PRECISION TESTS OF THE ELECTROWEAK GAUGE THEORY

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The current status of electroweak measurements and related theoretical developments is presented, mainly reflecting updates and new results obtained during the past one year. Fits to all the electroweak data within the framework of the standard model are given demonstrating the internal consistency of the standard model and predictions for the Higgs mass. The overall conclusion is that the standard model describes the precision data well and the predicted mass of the Higgs continues to be low. Finally the short and long term outlook in this area is presented.

1 Introduction

The past decade has produced precision electroweak data at high energy from e^+e^- and $p\overline{p}$ colliders and from neutrino interactions: these consist of results from the LEP collaborations, ALEPH, DELPHI, L3 and OPAL, the TEVATRON collaborations, CDF and DZERO, the SLD collaboration at SLC, BES-II at BEPC and NuTeV at FNAL. Theoretical developments have kept pace with this experimental march towards precision enabling one to make meaningful precision tests of the standard model.

This talk will mainly report and review new results submitted to this conference, details of which appear in the parallel sessions. Most of these have come from LEP, SLC and BEPC. Brief mention of recent important theoretical advances in this area will be made and results from fits within the standard model framework will be presented. Owing to the restricted length of talks in the proceedings, all the material presented at the conference[1] is not covered here. For further details one may also consult the presentations made at the conference in the relevant parallel sessions[2], the papers contributed to the conference by the LEP collaborations[3,4,5,6], by the SLD collaboration[7] and the combinations made by the LEP Electroweak Working Group[8].

2 Results from LEP-I and SLC

2.1 *LEP-I: Z lineshape, lepton F-B asymmetries*

Three LEP collaborations ALEPH[9](A), DELPHI[10](D), L3[11](L) have final results and the fourth, OPAL (O), has a near-final analysis[12]. The full LEP data sample has 17 million hadronic and 1.7 million leptonic events collected between 1990-95. Basic experimental data consists of hadronic and leptonic cross sections and leptonic forward-backward (F-B) asymmetry measurements at various energies around the Z-mass. Figure 1 illustrates the measurement of hadronic cross section as a function of the e^+e^- c.m. energy.

With such large statistics available, systematics dominate the errors on extracted Z parameters. Every effort has been made to reduce the systematic errors:
– LEP experiments upgraded the detectors, particularly for luminosity and tracking
– to accurately determine the LEP beam energy the LEP machine/energy groups[13] developed a model incorporating environmental effects, e.g., earth tides, leakage currents due to passing trains etc, in addition to the machine related parameters
– notable contributions were made by theorists in refining SM calculations so that theory dependent systematic errors in the fit are minimised: ZFITTER[14], TOPAZ0[15], ALIBABA[16], BHLUMI[17] packages due to

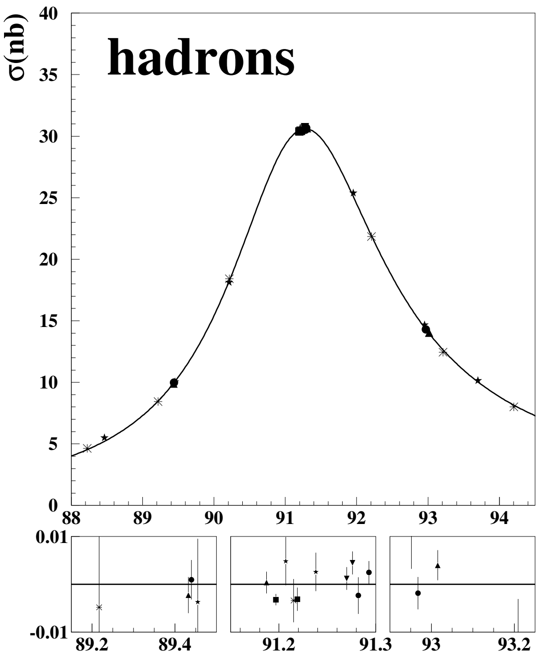

Figure 1. Hadronic lineshape: ALEPH

Bardin et al, Montagna et al, Beenaker et al, Jadach et al and Ward et al, respectively, and important contributions from Degrassi, Kniehl, Kuhn, Berends, Passarino, Was and many others. Thus theory dependent errors are very small: 0.3 MeV on M_Z, 0.2 MeV on Γ_Z, 0.02% on the hadronic pole cross section, σ°_h, and 0.004 on $R_\ell(=\Gamma_{hadrons}/\Gamma_\ell)$.
– procedures for combining LEP data including common errors have been developed by the LEP ElectroWeak Working Group[18].

With the definitions: $\sigma^\circ_{\rm had}= \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_{had}}{\Gamma_Z^2}$, $A^{\circ,\ell}_{\rm FB}= \frac{3}{4}A_eA_\ell$, $A_\ell = \frac{2\bar{g}^\ell_V\bar{g}^\ell_A}{(\bar{g}^\ell_V)^2+(\bar{g}^\ell_A)^2}$, the fit values of the Z parameters are as in table 1.

The Z partial decay widths, Γ_e, Γ_μ, Γ_τ, Γ_ℓ and $\Gamma_{\rm had}$ are derived to be 83.92±.12, 83.99±.18, 84.08±.22, 83.984±.086, and 1744.4±2.0 MeV respectively and the invisible width, $\Gamma_{\rm inv}$= 499.0±1.5 MeV. This leads to the number of light neutrino species, $N_\nu = 2.984 \pm .008$, and an upper limit on the invisible width due to decay into unknown particles $\Gamma^X_{inv} < 2.0$ MeV at 95% C.L.

