in each bin is the square root of the number of entries in each bin. Using "curve_fit" from the python package scipy, a subset of the data (masses from 89-91 GeV) was fit to a Breit-Winger peak which represents the distribution D at a reconstructed mass m. $D(m;\ m_0, \Gamma) = \frac{1}{\pi}\frac{\Gamma/2}{(m-m_0)^2+(\Gamma/2)^2}$. where m_0 represents the true rest mass of Z^0 and Γ represents a "width" parameter. The data was fit half the data points times D. where m is the invariant mass for each pair calculated earlier. m_0 and Γ were extracted as fit parameters. The fit true rest mass of Z^0, m_0, was found to be 90.3 ± 0.1 GeV. Using the fit parameters, and the data array of masses, a fit distribution was calculated based on $2500 * D$. The actual frequency of masses in each bin was compared to the fit distribution frequency values. The chi square of the data to the fit was found to be 10.0 with 12 degrees of freedom and the p-value was found to be 0.6. Since the p-value is larger than 0.01 (1%) it means that the difference between the fit and the data is not statistically significant, indicating good agreement. The p-value of 0.6 means there is a 60 percent chance that getting a chi square value as high as 10.0 is due to chance alone. Thus indicating good agreement. A plot of a histogram of the masses and the residuals are shown in Figure 1. The residuals were found by subtracting the fit distribution frequency values from the actual frequency of masses in each bin and taking the absolute value.

III The 2D Parameter Scan

As there are two fit parameters in this fit m_0 and Γ, the two values can not be calculated independently. This section the joint probability space is analyzed. A 2D chi-square scan was performed by scanning across masses from 89 to 91 GeV (the same as in the previous part) and scanning across the width from 5 to 8. This was performed by taking the chi square using both fit parameters in a 2D space using a double for loop in the code. The delta chi square was plotted as a contour map against the m_0 space on the x-axis and the Γ space on the y-axis . Where the delta chi square is the array of chi square values minus the minimum chi square value in the array. The m_0 space is the mass space from 89 to 91 GeV, and the Γ space is the width space from 5 to 8. The plot was clipped at 35 for a better visual of the plot. 1 sigma and 3 sigma confidence levels are plotted on top of the chi square map. These confidence levels are taken from a known table of values. Where the confidence level is indexed by how many fit parameters there are. Since I have 2 fit parameters Γ and m_0 I chose the 1 sigma and 3 sigma confidence levels that correspond with 2 fit parameters. The plot also has an x at the best fit location of m_0 from the previous part. A contour plot of the 2D delta chi square is shown below in Figure 2.

IV Discussion and Future Work

According to the Particle Data Group (PDG) the accepted value of the mass of Z Boson is about 91.189 ± 0.002 GeV. Comparing this value to the fit value m_0 which was 90.3 ± 0.1 GeV the ratio of the difference of the two values to the uncertainty in the difference was found to be 0.009. This value is much less than 2. Which means the difference of the two values are consistent with 0 at the 0.009 sigma level. Meaning the values agree.

In doing the calculations summarized in the report there have been some approximations made. For example, no systematic errors were incorporated into the calculations. The energy resolution of the ATLAS detector was also not taken into account. In doing future work and future calculations these parameters should be taken into account when computing the values above. Future work could also try to analyze newer data as this data is from 2020. Finally, as this report only analyzes 5000 points and only fits and scans across a subset of them, future work can extend the calculations to more data points and to being computed over the full range of the data.

Overall, through analyzing data of transverse momentum, pseudorapidity (η), azimuthal angle (ϕ), and energy, the invariant mass for each lepton pair can be calculated. From this the data can be fit to a Breit-Winger peak and the best fit m_0 value can be extracted. The fit m_0 was found to be 90.3 ± 0.1 GeV. Finally a 2D delta chi square map can be created showing how the chi square changes as m_0 and Γ change, since m_0 and Γ can not be determined completely independently, due to the fit being a 2D fit.

