SLAC-PUB-8302
OUNP-99-14
October 1999

Searches for Anomalous Effects in the $b\bar{b}g$ Coupling**

P N Burrows†

*Representing the SLD Collaboration**
Stanford Linear Accelerator Center,
Stanford University, Stanford, CA 94309

Abstract

The unique SLD CCD vertex detector combined with the highly-polarised electron beam allow us to search for an anomalous chromomagnetic coupling of the b-quark, as well as P-odd, T_N-odd and CP-odd processes at the $b\bar{b}g$ vertex.

Talk presented at the International Europhysics Conference on High Energy Physics, Tampere, Finland, 15-21 July 1999.

† Particle & Nuclear Physics, Keble Rd., Oxford, OX1 3RH, UK; E-mail: p.burrows@physics.ox.ac.uk. Supported by the UK Particle Physics & Astronomy Research Council

** Work supported by Department of Energy contract DE-AC03-76SF00515 (SLAC).

1 Introduction

One expects new high-mass-scale dynamics to couple preferentially to the massive third-generation fermions. The study of $e^+e^- \to b\bar{b}$ events is hence of considerable interest. Using inclusive $Z^0 \to b\bar{b}$ decays one can measure $R_b = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to q\overline{q})$ and the Z^0-b parity-violating coupling A_b. In recent years several reported determinations of these quantities have differed from Standard Model (SM) expectations at the few σ level, arousing considerable interest and speculation. Currently R_b is in good agreement with the SM, whereas A_b appears to be about 2.5σ low [1].

We have therefore investigated in detail the strong-interaction dynamics of the b-quark. We have compared the strong coupling of the gluon to b-quarks with that to light- and charm-quarks [2] and found all couplings to be equal to within the experimental sensitivity of a few per cent. We have also studied the structure of 3-jet $b\overline{b}g$ events [3], as well as tested parity (P) and charge$\oplus$parity (CP) conservation at the $b\overline{b}g$ vertex; here we present a preliminary update of the latter two measurements using a data sample more than 3 times larger. Full details can be found in [4, 5].

We used roughly 550,000 hadronic Z^0 decays recorded between 1993 and 1998 in the SLC Large Detector (SLD). The average magnitude of the electron-beam polarisation was 73%. We applied iterative clustering algorithms to select 3-jet events. In order to improve the energy resolution the jet energies were rescaled kinematically according to the angles between the jet axes, assuming energy and momentum conservation and massless kinematics. The jets were then labelled in order of energy such that $E_1 > E_2 > E_3$.

2 $b\overline{b}g$ Observables and Tagging Strategy

We considered the following $b\overline{b}g$ observables:

• the scaled gluon energy, $x_g = E_{gluon}/E_{beam}$, to test for anomalous $b\overline{b}g$ couplings, and the gluon polar angle w.r.t. the e^- beam, θ_g;

• the b-quark polar angle, θ_b, and azimuthal angle, χ (between the b-quark-gluon plane and the b-quark-e^- plane), to test for parity-violation at the $b\overline{b}g$ vertex;

• the polar angle, ω, of the normal to the $b\overline{b}g$ plane to test for T_N-odd final-state interactions. With the normal defined by $\vec{p_{b_i}} \times \vec{p_{b_j}}$ ($|p_{b_i}| > |p_{b_j}|$) the

forward-backward asymmetry of the angular distribution (see section 4) is CP-even; with the normal defined by $\vec{p_b} \times \vec{p_{\bar{b}}}$ it is CP-odd.

In order to define these observables we require two different tagging strategies: 1) which jet is the gluon? *i.e.* we need to tag two jets as being b or $\bar{b}$; 2) which jet is the gluon, and which is the b-quark? *i.e.* we need in addition to distinguish between the b and $\bar{b}$ jets.

In strategy 1 we reconstructed jets using the JADE algorithm with a scaled-invariant-mass criterion $y_{cut} = 0.02$; 126,871 3-jet events were selected. Charged tracks with a large transverse impact parameter (d) w.r.t. the interaction point were used to tag $b\bar{b}g$ events [4]. The flavour tag was based on the number of 'significant' tracks per jet, N_{sig}^{jet}, with $d/\sigma_d \geq 3$. 8196 events were selected in which exactly two jets were b-tagged by requiring each to have $N_{sig}^{jet} \geq 2$ and in which the remaining jet had $N_{sig}^{jet} < 2$ and was hence tagged as the gluon. The efficiency for selecting true $b\bar{b}g$ events is 12%. The inclusive gluon purity of the tagged-jet sample is 93%.