Table 1. LEP average Z parameters

M_Z	91187.6	±	2.1 MeV
Γ_Z	2495.2	±	2.3 MeV
$\sigma^\circ_{\rm had}$	41.541	±	0.037 nb
R_e	20.804	±	0.050
R_μ	20.785	±	0.033
R_τ	20.764	±	0.045
$A^{\circ,e}_{\rm FB}$	0.0145	±	0.0025
$A^{\circ,\mu}_{\rm FB}$	0.0169	±	0.0013
$A^{\circ,e}_{\rm FB}$	0.0188	±	0.0017
Under lepton universality:			
R_ℓ	20.767	±	0.025
$A^{\circ,\ell}_{\rm FB}$	0.01714	±	0.00095

2.2 Tau polarization at LEP-I

τ-polarization as a function of polar angle, θ, of the τ^- w.r.t. the e^- beam, is expressed as

$$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta)+2A_e\cos\theta}{1+\cos^2\theta+2A_\tau A_e\cos\theta}$$

Almost uncorrelated measurements of A_τ and A_e are obtained from a fit to $P_\tau(\cos\theta)$; averaged over $\cos\theta$ it yields A_τ. LEP average values are: $A_\tau = 0.1439 \pm .0042$, $A_e = 0.1498 \pm .0048$ whose average is $A_\ell = 0.1465 \pm .0032$. Combining with $A_\ell = 0.1512 \pm .0042$ derived from LEP averaged $A^{\circ,\ell}_{\rm FB}$, the overall LEP average $\mathbf{A_\ell = 0.1481 \pm .0026}$.

2.3 Asymmetry measurements at SLD

550,000 $e^+e^- \to$ hadrons events with polarised e^-, yield Left-Right Asymmetry: $A_{\rm LR} \equiv A_e = 0.1514 \pm 0.0022$. Measurement of Left-Right F-B Asymmetry in $\mathbf{e^+e^-} \to \ell^+\ell^-$ events yields: $A_e = 0.1544 \pm 0.0060$, $A_\mu = 0.142 \pm 0.015$ and $A_\tau = 0.136 \pm 0.015$. Combining with A_e from $A_{\rm LR}$ measurement, the overall SLD average for $\mathbf{A_\ell = 0.1513 \pm 0.0021}$.

2.4 Lepton universality in g_A, g_V

The lepton asymmetry and partial width values obtained above can be used to derive the

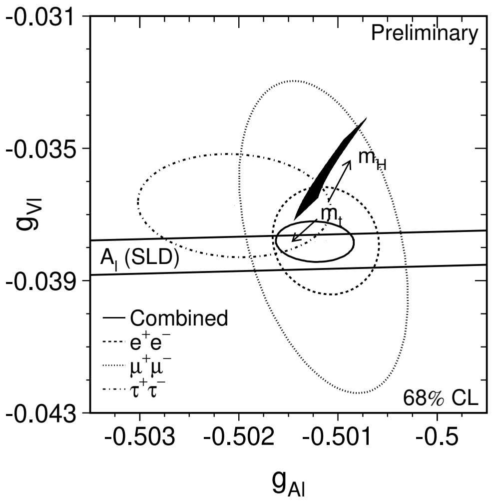

Figure 2. LEP, SLD g_A vs g_V

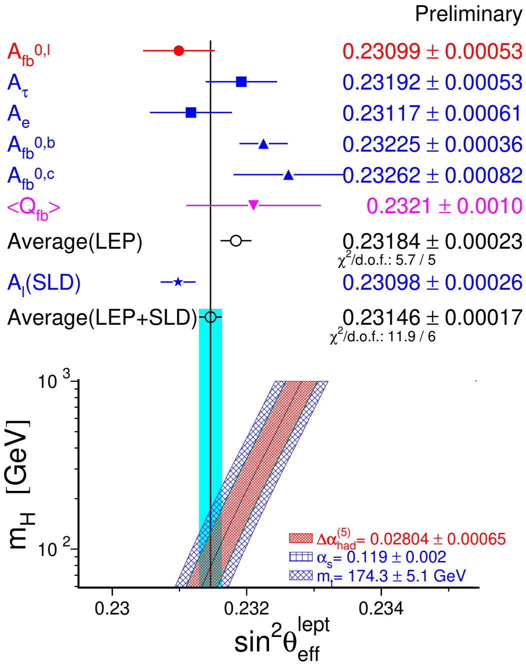

Figure 3. Determinations of $\sin^2\theta^{\rm lept}_{\rm eff}$

axial and vector couplings of the Z to the 3 species of charged leptons. Contours of g_A vs g_V are shown in figure 2. Contours for the 3 leptons overlap indicating lepton universality of Z couplings. The contour assuming lepton universality is also shown.

2.5 Z couplings to b, c quarks

Both LEP and SLD have determined the Z decay fractions into b and c quarks as ratios R_b, R_c, with $R_q = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \text{hadrons})}$. At LEP the F-B aysmmetries $A^{\circ,b}_{FB}$ and $A^{\circ,c}_{FB}$ have also been measured whereas SLD has directly determined A_b and A_c asymmetry parameters taking advantage of the polarised electron beam of SLC. The average values of R_b, R_c, $A^{\circ,b}_{FB}$, $A^{\circ,c}_{FB}$, A_b, A_c are: 0.21653±.00069, 0.1709±.0034, 0.0990±.0020, 0.0689±.0035, 0.922±.023, 0.631±.026 respectively. Except for $A^{\circ,b}_{FB}$, which is 2.4σ away from its SM value, all others agree very well with SM expectations.

2.6 $\sin^2\theta^{\rm lept}_{\rm eff}$ determinations

All the asymmetry measurements mentioned above can be converted into a common parameter, $\sin^2\theta^{\rm lept}_{\rm eff}$, the effective electroweak mixing angle at the Z mass:

$$\sin^2\theta^{\rm lept}_{\rm eff} = \frac{1}{4}\left(1 - \frac{g^\ell_V}{g^\ell_A}\right)$$

Figure 3 depicts the various determinations of this quantity along with its dependence on the mass of the Higgs within the SM.

2.7 A_s measurement at SLD

A beautiful new result from SLD[7] is the asymmetry measurement of the s quark tagged via high momentum $K^{\pm}, K^0_S$ and absence of B, D mesons. Polar angle distributions of the tagged events with positive and negative electron polarization yield $A_s = 0.895^{+.066}_{-.063}$, yielding $A_b/A_s = 1.02 \pm 0.10$, compatible with down-type quark universality.

