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First Symmetry Tests in Polarized Z^0 Decays to $b\bar{b}g$

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ABSTRACT

We have made the first direct symmetry tests in the decays of polarized Z^0 bosons into fully-identified $b\bar{b}g$ states, collected in the SLD experiment at SLAC. We searched for evidence of parity violation at the $b\bar{b}g$ vertex by studying the asymmetries in the b-quark polar- and azimuthal-angle distributions, and for evidence of T-odd, CP-even or odd, final-state interactions by measuring angular correlations between the three-jet plane and the Z^0 polarization. We found results consistent with Standard Model expectations and set 95% C.L. limits on anomalous contributions.

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Polarization is an essential tool in investigations of fundamental symmetries in elementary-particle interactions. Parity violation was first discovered using β decays of polarized ^{60}Co [1], and T, CP and CPT violations were searched for using polarized neutrons [2] and polarized positronium [3]. The unique sample of polarized Z^0 bosons produced in annihilations of longitudinally-polarized electrons with unpolarized positrons at the SLAC Linear Collider (SLC) can similarly be employed for fundamental symmetry tests. Here we use $e^+e^- \to Z^0 \to$ three-jet events to test symmetry properties of the Standard Model (SM). The $b\bar{b}g$ final state provides a particularly interesting probe for possible beyond-SM processes that couple to massive particles.

The tree-level differential cross section for $e^+e^- \to q\overline{q}g$ can be expressed [4]

$$2\pi \frac{d^4\sigma}{d(\cos\theta)d\chi dx d\overline{x}} = [\ \frac{3}{8}(1+\cos^2\theta)\,\sigma_U + \frac{3}{4}\sin^2\theta\,\sigma_L$$

$$+\frac{3}{4}\sin^2\theta\cos 2\chi\,\sigma_T + \frac{3}{2\sqrt{2}}\sin 2\theta\cos\chi\,\sigma_I]\ h_f^{(1)} +\ [\ \frac{3}{4}\cos\theta\,\sigma_P - \frac{3}{\sqrt{2}}\sin\theta\cos\chi\,\sigma_A\ ]\ h_f^{(2)}, \tag{1}$$

where θ is the polar angle of the thrust axis w.r.t. the electron beam, and χ is the azimuthal angle of the event plane w.r.t. the quark-electron plane. The thrust axis is defined to be along the most energetic jet and to point into (opposite) the hemisphere containing the quark (antiquark) if the quark (antiquark) has the higher energy. The sign of cosχ is defined in terms of momentum vectors, $\mathrm{sign}(\cos\chi) = \mathrm{sign}((\vec{q}\times\vec{g})\cdot(\vec{q}\times\vec{e^-}))$. The functions $h_f^{(1)}$ and $h_f^{(2)}$ contain the dependence on the beam polarization and the electroweak couplings [4]; QCD contributions are expressed in terms of $\sigma_i \equiv d^2\sigma_i/dxd\overline{x}$, with $i = U, L, T, I, A, P$, where x and $\bar{x}$ are the scaled momenta of the quark and antiquark, respectively, While the first four terms are even under P reversal, the last two terms are P-odd, and are sensitive to any parity-violating interactions at the Z^0q$\bar{\mathrm{q}}$ or $q\overline{q}g$ vertices. More generally there can be, in addition, three terms that are odd under T reversal [5]. However, these terms vanish at tree level in a theory that respects CPT invariance.

We report the first experimental study of angular asymmetries in polarized Z^0

decays to fully-identified $b\bar{b}g$ states. We present new tests of QCD using the P-odd asymmetries in the θ and χ distributions [6], as well as the first measurements of two T-odd triple-product correlations between the $b\bar{b}g$ plane and the Z^0 polarization. Integrating Eq. 1 over x, $\overline{x}$ and χ,

