Recent LEP results

Jan Timmermans [1]

NIKHEF
P.O. Box 41882, 1009 DB Amsterdam, The Netherlands

Abstract

Recent results from LEP are presented. They comprise the final measurement of the heavy flavour forward-backward asymmetry at the Z peak, four-fermion production and the measurement of the W mass. Also the results of the global electroweak fit as of Summer 2003 and the final combined results of the SM Higgs search at LEP are shown.

1 Introduction

The LEP e^+e^- collider, in its first phase has been running from 1989 to 1995 at a centre-of-mass energy $\sqrt{s} \approx m_Z$. Each of the four experiments collected about 200 pb^{-1} of data, corresponding to about 4.5M Z events. In the second phase (LEP2) from 1995 to 2000, the centre-of-mass energy was increased from 130 GeV in 1995, reaching a peak value of 209 GeV in 2000. Each of the experiments collected $\approx$ 700 pb^{-1}, yielding about 10,000 WW, 600 ZZ and 250 single W events per experiment. An example of cross-section measurements of various electroweak processes as a function of the centre-of-mass energy is given in Figure 1, illustrating a wide variation of cross-section values over more than five orders of magnitude. Detailed results on some of these measurements will be given in the following sections [2]. Also shown in this plot is the expected cross-section for the production of the Standard Model (SM) Higgs boson of a mass of 115 GeV, more than one order of magnitude smaller than the cross-section for ZZ production. The final LEP combined results from the search for the SM Higgs boson will be given in Section 7.

---

[1] E-mail: timmermans@nikhef.nl

[2] Results on electroweak gauge boson coupling measurements at LEP were presented at this conference by Gideon Bella [1].

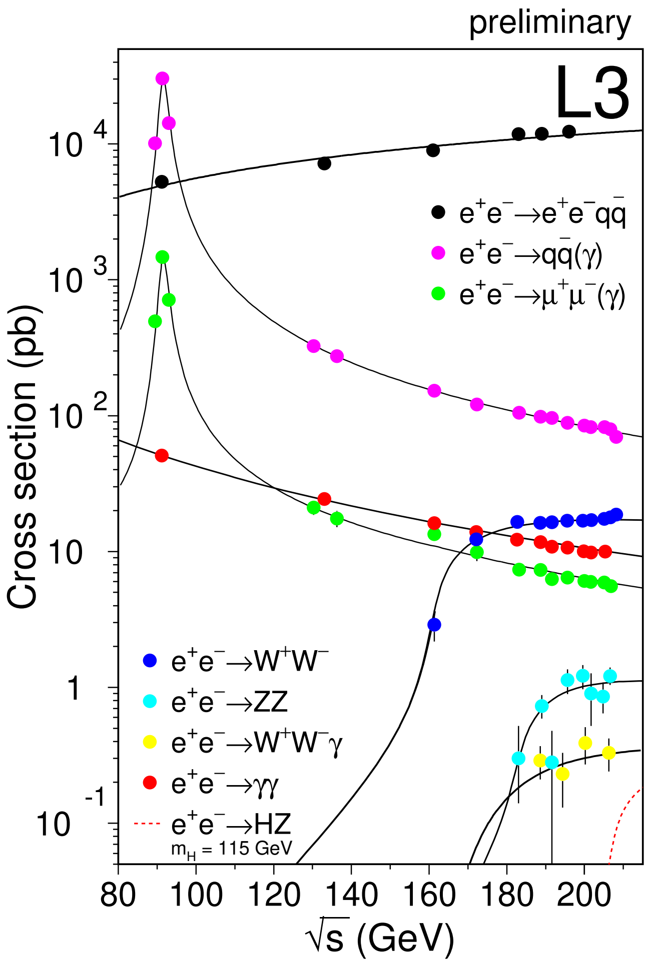

Figure 1: Standard Model cross-sections in the energy range of LEP with preliminary L3 measurements.

2 Heavy flavour forward-backward asymmetries

The measurement of the forward-backward asymmetries in the decay $Z \to b\bar{b}$ allows for one of the most precise determinations of the effective weak mixing angle $\sin^2\theta_{eff}^{lept}$. The differential cross-section for fermion pair production is given by

$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta. \tag{1}$$

The Z pole asymmetry $A_{FB}^{0,b}$ for the b quark can be written as a product of the polarisation parameters $\mathcal{A}_e$ and $\mathcal{A}_b$:

$$A_{FB}^{0,b} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b = \frac{3}{4}\frac{2g_{Ve}\,g_{Ae}}{g_{Ve}^2+g_{Ae}^2}\,\frac{2g_{Vb}\,g_{Ab}}{g_{Vb}^2+g_{Ab}^2} \tag{2}$$

with the ratio of the vector and axial-vector couplings given by

$$\frac{g_{Vf}}{g_{Af}} = 1 - 4|Q_f| \sin^2 \theta_{eff}^f. \tag{3}$$

$\mathcal{A}_b$ is almost insensitive to $\sin^2 \theta_{eff}^b$, but the measurement of $A_{FB}^{0,b}$ is very sensitive to $\sin^2 \theta_{eff}^{lept}$.

Very pure b quark samples are obtained through powerful b-tagging methods using displaced vertices and the selection of high p_T and high momentum leptons in the b decay. The charge of the b quark is obtained from the leptons or through an inclusive charge tag based on jet charge, vertex charge and identified particles in the decay. The purity of the sample and the charge tag efficiency are calibrated on the data itself using double-tag methods.

At the Summer 2003 conferences, OPAL presented their final and DELPHI their close to final measurements of $A_{FB}^{0,b}$. The LEP combined results for the b and c quark asymmetry and their energy dependence are shown in Figure 2. The average Z pole asymmetry from LEP is

$$A_{FB}^{0,b} = 0.0997 \pm 0.0016 \tag{4}$$

where the error includes a total systematic error of 0.0007. The extracted values of $\sin^2 \theta_{eff}^{lept}$ from the heavy quark asymmetries are compared with purely leptonic measurements from LEP and SLD in Figure 3. The two most precise measurements of $\sin^2 \theta_{eff}^{lept}$, from $A_{FB}^{0,b}$ at LEP and from A_{LR} at SLD, differ by 2.9σ. While the A_{LR} measurement prefers a very low Higgs boson mass, the A_{FB} measurements for b and c quarks prefer a rather high mass.