3 Results from LEP-II

LEP operated at c.m. energies between 130-140 GeV during end of 1995, and above the W-pair threshold (161 GeV) from 1996 onward. By now a total of ~475 pb^{-1}/experiment has been collected at energies between 161 and 208 GeV.

3.1 *Theoretical advances for LEP-II*

To match the superb performance of the machines (LEP,SLC,Tevatron,...), and excellent high resolution detectors and experimental analyses, one needs matching theoretical predictions in order to test the SM meaningfully. A large amount of work has been reported at the LEP2MC workshop[19] at CERN.
Some highlights are:
– RacoonWW[20], YFSWW3[21] packages which calculate $\sigma(W^+W^-)$ to 0.4% by using the Double-Pole Approximation - valid much above the W-pair production threshold
– WTO[22], WPHACT[23], grc4f[24] packages for σ(1-W) to 4-5% accuracy using the Fermion Loop Scheme
– YFSZZ[25], ZZTO[19] packages for σ(ZZ) to 2% accuracy
– GENTLE v2.10[26] now corrects for overestimated Coulomb correction and agrees well with RacoonWW; there is still ~0.75% ISR related uncertainty
– for 2-fermion processes ZFITTER[14], KKMC[27] give better than 0.2% accuracy in σ(tot), of hadrons and leptons and 0.2-0.4% on A_{FB}
– KKMC is the first MC generator for LEP, LC, μ-colliders, τ, b factories

There is now a good match between experimental and theoretical accuracies.

3.2 *2-fermion processes at LEP-II*

The presence of initial state radiation (ISR) results in "return to the Z" events at c.m. energies far above the Z mass. Figure 4 shows the distribution of events as a function of $\sqrt{s'/s}$, where $\sqrt{s'}$ is the mass of outgoing lepton pair or Z/γ^* propagator. The Z peak is clearly seen. Events are called inclusive for s'/s >0.01 and exclusive, or high energy, for s'/s >0.7-0.8.

Cross sections & asymmetries are determined for hadronic & leptonic events & heavy flavours (b,c). Figure 5 shows OPAL

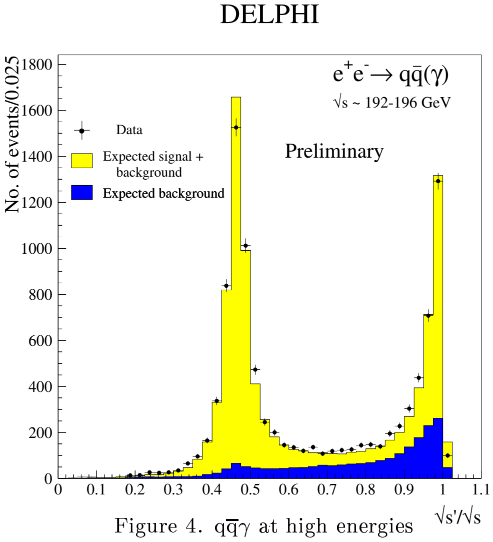

Figure 4. $q\bar{q}\gamma$ at high energies

results for lepton asymmetry measurements from LEP-I to LEP-II energies (note the difference in shape for the e^+e^- final state owing to additional t-channel and s-t interference). Comparison with SM provides limits on new physics: Contact Interactions, Z', $\tilde{\nu}$ exchange, extra dimensions,... These topics are covered under search for new physics.

3.3 *W-pair production, BR's*

Using SM branchings $B(W\to q\overline{q'}) = 67.6\%$, & $B(W\to \ell\,\overline{\nu}) = 10.8\%$ per lepton flavour:

– $B(W^+W^- \to q\overline{q'}q\overline{q'}) = 45.6\%$ (4 jet high multiplicity, balanced events)
– $B(W^+W^- \to q\overline{q'}\ell\,\overline{\nu}) = 14.6\%$ (2 jets, 1 lepton - hadronic events with 1 energetic lepton or narrow τ jet) for each lepton flavour
– $B(W^+W^- \to \ell\,\overline{\nu}\overline{\ell'}\,\nu') = 10.6\%$ (2 leptons, low multiplicity non-hadronic events with acoplanar isolated leptons) summed over lepton flavours.

The LEP averaged W^+W^- cross section as a function of c.m. energy is shown in figure 6. The data agrees very well with the latest theoretical models.

LEP average measurements of the hadronic and leptonic BR's of the W are as follows

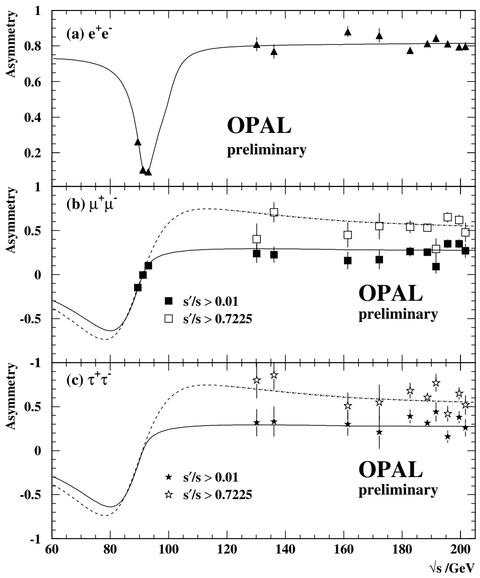

Figure 5. Lepton pair asymmetry measurements

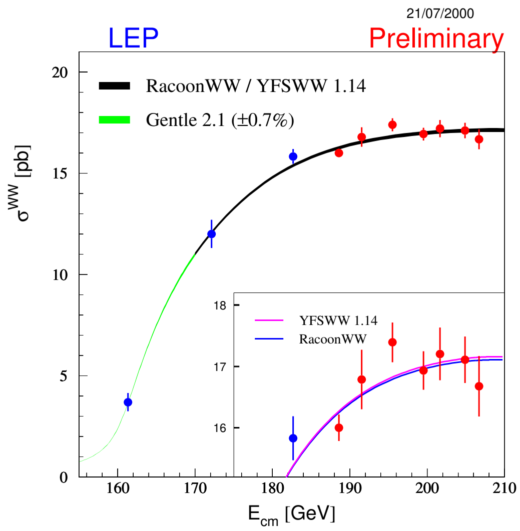

Figure 6. W^+W^- cross section

B(W→hadrons) = 67.78±0.32 %,
B(W→ $e\nu$) = 10.62±0.20 %,
B(W→ $\mu\nu$) = 10.60±0.18 %,
B(W→ $\tau\nu$) = 11.07±0.25 %,
B(W→ $\ell\nu$) = 10.74±0.10 %.

