Status of the physics of the Z and W bosons

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Abstract

The status of W- and Z-boson physics in the electroweak sector is reviewed. Recent results, including new measurements of forward-backward asymmetries at the Z pole and of WW production and decay at LEP2, are shown. The current bounds on trilinear anomalous couplings are discussed. A global fit of electroweak observables predicts the mass of the Standard Model Higgs boson to be less than 260 GeV/c^2 at 95% confidence level.

Introduction

It is now 21 years since the discovery of the W and Z bosons [1, 2]. The precision of their mass measurement has steadily increased, it reached 400 MeV/c^2 with the final UA2 result, 100 MeV/c^2 at the end of the Tevatron RUN I and it is now 39 MeV/c^2 if LEP published results are included. The combination of the latest preliminary measurement, presented at this conference, has an uncertainty of 34 MeV/c^2. The increase of precision was even more dramatic for the Z mass, thanks to LEP this fundamental constant is known with a relative precision of 10^5, one of the best known physical constants.

The W mass evolution can be compared with the prediction of the tree-level SM relation

$$m_W^2(1-\frac{m_W^2}{m_Z^2}) = \frac{\pi\alpha(m_Z)}{\sqrt{2}G_F}\,. \tag{1}$$

This tree level prediction (quasi-tree level since pure QED radiative corrections are incorporated in the running fine structure constant) has been less and less consistent with the direct measurement. The departure from Eq. 1 is $12\,\sigma$ if the latest published results are used [3], giving an impressive evidence of the need of pure electroweak high order corrections.

Since tree level is not enough radiative corrections are needed, they can be computed by taking into account three additional parameters, the top mass (m_t), the Higgs mass (m_H) and the strong coupling constant (α_s). Observables can be expressed as a function of the Z mass (m_Z), the Fermi constant (G_F), the fine structure constant and the additional parameters. For the W mass, for instance, the tree level relation is modified with the well known Δr term.

In this contribution to the QFTHEP 2004 Conference I will discuss some important observables very sensitive to the Higgs mass (the asymmetries at the Z), I will cover recent results on W physics from LEP and Tevatron and then move to the present constraints on the Standard Model Higgs mass. In the last part of this report the most recent measurements of Triple Gauge Couplings will be discussed.

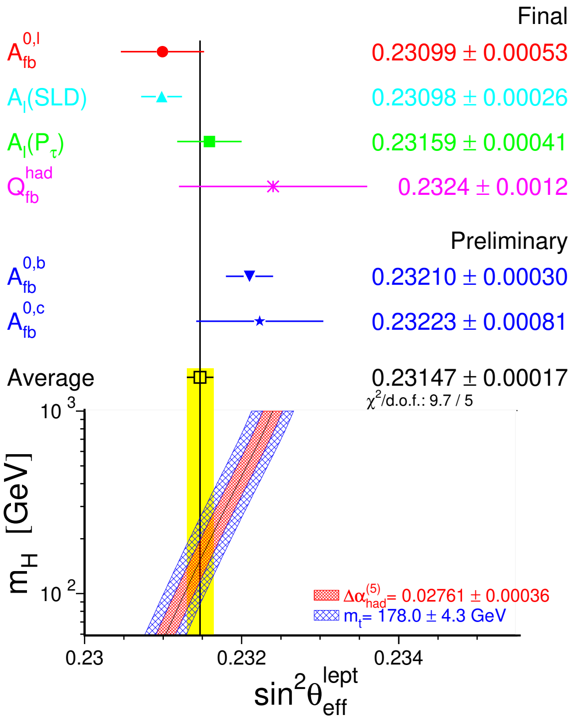
1 The asymmetries at the Z pole

At the Z pole parity violation at production and decay yields asymmetries in various distributions. With unpolarized beams one can measure the forward-backward asymmetry, that is related the product of initial and final state couplings. By analizing the tau polarization, or with polarized beams initial and final states can be disentangled. Thanks to the measurements at LEP and SLC a huge increase of precision has been achieved in the measurement of the couplings. Since the times of deep inelastic scattering the precision on the lepton couplings, and on the effective electroweak mixing angle that is related to them by the relation

$$sin^2\theta^l_{eff} = \frac{1}{4}(1-\frac{g_{Vl}}{g_{Al}})\,, \tag{2}$$

has increased by two orders of magnitudes.