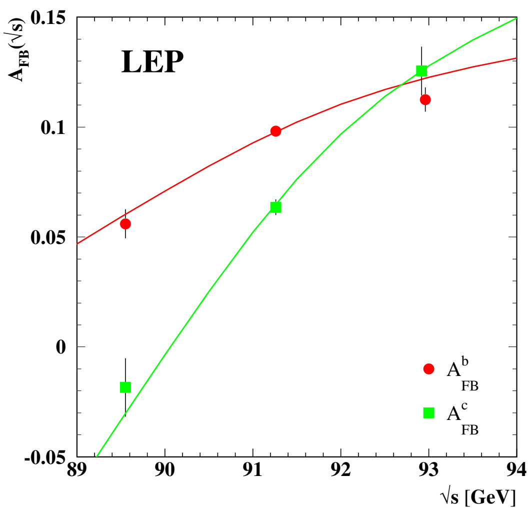

Figure 2: Measured asymmetries for b and c quark final states as a function of the centre-of-mass energy. The Standard Model expectations are shown as the lines calculated for $m_t = 175$ GeV and $m_H = 300$ GeV.

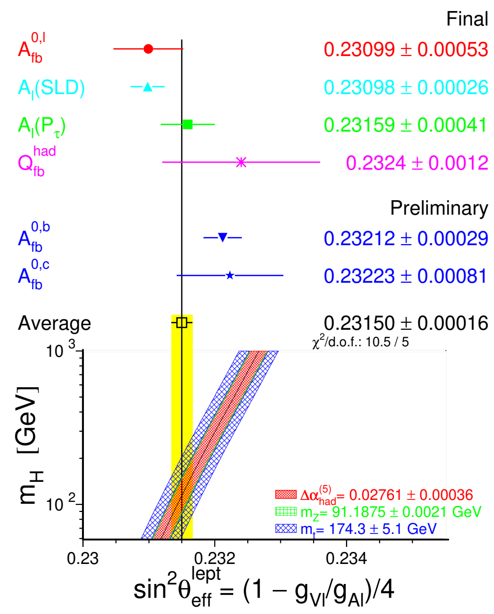

Figure 3: Comparison of several determinations of $\sin^2\theta_{eff}^{lept}$ from asymmetries. Also shown is the prediction of the Standard Model as a function of m_H.

3 W pair production

From 1996 onwards LEP ran at energies between 161 and 209 GeV and W pair production could be studied. Each of the experiments collected a total of $\approx$ 10,000 WW events. Three different final states, comprising 10 different channels are available: 1) the fully-hadronic final state $e^+e^- \rightarrow q\bar{q}q\bar{q}$ where both W bosons decay into a quark-antiquark pair (45.6% of the events), 2) the semi-leptonic final state $e^+e^- \rightarrow q\bar{q}\ell\nu$ (43.8%) where one W boson decays hadronically and the other W decays into a lepton and a neutrino, and 3) the fully-leptonic final state $e^+e^- \rightarrow \ell\bar{\nu}\bar{\ell}\nu$ (10.6%) where both W bosons decay leptonically ($\ell = e, \mu, \tau$). Event selection efficiencies range from $\approx$ 60% (fully-leptonic) to $\approx$ 90% (fully-hadronic) with sample purities of $\approx$ 85% for the fully-hadronic final state and 90% or higher for the (semi-)leptonic final states.

The LEP combined W pair production cross-sections [2] are shown in Figure 4 as a function of the centre-of-mass energy, together with the theoretical predictions from YFSWW [3] and RACOONWW [4]. At tree level three diagrams (CC03) are present in the production of W pairs. The figure shows also the expected cross-section behaviour if only the ν-exchange diagram is active and if there would be no Z-exchange diagram involved. This textbook plot reveals the clear evidence for the $SU(2) \times U(1)$ gauge structure of the interaction, where large cancellations between the contributions of the three diagrams occur. The right-hand side graph shows the comparison of the measured cross-section with one of the theoretical predictions. The combined ratio exp./theory is measured with a 1% precision to be 0.997 ± 0.010 (0.999 ± 0.010 for RACOONWW). The measurements clearly show the need for the full non-leading, non-factorizable $\mathcal{O}(\alpha_{em})$ radiative corrections in these calculations, as earlier theoretical predictions by GENTLE [5] and KORALW [6] were more than 2% too high.

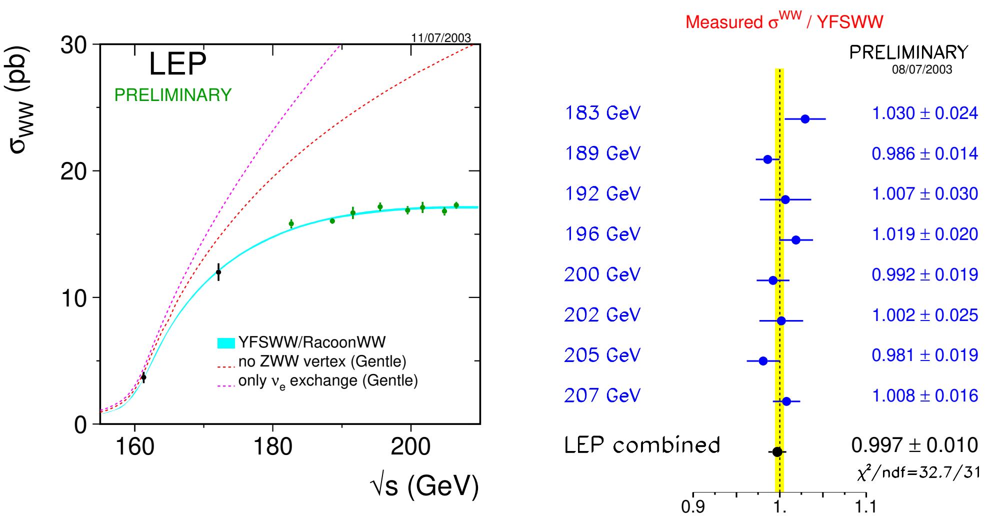

Figure 4: Left: measurements of the W pair production cross-section, compared to the predictions of YFSWW and RACOONWW. Right: ratios of the LEP combined W pair cross-sections compared to the expectations according to YFSWW.

