First Study of Rapidity Gaps in e^+e^- Annihilation

K. Abe,[20] K. Abe,[30] I. Abt,[14] T. Akagi,[28] N. J. Allen,[4] W. W. Ash,[28,*] D. Aston,[28] K. G. Baird,[25] C. Baltay,[34]
H. R. Band,[33] M. B. Barakat,[34] G. Baranko,[10] O. Bardon,[16] T. Barklow,[28] G. L. Bashindzhagyan,[19] A. O. Bazarko,[11]
R. Ben-David,[34] A. C. Benvenuti,[2] G. M. Bilei,[23] D. Bisello,[22] G. Blaylock,[7] J. R. Bogart,[28] T. Bolton,[11] G. R. Bower,[28]
J. E. Brau,[21] M. Breidenbach,[28] W. M. Bugg,[29] D. Burke,[28] T. H. Burnett,[32] P. N. Burrows,[16] W. Busza,[16]
A. Calcaterra,[13] D. O. Caldwell,[6] D. Calloway,[28] B. Camanzi,[12] M. Carpinelli,[24] R. Cassell,[28] R. Castaldi,[24,†]
A. Castro,[22] M. Cavalli-Sforza,[7] A. Chou,[28] E. Church,[32] H. O. Cohn,[29] J. A. Coller,[3] V. Cook,[32] R. Cotton,[4]
R. F. Cowan,[16] D. G. Coyne,[7] G. Crawford,[28] A. D'Oliveira,[8] C. J. S. Damerell,[26] M. Daoudi,[28] R. De Sangro,[13]
P. De Simone,[13] R. Dell'Orso,[24] P. J. Dervan,[4] M. Dima,[9] D. N. Dong,[16] P. Y. C. Du,[29] R. Dubois,[28] B. I. Eisenstein,[14]
R. Elia,[28] E. Etzion,[4] D. Falciai,[23] C. Fan,[10] M. J. Fero,[16] R. Frey,[21] K. Furuno,[21] T. Gillman,[26] G. Gladding,[14]
S. Gonzalez,[16] G. D. Hallewell,[28] E. L. Hart,[29] A. Hasan,[4] Y. Hasegawa,[30] K. Hasuko,[30] S. Hedges,[3] S. S. Hertzbach,[17]
M. D. Hildreth,[28] J. Huber,[21] M. E. Huffer,[28] E. W. Hughes,[28] H. Hwang,[21] Y. Iwasaki,[30] D. J. Jackson,[26] P. Jacques,[25]
J. Jaros,[28] A. S. Johnson,[3] J. R. Johnson,[33] R. A. Johnson,[8] T. Junk,[28] R. Kajikawa,[20] M. Kalelkar,[25] H. J. Kang,[27]
I. Karliner,[14] H. Kawahara,[28] H. W. Kendall,[16] Y. Kim,[27] M. E. King,[28] R. King,[28] R. R. Kofler,[17] N. M. Krishna,[10]
R. S. Kroeger,[18] J. F. Labs,[28] M. Langston,[21] A. Lath,[16] J. A. Lauber,[10] D. W. G. S. Leith,[28] V. Lia,[16] M. X. Liu,[34]
X. Liu,[7] M. Loreti,[22] A. Lu,[6] H. L. Lynch,[28] J. Ma,[32] G. Mancinelli,[23] S. Manly,[34] G. Mantovani,[23]
T. W. Markiewicz,[28] T. Maruyama,[28] R. Massetti,[23] H. Masuda,[28] E. Mazzucato,[12] A. K. McKemey,[4] B. T. Meadows,[8]
R. Messner,[28] P. M. Mockett,[32] K. C. Moffeit,[28] B. Mours,[28] D. Muller,[28] T. Nagamine,[28] S. Narita,[30] U. Nauenberg,[10]
H. Neal,[28] M. Nussbaum,[8] Y. Ohnishi,[20] L. S. Osborne,[16] R. S. Panvini,[31] H. Park,[21] T. J. Pavel,[28] I. Peruzzi,[13,†]
M. Piccolo,[13] L. Piemontese,[12] E. Pieroni,[24] K. T. Pitts,[21] R. J. Plano,[25] R. Prepost,[33] C. Y. Prescott,[28] G. D. Punkar,[28]
J. Quigley,[16] B. N. Ratcliff,[28] T. W. Reeves,[31] J. Reidy,[18] P. E. Rensing,[28] L. S. Rochester,[28] P. C. Rowson,[11]
J. J. Russell,[28] O. H. Saxton,[28] T. Schalk,[7] R. H. Schindler,[28] B. A. Schumm,[15] S. Sen,[34] V. V. Serbo,[33]
M. H. Shaevitz,[11] J. T. Shank,[3] G. Shapiro,[15] D. J. Sherden,[28] K. D. Shmakov,[29] C. Simopoulos,[28] N. B. Sinev,[21]
S. R. Smith,[28] J. A. Snyder,[34] P. Stamer,[25] H. Steiner,[15] R. Steiner,[1] M. G. Strauss,[17] D. Su,[28] F. Suekane,[30]
A. Sugiyama,[20] S. Suzuki,[20] M. Swartz,[28] A. Szumilo,[32] T. Takahashi,[28] F. E. Taylor,[16] E. Torrence,[16] A. I. Trandafir,[17]
J. D. Turk,[34] T. Usher,[28] J. Va'vra,[28] C. Vannini,[24] E. Vella,[28] J. P. Venuti,[31] R. Verdier,[16] P. G. Verdini,[24]
S. R. Wagner,[28] A. P. Waite,[28] S. J. Watts,[4] A. W. Weidemann,[29] E. R. Weiss,[32] J. S. Whitaker,[3] S. L. White,[29]
F. J. Wickens,[26] D. A. Williams,[7] D. C. Williams,[16] S. H. Williams,[28] S. Willocq,[34] R. J. Wilson,[9] W. J. Wisniewski,[28]
M. Woods,[28] G. B. Word,[25] J. Wyss,[22] R. K. Yamamoto,[16] J. M. Yamartino,[16] X. Yang,[21] S. J. Yellin,[6] C. C. Young,[28]
H. Yuta,[30] G. Zapalac,[33] R. W. Zdarko,[28] C. Zeitlin,[21] and J. Zhou[21]