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \alpha\cos^2\theta + 2P_Z\, A_P\, \cos\theta, \qquad (2)$$

where $P_Z = (P_{e^-} - A_e)/(1 - P_{e^-}\cdot A_e)$, P_{e^-} is the signed electron-beam polarization, the parity-violation parameter $A_P = A_b \cdot \hat{\sigma}_P/(\hat{\sigma}_U + \hat{\sigma}_L)$, A_e (A_b) is the electroweak coupling of the Z^0 to the initial (final) state, and $A_j = 2v_j a_j/(v_j^2 + a_j^2)$ in terms of the vector, v_j, and axial-vector, a_j, couplings of fermion j to the Z^0; $\alpha = (\hat{\sigma}_U - 2\hat{\sigma}_L)/(\hat{\sigma}_U + 2\hat{\sigma}_L)$, and $\hat{\sigma}_i \equiv \int d^2\sigma_i$. Similarly,

$$\frac{d\sigma}{d\chi} \propto 1 + \beta\cos 2\chi - \frac{3\pi}{2\sqrt{2}}\, P_Z\, A'_P\, \cos\chi, \qquad (3)$$

where $A'_P = A_b \cdot \hat{\sigma}_A/(\hat{\sigma}_U + \hat{\sigma}_L)$, and $\beta = \hat{\sigma}_T/(\hat{\sigma}_U + \hat{\sigma}_L)$. Given the value of A_b, measurement of A_P and A'_P allows one to test the QCD predictions for $\hat{\sigma}_P/(\hat{\sigma}_U + \hat{\sigma}_L)$ and $\hat{\sigma}_A/(\hat{\sigma}_U + \hat{\sigma}_L)$. Furthermore, the ratio A'_P/A_P yields $\hat{\sigma}_A/\hat{\sigma}_P$ independently of A_b.

In terms of the polar angle ω, w.r.t. the electron-beam direction, of the vector $\vec{n}$ normal to the event plane,

$$\frac{d\sigma}{d\cos\omega} \propto 1 + \gamma\cos^2\omega + \frac{16}{9}\, P_Z\, A_T\cos\omega, \qquad (4)$$

where $\gamma = (2\hat{\sigma}_L - \hat{\sigma}_U - 6\hat{\sigma}_T)/(3\hat{\sigma}_U + 2\hat{\sigma}_L + 2\hat{\sigma}_T)$; the asymmetry term is one of the three T-odd terms mentioned above. The vector $\vec{n}$ can be defined in several ways; for example: 1) using the two highest-energy jets, $\vec{n} = \vec{p}_1 \times \vec{p}_2$; or 2) using the quark and anti-quark momenta, $\vec{n} = \vec{p}_b \times \vec{p}_{\bar{b}}$. The asymmetry is CP-even in the first definition, and CP-odd in the second; in both cases in the SM $A_T = 0$ at tree level. Higher-order corrections to $e^+e^- \rightarrow b\bar{b}g$ yield $|A_T| < 10^{-5}$ [7]. The asymmetry in $\cos\omega$ is hence potentially sensitive to beyond-SM processes [8].

The measurement was performed using approximately 550,000 $Z^0 \rightarrow$ hadrons decays produced in collisions of longitudinally-polarized electrons with unpolarized positrons at the SLC between 1993 and 1998. In order to reduce systematic effects on polarization-dependent asymmetries the electron polarization direction was reversed randomly pulse-by-pulse; the magnitude of the average polarization was 0.73. The data were recorded in the SLC Large Detector (SLD) [9]. The trigger and hadronic event selection criteria are described elsewhere [10]. This analysis used charged tracks measured in the central drift chamber and in the CCD-based vertex detectors (VXD) [11]. About 70% of the data were taken with the new VXD installed in 1996 (VXD3), and the rest with the previous detector (VXD2). Only well-reconstructed tracks [12] were used for the b-jet tagging. Particle energies were measured in the liquid-argon and warm-iron calorimeters; the calorimetric information was used only to reconstruct the thrust axis.

In each event jets were reconstructed using the "Durham" algorithm [13]. To select planar three-jet events we required exactly three reconstructed jets to be found with a jet-resolution parameter value of y_c=0.005, the sum of the angles between the three jets to be greater than 358°, and that each jet contain at least two charged tracks; 74,886 events satisfied these criteria. The jet energies were calculated by using the measured jet directions and solving the three-body kinematics assuming massless jets. The jets were then labeled such that $E_1 > E_2 > E_3$.

