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Lab 3 Report

I. Introduction

The next goal of our lab group here at the Large Hadron Collider, at CERN, in Geneva, Switzerland, is to learn more about the mass of the Z^0-boson. As we know, the Z^0-boson is a result of a proton-proton collision and is the neutral carrier of the weak force. We also know that it is unstable and decays into two leptons. Through this project, we hope to get an accurate prediction of the mass of the Z^0-boson.

We started by working with ATLAS data which contained 5,000 events of a Z^0-boson decaying into two leptons and measuring certain parameters of the leptons. With each of these 5,000 data points, we backtracked and found the Z^0-boson's invariant mass at each point. We then plotted the distribution of masses. Our next step was to fit the data to a Breit-Wigner distribution and find the best fit value of the mass of the Z^0-boson. We calculated the accuracy of the fit to the data to learn how precise the mass we found was using a χ^2 analysis. We then found the p-value as being within 2σ. Lastly, we created a 2D contour plot for all the possible mass and width values of the Z^0-boson, to confirm the validity of our best fit mass.

II. The Invariant Mass Distribution and its Fit

We started this project by working with the ATLAS data consisting of 5,000 data points. The data consisted of eight parameters: transverse momentum of both leptons, the pseudorapidity or angle the particle makes with respect to the beamline of both leptons, the azimuthal angle about the beam of both leptons, and the total energy of both leptons. We used Equations 1, 2, 3, and 4 to find the invariant mass in the Z^0-boson using the data. We used Equations 1, 2, and 3 twice, once for each lepton and added them together to use in Equation 4.

$$p_x = p_T cos(\phi)$$

Equation 1. Where p_x is the momentum of the lepton in the x direction, p_T is the transverse-momentum of the lepton, and ϕ is the azimuthal angle about the beam.

$$p_y = p_T sin(\phi)$$

Equation 2. Where p_y is the momentum of the lepton in the y direction, p_T is the transverse-momentum of the lepton, and ϕ is the azimuthal angle about the beam.

$$p_z = p_T sinh(\eta)$$

Equation 3. Where p_z is the momentum of the lepton in the z direction, p_T is the transverse-momentum of the lepton, and η is the pseudorapidity or the angle the particle makes with respect to the beamline.

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

Equation 4. Where E is the total energy of the lepton, p_x is the momentum of the lepton in the x direction, p_y is the momentum of the lepton in the y direction, and p_z is the momentum of the lepton in the z direction.

After using the equations above, we had a list of 5,000 masses of the Z^0-boson. We created a histogram of the various masses we calculated, including the errors. Following this, we used Equation 5 to fit our data and find the best fit value for the mass of the Z^0-boson.

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

Equation 5. Where M is the mass we found using Equation 4, m_0 is the mass of the Z^0-boson which we are fitting, and Γ is the true width of the distribution which we are also fitting, D represents the Breit-Wigner fit.

Next found the best fit values for the mass of the Z^0-boson to be $90.3 \pm 0.1\ GeV$. We also found the residuals between the data and the theory and plotted them as well. Both of these plots can be seen below in Figure 1: subplot 1 and subplot 2.

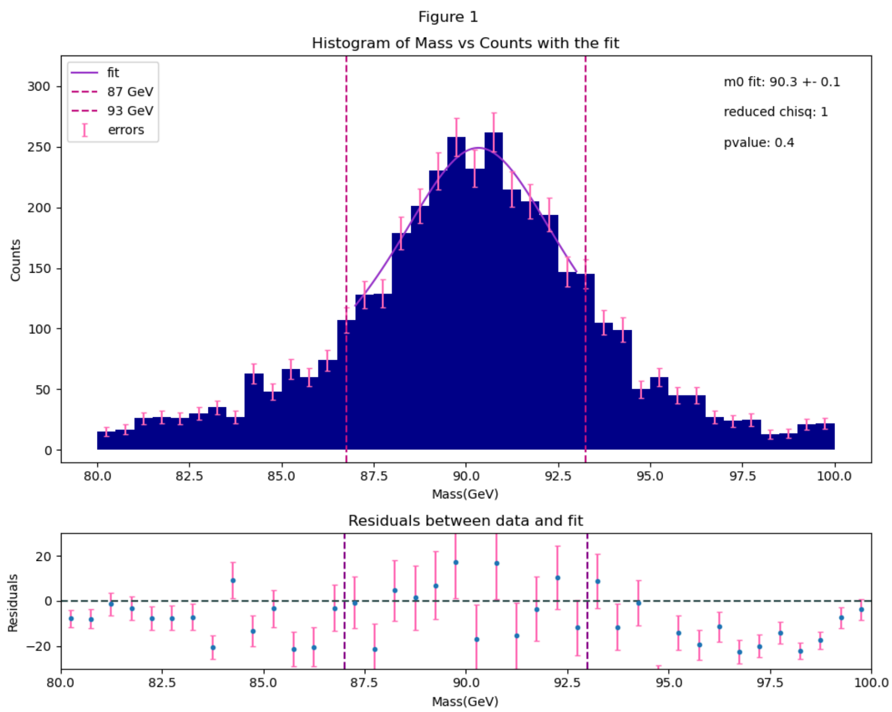

Figure 1. Subplot 1 (Histogram): shows the distribution of the masses of the Z^0-boson, and errors on all of these values using 40 bins. The fit line in the Breit-Wigner fit plotted using Equation 5. Displayed is the mass of the Z^0-boson that we found, the reduced χ^2 and the p-value. Subplot 2 (Residuals): shows the residuals between the data and Breit-Wigner fit, the dashed horizontal line shows complete agreement between the data and theory. The dashed vertical lines show where 50% of the data lies.

