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Author
Aihara, H.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Physics Division

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H. Aihara, M. Alston-Garnjost, J.A. Bakken, A. Barbaro-Galtieri, A.V. Barnes, B.A. Barnett, H.-U. Bengtsson, B.J. Blumenfeld, A.D. Bross, C.D. Buchanan, O. Chamberlain, C-Y. Chien, A.R. Clark, A. Cordier, O.I. Dahl, C.T. Day, K.A. Derby, P.H. Eberhard, D.L. Fancher, H. Fujii, T. Fujii, B. Gabioud, J.W. Gary, W. Gorn, N.J. Hadley, J.M. Hauptman, W. Hofmann, J.E. Huth, J. Hylen, T. Kamae, H.S. Kaye, R.W. Kenney, L.T. Kerth, R.I. Koda, R.R. Kofler, K.K. Kwong, J.G. Layter, C.S. Lindsey, S.C. Loken, X.Q. Lu, G.R. Lynch, L. Madansky, R.J. Madaras, K. Maruyama, J.N. Marx, J.A.J. Matthews, S.O. Melnikoff, W. Moses, P. Nemethy, D.R. Nygren, P.J. Oddone, D.A. Park, A. Pevsner, M. Pripstein, P.R. Robrish, M.T. Ronan, R.R. Ross, F.R. Rouse, R.R. Sauerwein, G. Shapiro, M.D. Shapiro, B.C. Shen, W.E. Slater, M.L. Stevenson, D.H. Stork, H.K. Ticho, N. Toge, R.F. van Daalen Wetters, G.J. VanDalen, R. van Tyen, E.M. Wang, M.R. Wayne, W.A. Wenzel, H. Yamamoto, M. Yamauchi, W-M. Zhang

Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720,
University of California, Los Angeles, CA 90024,
University of California, Riverside, CA 92521,
Johns Hopkins University, Baltimore, MD 21218,
University of Massachusetts, Amherst, MA 01003,
University of Tokyo, Tokyo 113, JAPAN

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Abstract

We study long-range correlations between hadrons in opposite jets in e^+e^- annihilation events at $\sqrt{s}$ = 29 GeV. We use the data to measure differences between quark and antiquark fragmentation functions into charged hadrons, and to estimate the variation of fragmentation properties among quark flavors. We find large variations in longitudinal fragmentation functions, but universal mean transverse momenta of hadrons in jets.

The investigation of electron-positron annihilation into hadrons has contributed significantly to the present understanding of quark fragmentation. The main advantage over other hard-scattering processes is the well-defined initial quark energy; the main disadvantage (e.g. compared to neutrino-nucleon scattering) is the difficulty or impossibility of distinguishing between quark and antiquark jets or between the different quark flavors. Hence, measured jet properties usually represent averages over quarks and antiquarks and over flavors. Results on tagged heavy-quark jets have only recently become available[1], and schemes to tag light quarks are being considered[2]. In this paper we discuss a method to circumvent these problems, and apply it to a 77 pb^{-1} data sample collected with the PEP4-TPC detector at the PEP storage ring operated at $\sqrt{s}$ = 29 GeV. The technique is complementary to quark tagging methods and was originally proposed by Hoyer[3]. It relies on long-range correlations (LRC)[4,5] between hadrons in opposite jets: both the magnitude and the sign of these correlations are closely related to differences in the fragmentation properties between quark flavors, and between quarks and antiquarks.

Let $D_{q\to h}(\xi) \equiv (1/\sigma_q)(d\sigma_h/d\xi)$ denote the distribution of fragmentation products h of a quark of flavor q in a kinematic variable ξ such as the scaled energy $x = 2E/\sqrt{s}$. For example, inclusive spectra of charged pions in u-jets are described by the two functions $D_{u\to\pi^+} = D_{\bar{u}\to\pi^-}$ and $D_{u\to\pi^-} = D_{\bar{u}\to\pi^+}$. An equivalent and, for our purpose, more convenient description can be given in terms of the flavor singlet and non-singlet fragmentation functions defined as $S_{u\to\pi} = D_{u\to\pi^+} + D_{u\to\pi^-} = D_{u\to\pi^+} + D_{\bar{u}\to\pi^+}$ and $N_{u\to\pi} = D_{u\to\pi^+} - D_{u\to\pi^-} = D_{u\to\pi^+} - D_{\bar{u}\to\pi^+}$, respectively. This nomenclature[6] is analogous to the one used in the analysis of structure functions in deep-inelastic lepton-nucleon scattering. Generally, singlet and non-singlet quantities are characterized by their transformation properties, $S_q = S_{\bar{q}}$ and $N_q = -N_{\bar{q}}$ (here and in the following, the index indicating the hadron type has been omitted). Singlet quantities describe properties common to both quark and antiquark jets, whereas non-singlet quantities describe differences between quark and antiquark jets.