To select $b\bar{b}g$ events the long lifetime and large invariant mass of B-hadrons were exploited. An algorithm [14, 15] was applied to the set of well reconstructed tracks in each jet in an attempt to reconstruct a decay vertex. Vertices were required to contain at least two tracks, and to be separated from the interaction point (IP) by at least 1 mm. We calculated (described below) that the probability for reconstructing at least one such vertex was $\sim$ 91% (77%) in $b\bar{b}g$ events, $\sim$ 45% (26%) in $c\bar{c}g$ events, and $\sim$ 2% (2%) in light-quark events recorded in VXD3 (VXD2).

An event was selected as $b\bar{b}g$ if at least one jet contained a vertex with invariant mass [15] > 1.5 GeV/c^2. A total of 14,658 events satisfied this requirement and were subjected to further analysis. We calculated that this selection is 84% (69%) efficient for identifying a sample of $b\bar{b}g$ events with 84% (87%) purity, and containing 14% (11%) $c\bar{c}g$ and 2% (2%) light-flavor backgrounds.

In order to isolate the gluon jet, a b-tag was evaluated for each jet in the selected event sample. This tag was defined to be positive if the jet contained a vertex, or if it contained at least 3 "significant" tracks, *i.e.* with normalized impact parameter w.r.t the IP $d/\sigma_d > 3$ [12]; otherwise the tag was defined to be negative. Jet 1 was tagged as the gluon jet (g) if it had a negative b-tag and both jets 2 and 3 had positive b-tags. Jet 2 was tagged as the gluon-jet if it had a negative b-tag and jet 3 a positive one. Otherwise, jet 3 was tagged as the gluon jet. We calculated that, on average, the purity of the tagged gluon jet sample was 91% (88%).

In order to distinguish the b and $\bar{b}$ jets we evaluated for each jet j the momentum-weighted charge, $Q_j = \sum q_i|\vec{p}_i \cdot \hat{\vec{t}}|^\kappa$, where κ=0.5, $\hat{\vec{t}}$ is the unit vector along the thrust axis and q_i and $\vec{p}_i$ are the charge and momentum of the i^{th} track in jet j. We calculated the charge difference, $Q_{diff} \equiv Q_1 - Q_2 - Q_3$. If Q_{diff} was negative (positive) we assigned jet 1 as the b ($\bar{b}$) jet, unless jet 1 was gluon tagged, in which case we assigned jet 2 as the b ($\bar{b}$) jet if Q_{diff} was positive (negative). The probability of correct $b/\bar{b}$ assignment, $\mathcal{P}(\mathcal{Q}_{\rceil\rangle\{\{})$, was calculated from the data by using a self-calibration technique [16], $\mathcal{P}(\mathcal{Q}_{\rceil\rangle\{\{}) = \infty/(\infty + \rceil^{-\alpha_\lfloor|\mathcal{Q}_{\rceil\rangle\{\{}|})$, where α_b is a fitted parameter. Averaged over $\cos\theta$ $\alpha_b = 0.218 \pm 0.018$ (VXD3) (0.248 ± 0.030 (VXD2)), corresponding to $< \mathcal{P} >$ = 0.68 (VXD3) (0.67 (VXD2)).

A JETSET 7.4 [17]-based Monte Carlo simulation of hadronic Z^0 decays combined with a simulation of the detector response was used to evaluate the efficiency and purity of the $b\bar{b}g$ event selection and the purity of the jet flavor tags. For those simulated events satisfying the three-jet criteria, exactly three jets were reconstructed at the parton level by applying the jet algorithm to the parton four-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 jet axes, and the energies and charges of the matching jets were compared.

Figs. 1(a) and (b) show the observed $\cos\theta$ distributions for event samples produced by left- and right-handed electron beams, respectively. The distributions may be described by

$$\frac{d\sigma}{d\cos\theta} \propto 1+\alpha\cos^2\theta \ +2P_Z\,\cos\theta\,[A_P\,f_b\,(2\,p_\theta^b-1)+ \\ A_{P,c}\,f_c\,(2\,p_\theta^c-1)+A_{P,uds}\,(1-f_b-f_c)\,(2\,p_\theta^{uds}-1)\ ], \qquad (5)$$

where f_b and f_c are the fractions of $b\bar{b}g$ and $c\bar{c}g$ events in the sample, respectively, $A_{P,c}$ and $A_{P,uds}$ are the asymmetry parameters for the respective backgrounds (Fig. 1), and p_θ^b, p_θ^c and p_θ^{uds} are the probabilities to sign $\cos\theta$ correctly in $b\bar{b}g$, $c\bar{c}g$ and light-quark events, respectively. The data were used to calculate p_θ^b ($=\mathcal{P}$ above); all other quantities were calculated from the simulation. A maximum-likelihood fit of Eq. 5 yielded $A_P = 0.855 \pm 0.050$ (stat.).

