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FIRST MEASUREMENT OF THE TRIPLE-PRODUCT CORRELATION IN POLARIZED Z^0 DECAYS TO THREE JETS*

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ABSTRACT

We present the first measurement of the triple-product correlation in polarized Z^0 decays to three jets using the SLD detector at SLAC and utilizing a longitudinally polarized electron beam. The CP-even and T-odd triple product $\vec{S_Z} \cdot (\vec{k_1} \times \vec{k_2})$ formed from the two fastest jet momenta $\vec{k_1}$ and $\vec{k_2}$ and the Z^0 polarization vector $\vec{S_Z}$ is sensitive to physics beyond the Standard Model. We measure the expectation value of this quantity to be consistent with zero and set an upper limit on correlations between the Z^0-spin and the three-jet plane orientation.

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1 Introduction

Polarized beams have been used to investigate fundamental symmetries in particle physics. Parity violation was first discovered in β decays from polarized ^{60}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, enabling investigations of fundamental symmetries at the Z^0 resonance.

The Z^0 bosons produced by longitudinally polarized electron beams are highly polarized with polarization $A_Z = (P_{e^-} - A_e)/(1 - P_{e^-} \cdot A_e)$, where P_{e^-} is the electron beam polarization, defined to be negative (positive) for a left-(right-) handed beam, and $A_e = 2v_e a_e/(v_e^2 + a_e^2)$ with v_e and a_e the vector and axial vector coupling parameters of the electron, respectively; $A_Z = -0.82$ $(+0.71)$ for $P_{e^-} = -0.77$ $(+0.77)$. Since 1993 the SLC polarized electron source has been running with strained-lattice GaAs cathodes, and the electron-beam polarization was approximately 0.77 in magnitude at the e^+e^- interaction point in the 1994-95 run. A unique feature of the SLC polarized electron source is a random pulse-by-pulse reversal of the spin direction, thus reducing systematic effects and achieving higher sensitivities to polarization asymmetries. For polarized Z^0 decays to three hadronic jets, one can define the triple-product correlation:

$$\vec{S_Z} \cdot (\vec{k_1} \times \vec{k_2}), \tag{1}$$

where $\vec{k_1}$ and $\vec{k_2}$ are the momenta of the highest- and the second-highest-energy jets, and $\vec{S_Z}$ is the Z^0 boson polarization vector. The jets are labeled according to their energies $E_1 > E_2 > E_3$, and no flavor identification is made. This paper reports on the first experimental measurement of the triple-product correlation.

2 The Triple-Product Correlation

The triple-product correlation (1) is even under C and P reversals, and odd under T_N, where T_N reverses momenta and spin-vectors without exchanging initial and final states. Since T_N is not a true time reversal operation a non-zero value does not signal CPT violation and is possible even in a theory that respects CPT invariance [5]. This observable was first proposed as a method for direct experimental observation of the non-Abelian character of QCD in $e^+e^- \to \Upsilon \to ggg$ [6] and $e^+e^- \to q\bar{q}g$ [7]. Although a detectable signal is expected in $e^+e^- \to q\bar{q}g$ at $\sqrt{s} < 40$ GeV, no experimental measurements have been performed since a longitudinally polarized electron beam is required. A similar triple-product correlation was also studied theoretically in neutrino scattering [8] and lepton-nucleon scattering [9]. More recently, other observables to explore CP-/T-violation have been investigated in high-energy jet physics [10].

After integrating over the parton energies and angles within the event plane, the differential cross section for $e^+e^- \to q\bar{q}g$ for a longitudinally polarized electron beam and massless quarks is given by [7] [11]:

$$\frac{d\sigma}{d\cos\omega} \propto \frac{16}{9}[(1 - \frac{1}{3}\cos^2\omega) + \beta \cdot A_Z \cdot \cos\omega], \tag{2}$$

where ω is the polar angle of the vector normal to the jet plane, defined by $\vec{k_1} \times \vec{k_2}$, and A_Z is the spin-polarization of the Z^0 . With the constant β representing the magnitude [12], the second term is proportional to the T_N-odd triple-product correlation (1), and appears as a forward-backward asymmetry of the jet-plane-normal relative to the Z^0 spin-polarization. Since the sign of this term is different for the two beam polarizations, the $\cos\omega$ distribution is examined separately for events produced by left- and right-handed beams, and the forward-backward asymmetry and the average value of $\cos\omega$ are evaluated in each case.

