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Determination of the Leptonic Branching Ratios of the Z

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Abstract

The ratios of the numbers of Z bosons decaying to e^+e^- , $\mu^+\mu^-$ and $\tau^+\tau^-$ pairs to the number decaying to hadrons have been measured. The branching ratios and partial widths for each channel were determined and found to be equal, consistent with lepton universality. The mean leptonic branching ratio was found to be 0.0321 ± 0.0013 and the leptonic partial width to be 85.4 ± 5.3 MeV. The partial widths for hadronic decays and for invisible decays were deduced to be 1833 ± 116 MeV and 569 ± 92 MeV, respectively. The number of light neutrino types, assuming only the standard model value for the ratio Γ_e/Γ_ν , was found to be 3.35 ± 0.41 .

Introduction

The advent of the LEP e^+e^- collider [1] allows the decays of the Z, the neutral weak boson [2], to be studied in more detail than ever before. In this paper we present measurements of the ratios of the numbers of e^+e^- , $\mu^+\mu^-$ and $\tau^+\tau^-$ decays to hadronic decays of the Z. The data were taken at centre of mass energies close to the peak of the Z resonance, for which the line shape has been measured previously in this experiment [3]. These ratios, together with the peak cross section to hadrons, allow the leptonic, hadronic and invisible branching ratios to be determined. The partial widths of the Z are then obtained using the measured total width.

The experiment was performed at the LEP e^+e^- collider at CERN using the ALEPH apparatus [3,4] to detect the decays of the Z. The data were taken in the first long run of LEP ending in October 1989. For this analysis the centre of mass energy was restricted to the range 90 to 92.5 GeV i.e. close to the Z peak and the integrated luminosity was 104 nb^{-1} . The parts of the ALEPH detector relevant to this analysis are shown in fig. 1. They consist of an inner tracking chamber (ITC) and a time projection chamber (TPC) inside a magnetic field of 1.5 T. This system served to detect and momentum analyse the charged particle tracks produced by the annihilation of the colliding electrons and positrons. External to the TPC, an electromagnetic calorimeter (ECAL) was used to measure the energy of electrons and to detect and measure photons. The whole of this system is situated inside a superconducting coil. A hadronic calorimeter (HCAL), outside the coil, was used to measure the energy of hadrons and to identify muons.

The apparatus was triggered independently by several separate conditions, three of which were important for the detection of Z decays. The first demanded a total deposition of energy greater than 6 GeV in the ECAL central section (the barrel), or greater than 3 GeV in either ECAL endcap, or greater than 1 GeV in both endcaps. The second trigger required a charged track in the ITC associated in azimuth with energy deposition of more than 1 GeV in the ECAL. The third trigger was defined by a coincidence between any of the HCAL azimuthal segments with a corresponding azimuthal segment of the ITC. A signal in an HCAL segment was registered if hits were recorded at a depth of at least 30 cm of iron in the barrel region or at least 55 cm of iron in the endcap region. A signal in any ITC segment was registered by at least five of its eight cylindrical wire layers. For each trigger, flags were set in the data to indicate the trigger source and its azimuthal segment. The trigger efficiency was measured for each decay mode by comparing the different triggers, as discussed below.

The data were processed through a chain of computer programmes in order to perform the operations of pattern recognition, track reconstruction and momentum analysis. Good tracks were each required to have a polar angle θ with $|\cos \theta| < 0.95$, to be reconstructed from

at least four TPC hits and to originate from within a cylinder, centred on the interaction point, radius 2 cm and length 20 cm along the beam. The reconstruction efficiency for isolated tracks was measured by selecting Bhabha events ($e^+e^- \rightarrow e^+e^-$) defined by ECAL clusters of more than 35 GeV energy. The fraction of these in which both tracks were reconstructed was found to be $99.0 \pm 0.6\%$, in good agreement with the predicted fraction from a Monte Carlo simulation of $99.2 \pm 0.1\%$. Thus correction for track reconstruction efficiency was unnecessary since the observed small losses were well simulated by the Monte Carlo.

Hadronic decays of the Z were selected, as in [3], by requiring a minimum of five charged tracks which carried in total at least 10% of the centre of mass energy. A total of 2619 Z to hadron decays satisfied these selection criteria. The acceptance for these decays was calculated to be 0.975 ± 0.006 [3] from a Monte Carlo simulation in which the generated digitizations were passed through the same reconstruction programmes as the data.

The lepton final states of the Z are distinguished from the hadronic final states by their low multiplicity. For a first lepton preselection the number of charged tracks was required not to exceed six. This limit was chosen to retain leptonic decays of the Z which were accompanied by e^+e^- pairs from photon conversions and to have high efficiency for tau decays. Further procedures were then implemented to identify the individual leptonic decay channels, as described below.

