SLAC–PUB–7223
August 1996

Tests of QCD with Polarized Electrons*

T. J. Pavel
Representing
The SLD Collaboration†
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

Abstract

We present three measurements that exploit the highly-polarized incident electrons of the SLC facility to probe QCD and the hadronization process. We observe preliminary evidence for leading particle production in hadronic decays of the Z^0 to light-quark pairs. In a high-purity sample of quark jets, the momentum spectra of p, Λ^0, and K^- are harder than those of $\bar{p}$, $\bar{\Lambda}^0$, and K^+, supporting the hypothesis that faster particles in jets are more likely to carry the primary quark or antiquark of the jet. Second, we present an improved limit on jet-handedness, which seeks to measure the transport of quark spin through the hadronization process. Finally, we search for a correlation of the three-jet event orientation with the Z^0 spin direction, which would indicate new physics beyond the Standard model.

Invited talk presented at 31st Recontres de Moriond:
QCD and High Energy Hadronic Interactions
Les Arcs, Savoie, France
March 23–30, 1996

*Work supported in part by Department of Energy contract DE–AC03–76SF00515.
†Members of the SLD collaboration are listed following the references.

1 Introduction

The use of highly-polarized electron beams in e^+e^- collisions provides a valuable tool to probe various aspects of quantum chromodynamics (QCD). We exploit the polarized incident electrons of the SLAC Linear Collider (SLC) with the SLC Large Detector (SLD) in three separate measurements. First, we present measurements of hadronic spectra in Z^0 decays and the observation of a "leading particle effect" in e^+e^- annihilation, in which hadrons containing the initial quark flavor of a jet are enhanced at higher momenta. Second, we present an update of the previous SLD measurement of jet-handedness [1], in which we seek to measure the transport of spin through the hadronization process. Finally, we review a measurement of the correlation of the orientation of the three-jet event plane with the Z^0 spin [2]. Such a correlation is expected to be very small in the Standard Model, and therefore, provides a window on new physics beyond the Standard Model.

2 Hadron Spectra and Leading Particle Effect

Many properties of jets in e^+e^- annihilation are well-described by perturbative methods in QCD. What is not currently understood quantitatively is the process of fragmentation by which partons transform into the "primary" hadrons of a jet. Measurements of the production rates and momentum distributions of identified hadrons in jets are useful for probing this process, since the mass of the primary hadron may influence the dynamics. However, the decays of unstable primary hadrons complicate the interpretation of inclusive measurements. Additional complications arise in jets initiated by heavy quarks, where the leading heavy hadron carries a large fraction of the beam energy, restricting the energy available to other primary particles. Furthermore, heavy hadrons have large decay multiplicities and produce a sizeable fraction of the stable particles in a jet. Therefore, it is of interest to measure hadron production in jets initiated by light-quarks only (*i.e.*, $Z^0 \to u\bar{u}$, $d\bar{d}$, and $s\bar{s}$).

Given the hadron spectra in light-quark events, we can then separate the hadron production in quark and antiquark jets via the large electroweak production asymmetry in polar angle induced by the electron beam polarization. Since we expect the production of hadrons from secondary gluons to be identical in quark and antiquark jets, any differences observed in the quark and antiquark hadron spectra are attributable to hadrons coming from the initial parton of the jet.

These measurements were performed on a sample of $\sim$ 150k hadronic Z^0 decays collected between 1993 and 1995, using the barrel portion ($|\cos\theta| < 0.68$) of the SLD Cherenkov Ring Imaging Detector (CRID) to identify $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$ species [3], and using a conventional V^0 analysis to identify K^0_s and $\Lambda^0/\bar{\Lambda}^0$ decays [4]. Particle identification in the CRID is performed by detection of Cherenkov photons from two radiators and reconstruction of the angles of those photons relative to the incident track. A maximum-likelihood technique [5] allows excellent identification efficiency over most of the available momentum range $0.2 < p < 30$ GeV/c.