Using the average B(W→hadrons) the CKM matrix element $\mid V_{cs} \mid$ can be determined indirectly:
$B_{had}/(1-B_{had}) = \sum \mid V_{ij}^2 \mid (1+\frac{\alpha_s}{\pi})$, leading to $\mid V_{cs} \mid = 0.989 \pm 0.016$, where the other matrix elements are taken from Groom et al[28]. $\mid V_{cs} \mid$ can also be directly determined by identifying charm in W jets. A new measurement from OPAL yields a value of $0.91 \pm 0.07 \pm 0.11$, and the LEP average of such direct measurements is 0.95±0.08.

Tevatron measurements of B(W $\rightarrow$ eν) from D0 and CDF are 10.50±0.30% and 10.39±0.35% respectively giving an average of 10.43±0.25% (this conference) which agrees very well with the LEP result.

3.4 WWV Triple gauge couplings

There are 7 complex couplings for each of the vertices γWW and ZWW: g_1^V, g_4^V, g_5^V, κ_V, λ_V, $\tilde{\kappa}_V$, $\tilde{\lambda}_V$ ($V = Z$ *or* γ). Three of these conserve C- & P-, three violate CP and one violates C-, P- but conserves CP (g_5^V). Initial studies determined only the C- and P- conserving TGC's g_1^Z, κ_γ, λ_γ and fitted one TGC at a time setting others to their SM values (1,1,0 respectively). With increased statistics and higher c.m. energies C-, P- and CP- violating couplings are also determined and simultaneous 2- and 3- parameter fits are being carried out. The sensitive observables are the cross sections, energy and angular distributions. Figure 7 depicts the processes at LEP which are used to determine TGC's. Figure 8 exemplifies the use of the photon energy distribution in the single-photon final state to determine the WWγ coupling.

The single-W cross section at various LEP energies is another good observable for the determination of the WWγ coupling. In

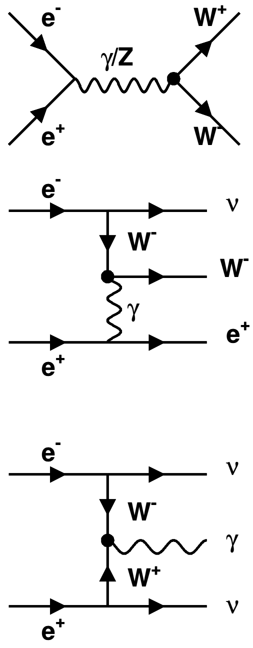

Figure 7. Final states for TGC studies at LEP

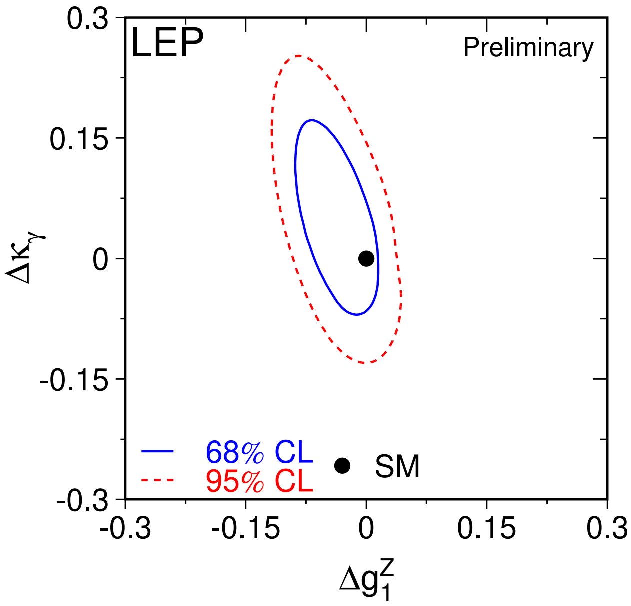

Figure 9. LEP: Δg_1^Z vs $\Delta\kappa_\gamma$

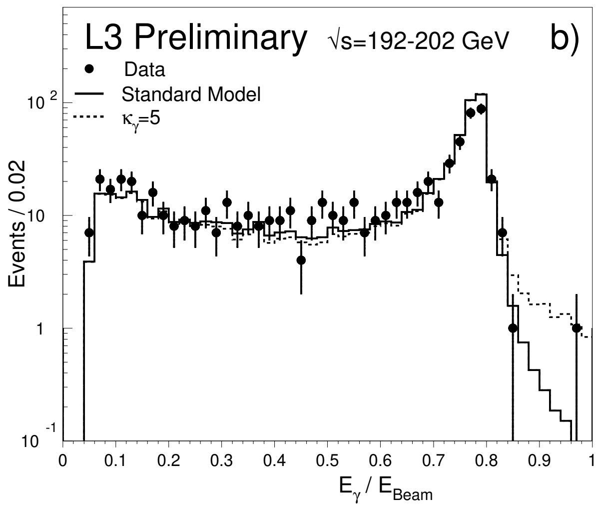

Figure 8. $E_\gamma/E_{\rm beam}$ in the $\nu\nu\gamma$ final state

the W-pair final state the various angular distributions are the most sensitive observables. The LEP averages for the three C- and P- conserving couplings obtained from 1-parameter fits are:
$\Delta\kappa_\gamma = -0.002^{+.067}_{-.065}$, $\Delta g_1^Z = -0.025 \pm .026$, $\lambda_\gamma = -0.036^{+.028}_{-.027}$.

