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*Published in:*  
Physics Letters B

*DOI:*  
[10.1016/0370-2693\(90\)90476-M](https://doi.org/10.1016/0370-2693(90)90476-M)

[Link to publication](#)

*Citation for published version (APA):*

Adeva, B., Adriani, O., Aguilar-Benitez, M., Akbari, H., Alcaraz, J., Aloisio, A., ... Linde, F. L. (1990). Measurement of Z0 decays to hadrons and a precise determination of the number of neutrino species. *Physics Letters B*, 237, 136-146. DOI: 10.1016/0370-2693(90)90476-M

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**MEASUREMENT OF  $Z^0$  DECAYS TO HADRONS,  
AND A PRECISE DETERMINATION OF THE NUMBER OF NEUTRINO SPECIES**

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Received 9 January 1990

We have made a precise measurement of the cross section for  $e^+e^- \rightarrow Z^0 \rightarrow \text{hadrons}$  with the L3 detector at LEP, covering the  $\sqrt{s}$  range from 88.28 to 95.04 GeV. From a fit to the  $Z^0$  peak, we determined the  $Z^0$  mass, total width, and the hadronic cross section to be  $M_{Z^0} = 91.160 \pm 0.024$  (experiment)  $\pm 0.030$  (LEP) GeV,  $\Gamma_{Z^0} = 2.539 \pm 0.054$  GeV, and  $\sigma_h(M_{Z^0}) = 29.5 \pm 0.7$  nb. We also used the fit to the  $Z^0$  peak cross section and the width to determine  $\Gamma_{\text{invisible}} = 0.548 \pm 0.029$  GeV, which corresponds to  $3.29 \pm 0.17$  species of light neutrinos. The possibility of four or more neutrino flavors is thus ruled out at the  $4\sigma$  confidence level.

## 1. Introduction

Accurate measurements of the cross section for  $e^+e^- \rightarrow \text{hadrons}$  in the mass region of the neutral intermediate vector boson  $Z^0$  are important in providing a precise determination of the  $Z^0$  properties, and of the number of light neutrino-like particles in the universe. The fundamental parameters of the standard electroweak model [1], and their internal consistency, may then be tested with higher sensitivity by combining measurements of hadronic decays, leptonic decays, and the forward-backward charge asymmetry for muon pairs [2,3].

We report on measurements of the  $Z^0$  mass  $M_{Z^0}$ , the total width  $\Gamma_{Z^0}$ , and the partial width into neutrinos  $\Gamma_{\text{invisible}}$  obtained with the L3 detector at LEP. The data, which were taken at ten center of mass energies covering the range of the  $Z^0$  peak:  $88.28 \text{ GeV} \leq \sqrt{s} \leq 95.04 \text{ GeV}$ , were used to determine the number of neutrino flavors precisely. Earlier measurements of  $Z^0$  properties may be found in refs. [2,4] <sup>#1</sup>.

Thanks to the increased luminosity of LEP (typically  $3 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ ) we were able to increase our statistics by a factor of six over our previous analysis [2]. The systematic accuracy of our result on the  $Z^0$

<sup>1</sup> Supported by the German Bundesministerium für Forschung und Technologie.

<sup>#1</sup> After the completion of this analysis we learned of similar results from ref. [5].

cross section has been substantially improved by use of the hadron calorimeter end caps, which cover the angular range down to  $5^\circ$  from the beam line. The systematic accuracy of our  $Z^0$  mass measurements also has been improved through the recent energy scale determination performed by the LEP Machine Group, which includes calibrations performed with protons stored in LEP [6].

## 2. The L3 detector

The L3 detector [2,7] covers 99% of  $4\pi$  sr. The detector includes a central vertex chamber, a precise electromagnetic calorimeter composed of BGO crystals, a uranium and brass hadron calorimeter with proportional wire chamber readout, a high accuracy muon chamber system, and a ring of scintillation trigger counters. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction. The luminosity is determined by measuring small-angle Bhabha events in two calorimeters consisting of BGO crystals, which are situated on either side of the interaction point. A detailed description of each detector subsystem, and its performance, may be found in ref. [7].

For the present analysis, we used the data collected in the following ranges of polar angles:

- for the hadron calorimeter,  $5^\circ < \theta < 175^\circ$ ,
- for the muon chambers,  $35.8^\circ < \theta < 144.2^\circ$ ,
- for the electromagnetic calorimeter,  $42.4^\circ < \theta < 137.6^\circ$ .

The data from the vertex chamber were not used in this analysis.

## 3. Triggers for hadron events

The primary trigger used for hadronic events in this analysis requires a total energy in the large-angle calorimeters of 15 GeV. For the bulk of the data, this trigger was put into a logical OR with a second independent trigger, which required six of sixteen scintillation counter  $\phi$  sectors to be fired. An analysis of the accepted hadronic events, during the period when both triggers were in operation, showed that the calorimetric trigger is at least 99.9% efficient, and the scintillation counter trigger is 93% efficient.

