Z-Resonance

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Abstract

In this experiment, we analyzed data recorded by the L3 detector at CERN to study the Z boson. The main goal was to measure the particle's properties and see if they match the Standard Model. We used Python to look at real collision data and compared it with simulations to understand what different particle decays look like. This helped us separate the signal events—where the Z boson decays into hadrons or muons—from background noise. We calculated the cross-sections for these decays and fitted the results with a Breit-Wigner curve to find the mass and lifetime of the Z boson. Finally, we used these numbers to calculate the electroweak mixing angle and the number of quark colors. Gaining insight on the particle properties that could be identified and confirmed during the original experiment in the process.

1 Physical Theory

1.1 The Standard Model and Electroweak Interaction

The Standard Model of particle physics explains how the fundamental building blocks of the universe interact. It states that forces are mediated by the exchange of specific particles. For example, the electromagnetic force is carried by photons, while the weak force—which is responsible for processes like radioactive beta decay—is carried by W and Z bosons.
These two forces are actually part of a single, unified theory called the electroweak model. A central parameter in this model is the electroweak mixing angle, also known as the Weinberg angle ($\sin^2\theta_W$). This number describes how the electromagnetic and weak forces mix together. We cannot predict this angle using theory alone; it must be determined experimentally.

1.2 The Z-Resonance

In this experiment, we analyze data from the LEP collider, resulting from the collision of accelerated electrons (e^-) and positrons (e^+). When these particles collide at an energy close to the mass of the Z boson (approximately 91 GeV), they annihilate and have a great chance to create a Z boson in the process.
The Z boson is unstable and decays almost immediately into a pair of fermions ($f\bar{f}$). These can be leptons (such as muons or neutrinos) or quarks. Because of the strong interaction, quarks cannot exist individually and quickly turn into showers of particles called "jets."
The probability of producing a Z boson is called the cross-section. This probability depends heavily on the energy of the collision. If we plot the cross-section against the center-of-mass energy, we see a sharp peak at the mass of the Z boson. This peak shape is called a resonance.
We describe this curve mathematically using the Breit-Wigner distribution:

$$\sigma_f(s) = \sigma_0 \frac{s\Gamma_Z^2}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2} \tag{1}$$

In this formula the index Z stands for properties regarding the Z-Boson and

- s represents the square of the center-of-mass energy.
- M_Z is the mass of the Z boson (the location of the peak).
- Γ_Z is the total decay width.
- σ_0 is the cross-section at the very top of the peak.

However, the data we measure does not follow this curve perfectly. This is because charged particles radiate photons before colliding, which reduces the effective collision energy. This is a Quantum Electrodynamic (QED) effect. To get accurate results, we must correct for this radiation when fitting the curve to our data.

1.3 Decay Widths and Properties

The total decay width (Γ_Z) is inversely proportional to the lifetime of the particle (τ_Z). It is calculated by adding up the partial widths of all the different ways the boson can decay:

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_\nu + 3\Gamma_l \quad (2)$$

These partial widths depend on the Fermi constant (G_F), the mass of the Z boson, and the Weinberg angle mentioned earlier. When calculating the width for hadronic decays (quarks), we must also account for the fact that quarks carry "colour" charge. We use a colour factor (N_C) and a small correction for gluon emission (k_{QCD}) in this calculation:

$$\Gamma_{had} = N_C k_{QCD}(2\Gamma_u + 3\Gamma_d) \quad (3)$$

For the entirety of the analysis, uncertainties were calculated using Gaussian error propagation. The only exceptions are the integrated luminosity L of the accelerator with a systematic uncertainty of $\Delta L = 1\%$ (see [2]) and the efficiencies ϵ of our chosen cuts and their related units. These had their statistical uncertainty calculated via a Poissonian error calculation, meaning the square root of the event amount after the cut $\Delta_{stat}\epsilon = \sqrt{N_{MC}^{cut}}$ and a systematic uncertainty $\Delta_{stat}\epsilon$ estimated by slightly varying the boundaries of our data cuts.