(SLD Collaboration)

[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 Università di Ferrara, I-44100 Ferrara, Italy*
[13]*INFN Laboratori 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]*Moscow State University, Institute of Nuclear Physics, 119899 Moscow, Russia*
[20]*Nagoya University, Chikusa-ku, Nagoya 464, Japan*
[21]*University of Oregon, Eugene, Oregon 97403*

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[22]*INFN Sezione di Padova and Università di Padova, I-35100 Padova, Italy*
[23]*INFN Sezione di Perugia and Università di Perugia, I-06100 Perugia, Italy*
[24]*INFN Sezione di Pisa and Università di Pisa, I-56100 Pisa, Italy*
[25]*Rutgers University, Piscataway, New Jersey 08855*
[26]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[27]*Sogang University, Seoul, Korea*
[28]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[29]*University of Tennessee, Knoxville, Tennessee 37996*
[30]*Tohoku University, Sendai 980, Japan*
[31]*Vanderbilt University, Nashville, Tennessee 37235*
[32]*University of Washington, Seattle, Washington 98195*
[33]*University of Wisconsin, Madison, Wisconsin 53706*
[34]*Yale University, New Haven, Connecticut 06511*

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We present the first study of rapidity gaps in e^+e^- annihilations, using Z^0 decays collected by the SLAC Linear Collider Large Detector experiment. Our measured rapidity gap spectra fall exponentially with increasing gap size over five decades, and we observe no anomalous class of events containing large gaps. This supports the interpretation of the large-gap events measured in $p\overline{p}$ and ep collisions in terms of exchange of color-singlet objects. The presence of heavy flavors or additional jets does not affect these conclusions. [S0031-9007(96)00455-3]

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Since the initial observation of hadronic jets, rapidity has been used to characterize the momentum of particles in jets in a frame-invariant manner. The rapidity distribution has been studied in e^+e^- annihilation, *ep* and hadron-hadron collisions, and fixed-target experiments, and is a characteristic of strong interactions that is well described by perturbative QCD combined with iterative models of jet fragmentation [1]. Hard scattering of quarks or gluons can be modeled by color fields between the outgoing partons that fragment into the observed final-state particles, typically populating the whole rapidity range.

