REVIEW OF FINAL LEP RESULTS
OR
A TRIBUTE TO LEP

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After a comment on the performance of LEP some highlights of the LEP1 and LEP2 physics programmes are reviewed. The talk concentrates on the precision measurements at the Z resonance, two fermion production above the Z, W^+W^- production, ZZ production, indirect limits on the Higgs mass, LEP contributions to the exploration of the CKM matrix, and on the LEP measurements of α_s.

1 Introduction

1.1 A comment on the machine and the detectors

LEP delivered the last beam on November 2^{nd} 2000. By now the storage ring and the detectors are dismantled. What remains is the LEP saga and a rich harvest of physics results. So far more than 1100 scientific papers have been published covering an enormous range of physics. The main topics centre on the study of the properties of the gauge and scalar bosons, on heavy fermions and on searches for the Higgs boson and for new physics. Many analyses are still continuing, 220 papers have been submitted to this symposium by the LEP collaborations.

The performance of LEP during the 12 years of operation can best be illustrated by showing in Fig. 1 the integrated luminosity as a function of time for each year. During the phase 1 where LEP operated in the vicinity of the Z resonance luminosities up to 65 pb^{-1} have been reached. After raising the energy the luminosity increased to more than 200 pb^{-1} per year. The total luminosity delivered per experiment above W^+W^- production threshold was about 700 pb^{-1}, while only 500 pb^{-1} had been hoped for.

In the hunt for the Higgs boson higher and higher energies were achieved in 2000 which was a particularly good year for LEP. As shown in Fig. 2 a record beam energy of 104.4 GeV was reached, much more than originally foreseen. In 200 days of running more than 130 pb^{-1} above 103 GeV were delivered to the experiments, 110 pb^{-1} in the last 110 days mainly at beam energies above 103 GeV.

Crucial for the success of LEP2 have been the superconducting cavities. Let me quote here S. Myers[1]: *For superconducting cavities the power needed is only proportional to the* 4^{th} *power of energy. To operate LEP at 103 GeV with copper cavities (where the power would be proportional to* E^8_{beam}*) would have needed 1280 cavities and 160 MW of power! Impossible for many reasons.*

At the time when plans for superconducting cavities were developed little was known about their performance[2]. The final success was due to a long term development programme, which started already in 1980 together with outside laboratories, pursuing the goal to reach thermal stability for 350 MHz niobium coated copper cavities at reduced costs. In 2000 a total of 272 Nb film and 16 Nb bulk cavities were installed. At 104 GeV beam energy an average accelerating field of 7.5 MV/m at a quality factor of Q $> 3 \times 10^9$ at 4.5 K was achieved, much better than the design value of 6 MV/m. More than 80% of the superconducting cavities had Q $\geq 2.5 \times 10^9$ even at 8 MV/m. Fig. 3 shows a 4 cell cavity with its typical rounded structure.

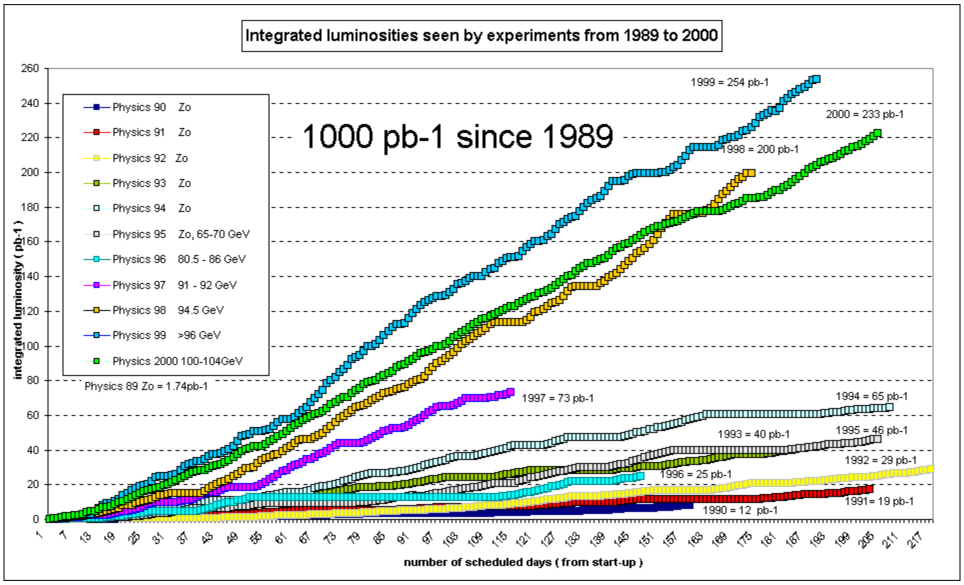

Figure 1. Integrated luminosity delivered by LEP to each of the four experiments from 1989 to 2000.

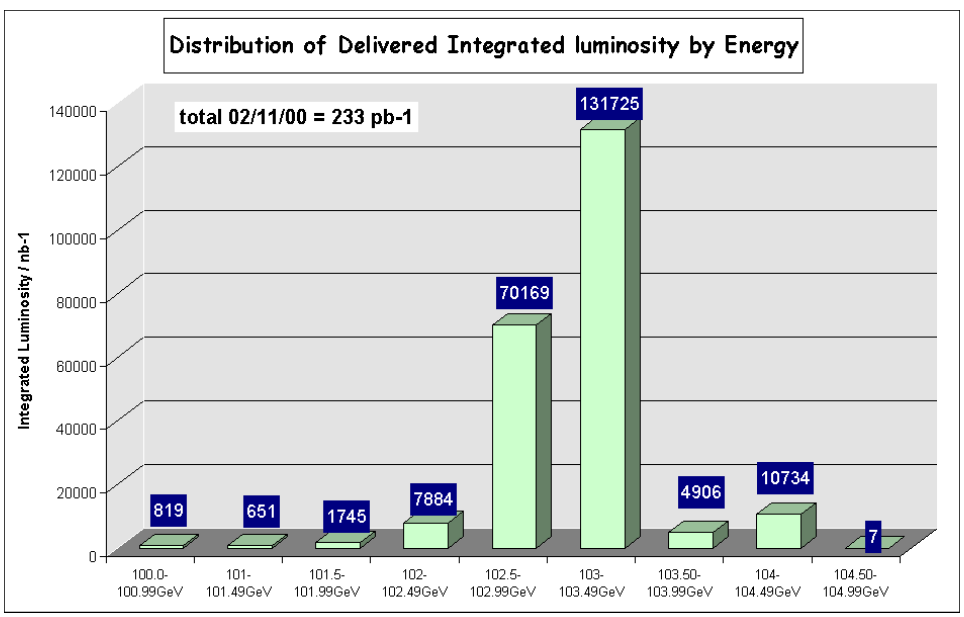

Figure 2. Distribution of the integrated luminosity delivered to each of the experiments in 2000 as function of the beam energy.

Figure 3. A 4 cell Niobium coated cavity in the clean room.

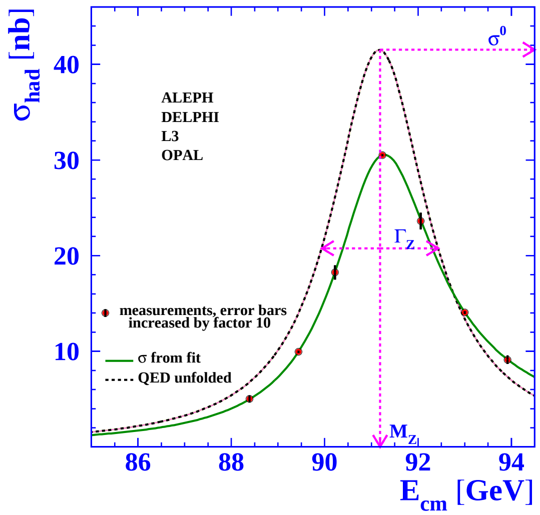

Figure 4. The final hadronic cross-section as measured (solid line) and QED deconvoluted (dotted line).

A word on the four LEP detectors ALEPH, DELPHI, L3, OPAL. All collaborations improved their detectors substantially during the years of data taking, the most important improvements being:

1. The development of silicon micro vertex detectors for high resolution secondary vertex measurements. The installation of these detectors greatly improved the quality of heavy flavour physics.

2. All experiments replaced their first luminosity detectors by new high-precision detectors capable of measuring small angle Bhabha scattering with an accuracy well below 0.1 %.

The LEP Collaborations also created a new style of working together, the LEP Working Groups, of which the Electroweak Working Group (EWWG) is best known. These groups have the task to combine the results obtained by the four LEP Collaborations and also by the SLD Collaboration working at the SLAC e^+e^- linear collider SLC taking proper account of all systematic correlations between the data.

2 Precision at the Z

2.1 Determination of the Z Resonance Parameters

If one asks the question, what are the most important results from LEP1, the answer has to be: the precision electroweak measurements at the Z resonance. During the data taking periods from 1990 to 1995 the four experiments collected 15.5 million Z decays into quarks plus 1.7 million decays to charged leptons corresponding to an integrated luminosity of 200 pb^{-1} per experiment. Fig. 4 shows the hadronic cross-section measured by the four collaborations as a function of the centre-of-mass energy. Also shown is the cross-section after unfolding all effects due to photon radiation. Radiative corrections are large but very well known. At the peak the QED deconvoluted cross-section is 36% larger and the peak position is shifted by -100 MeV. The figure illustrates the difference between the measurements and the so-called pseudo-observables like m_Z, Γ_Z, σ^0_{had} which are averaged by the Electroweak Working Group.

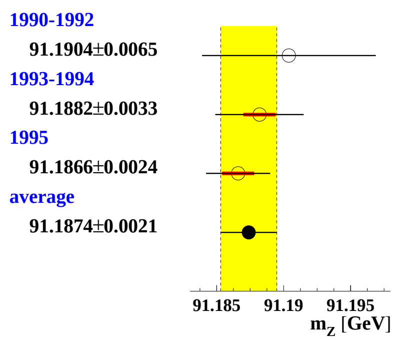

Figure 5. m_Z combined by EWWG for the different periods of data taking.

The most impressive final result of the Z lineshape studies is the 2×10^{-5} accuracy for one of the most fundamental constants of nature, the Z mass:

$$m_Z = 91.1874 \pm 0.0021\, GeV. \tag{1}$$

This precision cannot be exceeded by any one of the future machines, not even with a GigaZ linear collider. Two essential points have to be mentioned:
- The beam energy measurement using the technique of resonant spin depolarisation plus careful control of all machine parameters. Still the beam energy contributes 1.7 MeV to the total uncertainty of m_Z. Fig. 5 shows the consistency of the energy calibration for the different data taking periods.
- The close cooperation with theory groups essential for understanding radiative corrections with the necessary accuracy.

