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**Hadron Production in Light and Heavy,
Quark and Antiquark Jets**

KENNETH G. BAIRD

*Rutgers University
Department of Physics and Astronomy
New Brunswick, New Jersey*

Representing

The SLD Collaboration*

*Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309*

We review four hadronization studies performed by the SLD experiment at SLAC, involving separation of "light" ($Z^0 \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$), c, and b flavors using precision vertexing, and separation of q - and \bar{q} -jets using the highly polarized SLC electron beam. We measured the differences between the average charged multiplicities in $Z^0 \rightarrow \text{light}, \rightarrow c\bar{c},$ and $\rightarrow b\bar{b}$ events, and found that our results were consistent with predictions of perturbative QCD. Next, we measured $\pi/K/p/K^0/\Lambda^0$ production in light events for the first time, and compared with production in c - and b -flavor events. We then examined particle production differences in light quark and antiquark hemispheres, and observed more high momentum baryons and K^- 's than antibaryons and K^+ 's in quark hemispheres, consistent with the "leading particle" hypothesis. Lastly, we performed a search for jet handedness in light q - and \bar{q} -jets. Assuming Standard Model values of quark polarization in Z^0 decays, we have set an improved upper limit on the analysing power of the handedness method.

1 Introduction

The process by which final state partons hadronize into observable particles is not well understood. Useful measurements to try to probe more deeply into fragmentation include the measurements of total charged multiplicities and identified particles in inclusive $e^+e^- \rightarrow \text{hadrons}$ samples at various center of mass energies. Important additional information can be gained by flavor separation and by quark/antiquark-jet separation. Heavy events with primary

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quark flavor Q ($Q = c, b$) are known to produce fast heavy hadrons whose decay products overshadow the particle composition from fragmentation. Thus, by studying particle production in “light” ($Z^0 \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$) quark events, we get closer to the true “fragmentation” spectrum. In particular, heavy quarks are predicted to radiate fewer collinear gluons than massless quarks, due to mass/phase-space, and QCD predictions exist for the resulting differences in gluon multiplicity. Another aspect is that in many fragmentation models, the primary quark and antiquark appear in a specific hadron, and this “leading” hadron tends to have large momentum. Experimentally, by separating quark hemispheres from antiquark hemispheres, it is possible to look for differences in identified particle production which would be attributable to such “leading” particles. Also, at the Z^0 -pole, the quark and antiquark are expected to be highly longitudinally polarized. By separating quark from antiquark hemispheres, we are able to search for signals of spin transport through the hadronization process.

We present four analyses dealing with these aspects of fragmentation. The analyses are based upon the sample of about 150,000 hadronic Z^0 decays collected by SLD between 1993 and 1995, with average electron beam polarization of 73%, and used the charged tracks measured in the central drift chamber (CDC) ¹ and in the vertex detector (VXD) ². For each, a set of cuts was applied to the data to select well-measured tracks, and events were required to be well-contained within the detector acceptance. Flavor tagging was performed by counting the number of well measured tracks n_{sig} that were inconsistent with the interaction point (IP) as the origin. Charged particle identification was performed with the Cherenkov Ring Imaging Detector (CRID) ³. Standard mass reconstruction techniques were used for neutral particle identification ⁴. For the last two analyses discussed, the large forward-backward asymmetry due to the highly polarized electron beam was used to separate quark from antiquark hemispheres. As the primary quarks from Z^0 decays are left handed, they tend to follow the direction of the incident left-handed fermion. The event was divided in two by a plane perpendicular to the thrust axis, and when the electron beam was left(right)-handed, the hemisphere whose normal satisfied $\vec{n} \cdot \vec{p}_e > 0$ was labeled as the quark (antiquark) hemisphere.

2 Charged Multiplicity in uds , c , and b Events

We first examined, the multiplicity of charged hadrons produced in the final state as a function of primary quark flavor. We divided each event into two hemispheres separated by the plane perpendicular to the thrust axis. We then applied three flavor tags to each hemisphere. In order to reduce poten-

tial tagging bias we measured the average charged multiplicity in hemispheres opposite those tagged. The light and b-quark hemispheres were tagged by requiring $n_{sig}=0$ and $n_{sig} \geq 3$, respectively, in the hemisphere. The presence of a reconstructed D^+ or D^{*+} that was consistent with originating from the IP was used as a c -quark tag. A total of 154151, 976 and 9480 hemispheres were tagged for the three samples. The sample purities were estimated to be 75%, 64%, and 94%, respectively.