The measurements of the three leptonic branching ratios are found to be in agreement with lepton universality. The combined leptonic branching ratio is $Br(W \to \ell\nu) = (10.74 \pm 0.06(stat.) \pm 0.07(syst.))\%$ and is in good agreement with the SM expectation of 10.83%. The W leptonic branching fraction depends on the six CKM mixing matrix elements $|V_{qq'}|$ not involving the top quark, via the relation

$$\frac{1}{\mathcal{B}(W \to \ell\nu)} = 3\left\{1 + \left[1 + \frac{\alpha_s(\mathrm{M_W^2})}{\pi}\right] \sum_{\substack{i=(u,c),\\ j=(d,s,b)}} |\mathrm{V}_{ij}|^2\right\}. \tag{5}$$

The branching ratio measurement then allows the determination of the least well known element $|V_{cs}|$ using the experimental values for the other five and gives $|V_{cs}| = 0.989 \pm 0.014$, where the total error is dominated by the experimental error on the branching ratio measurement.

The W production and decay angular distributions provide another sensitive test of the Standard Model and allow the measurement of the electroweak triple gauge boson couplings (TGCs). They have been presented at this conference by Gideon Bella [1].

4 Other four-fermion processes

Single W production $e^+e^- \to We\nu$ involves also a triple gauge boson coupling $WW\gamma$. The process $e^+e^- \to WW\gamma$ involves even a quartic gauge boson coupling. Anomolous triple gauge boson couplings between the neutral gauge bosons are studied in the reactions $e^+e^- \to ZZ$ and $e^+e^- \to Z\gamma^*$. Results on these four-fermion processes are reported in [1].

4.1 Single Z production

The production of a single Z boson in the reaction $e^+e^- \to e^+e^-Z$ proceeds through an electroweak Compton scattering process $\gamma e \to eZ$ where a quasi-real photon is radiated from one of the beam electrons and scattered off the other beam. The electron radiating the quasi-real photon is usually lost along the beam line. The measured e^+e^-Z cross-section refers to the complete set of 48 diagrams (NC48) contributing at tree level to the $e^+e^-f\bar{f}$ final state ($f = q, \mu$) with the following phase space cuts to enhance the single Z contribution: $m_{f\bar{f}} > 60$ GeV, $\theta_{e^-} < 12°, 12° < \theta_{e^+} < 120°$ and $E_{e^+} > 3$ GeV for a visible positron (and complementary angles when the electron is visible). The results in the hadronic channel $e^+e^-q\bar{q}$ [2] are shown in Figure 5 as a function of the centre-of-mass energy and compared to predictions from the programs WPHACT [7] and GRACE [8]. The combined ratio of the experimental and WPHACT predicted cross-sections is $\sigma^{Zee}_{exp.}/\sigma^{Zee}_{WPHACT} = 0.932 \pm 0.068$, where the accuracy of the theory prediction is $\approx 5\%$.

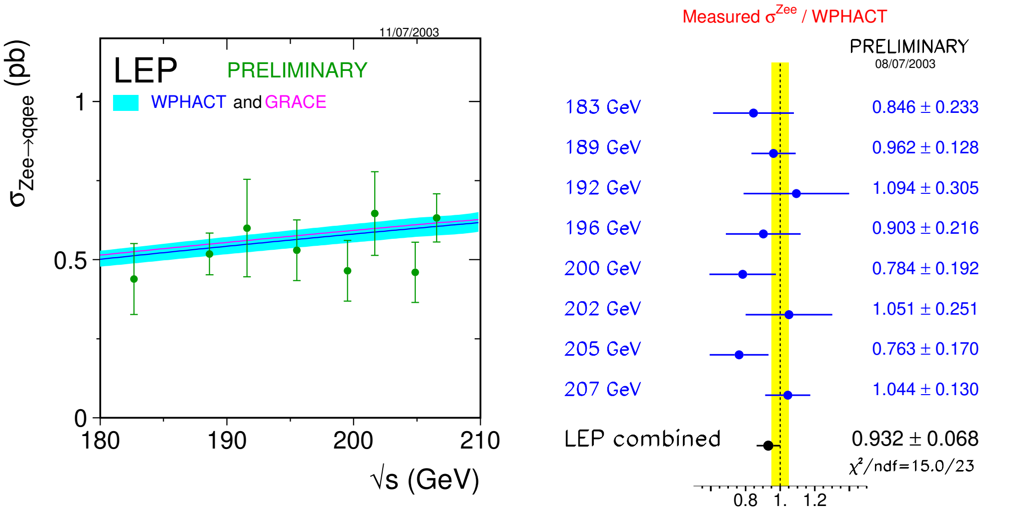

Figure 5: Left: measurements of the single Z hadronic production cross-section, compared to the predictions of WPHACT and `grc4f`. The shaded area represents the $\pm 5\%$ uncertainty on the predictions. Right: ratios of LEP combined single Z hadronic cross-section measurements to the expectations according to WPHACT.

5 W boson mass and width

Radiative corrections to the W propagator provide a handle on the top quark mass and on the Higgs boson mass. The correction to the W mass from a $t\bar{b}$ loop is proportional to m_t^2, while the correction due to the Higgs loop is proportional to $\ln m_H$. The precision with which the top quark mass and W boson mass are directly measured match rather well the uncertainties on these quantities as obtained from the global electroweak fit (see Section 6): 5 GeV resp. 10 GeV for m_t and 34 MeV resp. 32 MeV for m_W. The present precision on the W mass measurement of 0.04% will therefore provide a powerful constraint on the Higgs boson mass.