The full set of nearly uncorrelated pseudo-observables used to describe the precise electroweak measurements on the Z resonance and combined by EWWG includes:

- The total Z width:

$$\Gamma_Z = 2.4952 \pm 0.0023\, GeV. \tag{2}$$

- The Z peak cross-section:

$$\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2} \cdot \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}. \tag{3}$$

- The ratios of the Z partial decay widths:

$$R^0_l \equiv \frac{\Gamma_{had}}{\Gamma_{ll}}\; with\, l = e, \mu, \tau. \tag{4}$$

$$R^0_q \equiv \frac{\Gamma_{qq}}{\Gamma_{had}}\; with\, q = b, c, s. \tag{5}$$

- The pole forward-backward asymmetries:

$$A^{0,f}_{FB} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \; with\, \mathcal{A}_f \equiv \frac{2g_{Vf}g_{Af}}{g^2_{Vf} + g^2_{Af}}, \tag{6}$$

for $f = e, \mu, \tau, b, c, s$. Here g_{Vf} and g_{Af} denote the effective vector and axial-vector couplings to fermion *f*.

- The τ polarisation:

$$P_\tau(cos\theta) = -\frac{\mathcal{A}_\tau(1 + cos^2\theta) + 2\mathcal{A}_e cos\theta}{1 + cos^2\theta + 2\mathcal{A}_\tau\mathcal{A}_e cos\theta}. \tag{7}$$

Details on the final combination and an extended list of references can be found in[3]. The final measurements of Z line shape and of the leptonic forward-backward asymmetries performed by the four LEP Collaborations are documented in[5,6,7,8]. The measurements of the τ polarisation are obtained by the four collaborations by studying five τ decay modes[9,10,11,12].

Before summarizing the final results for the effective lepton couplings and the still preliminary results for the quark couplings I would like to mention two measurements of special interest. One of the questions asked by the LEPC before recommending approval of the experiments was: What is the expected accuracy for neutrino counting? I will come back to the answer given in 1982 at the end of the talk but here is the final measurement. The present best value results from the accurate measurement of Γ_{inv}/Γ_{ll} divided by $\Gamma_{\nu\nu}/\Gamma_{ll}$, the latter evaluated from the Standard Model ($\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - \Gamma_{ll}(3 - \delta_\tau)$, δ_τ corrects for the τ mass effect):

$$N_\nu = 2.9841 \pm 0.0083. \tag{8}$$

The value is consistent with 3 but 2 standard deviations below leaving room for a contribution of a new object to the invisible width of $\Gamma^{x}_{inv} = -2.7^{+1.7}_{-1.5}\,MeV$.

The second special quantity is the Veltman ρ-parameter. Assuming lepton universality ρ can be determined from the measured leptonic width:

$$\rho^{lept}_{eff} = 1.0050 \pm 0.0010. \qquad (9)$$

The resulting ρ^{lept}_{eff} value is found to be 5 standard deviations above the tree level of 1 thus proving the presence of genuine electroweak radiative corrections. It should be added that the experimental value agrees with the Standard Model expectation.

2.2 Z couplings to charged leptons

By combining the measurements of the partial decay width of the Z boson, which is proportional to the sum of the squares of the vector and axial-vector couplings, with asymmetry measurements the vector and axial-vector couplings can be determined separately. For the three charged leptons the final results are presented in Fig. 6. It has to be noted that many data enter this analysis. LEP contributes the measurements of the three partial widths Γ_{ll}, the forward-backward asymmetries at the Z (which yield $\mathcal{A}_e, \mathcal{A}_\mu, \mathcal{A}_\tau$), and the τ polarisation ($\mathcal{A}_\tau, \mathcal{A}_e$). SLD contributes the asymmetry for left and right handed e^- polarisation (yielding the most precise individual measurement of $\mathcal{A}_e$)[13] and the left-right forward-backward asymmetry for the three leptons ($\mathcal{A}_e, \mathcal{A}_\mu, \mathcal{A}_\tau$)[14]. Assuming lepton universality the result presented by the solid ellipse in Fig. 6 is found. The comparison with the Standard Model prediction shows the preference of the combined lepton data for a low value of the Higgs mass.

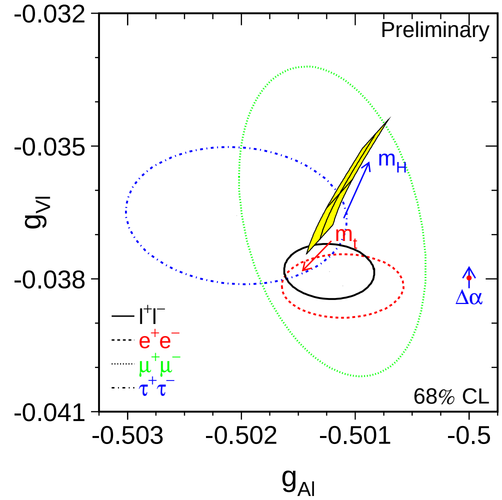

Figure 6. The effective vector and axial-vector couplings for leptons. The shaded area shows the prediction of the SM for $m_{top} = 174.3 \pm 5.2\,GeV$ and $m_H = 300^{+700}_{-186}\,GeV$. The arrows indicate increasing values of m_{top} or m_H.

2.3 Z couplings to b and c quarks

Information on the b and c quark couplings is obtained from three types of observables: The ratios $R^0_b \equiv \Gamma_{b\bar{b}}/\Gamma_{had}$ and $R^0_c \equiv \Gamma_{c\bar{c}}/\Gamma_{had}$, which are measured by the LEP Collaborations and by SLD, the forward-backward asymmetries $A^{0,b}_{FB}$ and $A^{0,c}_{FB}$, which are measured at LEP, and the direct measurements of $\mathcal{A}_b$, $\mathcal{A}_c$ by SLD. Though the measurement of R_b and R_c is conceptually simple, one has to separate an enriched sample of b or c quark events from the bulk of the hadronic events, some problems have been experienced in the past. A measurement of R_b, for instance, requires extremely high quality of b tagging, one has to know the tagging efficiency and the background with sufficient precision and one must control the correlations between the two event hemispheres. The most precise measurements use double or multi tag methods which allow the simultaneous experimental determination of the tagging efficiency and the b quark rate. Combining the results of the five experiments results in[3]:

$$R^0_b = 0.21646 \pm 0.00065,$$

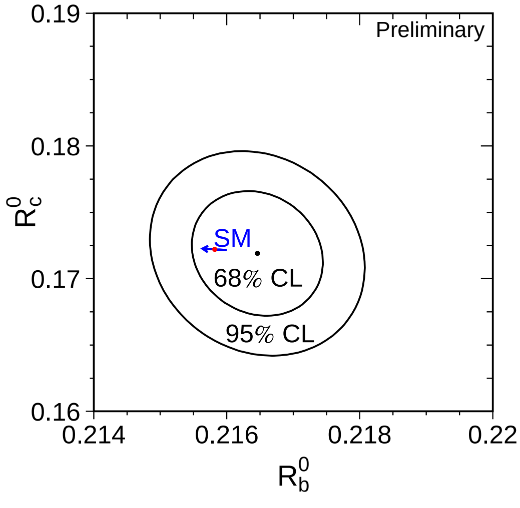

Figure 7. Confidence level contours in the R_c^0, R_b^0 plane obtained from the LEP and SLD data compared to the Standard Model prediction for $m_{top} = 174.3 \pm 5.2\, GeV$.

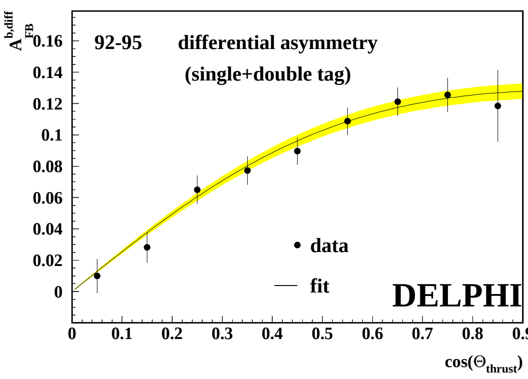

Figure 8. The differential forward-backward b asymmetry as function of the polar thrust angle. The line is the result of a fit with its statistical error indicated as a band.

$$R_c^0 = 0.1719 \pm 0.0031. \tag{10}$$

The most recent R_b work of the collaborations, all using a lifetime tag based on micro vertex detector information plus additional information from high p_T leptons and the hadronic structure of the event, can be found in references [15,16,17,18,19]. An updated comparison with the SM expectation is shown in Fig. 7. Obviously the new R_b and R_c data agree with the prediction.

This is not the case for the b forward-backward asymmetries. Two new analyses of the pole asymmetry $A_{FB}^{0,b}$ by ALEPH[20] and by DELPHI[21] have been submitted to this conference. These measurements are notoriously difficult. One not only has to produce a high purity b quark sample, accurately control the background and understand the hemisphere correlations, one also has to know whether a b quark or an anti-b was produced in the forward hemisphere. Both collaborations made optimal use of neural networks. ALEPH used a neural network b-tag based on lifetime measurement, high p_T leptons and event structure and obtains finally a 30% increase in the data sample. The b hemisphere charge is estimated by an optimal merging of the information from the primary and secondary vertex charge, leading kaons and the jet charge. Their final result is:

$$A_{FB}^{0,b} = 0.1009 \pm 0.0031. \tag{11}$$

DELPHI uses a very high purity b sample (96%), and a neural network tag for the hemisphere charge combining the information from vertex charge, jet charge, and from identified leptons and kaons. Self calibration from double tagging is used to measure the probabilities for b or anti-b tagging. The still preliminary result is:

$$A_{FB}^{0,b} = 0.0997 \pm 0.0042. \tag{12}$$

Fig. 8 shows the differential b quark forward-backward asymmetry from the DELPHI single and double tag data. The analysis includes all data collected from 1992 to 1995.

These two measurements improve the accuracy of $sin^2\theta_{eff}^{lept}$ evaluated from $A_{FB}^{0,b}$.

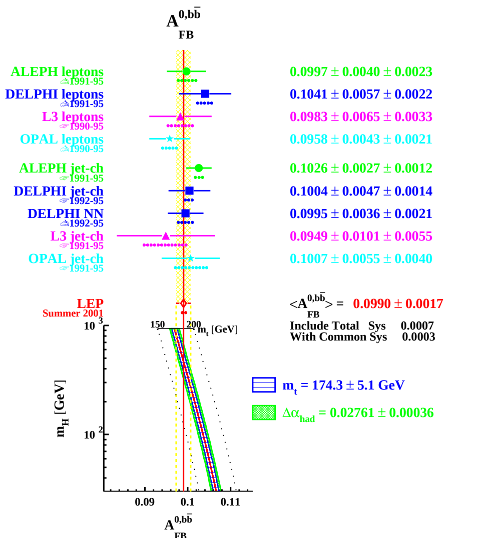

Figure 9. $A_{FB}^{0,b}$ measurements from the LEP collaborations using high p_T leptons and various jet-charge techniques.