Recently Brandenburg, Dixon and Shadmi have investigated the T_N-odd contributions from the Standard Model at the Z^0 resonance [11]. The correlation vanishes identically at tree level, but non-zero contributions are expected from the interference terms between the tree level and higher order terms. Fig. 1 shows three higher order rescattering processes expected to contribute to the correlation and calculated in Ref. [11]; 1) QCD rescattering of massive quarks [7], 2) QCD triangle of massive quarks [13], and 3) electroweak rescattering via W and Z exchange loops. Due to various cancellations the Standard Model contributions for the correlation are found to be very small at the Z^0 resonance and yield $|\beta| \lesssim 10^{-5}$ [11]. Because of this background-free situation the measurement is potentially sensitive to physics processes beyond the Standard Model that give $\beta \neq 0$.

3 Apparatus and Hadronic Event Selection

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 during the 1994-95 run. The magnitude of the average electron beam polarization was 0.63 for the 1993 run, and 0.77 for the 1994-95 run. A general description of the SLD can be found elsewere [14]. Charged particle tracking and momentum analysis is provided by the Central Drift Chamber (CDC) [15] and the CCD-based vertex detector [16] in a uniform axial magnetic field of 0.6 T. Particle energies are measured in the Liquid Argon Calorimeter (LAC) [17] and in the Warm Iron Calorimeter [18]. 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. 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.

In the present analysis, the hadronic event selection and three-jet analysis are based on the LAC, taking advantage of its large solid angle coverage. The LAC is a lead liquid-argon sampling calorimeter 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 with two electromagnetic sections (21 radiation length thickness) and two hadronic sections (2.8 interaction length thickness for the entire LAC), and consists of 192 azimuthal and 96 polar angle segmentations with projective towers of constant solid angle.

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

Although the LAC offers a uniform and stable energy response for most of its solid angle coverage, the energy response is degraded around $|\cos\theta| \approx 0.82$ where the barrel and endcap sections meet. In order to achieve a uniform energy response over the detector acceptance the energy response of the LAC towers is calibrated using back-to-back two-jet events. The total detected energy is expressed as a linear combination of the LAC tower energies weighted by energy-independent calibration constants as:

$$E_{detect} = \sum_i (a_i \cdot E^i_{em} + b_i \cdot E^i_{had}), \tag{3}$$

where E^i_{em} and E^i_{had} are detected energies in the electromagnetic and hadronic sections, and the sum is taken over all the polar angle segmentations [19]. The constants a_i and b_i are the calibration factors which are determined by minimizing the sum taken for the two-jet events:

$$\sum_{events} \frac{(E_{detect} - E_{CM})^2}{\sigma^2}, \tag{4}$$

where E_{CM} is the e^+e^- collision energy [20] and σ is the measured LAC energy resolution for hadronic Z^0 events.

After correcting for the energy response calorimeter towers are grouped into clusters using the algorithm developed by Youssef [21]. A cluster is accepted if: 1) at least two towers contribute, 2) its energy is at least 100 MeV, and 3) the energy correlation in the electromagnetic section $4E_{em1} \cdot E_{em2}/(E_{em1}+E_{em2})^2 > 0.1$, where E_{em1} and E_{em2} are the detected energies in the front and back electromagnetic sections, respectively. Using the selected clusters the total visible energy E_{vis}, normalized energy imbalance $E_{imb} = |\sum \vec{E}_{cluster}|/E_{vis}$, number of selected clusters $N_{cluster}$, and polar angle of the event thrust axis $\cos\theta^{thrust}$ [22] are calculated for each event, and multi-hadron events are selected by requiring that: 1) $E_{vis} > 20$ GeV, 2) $E_{imb} < 0.6$, and $N_{cluster} \geq 9$ for $|\cos\theta^{thrust}| < 0.8$ and $N_{cluster} \geq 12$ for $|\cos\theta^{thrust}| > 0.8$. In total 50,144 events in the 1993 run and 99,265 events in the 1994-95 run are selected. The efficiency for selecting hadronic events was estimated to be $92 \pm 2\%$, with an estimated background in the selected sample of $0.4 \pm 0.2\%$, dominated by $Z^0 \rightarrow \tau^+\tau^-$ and $Z^0 \rightarrow e^+e^-$events.