In strategy 2 we reconstructed jets using the Durham algorithm and y_{cut} = 0.005; roughly 75,000 3-jet events were selected. A topological algorithm was applied to the set of tracks in each jet to search for a secondary decay vertex. An event was selected as $b\bar{b}g$ if at least one jet contained a vertex with invariant mass larger than 1.5 GeV/c^2 [5]. 14,658 events satisfied this requirement. With the new SLD VXD this selection is 84% efficient for identifying a sample of $b\bar{b}g$ events with 84% purity, and containing 14% $c\bar{c}g$ and 2% light-flavor backgrounds. Jet 1 was chosen as the gluon jet only if it contained no significant track and both jets 2 and 3 contained at least one such track. Jet 2 was chosen as the gluon jet if it contained no significant track and jet 3 contained at least one significant track. Otherwise jet 3 was tagged as the gluon. The momentum-weighted charge was calculated for each 'b' jet; if the difference in charge, $Q_i - Q_j$, was negative (positive) jet i was tagged as the b-jet ($\bar{b}$-jet). The probability of correctly identifying the b-jet charge is 68%.

3 Anomalous $b\bar{b}g$ Chromomagnetic Coupling

We formed the distributions of x_g and θ_g. The non-$b\bar{b}g$-event backgrounds were subtracted, and the distributions were corrected for the efficiency for accepting true $b\bar{b}g$ events into the tagged sample, as well as for bin-to-bin

migrations caused by hadronisation, the resolution of the detector, and bias of the jet-tagging technique. Fig. 1 shows the fully-corrected normalised distributions.

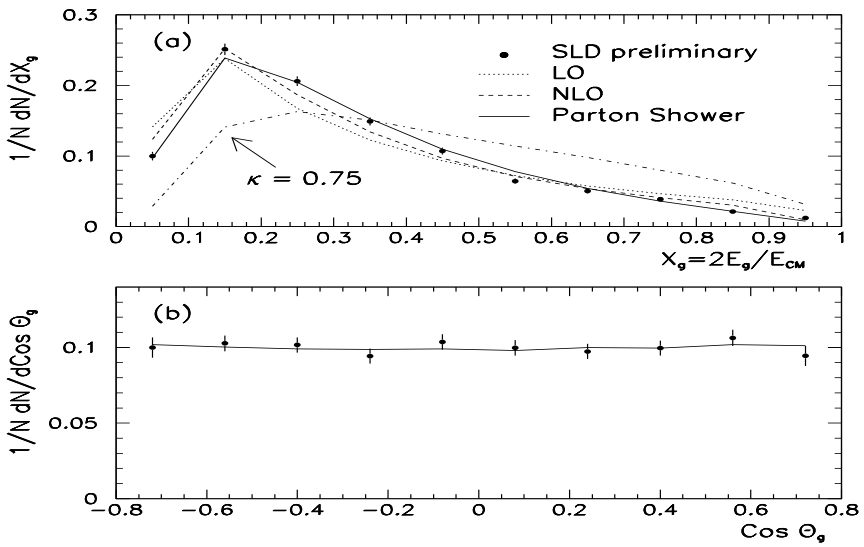

Figure 1: (a) x_g, (b) $\cos\theta_g$ (dots); errors are statistical. PQCD predictions (see text) are also shown.

We compared the data with PQCD predictions for the same jet algorithm and y_c value. We used leading-order (LO) and NLO results based on recent calculations [6] in which quark mass effects were explicitly taken into account; a b-mass value of $m_b(m_Z) = 3\mathrm{GeV}/c^2$ was used. We also derived these distributions using the 'parton shower' (PS) implemented in JETSET 7.4. The calculations reproduce the measured $\cos\theta_g$ distribution, which is insensitive to the details of higher-order soft parton emission. For x_g, although the LO calculation reproduces the main features of the shape of the distribution, it yields too few events in the region $0.2 < x_g < 0.5$, and too many events for $x_g < 0.1$ and $x_g > 0.5$. The NLO calculation is noticeably better, but also shows a deficit for $0.2 < x_g < 0.4$. The PS calculation describes the data across the full x_g range. This suggests that multiple orders of parton radiation need to be included. We conclude that PQCD in the PS approximation accurately reproduces the gluon distributions in $b\bar{b}g$ events.

