SLAC-PUB-6550
July 1994
(N)

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 $Z^0 \rightarrow q\bar{q}$ 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. We find no evidence for jet handedness in our global sample nor in a sample of light quark jets. We set upper limits of 5.1% and 9.1% 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.

Presented at the 27th International Conference on High Energy Physics (ICHEP), Glasgow, Scotland, July 20-27, 1994

* Work supported by the Department of Energy contracts: DE-FG02-91ER40676 (BU), DE-FG03-92ER40701 (CIT), DE-FG03-91ER40618 (UCSB), DE-FG03-92ER40689 (UCSC), DE-FG03-93ER40788 (CSU), DE-FG02-91ER40672 (Colorado), DE-FG02-91ER40677 (Illinois), DE-AC03-76SF00098 (LBL), DE-FG02-92ER40715 (Massachusetts), DE-AC02-76ER03069 (MIT), DE-FG06-85ER40224 (Oregon), DE-AC03-76SF00515 (SLAC), DE-FG05-91ER40627 (Tennessee), DE-AC02-76ER00881 (Wisconsin), DE-FG02-92ER40704 (Yale); National Science Foundation grants: PHY-91-13428 (UCSC), PHY-89-21320 (Columbia), PHY-92-04239 (Cincinnati), PHY-88-17930 (Rutgers), PHY-88-19316 (Vanderbilt), PHY-92-03212 (Washington); the UK Science and Engineering Research Council (Brunel and RAL); the Istituto Nazionale di Fisica Nucleare of Italy (Bologna, Ferrara, Frascati, Pisa, Padova, Perugia); and the Japan-US Cooperative Research Project on High Energy Physics (Nagoya, Tohoku).

The transport of parton polarization in strong interactions is of fundamental interest. It is at present an open question whether the polarization of quarks 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 fermions in Z^0 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, elucidating the spin dynamics of the underlying interactions.

In the process $e^+e^- \to Z^0 \to q\bar{q}$ the polarization of the outgoing quark of flavor f, P_f, is given at tree level by [1] :

$$P_f(\theta) \equiv \frac{\sigma_R^q - \sigma_L^q}{\sigma_R^q + \sigma_L^q} = -\frac{A_f(1+\cos^2\theta) + 2A_Z\cos\theta}{1 + 2A_fA_Z\cos\theta + \cos^2\theta}, \quad (1)$$

where $A_Z = (A_e - P_{e^-})/(1 - A_eP_{e^-})$, $A_f = 2v_fa_f/(v_f^2 + a_f^2)$, 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. The SM predicts $A_{e,\mu,\tau} = 0.16$, $A_{u,c} = 0.67$ and $A_{d,s,b} = 0.94$. The corresponding $\bar{q}$ has opposite polarization, so in order to observe a net polarization, it is necessary to distinguish quark jets from antiquark jets.

Experimentally this is problematic, however Z^0 bosons are produced at the SLAC Linear Collider (SLC) in collisions of highly polarized electrons with unpolarized positrons. In 1993 the average electron beam polarization was 63.0±1.1% [2]. 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' of jets at a given $\cos\theta$

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

This polarization is independent of quark flavor, and reaches 0.72 and 0.52 in magnitude at large $|\cos\theta|$ for beam polarizations of -0.63 and $+0.63$, respectively. The experimental challenge is to find an observable sensitive to this expected underlying polarization.

Nachtmann [3] and Efremov *et al.* [4] have speculated that the polarization of the underlying quarks may be observable inclusively via a triple product of track momenta in jets. Arguing that quark fragmentation may resemble an n-body strong decay, they note that the simplest observable with the same parity properties as P_{hel} has the form

$$\Omega \equiv \vec{t}\cdot(\vec{k_1}\times\vec{k_2}) \quad (3)$$

where $\vec{t}$ is a unit vector along the jet axis, corresponding to the spin direction of a longitudinally polarized quark which 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 and taken in some suitable rest frame. Although no quantitative estimate of the size of Ω is given, it is argued in [5] that such a term must arise from interference between two processes, for example fragmentation into $\pi\pi\pi$ and fragmentation into

$\rho\pi$ where $\rho \rightarrow \pi\pi$. Thus $< \Omega >$ might be maximized for triplets of pions nearby in rapidity in which an oppositely charged pair has invariant mass near the ρ mass, and the unpaired track along with the oppositely charged track in the pair are 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 leading tracks in jets. Ryskin has proposed [6] a physical model of the transport of quark 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 quarks from the same string breakup.

