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MEASUREMENT OF THE LEFT-RIGHT CHARGE ASYMMETRY IN HADRONIC Z DECAYS AND A_e DETERMINATION*

SLD COLLABORATION

represented by

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ABSTRACT

We present a new method for determining the electron left-right asymmetry factor, A_e, by measuring the forward-backward charge flow in samples of hadronic Z events, produced in e^+e^-collisions, with left-handed and right-handed electron-beam polarizations. The raw, left-right charge asymmetry, Q_{LR}^{raw}, is defined. After correction by the measured beam polarization, it provides A_e with greatly reduced dependence on Monte Carlo corrections for acceptances and jet charge measurement. The Q_{LR}^{raw} is also combined with the raw, left-right cross section asymmetry, A_{LR}^{raw}, to obtain A_e without the use of the measured electron-beam polarization, and with half the statistical error as that obtained for A_e using the polarization corrected Q_{LR}^{raw} alone. This method gives $\sin^2\theta_W^{\rm eff} = 0.2291 \pm 0.0039(stat.)\ \pm 0.0012(syst.)$. The measurement was performed at a center-of-mass energy of 91.26 GeV with the SLD detector at the SLAC Linear Collider (SLC).

1. Introduction

SLD has measured the left-right cross section asymmetry, $A_{LR} = (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$, in the production of Z bosons by e^+e^-collisions.[1,2] In the Standard Model of the electroweak interactions, this gives the electron left-right asymmetry, $A_e = 2v_e a_e/(v_e^2 + a_e^2)$, from:

$$A_{LR}^{raw} \ = \ |\mathcal{P}_e| A_{LR} \ = \ |\mathcal{P}_e| \ A_e \tag{1}$$

where $\mathcal{P}_e$ is the electron-beam polarization. Since only the total cross sections were observed in this measurement, the forward-backward asymmetries can also be used to

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provide independent information on the couplings to the Z. At Born level, the forward-backward fermion asymmetry at the Z pole (excluding e^+e^-final states) is given by:

$$A_{FB,f}(\mathcal{P}_e) = -g(a)\frac{\mathcal{P}_e - A_e}{1-\mathcal{P}_e A_e}\ A_f \tag{2}$$

where $g(a)=a/(1+\frac{1}{3}a^2)$, $0<a\leq 1$, $a=|\cos\theta|_{max}$, $\cos\theta$ describes the angle between the outgoing fermion f and the direction of the incident electron, and $A_f = 2v_f a_f/(v_f^2+a_f^2)$. Assuming equal polarization magnitudes and luminosities, we can define $A_{FB,L,f} \equiv A_{FB,f}(-|\mathcal{P}_e|)$ and $A_{FB,R,f} \equiv A_{FB,f}(|\mathcal{P}_e|)$ as the forward-backward asymmetries for events produced with left and right beam polarizations.

For a flavor-inclusive sample of Z hadronic final states, we must relate the fermion asymmetries above to *charge* asymmetries.[3–5] At parton level the fermion asymmetries would give nonzero, average forward and backward charges for a $q_f\bar{q}_f$ final state:

$$\begin{aligned}
< Q^{raw}_{F,L,f} > &= q_f\ A_{FB,L,f} & \qquad < Q^{raw}_{F,R,f} > &= q_f\ A_{FB,R,f} \\
< Q^{raw}_{B,L,f} > &= -q_f\ A_{FB,L,f} & \qquad < Q^{raw}_{F,R,f} > &= -q_f\ A_{FB,R,f}
\end{aligned} \tag{3}$$

where we can separate "left" and "right" events for SLD. The charge magnitudes can then be averaged into the left and right, forward-backward charge flows:

$$\begin{aligned}
< Q^{raw}_{FB,L,f} > &= < Q^{raw}_{F,L,f} > - < Q^{raw}_{B,L,f} > = 2\ q_f\ A_{FB,L,f} \\
< Q^{raw}_{FB,R,f} > &= < Q^{raw}_{F,R,f} > - < Q^{raw}_{B,R,f} > = 2\ q_f\ A_{FB,R,f}.
\end{aligned} \tag{4}$$

