Multiple Jet Production at Low Transverse Energies in $p\overline{p}$ Collisions at $\sqrt{\mathrm{s}} = 1.8$ TeV

The DØ Collaboration *

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

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Abstract

We present data on multiple jet production for transverse energies greater than 20 GeV in $p\overline{p}$ collisions at $\sqrt{\mathrm{s}} = 1.8$ TeV. QCD calculations in the parton shower approximation (PYTHIA) and in the next-to-leading order approximation (JETRAD) show discrepancies with data for three and four-jet production. This disagreement is especially apparent in multiple jet angular and transverse momentum distributions.

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V.M. Abazov,[23] B. Abbott,[58] A. Abdesselam,[11] M. Abolins,[51] V. Abramov,[26]
B.S. Acharya,[17] D.L. Adams,[60] M. Adams,[38] S.N. Ahmed,[21] G.D. Alexeev,[23] G.A. Alves,[2]
N. Amos,[50] E.W. Anderson,[43] M.M. Baarmand,[55] V.V. Babintsev,[26] L. Babukhadia,[55]
T.C. Bacon,[28] A. Baden,[47] B. Baldin,[37] P.W. Balm,[20] S. Banerjee,[17] E. Barberis,[30]
P. Baringer,[44] J. Barreto,[2] J.F. Bartlett,[37] U. Bassler,[12] D. Bauer,[28] A. Bean,[44] M. Begel,[54]
A. Belyaev,[35] S.B. Beri,[15] G. Bernardi,[12] I. Bertram,[27] A. Besson,[9] R. Beuselinck,[28]
V.A. Bezzubov,[26] P.C. Bhat,[37] V. Bhatnagar,[11] M. Bhattacharjee,[55] G. Blazey,[39]
S. Blessing,[35] A. Boehnlein,[37] N.I. Bojko,[26] F. Borcherding,[37] K. Bos,[20] A. Brandt,[60]
R. Breedon,[31] G. Briskin,[59] R. Brock,[51] G. Brooijmans,[37] A. Bross,[37] D. Buchholz,[40]
M. Buehler,[38] V. Buescher,[14] V.S. Burtovoi,[26] J.M. Butler,[48] F. Canelli,[54] W. Carvalho,[3]
D. Casey,[51] Z. Casilum,[55] H. Castilla-Valdez,[19] D. Chakraborty,[39] K.M. Chan,[54]
S.V. Chekulaev,[26] D.K. Cho,[54] S. Choi,[34] S. Chopra,[56] J.H. Christenson,[37] M. Chung,[38]
D. Claes,[52] A.R. Clark,[30] J. Cochran,[34] L. Coney,[42] B. Connolly,[35] W.E. Cooper,[37]
D. Coppage,[44] M.A.C. Cummings,[39] D. Cutts,[59] G.A. Davis,[54] K. Davis,[29] K. De,[60]
S.J. de Jong,[21] K. Del Signore,[50] M. Demarteau,[37] R. Demina,[45] P. Demine,[9] D. Denisov,[37]
S.P. Denisov,[26] S. Desai,[55] H.T. Diehl,[37] M. Diesburg,[37] G. Di Loreto,[51] S. Doulas,[49]
P. Draper,[60] Y. Ducros,[13] L.V. Dudko,[25] S. Duensing,[21] L. Duflot,[11] S.R. Dugad,[17]
A. Duperrin,[10] A. Dyshkant,[26] D. Edmunds,[51] J. Ellison,[34] V.D. Elvira,[37] R. Engelmann,[55]
S. Eno,[47] G. Eppley,[62] P. Ermolov,[25] O.V. Eroshin,[26] J. Estrada,[54] H. Evans,[53]
V.N. Evdokimov,[26] T. Fahland,[33] S. Feher,[37] D. Fein,[29] T. Ferbel,[54] F. Filthaut,[21]
H.E. Fisk,[37] Y. Fisyak,[56] E. Flattum,[37] F. Fleuret,[30] M. Fortner,[39] K.C. Frame,[51] S. Fu,[53]
S. Fuess,[37] E. Gallas,[37] A.N. Galyaev,[26] M. Gao,[53] V. Gavrilov,[24] R.J. Genik II,[27]
K. Genser,[37] C.E. Gerber,[38] Y. Gershtein,[59] R. Gilmartin,[35] G. Ginther,[54] B. Gómez,[5]
G. Gómez,[47] P.I. Goncharov,[26] J.L. González Solís,[19] H. Gordon,[56] L.T. Goss,[61]
K. Gounder,[37] A. Goussiou,[28] N. Graf,[56] G. Graham,[47] P.D. Grannis,[55] J.A. Green,[43]
H. Greenlee,[37] S. Grinstein,[1] L. Groer,[53] S. Grünendahl,[37] A. Gupta,[17] S.N. Gurzhiev,[26]
G. Gutierrez,[37] P. Gutierrez,[58] N.J. Hadley,[47] H. Haggerty,[37] S. Hagopian,[35] V. Hagopian,[35]
R.E. Hall,[32] P. Hanlet,[49] S. Hansen,[37] J.M. Hauptman,[43] C. Hays,[53] C. Hebert,[44]
D. Hedin,[39] J.M. Heinmiller,[38] A.P. Heinson,[34] U. Heintz,[48] T. Heuring,[35] M.D. Hildreth,[42]
R. Hirosky,[63] J.D. Hobbs,[55] B. Hoeneisen,[8] Y. Huang,[50] R. Illingworth,[28] A.S. Ito,[37]
M. Jaffré,[11] S. Jain,[17] R. Jesik,[41] K. Johns,[29] M. Johnson,[37] A. Jonckheere,[37] M. Jones,[36]
H. Jöstlein,[37] A. Juste,[37] S. Kahn,[56] E. Kajfasz,[10] A.M. Kalinin,[23] D. Karmanov,[25]
D. Karmgard,[42] Z. Ke,[4] R. Kehoe,[51] A. Kharchilava,[42] S.K. Kim,[18] B. Klima,[37]
B. Knuteson,[30] W. Ko,[31] J.M. Kohli,[15] A.V. Kostritskiy,[26] J. Kotcher,[56] B. Kothari,[53]
A.V. Kotwal,[53] A.V. Kozelov,[26] E.A. Kozlovsky,[26] J. Krane,[43] M.R. Krishnaswamy,[17]
P. Krivkova,[6] S. Krzywdzinski,[37] M. Kubantsev,[45] S. Kuleshov,[24] Y. Kulik,[55] S. Kunori,[47]
A. Kupco,[7] V.E. Kuznetsov,[34] G. Landsberg,[59] W.M. Lee,[35] A. Leflat,[25] C. Leggett,[30]
F. Lehner,[37] J. Li,[60] Q.Z. Li,[37] X. Li,[4] J.G.R. Lima,[3] D. Lincoln,[37] S.L. Linn,[35]
J. Linnemann,[51] R. Lipton,[37] A. Lucotte,[9] L. Lueking,[37] C. Lundstedt,[52] C. Luo,[41]
A.K.A. Maciel,[39] R.J. Madaras,[30] V.L. Malyshev,[23] V. Manankov,[25] H.S. Mao,[4]
T. Marshall,[41] M.I. Martin,[37] R.D. Martin,[38] K.M. Mauritz,[43] B. May,[40] A.A. Mayorov,[41]
R. McCarthy,[55] J. McDonald,[35] T. McMahon,[57] H.L. Melanson,[37] M. Merkin,[25]
K.W. Merritt,[37] C. Miao,[59] H. Miettinen,[62] D. Mihalcea,[58] C.S. Mishra,[37] N. Mokhov,[37]
N.K. Mondal,[17] H.E. Montgomery,[37] R.W. Moore,[51] M. Mostafa,[1] H. da Motta,[2] E. Nagy,[10]
F. Nang,[29] M. Narain,[48] V.S. Narasimham,[17] H.A. Neal,[50] J.P. Negret,[5] S. Negroni,[10]

