INCLUSIVE CHARGE FLOW MEASUREMENTS OF THE EFFECTIVE MIXING ANGLE

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The LEP results for the effective mixing angle $\sin^2\theta_{eff}^{lept}$ from measurements of the inclusive charge flow in hadronic Z decays are presented. Using the very precise LEP data on exclusive and inclusive particle spectra to constrain the predictions of hadronization models systematic uncertainties have been reduced. The combined LEP result is $\sin^2\theta_{eff}^{lept} = 0.2320 \pm 0.0010$.

1 Introduction

The inclusive charge flow is a sensitive measurement of the effective weak mixing angle $\sin^2\theta_{eff}^{lept}$. In the framework of the Standard Model the forward-backward asymmetry A_{FB}^{f} at the Z pole is a function of the ratio of the couplings of the fermions to the Z and therefore sensitive to $\sin^2\theta_{eff}^{lept}$

$$\begin{aligned} A_{FB}^{0,f} &= \frac{3}{4}\cdot\frac{2\bar{v}_e\bar{a}_e}{\bar{v}_e^2+\bar{a}_e^2}\cdot\frac{2\bar{v}_f\bar{a}_f}{\bar{v}_f^2+\bar{a}_f^2} && (1)\\ \frac{\bar{v}_f}{\bar{a}_f} &= 1-4|Q_f|\sin^2\theta_{eff}\,. && (2)\end{aligned}$$

In the presence of this asymmetry the propagation of the primary quark (parton) charge to the hadronic final state leads to an observable charge flow. A good understanding of this charge propagation is crucial for such a measurement. Therefore precise exclusive and inclusive particle spectra measured at LEP are used to constrain hadronization models leading to an improved control of systematic uncertainties. In the following the measurements presented by ALEPH [1], DELPHI [2] and OPAL [3] are reviewed.

2 The inclusive charge flow

The primary quark charge is estimated from the charged particles in an event hemisphere as defined by the thrust axis. The hemisphere charge Q_{hem} is obtained from

$$Q_{hem} = \frac{\sum_i q_i\cdot p_{\|i}^{\kappa}}{\sum_i p_{\|i}^{\kappa}}\,, \qquad (3)$$

where q_i is the charge of the particle and $p_{\|i}$ is its momentum vector projected onto the thrust axis. κ is a weight parameter. Different choices of κ exploit different aspects of the event. In the limit of $\kappa\to 0$, the hemisphere charge is just the average over the charges, while for $\kappa\to\infty$ only the leading particle contributes to Q_{hem}.

The charge flow Q_{FB} is given by the difference of the forward and backward hemisphere charge

$$\begin{aligned} <Q_{FB}>_f &= <Q_F - Q_B>_f && (4)\\ &= <Q_f - Q_{\bar{f}}>\cdot\frac{N_F-N_B}{N_F+N_B} && (5)\\ &= \delta_f\cdot A_{FB}^{f}\,. && (6)\end{aligned}$$

The charge flow is linked to the forward-backwards asymmetry via the charge separation $\delta_f =< Q_f - Q_{\bar{f}} >$ between the fermion and antifermion hemisphere. For hadronic events one obtains

$$<Q_{FB}> = \sum_f R_f\delta_f A_{FB}^{f}\,, \qquad (7)$$

where R_f is the fraction of $Z\to f\bar{f}$ events in the sample.

The charge separation δ_f for the different flavours has to be measured from the data or can be taken from predictions of hadronization models. A very useful observable is the mean squared charge separation

$$\begin{aligned} \bar{\delta}^2 &= \sigma_{FB}^2 - \sigma_Q^2 && (8)\\ &\simeq -4 < Q_F\cdot Q_B > \simeq \sum_f R_f\delta_f^2\,. && (9)\end{aligned}$$

$\bar{\delta}^2$ can be measured either from the width of the charge flow σ_{FB} and the total charge σ_Q, or from the product of Q_F and Q_B.

Table 1: Comparison of results for δ_b for a given κ.

