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Experimental Studies of Electroweak Physics*

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Experimental Studies of Electroweak Physics

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Some experimental new Electroweak physics results measured at the LEP/SLD and the TEVATRON are discussed. The excellent accuracy achieved by the experiments still yield no significant evidence for deviation from the Standard Model predictions, or signal to physics beyond the Standard Model. The Higgs particle still has not been discovered and a low bound is given to its mass.

1. INTRODUCTION

The Electroweak (EW) theory of the Standard Model (SM) [1] went through numerous tests of its predictions. The large number of free parameters suggest that even if it is the correct theory, it is still not the final one, and there is the one missing part, the undiscovered Higgs particle [2].

From the gauge structure of the theory [3] and the fact that the W and the Z gauge bosons as well as the fermions are massive can be explained by a symmetry breaking procedure [2]. The easiest way this is achieved is by a doublet of scalar fields, which after the absorption of additional degrees of freedom results in neutral physical particle, the Higgs. This scheme can imply simple relation between the masses of the W and the Z gauge bosons and the strength of the weak couplings (which can be expressed in terms of the weak mixing angle) as following:

$$\sin\theta_W = 1 - \frac{M_Z}{M_W} \tag{1}$$

This work is a compilation of the conference 16 EW-session talks, describing measurements of these three parameters as well as other EW measurements done recently by the LEP, SLD and the TEVATRON experiments. Some other EW results were discussed at the Heavy Flavour physics session [4].

The next section discusses the LEP beam energy, luminosity and cross-section measurements. Section 3 discusses Weak Neutral Current measurements through forward backward asymmetries and tau polarization measurements at LEP and polarized asymmetries at SLD. Charged weak couplings of the tau measurements at LEP and SLD are described in the following section. Section 5 discusses W mass measurements at LEP-2, Trilinear Gauge Coupling and W properties measurements at the TEVATRON. Section 6 discusses some of the searches for new particles at LEP-2, and the EW measurements status is summarized in section 7.

Many people have contributed to these results, I would like to thank them all, and apologize for any omissions.

2. LEP BEAM MEASUREMENTS

- Determination of E_{CM} at LEP-1 and LEP-2 - Paul Bright-Thomas.
- Measuring the Luminosity at LEP-1 - Philip Hart.
- LEP-1 cross-sections - Marco Bigi.

2.1. LEP Energy measurements

The four LEP experiments (ALEPH, DELPHI, L3 and OPAL) have collected 4×10^6 events each during the years 1989-1995. The 1990-91 consist of data collected during energy scan with steps of 1 GeV each around the Z^0 peak. In 1993 and 1995 LEP scanned through 3 energies (peak ± 1760 MeV), while the 1992 and 1994 data were taken approximately on the Z^0 resonance.

The Average energy is set by the integral magnetic field $E^{av} \propto \oint Bd\ell$ where the beam path length is fixed by the RF frequency $\oint Bd\ell \propto f_{RF}$. The storage ring transverse spin polarization (Sokolov and Ternov effect [5]) provides the best tool for calibration of the beam energy using resonant depolarization of the e^-

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beam. The intrinsic precision of this method is to better than 200 KeV, however the main problem is that it can not be applied during normal data taking conditions, but only in special time allocated for that. In 1995 most of the fills were calibrated at the end of the storage ring fill, but for consistency check a few were also read at the beginning of the fill.

In order to obtain high precision measurement using the whole scan data, one would like to have continuous measurements of the E_{CM} at the interaction points (IP). However, one only have occasional measurements of the average energy, and continual measurements of the magnetic field in a few dipoles. Therefore an extrapolation algorithm was developed to calculate the energy while taking into account the time behavior of the magnets, current, field, temperature as well as the geometrical properties of the LEP ring. It is somewhat surprising how tiny ground motions are amplified by the strong LEP focusing causing an energy variation of a few MeV. It is impressive to see how well these effects resulting from terrestrial tides, or even heavy rainfall and the level of water in the lake of Geneva are nicely tracked by orbit measurements, and with other known energy variation sources, such as temperature, day night effect etc. are included in the energy calibration model.

Unexplained energy jumps during the 1993 run, triggered the installation of NMR probes inside the LEP magnets to track this 5 MeV energy variation. The source of these unexplained jumps was identified to be the leakage current from the .. TGV the Geneva-Bellegarde railway.

Special conditioned at the 1995 run caused by the train-bunch mode operation, and the development of superconducting cavities have required special corrections and have introduced extra small systematic uncertainties.

Correction due to the beam energy spread (55 ± 1.5 MeV) determined partly by the bunch length measured in the experiments are included in the Z width calculation.

The energy uncertainties are specific to the year, energy point, IP and so on. Table 2.1 illustrates typical energy uncertainties used during the 1995 run.

The energy uncertainties for the 1993-95 runs are detailed in ref. [6], it is translated to uncertainties of 1.6 MeV on the determined mass and width of the Z boson.

In June 1996 LEP-2 began to take data (10 pb^{-1}) at the WW threshold, $E_{CM} = 161$ GeV. Five months later LEP energy increased to 172 GeV, allowing reconstruction of the W mass from its decay products, and the plan is to keep ramping to 184, 196 GeV and to accumulate 500 pb^{-1} per experiment. The lower precision required is still very challenging, and techniques similar to the LEP-1 calibration are employed for LEP-2 operation mode. The main caviate is that the depolarization technique is still limited to 50 GeV, and therefore calibration is extrapolated from reading at 50 GeV to 80 GeV. The extrapolation is the dominant source of systematic error contributing 24/27 MeV (29/30) MeV in the 161 GeV (172 GeV) run.

Table 1
Typical LEP energy uncertainty values for E_{CM}^{IP} during 1995.

