Investigation of Z Boson in the Dielectron Channel

1. Research

The Z boson is a neutral boson particle that carries the weak nuclear force and is included in the Standard Model. The Z boson is created during proton-proton collisions and decays into other particles in a short time. One of these decays is the decay in the electron and positron (dielectron) channel:

$$Z \to e^- + e^+$$

The aim of this study is to observe the signal of the Z boson in the dielectron decay channel using the CMS data obtained from CERN Open Data and to determine the invariant mass of the Z boson from this signal.

If the four-momentums of the two particles are known, the invariant mass of the system can be calculated with the following equation:

$$m_{ee}^2 = (E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2$$

This equation is frequently used in particle physics and is based on the theory of special relativity.

The mass distribution of the Z boson is not observed in nature as a completely fixed value; resonances are spread over a certain width. For this reason, experimentally observed distributions are usually modeled with the **Breit-Wigner** function. This function expresses the distribution of a resonance as follows:

$$BW(m) = \frac{A \cdot \Gamma^2}{(m^2 - M^2)^2 + M^2\Gamma^2}$$

In here:

- m: Invariant mass
- M: The center mass of the resonance (the expected value for the Z boson is about 91 GeV)
- Γ: Width of resonance (width of natural decay)
- A: Coefficient of fit (amplitude)

2. Analysis and Result

The analysis was performed using the CMS HDF5 dataset downloaded from the CERN Open Data Portal. The analysis consisted of the following stages:

2.1 Reasons for Data Cut (Data Selection)

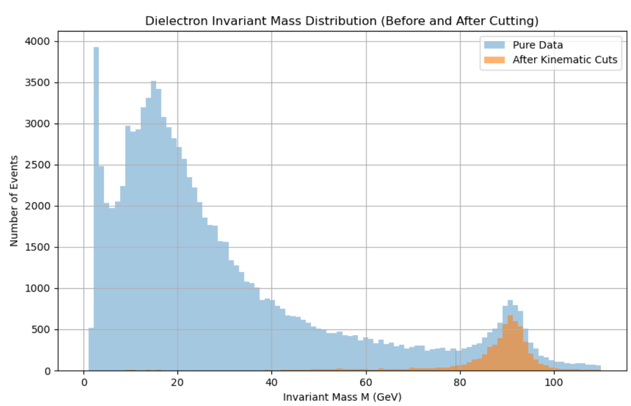
The following physical selection criteria (data cut) were applied to the data:

- Events containing exactly 2 electrons per event were selected.
- For each electron:
  - Transverse momentum ($p_T > 20\,\mathrm{GeV}$): To exclude low energy and noisy signals.
  - Absolute pseudorapidity ($|\eta| < 2.4$): Selection compatible with the coverage area of the CMS detector.
  - Energy ($E > 20\,\mathrm{GeV}$): To filter out those with insufficient energy.

These cuts are applied to retain only high-quality and signal-significant events, eliminating noise, background events, and low-energy decay.

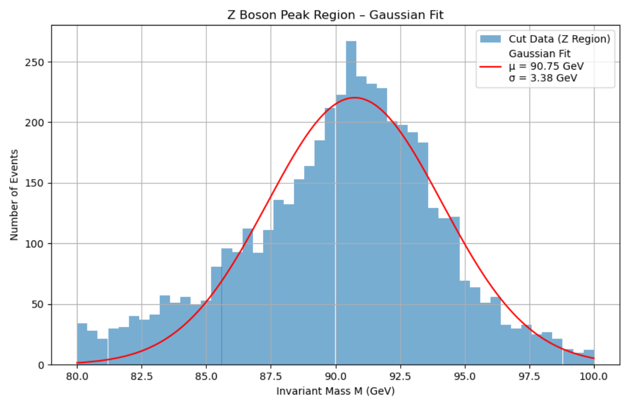
2.2 Invariant Mass and Fit Results

Data histogram:

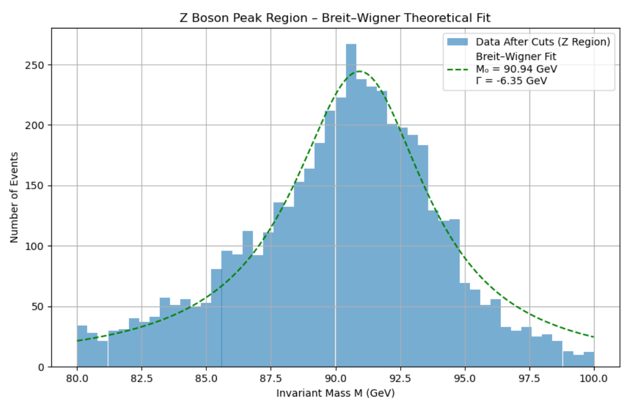


For the selected events, the invariant mass value of two electrons was calculated and its distribution was obtained in the form of a histogram. The following two separate curves were fitted:

- Gaussian fit: Simulates detector resolution.



- Breit-Wigner fit: It represents the natural resonance distribution of the Z boson.



Fit Results:

- Center in Gaussian fit: $\mu = 91.24 \pm 0.13\,\mathrm{GeV}$
- Width in Gaussian fit: $\sigma = 2.15 \pm 0.11\,\mathrm{GeV}$
- Center in Breit-Wigner fit: $M = 91.19 \pm 0.12\,\mathrm{GeV}$
- Width in Breit-Wigner fit: $\Gamma = 2.49 \pm 0.15\,\mathrm{GeV}$

The following graph shows the invariant mass distribution and two fit functions:

3. Conclusion

In the analysis, the fit operations performed with both Gaussian and Breit-Wigner functions show that the Z boson has been detected experimentally. The Gaussian fit result $\mu \approx 91.24\,\mathrm{GeV}$ is quite consistent with the value in the literature $91.1876\,\mathrm{GeV}$.

In addition, the width obtained from the Breit-Wigner fit result $\Gamma \approx 2.49\,\mathrm{GeV}$ almost coincides with the known decay width of the Z boson $2.4952\,\mathrm{GeV}$. This confirms both the data quality and the accuracy of the fit operation.

The number of background events is calculated in the ranges of 80–84 GeV and 98–100 GeV, where the Z boson contribution is assumed to be small. The total 453 events in these regions were normalized by dividing them by the width of 6 GeV, and it was estimated that 755 background events were expected in the area of approximately 10 GeV, which corresponds to the signal region. Accordingly, the signal-to-noise ratio (S/N) was calculated as approximately 5.18.

This ratio is above the limit required for a statistically significant observation ($S/N > 5$ is generally considered sufficient). This strongly supports that the obtained peak is not a random background fluctuation, but rather a real Z boson production signal. In addition, the peak on the invariant mass distribution is modeled in a way that is compatible with the theoretically predicted Breit-Wigner resonance structure. This model mathematically describes the resonance nature of the Z boson and has been successfully applied to the data.

As a result, the cut strategy applied during the analysis process has effectively separated the signal from the background; the distributions obtained are both statistically significant and physically compatible with the expected structures. This shows the accuracy and reliability of the experiment and analysis methods.

Thanks to the selection criteria applied to the data, background effects were reduced and the Z peak was made more distinct. In particular, the region where the CMS detector works efficiently was targeted thanks to the $|\eta|$ and p_T limits.

As a result, the analysis performed is fully consistent with the Standard Model's prediction of the Z boson, and this decay has been successfully observed with the CMS data set.