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 [2] 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 [1].

The next section discusses the LEP beam energy, luminosity and cross-section measurements. Section 2 discusses Weak Neutral Current measurements through forward backward asymmetries and tau polarization measurements at LEP and polarized asymme-

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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 $4 \times 10^8$ 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 $\pm 1760$ 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 $E_{av} \propto \frac{1}{f_{RF}} \int B dt$ where the beam path length is fixed by the RF frequency $\frac{1}{f_{RF}} \int B dt \propto f_{RF}$. The storage ring transverse spin polarization (Sokolov and Ternov effect [3]) 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 $(55 \pm 1.5$ 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 1 illustrates typical energy uncertainties used during the 1995 run.

### Table 1: Typical LEP energy uncertainty values for $E_{CM}$ 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 correctors | 0.3                     |
| Tide                  | 0.4                     |
| Orbit drifts          | 0.5                     |
| RF corrections        | 1.0                     |
| Dispersion            | 0.7                     |
| Total                 | 2.0                     |

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. 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 $\tau$-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 $\Gamma_{ee}$, $\Gamma_{\mu\mu}$ and $\Gamma_{\tau\tau}$ respectively. The total statistics of the four LEP collaborations are given in Table 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 | 3385 | 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 $R_{lt} = \frac{\Gamma_{\text{had}}}{\Gamma_{l+\ell-}}$ 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 3.

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, $\frac{\Gamma_{\text{inv}}}{\Gamma_{l+\ell-}} = \frac{\Gamma_{Z} - 3\Gamma_{l++\ell-} - \Gamma_{h+}}{\Gamma_{l+\ell-}}$ 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 $\theta^{-3}$ 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.

| $\Delta L/L \times 10^{-4}$ | 1993 | 1994 | 1995 |
|---------------------------|------|------|------|
| Experimental | Theoretical |
| 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 $\Gamma_{l+\ell-} = 83.89 \pm 0.11$ MeV, $\Gamma_{\text{had}} = 1743.5 \pm 2.4$ MeV and $\Gamma_{\text{inv}} = 499.8 \pm 1.9$ MeV. With that one can derive $\Gamma_{\text{inv}}/\Gamma_{l+\ell-} = 5.957 \pm 0.022$, 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 $Z^0$, $\Delta \Gamma_{\text{inv}} < 2.9$ 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 $e^+e^- \rightarrow \tau^+\tau^-$ 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 $\gamma$ 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.

\[ 1 \quad \Gamma_f \propto g_L^2 + g_R^2 \propto v_f^2 + a_f^2 \]

\[ 2 \quad A_f = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{v_f^2 - a_f^2}{v_f^2 + a_f^2} \]

Here \( g_L(R)_f \) are the left (right) handed couplings, and \( v_f \) and \( a_f \) are the effective vector and axial-vector \( Z_f f \) couplings.

For unpolarized beams (LEP) the Forward-Backward asymmetry,

\[ A_{FB}^f = \frac{3}{4} A_e A_f, \]

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

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

\[ p_\tau = \frac{A_\tau(1 + \cos^2 \theta) + 2 A_e \cos \theta}{1 + \cos^2 \theta + 2 A_e A_\tau \cos \theta}, \]

enable to derive both the the electron and the \( \tau \) 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,

\[ A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = P_\tau A_e, \]

where \( P_\tau \) is the polarization of the incident \( e^- \) beam. One can also measure the FB polarized asymmetry,

\[ A_{FB}^{pol(f)} = \frac{(\sigma_{L,F} - \sigma_{R,F}) - (\sigma_{L,B} - \sigma_{R,B})}{(\sigma_{L,F} - \sigma_{R,F}) + (\sigma_{L,B} - \sigma_{R,B})} = \frac{3}{4} P_\tau A_f. \]

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, \( \sin^2 \theta_W \), 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:

\[ \sin^2 \theta_W = \frac{1}{4} (1 - \frac{ve}{ae}), \]

where the \( ve/ae \) 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.