Finally, the flavor-inclusive expressions for the polarized ($< \tilde{Q}^{raw}_{FB} >$) and unpolarized ($< Q_{FB} >$) forward-backward charge flows can be defined by summing over the flavors, weighting by production, and including modifications ($d_f \epsilon [0,1]$) to account for a reduction in the measured charge magnitudes due to QCD corrections, hadronization effects (including $B^0\bar{B}^0$ mixing), and decays:[6]

$$\begin{aligned}
< \tilde{Q}^{raw}_{FB} > &= < Q^{raw}_{FB,L} > f_L - < Q^{raw}_{FB,R} > f_R \\
&= 2\ g(a)\ |\mathcal{P}_e|\ \sum_f d_f q_f R_f A_f
\end{aligned} \tag{5}$$

$$\begin{aligned}
< Q_{FB} > &= < Q^{raw}_{FB,L} > f_L + < Q^{raw}_{FB,R} > f_R \\
&= 2\ g(a)\ A_e\ \sum_f d_f q_f R_f A_f
\end{aligned} \tag{6}$$

where $f_L = \frac{1}{2}(1+|\mathcal{P}_e|A_e)$ and $f_R = \frac{1}{2}(1-|\mathcal{P}_e|A_e)$ are the fractions of left and right events, $R_f = \Gamma_f/\Gamma_{had}$, $\Gamma_f \propto v_f^2 + a_f^2$, and $\Gamma_{had} = \sum_f \Gamma_f$. The quantities $< Q^{raw}_{FB,L} >$ and $< Q^{raw}_{FB,R} >$ are now the mean, flavor-inclusive, forward-backward charge flows in left and right events. Since $|\mathcal{P}_e|$ and A_e factor out of the sums, the ratio of these charge asymmetries (assuming the sum is not identically zero) has the simple form:

$$Q^{raw}_{LR} \equiv \frac{< \tilde{Q}^{raw}_{FB} >}{< Q_{FB} >}$$

$$= \frac{< Q^{raw}_{FB,L} > f_L - < Q^{raw}_{FB,R} > f_R}{< Q^{raw}_{FB,L} > f_L + < Q^{raw}_{FB,R} > f_R}$$

$$= \frac{|\mathcal{P}_e|}{A_e} \qquad (7)$$

Thus, by measuring the left-right charge asymmetry, $Q_{LR} = Q^{raw}_{LR}/|\mathcal{P}_e|$, A_e can be obtained in a manner largely independent from the A^{raw}_{LR} measurement.[7] At lowest order, the expression for Q^{raw}_{LR} shows that uncertainties in the acceptance and jet charge measurement are cancelled out, thus reducing the dependence on the Monte Carlo methods for such corrections, and subsequent systematic errors. Many of the remaining errors due to instrumental effects are also reduced in the $< \tilde{Q}_{FB} >$ measurement, but not in the $< Q_{FB} >$, and must be considered for corrections and systematic errors to Q^{raw}_{LR}. Comparing A_e obtained from Q^{raw}_{LR} to that obtained from A^{raw}_{LR} provides an inclusive test of our understanding of the charged final states of Z decays. Furthermore, since Q^{raw}_{LR} is formed from the ratio of $|\mathcal{P}_e|$ and A_e whereas A^{raw}_{LR} is formed from their product, the two measurements may be combined to measure A_e without the use of a direct measurement of the polarization:

$$A_e = \sqrt{\frac{A^{raw}_{LR}}{Q^{raw}_{LR}}}. \qquad (8)$$

This method takes advantage of both measurements of A_e and eliminates the systematic error due to the polarization measurement. Alternatively, Q^{raw}_{LR} and A^{raw}_{LR} may be combined to obtain a check on the measured polarization value:

$$|\mathcal{P}_e| = \sqrt{A^{raw}_{LR}\ Q^{raw}_{LR}}. \qquad (9)$$

2. Method of Analysis

Details of the SLAC Linear Collider (SLC), the polarized electron source, the measurement of the polarization with the Compton polarimeter, and the SLD experiment are described in Refs. 1 and 2. The results presented here are based on an integrated luminosity of 1.78 pb^{-1} at $\sqrt{s} = 91.260$ GeV, which SLD obtained during the 1993 run with $|\mathcal{P}_e| \approx 63\%$ at the interation point. Hadronic events are selected using track and event selection cuts that were used in a previous measurement of α_s by SLD,[8] with the following additions. Each event is divided by a plane perpendicular to the thrust axis that is determined using all accepted charged tracks in the event. It is required that $|\cos\theta_T| < 0.7$, $N_{ch}/hemis \geq 3$, $E_{ch}/hemis > 0.1\ E_{beam}$, and total $E_{ch} > 0.2\ E_{CM}$. Events are rejected if any track has $p_{tot} > 55$ GeV/c. A total of 14,723 left events and 12,000 right events are obtained. The measured $|\mathcal{P}_e|$ for this sample is 63.5% with a 1.7% systematic error and negligible statistical error as described in Ref. 2.

