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Examination of e^+e^--collisions and determination of mass and lifetime of the Z boson.

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Abstract. Here we summarize results from the L3 experiment using data the detector has taken in 1993. The analysis results in the determination of important parameters like mass m_z or lifetime τ_z of the Z boson with a precision of 0.4%. That knowledge allows testing the Standard Model of elementary particles. Furthermore, the number of different neutrinos could be determined. The e^+e^--annihilations has been realized at centre of mass energies around 91 GeV, the theoretically predicted mass of the Z boson. We calculated the properties of the Z boson by concentrating only on the hadronic decay channel of the Z particle.

1 Introduction

The Large Electron Positron Collider (LEP) was build in order to produce large numbers of Z bosons. This particle is one of the neutral field quantums that characterize the unified force of electromagnetic and weak interaction. The basic properties of Z boson are fundamental constants in our physical world view. By using the L3 detector within a precision experiment at LEP we could determine the Z parameters mass m_z and average lifetime τ_z with the highest accuracy so far.

2 Experiment

At the LEP, packages of electrons and of positrons collided with center of mass energies $\sqrt{s} \approx 91\,\text{GeV}$, because the Z boson has been most frequently produced, if the impulse energy was equivalent to the theoretically predicted mass of this particle. Afterwards the Z boson decayed in pairs of fermions, i.e. with the greatest probability of 0.7 in quark-antiquark-pairs.

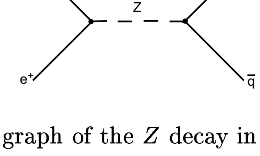

Fig. 1. Feynman graph of the Z decay in quark/antiquark

The quarks did not appear as observable particles but as hadronic jets. The signals of the hadronic jets were recorded by the fine-grain calorimeter of the L3 detector. Compared to other possible decay channels [1, S.27], the hadronic one was filtered out by the quantity and by the direction of their momentum and energy or by the number of registered energy clusters. By means of the number of hadronic events we calculated the total cross section by the following equation

$$\sigma = \frac{N}{\mathcal{L}} \,. \tag{1}$$

Here $\mathcal{L}$ is the luminosity that specifies the intensity of interaction of LEP with the particle beam. Depending on the impulse energy, the total cross section was resonantly elevated at $\sqrt{s} = m_z$ and could be described by a Breit-Wigner-distribution

$$\sigma = \sigma_o \frac{s\Gamma_z^2}{(s - m_z^2)^2 + m_z^2 \Gamma_z^2} \,. \tag{2}$$

By fitting our calculated results of the cross section on the Breit-Wigner-distribution, we determined the parameters σ_o, m_z and $\tau_z = \Gamma^{-1}$.

3 Data analysis

3.1 Event selection

Here we briefly describe the analysis method used for the hadronic decay channel. The selection of the hadronic decay was based on the deposition of momenta and energy in the hadron calorimeters. For ensuring a high agreement of data with Monte Carlo generated events, we had to consider the following criteria:
(1) For the total calorimetric energy E per event observed in the detector it is necessary, that

$$0.5 < \frac{E}{\sqrt{s}} < 1.5 \,. \tag{3}$$

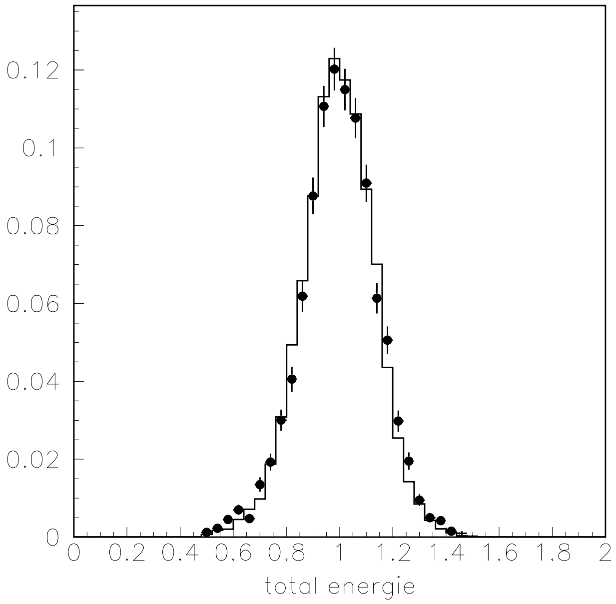

Fig. 2. Distribution of total energy excluding non-resonant background ('cut' between $0.5 \cdot \sqrt{s}$ and $1.5 \cdot \sqrt{s}$) in comparison to data of Monte-Carlo-Simulation for hadronic events (solid line).

