PRECISION ELECTROWEAK MEASUREMENT AT LEP*

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LEP started in 1989 and finished its operation in November 2000. The four experiments of LEP, ALEPH, DELPHI, L3 and OPAL, collected data and have been performing series of electroweak (EW) precision measurements. This article presents current status of the EW precision measurements at LEP.

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1. Introduction

The LEP machine started in 1989, and produced 27-million Z bosons in the e^+e^- collisions on the Z peak. The LEP four experiments, ALEPH, DELPHI, L3 and OPAL, collected data and have been performing analyses to determine the electroweak (EW) parameters of the Standard Model (SM). In 1996, the center of mass energy (CME) of LEP raised to 161 GeV which is slightly higher than W-boson pair production threshold. Since then, LEP raised the CME step by step to 210 GeV, and the four experiments performed continuous measurements of the EW parameters including the direct measurements of the W boson mass (m_W). LEP produced 46-kilo W-boson pairs in total and finished its operation in November 2000.

In this article, current status of the EW parameter measurements at LEP is presented as well as important results of the other experiments. Also presented is constraints to the Higgs mass (m_H) from overall EW parameter fit using full data set.

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2. Measured quantities and comparisons

Table I summarizes results from all LEP1 data. Figure 1 (Left) summarizes the measurements of the coupling parameters from LEP1 and SLD, where the SLD results are $A_l = 0.1513 \pm 0.0021$ [1] and $A_b = 0.922 \pm 0.020$ [2]. In the figure, the arrow pointing to the left shows the variation in the SM prediction for m_H in the range 300^{+700}_{-186} GeV, and the arrow pointing to the right for the top-quark mass (m_t) in the range 174.3 ± 5.1 GeV. Varying the

TABLE I

(Upper): Average line shape and leptonic asymmetry results from the Z-pole data at LEP, assuming the lepton universality. (Middle): A_τ, A_e and A_l measurements from LEP1 τ longitudinal polarization analysis. A_l is obtained assuming e-τ universality. (Lower): Results of b and c quark analyses using all LEP1 data set.

	Measurement with total error
M_Z / Γ_Z	91.1875 ± 0.0021 GeV / 2.4952 ± 0.0023 GeV
σ^0_{had}	41.540 ± 0.037 nb
R^0_l / $A^{0,l}_{\mathrm{FB}}$	20.767 ± 0.025 / 0.0171 ± 0.0010
A_τ / A_e	0.1439 ± 0.0043 / 0.1498 ± 0.0049
A_l	0.1465 ± 0.0033
R^0_b / R^0_c	0.21650 ± 0.00072 / 0.1688 ± 0.0047
$A^{0,b}_{\mathrm{FB}}$ / $A^{0,c}_{\mathrm{FB}}$	0.0993 ± 0.0017 / 0.0705 ± 0.0034

hadronic vacuum polarization by $\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2) = 0.02761 \pm 0.00036$ [3] yields an additional uncertainty on the SM prediction, oriented in direction of m_H arrow and size corresponding to the m_t arrow. As seen in the figure, the measurement of A_l (LEP+SLD) is significantly higher than the SM prediction and prefers low m_H. On the other hand, LEP $A^{0,b}_{\mathrm{FB}}$ measurement is in agreement with the SM expectation and prefers high m_H. The combined fit result with the SLD A_b, which is indicated by the contour in the figure, still prefers low m_H. The asymmetry measurements from LEP and SLD can be combined into a single parameter, the effective electroweak mixing angle, $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} = (1 - (gV_l/gA_l))/4$, without making strong model-specific assumptions. Also the hadronic asymmetries can be included assuming the difference between $\sin^2\theta^f_{\mathrm{eff}}$ for quarks and leptons in the SM. The combined averages of $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$, including the LEP $q\bar{q}$ charge forward-backward asymmetry ($\langle Q_{\mathrm{FB}}\rangle$) result, are shown in figure 1 (Right). The combinations based on the leptonic and hadronic results differ by 3.0 standard deviations, caused mainly by A_l(SLD) and $A^{0,b}_{\mathrm{FB}}$ (LEP). Also shown is the SM prediction of $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ as a function of m_H.

