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An Update of the Z^0 Line Shape and Lepton Asymmetry Measurements with the 1993 Data for the 1994 Summer Conferences

The OPAL Collaboration

Abstract

In this note we present a preliminary update of our published analysis of hadronic and leptonic cross sections and of the leptonic forward-backward asymmetries in e^+e^- collisions. The published results were based on a recorded total of 1 187 000 hadronic and 146 000 leptonic events. This analysis adds 653 000 hadronic and 81 000 leptonic events recorded in a high precision scan with centre-of-mass energies within ± 2 GeV of the Z^0 mass. The determination of the mass and width of the Z^0 also benefit from an improved understanding of the LEP energy calibration. The error on the ratio of the invisible to leptonic widths has been significantly reduced by using the new luminosity measurement from Silicon-Tungsten detectors installed before 1993 data taking.

1 Introduction

We present preliminary results from an analysis of hadronic and leptonic cross sections and leptonic forward-backward asymmetries measured in e^+e^- collisions during 1993 by the OPAL experiment at LEP. These data are combined with our published cross sections and asymmetries, from data accumulated to the end of 1992 [1, 2, 3], in order to improve the determination of electroweak parameters and provide more stringent tests of the Standard Model.

The integrated luminosity of the 1993 dataset used in this analysis is approximately 34 pb^{-1}. More than 18 pb^{-1} were recorded, during a series of scans, at two centre-of-mass energy ($\sqrt{s}$) points roughly 1.8 GeV above and below the Z^0 mass, M_Z, (termed "off-peak" data), while the remainder was within 200 MeV of M_Z. This provides a four-fold increase in our off-peak luminosity relative to that previously published [1, 2, 3]. Together with a more precise calibration of the LEP beam energy, this leads to a substantially improved determination of the Z^0 width, Γ_Z, as well as improvements to M_Z and related electroweak parameters. Other measurements also benefit from the overall increase in data statistics. In addition the accuracy of the luminosity measurement has been improved by the use of newly installed Silicon-Tungsten detectors, leading to a reduction of the error on the ratio of the invisible to leptonic widths.

Throughout the rest of this note the three parts of the 1993 dataset recorded at centre-of-mass energies below, close to and above M_Z will be referred to as "peak−2", "peak", and "peak+2" datasets respectively. About 6 pb^{-1} of the peak data were accumulated before the start of the precise energy scans. These will be referred to as "pre-scan" data.

2 Luminosity

A Silicon-Tungsten luminometer (SiW) was installed in OPAL before the start of data taking in 1993. This detector provides absolute luminosity measurements with a precision better than 10^{-3}. The fiducial acceptance of SiW is approximately 80 nb, about two and a half times as large as the multihadron cross section at the Z^0 peak.

For these preliminary results we use the SiW absolute luminosity measurements for all data for which SiW had good status: these comprise more than 90% of the scan data. The FD is used to provide relative luminosities for the small portion of the scan data for which the SiW status was bad and for the entire pre-scan data. Data for which both luminosity detectors had good status were used to normalize the FD luminosity measurement to the SiW measurement.

2.1 The SiW Luminosity Measurement

The SiW luminometer consists of two finely segmented, position sensitive silicon-tungsten calorimeters [4], symmetrically placed on the left and right sides of the OPAL detector, at small angles to the beam direction. The SiW luminometer system was installed in the spring of 1993 and commissioned during the early part of the 1993 LEP run.

Bhabha events were selected by requiring the event to contain two high energy clusters, one in each side of the detector. The two clusters were each required to be within fiducial volumes defined within the SiW detector, and to be back-to-back. The main sources of systematic error are due to the reconstruction of the cluster radial coordinate, and its energy. The full set of systematic errors on the luminosity measurement are discussed in [5] and the references therein.

2.2 The FD Luminosity Measurement

The SiW luminometer shadows the inner edge of the old Forward Detector (FD), effectively displacing the FD minimum acceptance angle from about 48 mrad to 60 mrad thus reducing its fiducial acceptance from approximately 52 nb to 28 nb.

FD Bhabha scattering events were selected by requiring the sum of energies deposited in the right and left detectors, $\mathrm{E_R} + \mathrm{E_L}$, to be greater than $0.82\sqrt{s}$. Events were also required to have acoplanarities of less than $10°$. The main systematic errors arise from variation in the beam spot position and from changes in the calibration of the forward calorimeters.

In previous years, the acceptance for Bhabha scattering events depended only upon the stability of the energy calibration of the forward calorimeters. In 1993, however, the presence of the SiW calorimeters in front of the FD imposed a sharp angular cut at both ends, so that the cross section was dependent on the position and dimensions of the interaction region.

The dependence of the cross section on the beam spot position was estimated to be 1.0% mm^{-1} for movements of the interaction point transverse to the beam and 0.1% mm^{-1} for movements along the beam axis. These estimates were made using a simple Monte Carlo model which assumed that the acceptance of the FD changes from one to zero at the boundary of the SiW.

Figure 1 shows the mean y positions* of the beam spot for the different OPAL data-taking periods in 1993. Because of the variation of the beam spot position, the absolute value of the accepted Bhabha cross section was time-dependent. During the scan, the mean beam spot positions for the different energy points were highly correlated, so although the absolute values of the cross sections changed with time, the relative values of cross sections at different energies remained nearly constant. Table 1 lists the luminosity weighted mean beam spot positions for the different energy points. Also listed are the estimated systematic errors arising from the differences in mean interaction points. The systematic errors represent 100 % of the estimated size of the effect. The only significant error arises for the pre-scan data, due to a large shift in the y position of the beam spot. However, the relative luminosity measurement for this data set has hardly any impact on the results quoted in section 6.

Fluctuations in the calibration of the forward calorimeter also affected the absolute values of the Bhabha cross sections. Using the observed energy spectra, the dependence of the cross section on changes in the energy calibration was determined to be

$$\frac{\delta\sigma}{\sigma} = 0.23\frac{\delta \mathrm{E}_{(\mathrm{R,L})}}{\mathrm{E}_{(\mathrm{R,L})}}, \tag{1}$$

where σ is the cross section for accepted events. Table 2 shows the total energy of accepted Bhabha events $(\mathrm{E_R} + \mathrm{E_L})$ divided by $\sqrt{s}$ for the different energy points. These variations were compensated by applying a global correction to the cross sections at each energy point.

For the majority of the scan data the trigger efficiency for events within the FD Bhabha acceptance was essentially 100 %. During the pre-scan and the initial 14 % of the scan data, the trigger efficiency

*A right-handed coordinate system is adopted by OPAL, where the x axis points to the centre of the LEP ring, and positive z is along the electron beam direction. The angles θ and ϕ are the polar and azimuthal angles, respectively.

was $99.67 \pm 0.10\%$. This inefficiency was due to the pre-trigger energy thresholds being higher in the early part of the data taking. Separate efficiencies were determined for the different energy points.

The energy dependence of the theoretical cross section was determined using BHAGEN [6] with geomtric cuts applied to simulate the FD acceptance. The effect of the γZ^0 interference terms was slightly enhanced with respect to that of the 1992 selection. This was due to the presence of the SiW calorimeters moving the inner edge of the acceptance from ~48 mrad to ~60 mrad. The theoretical point-to-point error was taken to be 0.1 % (about 10 % of the effect of the γZ^0 interference terms at $M_Z \pm 2GeV$).

2.3 Comparison and Combination of the Silicon-Tungsten and Forward Detector Luminosities.

As mentioned above, the multihadron and leptonic cross sections were calculated using the luminosity determined with the SiW detectors. When no such measurement was available the relative luminosity from the Forward Detector was used. This comprises the pre-scan data and amounts to less than 10% of the scan data. This was achieved by leaving the relative scale of the FD measurements with respect to the SiW measurements as a free parameter in the fits.

