A Search for Jet Handedness in Hadronic Z^0 Decays

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1

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 polar angle asymmetry induced by the high SLC electron-beam polarization was used to separate quark jets from antiquark jets, expected to be left- and right-polarized, respectively. We find no evidence for jet handedness in our global sample or in a sample of light quark jets and we set upper limits at the 95% C.L. of 0.063 and 0.099 respectively on the magnitude of the analyzing power of the method proposed by Efremov *et al.*

The transport of parton polarization in strong interactions is of fundamental interest. It is at present an open question whether the polarization of quarks or antiquarks produced in hard collisions is observable via the final-state fragmentation products in the resulting jets. The Z^0 resonance is an ideal place to study this issue as the partons in $Z^0 \to q\bar{q}$ decays are predicted by the Standard Model (SM) 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 in order to elucidate the spin dynamics of the underlying interactions.

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

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

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 a Z^0 decay have opposite helicities so that $\sigma_{L(R)}^{\bar{f}}(\cos\theta) = \sigma_{R(L)}^{f}(-\cos\theta)$. 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 that the quarks are produced predominantly left-handed and the antiquarks predominantly right-handed. In order to observe a net polarization in an ensemble of jets from Z^0 decays it is therefore necessary to distinguish quark jets from antiquark jets.

This separation 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 [2]. 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 $\cos\theta$:

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

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:

$$P_{chi}^f \equiv \frac{\sigma_R^f - \sigma_R^{\bar{f}} - \sigma_L^f + \sigma_L^{\bar{f}}}{\sigma_R^f + \sigma_R^{\bar{f}} + \sigma_L^f + \sigma_L^{\bar{f}}} = -A_f. \tag{3}$$

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.

Nachtmann [3] and Efremov *et al.* [4] have speculated that the polarization may be observable inclusively via a triple product of track momenta in jets. Arguing that quark fragmentation may resemble a multi-body strong decay, they note that the simplest observable with the same transformation properties under parity inversion as P_{hel} (Eq. 2) has the form $\Omega \equiv \vec{t}\cdot(\vec{k}_1 \times \vec{k}_2)$, where $\vec{t}$ is a unit vector along the jet axis, corresponding to the spin direction of a longitudinally polarized parton that produced the jet, and $\vec{k}_1$ and $\vec{k}_2$ are the momenta of two particles in the jet chosen by some charge-independent prescription, e.g.,

$$\Omega_{hel} = \vec{t}\cdot(\vec{k}_1 \times \vec{k}_2) \quad \text{where} \quad |\vec{k}_1| > |\vec{k}_2|, \tag{4}$$

and referred to some suitable frame. Alternatively, if $\vec{k}_1$ and $\vec{k}_2$ are the momenta of a positively and a negatively charged particle, the cross product can be ordered by charge, e.g.,

$$\Omega_{chi} = \vec{t}\cdot(\vec{k}_+ \times \vec{k}_-). \tag{5}$$

For a given flavor Ω_{chi} has the same transformation properties under parity inversion as P_{chi} (Eq. 3) and so might be sensitive to P_{chi}. Jets from Z^0 decays comprise a mixture of flavors that might yield different signals since quark charges and fragmentation properties depend on flavor. Taking into account only the sign s_f of the charge of quarks of flavor f, one expects a net

polarization $P_{chi} = -\Sigma_f s_f R_f A_f = 3R_d A_d - 2R_u A_u \approx 0.39$, where $R_u \approx 0.17$ and $R_d \approx 0.22$ are the SM fractions of hadronic Z^0 decays into $u\bar{u}$ or $c\bar{c}$ and $d\bar{d}$, $s\bar{s}$ or $b\bar{b}$ respectively.

Although no quantitative estimate of the size of Ω is given, it is argued in [5] that such a term can arise from interference between two processes, for example fragmentation into $\pi\pi\pi$ and fragmentation into $\rho\pi$ where $\rho \rightarrow \pi\pi$. Thus Ω might be largest for triplets of pions nearby in rapidity in which a zero-charge pair has invariant mass near the ρ mass, and the unpaired track together with the oppositely charged track in the pair is used to calculate Ω in the 3-pion rest frame. It is also argued that evidence of polarization is more likely to be visible in the highest-momentum tracks in jets. Ryskin has proposed [6] an alternative physical model of the transport of parton polarization in the context of a string fragmentation scheme, which gives a nonzero expectation value of Ω in the laboratory frame if $\vec{k}_1$ and $\vec{k}_2$ are the momenta of two hadrons containing partons from the same string breakup.