Well-measured charged tracks were counted in the hemispheres opposite those tagged, and multiplicity averages were determined. These average multiplicities were then “unfolded” for sample purities and tag biases to determine the true average multiplicities in uds , c , and b events ⁵:

$$\begin{aligned}\bar{n}_{uds} &= 20.21 \pm 0.10 \text{ (stat.)} \pm 0.22 \text{ (syst.)} \\ \bar{n}_c &= 21.28 \pm 0.46 \text{ (stat.)} \begin{matrix} +0.41 \\ -0.36 \end{matrix} \text{ (syst.)} \\ \bar{n}_b &= 23.14 \pm 0.10 \text{ (stat.)} \begin{matrix} +0.38 \\ -0.37 \end{matrix} \text{ (syst.)}.\end{aligned}$$

The largest systematic errors arise from uncertainties in the detector acceptance, and errors on the experimental knowledge of B hadron production and decay. We performed several consistency checks on our results, including studies of event selection criteria, tagging criteria, and the study of biases due to multi-jet events. In each case all the re-evaluated average multiplicities were found to be consistent with our central values within the statistical errors.

Subtracting $\bar{n}_c^{dk}=5.20$ and $\bar{n}_b^{dk} = 11.10$ from our measured \bar{n}_c and \bar{n}_b respectively ⁵, we obtained the average non-leading multiplicities $\bar{n}_c^{nl} = 16.08 \pm 0.46 \text{ (stat.)} \begin{matrix} +0.41 \\ -0.36 \end{matrix} \text{ (syst.)}$ and $\bar{n}_b^{nl} = 12.04 \pm 0.10 \text{ (stat.)} \begin{matrix} +0.38 \\ -0.37 \end{matrix} \text{ (syst.)}$. The hypothesis of “flavor-independent fragmentation” ^{6,7} implies that the non-leading multiplicity should equal the multiplicity in uds events at a center of mass energy (W) corresponding to that not taken by the heavy hadrons, i.e. $\bar{n}_Q^{nl}(W) = \bar{n}_{uds}([1 - \langle x_{E_Q}(W) \rangle]W)$. Fig. 1(a) shows our measurement of \bar{n}_{uds} plotted at $W = M_Z$, and our measurements of \bar{n}_c^{nl} and \bar{n}_b^{nl} plotted at the appropriately reduced non-leading energy. Previous measurements of these quantities (Ref. 5) are also shown. The curve is a fit to the energy dependence of the \bar{n}_{uds} measurements shown and those at $5 < W < 92$ GeV ⁸. Fig. 1(b) shows the differences between the non-leading data points in Fig. 1(a) and the curve. A linear fit to these differences yields a slope of $s = 1.14 \pm 0.32$ tracks/ $\ln(\text{GeV})$. This differs from the expectation for identical energy dependence, $s = 0$, by 3.6 standard deviations, indicating that the hypothesis of flavor-independent fragmentation is disfavored at this level.

A striking prediction of Perturbative QCD is that the multiplicity difference $\Delta\bar{n}_Q(W) = \bar{n}_Q(W) - \bar{n}_{uds}(W)$ between heavy-quark and light-quark

events is independent of center of mass energy W ^{9,10}. We obtain:

$$\begin{aligned}\Delta\bar{n}_c &= 1.07 \pm 0.47 \text{ (stat.)} \begin{matrix} +0.36 \\ -0.30 \end{matrix} \text{ (syst.)} \\ \Delta\bar{n}_b &= 2.93 \pm 0.14 \text{ (stat.)} \begin{matrix} +0.30 \\ -0.29 \end{matrix} \text{ (syst.)}.\end{aligned}$$

Fig. 1 (c,d) show our measurements of $\Delta\bar{n}_c$ and $\Delta\bar{n}_b$ together with those from other experiments⁵ at the respective c.m. energies. Our measurements are in good agreement with expectations^{9,10}.