4 Three-Jet Analysis

To measure the triple-product correlation for $e^+e^- \rightarrow q\bar{q}g$ three-jet events are selected and the three momentum vectors of the jets are reconstructed. Although the parton momenta are not directly measurable due to hadronization the partons appear as well collimated jets of hadrons due to the high center-of-mass energy. Jets are reconstructed using the "Durham" jet algorithm [23]. Three-jet events are selected by requiring that: 1) exactly 3 reconstructed jets are found by the jet algorithm for a resolution parameter y_c=0.005 [24], 2) the sum of the angles between the three jets is greater than 358°, and 3) each jet contains at least two clusters. A total of 14,894 events from the 1993 run and 29,789 events from the 1994-95 run satisfy these selection criteria and are subjected to further analysis.

It is well-established that such jet algorithms accurately reconstruct the parton directions but measure the parton energies poorly [25]. Therefore, the jet energies are calculated by using the measured jet directions and solving the three-body kinematics assuming massless jets. The calculated energies are then used to label the jets according to $E_1 > E_2 > E_3$. The energy of jet 1, for example, is calculated by:

$$E_1 = \sqrt{s}\frac{\sin\theta_{23}}{\sin\theta_{12} + \sin\theta_{23} + \sin\theta_{31}}, \tag{5}$$

where θ_{23} is the angle between jets 2 and 3.

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 is used to study the quality of the jet reconstruction. To account properly for the beam-related backgrounds in the calorimeter hit simulation real calorimeter hits taken by a random trigger are overlaid on the simulated events. These simulated events are 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 are reconstructed at the parton level by applying the jet algorithm to the parton momenta. The three parton-level jets are associated with the three detector-level jets by choosing the combination that minimizes the sum of the angular differences between the corresponding jets. The jet directions and energies are compared between jets at the parton level and the corresponding jets at the detector level. For $y_{cut} = 0.005$ the average angles between the parton-jet direction and the detector-jet direction are 2.3°, 3.8°, and 7.3°, for the highest, medium, and lowest energy jets, respectively. Fig. 2 shows the jet energy distributions. While the detected energy distributions are much degraded, the reconstructed energy distributions agree very well with the parton-jet energy distributions. The average energy difference between parton- and detector-jets are 2.2 GeV, 4.5 GeV, and 4.5 GeV for the highest, medium, and lowest energy jet, respectively. Since the vector normal to the jet plane is determined by the two highest energy jets, reconstructing the correct energy order is essential in this analysis. Six energy orderings are possible at the detector level for a three-jet event whose jets are labeled according to the energies ordered at the parton level. By comparing the energy order of the parton-jets and detector-jets, the probabilities for the six possible cases are estimated and shown in Table 1. For cases 2, 3, and 4, the direction of the jet-plane-normal vector is opposite between the parton level and detector level.

Using the reconstructed jet vectors, the vector normal to the jet plane and its polar angle $\cos\omega$ are determined. The observed angular distribution may be described by:

$$\frac{d\sigma}{d\cos\omega} \propto \epsilon(|\cos\omega|)\cdot[(1-\frac{1}{3}\cos^2\omega)+\beta\cdot A_Z\cdot(1-2\cdot P_{mis}(|\cos\omega|))\cdot\cos\omega], \qquad (6)$$

where $\epsilon(|cos\omega|)$ is the correction factor for detector acceptance and initial state radiation, determined using Monte Carlo events by taking the ratio of distributions at the parton level without initial state radiation and at the detector level, and $P_{mis}(|\cos\omega|)$ is the probability of measuring $\cos\omega$ with the wrong sign, and is also determined from Monte Carlo studies. Fig. 3 shows $\epsilon(|cos\omega|)$ and $P_{mis}(|cos\omega|)$. After correcting for the detector acceptance and initial state radiation, Fig. 4 shows the observed polar angle distribution of the jet-plane-normal for the 1994-95 data taken with left-handed (Fig. 4a) and right-handed (Fig. 4b) beams. We performed a maximum likelihood fit of eq. 6 to the total sample of the 1993 and 1994-95 data and find the T_N-odd contribution β to be:

