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A Search for Jet Handedness in Hadronic Z^0 Decays†

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Abstract

We have searched for signatures of polarization in hadronic jets from $Z^0 \to q\bar{q}$ decays using the 'jet handedness' method. The charge asymmetry induced by the high SLC electron beam polarization was used to select quark or antiquark jets, expected to be left- and right-polarized, respectively. From our preliminary study, we find no evidence for jet handedness in our global sample nor in a sample of light quark jets. Assuming Standard Model values of quark polarizations, we set upper limits of 5.1% and 9.1% (preliminary), respectively, on the magnitude of the analyzing power of this technique at the 95% C.L. We have studied several alternative definitions of jet handedness and find no signal by any method.

1. Introduction

The transport of parton polarization through the hadronization process is of fundamental interest in QCD. It is presently an open question whether the polarization of a parton produced in a hard collision is observable via the final state fragmentation products in its resulting jet. The Z^0 resonance is an ideal place to study this issue because quarks produced in Z^0 decays are predicted by the Standard Model (SM) [1] to be highly longitudinally polarized. If a method of observing such polarization were developed, it could be applied to jets produced in a variety of hard processes, elucidating the spin dynamics of the underlying interaction.

Nachtmann [2] and Efremov *et al.* [3] have speculated that the underlying parton polarization may be observable semi-inclusively via a triple product of track momenta in a jet. They note that the simplest parity-conserving and spin-dependent amplitude has the form

$$M \propto \vec{\sigma} \cdot (\vec{k}_1 \times \vec{k}_2), \tag{1}$$

where $\vec{\sigma}$ is the spin of the decaying particle, and the $\vec{k}_i$ are 3-momenta of two decay products. The simplest example of such a process is the strong decay of the a_1 meson [4]. For a jet an analogous triple vector product Ω may be defined which might contain information on the longitudinal parton polarization:

$$\Omega = \vec{t} \cdot (\vec{k}_1 \times \vec{k}_2), \tag{2}$$

where $\vec{t}$ is a unit vector defining the jet axis, and $\vec{k_1}$ and $\vec{k_2}$ are the momenta of two particles in the jet chosen by some prescription, *e.g.*, the two fastest particles. The jet is defined as left- (right-) handed if Ω is negative (positive). For an ensemble of jets the handedness is defined as the asymmetry in the number of left- and

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right-handed jets:

$$H = \frac{N_{\Omega<0} - N_{\Omega>0}}{N_{\Omega<0} - N_{\Omega>0}}. \qquad (3)$$

It can then be asserted that

$$H = \alpha P, \qquad (4)$$

where P is the average polarization of the underlying partons in the ensemble of jets, and α is the analyzing power of the handedness method.

A method which observes such a polarization in an e^+e^- annihilation experiment could be applicable to jets resulting from lepton-hadron or hadron-hadron collisions, where the underlying parton polarization is unknown, to determine the parton polarization.

2. Polarization

In the process $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$ the cross sections for production of left- and right-handed quarks of flavor f are given at tree level by [1]

$$\begin{aligned} \sigma_L^f &= (1 + A_f)(1 + \cos^2\theta + 2A_Z \cos\theta) \qquad (5) \\ \sigma_R^f &= (1 - A_f)(1 + \cos^2\theta - 2A_Z \cos\theta), \end{aligned}$$

where $A_Z = (A_e - P_{e^-})/(1 - A_e P_{e^-})$; $A_f = 2v_f a_f/(v_f^2 + a_f^2)$; P_{e^-} is the longitudinal polarization of the electron beam; v_f and a_f are the vector and axial-vector couplings of fermion f to the Z^0; and θ is the polar angle of the outgoing quark with respect to the electron beam direction. The quark and antiquark in an event have opposite helicities, so we get

$$\sigma_{L(R)}^{\bar{f}}(\cos\theta) = \sigma_{R(L)}^f(-\cos\theta). \qquad (6)$$

The SM predicts $A_{e,\mu,\tau} \approx 0.16$, $A_{u,c} \approx 0.67$, and $A_{d,s,b} \approx 0.94$, so the quarks are predominantly left-handed and the antiquarks are predominantly right-handed. In order to observe a net polarization in an ensemble of jets from Z^0 decay it is therefore necessary to distinguish quark jets from antiquark jets.

