Review of LEP Electroweak and Heavy Flavor Results

Simon C. Blyth[1]

Carnegie Mellon University
Pittsburgh, USA.

Abstract

Highlights of electroweak and heavy flavor results obtained from 12 years of LEP operation are presented. Precision measurements of electroweak observables obtained by SLD and the LEP and TEVATRON experiments are used to test the consistency of the Standard Model to an unprecedented level. The consistency observed allows a prediction of the mass of the Higgs boson to be made.

1 Introduction

The primary goals of the LEP e^+e^- collider were precision tests of the Standard Model of Electroweak Interactions (SM) [1] through measurements of the properties of the W and Z bosons. From 1989 to 1995 the four LEP experiments collected data at a center-of-mass energy $\sqrt{s} \approx m_Z$ at which Z bosons are resonantly produced and decay into fermion-antifermion pairs. During the LEP2 era from 1995 to 2000 the center-of-mass energy was progressively increased, ranging from 130 GeV to a maximum of 208.8 GeV, crossing the W-pair and Z-pair production thresholds in 1996 and 1997. The four experiments collected a total of 15.5M hadronic Z boson decays and 45k W-pair events.

The large LEP1 event samples, precise knowledge of the LEP beam energy and clean environment have yielded precision measurements of cross-sections of inclusive hadronic and charged lepton final states, leptonic forward-backward asymmetries, tau polarisation asymmetries and the $Z \to b\bar{b}$ and $Z \to c\bar{c}$ decay widths and forward-backward asymmetries. SLD also measured these quantities and in addition the polarised beams at SLC enabled the left-right polarisation asymmetry and left-right forward-backward polarisation asymmetries to be measured. Also of crucial importance to SM tests are the direct determinations of the top quark mass from the TEVATRON and the W boson mass from LEP2 and the TEVATRON.

Heavy Flavor studies at the Z were made possible by the capabilities of the Silicon Vertex detectors which together with the large boost given to heavy hadrons in Z decay and their comparatively long lifetimes enabled such processes as $B^0 - \bar{B}^0$ oscillations to be studied providing measurements of Δm_d and limits on Δm_s. These measurements together with determinations of $|V_{cb}|$ and $|V_{ub}|$ provide indirect constraints on the CKM matrix.

In addition to the direct m_W determination LEP2 running has enabled measurements of the branching ratios of the W boson and the W-pair and ZZ production cross sections as a function of the center of mass energy as well as the fermion-pair production cross sections and forward-backward charge asymmetries. Also triple gauge boson couplings have been studied and anomalous neutral couplings have been looked for.

[1]Based at CERN EP/LE, CH1211, Genève 23, Switzerland. E-mail:Simon.Blyth@cern.ch

2 Properties of the Z boson

2.1 Z resonance parameters

The data collected by the LEP experiments between 1989 and 1995 at the Z resonance have been used to make measurements of cross-sections and asymmetries for the pair production of charged leptons $e^+e^- \rightarrow \ell^+\ell^-$ where $\ell = e, \mu, \tau$ and cross-sections for hadron (quark-pair) production. The results of the four LEP experiments ALEPH [2], DELPHI [3], L3 [4] and OPAL [5] have been finalized and are combined [6] to yield precise determinations of the parameters of the Z boson.

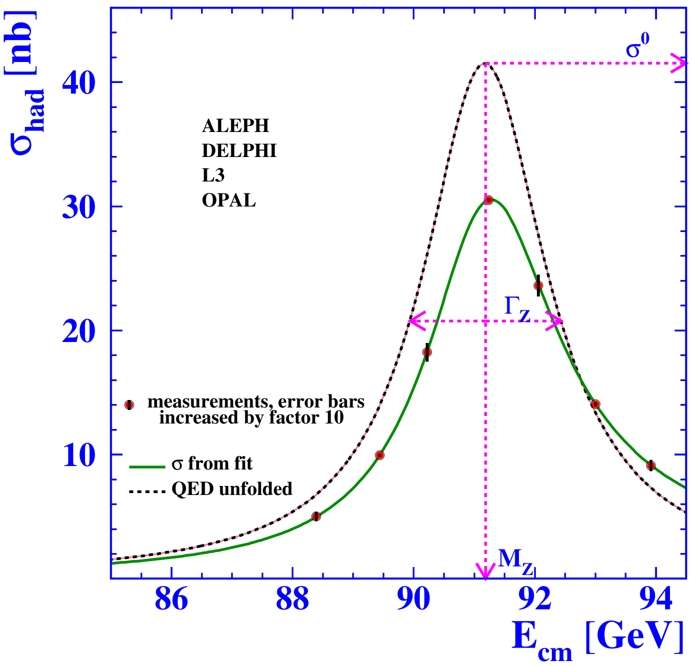

Figure 1: *Average over measurements of the hadronic cross-sections by the four experiments, as a function of centre-of-mass energy. The dashed curve shows the QED deconvoluted cross-section, which defines the Z parameters used.*

Figure 1 shows the average over the hadronic cross-section measurements by the four experiments, together with the fitted line shape curve before and after unfolding photon radiation. The extent of the correction and the precision of the measurements demonstrate the crucial requirement for accurate theoretical predictions to allow the Z parameters to be extracted and for interpretations to be made. The theoretical predictions are provided by the programs ZFITTER [7] and TOPAZ0 [8] which include calculations of the leading contributions up to $\mathcal{O}(\alpha^3)$. Estimates of theoretical uncertainties on the Z parameters are small compared to the experimental precision.

Precision determinations of the luminosity of the beams and the center-of-mass energy are essential requirements. The luminosity was determined by normalisation to the theoretical cross section for small angle Bhabha scattering which is dominated by t-channel photon exchange. In order to achieve luminosity precisions well below 0.1% all the LEP experiments upgraded their initial luminosity detectors. The beam energy was calibrated using the technique of resonant depolarisation [9] which provides very precise energies but not during datataking. The principal challenge was then to develop an energy model that incorporates all relevant machine parameters and environmental factors such as leakage currents from high speed trains as well as earth tide and water table effects that deform the accelerator geometry. The final energy calibration uncertainties on the mass and width of the Z achieved were 1.7 MeV and 1.3 MeV respectively.