$$\beta = 0.008 \pm 0.015. \qquad (7)$$

The fit result is shown by the solid curve in Fig. 4. The T_N-odd contribution is zero within the statistical error, and an upper limit is calculated to be:

$$-0.022 < \beta < 0.039 \quad @ \quad 95\% \quad C.L. \qquad (8)$$

5 Systematic Checks

A number of systematic checks was performed. The analysis was performed on samples of Monte Carlo events in which no T_N-odd effect was simulated, yielding β consistent with zero within ± 0.010. This implies that any analysis bias is less than ± 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. The T_N-odd contribution was consistent with zero within the statistical error. The three-jet rate was highest for $y_c \approx 0.002$, while the misassignment probability P_{mis} was smallest for $y_c \approx 0.012$. Combining these two factors together, the experimental sensitivity to the T_N-odd contribution was found highest for $y_c \approx 0.005$.

The analysis was performed with the "JADE" jet algorithm [27]. While P_{mis} was somewhat larger (0.25 averaged over $|\cos\omega|$) than the value with the "Durham" algorithm, the experimental sensitivity was comparable as a result of the larger three-jet rate. The T_N-odd contribution was found to be consistent with zero.

The analysis was performed using only charged tracks measured in the CDC. While the final 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 method for finding and reconstructing three-jet events. The T_N-odd contribution was again consistent with zero for a wide range of y_c.

6 Conclusions

We have made the first measurement of the triple-product correlation in polarized Z^0 decays to three-jets. We find the correlation to be consistent with zero and have set an upper limit on the rate β of T_N-odd Z^0 decays to three-jets of $-0.039 < \beta < 0.022$.

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Table 1: Probabilities of the six possible energy orders at the detector level for the three jets labeled according to their energies at the parton level $E_1 > E_2 > E_3$.

Case	Highest/Medium/Lowest at the detector level	Probability (%)
1	1 2 3	76.4
2	1 3 2	9.4
3	3 2 1	0.1
4	2 1 3	12.8
5	2 3 1	0.6
6	3 1 2	0.7

Figure captions

Figure 1. Representative Feynman diagrams of higher order interactions with non-vanishing contributions to the triple-product correlation: (a) the QCD rescattering contribution ($m_q \neq 0$ is required for a non-vanishing value), (b) triangle diagram via quark annihilation ($m_q \neq 0$ is required), and (c) electroweak rescattering contribution.

Figure 2. Energy distributions for a) highest-, b) medium-, and c) lowest-energy jets. The distributions of detected energy and reconstructed energy are shown as open and solid circles, respectively. The distributions of parton-jet energies in Monte Carlo events are shown as histograms.

Figure 3 Correction factor (solid circles) and misassignment probability (open circles) as a function of $|\cos\omega|$ determined from Monte Carlo events.

Figure 4. Polar angle distribution of the jet-plane-normal with respect to the electron beam direction for the 1994-95 data taken with a) left-handed and b) right-handed electron beams. The solid curve is the best fit to the combined 1993 and 1994-95 data.