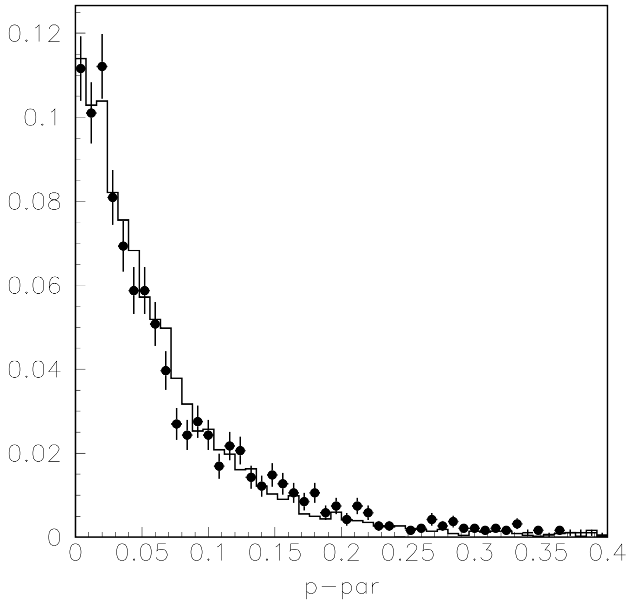

Fig. 4. Distribution of total parallel momentum $p_{\parallel} \approx E_{\parallel}$ ('cut' for $E_{\parallel} > 0.6 \cdot E$) in comparison to data of Monte-Carlo-Simulation (solid line).

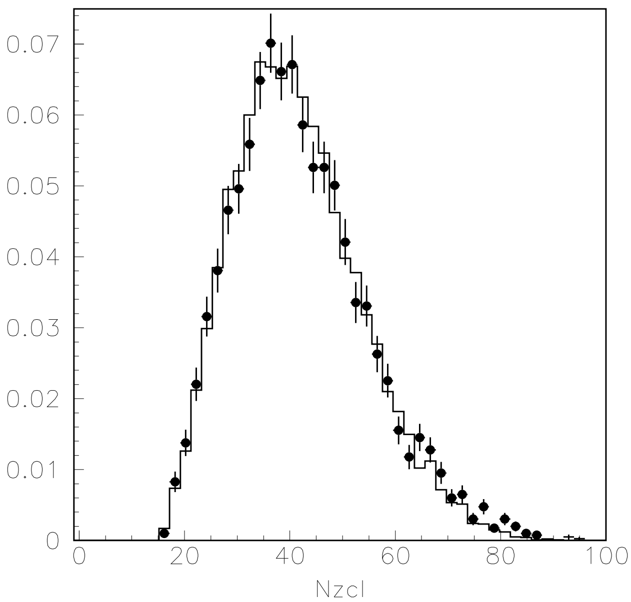

Fig. 3. Total number of registered energy clusters per event excluding values lower than 16 compared to data of Monte-Carlo-Simulation for hadronic events (solid line).

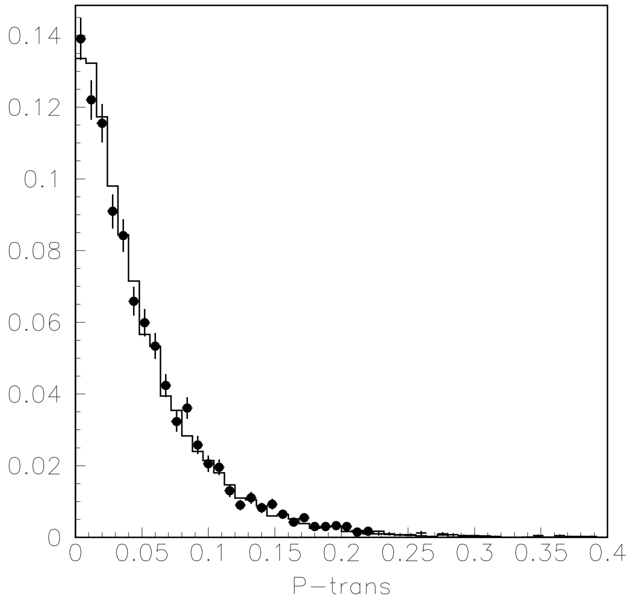

Fig. 5. The distribution of total transversal momentum $p_{\perp} = \sqrt{p_x^2 + p_y^2} \approx E_{\perp}$ ('cut' for $E_{\perp} > 0.5 \cdot E$) in comparison to data of Monte-Carlo-Simulation (solid line).