T. Nunnemann,[37] G.Z. Obrant,[65] D. O'Neil,[51] V. Oguri,[3] B. Olivier,[12] N. Oshima,[37]
P. Padley,[62] L.J. Pan,[40] K. Papageorgiou,[28] A. Para,[37] N. Parashar,[49] R. Partridge,[59]
N. Parua,[55] M. Paterno,[54] A. Patwa,[55] B. Pawlik,[22] J. Perkins,[60] M. Peters,[36] O. Peters,[20]
P. Pétroff,[11] R. Piegaia,[1] H. Piekarz,[35] B.G. Pope,[51] E. Popkov,[48] H.B. Prosper,[35]
S. Protopopescu,[56] J. Qian,[50] R. Raja,[37] S. Rajagopalan,[56] E. Ramberg,[37] P.A. Rapidis,[37]
N.W. Reay,[45] S. Reucroft,[49] M. Ridel,[11] M. Rijssenbeek,[55] T. Rockwell,[51] M. Roco,[37]
P. Rubinov,[37] R. Ruchti,[42] J. Rutherfoord,[29] B.M. Sabirov,[23] A. Santoro,[2] L. Sawyer,[46]
R.D. Schamberger,[55] H. Schellman,[40] A. Schwartzman,[1] N. Sen,[62] E. Shabalina,[25]
R.K. Shivpuri,[16] D. Shpakov,[49] M. Shupe,[29] R.A. Sidwell,[45] V. Simak,[7] H. Singh,[34]
J.B. Singh,[15] V. Sirotenko,[37] P. Slattery,[54] E. Smith,[58] R.P. Smith,[37] R. Snihur,[40]
G.R. Snow,[52] J. Snow,[57] S. Snyder,[56] J. Solomon,[38] V. Sorín,[1] M. Sosebee,[60] N. Sotnikova,[25]
K. Soustruznik,[6] M. Souza,[2] N.R. Stanton,[45] G. Steinbrück,[53] R.W. Stephens,[60]
F. Stichelbaut,[56] D. Stoker,[33] V. Stolin,[24] A. Stone,[46] D.A. Stoyanova,[26] M. Strauss,[58]
M. Strovink,[30] L. Stutte,[37] A. Sznajder,[3] M. Talby,[10] W. Taylor,[55] S. Tentindo-Repond,[35]
S.M. Tripathi,[31] T.G. Trippe,[30] A.S. Turcot,[56] P.M. Tuts,[53] P. van Gemmeren,[37]
V. Vaniev,[26] R. Van Kooten,[41] N. Varelas,[38] L.S. Vertogradov,[23] F. Villeneuve-Seguier,[10]
A.A. Volkov,[26] A.P. Vorobiev,[26] H.D. Wahl,[35] H. Wang,[40] Z.-M. Wang,[55] J. Warchol,[42]
G. Watts,[64] M. Wayne,[42] H. Weerts,[51] A. White,[60] J.T. White,[61] D. Whiteson,[30]
J.A. Wightman,[43] D.A. Wijngaarden,[21] S. Willis,[39] S.J. Wimpenny,[34] J. Womersley,[37]
D.R. Wood,[49] R. Yamada,[37] P. Yamin,[56] T. Yasuda,[37] Y.A. Yatsunenko,[23] K. Yip,[56]
S. Youssef,[35] J. Yu,[37] Z. Yu,[40] M. Zanabria,[5] H. Zheng,[42] Z. Zhou,[43] M. Zielinski,[54]
D. Zieminska,[41] A. Zieminski,[41] V. Zutshi,[56] E.G. Zverev,[25] and A. Zylberstejn[13]