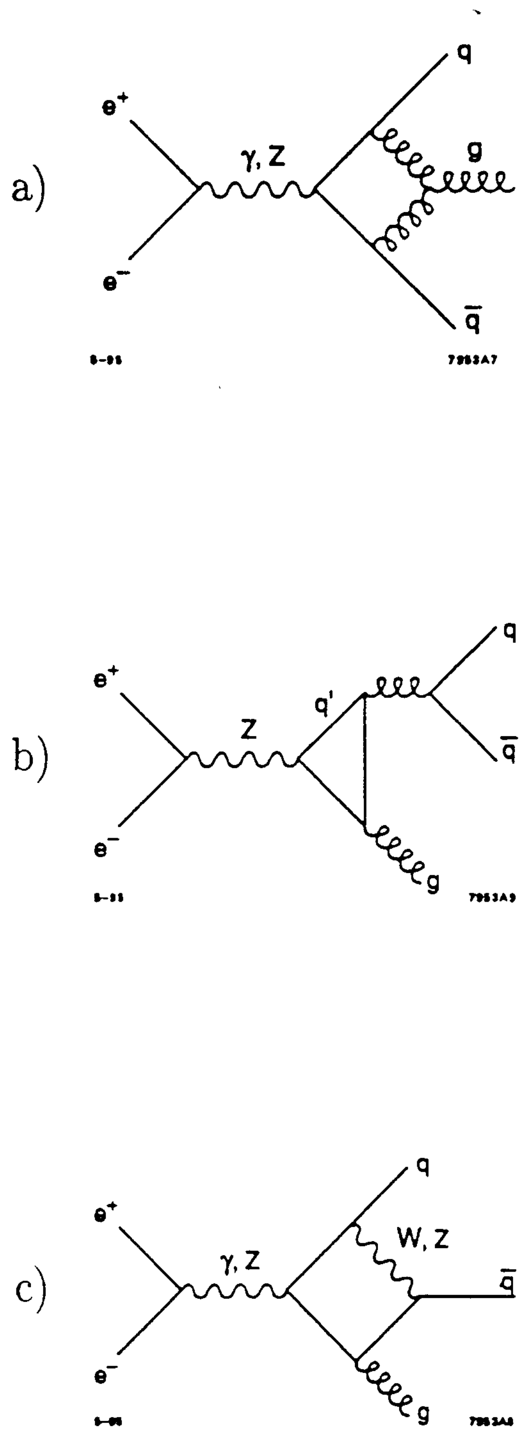


Figure 1

SLD (preliminary)