Experiment	κ	δ_b
ALEPH	1	-0.2057 ± 0.0061
DELPHI	1	-0.2010 ± 0.0056
OPAL	0.5	-0.1381 ± 0.0052
ALEPH	0.5	-0.1410 ± 0.0040

3 Measurements of δ_b and δ_c

The charge separation δ_b for b quarks is extracted from the data itself using the same method as used to measure A^b_{FB} from the charge flow. Using the lifetime information provided by silicon vertex detectors, the experiments are able to select b enriched samples from the data. The $\bar{\delta}^2$ in the lifetime tagged sample is given by

$$\bar{\delta}^2 = R_b \epsilon_b \delta_b^2 + R_c \epsilon_c \delta_c^2 + R_{uds} \epsilon_{uds} \delta_{uds}^2 \; . \qquad (10)$$

The b efficiency ϵ_b is measured directly from the data comparing the rate of events with single and double tagged hemispheres in the same manner as for the R_b measurement. OPAL imposes R_b from the Standard Model and extracts also ϵ_c from the data, while ALEPH and DELPHI use ϵ_c from the simulation. In all cases the remaining uds component has to be subtracted using the simulation. Table 1 shows the comparison of δ_b results for different choices of κ. These results include 10 % corrections for charge correlations between both hemispheres.

Using samples of different b purity ALEPH is able to extract also $\delta_c = +0.228 \pm 0.028\,(\kappa = 1)$ from a combined fit to the data [1]. This value agrees well with the direct measurement[1] of $\delta_c = +0.193 \pm 0.020\,(\kappa = 1)$ in events where one hemisphere is tagged by a high momentum D^{*+} leading to a c purity of 79 ± 3 %. The ALEPH Monte Carlo is able to reproduce δ_c after a careful tuning of inclusive D branching ratios and vector meson rates. DELPHI and OPAL use similar tunings to extract δ_c from the simulation.

4 Monte Carlo modelling of δ_u, δ_d and δ_s

The determination of the individual light quark charge separation relies on hadronization models due to the lack of an efficient tag to select u, d or s quark events. Therefore reliable predictions are crucial for a precise determination of $\sin^2\theta^{lept}_{eff}$ from this method.

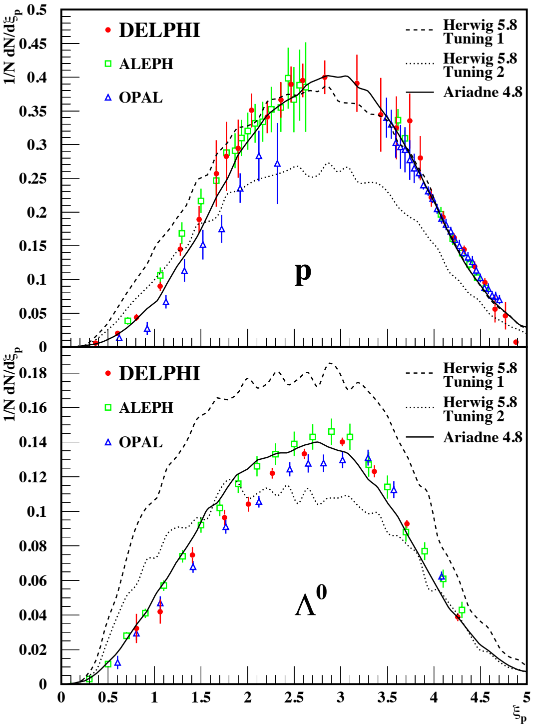

Figure 1: Comparison of measured baryon spectra at LEP to Monte Carlo predictions. HERWIG fails to describe the p and Λ spectra at the same time.

The measured inclusive $\bar{\delta}^2_{meas}$ agrees with the fully simulated Monte Carlo predicted $\bar{\delta}^2_{pred}$ to a few %. This is due to the charge separation properties that stem from a limited number of principles which are implemented in hadronization models. In the absence of strange particle and baryon production, the charge separations of light quark events are expected to be identical although the primary quark charges are unequal. The common scale depends on resonance production and properties of gluon radiation and longitudinal fragmentation functions determining the momentum spectra in hadronic events. It is tightly constrained by the measured $\bar{\delta}^2_{meas}$. Isospin symmetry breaking production of strange particles and baryons lead to systematic differences between δ_u and δ_d, which can not be observed in $\bar{\delta}^2_{meas}$. Therefore measured spectra of K°, $K^\pm$, p and Λ from LEP are essential to constrain the model