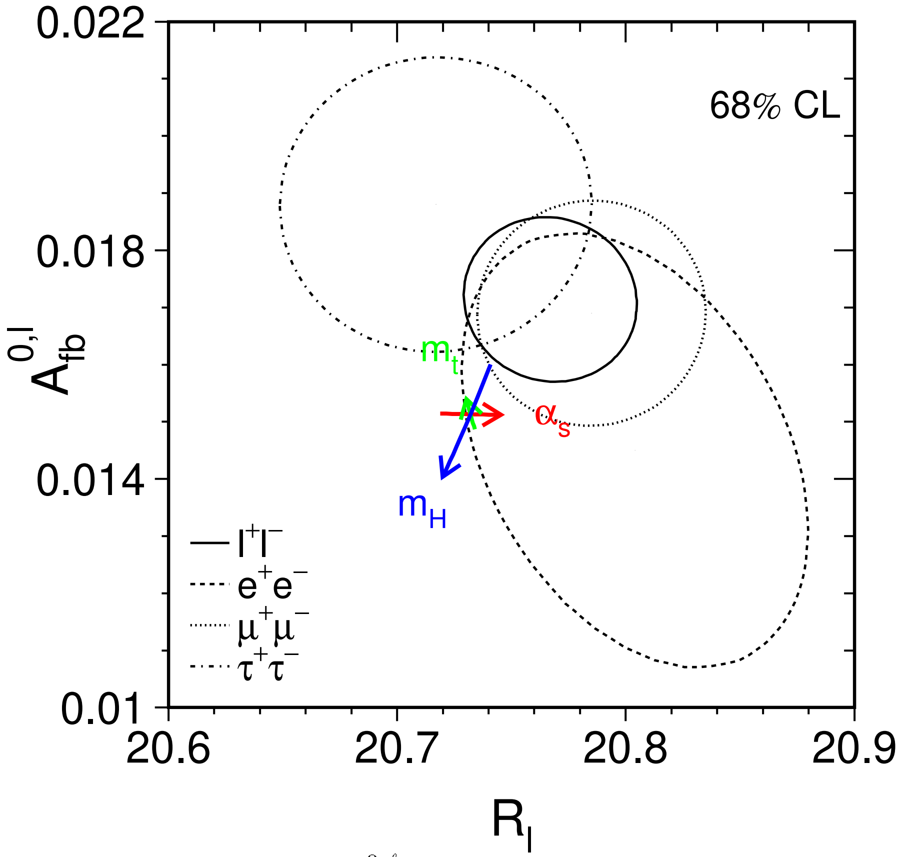

Figure 2: *68 % CL contours in the R_ℓ – $\mathrm{A}_{\mathrm{FB}}^{0,\ell}$ plane for $\mathrm{e}^+\mathrm{e}^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states and for all leptons combined. The arrows represent SM predictions with $m_\mathrm{t} = 174.3 \pm 5.1\,\mathrm{GeV}$, $m_\mathrm{H} = 300^{+700}_{-200}\,\mathrm{GeV}$, and $\alpha_s = 0.119 \pm 0.002$; they point in the direction of increasing values.*

Cross-section and asymmetry measurements are used to determine a set of nine nearly uncorrelated parameters: the mass m_Z and total width Γ_Z of the Z, the hadronic pole cross section σ^0_h and for the three charged leptons the ratios of hadronic to leptonic widths R_ℓ and the pole asymmetries $\mathrm{A}_{\mathrm{FB}}^{0,\ell}$. The pole forward-backward asymmetries are defined in terms of the effective Z couplings:

$$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{f}} \equiv \frac{3}{4}\mathcal{A}_\mathrm{e}\mathcal{A}_\mathrm{f} \quad \text{with} \quad \mathcal{A}_\mathrm{f} = \frac{2\,g_V^\mathrm{f}/g_A^\mathrm{f}}{1 + \left(g_V^\mathrm{f}\,/\,g_A^\mathrm{f}\right)^2}\,.$$

Figure 2 shows the 68 % level contours in the R_ℓ-$\mathrm{A}_{\mathrm{FB}}^{0,\ell}$ plane. The agreement of the three contours for the charged leptons supports lepton universality and allows the six leptonic parameters to be combined into two. These combined measurements are consistent with the SM expectation with a light Higgs boson.

The Z resonance is thus described with five parameters:

$$
\begin{array}{lcl}
m_{\mathrm{Z}} & = & 91.1875 \pm 0.0021\,\mathrm{GeV}\,, \\
\Gamma_{\mathrm{Z}} & = & 2.4952 \pm 0.0023\,\mathrm{GeV}\,, \\
\sigma^0_{\mathrm{h}} & = & 41.540 \quad \pm 0.037\,\mathrm{nb}\,, \\
R_\ell & = & 20.767 \quad \pm 0.025\,, \\
\mathrm{A}^{0,\ell}_{\mathrm{FB}} & = & 0.0171 \pm 0.0010\,,
\end{array}
$$

with a 2.1 MeV precision on the Z mass that represents an improvement of two orders of magnitude compared to the situation prior to LEP.

A parameter transformation allows the decay widths of the Z boson into hadrons, charged leptons and invisible particles to be obtained:

$$
\begin{array}{lcll}
\Gamma_{\mathrm{inv}} & = & 499.0 \quad \pm 1.5 & \mathrm{MeV}\,, \\
\Gamma_{\mathrm{had}} & = & 1744.4 \quad \pm 2.0 & \mathrm{MeV}\,, \\
\Gamma_{\ell\ell} & = & 83.984 \pm 0.086 & \mathrm{MeV}\,.
\end{array}
$$

Which assuming standard particles allows the number of neutrino families to be obtained,

$$
\frac{\Gamma_{\mathrm{inv}}}{\Gamma_{\ell\ell}} = N_\nu \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{\mathrm{SM}} = 2.9841 \pm 0.0083,
$$

which is two standard deviations short of the expected value.

2.2 LEP τ polarisation and SLD asymmetries

LEP studies of the process $\mathrm{e}^+\mathrm{e}^- \to \tau^+\tau^-$ where certain τ decays such as $\tau \to \pi\nu_\tau$ are identified allow the helicity of the decaying τ to be determined from sensitivities of kinematic distributions of the decay products to this helicity. Measurements of this helicity as a function of the polar angle of the τ enable almost independent determinations of the asymmetry parameters $\mathcal{A}_{\mathrm{e}}$ and $\mathcal{A}_\tau$. Results from five τ decay modes from all the LEP experiments are found to be consistent, after combination [10] with no assumption of lepton universality consistent results for $\mathcal{A}_{\mathrm{e}}$ and $\mathcal{A}_\tau$ are obtained; assuming lepton universality yields:

$$
\mathcal{A}_\ell \quad = \quad 0.1465 \pm 0.0033.
$$

Polarisation of the e^- beam of the SLC machine allows a measurement of the left-right cross-section asymmetry A_{LR} by simply counting Z produced by left and right longitudinally polarised electrons. This asymmetry together with accurate knowledge of the polarisation and the beam energy, presently yields the most precise single determination of this quantity:

$$
\mathcal{A}_\ell \quad = \quad 0.1513 \pm 0.0021,
$$

which is consistent with the τ polarisation measurement.

The forward-backward asymmetry measurements using charged lepton final states also benefit from the electron polarisation. At LEP the product of initial and final state asymmetry parameters is measured $\mathrm{A}^{0,\mathrm{f}}_{\mathrm{FB}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{f}}$, whereas at SLC a direct measurement of the final state asymmetry parameter $\mathcal{A}_\ell$ is made, $A_{\mathrm{fb,LR}} = \frac{3}{4}|\mathcal{P}_{\mathrm{e}}|\mathcal{A}_\ell$.

2.3 Z couplings to charged leptons

The measurements so far presented from LEP and SLD can be interpreted in terms of the effective couplings of the Z boson to charged leptons. Partial widths are proportional to the sum of the squares of the couplings while the asymmetry parameters $\mathcal{A}_\ell$ depend only on the ratio of the couplings. Figure 3 shows contours in the $g_A^\ell - g_V^\ell$ plane demonstrating consistency with lepton universality and indicating that the combined lepton results agree with SM expectations with a light Higgs boson. The position of the displaced $\Delta\alpha$ arrow represents the SM prediction accounting only for the running of α, indicating the need for higher order radiative corrections to describe the observations.

