# First Measurement of the T-odd Correlation between the $Z^{0}$ Spin and the Three-jet Plane Orientation in Polarized $Z^{0}$ Decays to Three Jets 

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#### Abstract

We present the first measurement of the correlation between the $Z^{0}$ spin and the three-jet plane orientation in polarized $Z^{0}$ decays into three jets in the SLD experiment at SLAC utilizing a longitudinally polarized electron beam. The CP-even and T-odd triple product $\overrightarrow{S_{Z}} \cdot\left(\overrightarrow{k_{1}} \times \overrightarrow{k_{2}}\right)$ formed from the two fastest jet momenta, $\overrightarrow{k_{1}}$ and $\overrightarrow{k_{2}}$, and the $Z^{0}$ polarization vector $\overrightarrow{S_{Z}}$, is sensitive to physics beyond the Standard Model. We measure the expectation value of this quantity to be consistent with zero and set $95 \%$ C.L. limits of $-0.022<\beta<0.039$ on the correlation between the $Z^{0}$-spin and the three-jet plane orientation.


Polarization is an essential tool in investigations of fundamental symmetries in particle physics. Parity violation was first discovered in $\beta$ decays from polarized ${ }^{60} \mathrm{Co}$ [1], and T, CP and CPT violations were searched for using polarized neutrons [2] and polarized positronium [3]. The recent development of high-polarization electron sources based on strained-lattice GaAs photocathodes [4], in conjunction with the high luminosity achieved at the SLAC Linear Collider (SLC), has allowed production of highly polarized $Z^{0}$ bosons by $\mathrm{e}^{+} \mathrm{e}^{-}$annihilation, enabling investigations of symmetries at the $Z^{0}$ resonance.

The $Z^{0}$ bosons produced using longitudinally polarized electrons have polarization along the beam direction $A_{Z}=$ $\left(P_{e^{-}}-A_{e}\right) /\left(1-P_{e^{-}} \cdot A_{e}\right)$, where $P_{e^{-}}$is the electron-beam polarization, defined to be negative (positive) for a left-(right-) hānded beam, and $A_{e}=2 v_{e} a_{e} /\left(v_{e}^{2}+a_{e}^{2}\right)$ with $v_{e}$ and $a_{e}$ the electroweak vector and axial vector coupling parameters of the electron, respectively. Since 1993 the SLC has run with a strained-lattice GaAs electron source; an electron-beam polarization at the $\mathrm{e}^{+} \mathrm{e}^{-}$interaction point of approximately 0.77 in magnitude was achieved in the 1994-95 run, yielding $A_{Z}=-0.82(+0.70)$ for $P_{e^{-}}=-0.77(+0.77)$ respectively, assuming $\sin ^{2} \theta_{w}=0.2319 \pm 0.0005$ [5]. In order to reduce systematic effects, the electron spin direction was randomly reversed pulse-by-pulse, thus achieving higher sensitivities to polarization-dependent asymmetries. For polarized $Z^{0}$ decays to three hadronic jets one can define the triple product:

$$
\begin{equation*}
\overrightarrow{S_{Z}} \cdot\left(\overrightarrow{k_{1}} \times \overrightarrow{k_{2}}\right), \tag{1}
\end{equation*}
$$

which correlates the $Z^{0}$ boson polarization vector $\overrightarrow{S_{Z}}$ with the normal to the three-jet plane defined by $\overrightarrow{k_{1}}$ and $\overrightarrow{k_{2}}$, the momenta of the highest- and the second-highest energy jets, respectively. Here we report the first experimental study of this quantity.

