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# AN IMPROVED LIMIT ON JET HANDEDNESS IN $Z^0$ DECAYS*

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## ABSTRACT

We present the results of an improved search for jet handedness in hadronic decays of $Z^0$ bosons collected by the SLD experiment at SLAC. Quark and antiquark jets, expected to be oppositely polarized in $Z^0$decays, were separated using the large forward-backward quark asymmetry induced by the highly polarized SLC electron beam. The larger data sample and beam polarization of the 1994/5 SLC/SLD run yield a factor of two improvement in our sensitivity to jet handedness. Assuming Standard Model values of quark polarizations we set an improved upper limit on the analysing power of the handedness method.

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# 1 Introduction

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 $\theta$ 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 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 for a fully polarized electron beam, $P_{e^-} = \pm 1.0$, reaches unity in magnitude as $|\cos\theta| \rightarrow 1$. 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 [2] and Efremov *et al.* [3] 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 $P_{hel}$ (eqn. 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 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, *e.g.*

$$\Omega_{hel} = \vec{t}\cdot(\vec{k}_1 \times \vec{k}_2) \tag{4}$$

where $|\vec{k}_1| > |\vec{k}_2|$, 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 $\Omega_{chi}$ has the same transformation properties under CP inversion as $P_{chi}$ (eqn. 3) and so might be sensitive to $P_{chi}$. Jets from $Z^0$ decays comprise a mixture of flavors which 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 $\Omega$ is given, it is argued in [4] 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 $\Omega$ might be largest for triplets of pions nearby in rapidity in which a zero charge pair has invariant mass near the $\rho$ mass, and the unpaired track together with the oppositely charged track in the pair is used to calculate $\Omega$ 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 [5] 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 $\Omega$ 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 $\Omega$ 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 $\alpha$ is the analyzing power of the method. We have applied the methods suggested in [3, 4] and [5], and have extended them to be more inclusive. For each method we used both helicity- and chirality-based definitions of $\Omega$ 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.

Dalitz *et al.* have concluded [6] that any effect resulting from $D^*$ or $B^*$ decays should be very small. We therefore divided our data into samples highly 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.

The results of the first search for jet handedness in $Z^0 \rightarrow q\bar{q}$ decays were presented in [7]. This study was based on the sample of approximately 50,000 hadronic $Z^0$ decays collected by the SLD experiment in 1993 with an average SLC electron beam polarisation of 0.63 [8]. Here we present preliminary improved limits on jet handedness based upon the sample of approximately 100,000 hadronic $Z^0$decays, produced with an average electron beam polarisation of magnitude about 0.78, collected in the 1994/5 SLC/SLD run. The combination of the larger data sample and the larger quark forward-backward polar angle asymmetry increase our sensitivity to jet handedness effects by a factor of roughly two.

We describe the detector and the event trigger and selection criteria applied to the data in Section 2. The analysis of the 1994/5 data is described in Section 3. In section 4 we combine these results with those from our 1993 data sample and present a summary and conclusions.

## 2 Apparatus and Hadronic Event Selection

The $e^+e^-$ annihilation events produced at the $Z^0$ resonance by the SLAC Linear Collider (SLC) have been recorded using the SLC Large Detector (SLD). A general description of the SLD can be found elsewhere [9]. Charged tracks are measured in the central drift chamber (CDC) and in the vertex detector (VXD) [10]. Momentum measurement is provided by a uniform axial magnetic field of 0.6 T. Particle energies are measured in the Liquid Argon Calorimeter (LAC) [11], which contains both electromagnetic and hadronic sections, and in the Warm Iron Calorimeter [12].

Three triggers were used for hadronic events. The first required a total LAC electromagnetic energy greater than 12 GeV; the second required at least two well-separated tracks in the CDC; and the third required at least 4 GeV in the LAC and one track in the CDC. A selection of hadronic events was then made by two independent methods, one based on the topology of energy depositions in the calorimeters, the other on the number and topology of charged tracks measured in the CDC.