Source	$\sigma(E_{CM})$ [MeV]
Depolarization	0.2
e^+e^- difference	0.3
Calibration statistics	1.0
Dipole rise model	1.0
Temperature model	1.0
Horizontal correctores	0.3
Tide	0.4
Orbit drifts	0.5
RF corrections	1.0
Dispersion	0.7
Total	2.0

2.2. LEP-1 Cross-sections

The results presented here are based on the 40 pb^{-1} collected in 1995 combined with those recorded in the previous years. Hadron selection is based on high multiplicity of tracks/calorimeter clusters, high and balanced energy deposition. Typical relative uncertainties on the hadronic cross-sections are $\frac{\Delta\sigma_{had}}{\sigma had} \approx 0.05-0.1\%$ introduced mainly by selection cuts, detector simulation, hadronization model and resonant background. The systematics has significantly improved in the last year due to further studies of hadronic selection, and the improved theoretical Bhabha scattering calculations [7]. The lepton selection is based on search for low track multiplicity and back to back topology. The electron-pair selection requires 2 high energy clusters (limited in $\cos\theta$ to avoid t-channel background). The muon-pair selection require 2 high momentum tracks pointing to minimum ionizing particles (MIP) deposition in the calorimeters and signal in the muon chambers. The τ-pairs are typical 2 narrow, back to back low multiplicity jets. The main background in each of the leptonic channels is contribution from the other leptonic channels. A self consistency check is a comparison between inclusive to single channels cross-sections. Typical relative uncertainties on the leptonic cross sections are 0.3-1%, 0.15-1% and 0.3-0.6% for Γ_{ee}, $\Gamma_{\mu\mu}$ and $\Gamma_{\tau\tau}$ respectively. The total statistics of the four LEP collaborations are given in Table 2.2. Details of the individual analyses can be found in Ref. [8]-[11].

Table 2
The LEP Statistics in units of 10^3 events used for the analysis of the Z line shape and lepton Forward-Backward Asymmetries.

	year	ALEPH	DELPHI	L3	OPAL
$q\bar{q}$	90-91	451	357	416	454
	92	680	697	678	733
	93 prel.	640	677	646	646
	94 prel.	1654	1241	1307	1524
	95 prel.	739	584	311	344
	Total	4164	3556	3358	3701
leptons	90-91	55	36	40	58
	92	82	70	58	88
	93 prel.	78	74	64	82
	94 prel.	190	135	127	184
	95 prel.	80	67	28	42
	Total	485	382	317	454

The measurement of the hadronic cross-section around the Z peak allows determination of the Z mass and width, and the peak hadronic cross-section. Measurement of the leptonic cross-sections allows determination of $R_\ell = \Gamma_{had}/\Gamma_\ell$ for each or all leptons combined. However it has become customary to include the lepton asymmetry measurements in a global fit machinery which will be discussed in section 7.

2.3. LEP-1 Luminosity measurements

An important aspect of the line shape measurement is related to Z^0 decays into invisible channels. Measurement of the ratio of Z decay width into invisible particles and the leptonic width, $\frac{\Gamma_{inv}}{\Gamma_{\ell^+\ell^-}} = \frac{\Gamma_Z - 3\Gamma_{\ell^+\ell^-} - \Gamma_{had}}{\Gamma_{\ell^+\ell^-}}$ provide an interesting window to new physics due to its relative insensitivity to top and Higgs masses or QCD corrections. With the large statistics accumulated at LEP this measurement was limited by the experiments measured luminosity uncertainty (0.5%). The method chosen by the LEP experiments to measure the luminosity is to use the well calculated (0.1%) low-angle t-channel Bhabha scattering process. The differential cross-section that is proportional to θ^{-3} gives a large statistics, enable to use small detector that is separated from the other part of the detector. The detectors can take advantage of the LEP relative small beam spot, well understood energy behavior (section 2.1), and the low backgrounds. DELPHI uses a sampling calorimeter with tungsten mask to define a volume, L3 combine their crystal forward detector with 3 planes of silicon to define their acceptance where OPAL and ALEPH are use silicon detector for position discrimination interleaved with tungsten radiator for energy determination. The preliminary LEP luminosity uncertainties are given in Table 3.

Table 3
Preliminary LEP luminosity uncertainties and the current theoretical (Monte Carlo) limitation.

	$\Delta L/L \times 10^{-4}$			
	Experimental			Theoretical
	1993	1994	1995	
ALEPH	8.7	7.3	9.7	16
DELPHI	24	9	9	11-16
L3	10	7.8	12.8	11
OPAL	4.6	4.6	4.6	11

Combining the LEP line shape results one gets $\Gamma_{\ell^+\ell^-} = 83.89 \pm 0.11$ MeV, $\Gamma_{had} = 1743.5 \pm 2.4$ MeV and $\Gamma_{inv} = 499.8 \pm 1.9$ MeV. With that one can derive $\Gamma_{inv}/\Gamma_{\ell^+\ell^-} = 5.957 \pm 0.022$ compared to the SM prediction ($n/3 \times 5.973 \pm 0.003$), or the number of light neutrinos $N_\nu = 2.992 \pm 0.011(exp.) \pm 0.005(M_t, M_H)$. Alternatively, one can assume 3 neutrino species to extract 95% C.L. upper limit on additional invisible decays of the Z^0, $\Delta\Gamma_{inv} < 2.9$ MeV.

3. ASYMMETRY MEASUREMENTS AND NEUTRAL CURRENT COUPLINGS

- Measurements of the leptonic FB asymmetries at LEP-1 - Wenwen Lu
- Fermion-pair cross-sections and Asymmetries at LEP-2 - Thorsten Siederburg
- Spin analysis of $e^+e^- \to \tau^+\tau^-$ at LEP - Reinhold Volkert
- Left-right Asymmetry measurement at SLD - Henry Band
- Leptonic couplings Asymmetries with polarized Z -Michael Smy
- LEP hadronic charge asymmetry - Pascal Perrodo

Around the Z^0 peak the fermion-pair are produced mainly through the Z^0 channel, where the γ exchange contribution is very small. Asymmetry measurements, Forward-Backward (FB) and polarized asymmetries are sensitive to the right handed Zff couplings complementary to the partial widths measurements which are more sensitive to the left handed couplings.

$$\begin{aligned} \Gamma_f \quad &\propto g_{Lf}^2 + g_{Rf}^2 \quad \propto v_f^2 + a_f^2 \qquad (2) \\ A_f = \frac{\sigma_f^L - \sigma_f^R}{\sigma_f^L + \sigma_f^R} \quad &= \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} \quad = \frac{2v_f a_f}{v_f^2 + a_f^2} \end{aligned}$$

Here $g_{L(R)f}$ are the left (right) handed couplings, and v_f and a_f are the effective vector and axial-vector Zff couplings.

For unpolarized beams (LEP) the Forward Backward asymmetry,

$$A_{FB}^f = \frac{3}{4} A_e A_f, \qquad (3)$$

is sensitive to the (initial) electron and the outgoing fermion couplings to the Z^0.

