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DELPHI Results on the Z^0 Resonance Parameters through its Hadronic and Leptonic Decay Modes

The DELPHI Collaboration

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[redacted]

Abstract

The measurement of the cross-sections for $e^+e^- \rightarrow$hadrons and the cross-sections and forward-backward charge asymmetries for $e^+e^- \rightarrow$ charged leptons at 17 different centre-of-mass energies on the Z^0 resonance has been performed with the DELPHI apparatus using samples of approximately 68,000 hadronic events and about 4,000 electron, muon and tau pair events. A fit applied simultaneously to the hadronic cross-sections and to the 3 leptonic cross-sections determines the following parameters:

$$M_Z = 91.188 \pm 0.013(\text{stat}) \pm 0.030(E_{cm})\text{GeV}/c^2$$
$$\Gamma_Z = 2.476 \pm 0.026(\text{stat}) \pm 0.010(\text{syst})\text{GeV}/c^2$$
$$\Gamma_l = 83.7 \pm 1.0(\text{stat}) \pm 1.1(\text{syst})\text{MeV}/c^2$$
$$\Gamma_h = 1.756 \pm 0.023(\text{stat}) \pm 0.020(\text{syst})\text{GeV}/c^2$$
$$\Gamma_{inv} = 469 \pm 19(\text{stat}) \pm 22(\text{syst})\text{MeV}/c^2$$
$$R = 21.00 \pm 0.38(\text{stat}) \pm 0.29(\text{syst})$$

From these numbers we determine:

$$N_\nu = 2.82 \pm 0.11(\text{stat}) \pm 0.13(\text{syst})$$
$$\sin^2(\overline{\theta_W}) = 0.2309 \pm 0.0048$$

The individual leptonic widths obtained are:

$$\Gamma_e = 82.0 \pm 1.4(\text{stat}) \pm 1.3(\text{syst})\text{MeV}/c^2$$
$$\Gamma_\mu = 87.2 \pm 2.7(\text{stat}) \pm 2.2(\text{syst})\text{MeV}/c^2$$
$$\Gamma_\tau = 86.0 \pm 3.1(\text{stat}) \pm 2.7(\text{syst})\text{MeV}/c^2$$

From a flavour blind analysis of the leptonic data we obtained:

$$\Gamma_l = 82.6 \pm 0.8(\text{stat}) \pm 1.3(\text{syst})\text{MeV}/c^2$$

The vector and axial-vector couplings of the Z to charged leptons are:

$$v_l = -0.111\,^{+0.049}_{-0.033}(\text{stat}) \pm 0.015(\text{syst})$$
$$a_l = -1.003 \pm 0.007(\text{stat}) \pm 0.01(\text{syst})$$

All values quoted above agree well with the Standard Model.

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1. Introduction

The measurement of the cross-sections for $e^+e^- \rightarrow hadrons$ and the cross-sections and forward-backward charge asymmetries for $e^+e^- \rightarrow \ell^+\ell^-$ at 17 different centre of mass energies on the $Z°$ pole are presented. The data analysis is based on approximately 68,000 hadronic events and about 4,000 electron, muon and tau-lepton pairs recorded between september 1989 and july 1990.

Results are presented on both a line-scan of the cross sections

$$\sigma_h(\sqrt{s}) = \sigma(e^+e^- \rightarrow hadrons),$$

$$\sigma_\ell(\sqrt{s}) = \sigma(e^+e^- \rightarrow \ell^+\ell^-),$$

where ℓ=leptons, $\sqrt{s}$ is the e^+e^- centre of mass energy, and of the forward-backward charge asymmetry

$$A_{FB} = \frac{\sigma_\ell^F - \sigma_\ell^B}{\sigma_\ell^F + \sigma_\ell^B}.$$

In this expression, $\sigma_\ell^F(\sigma_\ell^B)$ is the cross-section for the production of a ℓ^- with $\cos\theta >$ $0(< 0)$, where θ is the angle made by the particle with respect to the incident e^- direction. The results of a previous study of σ_h and σ_ℓ vs. $\sqrt{s}$, from data taken in 1989 by the Delphi collaboration, can be found in [1] and [2] respectively.

2. Apparatus and Luminosity Measurement

The apparatus is the same as that described in [1,2,3]. Besides several modifications and improvements to the trigger, the main change is the addition of a lead mask ("butterfly-wings") in front of one of the Small Angle Tagger (SAT) arms to cover a dead zone in the vertical plane which has reduced the systematic uncertainty on the luminosity measurement by 0.5%. The luminosity is measured with the same Bhabha selection criteria described in [1]. Further reductions in the luminosity uncertainty come from a smaller error on the SAT trigger efficiency and increased simulation statistics. Thus the overall systematic error on the 1990 luminosity measurement is 1.7%(expt.) $\pm$ 1.0%(theory), where the latter error is due to the theoretical uncertainty on the computation of the Bhabha scattering cross-section within the SAT acceptance. For the 1989 data we had an average systematic error on the luminosity measurement of 2.2%(expt.) $\pm$ 1.0%(theory).

The uncertainty on $\sqrt{s}$ is as last year ($\pm$30MeV) but the values of $\sqrt{s}$ for the 1990 data have been shifted down by about 58 MeV with respect to the nominal values at each point. This is an estimated average energy shift for all the 1990 data collected between march and july and is based on LEP beam energy calibration measurements made between december 1989 and may 1990, from which an average energy shift of 51 MeV for the data collected between march and may 1990 was estimated.

3 Event Selection and Cross-section Computation

The selection of hadronic and leptonic decays of the $Z°$ is quite similar to the methods described in [1,2]. However, where significant differences exist between the current analysis and the previous ones, we give details below.

3a. Hadronic Cross-section

The total sample of hadronic Z°'s amounts to about 75,000 events collected up to the 17th of july. A well understood subsample of about 68,000 events has been analysed. The details of the analysis of the 1990 data (about 58,000 events) are very similar to the description in [1], except for the following points:

The trigger is essentially unchanged except for the TOF-majority which is made of at least 2 quadrants instead of 3 and the addition of a majority-1 coincidence between the TOF and OD. The trigger of the EMF is also improved: its threshold is dropped from 4.0 to 3.5 GeV and it fires for back-to-back clusters as well as for clusters on one side only. Thus the trigger efficiency has slightly improved to $99.5 \pm 0.2\%$.