An alternative variable is the 'chirality' of jets,

$$P^q_{chi} \equiv \frac{\sigma^q_R - \sigma^{\bar{q}}_R - \sigma^q_L + \sigma^{\bar{q}}_L}{\sigma^q_R + \sigma^{\bar{q}}_R + \sigma^q_L + \sigma^{\bar{q}}_L} = -A_q. \quad (4)$$

This polarization is independent of $\cos\theta$ but depends on quark flavor. A corresponding observable is a triple product in which the two particle momenta are ordered by charge, *i.e.* $\Omega_{chi} \equiv \vec{t} \cdot (\vec{k}_+ \times \vec{k}_-)$, since the sign of Ω_{chi} in antiquark jets is the same as that in quark jets of the same flavor and opposite polarization. Jets from Z^0 decays comprise a mixture of quark flavors, and one might expect an effective total chirality $P_{chi} = -\Sigma_q s_q R_q A_q = 3R_d A_d - 2R_u A_u = 0.39$, where s_q is the sign of the charge of q and R_u =0.17 and R_d =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.

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

$$H \equiv \frac{N_{\Omega<0} - N_{\Omega>0}}{N_{\Omega<0} + N_{\Omega>0}}. \quad (5)$$

It can then be asserted that

$$H = \alpha P, \quad (6)$$

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

In this letter we present the results of a search for jet handedness using a sample of ~50,000 hadronic Z^0 decays collected by the SLD experiment [7]. We have applied the methods suggested in [4, 5] and [6], which we also extended to be more inclusive. In each case we used both the helicity and chirality methods of defining Ω and hence H. A handedness signal may be diluted in heavy quark events ($Z^0 \rightarrow c\bar{c}, b\bar{b}$), since many tracks are from decays of spinless heavy mesons, and Dalitz *et al.* have concluded [8] that any effect resulting from D^* or B^* decays should be very small. We therefore divided our data cleanly into samples of light (u, d, s) and heavy (b, c) quark events using the quark lifetime information, and sought evidence for polarization in each.

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 quark and antiquark jets 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 direction 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. Two-jet events were selected using the JADE clustering algorithm [10] at $y_{cut} = 0.03$, and the jet acollinearity angle was required to be less than 20°.

In addition to considering this global sample, events were classified as light (u, d or s) or heavy (c or b) events based on impact parameters of charged tracks measured in the SLD vertex detector. 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 [11]. From our 1993 data sample 17,853 events passed these cuts, of which 9,977 were assigned to the light quark sample.

Following [5] 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 $\Omega_{hel} = \hat{t}\cdot(\vec{k}_> \times \vec{k}_<)$ and $\Omega_{chi} = \hat{t}\cdot(\vec{k}_+ \times \vec{k}_-)$, where $|k_>| > |k_<|$ and $\hat{t}$ is the thrust axis signed so as to point along the jet direction. The distributions of Ω_{hel} and Ω_{chi} are shown in fig. 1 along with the predictions of the JETSET [12] Monte Carlo simulation program combined with a simulation of the SLD. No asymmetries are visible in these distributions. The widths of the distributions are reproduced by the simulation, although the exact shape is not.

The jet handedness was calculated according to eqn. (5) separately, in the case of the helicity analysis, for positive and negative electron beam polarization and for forward ($\hat{t}_z > 0$) and backward ($\hat{t}_z < 0$) jets. Results are summarized in table 1. In all cases, the measured handeness is consistent with zero. Analyzing powers were calculated from eqn. (6), where the expected P_{hel} or P_{chi} was averaged over the acceptance in $\cos\theta_T$ for each sample. The analyzing powers of the four helicity samples were then combined. Results are shown in table 2. Since all α are consistent with zero, we set upper limits at the 95% confidence level on the magnitudes of the analyzing powers, also shown in table 2.