For the τ lepton one can measure its polarization through the angular distribution of its decay products. Measuring the polarization as a function of the τ polar angle,

$$p_\tau = -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_eA_\tau\cos\theta}, \qquad (4)$$

enable to derive both the the electron and the τ coupling to the Z^0 separately.

Given the longitudinal polarization of the electron beams at SLD, one can use that knowledge to simply measure the difference between left and right handed cross-section,

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = P_e A_e, \qquad (5)$$

where P_e is the polarization of the incident e^- beam. One can also measure the FB polarized asymmetry,

$$A_{FB}^{pol(f)} = \frac{(\sigma_{L,F} - \sigma_{R,F}) - (\sigma_{L,B} - \sigma_{R,B})}{(\sigma_{L,F} - \sigma_{R,F}) + (\sigma_{L,B} - \sigma_{R,B})} = \frac{3}{4} P_e A_f . (6)$$

While the Asymmetries expected from neutrinos, charged leptons, u-type quarks and d-type quarks are: 1, 0.15, 0.67 and 0.94 respectively, the sensitivity of these to the weak mixing angle, $\frac{\delta A_f}{\delta \sin\theta_W}$ are 0, -7.9, -3.5 and -0.6. For comparison all the LEP and SLD asymmetries are given in terms of the effective mixing angle which is defined as:

$$\sin^2\theta_W^{eff} \equiv \frac{1}{4}(1 - \frac{v_e}{a_e}), \qquad (7)$$

where the v_e/a_e is extracted from the asymmetry measurements.

Where Heavy Flavour measurements $(R_{b/c}, A_{b/c})$ test the SM through vertex corrections, the leptonic asymmetries are sensitive to the oblique radiative corrections.

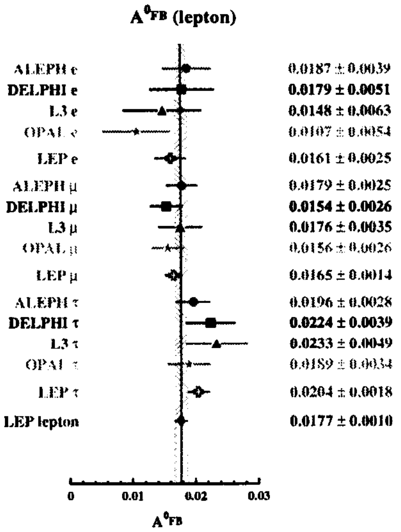

Figure 1. Summary of the 4 LEP experiments e, μ and τ FB asymmetries.

3.1. Leptonic Forward Backward asymmetries at LEP-1

Two main techniques been used to measure the FB asymmetry: fitting the differential cross section $d\sigma/d\cos\theta \propto 1 + \cos^2\theta + \frac{8}{3}A_{FB}\cos\theta$, and counting $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$. With about $4 \times 400K$ lepton events at LEP, A_{FB} measurements have achieved precision of 10^{-3}. The LEP-1 leptons FB asymmetries are shown in Fig. 1.

3.2. Cross section and FB asymmetries at LEP-2

The fermion-pair measurements at LEP-2 [12] can achieve a better, less model dependent determination of M_Z, and cross check lepton universality. Compared with LEP-1 it is characterized by lower cross section (about two order of magnitude) and large radiative corrections dominated by Initial State Radiation (ISR, so called "the return to the Z"). The differential cross-section of fermion-pair production at LEP-2 is:

$$\begin{aligned} \frac{d\sigma}{d\cos\theta} = \frac{4\pi\alpha^2}{3}\{ &\frac{(\frac{\alpha(s)}{\alpha}Q_f)^2}{s}\frac{8}{3}(1+\cos^2\theta) \qquad (8) \\ + &\frac{s - M_Z{}^2}{(s - M_Z{}^2)^2 + (\Gamma_Z M_Z)^2}[J_{tot}^f \tfrac{8}{3}(1+\cos^2\theta) + J_{FB}^f\cos\theta] \\ + &\frac{s}{(s - M_Z{}^2)^2 + (\Gamma_Z M_Z)^2}[R_{tot}^f \tfrac{8}{3}(1+\cos^2\theta) + R_{FB}^f\cos\theta]\} \end{aligned}$$

Where

$$R_{tot}^f = \frac{9}{\alpha^2 M_Z{}^2}\Gamma_e\Gamma_f \ ; \qquad J_{tot}^f = \frac{G_F M_Z{}^2}{\sqrt{2}\pi\alpha} v_e v_f$$

$$\Gamma_f = \frac{G_F M_Z{}^3}{6\pi\sqrt{2}}(v_f^2 + a_f^2) \qquad (9)$$

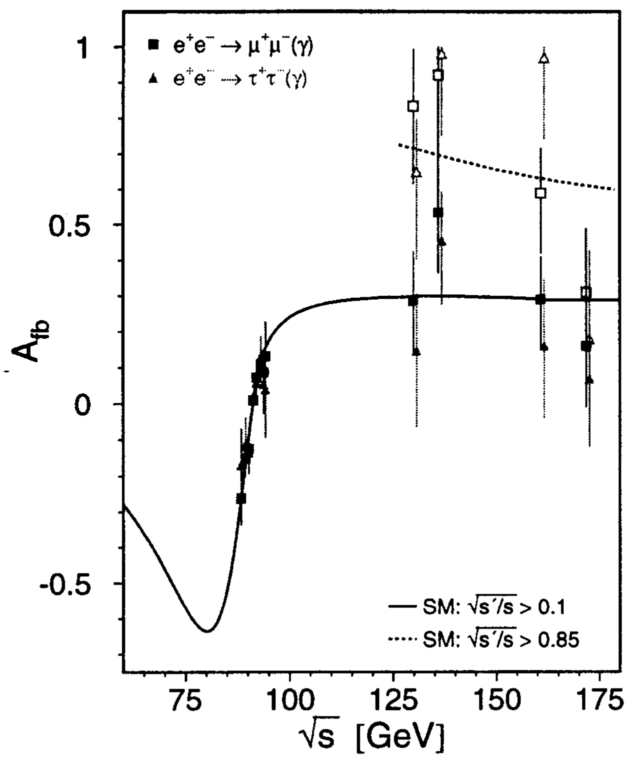

Figure 2. L3 μ and τ pair FB asymmetries at LEP-1 and LEP-2 energies, $\sqrt{s}$ is the E_{CM}, where s' is corrected for the "return for the Z" radiation $s' = s - 2E_{\gamma ISR}\sqrt{s}$

$$R^f_{FB} = \frac{3G_F^2 {M_Z}^2}{8\pi\alpha^2} v_e a_e v_f a_f \quad ; \qquad J^f_{FB} = \frac{3\sqrt{2}G_F}{8\alpha} a_e a_f$$

and the total cross section is:

$$\sigma^f_{tot} = \frac{4\pi\alpha^2}{3} \{ \frac{(\alpha(s)Q_f)^2}{s} + \frac{J^f_{tot}(s - {M_Z}^2) + R^f_{tot} s}{(s - {M_Z}^2)^2 + (\Gamma_Z M_Z)^2} \quad (10)$$