Figs. 2(a) and (b) show the observed χ distributions for events produced with left- and right-handed electron beams, respectively. They may be described by

$$\frac{d\sigma}{d\chi} \propto 1\,+\,\beta\cos 2\chi\,-\,\frac{3\pi}{2\sqrt{2}}\,P_Z\,\cos\chi\,[A'_P\,f_b\,(2p_\chi^b-1)+ \\ A'_{P,c}\,f_c\,(2p_\chi^c-1)+A'_{P,uds}\,(1-f_b-f_c)\,(2p_\chi^{uds}-1)\ ], \qquad (6)$$

where $A'_{P,c}$ and $A'_{P,uds}$ are the asymmetry parameters for the respective backgrounds, and p_χ^b, p_χ^c and p_χ^{uds} are the probabilities to sign $\cos\chi$ correctly in $b\bar{b}g$, $c\bar{c}g$ and light-quark events, respectively. Averaged over χ, $p_\chi^b = 0.64$ (0.63), which was derived using the measured value of $\mathcal{P}$ (above) combined with the simulated probability to tag the gluon jet correctly. All other parameters were calculated from the simulation. A maximum-likelihood fit of Eq. 6 yielded $A'_P = -0.013 \pm 0.033$ (stat.).

Figs. 3(a) and (b) show the left-right-forward-backward asymmetry in $|\cos\omega| \equiv z$,

$$\tilde{A}_{FB}(z) \equiv \frac{\sigma_L(z)-\sigma_L(-z)+\sigma_R(-z)-\sigma_R(z)}{\sigma_L(z)+\sigma_L(-z)+\sigma_R(-z)+\sigma_R(z)}$$

for the two definitions of the direction of $\vec{n}$: (1) $\vec{p_1}\times\vec{p_2}$, and (2) $\vec{p_b}\times\vec{p_{\bar{b}}}$. No asymmetry is apparent. The $\cos\omega$ distributions may be described, assuming no asymmetries in the

$c\bar{c}g$ and light-quark backgrounds, by

$$\frac{d\sigma}{d\cos\omega} \propto 1 - \frac{1}{3}\cos^2\omega + \frac{16}{9} P_Z\, A_T^{\pm} f_b (2p_{\pm}^b - 1)\cos\omega, \tag{7}$$

where $p_{\pm}^b$ is the probability to sign $\cos\omega$ correctly in the CP-even (+) and CP-odd (−) cases, respectively. In the CP-even case, in which the jets were labeled according to their energy, six detector-jet energy orderings were possible for a given parton-jet energy ordering. Using the simulation we calculated that, averaged over cosω, $p_+^b =$ 0.76 (0.76). In the CP-odd case, both the gluon jet and the b-jet must be tagged correctly, and p_-^b ($= p_\chi^b$ above) = 0.64 (0.63). Maximum-likelihood fits (Fig. 3) of Eq. 7 yielded $A_T^+ = -0.014 \pm 0.016$ (stat.) and $A_T^- = -0.035 \pm 0.024$ (stat.).

We considered sources of systematic error [16, 18] which potentially affect our results. The modeling of the detector response was studied by varying the tracking efficiency and resolution within their estimated uncertainties, and by varying the vertex-mass and significant-track requirements. In addition, the error on the probability for correct jet-energy ordering was estimated from the difference between results derived using HERWIG [19] and JETSET. The error on the $b/\bar{b}$-jet identification probability was derived from the statistical uncertainty in the α_b determination using the self-calibration technique. Contributions from the modeling of underlying physics processes were also studied. In $b\bar{b}$ events we considered the uncertainties on: the branching fraction for $Z^0 \to b\bar{b}$, the B-hadron fragmentation function, the rates of production of $B^\pm$, B^0 and B_s^0 mesons, and B baryons, the lifetimes of B mesons and baryons, and the average B-hadron decay charge multiplicity. In $c\bar{c}$ events we considered the uncertainties on: the branching fraction for $Z^0 \to c\bar{c}$, the charmed hadron fragmentation function, the rates of production of D^0, D^+ and D_s mesons, and charmed baryons, and the charged multiplicity of charmed hadron decays. We also considered the rate of production of $s\bar{s}$ in the jet fragmentation process, and the production of secondary $b\bar{b}$ and $c\bar{c}$ from gluon splitting. The uncertainty on the beam polarization was also taken into account.

