



Measurement of the Mass and Width of the Z^0 -Particle from Multihadronic Final States Produced in e^+e^- Annihilations

DELPHI collaboration

Abstract

First measurements of the mass and width of the Z^0 performed at the newly commissioned LEP Collider by the DELPHI collaboration are presented. The measurements are derived from the study of multihadronic final states produced in e^+e^- annihilations at several energies around the Z^0 mass. The values found for the mass and width are $M(Z^0) = 91.06 \pm 0.09$ (stat) ± 0.045 (syst) GeV and $\Gamma(Z^0) = 2.42 \pm 0.21$ (stat) GeV respectively, from a three-parameter fit to the line shape. A two parameter fit in the framework of the Standard Model yields for the number of light neutrino species $N_\nu = 2.4 \pm 0.4$ (stat) ± 0.5 (syst).

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1. INTRODUCTION

The newly commissioned Large Electron Positron Collider (LEP) has devoted its first physics run of three weeks to an energy scan in a narrow interval around the expected mass of the Z^0 , relying on the recently published results on the Z^0 mass by the CDF [1] and Mark II [2] Collaborations. This report will present the results obtained by the DELPHI Collaboration on the multi-hadronic annihilation cross-section at seven collision energies.

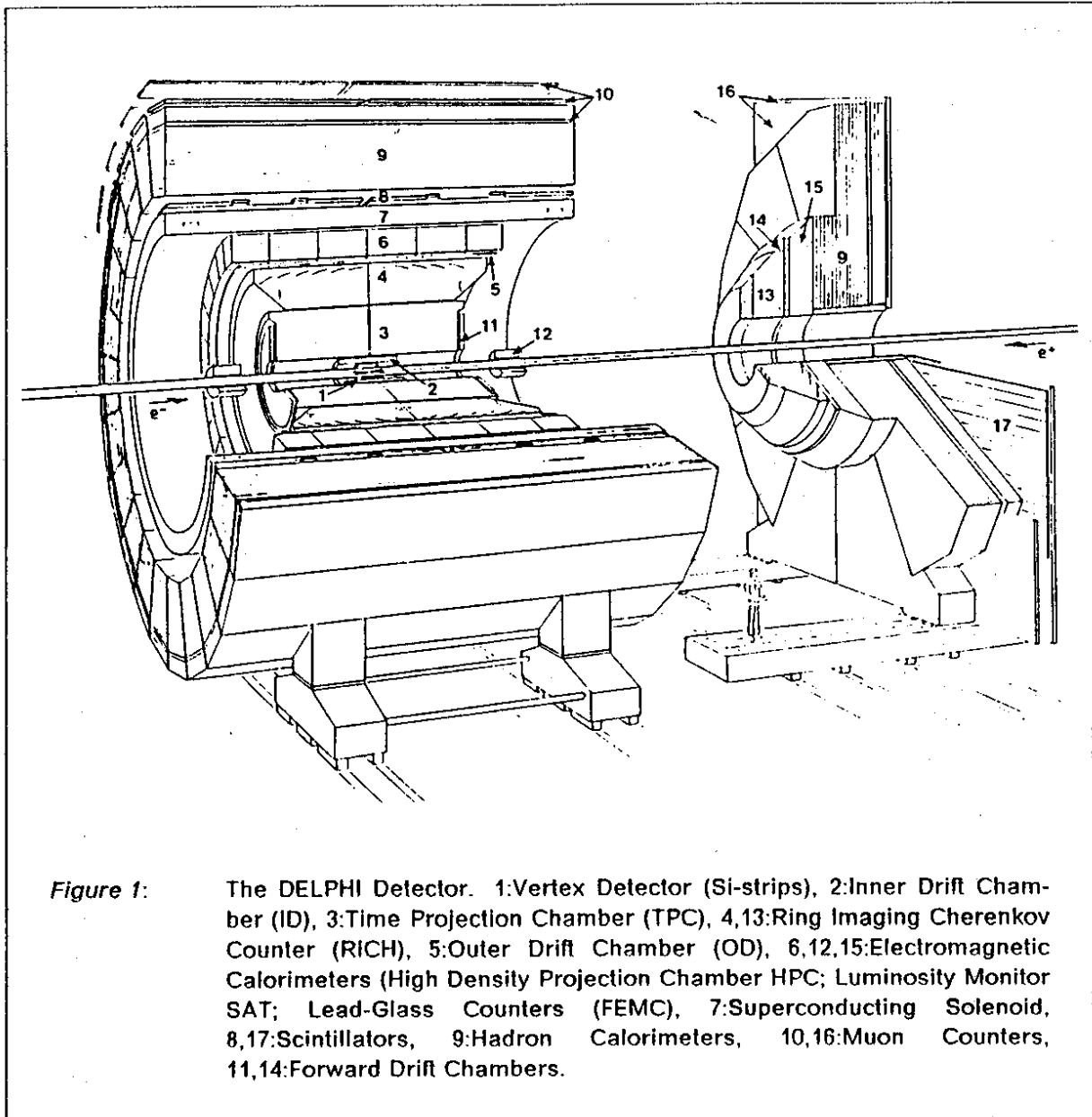
Since this was an early stage in the commissioning of the DELPHI detector, the analysis has been concentrated on a few components which were operational before the start of the energy scan. The amount of data recorded was limited by the efficiency of the data acquisition system which was not completely commissioned by the time of the scan.

