Overview of Standard Model Results from LEP and Tevatron

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Abstract

This article describes the status of experimental tests of the Standard Model of Electroweak Interactions in e^+e^-- and $p\bar{p}$-collisions. Precision measurements from the LEP and SLC experiments at the Z resonance are discussed as well as results obtained above the Z pole. Precise determinations of the properties of the W boson are achieved at LEP and the Tevatron. A combined analysis of precision electroweak measurements in the framework of the Standard Model leads to an estimate and an upper limit for the mass of the Higgs boson.

1 Introduction

For one decade precision tests of the Standard Model of Electroweak Interactions (SM) [1] in e^+e^--collisions have been performed by the experiments at the LEP and SLC colliders. The properties of the Z boson, its mass, total and partial decay widths as well as the couplings to fermions, have been measured to very high accuracy. These measurements are sensitive to higher order electroweak radiative corrections and enable tests of the theory beyond the tree level.

The LEP collider continued the experimental program providing e^+e^--collisions up to center-of-mass energies of 208 GeV. At these energies photon and Z boson exchange contribute both to the production of fermion pairs allowing the test of electroweak unification. All gauge bosons of the SM are produced in pairs permitting studies of their self-couplings, some of which are predicted by the non-abelian gauge structure of the model. An important measurement is the precise determination of the W boson mass which confronted to the measurements at the Z resonance consists a crucial test of the theory.

The tests of the SM in e^+e^--annihilations are complemented by the experiments performed at the Tevatron $p\bar{p}$-collider. Most importantly, the discovery of the top quark and the measurements of the top quark and W boson masses contribute to the experimental verification of the theory.

Comparing the direct mass measurements of the W boson and the top quark with values derived from the measurements of electroweak couplings and higher

Table 1: Combined result of the four LEP experiments on Z boson parameters.

$$\begin{aligned}
m_Z &= 91\,187.5 \pm 2.1\ \text{MeV} \\
\Gamma_Z &= 2\,495.2 \pm 2.3\ \text{MeV} \\
\sigma^0_{\text{had}} &= 41.540 \pm 0.037\ \text{nb} \\
R_\ell &= 20.767 \pm 0.025 \\
A^{0,\ell}_{\text{FB}} &= 0.0171 \pm 0.0010
\end{aligned}$$

order weak corrections allows to verify the SM beyond the tree level. The observed consistency provides great confidence into the validity of the SM and encourages the use of all experimental data to predict the mass of the last unobserved particle of the model: the Higgs boson.

2 Measurements at the Z Resonance

Between 1989 and 1995 the LEP experiments ALEPH, DELPHI, L3 and OPAL have performed precision measurements at the Z resonance of total cross sections and leptonic forward-backward asymmetries of the reactions:

$$e^+e^- \to \text{hadrons}\,,\ e^+e^- \to e^+e^-\,,\ e^+e^- \to \mu^+\mu^-\,,\ e^+e^- \to \tau^+\tau^-\,. \tag{1}$$

In total about 17 million Z decays have been observed by the four experiments allowing measurements at the permille level. From these measurements the properties of the Z boson are extracted and averages [2] over the four LEP experiments are obtained as listed in Tab. 1. In addition to the mass m_Z and total width Γ_Z of the Z, the results are parametrized in terms of the hadronic pole cross section $\sigma^0_{\text{had}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_{\text{had}}}{\Gamma_Z^2}$, the ratio of hadronic to the common leptonic width $R_\ell = \frac{\Gamma_{\text{had}}}{\Gamma_\ell}$, and the leptonic pole forward backward asymmetry $A^{0,\ell}_{\text{FB}} = \frac{3}{4}A_e A_\ell$, where the polarization parameter $A_\ell = \frac{2\bar{g}^\ell_V\bar{g}^\ell_A}{(\bar{g}^\ell_V)^2+(\bar{g}^\ell_A)^2}$ $(\ell = e, \mu, \tau)$ is defined by the effective vector- and axial-vector coupling constants of leptons, $\bar{g}^\ell_V$ and $\bar{g}^\ell_A$ [3]. These parameters are chosen as they reveal small correlations and are therefore suitable for averaging over the experiments. Two examples of the measurements are shown in Fig. 1.

One of the most important achievements of the experiments at the Z is the determination of the number of neutrino generations. The most sensitive measurement is the hadronic pole cross section σ^0_{had} which due to the increase in the total width Γ_Z would be lower than the observed value if there was an additional neutrino generation. This is illustrated by the result of the L3 experiment shown in Fig. 2.