This can be achieved at the SLAC Linear Collider (SLC) where Z^0 bosons are produced in collisions of highly longitudinally polarized electrons with unpolarized positrons. In 1993 the average electron beam polarization was 0.630 ± 0.011 [6]. In this case the SM predicts a large difference in polar angle distributions between quarks and antiquarks, providing an unbiased separation of quark and antiquark jets. We define the 'helicity-based' polarization of jets at a given $\cos\theta$:

$$P_{hel}(\cos\theta) \equiv \frac{\sigma_R^f + \sigma_R^{\bar{f}} - \sigma_L^f - \sigma_L^{\bar{f}}}{\sigma_R^f + \sigma_R^{\bar{f}} + \sigma_L^f + \sigma_L^{\bar{f}}} = -2\frac{A_Z \cos\theta}{1 + \cos^2\theta}. \qquad (7)$$

This jet polarization is independent of flavor, and reaches 0.72 and 0.52 in magnitude at large $|\cos\theta|$ for beam polarizations of -0.63 and $+0.63$, respectively. An alternative variable is the 'chirality-based' polarization of jets:

$$P_{chi}^f \equiv \frac{\sigma_R^f - \sigma_R^{\bar{f}} - \sigma_L^f + \sigma_L^{\bar{f}}}{\sigma_R^f + \sigma_R^{\bar{f}} + \sigma_L^f + \sigma_L^{\bar{f}}} = -A_f. \qquad (8)$$

This jet polarization is independent of $\cos\theta$ and electron beam polarization but depends on quark flavor. It is accessible by charge ordering of the tracks used in the analysis as described below. The experimental challenge is to find observables sensitive to one or both of these expected jet polarizations.

3. Handedness Measurement

In this paper we present the preliminary results of a search for jet handedness using a sample of approximately 50,000 hadronic Z^0 decays collected by the SLD experiment [5] in 1993. Electrons of mean longitudinal polarization $\pm 63\%$ were used to produce Z^0 bosons at the SLC. We have applied the methods suggested in [3, 4] and [10], which we also extended to be more inclusive. In each case we used both the helicity- and chirality-based methods of defining Ω and hence H. A handedness signal may be diluted in heavy quark events, $Z^0 \rightarrow c\bar{c}$ or $b\bar{b}$, since a large fraction of tracks in each jet are from the decays of a spinless heavy meson, and Dalitz *et al.* have concluded [7] that any effect resulting from D^* or B^* decays should be very small. We therefore divided our data cleanly into samples of light, $Z^0 \rightarrow u\bar{u}$, $d\bar{d}$ or $s\bar{s}$, and heavy flavor events using hadron lifetime information and sought evidence for jet handedness in each.

The trigger and initial selection of hadronic events is described in [6]. The analysis presented here is based on charged tracks measured in the Central Drift Chamber, and in the vertex detector. A set of cuts was applied to the data to select well-measured tracks and quark and antiquark jets in $Z^0 \rightarrow q\bar{q}$ events well contained within the detector acceptance. Tracks were required to have (i) a closest approach to the beam axis within 5 cm, and within 10 cm along the beam axis from the measured interaction point, (ii) a polar angle θ with respect to the beam axis with $|cos\theta| < 0.8$, and (iii) a minimum momentum transverse to this axis of $p_\perp > 150$MeV/c. Events were required to contain a minimum of five such tracks, a thrust axis direction with respect to the beam axis, θ_T, within $|\cos\theta_T| < 0.71$, and a minimum charged visible energy greater than 20 GeV, where all tracks were assigned the charged pion mass. Two-jet events were selected using the JADE clustering algorithm [8] at $y_{cut} = 0.03$, with the requirement that the jet acollinearity angle be less than 20°. From our 1993 data samples, a total of 17,853 events survived these cuts. The contamination from background sources was estimated to be $0.3 \pm 0.1\%$, dominated by $\tau^+\tau^-$ events.

In addition to considering this global sample, events were classified as being of light (u, d, or s) or heavy (c or b) quark origin based on impact parameters of charged tracks. The 9,977 events containing no track with impact parameter transverse to the beam axis more than 3σ from the collision point were assigned to the light quark sample, and all other events were assigned to the heavy quark sample. The purities of these two samples were estimated from simulations to be 84% and 70% respectively [9].

3.1. *Method A*

Following [4] we first considered the three highest momentum tracks in each jet in their rest frame if they had total charge ± 1. The invariant mass of both oppositely charged pairs was required to be in the range $0.6 < m < 1.6$ GeV/c^2. The tracks forming the higher mass pair were used to calculate $\Omega_{hel} = \vec{t} \cdot (\vec{k}_> \times \vec{k}_<)$ and $\Omega_{chi} = \vec{t} \cdot (\vec{k}_+ \times \vec{k}_-)$, where $|k_>| > |k_<|$, and $\vec{t}$ is the thrust axis signed so as to point along the jet direction. The distribution of Ω_{hel} for left- and right-handed electron beams and for forward ($\vec{t}_Z > 0$) and backward ($\vec{t}_Z < 0$) jets, and Ω_{chi} are shown in Fig. 1 for the light flavor sample.