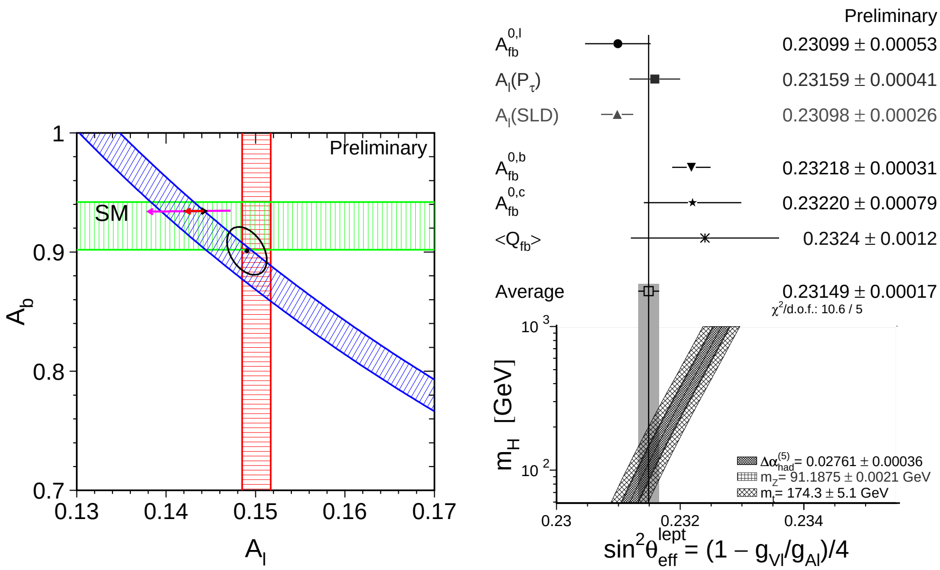

Fig. 1. (Left): The measurements of the combined LEP+SLD $A_l = 0.1501 \pm 0.0016$ (vertical band), SLD A_b (horizontal band) and LEP $A_{\rm FB}^{0,b}$ (diagonal band), compared to the SM expectations (arrow). Also shown is the 68 % CL contour for the two asymmetry parameters resulting from the joint analysis.
(Right): Comparison of several determinations of $\sin^2\theta_{\rm eff}^{\rm lept}$ from $A_{\rm FB}^{0,l}$, $A_l(P_\tau)$, A_l(SLD), $A_{\rm FB}^{0,b}$, $A_{\rm FB}^{0,c}$ and $\langle Q_{\rm FB}\rangle$ measurements. Also shown is the SM prediction as a function of m_H. The width of the Standard Model band is due to the uncertainties in $\Delta\alpha_{\rm had}^{(5)}(m_Z^2)$, $\Delta\alpha_{\rm s}(m_Z^2)$ and $m_{\rm t}$.

Figure 2 (Left) shows the direct measurements of the W boson mass (m_W) from $p\bar{p}$ colliders [4] and LEP2. Also shown are the world average of direct m_W measurements, and the indirect measurements by NuTeV [5] and LEP1+SLD. The NuTeV result is not in agreement with the other measurements. Figure 2 (Center) shows the comparison of the indirect measurements of m_W and $m_{\rm t}$ from all Z-pole data (LEP1+SLD) and the direct measurements by the $p\bar{p}$ colliders [4,6] and LEP2. Also shown are the SM predictions for m_H between 114 and 1000 GeV. As seen in the figure, the indirect and direct measurements are in agreement, and both sets prefer low m_H. Figure 2 (Right) shows how the indirect and direct measurements constrain $m_{\rm t}$ and m_H. The three contours by (1) all Z data, (2) all Z data except SLD A_e and (3) all Z data except $A_{\rm FB}^{0,b}$, again show that A_e and $A_{\rm FB}^{0,b}$ measurements prefer low and high m_H, respectively. Also hatched band indicated by m_W shows the constraints from the direct m_W measurements, compared with the above three contours.