2 The L3 Detector

The data used in this experiment was recorded by the L3 detector at CERN between 1989 and 2000. The L3 was one of four large detectors at the LEP collider. It was built as a series of concentric layers around the collision point, designed to measure the properties of particles flying outward.
Each layer has a specific function:

1. **Vertex Chamber / SMD:** This is the innermost layer. Its job is to track charged particles right after they are created. It measures their position very precisely to reconstruct their paths.
2. **Electromagnetic Calorimeter (BGO):** Surrounding the tracking chamber, this layer measures the energy of light particles, specifically electrons and photons.
3. **Hadronic Calorimeter:** Heavier particles, like the hadrons produced in quark jets, pass through the electromagnetic layer and deposit their energy here.
4. **Muon Chamber:** Muons are unique because they can penetrate through all the inner layers. The muon detector is placed on the very outside to catch them.
5. **Magnet:** The detector is enclosed in a large magnet. The magnetic field bends the paths of charged particles. By measuring how much a track curves, we can calculate the particle's momentum.

2.1 Identifying Particle Events

We can tell what kind of decay happened by looking at the signals in these layers:

- **Muon Decays:** These look like two clean tracks going in opposite directions, passing through the whole detector and hitting the outer muon chambers.
- **Hadronic Decays:** These appear as two large bursts of particles (jets) back-to-back. They deposit a lot of energy in the calorimeters and have many tracks in the center.

By selecting events that match these patterns and rejecting others (background), we can measure the properties of the Z boson.

3 Discussion

3.1 Setup For The Data Analysis

Based on our Monte Carlo MC example data, calculated at a center of mass energy of $\sqrt{s} = 91GeV$ for the hadron and muon decays, we set cuts in our data set that allowed us to identify and seperate those events in the actual data sets.
Hadronic Cut Boundaries

1. Due to the unique characteristics of our particle collision at a specific center of mass energy $\sqrt{s}$ and the conservation of energy, we expect to find that the total amount of energy disposed in the detectors during one collision lies somewhere in its vicinity. With the total amount of visible energy corresponding to $E_{vis} = \sqrt{p_x^2 + p_y^2 + p_z^2}$ from our data. We set our first boundaries as following.
$$0.3 < \frac{E_{vis}}{\sqrt{s}} < 1.7$$
2. One of the characteristic properties to identify hadronic decays is the large amount of particles detected during its process due to the hadronic showers within the detectors. We therefore set the minimum amount of particle events to 12.
3. Lastly we cut all events containing 100000 or more data events. These events would more likely be created due to measurement errors instead of actual events and therefore should not contribute to our data.

Muonic Cut Boundaries

1. Just like with the hadronic decays we expect to find our visible detected energy to be within range of the center of mass energy $\sqrt{s}$. Due to an overlap in energy events below $\sqrt{s}$ with tauonic decays, which have very similiar characteristics with the muonic decay, we use a higher upper than lower boundary (see [3], Fig. 5.3).
$$0.8 < \frac{E_{vis}}{\sqrt{s}} < 1.4$$

2. Due to the muon decay of the Z-boson always producing two muon particles, a muon and an anti muon, we set our number of detected muon particles as two. These can be identified using the mass of the detected particles.

3. Muon events should also produce a low amount of secondary events in the detectors. Because of this we cut out all detected events with more than 10 detected particles.

4. We also expect the muons in these events to still hold the majority of the energy of the decay event. We therefore set
$$\frac{E_{vis,\mu}}{E_{vis,total}} >= 0.6$$
Meaning, that the detected muons hold 60% or more of the total detected energy.

These cuts then give us an efficiency value ϵ based on our MC-Data, which corresponds to the ratio of the cut out data events N_{MC}^{cut} and actual total events N_{MC} in that dataset. In the future this will allow us to approximate the efficiency at which we can identify those events, compared to the actual amount of events that took place during our measurements.

$$\epsilon = \frac{N_{MC}^{cut}}{N_{MC}} \tag{4}$$

Due to our chosen cuts, this value can vary slightly for different center of mass energies $\sqrt{s}$ therefore giving different values for each of our datasets as well.
We found that for both cuts the statistical uncertainty of ϵ was greater than the estimated systematical one. Nevertheless, for each calculated value, the systematic uncertainty corresponded to at least 10% of the statistical uncertainty. It is therefore not possible to speak of a dominant source of uncertainty between the two. For example we take the uncertainty of the $91.33GeV$ values. For the hadronic cut we had statistical uncertainty of $\Delta_{stat}\epsilon = 1.00\%$ and a systematic uncertainty of $\Delta_{stat}\epsilon = 0.26\%$ and for the muonic cut $\Delta_{stat}\epsilon = 0.78\%$ and $\Delta_{stat}\epsilon = 0.55\%$ (see Tables 1 and 2).

