SLAC-PUB-7234
ICHEP-96 PA07-063
July 22, 1996

Measurement of the Z^0-Lepton Coupling Asymmetries A_l *

The SLD Collaboration**

Abstract

We present a direct measurements of the Z^0-lepton coupling asymmetries, A_e, A_μ, and A_τ. It is based on a data sample selected from 170k Z^0 decays collected by the SLD detector. The Z's are produced by collisions of polarized e^- with unpolarized e^+ bunches at SLC. The couplings are extracted from the measurement of the left-right forward-backward asymmetry for each lepton species. The preliminary results (using information from all leptonic data for A_e) are: $A_e = 0.148 \pm 0.016$, $A_\mu = 0.102 \pm 0.033$ and $A_\tau = 0.190 \pm 0.034$.

Paper Contributed to the XXVIII International Conference on High Energy Physics, July/96, Warsaw, Poland

*This work was supported by Department of Energy contracts: DE-FG02-91ER40676 (BU), DE-FG03-92ER40701 (CIT), DE-FG03-91ER40618 (UCSB), DE-FG03-92ER40689 (UCSC), DE-FG03-93ER40788 (CSU), DE-FG02-91ER40672 (Colorado), DE-FG02-91ER40677 (Illinois), DE-AC03-76SF00098 (LBL), DE-FG02-92ER40715 (Massachusetts), DE-AC02-76ER03069 (MIT), DE-FG06-85ER40224 (Oregon), DE-AC03-76SF00515 (SLAC), DE-FG05-91ER40627 (Tennessee), DE-AC02-76ER00881 (Wisconsin), DE-FG02-92ER40704 (Yale); National Science Foundation grants: PHY-91-13428 (UCSC), PHY-89-21320 (Columbia), PHY-92-04239 (Cincinnati), PHY-88-17930 (Rutgers), PHY-88-19316 (Vanderbilt), PHY-92-03212 (Washington); the UK Science and Engineering Research Council (Brunel and RAL); the Istituto Nazionale di Fisica Nucleare of Italy (Bologna, Ferrara, Frascati, Pisa, Padova, Perugia); and the Japan-US Cooperative Research Project on High Energy Physics (Nagoya, Tohoku).

1 Introduction

Production of the vector Z boson in electron-positron collisions requires the longitudinal spin projections of the electron and positron to be parallel. The two configurations with non-zero Z production cross section are shown in figure 1). The couplings of the Z boson to the fermions are parity violating, so the Z production cross sections for figures 1a) and 1b) are not equal. By convention figure 1a) is referred to as the 'Left handed' cross section since it contains a left handed electron; figure 1b) is called 'Right handed'. In addition to the asymmetry in Z production cross section (called A_{LR}, the Left-Right Asymmetry) the parity-violating Z couplings to fermions also produce asymmetries in the angular distributions of the Z decay products with respect to the production axis.

In this paper we report on measurements of production and decay asymmetries of $Z^0 \rightarrow \mu^+\mu^-, \tau^+\tau^-$ made by the SLD collaboration at the Stanford Linear Accelerator Center. The SLAC Linear Collider (SLC) produces Z bosons at the center of the SLD detector in e^+e^- collisions with a polarized electron beam. The data were collected during the 1993 (63% polarization, $5 \cdot 10^4 Z$'s analyzed) and 1994-5 (77% polarization, $1 \cdot 10^5 Z$'s analyzed) runs of the SLC.