As a cross check, the luminosities from SiW and FD were compared for all the data where both had good detector and trigger status. Table 3 lists the ratios of SiW to FD luminosities for the peak−2, peak and peak+2 energy points. A chi-squared test indicated that the probability that the observed ratios were consistent with a single value was 0.24.

There was no evidence for any time dependence of the ratio of FD and SiW luminosities within the statistical precision of the comparison. Nevertheless a systematic error was assigned to account for possible drifts in the above ratio at the 1 standard deviation level of the comparison. Table 4 lists the systematic errors on the FD relative luminosity for the data where a measurement from the Silicon Tungsten luminometer was unavailable.

3 The Hadronic Decay Channel

The criteria used to select multihadronic events were similar to those of the large acceptance multihadron selection used for the previous publications [1, 2] and described in detail in [7]. Since the FD acceptance was reduced due to the inclusion of SiW for the 1993 data taking, the acceptance and background estimates of the multihadron selection, which uses FD, had to be reevaluated.

The distributions of the cut variables (Figure 2) show good agreement between data and the JETSET [8] Monte Carlo. Notably the visible energy is now much better described by the Monte Carlo as compared to previous years. The absolute acceptance was calculated to be $99.51 \pm 0.01\%$.

The comparison of the data and Monte Carlo distributions revealed small shifts in the visible energy and multiplicity. The effects of these shifts on the acceptance calculation were investigated. Furthermore, cuts were varied over reasonable intervals in order to quantify the effects of possible local distortions in the distributions of the selection variables. These studies resulted in assigning a systematic error due to the detector simulation of $\pm 0.07\%$. However, we found significant changes between the older Monte Carlo samples from 1990 and 1991 and the newer samples from 1992 and 1993, which are not yet fully understood. Therefore we retain for the moment the previous estimate of the detector simulation uncertainty of $\pm 0.14\%$, which safely covers the differences between the Monte Carlo samples. The other large contribution to the systematic error is the fragmentation uncertainty. No new studies of these effects were done, so we kept the previous estimate of 0.11%.

The $\tau^+\tau^-$ background was estimated with Monte Carlo to be 0.11%. Distributions sensitive to $\tau^+\tau^-$ background showed small discrepancies between data and Monte Carlo, a slight excess of events was found in the data compared to the Monte Carlo. The uncertainty due to this effect was $\pm 0.03\%$.

The background from non-resonant processes (mainly two-photon processes) was estimated with the data by measuring the ratio of the numbers of events with high and low visible energies and the ratio of the numbers of events with high and low energy imbalances as functions of the beam energy. Only the data from 1993 was used for this estimate, as the changes in the luminosity detector configuration also influence the level of this background. It gave a non-resonant cross section of 0.046 ± 0.009 nb, which corresponds to $0.15 \pm 0.03\%$ at the peak point.

Possible failures in the detector operation and in the data acquisition were investigated by examining distributions for events selected by a track-based selection and a calorimeter-based selection and by checking the events at the edge of the acceptance. An upper limit of 0.05% was obtained on the inefficiency due to such failures, which was assigned as a systematic error.

The correction factors for the peak energy point that account for selection efficiency and background are listed in Table 5. The overall correction, f, which relates the cross section, σ, to the number of observed events, N_{obs}, and the integrated luminosity, $\mathcal{L}$, via $\sigma = fN_{obs}/\mathcal{L}$ was 1.0023 with an uncertainty $\Delta f/f = 0.20\%$. At the off-peak points the acceptance is slightly decreased by 0.10% and 0.06% at the -2 and $+2$ points, respectively. This change is due to the very small fraction of events with hard initial state photon radiation (>40 GeV), which is slightly increased at the off-peak points. Since detailed checks of this effect have not yet been performed with the data, this change is assigned as an extra systematic error for the off-peak points.

4 The Leptonic Decay Channels

The analysis of leptonic final states was performed using techniques very similar to those described in our previous publications [1, 2, 3]. Events were required to lie within the angular ranges $|\cos\theta| < 0.70$, $|\cos\theta| < 0.95$ and $|\cos\theta| < 0.90$ for the e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ channels, respectively. Studies of the selection efficiency were made using the KORALZ [9] program for $Z^0 \to \mu^+\mu^-$ and $Z^0 \to \tau^+\tau^-$, and the BABAMC [10] program for the process $e^+e^- \to e^+e^-$. The factors by which the selected numbers of candidate events were corrected in order to account for experimental efficiency and background are given in Tables 6, 7 and 8, for electron, muon and tau pairs, respectively. For electron pairs, the correction factors have been evaluated separately at the three centre-of-mass energies in order to take into account the effect of t-channel and s-t interference contributions, which lead to different angular distributions of both electron pair and background events at the three energies. The level of background and the selection efficiency have also been found to differ at the three centre-of-mass energies in the case of tau pairs. For muon pairs, the absence of such effects means that the same correction factor can be applied at all three energies.

For the measurement of the forward-backward asymmetry, events were required to have acollinearity angles of less than 10° for the e^+e^- channel and less than 15° for the $\mu^+\mu^-$ and $\tau^+\tau^-$ channels. For the $\mu^+\mu^-$ and $\tau^+\tau^-$ channels, the forward-backward asymmetry was calculated using an unbinned maximum likelihood fit to the angular distribution. This was checked by simply counting the numbers of forward and backward events. For the e^+e^- channel, in the absence of a convenient parametrization for the differential cross section, the forward-backward asymmetry was calculated with the simple counting method. The angular distributions at the three centre-of-mass energies are shown in figures 3, 4 and 5 for electron, muon and tau pairs, respectively.

4.1 The e^+e^- Channel

An electron was identified by a high energy electromagnetic cluster associated to a charged track. Events were required to contain two electron candidates with an acollinearity of less than $10°$. Cuts on the numbers of electromagnetic clusters and charged tracks rejected hadronic events. A high visible energy was required in order to remove remaining background, in particular from tau pairs. These criteria selected 23 728 events from the 1993 data.

The selection efficiency and backgrounds were estimated using a sample of Monte Carlo events. Checks similar to those described in [1] were repeated to obtain corrections to these estimates and to evaluate systematic errors.

Checks of the dominant corrections, due to the energy cut and τ backgrounds, were made separately for the data samples at the three different centre-of-mass energies. The efficiencies for e^+e^- and backgrounds were found to be consistent at these three energy points. The differences between the separately evaluated efficiencies were assigned as systematic errors at the off-peak energy points.

The edge of the acceptance was defined by the measurement of θ with the electromagnetic cluster. A possible systematic bias was checked by comparing this with an independent measurement using the associated high quality track. An example of such a comparison is shown in figure 6, in which the value of $\cos\theta$ measured by tracks is plotted for two classes of events: those classified by the cluster $\cos\theta$ as lying inside the angular acceptance and those lying outside. A comparison of the accepted number of events for different θ definitions was also made. From these studies, the error on the cross section due to uncertainty on the edge of acceptance was estimated to be 0.12% as in [1] at the peak energy. At the off-peak energies, the relative size of the t-channel forward peak increases. This leads to a larger systematic error at off-peak points, 0.18% and 0.13% at peak$-$2 and peak+2, respectively.

The full set of correction factors and associated systematic errors for the electron pair cross section measurement are summarised in Table 6. The overall correction factor, f, was 1.0049 at the peak with an uncertainty $\Delta f/f = 0.23\%$. This correction factor differed by $+0.12\%$ and -0.04% at the peak$-$2 and peak+2 points respectively.

The forward-backward asymmetry of $e^+e^- \to e^+e^-$ was calculated, and the systematic error evaluated, using techniques similar to those described in [1]. The measured asymmetry was corrected for small contributions due to the background and charge misassignment. These corrections amount to at most 0.0006 and depend slightly on the centre-of-mass energy. For the same reason as for the cross section measurement, a possible bias in the edge of the acceptance contributes differently at the three centre-of-mass energies. The systematic error on the forward-backward asymmetry is 0.0016 at the Z^0 peak, and 0.0021 and 0.0015 at peak$-$2 and peak+2, respectively.