The systematic errors on A_P' and $A_T^\pm$ are negligibly small as the uncertainty diminishes with the measured asymmetry, which in all three cases is small and consistent with zero. In the case of A_P the largest error contributions arose from the α_b uncertainty ($\delta A_P/A_P \sim$5.7%) and from the uncertainty in the background level ($\delta A_P/A_P \sim$3.9%); other contributions were at the level of 1% or less.

From the measured values of A_P and A'_P, and assuming the SM expectation of $A_b \simeq 0.935$ for $\sin^2\theta_w$=0.232, we find, respectively

$$\frac{\hat{\sigma}_P}{\hat{\sigma}_U + \hat{\sigma}_L} = 0.914 \pm 0.053\,(stat.) \pm 0.063\,(syst.),$$

$$\frac{\hat{\sigma}_A}{\hat{\sigma}_U + \hat{\sigma}_L} = -0.014 \pm 0.035\,(stat.) \pm 0.002\,(syst.).$$

These values are consistent with the $\mathcal{O}(\alpha_s^2)$ QCD expectation (for massless quarks) of $\hat{\sigma}_P/(\hat{\sigma}_U + \hat{\sigma}_L) = 0.93$ and $\hat{\sigma}_A/(\hat{\sigma}_U + \hat{\sigma}_L) = -0.06$, respectively, calculated using JETSET 7.4. These yield $\hat{\sigma_A}/\hat{\sigma_P} = -0.015 \pm 0.038$ independent of the assumed A_b, and consistent with the expected value -0.065. We also used the A_P and A'_P values to set a 95% C.L. limit on an anomalous axial-vector coupling of the gluon to the b-quark, parametrized [20] by a factor $(1+\epsilon\gamma_5)\gamma_\nu$ in the $b\bar{b}g$ coupling, of $\epsilon < 0.34$. The measured values of A_T^+ and A_T^- correspond to 95% C.L. limits of $-0.045 < A_T^+ < 0.016$ and $-0.082 < A_T^- < 0.012$ (Fig. 3).

In conclusion, we have made the first symmetry tests in polarized Z^0 decays to $b\bar{b}g$. From the forward-backward polar-angle asymmetry of the signed-thrust axis and the azimuthal-angle asymmetry we found the parity-violation parameters A_P and A'_P, respectively, to be consistent with $\mathcal{O}(\alpha_s^2)$ QCD expectations. We set a corresponding 95% C.L. limit on parity violation at the $b\bar{b}g$ vertex. Using the event-plane normal polar-angle distributions we set 95% C.L. limits on the T-odd, CP-even and odd asymmetry parameters A_T^+ and A_T^-, respectively.

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References

[1] C.S. Wu *et al.*, Phys. Rev. **105** 1413 (1957).

[2] E.M. Henley, Proc. International Symposium on Weak and Electromagnetic Interactions in Nuclei, Montreal, 1989; ed. P. Depommier, p. 181.

[3] B.K. Arbic *et al.*, Phys. Rev. **B37** 3189 (1988); M. Skalsey, J. Van House, Phys. Rev. Lett. **67** 1993 (1991).

[4] H. A. Olsen *et al.*, Nucl. Phys. **B171** 209 (1980).

[5] K. Hagiwara *et al.*, Nucl. Phys. **B358** 80 (1991).

[6] P. N. Burrows, P. Osland, Phys. Lett. **B400** 385 (1997).

[7] A. Brandenburg, L. Dixon, Y. Shadmi, Phys. Rev. **D53** 1264 (1996).

[8] See, *eg.* C. D. Carone, H. Murayama, Phys. Rev. Lett. **74** 3122 (1995).

[9] SLD Design Report, SLAC Report 273 (1984).

[10] K. Abe *et al.*, Phys. Rev. **D56** 5310 (1997).

