Jet Production via Strongly-Interacting Color-Singlet Exchange in $p\bar{p}$ Collisions

S. Abachi,[12] B. Abbott,[34] M. Abolins,[23] B.S. Acharya,[42] I. Adam,[10] D.L. Adams,[35] M. Adams,[15] S. Ahn,[12] H. Aihara,[20] J. Alitti,[38] G. Álvarez,[16] G.A. Alves,[8] E. Amidi,[27] N. Amos,[22] E.W. Anderson,[17] S.H. Aronson,[3] R. Astur,[40] R.E. Avery,[29] A. Baden,[21] V. Balamurali,[30] J. Balderston,[14] B. Baldin,[12] J. Bantly,[4] J.F. Bartlett,[12] K. Bazizi,[37] J. Bendich,[20] S.B. Beri,[32] I. Bertram,[35] V.A. Bezzubov,[33] P.C. Bhat,[12] V. Bhatnagar,[32] M. Bhattacharjee,[11] A. Bischoff,[7] N. Biswas,[30] G. Blazey,[12] S. Blessing,[13] P. Bloom,[5] A. Boehnlein,[12] N.I. Bojko,[33] F. Borcherding,[12] J. Borders,[37] C. Boswell,[7] A. Brandt,[12] R. Brock,[23] A. Bross,[12] D. Buchholz,[29] V.S. Burtovoi,[33] J.M. Butler,[12] W. Carvalho,[8] D. Casey,[37] H. Castilla-Valdez,[9] D. Chakraborty,[40] S.-M. Chang,[27] S.V. Chekulaev,[33] L.-P. Chen,[20] W. Chen,[40] L. Chevalier,[38] S. Chopra,[32] B.C. Choudhary,[7] J.H. Christenson,[12] M. Chung,[15] D. Claes,[40] A.R. Clark,[20] W.G. Cobau,[21] J. Cochran,[7] W.E. Cooper,[12] C. Cretsinger,[37] D. Cullen-Vidal,[4] M.A.C. Cummings,[14] D. Cutts,[4] O.I. Dahl,[20] K. De,[43] M. Demarteau,[12] R. Demina,[27] K. Denisenko,[12] N. Denisenko,[12] D. Denisov,[12] S.P. Denisov,[33] H.T. Diehl,[12] M. Diesburg,[12] G. Di Loreto,[23] R. Dixon,[12] P. Draper,[43] J. Drinkard,[6] Y. Ducros,[38] S.R. Dugad,[42] S. Durston-Johnson,[37] D. Edmunds,[23] J. Ellison,[7] V.D. Elvira,[12,*] R. Engelmann,[40] S. Eno,[21] G. Eppley,[35] P. Ermolov,[24] O.V. Eroshin,[33] V.N. Evdokimov,[33] S. Fahey,[23] T. Fahland,[4] M. Fatyga,[3] M.K. Fatyga,[37] J. Featherly,[3] S. Feher,[40] D. Fein,[2] T. Ferbel,[37] G. Finocchiaro,[40] H.E. Fisk,[12] Y. Fisyak,[5] E. Flattum,[23] G.E. Forden,[2] M. Fortner,[28] K.C. Frame,[23] P. Franzini,[10] S. Fuess,[12] E. Gallas,[43] A.N. Galyaev,[33] T.L. Geld,[23] R.J. Genik II,[23] K. Genser,[12] C.E. Gerber,[12,†] B. Gibbard,[3] V. Glebov,[37] S. Glenn,[5] B. Gobbi,[29] M. Goforth,[13] A. Goldschmidt,[20] B. Gómez,[1] P.I. Goncharov,[33] J.L. González Solís,[9] H. Gordon,[3] L.T. Goss,[44] N. Graf,[3] P.D. Grannis,[40] D.R. Green,[12] J. Green,[28] H. Greenlee,[12] G. Griffin,[6] N. Grossman,[12] P. Grudberg,[20] S. Grünendahl,[37] W.X. Gu,[12,‡] G. Guglielmo,[31] J.A. Guida,[2] J.M. Guida,[3] W. Guryn,[3] S.N. Gurzhiev,[33] P. Gutierrez,[31] Y.E. Gutnikov,[33] N.J. Hadley,[21] H. Haggerty,[12] S. Hagopian,[13] V. Hagopian,[13] K.S. Hahn,[37] R.E. Hall,[6] S. Hansen,[12] R. Hatcher,[23] J.M. Hauptman,[17] D. Hedin,[28] A.P. Heinson,[7] U. Heintz,[12] R. Hernández-Montoya,[9] T. Heuring,[13] R. Hirosky,[13] J.D. Hobbs,[12] B. Hoeneisen,[1,§] J.S. Hoftun,[4] F. Hsieh,[22] Tao Hu,[12,‡] Ting Hu,[40] Tong Hu,[16] T. Huehn,[7] S. Igarashi,[12] A.S. Ito,[12] E. James,[2] J. Jaques,[30] S.A. Jerger,[23] J.Z.