At LEP the mass of the two W bosons in an event are directly reconstructed from the decay products. The final analysis errors are degraded by a factor of about 4 with respect to the 'generated' masses (according to two Breit-Wigners), because of initial state radiation (ISR), hard gluon radiation, event selection, background, detector inefficiencies and resolutions, and ambiguities in assigning jets to the W bosons in the fully-hadronic final state. Applying constrained fits, using energy and momentum conservation improves the mass resolution from ≈ 8 GeV to ≈ 3 GeV. Even though different selections and analysis techniques have been used by the four experiments, the final statistical errors on the W mass do not differ by more than 20%. Basically two different analysis methods are used. ALEPH, L3 and OPAL obtain their final m_W from maximum likelihood fits to the distribution of reconstructed masses and errors obtained from the constrained kinematic fits, by Monte Carlo reweighting (varying m_W in the Breit-Wigner) of the expected distributions. DELPHI performs a convolution analysis, in which the event-by-event fitted masses and errors are folded with the Breit-Wigner functions, taking into account the probability for initial state radiation, the event purity and the probability of each of the jet pairings in the fully-hadronic events. This combined likelihood is then minimised as a function of m_W. Examples of reconstructed mass distributions in the different final states are shown in Figure 6.

In Spring 2003 ALEPH updated their preliminary earlier W mass results, after they had discovered a problem in the treatment of low energy neutral clusters ("shower satellites") in the electromagnetic calorimeters. These satellites were wrongly associated to the nearest jet, thereby introducing a bias in the jet angle and thus in the jet mass. The solution was found through an improved shower simulation, removing unassociated clusters observed in a single calorimeter stack and removing satellite clusters within 8° of an electron. The result was a rather large shift of -79 MeV with respect to the previous W mass result of ALEPH. No such problems have been observed in the other three experiments.

The LEP Working Group on W mass combines the results of the four experiments [9], taking into account the different contributions to the systematic errors and their correlations. These correlations can be a) common

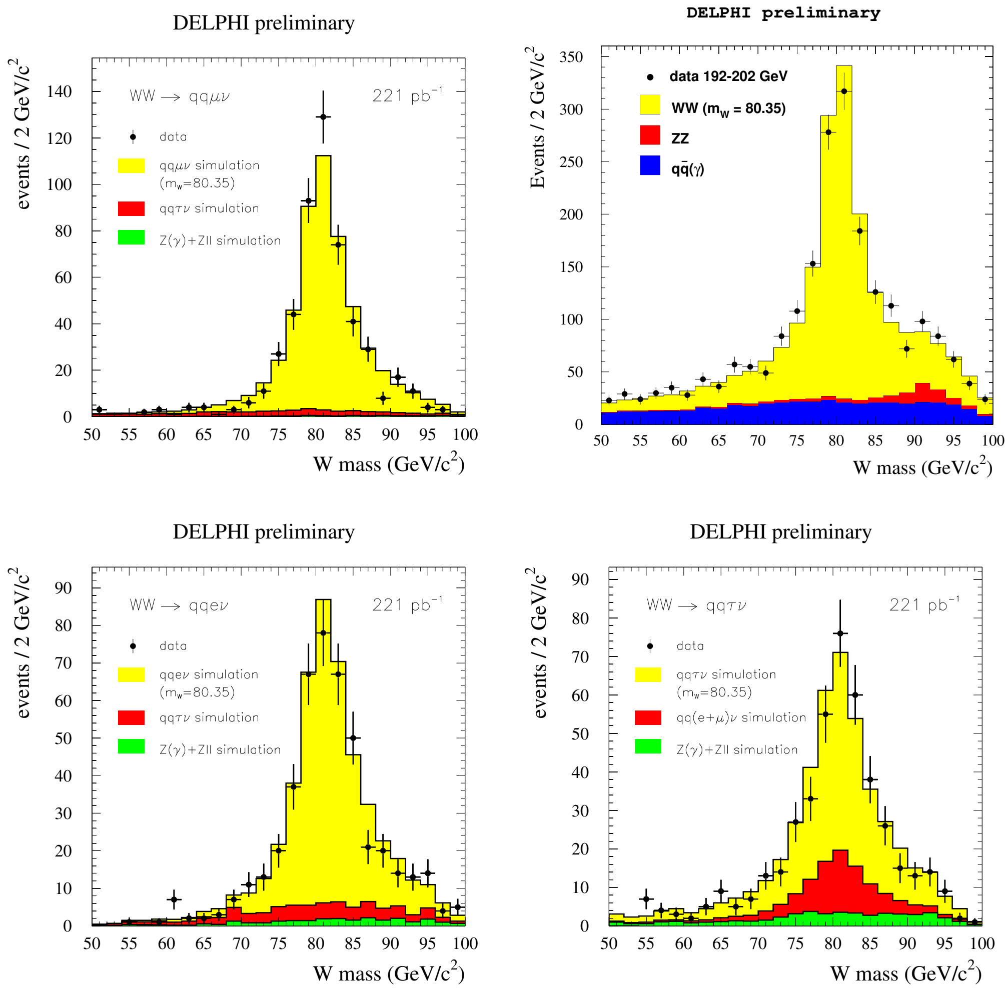

Figure 6: Reconstructed W mass distributions from DELPHI for the 1999 data taken at centre-of-mass energies 192-202 GeV.

between experiments but not between channels, b) common between experiments and channels, c) common between channels but not between experiments, d) correlated or not between the different data taking periods at different centre-of-mass energies. For instance, systematic errors due to fragmentation or from the beam energy lead to correlations between the mass results from different channels. The results of the four experiments and their combination are shown in Figure 7. There is good agreement between the four measurements. The result is $m_W = 80.412 \pm 0.029(stat) \pm 0.031(syst)$ GeV. Also shown in the plot is the dependence of the SM expectation on the Higgs boson mass. A low Higgs mass is preferred by the data. The weight of the fully-hadronic channel in the combination is only 10% due to the current estimate of the systematic errors from final state interactions (Colour Reconnection and Bose-Einstein Correlations), see Table 1. Also the different W width measurements agree well and the LEP combination gives $\Gamma_W = 2.150 \pm 0.068(stat) \pm 0.060(syst)$ GeV.

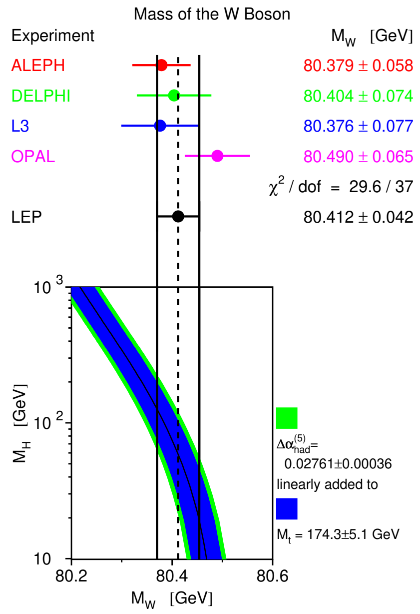

Figure 7: W mass results from the four LEP experiments and their combination. Also shown is the SM expectation as a function of the Higgs boson mass.