In QCD the quark chromomagnetic moment is induced at the one-loop level and is of order α_s/π. A more general $b\overline{b}g$ Lagrangian term with a modified coupling may be written:

$$\mathcal{L}^{b\overline{b}g} = g_s \overline{b} T_a \{\gamma_\mu + \frac{i\sigma_{\mu\nu}k^\nu}{2m_b}(\kappa - i\tilde{\kappa}\gamma_5)\} b G_a^\mu$$

where κ and $\tilde{\kappa}$ parameterize the anomalous chromomagnetic and chromoelectric moments, respectively, which might arise from physics beyond the SM. The effects of $\tilde{\kappa}$ are sub-leading w.r.t. those of κ, so for convenience we set $\tilde{\kappa}$ to zero. A non-zero κ would modify the x_g distribution in $b\overline{b}g$ events relative to the standard QCD case. In each x_g bin we parametrised the LO κ dependence and added it to the PS calculation. A χ^2 minimisation fit was performed to the data, yielding $\kappa = -0.011 \pm 0.048(\text{stat.})^{+0.013}_{-0.003}(\text{syst.})$. This corresponds to 95% c.l. limits of $-0.11 < \kappa < 0.08$ (preliminary).

4 Tests of Parity Violation at the $b\overline{b}g$ Vertex

New tests of parity-violation in strong interactions have recently been proposed using polarized $e^+e^- \to q\overline{q}g$ events [7]. The quark polar-angle distribution can be written:

$$\frac{d\sigma}{d\cos\theta_b} \propto (1 - P_e A_e)(1 + \alpha\cos^2\theta_b) + 2A_P(P_e - A_e)\cos\theta_b$$

where P_e is the electron polarisation, A_e (A_f) is the parity-violating electroweak coupling of the Z^0 to the initial (final) state, given by $A_i = 2v_i a_i/(v_i^2 + a_i^2)$ in terms of the vector v_i and axial-vector a_i couplings, and A_P characterizes the degree of parity violation. One can write $A_P = A_f \cdot A_\theta^{QCD}$, where the second factor modulates the electroweak parity violation and can be calculated in QCD. Similarly, for the azimuthal angle χ:

$$\frac{d\sigma}{d\chi} \propto (1 - P_e A_e)(1 + \beta\cos 2\chi) - \frac{\pi}{2}A'_P(P_e - A_e)\cos\chi$$

and $A'_P = A_f \cdot A_\chi^{QCD}$. Given the SM value $A_b \simeq 0.935$, measurement of A_P and A'_P in $Z^0 \to b\overline{b}g$ events allows one to test the QCD prediction for A_θ^{QCD} and A_χ^{QCD}.

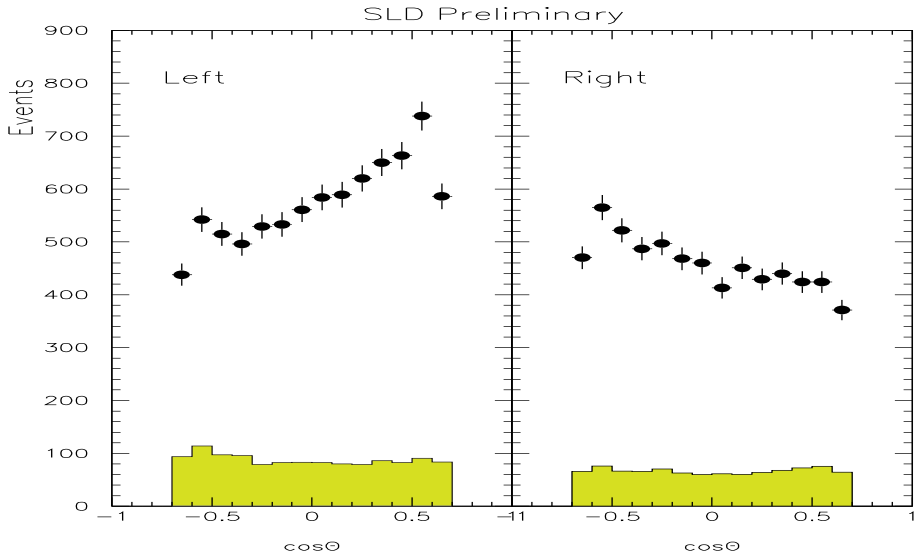

Figure 2: Distributions of $\cos\theta_b$ (dots) for (a) left- and (b) right-handed polarised electrons.

