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W physics at LEP

Elisabetta Barberio
Physics Department, Southern Methodist University, Dallas, USA

ABSTRACT

Studying the properties of the W boson plays a key role in precision tests of the Standard Model. The key measurements performed over the last decade will be reviewed. W-pair and single-W cross-sections and W decay branching fractions are determined and agree well with theoretical predictions. Including the analysis of differential distributions, trilinear and quartic couplings of the W boson to the other gauge bosons are extracted. The trilinear, C and P conserving couplings are found to be $\kappa_\gamma = 0.943 \pm 0.055$, $\lambda_\gamma = -0.020 \pm 0.024$, and $g_1^{\rm Z} = 0.998^{+0.023}_{-0.025}$, consistent with the Standard Model expectations. A precise measurement of the mass and width of the W boson yields $M_{\rm W} = 80.412 \pm 0.042$GeV and $\Gamma_{\rm W} = 2.150 \pm 0.091$GeV. The W mass is in good agreement with the one obtained indirectly from an analysis of other electroweak data measured at LEP and SLD. Some of the results presented in this article are preliminary.

1 Introduction

One of the main motivations for the second phase of the LEP e^+e^- storage ring at CERN (LEPII) is the study of the W properties and production for a thorough test of the Standard Model (SM) of electroweak interactions [1]. Between 1996 and 2000, the LEP collider was operated at centre-of-mass energies above the W^+W^- production threshold, allowing for investigation of different aspects of W-pair production in e^+e^- annihilation, which are crucial test of the Standard Model of electroweak interactions. The four LEP collaborations (ALEPH, DELPHI, L3, and OPAL) collected a total sample of around 40,000 W pairs in the 2.8 fb^{-1} of data recorded.

2 W-pair and single-W production

The process $e^+e^- \to W^+W^-$ can be identified with high efficiency in all decay modes of the W boson. W^+W^- events are classified into three final states, according to their decay modes. $W^+W^- \to q\overline{q}q\overline{q}$ events comprise 45% of the total W^+W^- cross-section and are characterised by four energetic jets of hadrons with little or no missing energy. Semi-leptonic $W^+W^- \to q\overline{q}\ell^\pm\nu_\ell$ decays comprise 44% of the total W^+W^- cross-section and are characterised by two distinct hadronic jets, a high-momentum lepton and missing momentum due to the prompt neutrino from the leptonic W decay. The $W^+W^- \to \ell^+\nu_\ell\ell'^-\overline{\nu}_{\ell'}$ channel events have at least two unobserved neutrinos and a relatively low branching fraction, 11% .

At LEP W bosons are produced in pairs in the process $eetoWW$. About 95% of the resonant W-pair production is described in the SM by three charged current Feynman diagrams, one t-channel diagram with neutrino exchange and two s-channel diagrams with γ and Z exchange. The total production cross-section, σ_{WW}, measured by the four LEP experiments [2] at the centre of mass energies between 161 and 209 GeV is shown in Figure 1, where data points are compared with the theoretical calculations, [3]. The σ_{WW} evolution in case the γWW or additionally the ZWW are missing is also shown in Figure 1. The measurements clearly indicate the non-Abelian nature of the SM of electroweak interactions.

Measurement of the W branching fractions is a test of lepton universality at high q^2. The measured values of the individual leptonic W branching fraction support lepton universality, Figure [3], and can be combined to give $Br(W \to \ell\nu) = (10.74 \pm 0.09)\%$ [2], in agreement with the SM expectations. The W decay rate into quarks pairs is measured to be $Br(W \to qq') = (60.77 \pm 0.28)\%$, [2], in agreement with the SM expectations.

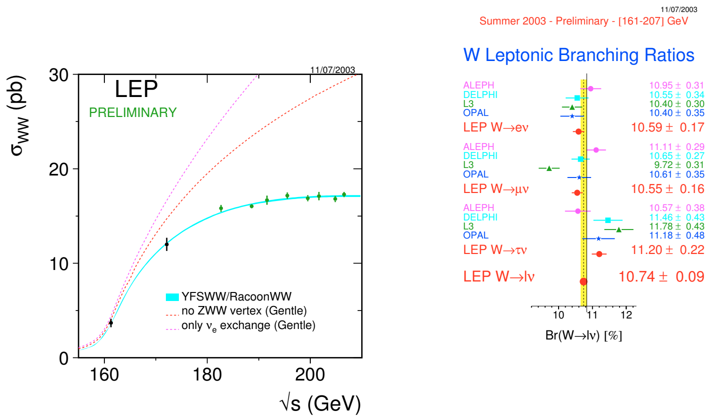

Figure 1: Measurements of the W-pair production cross-section and W leptonic branching fractions. The measured e W-pair production cross-section is compared to theoretical predictions (curve).