Example of a 2-parameter fit is shown in figure 9.

Details on the limits on TGC's from various LEP experiments are given in one of the EW parallel session talks at this conference[2]. From Tevatron there is no submission to this conference. D0 published results combine $W\gamma; WW \rightarrow$ dilepton; $WW/WZ \rightarrow e\nu jj, \mu\nu jj; WZ \rightarrow$ trilepton data and obtain: $\Delta\kappa_\gamma = -0.08 \pm 0.34$, $\lambda_\gamma = 0.00^{+0.10}_{-0.09}$, and $-0.37 < \Delta g_1^Z < 0.57$, fixing $\lambda_Z = \Delta\kappa_Z = 0$ & assuming SM values for $WW\gamma$ couplings.

3.5 LEP-II: ZZV Triple gauge couplings

The ZZV TGC's are studied via ZZ and $Z\gamma$ production. In the SM the ZZV couplings practically do not exist and ZZ and $Z\gamma$ production occurs predominantly via t-channel

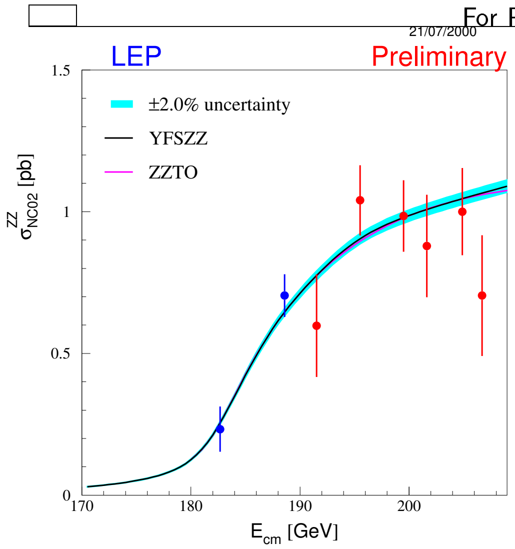

Figure 10. LEP: ZZ production cross section

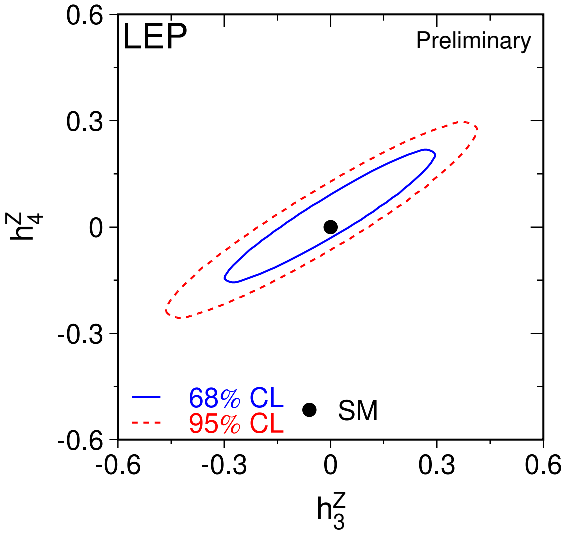

Figure 12. LEP: ZγV coupling contours

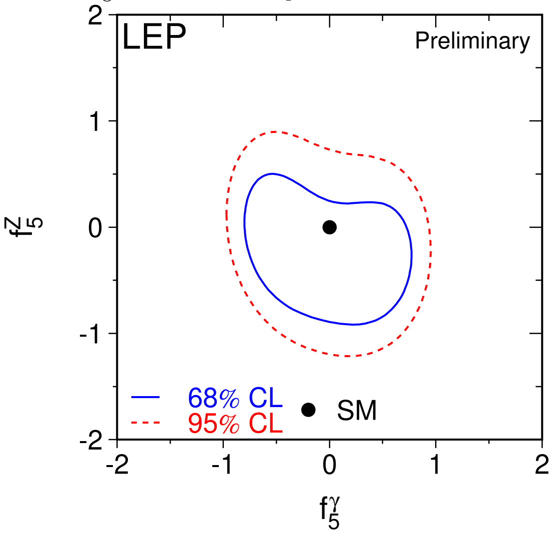

Figure 11. LEP: ZZV coupling contours

exchange of e. Anomalous ZZV (s-channel type) couplings, if they exist, increase the cross sections of ZV production and modify the γ polar angle, specially at large angles.

For ZZV couplings the formalism of Hagiwara et al[29] is used which expresses these couplings in terms of two parameters, f^V_4, which is CP-violating and f^V_5, which is CP-conserving. The ZZ cross section at LEP-II is shown in figure 10.

Contours of f^Z_i vs f^γ_i are obtained for combined LEP data. Example of f^Z_5 vs f^γ_5 is shown in figure 11.

For ZγV (Zγ production) one uses the general formalism of Mery et al[30] and Gounaris et al[31]. This incorporates an energy scale of new physics (Λ):

$$\frac{\sqrt{\alpha} h^V_i}{m^2_Z} \equiv \frac{1}{\Lambda^2_{iV}}, i = 1,3$$

$$\frac{\sqrt{\alpha} h^V_i}{m^4_Z} \equiv \frac{1}{\Lambda^4_{iV}}, i = 2,4$$

i = 1,2 are CP violating and i = 3,4 are CP conserving. Requirement of unitarity leads to $h^V_i \rightarrow 0$ as $s \rightarrow \infty$. Example of LEP combined contours of h^Z_3 vs h^Z_4 are shown in figure 12.