A closer look to the $sin^2\theta^l_{eff}$ results, however, reveals disagreement (Fig. 1, top) among the two more precise measurements, coming from the left-right asymmetry at SLD [4] and the b forward-backward



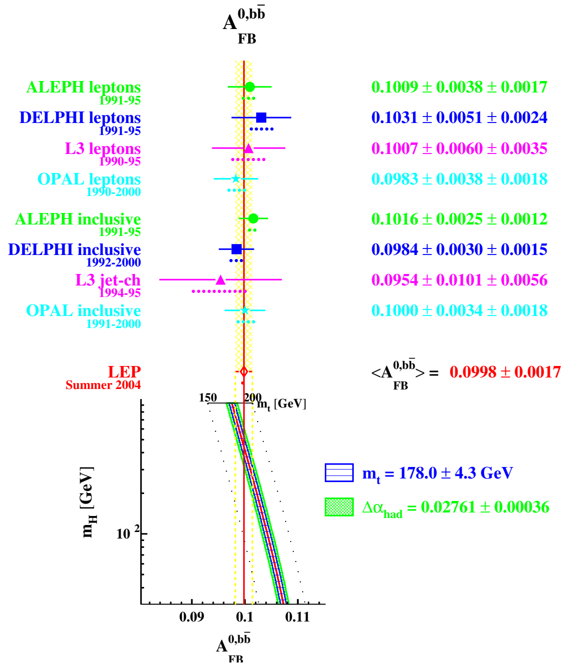


Figure 1: First bar-chart: measurements of the electroweak mixing angle, $sin^2\theta^l_{eff}$, at the Z pole and their combination. From the top to the bottom: the lepton forward-backward asymmetry, the left-right asymmetry, the tau polarization, the charge-flow asymmetry, the $b\bar{b}$ and $c\bar{c}$ forward-backward asymmetries. Second bar-chart: the measurements of the $b\bar{b}$ forward-backward asymmetry at the Z pole and their combination. For both bar-charts the dependence on the mass of the Higgs boson is indicated.

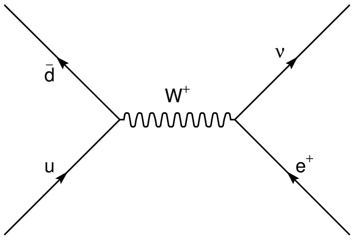


Figure 2: An example of W production and decay through the Drell-Yan process.

asymmetry at LEP [5]. The about $3\,\sigma$ discrepancy among the two measurements is a long standing issue. As far as the b couplings are concerned there is no independent evidence of any anomaly, that could possibly cause the disagreement. The b couplings can be determined by combining the measurement of the b polarized asymmetry at SLD, giving the ratio of vector to axial couplings, with the precision measurement of R_b, that is related to the sum of the squares of the couplings. Both measurements agree with the Standard Model expected values [6].

From the experimental side the b asymmetry is measured by four experiments with two almost uncorrelated techniques, with very different systematic effects. All measurements and the average itself are dominated by statistics. The most important common error (from QCD corrections) is a factor five lower than the statistical error and over the years an impressive number of experimental cross checks have been done [5] leaving little room for unexpected experimental effects.

The final b-asymmetry result is given in Fig. 1(bottom), the experiments agree and the two experimental techniques agrees among each other. Indeed the combination of lepton-only measurements gives $A^0_{FB}(b) = 0.0996 \pm 0.0025$ to be compared with the inclusive-measurement combination $A^0_{FB}(b) = 0.1000 \pm 0.0019$.

It is likely that this discrepancy will stand for a long time. It will presumably be solved at future linar colliders if polarization of both beams is available and a very high statistics run at the Z takes place.

2 W physics

At hadron colliders the Drell-Yan process, $q\bar{q}' \to W$, is the main W production mechanism (Fig. 2). This process represents at the same time the past and the future of W physics, since it allowed the W discovery and it is currently providing large samples of W's at the Tevatron Run II. We should have soon news concerning the W mass from the Tevatron. The preliminary transverse mass from high $\mathrm{p_t}$ leptons from CDF (Fig. 3) and D0 at Run II is clearly very promising for a mass measurement. Run II results for the W and Z cross sections are available [7].