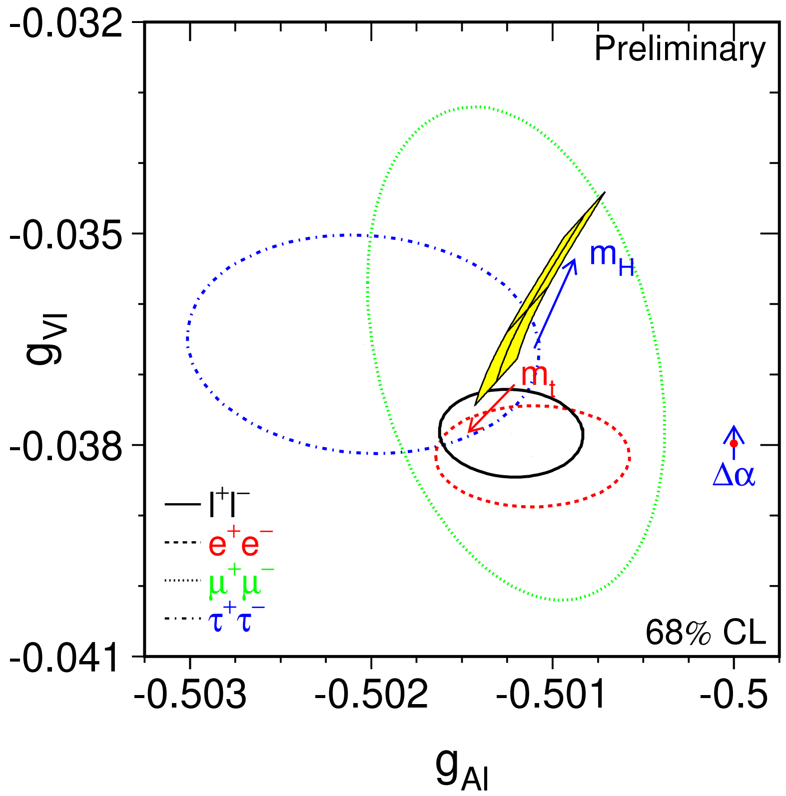

Figure 3: *68% CL contours in the $g_A^\ell - g_V^\ell$ plane for* e^+e^-, $\mu^+\mu^-$ *and* $\tau^+\tau^-$ *and for all leptons combined. The shaded region represents the SM prediction for* $m_t = 174.3 \pm 5.1\,\mathrm{GeV}$, $m_H = 300^{+700}_{-186}\,\mathrm{GeV}$, $\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2) = 0.02761 \pm 0.00036$, *with arrows pointing in the direction of increasing values. The hadronic vacuum polarisation uncertainty is represented by the displaced arrow* $\Delta\alpha$.

Results of the combination assuming lepton universality are:

$$\begin{aligned} g_V^\ell &= -0.03783 \pm 0.00041, \\ g_A^\ell &= -0.50123 \pm 0.00026. \end{aligned}$$

The extreme precision represents an improvement of several orders of magnitude compared to the situation prior to LEP and SLD.

2.4 Z couplings to b and c quarks

The properties of the heavy quarks and the capabilities of the silicon vertex detectors of the LEP experiments and SLD enable high purity samples of the decays $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ and $\mathrm{Z} \rightarrow \mathrm{c\bar{c}}$ to be made with good efficiency. Measurements of the ratios of partial widths $R_{\mathrm{q}} = \Gamma_{\mathrm{q\bar{q}}}/\Gamma_{\mathrm{had}}$ by the LEP experiments and SLD and the forward-backward asymmetries $\mathrm{A_{FB}^{0,q}}$ by the LEP experiments and the left-right forward-backward asymmetries $\mathrm{A_{FB}^{0,q}}$ by SLD are interpreted in terms of the couplings of the Z to b and c quarks. Figure 4 compares the direct measurements of the asymmetry parameters for b quarks and for leptons with the quark pole asymmetry measurement, which determines their product. The SM expectation for

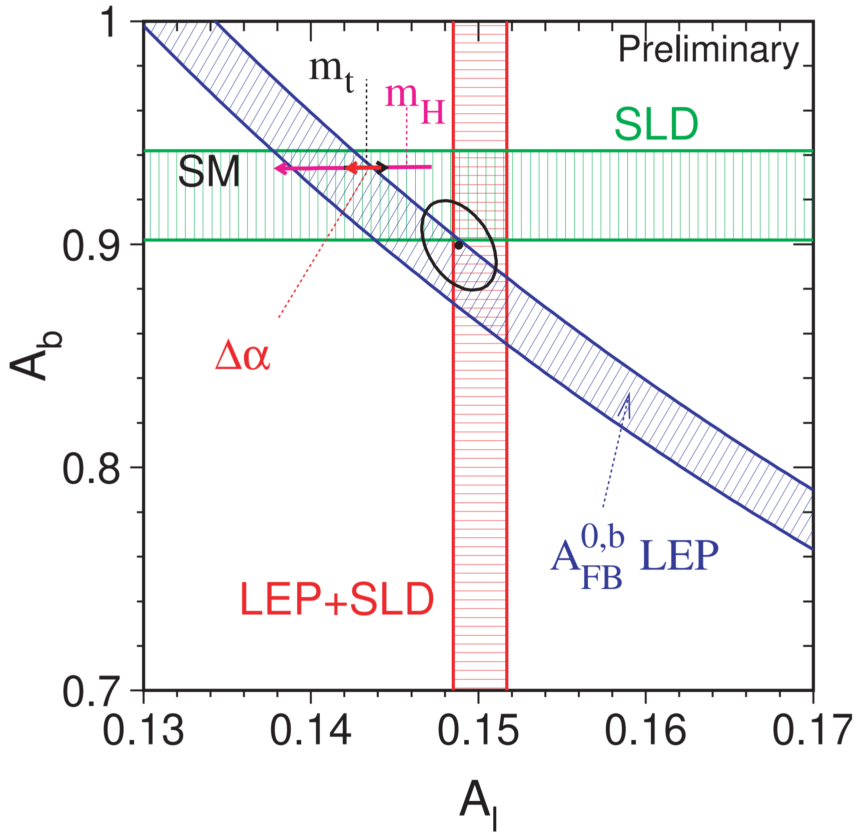

Figure 4: *Comparison of* $\pm 1\sigma$ *measurement bands of asymmetry parameters* $\mathcal{A}_\ell$ *and* $\mathcal{A}_\mathrm{b}$ *from direct determinations and from b quark pole asymmetries* $\mathrm{A_{FB}^{0,b}} = 3/4\mathcal{A}_\mathrm{e}\mathcal{A}_\mathrm{b}$. *The 68 % CL contour from a combination of the measurements is also indicated. The horizontal arrows represent the SM expectations for* $m_\mathrm{t} = 174.3 \pm 5.1\,\mathrm{GeV}$, $m_\mathrm{H} = 300^{+700}_{-186}\,\mathrm{GeV}$ *and* $\Delta\alpha^{(5)}_{\mathrm{had}}(m_\mathrm{Z}^2) = 0.02761 \pm 0.00036$ *where the arrows point in the direction of increasing values.*

$\mathcal{A}_\mathrm{b}$ is almost insensitive to the SM parameters m_t, m_H and $\Delta\alpha$ while the expectation for $\mathcal{A}_\ell$ has a strong dependence on these parameters. The measurement of $\mathcal{A}_\ell$ from SLD and LEP is consistent with SM expectations with a low Higgs mass, whereas the $\mathcal{A}_\mathrm{b}$ measurement from SLD in combination with the $\mathrm{A_{FB}^{0,b}}$ measurement from LEP favors a much higher Higgs mass.

The LEP b quark pole asymmetry measurements are performed by two main types of analyses, relatively straightforwardly using leptons from semi-leptonic decays and with complex analyses combining lifetime and jet charge information. Analyses of both types from the four LEP experiments yield consistent results, with roughly equal weight from the two types of analysis. Combining these measurements yields the average Z pole asymmetry of

$$A_{FB}^{0,b} = 0.0990 \pm 0.0017.$$

Assuming SM values for b quark couplings allows this measurement to be converted into a $\sin^2\theta_{\rm eff}^{\rm lept} = (1 - g_V^\ell/g_A^\ell)/4$ value, enabling comparisons with purely leptonic determinations as shown in Figure 5. The two most precise determinations, from $A_{FB}^{0,b}$ and A_{LR}, differ by 3.2σ. Although the LEP $A_{FB}^{0,b}$ is not yet finalized this statistics dominated result is unlikely to change significantly.