The forward-backward charge asymmetries are determined as follows. A unit vector along the thrust axis, $\hat{\mathbf{T}}$, is chosen such that $\hat{\mathbf{T}}\cdot\mathbf{p}_{e^-} > 0$. Tracks are then defined as forward if $\mathbf{p}\cdot\hat{\mathbf{T}} > 0$, and backward otherwise. The weighted charge in the forward hemisphere is then calculated for each event from:

$$Q_F = \frac{\sum_{\mathbf{p}_i\cdot\hat{\mathbf{T}}>0} |\mathbf{p}_i\cdot\hat{\mathbf{T}}|^\kappa q_i}{\sum_{\mathbf{p}_i\cdot\hat{\mathbf{T}}>0} |\mathbf{p}_i\cdot\hat{\mathbf{T}}|^\kappa} \qquad (10)$$

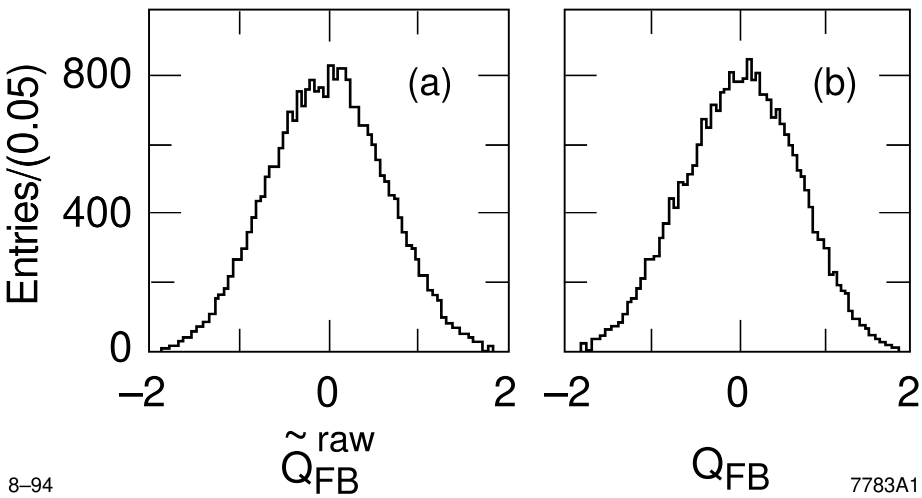

Fig. 1. Distributions of the polarized (a) and unpolarized (b), forward-backward charge flows.

where q_i is the charge of particle i, and κ is a weighting factor. The results presented here take $\kappa = 1$. The charge in the backward hemisphere, Q_B, is determined in a similar manner for tracks with $\mathbf{p} \cdot \hat{\mathbf{T}} < 0$. The quantity $Q_{FB} = Q_F - Q_B$ is then found for each event, and averaged for all left events as $< Q^{raw}_{FB,L} >$, and all right events as $< Q^{raw}_{FB,R} >$. Finally, $< \tilde{Q}^{raw}_{FB} >$, $< Q_{FB} >$, and Q^{raw}_{LR} are obtained from Eqs. 5, 6, and 7, respectively.

3. Preliminary Results

Distributions for $\tilde{Q}^{raw}_{FB}$ and Q_{FB} are shown in Fig. 1. Having applied a $-17.5 \pm 7.3\%$ correction for a charge-dependent, forward-backward bias to the track sagittas, we obtain the following: $< Q^{raw}_{FB,L} > = -0.0467 \pm 0.0052$, $< Q^{raw}_{FB,R} > = 0.0330 \pm 0.0058$, $< \tilde{Q}^{raw}_{FB} > = -0.0405 \pm 0.0039$, $< Q_{FB} > = -0.0109 \pm 0.0039$, $(Q^{raw}_{LR})^{-1} = 0.269 \pm 0.096$, and $A^{raw}_{LR} = 0.1019 \pm 0.0061$.[9]

We have investigated a number of possible systematic errors due to biases of the instrumentation, analysis, and various backgrounds. The relative uncertainties in Q_{LR} due to these errors are summarized in Table 1.