3 Triple Gauge coupling

The non-Abelian structure of the SM predicts the existence of coupling between the gauge bosons. The existence of the Triple Gauge Coupling (TGC) γWW and ZWW is unambiguously confirmed by measurements of σ_{WW} at LEP2 (see above). In the most general Lorentz invariant ansatz the TGC vertices are parametrised by 14 couplings [4]. Imposing C and P invariance and SU(2) symmetry, only three couplings are left to be studied: λ_γ, k_γ and g_1^Z. In the SM the values of these couplings are: $\lambda_\gamma = 0$, $k_\gamma = 1$, $g_1^Z = 1$. g_1^Z describes the ZWW vertex, while λ_γ and k_γ are related to the static magnetic dipole and electric quadrupole of the W boson.

TGCs affect the total production cross-section, the shape of the differential cross-section as a function of the polar W^- production angle and the polarization of the W. Deviations from the SM would lead to a modification of these quantities. Studies of the TGCs are performed by exploiting the information contained in the differential distributions of W boson production (θ_W) and decay angles. The analyses presented by each experiment make use of different combinations of each of these quantities. In general, however, all analyses use at least the expected variations of the total production cross-section and the W^- production angle. The measured multi-differential cross-section is compared to theoretical expectation, for which it is as important as for the total cross-section to take high-order electroweak corrections into account. At LEP additional information on TGCs can be obtained from single W production, which is particularly sensitive to κ_γ. Hence, some experiments include this channel in their analyses.

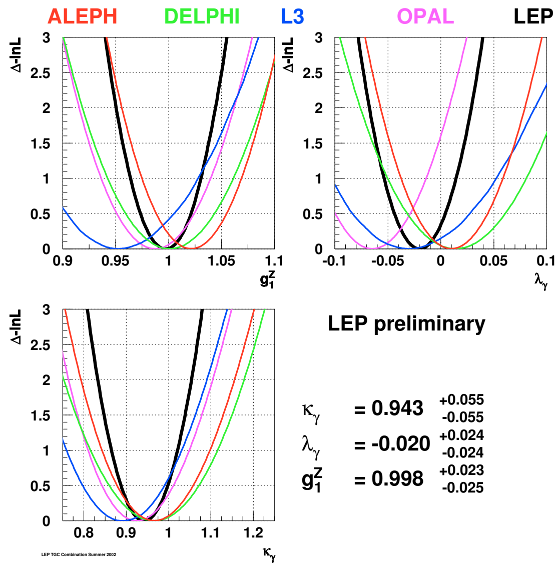

Figure 2: Likelihood curves for λ_γ, k_γ and g_1^Z for the four LEP experiments and the LEP combination.

The likelihood curves for λ_γ, k_γ and g_1^Z for the four LEP experiments [5] are shown in Figure 2. The combination of these measurement yields, [5]:

$$k_\gamma = 0.943 \pm 0.055,\ \ \lambda_\gamma = -0.020 \pm 0.024,\ \ g_1^Z = 0.998^{+0.023}_{+0.025},$$

a 5% precision measurement in good agreement with SM prediction. The dominant error is from higher electroweak corrections.

4 W polarization

In addition to the two possible transverse polarization states of massless spin-1 particle (e.g.γ), massive gauge boson should exist also in the longitudinal state. In the SM the polarization state is related to the mechanism of electroweak symmetry breaking in which three degrees of freedom of the scalar Higgs field generate the longitudinal states of the W and Z. Only transverse bosons are produced in weak process involving light fermions, while a considerable contribution from longitudinal prolarized W is expected in in W-pair production at LEP, making this helicity state experimentally accessible.

L3 extracted the different helicity states of the W boson by exploiting the angular distribution of the W decay products in the W rest frame. They fitted the expected angular distribution for the different helicity states to the data, corrected for efficiency and background The result clearly establish the existence of the longitudinal helicity state, Figure 3. OPAL measured the W polarization using the

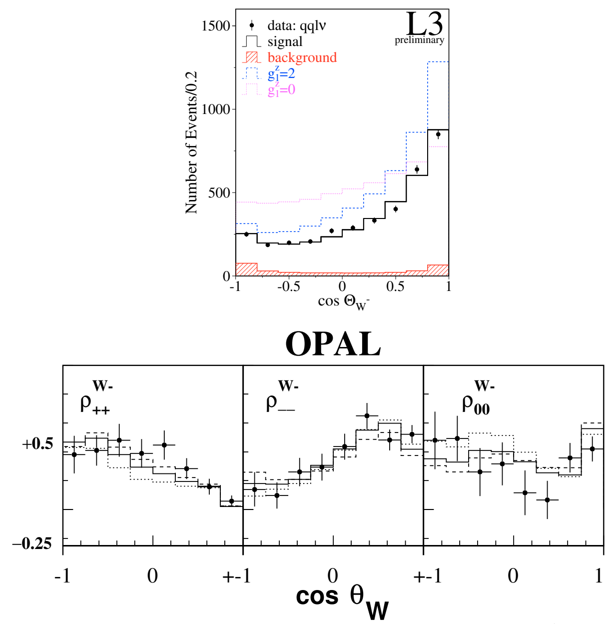

Figure 3: At the top, the L3 polar angular distribution. At the bottom, the OPAL SDM distribution.