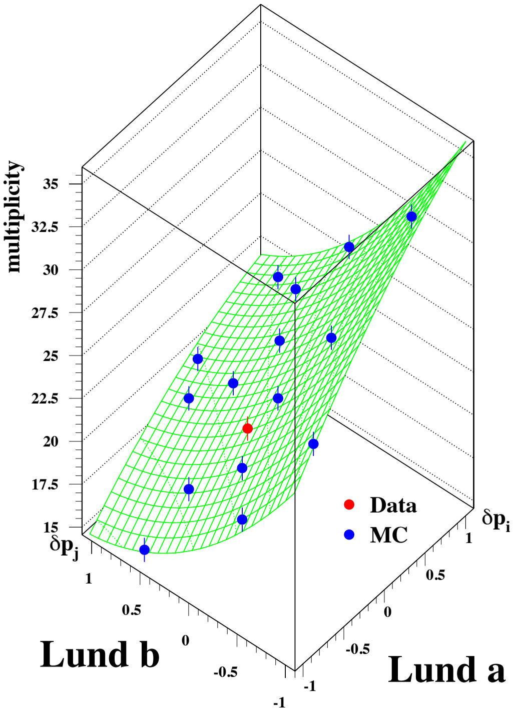

Figure 2: Example for a random walk in the DELPHI parameterization of the multiplicity as a function of *LUND a* and *LUND b*.

predictions. Here the HERWIG [4] model fails to describe the baryon production (figure 1) and is therefore not used by the experiments to predict δ_f. ALEPH and OPAL are using JETSET 7.4 [5], while DELPHI uses a different parton shower model implemented in ARIADNE 4.08 [6].

Different approaches are used to extract $\delta_{u,d,s}$ from the fragmentation models. OPAL uses the best tuning of the model parameters (≥ 15) as the central value and varies each parameter independently within its uncertainty. ALEPH and DELPHI constrain the parameters in a correlated way using a fit of the model to the data of event shapes, inclusive spectra, K°, $K^\pm$, p and Λ spectra, baryon correlation measurements and resonance spectra. The charge separations $\delta_{u,d,s}$ are extracted directly from the fit.

ALEPH parameterizes the dependence of the JETSET 7.4 prediction as a function of the model parameters using a linear ansatz. A χ^2 is then constructed comparing this parameterization to the measured input spectra. To allow for deficits in the model description, the χ^2/NDF is scaled to be 1 for each input distribution. Here the extreme is p_t^{out}, where an scaling of 1/590 has been used. Also the parameters for the popcorn mechanism and for fast baryon suppression are fixed to the central values and varied separately. The charge separations for $\kappa = 1$ are determined minimizing the χ^2 to be

$$\begin{aligned} \delta_u &= +0.4062 \pm 0.0081 & (11)\\ \delta_d &= -0.2294 \pm 0.0087 & (12)\\ \delta_s &= -0.3287 \pm 0.0047\,. & (13) \end{aligned}$$

These numbers include acceptance effects of the detector.

DELPHI uses a slightly different approach based on a full 2nd order approximation including correlations of the ARIADNE 4.08 hadronization model. Here a random walk in the n-dimensional space of parameters is performed (figure 2) and the χ^2 for the comparison of the prediction to the data is calculated. For each of these parameter sets the charge separations δ_f are calculated leading to χ^2 vs δ_f clouds. Applying the criteria $\chi^2 \leq 2 \cdot \chi^2_{min}$ lead for $\kappa = 1$ to mean values

$$\begin{aligned} \delta_u = +0.370 \quad &, \quad \delta_d = -0.192 & (14)\\ \delta_s = -0.300 \quad &, \quad \delta_c = +0.163\,. & (15) \end{aligned}$$

No errors are quoted because parameters are highly correlated.

5 Determination of $\sin^2 \theta_{eff}^{lept}$

After the charge separations δ_f are determined, the effective mixing angle is extracted from the measured $< Q_{FB} >$ using equation 7. The rates R_f for the different flavours are taken from the standard model. ZFITTER [7] is used to relate $sin^2\theta_{eff}^{lept}$ to A_{FB}^f.