The Decay Mode $Z \rightarrow e^+ e^-$.

The events for this process were separated from the other reactions by a combination of cuts on charged particle multiplicity, particle momenta and energy deposition in ECAL. Events were retained if there were at least two tracks and the sum of the momenta of the two most energetic tracks exceeded 35 GeV/c. The sum of the ECAL energies associated with these two tracks was required to exceed 40 GeV and their acollinearity to be less than 20 degrees. Furthermore, the scattering angle, η , defined as the angle between the beam and the bisector of the external angle of the two tracks, was required to satisfy $|\cos \eta| < 0.90$. The resulting sample contained 168 events.

With the cuts listed above, the acceptance for events generated with the programme BABAMC [5] and passed through a Monte Carlo simulation and reconstruction was 93.5%. The loss was made up of 2.5% due to the acollinearity cut, and the remainder from the momentum and energy cuts. The systematic error on this acceptance was estimated to be 2%, mainly due to the uncertainty in the effect of the energy cut. This was obtained by varying the cuts and observing the change in the acceptance. The change in the measured number of events was well reproduced by the Monte Carlo simulation, showing that the acceptance and backgrounds were well understood.

The angular distribution for these events, corrected bin by bin for the acceptance, is shown in fig. 2. The contribution from t channel photon exchange must be subtracted to obtain the number of $Z \rightarrow e^+ e^-$ events. Because this contribution peaks in the forward direction, only the region $\cos \eta < 0.7$ was used to extract the $Z \rightarrow e^+ e^-$ signal. The t channel cross section was evaluated by first generating $e^+ e^-$ and $\mu^+ \mu^-$ events with BABAMC and MUONMC [5]. The Monte Carlo events were generated at the experimental energies to account for the change in the interference effects with energy. At the Z pole these interference effects disappear and they largely cancel when averaging data taken equally above and below the Z peak. The Monte Carlo programmes are first order generators, identical except for the t channel effects which can therefore be extracted to the same first order by comparing the event distributions. The generated events were used only to obtain the shape of the t channel contribution, which was then normalised to reproduce the observed excess of events in the forward direction. The final correction was 15.3% with interference effects contributing only 1.5%.

The trigger efficiency was measured by observing the number of times the ITC-ECAL and ECAL energy trigger flags were both set. It was found to be 100% and no correction was applied. The correction for the τ background was estimated from a Monte Carlo calculation to be $(4.5 \pm 1.0)\%$. Correcting for this and for the extrapolation into the unmeasured angular intervals $\cos \eta < -0.9$ and $\cos \eta > 0.7$ (assuming a $1 + \cos^2 \eta$ distribution) gives the corrected number of events to be $126.7 \pm 15.7(\text{stat}) \pm 3.4(\text{syst})$. Here the systematic error represents the uncertainties of acceptance (2%), τ subtraction (1%) and the t channel subtraction (1.5%) added in quadrature. The ratio of the number of electronic to hadronic decays of the Z is then found to be

$$P_e = \frac{\Gamma_e}{\Gamma_h} = 0.0472 \pm 0.0061, \quad (1)$$

Here Γ_e is the electronic and Γ_h the hadronic decay width of the Z. The systematic and statistical errors have been added in quadrature.

The Decay Mode $Z \rightarrow \mu^+ \mu^-$.

The events for this process were separated from the preselected lepton sample using only the HCAL barrel data, corresponding to polar angle satisfying $|\cos \theta| < 0.61$, since the HCAL endcap digital readout was not yet operational. Cuts were applied to eliminate $\tau^+ \tau^-$ decays from the sample by demanding that the particle with the largest momentum had at least 35 GeV, that the second largest momentum had at least 22 GeV and that the angle of acollinearity was less than 15° . According to Monte Carlo studies using the KORALZ generator [6], this cut retained $(97.9 \pm 0.2)\%$ of the μ pairs, $(1.4 \pm 0.1)\%$ of the τ pairs

and the majority of the e^+e^- pairs. After these cuts the background from two photon interactions and from hadronic Z decay was negligible.

The $\mu^+ \mu^-$ pairs were then separated from the e^+e^- pairs by using the muon identification capability of the HCAL barrel. An event was selected as a $\mu^+ \mu^-$ pair if at least one of the two tracks was identified as a muon, i.e. it had produced an ITC-HCAL trigger in that segment and had penetrated to a depth of more than 30 cm of iron in HCAL. We observed 57 such events, 22 with only one and 35 with both muons identified. The overall trigger and identification efficiency for $\mu^+ \mu^-$ events in the accepted polar angular region was found to be 0.95 ± 0.03 .