Spin Density Matrix (SDM) method. The polarised differential cross sections are derived by multiplying the measured differential cross section with the corresponding diagonal elements of the single particle SDM element, corrected for efficiency and background. The polarization is then obtained by integrating over $\cos\theta_W$. The OPAL result also clearly show the existence of the longitudinal helicity state, Figure 3.

5 Quartic Gauge coupling

Within the Standard Model, quartic electroweak gauge boson vertices with at least two charged gauge bosons exist. In e^+e^- collisions at LEP2 centre-of-mass energies, WWZγ and WW$\gamma\gamma$ vertices contribute to WWγ production. However, their existence cannot be proven because at LEP energies the effect of SM quartic coupling is too small to be measurable. Hence, only limits on anomalous contributions to the quartic vertices are derived. Recently, OPAL performed an analysis in the WWγ final state [6]. The measured photon rate and spectrum is in agreement with the SM calculations. These data are used to derive 95 % confidence level upper limits on possible anomalous contributions to the WWZγ and WW$\gamma\gamma$ vertices:

$$-0.020\ \mathrm{GeV}^{-2} < \quad a_0/\Lambda^2 \quad < 0.020\ \mathrm{GeV}^{-2},$$
$$-0.053\ \mathrm{GeV}^{-2} < \quad a_c/\Lambda^2 \quad < 0.037\ \mathrm{GeV}^{-2},$$

$$-0.16\ \mathrm{GeV}^{-2} < \quad a_n/\Lambda^2 \quad < 0.15\ \mathrm{GeV}^{-2},$$

where Λ represents the energy scale for new physics and a_0, a_c and a_n are dimensionless coupling constants.

6 W boson mass

At tree level, the electroweak observables are fully determined by the mass of the Z boson, the Fermi constant, the electromagnetic coupling and the CKM matrix elements. Due to higher-order radiative corrections, the simple tree -level predictions are modified such Standard Model observables depend also on the strong coupling constant, the top mass and to lesser extent to the Higgs mass. In this context, the mass of the W boson provides indirect knowledge on the Higgs mass through higher-order radiative corrections ($\log(m_H^2/m_Z^2)$) and its precise measurement allows predictions of the Higgs mass. The final goal of LEP2 is to measure m_{W} with a precision of about 30-35 MeV; a lower uncertainty will not improve the knowledge on the Higgs mass, as the limiting factor is the current experimental precision of the top mass.

The first precision measurements of the W-boson mass were performed at $\mathrm{p\bar{p}}$ colliders. Using a W sample exceeding 200,000 events, CDF and D0 combined achieved: $m_{\mathrm{W}} = 80.454 \pm 0.060$ GeV, [7]. The sample of W bosons collected at LEP2 is significantly smaller, but the mass measurement benefits from a clean environment which allows more information to be extracted from each recorded event.

At an e^+e^- collider m_{W} can be either derived from the $\mathrm{W^+W^-}$ threshold cross section or from he direct reconstruction of the W boson's invariant mass from the observed W decay products on an event-by-event basis. For most of the time LEP2 has operated at energies significantly above the $\mathrm{W^+W^-}$ threshold, where the $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$ cross section has little sensitivity to m_{W}. Hence, only the direct reconstruction method is discussed here. Also the $\mathrm{W^+W^-} \to \ell^+\nu_\ell \ell'^- \overline{\nu}_{\ell'}$ channel has limited m_{W} sensitivity and is not discussed.

The invariant masses of the two W bosons are determined directly from the reconstructed momenta of observed decay products. Hadrons are grouped together into jets using clustering algorithms such as $k_\perp$. In $\mathrm{qq}\ell\nu$ events, charged leptons are identified and neutrinos are inferred from the missing energy and momentum.

Experimentally, the limiting factor in the mass resolution is the uncertainty in the jet energy measurement, which is poor in contrast to the measured jet directions. As the centre-of-mass energy is well known, the mass resolution can be improved significantly (factor ∼2–3) by imposing the constraints of energy and momentum conservation.