We extended this method to use the N_{lead} highest momentum particles in each jet. We considered all oppositely charged pairs i,j among these N_{lead} particles, without imposing mass cuts, and calculated Ω^{ij}_{chi} and Ω^{ij}_{hel} for each in the N_{lead}-particle rest frame. The Ω^{ij} were then averaged to give Ω^{jet}_{chi} and Ω^{jet}_{hel}. The jet handedness measured by this method is consistent with zero for all N_{lead}, both Ω definitions and all data samples. For $N_{lead} \leq 10$, upper limits in the range 5-8% can be derived, after which the sample size limits our accuracy.

Following [6] we then attempted to select pairs of tracks likely to contain quarks from the same string breakup. In studies using the JETSET [12] Monte Carlo we

Method	Expected Polarization	Jet Handedness (%) All jets	Light Jets	Heavy Jets
Helicity:				
$P_{e^-} < 0$, $\hat{t}_z > 0$	−0.44	0.6±1.9	2.1±2.5	-1.2± 2.8
$P_{e^-} < 0$, $\hat{t}_z < 0$	+0.44	-2.5±1.9	-5.1±2.5	0.8± 2.8
$P_{e^-} > 0$, $\hat{t}_z > 0$	+0.32	1.8±2.1	3.2±2.8	0.1± 3.1
$P_{e^-} > 0$, $\hat{t}_z < 0$	−0.32	-2.4±2.1	-1.5±2.8	-3.4± 3.1
Chirality:	0.39	-0.9±1.0	-0.8±1.3	-1.1± 1.5

Table 1: Measured jet handedness in % using the first method.

Method	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±2.5	(6.6)	-2.0±3.4	(7.8)	-2.9±3.8	(9.2)

Table 2: Analyzing powers of the helicity and chirality jet handedness methods. Upper limits at the 95% C.L. on the magnitudes are shown in parentheses.

found the relative rapidity of tracks in a pair with respect to the jet axis to be useful for this. Requiring opposite charge does not improve this selection, but was used in the chirality analysis.

In each jet the tracks were ordered in rapidity and assigned a number $n_i = 1...n_{tracks}$, where $n = 1$ 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 averaged them to obtain Ω^{jet}. Δn, n_{max}, and p_{min} were then varied in an attempt to maximize the handedness signal. In no case do we find evidence for non-zero jet handedness. We obtain upper limits in the range 5-9% for all data samples and for all n_{max} and Δn for p_{min} <2 GeV/c. Statistics become poor in the potentially interesting, high-p_{min} region.

A number of systematic checks were performed for each method. All analyses 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 [13]) 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 no handedness was simulated. All results were consistent with zero, implying no analysis biases at the level of 1% in H. We found no correlation between the Ω values in the two jets in an event at the 1% level.

In conclusion, we have searched for evidence of quark polarization in hadronic Z^0 decays using two jet handedness techniques. To optimize a signal, we studied a wide range of parameters for each technique. In each case we employed both helicity and chirality 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. This implies that the transport of quark polarization through the jet fragmentation process is small, and gives upper limits of 9% on the analyzing power of the methods presented here for light quark jets, and 6% averaged over jets of all flavors.

We thank the personnel of the SLAC accelerator department and the technical staffs of our collaborating instutions for their outstanding efforts on our behalf. We thank R. Dalitz, A. Efremov and M. Ryskin for helpful comments relating to this analysis. This work was supported by the Department of Energy; the National Science Foundation; the Natural Science Research Council of Canada; the Instituto Nazionale di Fisica Nucleare of Italy; the Ministry of Science, Culture, and Education of Japan; and the Science and Engineering Research Council of the United Kingdom.

Figure Caption

1. Measured distribution of (a) Ω_{hel} and (b) Ω_{chi} as the solid histogram. The same distributions from a Monte Carlo simulation are shown as the dashed histogram.

