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Measurements of Hadronic Asymmetries in e^+e^- Collisions at LEP and SLD [1]

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Abstract

High precision experimental new electroweak results measured at the four LEP experiments and the SLD collaboration are discussed. Heavy quark ($b\bar{b}$ and $c\bar{c}$) forward-backward asymmetries measured at LEP are presented along with polarized forward-backward and left-right asymmetries measured at SLD. The results are compared, and the combined averages are used to evaluate the Standard Model parameters.

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Introduction

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 $Zf\bar{f}$ couplings complementary to the partial widths measurements which are more sensitive to the left handed couplings. For unpolarized beams (LEP) the FB asymmetry, $A^f_{FB} = \frac{3}{4}A_e A_f$, is sensitive to the (initial) electron and the outgoing fermion couplings to the Z^0.
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, $A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = P_e A_e$, where P_e is the polarization of the incident e^- beam. One can also measure the FB polarized asymmetry,

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

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: $\sin^2\theta^{eff}_W \equiv 0.25(1 - v_e/a_e)$, where the v_e/a_e is extracted from the asymmetry measurements.
Complementary to the leptonic asymmetries which are sensitive to the oblique radiative corrections, the heavy flavour measurements ($R_{b/c}, A_{b/c}$) test the Standard Model (SM) [1] through vertex corrections. The c and the b quarks being the heaviest quarks accessible at the Z^0 peak, may provide a potential window to physics beyond the SM.
The measurements are based on about 4.4M events collected at each of the LEP experiments and the 200K events accumulated at SLD, produced with highly polarized electron beam. All the experiments have a good leptonic identification, DELPHI and SLD use Cerenkov ring imagine devices for particle identification, where the other 3 experiments use dE/dx for that purpose. The b and c event tag is based mainly on the experiments vertexing capability. All LEP experiments have installed double sided silicon micro-strip vertex detector, providing a typical high momentum track impact parameter resolution of $\sim 25\mu$m, where SLD uses silicon pixel detector which its upgraded version, installed before the 1996 run, gives a high momentum track impact parameter resolution of $\sim 13\mu$m.

Polarized Asymmetries

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

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

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:

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

The 1996 measurement combined with the previous measurements [2] yield:

$$A^0_{LR} = 0.1550 \pm 0.0034 \;\; ; \quad \sin^2\theta_W^{eff} = 0.23051 \pm 0.00043,$$

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 [3]. 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 for each lepton species. This measurement has a statistical advantage of $(P_e/A_e)^2 \sim 25$ 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: $A_e = 0.152 \pm 0.012(stat) \pm 0.001(sys)$, $A_\mu = 0.102 \pm 0.034 \pm 0.002$, and $A_\tau = 0.195 \pm 0.034 \pm 0.003$ or assuming universality $A_\ell = 0.151 \pm 0.011$. A new preliminary measurement based on the μ pairs collected at the 1996 run $A_\mu(1996) = 0.164 \pm 0.046$ is given, and combined with the 93-95 yield $A_\mu = 0.123 \pm 0.027$.
The SLD preliminary weak mixing angle value combining A_{LR}, Q_{LR} and leptons asymmetries measurements is: $\sin^2\theta_W^{eff} = 0.23055 \pm 0.00041$, which is more than 3σ below the LEP average.

Heavy Quark Asymmetries

The heavy quark final state asymmetries at the Z^0 peak are large and more sensitive to the EW parameters than the leptonic asymmetries. Since the LEP FB asymmetries are sensitive to both the electron and the out going fermion coupling to the Z^0 it can be interpreted in two ways:

1. Assume universal SM coupling of the out going quarks and derive $\sin\theta_W$, with a much higher sensitivity than the leptonic measurements gaining from the high asymmetry values of $A_c \sim 0.67$ and even better $A_b \sim 0.94$.

2. Use A_e value as given by the leptonic (LEP+SLD) measurements to determine the parity violation parameters, $A_{b,c}$.