-Y. Jiang,[40] T. Joffe-Minor,[29] H. Johari,[27] K. Johns,[2] M. Johnson,[12] H. Johnstad,[41] A. Jonckheere,[12] M. Jones,[14] H. Jöstlein,[12] S.Y. Jun,[29] C.K. Jung,[40] S. Kahn,[3] G. Kalbfleisch,[31] J.S. Kang,[18] R. Kehoe,[30] M.L. Kelly,[30] A. Kernan,[7] L. Kerth,[20] C.L. Kim,[18] S.K. Kim,[39] A. Klatchko,[13] B. Klima,[12] B.I. Klochkov,[33] C. Klopfenstein,[5] V.I. Klyukhin,[33] V.I. Kochetkov,[33] J.M. Kohli,[32] D. Koltick,[34] A.V. Kostritskiy,[33] J. Kotcher,[3] J. Kourlas,[26] A.V. Kozelov,[33] E.A. Kozlovski,[33] M.R. Krishnaswamy,[42] S. Krzywdzinski,[12] S. Kunori,[21] S. Lami,[40] G. Landsberg,[12] J-F. Lebrat,[38] A. Leflat,[24] H. Li,[40] J. Li,[43] Y.K. Li,[29] Q.Z. Li-Demarteau,[12] J.G.R. Lima,[36] D. Lincoln,[22] S.L. Linn,[13] J. Linnemann,[23] R. Lipton,[12] Y.C. Liu,[29] F. Lobkowicz,[37] S.C. Loken,[20] S. Lökös,[40] L. Lueking,[12] A.L. Lyon,[21] A.K.A. Maciel,[8] R.J. Madaras,[20] R. Madden,[13] I.V. Mandrichenko,[33] Ph. Mangeot,[38] S. Mani,[5] B. Mansoulié,[38] H.S. Mao,[12,‡] S. Margulies,[15] R. Markeloff,[28] L. Markosky,[2] T. Marshall,[16] M.I. Martin,[12] M. Marx,[40] B. May,[29] A.A. Mayorov,[33] R. McCarthy,[40] T. McKibben,[15] J. McKinley,[23] T. McMahon,[31] H.L. Melanson,[12] J.R.T. de Mello Neto,[36] K.W. Merritt,[12] H. Miettinen,[35] A. Milder,[2] A. Mincer,[26] J.M. de Miranda,[8] C.S. Mishra,[12] M. Mohammadi-Baarmand,[40] N. Mokhov,[12] N.K. Mondal,[42] H.E. Montgomery,[12] P. Mooney,[1] M. Mudan,[26] C. Murphy,[16] C.T. Murphy,[12] F. Nang,[4] M. Narain,[12] V.S. Narasimham,[42] A. Narayanan,[2] H.A. Neal,[22] J.P. Negret,[1] E. Neis,[22] P. Nemethy,[26] D. Nešić,[4] M. Nicola,[8] D. Norman,[44] L. Oesch,[22] V. Oguri,[36] E. Oltman,[20] N. Oshima,[12] D. Owen,[23] P. Padley,[35] M. Pang,[17] A. Para,[12] C.H. Park,[12] Y.M. Park,[19] R. Partridge,[4] N. Parua,[42] M. Paterno,[37] J. Perkins,[43] A. Peryshkin,[12] M. Peters,[14] H. Piekarz,[13] Y. Pischalnikov,[34] A. Pluquet,[38] V.M. Podstavkov,[33] B.G. Pope,[23] H.B. Prosper,[13] S. Protopopescu,[3] D. Pušeljić,[20] J. Qian,[22] P.Z. Quintas,[12] R. Raja,[12] S. Rajagopalan,[40] O. Ramirez,[15] M.V.S. Rao,[42] P.A. Rapidis,[12] L. Rasmussen,[40] A.L. Read,[12] S. Reucroft,[27] M. Rijssenbeek,[40] T. Rockwell,[23] N.A. Roe,[20] P. Rubinov,[29] R. Ruchti,[30] S. Rusin,[24] J. Rutherfoord,[2] A. Santoro,[8] L. Sawyer,[43] R.D. Schamberger,[40] H. Schellman,[29] J. Sculli,[26] E. Shabalina,[24] C. Shaffer,[13] H.C. Shankar,[42] Y.Y. Shao,[12,‡] R.K. Shivpuri,[11] M. Shupe,[2] J.B. Singh,[32] V. Sirotenko,[28] W. Smart,[12] A. Smith,[2] R.P. Smith,[12] R. Snihur,[29] G.R. Snow,[25] S. Snyder,[3] J. Solomon,[15] P.M. Sood,[32] M. Sosebee,[43] M. Souza,[8] A.L. Spadafora,[20] R.W. Stephens,[43] M.L. Stevenson,[20] D. Stewart,[22] D.A. Stoianova,[33] D. Stoker,[6] K. Streets,[26] M. Strovink,[20] A. Sznajder,[8] A. Taketani,[12] P. Tamburello,[21] J. Tarazi,[6] M. Tartaglia,[12] T.L. Taylor,[29] J. Teiger,[38] J. Thompson,[21] T.G. Trippe,[20] P.M. Tuts,[10] N. Varelas,[23] E.W. Varnes,[20] P.R.G. Virador,[20] D. Vititoe,[2] A.A. Volkov,[33] A.P. Vorobiev,[33] H.D. Wahl,[13] G. Wang,[13] J. Warchol,[30] M. Wayne,[30] H. Weerts,[23] F. Wen,[13] A. White,[43] J.T. White,[44] J.A. Wightman,[17] J. Wilcox,[27] S. Willis,[28] S.J. Wimpenny,[7] J.V.D. Wirjawan,[44] J. Womersley,[12] E. Won,[37] D.R. Wood,[12] H. Xu,[4] R. Yamada,[12] P. Yamin,[3] C. Yanagisawa,[40] J. Yang,[26] T. Yasuda,[27] C. Yoshikawa,[14] S. Youssef,[13] J. Yu,[37] Y. Yu,[39] D.H. Zhang,[12,‡] Q. Zhu,[26] Z.H. Zhu,[37] D. Zieminska,[16] A. Zieminski,[16] and A. Zylberstejn[38]