In order to extract electroweak parameters from the measurements, precise theoretical calculations are as important as the experiments themselves. Two computer programs were used by the LEP collaborations to calculate cross

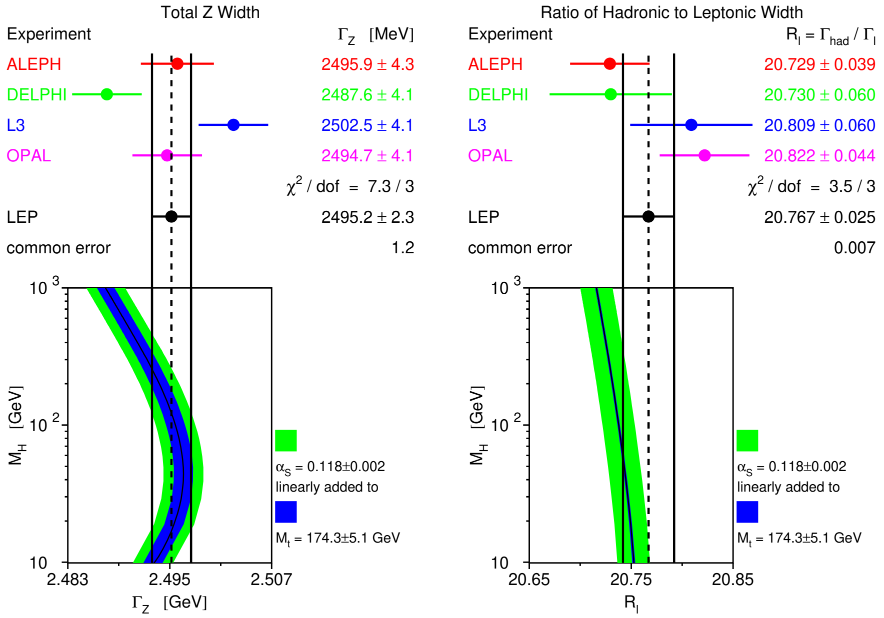

Figure 1: Comparison and average of observables at the Z resonance as measured by the four LEP experiments. Left: the total width of the Z boson, Γ_Z. Right: the ratio of the hadronic partial width to the width in one charged lepton species, R_ℓ.

sections, asymmetries and other electroweak observables: ZFITTER [4] and TOPAZ0 [5]. The contributions from t-channel boson exchange and the s-t interference in $e^+e^- \to e^+e^-$ were calculated using ALIBABA [6]. Many authors have contributed with higher order calculations to these programs such that theoretical uncertainties which are included in the results do not limit the experimental precision. The success of the LEP experiments is to large extent due to this very fruitful collaboration between experimentalists and theorists.

Very important contributions to the precise determination of effective couplings of leptons and quarks to the Z boson are provided by the SLD experiment at the SLC e^+e^--collider which has the unique feature of a high degree of polarization of the electron beam. From the relative difference of total cross sections at the Z for left- and right-polarized incoming electrons, $A_{LR} = (\sigma_{e_L} - \sigma_{e_R})/(\sigma_{e_L} + \sigma_{e_R}) = A_e$, the couplings of the electron can be measured precisely. Between 1989 and 1998 the SLD experiment collected approximately 550 000 $e^+e^- \to$ hadrons events with polarization of about 75% for most of these data which results in a measurement of the electron polarization parameter:

$$A_e = 0.1514 \pm 0.0022\,. \tag{2}$$

Due to helicity conservation at the vertex the couplings of the final state fermions in $e^+e^- \to f\bar{f}$ can be determined from the polar angular distributions