A jet may be defined as left- or right-handed if Ω is negative or positive respectively. For an ensemble of jets the jet handedness H is defined as the asymmetry in the number of left- and right-handed jets:

$$H \equiv \frac{N_{\Omega<0} - N_{\Omega>0}}{N_{\Omega<0} + N_{\Omega>0}}. \tag{6}$$

It can then be asserted that

$$H = \alpha P, \tag{7}$$

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

In this letter we present the results of the first search for jet handedness in $Z^0 \to q\bar{q}$ decays using a sample of approximately 50,000 hadronic Z^0 decays collected by the SLD experiment [7] in 1993. We have applied the methods suggested in [4, 5] and [6], and have extended them to be more inclusive. For each method we used both helicity- and chirality-based definitions of Ω to calculate H. A handedness signal may be diluted in heavy flavor events, $Z^0 \to c\bar{c}$ or $b\bar{b}$, since a large fraction of the tracks in each jet is from the decay of a spinless heavy meson. Dalitz *et al.* have concluded [8] that any effect resulting from D^* or B^* decays should be very small. We therefore divided our data into samples enriched in light, $Z^0 \to u\bar{u}$, $d\bar{d}$ 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 [2]. The analysis presented here is based on charged tracks measured in the central drift chamber and vertex detector. A set of cuts was applied to select 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 of the measured interaction point, (ii) a polar angle θ with respect to the beam axis with $|\cos\theta| < 0.80$, 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 [9] axis polar angle with respect to the beam axis θ_T within $|\cos\theta_T| < 0.71$, and a minimum charged visible energy $E_{vis} > 20$ GeV, where all tracks were assigned the charged pion mass. Events with hard gluon radiation were rejected by requiring events to contain only two jets, defined using the JADE clustering algorithm [10] at $y_{cut} = 0.03$,

6

which were back-to-back within $20°$. A data sample comprising 17,853 events passed these cuts.

In addition to considering this global sample, events were classified as being of light or heavy flavor based on impact parameters of charged tracks measured in the vertex detector. The 9,977 events containing no track with normalized transverse impact parameter with respect to the interaction point $b/\sigma_b > 3$ were assigned to the light-flavor sample and all other events were assigned to the heavy-flavor sample. The light-flavor contents of these two samples were estimated from Monte Carlo simulations to be 84% and 30% respectively [11].

Following [5] we first considered jets in which the three highest-momentum tracks had total charge ± 1 and the invariant mass of each zero-charge pair satisfied $0.6 < m < 1.6$ GeV/c^2. All tracks were assigned the charged pion mass and their momenta were boosted into the three-track rest frame. The tracks forming the higher-mass zero-charge pair were used to calculate $\Omega_{hel} = \hat{t} \cdot (\vec{k}_1 \times \vec{k}_2)$ and $\Omega_{chi} = \hat{t} \cdot (\vec{k}_+ \times \vec{k}_-)$, where $|\vec{k}_1| > |\vec{k}_2|$ and $\hat{t}$ is the thrust axis signed so as to point along the jet direction. A signal would be visible as a nonzero mean Ω, which in the case of the helicity-based analysis would be of opposite sign for events produced with positive and negative electron-beam polarization and for jets with positive and negative $\cos\theta = \hat{t}_z$. The distributions of $\text{sgn}(P_{e^-} \cos\theta)\Omega_{hel}$ and Ω_{chi} are shown for the light-flavor sample in Fig. 1. Both distributions appear to be symmetric about zero, implying that any jet handedness is small. Also shown in Fig. 1 are the predictions of the JETSET [12] Monte Carlo simulation program for $Z^0 \to q\bar{q}$ decays, in which spin transport was not simulated, combined with a simulation of the

7

SLD. These simulations give a good description of our measured inclusive track and event topology distributions [13]. The means of the simulated Ω distributions are consistent with zero within statistical errors, limiting any analysis bias to 0.008 on H. The variances of the measured distributions are reproduced by the simulation to within 5% relative, although the details of the shapes are not.

The jet handedness for the helicity-based analysis was calculated in bins of jet $\cos\theta$ according to Eq. (6) separately for events produced with positive and negative electron-beam polarization. Results are shown in Fig. 2 for the light-flavor sample; similar results (not shown) are obtained for the global and heavy-flavor samples. In all cases the measured jet handeness is consistent with zero, and there is no evidence for an angular dependence. Equation (7) was fitted simultaneously to the $H(\cos\theta)$ measured in events produced with positive and negative electron-beam polarizations, by averaging $P = P_{hel}$ (Eq. 2) over each $\cos\theta$ bin and allowing the analyzing power α to vary. The result of the fit to the light-flavor sample is shown as the solid lines in Fig. 2, and the fitted analyzing powers for all three samples are listed in Table I.