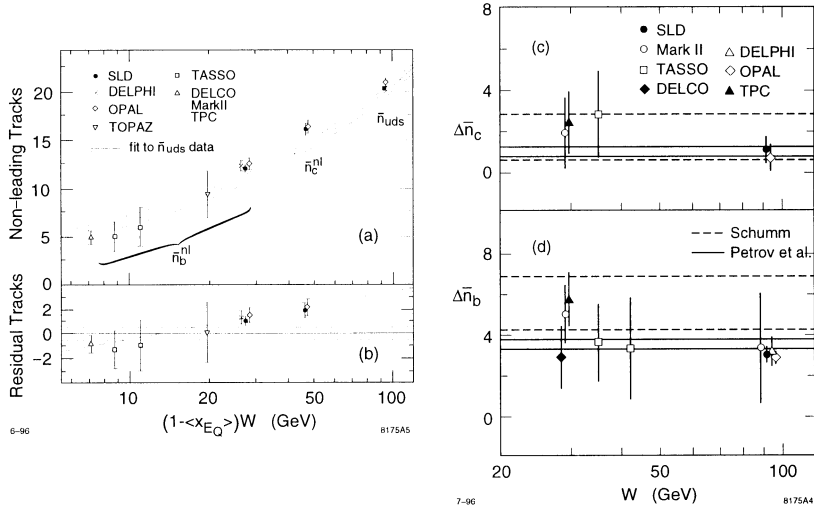


Figure 1: Multiplicity Results

3 Identified Particle Fragmentation Functions in uds , c , and b Events

We present an analysis of $\pi^\pm, K^\pm, p/\bar{p}, K^0$, and $\Lambda^0/\bar{\Lambda}^0$ production in $Z^0 \rightarrow \text{light}, c\bar{c}$, and $b\bar{b}$ decays. Samples of events enriched in light, c and b primary flavors were selected based upon the number of significant tracks per event; $n_{sig} = 0, 1 - 2$, and > 3 respectively. The light-, c -, and b -tagged samples comprised 53,526, 22684, and 14,039 events respectively, with approximate purities of 85%, 33% and 89%. The identified particle analysis described in Ref. 11 was applied to each sample. The production spectra in the tagged

samples were unfolded for sample purity and tag biases to yield production rates for the *light*- and *b*-quark samples. The unfolding systematic are typically small compared with the statistical errors and the particle identification systematic.

In Fig. 2 are shown the unfolded production rates per event per unit scaled momentum x_p ($x_p = p/p_{beam}$) for the five hadron species in light-flavor events. These unfolded momentum distributions for the light-flavor events are free from effects of heavy quark production and decay. Although the influence of decay products of other unstable primary hadrons remains, these measurements are more appropriate for comparison with QCD predictions (which generally assume massless quarks) as well as for testing the predictions of fragmentation models. The production of charged kaons is consistent with that of neutral kaons. The production ratios $K:\pi$ and $\Lambda:p$ show similar momentum dependence.

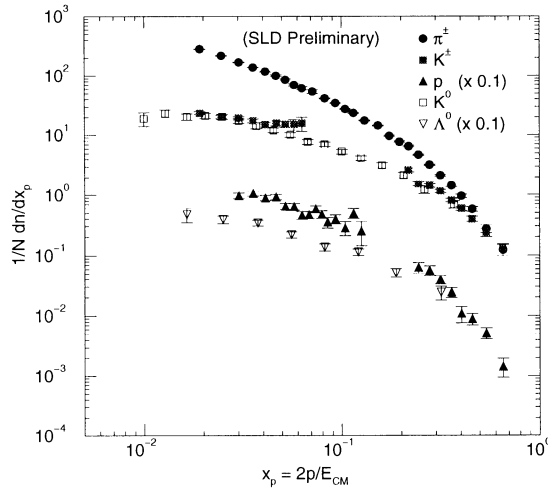


Figure 2: Identified particle fragmentation functions in $Z^0 \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ events