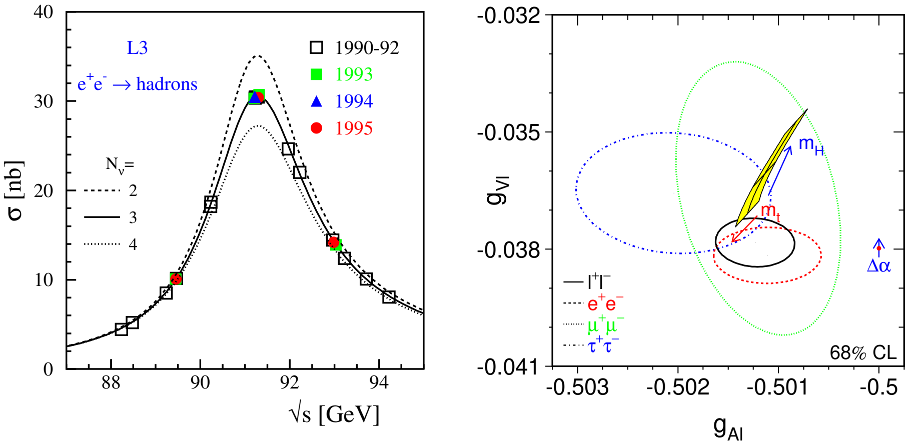

Figure 2: Left: The total hadronic cross section measured by the L3 experiment compared to expectations with different numbers of neutrino generations. Right: Contours in the plane of the effective coupling constants $\bar{g}_{\mathrm{A}}^{\ell}$ and $\bar{g}_{\mathrm{V}}^{\ell}$ obtained from measurements of the partial widths and various asymmetries by the experiments at the Z resonance.

observed for different polarizations of the electrons [7], the left-right forward-backward asymmetry. This allows the determination of A_μ and A_τ which together with the LEP measurements of Γ_ℓ, $A_{\mathrm{FB}}^{0,\ell}$ and the tau polarization results in precise determinations of the effective couplings of charged leptons to the Z. The combined result is shown in Fig. 2 as contours in the $\bar{g}_{\mathrm{A}}^{\ell}$-$\bar{g}_{\mathrm{V}}^{\ell}$-plane for the three lepton species and their average. The overlap of the contours is a strong confirmation of lepton universality in neutral current interactions which can be quantified by forming ratios of coupling constants:

$$
\begin{aligned}
\bar{g}_{\mathrm{A}}^{\mu}/\bar{g}_{\mathrm{A}}^{\mathrm{e}} &= 1.0002 \pm 0.0014\,, \\
\bar{g}_{\mathrm{A}}^{\tau}/\bar{g}_{\mathrm{A}}^{\mathrm{e}} &= 1.0019 \pm 0.0015\,, \\
\bar{g}_{\mathrm{V}}^{\mu}/\bar{g}_{\mathrm{V}}^{\mathrm{e}} &= 0.962 \pm 0.063\,, \\
\bar{g}_{\mathrm{V}}^{\tau}/\bar{g}_{\mathrm{V}}^{\mathrm{e}} &= 0.958 \pm 0.029\,. \qquad (3)
\end{aligned}
$$

In particular for the axial-vector coupling constant lepton universality holds to the 10^{-3} level.

Because Z decays into b- and c-quarks can be identified with reasonable efficiency in hadronic events the couplings of these heavy quarks can be determined using the same observables as for charged leptons. The results are shown in Fig. 3 as contours together with the combined leptonic polarization parameter A_ℓ which is shown as vertical band. The horizontal bands display the measurements of A_{b} and A_{c} by SLC whereas the curves stem from the measurements of the quark forward-backward asymmetries. The curves overlap for

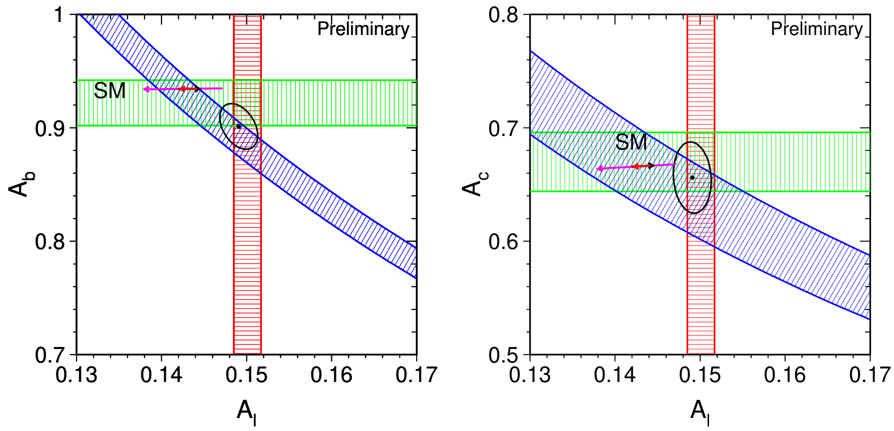

Figure 3: Polarization parameters for heavy quarks, A_{b} and A_{c}, versus A_ℓ as measured from observables at LEP and SLD.

both quarks but in the case of the b-quark the value of A_{b} is about two standard deviations away from the SM prediction. A more detailed analysis reveals that this potential discrepancy with the SM can be cast into the right-handed b-quark coupling [2].