The hadronic event selection relies only on charged tracks measured in the barrel region. The track selection criteria are the same as for the 1989 data. The hadronic events are selected by requiring at least 5 charged tracks and a minimum charged energy of 14% of the c.m. energy. The efficiency is estimated as before and is $92.7 \pm 1.1\%$. The tau contamination remains unchanged (viz. $0.3 \pm 0.1\%$).

The overall normalisation uncertainty for the 1989 data remains unchanged at 2.6%. For the 1990 data, the reduced systematic error on the luminosity measurement gives an overall normalisation uncertainty of 2.3% (i.e. 1.1% for the hadronic event selection and 2.0% for the luminosity).

The cross-section as a function of $\sqrt{s}$ is given for the 1989 and 1990 data in table 1 along with the number of events at each point.

3b. The $e^+e^- \to e^+e^-$ Cross-section

The present analysis follows very closely the one described in [2] but with the following important changes:

- at least one HPC (barrel EM calorimeter) cluster is required with energy > 30 GeV (this used to be 25 GeV); a second cluster is required to have > 10 GeV in the HPC (as before).
- as before, no more than 4 HPC clusters and no more than 3 tracks with momentum > 1.5 GeV are permitted and finally an acollinearity angle cut of 10 degrees is applied.
- the fiducial cut (to avoid the border regions of the HPC modules) is better understood
- the tau pair background is reduced to $2 \pm 1\%$ due to the 30 GeV cut on the most energetic cluster (used to be $6 \pm 2\%$)
- the t-channel subtraction is made to the observed cross-section using reference [4]. This procedure has an error associated with it which amounts to an additional 1% uncertainty on the t-channel subtracted cross-section near the Z° peak (about 0.7% due to theoretical uncertainty in the calculation and 0.7% coming from the uncertainty in the LEP energy scale).

A total sample of 1389 events were selected (263 from 1989 added to 1126 collected this year) corresponding to an integrated luminosity of 2611nb^{-1} (510nb^{-1} from 1989 added to 2101nb^{-1} collected this year). The cross-sections are given in table 2. For the 1989 data, the point at 95.04 GeV is not taken into account

The systematic error on the e^+e^- cross-section (apart from the luminosity uncertainty) is estimated to be 1.6%, due to 0.1% from the trigger, 1.0% from the tau-lepton background subtraction, 0.8% for the selection efficiency and 1.0% for the t-channel subtraction.

3c. The $e^+e^- \to \mu^+\mu^-$ Cross-section

The present analysis has several significant changes from the one described in [2] The main emphasis has been put on increasing the muon pair identification efficiency inside an "extended-barrel" region defined to lie in the polar angle range $43° < \theta < 137°$. In addition to positive muon identification from the barrel muon drift chambers and HPC, the barrel hadron calorimeter is used to provide a third muon identifier within the "extended barrel" region. The cuts applied to the 1990 data are:

- 2 tracks produced near the interaction region ($|\delta z| < 4.5$cm and $\delta r < 1.5$cm) are required to be reconstructed by the TPC and preferably also by the Outer Detector with momentum above 15 GeV/c, with an acollinearity $< 10°$ and at least one of them must satisfy the condition $43° < \theta < 137°$.
- Both tracks satisfying the above conditions must be identified as muons in either the HPC ($0 < E < 1$ GeV), hadron calorimeter ($0 < E < 10$ GeV, with some angle dependence) or the muon chambers (hits associated with extrapolated tracks).
- The trigger efficiency varied between 91-99% due to variable running conditions with an average value of $96. \pm 1.$%
- Track reconstruction efficiency is $95. \pm 0.5$%
- Efficiency after momentum and acollinearity cuts is 97.3%
- Muon identification efficiency is 98.5 ± 0.5%
- Tau background is 4.0 ± 1.0%
- Cosmic background is 2.1 ± 0.3%

A total sample of 1618 events were selected (195 from 1989 added to 1423 collected this year) corresponding to an integrated luminosity of 2534nb^{-1} (390nb^{-1} from 1989 added to 2144nb^{-1} collected this year). The cross-sections are given in table 3 and the forward-backward asymmetry can be found in table 4. For the 1989 data, the point at 95.04 GeV is not taken into account

The systematic error on the $\mu^+\mu^-$ cross-section is (apart from the luminosity uncertainty) estimated to be 1.9% due to 1.0% from the trigger, 1.35% from selection efficiency, 0.5% for particle identification, 1.0% from the tau-lepton background subtraction and 0.3% from the cosmic ray background. A 1.0% systematic errror on the asymmetry is estimated from the number of like sign pairs (3(++) and 5(−−) events from 1423) and from the charge asymmetry in each hemisphere taken separately.

3d. The $e^+e^- \to \tau^+\tau^-$ Cross-section

The present analysis follows very closely the one described in [2] but with the following important differences:

- the polar angle cut described in the paper has been changed from 50° (130°) to 43° (137°)
- there is a much better understanding of selection efficiencies and backgrounds. The effects of the visible momentum cut (60 GeV) applied to the 1-1 topology and the electromagnetic energy cut (30 GeV), associated to each track for the 1-1 topology or in each hemisphere for the 1-2 topology, are better estimated and the

background from e^+e^- and $\mu^+\mu^-$ is estimated at the level of 0.7% (in the total sample).

A total sample of 1016 events were selected (158 from 1989 added to 858 collected this year) corresponding to an integrated luminosity of 2327nb^{-1} (457nb^{-1} from 1989 added to 1870nb^{-1} collected this year). The cross-sections are given in table 5 and the forward-backward asymmetry can be found in table 6. For the 1989 data, the point at 95.04 GeV is not taken into account

The systematic error on the $\tau^+\tau^-$ cross-section is (apart from the luminosity uncertainty) estimated to be 2.7% due to 1.0% from the trigger, 1.5% from selection efficiency, and 2.0% from hadronic background subtraction and secondary interactions not correctly estimated by the Monte Carlo. A 1.0% systematic errror on the asymmetry is estimated from the charge asymmetry in each hemisphere taken separately.

3e. The $e^+e^- \to \ell^+\ell^-$ ("Flavour-blind lepton") Cross-section

In this new analysis we attempt to select the leptonic pair final states without distinguishing the leptonic flavor. The event selection depends only on the information from the TPC (2 to 7 good tracks, where a good track must have more than 200 MeV transverse momentum, be contained inside a polar angle region of 50°-130° and come from near the interaction point of the beams).