The reconstructed mass spectrum looks rather different from a pure relativistic Breit–Wigner distribution for several reasons. For example, the presence of initial state radiation (ISR) means that the energy producing the W pairs is always less than twice the incoming beam energy. This causes a tail toward higher invariant masses, as the collision energy assumed in the kinematic fit is overestimated. The detector resolution also tend to significantly smear out the line-shape as the experimental resolution is not significantly better than the W boson width for most channels. As a result, the W boson mass cannot be extracted by simply fitting an analytic Breit–Wigner shape, but all extraction methods need to be calibrated on a Monte Carlo simulation which includes all the various effects to model the dependence of the spectrum on m_{W}. Most of the systematic errors associated to m_{W} account for effects which may be missing in this Monte Carlo. Figure 4 shows some reconstructed mass spectra compared to the Monte Carlo predictions.

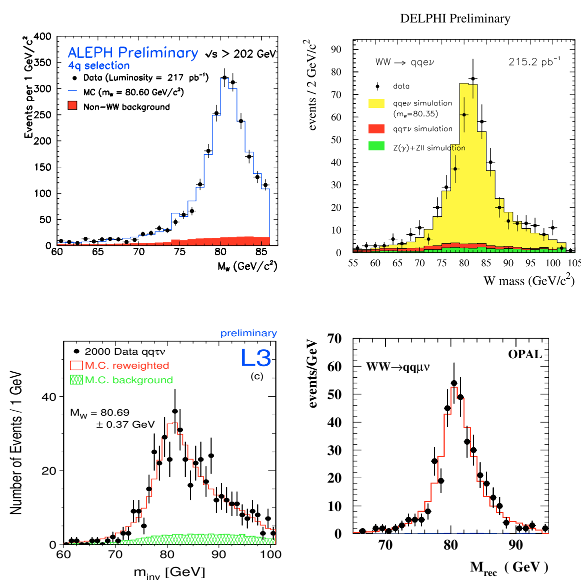

Figure 4: Reconstructed mass spectra from the LEP collaborations.

The most important uncertainties for the LEP W mass measurement are related to the modeling of the detector response, modeling the hadronization of quarks into jets, understanding the LEP beam energy, and final state interactions. To limit the uncertainty from detector modeling, the LEP collider was run from time to time throughout each running year at the Z^0 resonance to take large samples of Z^0 decays. These data, as well as similar samples at high energy, are used to study the detector response to leptons and jets and limit the deficiencies in the detector models.

Hadronization uncertainties are estimated by comparing different Monte Carlo implementations of the hadronization process and re-weighting key variables in Monte Carlo to correspond to data and propagating the effect to m_{W}.

The relative uncertainty in the LEP beam energy enters directly into the uncertainty in m_{W}, due to the use of kinematic fits. Uncertainties in beam energy are taken from the extrapolation to high energy the result of the resonant depolarisation measurement, which can only be done for beam energies below 60 GeV [8].

A significant bias in the apparent W mass measured in the $\mathrm{q\overline{q}q\overline{q}}$ channel could arise if the hadronisation of the two W bosons is not independent and correctly modeled. Standard Monte Carlo models assume that the two systems decay independently. However, interactions that can exchange momentum between the two W systems could distort the final W line-shape. Two specific phenomena are known to exist, but with rather uncertain strengths: colour reconnection (CR) [9] and Bose–Einstein correlations (BEC) [11]. Effects on the mass of such interactions are estimated by using phenomenological models and direct searches for these effects limit the viable set of such models.

The four LEP collaborations combine their results taking into account systematic uncertainties which are correlated between channels, experiments, and years of LEP running. This combination procedure is still evolving, as better information about the nature of these various correlations becomes available.

At present, the preliminary combined LEP W mass result from direct reconstruction is [13]: $m_{\mathrm{W}} = 80.412 \pm 0.042, \mathrm{GeV}$. As can be seen in the detailed breakdown of the direct measurements uncertainties shown in Table 1, the qqqq channel has rather large uncertainties associated with Bose–Einstein correlations and colour reconnection. Due to these uncertainties, the qqqq channel carries a weight of only 9% in the combined result, even though it is statistically more precise.

The direct reconstruction method employed at LEP2 is sensitive to the W width as well as the W mass. In the standard mass analyses, the width i fixed to the Standard Model expectation for a given mass value. The width is extracted allowing it to be a second free parameter in the fits. The LEP combined value of measurements is $\Gamma_{\mathrm{W}} = 2.150 \pm 0.091$ GeV in agreement with the the SM expectation.

Source	δm_{W} (MeV)		
	$\mathrm{q\overline{q}}\ell^{\pm}\nu_{\ell}$	$\mathrm{q\overline{q}q\overline{q}}$	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

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

6.1 Colour Reconnection

In qqqq events, the products of the W decays in general have a significant space-time overlap as the separation of their decay vertices is small compared to characteristic hadronic distance scales. Colour reconnection refers to a rearrangement of the colour flow between the two W bosons. The effects of interactions between the colour singlets during the perturbative phase are expected to be small. The situation is less clear in the non-perturbative phase, where phenomenological models are implemented in hadronic Monte Carlos. A higher susceptibility to CR (and more $\mathrm{Z}^0 \rightarrow \mathrm{q\overline{q}}$ background) is expected when W^+ and W^- hadronisation regions overlap, so the space-time picture of the QCD shower development is important.