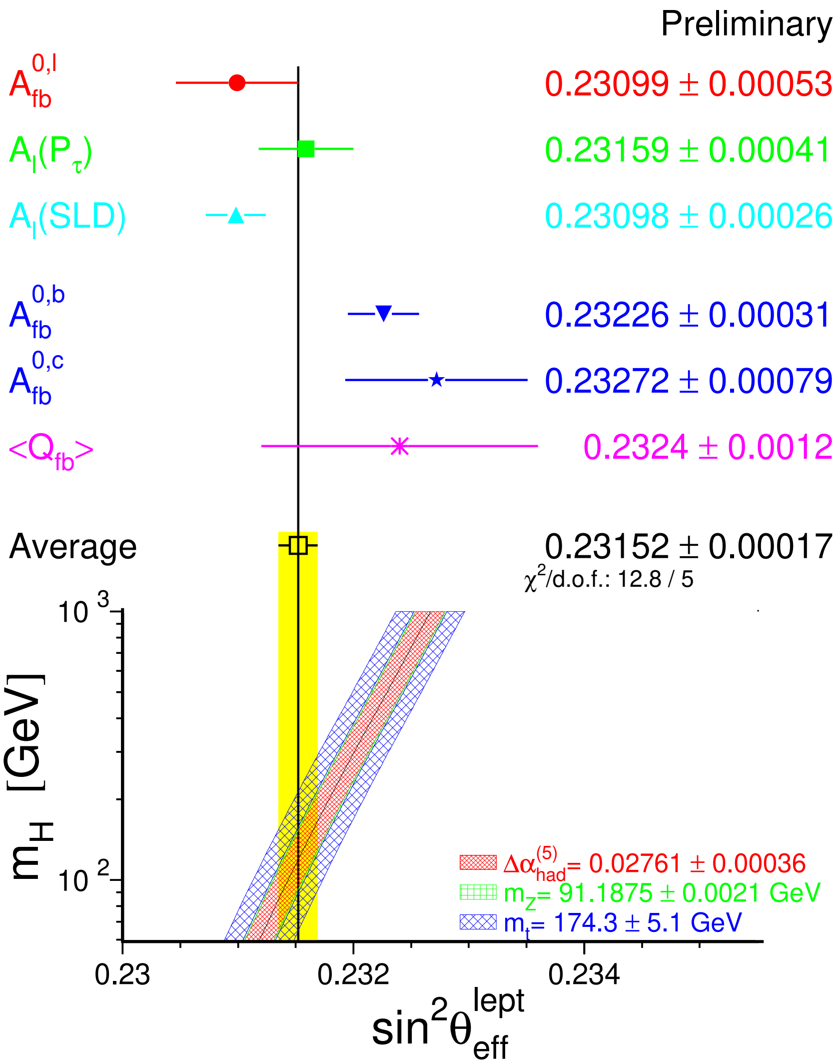

Figure 5: *Comparison of* $\sin^2\theta_{\rm eff}^{\rm lept}$ *derived from various measurements grouped into leptonic and hadronic observables together with SM expectations for a range of Higgs masses. Dependencies on* $m_{\rm t}$, $\Delta\alpha_{\rm had}^{(5)}(m_{\rm Z}^2)$ *and* $m_{\rm Z}$ *are indicated by the bands.*

3 Heavy Flavor measurements

During Z pole running each of the LEP experiments collected approximately 1 million Z decays into back-to-back 45 GeV b-jets, while SLD collected approximately 0.1 million Z decays. These samples have made possible a very rich harvest of measurements [11], that have greatly improved our understanding of the Heavy Flavor sector. The measurements include first signals of b-baryons and first direct signals of $\bar{\mathrm{B}}^0_{\mathrm{s}}$ mesons and first evidence for time modulation of the $\mathrm{B}^0_{\mathrm{d}} - \bar{\mathrm{B}}^0_{\mathrm{d}}$ oscillation signal.

The SM describes oscillations $\mathrm{B}^0_{\mathrm{q}} - \bar{\mathrm{B}}^0_{\mathrm{q}}$ via weak interactions of quarks. The probability to observe a $\bar{\mathrm{B}}^0$ meson from an initially produced B^0 after time t is given by:

$$P[\mathrm{B}^0_{\mathrm{q}} \to \bar{\mathrm{B}}^0_{\mathrm{q}}] = \frac{1}{2} \mathrm{e}^{-\mathrm{t}/\tau_{\mathrm{q}}} (1 - \cos \Delta \mathrm{m}_{\mathrm{q}} \mathrm{t}),$$

a similar expression with a positive sign corresponds to the reverse situation. The mass difference between the mass eigenstates of the system $\Delta \mathrm{m}_{\mathrm{q}}$ and the meson lifetime τ_{q} determine the form of the time distribution. In order to measure the time dependent oscillation, tagging of the meson as a $\mathrm{B}^0_{\mathrm{q}}$ or $\bar{\mathrm{B}}^0_{\mathrm{q}}$ at both production and decay are required together with the decay proper time. The large boost of the $b$jets from Z decay results in an observable decay length of order several millimeters and reconstruction of the decay products of the b-hadron enables a tag to be made. Measurements of $\Delta \mathrm{m}_{\mathrm{d}}$ from the

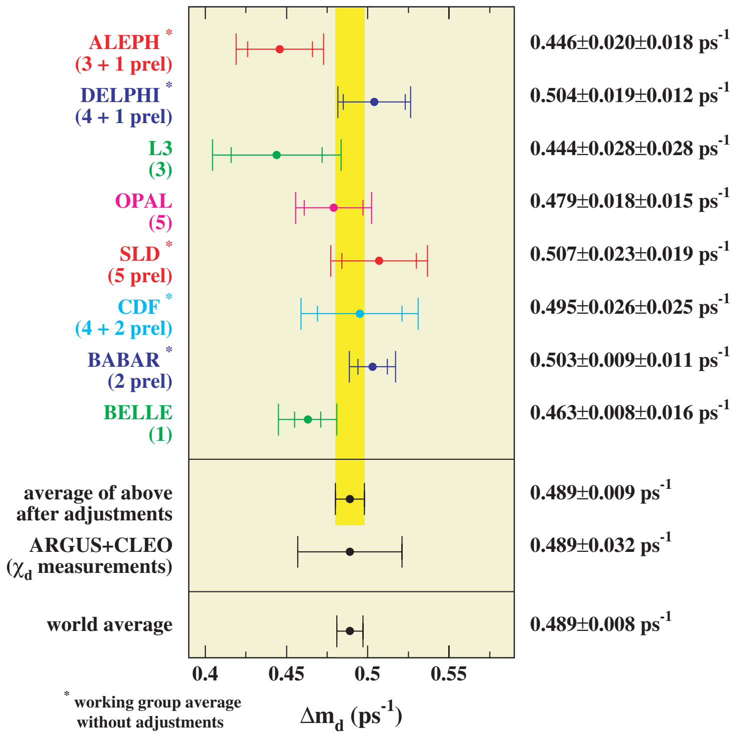

Figure 6: *Comparison of measurements of* $\Delta \mathrm{m}_{\mathrm{d}}$. *Many of the points correspond to combinations of several analyses.*

LEP experiments, SLD, BABAR and BELLE are consistent as demonstrated in Figure 6. Combining these results yields the world average value:

$$\Delta \mathrm{m}_{\mathrm{d}} \quad = \quad 0.489 \pm 0.008 \, \mathrm{ps}^{-1}.$$

Measurements of $B_s^0 - \bar{B}_s^0$ oscillations are difficult due to the small production fraction of the mesons $\approx 10\%$ and the expected factor 20 shorter oscillation period than for B_d^0 mesons. In the absence of significant oscillation signals in the decay time distributions an amplitude method was devised in order to place limits on Δm_s. An amplitude coefficient A is applied to the cosine term of the time distribution function and is left free in fits to the observations for a range of possible Δm_s values. In the absence(presence) of oscillations at a particular Δm_s the A should be compatible with zero(unity).