At the Z^0 pole the line shape measurements were less sensitive to the γ propagation and γ-Z interference term, hence the combined LEP results were quoted with J^{had}_{tot} fixed to its SM value. For a comparison the following are the LEP-1 quoted values for the Z mass

$M_Z = 91186.3 \pm 1.9$ $\quad J^{had}_{tot}$ *a free parameter,*

$M_Z = 91189.3 \pm 6.2$ $\quad J^{had}_{tot}$ *a fixed SM Value*

However LEP-2 energy allows one to improve the M_Z determination while J^{had}_{tot} kept unconstrained M_Z (LEP-2) $= 91187.6 \pm 3.3$.

Fig. 2 shows L3 muon and tau pairs FB asymmetry results at LEP-1 and LEP-2 energy compared with the SM predictions. The measured cross-sections and leptonic FB asymmetries agree well with the SM predictions.

3.3. Tau Polarization

All LEP experiments extract separate tau polarization (p_τ) by reconstructing the decay of the tau to the five different channels: $e\nu_\tau\bar{\nu_e}$, $\mu\nu_\tau\bar{\nu_\mu}$, $\pi\nu_\tau$, $\rho\nu_\tau$ and $a_1\nu_\tau$ [13]-[16]. While the first three are one dimensional fit, in order to obtain maximum information from the ρ and the a_1 channels one has to investigate the distribution of the charged and neutral πs. With that the a_1 channel becomes more sensitive than the leptonic channels where the ρ and the π are the most sensitive channels, contributing weights of about 40% each in the average. Measuring the angular dependence of the p_τ (Eq. 4) provides nearly independent determination of the τ and electron coupling asymmetries, A_τ and A_e. Not all the LEP 90-95 has been analyzed, OPAL (final), L3 and DELPHI (both preliminary) have analyzed data up to 1994 where ALEPH has published data up to 1992 only. The LEP results are given in Table 4 and they are consistent with lepton universality giving on average $A_\tau = 0.1401 \pm 0.0067$, $A_e = 0.1382 \pm 0.0076$ and assuming $e - \tau$ universality $A_\ell = 0.1393 \pm 0.0050$.

Table 4
LEP results for A_τ and A_e. The $\chi^2/d.o.f$ for the average is 1.1/3 and 1.8/3 respectively.

Exp.	A_τ	A_e
ALEPH	$0.136 \pm 0.012 \pm 0.009$	$0.129 \pm 0.016 \pm 0.005$
DELPHI	$0.138 \pm 0.009 \pm 0.008$	$0.140 \pm 0.013 \pm 0.003$
L3	$0.152 \pm 0.010 \pm 0.009$	$0.156 \pm 0.016 \pm 0.005$
OPAL	$0.134 \pm 0.009 \pm 0.010$	$0.129 \pm 0.014 \pm 0.005$

For a more complete determination of the spin related structure of the $Z^0 \rightarrow \tau^+\tau^-$ process, ALEPH, DELPHI and L3 have provided an independent check measuring C_{TT} and C_{TN} the transverse-transverse and transverse-normal spin correlations. The measurement is based on full angular distribution of the decay product (excluding the ν, hence it is not necessary to reconstruct the τ direction) where different decay combinations have different sensitivities. The LEP average values are $C_{TT} = 0.98 \pm 0.11$ and $C_{TN} = 0.02 \pm 0.13$ in good agreement with the SM predication of ≈ 0.99 and $\approx 0.025 - 0.012$

3.4. Polarized asymmetries measurements

SLD has a new preliminary measurement of A_{LR} (Eq. 5) based on the data collected in 1996. The event sample, mostly consists of hadronic Z^0 decays, has 28,713 and 22,662 left- and right-handed electrons respectively. The resulting measured asymmetry is thus

$A_m = (N_L - N_R)/(N_L + N_R) = 0.1178 \pm 0.0044(\text{stat})$. To obtain the left-right cross-section asymmetry at the SLC center-of-mass energy of 91.26 GeV, a very small correction $\delta = (0.240 \pm 0.055)\%(\text{syst})$ is applied which takes into account residual contamination in the event sample and slight beam asymmetries. As a result,

$$\begin{aligned} A_{LR}(91.26\text{ GeV}) &= \frac{A_m}{\langle P_e\rangle}(1+\delta) = 0.1541 \qquad (11) \\ &\pm 0.0057(\text{stat}) \pm 0.0016(\text{syst}) \end{aligned}$$

where the systematic uncertainty is dominated by the systematic understanding of the beam polarization. Finally, this result is corrected for initial and final state radiation as well as for scaling the result to the Z^0 pole energy:

$$\begin{aligned} A^0_{LR} &= 0.1570 \pm 0.0057(\text{stat}) \pm 0.0017(\text{syst}) \qquad (12) \\ \sin^2\theta_W^{eff} &= 0.23025 \pm 0.00073(\text{stat}) \pm 0.00021(\text{syst}). \end{aligned}$$

The 1996 measurement combined with the previous (published) measurements yield:

$$\begin{aligned} A^0_{LR} &= 0.1550 \pm 0.0034 \qquad (13) \\ \sin^2\theta_W^{eff} &= 0.23051 \pm 0.00043. \end{aligned}$$

Which is the single most precise determination of weak mixing angle.

SLD has presented a direct measurement of the Z^0-lepton coupling asymmetry parameters based on a sample of 12K leptonic Z^0 decays collected in 1993-95 [18]. The couplings are extracted from the measurement of the double asymmetry formed by taking the difference in number of forward and backward events for left and right beam polarization data samples (Eq. 6) for each lepton species. This measurement has a statistical advantage of $(P_e/A_e)^2 \approx 0.25$ on the LEP FB asymmetry measurements. It is independent of the SLD A_{LR} using Z^0 decays to hadrons, and it is the only measurement which determines A_μ not coupled to A_e. The results are: $A_e = 0.152 \pm 0.012(stat) \pm 0.001(sys)$, $A_\mu = 0.0102 \pm 0.034 \pm 0.002$, and $A_\tau = 0.195 \pm 0.034 \pm 0.003$ or assuming universality $A_\ell = 0.151 \pm 0.011$.