5.1 Final State Interactions (FSI)

In fully-hadronic WW events the decay products of the two W bosons can have a large space-time overlap as the decay vertices are typically separated by ≈ 0.1 fm, which is small compared to the hadronisation scale of ≈ 1 fm. This can lead to possible non-independent hadronisation of both W bosons in the final state, which may then affect the direct reconstructed mass of the two W bosons. There are two possible sources of FSI:

1) Colour Reconnection (CR) refers to the reorganisation of the colour flow between the two W bosons. This has been studied using the particle flow method, where one measures the particle density between jets originating from the same W and compares to the particle density in between jets coming from different W bosons. The ratios of these two particle densities are then compared to model predictions: SK-I (which contains a free parameter κ that governs the colour reconnection probability), ARIADNE-II and HERWIG which do not have adjustable colour reconnection parameters, but CR can only be switched on or off. The particle flow method shows only sensitivity to colour reconnection for the SK-I model. In Figure 8(left) the ratio r of these particle density ratios to the model prediction without CR is shown for the four experiments together with the expectation (experiment analysis dependent) of the SK-I model with 100% colour reconnection prob-

Source	Systematic Error on m_W (MeV)		
	$qq\ell\nu$	$qqqq$	Combined
ISR/FSR	8	8	8
Hadronisation	19	18	18
Detector Systematics	14	10	14
LEP Beam Energy	17	17	17
Colour Reconnection	–	90	9
Bose-Einstein Correlations	–	35	3
Other	4	5	4
Total Systematic	31	101	31
Statistical	32	35	29
Total	44	107	43
Statistical in absence of Systematics	32	28	21

Table 1: Error decomposition for the combined LEP W mass results.

ability. The LEP combined result corresponds to a preferred value of 1.18 for κ, equivalent to a 49% reconnection probability.

DELPHI has proposed an alternative method for inferring the value of the κ parameter in the SK-I model. Neglecting low momentum particles in the reconstruction of jets or using a cone algorithm (with optimum cone size of 0.5 rad), the W mass estimator becomes less sensitive to the actual value of the κ parameter. Comparing the difference between the W mass result from the 'standard' mass estimator and the one from this alternative estimator with the model expectation as function of κ yields another estimate of this parameter. The two methods can be combined and will be used for the final estimate of the systematic error due to CR.

2) Bose-Einstein Correlations (BEC) are a quantum-mechanical effect, enhancing the production of like-sign bosons at low four-momentum difference $Q^2 = -(p_2 - p_1)^2$. The presence of such correlations between hadrons from different W decays will therefore also affect the direct reconstruction of the W mass in the fully-hadronic final states. The experimental method consists of comparing the inclusive two-particle densities from *real* fully-hadronic WW events with those obtained from a sample of *mixed* WW events. By mixing the hadronic parts of two semi-leptonic WW events, this sample is by construction free of correlations between particles coming from different W bosons. The measured ratio D of these two-particle densities (or their difference $\Delta\rho$) is then compared with expectations of the model with and without correlations between the like-sign bosons from different W bosons ('inter W' correlations). The measured fractions of the model seen are shown in Figure 8(right). Three of the experiments are compatible with zero 'inter W' correlations, while DELPHI sees a 3σ effect, although less than predicted

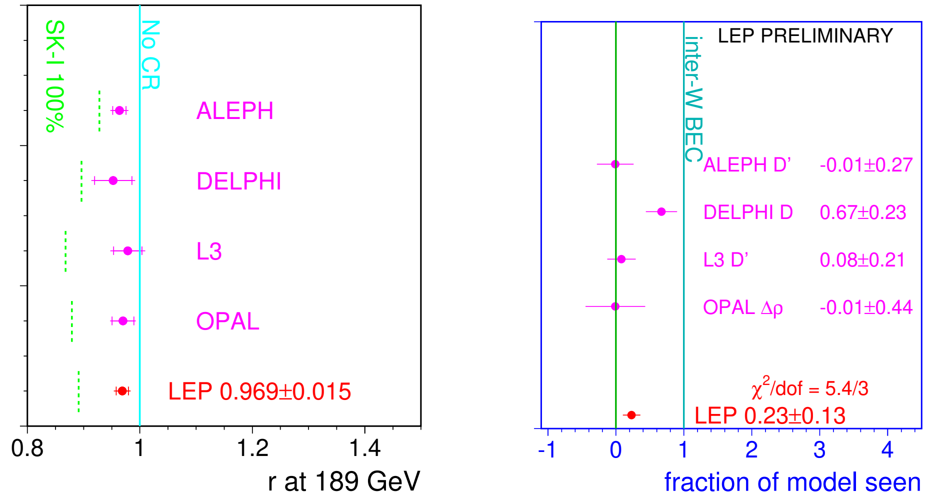

Figure 8: Left: particle flow results for Colour Reconnection. The predicted values of r for the SK-I model with 100% reconnection probability are indicated as dashed lines. Right: measured size of the Bose-Einstein Correlations expressed as the relative fraction of the model with inter-W correlations.

by a full correlation between like-sign bosons from different W bosons. The combined value for the fraction of the model seen is 0.23 ± 0.13. This corresponds to a 68% CL upper limit of 13 MeV for the W mass shift due to Bose-Einstein correlations.

6 Global electroweak fits

A global fit to all electroweak observables can be made within the framework of the Standard Model. The present accuracy of the measurements make them sensitive to the the top quark mass m_t and the Higgs boson mass m_H through loop corrections. The leading electroweak radiative corrections depend quadratically on m_t and logarithmically on m_H. Figure 9 summarizes the measurements at the time of the Summer 2003 conferences [10], from LEP and SLD, direct measurements of m_W, Γ_W and m_t from $p\bar{p}$ colliders, $\sin^2\theta_W$ from NuTeV, the electromagnetic coupling constant $\alpha(m_Z^2)$ evaluated at the Z mass, the Fermi constant $G_F = 1.16637(1) \cdot 10^{-5}$ GeV^{-2} and the measurement of atomic parity violation in caesium. Also shown in the plot are the differences between the measurements and their SM prediction in units of the total measurement error. Figure 10 shows the combination of the m_W and Γ_W results from $p\bar{p}$ colliders and from LEP. Also shown is the NuTeV result on m_W derived from $\sin^2\theta_W = 1 - m_W^2/m_Z^2$ obtained in CC and NC νN and $\bar{\nu}N$ scattering.