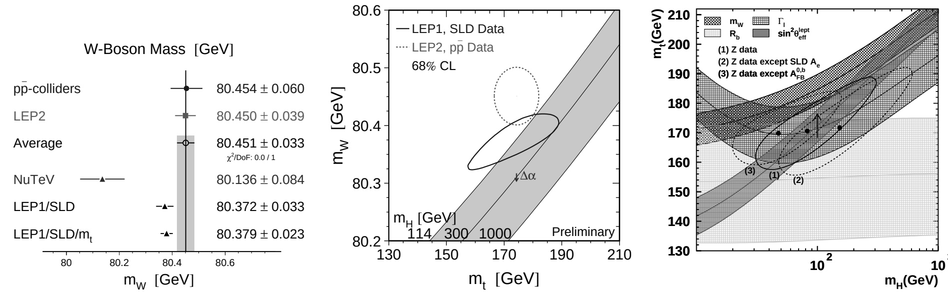

Fig. 2. (Left): The world average of the direct m_W measurements from $p\bar{p}$ colliders and LEP2. Also shown are the indirect m_W measurements by NuTeV, LEP1+SLD and LEP1+SLD with m_t measurements.
(Center): The comparison of the indirect measurements of m_W and m_t (LEP1+SLD data) (solid contour) and the direct measurements ($p\bar{p}$ colliders and LEP2 data) (dashed contour) by 68 % CL contours. Also shown is the SM relationship for the masses as a function of the Higgs mass.
(Right): Constraints to m_t and m_H by the measurements of m_W (direct), Γ_l, R_b and $\sin^2\theta_\mathrm{eff}^\mathrm{lept}$. Also shown are the 68 % CL contours for (1) all Z data (2) all Z data except SLD A_e and (3) all Z data except $A_\mathrm{FB}^{0,b}$.

3. Higgs mass constraints

Full electroweak (EW) fit using all measurements was performed, including the W boson width of $\Gamma_W = 2.134 \pm 0.0067$ ($p\bar{p}$ colliders and LEP2) and measurements of atomic parity violation in cesium [7]. Figure 3 (Left) shows the pulls from the fitted values in this full EW fit, where the heavy flavour measurements in the figure are LEP+SLD combinations. The χ^2/d.o.f and the probability of χ^2 for this fit are 28.8/15 and 1.7 %, respectively. Sizable contribution to χ^2 comes from $A_\mathrm{FB}^{0,b} = 0.0994 \pm 0.0017$ (LEP+SLD) and $\sin^2\theta_W = 0.2277 \pm 0.0016$ (NuTeV). Figure 3 (Center) shows the Higgs mass region which is preferred by each measurement. As seen in the figure, the b-quark asymmetry and $\sin^2\theta_W$ by NuTeV prefer high m_H, and the leptonic asymmetries and direct W mass measurements prefer low m_H. Finally, the best constraints on m_H are obtained when all data are used in the fit. The results of this fit are shown in Figure 3 (Right). The 95 % CL upper limit on m_H (taking the band in the figure into account) is 196 GeV.

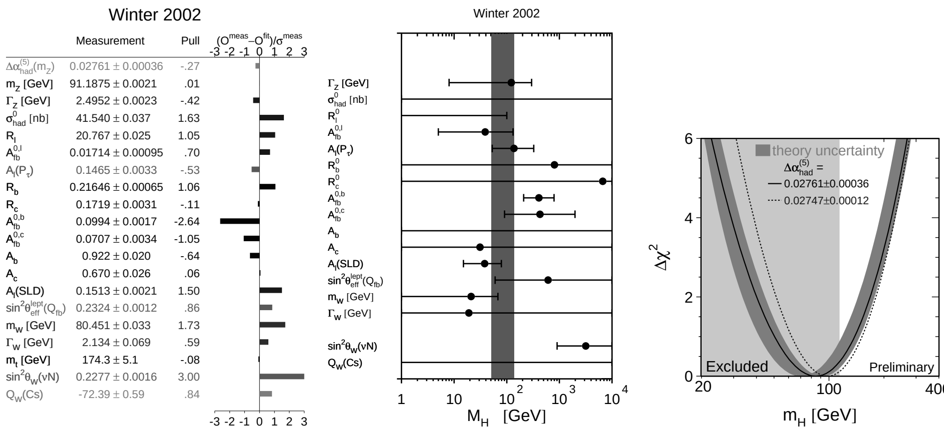

Fig. 3. (Left): The pulls (difference between measurement and fit in units of the total measurement error) of the SM fit including all data.
(Center): Preferred values of the Higgs mass are shown for various measurements.
(Right): $\Delta\chi^2 = \chi^2 - \chi^2_{\min}$ *vs* m_H curve using all data; the band represents an estimate of the theoretical error due to missing higher order corrections. The vertical band shows the 95 % CL exclusion limit on m_H from the direct search. The dashed curve is the result obtained using $\Delta\alpha^{(5)}_{\rm had}(m_Z^2)$ [8].

4. Conclusions

The overall EW fit using full data set was performed. The low fit probability of 1.7 % is mainly due to $A_{\rm FB}^{0,b}$ and $\sin^2\theta_W$ measurements. The 95 % CL upper limit of 196 GeV is obtained on m_H using the full data set.

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