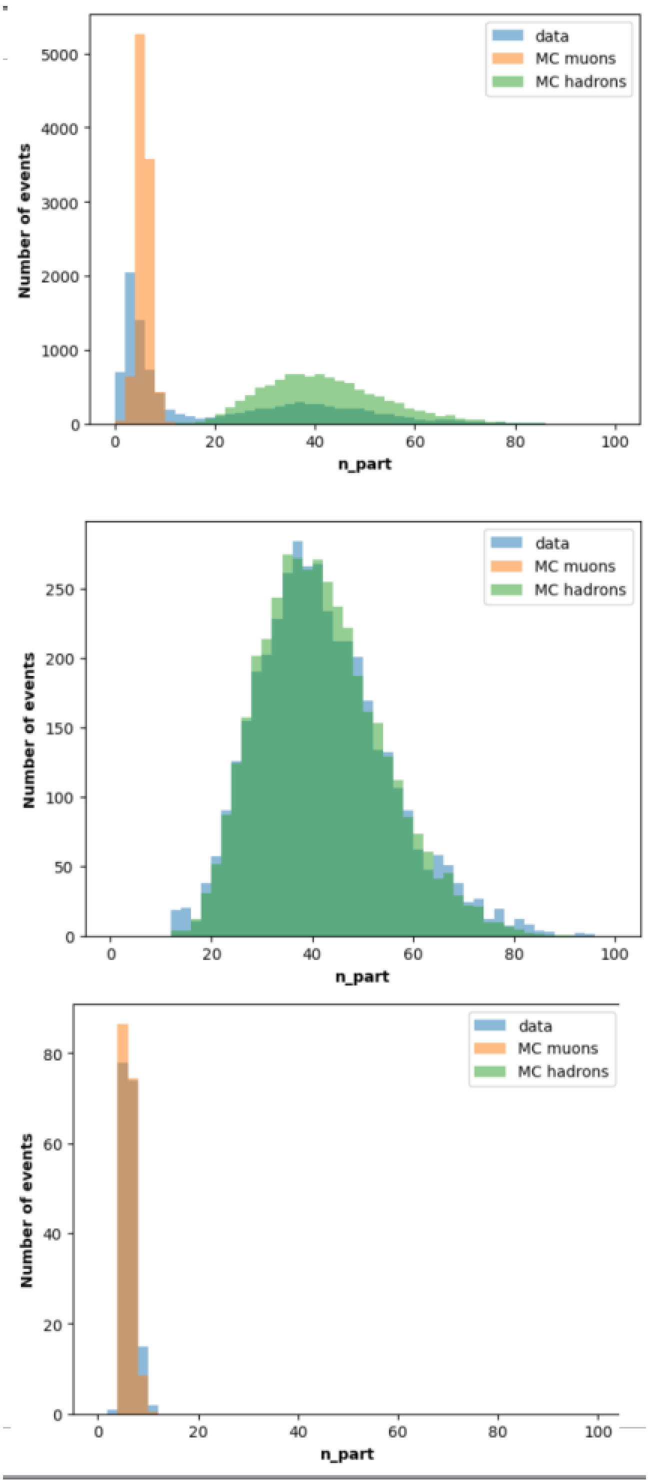

Abb. 1: Number of events in the $\sqrt{s} = 91.33GeV$ dataset for n-detected particles during that event compared to the Monte Carlo data; from top to bottom: direct comparison, comparison of hadron cut with normalized MC data, comparison of muon cut with normalized MC data

We further approximate the amount of remaining background events N_{bkg}^{cut} in our cut out events N_{tot}^{cut} for each of the measured data sets. In this case we use a normalization of the MC-Data to compare it with our measured data and approximate the background by comparing the difference in event numbers per chosen interval. Adding those together, results in a sufficiently accurate value for our background events including a Poissonian uncertainty of $\sqrt{N_{bkg}^{cut}}$.