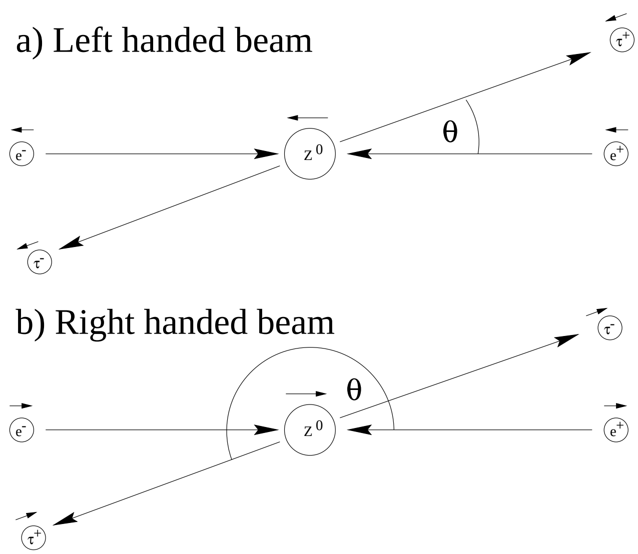

Figure 1: Electron helicities in Z production. a) shows the Left cross section and b) the Right cross section. Long arrows represent the lepton momentum; short arrows indicate the longitudinal spin projections.

The SLC collides unpolarized positron bunches with polarized electron bunches at center of mass energy at the peak of the Z resonance. The SLD detector [1] and the SLC machine [2] have been described elsewhere.

2 Extracting Asymmetry Parameters

The main terms in the cross section for polarized production of a pair of leptons at the Z resonance are

$$\frac{d\sigma}{dx} \propto (1 + PA_e)(1 + x^2) + (P + A_e)A_l 2x \quad (x = \cos\theta) \tag{1}$$

where A_l is the Z coupling parameter for lepton l (itself a function of the vector and axial-vector couplings of lepton l to the Z), P is the electron beam polarization, and x =cos θ, where θ is the angle of Z decay axis with respect to the beam electron direction. The relevant information for extracting the Z coupling parameters from the SLD polarized asymmetries is contained in equation(1). For the forward-backward asymmetries we must measure cos θ. Events with cos $\theta < 0$ will be called 'backward' events, 'forward' events have cos $\theta > 0$. The sign of the polarization is switched randomly on each beam pulse; during 1994-5 running half the data were taken with $P = -0.77$ and half with $P = 0.77$.

2.1 The Left-Right Asymmetry

The left-right asymmetry measures the difference in Z production for the right and left polarized electron beams. Using a symmetric range in polar angle the asymmetry is

$$A_{LR} = \frac{N_L - N_R}{N_L + N_R} = P \cdot A_e$$

where $N_L(N_R)$ is the number of Z's produced using the left (right) handed electron beam. SLD's main A_{LR} analysis that accepts mostly hadronic Z decays is described elsewere [3]. This analysis uses A_{LR} in the tau and muon final state sample to measure A_e.

To extract A_e from A_{LR} it is necessary to measure the e^- beam polarization This is done with the Compton polarimeter [4] which (consisting basically of a bending magnet and a Cerenkov electron detector) measures beam electrons scattered from photons from a YAG laser which collide head-on with the polarized electron beam after it passes through the SLD detector. The Compton scattering cross section (and thus the scattered electron energy) depends on the relative spin directions of the electron and photon and this effect is exploited to extract the electron beam polarization given a measured laser polarization. Polarization measurements are made continually during running; accurate beam polarization measurements are available about every 10 minutes. The uncertainty in the polarization is thus virtually all systematic. Major contributions to the systematic error in the polarization measurement for the 1994-5 run were from detector linearity, internal cross checks, and the analyzing power of the Cerenkov detector. The preliminary polarization measurement for the 1994-5 run is $P = 77.23 \pm 0.52\%$.

2.2 Polarized Forward-Backward Asymmetries

The polarized forward-backward asymmetry is a double asymmetry which can be formed by taking the difference in the number of forward and backward events for left and right beam polarization data samples. The asymmetry can be written, with obvious subscripts,

$$\tilde{A}_{FB}^{l} = \frac{(N_{LF} - N_{LB}) - (N_{RF} - N_{RB})}{(N_{LF} + N_{LB}) + (N_{RF} + N_{RB})} \tag{2}$$