For the charged-hadron analysis, a set of hard cuts was applied to tracks in order to ensure that the CRID performance was well-modelled by our simulation. For each momentum bin, the number of observed particles of a given type were related to the true production fraction by an efficiency matrix. This matrix was determined using high-purity samples of pions from K^0_s and τ decays, protons from Λ^0 decays, and a detailed detector simulation. The true fractions were determined by inverting this efficiency matrix and unfolding the measured fractions. We did not constrain the fractions to sum to one; instead, the sum of fractions was used as a consistency check and was found to be in good agreement with unity for the entire momentum range.

Samples of events enriched in light-quark (*uds*) and *b*-quark primary flavors were selected based on the impact parameters, b, of charged tracks with respect to the interaction point in the plane transverse to the beam [6]. For each event, we used as a tagging variable the number n_{sig} of tracks passing a set of quality cuts that have an impact parameter greater than three times its estimated error,

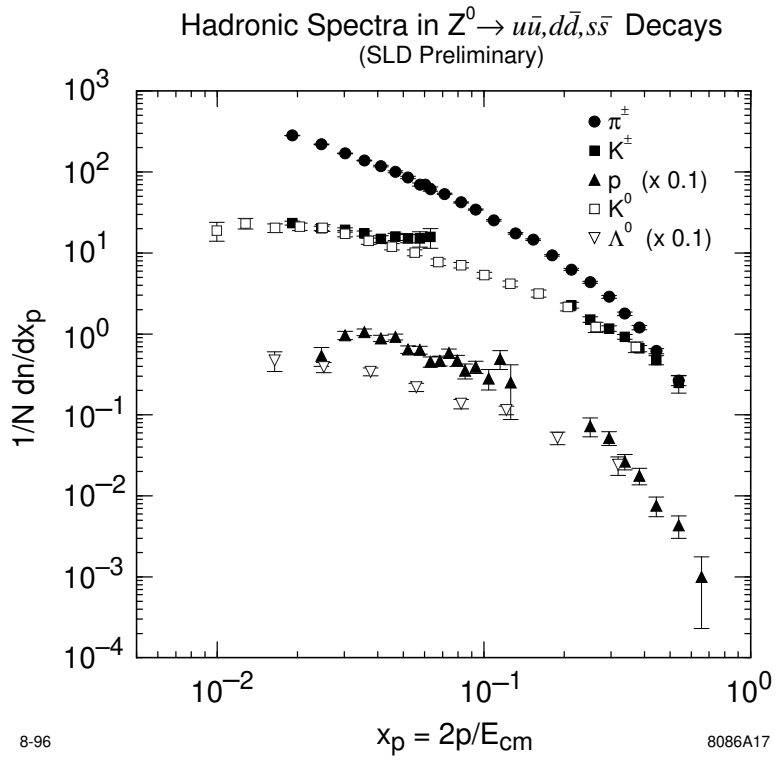

Figure 1: Normalized particle production rates $\mathcal{F}^h(x_p)$ for various hadron species in $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}$ events are shown as a function of scaled momentum $x_p = 2p/\sqrt{s}$.

$b > 3\sigma_b$. Events with $n_{sig} = 0$ were assigned to the light-tagged sample, and those with $n_{sig} \geq 3$ were assigned to the b-tagged sample. The light- and b-tagged samples have purities of 86% and 90%, respectively, as estimated from our Monte Carlo simulation [6].

Production spectra of the five hadronic species were measured in the light- and b-tagged samples, and also in the remaining sample. These rates were unfolded for the tagging purities and biases, and the resulting light-quark spectra $\mathcal{F}^h(x_p)$ are shown in Fig. 1 as a function of scaled momentum $x_p = 2p/\sqrt{s}$. The errors on the charged species are dominated by the correlated systematic uncertainty in the particle identification efficiencies. These measurements represent the first determination of hadron spectra in light-quark events, and are relevant for

comparison with QCD predictions based on the assumption of massless quarks, as well as for testing the predictions of fragmentation models.