The triple product (1) is even under $C$ and $P$ reversals, and odd under $\mathrm{T}_{\mathrm{N}}$, where $\mathrm{T}_{\mathrm{N}}$ reverses momenta and spin vectors without exchanging initial and final states. Since $\mathrm{T}_{\mathrm{N}}$ is not a true time-reversal operation, a non-zero value does not signal CPT violation and is possible in a theory that respects CPT invariance [6]. Similar observables were first proposed for direct experimental observation of the non-Abelian character of QCD in $e^{+} e^{-} \rightarrow \Upsilon \rightarrow g g g[7]$, and
in $e^{+} e^{-} \rightarrow q \bar{q} g[8]$ where a sizable signal is expected at c.m. energies $\sqrt{s}$ below 40 GeV ; no experimental measurements have been performed since a longitudinally polarized electron beam is required. A similar triple product was studied theoretically in neutrino scattering [9] and lepton-nucleon scattering [10]. More recently other observables have been proposed for high-energy jet physics to explore CP or $\mathbf{T}$ violation [11].

The differential cross section for $e^{+} e^{-} \rightarrow q \bar{q} g$ for a longitudinally polarized electron beam and massless quarks may be written [8] [12]

$$
\begin{equation*}
\frac{1}{\sigma} \frac{d \sigma}{d \cos \omega}=\frac{9}{16}\left[\left(1-\frac{1}{3} \cos ^{2} \omega\right)+\beta A_{Z} \cos \omega\right], \tag{2}
\end{equation*}
$$

where $\omega$ is the polar angle of the vector normal to the jet plane, $\overrightarrow{k_{1}} \times \overrightarrow{k_{2}}$, w.r.t. the electron-beam direction. With $\left|\beta A_{Z}\right|$ representing the magnitude [13], the second term is proportional to the $\mathrm{T}_{N}$-odd triple product (1), and appears as a forward-backward asymmetry of the jet-plane normal relative to the $Z^{0}$ polarization axis. The sign and magnitude of this term are different for the two beam helicities.

Recently Brandenburg, Dixon, and Shadmi have investigated Standard Model $\mathrm{T}_{\mathrm{N}}$-odd contributions of the form (1) at the $Z^{0}$ resonance [12]. The triple product vanishes identically at tree level [6], but non-zero contributions arise from higher-order processes such as those shown in Fig. 1: (a) QCD rescattering of massive quarks [8], (b) QCD triangle of massive quarks [14], and (c) electroweak rescattering via $W$ and $Z$ exchange loops. Due to various cancellations these contributions are found to be very small at the $Z^{0}$ resonance and yield values of the correlation parameter $|\beta| \lesssim 10^{-5}[12]$. Because of this background-free situation, measurement of the cross section (2) is sensitive to physics processes beyond the Standard Model that give $\beta \neq 0$.

The measurement was performed with the SLC Large Detector (SLD) using approximately $50,000 Z^{0}$ decays into multi-hadrons collected in 1993 and 100,000 decays collected in 1994-95, for which the magnitude of the average electron-beam polarization was 0.63 and 0.77 respectively. A general description of the SLD can be found elsewhere [15]. Charged particle tracking and momentum analysis is provided by the central drift chamber (CDC) and the CCD-based vertex detector in a uniform axial magnetic field of 0.6 T . Particle energies are measured in the liquid argon calorimeter (LAC) [16] and in the warm iron calorimeter [17]. 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; the third required at least 4 GeV in the LAC and one track in the CDC.

In this analysis the hadronic event selection and three-jet reconstruction were based on the topology of energy depositions in the LAC, taking advantage of its large solid-angle coverage. The LAC is a lead liquid argon sampling calorime-
ter composed of barrel and endcap sections, covering the angular ranges $|\cos \theta|<0.82$ and $0.82<|\cos \theta|<0.98$, respectively. It is segmented radially into projective towers of constant solid angle with 192 azimuthal and 96 polarangle segmentations. The longitudinal segmentation comprises two electromagnetic sections with a combined thickness of 21 radiation lengths, and two hadronic sections, giving a total thickness of 2.8 interaction lengths.