(DØ Collaboration)

[1]Universidad de Buenos Aires, Buenos Aires, Argentina
[2]LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[3]Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[4]Institute of High Energy Physics, Beijing, People's Republic of China
[5]Universidad de los Andes, Bogotá, Colombia
[6]Charles University, Center for Particle Physics, Prague, Czech Republic
[7]Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic
[8]Universidad San Francisco de Quito, Quito, Ecuador
[9]Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France
[10]CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France
[11]Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS, Orsay, France
[12]LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France
[13]DAPNIA/Service de Physique des Particules, CEA, Saclay, France
[14]Universität Mainz, Institut für Physik, Mainz, Germany
[15]Panjab University, Chandigarh, India
[16]Delhi University, Delhi, India
[17]Tata Institute of Fundamental Research, Mumbai, India
[18]Seoul National University, Seoul, Korea
[19]CINVESTAV, Mexico City, Mexico
[20]FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands

[21]University of Nijmegen/NIKHEF, Nijmegen, The Netherlands
[22]Institute of Nuclear Physics, Kraków, Poland
[23]Joint Institute for Nuclear Research, Dubna, Russia
[24]Institute for Theoretical and Experimental Physics, Moscow, Russia
[25]Moscow State University, Moscow, Russia
[26]Institute for High Energy Physics, Protvino, Russia
[27]Lancaster University, Lancaster, United Kingdom
[28]Imperial College, London, United Kingdom
[29]University of Arizona, Tucson, Arizona 85721
[30]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
[31]University of California, Davis, California 95616
[32]California State University, Fresno, California 93740
[33]University of California, Irvine, California 92697
[34]University of California, Riverside, California 92521
[35]Florida State University, Tallahassee, Florida 32306
[36]University of Hawaii, Honolulu, Hawaii 96822
[37]Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[38]University of Illinois at Chicago, Chicago, Illinois 60607
[39]Northern Illinois University, DeKalb, Illinois 60115
[40]Northwestern University, Evanston, Illinois 60208
[41]Indiana University, Bloomington, Indiana 47405
[42]University of Notre Dame, Notre Dame, Indiana 46556
[43]Iowa State University, Ames, Iowa 50011
[44]University of Kansas, Lawrence, Kansas 66045
[45]Kansas State University, Manhattan, Kansas 66506
[46]Louisiana Tech University, Ruston, Louisiana 71272
[47]University of Maryland, College Park, Maryland 20742
[48]Boston University, Boston, Massachusetts 02215
[49]Northeastern University, Boston, Massachusetts 02115
[50]University of Michigan, Ann Arbor, Michigan 48109
[51]Michigan State University, East Lansing, Michigan 48824
[52]University of Nebraska, Lincoln, Nebraska 68588
[53]Columbia University, New York, New York 10027
[54]University of Rochester, Rochester, New York 14627
[55]State University of New York, Stony Brook, New York 11794
[56]Brookhaven National Laboratory, Upton, New York 11973
[57]Langston University, Langston, Oklahoma 73050
[58]University of Oklahoma, Norman, Oklahoma 73019
[59]Brown University, Providence, Rhode Island 02912
[60]University of Texas, Arlington, Texas 76019
[61]Texas A&M University, College Station, Texas 77843
[62]Rice University, Houston, Texas 77005
[63]University of Virginia, Charlottesville, Virginia 22901
[64]University of Washington, Seattle, Washington 98195
[65]Petersburg Nuclear Physics Institute, Gatchina, Russia