The SLD preliminary weak mixing angle value combining A_{LR}, Q_{LR} and leptons asymmetries measurements is:

$$\sin^2\theta_W^{eff} = 0.23055 \pm 0.00041. \qquad (14)$$

which is more than 3σ below the LEP average.

3.5. The Hadronic Charge Asymmetry $\langle Q_{FB}\rangle$

The LEP experiments [20]- [23] have provided measurements of the average charge flow in the inclusive samples of hadronic decays which is related to FB of the individual quarks asymmetry as following:

$$< Q_{FB} >= \sum_{quark\ flavour} \delta_f A^f_{FB} \frac{\Gamma_f}{\Gamma_{had}}. \qquad (15)$$

The charge separation, δ_f, is the average charge difference between quark and antiquark in an event. The b and c are extracted from the data, the δ_b as a by-product of the b asymmetry measurement (self calibration) where the charm separation is obtained using the hemisphere opposite to a fast $D^{*\pm}$. Light quark separations are derived from MC hadronization models which is the main systematic source. The results expressed in terms of the weak mixing angle are:

$$\begin{aligned} &0.2322 \pm 0.0008(stat) \pm 0.0007(sys.\ exp) \pm 0.0008(sep.) \\ &0.2311 \pm 0.0010(stat) \pm 0.0010(sys.\ exp) \pm 0.0010(sep.) \\ &0.2336 \pm 0.0013(stat) \pm 0.0014(sys.\ exp)\ \ (New!) \\ &0.2321 \pm 0.0017(stat) \pm 0.0027(sys.\ exp) \pm 0.0009(sep.) \end{aligned}$$

for ALEPH, DELPHI, L3 and OPAL respectively.

4. TAU LORENTZ STRUCTURE

- Measurements At LEP - Joachim Sommer
- Measurements At SLD - Erez Etzion

Measurements of the Charged Current structure in the leptonic and semi-leptonic decays of the tau searching for deviation from V-A which was measured to a good accuracy at the muon sector. The measurements of the 4 Michel parameters (ρ, η, ξ and $\xi\delta$) in the leptonic decays, and $\xi_{had} \sim h_\nu$, the helicity of the tau neutrino in the hadronic decays are extracted from reconstructed kinematic parameters of the decay particles. The ρ and η parameters are measured from the leptonic decays energy spectrum, were the correlation between the two taus is utilized in the LEP experiments (ALEPH, OPAL, l3) as well as CLEO and ARGUS for the determination of ξ, $\xi\delta$ and h_ν. SLD exploits the high polarization of the incident electron beam to extract these quantities directly from a measurement of the tau decay spectra. The results are still not as precise as in the muon sector, but are also consistent with the $V-A$ SM prediction. Table 5 summarizes the various measurements.

Due to the $\frac{M_\ell}{M_\tau}$ factor current experiments are not sensitive to η_e. A few experiments "improved" η_μ measurement using the high $\rho-\eta$ correlation and assumed $e-\mu$ universality. However this is an *inconsistent* assumption because generally a non zero η would imply non universal ρ.

ALEPH has presented a new method that includes the reconstruction of the τ direction. L3 published a global analysis with 50% of their data. OPAL measured the ξ_{had} in the $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ as part of the measurement of the hadronic structure function. SLD published their results for 1993-95 data [24]. Most of the LEP data still haven't been analyzed, and SLD is still taking data, so we do expect (and there is room for) improvements from the Z machines and maybe

Table 5
Summary of present present experimental measurements and SM predictions for the τ Charged Current parameters.

exp.	ρ	η	ξ	$\xi\delta$	h_ν
SM	0.75	0	1	0.75	1
ARGUS	0.738 ± 0.038	0.03 ± 0.22	0.97 ± 0.14	0.65 ± 0.12	1.017 ± 0.039
CLEO	0.747 ± 0.012	-0.015 ± 0.08	1.007 ± 0.043	0.745 ± 0.028	1.03 ± 0.07
ALEPH 92	0.751 ± 0.045	-0.04 ± 0.19	1.18 ± 0.16	0.88 ± 0.13	1.006 ± 0.037
ALEPH (stat.)	0.749 ± 0.019	0.047 ± 0.08	1.032 ± 0.077	0.79 ± 0.052	0.996 ± 0.008
L3	0.794 ± 0.05	0.25 ± 0.2	0.94 ± 0.22	0.81 ± 0.15	0.97 ± 0.054
SLD	0.72 ± 0.09	-0.6 ± 0.9 (μ)	1.05 ± 0.35	0.88 ± 0.27	0.93 ± 0.11
OPAL					1.29 ± 0.28
Average	0.748 ± 0.009	0.028 ± 0.051	1.017 ± 0.035	0.761 ± 0.023	0.997 ± 0.008

more than that from CLEO with its very large τ-pairs sample.

5. GAUGE BOSONS PROPERTIES

- W Mass Measurements at LEP-2 - Carla Sbarra.
- Trilinear Gauge Couplings (D0, CDF) - Chris Klopfenstein.
- W physics at the TEVATRON - Arie Bodek.

5.1. W mass measurements at LEP-2

The W discovery and first studies of its properties all took place at $p\bar{p}$ collisions. In 1996 all 4 LEP collaborations have used two complementary methods to determine M_W: With the data recorded at 161 GeV (just above the W pair threshold) the measured cross-section was compared with the predicted one [25]. The statistics is rather low due to the low cross section . Systematic error is dominated by the background rejection. The LEP average cross-section is: $\sigma_{W^+W^-} = 3.69 \pm 0.45$ pb and the mass derived using an average energy of 161.33 ± 0.05 is: $M_W = 80.40^{+0.22}_{-0.21} \pm 0.03$ GeV.

At 172 GeV the cross section is about three times larger and each experiment has recorded about 100 W pairs. At this energy the W mass was determined by directly reconstructing the invariant mass of the W decay products [26]. Averaging the results treating the smallest systematic error as 100% correlated yields: $M_W = 80.37 \pm 0.18 \pm 0.05(color) \pm 0.03(LEP)$, where the second error is due to color reconnection and the third error is due to LEP energy uncertainty of 30 MeV. Combining the two methods yield LEP average of: $M_W = 80.38 \pm 0.14$ GeV.