The calorimetric analysis must distinguish $Z^{0}$ events from backgrounds; in addition it should remove any background hits coincident with $Z^{0}$ events. The dominant source of beam-related backgrounds in the LAC was high-energy muons produced in the SLC that were characterized by small amounts of energy in a large number of towers parallel to the beam direction. An algorithm was used to identify this characteristic signal and background hits were removed before the hadronic event selection [18].

Although the LAC offers a uniform energy response over most of its solid-angle coverage, the response is degraded around $|\cos \theta| \approx 0.82$, where the barrel and endcap sections meet. In order to achieve a uniform response over the whole acceptance, the energy response of the towers was corrected. The total detected energy was expressed as a linear combination of the tower energies weighted by energy-independent constants

$$
\begin{equation*}
E_{d e t e c t}=\sum_{i}\left(a_{i} \cdot E_{e m}^{i}+b_{i} \cdot E_{h a d}^{i}\right) \tag{3}
\end{equation*}
$$

where $E_{e m}^{i}$ and $E_{h a d}^{i}$ are the recorded energies in the electromagnetic and hadronic sections, and the sum was taken over all the polar-angle segmentations [19]; $a_{i}$ and $b_{i}$ are correction factors determined by minimizing the sum $=$

$$
\begin{equation*}
\sum_{\text {events }} \frac{\left(E_{\text {detect }}-E_{C M}\right)^{2}}{\sigma^{2}} \tag{4}
\end{equation*}
$$

where $E_{C M}$ is the $e^{+} e^{-}$collision energy corrected for the detector acceptance and for the undetectable energy carried by neutrinos, and $\sigma$ is the measured LAC energy resolution for hadronic $Z^{0}$ events as a function of thrust axis [20] polar angle $\theta^{\text {thrust }}$. The sum was taken over recorded back-to-back two-jet events that form a statistically-independent sample to the three-jet events used for this study.

After applying the energy-response correction, calorimeter towers were grouped into clusters [21]. A cluster was selected if at least two towers contributed, its energy $E_{\text {cluster }}$ was at least 100 MeV , and the energy correlation in the electromagnetic section $4 E_{e m 1} \cdot E_{e m 2} /\left(E_{e m 1}+E_{e m 2}\right)^{2}>0.1$, where $E_{e m 1}$ and $E_{e m 2}$ are the detected energies in the front and back electromagnetic sections, respectively [22]. Using the selected clusters the total visible energy $E_{v i s}$, normalized energy imbalance $\overline{E_{i m b}}=\left|\sum \vec{E}_{c l u s t e r}\right| / E_{v i s}$, number of selected clusters $N_{\text {cluster }}$, and $\cos \theta^{\text {thrust }}$ were calculated for each event, and multi-hadron events were selected by requiring well-balanced events containing
large energy deposits and a large number of clusters, namely $E_{v i s}>20 \mathrm{GeV}, E_{\text {imb }}<0.6$, and $N_{\text {cluster }} \geq 9$ for $\left|\cos \theta^{\text {thrust }}\right|<0.8$ and $N_{\text {cluster }} \geq 12$ for $\left|\cos \theta^{\text {thrust }}\right|>0.8$. In total 50,144 events from the 1993 run and 99,265 events from the 1994-95 run were selected. The efficiency for selecting hadronic events was estimated to be $92 \pm 2 \%$, with a background in the selected sample of $0.4 \pm 0.2 \%$, dominated by $Z^{0} \rightarrow \tau^{+} \tau^{-}$and $Z^{0} \rightarrow \mathrm{e}^{+} \mathrm{e}^{-}$events.

To measure the triple-product correlation for $e^{+} e^{-} \rightarrow q \bar{q} g$, three-jet events were selected and the three momentum vectors of the jets were reconstructed. Although the parton momenta are not directly measurable, at $\sqrt{s} \approx 91$ GeV the partons usually appear as well-collimated jets of hadrons. Jets were reconstructed using the "Durham" jet algorithm [23]. Planar three-jet events were selected by requiring exactly three reconstructed jets to be found with a jet-resolution parameter value of $y_{c}=0.005$ [24], the sum of the angles between the three jets to be greater than $358^{\circ}$, and that each jet contain at least two clusters. A total of 44,683 events satisfied these criteria and were subjected to further analysis.