A topology cut is then applied to the selected events. The event is divided into two hemispheres by a plane perpendicular to the thrust axis. One of the hemispheres is required to have a single track with transverse momentum larger than 1.5 GeV. The other hemisphere can have 1 to 5 tracks. The total transverse momentum in the second hemisphere has to be greater than 1.5 GeV. The acollinearity between the single track and the resultant momentum of the recoiling jet has to be smaller than 20°. The opening angle between any track in the jet and the resultant momentum has to be smaller than 30°. These requirements are equivalent to requiring a two jet configuration with topology 1.vs.N (N=1,...5) and isolation angle of 150° between the isolated track and the jet.

There must be at least one track in the event with momentum larger than 3 GeV.

Cosmic rays are removed with a tighter cut on the vertex position relative to the interaction point for those events with only two good tracks.

The efficiency for detecting each type of charged lepton with these cuts has been calculated with a Monte Carlo simulation giving 95% for e^+e^-, 96% for $\mu^+\mu^-$ and 84% for $\tau^+\tau^-$. The overall trigger efficiency is taken to be 98%.

The main sources of background have been estimated from Monte Carlo and the real data to be $0.6 \pm 0.3\%$ from hadronic events and less than 0.5% and less than 0.1% respectively for two-photon collisions and cosmic rays.

A total sample of 3187 events were selected corresponding to an integrated luminosity of 1889nb^{-1}. The cross-sections are given in table 7.

The systematic error on the flavour-blind lepton cross-section is (apart from the luminosity uncertainty) estimated to be 1.3% due to 1.0% from the trigger, 0.5% from track selection efficiency, and 0.6% from background subtraction.

4. Extraction of the $Z°$ Resonance Parameters from the data

The $Z°$ resonance parameters were determined by fitting the hadronic and leptonic data with the theoretical cross-sections computed in [5]. For the e^+e^- final state the t-channel contributions were subtracted using the theoretical formula of [4].

The systematic errors propagated in the fits were:

Luminosity:	1.7% (Expt) ±1.0% (Theory)
Hadron selection:	1.1%
e^+e^- channel:	1.6%
$\mu^+\mu^-$ channel:	1.9%
$\tau^+\tau^-$ channel:	2.7%
flavour-blind leptons:	1.3%

4a. Fit to the hadron cross-section alone

A 3 parameter fit performed with the formula of [5] (and checked with the formulae of [6]) where the free parameters are the mass, the total with of the Z and the Born peak cross-section gives

$$M_Z = 91.191 \pm 0.014(\mathrm{stat}) \pm 0.030(E_cm)\mathrm{GeV}/c^2$$

$$\Gamma_Z = 2.466 \pm 0.027(\mathrm{stat}) \pm 0.010(\mathrm{syst})\mathrm{GeV}/c^2$$

$$\sigma_0 = 42.38 \pm 0.30(\mathrm{stat}) \pm 0.97(\mathrm{syst})\mathrm{nb}$$

$$\chi^2/d.o.f = 12.4/(17-3)$$

The systematic error on σ_0 originates from the overall normalisation uncertainty of 2.3%. This can be reduced to ±0.87 nb if the 1.% theoretical uncertainty on the Bhabha scattering cross-section (i.e. ±0.43 nb) common to all the LEP experiments is taken out. A systematic error of ±10 MeV has been assigned to Γ_Z due to a possible 0.3% point-to-point variation in the normalisation of the cross-section, to the variations in the LEP beam energy setting and to the method of extracting Γ_Z from the measured lineshape.

The correlation between Γ_Z and σ_0 = -0.66.

4b. Combined fit to the hadronic and leptonic cross-sections

A 4 parameter fit applied simultaneously to the hadronic cross-section and to the 3 leptonic cross-sections determines the hadronic and total widths in addition to the Z^0 mass and the ratio R of the hadronic to leptonic partial widths:

$$M_Z = 91.188 \pm 0.013(\mathrm{stat}) \pm 0.030(E_{cm})\mathrm{GeV}/c^2$$

$$\Gamma_Z = 2.476 \pm 0.026(\mathrm{stat}) \pm 0.010(\mathrm{syst})\mathrm{GeV}/c^2$$

$$\Gamma_h = 1.756 \pm 0.023(\mathrm{stat}) \pm 0.020(\mathrm{syst})\mathrm{GeV}/c^2$$

$$R = 21.00 \pm 0.38(\mathrm{stat}) \pm 0.29(\mathrm{syst})$$

$$\chi^2/d.o.f = 46.8/(61-4)$$

These values of the total and hadronic widths and R are in good agreement with the predictions of the standard model ($2.500 \pm 0.042 \mathrm{GeV/c^2}$, $1.747 \pm 0.034 \mathrm{GeV/c^2}$ and 20.86 ± 0.20 respectively).

For this 4 parameter fit the corresponding values of the leptonic partial width (assuming lepton universality) and the invisible partial width are:

$$\Gamma_l = 83.7 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst}) \mathrm{MeV/c^2}$$

$$\Gamma_{\mathrm{inv}} = 469 \pm 19(\mathrm{stat}) \pm 22(\mathrm{syst}) \mathrm{MeV/c^2}$$

These values are also in good agreement with standard model predictions: $83.8 \pm 0.9 \mathrm{MeV/c^2}$ and $502 \pm 5 \mathrm{MeV/c^2}$ respectively.

i) The effective weak mixing angle:

In the minimal standard model the leptonic partial width can be expressed in terms of an effective weak mixing angle $\sin^2(\overline{\theta_W})$ [7]. Using the measurement of Γ_l we find:

$$\sin^2(\overline{\theta_W}) = 0.2309 \pm 0.0048$$

ii) The number of neutrino generations:

Using the standard model value for the partial width of Z^0 decays into a neutrino pair ($166.6 \mathrm{MeV/c^2}$) the number of light neutrino generations can be derived from Γ_{inv}:

$$N_\nu = 2.82 \pm 0.11(\mathrm{stat}) \pm 0.13(\mathrm{syst})$$

All these results are displayed in Figure 1.