Using the full range in cos θ, equations 1 and 2 give

$$\tilde{A}_{FB}^{l} = \frac{3}{4} P A_l \tag{3}$$

illustrating how the final state lepton coupling can be extracted from the data. The Left-Right Asymmetry of these same events is also used to extract the initial electron-Z coupling parameter. In practice for the muon and tau final states events are reconstructed and accepted for analysis only within $|\cos\theta| < 0.7$ since SLD trigger and reconstruction efficiencies drop quickly outside that range (A geometric factor also appears in equation (3)). Additionally, instead of counting events as suggested by equation (2), a maximum likelihood fit is performed, event by event using equation (1), to determine simultaneously A_e and A_μ with the mu-pair events (or A_e and A_τ using the tau- pair events). The maximum likelihood fit is less sensitive to detector acceptance as a function of polar angle than the counting method, and it is a bit more powerful statistically.The preliminary results for A_e, A_μ and A_τ are

$$A_e = 0.148 \pm 0.016$$

$$A_\mu = 0.102 \pm 0.033$$

$$A_\tau = 0.190 \pm 0.034$$

3 Event Selection

Leptonic decays of the Z are characterized by low charged multiplicity and two back-to-back jets containing the leptons (or in the case of the tau pair events, the tau decay products). This analysis relies entirely on the charged track reconstruction and the measurement of the energies in the liquid argon calorimeter (LAC) associated with the tracks. A pre-selection for muons and taus requires events to have between 2 and 8 (inclusive) charged tracks, each of which must pass within 1 cm of the nominal e^+e^- interaction point. This excludes most hadronic Z decays, which have an average charged multiplicity around 20. Since the leptons have about 45 GeV energy, there is little problem assigning reconstructed tracks to one of two event hemispheres, corresponding to the two leptons. The product of the sum of the charges of the tracks in each hemisphere is required to be -1 to ensure proper measurement of the sign of the scattering angle. Each event is assigned a polar production angle based on the thrust axis defined by the charged tracks.

Additional requirements are imposed to select $Z \to \mu^+\mu^-$ and $Z \to \tau^+\tau^-$ events and further reduce backgrounds.

3.1 Muon event selection

Events of the type $Z \to \mu^+\mu^-$ are very distinctive and relatively easy to select at SLD. In addition to the preselection, we require the invariant mass of the measured charged tracks to be above 70 GeV. This removes most $Z \to \tau^+\tau^-$ events and virtually all two-photon events and any remaining hadronic Z decays. The majority of events remaining are $Z \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-$. We remove the e^+e^- final state by requiring that the energy deposited in the LAC by the highest momentum track in each hemisphere be less than 10 GeV (but more than 0 GeV to eliminate events with both tracks entering spaces between calorimeter modules). Table (1) summarizes the muon and tau event selections.

3.2 Tau event selection

The tau selection takes the complement of the muon sample and requires the event mass to be less than 70 GeV. Bhabhas are removed by requiring maximum of the energies in the LAC associated to the highest momentum track in each hemisphere be non-zero but below 27.5 GeV. Two-photon events are suppressed by requiring the angle between the momenta of the two hemispheres (as measured by the sum of the charged track momenta in each hemisphere) to be greater than 160^0. Requiring one charged track to have momentum greater than 3 GeV also reduces two-photon background. Remaining background from hadronic Z decays is suppressed by requiring each hemisphere invariant mass (as measured using the charged tracks) to be less than 1.8 GeV.

event sample	backgr. as % of sel. events	eff. in $\|\cos\theta\| < 0.7$	# of selected events
$Z \to \mu^+\mu^-$	0.4% $Z \to \tau^+\tau^-$	95%	1993 run: 1185 1994-5 run: 2603
$Z \to \tau^+\tau^-$	1% e^+e^- 2% $Z \to \mu^+\mu^-$ 0.5% two-photon 0.5% hadrons	89%	1993 run: 1211 1994-5 run: 2537

Table 1: Summary of event selections for $Z \to \mu^+\mu^-$ and $Z \to \tau^+\tau^-$.

4 Systematic Effects

The uncertainty on the beam polarization is correlated among all the measurements and corresponds to an uncertainty on A_l of ± 0.001.