Using our previously identified efficiency ϵ and the measured luminosity at different $\sqrt{s}$ values, we can now calculate the corresponding cross section for those data sets.

$$\sigma = \frac{N_{tot}^{cut} - N_{bkg}^{cut}}{\epsilon \cdot L} \tag{5}$$

$\sqrt{s}$ in GeV	ϵ	L in nb^{-1}	σ in nb
89.49	99.83 ± 1.30	179.3 ± 1.8	9.04 ± 0.20
91.33	99.83 ± 1.26	135.9 ± 1.4	27.62 ± 0.53
93.02	99.81 ± 1.32	151.1 ± 1.6	13.09 ± 0.27

Table 1: Center of mass energy $\sqrt{s}$, efficiency ϵ, integrated luminosity L of the accelerator and cross section σ resulting from the chosen hadron cuts

$\sqrt{s}$ in GeV	ϵ in %	L in nb^{-1}	σ in nb
89.49	60.11 ± 1.33	179.3 ± 1.8	0.73 ± 0.08
91.33	60.14 ± 1.33	135.9 ± 1.4	1.86 ± 0.08
93.02	60.15 ± 1.28	151.1 ± 1.6	0.91 ± 0.08

Table 2: Center of mass energy $\sqrt{s}$, efficiency ϵ, integrated luminosity L of the accelerator and cross section σ resulting from the chosen muon cuts

We find that the efficiency of the muonic cut is around 30% lower than that of the hadronic cut that has an almost 100% efficiency. This can be explained using the Figures 1, 4 and 5. If we compare the graphics in the middle and on the right with the one on the left, we can see that for the muonic cut, the one in the middle, a lot of events were cut out with a higher amount of particles. This was necessary due to a potential higher background of these areas of data with other potential decays in opposition to the hadronic cut, which shows that this event has unique characteristics which seemingly allowed us to seperate it from other decays with a higher accuracy.

We can also see from Tables 1 and 2 that the cross section of our two decays is the highest for the $91.33GeV$, which is in line with our expectations stating that it should be highest near the Z-boson mass of $M_{Z,ref} = (91.188 \pm 0.002)GeV$ (see [1], for current reference value). The cross section is also siginificantly lower for the muonic than the hadronic decays at the same $\sqrt{s}$ values. This means that the probability of a muon decay is much lower than that of a hadronic decay, which is in line with the current understanding of the Z-boson decay process.

Using our now calculated values we can extrapolate the Z-resonance parameters. For this we use a combination of the Breit-Wigner probability density function (see Eq. 1) and an additional term corresponding to the probability of photon emission, therefore taking QED effects into account. For further information you can look at the attached code excerpts that were used to fit our data.

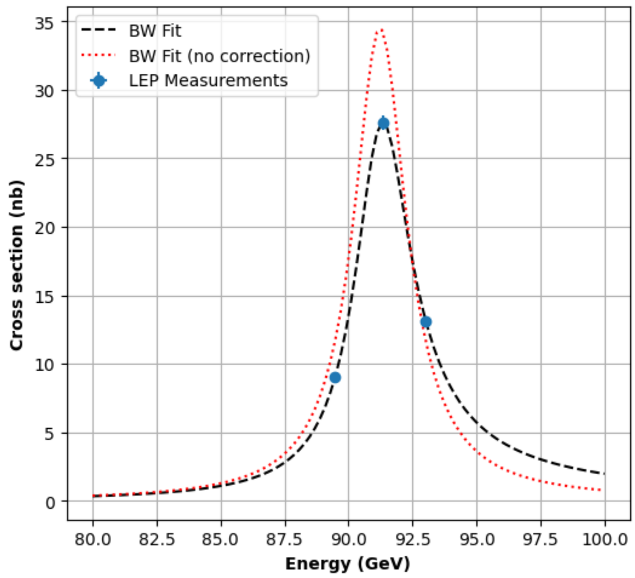

Abb. 2: Fit of the hadronic cross section σ over their respective center of mass energies $\sqrt{s}$ from Table 1 and the corresponding correction due to QED effects

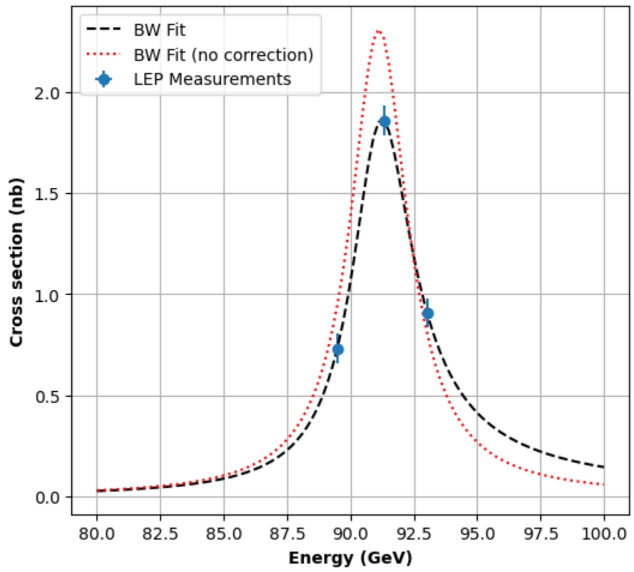

Abb. 3: Fit of the muon cross section σ over their respective center of mass energies $\sqrt{s}$ from Table 2 and the corresponding correction due to QED effects