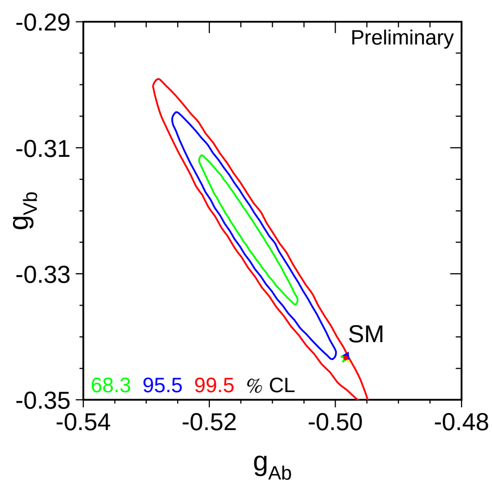

Figure 10. LEP and SLD measurements of g_{Vb} versus g_{Ab} compared to the Standard Model prediction.

However, as in the past[22], there is still a significant deviation of $3.3\,\sigma$ from the $sin^2\theta_{eff}$ value determined from the lepton asymmetries. One then has to ask two questions:

1. Are all LEP measurements consistent? This is clearly the case as demonstrated in Fig. 9, where the pole asymmetries as measured by all LEP collaborations using different analysis methods are collected. It should be remarked that the numerical $A_{FB}^{0,b}$ values quoted in Fig. 9 correspond to the measurements at the Z peak only. They do not include measurements above and below the Z peak whose results are included in Eq. (11). Including the off peak data the average LEP value is:

$$A_{FB}^{0,b} = 0.0990 \pm 0.0017. \qquad (13)$$

The error is dominated by statistics, the statistical error alone being ± 0.00156. The dominant contribution to the systematic uncertainty is due to internal effects uncorrelated between the experiments, the correlated systematic uncertainty is only ± 0.00039.

2. Is the LEP result on $\mathcal{A}_b = \frac{4A_{FB}^{0,b}}{3\mathcal{A}_e}$ consistent with the direct measurements of $\mathcal{A}_b$ from the polarised b quark forward-backward asymmetry? The results are $\mathcal{A}_b(LEP\,only) = 0.891 \pm 0.022$ (last year 0.890 ± 0.024) and $\mathcal{A}_b(SLD) = 0.921 \pm 0.020$. Both agree within 1 standard deviation.

Using the information from all b quark data, R_b, $A_{FB}^{0,b}$, and $\mathcal{A}_b$, one can separate the vector and axial-vector couplings g_{Vb}, g_{Ab} or the right and left handed couplings g_{Rb}, g_{Lb} respectively. They are related by

$$g_{Rb} = (g_{Ab} - g_{Vb})/2,$$
$$g_{Lb} = (g_{Ab} + g_{Vb})/2. \qquad (14)$$

The results are presented in Figures 10 and 11. Compared to the Standard Model prediction the data show a deviation of about 3 standard deviations. The strong anti-correlation in Fig. 10 is due to the constraint on the sum of the squares from the precise R_b measurement. Fig. 11 shows that the deviation from the SM is mainly for g_{Rb}.

An update of the measurements of

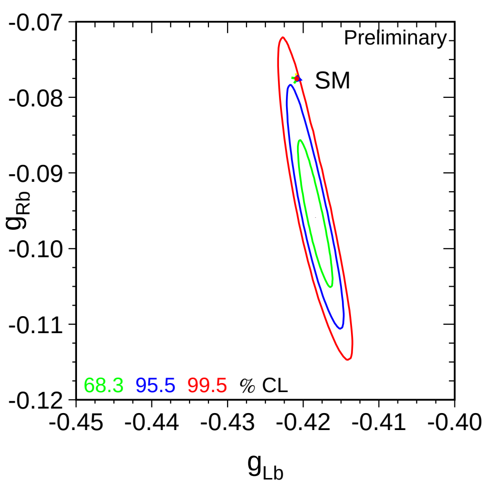

Figure 11. LEP and SLD measurements of g_{Rb} versus g_{Lb} compared to the Standard Model prediction.

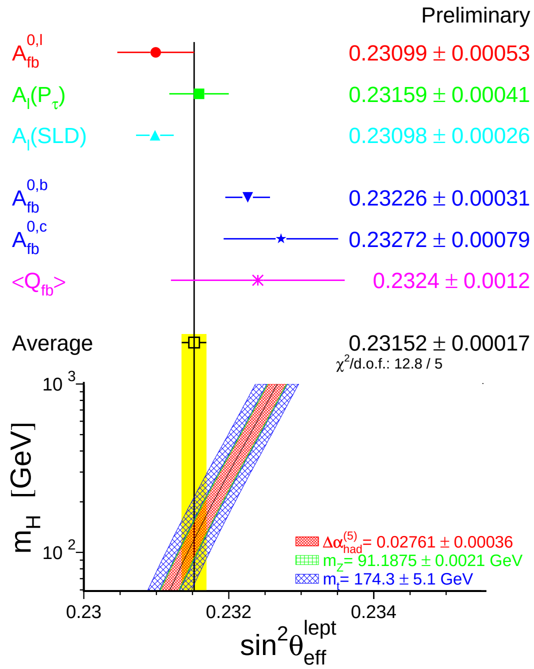

Figure 12. The effective electroweak mixing angle $sin^2\theta_{eff}^{lept}$ derived from data depending on lepton couplings only (top) and from data depending on lepton and quark couplings (bottom). Also shown is the prediction of the Standard Model as a function of m_H. The band indicates the uncertainty of the SM prediction due to the uncertainty of our knowledge on $\Delta\alpha_{had}^{(5)}$, m_Z, and m_t.

$sin^2\theta_{eff}^{lept}$ as determined from lepton and quark data is presented in Fig. 12. While the lepton data prefer a small value of $sin^2\theta_{eff}^{lept}$ and thereby a small Higgs mass the quark asymmetries tend to larger $sin^2\theta_{eff}^{lept}$ and m_H values. Evaluating the average from the lepton data alone yields:

$$sin^2\theta_{eff}^{lept}(leptons) = 0.23113 \pm 0.00021. \tag{15}$$

The corresponding average from the quark asymmetries is:

$$sin^2\theta_{eff}^{lept}(quarks) = 0.23230 \pm 0.00029. \tag{16}$$

The two values differ by 3.3 standard deviations. Presently this deviation is unexplained. It could either be due to a statistical fluctuation (the error of the most precise quark asymmetry $A_{FB}^{0,b}$ is completely dominated by statistics), or due to unknown sources of systematic errors (this is unlikely due to the small systematic uncertainty correlated between the different measurements of $A_{FB}^{0,b}$) or due to completely unexpected new physics. However, one has to keep in mind that four of the nine $A_{FB}^{0,b}$ measurements shown in Fig. 9 are still preliminary. One should note that only the average of lepton and quark $sin^2\theta_{eff}^{lept}$ measurements is consistent with a Higgs mass of $\mathcal{O}(100)$ GeV.

3 Two Fermion Production above the Z

Two fermion production at high energies provides a beautiful laboratory for searching for new physics. Compared to other processes the cross-section for $q\bar{q}$ production is still high as shown in Fig. 13 prepared by the L3 Collaboration[23], where the energy dependences of cross-sections for various final states in e^+e^- annihilation are collected. At

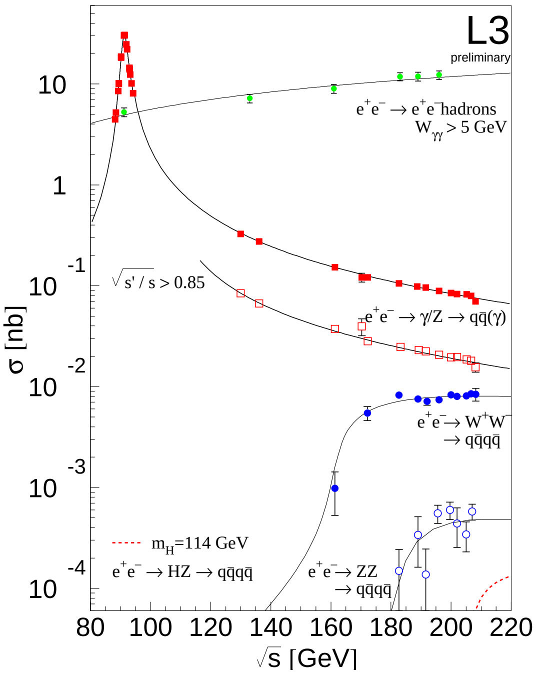

Figure 13. Energy dependence of cross-sections in e^+e^- annihilation. The data are from the L3 Collaboration. The cross-sections for $e^+e^- \rightarrow q\bar{q}$ are shown for the inclusive sample (full squares) and the non-radiative sample (open squares).

energies above the Z radiative processes are important. Due to the large cross-section for radiative return to the Z resonance only a fraction of the detected events have large s', the square of the centre-of-mass energy transferred to the $f\bar{f}$ final state. The Electroweak Working Group defines the interesting non-radiative cross-section by $\sqrt{s'/s} > 0.85$ [24]. For this cut the cross-sections for hadron, $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, $c\bar{c}$ production have been combined. Some results are shown in Fig. 14. The lower part of the figure presents the ratio of the data divided by the SM prediction. Obviously the data are in agreement with the prediction but one should notice that the hadronic cross-section is $1.8\,\sigma$ high. The combined measurements of forward-backward asymmetries for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states are collected in Fig. 15.

The combined cross-sections and asymmetries and the results on b and c quark production have been used to study models with an additional heavy neutral Z' boson. Limits for the Z' mass have been obtained, for instance, for an E(6) χ model $m_{Z'} > 0.68$ TeV or for the left-right symmetric model $m_{Z'} > 0.80$ TeV. In both cases the 95% confidence level lower limits are quoted and zero mixing with the Z boson is assumed. It should be remarked that the LEP2 data alone are not sufficient to constrain the mixing angle. But fits including the LEP1 data of a single experiment are consistent with zero mixing, see e.g. [26].

Many models for physics beyond the SM can be investigated in the general framework of four-fermion contact interactions (analogous to the low energy approximation of the weak force by Fermi theory). Using the combined data, constraints have been placed on the characteristic high energy scale Λ describing the low energy phenomenology of hypothetical new interactions. Limits for contact interactions between leptons range from $\sqrt{4\pi}\Lambda/g > 8.5$ to 26 TeV depending on the helicity coupling between initial and final state fermions and on the sign of the interference with the SM. Here g is the coupling of the new interaction. The corresponding limits for contact interactions between leptons and b quarks are $\sqrt{4\pi}\Lambda/g > 2.2$ to 15 TeV, for leptons and c quarks $\sqrt{4\pi}\Lambda/g > 1.4$ to 7.2 TeV.