The jet-handedness values for the chirality-based analysis were calculated from the unbinned Ω_{chi} distributions and the analyzing powers were calculated from Eq. (7), where $P = P_{chi}$ (Eq. 3) was averaged over the flavor composition of each sample, estimated from the simulations and weighted by the sign of the quark charge. The analyzing powers are shown in Table I. Since all α are consistent with zero, we set upper limits at the 95% confidence level on their magnitudes, also shown in Table I.

8

Since the helicities of the quark and antiquark in a given event are opposite, one might expect a correlation between Ω values in the two jets in an event, which would be negative for the helicity-based analysis and positive for the chirality-based analysis. We found correlation coefficients to be consistent with zero, within statistical errors of ± 0.02, for both analyses and for the global, light-, and heavy-flavor samples.

We extended this method to use the N_{lead} highest-momentum particles in each jet, with $3 \leq N_{lead} \leq 24$. We considered all zero charge pairs i,j among these N_{lead} particles, without imposing mass cuts, and calculated Ω_{hel}^{ij} and Ω_{chi}^{ij} for each pair in the N_{lead}-particle rest frame. Jets with fewer than N_{lead} tracks were excluded. We then considered both the average, $< \Omega^{ij} >$, and the Ω^{ij} with largest magnitude Ω^{max}. In both cases the jet handedness calculated from the global, light- and heavy-flavor samples was consistent with zero for all N_{lead} and for both helicity- and chirality-based analyses. For $N_{lead} \leq 11$ upper limits on the magnitudes of the analyzing powers in the range 0.05-0.11 were derived. For larger N_{lead} the reduced sample size limits our accuracy.

Following [6] we then attempted to select pairs of tracks likely to contain partons from the same string breakup. In studies using JETSET we found the relative rapidity with respect to the jet axis of the tracks in a pair to be useful for this. Requiring zero charge does not improve this selection, but was used in the chirality-based analysis.

In each jet the tracks were ordered in rapidity and assigned a number $1 \leq n_i \leq n_{tracks}$, 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 [6] to increase with momentum p_t transverse to

9

the thrust axis, we also required $|p_{ti}| + |p_{tj}| > p_{min}$. We calculated Ω_{chi}^{ij} and Ω_{hel}^{ij} in the laboratory frame for each pair satisfying these criteria and then considered both the average, $< \Omega^{ij} >$, and the Ω^{ij} with largest magnitude Ω^{max}. We varied Δn, n_{max}, and p_{min} in an attempt to maximize the handedness signal. In all cases the jet handedness calculated from the global, light- and heavy-flavor samples was consistent with zero. We obtained upper limits in the range 0.05-0.11 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.

A number of systematic checks was performed. The results of all analysis methods were found to be insensitive to the track and event selection cuts, to the jet-finding algorithm and y_{cut} values used to select 2-jet events, and 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 ± 0.004.

In conclusion, we have searched for evidence of parton polarization in hadronic Z^0 decays using the jet handedness methods proposed in [4, 5] and [6]. In an attempt to optimize a signal we studied a wide range of parameters for each method. In each case we applied both helicity- and chirality-based analyses, and sought signals separately in samples of light- and heavy-flavor jets as well as in the global sample. We found no evidence for a non-zero jet handedness, implying that the transport of polarization through the quark fragmentation process is small. The method proposed in [5], applied to a sample of light-flavor jets, yielded upper limits of 0.099 and 0.070 on the magnitudes of the analyzing powers of helicity- and chirality-based analyses respectively. Similar limits were derived for all other methods we applied.