Such jet algorithms accurately reconstruct the parton directions but measure the parton energies poorly [25]. Therefore, the jet energies were calculated by using the measured jet directions and solving the three-body kinematics assuming massless jets, and were then used to label the jets such that $E_{1}>E_{2}>E_{3}$. The energy of jet 1, for example, is given by

$$
\begin{equation*}
E_{1}=\sqrt{s} \frac{\sin \theta_{23}}{\sin \theta_{12}+\sin \theta_{23}+\sin \theta_{31}}, \tag{5}
\end{equation*}
$$

where $\theta_{k l}$ is the angle between jets $k$ and $l$.
Since the energy and angular resolutions of the jet reconstruction procedure determine the sensitivity of the present measurement, a Monte Carlo simulation of hadronic $Z^{0}$ decays [26] combined with a simulation of the detector response was used to study the quality of the jet reconstruction. To account properly for beam-related backgrounds in the simulation, real calorimeter hits taken by a random trigger were overlaid on the simulated $Z^{0}$ events. These events were then subjected to the same reconstruction, hadronic event selection, and three-jet analysis procedures as the real data. For those events satisfying the three-jet criteria, exactly three jets were reconstructed at the parton level by applying the jet algorithm to the parton momenta. The three parton-level jets were associated with the three detector-level jets by choosing the combination that minimized the sum of the angular differences between the corresponding jets. The directions and energies of jets at the parton level were then compared with those for the corresponding jets at the detector level. The average angles between the parton-jet and detector-jet directions were $2.9^{\circ}, 4.0^{\circ}$, and $7.2^{\circ}$, for the highest, medium, and lowest energy jets, respectively. Although the detector-jet
energies were much degraded, the reconstructed energies agreed well with the parton-jet energies; the r.m.s energy difference between parton and detector jets was $2.8,5.2$, and 5.2 GeV for the highest, medium, and lowest energy jet, respectively.

Since in this analysis the vector normal to the jet plane is determined by the two highest energy jets, reconstruction of the correct jet-energy ordering is essential. For a three-jet event whose jets are labeled according to the parton-jet energy ordering, six detector-jet energy orderings are possible. For the three cases where the energy ordering of any two jets does not agree between parton and detector levels, the direction of the jet-plane normal vector is opposite between the parton level and detector level and $\cos \omega$ will be measured with the wrong sign. The probability of this, $P_{m i s}(|\cos \omega|)$, was determined as a function of $\cos \omega$ from Monte Carlo studies. Although the three-jet rate was largest for $y_{c} \approx 0.002$, the misassignment probability $P_{m i s}$ was found to be smallest for $y_{c} \approx 0.012$. Combining these two factors, the experimental sensitivity to the $\mathrm{T}_{\mathrm{N}}$-odd contribution was found highest for the $y_{c}$ value of 0.005 used in this analysis. For this $y_{c}$ value $P_{m i s}$ varied from 0.25 around $\cos \omega=0$ to 0.21 as $|\cos \omega| \rightarrow 1$; averaged over all $\cos \omega$, $<P_{m i s}(|\cos \omega|)>\approx 0.22$.