The $e^+e^- \to W^+W^-$ process is the source of most W's at LEP. Three diagrams, the s-channel γ and Z diagrams and the t-channel neutrino exchange diagram (Fig. 4), contribute to WW production at Born level. One has to bear in mind that experimentally the final state is a 4-fermion process due to the subsequent decay into 4-fermions. Event selections are needed to disentangle WW events from the competing 2-fermion processes and to classify the events in three different channels (hadronic, leptonic and semileptonics). Decays to electrons, muons and taus can further be tagged. The typical signatures of the three topologies allow to separate WW events among each others and from background with good efficiencies and excellent purities. The cross sections can be readily computed from the events selected by each selection, from the total luminosity and from the efficiency matrix where cross contamination among channels is taken into account. The residual background and the four fermion interference must be considered. The four fermion interference arises from difference processes with the same final state, as may happen, for instance, for WW and single-W production. The correction is small, of the order

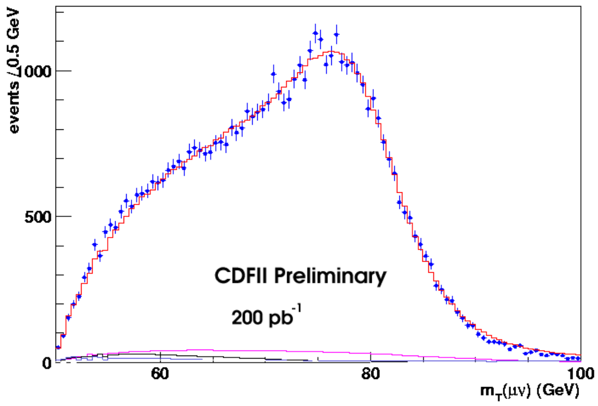


Figure 3: Transverse mass distribution from high p_T muons collected by the CDF experiment at the Tevatron Collider during the Run II.

of 1% relative, and the most important non WW 4-fermion processes can be directly measured. The new combination of LEP results on the total $e^+e^- \to W^+W^-$ cross section (Fig. 5) reaches a 9 permil precision, challenging theoretical predictions: computations without an adequate treatment of O(α) radiative corrections are definitively discarded. Indeed the average of the ratio of the measured to predicted [8] cross sections at centre-of-mass energies larger than 180 GeV is

$$R_{with\ O(\alpha)} = \frac{\sigma_{LEP}}{\sigma_{YFSWW}} = 0.9932 \pm 0.0089 \tag{3}$$

while the same ratio computed with the predictions used during the preparation of the LEP2 phase [11] yields a value 3σ lower than one. It must be stressed that the measurements presented in Fig. 5 show strong evidence for the existence of trilinear WWZ and WWγ couplings.

From the cross sections in the various sub-channels the branching ratios can be computed. Both leptonic and hadronic branching ratios are in good agreement with the Standard Model

$$BR(\mathrm{W} \to \mathrm{hadrons}) = (67.49 \pm 0.28)\% \tag{4}$$
$$BR(\mathrm{W} \to \mathrm{l}\nu) = (10.84 \pm 0.09)\% \tag{5}$$

to be compared with the expected 67.5% and 10.8% . The lepton universality test, however, does not work so well. The tau result is significantly higher than electrons and muons as can be seen from the ratios of couplings:

$$\frac{g(\mu)}{g(e)} = 0.997 \pm 0.010 \tag{6}$$
$$\frac{g(\tau)}{g(e)} = 1.034 \pm 0.015 \tag{7}$$
$$\frac{g(\tau)}{g(\mu)} = 1.037 \pm 0.014. \tag{8}$$

The electron and muon couplings are consistent. If the electron and muon couplings are assumed to be the same and combined, the tau result is 3 σ higher.