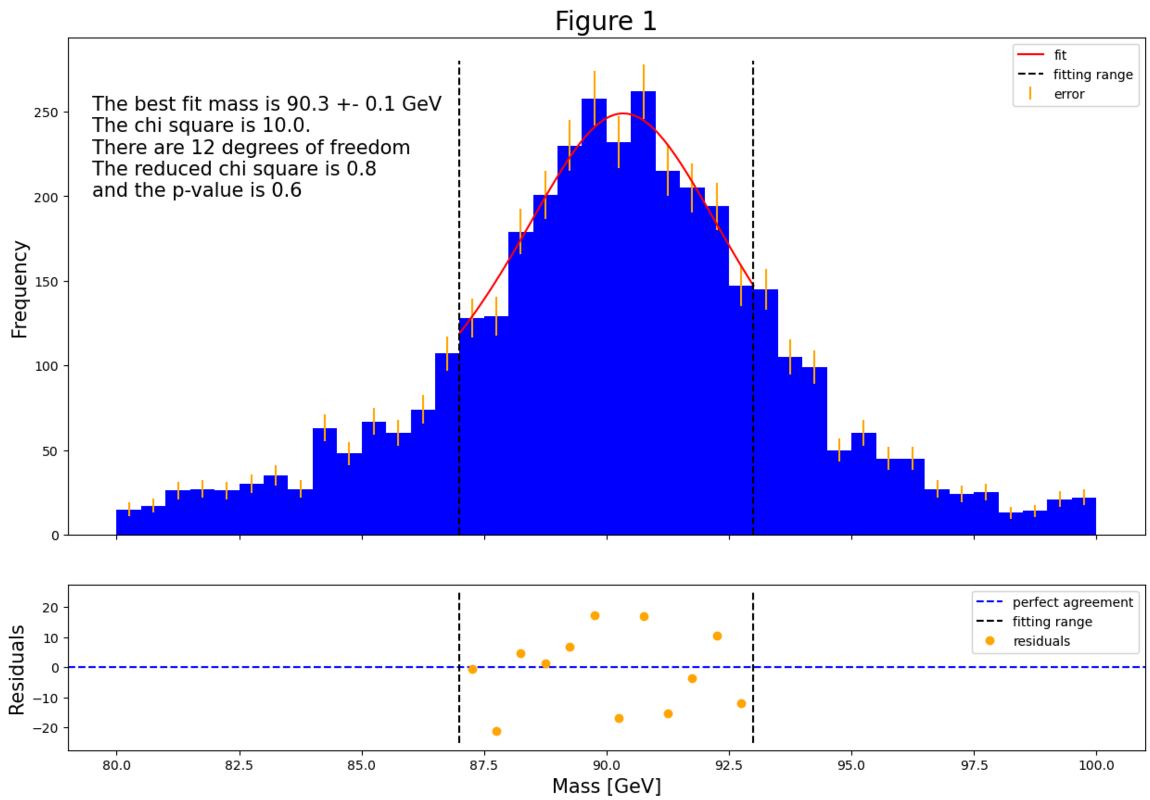

Figure 1: Top plot - Histogram of the actual mass data split over 41 bins. The uncertainties are graphed on top, found by the square root of the number of entries in each bin. Finally, the Breit-Winger fit is plotted on top. The black lines indicate the fitting range. Bottom plot - The residuals of the frequency of masses in each bin and the fit frequency for each bin are plotted as a function of mass. The black lines indicate the fitting range.

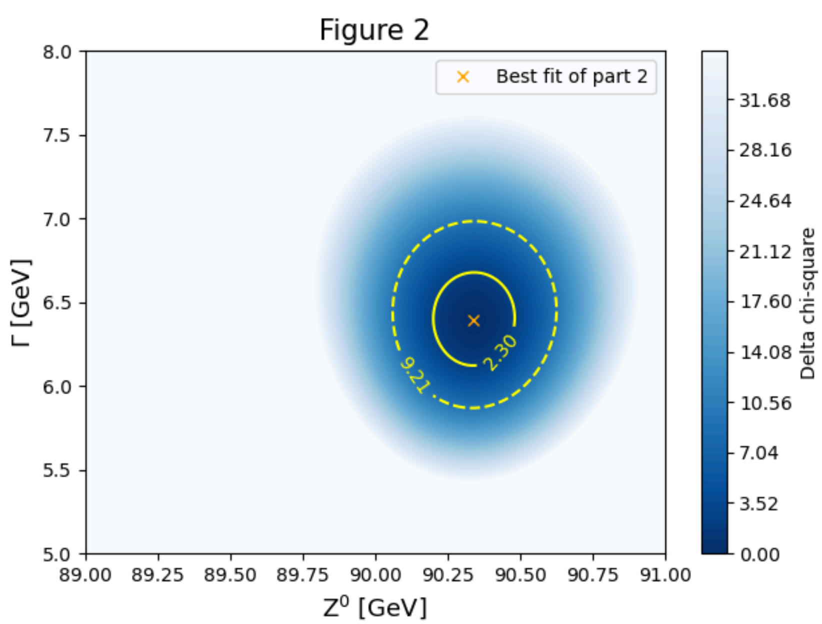

Figure 2: Contour plot of the 2D delta chi (clipped at 35 units) as a function of true rest mass (m_0) and width (Γ).

The yellow solid ring indicates the 1 sigma confidence level. The yellow dotted line indicates the 3 sigma confidence level. The x indicates the best fit value found in part II.