The analysis presented here used the charged tracks measured in the CDC and VXD. A set of cuts was applied to the data to select well-measured tracks and events well-contained within the detector acceptance. The charged tracks were required to have (i) a closest approach transverse to the beam axis within 5 cm, and within 10 cm along the axis from the measured interaction point; (ii) a polar angle $\theta$ with respect to the beam axis within $|\cos\theta| < 0.80$; and (iii) a momentum transverse to the beam axis, $p_\perp > 0.15$ GeV/c. Events were required to have (i) a minimum of five such tracks; (ii) a thrust axis [13] direction within $|\cos\theta_T| < 0.71$; and (iii) a total visible energy $E_{vis}$ of at least 20 GeV, which was calculated from the selected tracks assigned the charged pion mass. From our 1994/5 data sample 71,529 events passed these cuts. The efficiency for selecting hadronic events satisfying the $|\cos\theta_T|$ cut was estimated to be above 96%. The background in the selected event sample was estimated to be $0.3 \pm 0.1\%$, dominated by $Z^0 \rightarrow \tau^+\tau^-$ events. Distributions of single particle and event topology observables in the selected events were found to be well described by Monte Carlo models of hadronic $Z^0$ decays [14, 15] combined with a simulation of the SLD.

Events with hard gluon radiation were rejected by requiring events to contain only two jets, defined using the JADE clustering algorithm [16] at $y_{cut} = 0.03$, which were back-to-back within 20°. A sample comprising 41,651 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 22,939 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 [17].

# 3 Jet Handedness Analysis

Following [4] we first considered jets in which the three highest momentum tracks had total charge $\pm 1$ 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 $\Omega$, which in the case of the helicity-based analysis would be of opposite sign for events produced with positive and negative beam polarization and for jets with positive and negative $\cos\theta = \hat{t}_z$. The distributions of $\mathrm{sgn}(P_{e^-} \cos\theta)\Omega_{hel}$ and $\Omega_{chi}$ 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 [14] Monte Carlo simulation program for $Z^0 \rightarrow q\bar{q}$ decays, in which spin transport was not simulated, combined with a simulation of the SLD. These simulations give a good description of our measured inclusive track and event topology distributions [18]. The means of the simulated $\Omega$ distributions are consistent with zero within statistical errors, limiting any analysis bias to 0.024 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 eqn. (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. Eqn. (7) was fitted simultaneously to the $H(\cos\theta)$ measured in events produced with positive and negative electron beam polarizations, by averaging $P = P_{hel}$ (eqn. 2) over each $\cos\theta$ bin and allowing the analyzing power $\alpha$ 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 1.

The jet handedness values for the chirality-based analysis were calculated from the unbinned $\Omega_{chi}$ distributions and the analyzing powers were calculated from eqn. (7), where $P = P_{chi}$ (eqn. 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 1. Since all $\alpha$ are consistent with zero, we set upper limits at the 95% confidence level on their magnitudes, also shown in table 1.

Since the helicities of the quark and antiquark in a given event are opposite, one might expect a correlation between $\Omega$ 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 $\pm 0.04$, 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 $\Omega^{ij}_{hel}$ and $\Omega^{ij}_{chi}$ 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 $\Omega^{ij}$ with largest magnitude, $\Omega^{max}$. 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 0.018–0.063 were derived. For larger $N_{lead}$ the reduced sample size limits our accuracy.

Following [5] 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 [5] to increase with momentum $p_t$ transverse to the thrust axis, we also required $|p_{ti}| + |p_{tj}| > p_{min}$. We calculated $\Omega^{ij}_{chi}$ and $\Omega^{ij}_{hel}$ in the laboratory frame for each pair satisfying these criteria and then considered both the average, $< \Omega^{ij} >$, and the $\Omega^{ij}$ with largest magnitude, $\Omega^{max}$. $\Delta n$, $n_{max}$, and $p_{min}$ were varied 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 0.018–0.139 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 (the E, E0 and P versions of the JADE algorithm, as well as the Geneva and Durham algorithms were also studied [19]) and $y_{cut}$ values used to select 2-jet events, and to the values of the selection criteria for tracks used to define $\Omega$. Each analysis was performed on samples of Monte Carlo events in which spin transport was not simulated, yielding $H$ consistent with zero within $\pm 0.012$.

# 4 Summary and Conclusions

In conclusion, we have searched for evidence of parton polarization in hadronic $Z^0$ decays using the jet handedness methods proposed in [3, 4] and [5]. 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. Combining these results with those from our earlier study [7] we obtain analysing powers of:

$$\alpha^{hel} = 0.006 \pm 0.015 \qquad \text{(PRELIMINARY)}$$

$$\alpha^{chi} = 0.016 \pm 0.021 \qquad \text{(PRELIMINARY)}$$

These combined results are consistent with zero, so we set upper limits, at the 95% confidence level, of:

$$\alpha^{hel} < 0.033 \qquad \text{(PRELIMINARY)}$$

$$\alpha^{chi} < 0.053. \qquad \text{(PRELIMINARY)}$$

These imply that the transport of polarization through the quark fragmentation process is small. Similar limits were derived for all other methods we applied.