Uncertainties in the amount of background and its effect on the fitted parameters must also be taken into account. For the $Z \to \mu^+\mu^-$ sample background actually has a negligible effect. For the tau sample we have studied specially selected samples of background-rich events from the data. These events were used to approximate the polar angle distribution of the background events which slip into the final samples. Those polar angle distributions were used in toy Monte Carlo to measure the effect of the background on the extraction of the lepton coupling parameters. Background is the dominant systematic in the tau final state.

Another large systematic effect for the tau analysis comes about because we measure not the taus themselves, but their decay products. The longitudinal spin projections of the two taus from Z decay are 100% anti-correlated: one will be left-handed and the other right-handed. So, given the V-A structure of tau decay, the decay products from the τ^+ and the τ^- from a particular Z decay will take their energies from the same set of spectra. For example, if both taus decay to $\pi\nu$, then both pions will generally be low in energy (in the case of a left handed τ^- and right handed τ^+) or both will be generally higher in energy. The effect is strong at SLD because the high beam polarization induces very high tau polarization as a function of polar production angle. And, most importantly, the sign of the polarization is basically opposite for left and right beam events. So a cut on event mass, say, may cause polar angle dependence in selection efficiency for taus which has opposite effect for taus from events produced with the left and right polarized electron beam. Taking all tau decay modes into account, using Monte Carlo simulation, we find an overall shift of $+0.0079 \pm 0.0025$ on A_τ (the value extracted from the fit must be reduced by this amount). A_e is not affected since the overall relative efficiencies for left-beam and right-beam events are not changed much (only the polar angle dependence of the efficiencies are changed).

We have also studied the effect of the uncertainty in the thrust axis determination and the effect of higher order terms in equation(1) that are associated with the photon propagator. We find that their contribution is negligible.

	statistical	polarization	backgr.	τ accept. bias	γ propagator	total
A_e	0.016	0.001	0.002	negl.	0.0005	0.016
A_μ	0.033	0.001	negl.	n.a.	0.0005	0.033
A_τ	0.034	0.001	0.004	0.0025	0.0005	0.034

Table 2: Uncertainties on A_e, A_μ and A_τ in the polarized forward backward asymmetry analysis of Z decays to muons and taus. The first column shows the statistical uncertainties from the fit. The other columns show systematics and the total uncertainties. A_e is measured using both the muon and tau event samples.

Figure (2) shows the cos θ distributions for muon and tau final states for the 1994-5 data. The solid line represents the fit, while the points with error bars show the data in bins of 0.1 in cos θ. The maximum likelihood fit to extract the lepton coupling parameters is performed event-by-event using equation (1).

5 Summary and Combined Preliminary 1993-95 SLD Results on Z-Lepton Couplings

We have presented a measurement of the Z-lepton coupling asymmetries A_e, A_μ, and A_τ using $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$ events. The preliminary results are

$$A_e = 0.148 \pm 0.016$$

$$A_\mu = 0.102 \pm 0.033$$

$$A_\tau = 0.190 \pm 0.034$$

SLD had performed a measurement of A_e using three other techniques [3] [5] [6]. The results are summarized in table (3). The hadronic A_{LR} measurement [3] alone gives the final result $\sin^2\theta_W^{eff} = 0.23060 \pm 0.00050$. The electron, muon, and tau coupling measurements are consistent with lepton universality and the combined preliminary SLD result yields a weak mixing angle measurement of $\sin^2\theta_W^{eff} = 0.23061 \pm 0.00047$. Table (3) summarizes the SLD measurements of lepton-Z couplings, including three results not discussed in this report.