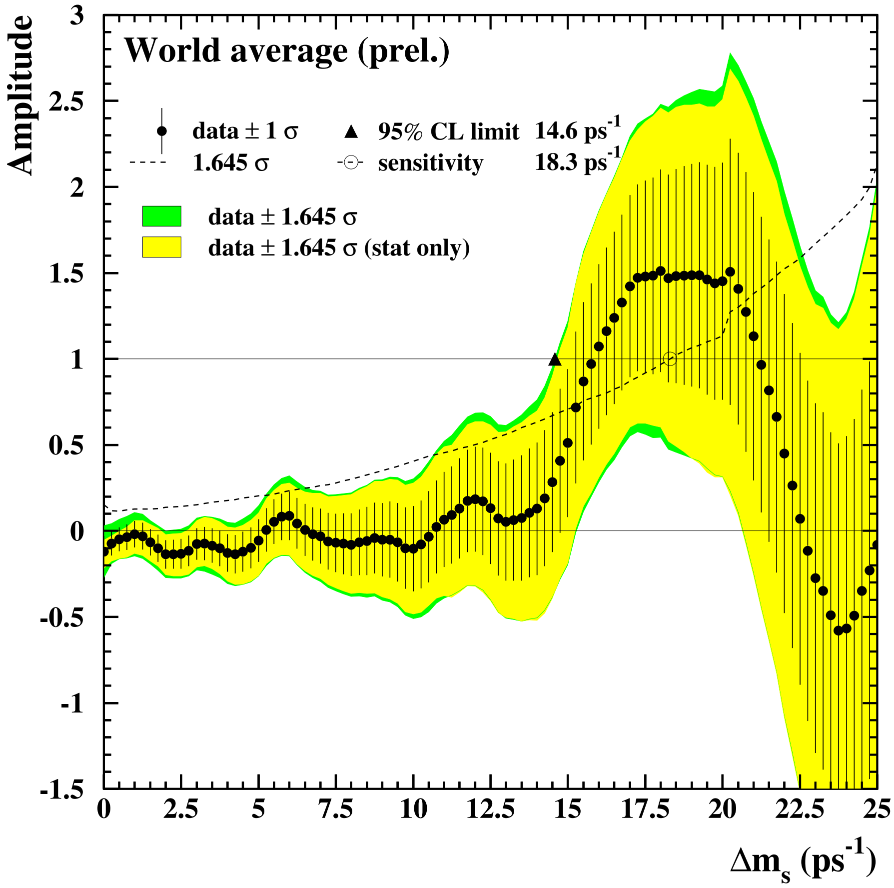

Figure 7: *Combined B_s^0 amplitude as function of Δm_s. The triangle and circle indicated the 95% CL limit and 95% sensitivity on Δm_s of the combined measurements.*

Figure 7 shows the combined amplitude from measurements of the LEP experiments, SLD and CDF. All values of Δm_s for which the amplitude plus 1.645 times its total uncertainty is smaller than 1 are excluded at 95% CL, corresponding to the limit $\Delta m_s > 14.6\,\mathrm{ps}^{-1}$; marked by the triangle in the figure. The sensitivity for 95% CL exclusion is defined as the value of Δm_s at which the total uncertainty on the measured amplitude is 1/1.645, where the measurements cannot distinguish between zero and unity. This combined sensitivity is $18.3\,\mathrm{ps}^{-1}$, and is marked by the circle in the figure. The enhancement in the amplitude just below the sensitivity limit is tantalising but is not of sufficient significance to be regarded as the first observation $B_s^0 - \bar{B}_s^0$ oscillations.

4 CKM constraints from Heavy Flavor results

Weak interactions between quarks are described by the CKM matrix. Unitarity of the matrix implies relationships between its elements, including:

$$\mathrm{V_{ud}V_{ub}^{*}} + \mathrm{V_{cd}V_{cb}^{*}} + \mathrm{V_{td}V_{tb}^{*}} = 0,$$

which can be represented by a triangle in the complex plane. Conventionally this unitarity triangle is rescaled by $|\mathrm{V_{cd}V_{cb}^{*}}|$ and the side of unit length is placed on the real axis with vertices $(0,0)$ and $(1,0)$ leaving the remaining vertex at $(\bar{\rho},\bar{\eta})$. Where $\bar{\rho},\bar{\eta}$ are two of the four parameters of the Wolfenstein parametrisation of the CKM matrix.

Measurements of $\Delta \mathrm{m_d}$ and the $b \to u$ and $b \to c$ branching ratios as well as limits on $\Delta \mathrm{m_s}$ and measurements from the kaon system can be expressed in terms of elements of the CKM matrix allowing these observations to constrain the vertex $(\bar{\rho},\bar{\eta})$ of the unitarity triangle [11]. Figure 8 demonstrates the consistency of the indirect determination of the vertex from measurements by the LEP experiments, SLD, CDF and CLEO with the direct determinations of $\sin 2\beta$ from BABAR and BELLE. The significance of the indirect determination is reduced by the many theoretical inputs such as bag and decay parameters.

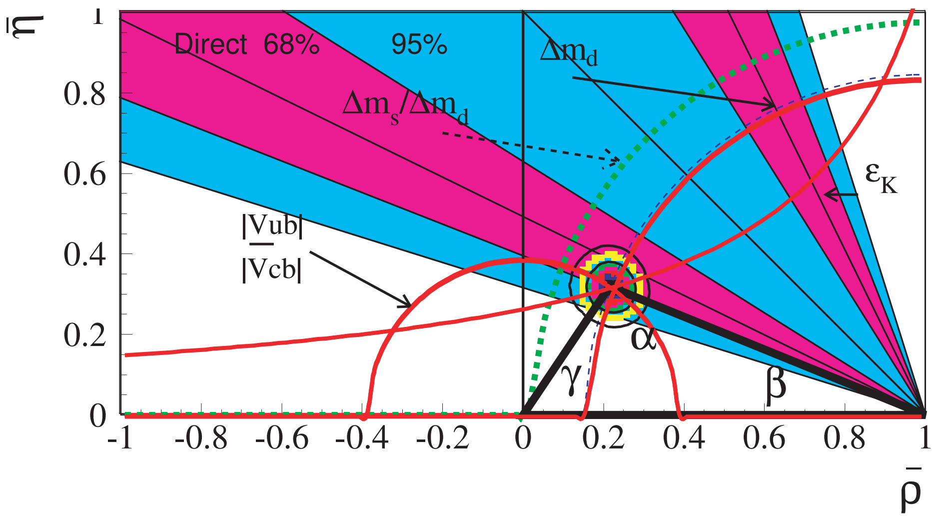

Figure 8: *The 68% and 95% CL contours of the vertex* $(\bar{\rho},\bar{\eta})$ *of the unitarity triangle from the measurements of LEP, SLD, CDF and CLEO are compared with the direct determinations of the angle* $\sin 2\beta$ *from BABAR and BELLE, represented by the shaded areas.*

The indirect measurements [11] yield results:

$$\sin 2\beta = 0.696 \pm 0.068 \ , \ \sin 2\alpha = -0.42 \pm 0.24$$

which are consistent with a combination of the direct results from BABAR and BELLE, $\sin 2\beta = 0.79 \pm 0.11$. Significant improvements in the direct determinations from BABAR and BELLE, which are currently statistics limited, are to be expected in the coming years.

5 Fermion-pair production above the Z resonance

The fermion-pair production cross sections at center-of-mass energies $\sqrt{s}$ above the Z pole are greatly influenced by initial state radiation. Radiation of photons by the incoming electrons results in the annihilation and production occurring at a lower effective center-of-mass energy $\sqrt{s'}$. A significant contribution to the total cross section at energy $\sqrt{s}$ is due to "radiative return to the Z" where the effective center-of-mass energy $\sqrt{s'}$ is close to the Z mass, arising due to the much higher cross section at the Z pole. In order to study the high energy process the radiative returns are rejected by requiring $\sqrt{s'} > 0.85\sqrt{s}$.