A signal would be visible as a shift in this distribution, which in the case of the helicity-based analysis is of opposite sign for events produced with left- and right-handed electron beam polarization and for forward and backward jets. All the distributions appear to be symmetric about $\Omega = 0$, implying that any jet handedness is small.

The jet handedness was calculated according to Eq. (3) separately for each case. Results are summarized in Table 1. In all cases, the measured handedness is consistent with zero. Analyzing powers were calculated from Eq. (4). For the helicity-based analysis, the analyzing powers of the four helicity samples were then combined. The results are shown in Table 2. Since all analyzing powers are consistent with zero, we set upper limits at the 95% confidence level on the magnitudes of the analyzing power, also shown in Table 2.

We extended this method to use the N_{lead} highest momentum particles in each jet, with $3 \leq N_{lead} \leq 12$. We considered all zero charge pairs i,j among these N_{lead} particles, without imposing mass cuts, and calculated Ω^{ij}_{hel} and Ω^{ij}_{chi} for each pair in the N_{lead}-particle rest frame. Jets with fewer than N_{lead} tracks were excluded. The Ω^{ij} were then averaged to give Ω^{jet}_{chi} and Ω^{jet}_{hel}. The calculated jet handedness for this method

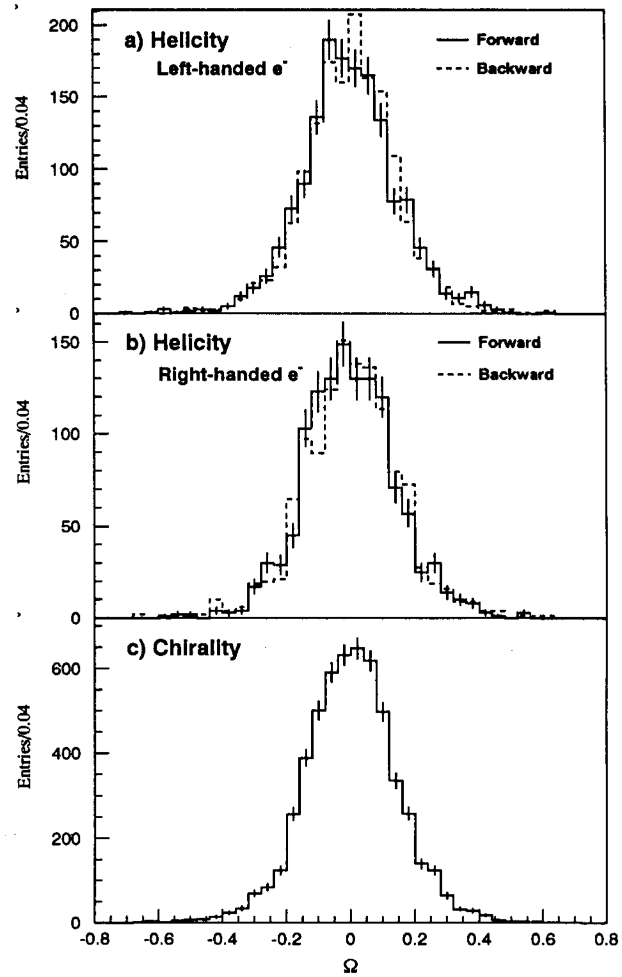

Figure 1. Measured distribution of (a) Ω_{hel} in forward hemisphere (solid histogram) and backward hemisphere (dashed histogram) with left-handed electron beam, (b) with right-handed electron beam, and (c) Ω_{chi} for the light flavor sample. Errors are statistical only. Errors on Ω_{chi} in the forward and backward hemispheres are added in quadrature and plotted only with Ω_{chi} in the forward hemisphere for clarity.

is consistent with zero for all N_{lead}, both helicity- and chirality-based Ω definitions, and the global, light, and heavy flavor samples. For $N_{lead} \leq 10$, upper limits on the magnitudes of the analyzing powers in the range 5–9% can be derived, after which the sample size limits our accuracy.