Using only Z pole data from LEP and SLD in the fit results in the following values for the top quark and Higgs boson masses: $m_t = 172^{+12}_{-9}$ GeV and $m_H = 89^{+122}_{-45}$ GeV with a $\chi^2/ndof$ of 14.7/10 (χ^2 probability of 14.3%).

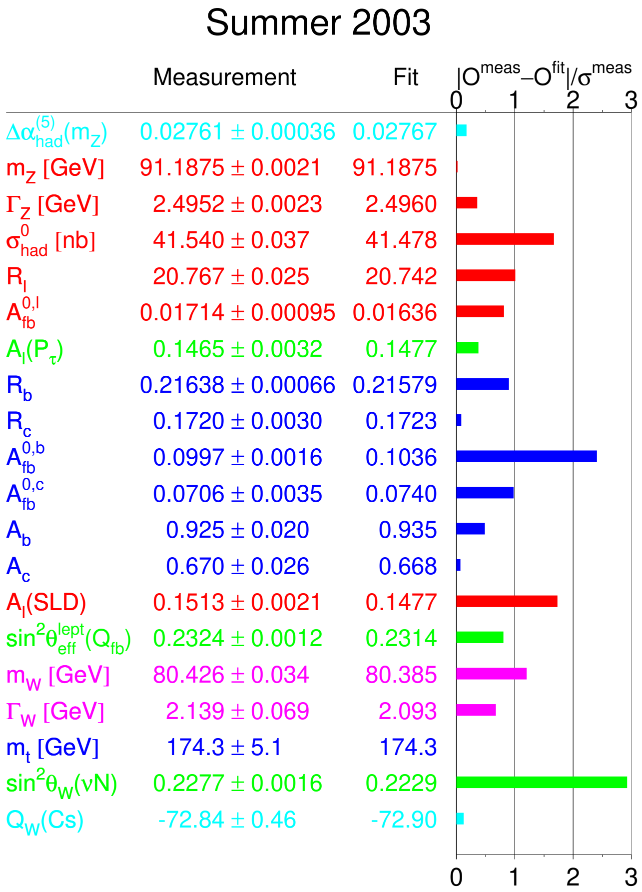

Figure 9: Summary of measurements included in the combined analysis of Standard Model parameters. The result and pull numbers are from the Standard Model fit using all data with the Higgs mass as a free parameter.

The W mass predicted by this fit is 80.373 ± 0.032 GeV. The consistency between the direct measurement of the W boson and top quark masses and the indirect measurement from this electroweak fit is good, as can be seen in the left plot of Figure 11. Both results prefer a low Higgs mass. Using all data in the fit, the resulting masses do not change much ($m_t = 174.3^{+4.5}_{-4.4}$ GeV and $m_H = 96^{+60}_{-38}$ GeV), but the χ^2 probability is only 4.5% ($\chi^2/ndof = 25.4/15$), mainly due to the NuTeV result. Using all data except NuTeV, the mass values remain stable ($m_t = 175.3^{+4.4}_{-4.3}$ GeV and $m_H = 91^{+55}_{-36}$ GeV) with a good χ^2 probability of 27.5% for $\chi^2/ndof = 16.7/14$. The right-hand side plot of Figure 11 shows the behaviour of the χ^2 as a function of m_H both for the fit with and without the NuTeV result. From this a 95% CL upper limit on the Higgs boson mass of 219 GeV can be derived. The effect of the NuTeV measurement on this limit is not big.

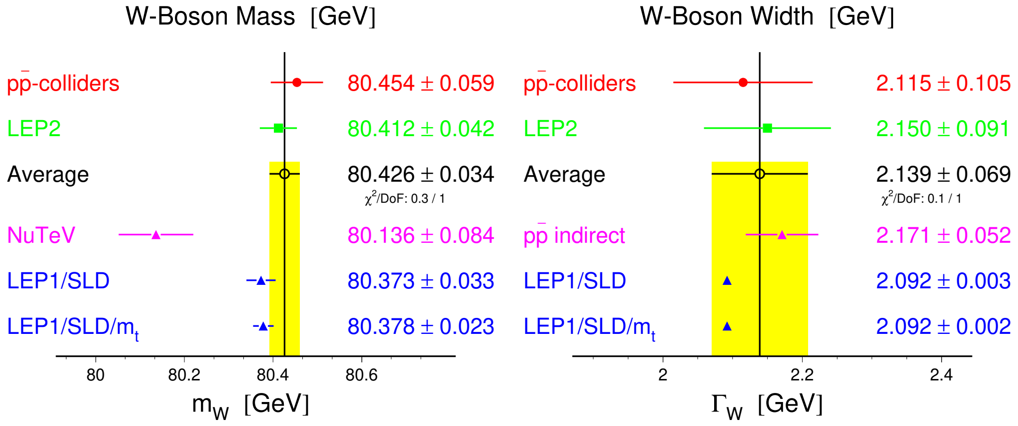

Figure 10: Combination of the direct measurements of m_W and Γ_W and comparison with the indirect measurements from NuTeV in neutrino scattering and from Standard Model fits.

7 Final LEP result on SM Higgs search

The final combined results from the four LEP collaborations on the Standard Model Higgs search were published earlier in 2003 [11]. These results are based on final calibrations of the detector data and LEP beam energy. In some cases also analysis procedures were modified with respect to the initial publications shortly after LEP stopped data taking in 2000.