4c. Individual fits to the leptonic cross-sections

With the values of the Z^0 mass and total width fixed to the values obtained in section 4b, the individual leptonic widths were obtained:

$$\Gamma_e = 82.0 \pm 1.4(\mathrm{stat}) \pm 1.3(\mathrm{syst}) \mathrm{MeV/c^2}$$

$$\Gamma_\mu = 87.2 \pm 2.7(\mathrm{stat}) \pm 2.2(\mathrm{syst}) \mathrm{MeV/c^2}$$

$$\Gamma_\tau = 86.0 \pm 3.1(\mathrm{stat}) \pm 2.7(\mathrm{syst}) \mathrm{MeV/c^2}$$

The results of these fits are displayed in Figure 2.

4d. Fit to the "flavour-blind lepton" cross-section alone

Fixing the mass and width of the Z^0 to the values given in section 4b, a one parameter fit to the "flavour-blind lepton" lineshape yields:

$$\Gamma_l = 82.6 \pm 0.80(\mathrm{stat}) \pm 0.80(\Gamma_Z) \pm 0.83(\mathrm{Lumi}) \pm 0.53(\mathrm{syst}) \mathrm{MeV/c^2}$$

where the quoted systematic errors are due to the uncertainty on Γ_Z, the overall luminosity uncertainty and the method of analysis respectively.

The results of this fit are also displayed in Figure 2.

Combining the errors in quadrature gives $\Gamma_l = 82.6 \pm 1.5$ MeV from which we can compute another value for the effective weak mixing angle:

$$\sin^2(\overline{\theta_W}) = 0.2346 \pm 0.0053$$

4e. Standard model fit to the hadron cross-section alone

The hadronic cross-section was compared to the standard model expectations via a fit in which only M_Z and an overall normalisation factor K were left free to vary. All the other parameters were computed from the standard model, assuming 3 massless neutrino species. The results are:

$$M_Z = 91.193 \pm 0.013(\mathrm{stat}) \pm 0.030(E_c m)\mathrm{GeV}/c^2$$

$$K = 1.019 \pm 0.005(\mathrm{stat})$$

$$\chi^2/d.o.f = 13.1/(17-2)$$

The quality of the fit shows that the standard model reproduces the data well. Figure 3 diplays the cross-section measured at each energy together with the result of the fit (full line). The cross-sections predicted by the standard model for the same value of M_Z but for 2 and 4 neutrino generations are shown by the dotted and dashed lines respectively. The data clearly favour 3 light neutrino species.

5. Extraction of the Z° Couplings from the Leptonic Data

A 2 parameter fit to the tau and muon pair cross-sections and forward-backward charge asymmetries given as a function of centre of mass energy (not corrected for geometrical acceptance) with M_Z and Γ_Z fixed to the values given in section 4a (i.e. hadron cross-section only) yields a measurement of the vector and axial-vector couplings of the Z^0 to charged leptons (assuming universality):

$$v_l{}^2 = 0.0123 \pm 0.0085(\mathrm{stat}) \pm 0.003(\mathrm{syst})$$

$$a_l{}^2 = 1.0061 \pm 0.0138(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

$$\chi^2/d.o.f = 20.8/(28-2)$$

If we take the sign of these couplings to be negative, as determined[7] by previous experiments, then we obtain

$$v_l = -0.111 {}^{+0.049}_{-0.033}(\mathrm{stat}) \pm 0.015(\mathrm{syst})$$

$$a_l = -1.003 \pm 0.007(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$

The systematic error has been estimated from the systematic uncertainties on the cross-sections and asymmetries. For this analysis only the 1990 data sample has been used.

These results agree well with standard model expectations of -0.998 to -1.007 for the axial coupling and -0.056 to -0.095 for the vector coupling (by varying the top quark mass from 50 to 230 GeV and the Higgs mass from 30 to 1000 GeV).

The results of this fit are displayed in Figure 4.

6. Summary

The measurement of the cross-sections for $e^+e^- \to$hadrons and the cross-sections and forward-backward charge asymmetries for $e^+e^- \to$ charged leptons at 17 different centre-of-mass energies on the Z^0 resonance has been performed with the DELPHI apparatus using samples of approximately 68,000 hadronic events and about 4,000 electron, muon and tau pair events. A 4 parameter fit applied simultaneously to the hadronic cross-section and to the 3 leptonic cross-sections using the theoretical cross-sections of [5] determines the following:

$$M_Z = 91.188 \pm 0.013(\mathrm{stat}) \pm 0.030(E_{cm})\mathrm{GeV}/c^2$$

$$\Gamma_Z = 2.476 \pm 0.026(\mathrm{stat}) \pm 0.010(\mathrm{syst})\mathrm{GeV}/c^2$$

$$\Gamma_l = 83.7 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})\mathrm{MeV}/c^2$$

$$\Gamma_h = 1.756 \pm 0.023(\mathrm{stat}) \pm 0.020(\mathrm{syst})\mathrm{GeV}/c^2$$

$$\Gamma_{inv} = 469 \pm 19(\mathrm{stat}) \pm 22(\mathrm{syst})\mathrm{MeV}/c^2$$

$$R = 21.00 \pm 0.38(\mathrm{stat}) \pm 0.29(\mathrm{syst})$$

$$\chi^2/d.o.f = 46.8/(61-4)$$

Using the standard model value for the partial width of Z^0 decays into a neutrino pair (166.6 MeV/c^2) the number of light neutrino generations can be derived from Γ_{inv}:

$$N_\nu = 2.82 \pm 0.11(\mathrm{stat}) \pm 0.13(\mathrm{syst})$$

In the minimal standard model the leptonic partial width can be expressed in terms of an effective weak mixing angle $\sin^2(\overline{\theta_W})$. Using the measurement of Γ_l we find:

$$\sin^2(\overline{\theta_W}) = 0.2309 \pm 0.0048$$

With the values of the Z^0 mass and total width fixed to the values quoted above, the individual leptonic widths were obtained:

$$\Gamma_e = 82.0 \pm 1.4(\mathrm{stat}) \pm 1.3(\mathrm{syst})\mathrm{MeV}/c^2$$

$$\Gamma_\mu = 87.2 \pm 2.7(\mathrm{stat}) \pm 2.2(\mathrm{syst})\mathrm{MeV}/c^2$$

$$\Gamma_\tau = 86.0 \pm 3.1(\mathrm{stat}) \pm 2.7(\mathrm{syst})\mathrm{MeV}/c^2$$

Using the same procedure, a value for the leptonic width (assuming universality) was obtained from the "flavour-blind lepton" lineshape:

$$\Gamma_l = 82.6 \pm 0.8(\text{stat}) \pm 1.3(\text{syst})\text{MeV}/c^2$$

Finally, the vector and axial-vector couplings of the Z to charged leptons (assuming universality) were obtained from the measurements of the muon pair and tau pair cross-sections and forward-backward charge asymmetries:

$$v_l = -0.111 {}^{+0.049}_{-0.033}(\text{stat}) \pm 0.015(\text{syst})$$

$$a_l = -1.003 \pm 0.007(\text{stat}) \pm 0.01(\text{syst})$$

All values determined above agree well with the Standard Model. They are also in agreement with other experiments[8].