The LEP FB asymmetries [4]- [7] were measured on the Z^0 peak and above and below the peak. Off peak measurements were corrected to the peak energy before combining to a pole asymmetries $A^{0,f}_{FB}$.
The SLD LR FB asymmetries [8] are independent of the electron coupling and therefore provide a direct measurement of $A_{b,c}$ again with that statistical advantage of $(P_e/A_e)^2 \sim 25$ compared to the LEP measurements.
Three different principal methods to select a sample of $b\bar{b}$ and measure the b asymmetry have been presented:

- Use the charge of the e or μ in b leptonic decays to sign the b quark direction, where the analyzing power is estimated from the momentum and transverse momentum distribution studied with simulation. (Used by ALEPH, DELPHI, L3, OPAL and SLD).

- Selection of b sample based on lifetime/mass distribution, and momentum weighted track charge to sign the b quark direction. This is a self calibrated technique where the analyzing power is derived directly from the data. (Done by DELPHI, L3, OPAL and SLD).

- A unique method introduced by SLD using mass tag to select the $b\bar{b}$ events and the Cerenkov Ring Imagine Detector (CRID) to identify kaons. The b quark charge is assigned on the basis of the charge of the kaons from the B decay chain.

The new b asymmetry analyses presented at 1997 are jet charge measurements by L3 (new), OPAL (final numbers - winter 97) and SLD (updated at winter 97), lepton tag by L3 and SLD (both updated for winter 97) and the SLD k-tag analysis updated for summer 97. The ALEPH preliminary jet charge analysis introduced in summer 96 which gave the single most precise determination of A^b_{FB} has been withdrawn before the conference and a correction is expected. The LEP measurements of A^b_{FB} and A^c_{FB} extrapolated to the Z^0 peak are given in Fig. 1 (a) and (c). The LEP measurements translated to a b or c quark asymmetry using the LEP/SLD combined value for $A_e = 0.1505 \pm 0.0023$, are given in Fig. 1 (b) and (d) along with the SLD direct parity violating parameters $A_{b/c}$ measurements.
The measurement of the charm hadrons asymmetry is performed in a similar way, and again three principal methods were used for these analyses:

- Lepton tag similar to the b asymmetry analysis used by all five experiments. (SLD's number updated at the winter conferences).

- D^*, D^0 and D^+ exclusive or semi-exclusive reconstruction used by ALEPH, DELPHI, OPAL and SLD to select a sample enriched with c hadron events, and to determine the direction of the c quark direction.

- In a new method introduced by SLD, charm quarks were tagged by an inclusive mass tag based on topological vertexing, resulting in efficiency of 20% with a purity of 75%. Again the CRID was used to identify kaons and the charge separation is obtained from a combination of the vertex charge and sign of kaon from the D decay chain.

After calculating the overall averages, the following corrections are applied (using ZFITTER [9]) in order to derive the quark pole asymmetries $A^{0,b}_{FB}$ ($A^{0,c}_{FB}$): -0.0013 (-0.0034) for the energy shift from 91.26 GeV/c^2 to M_z, +0.0041 (+0.0104) QED correction and -0.0003 (-0.0008) for γ exchange and γZ interference. QCD corrections (see e.g. [10]) depend strongly on the experimental analyses. Therefore the numbers quoted for the experiments were already corrected for QCD effects as described in [11].
A fit to the LEP and SLD data [12] gives the following combined results for the electroweak parameters:

$$
\begin{array}{ll}
R^0_b = 0.2170 \pm 0.0009 & R^0_c = 0.1734 \pm 0.0048 \\
A^{0,b}_{FB} = 0.0984 \pm 0.0024 & A^{0,c}_{FB} = 0.0741 \pm 0.0048 \\
A_b = 0.900 \pm 0.050 & A_c = 0.650 \pm 0.058
\end{array}
$$

with $\chi^2/d.o.f = 0.65$. The R_b-R_c correlation is -20%, the $A^{0,b}_{FB}$-$A^{0,c}_{FB}$ correlation is 13% and other elements in the correlation matrix are between 1 to 8%, where the parameters A_b and A_c have been treated as independent of the FB asymmetries.