Figure 3 shows a scatter plot of the distance of closest approach to the beam line (d) versus the corresponding distance along the beam from the interaction point (z), for each muon track in the final sample. It can be seen that all of these muons come from the beam interaction region, whereas cosmic ray muons would populate the entire plot. In figure 4 the z distribution for the tracks of the final sample is compared to that of the preselected sample. The entries in the preselected sample with $|z| > 4$ cm are mostly due to the cosmic ray background, which is found to give a negligible contribution to the final sample.

After correcting for the geometrical acceptance (52.3%) and the τ background (0.6%), the total number of μ pairs was found to be 116.8 ± 15.8 (stat) ± 3.0 (syst). The systematic error was determined by changing the kinematic cuts. The main contribution came from a systematic inaccuracy in the momentum scale, which is currently being calibrated, of up to 10% at 45 GeV. Thus the ratio of the number of $Z \rightarrow \mu^+ \mu^-$ decays to the number of Z decays to hadrons is

$$P_\mu = \frac{\Gamma_\mu}{\Gamma_h} = 0.0433 \pm 0.0060. \quad (2)$$

The Decay Mode $Z \rightarrow \tau^+ \tau^-$.

The decays of the $Z \rightarrow \tau^+ \tau^-$ were chosen from the preselected sample by first demanding events with at least one track with momentum of more than 3 GeV. The thrust axis was determined and events were retained if they had at least one track in each hemisphere and a total transverse momentum relative to the beam greater than 2.5 GeV in one or both hemispheres. The acollinearity angle between the axes of the jets defined in each hemisphere was then required to be less than 26° . These cuts eliminated most of the background from two photon interactions. The angle between any track in the jet and the jet axis was required to be less than 18.2° . This eliminated the majority of the residual decays of the Z to hadrons. At this stage, the surviving events consisted mainly of the decays of the Z to leptons.

Events with single charged tracks in each hemisphere were excluded if both track momenta were larger than 35 GeV, or 30 GeV if the tracks were identified in the calorimeters as both electrons or both muons. This eliminated most of the decays of the $Z \rightarrow e^+e^-$ and $\mu^+\mu^-$. To reinforce this, a cut was also made demanding that the energy in the ECAL associated with each track was less than 30 GeV. In addition, to eliminate e^+e^- pairs with final state radiated photons, the summed energy in ECAL was required to be less than 70 GeV. Furthermore, to eliminate $\mu^+\mu^-$ pairs with a final state radiated photon, events with two muons and an energy cluster in ECAL were kinematically identified and rejected.

The data and Monte Carlo have been compared and found to be consistent. Fig. 5 shows the total energy spectrum of the charged tracks from the data compared to the predictions of the Monte Carlo simulation. The final sample contained 115 events. The backgrounds in this sample were estimated by Monte Carlo calculation to consist of 1.0 ± 0.6 events from two photon interactions and a negligible number of events from the decays of the Z to hadrons. The backgrounds from residual e^+e^- and $\mu^+\mu^-$ pairs were estimated to be 4 ± 3 and 0 ± 1 events, respectively. These were measured from the data by observing the number of times an event identified as an e^+e^- or $\mu^+\mu^-$ in one hemisphere was misidentified as a τ in the opposite hemisphere. The cosmic ray muon background was estimated to be 0.5 ± 0.2 events by taking the observed number of events at large values of d (the closest distance of approach to the interaction point) and extrapolating, under the peak at small values of d coming from beam interactions. Correcting for all these backgrounds gives the total number of $\tau^+\tau^-$ events to be 109.5 ± 10.8 (stat) ± 3.2 (syst), where the systematic error comes from adding in quadrature the errors on the number of background events.

The detection efficiency for $\tau^+\tau^-$ pair production was calculated to be $0.859 \pm .020$ (syst), from a Monte Carlo simulation which included the effects of all the cuts. The trigger efficiency was measured from the data by comparing the number of events in which only one or both azimuthal segments of the trigger along each τ direction were set. The average efficiency for a single τ to produce a trigger was found to be 93.4%. The efficiency for either τ to produce a trigger was then calculated to be $98.3 \pm 0.7\%$, taking into account a dead region in the ITC for part of the data. The corrected number of $\tau^+\tau^-$ events becomes 129.7 ± 12.7 (stat) ± 4.9 (syst), giving

$$P_\tau = \frac{\Gamma_\tau}{\Gamma_h} = 0.0483 \pm 0.0051 . \quad (3)$$

Discussion of the Results

The three measured values of the ratio P_λ , for the decay to each lepton type λ , are shown in column 2 of table 1. They are equal within the errors, in agreement with lepton universality. The branching ratios $B_\lambda = \Gamma_\lambda / \Gamma_Z$ can be deduced from the ratios P_λ as follows. The cross section for hadron production in $e^+ e^-$ collisions at the energy of the Z mass, after correction for initial state radiation, is given by

$$\sigma_o^h = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_h}{\Gamma_Z^2} = \frac{12\pi}{M_Z^2} B_e \frac{B_\lambda}{P_\lambda}. \quad (4)$$