Decay	Hadronic	Muonic
$\sigma_{0\ \max}$ in nb	34.50 ± 0.70	2.31 ± 0.11
M_Z in GeV	91.21 ± 0.03	91.10 ± 0.11
Γ_Z in GeV	2.53 ± 0.06	2.76 ± 0.20

Table 3: Resulting fit parameters from Figure 2 and 3 with their respective uncertainties

3.2 Property Calculation

$$\sigma_0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_i \Gamma_f}{\Gamma_Z^2} \tag{6}$$

Using the formula for the calculation of the maximum cross-section σ_0 for the decay via a Z-Boson, from an initial state i to a specific final state f we can now approximate the partial width of the electron Γ_e. This is possible due to the initial state corresponding to an electron, positron collision, meaning $i = e$ and the final state, in our case, corresponding to either the muon or hadron partial width depending on the data being used.

3.2.1 Calculation On Muon Data

Due to the properties of the Z-boson decay, we can assume that Lepton universality applies for our decays.

$$\Gamma_l = \Gamma_e = \Gamma_\mu = \Gamma_\tau \tag{7}$$

By inserting $\Gamma_{f=\mu} = \Gamma_e$ into Eq. 6 and rearranging to the Γ_e partial width, we can now calculate the partial width of the electron decay.

$$\Gamma_e = M_{Z,\mu}\Gamma_{Z,\mu}\sqrt{\frac{\sigma_{0,\mu}}{12\pi}} = (99.69 \pm 7.38)MeV \tag{8}$$

3.2.2 Calculation On Hadron Data

In order to calculate the partial width of the electron decay using our hadron data, we need to substitute the partial width of the hadron Γ_{had}, that we use in Eq. 6 as our final state partial width Γ_f. For this we can use Eq. 2. Rearranged to Γ_{had} we get:

$$\Gamma_{had} = \Gamma_Z - 3\Gamma_\nu - 3\Gamma_l \tag{9}$$

Here Γ_Z corresponds to the Z-resonance partial width from our hadron data fit. Γ_l is under lepton universality (Eq. 7) the partial width of the electron decay that we are searching for and Γ_ν stands for the partial width of the decay into a neutrino. The factor 3 in front of it corresponds to the possible leptons created during the decays, and therefore the possible neutrinos that could be generated.
We can estimate Γ_ν utilizing the equation for the partial width of the final fermion state of a Z-boson decay depending on the electroweak mixing angle or Weinberg angle θ_W:

$$\Gamma_f = \frac{G_F M_Z^3}{24\sqrt{2}\pi}[1 + (1 - 4|Q_f|sin^2(\theta_W))^2] \tag{10}$$

Here Q_f stands for the fermion charge corresponding to 0 for neutrinos ν, ±1 for charged leptons, $+\frac{2}{3}$ for u and c quarks and $-\frac{1}{3}$ for d, s and b quarks. We do not expect that a t quark can be generated, due to its rest mass being higher than those of the Z-boson in our reference values and in Table 4. The Fermi constant is given as $G_F = 1.166 \cdot 10^{-5} GeV^{-2}$.
This means we can calculate the final state partial width for the neutrinos Γ_ν without knowing the electroweak mixing angle θ_W. By inserting $f = \nu$ and $Q_\nu = 0$ we get

$$\Gamma_\nu = (165.97 \pm 0.14)MeV \tag{11}$$

Putting Eq. 9 into Eq. 6 with $\Gamma_{f=had}$ then rearranging to Γ_e and solving the resulting quadratic equation we get:

$$\Gamma_e^\pm = \frac{1}{2}(\frac{1}{3}\Gamma_Z - \Gamma_\nu) \pm \sqrt{[\frac{1}{2}(\Gamma_\nu - \frac{1}{3}\Gamma_Z)]^2 - \frac{\sigma_0 \Gamma_Z^2 M_Z^2}{36\pi}} \tag{12}$$