Acknowledgements

We are greatly indebted to our technical staff and collaborators and funding agencies for their support in building the DELPHI detector, and to the members of the SPS-LEP Division for the speedy commissionning and superb performance of the LEP collider.

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Table 1. The number of selected events and cross sections σ_h for $e^+e^- \to$ ***hadrons*** for different centre of mass energies. The cross-sections are corrected for acceptance to the full solid angle and the errors are statistical only. The corresponding integrated luminosity is 3260 nb^{-1}. The overall systematic error on these points is 2.3%.

$\sqrt{s}$ (GeV)	No. of hadronic events	σ_h (nb)
88.22	744	4.90 ± 0.19
88.28	236	4.74 ± 0.32
89.22	1600	8.48 ± 0.23
89.28	416	9.42 ± 0.50
90.22	5679	18.23 ± 0.30
90.28	1060	19.51 ± 0.73
91.04	1930	29.15 ± 0.89
91.22	42266	31.34 ± 0.22
91.28	2321	31.02 ± 0.89
91.54	2918	29.97 ± 0.76
92.22	4106	22.21 ± 0.45
92.28	768	20.92 ± 0.96
93.22	1956	12.94 ± 0.35
93.28	575	11.57 ± 0.55
94.22	1287	7.89 ± 0.24
94.28	270	8.54 ± 0.57
95.04	93	6.19 ± 0.69

Table 2. The number of selected events and cross sections σ_e for $e^+e^- \to e^+e^-$ for different centre of mass energies. The cross-sections are corrected for acceptance to the full solid angle and the errors are statistical only. The corresponding integrated luminosity is 2611 nb^{-1}. The overall systematic error on these points is 2.6%.

$\sqrt{s}$ (GeV)	No. of e^+e^- events	σ_e (nb)
88.22	38	0.418 ± 0.125
88.28	15	0.34 ± 0.19
89.22	73	0.495 ± 0.103
89.28	16	0.45 ± 0.21
90.22	130	0.879 ± 0.113
90.28	37	1.10 ± 0.28
91.04	47	1.10 ± 0.24
91.22	758	1.434 ± 0.061
91.28	43	1.28 ± 0.24
91.54	66	1.40 ± 0.20
92.22	64	1.043 ± 0.137
92.28	13	0.92 ± 0.28
93.22	41	0.686 ± 0.112
93.28	12	0.57 ± 0.17
94.22	22	0.333 ± 0.080
94.28	10	0.65 ± 0.21

Table 3. The number of selected events and cross sections σ_μ for $e^+e^- \to \mu^+\mu^-$ for different centre of mass energies. The cross-sections are corrected for acceptance to the full solid angle and the errors are statistical only. The corresponding integrated luminosity is 2534 nb^{-1}. The overall systematic error on these points is 2.8%.

$\sqrt{s}$ (GeV)	No. of $\mu^+\mu^-$ events	σ_μ (nb)
88.22	15	0.183 ± 0.049
88.28	5	0.24 ± 0.11
89.22	62	0.503 ± 0.065
89.28	7	0.44 ± 0.16
90.22	184	1.098 ± 0.082
90.28	14	0.64 ± 0.16
91.04	30	1.32 ± 0.24
91.22	990	1.509 ± 0.050
91.28	33	1.46 ± 0.26
91.54	70	1.64 ± 0.20
92.22	85	1.148 ± 0.124
92.28	13	0.91 ± 0.26
93.22	41	0.561 ± 0.088
93.28	17	0.71 ± 0.16
94.22	46	0.453 ± 0.068
94.28	3	0.68 ± 0.38

Table 4. Results of measurements of the forward-backward asymmetry A_μ for different centre of mass energies. The results are corrected for acceptance to the full solid angle and the errors are statistical only. The overall systematic error on these points is 1.0%

$\sqrt{s}$ (GeV)	A_μ
88.22	-0.564 ± 0.312
89.22	-0.195 ± 0.153
90.22	-0.113 ± 0.090
91.22	0.076 ± 0.039
92.22	-0.043 ± 0.131
93.22	0.324 ± 0.189
94.22	0.188 ± 0.180

Table 5. The number of selected events and cross sections σ_τ for $e^+e^- \rightarrow \tau^+\tau^-$ for different centre of mass energies. The cross-sections are corrected for acceptance to the full solid angle and the errors are statistical only. The corresponding integrated luminosity is 2327 nb^{-1}. The overall systematic error on these points is 3.4%.

$\sqrt{s}$ (GeV)	No. of $\tau^+\tau^-$ events	σ_τ (nb)
88.22	8	0.217 ± 0.079
88.28	7	0.49 ± 0.18
89.22	32	0.496 ± 0.087
89.28	5	0.66 ± 0.29
90.22	92	0.992 ± 0.103
90.28	12	0.75 ± 0.22
91.04	34	1.55 ± 0.27
91.22	617	1.520 ± 0.061
91.28	34	1.13 ± 0.20
91.54	47	1.70 ± 0.26
92.22	51	0.992 ± 0.139
92.28	12	0.86 ± 0.26
93.22	35	0.713 ± 0.120
93.28	3	0.22 ± 0.13
94.22	23	0.403 ± 0.086
94.28	2	0.46 ± 0.33

Table 6. Results of measurements of the forward-backward asymmetry A_τ for different centre of mass energies. The results are corrected for acceptance to the full solid angle and the errors are statistical only. The overall systematic error on these points is 1.0%

$\sqrt{s}$ (GeV)	A_τ
88.22	-0.699 ± 0.277
89.22	0.000 ± 0.191
90.22	-0.170 ± 0.113
91.22	0.003 ± 0.044
92.22	0.000 ± 0.151
93.22	0.183 ± 0.210
94.22	0.121 ± 0.270

Table 7. The number of selected events and cross sections σ_l for $e^+e^- \to l^+l^-$ for different centre of mass energies. The cross-sections are corrected for acceptance to the full solid angle and the errors are statistical only. The corresponding integrated luminosity is 1889 nb^{-1}. The overall systematic error on these points is 2.4%.