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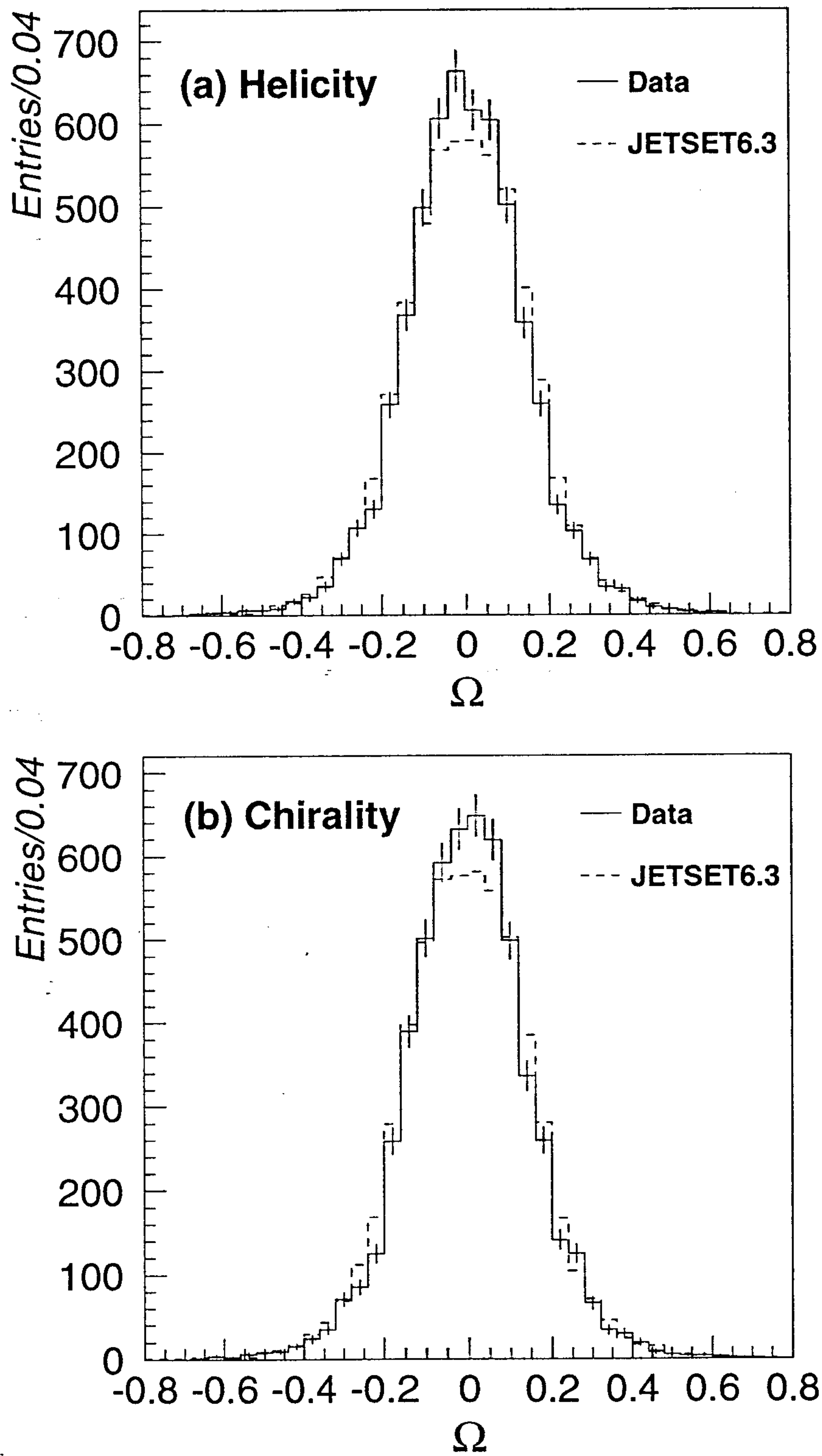
(a) Helicity
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Entries/0.04
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100
200
300
400
500
600
700
-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8
Ω
(b) Chirality
Data
JETSET6.3
Entries/0.04
0
100
200
300
400
500
600
700
-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8
Ω

Fig. 1