$$\Gamma_e^- = (68.60 \pm 1.92)MeV \tag{13}$$

$$\Gamma_e^+ = (609.96 \pm 1.92)MeV \tag{14}$$

We can see that we get two possible values for the electron partial width Γ_e. Due to our previous calculations from the muonic decay and our reference values we choose to accept Γ_e^- as our result. This value aligns better with our previous value and expectations compared to Γ_e^+ which exceeds them by almost a factor of 10 and does not compensate for it with a higher uncertainty.
We can also see that our Γ_e for the hadronic decay and that for the muonic decay do not lie within each others uncertainties. We expect this to result from an insufficiently estimated systematic uncertainty for the values used in the Breit-Wigner fits as seen in Tables 1 and 2 or from a potential higher uncertainty of the fit, which was not considered during its process. Since our reference value of the electron partial width lies between these two values at $\Gamma_{e,ref} = (83.91 \pm 0.12)MeV$ and both values should be considered equally accurate from our calculations, we decided to use the average value of our two values in our following calculations: $\Gamma_{e,avg} = (84.30 \pm 3.81)MeV$. We did the same for our measured Z-boson mass $M_{Z,avg} = 91.16 \pm 0.06$ and partial width $\Gamma_{Z,avg} = 2.65 \pm 0.11$

3.2.3 Hadronic Decay Width Γ_{had}

Putting our now estimated partial width of the leptons Γ_l and the Z-boson Γ_Z into Eq. 9, we can estimate the partial width of the hadron during this decay as

$$\Gamma_{had} = (1895.65 \pm 106.41)MeV \tag{15}$$

3.2.4 Weinberg Angle θ_W

Again using the Equation 10 we can now also calculate the Weinberg angle. To do this, we set the final state as the lepton state and convert to θ_W.

$$sin^2(\theta_W) = \frac{1}{4}(\pm\sqrt{\frac{24\sqrt{2}\pi\Gamma_{l=e}}{G_f M_Z^3}} - 1 + 1) \qquad (16)$$

$$sin^2(\theta_W)^- = 0.219 \pm 0.046 \qquad (17)$$

$$sin^2(\theta_W)^+ = 0.281 \pm 0.046 \qquad (18)$$

The calculated values have an overlapping uncertainty and both include our reference value of $sin^2(\theta_W) = 0.23148 \pm 0.00013$ within their range. We decided to continue calculating with $sin^2(\theta_W)^-$, since it lies closer to our reference value.

3.2.5 Number Of Colours N_C

We can calculate the number of colours utilizing Eq. 3. Here $k_{qcd} = 1.04$, taking the gluon emission of the quarks into account.
With Eq.10 and our Weinberg angle θ_W we can additionally calculate the remaining quark decay widths.

$$\Gamma_u = (97.25 \pm 8.44) MeV \qquad (19)$$

$$\Gamma_d = (124.43 \pm 7.17) MeV \qquad (20)$$

Using these we can now estimate the number of colours of the hadronic decay by rearranging the equation to

$$N_C = \frac{\Gamma_{had}}{k_{qcd} \cdot (2\Gamma_u + 3\Gamma_d)} = 3.21 \pm 0.24 \qquad (21)$$

Which includes the known number of 3 different quark colours within its margin of error.

4 Comparison To Literature And Error Discussion

Variable	Reference Value	Hadronic Decay	Muonic Decay	Average
Maximum Cross Section σ_0 in nb	-	34.50 ± 0.70	2.31 ± 0.11	-
Z-Boson Mass M_Z in GeV	91.188 ± 0.002	91.21 ± 0.03	91.10 ± 0.11	91.16 ± 0.06
Z-Boson Partial Width Γ_Z in GeV	2.4955 ± 0.0023	2.53 ± 0.06	2.76 ± 0.20	2.65 ± 0.11
Electron Partial Width Γ_e in MeV	83.91 ± 0.12	68.60 ± 1.92	99.69 ± 7.38	84.30 ± 3.81
Neutrino Partial Width Γ_ν in MeV	-	165.97 ± 0.14	-	165.66 ± 0.31
Hadron Partial Width Γ_{had} in MeV	1744.4 ± 2.0	-	-	1895.65 ± 106.41
Up Quark Partial Width Γ_u in MeV	-	-	-	97.25 ± 8.44
Down Quark Partial Width Γ_d in MeV	-	-	-	124.43 ± 7.17
Weinberg Angle $sin^2(\theta_W)$	0.23148 ± 0.00013	-	-	0.219 ± 0.046 0.281 ± 0.046
Number of Colours N_C	3	-	-	3.21 ± 0.24