The experiments searched for SM Higgs boson production via the dominant Higgs-strahlung process $e^+e^- \to HZ$. At a Higgs boson mass of around 115 GeV the dominant decay of the Higgs boson is into a $b\bar{b}$ pair (74%) followed by the $\tau\tau$ decay mode (8%) and $H \to WW$ (8%). The final states analysed are $bbqq$ (4-jet channel), $bb\nu\nu$ (missing energy channel), $bbee$ and $bb\mu\mu$ (leptonic channel), $bb\tau\tau$ and $\tau\tau bb$ (tau channel). In the missing energy channel there is also a (small) contribution from the WW fusion diagram, which allows the production of a Higgs boson with a mass beyond the 'kinematical limit' of the Higgs-strahlung diagram. Extensive use of b-tagging techniques is made, to exploit the $b\bar{b}$ decay of the Higgs. In the final analysis not only the mass information is used, but other discriminating information is used in a variable $\mathcal{G}$ (event likelihod or Neural Net output) containing e.g. b-tags, kinematics and jet properties. The observed data in this two-dimensional plane $(m_H^{rec}, \mathcal{G})$ is then subjected to a likelihood ratio test of the hypothesis of a SM Higgs signal + background versus the hypothesis of background alone, as a function of the test mass m_H. For each event the likelihood ratio $\mathcal{Q}_i(m_H) = \mathcal{L}(s_i + b_i)/\mathcal{L}(b_i)$ is established and the final test statistic is then defined as $-2\ln\mathcal{Q} = \sum_i -2\ln\mathcal{Q}_i$, where the sum runs over all events preselected by each of the experiments in all channels studied.

Figure 12 shows in the two top plots the mass distribution of the candidates after two selections with different signal purities. The bottom left plot shows the final observed test statistic $-2\ln\mathcal{Q}$ as a function of the test mass,

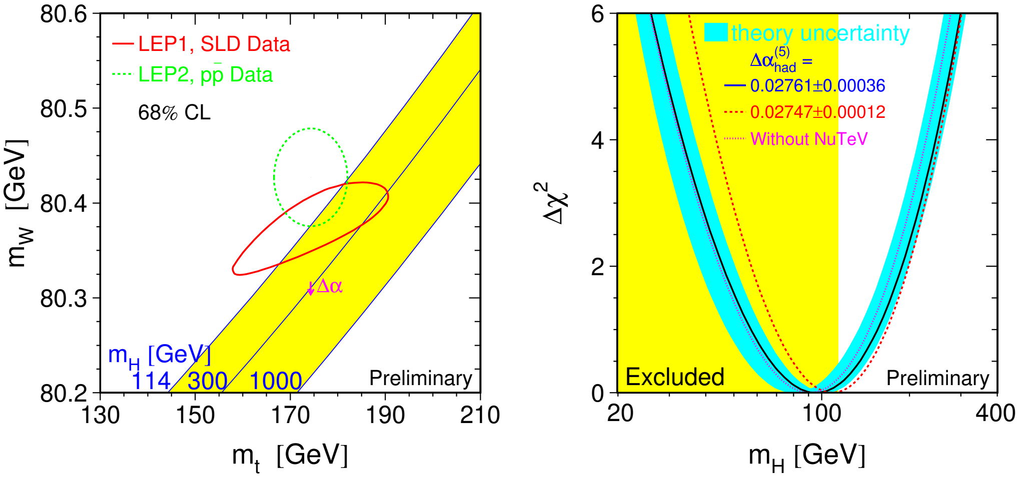

Figure 11: Left: Comparison of the indirect measurements of m_W and m_t (LEP1 and SLD data) (solid contour) and the direct measurements ($p\bar{p}$ colliders and LEP2)(dashed contour). In both cases the 68% CL contours are plotted. Also shown is the Standard Model relationship for the masses as a function of the Higgs mass. Right: $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ versus m_H. The line is the result of the fit using all data. The (blue) band represents an estimate of the theoretical error due to missing higher order corrections. The (yellow) vertical band corresponds to the 95% CL exclusion limit on m_H from the direct search.

together with the expected curves for the signal + background and background only hypotheses, obtained from a large number of simulated equivalent experiments. For the background hypothesis also the 68% and 95% probability bands are shown. There is a broad minimum around 115-116 GeV with negative values of the test statistic, indicating that the hypothesis of signal + background at these masses is favoured, but the significance is low. A vertical slice in this plot at a test mass of $m_H = 115$ GeV is shown in the bottom right plot. The integral $1 - CL_b$ measures the incompatibility with background only and CL_{s+b} is a measure of the compatibility with the signal + background hypothesis. It is clear that at 115 GeV the combined experiments have discriminating power between the two hypotheses. The behaviour of $1 - CL_b$ as a function of the test mass is shown in Figure 13(left). There is a small excess around 116 GeV corresponding to 1.7σ and is mainly coming from ALEPH candidates in the four-jet channel. In the region around 98 GeV the excess in data events corresponds to 2.3σ but a SM Higgs signal at that mass would produce an excess about one order of magnitude larger. Not having observed a significant excess consistent with the SM Higgs hypothesis, a 95% CL lower limit on the mass is then obtained from the point where the value of $CL_s = CL_{s+b}/CL_b$ equals 0.05, see Figure 13(right). The