The predicted (barely) observable effects of CR include changes to the charged particle multiplicity, momentum distributions and the particle flow relative to the 4-jet topology.

Colour reconnection effects tend to enhance or suppress particle production in the regions between the main jets. Currently, all four LEP collaborations are pursuing analyses aimed at measuring the particle flow distribution in qqqq final states with the ultimate aim of discriminating between various CR models. Combining the results of these analyses, taking into account their different sensitivities, it is found that the no-CR scenario agrees with data only at the level of 2σ and a moderate reconnection fraction is preferred. However, no definitive conclusion can be drawn.

The most sensitive estimator of CR is the invariant mass of the W boson measured in the qqqq channel. Removing low momentum particles reduces the bias due to CR for all investigated models. This can be achieved in two ways, either with a cut on the particle momentum either using a modified jet algorithm. Both methods give similar results. All LEP experiment are doing this analyses and DELPHI already presented some preliminary results in [10]. Since this method is almost uncorrelated with the particle flow method, a combination of the two is foreseen.

With all four LEP experiments combined, it is likely that one can achieve a 5σ evidence of CR and be able to reduce the significantly the uncertainty on the W mass from its current value.

6.2 Bose-Einstein correlation

Bose-Einstein correlation leads to the enhanced production of identical boson pairs, such as $\pi_1^+\pi_2^+$ or $\pi_1^-\pi_2^-$, at small 4-momentum difference, $Q^2_{1,2}$. This phenomena is firmly established in hadronic Z^0 at LEP1 and between the particles of a single W boson at LEP2. Since the W boson decay length (0.1 fm) is significantly shorter than the hadronization scale (1 fm), it is entirely plausible that there can be additional BE effects between particles originating from different W bosons in qqqq events.

Traditionally, BEC is studied using a 2-particle correlation function: $R_{1,2} = \rho_2(1,2)/\rho_0(1,2)$, where ρ_2 and ρ_0 are 2-particle densities with and without BEC, respectively. One serious problem in this area is the construction of the reference sample, ρ_0, in a model independent way. All four LEP collaborations use the technique described in [12] to construct such a sample (apart from background subtraction). This method involves mixing pairs of data events, such as the hadronically decaying W in $qq\ell\nu$Ḋata from two semi-leptonic $qq\ell\nu$ events are mixed (without the lepton) and compared to data from genuine qqqq events. In a rigorously model–independent test, these two samples should look identical if there is no BEC present between the decay products of different W bosons. Some of the LEP experiments are still finalizing their results.

The systematic uncertainty on m_{W} due to BEC will be derived from the final combined LEP results. The mass bias is expected to be reduced to few MeV.

7 Conclusions and Perspectives

The combined electroweak data is often summarized as shown in Figure 6. The first plot in this figure shows m_{W} versus m_{t} : the direct measurements, the indirect electroweak data, and the Standard Model prediction as a function of the Higgs mass. It can be seen that the precise input data from LEP and SLD predicts values of m_{W}

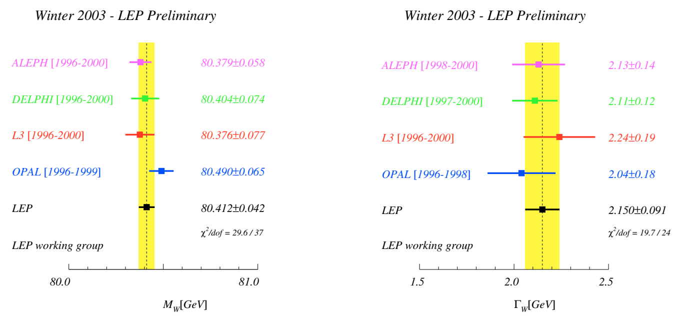

Figure 5: LEP results on the mass and width of the W boson.