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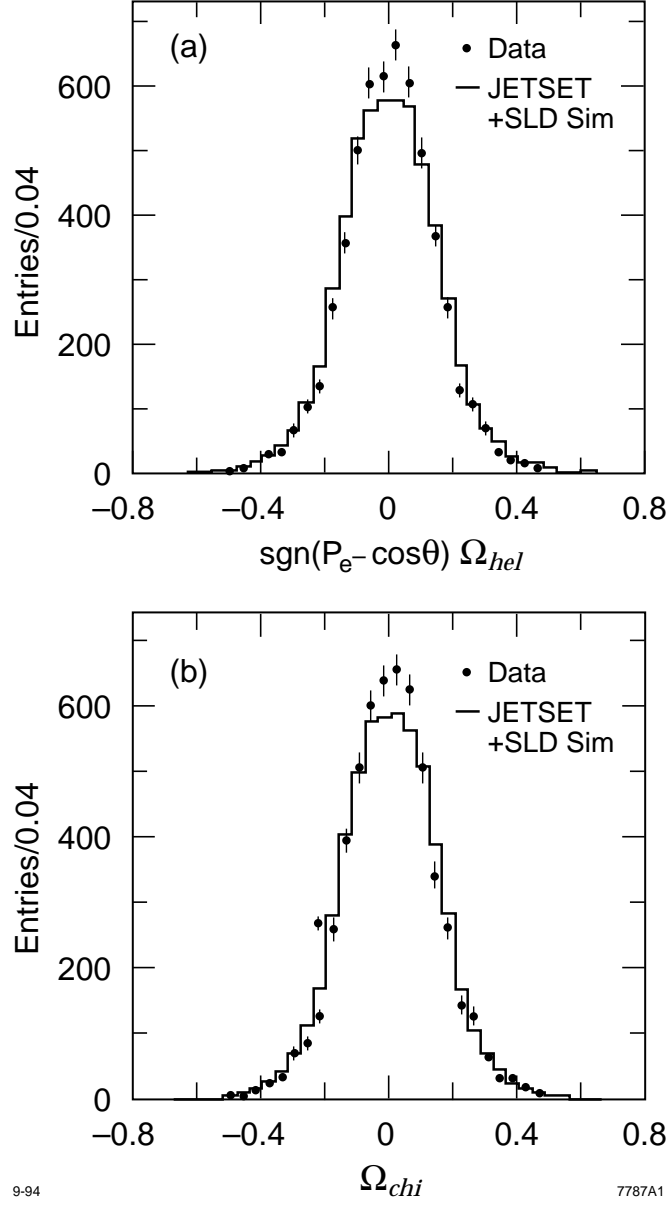
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Figure 1: Measured distributions of (a) $\mathrm{sgn}(P_{e^-}-\cos\theta)\Omega_{hel}$ and (b) Ω_{chi} (points with error bars) for the light-flavor sample. The corresponding distributions from a Monte Carlo simulation are also shown (histograms).

15

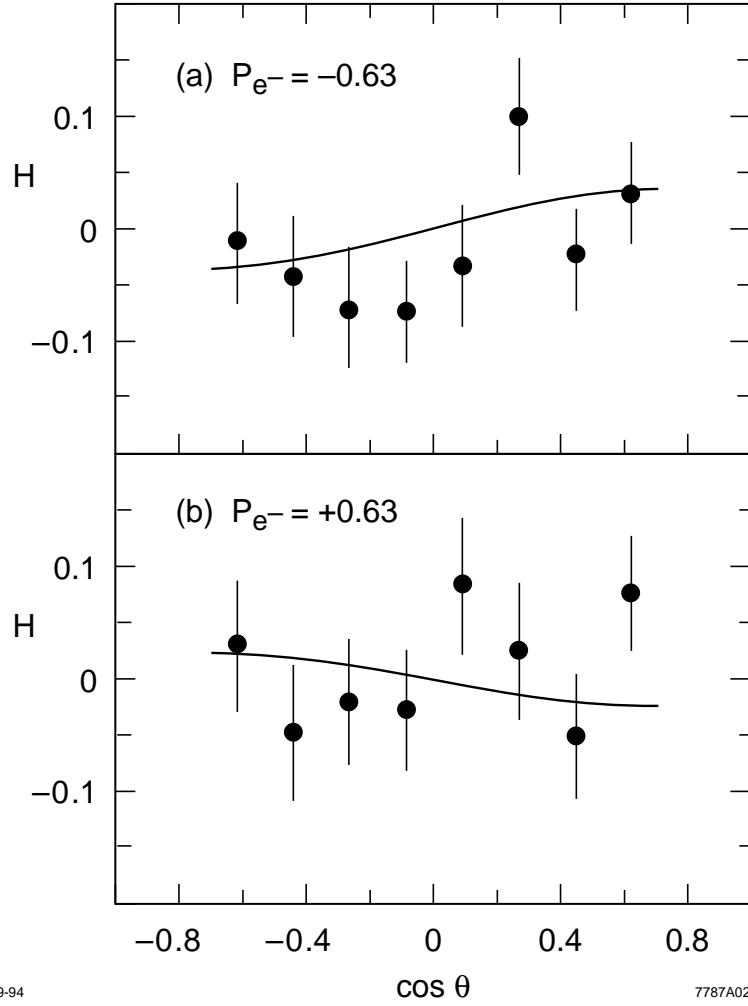Figure 2: Helicity-based jet handedness as a function of jet $\cos\theta$ for the light-flavor sample using jets produced with (a) negative and (b) positive electron-beam polarization. The solid lines are the result of a fit of Eq. (6).

16

Analysis	Analyzing Power		
	Light-flavor jets	Heavy-flavor Jets	All Jets
Helicity	−0.051±0.029 (0.099)	0.000±0.032 (0.063)	0.028±0.022 (0.063)
Chirality	−0.018±0.031 (0.070)	−0.033±0.043 (0.104)	−0.024±0.026 (0.066)

Table 1: Analyzing powers of the helicity- and chirality-based definitions of jet handedness. Upper limits at the 95% C.L. on the magnitudes are shown in parentheses.