At LEP the W mass is measured from the direct reconstruction of the invariant mass in the semileptonic and hadronic channels. Kinematic fits imposing energy momentum conservation are a key tool to

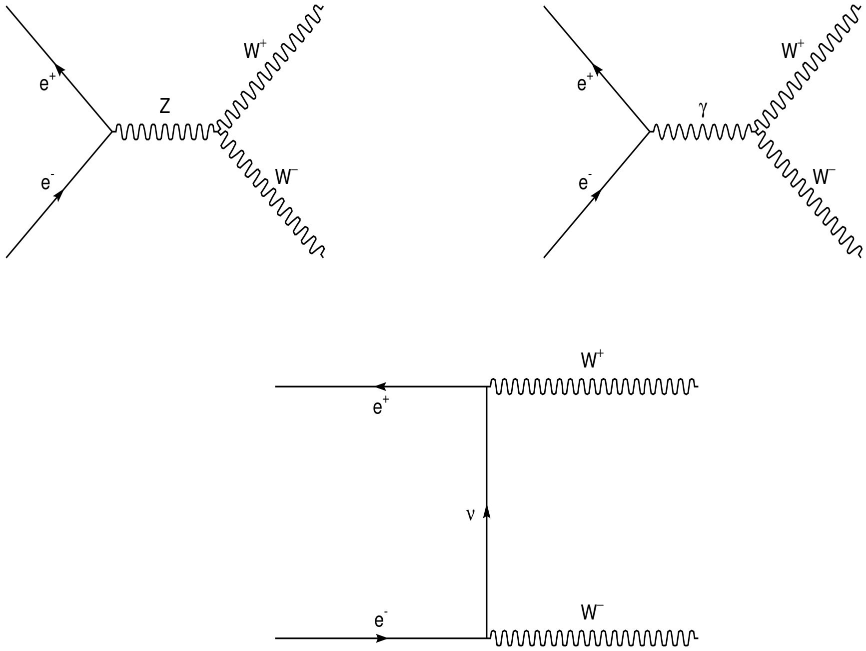


Figure 4: Diagrams contributing to WW production at LEP.

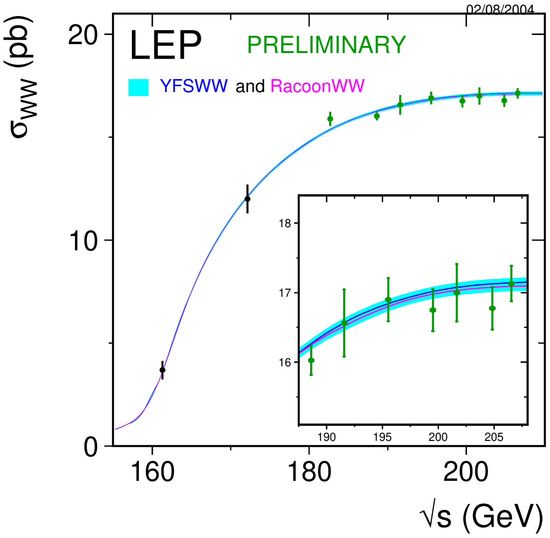


Figure 5: The $e^+e^- \to W^+W^-$ cross section as a function of the centre-of-mass energy. Predictions from recent calculations [8, 9] are shown.

improve the invariant mass resolution. For this a precise determination of the beam energy is required. The final LEP energy files are now available, opening the road for the final W mass measurements at LEP [12]. The remaining hot issue is the fight against an important systematic error depressing the weight of the four-quark channel in the LEP combination: the uncertainty due to final state hadronic interactions, that is by far the largest error in this channel. Interconnection phenomena in the final states (colour reconnection and Bose-Einstein correlations) are a non perturbative effect and data must be used to get a robust limit on the related uncertainties. The present LEP result uses constraints from a particle flow analysis to set limits on colour reconnection (CR) effects. CR models predict modified particle flow in the intra-W regions. By measuring the particle flow ratio between the inter- and intra-W regions limits can be set on extreme scenarios. This method sets an uncertainty of 90 MeV/c^2, used in the present LEP combination.