3.6 LEP-II: W/Z Quartic couplings

The SM predictions for WWWW, WWZZ, WWZγ, WW$\gamma\gamma$ couplings are small at LEP, but expected to become important at a TeV linear Collider. At LEP such possible couplings, a_0, a_c, a_n, are expressed in terms of six dimensional operators:

$$L^0_6 = -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha,$$
$$L^c_6 = -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha,$$
$$L^n_6 = -\frac{e^2}{16\Lambda^2} a_n \epsilon_{ijk} W^{(i)}_{\mu\alpha} W^{(j)}_\nu W^{(k)\alpha} F^{\mu\nu}$$

where F, W are photon and W fields, L^0_6 & L^c_6

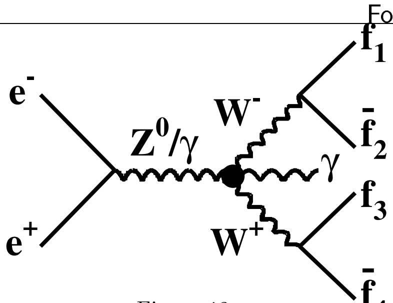

Figure 13.

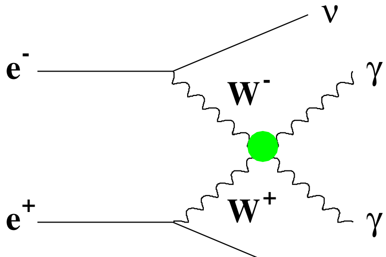

Figure 14.

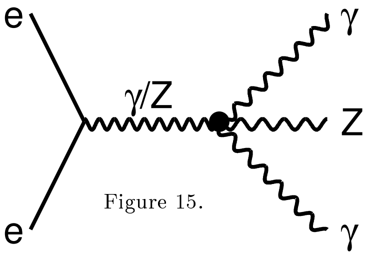

Figure 15.

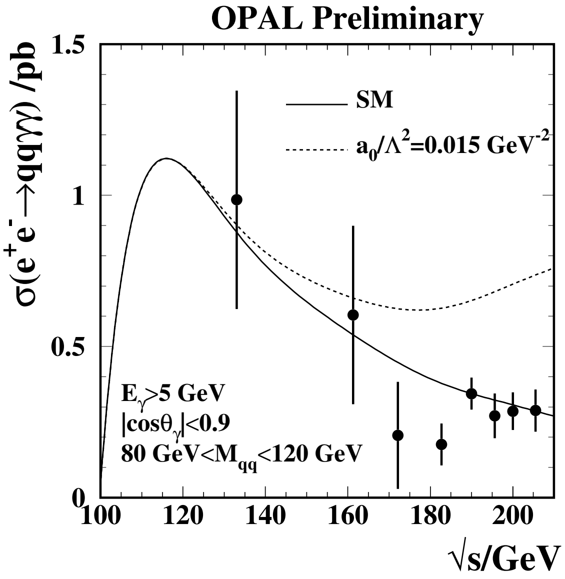

Figure 16.

conserve C-, P- separately, L_6^n violates CP and Λ is a scale for new physics.

The processes studied in search of these quartic couplings are illustrated in figures 13-15, i.e., one looks for the WWγ, 2-$\gamma(\nu\nu)$ and Z$\gamma\gamma$ final states. The cross section for Z$\gamma\gamma$ with Z$\rightarrow$ q$\overline{\text{q}}$ is shown in figure 16 for OPAL who used it to set limits on a_0/Λ^2. The LEP combined 95% C.L. limits, in GeV^{-2}, using 1-parameter fits utilizing all channels are as follows: -0.0049 $< a_0/\Lambda^2 <$ 0.0056, -0.0054 $< a_c/\Lambda^2 <$ 0.0098 and -0.45 $< a_n/\Lambda^2 <$ 0.41.

3.7 LEP-II: W mass & width

Precision determination of $\mathrm{M_W}$ and Γ_W is a major goal of LEP II, firstly to check of internal consistency of the SM and, secondly, to improve the prediction for the Higgs mass. At LEP the c.m. energy is precisely known and the final states are clean thus enabling the reconstruction of W's using kinematic fits. The reconstructed W invariant mass distribution can then be fitted to obtain the best value of $\mathrm{M_W}$ and Γ_W. The four final states qqqq, qqeν, qq$\mu\nu$ and qq$\tau\nu$ are used. An example of a reconstructed mass distribution from Delphi is shown in figure 17.

In individual LEP experiments the systematic error is now comparable to the statistical error ($\simeq$50 MeV). Thus, when one combines LEP results it is the common systematics which now dominates. Systematic errors on $\mathrm{M_W}$ may be classified as (1) uncorrelated between channels & experiments, (2) correlated between channels within an experiment, e.g., detector calibration, simulation, etc, and (3) correlated between experiments, e.g., those due to (a) Bose-Einstein, Color Reconnection effects in the qqqq channel, (b) Initial State Radiation, fragmentation effects and (c) LEP energy error, its correlation between years.

Of major concern are the correlated errors between experiments. Of these the error on $\mathrm{M_W}$ due to LEP energy uncertainty