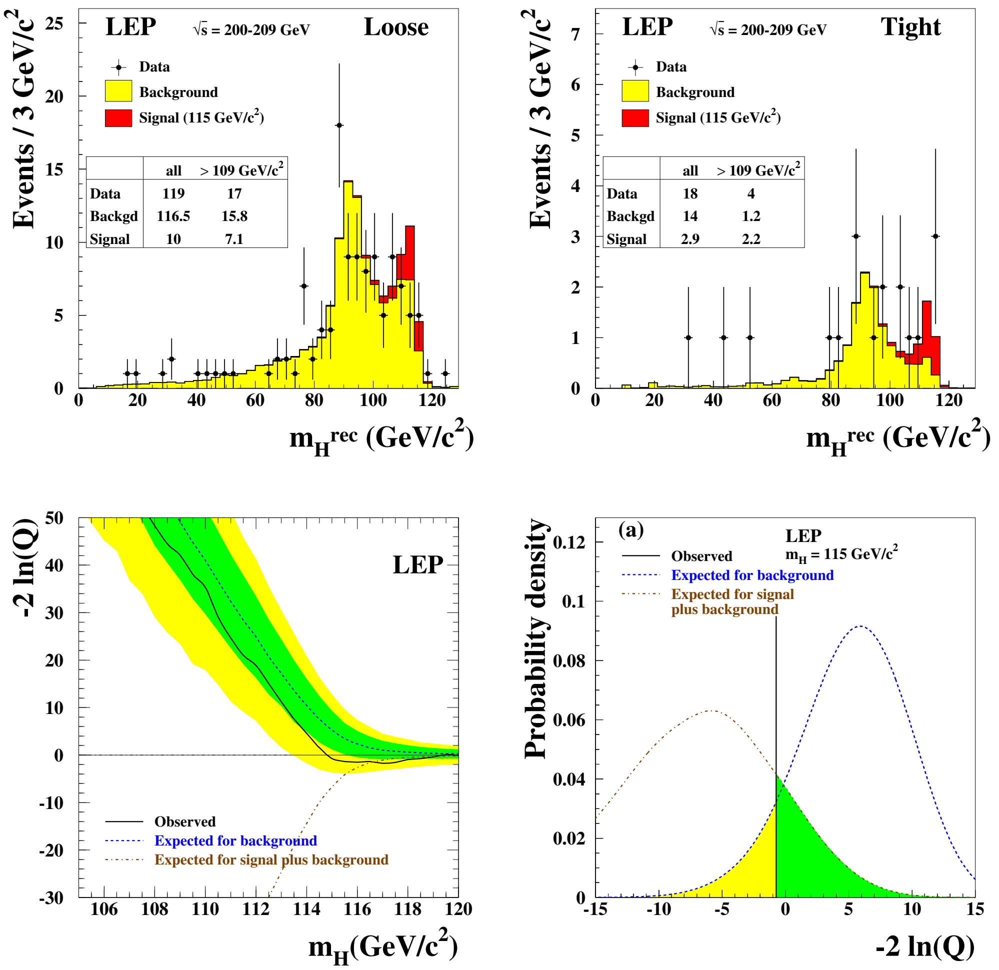

Figure 12: Top: distributions of the reconstructed Higgs boson mass, m_H^{rec}, obtained from two selections with different expected signal purities. Bottom, left: observed and expected behaviour of the test statistic $-2\ln\mathcal{Q}$ as a function of the test mass m_H. Bottom, right: probability density functions corresponding to a test mass $m_H = 115$ GeV for the background and signal + background hypotheses. The vertical line indicates the observed value of the test statistic $-2\ln\mathcal{Q}$.

observed lower limit is 114.4 GeV where the median expected limit is 115.3 GeV.

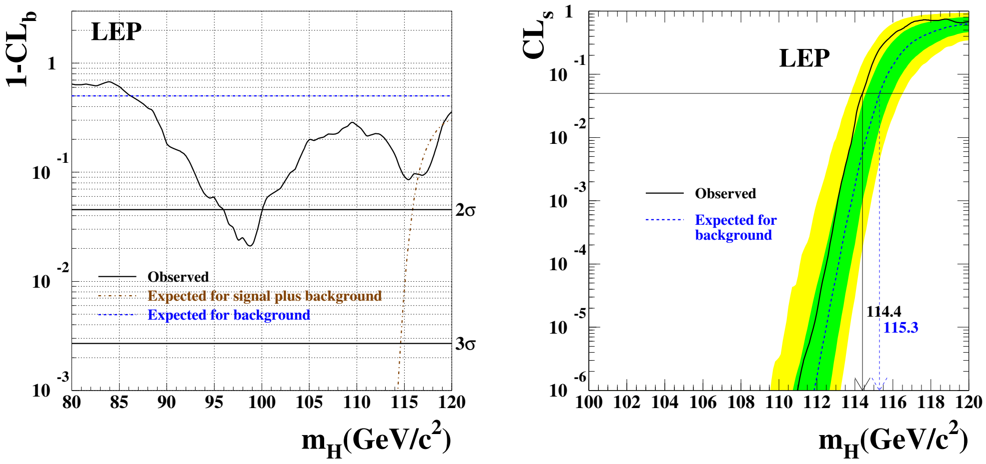

Figure 13: Left: the backgound confidence $1 - CL_b$ as a function of the test mass m_H. Right: the ratio $CL_s = CL_{s+b}/CL_b$ for the signal + background hypothesis as a function of the test mass m_H.

8 Conclusions

LEP was a great and successful experience. Some recent (and sometimes final) results have been presented here, but many final results are still to come. Many measurements are in good agreement with the Standard Model predictions. The largest discrepancy between the various electroweak measurements is between the asymmetries A^b_{FB} (measured at LEP) and A_{LR} (measured by SLD) and is at the 2.9σ level. There exists also a slightly 'annoying' discrepancy between the m_W value inferred from the NuTeV measurement of $\sin^2\theta_W$ and the direct measurement of m_W at LEP and the $p\bar{p}$ colliders. The SM Higgs boson has not yet been found and a 95% CL lower limit of 114.4 GeV on its mass has been set.

Acknowledgments

I would like to thank the LEP/SLC Collaborations and the members of the Electroweak and Higgs Working Groups for making this vast amount of combined results available, without which it would have been impossible for me to give this talk.

References

[1] G. Bella, *Electroweak gauge coupling measurement at LEP*, these Proceedings

[2] http : //lepewwg.web.cern.ch/LEPEWWG/lepww/4f/Summer03/

[3] S. Jadach et al., Comp. Phys. Comm. 140 (2001) 432

[4] A. Denner et al., Phys. Lett. B475 (2000) 127

[5] D. Bardin et al., Comp. Phys. Comm. 104 (1997) 161

[6] S. Jadach et al., Comp. Phys. Comm. 140 (2001) 475

[7] E. Accomando and A. Ballestrero, Comp. Phys. Comm. 99 (1997) 270
E. Accomando, A. Ballestrero and E. Maina, Comp. Phys. Comm. 150 (2003) 166

[8] J. Fujimoto et al., Comp. Phys. Comm. 100 (1997) 74
Y. Kurihara et al., Prog. Theor. Phys. 103 (2000) 1199

[9] http : //lepewwg.web.cern.ch/LEPEWWG/lepww/mw/Winter03/

[10] The LEP Collaborations ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavour Groups, hep-ex/0312023

[11] ALEPH, DELPHI, L3, OPAL Collaborations and The LEP Working Group for Higgs Boson Searches, Phys. Lett. B565 (2003) 61