(DØ Collaboration)

[1] *Universidad de los Andes, Bogotá, Colombia*
[2] *University of Arizona, Tucson, Arizona 85721*
[3] *Brookhaven National Laboratory, Upton, New York 11973*
[4] *Brown University, Providence, Rhode Island 02912*
[5] *University of California, Davis, California 95616*
[6] *University of California, Irvine, California 92717*
[7] *University of California, Riverside, California 92521*
[8] *LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[9] *CINVESTAV, Mexico City, Mexico*
[10] *Columbia University, New York, New York 10027*
[11] *Delhi University, Delhi, India 110007*
[12] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[13] *Florida State University, Tallahassee, Florida 32306*
[14] *University of Hawaii, Honolulu, Hawaii 96822*
[15] *University of Illinois at Chicago, Chicago, Illinois 60607*
[16] *Indiana University, Bloomington, Indiana 47405*
[17] *Iowa State University, Ames, Iowa 50011*
[18] *Korea University, Seoul, Korea*
[19] *Kyungsung University, Pusan, Korea*
[20] *Lawrence Berkeley Laboratory and University of California, Berkeley, California 94720*
[21] *University of Maryland, College Park, Maryland 20742*
[22] *University of Michigan, Ann Arbor, Michigan 48109*
[23] *Michigan State University, East Lansing, Michigan 48824*
[24] *Moscow State University, Moscow, Russia*
[25] *University of Nebraska, Lincoln, Nebraska 68588*
[26] *New York University, New York, New York 10003*
[27] *Northeastern University, Boston, Massachusetts 02115*
[28] *Northern Illinois University, DeKalb, Illinois 60115*
[29] *Northwestern University, Evanston, Illinois 60208*
[30] *University of Notre Dame, Notre Dame, Indiana 46556*
[31] *University of Oklahoma, Norman, Oklahoma 73019*
[32] *University of Panjab, Chandigarh 16-00-14, India*
[33] *Institute for High Energy Physics, 142-284 Protvino, Russia*
[34] *Purdue University, West Lafayette, Indiana 47907*
[35] *Rice University, Houston, Texas 77251*
[36] *Universidade Estadual do Rio de Janeiro, Brazil*
[37] *University of Rochester, Rochester, New York 14627*
[38] *CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, France*
[39] *Seoul National University, Seoul, Korea*
[40] *State University of New York, Stony Brook, New York 11794*
[41] *SSC Laboratory, Dallas, Texas 75237*
[42] *Tata Institute of Fundamental Research, Colaba, Bombay 400005, India*
[43] *University of Texas, Arlington, Texas 76019*
[44] *Texas A&M University, College Station, Texas 77843*

