Search for Jet Handedness in Hadronic Z^0 Decays

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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 SLAC Linear Collider 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.*

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The transport of parton polarization in strong interactions is of fundamental interest. It is 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 expected to be highly longitudinally polarized. If a method of observing such polarization were developed, it could be applied to jets produced in other hard processes in order to elucidate the underlying spin dynamics.

In the process $e^+e^- \to Z^0 \to q\bar{q}$ the relative production cross sections for left- and right-handed quarks of flavor f are given at tree level in the standard model (SM) by

$$\sigma_L^f = (1 + A_f)(1 + \cos^2\theta + 2A_Z \cos\theta), \qquad (1)$$
$$\sigma_R^f = (1 - A_f)(1 + \cos^2\theta - 2A_Z \cos\theta),$$

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. Since the quark and antiquark in a Z^0 decay have opposite helicities, $\sigma_{L(R)}^{\bar{f}}(\cos\theta) = \sigma_{R(L)}^f(-\cos\theta)$. 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 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.

At the SLAC Linear Collider (SLC) Z^0 bosons are produced in collisions of longitudinally polarized electrons with unpolarized positrons. In 1993 the average polarization was 0.630 ± 0.011 [1]. 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:

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

which is independent of flavor, and reaches 0.72 and 0.52 in magnitude as $|\cos\theta| \to 1$ for beam polarizations of -0.63 and $+0.63$, respectively. We define the "chirality-based" polarization of jets:

$$P_{\rm chi}^f \equiv \frac{\sigma_R^f - \sigma_R^{\bar{f}} - \sigma_L^f + \sigma_L^{\bar{f}}}{\sigma_R^f + \sigma_R^{\bar{f}} + \sigma_L^f + \sigma_L^{\bar{f}}} = -A_f, \qquad (3)$$

which is independent of $\cos\theta$ and electron-beam polarization, and is accessible by charge ordering of tracks as described below. The experimental challenge is to find observables sensitive to these jet polarizations.

Nachtmann [2] and Efremov *et al.* [3] have speculated that polarization may be observable inclusively via a triple product of track momenta in jets. Arguing that quark fragmentation may resemble a multibody strong decay, they note that the simplest observable with the same transformation properties under parity inversion as $P_{\rm hel}$ 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 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., $\Omega_{\rm hel} = \vec{t} \cdot (\vec{k}_1 \times \vec{k}_2)$, where $|\vec{k}_1| > |\vec{k}_2|$, and referred to a suitable frame. If the cross product can be ordered by particle charge, then $\Omega_{\rm chi} = \vec{t} \cdot (\vec{k}_+ \times \vec{k}_-)$ has the same transformation properties under CP inversion as $P_{\rm chi}$ for a given flavor and so might be sensitive to $P_{\rm chi}$. Jets from Z^0 decays comprise a mixture of flavors that might yield different signals since quark charges and fragmentation properties depend on flavor. Considering only the sign s_f of the charge of quarks of flavor

f, one expects a net polarization $P_{\rm chi} = -\Sigma_f s_f R_f A_f = 3R_d A_d - 2R_u A_u \approx 0.39$, 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 Ω is given, it is argued in [3] 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 a consistently chosen pair is used to calculate Ω in the three-pion rest frame. It is also suggested that only the highest momentum tracks in each jet be used. Ryskin has proposed [4] a model of the transport of parton polarization in 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:

$$H \equiv \frac{N_{\Omega<0} - N_{\Omega>0}}{N_{\Omega<0} + N_{\Omega>0}}. \tag{4}$$

It can then be asserted that

$$H = \alpha P, \tag{5}$$

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

In this Letter we present the results of the first search for jet handedness in $Z^0 \rightarrow q\bar{q}$ decays using a sample of approximately 50 000 hadronic Z^0 events collected by the SLD experiment [5] in 1993. We have applied the methods suggested in [3] and [4], 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, $Z^0 \rightarrow c\bar{c}$ or $b\bar{b}$, since a large fraction of the tracks in each jet is from the decay of a spinless heavy meson. In a study of jets containing D^* and B^* mesons Dalitz *et al.* have concluded that any handedness should be below 10^{-4} [6]. We therefore divided our data into samples enriched in 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.

This analysis used charged tracks measured in the central drift chamber and vertex detector. The trigger and selection criteria for hadronic events are described in [1,7]. Events with hard gluon radiation were rejected by requiring events to contain only two jets, defined using the JADE clustering algorithm [8] at $y_{\rm cut} = 0.03$, which were back to back within 20°. The 17 853 events passing these cuts comprised the global sample. In addition, events were classified as being of light or heavy flavors based on impact parameters of charged tracks measured in the vertex detector. The 9977 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 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 [9].

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-pion rest frame. The tracks forming the higher-mass zero-charge pair were used to calculate $\Omega_{\rm hel} = \hat{t} \cdot (\vec{k}_1 \times \vec{k}_2)$ and $\Omega_{\rm chi} = \hat{t} \cdot (\vec{k}_+ \times \vec{k}_-)$, 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 left- and right-polarized electrons and for jets with positive and negative $\cos\theta = \hat{t}_z$. The distributions of ${\rm sgn}(P_{e^-}\cos\theta)\Omega_{\rm hel}$ and $\Omega_{\rm chi}$ are shown for the light-flavor sample in Fig. 1. They are symmetric about zero, with means $-1.3 \pm 1.9 \times 10^{-3}$ and $(-2.0 \pm 1.9) \times 10^{-3}$, respectively. Also shown in Fig. 1 are the predictions of the JETSET [10] Monte Carlo