Recently, exchange of color-singlet objects in hard diffractive hadron-hadron scattering processes characterized by events containing large gaps in the particle rapidity spectrum has been discussed [2]. Subsequent studies of $p\overline{p}$ collisions at the Fermilab Tevatron collider found that roughly 1% of events comprising at least two high-transverse-energy (E_T) jets contain a large rapidity region between the two highest-E_T jets with no particle activity [3–5]. These events have been interpreted in terms of color-singlet exchange between the interacting partons. Exchange of electroweak bosons is estimated to contribute only a small fraction of the observed rate of gap events, and a model incorporating pomeron exchange is in agreement with the data [4,5]. Large rapidity gaps have also been observed in roughly 10% of all photoproduced dijet events in deep-inelastic scattering at the HERA *ep* collider [6,7] and have also been interpreted in terms of color-singlet exchange. Models involving either vector meson dominance of the exchanged virtual photon or hard diffractive scattering via pomerons describe the data [6,7].

Color exchange processes account successfully for the properties of the majority of dijet events and may give rise to large rapidity gaps due to random fluctuations. In both the *ep* and $p\overline{p}$ cases the interpretation of rapidity-gap events in terms of color-singlet exchange depends upon an understanding of this color-exchange background. In the $p\overline{p}$ experiments this was estimated by extrapolation of fits to the particle multiplicity distribution in rapidity intervals into the zero-particle, or rapidity gap, region [4,5]. In the *ep* experiments the background was estimated using both a Monte Carlo simulation and an *ad hoc* parametrization of color exchange [7]. In both cases direct measurement of the spectrum of rapidity gaps arising in color-exchange jet fragmentation is preferable and would clarify the interpretation of the large-gap events.

Electron-positron annihilation into hadronic final states provides an ideal laboratory for study of this issue as, in QCD, it proceeds via creation of a primary quark and antiquark connected by a color field which fragments into the observed hadrons. The inclusive particle rapidity distribution has a broad plateau centered at zero [8]. Inclusive studies of the local rapidity density of particles have been performed [9] with the aim of investigating scale-invariant cascade mechanisms in multiparticle production, but no previous study has been made of the size of rapidity gaps between adjacent particles. Large gaps are expected to occur in $e^+e^- \to Z^0 \to q\overline{q}q\overline{q}$ or $q\overline{q}gg$ events when two color-singlet pairs of partons are formed. The production rate of such events with a gap of at least two units of rapidity is estimated [10] to be about 10^{-5} of all hadronic Z^0 decays, but with an unknown background from fluctuations in $Z^0 \to q\overline{q}$ fragmentation.

Here we present the first measurements of rapidity gaps in $e^+e^- \to$ hadrons, using Z^0 decays. We compare our results with the JETSET 7.4 [11] jet fragmentation model and with the perturbative QCD prediction [10] for the rate of large-gap events. We compare our results with measurements from $p\overline{p}$ collisions where hadronic jets are initiated by scattering of u and d quarks or gluons, and with measurements from ep collisions where jets are initiated predominantly by u or d quarks. We have isolated event samples enriched in primary light (u, d, s) and heavy (b) quarks, and have measured rapidity gap spectra in both. Finally, we have studied the dependence of the rapidity gap spectra on the event jet topology.