A more sensitive method will be used for the forthcoming final result. A general feature of all models is the correlation between the mass shift predicted by a model and the difference between the mass measured in a standard analysis and the mass measured using only particles in the jet core. To a larger mass shift caused by CR a larger mass difference corresponds. Since the mass variation can be measured in data, direct limits on the mass shift can be set. The CR systematic uncertainty is expected to go down to about 50 MeV/c^2 in the final LEP result.

The present LEP measurements in the two channels are (for all numerical results given in the following lines see [13])

$$\mathrm{m_W}(\mathrm{l}\nu\mathrm{qq}) = 80.411 \pm 0.032(stat) \pm 0.030(syst)\ \mathrm{GeV/c^2} \quad (9)$$
$$\mathrm{m_W}(4\mathrm{q}) = 80.420 \pm 0.035(stat) \pm 0.101(syst)\ \mathrm{GeV/c^2}\ . \quad (10)$$

The two results are consistent with similar statistical error, but, as expected, a large systematic error in the 4q channel is present. The current W mass results from LEP and Tevatron are

$$\mathrm{m_W}(\mathrm{LEP}) = 80.412 \pm 0.042\ \mathrm{GeV/c^2} \quad (11)$$
$$\mathrm{m_W}(\mathrm{Tevatron}) = 80.452 \pm 0.059\ \mathrm{GeV/c^2}\ . \quad (12)$$

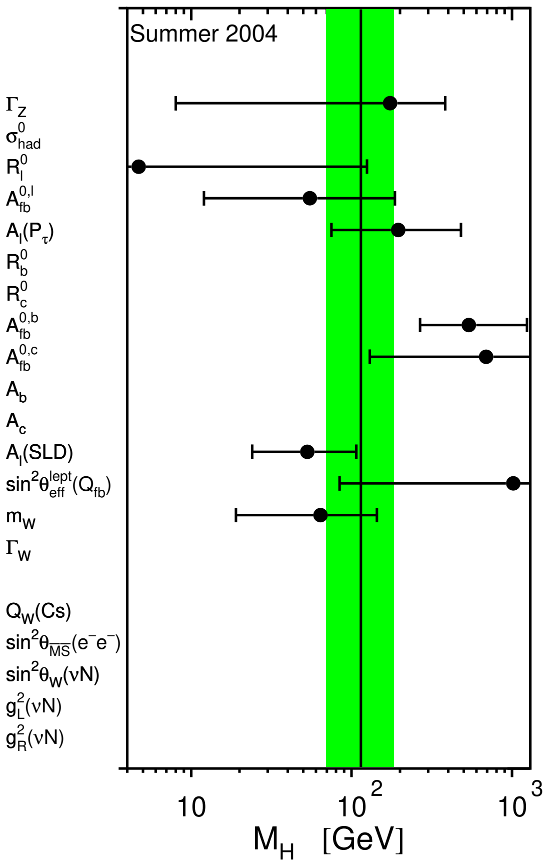


Figure 6: The 68% CL allowed intervals for the Standard Model Higgs boson mass (m_H) from various electroweak Z-pole observables. The most sensitive observables are: the Z width (Γ_Z), the lepton forward-backward asymmetry ($A_{fb}^{0,l}$), the tau polarization ($A_l(P_\tau)$), the b forward-backward asymmetry ($A_{fb}^{0,b}$), the c forward-backward asymmetry ($A_{fb}^{0,c}$), the left-right asymmetry (A_l(SLD)), the W mass (m_W).

The two results are consistent and their combination is $m_W = 80.425 \pm 0.034\,\mathrm{GeV/c^2}$. This combination can be compared with the Standard Model prediction computed using electroweak radiative corrections, measured by Z-pole observables as the asymmetries described in the previous section. The indirect determination gives $m_W = 80.373 \pm 0.033\ \mathrm{GeV/c^2}$, in agreement with the direct measurement. This agreement must be compared with the original 12 σ deviation of the tree level calculation.

3 Contraints on the Standard Model Higgs mass

The W mass and Z-pole asymmetries depends quadratically on the top mass through electroweak radiative corrections. The W mass, for instance, is modified by the already mentioned Δr term, whose top mass dependence is $\Delta r \sim G_F m_t^2$. The top mass can be indirectly evaluated by the measured observables, giving

$$m_t = 178^{+12}_{-9}\ \mathrm{GeV/c^2} \tag{13}$$

in agreement with the direct measurement, given by the combination of the CDF and D0 results, $m_t = 178 \pm 4.3\,\mathrm{GeV/c^2}$.