We also used this light-quark sample as the basis for our separation of quark and antiquark jets. The electron beam polarization (63% for the 1993 run and 77% for the 1994–95 run) induces a large asymmetry in the polar-angle distribution of quark jets, which prefer to follow the electron (positron) direction for left-(right-)handed incident beam. We approximate the quark direction by the thrust axis $\hat{t}$ and divide each event into two hemispheres by the plane perpendicular to the thrust axis. Tracks with $\vec{p}\cdot\hat{t} > 0$ are defined to come from a jet with polar angle $\theta_h = \cos^{-1}(t_z)$, where t_z is the component of the thrust axis $\hat{t}$ along the electron beam direction. The remaining tracks are assigned $\theta_h = \cos^{-1}(-t_z)$. Hemispheres with $\cos\theta_h > 0.2$ produced with left-handed beam and those with $\cos\theta_h < -0.2$ produced with right-handed beam are tagged as quark jets. Hemispheres opposite the quark-tagged jets are tagged as antiquark jets. The Standard Model at tree level predicts the purities of the quark- and antiquark-tagged samples to be 73%.

Using these tagged hemispheres, we derived differential production rates of π^-, K^-, p, and Λ^0 in quark-tagged and antiquark-tagged jets. The oppositely charged hadrons in the antiquark sample were combined with the quark sample in order to improve statistics. The contributions to these samples from residual heavy-quark events (determined from Monte Carlo simulation) were subtracted and the tagging purity is unfolded to arrive at the production $\mathcal{F}_q^h$ of hadron h in quark jets and in antiquark jets $\mathcal{F}_{\bar{q}}^h$. These are shown in Fig. 2 in terms of the normalized difference $D_h(x) \equiv (\mathcal{F}_q^h(x) - \mathcal{F}_{\bar{q}}^h(x))/(\mathcal{F}_q^h(x) + \mathcal{F}_{\bar{q}}^h(x))$. For all four hadron species, the normalized differences are consistent with zero at low x_p. For the pions, the difference is also consistent with zero at high x_p, while for the other three species, a significant positive difference is observed for x_p above ~ 0.2.

Since baryons contain no constituent antiquarks, we interpret the positive normalized differences as clear evidence for leading baryon production in quark jets. The steep rise in D_p and D_Λ with increasing x_p suggests that baryon production is dominated by leading baryon production as $x_p \to 1$. If production of $\pi^\pm$ ($K^\pm$) were