Fig. 2 shows the observed $\cos\theta_b$ distributions. The shaded histograms show the estimated backgrounds, evaluated using JETSET, which are mostly $c\bar{c}g$ events. A maximum likelihood fit yields A_θ^{QCD}=0.906 $\pm$ 0.052 $\pm$ 0.064 (prelim.), consistent with the O(α_s^2) expectation of 0.93, evaluated using JETSET. The χ distribution is shown in Fig. 3. A corresponding fit yields $A_\chi^{QCD} = -0.014 \pm 0.035 \pm 0.002$ (prelim.), to be compared with the O(α_s^2) expectation of -0.064. The asymmetry parameters are consistent with the expected degree of parity violation in the SM, and we see no evidence for any anomalous effects.

5 T_N-odd Final-State Interactions

Consider the polar angle, ω, of the normal to the $b\bar{b}g$ plane. In PQCD one expects:

$$\frac{d\sigma}{d\cos\omega} \propto (1 - P_e A_e)(1 + \gamma\cos^2\omega) + 2A_T(P_e - A_e)\cos\omega$$

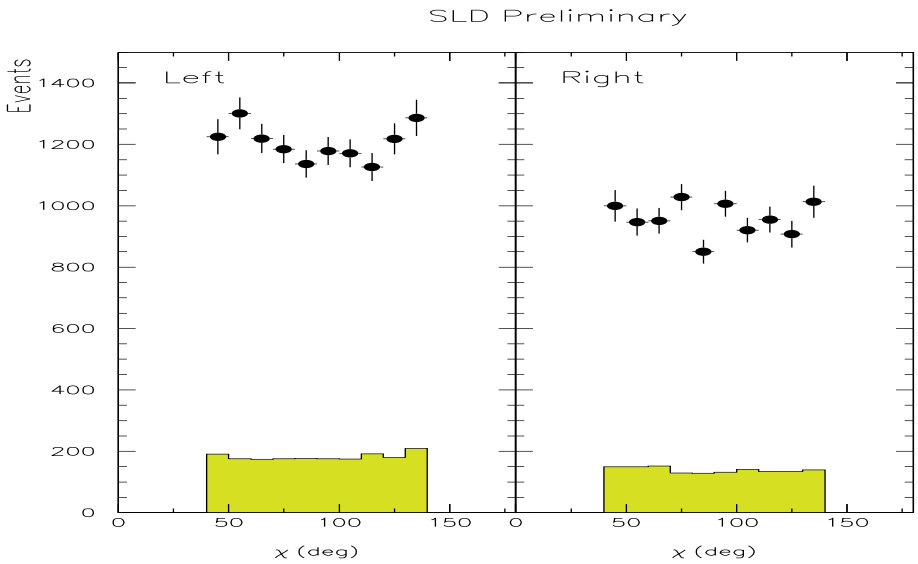

Figure 3: Distributions of χ (dots) for (a) left- and (b) right-handed polarised electrons.

Taking the left-right forward-backward asymmetry projects out the cosω term. This term is proportional to the triple product $\vec{\sigma}_Z \cdot (\vec{p_{b_i}} \times \vec{p_{b_j}})$, where $\vec{\sigma}_Z$ is the Z^0 polarization vector. When the vector product is ordered by jet momentum the term is T_N-odd and CP-even ("A_T^+"). Since the true time-reversed experiment is not performed non-zero contributions can arise from final-state interactions in the SM. A 1-loop SM calculation [8] shows that A_T^+ is largest for $b\bar{b}g$ events, but is only $\sim 10^{-5}$. We have previously set limits on A_T^+ using events of all flavours [9]. When the vector product is ordered by flavour, *i.e.* $\vec{p_b} \times \vec{p_{\bar{b}}}$ the cosω term is both T_N-odd and CP-odd ("A_T^-").