4.2 The $\mu^+\mu^-$ Channel

Candidate muon pairs were required to contain at least two tracks each having a momentum greater than 6 GeV, matched to the beam interaction point and identified as a muon by at least one outer detector (electromagnetic calorimeter, hadron calorimeter or muon chambers). Multihadrons were rejected by a requirement that the event contain 3 or fewer charged tracks, after correction for photon conversions and tracks split by the reconstruction algorithm. Remaining tau pair and two photon backgrounds were rejected by a requirement that the visible energy, defined as the sum of the two highest momentum tracks plus the highest energy electromagnetic cluster, be at least 0.60 $\sqrt{s}$.

These criteria selected 30 978 events from the 1993 data. The signal selection efficiency measured from a Monte Carlo detector simulation of 200 000 $Z^0 \to \mu^+\mu^-$ events is estimated as 91.40±0.06%. A number of studies have been undertaken to ensure that discrepancies in selection efficiency between the data and Monte Carlo have been accounted for. These are discussed in more detail below.

The dominant systematic errors in the analysis, as in 1992, are the estimation of the tau pair background in the sample and the estimation of the effect of track reconstruction problems in the regions close to the jet chamber sense wire planes. In addition, evaluation of the trigger efficiency has shown a slight decrease compared to 1992. The overall efficiency from an analysis of individual triggers for single muons is estimated in 1993 as 99.79±0.10%, the observed decrease being due to a reduced efficiency of the track trigger in some periods.

The estimate of the background in the sample coming from $e^+e^- \to \tau^+\tau^-$ is dependent on accurate simulation of the visible energy distribution in the tau pair Monte Carlo sample. As in [1], the quality of this simulation was checked by studying the visible energy, acoplanarity and acollinearity distributions in data and Monte Carlo subsamples of the selected muon pair candidates for which the level of background was enhanced. To obtain the highest statistical precision, the background-enriched subsample was taken from the 1991, 1992 and 1993 data samples combined, a total of 81 310 events. In the region of visible energy between 0.60 $\sqrt{s}$ and 0.80 $\sqrt{s}$ there were 332 events in the data and 319 events predicted by the Monte Carlo simulation, of which 97% were tau pair events. This subsample contains 45% of the tau pair background events expected in the main selection, and so provides a statistically sensitive check of the level of this background.

The precision of this assessment was further enhanced by a similar check using an independent sample of purely tau pair events, selected by demanding a final state electron and muon. In the region of visible energy between 0.60 $\sqrt{s}$ and 0.90 $\sqrt{s}$ there were 442 events in the data and 451 in Monte Carlo, all of which were simulated tau pairs.

The distributions of visible energy for the two subsamples are shown for data and Monte Carlo in figure 7. The good agreement between data and Monte Carlo in the regions of interest allows us to estimate an upper limit of 0.10% on the uncertainty of the predicted tau pair background level of 0.96%.

The fraction of data events lost due to tracking inefficiencies was studied using an alternative muon pair selection which was almost independent of the central tracking [2]. This selection requires highly collinear hits in the electromagnetic calorimeter (acollinearity<50 mrad) and the muon chambers (acollinearity<30 mrad) and makes no requirements on the presence or quality of tracks in the central detector. This selection has a high purity for selecting $Z^0 \to \mu^+\mu^-$ events and an efficiency well-duplicated by the Monte Carlo. Within this selection, events in the data failing the main muon pair selection are flagged if they show evidence of being genuine muon pair events (likely cosmic and tau pair events are rejected). Such problem events are mainly due to poor track reconstruction causing the track either not to be identified as a muon candidate or its momentum to be mis-measured to such an extent that the event fails the visible energy cut. The number of events thus found is corrected by the efficiency of the tracking-independent selection bin-by-bin in $|\cos\theta|$ to derive an estimate of the number of events missed by the main muon pair selection

Figure 8 shows the comparison between data and Monte Carlo of the tracking-independent selection efficiencies and numbers of problem events before and after correction for selection efficiency. The detector simulation models reconstruction problems to some extent in the forward region but fails almost entirely to predict problem events for $|\cos\theta| < 0.80$. In the 1993 data sample there were 270$\pm$20 problem events after correction (0.86$\pm$0.06% of the data sample), of which 80% had one or more tracks poorly reconstructed close to a jet chamber wire plane. In the Monte Carlo sample there were 85$\pm$4 problem events after correction (0.27$\pm$0.01%). On the basis of this discrepancy between data and Monte Carlo in the number of missed events, a correction of 0.59$\pm$0.10% is applied to the data.

The full set of correction factors for the muon pair cross section measurement, together with the corresponding systematic uncertainties, are summarized in Table 7. The overall correction factor, f, was 1.0933 with an uncertainty $\Delta f/f = 0.22\%$, and was the same at all points of the energy scan.

The forward-backward charge asymmetry was measured using high-quality tracks of randomly chosen charge, a method independent of local inefficiencies in the selection. As in our previous publication [1], comparison was made amongst several methods of measurement, which showed good agreement. As a result of these checks, an uncertainty of 0.001 was assigned to the asymmetry measurement at each energy point.

4.3 The $\tau^+\tau^-$ Channel

Tau pair events were required to contain two back-to-back, collimated, low multiplicity jets identified using information from the central tracking chambers and the electromagnetic calorimeters. Time-of-flight measurements were used to reject cosmic ray events and muon identification to reject $e^+e^- \rightarrow \mu^+\mu^-$. The remaining backgrounds from multihadrons, two-photon processes and $e^+e^- \rightarrow e^+e^-(\gamma)$ were rejected using multiplicity cuts, and by demanding that the two jets be narrow, with an acollinearity of less than 15°. These criteria selected 26 129 events from the 1993 data.

The systematic uncertainties in the backgrounds and selection efficiency were evaluated using methods similar to those described in [1]. In the 1993 data, a slight shift in track multiplicity distribution was seen with respect to 1992 (figure 9), which resulted in a systematic error of 0.26%.

The background contamination from resonant processes was studied using the combined 1992 and 1993 data samples and the increase in statistics has allowed most of the associated systematic errors to be reduced. The increase in statistics at off-peak energies has enabled a direct measurement of non-resonant backgrounds to be performed. The dominant processes $e^+e^- \rightarrow e^+e^-e^+e^-$ and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ were tagged by requiring a pair of final state electrons or muons. These backgrounds in general have low $\vec{p_t}$ and low visible energy, together with missing momentum vectors that point along the beam direction. The number of candidate events with $\Sigma\vec{p_t}$ less than 5% of the centre-of-mass energy, scalar sum of track momenta less than 50% of centre-of-mass energy and $|\cos\theta|$ of the missing momentum direction greater than 0.8, was observed to be in excess of that expected from a Monte Carlo simulation of tau pair production. The cross sections for $e^+e^-e^+e^-$ and $e^+e^-\mu^+\mu^-$ events that satisfied the tau pair selection cuts were thus estimated to be 4.2$\pm$0.7pb and 1.3$\pm$0.3pb, respectively. These estimates agreed with the Monte Carlo prediction [11] for two-photon processes; 3.9$\pm$0.3pb and 1.3$\pm$0.2pb.

The full set of correction factors are summarized in Table 8. At the Z^0 peak energy, the overall correction factor, f, was 1.3026 with an uncertainty $\Delta f/f = 0.46\%$, of which 0.40% was correlated with 1992 data. The acceptance for tau pair events was slightly energy dependent mainly due to the acollinearity cut. Taking into account also the energy dependent contribution from the non-resonant and e^+e^- backgrounds, the correction factors at peak-2 and peak$+2$ differed by -0.77% and -0.44% from that for the peak energy point. A common systematic error of 0.45% was taken as 100% correlated between the energy points while the remainder was taken as uncorrelated.