Constraints have further been placed on the energy scale of quantum gravity in compactified extra dimensions. Including data from the Bhabha channel the typical result from the analysis of a single experiment is $M_s \geq 1$ TeV. Furthermore limits have been set on the masses of leptoquarks. The $\gamma - Z$ interference has been investigated in terms of the S-Matrix framework. In all cases no deviations from the SM expectation have been observed. Details on the two fermion analyses can be found in[25,26,27,28,29]. For a more

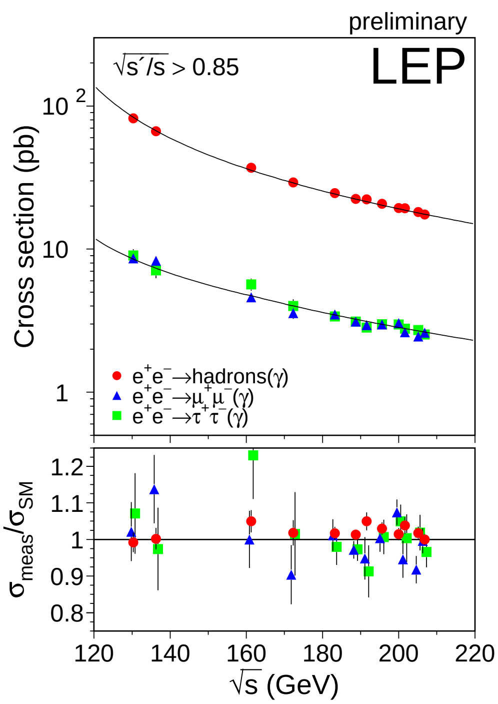

Figure 14. Combined LEP measurements of the cross-sections for $q\bar{q}$, $\mu^+\mu^-$, $\tau^+\tau^-$ production. The curves show the SM expectation evaluated with ZFITTER. The lower part shows the ratio data to SM prediction.

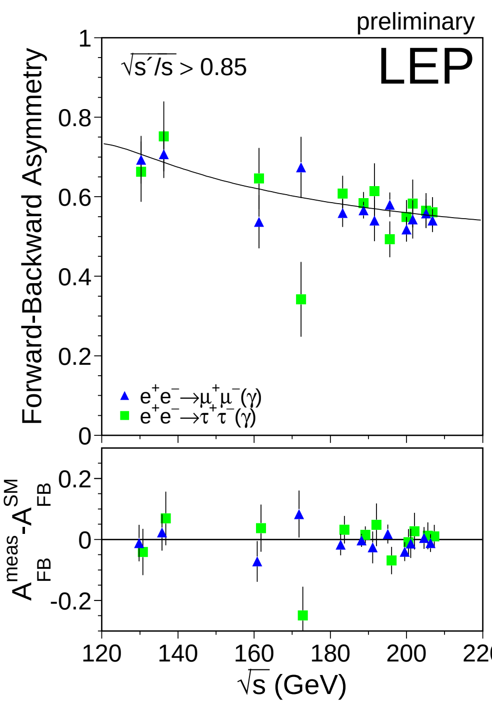

Figure 15. Combined LEP results for the forward-backward asymmetries for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states. The curves represent the SM expectation. The lower part shows the differences between measurements and SM prediction.

complete recent summary of the two fermion data and their interpretation see[30].

4 W^+W^- Production

Experimental studies of W-pair production have been a focus of the LEP2 physics programme with two main goals: the measurements of the W mass and the investigation of the structure of triple gauge boson couplings. In e^+e^- annihilation double resonant W pairs are produced via the so-called CC03 diagrams shown in Fig. 16. Near threshold the cross-section is dominated by the neutrino t-channel exchange. Contributions from the more interesting s-channel exchange of a Z boson or a photon have been measured at centre-of-mass energies from 172 to 209 GeV.

Each LEP experiment has finally collected about 10000 W^+W^- events which are analysed in terms of five decay classes: fully hadronic events where both W's decay into quarks, three semileptonic decays and fully leptonic decays. In the SM the branching ratio for the four quark class is 45.5 %, for each semileptonic class 14.6 %, and for the fully leptonic class 10.6 %. Powerful tools to separate the four fermion events originating from W production from the background have been developed involving, for instance, neural networks. The efficiency for WW selection is high, typically around 85%, at very high purity.

The total CC03 cross-sections measured by the four collaborations have been combined[31], the results are summarised in Fig. 17. All experiments have published their final results for centre-of-mass energies up to

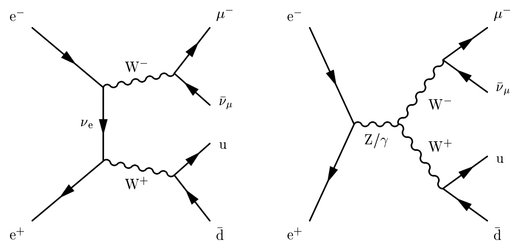

Figure 16. CC03 diagrams for W^+W^- production with subsequent decay into $u\bar{d}$ and $\mu\bar{\nu}_\mu$.

189 GeV [32,33,34,35]. The results for energies up to 207 GeV are still preliminary [36,37,38,28]. Inspection of Fig. 17 immediately shows that all t- and s-channel contributions are needed to understand the data. More subtle is the comparison with predictions of the new four fermion generators RacoonWW[39] and YFSWW[40] with improved radiative corrections. The calculations of both programmes are based on the so-called double pole approximation for virtual $\mathcal{O}(\alpha)$ corrections in resonant W-pair production plus all other QED corrections needed for a 0.5% accuracy. It is quite remarkable that for $\sqrt{s} > 180\,GeV$:

$$\sigma_{measured}/\sigma_{RacoonWW} = 1.000 \pm 0.009. \tag{17}$$

A very similar result is obtained for the calculation with YFSWW.

4.1 Measurements of the W mass

Even before crossing the W-pair threshold a precise value of the W mass was evaluated from the LEP1 measurement of m_Z using SM relations. The updated indirect value obtained from a fit to all data excluding the direct W mass measurements but including the measured value of the top mass is $m_W = 80.368 \pm 0.023\,GeV$ [4]. The small error sets the scale for all direct measurements. In the SM m_W depends on electroweak loop corrections. A recent complete two-loop calculation yields the dependence on the top mass, the Higgs mass, and the QED induced shift of the fine structure constant $\Delta\alpha$ as expressed in Eq. (18).

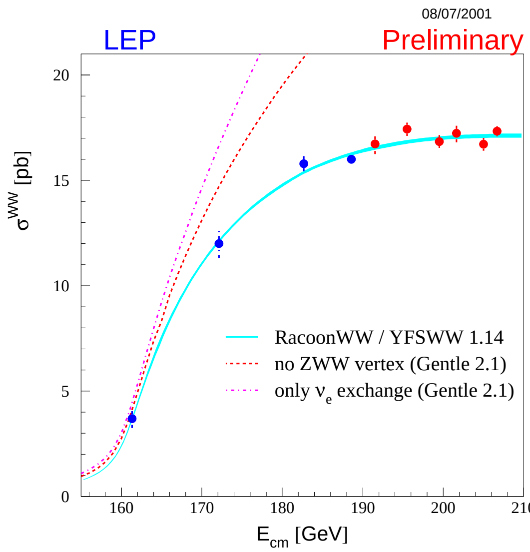

Figure 17. The W-pair production cross-section as a function of the centre-of-mass energy compared to the predictions of the Monte Carlo generators RacoonWW and YFSWW.

In the Eq. (18) only the numerically most important terms are shown, all masses are in GeV. For the complete expression see[41]. An increase of m_t will increase, an increase of m_H or $\Delta\alpha$ will decrease the SM prediction for m_W. A significant deviation of a direct measurement from the indirect value would indicate new physics and the existence of new fundamental particles.

At LEP2 two independent and complementary methods have been used to measure m_W. The first is based on the measurement of the cross-section near threshold, which depends strongly on m_W. Combining the measurements at a centre-of-mass energy of 161 GeV the LEP groups obtain[4] $m_W = 80.40 \pm 0.22\,GeV$, where the largest contribution to the total error is due to the low event statistics. One should remark, however, that in principle the threshold method can give a precise result, the estimated error for a GigaZ Linear Collider[42] is $\Delta m_W = 0.006\,GeV$,

$$m_W = 80.3767 + 0.5235((\frac{m_t}{174.3})^2 - 1) - 0.05613\, ln(\frac{m_H}{100}) - 1.081(\frac{\Delta\alpha}{0.05924} - 1) \pm .... \quad (18)$$

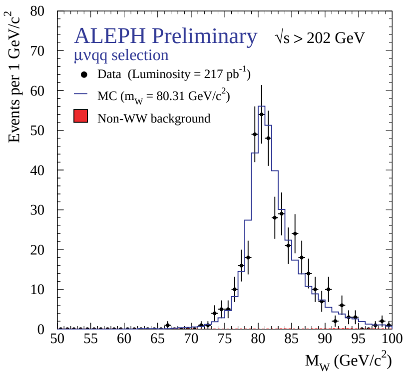

Figure 18. Reconstructed invariant mass distribution from the ALEPH experiment for the $q\bar{q}\mu\nu_\mu$ channel.

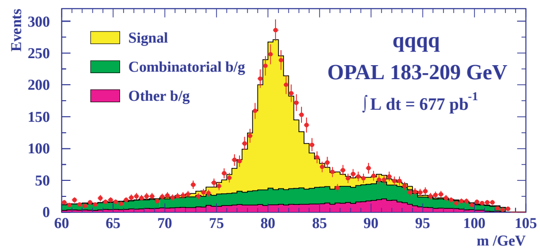

Figure 19. Reconstructed W mass distribution for all OPAL $W^+W^- \rightarrow q\bar{q}q\bar{q}$ data from $\sqrt{s} = 183$ to 209 GeV. The histogram shows the SM expectation for $M_W = 80.42$ GeV.

supposing that radiative corrections are controlled to this level.

At higher energies the W mass is directly reconstructed from the invariant mass distribution of the decay products of the two W's. Using constraints set by energy and momentum conservation clean reconstructed mass distributions for the semileptonic and hadronic decay channels are obtained. An example from the semileptonic data taken at $\sqrt{s} > 202\ GeV$ [43] is reproduced in Fig. 18. Note that there is practically no background in the $\mu\nu_\mu q\bar{q}$ channel. This also holds for $e\nu_e q\bar{q}$ channel, the background in the $\tau\nu_\tau q\bar{q}$ and 4q channels is small. The statistical power of the data is illustrated in Fig. 19, where the mass distribution for the fully hadronic channel as reconstructed by the OPAL Collaboration is shown for all data taken at $\sqrt{s}$ above 183 GeV [28]. The data are compared to the Monte Carlo prediction for $m_W = 80.42\ GeV$.

From the measured masses in each event the final value of the W mass is extracted by means of sophisticated analysis techniques, which are somewhat different for the four experiments and in each case require the comparison with a large number of Monte Carlo events. ALEPH, L3, and OPAL use a reweighting technique to determine the W mass, DELPHI uses a convolution technique. Details on the analysis of the four experiments can be found in the final publications for the data taken up to $\sqrt{s} = 189$ GeV [44,45,47] or up to $\sqrt{s} = 183\ GeV$ [46] and in more recent analyses contributed to this conference[43,48,49].