A measurement of inclusive hadron spectra $D(\xi)$ in the jets of e^+e^- annihilation events yields

$$D(\xi) = (1/\sigma_{jet})(d\sigma/d\xi) = \Sigma\epsilon_q\{D_q(\xi)+D_{\bar{q}}(\xi)\}/2 \qquad (1),$$

where the sum extends over all quark flavors weighted with their production probability ϵ_q; $\Sigma\epsilon_q = 1$. Possible gluon emission is taken into account via a Q^2-dependence of the $D_{q,\bar{q}}(\xi)$ in Eq. (1). For the special case in which $D(\xi)$ stands for a singlet distribution $S(\xi)$ (i.e. a quantity which is invariant under charge conjugation of the final state hadrons), the measurement yields

$$S(\xi) = \Sigma\epsilon_q S_q(\xi) \qquad (1a).$$

For a non-singlet distribution $N(\xi)$ (i.e. a quantity which changes sign under charge conjugation), we find

$$N(\xi) = 0 \qquad (1b).$$

Hence the information obtainable from inclusive measurements in e^+e^- annihilation into hadrons is limited to averages over singlet densities.

Information more detailed than what is provided by single-particle inclusive spectra can be derived from correlation studies. A simultaneous measurement of particle distributions in both jets of annihilation events yields the two-particle density $D^{(2)}$,

$$D^{(2)}(\xi_1,\xi_2) \equiv (1/\sigma_{tot})(d^2\sigma/d\xi_1 d\xi_2) \qquad (2).$$

Note that ξ_1 and ξ_2 denote the descripitive variable of a particle in the first and second jet, respectively, and that we consider the same type of particle (such as π^+), or combination of particle types (such as π^+ plus π^-), in both jets. Let us now consider a measurement of $D^{(2)}(\xi,\xi)$ at the same value of ξ in opposite jets. Both in the naive quark-parton model and in QCD we expect (approximate) factorization of soft and hard physics, i.e. the fragmentation of a quark (of a given virtuality Q^2) should be independent of the way it is produced. We predict therefore[3]

$$D^{(2)}(\xi,\xi) = \Sigma\epsilon_q D_q(\xi) D_{\bar{q}}(\xi) \qquad (3).$$

This relation is expected to hold for reasonably "fast" particles. The factorization property will be violated for very soft hadrons (say $x < 0.05-0.1$) since, in this case, two particles in opposite jets may be close enough in phase space in order to exhibit short range correlations due to resonance decays or local conservation of quantum numbers in the confinement process. For particles very close to the limits of phase space, the constraints of energy-momentum conservation may cause a violation of factorization. At PEP energies, such influences should be negligible except for the very few particles at extremely high $x > 0.9$.

We express the experimental results in terms of a correlation function C,

$$C(\xi,\xi) \equiv D^{(2)}(\xi,\xi) - D(\xi)D(\xi) \qquad (4).$$

For the case in which D represents a non-singlet singlet distribution, it is easy to derive from Eqs. (1) and (3) that

$$C_N(\xi,\xi) = -\Sigma\epsilon_q N_q^{\,2}(\xi) \equiv -N_{rms}^{\,2}(\xi) \qquad (5).$$

If D stands for a non-singlet quantity, we obtain

$$C_S(\xi,\xi) = \Sigma\epsilon_q \{S_q(\xi)-S(\xi)\}^2 \equiv \Delta^2(\xi) \qquad (6).$$