The e^+e^- annihilation events produced at the Z^0 resonance by the SLAC Linear Collider (SLC) have been recorded using the SLC Large Detector (SLD) [12]. This analysis used the charged tracks measured in the central drift chamber [13] and in the vertex detector [14]. The trigger and initial hadronic event selection criteria are described elsewhere [15]. Events were required to have a minimum of five well-measured tracks [15], a thrust axis [16] direction within $|\cos\theta_T| < 0.71$, and a charged energy calculated from the selected tracks assuming the $\pi^\pm$ mass of at least 20 GeV. From our 1993–95 data samples 101 676 events passed these cuts, including the background of $(0.3 \pm 0.1)\%$ dominated by $Z^0 \rightarrow \tau^+\tau^-$ events.

Particle rapidity $y = 0.5\ln(E + p_\parallel)/(E - p_\parallel)$, where E is the particle energy and $p_\parallel$ its momentum component along the thrust axis of the event, was calculated from the measured momentum assuming the $\pi^\pm$ mass. The charged track rapidity spectrum is shown in Fig. 1(a). We ordered the N tracks in each event by their rapidity, which defined $N - 1$ rapidity gaps, Δy, between pairs of adjacent tracks. For each event we considered the largest gap Δy_{max}, the average gap $\langle \Delta y \rangle$, and the size of the central gap Δy_{cent}, i.e., that gap containing the mean rapidity of the tracks. The Δy_{max} distribution is shown in Fig. 1(b); as Δy_{max} increases it rises to a peak around $\Delta y_{\mathrm{max}} = 1$, and for $1 \leq \Delta y_{\mathrm{max}} \leq 6$ it falls approximately exponentially; for $\Delta y_{\mathrm{max}} \geq 6$ a "shoulder" is apparent, suggesting that the data sample contains a class of events characterized by large rapidity gaps.

This feature was found to be due to the 0.3% contamination of $\tau^+\tau^-$ events in the $q\overline{q}$ sample. The y and Δy_{max} distributions for a sample of JETSET 7.4 [11] $q\overline{q}$ and KORALZ 3.8 [17] $\tau^+\tau^-$ Monte Carlo events, combined according to their standard model fractions of Z^0 decays and subjected to a simulation of the detector and to the same selection cuts as the data, are also shown in Figs. 1(a) and 1(b), respectively; the simulation describes the data well. The requirement on the minimum number of charged tracks per event n_{ch} was increased from 5 to 7, yielding 100 964 events with a reduced contribution from $\tau^+\tau^-$ events of 0.13%. The resulting Δy_{max} distributions for the data and simulated events are shown in Fig. 1(b); for $\Delta y_{\mathrm{max}} \geq 1.0$ the data fall exponentially and are well modeled by the simulation. Similar results were obtained for $\langle \Delta y \rangle$ and Δy_{cent} (not shown). All further analysis was based upon the requirement $n_{\mathrm{ch}} \geq 7$.

Also shown in Fig. 1(b) is the Δy_{max} distribution from JETSET $q\overline{q}$ events at the generator level; all particles, except neutrinos, with lifetimes larger than 3×10^{-10} sec, as well as π^0's, were considered stable and were used in the analysis. Comparison of this with the measured distribution indicates the effects of the detector and of the track and event selection criteria, in particular, the exclusion of neutral particles, on the Δy_{max} spectrum. The generator-level spectrum exhibits the same structure as the data, and it is shifted to smaller values of Δy_{max} and has a steeper exponential decrease due to the larger number of particles considered in each event.