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A study of the particle multiplicity between jets with large rapidity separation has been performed using the DØ detector at the Fermilab Tevatron $p\bar{p}$ Collider operating at $\sqrt{s} = 1.8\,\mathrm{TeV}$. A significant excess of low-multiplicity events is observed above the expectation for color-exchange processes. The measured fractional excess is $1.07 \pm 0.10(\mathrm{stat})^{+0.25}_{-0.13}(\mathrm{syst})\%$, which is consistent with a strongly-interacting color-singlet (colorless) exchange process and cannot be explained by electroweak exchange alone. A lower limit of 0.80% (95% C.L.) is obtained on the fraction of dijet events with color-singlet exchange, independent of the rapidity gap survival probability.

Jet production in hadron-hadron collisions is typically associated with the exchange of a quark or gluon between interacting partons. In addition to these color-exchange processes, the exchange of an electroweak color singlet (photon, W or Z boson) or a strongly-interacting color singlet (such as two gluons in a colorless state), can also produce jets. Two jets separated by a rapidity gap, defined as a region of rapidity containing no final-state particles, has been proposed as a signature for jet production via the exchange of a color-singlet (colorless) object [1,2]. Theoretical calculations have confirmed that gluon radiation between scattered partons is highly suppressed for color-singlet exchange relative to color exchange [3,4].

The multiplicity of final-state particles in the rapidity interval between jets offers a convenient way to distinguish color-singlet exchange from color exchange. Color-singlet exchange is expected to give a multiplicity near zero for events that have no spectator interactions and a minimum bias-like multiplicity distribution for events that contain spectator interactions [2,3]. In contrast, color-exchange events are expected to have a much higher mean multiplicity and to be described by a negative binomial distribution (NBD) or a sum of two NBD's (double NBD) [5,6]. Low-multiplicity color-exchange events, which are a background to color-singlet exchange, become suppressed as the rapidity interval between the jets increases. An excess of low-multiplicity events with respect to the distribution for color exchange would indicate the presence of a color-singlet exchange process.

The magnitude of any observed excess can be used to distinguish between a strongly-interacting or purely electroweak color singlet. The exchange of a two-gluon color-singlet, which has been proposed as a model for the pomeron, is roughly estimated to account for 10% of the dijet cross section [2,7,8], while the contribution from electroweak exchange is calculated to be about 0.1% [7]. The survival probability (S) for rapidity gaps to contain no particles from spectator interactions is estimated to be 10–30% in proton-antiproton collisions [2,3,9]. Thus, the fraction of dijet events with an observable rapidity gap is expected to be about 1–3% for two-gluon color-singlet exchange and 0.01–0.03% for electroweak exchange.

Although evidence exists for color-singlet (pomeron) exchange in single-diffractive jet events [10,11], these events are typically produced with low momentum transfer, $0 < |t| < 2$ $(\mathrm{GeV}/c)^2$. The DØ and CDF Collaborations have previously reported the observation of rapidity gaps in dijet events [12,13], which, in contrast to single-diffractive jet events, have a rapidity gap between the jets and $|t| > 900\,(\mathrm{GeV}/c)^2$. Recently, rapidity gaps between jets also have been observed in electron-proton collisions [14]. This letter presents a new analysis, based on the same data as in Ref. [12], that provides clear experimental evidence for jet production via color-singlet exchange at a level inconsistent with an electroweak exchange process alone. In this work, pseudorapidity, $\eta \equiv -\ln\tan(\theta/2)$, is used as an approximation for true rapidity.