The measured asymmetries at the Z discussed above can be compared in terms of the effective weak mixing angle $\sin^2\overline{\vartheta}_{\mathrm{W}}$ (Fig. 4). Averaging all measurements yields:

$$\sin^2\overline{\vartheta}_{\mathrm{W}} = 0.23148 \pm 0.00017\,. \tag{4}$$

The relatively poor χ^2 value of 10.2/5 is caused by the different tendencies of leptonic and hadronic asymmetries mentioned above.

The world average of $\sin^2\overline{\vartheta}_{\mathrm{W}}$ points to a low value of the Higgs mass as can be seen at the bottom of Fig. 4 (left) where the SM expectation is shown as a function of m_{H}. Apart from the unknown Higgs mass, the knowledge of the top quark mass and the contribution of the five light quarks to the running of the QED coupling constant, $\Delta\alpha^{(5)}_{\mathrm{had}}$, contribute to the uncertainty in the calculation of $\sin^2\overline{\vartheta}_{\mathrm{W}}$.

3 Measurements Above the $\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^-$ Threshold

The second part of the program of the LEP experiments (LEP II) explored the energy region above the threshold for W-pair production, i.e. for center-of-mass energies between 160 and 208 GeV. This physics is illustrated in Fig. 4 (right) where cross sections for most reactions in $\mathrm{e}^+\mathrm{e}^-$-annihilation are plotted from the Z resonance to the highest LEP energy. One observes that the measurements are

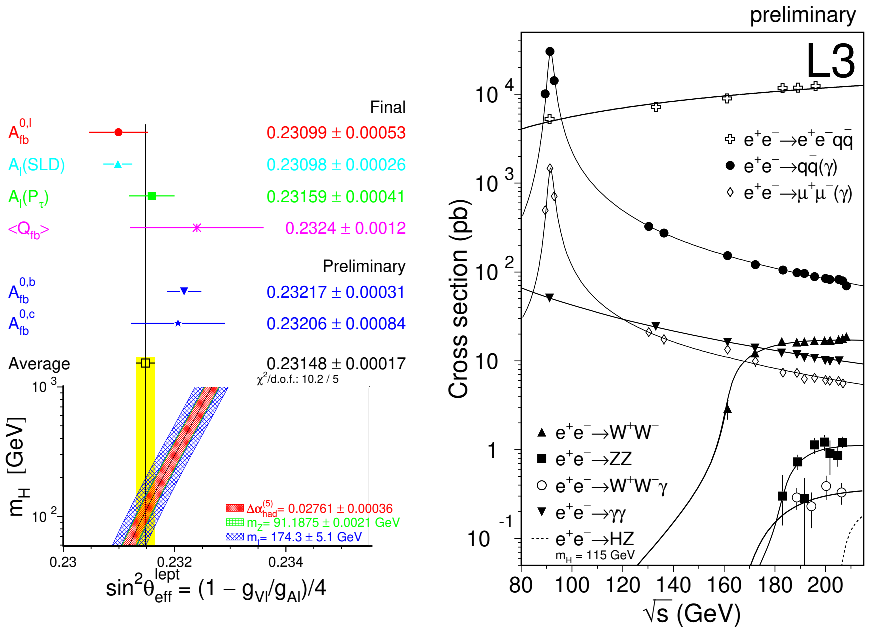

Figure 4: Left: Comparison of the effective weak mixing angle $\sin^2\overline{\vartheta}_{\rm W}$ from different measurements at the Z pole. Right: Comparison of SM cross sections from the Z resonance to 208 GeV as measured by the L3 experiment.

in excellent agreement with the SM expectations for two-photon interactions, fermion-pair production and the production of boson pairs, in particular $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$ and $\mathrm{e^+e^-} \to \mathrm{ZZ}$ which was studied for the first time at LEP. The production of Higgs bosons, shown by the cross section $\mathrm{e^+e^-} \to \mathrm{HZ}$ for a mass value at the edge of the reach of the experiments, $M_{\rm H} = 115$ GeV, was not observed.

A more detailed comparison of the measurements and the SM predictions of the s-channel production of fermion-pairs is given in Fig. 5. The figures show the measurements averaged over the four experiments of the total cross sections $\mathrm{e^+e^-} \to$ hadrons, $\mu^+\mu^-$, $\tau^+\tau^-$ and the leptonic forward-backward asymmetries. Agreement at the percent level is observed.