3.1. Leptonic Forward Backward asymmetries at LEP-1

Two main techniques been used to measure the FB asymmetry: fitting the differential cross section \( \frac{d\sigma}{d\cos \theta} \propto 1 + \cos^2 \theta + \frac{g}{s} A_{FB} \cos \theta \), and counting \( A_{FB} = \frac{N_{FB} - N_{0}}{N_{FB} + N_{0}} \). 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 \cite{1} 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:

\[ \frac{d\sigma}{d\cos \theta} = \frac{4\pi\alpha^2}{3} \left\{ \left( \frac{\alpha_e}{\alpha} \right)^2 \frac{\sin^2 \theta_W}{s} \right\}^2 (1 + \cos^2 \theta) \]

\[ + \frac{s - M_Z^2}{(s - M_Z^2)^2 + (1 - 2 \cos \theta + 1)^2} [J_f^t \frac{s}{2} (1 + \cos^2 \theta) + J_{FB}^t \cos \theta] \]

\[ + \frac{s - M_Z^2}{(s - M_Z^2)^2 + (1 - 2 \cos \theta + 1)^2} [R_{tot}^f \frac{s}{8} (1 + \cos^2 \theta) + R_{FB}^f \cos \theta] \]

Where

\[ R_{tot}^f = \frac{G_F M_Z^2}{\sqrt{2} \pi \alpha} \frac{9}{a^2 M_Z^2} v_e v_f \]

\[ J_f^t = \frac{G_F \Gamma_f}{\sqrt{2} \pi \alpha} (v_f^2 + a_f^2) \]

\[ \Gamma_f = \frac{G_F M_Z^2}{\sqrt{2} \pi \alpha} (v_f^2 + a_f^2) \]

![Figure 1. Summary of the 4 LEP experiments e, µ and τ FB asymmetries.](image-url)
3.3. Tau Polarization

All LEP experiments extract separate tau polarization ($p_{\tau}$) by reconstructing the decay of the tau to the five different channels: $e\nu_e\tau$, $\mu\nu_\mu\tau$, $\pi\nu_\pi\tau$, $\rho\nu_\rho\tau$, and $a_1\nu_{a_1}$ (Eq. 3). While the first three are one-dimensional fit, in order to obtain maximum information from the $\rho$ and the $a_1$ channels one has to investigate the distribution of the charged and neutral $\pi$s. With that the $a_1$ channel becomes more sensitive than the leptonic channels where the $\rho$ and the $\pi$ are the most sensitive channels, contributing weights of about 40% each in the average. Measuring the angular dependence of the $p_{\tau}$ (Eq. 3) provides nearly independent determination of the $\tau$ and electron coupling asymmetries, $A_e$ and $A_\tau$. 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 $A_\ell = 0.1393 \pm 0.0050$.

![Figure 2](image)

**Figure 2.** $\mu$ and $\tau$ 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 $s' = s - 2E_{ISR}\sqrt{s}$.

\[
R_{FB}^f = \frac{3G_F^2M_Z^2}{8\sqrt{s}a_f} v_ea_ev_f a_f ; \quad J_{FB}^f = \frac{3\sqrt{2}G_F}{8\alpha} a_ea_f
\]

and the total cross section is:

\[
\sigma_{tot}^f = \frac{4\pi\alpha^2}{3} \frac{(\alpha(s)Q_f)^2}{s} + \frac{J_{FB}^f(s - M_Z^2) + R_{FB}^f}{(s - M_Z^2)^2 + (T Z M_Z)^2} (10)
\]

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

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

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

However LEP-2 energy allows one to improve the $M_Z$ determination while $J_{tot}^{had}$ 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.

### Table 4

| Exp.     | $A_\tau$       | $A_e$       |
|----------|----------------|-------------|
| 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 $\nu$, hence it is not necessary to reconstruct the $\tau$ 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 $\approx 0.99$ and $\approx 0.025 - 0.012$