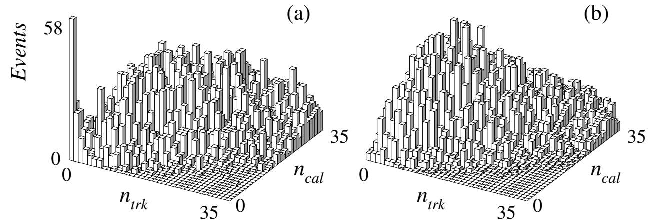

FIG. 1. The calorimeter tower multiplicity (n_{cal}) versus the charged track multiplicity (n_{trk}) in the pseudorapidity region $|\eta| < 1.3$ for the (a) opposite-side and (b) same-side samples as described in the text.

The DØ detector and trigger system are described elsewhere [15]. The primary trigger used in the present analysis was previously discussed in Ref. [12] and required "opposite-side" jets with a large pseudorapidity separation. In the offline analysis, the two leading E_T (highest transverse energy) jets are required to have $E_T > 30\,\mathrm{GeV}$, $|\eta| > 2$, and $\eta_1 \cdot \eta_2 < 0$. A cone algorithm with radius $\mathcal{R} = (\Delta\eta^2 + \Delta\phi^2)^{\frac{1}{2}} = 0.7$ is used for jet finding. Events with more than one proton-antiproton interaction are removed since extra interactions would obscure a color-singlet signature and alter the multiplicity distribution. This single interaction requirement yields a final data sample of 22,400 opposite-side jet events.

An independent trigger required events on the "same-side" of the detector in pseudorapidity. A final sample of 23,200 same-side jet events is obtained by requiring a single interaction and two jets with $E_T > 30\,\mathrm{GeV}$, $|\eta| > 2$, and $\eta_1 \cdot \eta_2 > 0$. The same-side sample provides a qualitative measure of the color-exchange background multiplicity in the central rapidity region due to the color flow between the scattered and spectator partons. Hard single diffraction, which could produce a central rapidity gap with two forward jets, is highly suppressed by the trigger which required a coincidence of hits between the forward and backward luminosity counters ($1.9 \lesssim |\eta| \lesssim 4.3$).

The electromagnetic (EM) section of the calorimeter is used as the primary means of measuring the particle multiplicity. The EM calorimeter has a low level of noise and the ability to detect (with an energy-dependent efficiency) both neutral and charged particles for $|\eta| \lesssim 4$. A particle is tagged by the deposition of more than 200 MeV transverse energy in an EM calorimeter tower ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$). The DØ detector has no central magnetic field, but the central drift chamber (CDC) is efficient for detecting charged particles for $|\eta| \lesssim 1.3$ and provides an independent measurement of the multiplicity.

Figure 1 shows the number of EM calorimeter towers above threshold (n_{cal}) versus the number of CDC tracks (n_{trk}) in the region $|\eta| < 1.3$ for the (a) opposite-side and (b) same-side samples. The two distributions are similar in shape except at very low multiplicities, where the

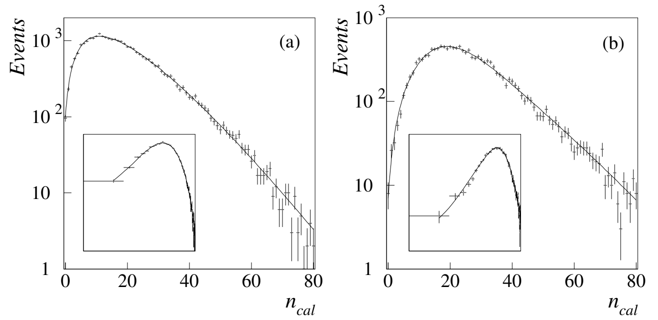

FIG. 2. The calorimeter tower multiplicity ($n_{\rm cal}$) for the (a) same-side and (b) color-singlet exchange suppressed data samples. The solid lines are double NBD fits to the data. The insets show each plot on a log-log scale.

opposite-side sample has a striking excess of events, consistent with a color-singlet exchange process. For both samples, $n_{\rm cal}$ and $n_{\rm trk}$ are strongly correlated, confirming that either can be used as a measure of particle multiplicity. Events for which CDC information was unavailable (roughly 30% of the opposite-side sample) do not appear in the figure.