During the early running-in of the hadronic calorimeter end caps, we found and corrected a small trigger inefficiency in the end cap region. The effect on the acceptance was determined to be  $(1.8 \pm 0.3)\%$ .

## 4. Measurement of luminosity

The luminosity is measured by eight radial layers of small-angle BGO crystals ( $24.7 \text{ mrad} < \theta < 69.3 \text{ mrad}$ ) situated on either side of the interaction point, at  $z = \pm 2.765 \text{ m}$ . The energy resolution of the calorimeters is dominated by the calibration accuracy, and was typically 2% during running. The  $\theta$  and  $\phi$  impact coordinates of the electron and positron in the BGO calorimeters were determined from the observed energy sharing among the crystals, and from a fitting function derived from the known average shape of electromagnetic showers. The energy of the incident particle was also corrected for the lateral loss from the calorimeters (typically by a few percent) using this technique.

We used the following cuts to select the Bhabha event candidates:

- (1)  $170^\circ < \Delta\phi < 190^\circ$ ,
- (2)  $30.1 \text{ mrad} \leq \theta_1 \leq 63.9 \text{ mrad}$  and  $24.7 \text{ mrad} \leq \theta_2 \leq 69.3 \text{ mrad}$ ,
- (3)  $E_1 > \frac{2}{3} E_{\text{Beam}}$  and  $E_2 > \frac{1}{3} E_{\text{Beam}}$ ,

where  $\Delta\phi$  is the coplanarity angle between the incident electron and positron, and  $\theta_{1,2}$ ,  $E_{1,2}$  are their polar angles and energies. The definition of cut (2) above means that one particle enters a small fiducial region on either side of the interaction region, and the second particle enters a larger fiducial region on the other side. Two event samples were collected. In the first sample a particle was required to enter the smaller fiducial region ( $30.1 \text{ mrad} \leq \theta_1 \leq 63.9 \text{ mrad}$ ) in the BGO calorimeter at  $z > 0$ , while in the second sample the smaller fiducial region was used in the calorimeter at  $z < 0$ . The number of events used to calculate the luminosity was the average of the number of events in the two samples. The use of this method reduces the systematic effect of possible offsets in position and angle of the calorimeters relative to the beam line (at most 2 mm and 1 mrad) to the 0.1% level.

The trigger used to select Bhabha events, for the luminosity measurement, requires a back-to-back co-

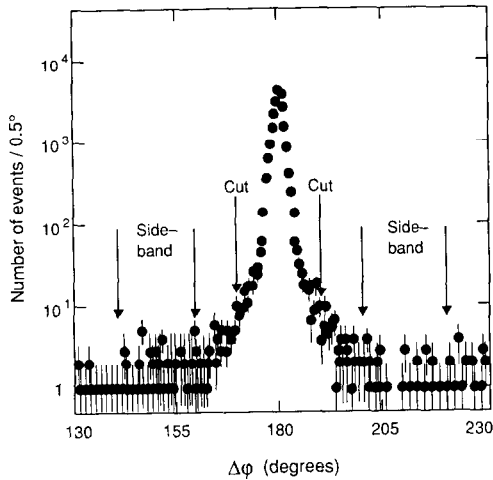


Fig. 1. The coplanarity distribution  $\Delta\phi$  of the events in the luminosity monitor. The cut  $170^\circ < \Delta\phi < 190^\circ$ , and the sidebands used to correct for background (determined to be 0.1%) are indicated by the arrows in the figure.

incidence with at least 16.5 GeV in each small-angle BGO calorimeter. The efficiency of this trigger was checked by using an asymmetric loose trigger which required a high energy hit (30 GeV or more) in one BGO calorimeter, and a second hit above a low energy threshold (7.5 GeV) in the other calorimeter. Using the second trigger, we found that the trigger inefficiency for selecting Bhabha events was  $(1.4 \pm 0.2)\%$ . This was traced to a small geometrical region found to be inefficient. The  $\phi$  distribution of accepted events showed the same net inefficiency:  $(1.5 \pm 0.1)\%$ . Outside of this region the trigger was found to be at least 99.9% efficient. We therefore assigned a systematic error due to the uncertainty in the trigger inefficiency of 0.2%.

Fig. 1 shows the coplanarity distribution  $\Delta\phi$  reconstructed in the calorimeters, which clearly demonstrates that the  $e^+e^-$  Bhabha scattering peak is nearly background free. The background level was determined to be 0.1%, with a systematic error well below 0.1%. We corrected for the background run by run, by using the rate of events in the side bands of the  $\Delta\phi$  distribution (indicated in the figure).