The data were normalised to the Bhabha rates at small scattering angles. From these measurements, the mass and width of the Z^0 peak were obtained.

2. APPARATUS

A detailed description of the complete DELPHI detector is published elsewhere [3]. Only those features relevant for the present analysis are summarised below (see Figure 1.):

- The INNER DETECTOR is a cylindrical drift chamber (inner radius = 12 cm, outer radius = 22 cm) covering polar angles between 29° and 151° . A jet-chamber section providing 24 $r\phi$ coordinates is surrounded by 5 layers providing $r\phi$ and longitudinal coordinates.
- The TIME PROJECTION CHAMBER (TPC) is a cylinder with 28 cm inner and 122 cm outer radius and a length of 2.7 m. For polar angles between 22° and 158° at least 4 space points are available for track reconstruction, while for angles between 39° and 141° up to 16 space points can be used.
- The OUTER DETECTOR has five layers of drift cells at a radius between 192 and 208 cm and covers a polar angle from 50° to 130° . All layers provide precise $r\phi$ coordinates, and three of them in addition provide crude but fast longitudinal information.
- The HIGH DENSITY PROJECTION CHAMBER (HPC) measures electromagnetic energy with high granularity over polar angles from 40° to 140° . For fast triggering, a scintillator layer is inserted behind the first five radiation lengths. The light signals are carried by optical fibres to the outside of the iron yoke.
- The SUPERCONDUCTING SOLENOID had been commissioned during the pilot run at its nominal field of 1.2 T. After a normal run down, just before the physics period, a fault occurred and the field could no more be raised to its nominal value. As there was no time for detailed investigations, a reduced field of 0.7 T was chosen to guarantee stable condition during the energy scan. This entailed recalibration of many detector parameters.
- The TIME OF FLIGHT (TOF) system is composed of a single layer of 172 counters surrounding the solenoid, and covering $|\cos \theta| < 0.75$.



- The ELECTROMAGNETIC CALORIMETER in the endcaps (FEMC) consists of 2×4500 lead glass blocks (granularity = $1^\circ \times 1^\circ$) with phototriode read-out, covering polar angles from 10° to 35.5° and from 144.5° to 170° .
- The SMALL ANGLE TAGGER CALORIMETERS (SAT) cover polar angles from 43 to 125 mrad. They are composed of alternating layers of lead sheets - concentric with the beam axis - and scintillating fibres running parallel to the beam. The light is collected behind the calorimeter and measured by photodiodes. The inner four rings of read-out elements have an azimuthal segmentation of 15° , the outer four rings 7.5° . A small dead region, 2 cm wide, appears at the vertical junction of the two half-cylinders. A lead ring was added to the electron arm, to improve the precision of the acceptance cut. The ring is ten radiation lengths thick and covers $2/3$ of the innermost SAT ring, with a conical outer surface pointing to the vertex.

3. TRIGGER

Our trigger on hadronic events was based on the HPC and TOF scintillation counters. The individual counters were arranged in two groups of four quadrants placed symmetrically on both sides of the crossing point. The HPC counters were sensitive to electromagnetic showers with an energy ≥ 2 GeV while the TOF counters were sensitive to minimum ionizing particles penetrating the electromagnetic calorimeter and the coil. The following subtriggers were formed :

1. coincidences of back-to-back TOF sectors
2. majority ≥ 3 TOF sectors
3. majority ≥ 2 HPC sectors
4. coincidence of any TOF with any HPC sector.