For each event the reconstructed jet vectors were used to determine the vector normal to the jet plane and its polar angle $\omega$, from which the measured distribution of $\cos \omega$ was derived. A bin-by-bin correction factor $\epsilon(|\cos \omega|)$, for detector acceptance and initial-state radiation, was determined from Monte Carlo simulations by taking the ratio of the distribution at the parton level for an event sample generated without initial-state radiation to the distribution at $=$ the detector level for an event sample generated with initial-state radiation and subjected to the same reconstruction, selection, and anlysis as the data. Figure 2 shows the corrected $\cos \omega$ distribution separately for left- and right-handed beam events in the 1994-95 data sample. A $\mathrm{T}_{N^{-}}$-odd contribution would appear as a forward-backward asymmetry, of opposite sign between the left- and right-handed events; no asymmetry is apparent. The distributions may be described by

$$
\begin{equation*}
\frac{1}{\sigma} \frac{d \sigma}{d \cos \omega}=\frac{9}{16}\left[\left(1-\frac{1}{3} \cos ^{2} \omega\right)+\beta A_{Z}\left(1-2 P_{m i s}(|\cos \omega|)\right) \cos \omega\right] \tag{6}
\end{equation*}
$$

We performed a maximum-likelihood fit of Eq. 6 simultaneously to the $\cos \omega$ distributions from the 1993 and 19941995 left- and right-handed event samples, with the relevant values of $A_{Z}$, and allowing the parameter $\beta$ to vary. We found

$$
\begin{equation*}
\beta=0.008 \pm 0.015 \tag{7}
\end{equation*}
$$

where the error is statistical only [27]. The result of this fit is shown in Fig. 2; the $\chi^{2}$ is 26.0 for 20 data points. The $\mathrm{T}_{N \text {-odd }}$ contribution is consistent with zero within the statistical error and we calculate limits of

$$
\begin{equation*}
-0.022<\beta<0.039 @ 95 \% \quad \text { C.L. } \tag{8}
\end{equation*}
$$

A number of systematic checks was performed. The analysis was performed on samples of Monte Carlo events in which no $\mathrm{T}_{N}$-odd effect was simulated, yielding $\beta$ consistent with zero within $\pm 0.010$, implying that any analysis bias is less than $\pm 0.02$ at $95 \%$ C.L. The dependence on the jet-resolution parameter was studied by varying $y_{c}$ between 0.001 and 0.03 , and in each case the $\mathrm{T}_{N}$-odd contribution was found to be consistent with zero within the statistical error. The analysis was also performed using the JADE jet algorithm [28] and $y_{c}=0.01$. While $P_{m i s}$ was somewhat larger than the value for the Durham algorithm, 0.25 averaged over $|\cos \omega|$, the experimental sensitivity was comparable as a result of the larger three-jet rate [29]. The $\mathrm{T}_{N^{\text {-odd }}}$ contribution was found to be consistent with zero. Finally, the analysis was performed using only charged tracks measured in the CDC. While the event sample was reduced to about $50 \%$ of the calorimetric sample as a result of the smaller solid-angle coverage of the CDC, the charged tracks provided an independent basis for selecting and reconstructing three-jet events [29]. The $\mathrm{T}_{N}$-odd contribution was again consistent with zero for the same range of $y_{c}$.

In conclusion, we have made the first measurement of the $\mathrm{T}_{N}$-odd correlation in polarized $Z^{0}$ decays to three-jets. We find the correlation to be consistent with zero and set $95 \%$ C.L. limits on beyond-the-Standard-Model $\mathrm{T}_{N}$-odd contributions to $Z^{0}$ decays to three-jets of $-0.022<\beta<0.039$.

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## FIGURE CAPTIONS

Figure 1. Representative Feynman diagrams of higher-order interactions with non-vanishing contributions to the triple product: (a) QCD rescattering ( $m_{q} \neq 0$ is required), (b) triangle diagram via quark annihilation ( $m_{q}^{\prime} \neq 0$ is required), and (c) electroweak rescattering.

Figure 2. Polar-angle distribution of the jet-plane normal with respect to the electron-beam direction for the 1994-95 data sample with (a) left-handed and (b) right-handed electron beam. The solid curve is the best fit to the combined 1993 and 1994-95 data samples.


Fig. 1


Fig. 2


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