To determine the acceptance,  $e^+e^- \rightarrow e^+e^-(\gamma)$  events were generated at  $\sqrt{s} = M_{Z^0}$  using the BHLUMI program described in ref. [8]. The generated events were passed through the L3 detector simulation program, which includes the effects of energy loss, multiple scattering and showering in the detector materials and the beam pipe. The simulated events were analyzed by the same program used to analyze the data. The accepted cross section was corrected by 0.5% for contamination from the process  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  [9] #2. The correction for the contribution from  $e^+e^- \rightarrow Z^0 \rightarrow e^+e^-$  is zero at the  $Z^0$  peak and at most  $\pm 0.2\%$  near the peak [10].

The systematic uncertainty in the accepted cross section includes contributions from Monte Carlo statistics (0.8%) and internal detector geometry (0.8%). The theoretical uncertainty, resulting from approximations in the calculation used in BHLUMI, and the effect of higher order terms, is estimated to be less than 1%. (A comparison with the Bhabha scattering program of Berends and Kleiss [11] #2 showed that the two programs agreed to within 0.6%.) Adding these numbers in quadrature, we obtain an overall systematic uncertainty in the accepted cross section of 1.5%.

The systematic error in the event selection, and its

#2 Programs supplied to L3 by the authors.

Table 1  
Change of acceptance  $\epsilon$  (%) and luminosity  $L$  with different cuts.

| $\theta_1$ cut (mrad)          | $\Delta\phi$ cut (deg.)  | $E_{1,2}$ cuts (GeV)          | Data $\epsilon$ (%) | MC $\epsilon$ (%) | $\Delta L$ (%) |
|--------------------------------|--------------------------|-------------------------------|---------------------|-------------------|----------------|
| $30.1 \leq \theta_1 \leq 63.9$ | $170 < \Delta\phi < 190$ | $\frac{2}{3} E_{\text{Beam}}$ | —                   | —                 | —              |
| $35.6 \leq \theta_1 \leq 63.9$ | $170 < \Delta\phi < 190$ | $\frac{3}{5} E_{\text{Beam}}$ | -35.35              | -35.43            | 0.12           |
| $41.1 \leq \theta_1 \leq 63.9$ | $170 < \Delta\phi < 190$ | $\frac{2}{3} E_{\text{Beam}}$ | -59.30              | -59.24            | -0.15          |
| $30.1 \leq \theta_1 \leq 63.9$ | $173 < \Delta\phi < 187$ | $\frac{2}{3} E_{\text{Beam}}$ | 0.31                | 0.25              | 0.06           |
| $30.1 \leq \theta_1 \leq 63.9$ | $165 < \Delta\phi < 195$ | $\frac{2}{3} E_{\text{Beam}}$ | -0.40               | -0.32             | -0.08          |
| $30.1 \leq \theta_1 \leq 63.9$ | $170 < \Delta\phi < 190$ | $0.56 E_{\text{Beam}}$        | 2.89                | 2.11              | 0.77           |

effect on the integrated luminosity  $L$ , is shown in table 1. The value of  $L$  is very stable against changes in the cuts. By adding in quadrature the RMS change in  $L$  as the cuts in each variable  $\theta$ ,  $\Delta\phi$  and  $E$  are varied over a relatively large range, we estimated a systematic error in  $L$  due to event selection of 0.8%.

Combining the systematic uncertainties in the trigger efficiency (0.2%), in the accepted cross section (1.5%), and in the Bhabha event selection (0.8%), we obtain a total systematic uncertainty in the luminosity of 1.7%.

The number of Bhabha events and the corresponding integrated luminosity for each center of mass energy for the recent runs at LEP, are listed in table 2.

### 5. Event selection and acceptance for hadron events

The events from the process  $e^+e^- \rightarrow Z^0 \rightarrow \text{hadrons}$  were selected and analyzed by two independent groups of physicists. Each group decided on its own event selection criteria and cuts (one set of criteria is described in detail below). The two event samples obtained differed by 1%, and the acceptances for hadronic events (97% and 98% respectively) varied by 1% in the same direction, resulting in a difference in the calculated cross sections of less than 0.5%. The agreement in the event samples and cross sections gives us added confidence in the validity of the results, and in the systematic errors which we quote.

The event selections were both based entirely on the energy measured in the BGO and hadron calorimeters. The Monte Carlo distributions were generated by the LUND parton shower program, JETSET 6.3, which is described in ref. [12]. The b and c quark fragmentation functions were adjusted to match the inclusive muon spectra observed in the L3 detector. The generated events were passed through the L3 detector simulation (which is based on GEANT 3.13 [13]) which includes the effects of energy loss, multiple scattering, interactions and decays in the detector materials and beam pipe. After simulation, the events were analyzed by the same program used to analyze the data.

The hadronic events listed in table 2 were selected using the following criteria:

- (1)  $0.5 < E_{\text{vis}}/\sqrt{s} < 1.5$ ,
- (2)  $|E_{\parallel}|/E_{\text{vis}} < 0.37$ ,

$$(3) E_{\perp}/E_{\text{vis}} < 0.37,$$

where  $E_{\text{vis}}$  is the total energy observed in the detector,  $E_{\parallel}$  is the energy imbalance along the beam direction, and  $E_{\perp}$  is the transverse energy imbalance.