Another very important test of the SM was performed by the study of boson pairs. The combined cross sections measurements of $\mathrm{W^+W^-}$ and ZZ final states are compared in Fig. 6 to the SM expectations. The important conclusion to be drawn from the agreement of the $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$ cross section is that the triple boson vertices ZWW and γWW do exist and that their couplings are just as predicted by the theory which keeps this cross section finite. A more detailed analysis taking into account differential distributions and other sensitive channels (single W and single photon production) limits possible deviations from the SM values of these couplings to the percent level [2]. Likewise, from the

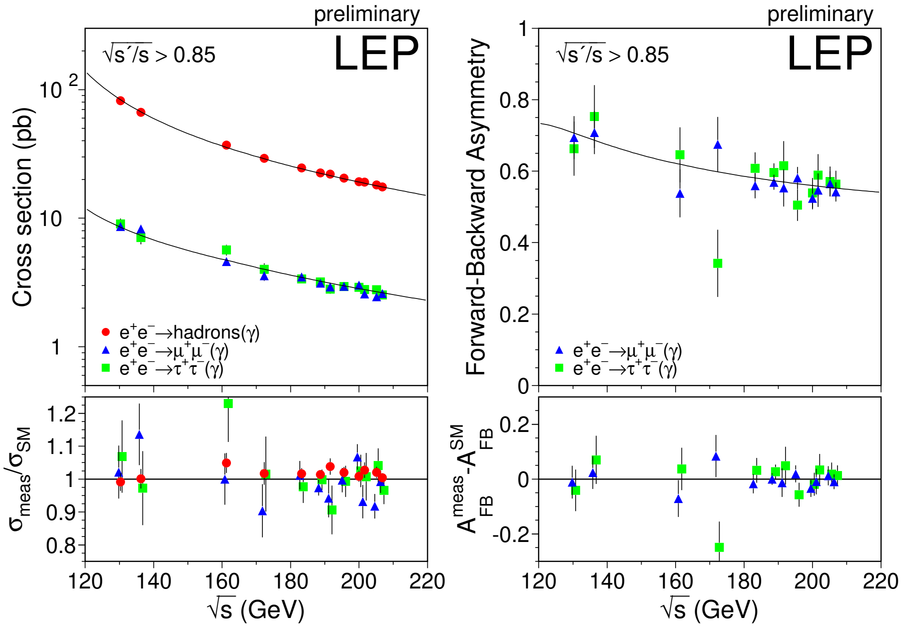

Figure 5: Combined measurements of total cross sections and forward-backward asymmetries at the highest LEP energies.

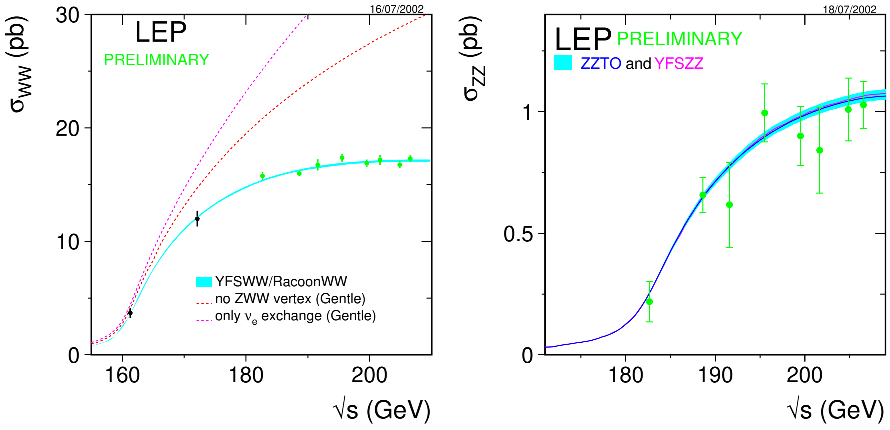

Figure 6: Cross sections of boson-pair production $e^+e^- \to W^+W^-$ and $e^+e^- \to ZZ$ at LEP.

study of $e^+e^- \rightarrow$ ZZ, which has a cross section about an order of magnitude smaller, one concludes that triple vertices involving neutral bosons, ZZZ or γZZ, do not exist which is again in agreement with the SM.

Complementing the studies of the properties of the Z boson during the first part of the LEP program the second phase provided an ideal place to study the W boson. The first example discussed here is the observation of the longitudinal polarization state which a massive spin-1 boson like the W should possess in addition to the two states of transverse polarization of the photon. The W helicity is inferred from the angular distribution of the fermions in the W rest frame and the experimental result of the L3 experiment (Fig. 7) shows that the third state is required to explain the data. The quantitative results is that a fraction of 0.218 ± 0.0031 of the W bosons is in the longitudinal polarization state which compares well to the expectation of 0.24.