$\sqrt{s}$ (GeV)	No. of l^+l^- events	σ_l (nb)
88.22	57	0.204 ± 0.027
89.22	82	0.454 ± 0.051
90.22	382	0.968 ± 0.051
91.22	2306	1.442 ± 0.031
92.22	165	1.022 ± 0.082
93.22	108	0.613 ± 0.060
94.22	87	0.402 ± 0.044

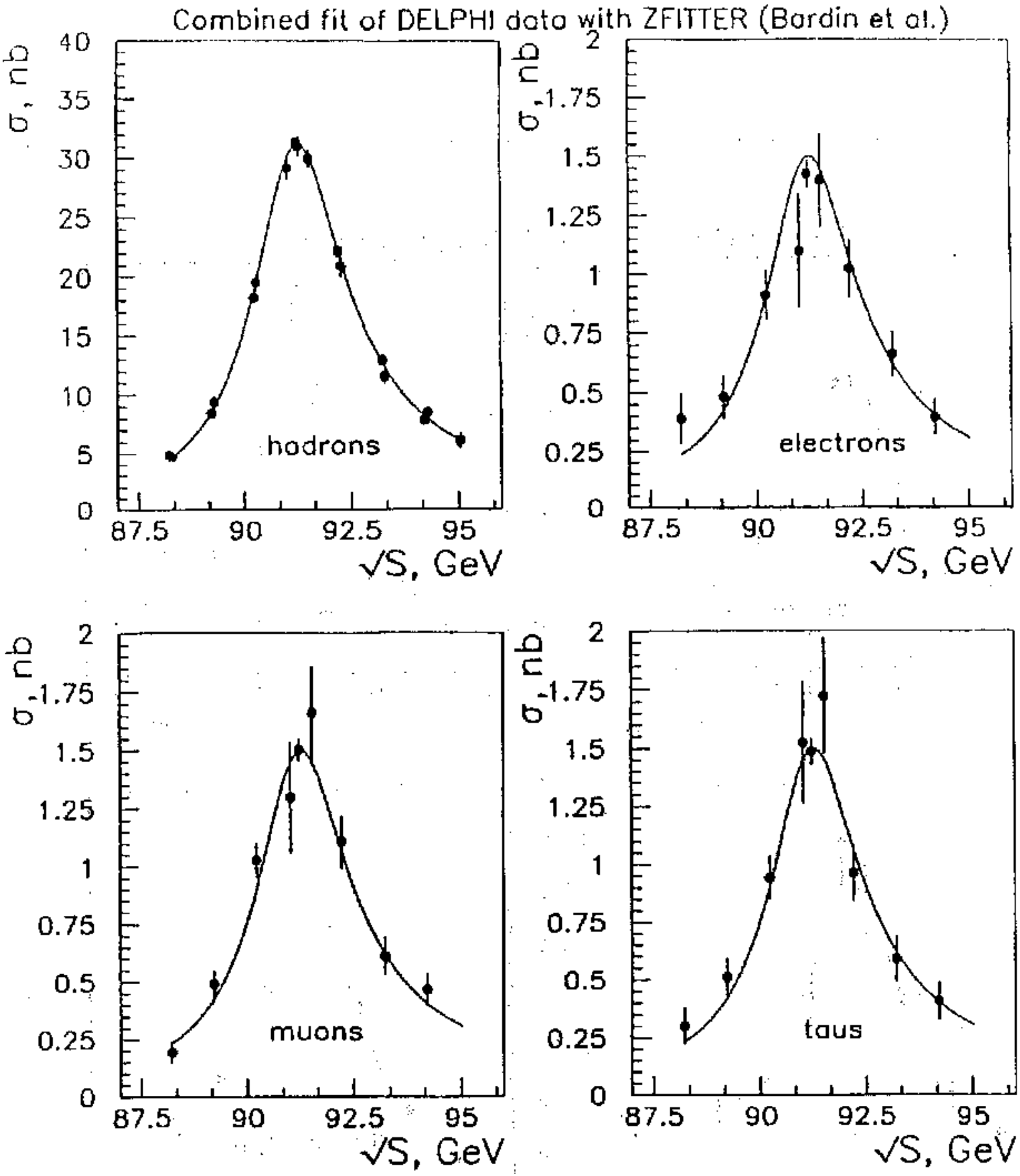
Figure Captions

Fig.1. Cross sections for $e^+e^- \to$ *hadrons*, $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ as a function of the centre of mass energy around the Z° pole. The cross sections are corrected for acceptance to the full solid angle. The curves are the results of a four parameter combined fit to the lineshapes as described in the text.

Fig.2. Cross sections for $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to l^+l^-$ (flavour-blind analysis) as a function of the centre of mass energy around the Z° pole. The cross sections are corrected for acceptance to the full solid angle. The curves are the results of a one parameter fit to each individual cross-section with the mass and total width of the Z° fixed as described in the text.

Fig.3. Cross-sections for $e^+e^- \to$ *hadrons* as a function of centre of mass energy around the Z° pole. The solid curve is the result of a 2 parameter standard model fit to the lineshape as described in the text (assuming 3 neutrino species). The other curves indicate the expected cross-sections for 2 and 4 neutrino species.

Fig.4. Cross sections and forward-backward asymmetries for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ as a function of centre of mass energy. The cross sections are corrected for acceptance to the full solid angle. The asymmetry data correspond to the angular region $43^\circ < \theta < 137^\circ$. The curves are the results of a two parameter fit to the data with the mass and width of Z° fixed as described in the text.