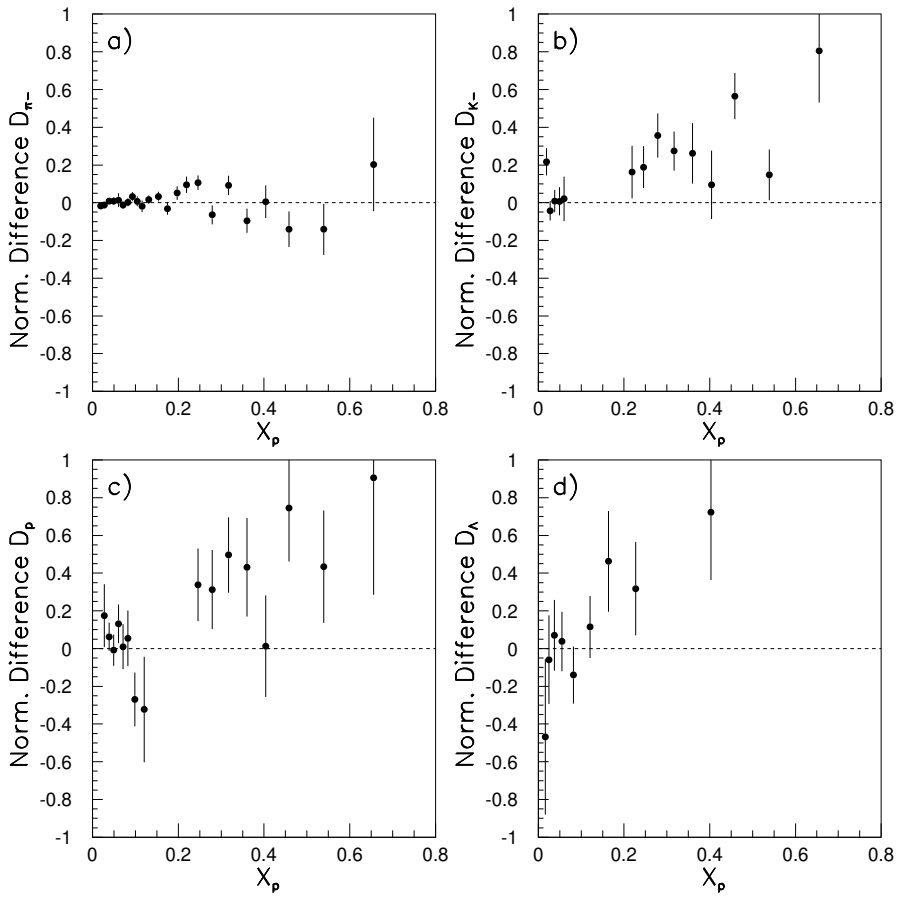

Figure 2: The normalized difference $D_h(x) = (\mathcal{F}_q^h(x) - \mathcal{F}_{\bar{q}}^h(x))/(\mathcal{F}_q^h(x) + \mathcal{F}_{\bar{q}}^h(x))$ in production rates between quark and antiquark jets are shown for $h = \pi^-$ (a), K^- (b), p (c), and Λ^0 (d). Evidence for differences in quark and antiquark fragmentation is clear. This difference is interpreted as evidence for the leading particle effect in e^+e^- annihilation.

dominated by leading meson production, *and* if π^- (K^-) were produced equally in jets containing primary $\bar{u}$ and d (s) quarks, then we would expect to observe D_π (D_K) of 0.13, due to the 22:17 production ratio for $Z^0 \to d\bar{d}$ ($s\bar{s}$) : $Z^0 \to u\bar{u}$. Our data are more consistent with $D_\pi = 0$ than $D_\pi = 0.13$ over the entire measured x_p range, suggesting some dilution of leading pions for $x_p \leq 0.7$. The effects of resonance decays, such as the ρ^0, might be one source of dilution. Our measured

D_K values above $x_p \simeq 0.2$ are consistently above 0.13, indicating both (*i*) that there is leading kaon production at high momentum, and (*ii*) that leading kaons are produced more often in $s\bar{s}$ events than in $u\bar{u}$ events.

3 Jet Handedness

Polarized incident electrons provide an excellent opportunity to test the transport of spin through the hadronization process since the Standard Model predicts high polarization of quarks from Z^0 decays with a strong dependence on polar angle and incident electron polarization. A first measurement of spin-transport, using the technique suggested by [7], was reported in [1]. This measurement has been updated with the 1994–95 SLD dataset.

The simplest observable with the same transformation properties under parity inversion as spin has the form $\Omega = \hat{t} \cdot (\vec{k}_1 \times \vec{k}_2)$, where $\hat{t}$ is a unit vector along the jet axis, corresponding to the spin direction of a longitudinally polarized parton, and $\vec{k}_1$ and $\vec{k}_2$ are the momenta of two particles in the jet chosen by some charge-independent prescription, such as $|\vec{k}_1| > |\vec{k}_2|$ [7]. A jet may be defined as left- or right-handed if Ω is negative or positive, respectively. The jet handedness H is then defined as the asymmetry in the number of left- and right-handed jets: $H \equiv (N_{\Omega<0} - N_{\Omega>0})/(N_{\Omega<0} + N_{\Omega>0})$. Using the expected parton polarization P_q from the Standard Model, the analyzing power α of the method is defined by $H = \alpha P_q$. The observed H in light-quark jets was found to be consistent with zero, and the 95% C. L. upper limit of the analyzing power was determined to be $|\alpha| < 0.033$. This improves the limit in [1] by a factor of 3.

4 Correlation of Three-Jet Orientation and Z^0 Spin

Another use of the polarized incident electrons is to search for correlations of the orientation of three-jet events with the spin of the Z^0 [2]. If $\vec{p}_1$ and $\vec{p}_2$ are the momenta of the highest- and second-highest energy jets, we can express the

cross section in terms of the polar angle ω of $\vec{p}_1 \times \vec{p}_2$ with respect to the incident electron direction:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\omega} = \frac{9}{16}\left[1 - \frac{1}{3}\cos^2\omega + \beta P_Z \cos\omega\right]. \quad (1)$$

Here $P_Z = (A_e - P_e)/(1 - A_e P_e)$ is the Z^0 polarization, and β is an asymmetry constant.