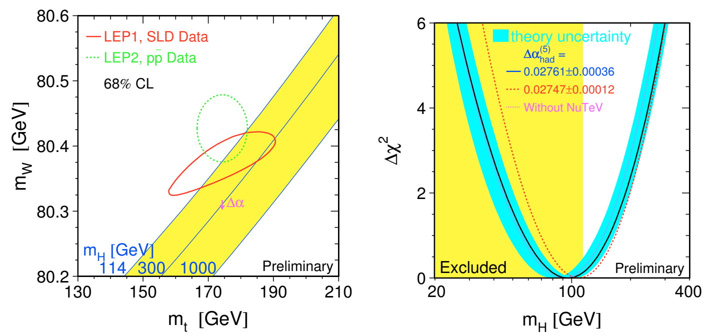

Figure 6: World combined electroweak results.

and $m_{\rm t}$ consistent with those observed, demonstrating that electroweak correction can correctly predict the mass of heavy particles. It is observed that both input data and direct measurement of $m_{\rm W}$ and $m_{\rm t}$ favour a light Higgs. It can also be seen from this plot that significant improvements in the uncertainty on $m_{\rm W}$ will not be very useful if they are not accompanied by comparable improvements in $m_{\rm t}$. The second plot shows the variation of the minimum value of the χ^2 as a function of $\rm M_H$ for the full electroweak fit. The best-fit value of the Higgs mass is $\rm M_H = 96^{+60}_{-38}GeV$, where the error is asymmetric as the leading corrections depends on $\rm log M_H$, from which the constraint $\rm M_H < 219 GeV$ at 95% C.L. can be derived.

The next five years will see measurements of similar precision performed at the Tevatron with the advent of Run II. Further substantial improvement in precision will have to wait for the Large Hadron Collider and the future Linear Collider.