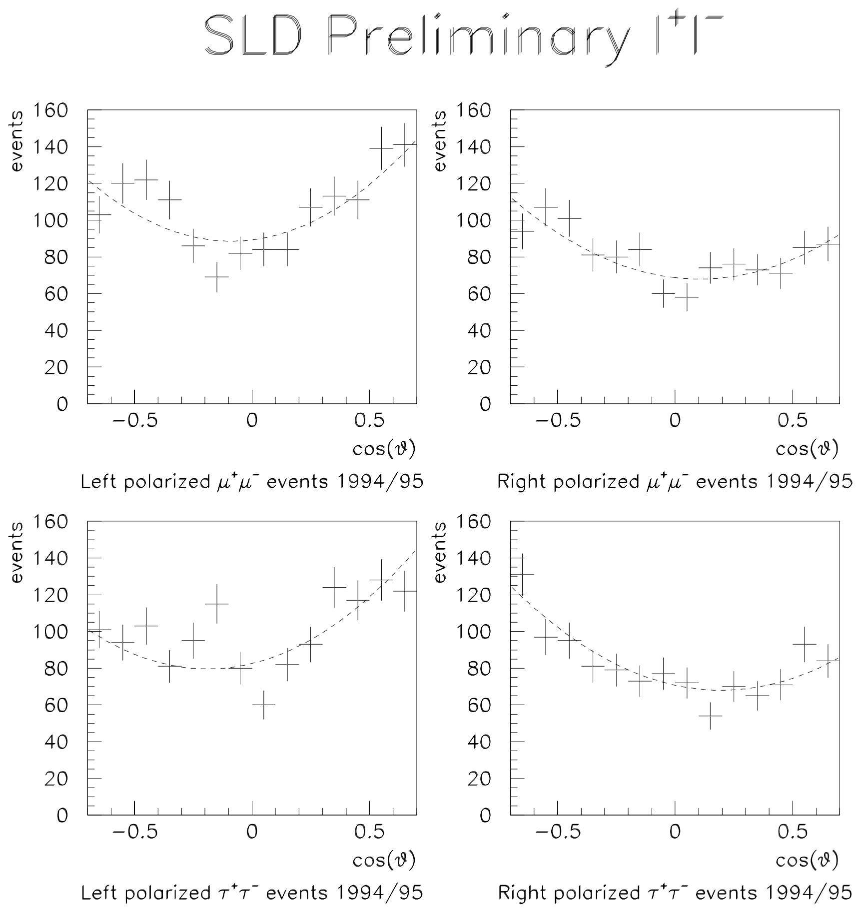

Figure 2: Polar angle distribution for Z decays to muons and taus for the 1994-5 SLD run. The left column shows the distributions for left beam polarization; events produced with the right beam polarization are on the right. The excess of events in the left plots illustrates A_{LR}. The difference in forward backward asymmetries for the left and right plots allows extraction of the final state lepton coupling parameter.

Method	Result
Polarized Muon and Tau Forward-backward Asymmetries	$A_e = 0.148 \pm 0.016$ $A_\mu = 0.102 \pm 0.033$ $A_\tau = 0.190 \pm 0.034$
Left-Right Asymmetry Hadronic A_{LR}	$A_e = 0.1543 \pm 0.0039$
Charge Flow Asymmetry in Hadr. Z decays Q_{LR} [5]	$A_e = 0.162 \pm 0.043$
Polarized Bhabha Scattering (1992-93 data only) [6]	$A_e = 0.202 \pm 0.038$
Combined SLD Preliminary	$A_{e-\mu-\tau} = 0.1542 \pm 0.0037$

Table 3: Summary of SLD results on Z-lepton coupling measurements.

References

[1] SLD Design Report, *SLAC Report No. 273*, 1984, unpublished.

[2] N. Phinney, *Int. J. Mod Phys. A, Proc. Suppl. 2A, 45*, (1993), also see ref. [3] and references therein.

[3] SLD Collaboration, K. Abe, et al., *Phys. Rev. Lett. 73, 25*, (1994)

[4] M. J. Fero, et al., *SLAC-PUB-6423, LBL-35974*

[5] SLD Collaboration, K. Abe, et al .*SLAC-PUB-7069, COLO-HEP-367.*

[6] SLD Collaboration, K. Abe, et al ., *Phys. Rev. Lett.74, 2880*, (1995)