Due to various cancellations, this β is expected to be very small [8] at the Z^0 resonance, $|\beta| < 10^{-5}$. Because of this background-free situation, measurement of the cross section asymmetry β is sensitive to physics processes beyond the Standard Model. A maximum likelihood fit of Eq. (1) to the observed $\cos\omega$ distributions for both left- and right-handed events yielded $\beta = 0.008 \pm 0.015$, or a 95% C. L. limit of $-0.022 < \beta < 0.039$.

5 Summary

We present three unique measurements that probe QCD using the polarized electron beam available at the SLC. We observe leading p, Λ^0, and K^- from light-quark (uds) jets at scaled momenta above $x_p > 0.2$. We present an improved limit on spin-transport through hadronization as measured by the method of jet-handedness. Finally, we search for the signature of new physics in the correlation of the three-jet event orientation with the Z^0 spin direction.

Acknowledgments

This work was supported in part by Department of Energy contract DE–AC03–76SF00515. We thank the personnel of the SLAC accelerator department and the technical staffs of our collaborating institutions for their outstanding efforts on our behalf.

References

[1] K. Abe *et al.*, Phys. Rev. Lett. **74** (1995) 1512.

[2] K. Abe *et al.*, Phys. Rev. Lett. **75** (1995) 4173.

[3] T. J. Pavel, Ph. D. dissertation, Stanford University, in preparation.

[4] K. G. Baird, Ph. D. dissertation, Rutgers University (1996); also SLAC-Report-483 (1996).

[5] K. Abe *et al.*, Nucl. Instrum. Methods **A371** (1996) 195.

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

[7] O. Nachtmann, Nucl. Phys. **B127** (1977) 314.
A. V. Efremov *et al.*, Phys. Lett. **B284** (1992) 394.