These equations can be exploited to test the factorization hypothesis Eq. (3) and to study quark fragmentation. Equations (5) and (6) imply $C_N(\xi,\xi) \leq 0$ and $C_S(\xi,\xi) \geq 0$, respectively. Any violation of these conditions (except for particles with very low or very high momentum) indicates a breakdown of factorization due to additional "dynamical" LRC's caused by confinement forces, and would mean that the separation of large q^2 processes into a perturbative and a non-perturbative part is not justified[7]. Assuming that factorization holds, on the other hand, we can use Eq. (5) to derive the otherwise inaccessible non-singlet densities $N_q^{\,2}$, averaged over quark flavors, and Eq. (6) to study differences in the singlet densities S_q for different quark flavors. In particular, the ratio

$$R_N(\xi) \equiv \sqrt{-C_N(\xi,\xi)}/S(\xi) = N_{rms}(\xi)/S(\xi) \qquad (7)$$

measures the ratio of average non-singlet to singlet fragmentation functions[8]. At a given ξ, $R_N(\xi)$ can be interpreted as the fraction of hadrons which remember if the jet was created by a quark or an antiquark. The ratio

$$R_S(\xi) \equiv \sqrt{C_S(\xi,\xi)}/S(\xi) = \Delta(\xi)/S(\xi) \qquad (8)$$

measures the relative rms variation of fragmentation properties among quark flavors.

The formalism summarized above serves multiple purposes:

1. It allows one to test the factorization hypothesis which is fundamental for the quark-parton picture.

2. It enables one to determine average non-singlet fragmentation functions, and to test if singlet fragmentation functions are universal or if they depend on the parent quark type.

3. Finally, it provides a relation between the observed long-range correlations and more basic quantities such as fragmentation functions.

The TPC detector and the criteria for track and event selection (which yield a sample of 29000 multihadron events with less than 2% contamination from other reaction types) have been described elsewhere[9]. Particles are identified in the TPC by a simultaneous measurement of momentum and dE/dx energy loss. The identification algorithms and the resulting efficiencies and sample purities have been discussed earlier[5]. To evaluate inclusive spectra for a specific particle type such as pions, the raw π, K, and p spectra are corrected for misidentified particles using an unfolding procedure. A similar unfolding technique is used for correlation studies. Results quoted below are corrected for misidentification, acceptance losses and effects of event selection and initial state radiation, unless otherwise indicated.

To evaluate the correlation coefficients C_N as defined in Eq. (4), we divide each event into two jets separated by a plane perpendicular to the sphericity axis. C_N is measured for non-singlet pion distributions $(1/\sigma_{jet})(\sigma_{\pi^+} - \sigma_{\pi^-})$ as a function of scaled particle energy $x = 2E/\sqrt{s}$ and of rapidity $y = 0.5 \ln((E+p_L)/(E-p_L))$, where p_L is the component of momentum parallel to the sphericity axis. For all x and y bins, C_N is found to be negative or consistent with zero, as expected in the absence of dynamical long-range correlations. Assuming the absence of such correlations, we use Eq. (5) to calculate the average non-singlet pion distribution N_{rms}. Figs. 1a) and 1b) show $\sqrt{-C_N(x,x)} = N_{rms}(x)$ and $\sqrt{-C_N(y,y)} = N_{rms}(y)$, together with the singlet distributions S(x) and S(y). Figs. 1c) and 1d) display the ratio of non-singlet to singlet distributions $R_N(x)$ and $R_N(y)$, respectively. In the first rapidity bin, $0 < y < 1$, the measured correlation function $C_N(y,y)$ is dominated by short range correlations, which are not taken into account in Eq. (3). For this bin and, to a certain extend, for the second bin, $\sqrt{-C_N(y,y)}$ overestimates the true $N_{rms}(y)$. (In fact, symmetry arguments show that $N_{rms}(y=0) = N_{rms}(x=0) = 0.$). The effect is less pronounced for the first x-bin covering $0.5 < E < 1$ GeV, since here the soft particles affected by short range effects are essentially excluded. The dotted lines in Fig. 1c),1d) indicate the influence of short range correlations as estimated using the LUND fragmentation model[10], demonstrating that those effects disappear rapidly as the separation of particles in phase space increases. $R_N(x)$ and $R_N(y)$ (Fig. 1c) and 1d)) rise as the energy of particles increases; this rise indicates that fast hadrons are more likely to contain the initial quark. Included in Fig. 1c) are results on $R_N(x)$ for charged pions from the BEBC neutrino experiment[11] and predictions of the LUND fragmentation model[10]. Both in the neutrino experiment and in the Monte-Carlo model the parent quark is known, so non-singlet distributions can be obtained directly, without distortions due to short range effects. The BEBC results refer to u and d quarks only; the model predictions are obtained using a weighted mean of the squares of non-singlet distributions according to Eq. (5). The e^+e^- and νN data sets are in good agreement with each other and support the assumption that quarks created in different environments fragment in the same manner.