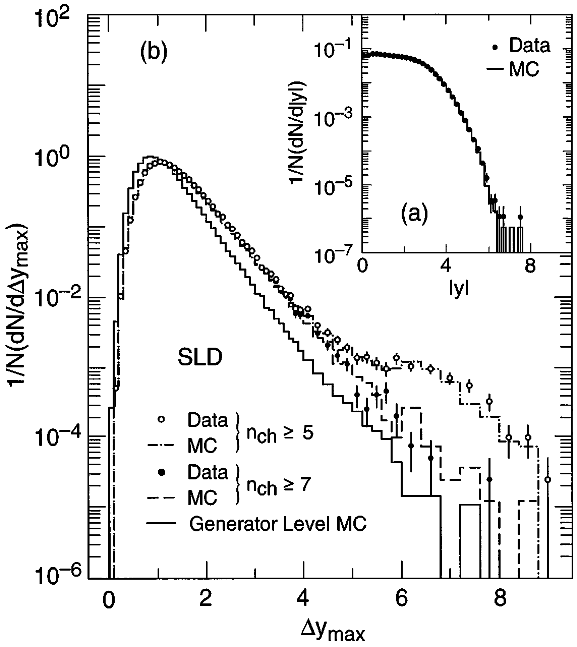

FIG. 1. (a) Normalized distribution of the absolute rapidity of charged particles; data (solid circles) and Monte Carlo simulation (histogram). (b) Normalized distribution of event maximum rapidity gap. For $n_{\mathrm{ch}} \geq 5$ $(n_{\mathrm{ch}} \geq 7)$ the data are shown as open (solid) circles and the combined $q\overline{q}$ and $\tau^+\tau^-$ Monte Carlo sample is shown as the dot-dashed (dashed) histogram. The solid histogram is the distribution for Monte Carlo $q\overline{q}$ events at the generator level.

We quantified our data sample in terms of the fraction of events $f(y_0)$ containing no charged particles in the interval $|y| \leq y_0/2$, shown in Fig. 2; it falls exponentially. The JETSET $q\overline{q}$ simulation falls below the data for $y_0 \geq 3$, but the data are well described by the simulation including $\tau^+\tau^-$ events, demonstrating that even for events with $n_{\mathrm{ch}} \geq 7$ the influence of $\tau^+\tau^-$ event contamination is noticeable at large gap values. In Fig. 2 we compare $f(y_0)$ with the perturbative QCD prediction [10] for the fraction of Z^0 decays into $q\overline{q}q\overline{q}$ and $q\overline{q}gg$, where in each case two color-singlet parton pairs are produced with rapidity separation y_0. The prediction, for $\alpha_s(M_Z^2) = 0.120 \pm 0.008$ [15], has a similar exponential falloff to the data, but is between 2 and 3 orders of magnitude smaller. The effect of neglect of neutral particles (Fig. 1) is much smaller than this difference. These results imply that the

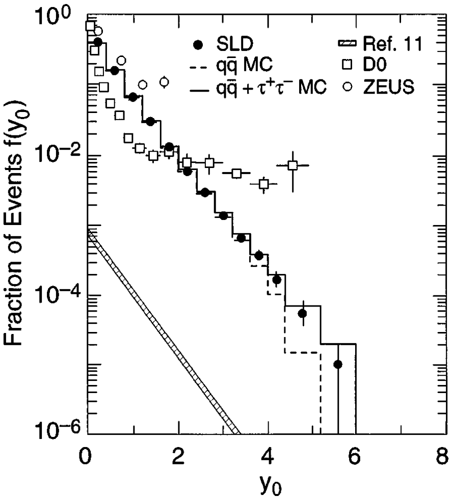

FIG. 2. Fraction of events containing no charged particle within $|y| \leq y_0/2$ (solid circles). Prediction from JETSET $q\overline{q}$ events (dashed histogram), and from the combined sample of $q\overline{q}$ and $\tau^+\tau^-$ events (solid histogram). The hatched region is the prediction from Ref. [10]. Similar results are shown from D0 [3] (squares) and ZEUS [7] (open circles).

production of events with large rapidity gaps in hadronic Z^0 decays is dominated by fluctuations in color-exchange jet fragmentation.