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[a] *Also at the Università di Genova*

[b] *Also at the Università di Perugia*

| Analysis | Analyzing Power<br>Light-flavor jets | Heavy-flavor Jets | All Jets |
|---|---|---|---|
| Helicity | 0.005±0.017 (0.037) | 0.025±0.019 (0.056) | -0.006±0.022 (0.047) |
| Chirality | 0.017±0.026 (0.062) | 0.014±0.013 (0.035) | 0.005±0.017 (0.036) |

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

# Figure captions

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

**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 eqn (7).

SLD PRELIMINARY

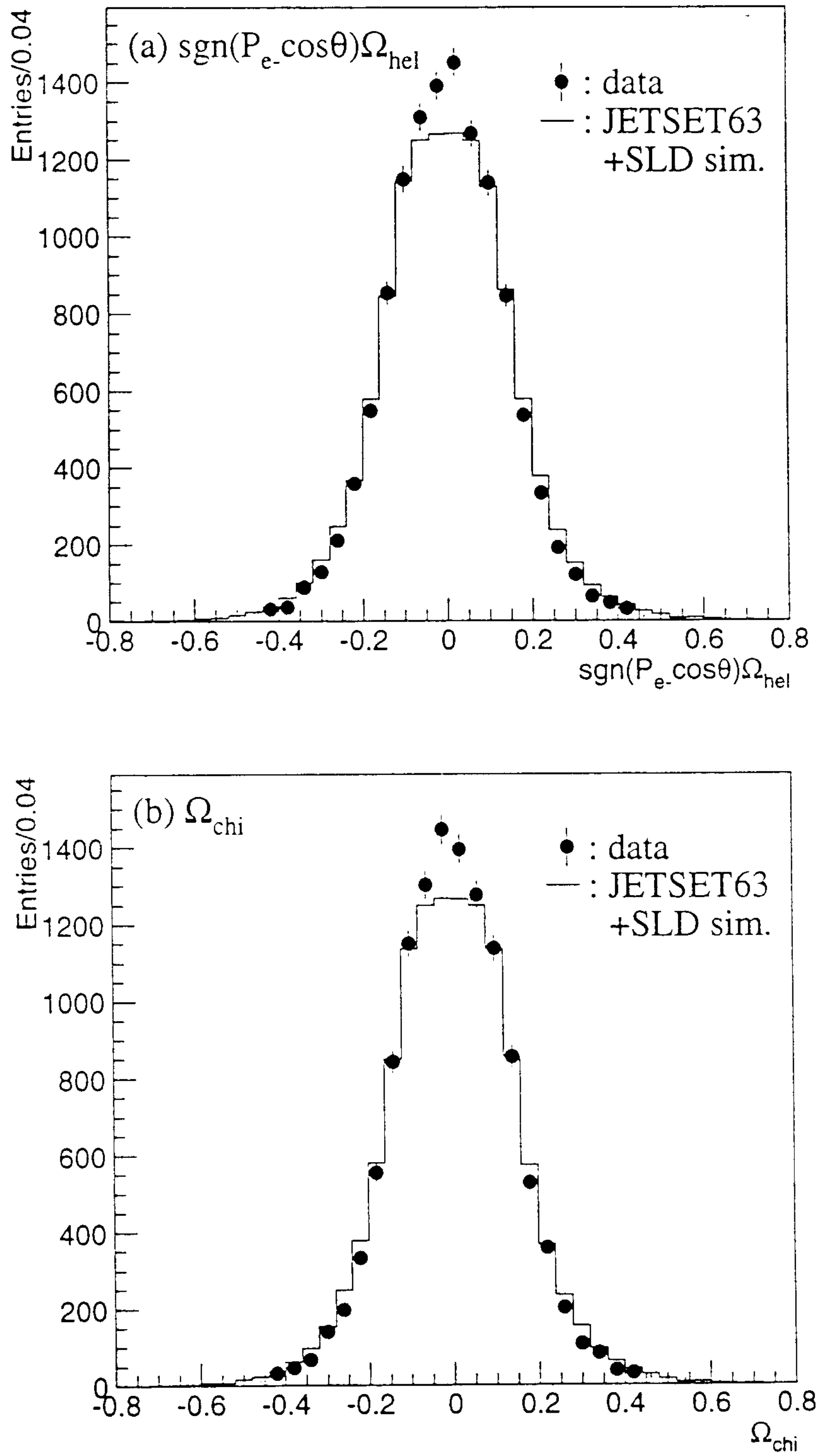


FIGURE 1

SLD PRELIMINARY

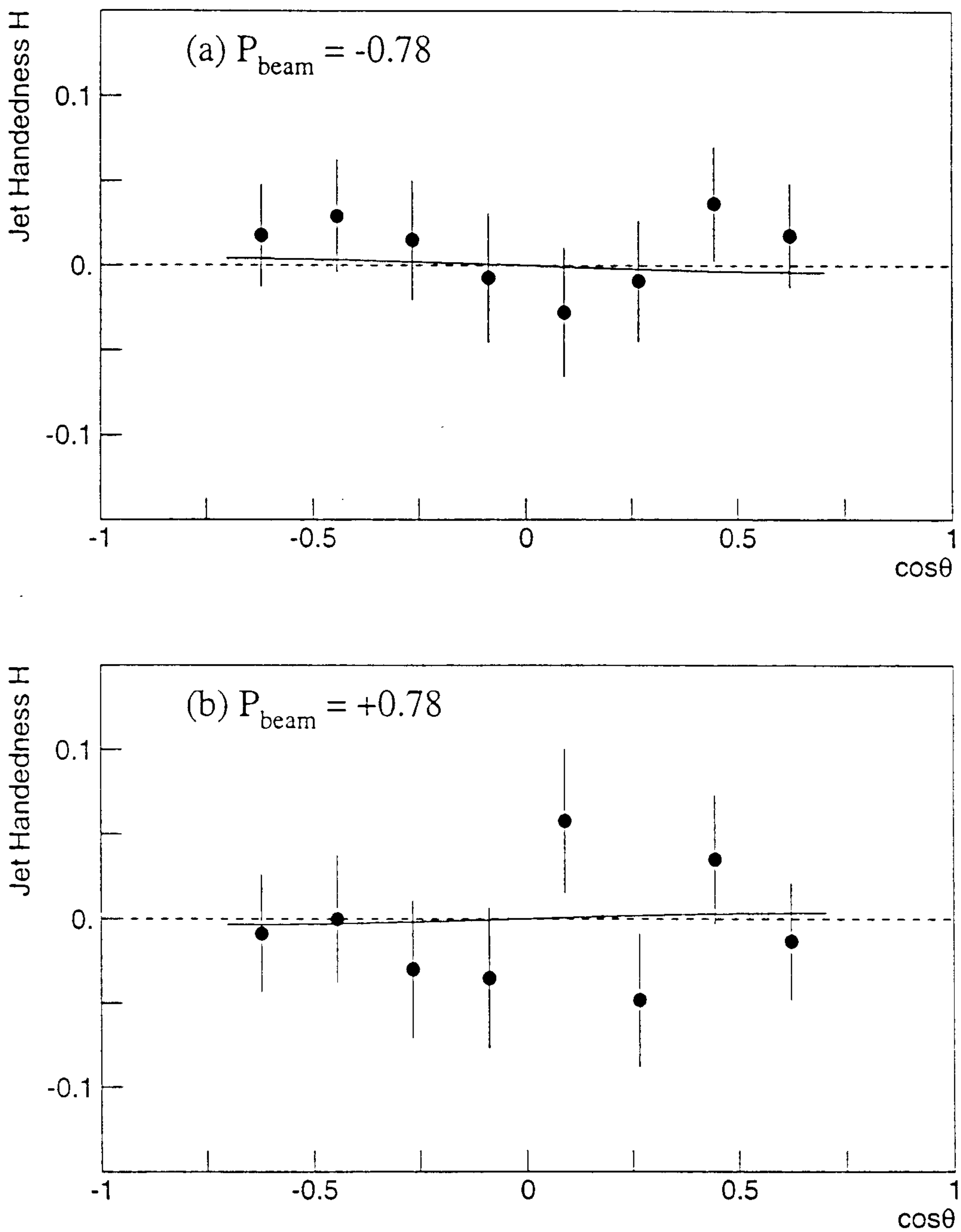


FIGURE 2