For tagged $b\bar{b}g$ events our measured left-right forward-backward asymmetries in the CP-even and odd cases are shown in Fig. 4. They are both consistent with zero and we set 95% c.l. limits on T_N-odd asymmetries of $-0.038 < A_T^+ < 0.014$ and $-0.077 < A_T^- < 0.011$, respectively (prelim.).

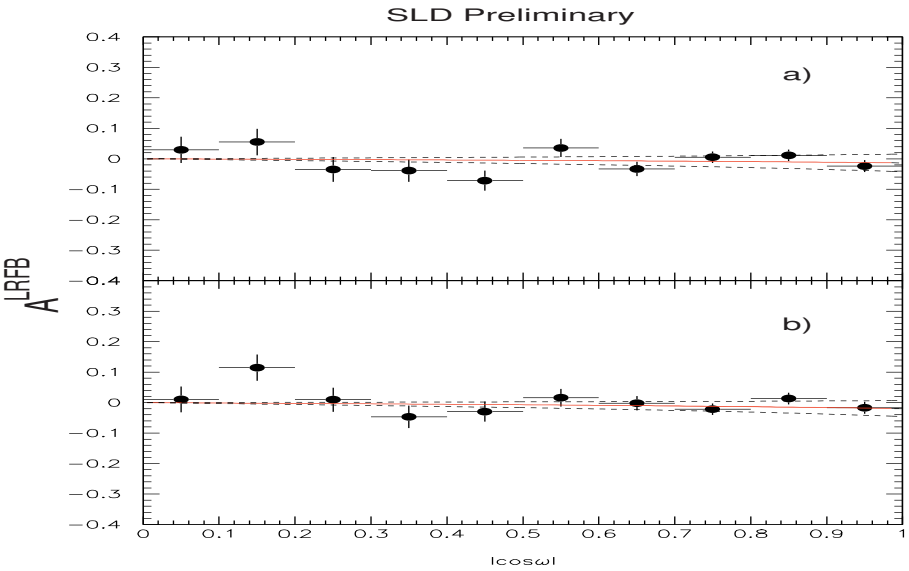

Figure 4: Left-right-forward-backward asymmetry vs. $|\cos\omega|$ for (a) CP-even, (b) CP-odd cases. In each case the solid curve is the best fit, and the dashed curves correspond to the 95% c.l. limits.

References

[1] J. Mnich, these proceedings.

[2] SLD Collab., Phys. Rev. **D59** (1999) 012002.

[3] SLD Collab., SLAC-PUB-7920; to appr. PRD.

[4] SLD Collab., SLAC-PUB-8155; contr. paper.

[5] SLD Collab., SLAC-PUB-8156; contr. paper.

[6] A. Brandenburg, P. Uwer, Nucl. Phys. **B515** 279.

[7] P. N. Burrows, P. Osland, Phys. Lett. **B400** 385.

[8] A. Brandenburg *et al.*, Phys. Rev. **D53** 1264.

[9] SLD Collab., Phys. Rev. Lett. **75** 4173.