The experiments use different choices of κ in order to maximize the sensitivity. DELPHI used $\kappa = 1$ to obtain $< Q_{FB} >$, while OPAL is using $\kappa = 0.5$ and determines $< Q_{FB} >$ as a function of $\cos\theta$. ALEPH does a full correlated fit to $< Q_{FB} >$ for five different κ between 0.3 and ∞. This way the maximum charge flow information is used to reduce the error. All experiments present results on $sin^2\theta_{eff}^{lept}$ based on the data up to 1994. The comparison is shown in figure 3. The combined average is $sin^2\theta_{eff}^{lept} = 0.2320 \pm 0.0010$ taking correlations into account.

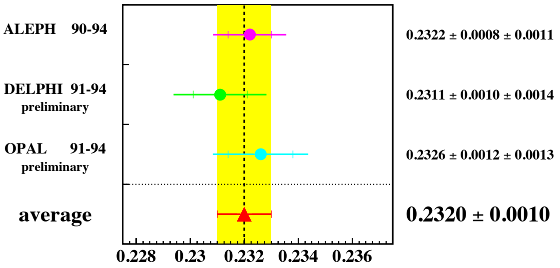

Figure 3: Comparison of the LEP results of $\sin^2\theta_{eff}^{lept}$ from inclusive charge flow measurements.

ALEPH and OPAL use the data at $\sqrt{s} = 89.52$ GeV and $\sqrt{s} = 92.94$ GeV from 1991 and 1993 to test the energy dependence of the $< Q_{FB} >$ due to the change in the asymmetries as predicted by the Standard Model. Good agreement with the data is found by both experiments.

6 Summary

The measurement of the effective mixing angle $\sin^2\theta_{eff}^{lept}$ from the inclusive charge flow has become very precise. Using the lifetime information provided by the silicon vertex detector to select b events the charge separation δ_b is measured directly from the data. Uncertainties of the hadronization models to predict light quark charge separations were limiting the experimental precision in the past. Constraining the models to the LEP results on exclusive and inclusive particle spectra leads to a better understanding of the model uncertainties. The results presented based on the measured inclusive charge flow from the data up to 1994 are

$$\sin^2\theta_{eff}^{lept} = 0.2322 \pm 0.0014 \quad (ALEPH) \quad (16)$$
$$\sin^2\theta_{eff}^{lept} = 0.2311 \pm 0.0017 \quad (DELPHI) \quad (17)$$
$$\sin^2\theta_{eff}^{lept} = 0.2326 \pm 0.0018 \quad (OPAL)\,. \quad (18)$$

A comparison of combined LEP and SLC results on $\sin^2\theta_{eff}^{lept}$ using different methods is shown in figure 4. The combined result $\sin^2\theta_{eff}^{lept} = 0.2320 \pm 0.0010$ based on the inclusive charge flow measurements is in good agreement with the results from the combined lepton, c and b asymmetries, A_{LR} and the τ polarization and the τ polarized asymmetry. Note that the two most precise measurements A_{FB}^b and A_{LR} are only in rough agreement. Also shown is the prediction of the Standard Model as a function of m_{top} and m_{Higgs}. Good agreement with the DO and CDF average[8] of $m_{top} = 175 \pm 6$ GeV/c^2 is found.

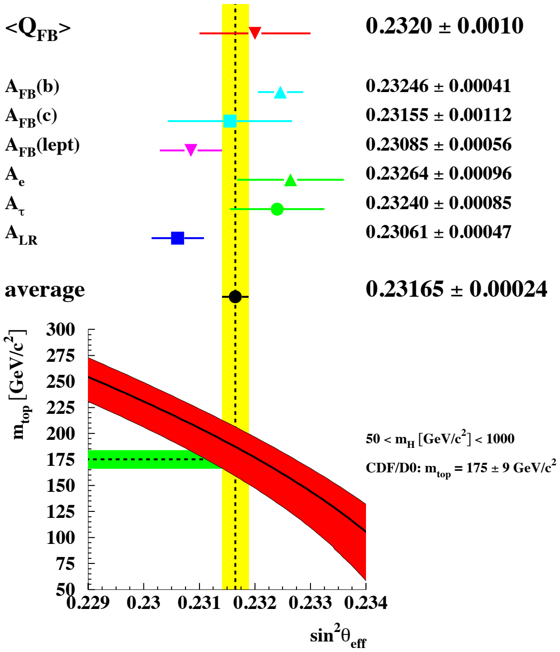

Figure 4: Comparison of results on $\sin^2\theta_{eff}^{lept}$ from LEP and SLC.

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