The anti-correlation of uncertainties due to cross-over of events from one leptonic channel into another was 0.08% between the $\mu^+\mu^-$ and $\tau^+\tau^-$ samples and 0.11% between e^+e^- and $\tau^+\tau^-$ channels.

For the forward-backward asymmetry measurement at least one of the tau jets in the event was required to have a charge of ± 1, and events in which the two tau jets were assigned the same charge sign were not used. These requirements rejected 1.9% of the $\tau^+\tau^-$ events. To account for the asymmetry of the e^+e^- background, the measured asymmetries were corrected by -0.003, -0.001 and -0.001 for peak-2, peak and peak$+2$, respectively. Possible biases to the asymmetry measurements were examined by comparing the results when tracks only, clusters only or both tracks and clusters were used to reconstruct the direction of the $\tau^+\tau^-$ pair, and also from comparison of results obtained using the polar angle of the τ^+, the τ^- or the average of the two. An uncertainty of 0.002 was estimated for the tau pair asymmetry measurement.

5 LEP Energy Calibration

A precise calibration of the LEP beam energy was achieved in 1993 by means of frequent measurements using the technique of resonant depolarization of a transversely polarized electron beam and by the reliable logging of many LEP machine parameters which were known to affect the energy scale [12, 13, 14]. Analysis of these energy data is still in progress, but preliminary results have been made available [15].

For the pre-scan peak dataset the mean centre-of-mass energy was 91.319 GeV†. The energy calibration was less precise during this period and a preliminary uncertainty of ± 18 MeV has been assigned, uncorrelated with other energy errors.

The luminosity-weighted mean centre-of-mass energies of the three 1993 scan points were 89.453, 91.211 and 93.036 GeV for the peak-2, peak and peak$+2$ datasets, respectively. The preliminary energy errors for the 1993 scan result in systematic uncertainties of 4 MeV on M_Z, 3 MeV on Γ_Z and 8.5 MeV on the centre-of-mass energy of the peak data point. There are no significant correlations among these energy errors, but they are fully correlated among the four LEP experiments. These uncertainties are incorporated into our fits by means of the energy error matrix given in Table 9. The energy error of the peak data point is higher than the energy error of the peak± 2 points as most of the calibrations were performed off-peak.

For combination with earlier data [1, 2, 3], the 1992 energy scale error and the 1991 point-to-point energy errors are considered to be uncorrelated with the 1993 energy errors. Hence the earlier Γ_Z measurement contributes to the combined result. The correlation between the systematic errors on the 1991 and 1993 M_Z measurements has not yet been studied. As recommended [15], for these preliminary results we do not use the information from the earlier M_Z measurement. This is accomplished by artificially inflating the error on the 1991 absolute energy scale in the fit.

The spread of the centre-of-mass energies, due to the energy spread of the particles in the beams,

†This value is different to that quoted in [17] due to the rejection of LEP fills 1578 and 1581 on the recommendation of the LEP energy working group.

was 46±5 MeV for the running periods in 1990-91 and 51±5 MeV for the running period in 1992 [14]. Based upon the results of a preliminary analysis [16] of the 1993 beam spread, a value of 55±5 MeV was used for the 1993 datasets. The energy spread was taken into account by correcting the measured cross sections in the fitting procedure as described in one of our previous publications [2].

6 Determination of Electroweak Parameters

Electroweak parameters were determined by the procedures outlined below from the 1993 measurements described in the previous sections. They were found to be in good agreement with our previous results [1, 2, 3]. The value of $\sigma^{\mathrm{pole}}_{\mathrm{had}}$ was found to be 41.40±0.17 nb. We then combined our 1993 measurements with our 1992 results (Tables 6-7 in [1]), our 1991 results (Tables 6-10 in [2]), our 1990 hadronic and leptonic cross sections (Tables 7-10 in [3]) and our combined 1989/1990 leptonic asymmetries (Tables 11-13 in [3]). Table 10 lists the contributions to the systematic error which were treated as fully correlated among the four data taking periods.

The theoretical parametrizations of the total and differential cross sections for the processes $e^+e^- \to$ hadrons, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$ and the contribution of s-channel diagrams to $e^+e^- \to e^+e^-$ were obtained using the program ZFITTER [18]. For the process $e^+e^- \to e^+e^-$ we used the program ALIBABA [19] to describe the contributions from the t-channel diagrams and from s-t interference. The procedure used to fit the cross sections and the leptonic asymmetries was essentially the same as that described in our previous publications [1, 2, 3]. We therefore restrict ourselves to tabulating the updated results in Tables 11−15 using identical nomenclature to [1, 2]. One change with respect to previous publications is that in performing the parameter transformations to produce Table 13 the C parameters referring to the γZ^0-interference have been fixed to their Standard Model values. This was done to conform with the procedures employed by the other LEP experiments.

Figure 10 shows a comparison of the results with the Standard Model prediction for the fitted parameters in Table 11. Figure 11 shows, for each leptonic species and their combination, the resulting one standard deviation contours in the R_ℓ-$A^{\mathrm{pole}}_{\mathrm{FB}}$ plane. Figures 12 and 13 show comparisons of the measured cross sections and asymmetries with the result of the Standard Model fit. Figure 14 shows the χ^2-curves, as a function of M_{t}, for the direct Standard Model fit to the corrected cross sections and forward-backward asymmetries. Figure 15 displays the one standard deviation contours in the ϵ_1-ϵ_3 plane.

7 Summary and Conclusions

We have presented a preliminary update of our published results by adding a total of 653 000 $e^+e^- \to$ hadrons, 23 728 $e^+e^- \to e^+e^-$, 30 978 $e^+e^- \to \mu^+\mu^-$ and 26 129 $e^+e^- \to \tau^+\tau^-$ events, recorded during 1993 within ±2 GeV of M_{Z}. The new M_{Z} measurement is consistent with the combined LEP value of $M_{\mathrm{Z}} = 91.187 \pm 0.007$ GeV which was published [13] after the 1991 energy scan. The uncertainty has been reduced to $\Delta M_{\mathrm{Z}} = 5$ MeV with a contribution of $\Delta M_{\mathrm{Z}} = 4$ MeV from the preliminary 1993 LEP energy calibration.

Compared to our most recent publication [1], which was based on data accumulated to the end of 1992, the uncertainties on parameters Γ_{Z}, $C^a_{\gamma\mathrm{Z}}$ and $C^s_{\gamma\mathrm{Z}}$ have been reduced by factors of approximately 1.8. This is due to the four-fold increase in off-peak luminosity, as well as the precise calibration of the LEP beam energy. The increased accuracy of the luminosity measurement as a result of using the SiW detector has reduced the error on the ratio of the invisible to leptonic widths by nearly one third.

After the 1991 energy scan we reported [2] a difference of two standard deviations between the measured value of $C^a_{\gamma\mathrm{Z}}$ and the Standard Model prediction. This arises from the energy-dependence of the forward-backward asymmetry. After combination with the 1993 scan data, our updated measurement of $C^a_{\gamma\mathrm{Z}}$ still lies about two standard deviations below the Standard Model prediction. Using 1993 data alone this difference is reduced to one standard deviation.

Data	x[mm]	y[mm]	z[mm]	sys err.
Pre-Scan	-0.372	+0.821	+2.96	0.445 %
Peak −2	-0.392	+0.309	+4.01	0.029 %
Peak	-0.375	+0.356	+3.30	0.067 %
Peak +2	-0.399	+0.308	+3.73	0.000 %

Table 1: FD luminosity: Luminosity weighted mean beam spot positions determined from tracks in the central detector. The systematic errors represent 100% of the estimated variation of luminosity due to the different beam spot position at the different energy points, expressed relative to the luminosity at the peak+2 point. The whole 1993 data set was used for this study.