The final trigger was the OR of these subtriggers. In addition, a trigger was used for several runs which was formed by a coincidence of the inner and outer tracking detectors. This enabled us to measure the efficiency of the above subtriggers from the data, by recording the trigger pattern event by event. For hadronic Z^0 events with a sphericity axis between 50° and 130° the following efficiencies were obtained:

TOF triggers alone, (1+2)	:	95.5 %
HPC trigger alone, (3)	:	81.4 %
TOF*HPC trigger, (4)	:	96.4 %
Overall trigger	:	99.5%

To enhance the number of Z^0 events recorded, a forward trigger based on the FEMC with a threshold of about 3 GeV, which had low efficiency for detection of single hadrons, was added. The contribution of this trigger is included in the global detection efficiency evaluated as described below (section 5).

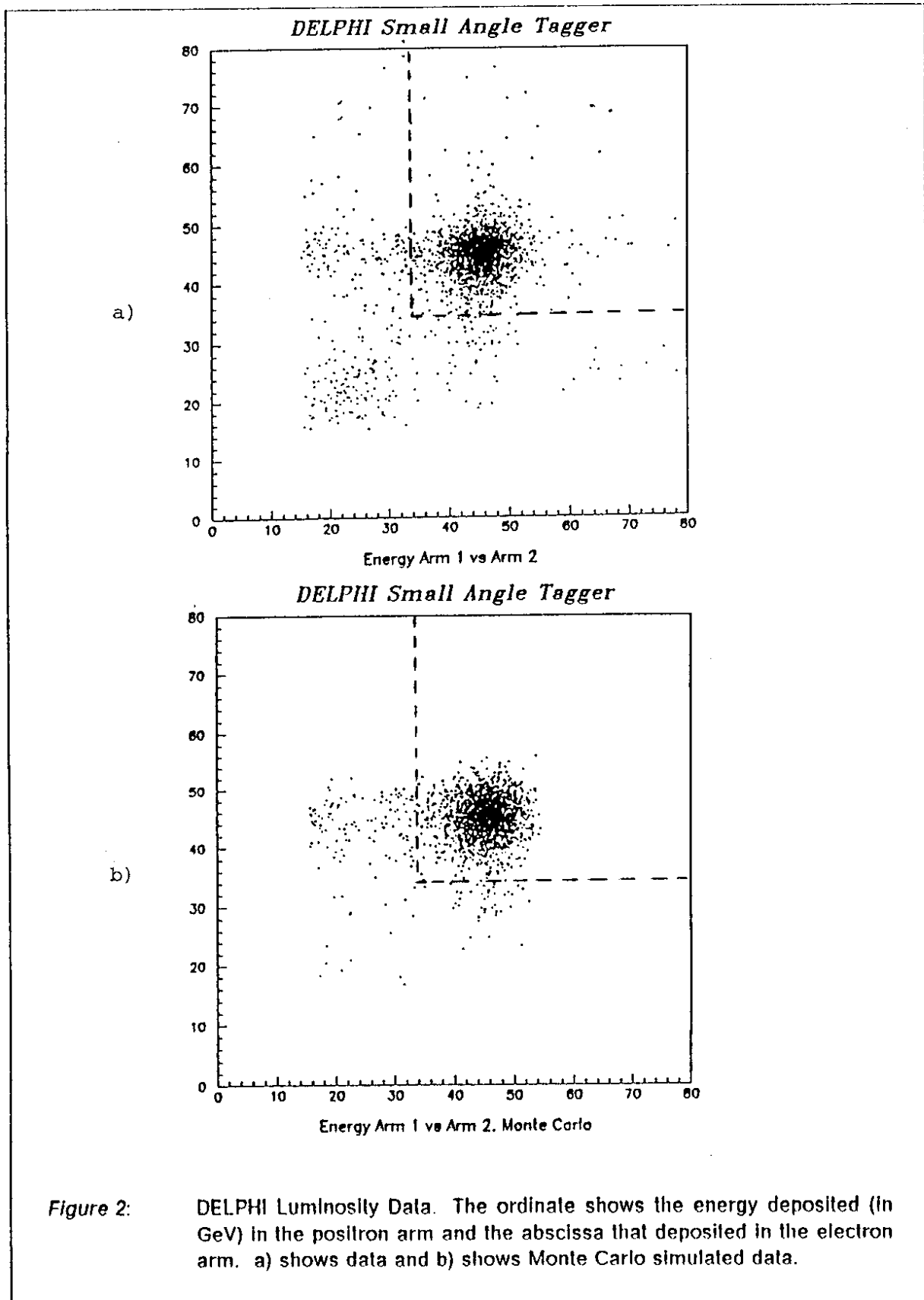
All types of events have been recorded with the same trigger- and data acquisition system in order to ensure equal live times for Z^0 - and Bhabha-events.