5.2. Trilinear Gauge Couplings measurements at the TEVATRON

The vector boson trilinear couplings predicted by the non-Abelian gauge symmetry of the SM can be measured directly in pair production processes such as $q\bar{q} \rightarrow W^+W^-$, $W^\pm\gamma$, $Z\gamma$ or $W^\pm Z$. Deviation from the SM couplings would signal new physics. CDF and D0 [27] have searched for $W\gamma, WW, WZ$ and $Z\gamma$ diboson final states, using several different techniques with high transverse momentum events of the TEVATRON, the 1.8 TeV $p\bar{p}$ collider. WWZ and $WW\gamma$ vertices have been observed and direct limits on non-SM, three-boson, WWZ and $WW\gamma$ anomalous couplings were set. Fig. 4 shows no clear difference between the transverse momentum distribution for WW and WZ candidate events from D0 1993-95 data to the total background estimate plus SM expectations. Limits were set on the $Z\gamma$ couplings while searching for the non-SM $ZZ\gamma/Z\gamma\gamma$ interactions. CDF has studied

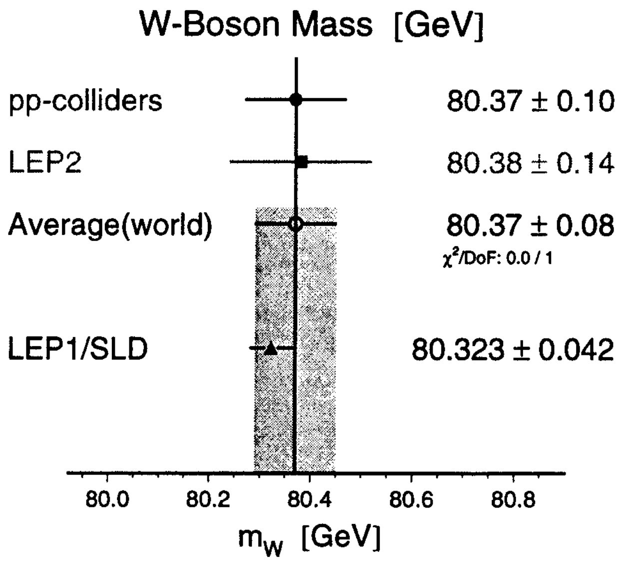

Figure 3. Comparison of direct and indirect Measurements of the W mass. The $p\bar{p}$ average represents the results of UA2, CDF and D0, where the LEP results is the combined 161 and 172 GeV runs. The indirect is calculated using LEP-1, SLD and ν-N results.

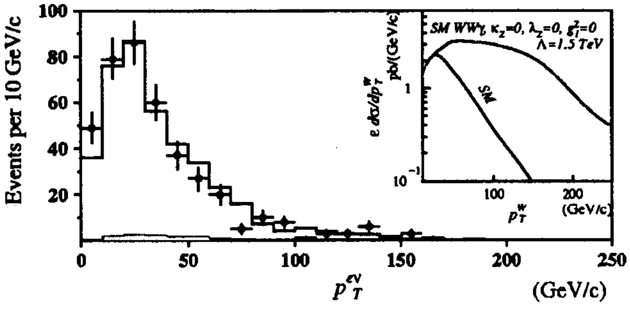

Figure 4. P_T distribution of the $e\nu$ system for the 1993-95 D0 data set. The points represent the data while the solid line stands for the total background estimate plus the SM prediction of WW and WZ production (shown as shaded histogram). The inset shows the predicted $d\sigma/dp_T^W$, folded with detection efficiencies, for SM WWγ and WWZ couplings (lower curve), and for SM WWγ and anomalous WWZ couplings (upper curve).

the $W\gamma$ interaction where SM predicts no radiation at $\cos\theta^* = \pm 1/3$ (θ^* is the angle between the incoming quark and the photon). A hint for that zero radiation has been observed by CDF. Limits were also set on the anomalous WWV and $ZV\gamma$ couplings. The results are in agreement with the SU(2) × U(1) model of SM electroweak interactions.

5.3. W properties studies at the TEVATRON

The run 1a (18 pb^{-1}) and 1b data (110 pb^{-1}) of the TEVATRON, was used in extracting the W asymmetry at CDF [28]. A new technique using the silicon tracking and energy in the electro-magnetic calorimeter has extended the electron rapidity coverage. The asymmetry results are used to reduce the systematic errors on the M_W measurement (from 100 to 50 MeV), and it can be even further reduce to the level of 20 MeV. W width was measured in two ways: indirectly from the W and Z cross sections, and indirectly from the tail of the transverse mass distribution.

Drel-Yan dilepton production at high invariant mass yield limits on extra Z' bosons, and place strong limits on quark substructure. New limits on quark-lepton compositness scales from dilepton production were recently published [29].

6. SEARCHES FOR NEW PARTICLES

- Searches at LEP-2 - Klas Hultqvist

The increase of LEP center of mass energy has opened a new window for new particle searches. The main missing piece in the frame of the electroweak puzzle is the scalar particle that breaks the symmetry, the Higgs particle, which its mass is the the only free parameter left in the electroweak fits. Searches at LEP-2 concentrate on looking for SM Higgs or an extension of 2-doublet Higgs model, and "new physics" mainly supersymmetric particles in the frame minimal supersymmetry model (MSSM) gauge sector (chargino and neutralino) and S-matter sector (slepton and squark), or extensions to MSSM, and also for exotic particles such as excited leptons or unexpected topologies. The Higgs reach increases with the increase of energy. Different topologies are used where due to the high branching ratio of Higgs to $b\bar{b}$, b-tagging plays an important role in the Higgs search. New preliminary lower limits for the SM Higgs mass at 95% CL are: L3 - 68.2 GeV/c^2, OPAL - 68.8 GeV/c^2, ALEPH 70.7 GeV/c^2 and last is DELPHI with a limit of 64.6 GeV/c^2 effected by a $h\nu\bar{\nu}$ candidate they have from the 161 GeV run with calculated mass of $64.6^{+5}_{-2.6}$ GeV (consistent with the background expectation of 1.3 events). Fig. 5 shows the region excluded by the SM Higgs searches at LEP compared with the mass predicted by the the electroweak fits (Section 7).