3.2. *Method B*

Following [10] we then attempted to select pairs of tracks likely to contain quarks from the same string breakup. In studies using the JETSET [11] Monte Carlo we found the relative rapidity with respect to the jet axis of tracks in a pair to be useful for this. Requiring opposite charge does not improve this selection, but was used in the chirality-based analysis.

Analysis	Maximum Expected Handedness (%)	Measured Jet Handedness (%) All jets	Light Jets	Heavy Jets
Helicity:				
Left e^-, *forward*	-44	0.6 ± 1.9	2.1 ± 2.5	-1.2 ± 2.8
Left e^-, *backward*	$+44$	-2.5 ± 1.9	-5.1 ± 2.5	0.8 ± 2.8
Right e^-, *forward*	$+32$	1.8 ± 2.1	3.2 ± 2.8	0.1 ± 3.1
Right e^-, *backward*	-32	-2.4 ± 2.1	-1.5 ± 2.8	-3.4 ± 3.1
Chirality:	$+39$	-0.9 ± 1.0	-0.8 ± 1.3	-1.1 ± 1.5

Table 1. Expected maximum jet handedness (assuming $\alpha = +1$) and measured jet handedness in % using the first analysis.

Analysis	Analyzing Power (%) All jets	Light Jets	Heavy Jets
Helicity	-0.4 ± 2.6 (5.1)	-3.4 ± 3.4 (9.1)	3.4 ± 3.9 (9.7)
Chirality	-2.4 ± 2.6 (6.6)	-2.0 ± 3.4 (7.8)	-2.9 ± 3.8 (9.2)

Table 2. Analyzing powers of the helicity- and chirality-based analysis of jet handedness using Method A. Upper limits at the 95% C.L. on the magnitudes are shown in parentheses.

In each jet the tracks were ordered in rapidity and assigned a number n_i, such that $1 \leq n_i \leq n_{tracks}$, where $n_i = 1$ for the track with highest rapidity. We then required pairs of tracks i,j to have $|n_i - n_j| < \Delta n$ and $\max(n_i, n_j) \leq n_{max}$. Since the signal is expected to increase with momentum transverse to the thrust axis, we also required $|p_{ti}| + |p_{tj}| > p_{min}$. We calculated Ω^{ij}_{chi} and Ω^{ij}_{hel} in the laboratory frame for each pair satisfying these criteria and took the average over all pairs for each case. Then Δn, n_{max}, and p_{min} were varied in an attempt to maximize the handedness signal. Figures 2 and 3 show the distributions of H for the light flavor sample in the helicity-based analysis for (a) left- and (b) right-handed electron beams for forward and backward jets as a function of p_{min} and Δn at fixed $n_{max} = 6$, respectively. Figure 4 shows the distribution of H for the light flavor sample in the chirality-based analysis as a function of (a) p_{min} and (b) Δn at fixed $n_{max} = 6$.

In no case did we find evidence for non-zero jet handedness. For all samples and both analyses we obtained upper limits in the range 5–9% for $n_{max} \leq 6$, $\Delta n \leq 6$, and $p_{min} < 2$ GeV/c. Statistics become poor in the potentially interesting, high-p_{min} region.

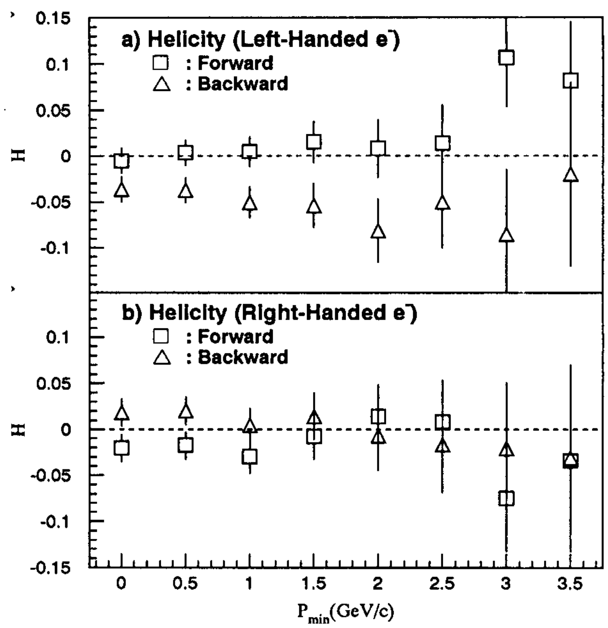

Figure 2. Measured distribution of H for (a) left- and (b) right-handed electron beams for forward (squares) and backward (triangles) as a function of p_{min} at fixed $n_{max} = 6$ for the light flavor sample in the helicity-based analysis. Errors are statistical only.