∗ **List of Authors**

Kenji Abe,[21] Koya Abe,[33] T. Abe,[29] I. Adam,[29] T. Akagi,[29]
H. Akimoto,[29] N.J. Allen,[5] W.W. Ash,[29] D. Aston,[29] K.G. Baird,[17]
C. Baltay,[40] H.R. Band,[39] M.B. Barakat,[16] O. Bardon,[19]
T.L. Barklow,[29] G.L. Bashindzhagyan,[20] J.M. Bauer,[18] G. Bellodi,[23]
A.C. Benvenuti,[3] G.M. Bilei,[25] D. Bisello,[24] G. Blaylock,[17]
J.R. Bogart,[29] G.R. Bower,[29] J.E. Brau,[22] M. Breidenbach,[29]
W.M. Bugg,[32] D. Burke,[29] T.H. Burnett,[38] P.N. Burrows,[23]
R.M. Byrne,[19] A. Calcaterra,[12] D. Calloway,[29] B. Camanzi,[11]
M. Carpinelli,[26] R. Cassell,[29] R. Castaldi,[26] A. Castro,[24]
M. Cavalli-Sforza,[35] A. Chou,[29] E. Church,[38] H.O. Cohn,[32]
J.A. Coller,[6] M.R. Convery,[29] V. Cook,[38] R.F. Cowan,[19]
D.G. Coyne,[35] G. Crawford,[29] C.J.S. Damerell,[27] M.N. Danielson,[8]
M. Daoudi,[29] N. de Groot,[4] R. Dell'Orso,[25] P.J. Dervan,[5]
R. de Sangro,[12] M. Dima,[10] D.N. Dong,[19] M. Doser,[29] R. Dubois,[29]
B.I. Eisenstein,[13] I.Erofeeva,[20] V. Eschenburg,[18] E. Etzion,[39]
S. Fahey,[8] D. Falciai,[12] C. Fan,[8] J.P. Fernandez,[35] M.J. Fero,[19]
K. Flood,[17] R. Frey,[22] J. Gifford,[36] T. Gillman,[27] G. Gladding,[13]
S. Gonzalez,[19] E.R. Goodman,[8] E.L. Hart,[32] J.L. Harton,[10]
K. Hasuko,[33] S.J. Hedges,[6] S.S. Hertzbach,[17] M.D. Hildreth,[29]
J. Huber,[22] M.E. Huffer,[29] E.W. Hughes,[29] X. Huynh,[29] H. Hwang,[22]
M. Iwasaki,[22] D.J. Jackson,[27] P. Jacques,[28] J.A. Jaros,[29]
Z.Y. Jiang,[29] A.S. Johnson,[29] J.R. Johnson,[39] R.A. Johnson,[7]
T. Junk,[29] R. Kajikawa,[21] M. Kalelkar,[28] Y. Kamyshkov,[32]
H.J. Kang,[28] I. Karliner,[13] H. Kawahara,[29] Y.D. Kim,[30] M.E. King,[29]
R. King,[29] R.R. Kofler,[17] N.M. Krishna,[8] R.S. Kroeger,[18]
M. Langston,[22] A. Lath,[19] D.W.G. Leith,[29] V. Lia,[19] C.Lin,[17]
M.X. Liu,[40] X. Liu,[35] M. Loreti,[24] A. Lu,[34] H.L. Lynch,[29] J. Ma,[38]
M. Mahjouri,[19] G. Mancinelli,[28] S. Manly,[40] G. Mantovani,[25]
T.W. Markiewicz,[29] T. Maruyama,[29] H. Masuda,[29] E. Mazzucato,[11]
A.K. McKemey,[5] B.T. Meadows,[7] G. Menegatti,[11] R. Messner,[29]
P.M. Mockett,[38] K.C. Moffeit,[29] T.B. Moore,[40] M.Morii,[29]
D. Muller,[29] V. Murzin,[20] T. Nagamine,[33] S. Narita,[33]
U. Nauenberg,[8] H. Neal,[29] M. Nussbaum,[7] N. Oishi,[21]
D. Onoprienko,[32] L.S. Osborne,[19] R.S. Panvini,[37] C.H. Park,[31]
T.J. Pavel,[29] I. Peruzzi,[12] M. Piccolo,[12] L. Piemontese,[11]
K.T. Pitts,[22] R.J. Plano,[28] R. Prepost,[39] C.Y. Prescott,[29]
G.D. Punkar,[29] J. Quigley,[19] B.N. Ratcliff,[29] T.W. Reeves,[37]