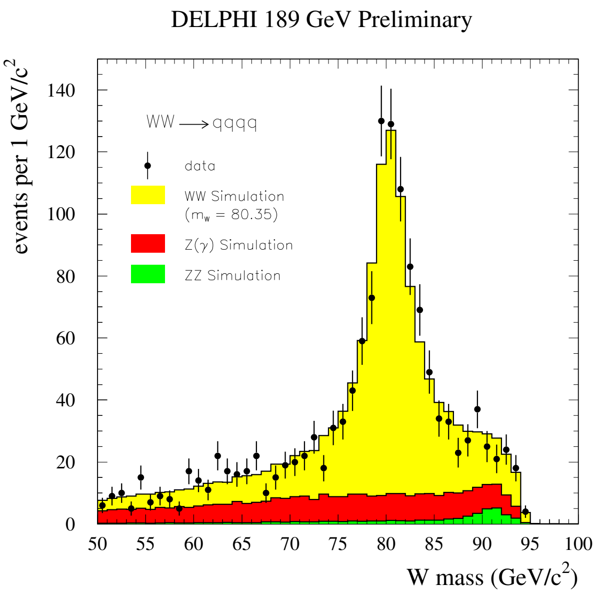

Figure 17. qq invariant mass in WW→qqqq

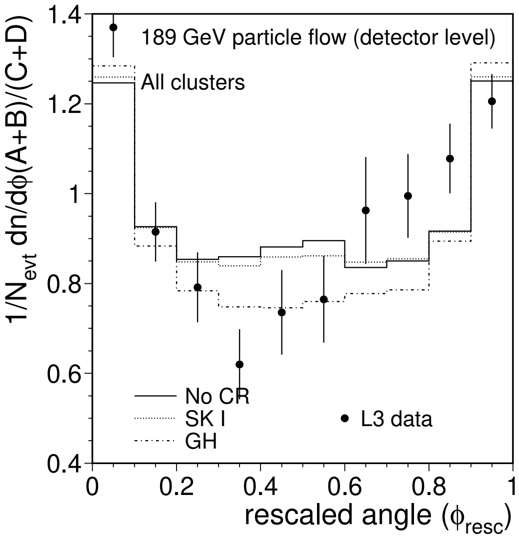

Figure 18. L3 Color Reconnection study

is ∼17 MeV currently and it is hoped it will reduce to ∼12 MeV eventually. Error due to ISR is small; due to fragmentation uncertainties is ∼25 MeV. Presently the major uncertainty on M_W comes due to unknown Bose-Einstein (BE) correlation and color reconnection (CR) effects in the qqqq channel: ∼25 and 50 MeV respectively. As qqqq forms ∼50% of all events used in W-mass determination, the overall error on M_W due to these is ∼30 MeV.

Color reconnection is the exchange of gluons between quarks from decays of different W's. BE correlation is the enhanced production of identical bosons at small 4-momentum difference. Both these may cause distortions in the qq invariant mass distribution in the qqqq channel leading to a possible shift in fitted the M_W. If one could measure these effects and correct for them then one would be left with a residual error on the correction applied.

For color reconnection L3 and Aleph have investigated the inter-jet particle and energy flow within the framework of the Sjostrand-Khoze[32] (SK) and Gustafson-Hakkinen[33] (GK) models. The effect of CR is to migrate particles from the angular regions (A,B) between quarks from the *same W* to angular regions between quarks from *different W's* (C,D). Figure 18 shows the L3 data on the ratio of particles in regions (A+B) to (C+D) as a function of the "rescaled" angle, ϕ_{resc}, which shows a significant deficit at central values of the angle as expected from the SK-I and GH models with CR. In the SK-I model the color reconnection probablity obtained is ∼40%. Aleph obtain compatible results with ≤45% CR probability at 1σ level. This corresponds to a 40 MeV shift in M_W.

BE correlation is a well known effect seen already at LEP-I. Aleph, L3 and Opal see BE effects within the same W→qq, but *inter-W* effects have not been seen yet (Aleph, L3 *disfavour* such effects). In a new result presented to this conference, Delphi[4] indicate a $\sim 2\sigma$ evidence for inter-W Bose-Einstein correlations in the qqqq state. The 2-particle correlation function $R(p_1,p_2) = \frac{P(p_1,p_2)}{P_0(p_1,p_2)}$, where P is the 2-particle probability density, p_i the 4-mom, and P_0 is a reference 2-particle density like P, but without BE correlation is

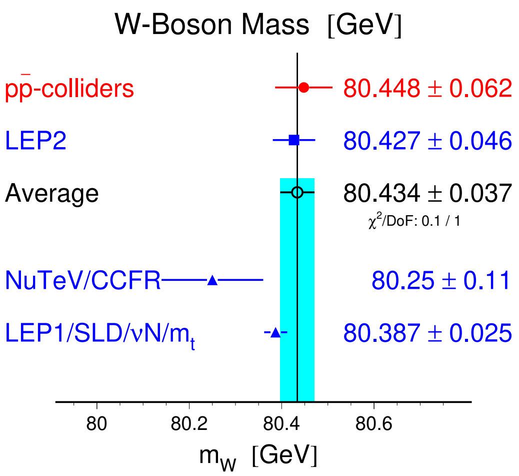

Figure 19. World average W-mass

parametrized as $\mathrm{R(Q) = K.(1 + \lambda e^{-r^2Q^2})}$, with $\mathrm{Q^2 = -(p_1 + p_2)^2 = M^2_{\pi\pi} - 4m^2_\pi}$, r = radius of a spherically symmetric pion source and λ= strength of correlation.

Delphi measured R(Q) in hadronic Z decays, WW$\rightarrow$qq$\ell\nu$ and qqqq decays. Comparison sample: event mixing, taking (qq)'s from 2 qq$\ell\nu$ events to fake qqqq with no inter-W BEC's. Correlation strength difference between 4q data and (a) mixed events: $\Delta\lambda = 0.062 \pm .025 \pm .021$, (b) qq$\ell\nu$: $\Delta\lambda = 0.077 \pm .026 \pm .020$.

On both CR and BE fronts more work is needed but the prospects of measuring these effects to correct $\mathrm{M_W}$ now look brighter than before.

Results on $\mathrm{M_W}$, Γ_W LEP average value of $\mathrm{M_W}$(qqqq) = 80.432$\pm$0.073 GeV and $\mathrm{M_W}$(qq$\ell\nu$) = 80.427$\pm$0.051 GeV, with difference $\mathrm{M_W}$(qqqq) - $\mathrm{M_W}$(qq$\ell\nu$) = 5$\pm$51 MeV, indicating that CR and BE effects can't be too large. The overall average LEP $\mathrm{M_W}$ = 80.427$\pm$0.046 GeV and Γ_W = 2.12$\pm$0.11 GeV. This value of Γ_W may be compared with CDF direct measurement of 2.055 $\pm$ 0.125 GeV and CDF+D0 "Extracted" value of 2.171 $\pm$ .052 GeV. The world average of W-mass is shown in figure 19.

4 Global Fits to Electroweak data

Fits are made to all electroweak data within the SM framework. The fitted parameters are $\mathrm{M_{top}}$, $\mathrm{M_Z}$, α_s, $1/\alpha^{(5)}(\mathrm{M_Z^2})$, and $\mathrm{M_{Higgs}}$ and the ZFITTER and TOPAZ0 packages are used.