Data	$(\mathrm{E_L} + \mathrm{E_R})/\sqrt{s}$	correction
Pre-Scan	0.9597	0.9977
Peak −2	0.9492	1.0000
Peak	0.9493	1.0000
Peak +2	0.9455	1.0009

Table 2: FD luminosity: Luminosity weighted mean energy in forward calorimeter for all accepted forward detector Bhabha scattering events.

Data	N_{SiW}	N_{FD}	$\mathcal{L}_{SiW}/\mathcal{L}_{FD}$
Peak −2	678945	241934	0.9990 ± 0.0024
Peak	625882	220709	1.0034 ± 0.0025
Peak +2	667267	234670	0.9978 ± 0.0024

Table 3: Ratio of SiW to FD luminosities for data where both detectors were fully operational. N_{FD} and N_{SiW} are the numbers of FD and SiW luminosity events respectively. $\mathcal{L}_{SiW}$ refers to the luminosity measured with the SiW calorimeters and $\mathcal{L}_{FD}$ to the luminosity measured with the FD. Since an absolute luminosity has not been determined with FD for 1993 data, the average ratio has been normalised to 1.0.

Source of error	Pre-scan	Peak-2	Peak	Peak+2
Beam spot uncertainties	0.44 %	0.11 %	0.10 %	0.00 %
Energy Calibration	0.05 %	0.05 %	0.00 %	0.07 %
Trigger Efficiency	0.10 %	0.02 %	0.05 %	0.02 %
Theory (interference term)	0.10 %	0.10 %	0.10 %	0.10 %
Comparison of FD and SiW Luminosities	0.09 %	0.09 %	0.13 %	0.15 %
Total Systematic Error	0.47 %	0.18 %	0.20 %	0.19 %
FD Statistics	0.27 %	0.88 %	0.54 %	1.10 %

Table 4: Errors on FD relative luminosities for the subset of data used in the lineshape anaysis, i.e. that where a SiW luminosity was unavailable. The comparison of FD and SiW luminosities for this table was performed using small windows of data where both detectors were available surrounding the data where only FD was available. Errors due to beam optics were not considered in this analysis, and were therefore assumed to be small.

	Correction Factor f	Uncertainty $\Delta f/f$ [%]
Acceptance/Efficiency:		
$e^+e^- \to$ hadrons Monte Carlo	1.0050	
quality of detector simulation	1.0000	0.14
failures in data acquisition / reconstruction	1.0000	0.05
Background:		
$e^+e^- \to \tau^+\tau^-$	0.9989	0.03
non-resonant background (0.046 ± 0.009 nb)	0.9985	0.03
Theoretical error:		
fragmentation	1.0000	0.11
overall	**1.0023**	**0.20**

Table 5: Summary of the correction factors and systematic errors for the 1993 hadronic cross section calculation for the peak energy point.

	peak		peak−2		peak+2	
	f	$\Delta f/f$ [%]	f	$\Delta f/f$ [%]	f	$\Delta f/f$ [%]
Acceptance/Efficiency:						
Edge of acceptance	1.0000	0.12	1.0000	0.18	1.0000	0.13
calorimeter energy cut	1.0023	0.10	1.0023	0.22	1.0023	0.22
track inefficiency	1.0059	0.13	1.0059	0.13	1.0059	0.13
multiplicity cut	1.0001	0.01	1.0001	0.01	1.0001	0.01
trigger efficiency	1.0000	<<0.01	1.0000	<<0.01	1.0000	<<0.01
Background:						
$e^+e^- \to \tau^+\tau^-$	0.9969	0.10	0.9980	0.14	0.9965	0.19
$e^+e^- \to$ hadrons	0.9998	0.02	0.9999	0.01	0.9998	0.02
$e^+e^- \to \gamma\gamma$	0.9999	0.01	0.9999	0.01	0.9999	0.01
$e^+e^- \to e^+e^-e^+e^-$	1.0000	<<0.02	1.0000	<<0.02	1.0000	<<0.02
overall	**1.0049**	**0.23**	**1.0061**	**0.34**	**1.0045**	**0.35**

Table 6: Summary of the correction factors f and systematic errors $\Delta f/f$ for the 1993 $e^+e^- \to e^+e^-$ cross section at the different energy scan points. The correction factors listed apply to the restricted angular range of $|\cos\theta| < 0.7$ used for this analysis.

	Correction Factor f	Uncertainty $\Delta f/f$ [%]
Acceptance/Efficiency:		
$e^+e^- \to \mu^+\mu^-$ Monte Carlo	1.0942	0.07
tracking losses	1.0059	0.10
trigger efficiency	1.0021	0.10
muon identification	1.0005	0.03
cut on number of tracks	1.0004	0.04
treatment of four-fermion events	1.0004	0.02
online filter efficiency	1.0000	0.05
edge of geometrical acceptance	1.0000	0.05
only one final-state photon in KORALZ	1.0000	0.05
Background:		
$e^+e^- \to \tau^+\tau^-$	0.9904	0.10
cosmic rays	0.9997	0.05
$e^+e^- \to e^+e^-\mu^+\mu^-$	0.9998	0.01
overall	**1.0933**	**0.22**

Table 7: Summary of the correction factors and systematic errors for the 1993 $e^+e^- \to \mu^+\mu^-$ cross section calculation. Note that the effects 'muon identification', 'tracking losses' and 'cut on number of tracks' were, in principle, simulated by the Monte Carlo. The quoted corrections were introduced to take into account the observed discrepancies between the data and Monte Carlo for these effects.

	peak		peak−2		peak+2	
	f	$\Delta f/f$ [%]	f	$\Delta f/f$ [%]	f	$\Delta f/f$ [%]
Acceptance/Eff.:						
$e^+e^- \to \tau^+\tau^-$ MC	1.3295	0.13	1.3384	0.13	1.3352	0.13
τ-pair selection cuts	1.0000	0.35	1.0000	0.35	1.0000	0.35
definition of $\vert\cos\theta\vert$	1.0000	0.16	1.0000	0.16	1.0000	0.16
vertex cut	1.0003	0.01	1.0003	0.01	1.0003	0.01
four-fermion events	1.0000	0.03	1.0000	0.03	1.0000	0.03
trigger efficiency	1.0008	0.08	1.0008	0.08	1.0008	0.08
time-of-flight efficiency	1.0011	0.02	1.0011	0.02	1.0011	0.02
uncertainty of tau Br.	1.0000	0.05	1.0000	0.05	1.0000	0.05
misclassification as e^+e^-	1.0007	0.04	1.0007	0.04	1.0007	0.04
misclassification as $\mu^+\mu^-$	1.0000	0.04	1.0000	0.04	1.0000	0.04
Background:						
$e^+e^- \to$ hadrons	0.9956	0.11	0.9956	0.11	0.9956	0.11
$e^+e^- \to e^+e^-$	0.9971	0.11	0.9936	0.24	0.9953	0.21
$e^+e^- \to \mu^+\mu^-$	0.9896	0.07	0.9896	0.07	0.9896	0.07
cosmic rays, beam-gas	0.9994	0.01	0.9982	0.03	0.9986	0.03
two-photon reactions	0.9951	0.07	0.9855	0.19	0.9891	0.15
overall	**1.3026**	**0.46**	**1.2927**	**0.54**	**1.2969**	**0.51**

Table 8: Summary of the correction factors f and systematic errors $\Delta f/f$ for the 1993 $e^+e^- \to \tau^+\tau^-$ cross section calculation at the different energy scan points.

Scan point		1	2	3
1	peak−2	20.8	12.5	12.5
2	peak	12.5	80.8	12.5
3	peak+2	12.5	12.5	21.7

Table 9: The centre-of-mass energy error matrix (MeV^2) for the three 1993 scan points resulting from uncertainties in the preliminary LEP energy calibration. These errors are fully correlated among the four LEP experiments.

luminosity	0.25%
$e^+e^- \rightarrow e^+e^-$, cross section	0.22%
$e^+e^- \rightarrow e^+e^-$, asymmetry	0.002
$e^+e^- \rightarrow \mu^+\mu^-$, cross section	0.19%
$e^+e^- \rightarrow \mu^+\mu^-$, asymmetry	0.001
$e^+e^- \rightarrow \tau^+\tau^-$, cross section	0.40%
$e^+e^- \rightarrow \tau^+\tau^-$, asymmetry	0.002
$e^+e^- \rightarrow$ hadrons, cross section	0.20%

Table 10: The contributions of the systematic errors on the luminosity determination and the event selections, which have been treated as fully correlated between the four data taking periods '90, '91, '92 and '93.