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

The SLD Collaboration

K. Abe,[29] I. Abt,[14] C.J. Ahn,[26] 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,[10] O. Bardon,[16] T. Barklow,[27] A.O. Bazarko,[11] R. Ben-David,[33]
A.C. Benvenuti,[2] G.M. Bilei,[22] D. Bisello,[21] G. Blaylock,[7] J.R. Bogart,[27]
T. Bolton,[11] 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,[16] W. Busza,[16] A. Calcaterra,[13]
D.O. Caldwell,[6] D. Calloway,[27] B. Camanzi,[12] M. Carpinelli,[23] R. Cassell,[27]
R. Castaldi,[23][a] A. Castro,[21] M. Cavalli-Sforza,[7] A. Chou,[27] E. Church,[31]
H.O. Cohn,[28] J.A. Coller,[3] V. Cook,[31] R. Cotton,[4] R.F. Cowan,[16] D.G. Coyne,[7]
G. Crawford,[27] A. D'Oliveira,[8] C.J.S. Damerell,[25] M. Daoudi,[27] R. De Sangro,[13]
P. De Simone,[13] R. Dell'Orso,[23] M. Dima,[9] P.Y.C. Du,[28] R. Dubois,[27]
B.I. Eisenstein,[14] R. Elia,[27] E. Etzion,[4] D. Falciai,[22] C. Fan,[10] M.J. Fero,[16]
R. Frey,[20] K. Furuno,[20] T. Gillman,[25] G. Gladding,[14] S. Gonzalez,[16]
G.D. Hallewell,[27] E.L. Hart,[28] A. Hasan,[4] Y. Hasegawa,[29] K. Hasuko,[29]
S. Hedges,[3] S.S. Hertzbach,[17] 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. Jaros,[27] A.S. Johnson,[3] J.R. Johnson,[32] R.A. Johnson,[8] T. Junk,[27]
R. Kajikawa,[19] M. Kalelkar,[24] H. J. Kang,[26] I. Karliner,[14] H. Kawahara,[27]
H.W. Kendall,[16] Y. Kim,[26] M.E. King,[27] R. King,[27] R.R. Kofler,[17]
N.M. Krishna,[10] R.S. Kroeger,[18] J.F. Labs,[27] M. Langston,[20] A. Lath,[16]
J.A. Lauber,[10] D.W.G.S. Leith,[27] M.X. Liu,[33] X. Liu,[7] M. Loreti,[21] A. Lu,[6]
H.L. Lynch,[27] J. Ma,[31] G. Mancinelli,[22] S. Manly,[33] G. Mantovani,[22]
T.W. Markiewicz,[27] T. Maruyama,[27] R. Massetti,[22] H. Masuda,[27]
E. Mazzucato,[12] A.K. McKemey,[4] B.T. Meadows,[8] R. Messner,[27]
P.M. Mockett,[31] K.C. Moffeit,[27] B. Mours,[27] D. Muller,[27] T. Nagamine,[27]
S. Narita,[29] U. Nauenberg,[10] H. Neal,[27] M. Nussbaum,[8] Y. Ohnishi,[19]
L.S. Osborne,[16] R.S. Panvini,[30] H. Park,[20] T.J. Pavel,[27] I. Peruzzi,[13][b]
M. Piccolo,[13] L. Piemontese,[12] E. Pieroni,[23] K.T. Pitts,[20] R.J. Plano,[24]
R. Prepost,[32] C.Y. Prescott,[27] G.D. Punkar,[27] J. Quigley,[16] B.N. Ratcliff,[27]
T.W. Reeves,[30] J. Reidy,[18] P.E. Rensing,[27] L.S. Rochester,[27] P.C. Rowson,[11]
J.J. Russell,[27] O.H. Saxton,[27] S.F. Schaffner,[27] T. Schalk,[7] R.H. Schindler,[27]
B.A. Schumm,[15] A. Seiden,[7] S. Sen,[33] V.V. Serbo,[32] M.H. Shaevitz,[11]
J.T. Shank,[3] G. Shapiro,[15] S.L. Shapiro,[27] D.J. Sherden,[27] K.D. Shmakov,[28]
C. Simopoulos,[27] N.B. Sinev,[20] S.R. Smith,[27] J.A. Snyder,[33] P. Stamer,[24]
H. Steiner,[15] R. Steiner,[1] M.G. Strauss,[17] D. Su,[27] F. Suekane,[29] A. Sugiyama,[19]
S. Suzuki,[19] M. Swartz,[27] A. Szumilo,[31] T. Takahashi,[27] F.E. Taylor,[16]
E. Torrence,[16] A.I. Trandafir,[17] J.D. Turk,[33] T. Usher,[27] J. Va'vra,[27]
C. Vannini,[23] E. Vella,[27] J.P. Venuti,[30] R. Verdier,[16] 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,[7] D.C. Williams,[16] S.H. Williams,[27] S. Willocq,[33] R.J. Wilson,[9] W.J. Wisniewski,[27] M. Woods,[27] G.B. Word,[24] J. Wyss,[21] R.K. Yamamoto,[16] J.M. Yamartino,[16] X. Yang,[20] S.J. Yellin,[6] C.C. Young,[27] H. Yuta,[29] G. Zapalac,[32] R.W. Zdarko,[27] C. Zeitlin,[20] Z. Zhang,[16] 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]*California Institute of Technology, Pasadena, California 91125*

[6]*University of California at Santa Barbara, Santa Barbara, California 93106*

[7]*University of California at Santa Cruz, Santa Cruz, California 95064*

[8]*University of Cincinnati, Cincinnati, Ohio 45221*

[9]*Colorado State University, Fort Collins, Colorado 80523*

[10]*University of Colorado, Boulder, Colorado 80309*

[11]*Columbia University, New York, New York 10027*

[12]*INFN Sezione di Ferrara and Universita di Ferrara, I-44100 Ferrara, Italy*

[13]*INFN Lab. Nazionali di Frascati, I-00044 Frascati, Italy*

[14]*University of Illinois, Urbana, Illinois 61801*

[15]*Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*

[16]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

[17]*University of Massachusetts, Amherst, Massachusetts 01003*

[18]*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 Universita di Padova, I-35100 Padova, Italy*

[22]*INFN Sezione di Perugia and Universita di Perugia, I-06100 Perugia, Italy*

[23]*INFN Sezione di Pisa and Universita 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 Universita di Genova*

[b]*Also at the Universita di Perugia*