J. Reidy,[18] P.L. Reinertsen,[35] P.E. Rensing,[29] L.S. Rochester,[29]
P.C. Rowson,[9] J.J. Russell,[29] O.H. Saxton,[29] T. Schalk,[35]
R.H. Schindler,[29] B.A. Schumm,[35] J. Schwiening,[29] S. Sen,[40]
V.V. Serbo,[29] M.H. Shaevitz,[9] J.T. Shank,[6] G. Shapiro,[15]
D.J. Sherden,[29] K.D. Shmakov,[32] C. Simopoulos,[29] N.B. Sinev,[22]
S.R. Smith,[29] M.B. Smy,[10] J.A. Snyder,[40] H. Staengle,[10] A. Stahl,[29]
P. Stamer,[28] H. Steiner,[15] R. Steiner,[1] M.G. Strauss,[17] D. Su,[29]
F. Suekane,[33] A. Sugiyama,[21] S. Suzuki,[21] M. Swartz,[14] A. Szumilo,[38]
T. Takahashi,[29] F.E. Taylor,[19] J. Thom,[29] E. Torrence,[19]
N.K. Toumbas,[29] T. Usher,[29] C. Vannini,[26] J. Va'vra,[29] E. Vella,[29]
J.P. Venuti,[37] R. Verdier,[19] P.G. Verdini,[26] D.L. Wagner,[8]
S.R. Wagner,[29] A.P. Waite,[29] S. Walston,[22] S.J. Watts,[5]
A.W. Weidemann,[32] E. R. Weiss,[38] J.S. Whitaker,[6] S.L. White,[32]
F.J. Wickens,[27] B. Williams,[8] D.C. Williams,[19] S.H. Williams,[29]
S. Willocq,[17] R.J. Wilson,[10] W.J. Wisniewski,[29] J. L. Wittlin,[17]
M. Woods,[29] G.B. Word,[37] T.R. Wright,[39] J. Wyss,[24]
R.K. Yamamoto,[19] J.M. Yamartino,[19] X. Yang,[22] J. Yashima,[33]
S.J. Yellin,[34] C.C. Young,[29] H. Yuta,[2] G. Zapalac,[39] R.W. Zdarko,[29]
J. Zhou.[22]

(The SLD Collaboration)

[1]*Adelphi University, Garden City, New York 11530,*
[2]*Aomori University, Aomori , 030 Japan,*
[3]*INFN Sezione di Bologna, I-40126, Bologna, Italy,*
[4]*University of Bristol, Bristol, U.K.,*
[5]*Brunel University, Uxbridge, Middlesex, UB8 3PH United Kingdom,*
[6]*Boston University, Boston, Massachusetts 02215,*
[7]*University of Cincinnati, Cincinnati, Ohio 45221,*
[8]*University of Colorado, Boulder, Colorado 80309,*
[9]*Columbia University, New York, New York 10533,*
[10]*Colorado State University, Ft. Collins, Colorado 80523,*
[11]*INFN Sezione di Ferrara and Universita di Ferrara, I-44100 Ferrara, Italy,*
[12]*INFN Lab. Nazionali di Frascati, I-00044 Frascati, Italy,*
[13]*University of Illinois, Urbana, Illinois 61801,*
[14]*Johns Hopkins University, Baltimore, Maryland 21218-2686,*
[15]*Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720,*

[16] *Louisiana Technical University, Ruston,Louisiana 71272,*
[17] *University of Massachusetts, Amherst, Massachusetts 01003,*
[18] *University of Mississippi, University, Mississippi 38677,*
[19] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139,*
[20] *Institute of Nuclear Physics, Moscow State University, 119899, Moscow Russia,*
[21] *Nagoya University, Chikusa-ku, Nagoya, 464 Japan,*
[22] *University of Oregon, Eugene, Oregon 97403,*
[23] *Oxford University, Oxford, OX1 3RH, United Kingdom,*
[24] *INFN Sezione di Padova and Universita di Padova I-35100, Padova, Italy,*
[25] *INFN Sezione di Perugia and Universita di Perugia, I-06100 Perugia, Italy,*
[26] *INFN Sezione di Pisa and Universita di Pisa, I-56010 Pisa, Italy,*
[27] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX United Kingdom,*
[28] *Rutgers University, Piscataway, New Jersey 08855,*
[29] *Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309,*
[30] *Sogang University, Seoul, Korea,*
[31] *Soongsil University, Seoul, Korea 156-743,*
[32] *University of Tennessee, Knoxville, Tennessee 37996,*
[33] *Tohoku University, Sendai 980, Japan,*
[34] *University of California at Santa Barbara, Santa Barbara, California 93106,*
[35] *University of California at Santa Cruz, Santa Cruz, California 95064,*
[36] *University of Victoria, Victoria, British Columbia, Canada V8W 3P6,*
[37] *Vanderbilt University, Nashville,Tennessee 37235,*
[38] *University of Washington, Seattle, Washington 98105,*
[39] *University of Wisconsin, Madison,Wisconsin 53706,*
[40] *Yale University, New Haven, Connecticut 06511.*