At present the precision of the combined result is limited by systematic uncertainties. They are smallest for the mass values extracted from semileptonic events. Here the total systematic uncertainty is 29 MeV with the largest contributions due to fragmentation effects, beam energy uncertainty, detector systematics, initial and final state photon radiation. The mass determination from the fully hadronic events contains additional uncertainties due to possible final state interactions between quarks originating from the decay of different W's (colour reconnection) or between hadrons (Bose-Einstein correlations). Both effects may lead to distortions in the invariant mass distribution, they

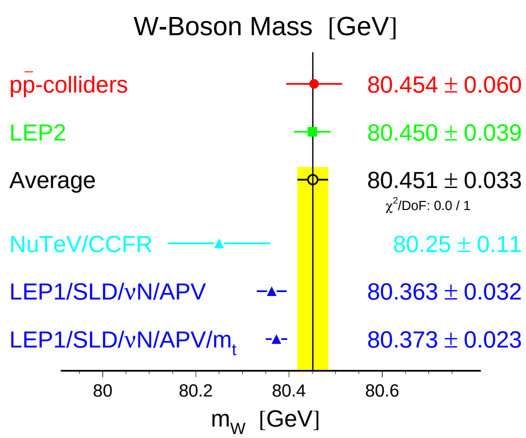

Figure 20. Direct and indirect W mass measurements.

are under study. Including such uncertainties in a conservative way, a total systematic uncertainty of 54 MeV is quoted for m_W from fully hadronic events. The difference in the masses obtained from the semileptonic and fully hadronic WW decay channels is:

$$\Delta m_W(q\bar{q}q\bar{q} - q\bar{q}l\bar{\nu}) = +9 \pm 44\, MeV. \quad (19)$$

Combining all LEP measurements[50] yields the nearly final result:

$$m_W = 80.450 \pm 0.026(stat.) \pm 0.030(syst.) GeV. \quad (20)$$

Here the weight of the fully hadronic channel in the combined fit is only 26%. All direct and indirect W mass measurements are summarised in Fig. 20. Since not all LEP data are included yet and studies of the final state interaction effects continue it is hoped that the final LEP error will decrease to about 35 MeV. There is still agreement between the indirect determination from a fit including the measured top mass and the direct measurements of m_W, but this year only within 1.9 σ.

The width of the W boson has also been measured at LEP: $\Gamma_W = 2.150 \pm 0.091\, GeV$. Within error there is good agreement with the SM prediction.

4.2 Charged Gauge Couplings

Measuring the specific form of the non-Abelian triple gauge boson self-coupling γWW or ZWW has been the second main goal of W physics at LEP. Assuming electromagnetic gauge invariance, charge conjugation and parity conservation and using also constraints from low energy data reduces the number of couplings from 14 in the most general case to three[51]: $g_1^Z, \kappa_\gamma, \lambda_\gamma$ which have been most intensively studied. Within the SM model these are given by 1,1,0 at tree level. They are related to the magnetic dipole moment μ_W and the electric quadrupole moment q_W of the W^+:

$$\mu_W = \frac{e}{2m_W}(1 + \kappa_\gamma + \lambda_\gamma),$$
$$q_W = -\frac{2}{m_W^2}(\kappa_\gamma - \lambda_\gamma). \quad (21)$$

A deviation of κ_γ or λ_γ from their SM values would therefore prove the presence of anomalous electromagnetic moments of the W boson and thus indicate completely new physics in the boson sector. Results have been derived using all available information from the total WW production cross-section, the polar angular distribution of the W^-, the $W^\pm$ helicities analysed via the fermion decay angles, single W production $e^+e^- \to e\nu W$, and $\nu\bar{\nu}\gamma$ production. Within errors the measurements agree with the SM expectation with the following precision evaluated from one parameter fits to the combined data[52]:

$$\delta g_1^Z = \pm 0.026,\ \delta\kappa_\gamma = \pm 0.066,\ \delta\lambda_\gamma = \pm 0.028. \quad (22)$$

Considering higher order effects the SM predicts small deviations from the tree level values, e.g. $\Delta\kappa_\gamma \simeq 0.005$. Such small effects, however, are outside the scope of present experimental verification.

In a more general approach the CP violating couplings have been studied by

ALEPH[53] and OPAL[54]. Within errors no deviation from the SM has been observed. One should mention that limits for the quartic charged gauge couplings have been presented by ALEPH[55], L3[56], and OPAL[57] albeit with large errors. All results can be summarised by stating: no evidence has been found for any anomalous W boson coupling.

4.3 ZZ production

Measurements of ZZ production at $\sqrt{s} \geq 183$ GeV allow an investigation of a sector of the SM not tested before. Deviations from the SM production cross-section, which is defined by the NC02 diagrams involving only t- and u-channel electron exchange, would be an indication for the existence of anomalous neutral gauge couplings absent in the SM at tree level. The ability to understand this process is also essential for the Higgs boson search, where ZZ production forms an irreducible background. All experiments have analysed ZZ decays into $q\bar{q}q\bar{q}$ (4 jets), $q\bar{q}\nu\bar{\nu}$ (2 jets plus missing energy), $q\bar{q}l^+l^-$ (2 jets plus 2 isolated leptons), and $l^+l^-l^+l^-$. New results have been submitted to this conference[58,59,60,28]. Since the cross-section is only about 1 pb, a factor $\simeq$ 17 smaller than the WW cross-section, the statistics is very limited. The comparison of the energy dependence of the LEP combined data to the SM prediction in Fig. 21 [31] proves the agreement within the large errors of the data.

The coupling of a virtual photon or Z boson to ZZ or Zγ final states is not forbidden by fundamental principles. Non SM contributions from the $\gamma^* ZZ$ or $Z^* ZZ$ vertex are described by $f_i^{\gamma,Z}$ $(i = 4, 5)$ couplings, from the $\gamma^* Z\gamma$ or $Z^* Z\gamma$ vertex by $h_i^{\gamma,Z}$ $(i = 1, 4)$ couplings. Experimental tools to search for such anomalous neutral triple gauge couplings are the measurement of the total ZZ or γZ cross-section (increase at high energies?), the polar angle distribution of the produced Z or γ (deviations at large θ?), and the γ energy distribution.

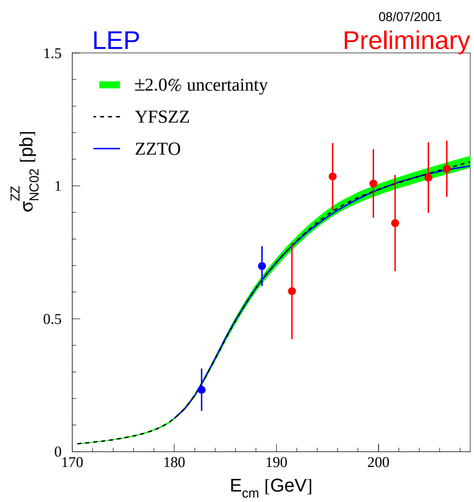

Figure 21. LEP combined NC02 cross-sections. The curve shows the SM expectation, the band corresponds to the ±2% uncertainty of the prediction.

New results submitted by all LEP collaborations[61,62,63,64] have been combined by the Electroweak Working Group[52]. For CP conserving anomalous amplitudes a large interference with the SM amplitude could arise. However, no evidence for anomalous neutral couplings has been found. To give a few examples, the 95% confidence level limits for the CP conserving couplings f_5^γ, h_3^Z and h_3^γ are:

$$\begin{array}{ll} f_5^Z & [-0.36,\ +0.39], \\ h_3^Z & [-0.20,\ +0.07], \\ h_3^\gamma & [-0.049,\ +0.008]. \end{array}$$

4.4 Consistency test of the SM

A consistency test of the SM can be performed by comparing the indirect and the direct measurements of the W and the top quark masses. In Fig. 22 the indirect contour has been obtained from an SM fit to the data from LEP1, SLD, neutrino nucleon scattering, and from atomic parity violation experiments[4]. Both the direct and the indirect data favour a low Higgs mass. The di-

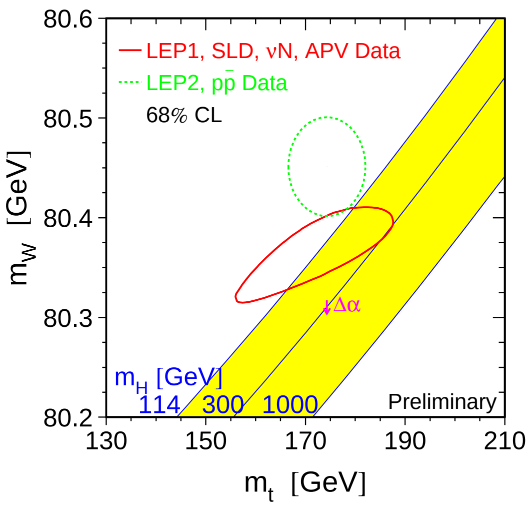

Figure 22. Comparison of the indirect (full line) and the direct (dotted line) measurements of m_W and m_t. The diagonal band shows the SM prediction for various values of the Higgs mass ranging from 114 GeV to 1000 GeV, $m_H \leq 114\,GeV$ has been excluded by direct searches.

rect and the indirect measurements still agree with each other though not as excellently as last year (Fig. 23).

The experimental results of the direct searches for the Higgs boson are discussed by G. Hanson[65], the theoretical aspects by F. Zwirner[66]. With no significant Higgs signal being observed, an indirect mass evaluation becomes again important. Fig. 24 presents the updated version of the traditional plot in form of a $\Delta\chi^2$ versus m_H curve. The solid curve shows the result of the SM fit to all data from LEP and SLD, the world data on m_W and m_t, $sin^2\theta_W$ from the neutrino experiments CCFR and NUTEV, the measurements of atomic parity violation parameters, and also to the new direct determination of $\Delta\alpha^{(5)}_{had}(m_Z)$ (the contribution of the 5 quarks to the running of the fine structure constant α) from[67]. The fit confirms the preference for a low Higgs mass. The 95% confidence level

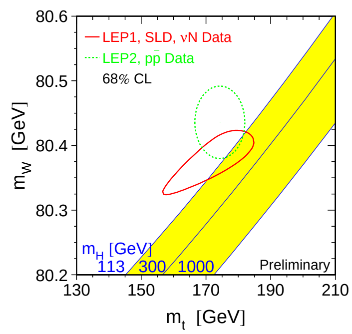

Figure 23. Same as Fig. 22 but with the data from summer 2000. The indirect result is obtained from an SM fit to the LEP1, SLD, and neutrino nucleon data.

upper limit for m_H is now 196 GeV. The dashed curve in Fig. 24 is the result of a fit with $\Delta\alpha^{(5)}_{had}$ from[68] but otherwise unchanged input data and indicates the sensitivity of the m_H prediction; for details see[4].

As discussed before the b quark forward-backward asymmetry deviates by about 3 σ from its SM expectation. One may therefore ask: what is the relative importance of including $A^{0,b}_{FB}$ in the SM fit. The answer is given in Fig. 25, where the dotted contour line presents the 68% probability of the SM fit to all data except $A^{0,b}_{FB}$. The preference for a low Higgs mass is even stronger, the one σ contour is then completely excluded by the direct Higgs search.