This cross section, the mass and width of the Z have been measured in this experiment [3] to be 39.1 ± 1.6 nb, $M_Z = 91.18$ GeV and $\Gamma_Z = 2.66 \pm 0.16$ GeV, respectively. Using these with the measured value of P_e , the electron branching ratio, B_e , can be obtained from equation 4. Then, substituting this value, B_μ and B_τ can be obtained from the measured values of P_μ and P_τ . These values of B_e , B_μ and B_τ are given in column 3 of table 1. The partial widths, Γ_λ , are then calculated using the measured value of Γ_Z and are shown in column 4 of table 1. The quoted errors take account of the correlation between the numbers of hadrons used in the determinations of P_λ and σ_o^h , and of the correlation between σ_o^h and Γ_Z .

Since the values of P_e , P_μ and P_τ are equal within errors, compatible with lepton universality, they have been combined giving $P_a = 0.0466 \pm 0.0034$ for an average charged lepton. Using this value in equation 4, the mean charged leptonic branching ratio is found to be $B_a = 0.0321 \pm 0.0013$. This corresponds to a partial width, $\Gamma_a = 85.4 \pm 5.3$ MeV, in agreement with the value 83.4 MeV predicted by the Standard Electroweak Model [7]. From this value of Γ_a , the branching ratio for Z decays to hadrons is deduced using equation 4 to be $B_h = 0.689 \pm 0.030$ and the partial width $\Gamma_h = 1833 \pm 116$ MeV.

Since the branching ratios add to unity, the ratio Γ_{inv} / Γ_a is given by

$$\frac{\Gamma_{inv}}{\Gamma_a} = \frac{1}{B_a} - \frac{1}{P_a} - 3 = 6.67 \pm 0.81 \quad (5)$$

where Γ_{inv} is the partial width to invisible decays assumed to be due to neutrinos. The correlations mentioned above lead to cancellations in the error which were previously noted by Feldman [8].

Taking the value $\Gamma_\nu / \Gamma_a = 1.99$ [7], expected from the Standard Electroweak Model, the number of neutrino types is 3.35 ± 0.41 . It should be noted that this ratio is the only assumption from the standard model made in this analysis. The result is still valid if additional unexpected hadronic states were to be present in Z decays. Taking Γ_a to be the value measured,

the invisible width is 569 ± 92 MeV. The values of the branching ratios and partial widths, derived above, are summarised in table 1.

In conclusion, the ratios of the leptonic to hadronic Z decays have been measured for electrons, muons and taus. The values obtained are compatible with each other, consistent with the principle of lepton universality. The mean leptonic branching ratio is found to be 0.0321 ± 0.0013 , corresponding to a partial width $\Gamma_a = 85.4 \pm 5.3$ MeV. The branching ratio and partial width for hadronic decays are found to be 0.689 ± 0.030 and 1833 ± 116 MeV, respectively. The number of light neutrino species is deduced to be 3.35 ± 0.41 and the partial width for the invisible decay modes of the Z is found to be 569 ± 92 MeV.

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TABLE 1

Decay	P	B	$\Gamma(\text{MeV})$
$Z \rightarrow e^+ e^-$	0.0472 ± 0.0061	0.0323 ± 0.0021	85.9 ± 6.9
$Z \rightarrow \mu^+ \mu^-$	0.0435 ± 0.0060	0.0298 ± 0.0046	79.3 ± 12.8
$Z \rightarrow \tau^+ \tau^-$	0.0483 ± 0.0051	0.0331 ± 0.0041	88.0 ± 11.7
$Z \rightarrow l^+ l^-$	0.0466 ± 0.0034	0.0321 ± 0.0013	85.4 ± 5.3
$Z \rightarrow \text{hadrons}$		0.689 ± 0.030	1833 ± 116
$Z \rightarrow \text{invisible}$		0.214 ± 0.029	569 ± 92

Figure Captions

1. A section through the ALEPH apparatus transverse to the beam direction, showing a τ pair decaying to a muon and three pions. The curvature of the muon in HCAL is opposite to that in the TPC since the magnetic field is in the opposite sense in HCAL which acts as the return path.
2. The angular distribution for $e^+ e^- \rightarrow e^+ e^-$ showing the t-channel peak in the forward direction.
3. Distance of closest approach to the beam line, d , versus distance along the beam line, z .
4. The distribution of distance along the beam, z
 - a) the preselected lepton sample
 - b) the final selected muon pairs.
5. The total charged energy distribution for the final $\tau^+ \tau^-$ sample.

Figure 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5