A model for the multiplicity in color-exchange events is necessary to measure the low-multiplicity excess observed in the opposite-side data. We use the double NBD, which has four parameters and a relative normalization, to parametrize the color-exchange component of the opposite-side multiplicity distribution between jets.

This parametrization is supported by color-exchange data and Monte Carlo samples. Figure 2(a) shows that the same-side $n_{\rm cal}$ distribution for $|\eta| < 1$ is well-parametrized by the double NBD over the full range of multiplicity giving a χ^2/df (degree of freedom) $= 0.9$. Additional support is given by a color-singlet-exchange-suppressed subset of the opposite-side data obtained by demanding the presence of a third jet (with $E_T > 8$ GeV) between the two leading jets. Figure 2(b) shows the multiplicity for these events in the pseudorapidity region between the jet cone edges, excluding the multiplicity of the third jet. The double NBD fits the distribution reasonably well ($\chi^2/df = 1.2$) over the full range of multiplicity. Monte Carlo color-exchange events, generated with HERWIG [16] and PYTHIA [17] and passed through a simulation of the DØ detector [5,18], provide further support for the double NBD (not shown). None of these color-exchange samples have a significant excess of events at low multiplicity from physics processes or detector effects.

The low-multiplicity excess observed in Fig. 1(a) is determined as follows. First, a double NBD is fit to the opposite-side calorimeter multiplicity distribution between the two leading jets using a binned maximum likelihood method. The overall normalization is set to the number of events in the fitted region and the relative normalization of the two NBD's is determined by minimizing a modified Kolmogorov-Smirnov (K-S) statistic, which is defined as the sum of the squared differences between the cumulative distributions of the data and the fit. Next, the starting bin (n_0) for the fit is incremented successively by one and the remaining bins refit until the χ^2/df in the first five bins of the fit is less than 2.0 (i.e. C.L. $> 7\%$). The final fit is then extrapolated to zero multiplicity to determine the excess above the expected color-exchange background for $n_{\rm cal} < n_0$. Note that any experimental effects that produce a smearing of zero multiplicity color-singlet events to slightly higher multiplicities are reduced by the integration over low-multiplicity bins.

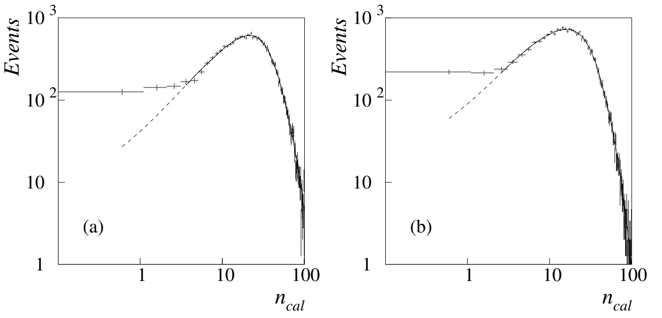

FIG. 3. The number of events versus $n_{\rm cal}$ (shifted up by half a unit in multiplicity) is plotted on a log-log scale for all opposite-side jet events, where (a) shows the multiplicity between the cone edges of the two leading jets and (b) shows the multiplicity in the region $|\eta| < 1$. The solid lines represent the double NBD fits for (a) $n_0 = 3$ and (b) $n_0 = 2$, while the dashed lines show the extrapolation of each fit to $n_{\rm cal} = 0$.

Figure 3(a) shows the $n_{\rm cal}$ distribution between the cone edges of the two leading jets for the opposite-side data sample. Also shown is the double NBD fit ($\chi^2/df = 0.9$, $n_0 = 3$) and its extrapolation to zero multiplicity. In contrast with the color-exchange data and Monte Carlo samples, the opposite-side sample has a significant excess at low multiplicity. The multiplicity in the central calorimeter ($|\eta| < 1$), a region well away from the jet edges, is plotted in Fig. 3(b) for the same events. Although the distribution has a lower mean multiplicity, its shape (excluding low-multiplicity bins) is also well-fit by a double NBD ($\chi^2/df = 1.0$, $n_0 = 2$), and a clear excess is again present at low multiplicity. The excess, defined as the integrated difference between the data and the double NBD fit in the extrapolated region, is 225 ± 20 and 237 ± 21 events for Figs. 3(a) and (b), respectively.