The number of jets was found using a two-step algorithm which groups the energy deposited in the BGO crystals and in the hadron calorimeter towers into clusters, before collecting the clusters into jets. We required:

$$(4) \text{Number of jets above } 5 \text{ GeV} \geq 2.$$

The clustering algorithm normally reconstructs only one cluster for each electron or photon shower, and a few clusters for  $\tau$ 's. We were therefore able to reject  $e^+e^-$  events in the hadron calorimeter, outside of the range covered by the BGO crystals, and  $\tau^+\tau^-$  events, by a cut on the number of clusters:

$$(5) N_{\text{cluster}} > 10.$$

Noise events in the detector were rejected by requiring that the total visible energy divided by the number of hit elements is large:

$$(6) E_{\text{vis}}/N_{\text{hit}} > 0.10 \text{ GeV}.$$

The remaining  $e^+e^-$  final-state events in the BGO electromagnetic calorimeter, at large scattering angles, were rejected by a cut on the visible energy:

$$(7) E_{\text{BGO}} < 0.8\sqrt{s}.$$

Applying these cuts to a sample of simulated events, we calculate an acceptance of  $(96.7 \pm 0.3)\%$  (statistical error) for hadronic decays of the  $Z^0$ . An analysis of simulated  $e^+e^-$  and  $\tau^+\tau^-$  final states yields a net contamination in the hadronic event sample of less than 0.06% and  $(0.11 \pm 0.02)\%$  respectively. The contribution to the event sample from the "two-photon process"  $e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow \text{hadrons}$  has been found to be negligible.

The simulated distributions in the visible energy, energy balance, and a wide range of jet shape variables agree very closely with the corresponding distributions obtained for the real data. Fig. 2 shows that the data distributions in  $E_{\text{vis}}/\sqrt{s}$ ,  $|E_{\parallel}|/E_{\text{vis}}$ ,  $E_{\perp}/E_{\text{vis}}$  and the number of energy clusters ( $N_{\text{clusters}}$ ) are in excellent agreement with the Monte Carlo predictions. Fig. 3 shows that the Monte Carlo also accurately predicts the event shapes, as measured by thrust ( $T$ ), Major, Minor, and oblateness ( $O$ ) [14].

On the basis of our study of the sensitivity of the cross sections to variations of the cuts, and because the event shapes have been demonstrated to be very accurately described, we are able to conservatively