5 Contributions to the CKM Matrix

LEP was part of the world wide effort to explore the structure of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. From the measurement of the W leptonic branching ratio one can determine V_{cs}. More important, the determination of the CKM elements V_{ub}, V_{cb}, and of the ratio V_{td}/V_{ts} has been a central part of the LEP B-physics programme. Strong points of the LEP b quark studies are:

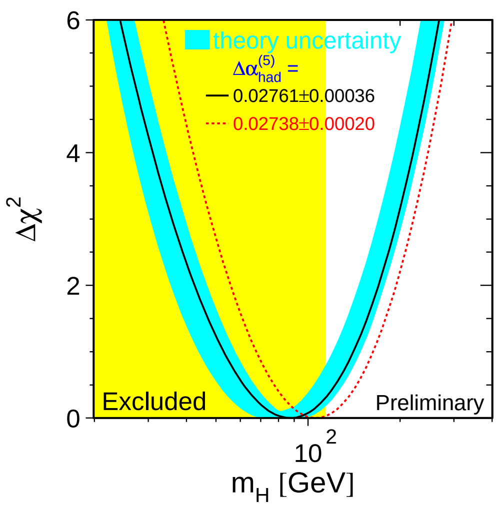

Figure 24. $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ as function of the Higgs mass. The solid curve presents the result of the SM fit, the band indicates the theoretical uncertainty. Also shown is the Higgs mass 95% CL exclusion limit from the direct search. The dashed curve shows an SM fit assuming a lower value of $\Delta\alpha^{(5)}_{had}(m_Z)$.

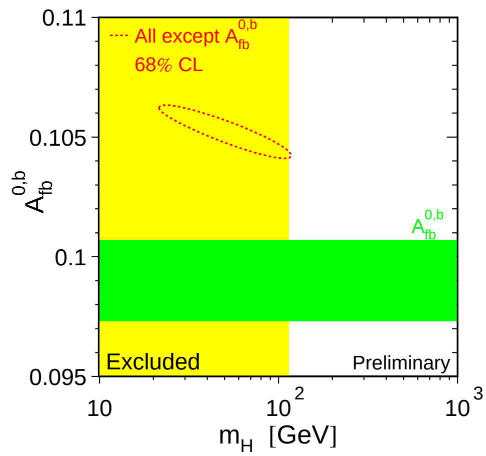

Figure 25. 68% probability contour curve in the $(A^{0,b}_{FB}, m_H)$ plane obtained from an SM fit to all data except $A^{0,b}_{FB}$. The direct measurement of $A^{0,b}_{FB}$ is shown as horizontal band of width $\pm 1\ \sigma$. Also shown is the exclusion limit from the direct Higgs search.

- Large statistics, in total about 4 million Z $\rightarrow b\bar{b}$ decays,
- fast moving B hadrons, the B hadron decay particles are well separated from the QCD rest,
- tools for particle identification including $K^\pm$,
- experience of 12 years of data analysis.

In the following only a few examples can be mentioned. A detailed summary of combined B-physics results including the data from the four LEP collaborations, from CDF and from SLD is available[69].

5.1 $|V_{cs}|$ from $BR(W \rightarrow l\bar{\nu})$

The leptonic branching fraction of the W boson is directly related to the squares of the six CKM matrix elements not depending on the t quark:

$$\frac{1}{3\,BR(W \rightarrow l\bar{\nu})} = 1+[1+\frac{\alpha_s(m_W)}{\pi}] \sum_{\substack{i=u,c,\\ j=d,s,b}} |V_{ij}|^2. \qquad (23)$$

Taking the LEP average branching fraction as determined under the assumption of lepton universality yields[31]:

$$\sum |V_{ij}|^2 = 2.039 \pm 0.025$$

consistent with the value of 2 expected from unitarity. With the world average values for the other five CKM elements:

$$| V_{cs} | = 0.996 \pm 0.013. \qquad (24)$$

5.2 Inclusive measurement of $|V_{ub}|$

At LEP the measurement of $|V_{ub}|$ relies on the inclusive reconstruction of the $b \rightarrow ul\bar{\nu}$ fraction:

$$|V_{ub}|^2 = \frac{BR(B \rightarrow X_u l\bar{\nu})}{\gamma_b\, \tau_b}, \qquad (25)$$

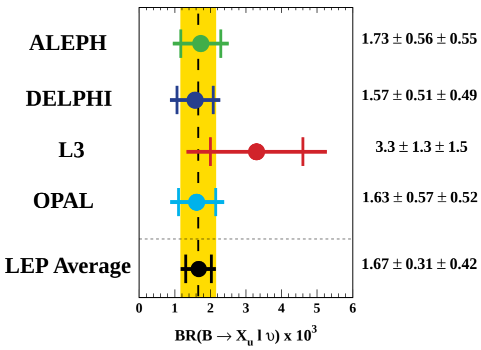

Figure 26. Measurements of the branching ratio $B \to X_u l \bar{\nu}$ by the four LEP experiments and the resulting average. The first error is due to statistics and experimental systematics uncorrelated between experiments, the second due to all other systematic uncertainties.

where τ_b is the average b lifetime and γ_b includes QCD corrections and b quark mass effects. Much progress has been made during the last years as a consequence of both, improved understanding of the theoretical uncertainties of γ_b and improved experimental analysis techniques[69].

Obviously it is very difficult to separate charmless b decays from the dominant $b \to c$ background. Several techniques have been applied in earlier publications[70,71,72] based, for instance, on inclusive analysis of semileptonic decays. In a new analysis submitted to this conference the OPAL Collaboration uses 7 kinematic variables as neural net input in order to enrich the $B \to X_u l \bar{\nu}$ sample[73]. All measurements of the four collaborations are collected in Fig. 26.

With the average branching ratio as determined by the LEP V_{ub} Group:

$$BR(B \to X_u l^- \bar{\nu}_l) = (1.67 \pm 0.52) \times 10^{-3}$$

and taking the world average B hadron lifetime $\tau_b = (1.564 \pm 0.014)$ ps one finds:

$$|V_{ub}| = (4.04\,^{+0.59}_{-0.69}) \times 10^{-3}. \qquad (26)$$

Here the error includes all theoretical uncertainties. The LEP value of Eq. (26) agrees very well with the most recent measurement of the CLEO Collaboration[75]. It should be mentioned that the accuracy of $|V_{ub}|$ achieved at LEP is far beyond of what was originally hoped for.

5.3 $B_s^0 - \bar{B}_s^0$ oscillations

Much progress has also been made recently in the search for B_s^0 oscillations. The main impact on the determination of the CKM elements is explained in Eq. (27):

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}}\, \xi^2\, \frac{|V_{ts}|^2}{|V_{td}|^2}. \qquad (27)$$

In the ratio of the B_s^0 and B_d^0 mass differences Δm_s to Δm_d many uncertainties cancel (see e.g.[76]) and the remaining non-perturbative quantity ξ^2 is well known from lattice gauge theory: $\xi^2 = 1.16 \pm 0.05$ [77]. No measurement of Δm_s has been performed yet, but upper limits have been set by each experiment applying the so-called amplitude method. The idea of the method is to replace the expression for the time dependent probability that a produced B_s^0 is detected as $\bar{B}_s^0$ by

$$P(B_s^0 \to \bar{B}_s^0) = \frac{1}{2}\,(1 - \mathbf{A}\, cos(\Delta m_s\, t))\, e^{-t/\tau_{B_s^0}} \qquad (28)$$

and then fit the amplitude A to the data for various fixed values of Δm_s. Fig. 27 shows the amplitude spectrum resulting from the combination of the spectra of all LEP experiments[69,78]. The combined spectrum includes the new results from DELPHI[79,80] and from OPAL[81]. From the LEP data in Fig. 27 a 95% confidence level lower limit of $\Delta m_s > 14.3\, ps^{-1}$ is derived. Including the data from SLD and CDF the present world limit increases to[82]:

$$\Delta m_s > 14.6\, ps^{-1}\ at\ 95\%\ CL. \qquad (29)$$

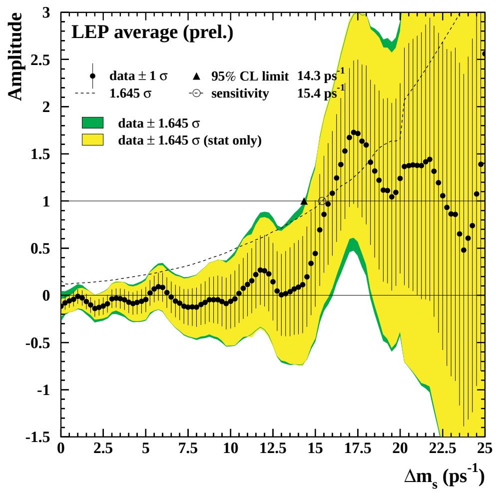

Figure 27. Combined B_s^0 oscillation amplitude A as a function of Δm_s. The 95% CL limit derived from this spectrum is marked by the small solid triangle.

With the measured B_s^0 and B_d^0 masses and the world average value of Δm_d the limit for the ratio of the CKM elements is now:

$$|V_{td}|/|V_{ts}| < 0.22\,.$$

6 Contributions to QCD

An important point to remember is that electroweak precision quantities depend on the strong coupling α_s. One of the best known examples is the ratio of the Z partial decay widths R_{lept}, which is known to $\mathcal{O}(\alpha_s^3)$ as given in Eq.(30). With the final value $R_{lept}^0 = 20.767 \pm 0.025$ (derived by assuming lepton universality) one gets the result of Eq. (31). The advantage of evaluating α_s from Eq. (30) is that nonperturbative corrections are suppressed and the dependence on the renormalization scale μ (which is often responsible for the dominant uncertainty of α_s measurements) is small. All theoretical uncertainties including the renormalization scale uncertainty amount to only $+0.003, -0.001$, for details see[83]. Varying m_t within ± 5 GeV and m_H from 100 to 1000 GeV leads to the additional small uncertainty of ± 0.002. A fit to all electroweak Z pole data from LEP and SLD and to the direct measurements of m_t and m_W yields: $\alpha_s(m_Z) = 0.1183 \pm 0.0027$ [4].

One may wonder whether these are the most reliable evaluations of $\alpha_s(m_Z)$ using the LEP data. The problem is, however, that the quoted results fully rely on the validity of the electroweak sector of the SM. Small deviations can lead to large changes. It is therefore necessary to measure α_s from infrared safe hadronic event shape variables like jet rates, thrust, jet mass, jet broadenings, etc. not depending on the electroweak theory. Such studies have been performed by all LEP experiments, for more recent publications see[84,85,86,87]. Measurements extracted by using resummed calculations in next-to-leading logarithmic approximation (NLLA) matched to $\mathcal{O}(\alpha_s^2)$ calculations have been combined by the LEP QCD Working Group[88]. As an example Fig. 28 shows α_s values from fits to event shape distributions at all LEP energies including measurements of the JADE Collaboration at lower energies. A fit to the combined data results in $\alpha_s(m_Z) = 0.1195 \pm 0.0047$, where the error is almost entirely due to theoretical uncertainties (renormalization scale). The figure also indicates to which extent the running of α_s can be tested.