The dependence of the electroweak observables on the Higgs mass shows, instead, a logarithmic ansatz.

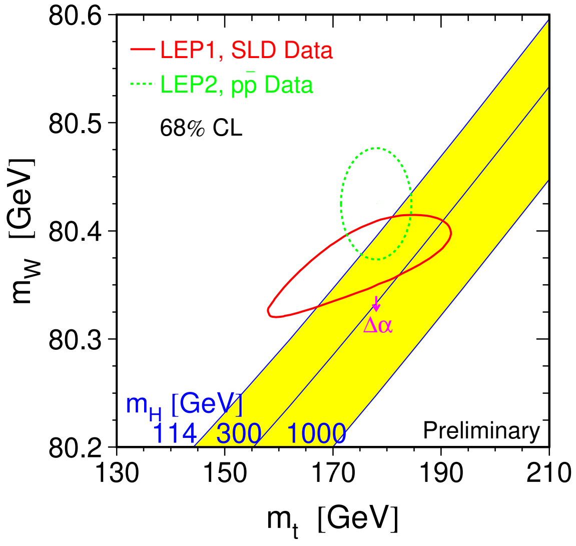


Figure 7: The direct (LEP2, $p\bar{p}$) and indirect (LEP1, SLD) determinations of the mass of the W boson (m_W) and of the top quark (m_t). The 68% CL allowed regions are indicated. The band represent the Standard Model expectations for different values of the Higgs boson mass (m_H).

Taking again as an example the W mass:

$$\Delta r \sim G_F m_W^2 \log(\frac{m_H^2}{m_W^2}). \tag{14}$$

The constraints on the Higgs mass, as computed using various electroweak observables, are given in Fig. 6. When combined together they give $m_H = 124^{+207}_{-69}$ GeV/c^2. The direct determination of the top mass greatly helps in constraining the mass of the Higgs, since the large quadratic term is fixed by the measurement. If this is done one gets $m_H = 114^{+69}_{-45}$ GeV/c^2, corresponding to $m_H < 260$GeV/c^2 at 95% CL.

The Higgs constraints from the W and top masses and from Z-pole observables are shown in Fig. 7. Direct and indirect measurements are consistent, showing a success of the electroweak theory.

4 Triple Gauge Couplings

The presence of tree level triple gauge boson interactions is a distinct signature of the non–abelian nature of the Standard Model and a consequence of its $SU(2)_L \times U(1)_Y$ gauge structure. The model predicts the same coupling g for the interaction of weak bosons to matter and among themselves. The existence of triple gauge couplings (TGCs) is proved by the behaviour of the $e^+e^- \rightarrow W^+W^-$ total cross section (Fig. 5); its energy dependence is consistent with the presence of both $WW\gamma$ and WWZ interactions and of a universal g coupling. Triple gauge interactions are also seen in other processes, such as single W production in e^+e^- interactions or associated Wγ production at hadron colliders, both testing the $WW\gamma$ vertex.

Triple gauge couplings do not only affect production rates, but also angular distributions of emitted weak bosons and of their decay products. Precision tests of triple gauge couplings, and of $SU(2)_L \times U(1)_Y$ predictions, require detailed measurements of differential cross sections. Angular distributions analyse different weak boson helicity states: since the longitudinal component of the helicity is directly linked to the symmetry breaking mechanism and to the mass generation these are fundamental tests of the theory.

Neutral triple gauge boson couplings, as ZZZ, $ZZ\gamma$ or $Z\gamma\gamma$, do not exist in the Standard Model at tree level. The existence of anomalous neutral couplings would affect processes as $e^+e^- \to ZZ$ or $e^+e^- \to Z\gamma$. No departure from the cross sections predicted by the Standard Model for these processes as been detected, todate.