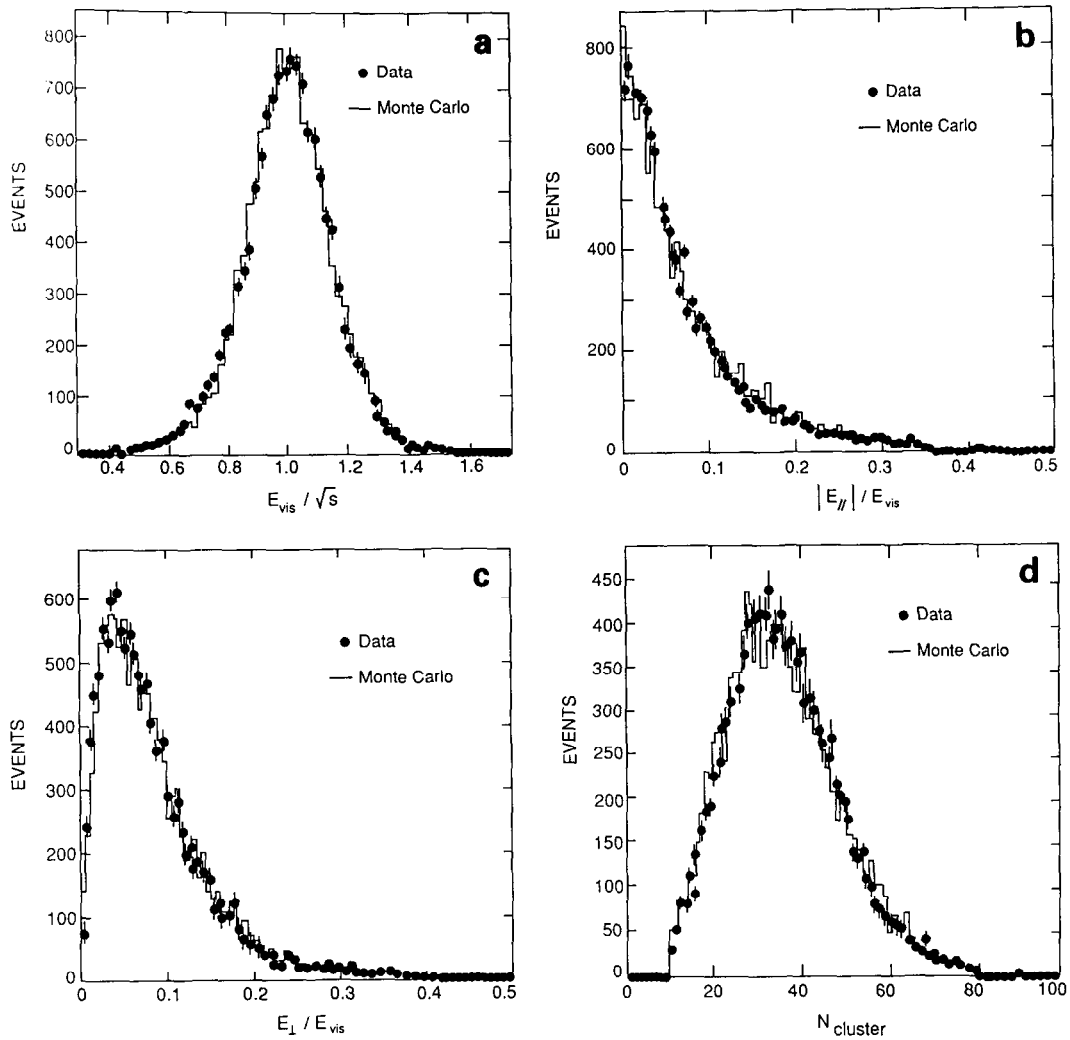


Fig. 2. (a) Distribution of the observed total energy  $E_{vis}$  normalized to  $\sqrt{s}$  compared to the Monte Carlo simulation for hadron events. (b) Distribution of the observed energy imbalance parallel to the beam direction  $|E_{\parallel}|$  normalized to the observed total energy  $E_{vis}$  compared with Monte Carlo. (c) Distribution of the observed energy imbalance perpendicular to the beam direction  $E_{\perp}$  normalized to the observed total energy  $E_{vis}$  compared with Monte Carlo. (d) Distribution of the observed number of energy clusters in the calorimeters  $N_{cluster}$  compared with Monte Carlo.

assign a total systematic error in the acceptance of 0.9%.

Visual scans of more than a thousand events confirmed that the background in the hadronic event sample (events not from high energy  $e^+e^-$  interactions) is not more than 0.3%. During these scans, pattern recognition of the tracks in the vertex chamber helped in the classification of the events.

Adding the statistical and systematic uncertainties in the acceptance, and the uncertainty in the trigger efficiency in quadrature, we obtain an overall systematic error in the corrected number of hadronic events of 1.0%. Combining this error with the 1.7% error on the luminosity in quadrature, the overall systematic error on the measured hadronic cross sections is 2.0%.