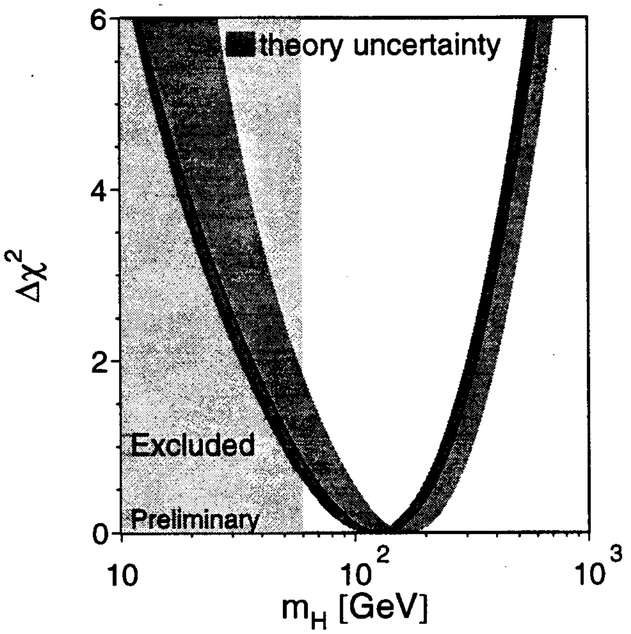

Figure 5. χ^2 curve for the Higgs boson in the minimal SM fit to the winter 1997 electroweak data and the region excluded by direct searches for the SM Higgs particle.

The MSSM Higgs limits are model dependent and one needs to assume for example a certain sfermion mixing in setting the limits. Typical MSSM M_h are greater than 60 GeV/c^2. For SUSY particles preliminary LEP-2 limits are above 84 GeV/c^2 for charginos and 25 GeV/c^2 for neutralinos. There are improved

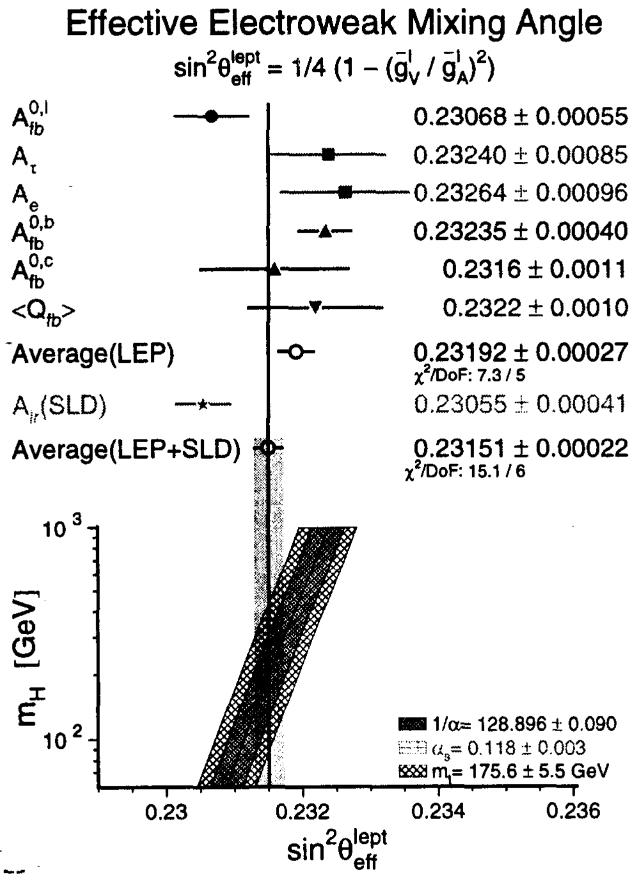

Figure 6. Summary of measurements of $\sin^2\theta_W^{eff}$ from the FB asymmetries of leptons, τ polarization, inclusive quarks, heavy quarks asymmetry and SLD polarization asymmetry. Also shown is SM prediction as a function of the Higgs mass.

limits for sfermions as well: 63, 58 and 70 GeV/c^2 for the supersymmetric partners of the top, muon and electron. Except for ALEPH's excess of 4 jet events at a mass of about 105 GeV/c^2 (discussed in [4]) no new particles were found and other searches have also set limits only on degenerate and long live SUSY, R-parity violation, compositness etc.. However the expectation from the coming LEP data with energies of 184 GeV and higher are to further improve the range for all searches.

7. SUMMARY

The Coupling parameters A_f (Eq. 2) are determined by the LEP FB asymmetry measurements (0.1536 ± 0.0043) and tau polarization (0.1393 ± 0.0050) and by the polarized measurements at SLD (0.1547 ± 0.0032). Using A_ℓ one can determine $A_{b/c}$ from LEP FB asymmetries in the heavy quarks sector. However one can turn it the other way around assume the hadronic couplings to be given by the SM and include the c/b quark asymmetry measurements in the determination of the effective weak mixing angle. Fig. 6 compares several determinations of the weak mixing angle, where the most significant disagreement is between LEP $A_{FB}(b)$ and A_{LR} measurement at SLD.

The combination of the numerous very precise electroweak measurements yield stringent constraints on the SM. The data taken so far and the theoretical predictions agree well. Radiative correction are well established as seen be the excellent agreement between the top mass predictions and the CDF/D0 measurements. The data show some sensitivity to the mass of a SM Higgs particle and the SM fits using all the data yield SM Higgs mass of 127^{+127}_{-72} GeV/c^2 (Fig. 5). One discrepancy which will be interesting to watch is the difference between the value of the weak mixing angle as derived from A_{LR} at SLD, to the one calculated at LEP dominated by the b quark asymmetry (Fig. 6). There are still many preliminary numbers or results that are using only sub-sample of the whole LEP data (e.g. tau polarization), and it would be interesting to see the final LEP numbers published along with the new results from LEP running in higher energies and SLD next year's data.

In the W physics the TEVATRON and LEP-2 are getting closer to the precision of the radiative corrections of the LEP-1 and SLD data, providing a new test of the SM (Fig. 3).

There is still no real clue for new particles and physics beyond the SM, hence further analysis of the existing and future data is still required.