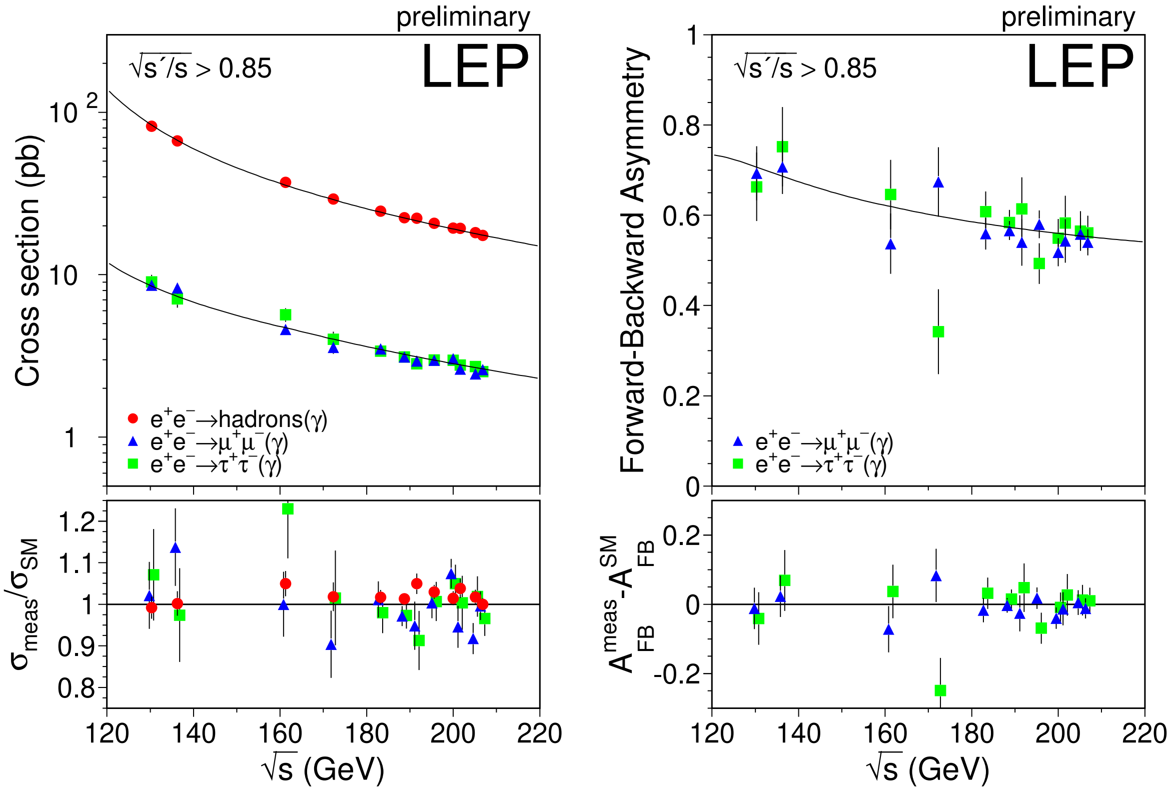

Figure 9: *Combined LEP measurements of the cross sections for* $e^+e^- \to$ hadrons, $e^+e^- \to \mu^+\mu^-$ *and* $e^+e^- \to \tau^+\tau^-$ *and asymmetries for* $e^+e^- \to \mu^+\mu^-$ *and* $e^+e^- \to \tau^+\tau^-$ *compared with the SM expectations of ZFITTER.*

Figure 9 shows the combined high energy LEP cross section results as a function of $\sqrt{s}$ for hadrons, muon-pairs and tau-pairs and the asymmetry results for muon-pairs and tau-pairs [12]. Precision measurements of the luminosity of the beams using low angle Bhabha scattering are essential in order to make full use of the relatively high statistics of these channels.

Analogous measurements have been made for electrons, $b\bar{b}$ and $c\bar{c}$ production. The SM predictions of ZFITTER have been found to describe the measurements well. These results have been used to place constraints on the parameters of various new physics extensions to the SM such as Z′ bosons and contact interactions.

6 Properties of the W boson

From 1996 when the threshold for W-pair production was first crossed until the end of LEP operation each of the experiments collected approximately 12000 W-pair events. Three topologies of W-pair decays are experimentally distinguished: fully hadronic $e^+e^- \to q\overline{q}q\overline{q}$ contributing 45.6%, semi-leptonic $e^+e^- \to q\overline{q}\ell\nu$ (43.8%) and purely leptonic $e^+e^- \to \ell\nu\ell\nu$ (10.6%); where ℓ corresponds to all three charged leptons. The samples are used to measure: W-pair production cross sections and W decay branching fractions [13] as well as the W boson mass and width [14].

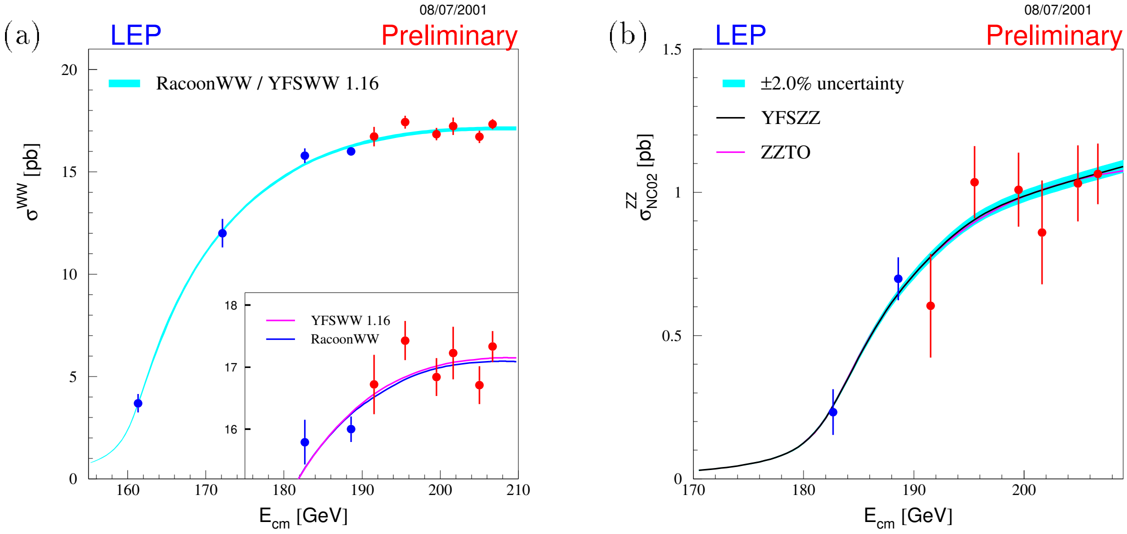

Figure 10: *Combined LEP cross section measurements for (a)* $e^+e^- \to W^+W^-$ *and (b)* $e^+e^- \to$ *ZZ (NC02), for center of mass energies from near their thresholds to the highest LEP energy of 208 GeV, together with the SM expectations.*

Figure 10a compares the W-pair production cross section measurements for center-of-mass energies from 161 GeV to 208 GeV with the SM expectations of new four-fermion generators RacoonWW and YFSWW. A normalization comparison of the measurements for $\sqrt{s} > 180$ GeV with expectations indicate agreement with a 1% uncertainty for these new generators whereas the older Gentle and KoralW expectations are 2-3% too high with a 1% uncertainty. Reference [13] provides details of the measurements and the comparison as well as references to the generators.