If initial state radiation and the finite W width are neglected, the the $e^+e^- \to W^+W^-$ process is described by 5 angles

- the angle θ_W between the W^- and initial e^- in the W^+W^- rest frame
- the polar (θ^*_f) and azimuthal (ϕ^*_f) angles of the fermion in $W^- \to f\bar{f}'$ measured in the rest frame of its parent W^-
- the corresponding polar and azimuthal angles of the fermion in the W^+ rest frame.

In semileptonic $W^+W^- \to qql\nu$ decays the charge of the lepton identifies without ambiguities the W^-. The missing momentum provides information on the direction and energy of the undetected neutrino; kinematic fitting is used to improve the measurement, similarly to what is done for the measurement of the W mass. Since quark and anti-quarks are not identified in the hadronic W decays, there are two ambiguous solutions that normally enters both with a weight 0.5 in the angular distributions used for the measurements. Ambiguities are more important in the fully hadronic and fully leptonic channels. In the first case jets are paired using the method used for the W mass measurement (here the closeness to the W mass can also be used); after pairing the charges of the charged particles associated to jets belonging to the individual W's are weighted to form a charge estimator. The correct charge can be identified with purity of $70 \div 80\%$. As far as the fully leptonic channel is concerned the constraint that the two $l\nu$ systems should have an invariant mass consistent with the W mass helps in reconstructing the neutrino momenta. The quadratic nature of the constraint, however, yield a two-fold ambiguity: solutions obtained by flipping both neutrinos with respect to the plane defined by the two leptons are equally valid. Again, both solutions enter the experimental distribution with equal weight. The semileptonic channel is clearly the best suited for TGC analyses, providing the highest sensitivity.

The most general form for an effective charged TGC lagrangian consistent with Lorentz invariance involves 14 complex couplings, 7 for the $WW\gamma$ vertex and 7 for the WWZ vertex [17]. Some couplings are C– or P–violating while in the Standard Model C– and P–conservation is predicted in triple gauge couplings.

All couplings have been experimentally tested with the $e^+e^- \to W^+W^-$ sample collected at LEP2. A fit of the total cross section and the angular distributions has been performed to models where only one coupling at the time is allowed to vary, while all the others were set to zero [18]. Bounds on several couplings can also be set from precision measurements at the Z pole [19] . In most analyses C– and P–conservation and electromagnetic gauge invariance is assumed and the 14 couplings are reduced to 5 : g_1^Z, κ_γ, κ_Z, λ_γ, λ_Z. Within the Standard Model $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$. The couplings can be related to physical properties of the gauge bosons, for instance the W anomalous magnetic moment (μ_W) and the W anomalous electric quadrupole moment (Q_W) can be written as

$$\begin{aligned} \mu_W &= \frac{e}{2M_W}(1+\kappa_\gamma+\lambda_\gamma) \\ Q_W &= -\frac{e}{M_W}(\kappa_\gamma-\lambda_\gamma). \end{aligned}$$

The requirement of local $SU(2)_L \times U(1)_Y$ gauge invariance introduce the further constraints

$$\begin{aligned} \Delta\kappa_Z &= -\Delta\kappa_\gamma tan^2\theta_W + \Delta g_1^Z \\ \lambda_\gamma &= \lambda_Z \end{aligned} \qquad (15)$$

with Δ indicating the deviation with respect to the Standard Model prediction (θ_W here is the electroweak mixing angle), leaving three independent couplings: $g_1^Z, \kappa_\gamma, \lambda_\gamma$. The three couplings have been measured