3.4. Polarized asymmetries measurements

SLD has a new preliminary measurement of $A_{LR}$ (Eq. 3 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
The charge separation, $\delta_f$, is the average charge difference between quark and antiquark in an event. The $b$ and $c$ are extracted from the data, the $\delta_b$ is 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:

$$\begin{align*}
\sin^2 \theta_W &= 0.2321 \pm 0.0008(stat) \pm 0.0007(sys. exp) \pm 0.0008(sep.) \\
\sin^2 \theta_W &= 0.2311 \pm 0.0010(stat) \pm 0.0010(sys. exp) \pm 0.0010(sep.) \\
\sin^2 \theta_W &= 0.2336 \pm 0.0013(stat) \pm 0.0014(sys. exp) (New!) \\
\sin^2 \theta_W &= 0.2321 \pm 0.0017(stat) \pm 0.0027(sys. exp) \pm 0.0009(sep.)
\end{align*}$$

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 lepton 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 ($\rho, \eta, \xi$, and $\xi\delta$) in the lepton 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 $\rho$ and $\eta$ 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 $\xi$, $\xi\delta$ and $h_{\nu}$. 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 $\frac{M_\tau}{M_\mu}$ factor current experiments are not sensitive to $\eta_e$. A few experiments ”improved” $\eta_e$ measurement using the high $\rho - \eta$ correlation and assumed $e - \mu$ universality. However this is an inconsistent assumption because generally a non zero $\eta$ would imply non universal $\rho$.

ALEPH has presented a new method that includes the reconstruction of the $\tau$ direction. L3 published a global analysis with 50% of their data. OPAL measured the $\xi_{had}$ in the $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ as part of the measurement of the hadronic structure function. SLD published their results for 1993-95 data [23]. 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 experimental measurements and SM predictions for the τ Charged Current parameters.

| exp. | ρ | η | ξ | ξδ | hν |
|------|---|---|---|----|----|
| 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 [24]. 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: \[ \sigma_{W^+W^-} = 3.69 \pm 0.45 \text{ pb} \] and the mass derived using an average energy of 161.33 ± 0.05 is: \[ M_W = 80.40^{+0.22}_{-0.21} \pm 0.03 \text{ GeV} \].

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 [20]. Averaging the results treating the smallest systematic error as 100% correlated yields: \[ M_W = 80.37 \pm 0.18 \pm 0.05(\text{color}) \pm 0.03(\text{LEP}) \], 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: \[ M_W = 80.38 \pm 0.14 \text{ GeV} \].

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 \( q\bar{q} \to W^+ W^- \), \( W^\pm \gamma \), \( Z\gamma \) 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. \( WW \) and \( W\gamma \) vertices have been observed and direct limits on non-SM, three-boson, \( WWZ \) and \( WW\gamma \) anomalous couplings were set. Fig. 3 shows no clear difference between the transverse momentum distribution for \( WW \) and \( W\gamma \) 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 \( Z \gamma \) interactions. CDF has studied

\[ W\text{-Boson Mass [GeV]} \]

\[ \begin{align*}
\text{pp-colliders} & \rightarrow 80.37 \pm 0.10 \\
\text{LEP2} & \rightarrow 80.38 \pm 0.14 \\
\text{Average(world)} & \rightarrow 80.37 \pm 0.08 \\
\text{LEP1/SLD} & \rightarrow 80.323 \pm 0.042 \\
\end{align*} \]

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 \( \nu-N \) 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 $\cos\theta^* = \pm 1/3$ ($\theta^*$ 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 $WZ\gamma$ couplings. The results are in agreement with the SU(2)$\times$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 $64.6^{+2.6}_{-2.1}$ 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 5).

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
Effective Electroweak Mixing Angle

$$\sin^2 \theta_{\text{eff}} = \frac{1}{4} \left(1 - \frac{g_V^2}{g_A^2}\right)$$

| $A_{b}^{c,j}$ | $0.23068 \pm 0.00055$ |
| $A_{s}$ | $0.23240 \pm 0.00085$ |
| $A_{t}$ | $0.23264 \pm 0.00096$ |
| $C_{b,c}^{b,b}$ | $0.23235 \pm 0.00040$ |
| $C_{b,c}^{b,c}$ | $0.2316 \pm 0.0011$ |
| $<Q_{b}>$ | $0.2322 \pm 0.0010$ |

Average(LEP) | $0.23192 \pm 0.00027$ |

$\chi^2$/DoF: 7.3/5

Average(LEP+SLD) | $0.23151 \pm 0.00022$ |

$\chi^2$/DoF: 15.1/6

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

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