We then evaluated the goodness of the fit to the data by doing a χ^2 analysis. We found the χ^2 value to be 10. We used this and the number of degrees of freedom, which was 10, to find the p-value as 0.4. The number of degrees of freedom is found by subtracting the number of fitting parameters from the data points. This p-value tells us that there is a 40% chance of the χ^2 value being 10 or higher. Using this information, we can conclude that the mass of the Z^0-boson we found agrees at the 2σ level with the Breit-Wigner distribution.

III. The 2D Parameter Scan

Lastly we wanted to confirm that the χ^2 and p-value represented the best fits of both mass of the Z^0-boson and the true width of the distribution. We did this by doing a parameter scan of the various mass and true width values and finding the $\Delta\chi^2$ value associated with each combination of the two. We used Equation 6 below to make this plot, which is shown in Figure 2.

$$\Delta\chi^2 = \chi^2 - \chi_{min}^{\ 2}$$

Equation 6. Where χ^2 is the χ^2 value at that point with the various mass and true width values, $\chi_{min}^{\ 2}$ is the minimum χ^2 value of all the combinations we scanned, and $\Delta\chi^2$ is the difference between the two.

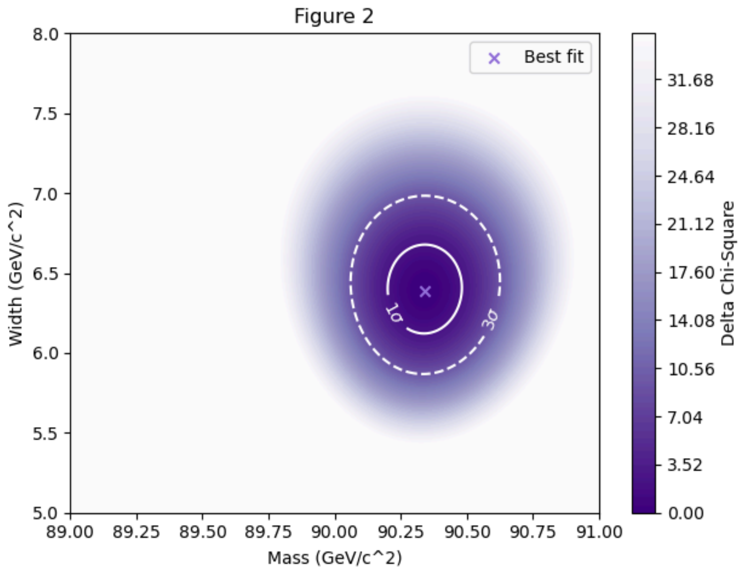

Figure 2. Where we see Equation 6 plotted. This plot proves that the best fit value we got gives us the minimum χ^2 value. The darkest color shows us the χ^2 values closest to the minimum χ^2 value, and the best fit "x" shows us the best fit value we found. The 1σ and 3σ circles show where the fit is in 1σ agreement and 3σ agreement with the data.

We can associate the 1σ line with a χ^2 value of 2.3, and the 3σ dashed line with a χ^2 value of 9.2 according to the literature.

IV. Discussion and Future Work

Through this project, we calculated the mass of a Z^0-boson by looking at properties of the leptons that Z^0-boson's decay into, and we used ATLAS data to do so. We plotted the various masses onto a histogram and found the accuracy of these values with the Breit-Wigner fit. We additionally calculated the residuals between the data and fit, and moved on to find the accuracy of our findings using a χ^2 analysis. Our p-value was found to be 0.4, which shows significant correlation between the data and theory at the 2σ level.

According to the Particle Data Group (PDG), the mass of the Z^0-boson is $91.1880 \pm 0.0020\ GeV$. This difference between our mass value and the PDG value is $0.8 \pm 0.1\ GeV$ This does not agree with our value at the 2σ level. This could be because of our assumptions. In this project, we assumed that there were no uncertainties in the ATLAS data. If there were, which there definitely were, the mass we found could be wrong. We also assumed that after the collision and before the data collection the leptons did not have a change in energy. This could affect the values in the ATLAS data which would consequently affect our mass value. In the future, we can use more data to hopefully get a more accurate mass of the Z^0-boson. While doing our calculations, we sometimes didn't use all of the data from ATLAS, this could be one of the root causes of our value not agreeing with the PDG value. We could also use more than 5,000 data points. In including more data, in either way, we could get a more accurate Z^0-boson rest mass that agrees better with the PDG value which can be a direction for us to go in next.

While this project was a success, as research scientists we can always correct and try again. Our next step is to hopefully retry the fitting and use all of the ATLAS data as opposed to cutting some of it off. We can also use more data than just 5,000 points, and we hope that these adjustments can give us a more accurate rest mass of the Z^0-boson.