Improved Born Approximation Equivalent	Without Lepton Universality	With Lepton Universality
$C^s_{\mathrm{ZZ}}(\mathrm{e^+e^-}) \equiv (\hat{g}_a^{\mathrm{e}\,2} + \hat{g}_v^{\mathrm{e}\,2})(\hat{g}_a^{\mathrm{e}\,2} + \hat{g}_v^{\mathrm{e}\,2})$	0.06333±0.00048	
$C^s_{\mathrm{ZZ}}(\mu^+\mu^-) \equiv (\hat{g}_a^{\mathrm{e}\,2} + \hat{g}_v^{\mathrm{e}\,2})(\hat{g}_a^{\mu\,2} + \hat{g}_v^{\mu\,2})$	0.06345±0.00040	
$C^s_{\mathrm{ZZ}}(\tau^+\tau^-) \equiv (\hat{g}_a^{\mathrm{e}\,2} + \hat{g}_v^{\mathrm{e}\,2})(\hat{g}_a^{\tau\,2} + \hat{g}_v^{\tau\,2})$	0.06340±0.00048	
$C^s_{\mathrm{ZZ}}(\ell^+\ell^-) \equiv (\hat{g}_a^{\ell\,2} + \hat{g}_v^{\ell\,2})^2$		0.06338±0.00035
$C^a_{\mathrm{ZZ}}(\mathrm{e^+e^-}) \equiv \hat{g}_a^{\mathrm{e}}\ \hat{g}_v^{\mathrm{e}}\ \hat{g}_a^{\mathrm{e}}\ \hat{g}_v^{\mathrm{e}}$	0.00013±0.00014	
$C^a_{\mathrm{ZZ}}(\mu^+\mu^-) \equiv \hat{g}_a^{\mathrm{e}}\ \hat{g}_v^{\mathrm{e}}\ \hat{g}_a^{\mu}\ \hat{g}_v^{\mu}$	0.000241±0.000076	
$C^a_{\mathrm{ZZ}}(\tau^+\tau^-) \equiv \hat{g}_a^{\mathrm{e}}\ \hat{g}_v^{\mathrm{e}}\ \hat{g}_a^{\tau}\ \hat{g}_v^{\tau}$	0.000396±0.000094	
$C^a_{\mathrm{ZZ}}(\ell^+\ell^-) \equiv (\hat{g}_a^{\ell}\ \hat{g}_v^{\ell})^2$		0.000275±0.000054
$C^a_{\gamma\mathrm{Z}}(\mathrm{e^+e^-}) \equiv \hat{g}_a^{\mathrm{e}}\ \hat{g}_a^{\mathrm{e}}$	0.244±0.029	
$C^a_{\gamma\mathrm{Z}}(\mu^+\mu^-) \equiv \hat{g}_a^{\mathrm{e}}\ \hat{g}_a^{\mu}$	0.223±0.015	
$C^a_{\gamma\mathrm{Z}}(\tau^+\tau^-) \equiv \hat{g}_a^{\mathrm{e}}\ \hat{g}_a^{\tau}$	0.238±0.017	
$C^a_{\gamma\mathrm{Z}}(\ell^+\ell^-) \equiv \hat{g}_a^{\ell\,2}$		0.233±0.010
$C^s_{\gamma\mathrm{Z}}(\mathrm{e^+e^-}) \equiv \hat{g}_v^{\mathrm{e}}\ \hat{g}_v^{\mathrm{e}}$	−0.042±0.018	
$C^s_{\gamma\mathrm{Z}}(\mu^+\mu^-) \equiv \hat{g}_v^{\mathrm{e}}\ \hat{g}_v^{\mu}$	0.000±0.012	
$C^s_{\gamma\mathrm{Z}}(\tau^+\tau^-) \equiv \hat{g}_v^{\mathrm{e}}\ \hat{g}_v^{\tau}$	−0.007±0.014	
$C^s_{\gamma\mathrm{Z}}(\ell^+\ell^-) \equiv \hat{g}_v^{\ell\,2}$		−0.0114±0.0086
M_{Z} [GeV]	91.1879±0.0055	91.1875±0.0055
Γ_{Z} [GeV]	2.4943±0.0061	2.4939±0.0061
$\sigma^{\mathrm{pole}}_{\mathrm{had}}$ [nb]	41.49±0.16	41.49±0.16
χ^2/NDOF	86.5/125	94.2/133

Table 11: Results of the model-independent fits to the leptonic cross sections and forward-backward asymmetries. The hadronic cross section measurements are also included in both fits. The uncertainties in the LEP centre-of-mass energy (c.f. section 5) are included in the errors quoted.

Without Lepton Universality:	
Γ_{ee}	83.63±0.32
$\Gamma_{\mu\mu}$	83.82±0.45
$\Gamma_{\tau\tau}$	83.60±0.58
Γ_{had}	1748.1±7.6
With Lepton Universality:	
$\Gamma_{\ell\ell}$	83.72±0.23
Γ_{had}	1746.7±6.4

Table 12: Z^0 partial decay widths [MeV] obtained by a parameter transformation from M_{Z}, Γ_{Z}, $\sigma_{\mathrm{had}}^{\mathrm{pole}}$ and the C_{ZZ}^s parameters in Table 11.

	Without Lepton Universality	With Lepton Universality	SM Prediction
R_{e}	20.90±0.13		
R_{μ}	20.855±0.097		
R_{τ}	20.91±0.13		
R_{ℓ}		20.864±0.076	$20.75^{+0.03}_{-0.04}$
$A_{\mathrm{FB}}^{\mathrm{pole}}(\mathrm{e}^+\mathrm{e}^-)$	0.0060±0.0066		
$A_{\mathrm{FB}}^{\mathrm{pole}}(\mu^+\mu^-)$	0.0124±0.0035		
$A_{\mathrm{FB}}^{\mathrm{pole}}(\tau^+\tau^-)$	0.0193±0.0044		
$A_{\mathrm{FB}}^{\mathrm{pole}}$		0.0137±0.0025	$0.014^{+0.006}_{-0.004}$
M_{Z} [GeV]	91.1862±0.0054	91.1862±0.0054	input
Γ_{Z} [GeV]	2.4945±0.0061	2.4946±0.0061	$2.489^{+0.027}_{-0.020}$
$\sigma_{\mathrm{had}}^{\mathrm{pole}}$ [nb]	41.47±0.16	41.48±0.16	$41.46^{+0.07}_{-0.04}$

Table 13: Results of a parameter transformation from M_{Z}, Γ_{Z}, $\sigma_{\mathrm{had}}^{\mathrm{pole}}$ and the C_{ZZ}^s parameters in Table 11 into the standard LEP parameter set. The C parameters referring to the $\gamma\mathrm{Z}^0$-interference have been fixed to their Standard Model values. The uncertainties in the LEP centre-of-mass energy (c.f. section 5) are included in the errors quoted. In the last column we give the Standard Model value for each parameter assuming $M_{\mathrm{t}} = 150$ GeV, $M_{\mathrm{H}} = 300$ GeV and $\alpha_s(M_{\mathrm{Z}}^2) = 0.12$, fixed. The range quoted for the Standard Model prediction reflects variations of M_{t} in the interval $50 < M_{\mathrm{t}}\,(\mathrm{GeV}) < 230$ and M_{H} in the interval $60 < M_{\mathrm{H}}\,(\mathrm{GeV}) < 1000$.

invisible width:	
Γ_{inv} [MeV]	496.8 ± 5.8
$\Gamma_{\mathrm{inv}}/\Gamma_{\ell\ell}$	5.935 ± 0.068
N_{ν}	$2.979 \pm 0.034(\mathrm{exp.}) \pm 0.005\ (M_{\mathrm{t}},\, M_{\mathrm{H}})$
lepton universality:	
$R_{e/\tau}$	0.9989 ± 0.0083
$R_{\mu/\tau}$	1.0008 ± 0.0072
Standard Model fit:	
M_{t} [GeV]	$144^{+24}_{-28}{}^{+18}_{-17}$
$\alpha_s(M_{\mathrm{Z}}^2)$	$0.133 \pm 0.008 \pm 0.002$

Table 14: Summary of results for electroweak parameters quoted in the text of [1].