The leptonic branching ratios $W \to \ell\nu$ ($\ell = e, \mu, \tau$) are found to be consistent with lepton universality. Combining the results yields an average leptonic branching ratio, corrected to massless charged leptons, of $\mathrm{Br}(W \to \ell) = 10.69 \pm 0.09\%$.

Measurements of the mass and width of the W boson from data taken at energies well above the W pair threshold are performed by direct reconstruction of the W decay products, principally from the fully hadronic and semi-leptonic decay channels. Kinematic fits are used to constrain the total reconstructed lepton, jet and unobserved neutrino (in the semi-leptonic case) momentum and energy to those of the incident beam particles; resulting in an improved W mass resolution. The W mass and width are extracted by fitting re-weighted Monte Carlo distributions to those observed or by deconvolution.

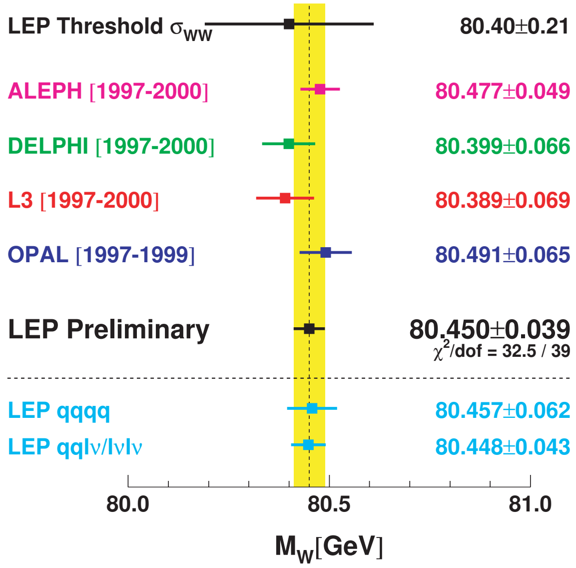

Figure 11: *W mass measurements of the LEP experiments from direct reconstruction together with the LEP average value. Results from fully hadronic decays are compared with those from decay channels including leptons.*

Figure 11 demonstrates the consistency of the direct reconstruction results of the LEP experiments and presents the combined preliminary result $m_W = 80.450 \pm 0.039$ GeV. The LEP combined W width result is $\Gamma_W = 2.150 \pm 0.091$ GeV. The weight of the fully hadronic channel in the average is only 27% due to systematic uncertainties from the modelling of the hadronisation and also from possible final state interactions between decay products of the W bosons. As hadronisation scales are similar to the decay distance between the W's when they decay it is unclear whether the decays of the two W's can be regarded as independent. Intensive studies are underway to understand and appropriately quantify these effects.

7 Gauge Couplings and ZZ Production

W-pair production at LEP2 proceeds via a triple gauge coupling vertex WWV(V $= \gamma, Z$) in two of the three lowest order (CC03) production mechanisms. Also single W and single photon production proceed via the WWγ coupling. The primary information on triple gauge boson couplings come from the W pair production cross section and decay angle distributions. Coupling measurements have previously been reported, but recent calculations of higher order corrections are similar to the experimental uncertainties necessitating a re-evaluation of uncertainties.

In 1997 the LEP center-of-mass energy crossed the threshold for Z-pair production, which is regarded to correspond in lowest order to $t-$channel and $u-$channel exchange of an electron (NC02). Final states $q\bar{q}q\bar{q}$, $q\bar{q}\nu\bar{\nu}$, $q\bar{q}\ell^+\ell^-$ and $\ell^+\ell^-\ell^+\ell^-$ have been selected requiring the invariant mass of reconstructed jet and lepton pairs to correspond to real Z production. Figure 10b shows the consistency of the combined LEP results [13] with the SM expectations from YFSZZ and ZZTO.

8 Interpretation of the electroweak measurements

The precise electroweak measurements presented above are used to test the SM and given consistency can constrain its parameters via global fits. Such fits are regularly performed by the LEP Electroweak working group [10]. The global fits use SM predictions for the measured quantities from ZFITTER 6.37 [7] and TOPAZ0 4.4 [8] that are based on a choice of SM parameters comprising the top quark, Higgs boson and Z boson masses and the strong $\alpha_s(\mathrm{M}_\mathrm{Z}^2)$ and electroweak $\alpha(\mathrm{M}_\mathrm{Z}^2)$ couplings and the Fermi coupling constant G_F. Uncertainties from G_F are negligible due to the precise knowledge of this quantity from muon decay measurements.

The measurements include the precise LEP, SLD and TEVATRON electroweak data as well as results from low energy experiments: BES for the hadronic vacuum polarisation, CCFR and NUTEV for neutrino-nucleon scattering results and also atomic parity violation results using caesium atoms. Consistency tests of the SM are performed by excluding from the fit direct determinations of the top mass from the TEVATRON and the W mass from both LEP and the TEVATRON, allowing the predictions for these quantities to be compared with these direct measurements, as shown in Figure 12a. Successful predictions of the heavy masses are evident as well as the preference of both direct and indirect results for a low Higgs mass.

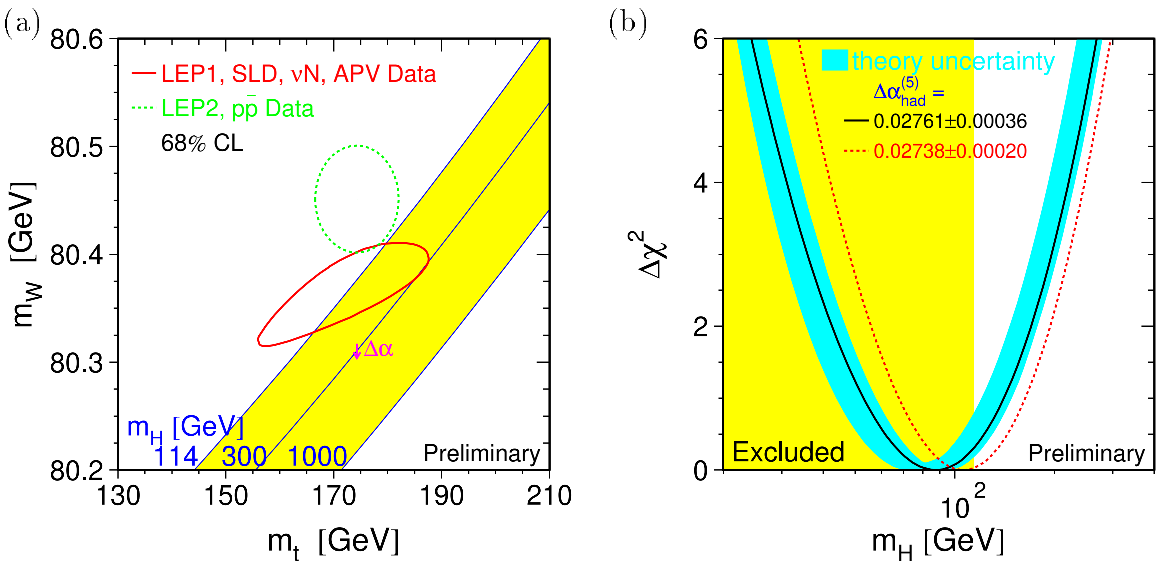

Figure 12: *(a) Comparison of direct and indirect determinations of W boson and top quark masses. The diagonal lines represent the SM relation between the masses for three Higgs boson masses. (b) Result of SM fit to all electroweak precision data. $\Delta\chi^2$ from the minimum as a function of the Higgs mass. The solid and dotted lines correspond to alternative values for the hadronic vacuum polarisation, the band represents the estimated theoretical uncertainty and the shaded region indicates the Higgs mass region excluded by direct searches at LEP.*

Including all the data results in a best fit value of the Higgs mass of $\mathrm{M}_\mathrm{H} = 88^{+53}_{-35}$ GeV with $\chi^2/\mathrm{dof} = 22.9/15$, corresponding to an 8.6% probability. The shape of the χ^2 above the minimum as a function of M_H is shown in Figure 12b, which also indicates the extent of the current estimate of the theoretical uncertainties. The curve allows a 95% CL limit of $M_H < 196\,\mathrm{GeV}$ to be derived. Also shown is the effect of using an alternative theory-driven estimate of the hadronic vacuum polarisation, which changes the 95% CL upper limit to $M_H < 222\,\mathrm{GeV}$. The causes of the level of fit consistency can be seen in the pulls presented in Figure 13 indicating a -2.9σ inconsistency for $A_{FB}^{0,b}$.