In addition to the results given in sections 2 and 3.7, the additional data used is $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$= 0.2321$\pm$0.0010 from $< Q_{FB} >$ at LEP[18], $\sin^2\theta_\mathrm{w}$= 0.2255$\pm$0.0021 from NuTeV[34], $\mathrm{M_{top}}$= 174.3$\pm$5.1 GeV[35], and $\Delta\alpha^{(5)}_{had}(M_Z^2)$ = 0.02804$\pm$0.00065[36].

The first fit using only LEP data yields $\mathrm{M_{top}}$= 179^{+13}_{-10} and $\mathrm{M_{Higgs}}$= 135^{+262}_{-83} GeV. Fitted $\mathrm{M_{top}}$ value agrees well with the direct measurement. The second fit uses all data except directly measured $\mathrm{M_W}$ & $\mathrm{M_{top}}$ and yields $\mathrm{M_{top}}$= 169^{+10}_{-8} & $\mathrm{M_W}$= 80.376$\pm$0.034 GeV, both values showing agreement with the direct measurements. The third fit excludes only the direct $\mathrm{M_W}$ measurement and yields $\mathrm{M_W}$= 80.386$\pm$0.025 GeV. The quality of fits is acceptable with χ^2/DOF ranging between 1.4 and 1.7. These fits thus demonstrate the compatibility and internal consistency of the SM with the existing precision electroweak measurements. Finally the fit to all data yields $\mathrm{M_{top}}$= $174.3^{+4.4}_{-4.1}$, $\mathrm{M_{Higgs}}$= 60^{+52}_{-29}, $\mathrm{M_W}$= 80.402$\pm$0.021 GeV and α_s= 0.1183$\pm$0.0027, the χ^2/DOF being 1.4. The 95% C.L. upper limit on $\mathrm{M_{Higgs}}$ is 165 GeV, as seen from figure 20.

5 Outlook, Summary

LEP-I and SLD results are (almost) final; LEP-II will increase statistics at the highest energies (>200 GeV) leading to more sensitive tests of couplings; and it is hoped that the CR & BE systematics on $\mathrm{M_W}$ will be better controlled & the final LEP error on $\mathrm{M_W}$, $\Delta\mathrm{M_W}$, will be $\simeq$35 MeV.

In the SM fits sector, new data on R (=hadrons/$\mu^+\mu^-$) from BES-II (BEPC) in the energy range 2-5 GeV was presented

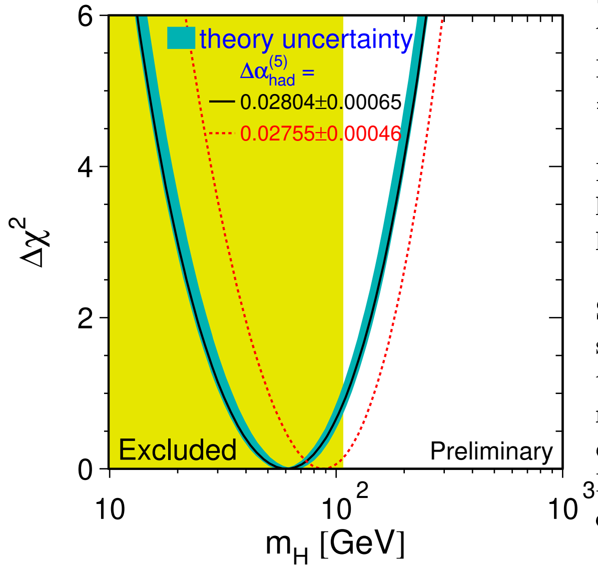

Figure 20. χ^2 variation with M_{Higgs}

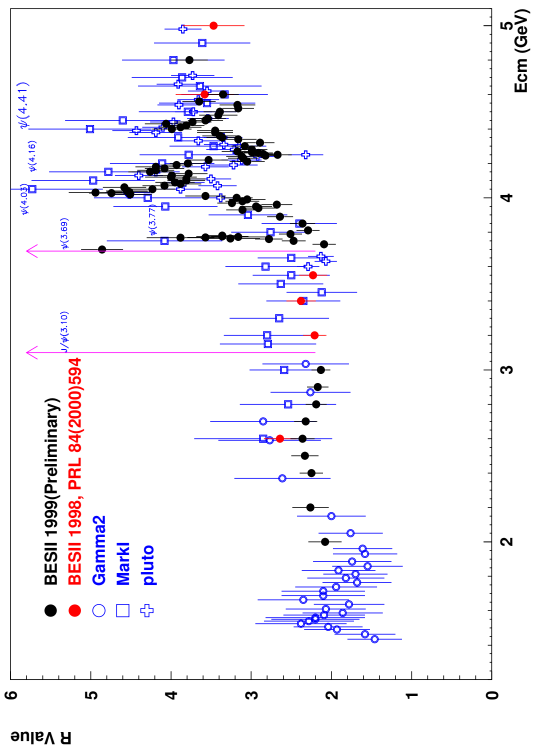

Figure 21. R(=hadrons/$\mu^+\mu^-$) vs c.m. energy

at this conference[2]. This is shown in figure 21. This input is critically used in determining $1/\alpha^{(5)}(M_Z^2)$. Including the new BES-II data yields the value $\Delta\alpha^{(5)}_{had}(M_Z^2)$ = 0.02755±0.00046 after a *very preliminary analysis*. Used in the SM fit one obtains $M_{Higgs}= 88^{+60}_{-37}$ GeV and a 95% C.L. upper limit of 203 GeV[2] (instead of 165 GeV). One hopes to finalize such an analysis soon.

To summarize, modulo ν oscillations, the SM is still in excellent shape and the Higgs is still predicted to be light ($\lesssim$200 GeV). From the upcoming Tevatron Run-II one expects reduced errors on M_W and possible Higgs discovery (if hints at LEP are not borne out). Eventually we await the LHC with its agenda of physics at the TeV scale.

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