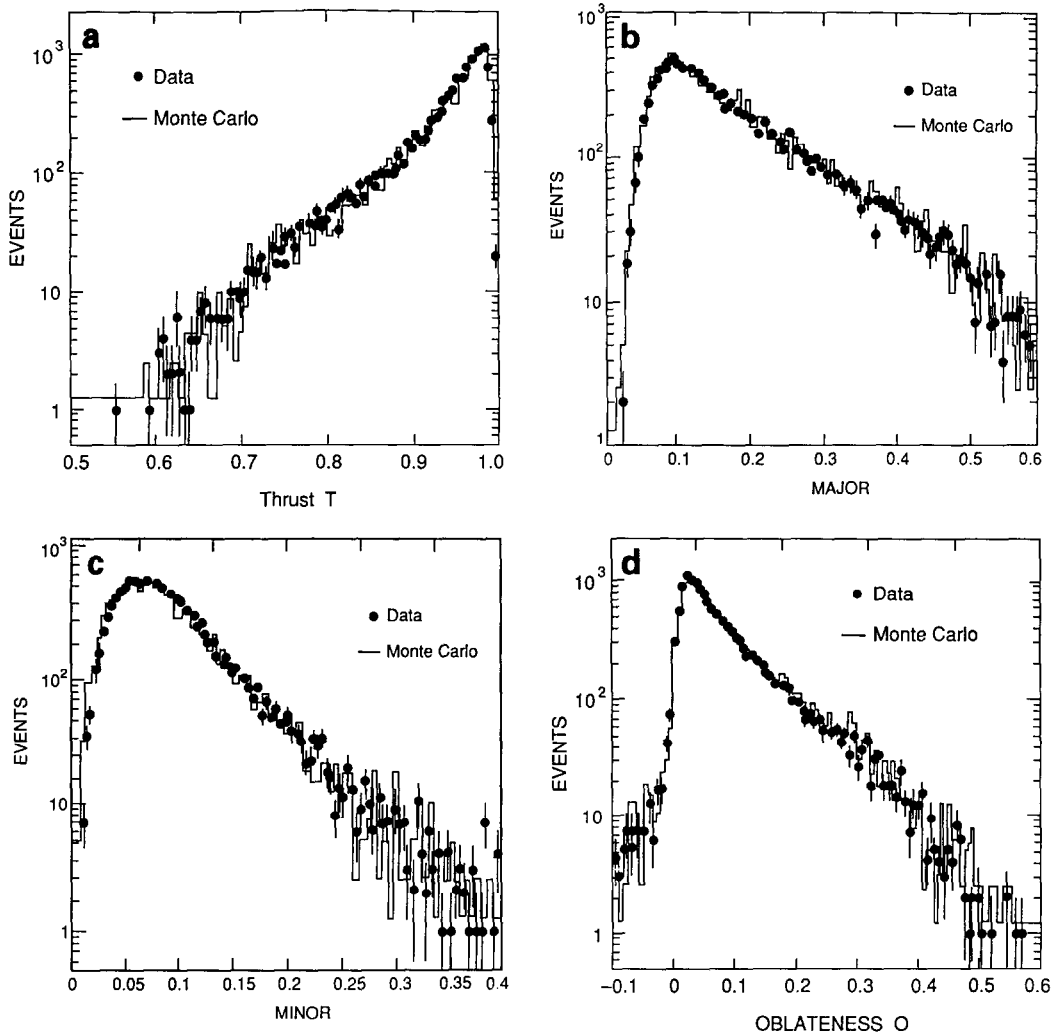


Fig. 3. (a) Distribution of the thrust  $T$  for the hadron events, compared to the Monte Carlo simulation. (b) Distribution of the Major [14], compared to Monte Carlo. The Major is the component of energy flow perpendicular to the thrust axis, where the direction of the axis  $\hat{n}_{\text{Major}}$  is chosen to make this component of the energy flow maximal. (c) Distribution of the Minor [14], compared to Monte Carlo. The Minor is the component of energy flow perpendicular to the Major and thrust axes, which tends to be normal to the event plane for three-jet events. (d) Distribution of the oblateness  $O$ , compared to Monte Carlo. The oblateness  $O \equiv \text{Major} - \text{Minor}$  tends to be large for events with three or more well-defined jets.

Studies of the energy dependence of the acceptance, and of the ratio of the number of events collected to integrated luminosity as a function of time during the run, show no evidence of significant point-to-point systematic errors in our scan over the  $Z^0$  peak.

## 6. Event sample and cross sections for $e^+e^- \rightarrow Z^0 \rightarrow \text{hadrons}$

Table 2 gives the cross section for  $e^+e^- \rightarrow Z^0 \rightarrow \text{hadrons}$  as a function of the center of mass energy, along with the number of hadron events, the number of accepted Bhabha events, and the integrated luminosity at each energy point. The data

Table 2

Measured cross section,  $\sigma_h$ , for  $e^+e^- \rightarrow Z^0 \rightarrow \text{hadrons}$ .

| $\sqrt{s}$<br>(GeV) | Hadron<br>events | Bhabha<br>events | Luminosity<br>(nb <sup>-1</sup> ) | $\sigma_h$<br>(nb) |
|---------------------|------------------|------------------|-----------------------------------|--------------------|
| 88.279              | 207              | 3565             | 42.1                              | $5.24 \pm 0.38$    |
| 89.277              | 521              | 5397             | 65.3                              | $8.42 \pm 0.39$    |
| 90.277              | 993              | 4389             | 54.4                              | $19.01 \pm 0.67$   |
| 91.030              | 2284             | 6492             | 81.7                              | $29.24 \pm 0.71$   |
| 91.278              | 3351             | 8776             | 121.0                             | $29.13 \pm 0.60$   |
| 91.529              | 3352             | 9742             | 123.8                             | $28.48 \pm 0.57$   |
| 92.280              | 897              | 3293             | 46.6                              | $20.02 \pm 0.76$   |
| 93.276              | 595              | 3977             | 51.2                              | $12.08 \pm 0.53$   |
| 94.278              | 193              | 2241             | 30.1                              | $6.89 \pm 0.52$    |
| 95.036              | 72               | 810              | 11.1                              | $6.77 \pm 0.83$    |
| all                 | 12465            | 48682            | 627.3                             |                    |

shown are for the runs since our first publication [2]. The errors on the cross sections in the table do not include the overall systematic error of 2.0%.

## 7. Determination of the $Z^0$ parameters

The measured cross sections from the latest series of runs (October–December 1989), and from the first physics runs (September 1989 [2]) have been used to derive precise values for  $M_{Z^0}$ ,  $\Gamma_{Z^0}$ , and the number of light neutrino species  $N_\nu$ . We will refer to the two running periods as Run 1 and Run 2 below. Following recent calibrations of the LEP energy scale by the LEP Machine Group [6], we have adjusted the center of mass energies of Run 1 upward by 0.047%, or about 43 MeV. Our previously published cross sections from Run 1 have not been changed in this analysis.

The measured cross sections have been fitted by three different methods:

(1) A fit in the framework of the standard model [15,16]. The only free parameters in the fit were  $M_{Z^0}$  and an overall scale factor which was allowed to vary within the systematic error quoted above.