Table 4: Final parameters taken from the reference source [1], the hadronic and muonic data and their average used in later calculations

We find that most of our data aligns well with our reference values following our use of the average calculated partial widths and Z-boson mass from both fits. Almost every value from our average calculation has an overlapping uncertainty with our reference values. For the electron line width the corresponding value Γ_e from our reference was used. The partial widths of muon $\Gamma_\mu = (83.99 \pm 0.18) MeV$and tauon$\Gamma_\tau = (84.08 \pm 0.22) MeV$ lie extremely close to it and well within the uncertainty range of our final value. Based on this it is safe to say that the principle of Lepton universality was acceptable within the scope of this experiment. However the Z-boson partial width and the Hadron Partial width do not. We assume since the hadron partial width uses the other one as a term in its calculation, that this is a follow-up error from the error-prone Z-boson partial width values. This is further supported by the fact, that both values with their respective uncertainties lie above the reference value, which aligns with our use of Γ_Z for the calculation of Γ_{had} as seen in Eq.9.
We expect that the excessive values for Γ_Z, from the hadronic and muonic fit results from the fact that our selected cuts were chosen on the MC data at $91GeV$. This should have resulted in a great selection of events for the data from the close by $\sqrt{s}$ value of $91.33GeV$, but not exactly for the lower and higher $\sqrt{s}$ values. This can further be seen in the Figures 4 and 5, were the difference between the MC data and filtered data is visibly higher for the muon and hadron cut compared to Figure 1. This means that our chosen cut does not represent this data well, resulting in more error-prone values for the cross section of these two energies. Since the maximum cross section of the Breit-Wigner fit (Abb.2, 3) σ_0 is a lot more dependent on the closest value to it, in our case the $\sqrt{s} = 91.33GeV$ that was well approximated, and the partial width of the Z-boson Γ_Z is more dependent on the shape of the curve, these lower and higher $\sqrt{s}$ values should have a higher influence on it.
To counteract this loss of accuracy we propose to either use seperate MC Data closer to these two energies in order to either choose a better cut for these datapoints or improve their efficiency value that was calculated using the MC Data. Both of these affect the calculated cross section and therefore our fit parameters.
In the case of our data we propose to increase the systematic uncertainty of these cross section values to represent the lower accuracy that is provided for these datasets following the choice of our MC data.
We also assume that an accurate result could be achieved from the data of the muonic or hadronic decay, without using the average of these two. This could probably result from choosing the cuts more carefully and with better insight. However, since our total result deliveres us an accurate representation of the currently known values, it is safe to say that our calculations were successful.

5 Conclusion

Over the course of this experiment we managed to use the Monte Carlo simulation data to successfully seperate the muonic and hadronic events in our experimental data. However the further away the center of mass energy $\sqrt{s}$ of our actual data was from the simulation data with a center of mass energy of $\sqrt{s} = 91GeV$, the less accurate were our results.

This lead us to assume that our corresponding uncertainties for the cross section of that data were chosen with too small of a systematic uncertainty and that the use of Monte Carlo data closer to those values for further analysis would provide better results.
However by using the average of the calculated electron decay widths Γ_e and our fit parameters from the different decay selections we managed to get values that align with the currently known properties of the particles in the context of the Z-boson decay.
We can therefore say that in the process of this experiment we gained a lot of insight about the analysis of this LEP experimental data and gained a better understanding of the properties of the Z-boson and its associated decays.

Literature

References

[1] Particle Data Group. *Z Boson, physical review*. 2024-2025. URL: `https://pdf.lbl.gov/2025/listings/rpp2025-list-z-boson.pdf`.

[2] M. zur Nedden; R D Parsons; U. Schwanke; F. Peri; *Instructions for the Z0 Praktikum*. 2025.

[3] EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH. *Results from the L3 Experiment at LEP*. February 22, 1993. URL: `http://physik.hu-berlin.de/de/eephys/teaching/lab/z0resonance/ppe93-031.pdf`.