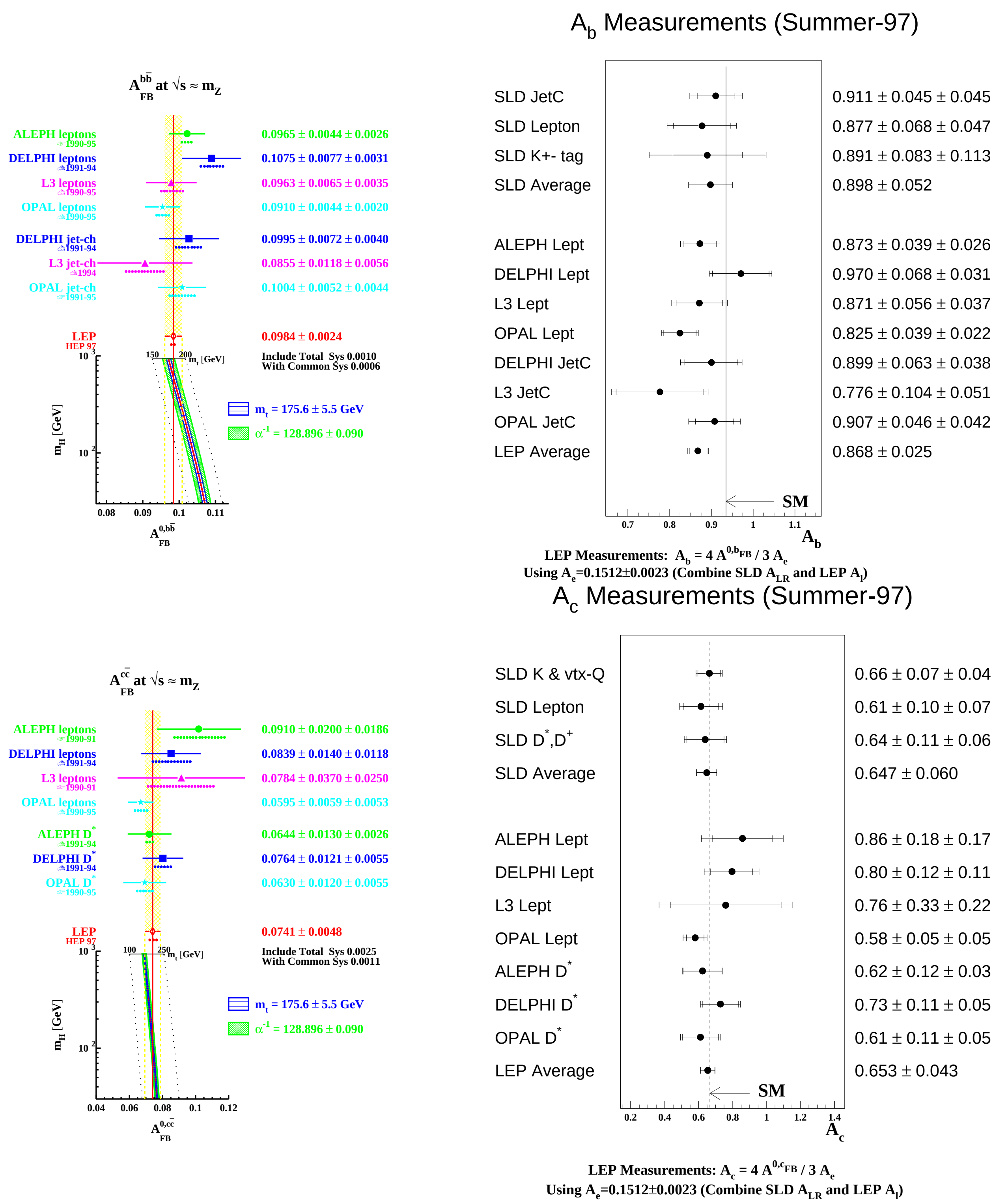

Figure 1: On the left the LEP measurements of A^b_{FB} (top) and A^c_{FB} (bottom), on the right A_b and A_c asymmetries as measured by SLD and LEP.

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

The LEP experiments [13]- [16] 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:

$$< Q_{FB} >= \sum_{quark \ \ flavour} \delta_f A_{FB}^f \frac{\Gamma_f}{\Gamma_{had}}.$$

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:

$$\begin{aligned}
0.2322 \pm 0.0008(stat) \pm 0.0007(sys.\ exp) \pm 0.0008(sep.) \\
0.2311 \pm 0.0010(stat) \pm 0.0010(sys.\ exp) \pm 0.0010(sep.) \\
0.2336 \pm 0.0013(stat) \pm 0.0014(sys.\ exp) \ \ (new - winter \ \ 97) \\
0.2321 \pm 0.0017(stat) \pm 0.0027(sys.\ exp) \pm 0.0009(sep.)
\end{aligned}$$

for ALEPH, DELPHI, L3 and OPAL respectively.