	$\epsilon_1 \cdot 10^3$	$\epsilon_3 \cdot 10^3$	χ^2/NDOF
Fit 1	2.7 ± 2.9	7.1 ± 4.9	7.8/8
Fit 2	3.1 ± 2.9	6.5 ± 4.8	12.8/10
Fit 3	2.9 ± 2.9	6.2 ± 4.8	13.2/11

Table 15: ϵ parameters obtained by the fits described in the text to M_Z, Γ_Z, σ^{pole}_{had} and the C parameters in Table 11. The fits are described in [1].

A Appendix: Correlation Matrices

Parameter	1	2	3	4	5
1 M_{Z}	1.00	0.15	0.04	0.00	0.06
2 Γ_{Z}	0.15	1.00	-0.26	0.01	0.01
3 $\sigma^{\mathrm{pole}}_{\mathrm{had}}$	0.04	-0.26	1.00	0.38	0.01
4 R_{ℓ}	0.00	0.01	0.38	1.00	0.01
5 $A^{\mathrm{pole}}_{\mathrm{FB}}$	0.06	0.01	0.01	0.01	1.00

Table 16: The parameter correlation matrix for the standard LEP parametrization assuming lepton universality. The results of this fit are summarized in Table 13 column 3.

Parameter	1	2	3	4	5	6	7	8	9
1 M_{Z}	1.00	0.15	0.04	-0.01	0.00	0.01	-0.01	0.06	0.05
2 Γ_{Z}	0.15	1.00	-0.26	0.00	0.01	0.01	0.02	0.01	0.00
3 $\sigma^{\mathrm{pole}}_{\mathrm{had}}$	0.04	-0.26	1.00	0.19	0.31	0.23	0.04	0.00	0.00
4 R_{e}	-0.01	0.00	0.19	1.00	0.19	0.10	-0.13	0.04	0.03
5 R_{μ}	0.00	0.01	0.31	0.19	1.00	0.16	0.00	0.01	0.00
6 R_{τ}	0.01	0.01	0.23	0.10	0.16	1.00	0.00	0.00	0.01
7 $A^{\mathrm{pole}}_{\mathrm{FB}}(\mathrm{e}^+\mathrm{e}^-)$	-0.01	0.02	0.04	-0.13	0.00	0.00	1.00	-0.02	-0.02
8 $A^{\mathrm{pole}}_{\mathrm{FB}}(\mu^+\mu^-)$	0.06	0.01	0.00	0.04	0.01	0.00	-0.02	1.00	0.02
9 $A^{\mathrm{pole}}_{\mathrm{FB}}(\tau^+\tau^-)$	0.05	0.00	0.00	0.03	0.00	0.01	-0.02	0.02	1.00

Table 17: The parameter correlation matrix for the standard LEP parametrization without assuming lepton universality. The results of this fit are summarized in Table 13 column 2.

Parameter	1	2	3	4	5	6	7
1 M_{Z}	1.00	0.07	-0.09	-0.05	-0.01	0.05	-0.18
2 $\sigma^{\mathrm{pole}}_{\mathrm{had}}$	0.07	1.00	0.20	-0.27	0.02	0.03	-0.04
3 C^{s}_{ZZ}	-0.09	0.20	1.00	0.69	0.09	0.04	0.07
4 Γ_{Z}	-0.05	-0.27	0.69	1.00	0.07	0.02	0.03
5 $C^{a}_{\gamma\mathrm{Z}}$	-0.01	0.02	0.09	0.07	1.00	0.13	-0.04
6 C^{a}_{ZZ}	0.05	0.03	0.04	0.02	0.13	1.00	0.02
7 $C^{s}_{\gamma\mathrm{Z}}$	-0.18	-0.04	0.07	0.03	-0.04	0.02	1.00

Table 18: The parameter correlation matrix for the extended effective Born approach assuming lepton universality. The results of this fit are summarized in Table 11 column 3.

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 M_{Z}	1.00	0.05	0.10	0.09	0.07	0.15	-0.01	0.01	0.01	-0.01	0.05	0.05	-0.09	-0.12	-0.11
2 $\sigma_{\mathrm{had}}^{\mathrm{pole}}$	0.05	1.00	0.19	0.19	0.16	-0.25	-0.03	0.02	0.02	0.04	0.01	0.01	-0.06	-0.01	-0.02
3 $C_{\mathrm{ZZ}}^{s}(\mathrm{e^+e^-})$	0.10	0.19	1.00	0.51	0.40	0.52	-0.08	0.04	0.04	0.14	-0.01	-0.01	-0.06	0.01	0.00
4 $C_{\mathrm{ZZ}}^{s}(\mu^+\mu^-)$	0.09	0.19	0.51	1.00	0.47	0.61	-0.03	0.07	0.04	0.04	0.04	0.02	-0.06	0.11	0.01
5 $C_{\mathrm{ZZ}}^{s}(\tau^+\tau^-)$	0.07	0.16	0.40	0.47	1.00	0.51	-0.02	0.04	0.09	0.03	0.02	0.04	-0.04	0.01	0.09
6 Γ_{Z}	0.15	-0.25	0.52	0.61	0.51	1.00	-0.01	0.04	0.05	0.02	0.03	0.02	-0.04	0.01	0.01
7 $C_{\gamma\mathrm{Z}}^{a}(\mathrm{e^+e^-})$	-0.01	-0.03	-0.08	-0.03	-0.02	-0.01	1.00	0.00	0.00	-0.07	0.00	0.00	0.15	0.00	0.00
8 $C_{\gamma\mathrm{Z}}^{a}(\mu^+\mu^-)$	0.01	0.02	0.04	0.07	0.04	0.04	0.00	1.00	0.00	0.00	0.16	0.00	-0.01	-0.09	0.00
9 $C_{\gamma\mathrm{Z}}^{a}(\tau^+\tau^-)$	0.01	0.02	0.04	0.04	0.09	0.05	0.00	0.00	1.00	0.00	0.00	0.14	-0.01	0.00	-0.09
10 $C_{\mathrm{ZZ}}^{a}(\mathrm{e^+e^-})$	-0.01	0.04	0.14	0.04	0.03	0.02	-0.07	0.00	0.00	1.00	-0.02	-0.02	-0.01	0.00	0.00
11 $C_{\mathrm{ZZ}}^{a}(\mu^+\mu^-)$	0.05	0.01	-0.01	0.04	0.02	0.03	0.00	0.16	0.00	-0.02	1.00	0.02	0.00	0.03	-0.01
12 $C_{\mathrm{ZZ}}^{a}(\tau^+\tau^-)$	0.05	0.01	-0.01	0.02	0.04	0.02	0.00	0.00	0.14	-0.02	0.02	1.00	0.00	-0.01	0.03
13 $C_{\gamma\mathrm{Z}}^{s}(\mathrm{e^+e^-})$	-0.09	-0.06	-0.06	-0.06	-0.04	-0.04	0.15	-0.01	-0.01	-0.01	0.00	0.00	1.00	0.03	0.03
14 $C_{\gamma\mathrm{Z}}^{s}(\mu^+\mu^-)$	-0.12	-0.01	0.01	0.11	0.01	0.01	0.00	-0.09	0.00	0.00	0.03	-0.01	0.03	1.00	0.04
15 $C_{\gamma\mathrm{Z}}^{s}(\tau^+\tau^-)$	-0.11	-0.02	0.00	0.01	0.09	0.01	0.00	0.00	-0.09	0.00	-0.01	0.03	0.03	0.04	1.00

Table 19: The parameter correlation matrix for the extended effective Born approach without assuming lepton universality. The results of this fit are summarized in Table 11 column 2.