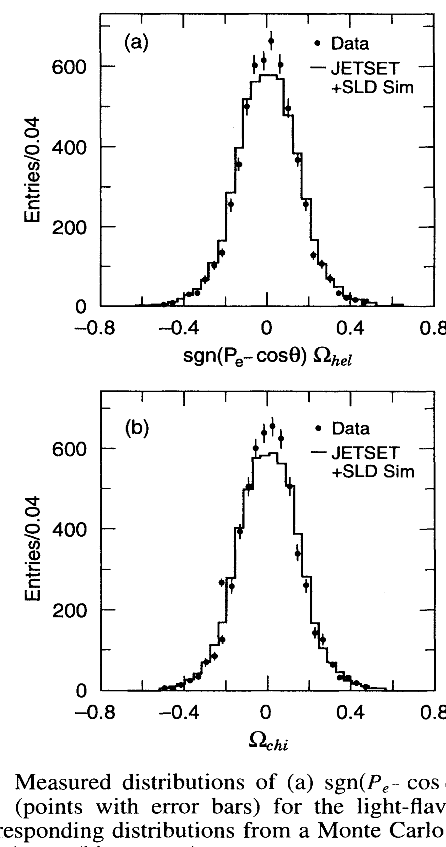

FIG. 1. Measured distributions of (a) ${\rm sgn}(P_{e^-}\cos\theta)\Omega_{\rm hel}$ and (b) $\Omega_{\rm chi}$ (points with error bars) for the light-flavor sample. The corresponding distributions from a Monte Carlo simulation are also shown (histograms).

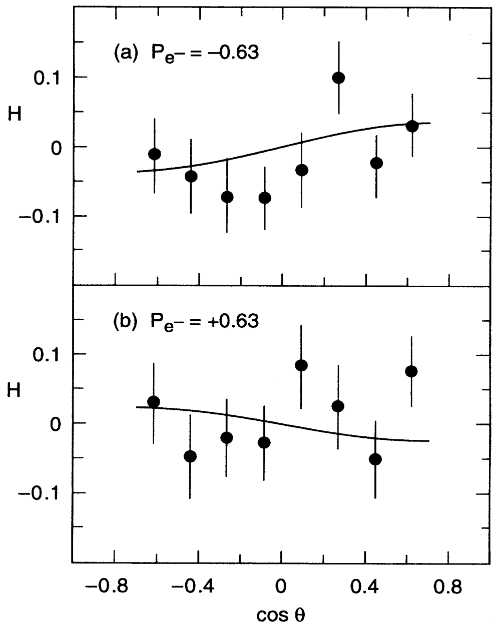

FIG. 2. Helicity-based jet handedness as a function of jet $\cos\theta$ for the light-flavor sample using jets produced with (a) negative and (b) positive electron-beam polarization. The solid lines are the results of a fit of Eq. (5).

simulation program for $Z^0 \rightarrow q\bar{q}$ decays, in which spin transport was not simulated, combined with a simulation of the SLD, which give a good description of our measured inclusive track and event topology distributions [7]. The means of the simulated Ω distributions are $(1.9 \pm 1.0) \times 10^{-3}$ and $(2.0 \pm 1.0) \times 10^{-3}$, respectively, consistent with zero analysis bias. 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. (4) separately for events produced with left- and right-polarized electrons. 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 handedness is consistent with zero, and there is no evidence for an angular dependence. Equation (5) was fitted simultaneously to the two $H(\cos\theta)$ by averaging $P = P_{\text{hel}}$ [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 flavor samples are listed in Table I.

The jet handedness for the chirality-based analysis was calculated from the unbinned Ω_{chi} distributions and the analyzing powers, shown in Table I, were calculated from Eq. (5), where $P = P_{\text{chi}}$ [Eq. (3)] was averaged over the flavor composition of each sample, estimated from the simulations and weighted by the sign of the quark charge. Since all α are consistent with zero, we set upper limits at the 95% confidence level on their magnitudes, also shown in Table I.

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, Ω_1 and Ω_2, which would be negative for the helicity-based analysis and positive for the chirality-based analysis. We found correlation coefficients, $(\langle\Omega_1\Omega_2\rangle - \langle\Omega_1\rangle\langle\Omega_2\rangle)/\sqrt{\langle\Omega_1^2\rangle - \langle\Omega_1\rangle^2}\sqrt{\langle\Omega_2^2\rangle - \langle\Omega_2\rangle^2}$, consistent with zero within statistical errors of ± 0.02 for both analyses and all flavor samples.

We extended this method and considered all zero charge pairs i,j among the N_{lead} highest-momentum particles in each jet, with $3 \leq N_{\text{lead}} \leq 24$. We calculated Ω_{hel}^{ij} and Ω_{chi}^{ij} for each pair in the N_{lead}-particle rest frame. For jets with at least N_{lead} tracks we then considered both the average, $\langle\Omega^{ij}\rangle$, and the Ω^{ij} with largest magnitude $\Omega^{\max}$. In both cases the jet handedness calculated from each flavor sample was consistent with zero for all N_{lead} and for both analyses. For $N_{\text{lead}} \leq 11$ 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 [4] 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 $1 \leq n_i \leq n_{\text{tracks}}$, 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 [4] to increase with

TABLE I. 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.

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)

momentum p_t transverse to 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 such pair and considered both $\langle\Omega^{ij}\rangle$ and $\Omega^{\max}$. We varied Δn, $n_{\max}$, and $p_{\min}$ in an attempt to maximize the handedness signal. In all cases the jet handedness calculated from each flavor sample 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 two-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 [3] and [4]. 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 nonzero jet handedness, implying that the transport of polarization through the quark fragmentation process is small. The method proposed in [3], 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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