Jet Charge Measurements in $Z \rightarrow q\bar{q}$ Decays

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Abstract

The propagation of initial quark charges to their final state particles is studied in a sample of 1.5 million hadronic $Z$ decays collected at ALEPH between 1990 and 1993, using a family of momentum weighted charge estimators. The mean charge separation between event hemispheres containing the original quark and antiquark is measured for $b\bar{b}$ and $c\bar{c}$ events in subsamples selected by their long lifetimes and using fast $D^*$'s. The corresponding charge separation for light quarks is measured in an inclusive sample from the anticorrelation between charges of opposite hemispheres which agrees with predictions of hadronisation models at the level of 2%. The mean difference between forward and backward hemisphere charges provides a sensitive measurement of the electroweak mixing angle which is determined to be:

$$\sin^2 \theta_W^{\text{eff}} = 0.2323 \pm 0.0010(\text{exp.}) \pm 0.0010(\text{seps.}).$$

The first error is due to purely experimental sources whereas the second error stems from uncertainties in the light quark fragmentation. These are estimated using hadronisation models, within experimental constraints provided by measurements of inclusive particle production.

Jet charge methods are used at LEP in the analysis of electroweak quark asymmetries [1, 2, 3, 4], and both integrated [5, 6] and time dependent [7] $B^0\bar{B}^0$ mixing measurements. This paper presents results of an extensive study of jet charge properties and applies them to the analysis of the inclusive charge asymmetry in hadronic $Z$ decays.

The quark charge is estimated by the momentum weighted hemisphere charge introduced in [1]:

$$Q_{\text{hem}} = \frac{\sum_{\text{hem}} p^\mu_i q_i}{\sum_{\text{hem}} p^\mu_i},$$

where the sum runs over the charged particles in an event hemisphere defined by the thrust axis. The charge, $q_i$, is that of particle $i$ and $p^\mu_i$ is its momentum projected onto the thrust axis. The parameter $\kappa$ can be varied from 0 to $\infty$, to provide a family of charge estimators. On average, the charges of the hemispheres containing the quark and the antiquark in a $q\bar{q}$ event with given flavour, $f$, differ by a quantity: $\delta_f = \langle Q_f - Q_{\bar{f}} \rangle$ which is referred to as the charge separation. Separations for specific quark flavours can be directly measured in events where one hemisphere is tagged and the charge measured in the opposite hemisphere. For example, events with high momentum $D^*$'s provide enriched samples of $c$ quarks, and are used to measure $\delta_c$ while those with high momentum $\Lambda$'s constrain $\delta_b$.

Another quantity sensitive to charge separations is the inclusive product of charges in opposite hemispheres: $\langle Q_F \cdot Q_B \rangle_f = -\delta_f^2/4 \simeq -\delta_f^2/4$ where $Q_F$ ($Q_B$) is the charge in the forward (backward) hemisphere. Using a lifetime-tagged sample [8] this method has been used [4] to measure $\delta_b$. By varying the lifetime-tag cuts, the composition of the sample is altered to enhance the charm fraction and the absolute value of $\delta_c$ extracted. The results for the measurements of $\delta_c$ from $D^*$ tagging are consistent with the results obtained using the lifetime method as shown in Figure 1. The results are combined to give the value of $\delta_c$. Also shown in the figure is a comparison to Monte Carlo computations of the $c$ quark charge separation based upon forcing the Monte Carlo to reproduce the branching ratios of either inclusive $D$ meson decays to charged and neutral kaons or exclusive $D$ meson decays. The figure shows that the experimentally determined jet charge is well described only when the inclusive branching ratios are used.
Determination of the individual light quark separations is difficult due to the lack of an efficient tag discriminating between $u$, $d$ and $s$ type quarks. The reliability of hadronisation models to predict them is therefore investigated.

The average separation is measured with a relative precision of $1\%$:

$$\bar{\delta} = 0.2909 \pm 0.0013 \pm 0.0022 \quad (\kappa = 1.0) \simeq \sqrt{\sum_{f=1}^{5} \frac{\delta_{f}^{u}}{\Gamma_{f}^{u}}} \Gamma_{f}^{\text{had}}.$$  

The value of $\bar{\delta}$ is within $2\%$ of the fully simulated Monte Carlo prediction of 0.2845 based on the ALEPH tuning [9] of JETSET [10]. This is because jet charge propagation properties stem from a limited number of general principles which are implemented in hadronisation models such as JETSET and HERWIG [11].