6 Attachments

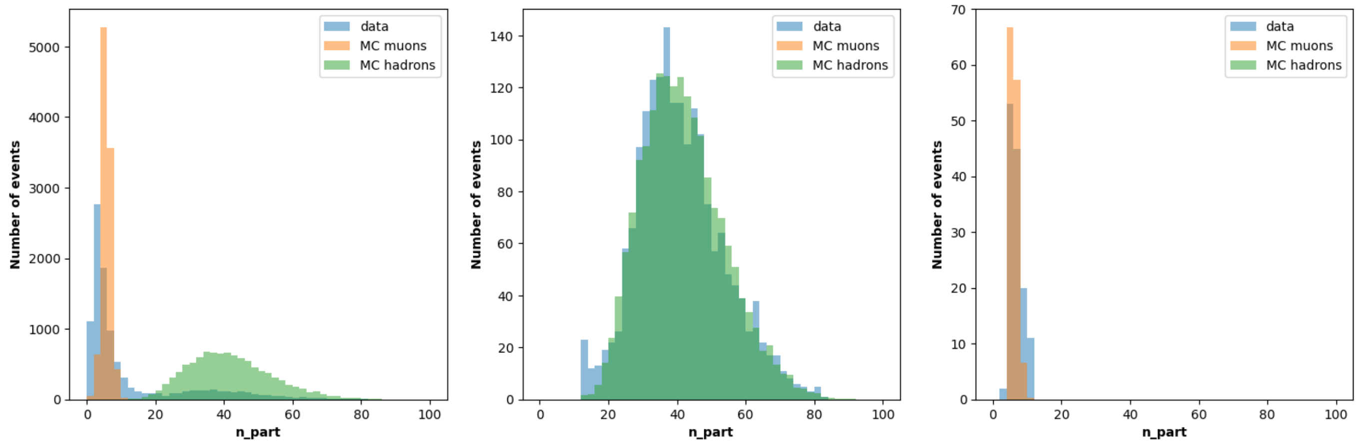

Abb. 4: Number of events in the $\sqrt{s} = 89.49GeV$ dataset for n-detected particles during that event compared to the Monte Carlo data; from left to right: direct comparison, comparison of hadron cut with normalized MC data, comparison of muon cut with normalized MC data

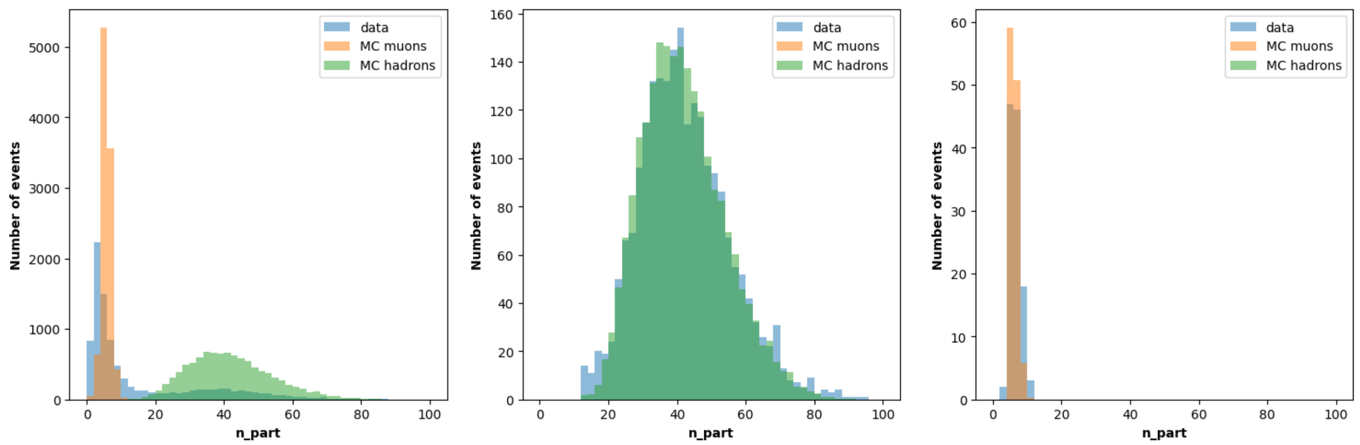

Abb. 5: Number of events in the $\sqrt{s} = 93.02GeV$ dataset for n-detected particles during that event compared to the Monte Carlo data; from left to right: direct comparison, comparison of hadron cut with normalized MC data, comparison of muon cut with normalized MC data