4. Summary

The value for the left-right charge asymmetry, before radiative corrections, but corrected for the measured polarization and including the systematic error, is:

$$Q^{-1}_{LR} = 0.171 \pm 0.061(stat.) \pm 0.019(syst.) \tag{11}$$

Source of uncertainty	$\delta Q_{LR}/Q_{LR}$ (%)
polarization measurement and chromaticity correction	1.7
q dependent, F-B sagitta bias, $(6.0 \pm 3.3)10^{-4}$ GeV^{-1}	8.9
q independent, F-B sagitta bias, $(8.0 \pm 3.2)10^{-4}$ GeV^{-1}	0.3
F-B asymmetry of SLD central material, $(0.22 \pm 0.81)\%$	0.5
q independent, F-B track losses from recon. and accept. biases	0.1
unphysical p_{tot} tracks	0.8
dependence of Q_{LR}^{raw} on the value of κ	5.0
polarization effects in hadronization and decays	0.5
SLC track backgrounds, $< Q_{FB} >_{SLC} = (-1.3 \pm 2.0)10^{-4}$	0.0
e^+e^- final state backgrounds, $(1.2 \pm 0.9)10^{-5}$	0.7
two photon backgrounds, $< 1. \times 10^{-4}$@$95\% C.L.$	1.0
charge dilution factors in calculations of radiative corrections	4.0
Total	11.2

Table 1. Summary of Systematic Errors

Radiative corrections are made to the measured asymmetries using the ZFITTER program.[10] After these corrections, the following values are obtained:

$$A_e = 0.169 \pm 0.061(stat.) \pm 0.019(syst.) \tag{12}$$

$$\sin^2\theta_W^{\rm eff} = 0.2288 \pm 0.0080(stat.) \pm 0.0024(syst.) \tag{13}$$

These results were obtained using $M_Z = 91.187$ GeV/c^2, $\alpha_s = 0.123$, Higgs mass $M_H = 300$ GeV/c^2, and top mass $m_t = 250^{+120}_{-240}(stat.)\ ^{+40}_{-50}(syst.) \pm 20(\delta M_H)$ GeV/c^2, where the last error on m_t is due to a variation of $M_H \epsilon$ [70,10^3 GeV/c^2]. These results are largely independent of those previously obtained by SLD from A_{LR}.

We can also obtain A_e from Q_{LR}^{raw} and A_{LR}^{raw} using Eq. 8, without the use of the measured polarization. After radiative corrections to the raw results, we obtain:

$$A_e = 0.1659 \pm 0.0302(stat.) \pm 0.0092(syst.) \tag{14}$$

$$\sin^2\theta_W^{\rm eff} = 0.2291 \pm 0.0039(stat.) \pm 0.0012(syst.) \tag{15}$$

with $m_t = 250^{+70}_{-100}(stat.) \pm 20(syst.) \pm 20(\delta M_H)$ GeV/c^2. These results are *alternative*, not independent, of those obtained from A_{LR}^{raw}, and Q_{LR}^{raw}, and using the measured polarization. From Eq. 9, they are also equivalent to $|\mathcal{P}_e| = 0.616\ ^{+0.153}_{-0.087}(stat.)\ ^{+0.037}_{-0.031}(syst.)$, which agrees well with the measured $|\mathcal{P}_e|$ of the selected data sample.

References

1. SLD Collab., K. Abe et al., *Phys. Rev. Lett.* **70** (1993) 2515.
2. SLD Collab., K. Abe et al., *Phys. Rev. Lett.* **73** (1994) 25.
3. ALEPH Collab., D. Decamp et al., *Phys. Lett.* **B 259** (1991) 377.
4. DELPHI Collab., P. Abreu et al., *Phys. Lett.* **B 277** (1992) 371.
5. OPAL Collab., P. D. Acton et al., *Phys. Lett.* **B 294** (1992) 436.

6. It is assumed here that the d_f factors are the same for both left and right events, or that the QCD corrections and effects of hadronization and decays are the same for both the polarized and unpolarized expressions. Final-state polarization effects would require further modifications. SLD has made a preliminary study of jet handedness at the Z. H. Masuda, SLAC–PUB–6550, 1994 (unpublished).
7. For the measurement presented here, the correlation coefficient between A_{LR}^{raw} and Q_{LR}^{raw} is estimated to be $\approx -6\%$ when the charge fluctuations are included in the flavor-inclusive sample. M. Swartz (private communication).
8. SLD Collab., K. Abe et al., *Phys. Rev. Lett.* **71** (1993) 2528.
9. The DPF conference proceedings show Q_{LR}^{raw} as having a symmetric error, but it is more appropriate for $(Q_{LR}^{raw})^{-1}$ to have the symmetric error, and it is amended here as such. This results in modifications to the errors of the final results shown here compared to those given in the DPF conference proceedings.
10. D. Bardin et al., CERN–TH. 6443/92, May 1992 (unpublished), and as adapted by M. Swartz (private communication).