$M_Z = 91.188 \pm .013_{stat}$ GeV

$\Gamma_h = 1.756 \pm .023_{stat} \pm .020_{syst}$ GeV

$\Gamma_l = 83.7 \pm 1.0_{stat} \pm 1.1_{syst}$ MeV

$\Gamma_{inv} = 0.469 \pm .019_{stat} \pm .022_{syst}$ GeV

$\chi^2/Ndf = 46.8/(61-4)$

$\Gamma_Z = 2.476 \pm 0.026_{stat} \pm 0.010_{syst}$ GeV

$R = 21.00 \pm 0.38_{stat} \pm 0.29_{syst}$

Figure 1

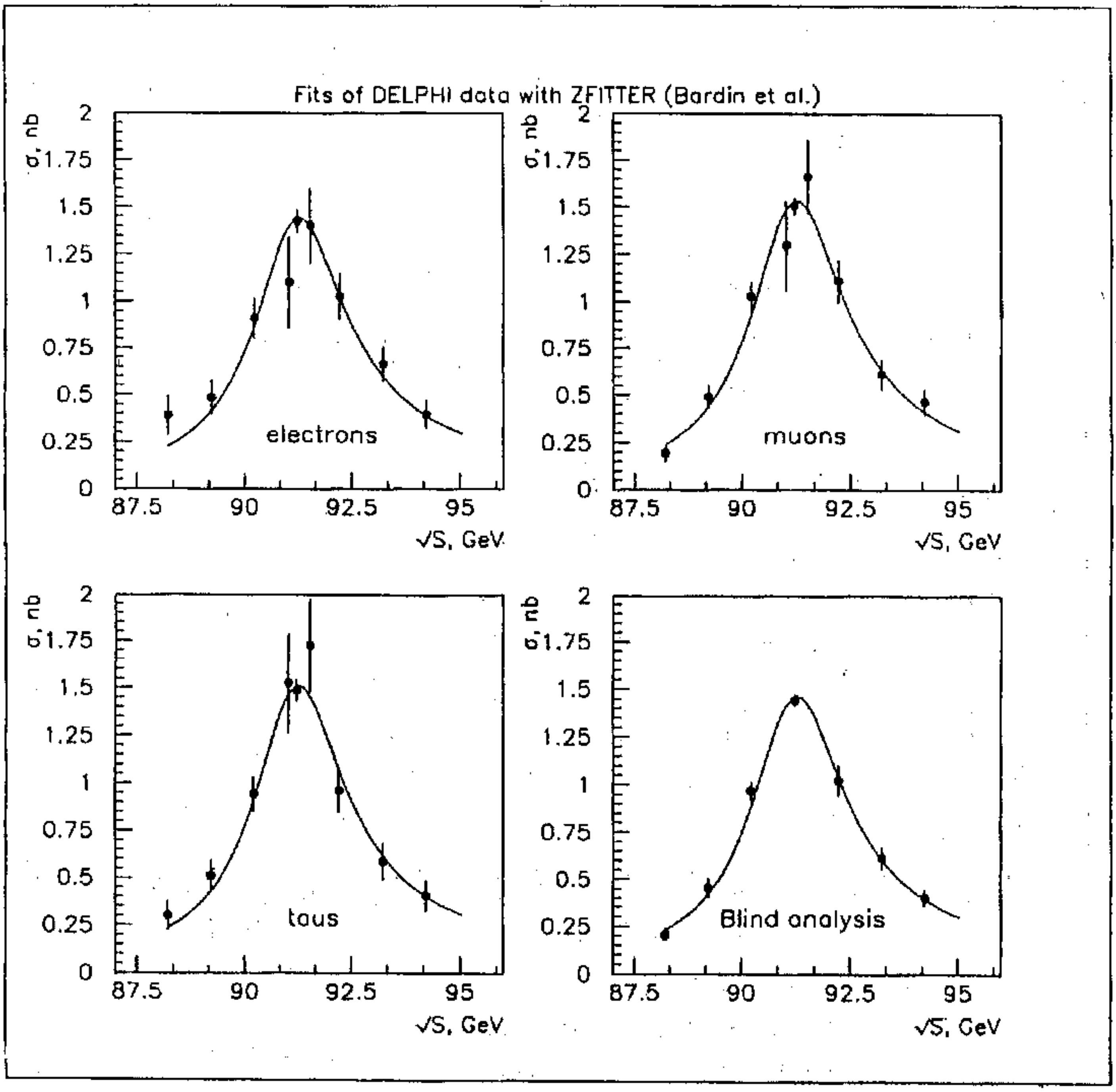
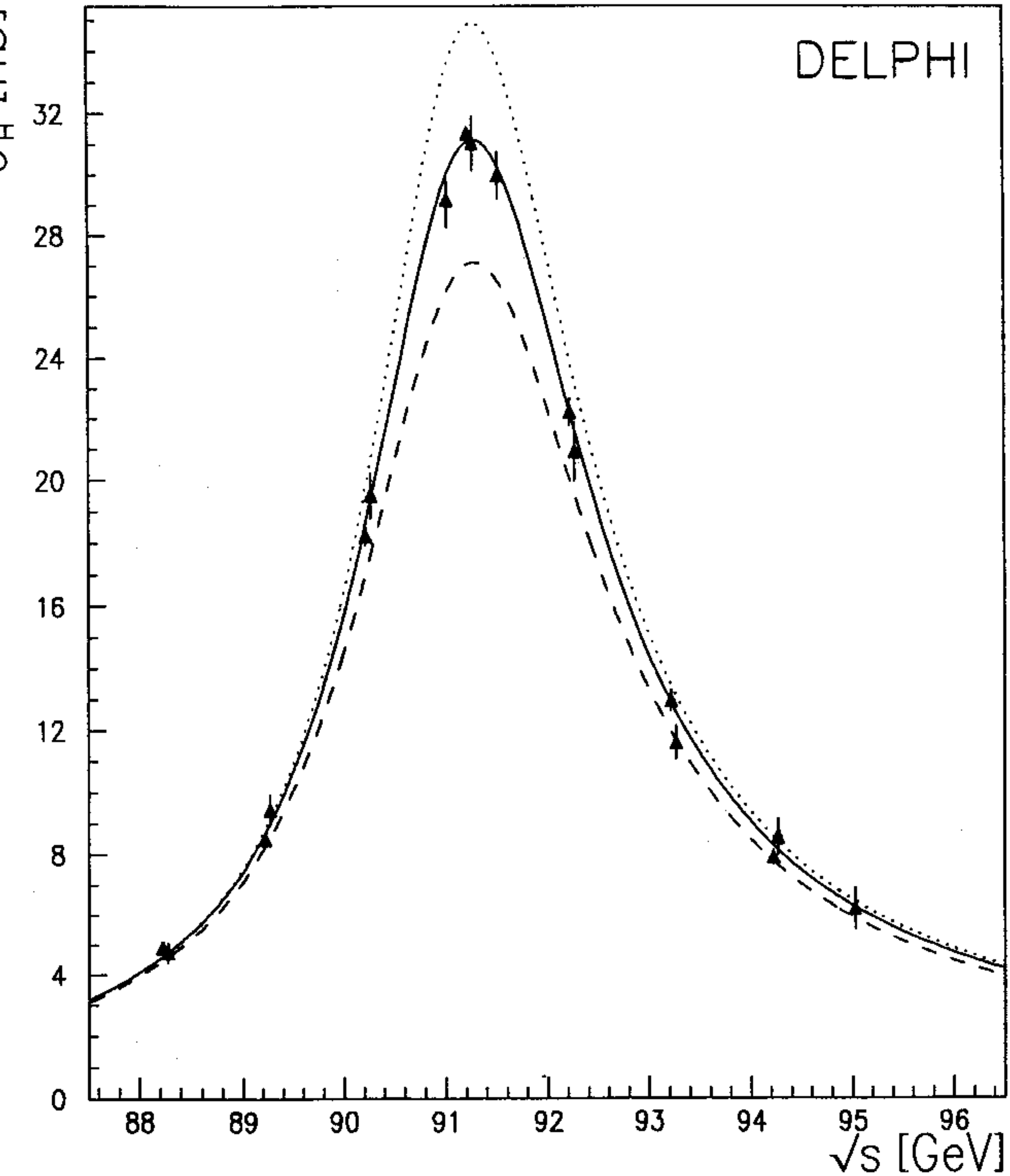
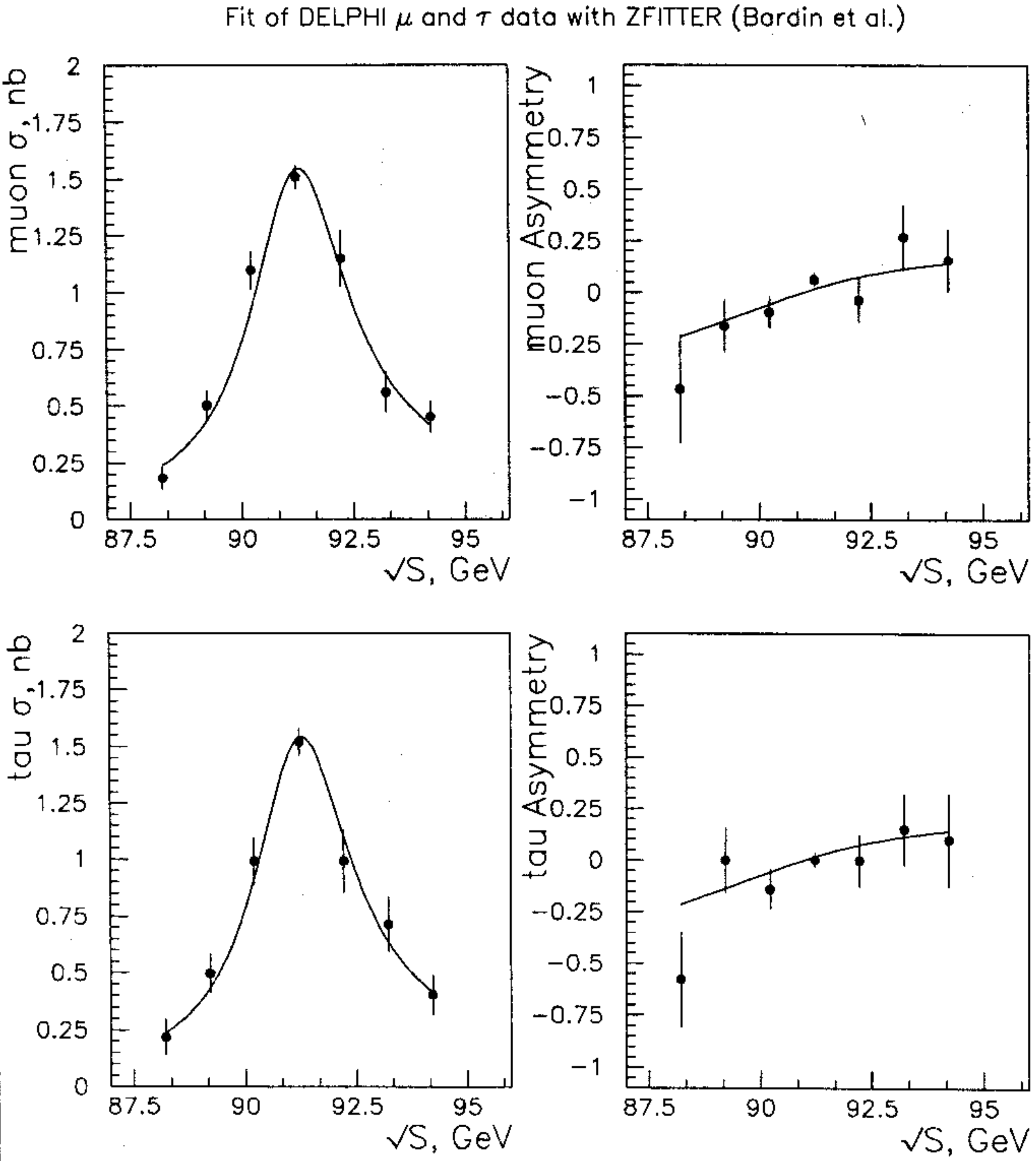

Fits of DELPHI data with ZFITTER (Bardin et al.)
σ, nb
electrons
muons
taus
Blind analysis
√S, GeV
87.5
90
92.5
95
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2

Figure 2



DELPHI
σ_H [nb]
32
28
24
20
16
12
8
4
0
88
89
90
91
92
93
94
95
96
$\sqrt{s}$ [GeV]

Figure 3



M_Z = 91.191 GeV (fixed)

Γ_Z = 2.466 GeV (fixed)

$v_l^2 = 0.0123 \pm 0.0085$

$a_l^2 = 1.0061 \pm 0.0138$

$\chi^2/\mathrm{Ndf} = 20.8/(28-2)$

Or for parameters v and a :

$v_l = -0.111 \pm {}^{0.049}_{0.033}$

$a_l = -1.003 \pm 0.007$

Figure 4

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