All LEP α_s measurements using a multitude of analysis methods are collected in Fig. 29 [89]. The three entries at the top present inclusive measurements for which perturbative calculations are known in $\mathcal{O}(\alpha_s^3)$. One of the most precise measurements is obtained from the ratio of the τ partial decay widths $R_\tau = \Gamma(\tau \to hadrons + \nu_\tau)/\Gamma(\tau \to e\bar{\nu}_e\nu_\tau)$, the quoted value is from[90]. The figure also includes the average values from each of five different methods to extract α_s from hadronic event shape distributions: four jet rates, 3 jet like observables analysed in $\mathcal{O}(\alpha_s^2)$ using either power corrections or hadronic Monte Carlo generators for evaluating hadronisation effects, three jet like observables analysed in

$$R^0_{lept} = \frac{\Gamma_{hadrons}}{\Gamma_{leptons}} = 19.934\,\{1 + 1.045\frac{\alpha_s}{\pi} + 0.94(\frac{\alpha_s}{\pi})^2 - 15(\frac{\alpha_s}{\pi})^3\} \tag{30}$$

$$\alpha_s(m_Z) = 0.124 \pm 0.004(exp.) \pm 0.002(m_H, m_t)\,^{+0.003}_{-0.001}(QCD). \tag{31}$$

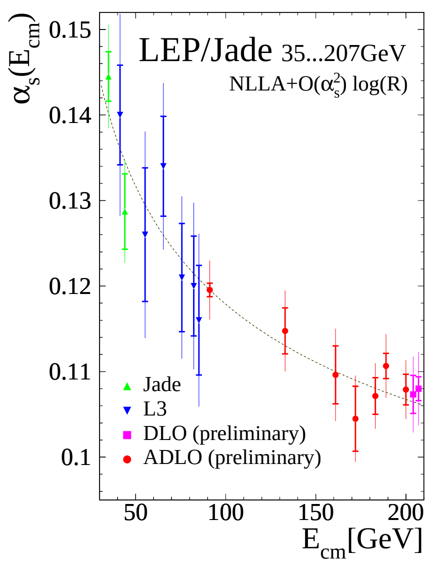

Figure 28. Energy dependence of α_s. The data are extracted from the analysis of infrared safe hadronic event shape distributions in the next-to-leading logarithmic approximation. The dotted curve presents the expected running of α_s.

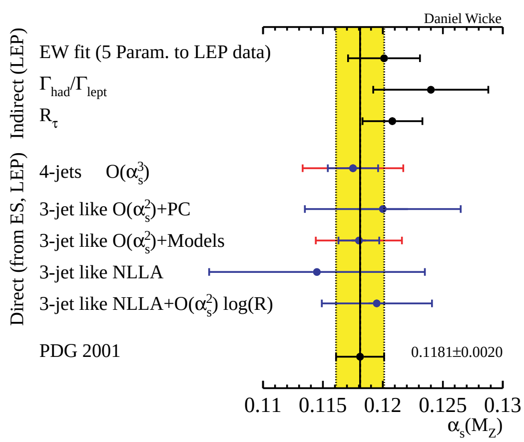

Figure 29. Summary of α_s measurements at LEP compared to the world average. The theoretical uncertainty for all 5 measurements from event shapes (ES) is evaluated by changing the renormalization scale μ by a factor of 2.

pure NLLA and in matched NLLA as mentioned above. All measurements agree well with each other and with the world average.

Studying QCD at LEP has several advantages: the centre-of-mass energy is high and well defined, jets are collimated, the environment is clean, statistics is high enough to investigate even rare topologies. In consequence more than 200 QCD papers have been published till now including detailed investigations of perturbation theory, hadronisation models, power corrections, quark and gluon jet fragmentation, local parton-hadron duality, soft gluon coherence etc. The experimental aspects are reviewed, e.g. in[91,92,93].

Of the many new QCD studies contributed by the LEP Collaborations to this conference only few can be briefly mentioned, for instance, measurements of the colour factors and/or of α_s based on 4-jet events[94,95,96], studies of the energy evolution of event shape distributions and of inclusive charged particle production including measurements at the highest energies compared to the prediction of hadronisation models[97,98,99,100,28], measurements of the b quark mass at the Z mass scale[101]. As the outcome of the work at LEP one can conclude that the understanding of QCD phenomenology has much improved and even rather subtle measurements are all consistent with QCD predictions.

7 Conclusion and Reflection

It is appropriate now to recall what was known in summer 1989, when LEP started and what was expected from LEP for the future. Some examples of what was known are given below:

$$m_Z = 91.12 \pm 0.16\,GeV,$$
$$m_W = 80.0 \pm 0.36\,GeV,$$
$$sin^2\theta_W = 0.227 \pm 0.006,$$
$$N_\nu = 3.0 \pm 0.9.$$

It was expected, of course, that LEP would improve the accuracy substantially. Looking back at the review talks presented by G. Altarelli[102] at the Lepton Photon Symposium 1989 in Stanford and by R. Barbieri[103] at the EPS Conference 1989 in Madrid one finds the expected experimental errors compared in Table 1 with those actually achieved. I should remark that the error for N_ν quoted as *expected* is from the answer which was given by the DELPHI Collaboration to the LEPC in 1982. In the end, all measurements turned out to be much more precise than expected. Despite this precision the SM continues to be in good shape.

Why was LEP so successful? Many fortunate facts had to come together:
- A highly dedicated machine group responsible for the excellent performance of LEP,
- low background in the detectors,
- good performance of all detectors from the pilot run in August 1989 till the end of data taking,
- effective division of work between CERN and the outside laboratories,
- close cooperation between the 4 collaborations and also between LEP and SLD (without avoiding competition),
- close cooperation between experiments and the machine group,
- and, very important, close cooperation with theory groups.

Many analyses are continuing and still more can be expected in the future.

Table 1. Expected and achieved precision at LEP.

Quantity	*Expected error*	*Achieved*
m_Z	50 to 20 MeV	**2.1** MeV
m_W	100 MeV	**39** MeV
N_ν	0.3	**0.008**
$A_{FB}^{0,\mu}$	0.0035	**0.0013**
$A_{FB}^{0,b}$	0.0050	**0.0017**
$\mathcal{A}_\tau$	0.0110	**0.0043**

Acknowledgments

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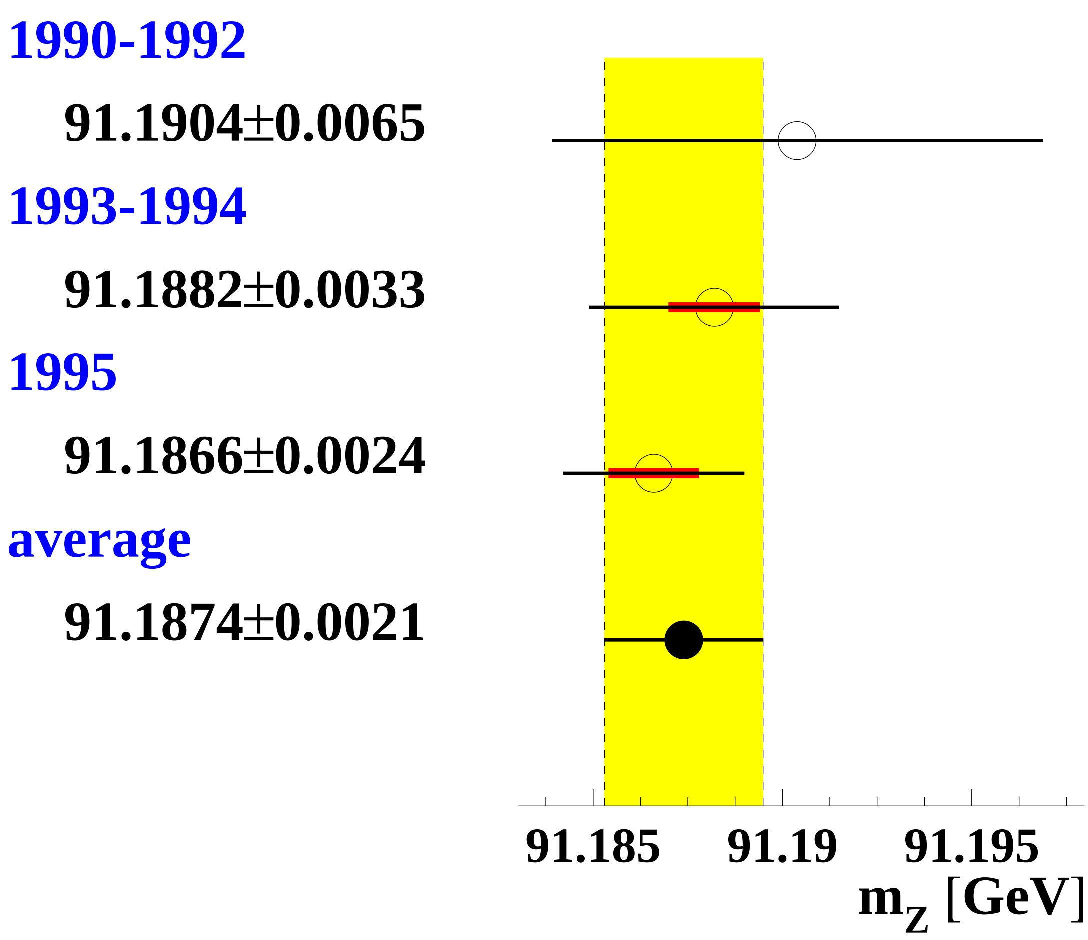
Discussion

Alberto Sirlin, New York University: I have an observation and a question.
i) With respect to the evidence for genuine electroweak corrections, I think there is a very simple argument that shows a very large signal. It consists of measuring the radiative correction Δr by using the experimental results for m_W and m_Z, and comparing with the value Δr would have if the only contribution arose from the running of α. Last time I did this, about a year ago, I found a difference amounting to many standard deviations.
ii) The question is: what is the χ^2 per degrees of freedom of the most recent electroweak global fit?

J. Drees: The most recent MSM fit to all electroweak data including the direct measurements of m_W and m_t has $\chi^2/ndf = 22.9/15$ corresponding to the still reasonable probability of 8.6%.