We also compare $f(y_0)$ with similar measurements from $p\overline{p}$ and ep collisions, although, due to differences in selected event topology, particle selection, and definition of rapidity, such a comparison can be made in qualitative terms only. The D0 Collaboration has studied [3] the fraction of events that have no tagged particles in pseudorapidity space between the two highest-E_T jets in their multijet event data sample. Jets were defined using a cone algorithm [3] and required to have $E_T > 30$ GeV; y_0 was taken to be the difference in pseudorapidity between the edges of the two jet cones, and a tagged particle was defined to be a tower in the D0 electromagnetic calorimeter with $E_T > 200$ MeV. For $y_0 \leq 1$ the D0 results decrease exponentially (Fig. 2); for $y_0 > 1$ they indicate a plateau, with $f(y_0 > 3) = 0.0053 \pm 0.0009$ [3]. The CDF Collaboration has reported similar results, $f(0.8 \leq y_0 \leq 4) = 0.0085^{+0.0026}_{-0.0017}$ [4], based upon absence of charged tracks of momentum larger than 400 MeV/c between jets. The ZEUS Collaboration has studied [7] photoproduced events containing two jets with $E_T > 6$ GeV. The fraction of events that have no calorimeter clusters with $E_T > 250$ MeV between the two jets, defined using a similar cone algorithm as D0 but with a larger cone radius, decreases with y_0 (Fig. 2) but may reach a plateau; $f(y_0 = 1.7) = 0.11^{+0.02}_{-0.03}$ [7].

For $y_0 < 1$ our measurement of an exponentially falling rate of gap events is qualitatively similar to both the $p\overline{p}$ and ep cases at low y_0. For $y_0 > 1$ our measured exponential decrease, which is well described by the JETSET model for color exchange between the primary quark and antiquark, contrasts with the onset of a plateau in the $p\overline{p}$ and ep data samples, and supports the interpretation of the large-gap events in $p\overline{p}$ and ep collisions in terms of hard colorless exchange processes [3–5].

The JADE jet-finding algorithm [18] was used to define jets and the rapidity and gap distribution were studied as a function of the jet multiplicity of the events. We considered 2-jet and ≥3-jet events defined for values of the scaled jet-pair invariant mass in the range $0.005 \leq y_{\text{cut}} \leq 0.13$. We show results for the 12 394 2-jet events at $y_{\text{cut}} = 0.005$ and the 6885 ≥3-jet events at $y_{\text{cut}} = 0.13$. The former are events with two narrow back-to-back jets, while the latter events contain at least 3 well-separated jets where the additional jet(s) are typically due to hard gluon radiation.

The 2-jet rapidity spectrum [Fig. 3(a)] peaks at $|y| \sim 2.5$ and the region $|y| < 2.5$ is depleted but nonzero, reflecting the color field between the q and $\overline{q}$. The ≥3-jet rapidity spectrum peaks at a lower value, which is expected from the lower-jet energies, the jet topology, and higher event track multiplicity. Corresponding effects are visible in the Δy_{max} distributions [Fig. 3(b)]; the 2-jet events peak at a gap of 1.5 units, and there is a long tail at high gap values; the 3-jet events peak at a gap size of about 0.7 unit and there are few events with $\Delta y_{\text{max}} > 2.5$. Similar results were observed at other values of y_{cut} and for the $\langle \Delta y \rangle$ and Δy_{cent} distributions (not shown). In all cases the high-gap tails demonstrate exponential falloff and are well described by hadronic Monte Carlo samples subjected to the same selection criteria.

The rapidity and gap spectra were studied as a function of event primary flavor using impact parameters of charged tracks measured in the vertex detector to tag samples enriched in light ($Z^0 \rightarrow u\overline{u}$, $d\overline{d}$, or $s\overline{s}$) and heavy ($Z^0 \rightarrow b\overline{b}$) flavor. The 65 243 events containing no track with normalized transverse impact parameter with respect to the interaction point $b/\sigma_b > 3$ were assigned to the light-flavor sample. The 13 269 events containing three or more tracks with $b/\sigma_b > 3$ were assigned to the heavy-flavor sample. The light-flavor content of the light sample was estimated to be 85% and the b flavor content of the heavy sample was estimated to be 89%. Details of flavor tagging are discussed in Ref. [19].