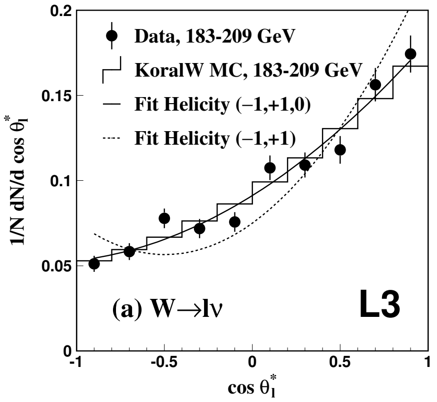

Figure 7: L3 measurement of the W polarisation from the energy spectrum in W decays to electrons and muons.

Only transverse W bosons are produced in weak processes involving light fermions and therefore at the moment the decay of top quarks is the only other place to observe longitudinal W bosons. The CDF experiments obtains 0.91 ± 0.52 for this fraction which agrees with the SM expectation of 70%.

An important measurement for precision tests of the SM is the determination of the W mass. At LEP the mass of the W boson is determined from invariant mass distributions in $e^+e^- \rightarrow$ WW events. To improve the mass resolution kinematic fits are employed imposing energy and momentum conservation. The four final states $q\bar{q}\,\ell\nu$, $(\ell = e, \mu, \tau)$ and $q\bar{q}\,q\bar{q}$ are used and the W mass is extracted by fitting re-weighted Monte Carlo samples to the observed distributions. About 10 000 W pairs have been collected by each experiment.

As the kinematic fit imposes energy conservation the absolute scale of the W mass is determined by the LEP beam energy. The method of resonant depolarization used at the Z resonance cannot be applied above the W pair threshold.

Therefore magnetic extrapolations are required which limit the knowledge of the beam energy to a precision of $2 \cdot 10^{-4}$ causing an error of ± 17 MeV on m_{W} common to all LEP experiments.

A particular problem of the W mass measurement in $\mathrm{e^+e^-} \to \mathrm{q\bar{q}q\bar{q}}$ final states are interactions between the decay products of the two different W bosons: colour reconnection and Bose-Einstein correlations. The first effect arises because the typical distance between the decay points of the two W bosons (0.1 fm) is much smaller than the hadronisation scale of the quarks (1 fm). Gluons are exchanged between quarks from different W bosons implying a momentum transfer and hence a possible bias in the measurement of the invariant masses.

Obeying Bose-Einstein statistics identical mesons from quark fragmentation tend to occupy the same place in momentum space. Such correlations are experimentally established in hadronic Z and W decays whereas they are not confirmed between mesons stemming from different W bosons. The uncertainty on these correlations together with the imperfections in their modelling may lead to a bias in the W mass reconstruction.

Although there is no experimental evidence for either of the two effects in $\mathrm{e^+e^-} \to \mathrm{q\bar{q}q\bar{q}}$ they cause a systematic error of $\mathcal{O}(100\ \mathrm{MeV})$ on m_{W} determined from these events and hence reduce significantly the weight of this channel as compared to the semi-leptonic channels. The results on m_{W} together with the average of the four experiments are displayed in Fig. 8.

4 Results on the W-Boson and the Top-Quark from the Tevatron

Precise measurements of the W mass are also performed by the experiments at the Tevatron CDF and DØ. About 50 000 $\mathrm{W} \to \ell\nu$ ($\ell = \mathrm{e}, \mu$) were collected by each detector in Run I which took place between 1988 and 1995. The mass of the W is derived from fits to the measured transverse mass and momentum distributions. The absolute scale of the W mass is determined from the observed leptonic Z boson decays where the measured Z mass is compared to the precise LEP measurement (Tab. 1). The combined result of the two experiment is of comparable precision to the LEP measurement:

$$m_{\mathrm{W}} = 80.454 \pm 0.059\ \mathrm{GeV} \qquad \text{(Tevatron)}. \tag{5}$$

A comparison of different determinations of the W mass is shown in Fig. 9. The direct determinations of m_{W} in $\mathrm{p\bar{p}}$ and $\mathrm{e^+e^-}$ collisons are in good agreement and their combination results in a precise measurement of m_{W}:

$$m_{\mathrm{W}} = 80.426 \pm 0.034\ \mathrm{GeV} \qquad \text{(LEP and Tevatron)}. \tag{6}$$

In passing we note that a discrepancy is observed with the indirect determination of m_{W} obtained from measurements of the weak mixing angle