**List of Authors

K. Abe,(19) K. Abe,(29) I. Abt,(13) T. Akagi,(27) N.J. Allen,(4) W.W. Ash,(27)†
D. Aston,(27) K.G. Baird,(24) C. Baltay,(33) H.R. Band,(32) M.B. Barakat,(33)
G. Baranko,(9) O. Bardon,(15) T. Barklow,(27) A.O. Bazarko,(10) R. Ben-David,(33)
A.C. Benvenuti,(2) G.M. Bilei,(22) D. Bisello,(21) G. Blaylock,(6) J.R. Bogart,(27)
B. Bolen,(17) T. Bolton,(10) G.R. Bower,(27) J.E. Brau,(20) M. Breidenbach,(27)
W.M. Bugg,(28) D. Burke,(27) T.H. Burnett,(31) P.N. Burrows,(15) W. Busza,(15)
A. Calcaterra,(12) D.O. Caldwell,(5) D. Calloway,(27) B. Camanzi,(11)
M. Carpinelli,(23) R. Cassell,(27) R. Castaldi,(23)(a) A. Castro,(21)
M. Cavalli-Sforza,(6) A. Chou,(27) E. Church,(31) H.O. Cohn,(28) J.A. Coller,(3)
V. Cook,(31) R. Cotton,(4) R.F. Cowan,(15) D.G. Coyne,(6) G. Crawford,(27)
A. D'Oliveira,(7) C.J.S. Damerell,(25) M. Daoudi,(27) R. De Sangro,(12)
R. Dell'Orso,(23) P.J. Dervan,(4) M. Dima,(8) D.N. Dong,(15) P.Y.C. Du,(28)
R. Dubois,(27) B.I. Eisenstein,(13) R. Elia,(27) E. Etzion,(4) D. Falciai,(22) C. Fan,(9)
M.J. Fero,(15) R. Frey,(20) K. Furuno,(20) T. Gillman,(25) G. Gladding,(13)
S. Gonzalez,(15) G.D. Hallewell,(27) E.L. Hart,(28) J.L. Harton,(8) A. Hasan,(4)
Y. Hasegawa,(29) K. Hasuko,(29) S. J. Hedges,(3) S.S. Hertzbach,(16)
M.D. Hildreth,(27) J. Huber,(20) M.E. Huffer,(27) E.W. Hughes,(27) H. Hwang,(20)
Y. Iwasaki,(29) D.J. Jackson,(25) P. Jacques,(24) J. A. Jaros,(27) A.S. Johnson,(3)
J.R. Johnson,(32) R.A. Johnson,(7) T. Junk,(27) R. Kajikawa,(19) M. Kalelkar,(24)
H. J. Kang,(26) I. Karliner,(13) H. Kawahara,(27) H.W. Kendall,(15) Y. D. Kim,(26)
M.E. King,(27) R. King,(27) R.R. Kofler,(16) N.M. Krishna,(9) R.S. Kroeger,(17)
J.F. Labs,(27) M. Langston,(20) A. Lath,(15) J.A. Lauber,(9) D.W.G.S. Leith,(27)
V. Lia,(15) M.X. Liu,(33) X. Liu,(6) M. Loreti,(21) A. Lu,(5) H.L. Lynch,(27) J. Ma,(31)
G. Mancinelli,(22) S. Manly,(33) G. Mantovani,(22) T.W. Markiewicz,(27)
T. Maruyama,(27) H. Masuda,(27) E. Mazzucato,(11) A.K. McKemey,(4)
B.T. Meadows,(7) R. Messner,(27) P.M. Mockett,(31) K.C. Moffeit,(27)
T.B. Moore,(33) D. Muller,(27) T. Nagamine,(27) S. Narita,(29) U. Nauenberg,(9)