[11] C. J. S. Damerell *et al.*, Nucl. Inst. Meth. **A288** 236 (1990); K. Abe *et al.*, Nucl. Inst. Meth. **A400** 287 (1997).

[12] K. Abe *et al.*, Phys. Rev. **D53** 1023 (1996).

[13] S. Catani *et al.*, Phys. Lett. **B263** 491 (1991).

[14] D. J. Jackson, Nucl. Inst. Meth. **A388** 247 (1997).

[15] K. Abe *et al.*, Phys. Rev. Lett. **84** 4300 (2000).

[16] SLD Collab, K. Abe *et al.*, Phys. Rev. Lett. **81** 942 (1998).

[17] T. Sjöstrand, Computer Phys. Commun. **82** 74 (1994).

[18] SLD Collab, K. Abe *et al.*, Phys. Rev. Lett. **80** 660 (1998).

[19] G. Marchesini *et al.*, Comput. Phys. Commun. **67**, 465 (1992).

[20] O.M. Ogreid, Cand. Scient. Thesis, Univ. of Bergen (1993); P. Osland, private communications.

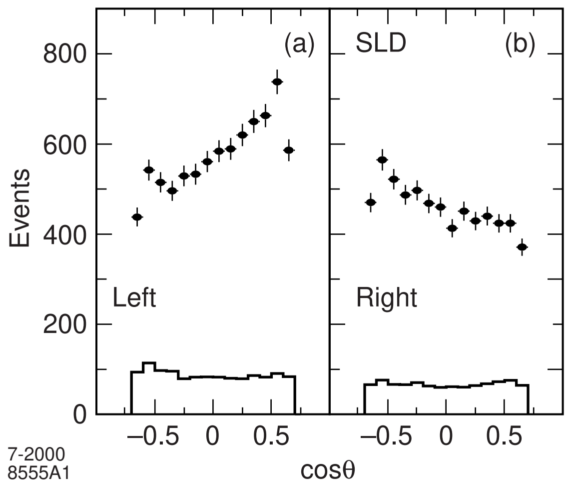

Figure 1. Polar-angle distribution of the signed-thrust axis direction (see text) for (a) left- and (b) right-handed electron beam. The histograms represent the simulated backgrounds.

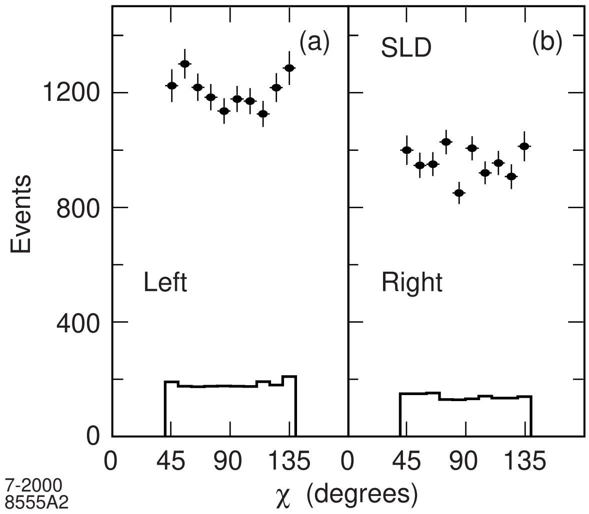

Figure 2. As Fig. 1, for the azimuthal-angle distribution (see text).

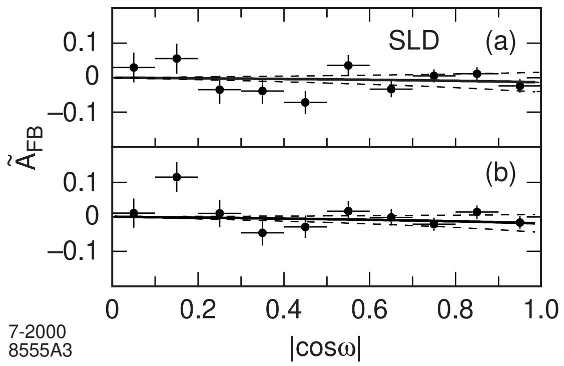

Figure 3. Left-right forward-backward asymmetry in $\cos\omega$ (see text) for (a) CP-even case, and (b) CP-odd case. The solid curve is the best fit to the data sample, and the dashed curves correspond to the 95% C.L. limits.