The rapidity spectrum of the b-tagged sample [Fig. 3(c)] is relatively flat out to $|y| \sim 2.4$ and falls sharply thereafter. The light quark spectrum peaks at $|y| \sim 0.6$ and falls more slowly at high rapidity. This difference can be explained by the fact that the rapidity of B hadrons in Z^0 decays peaks strongly at $|y| \approx 2.3$, corresponding to the average B momentum of 32 GeV/c [20], and the large number of B-hadron decay products contributes only a small additional spread about this value; additional tracks from fragmentation following the B-hadron formation are restricted to lower momenta and

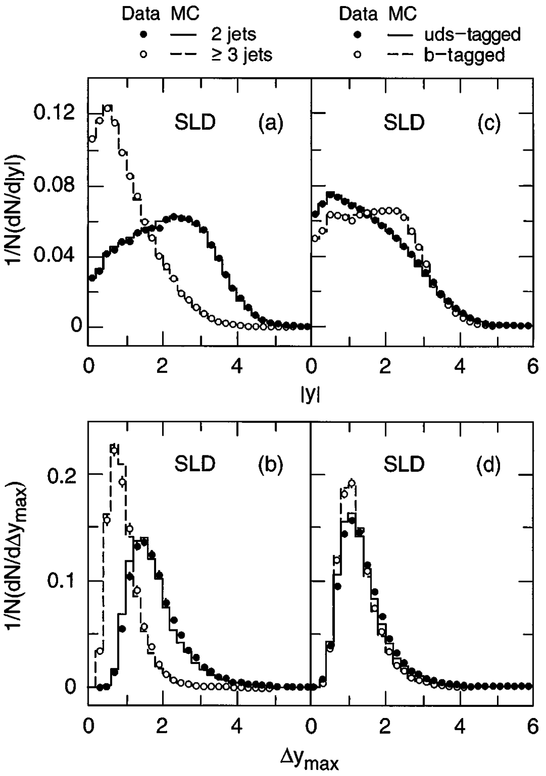

FIG. 3. Normalized distributions of (a) charged particle rapidity and (b) event maximum rapidity gap for 2-jet (solid circles) and ≥3-jet (open circles) events; the simulations are shown as solid (2-jet events) and dashed (≥3-jet events) histograms. Normalized distributions of (c) charged particle rapidity and (d) event maximum rapidity gap for *u*-, *d*-, *s*- (solid circles), and *b*-tagged (open circles) samples; the simulations are shown as solid (*u*-, *d*-, *s*-tagged) and dashed (*b*-tagged) histograms.

rapidities. For $\Delta y_{\max}$ [Fig. 3(d)], as well as $\langle \Delta y \rangle$ and Δy_{cent} (not shown), the distributions for the two flavor-tagged samples are found to peak at roughly the same value, but the *b*-tagged distribution falls faster at high values. These features are expected since the rapidity of *B* hadrons in Z^0 decays is limited to 2.8, and their high decay multiplicity populates the region $|y| < 2.8$ independent of the fragmentation process. The behavior of $f(y_0)$ is similar for both flavor-tagged samples (not shown), although the slope of the exponential decrease is greater in the *b*-tagged case.

In conclusion, we have studied distributions of rapidity and of rapidity gaps using charged particles in $e^+e^- \longrightarrow Z^0 \longrightarrow q\overline{q}$ decays, and their dependence on the jet topology and quark flavor of the events. After accounting for backgrounds from $\tau^+\tau^-$ events, we find that the inclusive distribution of the maximum rapidity gap per event peaks at about 1 unit and subsequently falls exponentially with increasing gap size. In contrast to results from $p\overline{p}$ and *ep* collisions we find no evidence for any anomalous class of events characterized by large rapidity gaps, and thus support the interpretation of the large-gap $p\overline{p}$ and *ep* events in terms of exchange of color-singlet objects. Differences in peak position and exponent of the falloff between samples of different jet multiplicity or flavor can be explained by differences in event topology, charged multiplicity, and the effects of *B*-hadron production and decay.

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*Deceased.

†Also at the Università di Genova, I-16146 Genova, Italy.

†Also at the Università di Perugia, I-06100 Perugia, Italy.

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