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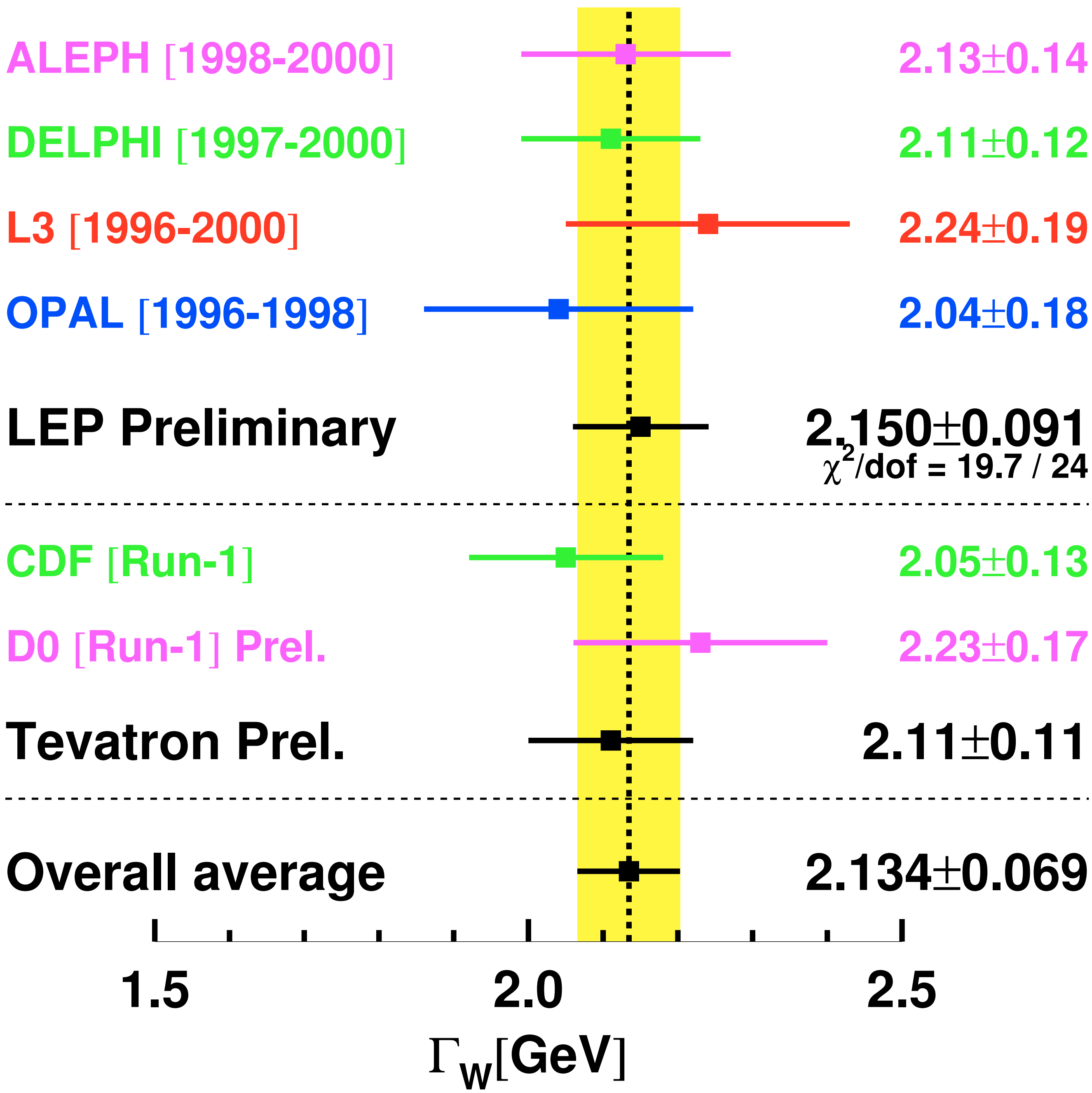
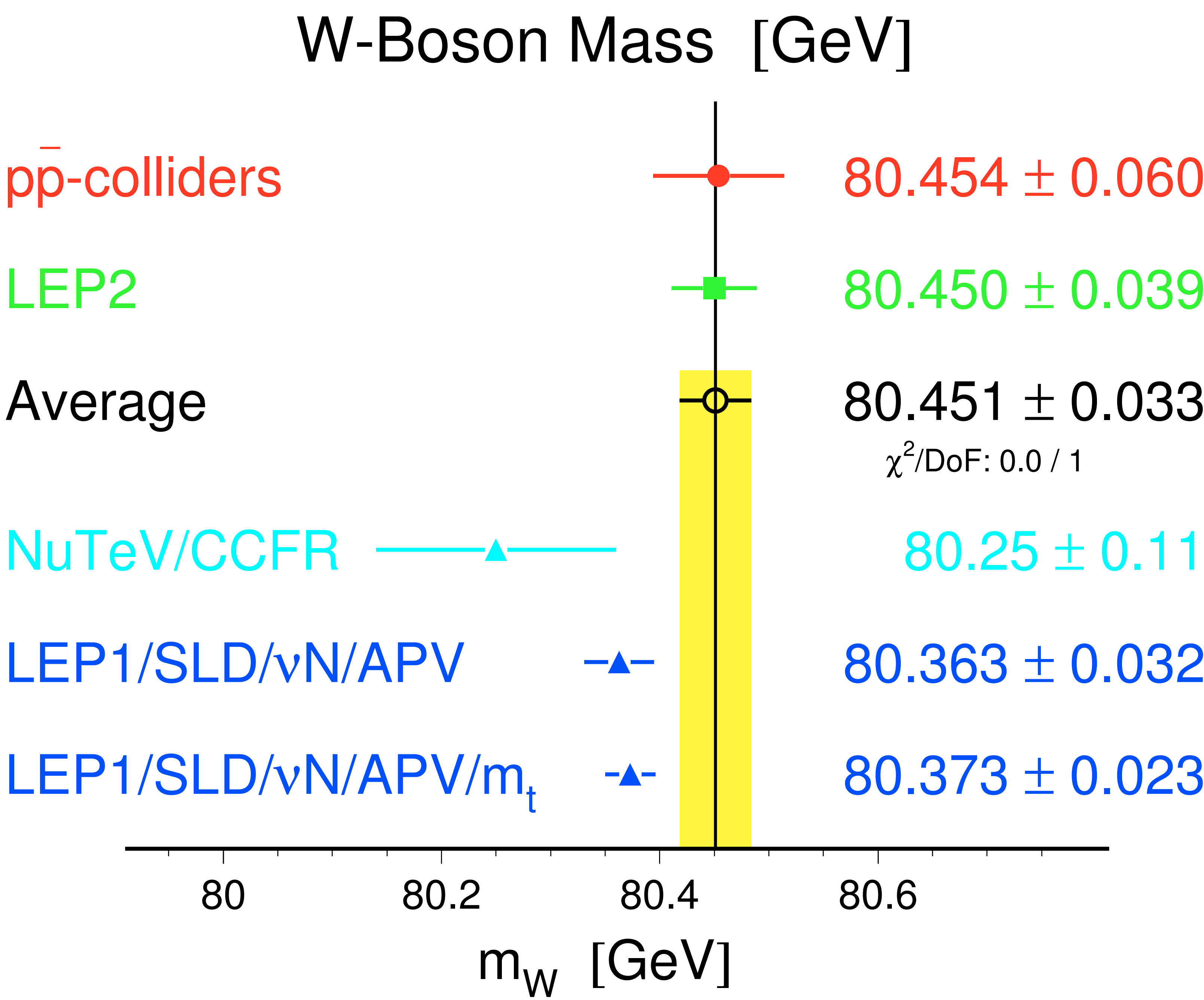
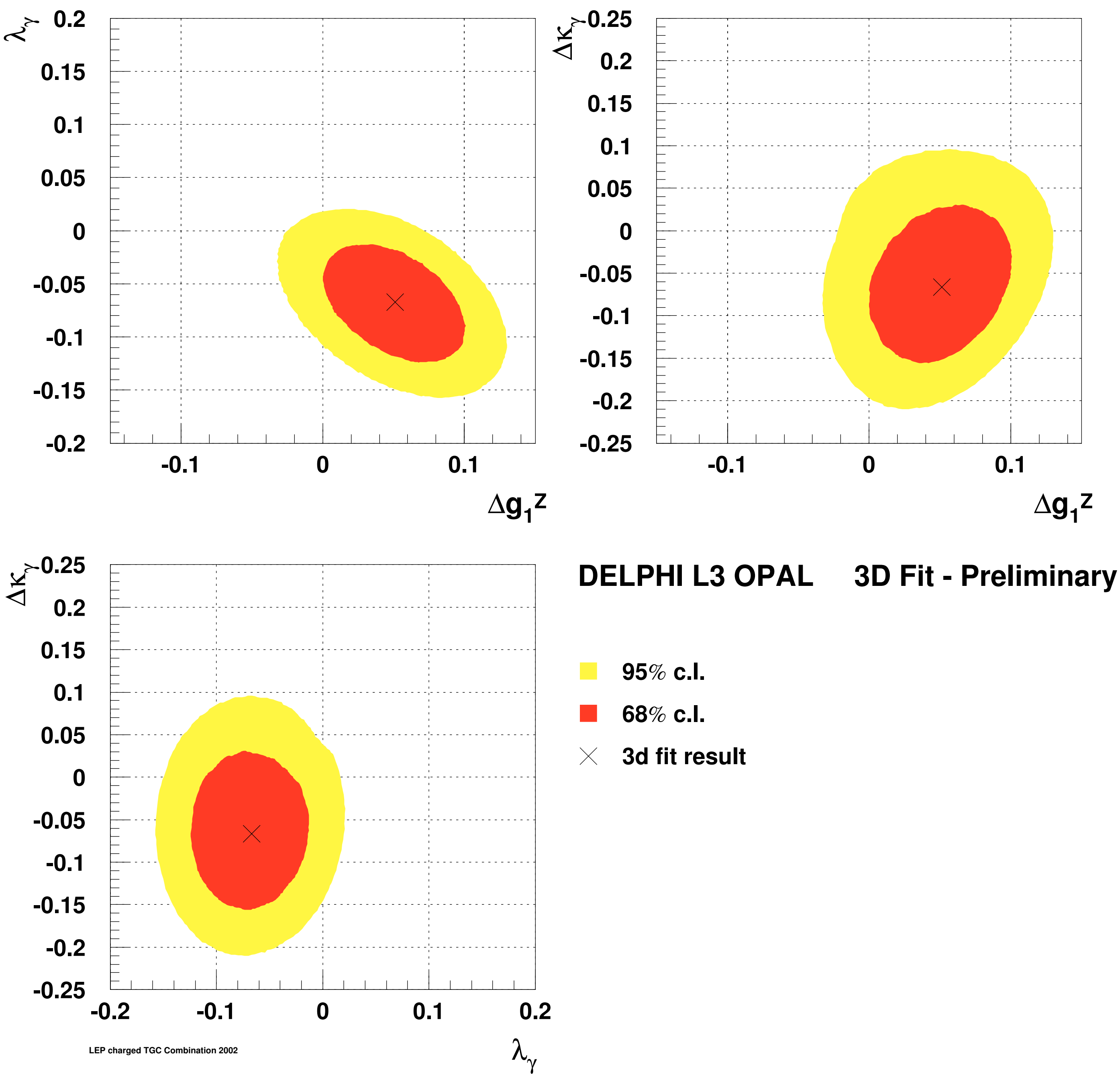


ALEPH [1998-2000]
2.13±0.14
DELPHI [1997-2000]
2.11±0.12
L3 [1996-2000]
2.24±0.19
OPAL [1996-1998]
2.04±0.18
LEP Preliminary
2.150±0.091
χ²/dof = 19.7 / 24
CDF [Run-1]
2.05±0.13
D0 [Run-1] Prel.
2.23±0.17
Tevatron Prel.
2.11±0.11
Overall average
2.134±0.069
1.5
2.0
2.5
Γ_W[GeV]


W-Boson Mass [GeV]
pp̄-colliders
80.454 ± 0.060
LEP2
80.450 ± 0.039
Average
80.451 ± 0.033
χ²/DoF: 0.0 / 1
NuTeV/CCFR
80.25 ± 0.11
LEP1/SLD/νN/APV
80.363 ± 0.032
LEP1/SLD/νN/APV/m_t
80.373 ± 0.023
80
80.2
80.4
80.6
m_W [GeV]



λ_γ
Δg_1^Z
$\Delta\kappa_\gamma$
Δg_1^Z
$\Delta\kappa_\gamma$
λ_γ
DELPHI L3 OPAL 3D Fit - Preliminary
95% c.l.
68% c.l.
3d fit result
LEP charged TGC Combination 2002