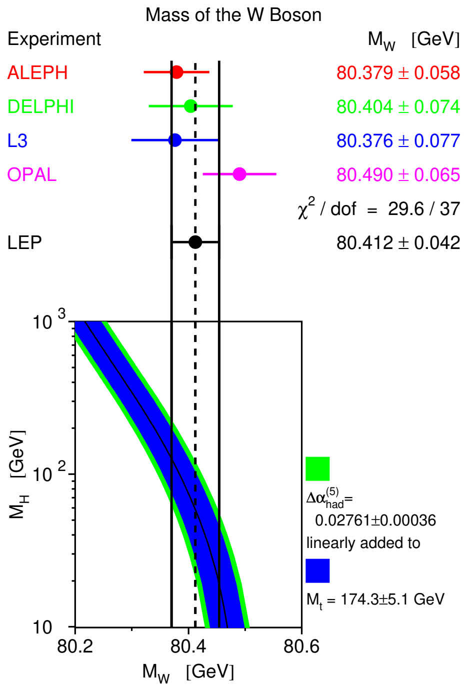

Figure 8: Measurements of the W mass at LEP. Correlated errors from final state interactions and the LEP beam energy calibration are included in the results.

$\sin^2\vartheta_{\mathrm{W}} = 1 - m_{\mathrm{W}}^2/m_{\mathrm{Z}}^2$ in neutrino-nucleon scattering by the NuTeV experiment. This problem is being investigated.

Fig. 9 also contains indirect measurements of m_{W} obtained from the precision measurements at the Z pole. For instance the W mass can be readily derived from the measurement of the weak mixing angle as can be seen from its on-shell definition $\sin^2\vartheta_{\mathrm{W}} \equiv 1 - m_{\mathrm{W}}^2/m_{\mathrm{Z}}^2$. The equality of the direct and indirect W mass measurements is an experimental confirmation of one of the cornerstones of the SM, namely the double role of the heavy gauge bosons as observable particles with masses determining electroweak couplings. In other words, the ratio of the W masses derived from the two approaches consists a measurement of the ρ-parameter which, apart from higher order corrections, is unity in the minimal SM with one Higgs doublet [8].

A unique contribution of the Tevatron experiments to precision tests of the SM is the measurement of the mass of the top quark. During Run I about 100 $\mathrm{t\bar{t}}$ events per experiment have been observed. The main production mode is quark annihilation $\mathrm{q\bar{q}} \to \mathrm{t\bar{t}}$ mediated by gluon exchange. The decay of the top proceeds through $\mathrm{t} \to \mathrm{Wb}$ such that the signature of $\mathrm{t\bar{t}}$ is given by the decay products of a $\mathrm{W^+W^-}$-pair as discussed for the case of LEP II plus two b-jets. The semi-leptonic decay $\mathrm{W^+W^-} \to \mathrm{q\bar{q}}\,\ell\nu$ is the most sensitive channel as it

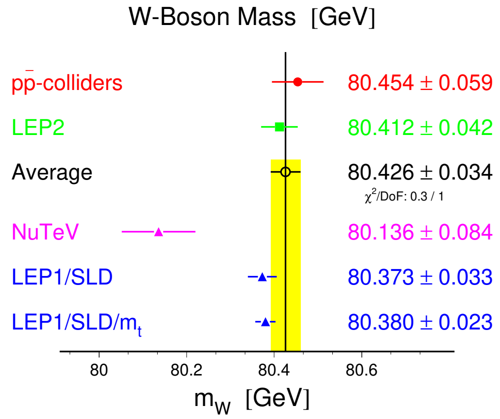

Figure 9: Comparison of W mass measurements. The direct measurements at $p\bar{p}$ colliders and at LEP are averaged and compared to indirect determinations.

combines a high branching ratio and signal purity. The result averaged over the decay channels and both experiments is

$$m_{\rm t} = 174.3 \pm 5.1 \text{ GeV} \qquad \text{(Tevatron)}. \tag{7}$$

A significant improvement of this number is expected in near future from an improved analysis of the data and the increased statistics from the ongoing Run II.

5 Interpretation of the Results and Tests of the Standard Model

The direct measurement of the top quark mass at the Tevatron can be used to test the SM beyond the tree level. Due to its large mass the top quark causes large quantum corrections to the W propagator in a similar way as the QED coupling constant is modified through loop diagrams. These weak radiative corrections depend quadratically on $m_{\rm t}$. Therefore the precision measurement of cross section and asymmetries at the Z pole depend on $m_{\rm t}$ and can be interpreted in terms of the top mass

$$m_{\rm t} = 172^{+12}_{-\ 9} \text{ GeV} \qquad \text{(from Z observables)}, \tag{8}$$

which is in perfect agreement with the direct measurement. This result is illustrated in Fig. 10 (left) where direct and indirect measurements of the W and the top mass are compared. The agreement of the directly measured top quark mass with the value inferred from electroweak observables confirms the existence of weak radiative corrections. Their magnitude is as predicted by the SM which shows that the theory is correct beyond the tree level.