8. ACKNOWLEDGMENT

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REFERENCES

1. S. L. Glashow, Nucl. Phys. **22** (1961) 579.
   A. Salam, Proc. 8^{th} Nobel Symposium, Aspengarden, Almqvist and Wiksell ed., Stockholm (1968) 367.
   S. Weinberg, Phys Rev. Lett. **19** (1967) 1264; Phys. Rev. **D5** (1972) 1412.
2. P. W. Higgs, Phys. Rev. Lett. **12** (1964) 132; **13** (1964) 508; Phys. Rev. **145** (1966) 1156
   F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 240;

G. S. Guralnik, C. R. Hagan and T. W. B. Kibble, Phys. Rev. **155** (1967) 1554.

3. F. Taylor, these proceedings;
   W. J. Marciano, these proceedings.
4. S. Manly, these proceedings.
5. A. A. Sokolov and I. M. Ternov, Sov. Phys. Doklady, **8** (1964) 1203.
6. G. Wilkinson, Proceedings of the ICHEP-96, Warsaw, 1996.
   LEP energy group note 96-05 (1996).
7. A. Arbuzo et al., Phys. Lett. **B383** (1996) 238; S. Jadach et al., "Upgrade of the Monte Carlo Program BHLUMI version 4.04", Comput. Phys. Commun. **102** (1997) 229;
8. ALEPH Collab, D. Camp et al., Z. Phys **C48** (1990) 365; **C53** (1992) 1; D. Buskulic et al., Z. Phys. **C60** (1993) 71; **C62** (1994) 539; "Preliminary results on Z production Cross Section and Lepton Forward-Backward Asymmetries using the 1990-1995 Data", contributed to ICHEP-96, Warsaw, 1996.
9. DELPHI Collab, P. Arnio et al., Nucl. Phys. **B367** (1991) 511; P. Abreu et al., Nucl. Phys. **B417** (1994) 3; **B418** (1994) 403; DLEPHI-Note 95-62 PHYS 497, July 1995; DELPHI-Note 97-31 PHY 684, March 1997.
10. L3 Collab, B. Adeva et al., Z. Phys. **C51** (1991) 179; O. Adriani et al., Phys. Rep. **236** 1; M. Acciary et al., Z. Phys. **C62** (1994) 551; "Preliminary L3 Results on Electroweak Parameters using 1990-96 Data", L3-Note 2065, March 1997.
11. OPAL Collab, G. Alexander et al., Z. Phys **C52** (1991) 175; P. D. Acton et al., Z. phys. **C58** (1993) 219; R. Akers etal., Z. Phys. **C61** (1994) 19; "A Preliminary Update of the Z line Shape and Lepton Asymmetry Measurements with 1993-94 Data", OPAL Phys Note PN166, Feb. 1995; "The Preliminary OPAL SiW luminosity analysis: Results for the summer 1994 conferences", OPAL PN142, July 1994; "A Preliminary Update of the Z Line Shape and Lepton Asymmetry Measurements with a revised 1993-94 LEP Energy and 1995 Lepton Asymmetry", PN242, July 1996; "Measurement of Lepton Pair Asymmetries Using the 1995 Data", Contributed to ICHEP-96, Warsaw, 1996; "A Preliminary Update of the Z Line Shape and Lepton Asymmetry Measurements with the 1995 Data" PN286, March 1997.
12. OPAL Collab, K. Ackerstaff et al., Phys. Lett. **B391** (1997) 221;
    L3 Collab, M. Acciari et al., CERN-PPE/97-52 to be published by Phys. Lett. **B** (1997).
13. ALEPH Collab, D. Buskulic et al., Z. Phys. **C69** (1996) 183.
14. DELPHI Collab, P. Abreu et al., Z. Phys. **C67** (1995) 183; DELPHI 96-114 conf 42, contributed to ICHEP-96, Warsaw, 1996.
15. L3 Collab, O. Acciari et al., Phys. Lett **B341** (1994) 245; "A preliminary Update of A_τ and A_e using 1994 data" contributed to ICHEP-96, Warsaw, 1996.
16. OPAL Collab, G. Alexander et al., Z. Phys. **C72** (1996) 365.
17. SLD Collab, K. Abe et al., Phys. Rev. Lett. **73** (1994) 25; **78** (1997) 2075.
18. SLD Collab, K. Abe et al., Phys. Rev. Lett. **79** (1997) 804.
19. SLD Collab, K. Abe et al., Phys. Rev. Lett. **74** (1995) 2880.
20. ALEPH Collab, D. Camp et al., Phys. Lett. **B259** (1991) 377; ALEPH-Note 93-041 (1993); 93-042 (1993); 93-044 (1993); D. Buskulic,,,,,et al., Z. Phys. **C71** (1996) 357.
21. DELPHI Collab, P. Abreu et al., Phys. Lett. **B277** (1992) 371; DELPHI 96-19.
22. L3 Collab, L3-note-2064, (1997).
23. OPAL Colab, P. D. Acton et al., Phys. Lett. **B294** (1992) 396; OPAL-Physics note **PN195** (1995).
24. SLD Collab, K. Abe et al., Phys. Rev. Lett. **78** (1997) 4691.
25. ALEPH Collab, R. Barate et al., Phys. Lett. **B401** (1997) 347;
    DELPHI Collab, P. Abreu et al., Phys. Lett. **B397** (1997) 158;
    L3 Collab, M. Acciarri et al., Phys. Lett. **B398** (1997) 223;
    OPAL Collab., K. Ackerstaff et al., Phys. Lett. **B389** (1996) 416.
26. ALEPH Collab., ALEPH 97-025 PHYSIC 97-020;
    DELPHI Collab, DELPHI 970-20 PHYS 676;
    L3 Collab, L3 Note 2057 (1997);
    OPAL Collab, OPAL PN 279 (1997).
27. CDF Collab, F. Abe et al., Phys. Rev. Lett. **75** (1995) 1017.
    D0 Collab, S. Abachi et al., FERMILAB-PUB-97-088-E, (1997) 77pp. hep-ex/9704004, To be published in Phys. Rev. D; FERMILAB-PUB-97/136-E.
28. Arie Bodek for CDF collab., Acta Phys. Polon. **B28** (1997) 477; Qun Fan, Arie Bodek, proceedings of ICCHEP 96, "Calorimetry in high energy physics" (1996) 553.
29. CDF Collab, F. Abe et al., Phys. Rev. Lett. **79** (1997) 2198.
30. LEP EW Working Group and SLD Heavy Flavor Group, "A combination of preliminary Electroweak measurements and constraints on the Standard Model", LEPEWWG/97-01 and SLD Physics Note 61, April 1997.