3.3. Systematic Checks

A number of systematic checks was performed for each method. All analysis methods were found to be insensitive to the track and event selection cuts, and to the jet-finding algorithm (we tried the E, E0, and P versions of the JADE algorithm, as well as the Geneva and Durham algorithms [12]) and y_{cut} values used to select 2-jet events. Each analysis was found to be insensitive to the values of the selection criteria for tracks used to define Ω. Each analysis was performed on samples of Monte Carlo events in which spin transport was not simulated, yielding H consistent with zero within $\pm 0.4\%$.

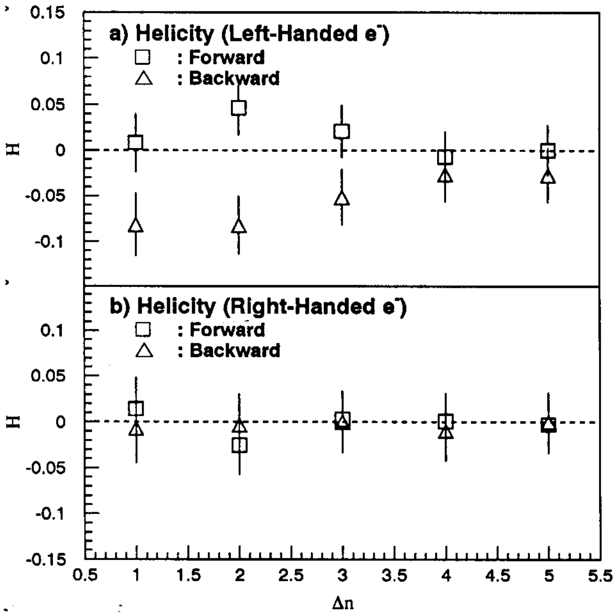

Figure 3. Same as Fig. 2 but as a function of Δn.

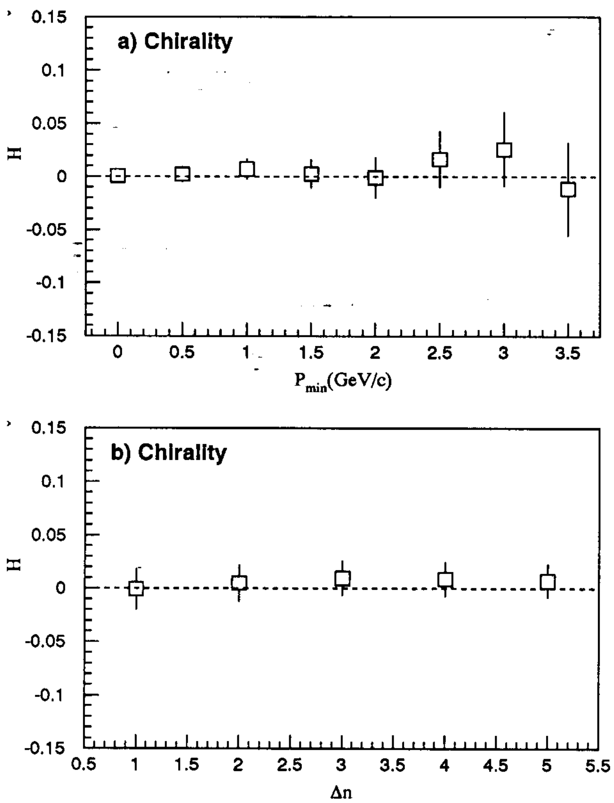

Figure 4. Same as Fig. 2 but in the chirality-based analysis as a function of (a) p_{min} and (b) Δn.

We found no correlation between the values of Ω in the two jets in an event for any analysis method.

4. Conclusion

We have searched for evidence of parton polarization in hadronic Z^0 decays using two jet handedness methods suggested in [3, 4] and [10]. In an attempt to optimize a signal, we studied a wide range of parameters for each method. In each case we employed both helicity- and chirality-based analyses, and sought signals separately in samples of light and heavy quark jets as well as in the global sample. We found no evidence for a non-zero jet handedness, implying that the transport of quark polarization through the jet fragmentation process is small. For the method suggested in [4] we derive an upper limit of 9.1% on the magnitude of the analyzing power of a helicity-based analysis applied to a sample of light flavor jets. Averaged over all jets from $Z^0 \rightarrow q\bar{q}$ decays, a limit of 5.1% is derived. Similar limits are derived for a chirality-based analysis, as well as for all other methods we applied.

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