In Fig. 3 we show the ratios of production in *b*-flavor to light-flavor events for the five species. The systematic errors on the particle identification largely cancel in the ratio, and the errors are predominantly statistical. There is higher production of charged pions in *b*-flavor at low momentum, with an approximately constant ratio for $0.02 < x_p < 0.07$. The production of both charged and neutral kaons is approximately equal in the two samples at $x_p \leq$

0.02, but the relative production in b -flavor events then increases with x_p , peaking at $x_p \approx 0.07$. There is approximately equal production of baryons in b -flavor and light-flavor events below $x_p = 0.15$. For $x_p > 0.07$, production of pions, kaons and protons falls off faster in b -flavor events. These features are consistent with expectations based on the known production and decay characteristics of heavy hadrons. Also shown in Fig. 3 are the predictions of the JETSET 7.4 and HERWIG 5.7 event generators^{12,13}, both of which reproduce these features qualitatively. The exact values of these ratios depend on details of the B and D hadron production energy spectrum and decay modelling, and so provide information complementary to that in Fig. 2.

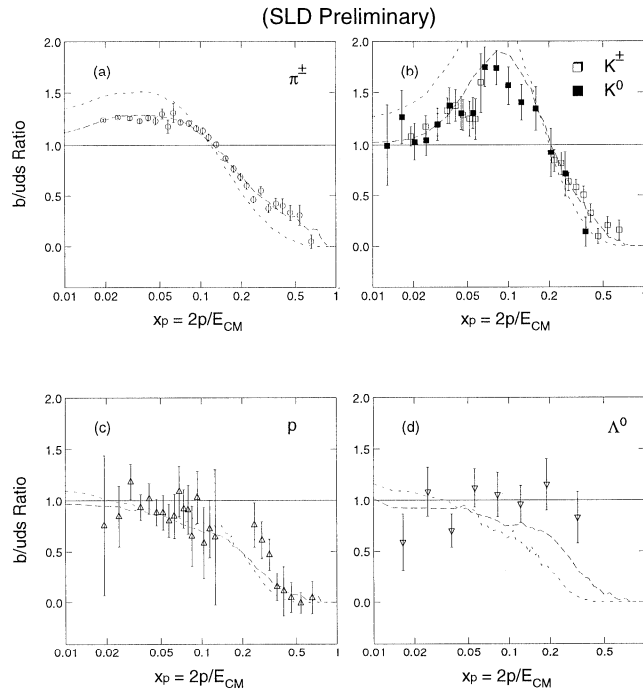


Figure 3: A comparison of identified particle production in $Z^0 \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ and $Z^0 \rightarrow b\bar{b}$ events. The dashed line is the prediction of JETSET 7.4, and the dashed line is that of HERWIG 5.7.

4 Leading Particle Production in uds Events

We define a particle to be leading if one of its constituent quarks is a primary quark, for example the u or \bar{u} in $e^+e^- \rightarrow Z^0 \rightarrow u\bar{u}$. Then the experimental question is whether the inclusive properties are different for particles that could be “leading” (e.g. a π^+ in a u -quark jet) and those that could not (e.g. a π^- in a u -quark jet). To study this question we must: i) separate q - and \bar{q} -jets; ii) remove heavy quark events so as to be insensitive to heavy hadron decay products; and iii) identify particle types. We then compare the scaled momentum distributions of given particles with those of their antiparticle in a pure sample of quark jets in order to determine whether the primary quark prefers a particular particle type or momentum.

To separate the quark jets from antiquark jets, we use the EW quark production asymmetry described in Section 1. A cut was applied to remove events whose thrust axis failed to satisfy $|\cos\theta_t| > 0.2$, where θ_t is the angle between the thrust axis and the e^- beam direction. The Standard Model at tree level predicts the purities of the quark- and antiquark-tagged samples to be about 72% for our average electron beam polarization of 73%.

Light quark events were selected by requiring $n_{sig} = 0$. In each hemisphere, the production rates as a function of x_p of identified hadrons were determined. We combined the positively charged tracks in the q -tagged jets with the negatively charged tracks in the \bar{q} -tagged jets (similarly, Λ 's in q -jets were combined with $\bar{\Lambda}$'s in \bar{q} -jets). We subtracted the contributions to these samples from heavy quark events, estimated from the Monte Carlo simulation. For each hadron type h , the resulting rates were unfolded for the purity of the quark tagging to obtain differential production rates $R(q \rightarrow h)$ in light quark jets.