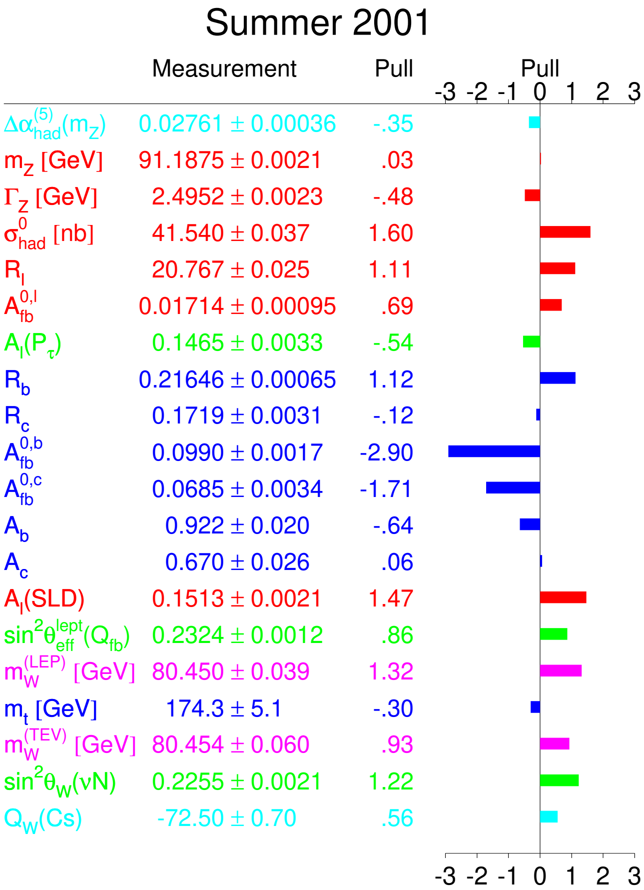

Figure 13: *Pulls for the Global electroweak fit, the differences between measurements and expectations divided by the measurement uncertainties.*

The LEP measurement of $A_{FB}^{0,b}$ is not finalised, however it is a statistics dominated measurement and the final result is not expected to differ significantly.

9 Summary, Outlook and Perspective

Twelve years of data taking by the LEP experiments and contributions from SLD have established through a plethora of precision measurements that the Standard Model of electroweak interactions describes our world to an unprecedented precision. The precision is such that two and three loop calculations are needed for an adequate description of some processes. Successful predictions of the top quark and W boson masses compared with LEP2 and TEVATRON direct measurements gives confidence in the prediction of a low Higgs boson mass. Small improvements in the LEP2 W mass precision are expected with great efforts to understand the effects of final state interactions. In addition LEP brought great improvements in understanding of heavy flavors with indirect CKM matrix constraints that set the stage for the B-factories. Also great improvements in knowledge of QCD and 2-photon physics have been made and rigorous and complete searches for Higgs and SUSY particlea have excluded most of the accessible phase space.

Future progressive improvements in the precision of the SM electroweak tests will come from improvements in top quark and W-boson masses, from the TEVATRON and LHC data. Dramatic improvements or surprises await the Higgs discovery and mass determination.

The enormous contribution of LEP to our knowledge can best be expressed with Figure 14, showing the effective coupling constants of the weak neutral current before and after LEP operation.

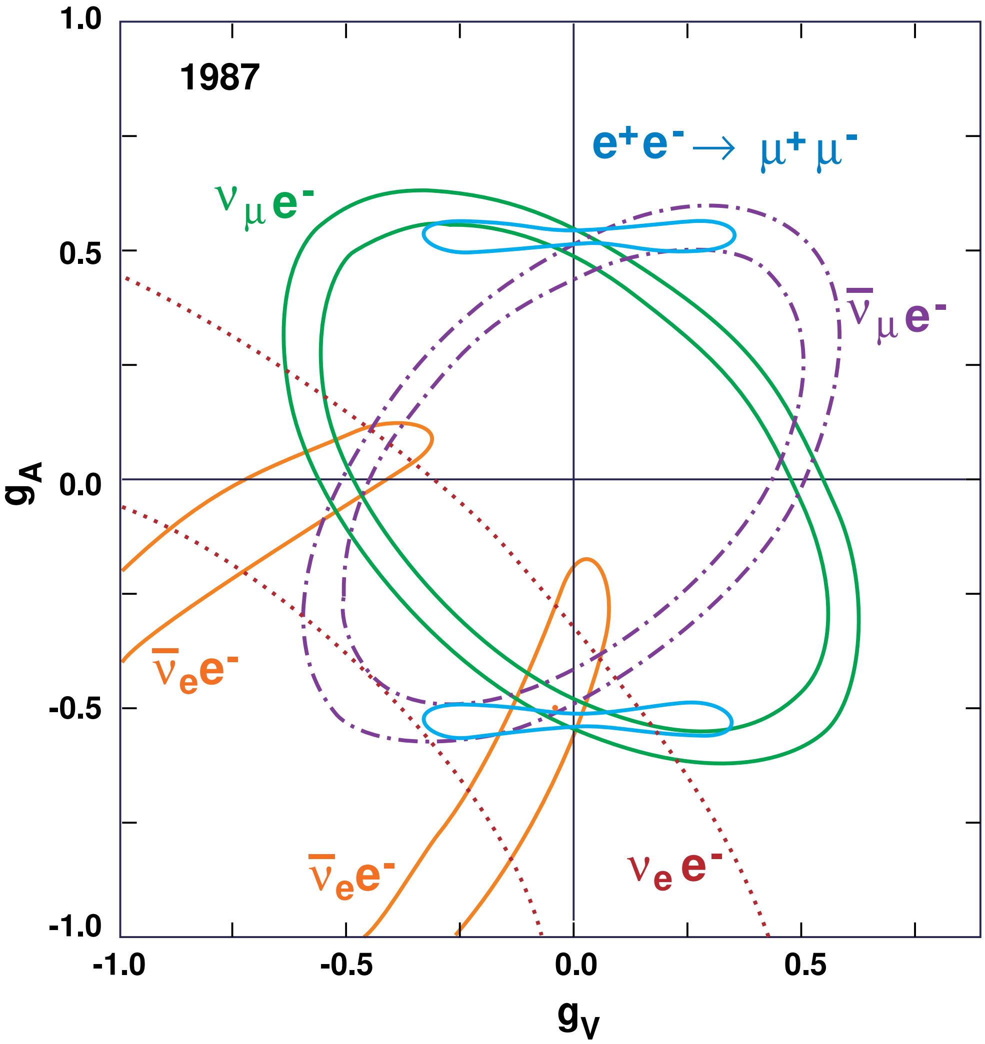

Figure 14: *Contours in the* $\mathrm{g_V} - \mathrm{g_A}$ *plane from 1987. The contours following LEP are too small to be visible at this scale.*

The values of the couplings obtained from the LEP and SLD data:

$$\begin{aligned} \mathrm{g_V} &= -0.03783 \pm 0.00041, \\ \mathrm{g_A} &= -0.50123 \pm 0.00026. \end{aligned}$$

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