Exploiting the particle identification capabilities of the TPC, we performed a similar study for kaon distributions. Since a sizeable fraction of kaons results from initial strange quarks and from charm or bottom decays, a kaon has a much better "memory" of the parent quark type and charge than has an average pion. Consequently, the ratio R_N of non-singlet and singlet fragmentation functions should be larger for kaons. Although lack of statistics prevents us from a detailed exploration of R_N for kaons, we indeed obtain for the rapidity region $y > 1$ a large value of $R_N(y) = 0.70 \pm 0.17$. The SRC-dominated region $y < 1$ yields $R_N(y) = 0.45 \pm 0.18$.

The measurement of R_S, and hence of the variation of fragmentation properties among quark flavors represents a more complicated task, since the event selection criteria introduce artificial long-range correlations. This is evident from Fig. 2a), where the mean number of charged hadrons in one jet is displayed as a function of the number of charged hadrons in the opposite jet. No acceptance corrections have been applied. The apparent anti-correlation for low multiplicities is caused by the event selection requirement of at least 5 charged hadrons in both jets together. Whereas such effects cancel in the charge-weighted non-singlet correlations, they distort the singlet correlation coefficients significantly. We therefore modify the event selection criteria such as to treat the two jets in an event independently of each other. For each event, we reconstruct two jets using a cluster algorithm and require each jet individually to have at least 3 particles and 3.5 GeV total energy. To reject $\tau\bar{\tau}$ events, each jet must either contain more than 3 charged hadrons or have an invariant mass above 2.1 GeV. Two jets have to be collinear within 15° in order to reject 2γ reactions and events with sizeable initial state radiation. Rapidities and transverse momenta of particles are defined with respect to the axis of the jet to which the particle belongs. The resulting sample of 11000 events contains less than 2% background. We have verified that differences in the shape of fragmentation functions are not obscured by this tighter selection. Fig. 2b) demonstrates the absence of induced jet-jet multiplicity correlations using the modified event selection. Note that here all fragmentation products of a given quark are considered to form one jet, including particles created by gluons radiated off that quark.

For pions in these events, we derive the correlation coefficients $C_S(x,x)$ and $C_S(y,y)$. We find that C_s is always positive or consistent with zero. Fig. 1e) shows the ratio $R_S(x)$ representing the rms variation of fragmentation functions over quark flavors, normalized to the average fragmentation function. Fig. 1f) dispays $R_S(y)$. The dashed lines again indicate our estimate of remaining short-range effects; the full lines show LUND-model predictions for

$R_S = \Delta/S$, as defined in Eqs. (6) and (8). The errors shown are statistical only. Monte-Carlo studies show that outside the range of short-range effects (i.e. outside the first bin) systematic deviations between the measured R_S and the true rms spread of fragmentation functions are below 0.1 units. The systematic error is mainly due to remaining correlations introduced by event selection and detector geometry, and due to events with high-momentum, large-angle gluons, which cannot be unambiguously assigned to either jet. Figs. 1e) and 1f) indicate that especially for higher momenta the fragmentation functions for different quark flavors differ appreciably. This observation agrees with conclusions obtained using flavor tagging techniques[1,2]. The deviations from a universal behaviour are quantitatively reproduced by the LUND Monte-Carlo model.

The technique can be used to study other jet properties in addition to fragmentation functions. For example, the mean transverse momentum $\langle p_T \rangle$ of hadrons in a jet is a flavor singlet quantity, and its variation over quark flavors can be investigated. In the color-string model, the mean transverse momentum of hadrons in a jet is related to the string tension. A universal value of $\langle p_T \rangle$ indicates a universal value of the string tension for light and heavy quarks. From a measurement of the correlation coefficient C_S (Eq. 6) of mean transverse momenta of particles in opposite jets we find that the rms-variation of $\langle p_T \rangle$ for the different quark flavors is less than 10% of the typical $<p_T>$:

$$\{\Sigma\epsilon_q <p_T>_q^2 - <<p_T>>^2\}^{1/2} < 40 \text{ MeV (90\% c.l.)}$$

Here $<<p_T>> \approx 400$ MeV stands for the mean transverse momentum averaged over flavors. Higher moments of p_T distributions exhibit a larger variation, indicating that the shapes of the distributions may differ.