4. LUMINOSITY MEASUREMENT

The trigger for luminosity events is based on analog sums of 24 channels arranged in 24 overlapping sectors of 30° per endcap. The trigger requires a simple forward-backward coincidence of energy depositions above 10 GeV. Due to the overlapping geometry, the trigger efficiency is believed to be $(98 \pm 2)\%$ away from the dead regions and in the energy range specified for the luminosity measurement.

The geometric acceptance for the luminosity measurement was defined by the outer radii of the calorimeters, the outer radius of the lead mask in front of the electron calorimeter, and the requirement that the azimuth of reconstructed showers be away from the dead regions.

In order to reduce backgrounds to the 1% level, the following cuts were applied. Reconstructed showers, defined by clusters of four or more neighbouring read-out elements with energy deposition above 0.5 GeV, were required to be coplanar within 8° . The showers were also required to have an RMS azimuthal width of less than 11.5° . In order to make use of the lead



mask to define the inner radius of the acceptance region, it was required that the energy fraction in ring 1 be less than 0.90. This guarantees that the electron has entered the calorimeter above the mask and not from below. The data remaining after these cuts are seen in the two dimensional energy plot shown in Figure 2.

The peak of the Bhabha scattering signal is well separated from the background of random coincidences of off-momentum electrons. The tail of the distribution at lower energies in the electron arm (E2) is caused by electron showers which penetrated the lead mask and is well reproduced by the Monte Carlo simulation as shown in Figure 2. The last cut to define the luminosity sample is the requirement that at least 75% of the beam energy was observed in both endcaps (see broken lines in Figure 2). This results in a luminosity sample of 1681 events distributed among the 7 beam energy points as shown in Table 1.

Table 1: DELPHI Z^0 Scan with Hadrons

Collision Energy	N_h	N_{Lum}	Integ. L [nb^{-1}]	Cross-Section[nb]
89.27	89	305	9.2	11.3 ± 1.3
90.27	79	152	4.7	19.5 ± 2.7
91.02	94	97	3.1	35.6 ± 5.1
91.27	598	654	21.0	33.3 ± 1.9
92.26	72	109	3.6	23.4 ± 3.5
92.52	41	86	2.9	16.6 ± 3.1
93.27	93	278	9.4	11.6 ± 1.4
Total	1066	1681	53.9	

The effective cross-section for the luminosity events was evaluated by a detector simulation of Bhabha scattering events generated to first order in α [4]. The simulation of interactions with the beam pipe and lead mask and the response of the detector was performed with the GEANT package [5]. The cross-section derived in this way is 33.0 ± 0.8 nb for $\sqrt{s} = 91$ GeV. The theoretical uncertainty in the cross-section is due to the absence of higher-order terms in the event generator, uncertainty in the calculation of vacuum polarisation and Monte Carlo statistics. Backgrounds from other physics processes are negligible.

From the measured number of events and the calculated effective cross-section, the integrated luminosity for the data-taking periods at each energy was derived, as shown in Table 1. The measured number of events have been corrected by 6% to take account of the trigger efficiency, the losses due to geometrical misalignment and vertex position, and selection efficiency. The various contributions to the systematic error in the luminosity are:

Trigger efficiency	2%
Selection criteria	2%
Background	2%
Effective cross-section	2.5%
Vertex position	2%

Thus an overall systematic error on luminosity of 5% has been assumed. The systematic errors in the selection criteria, background, and trigger efficiency are mostly due to uncertainty in the calibration of the read-out elements, which will certainly improve when the statistical sample of Bhabha events is greater.