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Figure Captions

Figure 1: Luminosity weighted mean y position of the beam spot plotted as a function of OPAL period number (the 1993 data taking was divided into periods of running which were labelled from 47 to 58). These positions were determined using tracks in the central detector. The energy scan started in period 51. Values are shown for the three energy points. Although trends can be observed, they are highly correlated between the three energy points during the scan.

Figure 2: The distributions of the multihadron selection variables:
(a) the visible energy $((\Sigma E_{clus} + 1/3 \cdot \Sigma E_{FD})/\sqrt{s})$;
(b) the energy imbalance along the beam direction $\mid \Sigma(E_{clus} \cdot \cos\theta) + \Sigma(E_{FD} \cdot \cos\theta) \mid / (\Sigma E_{clus} + \Sigma E_{FD})$;
(c) the multiplicity of charged tracks, electromagnetic clusters and forward detector segments;
(d) the sum of the invariant masses per hemisphere.
The points are for the 1993 data, the crosshatched histograms show the multihadron Monte Carlo distribution, the vertically hatched the $\tau^+\tau^-$ contribution and the open histogram the additional contribution from non-resonant background, estimated from the data.

Figure 3: Distribution in polar angle of the clusters from the 1993 data sample used for measurement of the electron pair forward-backward charge asymmetry. Corrections for selection efficiency and subtraction of background contributions have been applied. The curve shows the angular distribution as calculated by ALIBABA [19], taking into account the effects of t-channel and s-t interference contributions. (a), (b) and (c) show the distributions at the peak-2, peak and peak$+2$ energy points, respectively.

Figure 4: Distribution in polar angle of the tracks from the 1993 data sample used for measurement of the muon pair forward-backward charge asymmetry. The curve corresponds to the asymmetry measured by an event-by-event maximum likelihood fit to selected tracks of random charge. (a), (b) and (c) show the distributions at the peak-2, peak and peak$+2$ energy points, respectively.

Figure 5: Distribution in polar angle of the jets from the 1993 data sample used for measurement of the tau pair forward-backward charge asymmetry. A correction for selection efficiency has been applied. The curve corresponds to the asymmetry measured by an event-by-event maximum likelihood fit to selected jets of positive charge. (a), (b) and (c) show the distributions at the peak-2, peak and peak$+2$ energy points, respectively.

Figure 6: $e^+e^- \rightarrow e^+e^-$ selection: $\cos\theta$ distribution measured by central detector tracks for events with $\cos\theta_{cluster}$ greater than the acceptance cut (solid histogram) and less than the cut (dashed histogram). The three plots each corresponds to the $\cos\theta$ region near to the cut boundaries at 0.7, 0.0 and -0.7.

Figure 7: $e^+e^- \rightarrow \mu^+\mu^-$ selection: Comparison of the visible energy fraction for data and Monte Carlo events in the tau pair background studies. The points represent the combined 1991, 1992 and 1993 data. The unshaded area is the muon pair Monte Carlo, the singly hatched area is the tau pair Monte Carlo, and the cross-hatched area is the two-photon Monte Carlo [11]. The region between the arrows was considered in the systematic analysis. (a) Distributions for events in the tau-enriched muon pair sample. (b) Distributions for events in the tau pair sample selected by requiring both a muon and an electron in the final state .

Figure 8: $e^+e^- \rightarrow \mu^+\mu^-$ selection: Comparison of tracking reconstruction problems in the data and Monte Carlo samples. The solid points are 1993 data and the hollow points are muon and tau pair Monte Carlo combined. (a) Efficiency of the tracking-independent selection in $|\cos\theta|$. (b) Distribution in $|\cos\theta|$ of problem events which failed the main muon pair selection but were found by the tracking-independent selection and considered to be candidate muon pair events. (c) Distribution in $|\cos\theta|$ of problem events after correction by the efficiency of the tracking-independent selection.

Figure 9: $e^+e^- \rightarrow \tau^+\tau^-$ selection: The total number of tracks after all other selection cuts have been applied. The open histogram represents the 1992 data and the points represent the 1993 data.

Figure 10: Comparison of the parameters from the model independent fit (Table 11 column 3) with the Standard Model prediction as a function of M_t. The cross-hatched area shows the variation of the Standard Model prediction with M_H spanning the interval $60 < M_H\,(\mathrm{GeV}) < 1000$ and the singly-hatched area corresponds to a variation of $\alpha_s(M_Z^2)$ within the interval $0.11 < \alpha_s(M_Z^2) < 0.13$. The experimental errors on the parameters are indicated as vertical bands.

Figure 11: One standard deviation contours (39% probability content) in the R_ℓ-A_{FB}^{pole} plane for each leptonic species and for all leptons assuming lepton universality. The shaded area is the Standard Model prediction for $50 < M_t\,(\mathrm{GeV}) < 230$ and $60 < M_H\,(\mathrm{GeV}) < 1000$ for $\alpha_s(M_Z^2) = 0.120$.

Figure 12: Cross sections as functions of centre-of-mass energy for:
a) $e^+e^- \rightarrow$ hadrons, corrected for acceptance;
b) $e^+e^- \rightarrow e^+e^-$, integrated over $|\cos\theta| < 0.70$ and corrected for efficiency within the geometrical acceptance;
c) $e^+e^- \rightarrow \mu^+\mu^-$, corrected for acceptance;
d) $e^+e^- \rightarrow \tau^+\tau^-$, corrected for acceptance.
The solid lines are the results of the fit to the combined e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ and hadronic data described in the text. The solid circles show the 1993 data, the open triangles the 1992 data, the open squares the 1991 data and the open circles the 1990 data. The data are corrected for the centre-of-mass energy spread. The lower plots display the residuals to the Standard Model fit. Only statistical errors are shown.

Figure 13: Forward-backward asymmetries for:
a) $e^+e^- \rightarrow e^+e^-$, within $|\cos\theta| < 0.70$;
b) $e^+e^- \rightarrow \mu^+\mu^-$, within $|\cos\theta| < 0.95$;
c) $e^+e^- \rightarrow \tau^+\tau^-$, within $|\cos\theta| < 0.90$.
d) The difference averaged over all 3 leptonic species between the measured forward-backward asymmetry and the Standard Model fit result.
The solid lines are the results of the fit to the combined e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ and hadronic data described in the text. The solid circles show the 1993 data, the open triangles the 1992 data, the open squares the 1991 data and the open circles the 1990 data. Only statistical errors are shown.

Figure 14: The χ^2 curves for the fit to M_t and $\alpha_s(M_Z^2)$, using the OPAL cross section and forward-backward asymmetry measurements, for three different Higgs mass values spanning the interval $60 < M_H\,(\mathrm{GeV}) < 1000$. The minimum value of χ^2 from the $M_H = 300$ GeV curve has been subtracted from all curves. In these fits the strong coupling constant is unconstrained.

Figure 15: One standard deviation contours (39% probability content) in the ϵ_1-ϵ_3 plane for a fit to line shape and lepton asymmetry data. Also indicated is the Standard Model prediction for the ϵ parameters. The symbols refer to $M_t = 90$ GeV, 150 GeV and 200 GeV, where the symbol size increases with M_t. Circular, box and triangular symbols discriminate between $M_H = 60$ GeV, 300 GeV and 1000 GeV, respectively.