In summary, we observe significant long-range correlations in e^+e^- annihilation. Their pattern is consistent with the assumption that these LRC's have no dynamical origin, but are entirely due to the creation of different flavors of quark-antiquark pairs at the primary vertex. We emphasize the interpretation of the observed LRC's in terms of flavor-singlet and non-singlet fragmentation functions and present a first measurement of non-singlet distributions in e^+e^- annihilation.

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8. We will often refer to N_{rms} as the "average non-singlet fragmentation function" in a sense that $N_{rms}(\xi)$ approximates the average magnitude $\Sigma\epsilon_q|N_q(\xi)|$ of non-singlet distributions; given the statistical

accuracy of the data, the difference between this linear average and the quadratic average is essentially negligible.

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Other fragmentation models such as
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yield similar results.

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Figure captions

1. a,b) Full circles: average singlet fragmentation functions for charged pions $S(x) = (1/\sigma_{jet}\beta)(d\sigma/dx)$, $x = 2E/\sqrt{s}$, and $S(y) = (1/\sigma_{jet})(d\sigma/dy)$. Open circles: average non-singlet fragmentation functions $\sqrt{-C_N(x)} = N_{rms}(x)$, and $\sqrt{C_N(y)} = N_{rms}(y)$. See text and c,d) for comments on systematic errors.

c,d) Open squares: ratio $R_N = \sqrt{-C_N}/S$ as a function of x and y, respectively, for $\pi^{\pm}$. R_N measures the ratio of average flavor non-singlet to singlet fragmentation functions. Crosses in c): Ratio of singlet over nonsinglet fragmentation functions from νN and $\bar{\nu} N$ interactions[11]. Dotted lines: estimated increase of the measured over the true R due to contributions to C from short-range correlations[10]. Full lines: model predictions for the non-singlet/singlet ratio[10]. The structure around y = 2 is caused by charmed hadrons.

e,f) Ratio $R_S = \sqrt{C_S}/S$ as a function of x and y, respectively, for charged pions. R_S measures the relative rms variation of singlet fragmentation functions S_q over quark flavors. Dotted lines: see c,d). Full lines: model predictions for the relative rms variation of S_q.

2. Mean multiplicity of charged hadrons in one jet of an event vs. multiplicity in the other jet, using the standard event selection (a) and independent selection criteria for each jet (b).