H. Neal,[27] M. Nussbaum,[7] Y. Ohnishi,[19] L.S. Osborne,[15] R.S. Panvini,[30]
H. Park,[20] T.J. Pavel,[27] I. Peruzzi,[12][b] M. Piccolo,[12] L. Piemontese,[11]
E. Pieroni,[23] K.T. Pitts,[20] R.J. Plano,[24] R. Prepost,[32] C.Y. Prescott,[27]
G.D. Punkar,[27] J. Quigley,[15] B.N. Ratcliff,[27] T.W. Reeves,[30] J. Reidy,[17]
P.E. Rensing,[27] L.S. Rochester,[27] P.C. Rowson,[10] J.J. Russell,[27]
O.H. Saxton,[27] T. Schalk,[6] R.H. Schindler,[27] B.A. Schumm,[14] S. Sen,[33]
V.V. Serbo,[32] M.H. Shaevitz,[10] J.T. Shank,[3] G. Shapiro,[14] D.J. Sherden,[27]
K.D. Shmakov,[28] C. Simopoulos,[27] N.B. Sinev,[20] S.R. Smith,[27] M.B. Smy,[8]
J.A. Snyder,[33] P. Stamer,[24] H. Steiner,[14] R. Steiner,[1] M.G. Strauss,[16]
D. Su,[27] F. Suekane,[29] A. Sugiyama,[19] S. Suzuki,[19] M. Swartz,[27]
A. Szumilo,[31] T. Takahashi,[27] F.E. Taylor,[15] E. Torrence,[15] A.I. Trandafir,[16]
J.D. Turk,[33] T. Usher,[27] J. Va'vra,[27] C. Vannini,[23] E. Vella,[27]
J.P. Venuti,[30] R. Verdier,[15] P.G. Verdini,[23] S.R. Wagner,[27] A.P. Waite,[27]
S.J. Watts,[4] A.W. Weidemann,[28] E.R. Weiss,[31] J.S. Whitaker,[3]
S.L. White,[28] F.J. Wickens,[25] D.A. Williams,[6] D.C. Williams,[15]
S.H. Williams,[27] S. Willocq,[33] R.J. Wilson,[8] W.J. Wisniewski,[27]
M. Woods,[27] G.B. Word,[24] J. Wyss,[21] R.K. Yamamoto,[15] J.M. Yamartino,[15]
X. Yang,[20] S.J. Yellin,[5] C.C. Young,[27] H. Yuta,[29] G. Zapalac,[32]
R.W. Zdarko,[27] C. Zeitlin,[20] and J. Zhou,[20]

[1]*Adelphi University, Garden City, New York 11530*
[2]*INFN Sezione di Bologna, I-40126 Bologna, Italy*
[3]*Boston University, Boston, Massachusetts 02215*
[4]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[5]*University of California at Santa Barbara, Santa Barbara, California 93106*
[6]*University of California at Santa Cruz, Santa Cruz, California 95064*
[7]*University of Cincinnati, Cincinnati, Ohio 45221*
[8]*Colorado State University, Fort Collins, Colorado 80523*
[9]*University of Colorado, Boulder, Colorado 80309*
[10]*Columbia University, New York, New York 10027*
[11]*INFN Sezione di Ferrara and Università di Ferrara, I-44100 Ferrara, Italy*
[12]*INFN Lab. Nazionali di Frascati, I-00044 Frascati, Italy*
[13]*University of Illinois, Urbana, Illinois 61801*
[14]*Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*
[15]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[16]*University of Massachusetts, Amherst, Massachusetts 01003*
[17]*University of Mississippi, University, Mississippi 38677*
[19]*Nagoya University, Chikusa-ku, Nagoya 464 Japan*
[20]*University of Oregon, Eugene, Oregon 97403*
[21]*INFN Sezione di Padova and Università di Padova, I-35100 Padova, Italy*
[22]*INFN Sezione di Perugia and Università di Perugia, I-06100 Perugia, Italy*
[23]*INFN Sezione di Pisa and Università di Pisa, I-56100 Pisa, Italy*

[24] *Rutgers University, Piscataway, New Jersey 08855*
[25] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX United Kingdom*
[26] *Sogang University, Seoul, Korea*
[27] *Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[28] *University of Tennessee, Knoxville, Tennessee 37996*
[29] *Tohoku University, Sendai 980 Japan*
[30] *Vanderbilt University, Nashville, Tennessee 37235*
[31] *University of Washington, Seattle, Washington 98195*
[32] *University of Wisconsin, Madison, Wisconsin 53706*
[33] *Yale University, New Haven, Connecticut 06511*
† *Deceased*
[a] *Also at the Università di Genova*
[b] *Also at the Università di Perugia*