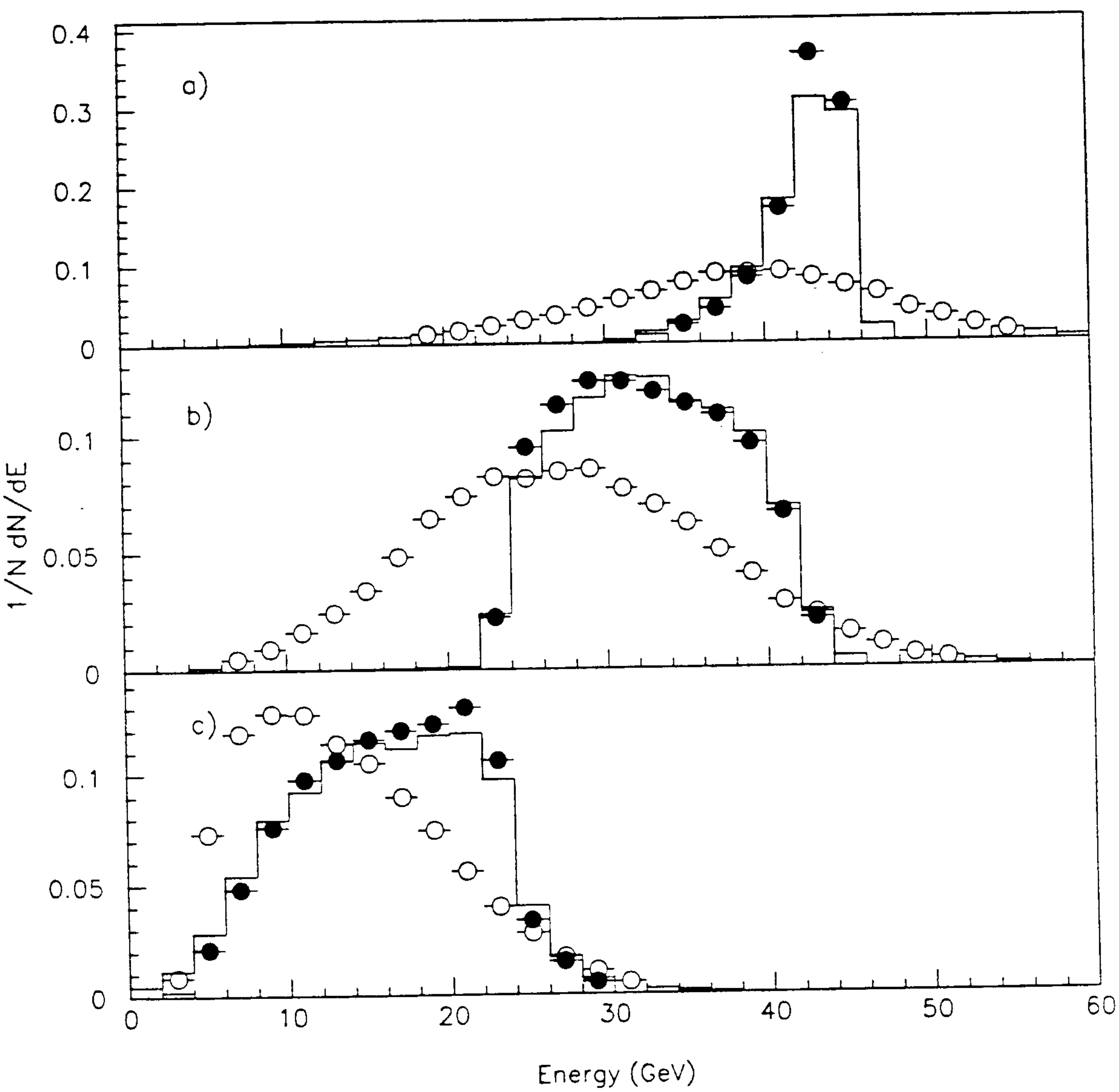
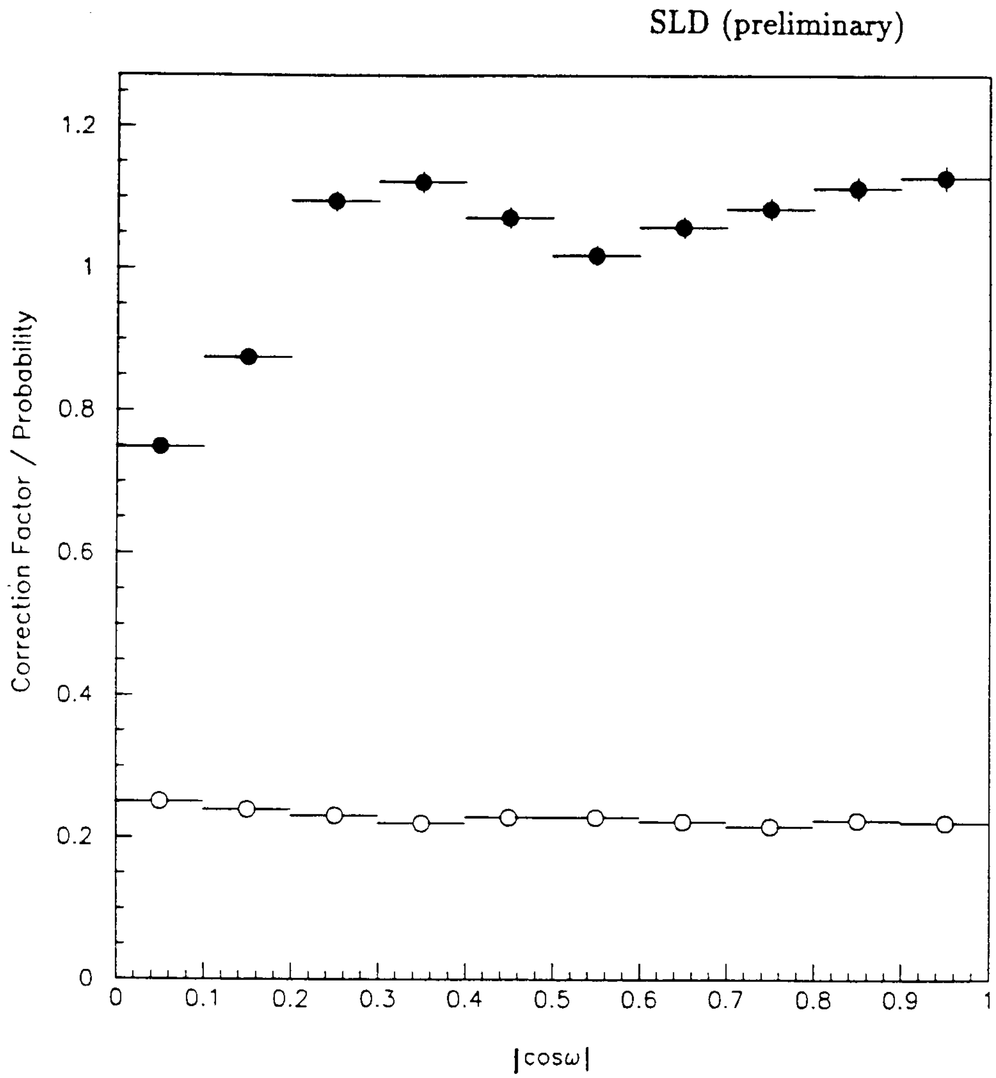