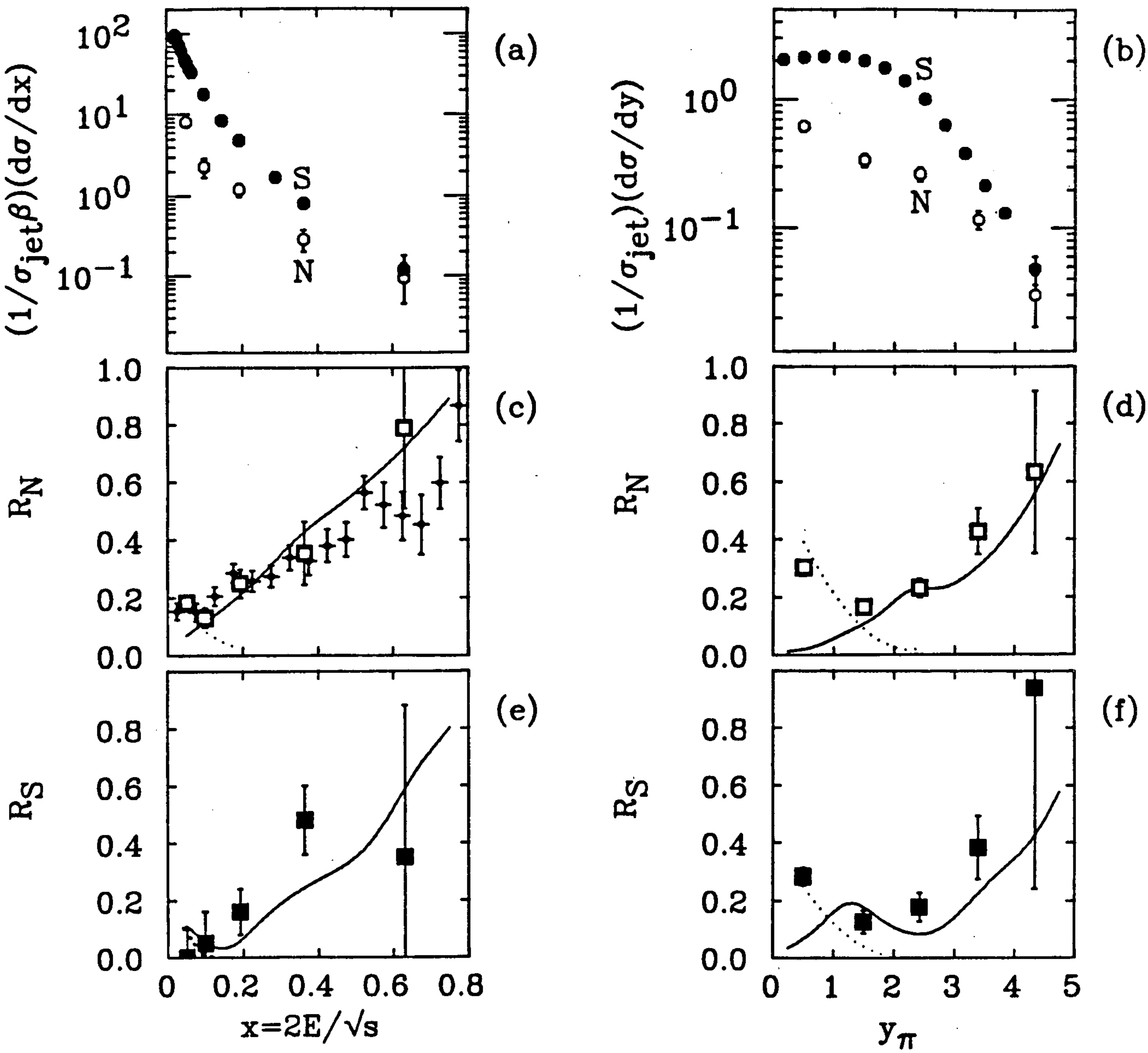

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Fig. 1

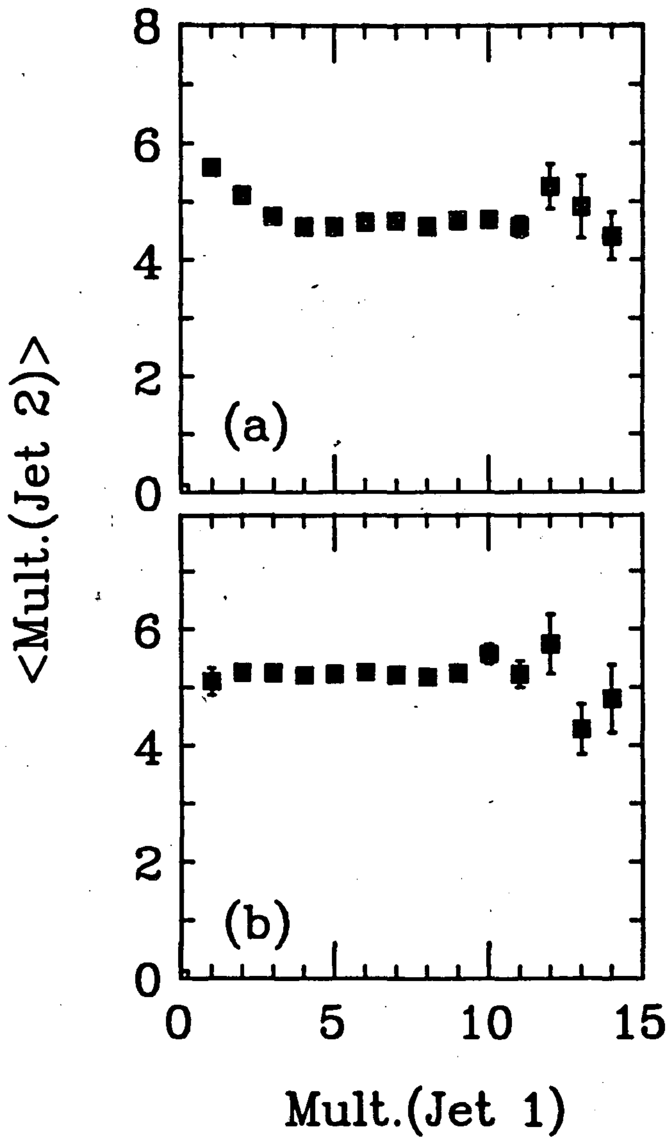

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Fig. 2

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