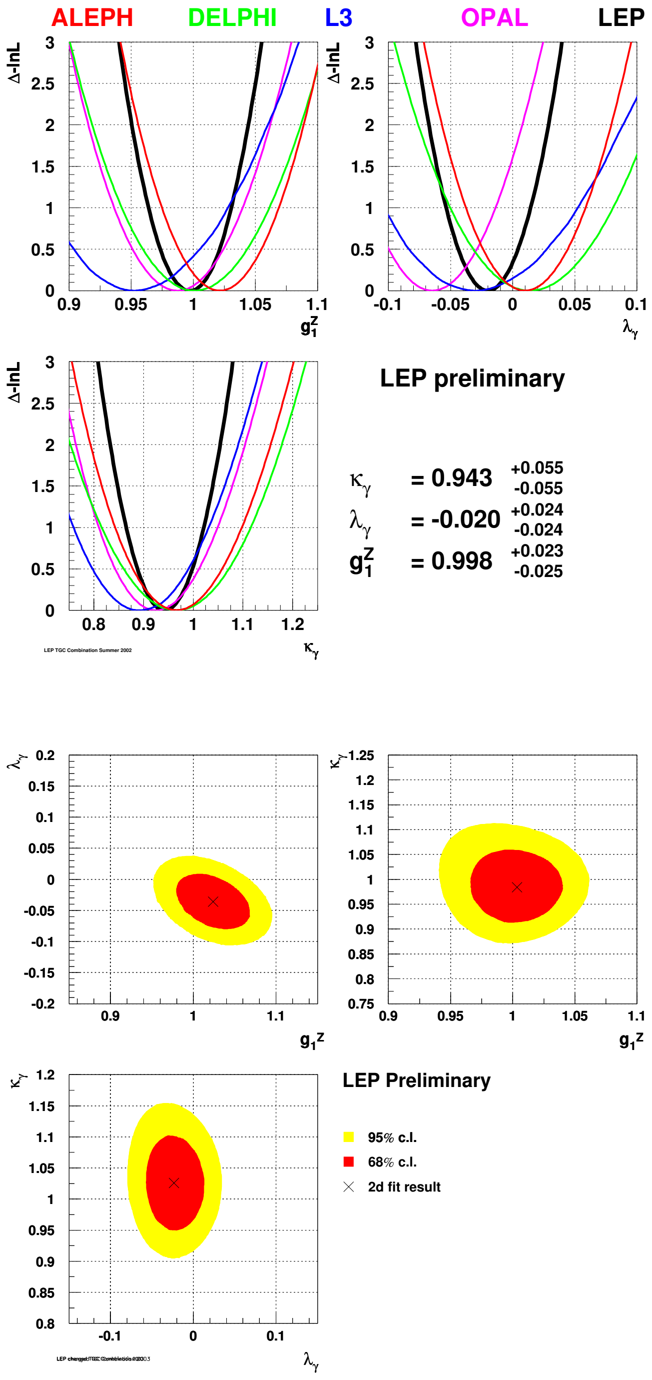


Figure 8: The triple gauge couplings $g_1^Z, \kappa_\gamma, \lambda_\gamma$. Top plots: the $\Delta(-\log \text{likelihood})$ curves for the four LEP experiments and their combination (bold line). In each of the three plots the two other couplings are fixed to the Standard Model value. Bottom plots: the 68% and 95% confidence level contours allowed by LEP data for the triple gauge couplings when one coupling is fixed to the Standard Model value, while the others are allowed to vary.

at LEP using $e^+e^- \rightarrow W^+W^-$ (Fig. 4) and $e^+e^- \rightarrow W^+e\nu$ events. The second process, single W production, is very useful to enhance sensitivity in the measurement of the $WW\gamma$ vertex. For this purpose also the single photon $e^+e^- \rightarrow \gamma\nu\bar{\nu}$ is useful. The analyses are based on the measurement of the total cross sections and of angular distributions. The constraints obtained from the combination of the LEP experiments are shown in Fig. 8.

The three couplings are consistent with the Standard Model expectation, in particular the g_1^Z and κ_γ measurements confirm the presence of triple gauge interactions with the expected strength, with a precision of $\sim 2\%$

5 Conclusions

Final results on the electroweak mixing angle from asimmetries at the Z-pole are now available. The combination of these measurements yields a precision of 1.6×10^{-4} (absolute) on $sin^2\theta^l_{eff}$. The W leptonic branching ratios to different lepton species are measured at LEP with a precision of $\sim 0.2\%$, providing a precision test of lepton universality. The combined LEP-Tevatron measurement of the W mass has an uncertainty of 34 MeV/c^2. The forthcoming final LEP results and the new measurements at Tevatron RUN II will soon decrease this error. The combination of several electroweak observables indicates a light Higgs boson: $\mathrm{m_H} < 260\mathrm{GeV/c^2}$ at 95% CL. Trilinear couplings have been measured with a precision of few percent at LEP and found to agree with the Standard Model expectation.

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