Figure 2



SLD (preliminary)
1.2
1
0.8
0.6
0.4
0.2
0
Correction Factor / Probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
|cosω|

Figure 3

SLD (preliminary)

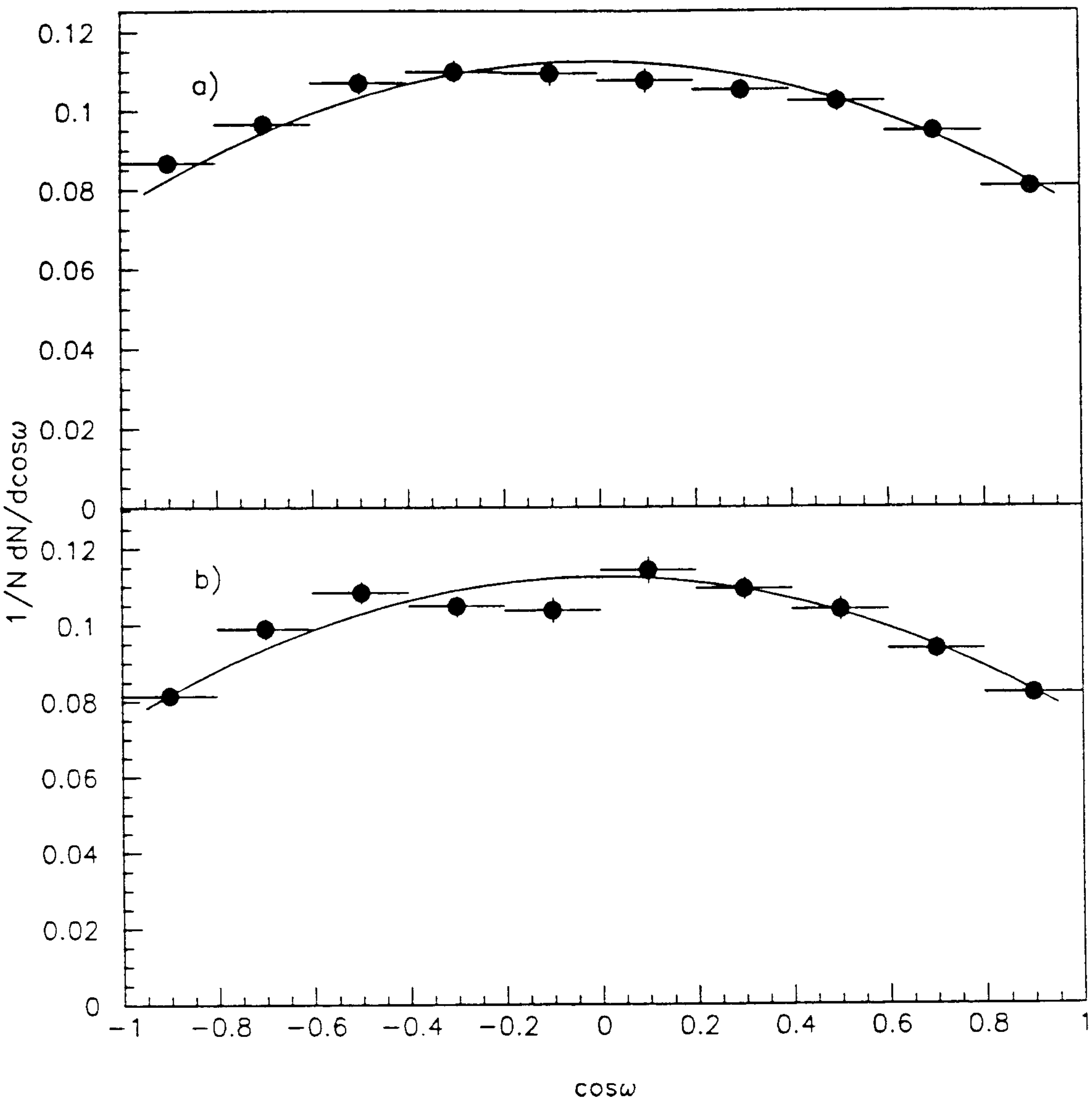


Figure 4