Using a single NBD instead of a double NBD to fit the data in Figs. 3(a) and (b), as done in Ref. [19], gives a significantly larger excess of 339 and 421 events, respectively. Although the single NBD fit gives a $\chi^2/df = 1.1$, likelihood and K-S tests show that the shape of the double NBD is significantly favored over the single NBD.

The excess observed at low multiplicity is consistent with the presence of color-singlet exchange, but the fractional excess is a more relevant quantity for theoretical comparisons. The fractional excess f_S is defined as the average excess above the double NBD fit for starting points of n_0 and n_0+1 divided by the total number of events. We obtain a fractional excess of $f_S = 1.07\%$ from the multiplicity distribution between the jet edges shown in Fig. 3(a). Using the distribution in the region $|\eta| < 1$ from Fig. 3(b), we obtain a consistent value of 1.14%.

The exact fit parameters depend on the definition of particle multiplicity, but the fractional excess is relatively independent of this definition. Varying the calorimeter tower E_T threshold and refitting the multiplicity yields a consistent value of f_S. Redefining a particle as a CDC track or a "cluster" of neighboring calorimeter towers results in an excess that is 3–15% greater. We thus assign a conservative +15% systematic error on f_S due to the uncertainty in defining particle multiplicity.

Systematic effects from uncertainties in jet reconstruction, energy scale, and acceptance result in a ±5% uncertainty in the measured excess. Uncertainty in the identification of single-interaction events gives an additional error of $^{+14}_{-4}\%$. A systematic error of ±10% due to the uncertainty in the background is determined by varying the fit parameters to produce a one unit change in χ^2 and remeasuring the excess. Combining the above errors in quadrature gives $f_S = 1.07 \pm 0.10(\text{stat})^{+0.25}_{-0.13}(\text{syst})\%$ from the multiplicity distribution between the jet edges.

Although a low-multiplicity excess is clearly present in the opposite-side sample, theoretical interpretation of f_S is complicated by uncertainties in the survival probability. In contrast with our previous measurement which used the number of events with zero multiplicity to place an upper limit on the rapidity gap fraction ($(\sigma_{\text{singlet}}/\sigma) \times S < 1.1\%$ at 95% C.L.) [12], the measurement of f_S may include some portion of the color-singlet events with low-multiplicity spectator interactions. Nevertheless, the value of f_S is consistent with the 1–3% expected for strongly-interacting color-singlet exchange. The measured value of f_S is used to obtain a lower limit of 0.80% (95% C.L.) on $\sigma_{\text{singlet}}/\sigma$, the fraction of dijet events produced via color-singlet exchange, independent of the actual value of the survival probability.

The opposite-side data can also be used to exclude pure electroweak exchange combined with color-exchange background as the source of the excess. A PYTHIA Monte Carlo study using simulated DØ jet acceptance and efficiency gives a value of 0.09% for the fraction of dijet events with electroweak exchange, which is comparable to the result in Ref. [7] but includes higher-order radiative corrections. We assume a survival probability of $S = 100\%$ to determine the maximum expected number of events from electroweak exchange, and add this to the number of color-exchange background events from the fit. The statistical and systematic uncertainty in the expected number of events is then used to determine the probability for a fluctuation to the number of observed events. Using only the zero multiplicity bin, the probability that the observed excess in Fig. 3(a) is due to the combination of electroweak and color exchange is less than 10^{-10}. Adding other low-multiplicity bins further decreases this probability.

In conclusion, we have presented evidence for strongly-interacting color-singlet exchange from a study of opposite-side dijet events with jet $E_T > 30\,\text{GeV}$ and $|\eta| > 2$. A striking enhancement of events with low multiplicity between the jets is observed independent of a parametrization for the color-exchange background. The double NBD parametrization provides a measurement of the color-exchange background and confirms that this background is small for the rapidity gap fraction previously measured in Ref. [12]. Using the multiplicity distribution between the jet edges, we obtain a fractional excess above the color-exchange background of $1.07 \pm 0.10(\text{stat})^{+0.25}_{-0.13}(\text{syst})\%$ which is consistent with the presence of strongly-interacting color-singlet exchange and inconsistent with electroweak exchange alone.

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* Visitor from CONICET, Argentina.
† Visitor from Universidad de Buenos Aires, Argentina.
‡ Visitor from IHEP, Beijing, China.
§ Visitor from Univ. San Francisco de Quito, Ecuador.

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