(2) A model independent fit to determine  $M_{Z^0}$ , the total width  $\Gamma_{Z^0}$ , and the product of the electronic and hadronic partial widths  $\Gamma_{ee}\Gamma_h$ .

(3) A fit in the framework of the standard model to determine  $M_{Z^0}$  and the partial width  $\Gamma_{\text{visible}}$  for  $Z^0$

decays into particles, like neutrinos, that are invisible in our detector.

Fits 1 and 3 depend on the standard model calculation of  $\Gamma_{ee}$  and  $\Gamma_h$ , on the values of the strong coupling constant  $\alpha_s$ , and of the masses of the top quark  $M_t$  and of the Higgs  $M_H$ . For these fits, we fixed  $\alpha_s=0.12$ ,  $M_H=100$  GeV and  $M_t=100$  GeV respectively. The effect on the fit results of varying these quantities is discussed below.

For Fits 2 and 3, data from Runs 1 and 2 were fitted simultaneously, allowing the normalization of the two sets to float relative to each other in accordance with their systematic errors (6 and 2.0% for Runs 1 and 2, respectively).

Analytical forms for the  $Z^0$  cross section given by Cahn [17] and Borelli et al. [18] were used in the fits. These include initial state radiation and a Breit–Wigner with an energy dependent width. The two expressions produce identical fit results and cross sections identical to the standard model programs [15,16] if the same values of the mass, width and branching ratios are used.

The result from Fit 1, applied to the Run 2 data, is  $M_{Z^0} = 91.156 \pm 0.026$  GeV. This agrees very well with our earlier result [2] for the Run 1 data,  $M_{Z^0} = 91.175 \pm 0.057$  GeV, which has been corrected (by 43 MeV) to take the recent LEP energy calibrations into account. The combined result for the  $Z^0$  mass, using the data from Runs 1 and 2, is  $M_{Z^0} = 91.160 \pm 0.024$  GeV. In addition to the experimental error on  $M_{Z^0}$  obtained from the fit, the error from the uncertainty

in the LEP center of mass energy is 30 MeV. Taking the experimental and LEP energy scale errors into account, for Runs 1 and 2 combined, we obtain an overall error on  $M_{Z^0}$  of 38 MeV.

The results of Fit 2 are:  $M_{Z^0} = 91.166 \pm 0.025$  GeV,  $\Gamma_{Z^0} = 2.539 \pm 0.054$  GeV and  $\Gamma_{ee}\Gamma_h = 0.1454 \pm 0.0058$  GeV<sup>2</sup>. From these results we derived the hadronic cross section at  $\sqrt{s} = M_{Z^0}$ :  $\sigma_h(M_{Z^0}) = 29.5 \pm 0.7$  nb. The value of  $\sigma_h$  corresponds to a cross section before radiative corrections  $\sigma_h^0 = 39.8 \pm 0.9$  nb, where  $\sigma_h^0 = 12\pi\Gamma_{ee}\Gamma_h/M_{Z^0}^2\Gamma_{Z^0}^2$ . The fitted scale factors for both sets of data are within 0.1% of unity. We used the results of this fit to derive the number of neutrino species, using only the total  $Z^0$  width, from the relation

$$N_\nu = 3 + \frac{\Gamma_{Z^0} - \Gamma_{Z^0}^{SM}}{\Gamma_{\nu\nu}^{SM}},$$

where  $\Gamma_{\nu\nu} = 166.3$  MeV is the partial width for  $Z^0$  decay into one neutrino species  $Z^0 \rightarrow \nu\bar{\nu}$ , and where  $\Gamma_{Z^0}^{SM} = 2.484$  GeV. In this way we obtained  $N_\nu = 3.32 \pm 0.32$ , where the error is dominated by statistics. We derived  $N_\nu$  by a second method based entirely on our measurement of the height of the  $Z^0$  peak, and we obtained  $N_\nu = 3.28 \pm 0.18$ .

The results for Fit 3 are  $M_{Z^0} = 91.166 \pm 0.024$  GeV and  $\Gamma_{invisible} = 0.548 \pm 0.029$  GeV. The result on  $M_{Z^0}$  is in agreement with the results of Fits 1 and 2. The value of  $\Gamma_{invisible}$  leads to a number of light neutrinos  $N_\nu = 3.29 \pm 0.17$ , where the error is predominantly systematic. The possibility of 4 or more neutrino species is therefore ruled out at the  $4\sigma$  confidence level. This fit is compared to the Run 2 data in fig. 4, where the standard model curves corresponding to  $N_\nu = 2$  and 4 are also shown for comparison. The curve for  $N_\nu = 3$  is nearly indistinguishable from the fitted curve in the figure.