In principle, the charge separations for light quark flavours are expected to be identical in the case when only $u\bar{u}$ and $d\bar{d}$ pairs are produced during hadronisation. This common scale depends on resonance production and is tightly constrained by the measured value of $\bar{\delta}$. The observed differences between the light quark separations arise from the additional production of strange particles and baryons during the hadronisation process. The two hadronisation models employ different philosophies in this sector, leading to systematic differences in the values of $\delta_u$, $\delta_d$, $\delta_s$. Consequently, the measured spectra of $K^\pm$, $K^0$, $p$ and $\Lambda$'s in data are studied and used to constrain model predictions. A fit of the models to inclusive event shape variables, particle production spectra and the measured value of $\bar{\delta}$ is used to determine the light quark charge separations. Systematic errors are assigned based on differences between the observed data and the Monte Carlo predictions in the quantities fit for the case that there is a discrepancy and upon the statistical precision of the comparison when there is agreement. Correlations between model parameters are taken into account. Spectra are closely reproduced by the JETSET model, while HERWIG fails to reproduce baryon production satisfactorily. Results for all the quark charge separations are shown in Table 1; those relying on the model predictions are consistent for the two models although the JETSET determination is more precise.

Finally, following the experimental method described in [1], the difference in the average charge of forward and backward hemispheres of hadronic events is measured to be:

$$\langle Q_{FB} \rangle = -0.00935 \pm 0.00049 \text{(stat.)} \pm 0.00023 \text{(sys)} \quad (\kappa = 1.0).$$

Its value depends on the electroweak asymmetry in $Z \rightarrow q\bar{q}$ decays:

$$\langle Q_{FB} \rangle = \sum_{\text{quark flavours}} \frac{\delta_f A_{FB}^{(q)}}{\Gamma_f^{\text{had}}} \Gamma_f^{\text{had}},$$

it is interpreted using the charge separations for $0.3 \leq \kappa \leq 2.0$ in terms of the electroweak mixing angle, $\sin^2 \theta_w^{\text{eff}}$. Results are given in Table 2 using light quark separations predicted by JETSET and HERWIG. The systematic uncertainty is significantly smaller for JETSET because it is able to reproduce the inclusive particle distributions more accurately and we take this result as our final value:

$$\sin^2 \theta_w^{\text{eff}} = 0.2323 \pm 0.0010 (Q_{FB}) \pm 0.0010 \text{(seps.)}.$$  

The dependency of $\langle Q_{FB} \rangle$ on energy is shown for $\kappa = 1.0$ in Figure 2 and compared to the expectation using the fit value of $\sin^2 \theta_w^{\text{eff}}$ and the JETSET separations. The three curves reflect the uncertainty in the separations.
Figure 1: Comparisons of (a) the lifetime tag and $D^{*\pm}$ measurements of $\delta_c$ and (b) the combined $\delta_c$ measurement in data with that expected from Monte Carlo simulation using different charm branching ratios.

Figure 2: $\langle Q_{FB} \rangle$ plotted as a function of center of mass energy for the data (points) and a prediction using the fitted values of the JETSET light quark charge separations, the measured values of the heavy quark charge separations and the fitted value of $\sin^2 \theta_W^Z$. The family of curves reflects the errors on the quark charge separations. The results are shown for $\kappa = 1.0$. 
\begin{table}
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\begin{tabular}{|c|c|c|}
\hline
\text{Separation} & \text{Value} & \\
\hline
\multicolumn{3}{|l|}{\text{JETSET}} \text{ | } \text{HERWIG} \\
\hline
\text{\d_{u}} & \text{+0.4100 \pm 0.0103} & \text{+0.3973 \pm 0.0316} \\
\text{\d_{d}} & \text{-0.2315 \pm 0.0119} & \text{-0.2516 \pm 0.0148} \\
\text{\d_{b}} & \text{-0.3308 \pm 0.0069} & \text{-0.3337 \pm 0.0186} \\
\hline
\end{tabular}
\caption{The charge separations for $\kappa = 1$}
\end{table}

\begin{table}
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\begin{tabular}{|c|c|c|}
\hline
\text{\sin^2 \theta_{w}^{\text{eff}}} & \text{\chi^2/DOF} \\
\hline
\text{JETSET} & \text{0.2323 \pm 0.0010 (Q_{FB}) \pm 0.0010 (seps.)} & \text{93/131} \\
\text{HERWIG} & \text{0.2331 \pm 0.0010 (Q_{FB}) \pm 0.0022 (seps.)} & \text{86/42} \\
\hline
\end{tabular}
\caption{Values of $\sin^2 \theta_{w}^{\text{eff}}$ using light quark charge separations from JETSET and HERWIG}
\end{table}

References