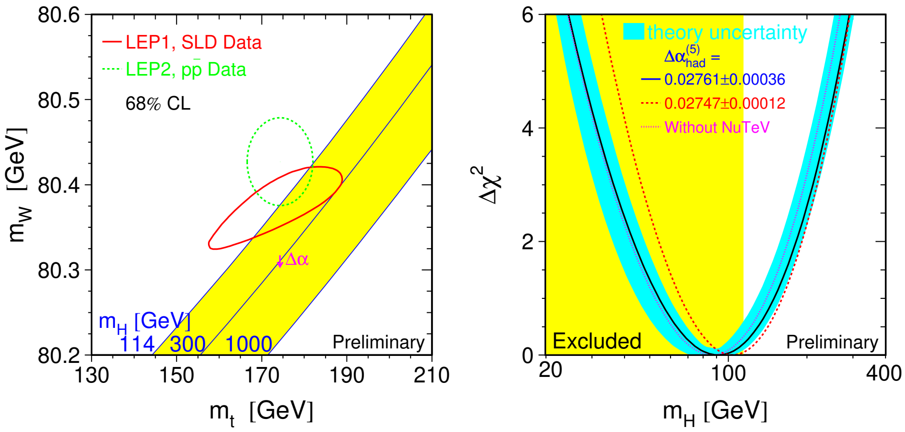

Figure 10: Left: Comparison of measurements of the W boson and top quark masses. Shown are the 68% confidence regions derived from precision measurements at the Z (solid ellipse) and the direct measurements at LEP and Tevatron (broken ellipse). The band shows the SM calculation for Higgs masses between 114 and 1000 GeV with the arrow indicating the uncertainty caused by the limited knowledge of $\alpha(m_Z)$. Right: Result of a fit to measurements of electroweak parameters. Shown is the difference of the χ^2-value to its minimum as function of the Higgs mass.

This non-trivial result is encouraging to go one step further and try to determine the mass of the Higgs boson in a similar way from its contribution to the weak radiative corrections. The Higgs boson enters through subleading corrections to the W and Z propagators. However, the dependence of the weak radiative corrections on m_H is only logarithmically. The band in Fig. 10 (left) shows the relation between m_W and m_t using SM relations for Higgs masses between the lower experimental limit of 114 GeV [9] and the upper theoretical bound of 1 TeV. Both experimental contours are in agreement with the SM relation and point to a low value for the Higgs mass.

Therefore all available mesurements are used in a SM fit to determine the Higgs boson mass as the only unkown parameter. The result of the fit is shown in the right part of Fig. 10 and compared to the lower limit obtained from the Higgs boson search at LEP. From this plot the mass of the SM Higgs boson is determined to be

$$\begin{aligned} \log m_\mathrm{H}/\mathrm{GeV} &= 1.98^{+0.21}_{-0.22}\,, \\ m_\mathrm{H} &= 96^{+60}_{-38}\ \mathrm{GeV}\,, \end{aligned} \tag{9}$$

which corresponds to an upper limit of

$$m_\mathrm{H} < 219\ \mathrm{GeV} \qquad 95\%\ \mathrm{CL}\,. \tag{10}$$

The search for the Higgs boson together with the limit obtained from electroweak measurements are now severely constraining the allowed mass range.

6 Summary and Outlook

The last decade of the 20th century was marked by precision electroweak physics experiments testing the SM to unpreceedented accuracy. The e^+e^--experiments at LEP and SLC have determined the properties of the heavy gauge boson $W^\pm$ and Z very accurately. These results are complemented by the Tevatron $p\bar{p}$ experiments which contributed with studies on the W boson and, most importantly, by the discovery of the top quark and the measurement of its mass.

These measurements allow the verification of quantum correction of the theory and the important result is that the SM is correct to the one-loop level. The quantitative analysis shows that the Higgs boson, the last unobserved SM particle, is light and that its mass should not be much above 200 GeV.

The LEP experiments are still analysing their data to better understand the W mass measurement and to improve the error. The Run II of the Tevatron and improved mesurements of m_{W} and m_{t} are expected soon. This will further constrain the mass of the Higgs boson which, if it exists, will be at the latest discovered at the LHC.

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