5. HADRONIC EVENT SELECTION

For the selection of hadronic Z^0 decays only charged tracks measured by the TPC and fulfilling the following criteria were used:

- $20^\circ < \theta < 160^\circ$
- $0.1 \text{ GeV} < p < 50 \text{ GeV}$
- track length $> 30 \text{ cm}$
- relative momentum error $< 100\%$
- projection of the impact parameter on the xy plane $< 4 \text{ cm}$
- z coordinate of track origin $< \pm 10 \text{ cm}$.

At least 3 charged tracks were required in one hemisphere and the sum of the p_T^2 of all the tracks in this hemisphere had to be larger than 2 GeV^2 . With the present magnetic field of 0.7 T, the average momentum resolution obtained from the TPC information alone is $\Delta p/p \simeq 1.3 \times 10^{-2} p$ (GeV/c). From analysis of the data in a z range outside the interaction region, the contribution from beam gas events was estimated to be about 0.2%. The 2-photon contribution was evaluated by Monte Carlo [6] and found to be negligible ($< 5 \text{ pb}$). The $\tau\tau$ background was estimated from the data and theoretically to be about 1% and was subtracted from the data.

All events with at least one charged track were visually scanned and no discrepancy with the selection criterion was found. Comparing data and Monte Carlo events for all kinematic variables relevant for this analysis we found good agreement in all distributions. As an example, Figure 3a) shows the sphericity distribution.

The measured $\cos \theta_s$ distribution of the sphericity axis (Fig. 3b) was used to obtain the total efficiency. A $(1 + \cos^2 \theta_s)$ behaviour was assumed to extrapolate beyond the region $0 < \cos \theta_s < 0.65$ (where the efficiency is $\simeq 100\%$) to the remainder of the full solid angle. By comparing the expected total number of Z^0 with the number actually found, the overall efficiency to trigger and reconstruct a hadronic Z^0 decay was found to be $\varepsilon = (84.7 \pm 2.5)\%$.