Light Quark Asymmetries

A measurement of the charge separation, the average charge difference between the quark and the antiquark hemispheres in an event, is required for inclusive measurement of the FB asymmetries of individual quarks. When the data is used to derive the charge separation in b and c quark asymmetry measurements, for light quark this is only obtained from the simulation and depend on the fragmentation model calibrated to the data. ALEPH, DELPHI and OPAL have published measurements of light quark asymmetries in the past. DELPHI has presented a new measurement of strange quark asymmetry based on a track by track identification of fast charged kaons, and anti b tag algorithm to reduce c and b contamination, resulting in: $A_{FB}^s = 0.114 \pm 0.019 \pm 0.005$. OPAL has performed a new analysis using all the 90-95 data to measure the branching fractions of the Z^0 into up and down type quarks, and the FB asymmetry in d and s quark events, using high momentum stable particles as a tag. The OPAL light quark asymmetry numbers are: $A_{FB}^{d,s} = 0.068 \pm 0.035 \pm 0.011$ or a correlated result $A_{FB}^u = 0.040 \pm 0.067 \pm 0.028$.

Weak Mixing Angle Measurement

The different values of $\sin \theta_W$ as obtained from the leptons and quark asymmetries, tau polarization and LR asymmetries are given in table 1. A χ^2/d.o.f of 12.6/6 is obtained where the largest disagreement at a level of 3 σ is between the most precise measurements A_{FB}^b at LEP and A_{LR} at SLD.

Observable	$\sin\theta_W$
Lepton FB	0.23102 ± 0.00056
τ polarization	0.23228 ± 0.00081
τ FB polarization	0.23243 ± 0.00093
b FB asymmetry	0.23237 ± 0.00043
c FB asymmetry	0.2315 ± 0.0011
Jet charge	0.2322 ± 0.0010
LEP average	0.23199 ± 0.00028
Left-Right (SLD)	0.23055 ± 0.00041
LEP+SLD	0.23152 ± 0.00023

Table 1: Summary of the LEP and SLD $\sin\theta_W$ measurements.

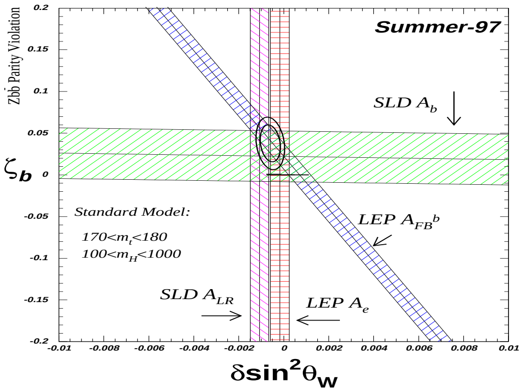

Fig. 2: The measured values of $\sin\theta_W$ as derived from SLD's A_{LR} and leptons asymmetries at LEP, LEP A^b_{FB} and SLD A_b measurements plotted on $\delta\sin\theta_W$ versus $Z_{b\bar{b}}$ parity violation plot (following Takeuchi, Grant and Rosner [17]).

Summary

Quark final state asymmetries provide experimmental powerful tools to study the SM. New measurements and some new techniques were preseted at the conference. The combination of many precise elctroweak results agree well with the theory predictions. The current LEP+SLD average value of A_b is 3 σ lower than predicted by the SM, or deriving the weak mixing angle from the LEP A_{FB} measurements makes the two most precise $\sin\theta_W$ measurements (A_{LR} and A^b_{FB}) disagree at a level of 3 σ. An interesting illustration of the current LEP and SLD $\sin\theta_W$ measurements plotted against the b parity asymmetry measurements is given in Fig. 2. The use of new tagging techniques which have been introduced in the R_b measurements [18] and analyzing the data which still has not being analyzed can further improve the precision of the b and c asymmetry measurements. SLD has started a new run and is expected to reach a precision on $\delta\sin\theta_W \sim 0.0002$.

Acknowledgment

I would like to thank the LEP and SLD collaborators and our colleagues from the LEP and SLC accelerators who brought the field to such an impressive level of precision. Many of the averages for this talk were derived by the detailed careful work of the LEP/SLD EW group [12]. It is a pleasure to thank the organizers for the interesting and successful conference.

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