The effect on the number of neutrino species of

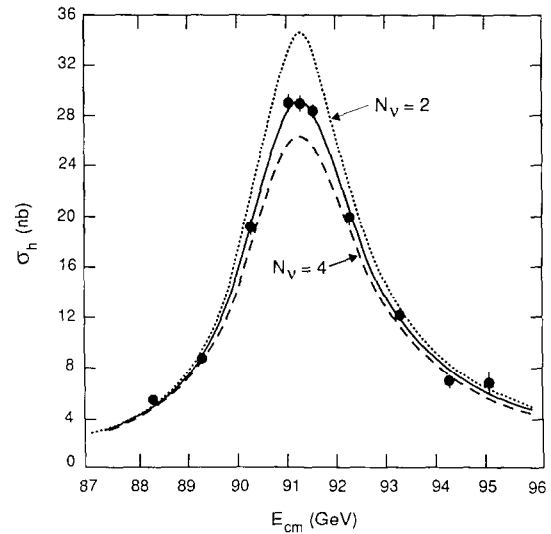


Fig. 4. The measured cross section for  $e^+e^- \rightarrow$  hadrons as a function of  $\sqrt{s}$ , for the Run 2 data as described in the text. Data are shown with statistical errors only. The solid curve is a fit to the formula of Borelli et al. [18] in which  $M_{Z^0}$  and  $\Gamma_{invisible}$  were left free. The partial widths  $\Gamma_{ee}$ ,  $\Gamma_{\mu\mu}$ ,  $\Gamma_{\tau,\tau}$  and  $\Gamma_{hadrons}$  were taken from the standard model. The dotted and dashed curves are the standard model curves corresponding to  $N_\nu = 2$  and 4 respectively. The curve for  $N_\nu = 3$  is nearly indistinguishable from the fitted curve in the figure.

varying  $\alpha_s$ ,  $M_t$  and  $M_H$  was studied for Fit 3. Varying these parameters in the range 0.10–0.14, 60–230 GeV and 50–1000 GeV respectively, we found a change of  $\Delta N_\nu = \pm 0.04$  around the central value of  $N_\nu$ .  $N_\nu$ , when determined from Fit 3, is relatively insensitive to changes in these constants because the fit is dominated by the measurement of  $\sigma_h^0 \propto \Gamma_{ee}\Gamma_h/\Gamma_{Z^0}^2$ , where most of the variations in the widths cancel. In contrast, the determination of  $N_\nu$  from the width alone, as derived from Fit 2, is more sensitive to changes in  $\alpha_s$ ,  $M_t$  and  $M_H$  ( $\Delta N_\nu \approx \pm 0.15$ ). A study of the effect

Table 3  
Summary of fitted  $Z^0$  parameters and the number of neutrinos  $N_\nu$ .

| Fit | $M_{Z^0}$<br>(GeV) | $\Gamma_{Z^0}$<br>(GeV) | $\Gamma_{invisible}$<br>(GeV) | $N_\nu$         | $\chi^2/D.F.$ |
|-----|--------------------|-------------------------|-------------------------------|-----------------|---------------|
| 1   | $91.160 \pm 0.024$ |                         |                               |                 | 14.9/15       |
| 2   | $91.166 \pm 0.025$ | $2.539 \pm 0.054$       |                               | $3.32 \pm 0.32$ | 12.6/14       |
| 3   | $91.166 \pm 0.024$ |                         | $0.548 \pm 0.029$             | $3.29 \pm 0.17$ | 12.6/15       |

of point-to-point systematic error on the central value of the beam energy taking 0.015 GeV as a conservative upper limit on the RMS value leads to an additional error of  $\pm 0.006$  GeV on  $M_{Z^0}$  and of  $\pm 0.02$  on  $N_\nu$ .

The results of the three fits, including the result of Fit 1 for the combined data, are summarized in table 3. The errors on the parameters given in the table include all statistical and systematic errors associated with our experiment, but do not include the 30 MeV systematic error in the LEP energy scale.

## 8. Conclusion

Thanks to the improved performance of LEP, we have made a precise measurement of the mass and width of the  $Z^0$ , and the number of neutrinos. Based on a data sample of approximately 17 000  $Z^0$  decays, and an overall normalization uncertainty of 2.0%, we have measured:

The mass of the  $Z^0$ :

$$M_{Z^0} = 91.160 \pm 0.024 \pm 0.030 (\text{LEP}) \text{ GeV} .$$

The width of the  $Z^0$ :

$$\Gamma_{Z^0} = 2.539 \pm 0.054 \text{ GeV} .$$

The hadronic cross section:

$$\sigma_h(M_{Z^0}) = 29.5 \pm 0.7 \text{ nb} .$$

The invisible width of the  $Z^0$ :

$$\Gamma_{\text{invisible}} = 0.548 \pm 0.029 \text{ GeV} .$$

The number of neutrino species:

$$N_\nu = 3.29 \pm 0.17 .$$

## Acknowledgement

We wish to thank CERN for its hospitality and help. We want particularly to express our gratitude to the LEP division: it is their excellent achievements which made this experiment possible. We acknowledge the support of all the funding agencies which contributed to this experiment.

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