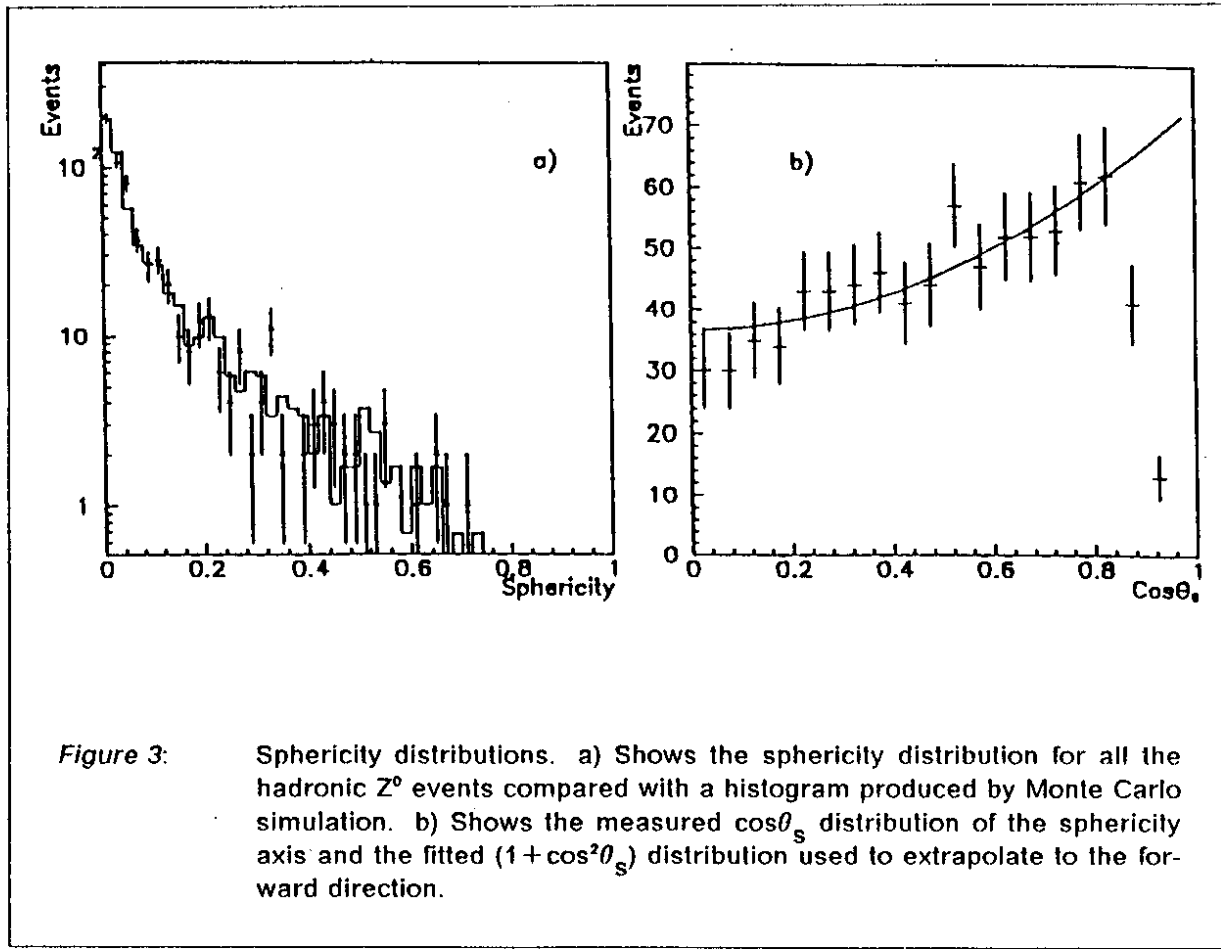


Figure 3: Sphericity distributions. a) Shows the sphericity distribution for all the hadronic Z^0 events compared with a histogram produced by Monte Carlo simulation. b) Shows the measured $\cos\theta_s$ distribution of the sphericity axis and the fitted $(1 + \cos^2\theta_s)$ distribution used to extrapolate to the forward direction.

6. RESULTS

At each energy the cross section for hadronic events was obtained from the relation $\sigma_h = N_h / L\epsilon$ where L is the integrated luminosity and ϵ is the total efficiency. The observed number of events N_h and the corresponding cross sections are listed in Table 1 where the quoted errors are only statistical. The systematic uncertainties on L and ϵ which were given above, imply a systematic error on the measured cross sections of $\simeq 6\%$.

The mass and width of the Z^0 were obtained by fitting the following theoretical expression [7], given by the Standard Model, to the data:

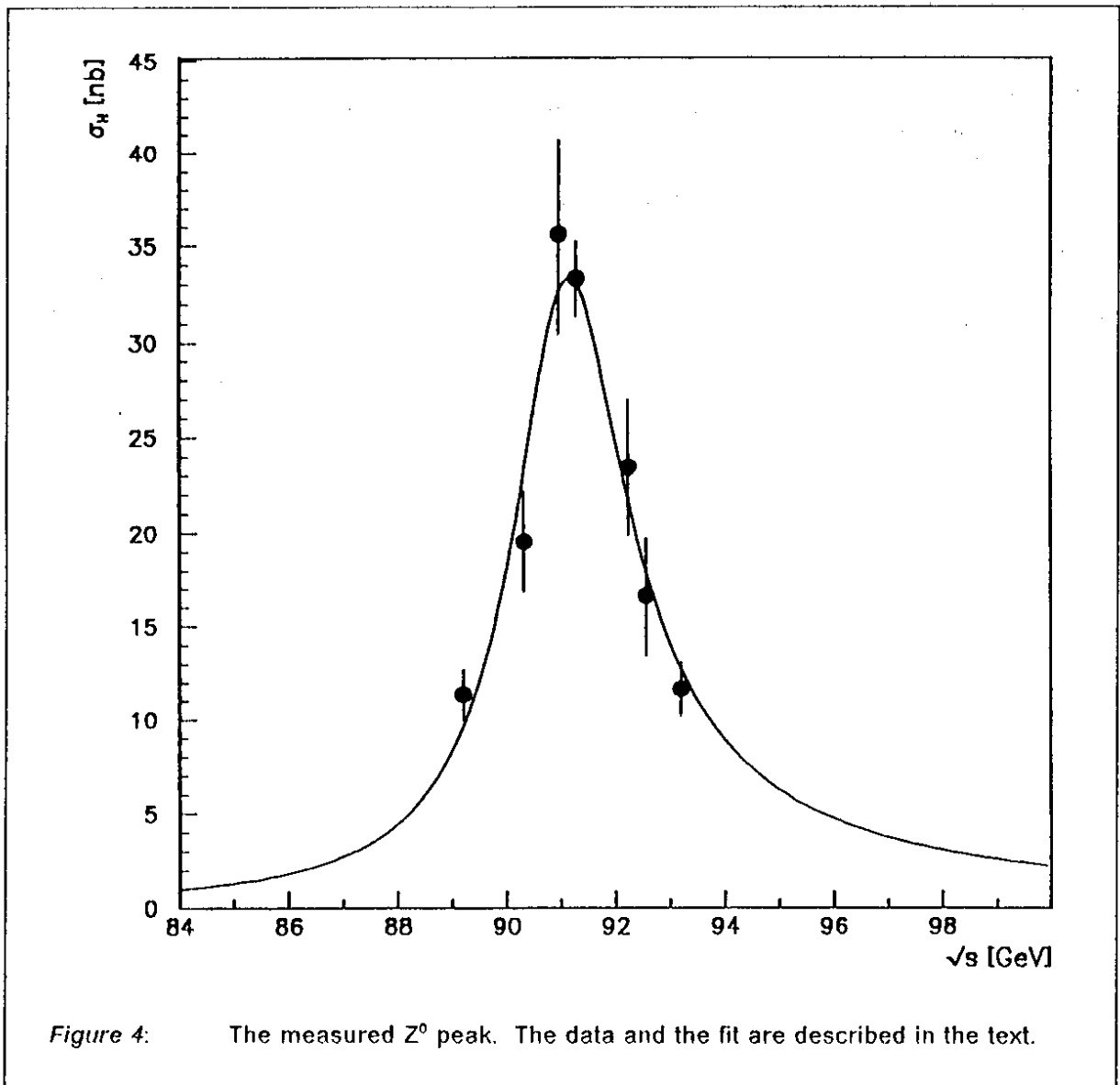
$$\sigma_h = 12\pi \frac{\Gamma_e \Gamma_h}{(s - M^2) + s^2 \Gamma^2 / M^2} F + \sigma_\gamma \quad (1)$$

The first term in eq. (1) describes the Z^0 line shape by an improved *Born* approximation with an energy dependent width. Radiative corrections are included in the function F where soft photon emission is computed with the usual exponentiation procedure. QCD corrections are applied to the hadronic partial width Γ_h . The continuum cross section is represented by the small term σ_γ . The interference term as well as higher order corrections were calculated assuming $m_t = 90$ GeV and are absorbed in the function F as discussed in reference [7]. Fits to the expressions

derived by [8] give the same results.

A three-parameter fit was performed by leaving free an overall normalization factor R in addition to the mass M and the width Γ of the Z^0 . The result of this fit is $M = 91.06 \pm 0.09$ GeV, $\Gamma = 2.42 \pm 0.21$ and $R = 1.03 \pm 0.14$ with $\chi^2 = 3.1$. The determination of the Z^0 mass is affected by an additional systematic error of ± 0.045 GeV due to uncertainties in the absolute calibration of the machine energy [9]. A systematic error of 6% on the absolute value of the cross section implies a systematic error on the Z^0 width of ≈ 0.09 GeV.

The data points and the result of the fit are shown in Figure 4.



A two parameter fit with the Z^0 mass and the number of light neutrino species N_ν left free gives: $M = 91.06 \pm 0.09$, $N_\nu = 2.4 \pm 0.4$ with $\chi^2 = 3.2$. A possible overall normalisation error of $\pm 6\%$ would shift the value of N_ν by ± 0.5 .

The limited statistics of the present measurement together with the sizeable systematic error on the cross-section gives only loose boundaries on the number of light neutrino species. However, the result of the fit shows that the data agree well with the predictions of the Standard Model with only three neutrino species. In fact, a fit where all the parameters except the mass of the Z^0 are fixed by the Standard Model gives $M = 91.13 \pm 0.10$ GeV with $\chi^2 = 4.1$.

These results compare well with the values of the Z^0 mass and width published in the literature from the pioneering hadron collider experiments at CERN [10], [11], the more recent hadron collider measurements at Fermilab [1] as well as from the Mark II experiment at SLC [2].

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