We define the difference between particle and antiparticle production rates normalized by their sum:

$$D_h = \frac{R(q \rightarrow h) - R(q \rightarrow \bar{h})}{R(q \rightarrow h) + R(q \rightarrow \bar{h})}$$

The systematic uncertainties on particle identification largely cancel in this variable, and the errors are dominated by statistics. Figure 4 shows these normalized differences as a function of x_p . For each particle type, the differences are consistent with zero at low x_p . For the π 's the difference is also consistent with zero at high x_p , whereas for the others a significant positive difference is observed for x_p above ~ 0.15 .

Since the baryons contain no constituent antiquarks, we interpret the steep rise in D_p and D_Λ with increasing x_p as an indication that baryon production

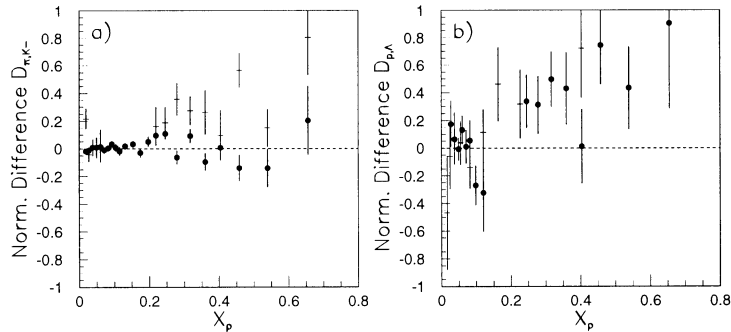


Figure 4: Normalized production differences as a function of scaled momentum for (a) charged pions (circles) and kaons (crosses), and (b) protons (circles) and Λ 's (crosses).

is dominated by leading particle production as $x_p \rightarrow 1$. If production of $\pi^\pm (K^\pm)$ mesons were dominated by leading meson production, *and* $\pi^- (K^-)$ were produced equally in jets containing primary \bar{u} and $d(s)$ quarks, then we would expect to observe normalized differences of ~ 0.22 for the mesons, due to (i) the 22:17 production ratio for $Z^0 \rightarrow d\bar{d}(s\bar{s}) : Z^0 \rightarrow u\bar{u}$, and (ii) the different electroweak asymmetries for u - and d -type quark production. Our data are more consistent with $D_\pi = 0$ than $D_\pi = 0.22$ over the entire measured x_p range, suggesting some dilution of leading pions from resonance decays such as the ρ^0 . Our measured D_K values above $x_p \simeq 0.2$ are consistently above 0.22, indicating both that *i*) there is leading kaon production at high momentum, and *ii*) leading kaons are produced more often in $s\bar{s}$ events than in $u\bar{u}$ events.

5 Measurement of Spin Propagation through Hadronization using the “Jet Handedness” Method

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 Ref. 14, was reported in Ref. 15.

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 $\Omega = \hat{t} \cdot (k_1 \times k_2)$, 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 $|\vec{k}_1| > |\vec{k}_2|$ ¹⁴. 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 Ref. 15 by a factor of 3, and reaffirms that inclusive transportation of spin through the hadronization process is small.

6 Summary

We have shown four measurements that exploit the capabilities of the SLC and SLD programs to expand our understanding of the fragmentation process. By separating events into *light*, *c*, and *b* flavors and measuring average charged particle multiplicities, we have confirmed a precise prediction of perturbative QCD. Combining this with excellent particle identification, we have made a first measurement of production of π^\pm , K^\pm , p/\bar{p} , K^0 and $\Lambda^0/\bar{\Lambda}^0$ in *uds* events. With the addition of the e^- beam polarization, we have observed leading baryon and kaon production in *uds* events. Finally, we have searched inclusively for spin transport through hadronization, and set limits on jet handedness.

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The SLD Collaboration*

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. Bardoun,⁽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. Koffer,⁽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. Piemontesc,⁽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*