1990-1992
91.1904±0.0065
1993-1994
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1995
91.1866±0.0024
average
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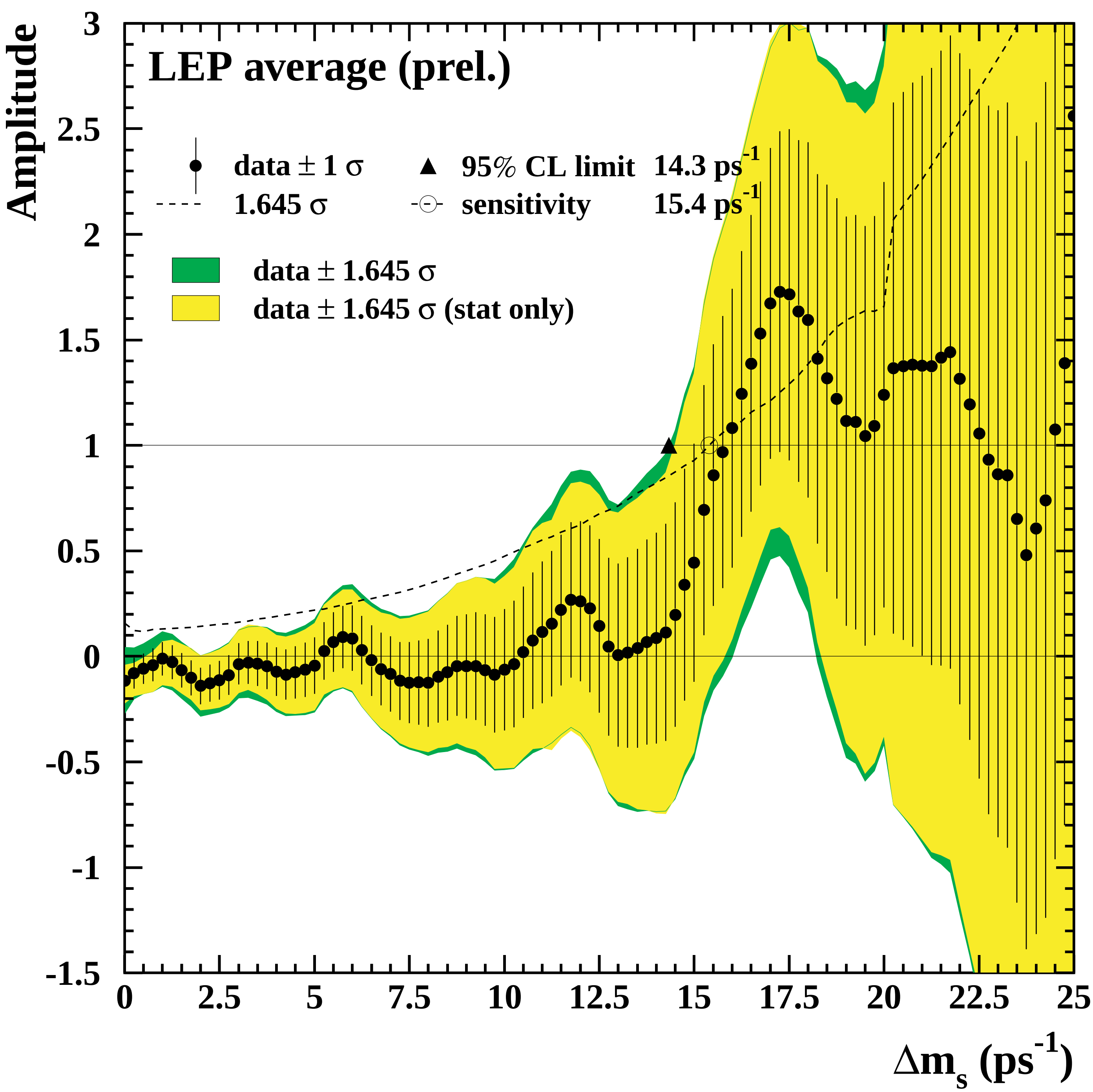
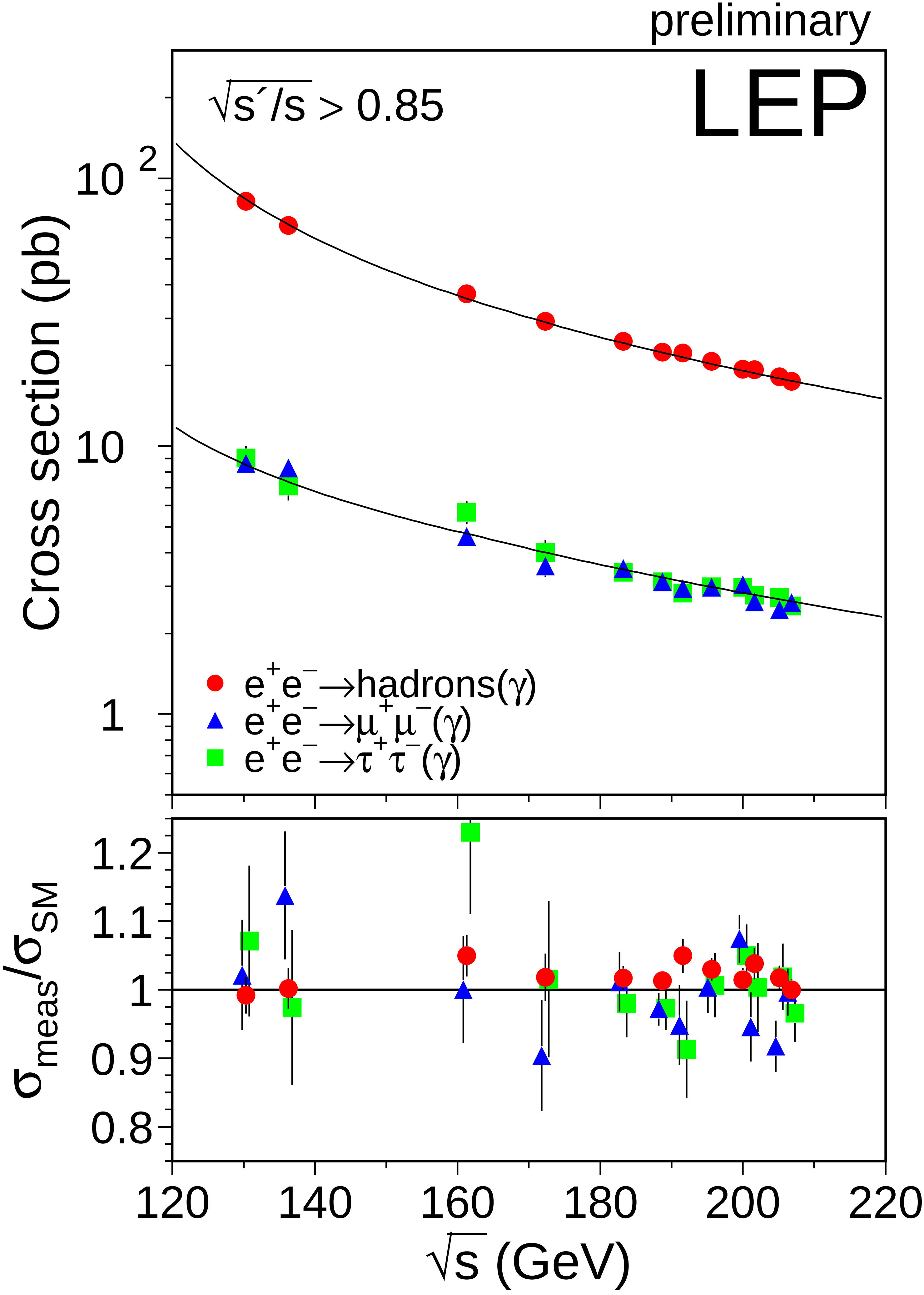
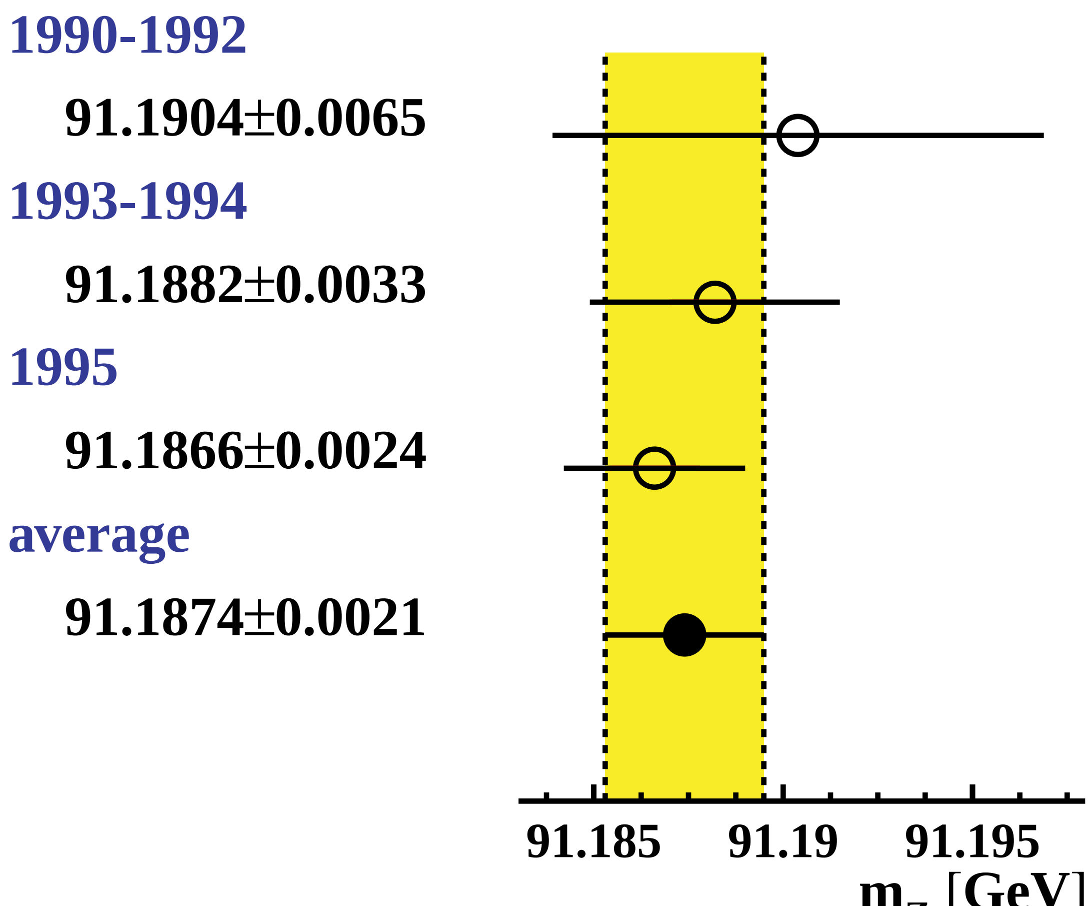
91.185
91.19
91.195
m_Z [GeV]


LEP average (prel.)
data ± 1 σ
95% CL limit 14.3 ps^-1
1.645 σ
sensitivity 15.4 ps^-1
data ± 1.645 σ
data ± 1.645 σ (stat only)
Amplitude
Δm_s (ps^-1)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25


preliminary
LEP
$\sqrt{s'/s} > 0.85$
Cross section (pb)
10^2
10
1
$e^+e^-\to$hadrons(γ)
$e^+e^-\to\mu^+\mu^-(\gamma)$
$e^+e^-\to\tau^+\tau^-(\gamma)$
$\sigma_{meas}/\sigma_{SM}$
1.2
1.1
1
0.9
0.8
120
140
160
180
200
220
$\sqrt{s}$ (GeV)


1990-1992
91.1904±0.0065
1993-1994
91.1882±0.0033
1995
91.1866±0.0024
average
91.1874±0.0021
91.185
91.19
91.195
m_Z [GeV]