This is because the event rate in the region lower than 0.5 represented non-resonant background from beam-gas interactions or two-photon events. In addition a total energy higher than 1.5 was very improbable for hadronic decays.
(2) The total number of energy clusters N_{cl}, reconstructed in the calorimeter required to satisfy

$$N_{cl} > 16 \qquad (4)$$

because the average number of charged grains in hadronic events was around 20 and much larger than in leptonic ones. Therefore, the decay in pairs of leptons (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$) could be excluded.
(3) The sum of all transversal/parallel momenta per event had to fulfill

$$p_{\parallel} \approx E_{\parallel} < 0.6 \cdot E \quad , \quad p_{\perp} \approx E_{\perp} < 0.5 \cdot E \qquad (5)$$

because we assumed, that the total energy was symmetrically distributed over all directions. Figures 2-5 show our results after the cuts (1)-(3) had been applied. At this moment we could check the efficiency by comparing the number of hadronic events N_{MC} which we knew from the Monte Carlo generated data, and from the number of events N'_{MC} after applying the criteria on the same data.

$$\epsilon = \frac{N'_{MC}}{N_{MC}} = 0.9901 \tag{6}$$

3.2 Calculating the total cross section

We used the developed method in order to determine the number of hadronic events N' for three different center of mass energies. If we consider the efficiency and the background events N_u, which accidentally lie within our selection criteria, than the corrected equation is

$$N = \frac{N' - N_u}{\epsilon} \stackrel{N_u \to 0}{=} \frac{N'}{\epsilon} \ . \tag{7}$$

To study the dependence of N on the selection rules, we varied our cuts within reasonable limits. The uncertainty can be estimated to be less than 0.3% and has to be added in quadrature to the statistical error $\sqrt{N}$. The error of luminosity $\mathcal{L}$ was assigned to 1%. By formula (1) we calculated the total cross sections σ including their uncertainties (Table 1).

$\sqrt{s}$ [GeV]	N	$\mathcal{L}$ [nb^{-1}]	σ [nb]
89.48	1802±46	179.33±1.8	10.05±0.36
91.33	4033±72	135.95±1.4	29.66±0.83
93.02	2051±50	151.07±1.5	14.25±0.47

Table 1. Centre of mass energy $\sqrt{s}$, the corrected number of hadronic events N, luminosity $\mathcal{L}$ and the calculated total cross section σ including their uncertainties.

The three values of σ describe the resonance curve (Fig. 6) of the Z quite well, so that a fit on the Breit-Wigner-distribution (2) seemed reasonable. Therefore we obtained the parameters mass m_z and average lifetime τ_z of Z boson with high accuracy.

$$\begin{aligned} m_z &= (91.173 \pm 0.040) \ \text{GeV} \\ \tau_z &= (2.58 \pm 0.09) \cdot 10^{-25} \, \text{s} \end{aligned}$$

4 Summary

Though the Z boson can generally not be observed as a single particle, its properties m_z and τ_z were accurately determined by the L3 experiment. Furthermore the experiment allowed to precisely test the Standard Model and the experiment proved its validity. In addition the resonance curve provided another important information, namely the number of different neutrinos. The total width Γ_z depends on the kind and number of other possible decay channels. The number of possible leptonic decay channels equally defines

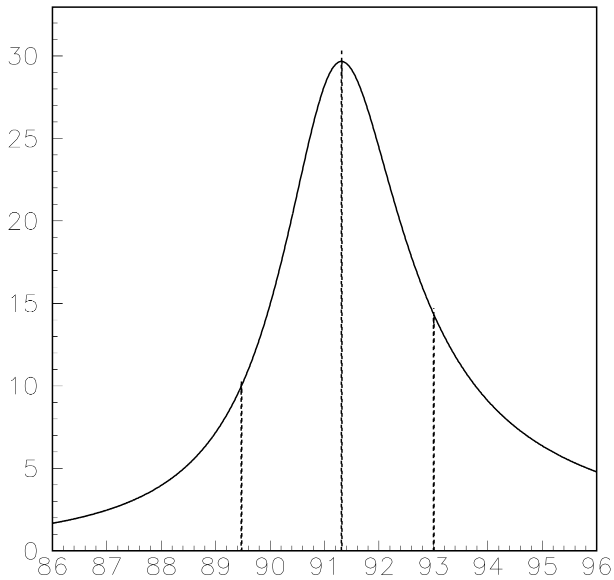

Fig. 6. The calculated cross sections we fitted on a Breit-Wigner-function. The x-value of the peak indicates m_z, the total width represents τ_z^{-1}.

the number of different neutrinos. In our experiment the measurement of Γ_z only corresponded to the assumption of three kinds of neutrinos. A more exact analysis by including further experiments (ALEPH, DELPHI and OPAL) resulted in

$$N_\nu = 2.96 \pm 0.06 \ .$$

Therefore, the periodic system of elementary particles is already complete with the three known families of quarks and leptons, because the existence of a fourth kind of neutrino was definitely excluded.

References

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