The study of jet production at high transverse energy was one of the main goals of the 1993–1995 run of the Fermilab Tevatron collider, and the results have been compared with leading-order QCD predictions by both the CDF [1] and DØ [2] collaborations. These high-E_{T} data, where E_{T} is the transverse energy of the jet were described satisfactorily by complete tree-level leading order $2 \to N$ QCD calculations [3] and by the HERWIG parton shower Monte Carlo [4]. In this paper, we describe studies of the complementary kinematic region of $Q^2/\hat{s} \ll 1$, where Q^2 is the square of the momentum transfer between partons, which we set equal to E_T^2, and $\hat{s}$ is the square of center of mass energy in the rest frame of the collision. Here the BFKL [5] description of jet production differs significantly from that of the high-E_{T} DGLAP [6] kinematic domain of $Q^2 \sim \hat{s}$. Measurement of jet production in this kinematic region can provide information on the evolution of higher-order jet processes.

We present results that extend our previous measurements of multiple jet production to lower E_{T}. The data were collected with the DØ detector during 1993–1995 at a proton-antiproton center-of-mass energy of 1800 GeV. Jets were measured in the liquid-argon calorimeter, which has a segmentation of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, where η is pseudorapidity and ϕ is azimuthal angle [7]. At least one calorimeter trigger tower ($\Delta\eta \times \Delta\phi = 0.2 \times 0.2$) with $E_{\mathrm{T}} \geq 2$ GeV was required by the Level-1 trigger, and at least one jet with $E_{\mathrm{T}} \geq 12$ GeV was required by the Level-2 trigger [8]. Jets were reconstructed using a fixed cone algorithm with radius $\Delta\mathcal{R} = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$ in $\eta - \phi$ space. The jet reconstruction threshold was 8 GeV. If two jets overlapped and the shared transverse energy was more than 50% of the transverse energy of the lower-energy jet, the jets were merged; otherwise they were split into two jets. The integrated luminosity of this data sample was 1.96±0.29 nb^{-1}. Instantaneous luminosity was restricted to be below 3 $\times 10^{30} cm^{-2} s^{-1}$ to minimize multiple $p\overline{p}$ interactions.

To provide events of high quality, online and offline selection criteria were used to suppress multiple interactions, cosmic ray backgrounds, and spurious jets. Jets were restricted to the pseudorapidity interval $|\eta| \leq 3$.

Jet energies have been corrected for calorimeter response, shower development, different sources of noise, and contributions from the underlying event [9]. These corrections comprise the largest source of systematic uncertainty on the jet cross section. The typical value of the correction to jet energy is 15 - 30%, with an uncertainty of 2-4%. In our study, we consider jets with $E_{\mathrm{T}} > 20$ GeV. For an n-inclusive jet event, the n leading jets must have transverse energy above the threshold value. The trigger efficiency is 0.85 for the inclusive ($n = 1$) jet sample for energies near threshold, rising rapidly to unity at larger E_{T}. The efficiency is essentially unity for $n > 1$.

To compare with data, Monte Carlo (MC) events were generated using the PYTHIA 6.127 [10] and JETRAD [11] programs. These generators simulate particle-level jets in the parton-shower approximation, and parton-level jets in the next-to-leading order approximation, for PYTHIA and JETRAD, respectively. The smearing of jet transverse energies was implemented using the experimentally determined jet energy resolution [9], which is $\approx 20\%$ at $E_{\mathrm{T}} = 20$ GeV. In PYTHIA, jets were reconstructed at the particle level using the DØ algorithm, and in JETRAD, at the parton level, using the Snowmass algorithm [8].

Distributions in transverse energy for the leading jet for n=1 to n=4 inclusive jet events are shown in Fig. 1, together with the results from PYTHIA simulations. In these and all other plots, the data has been corrected for inefficiencies and energy calibration, but not for contributions from an underlying event. Also, we normalize the theory (increased by a factor of 1.3) to the observed two-jet cross section Fig. 1(b) for $E_{\rm T} > 40$ GeV. Figure 2 shows the fractional difference (Data - Theory) / Theory for the $E_{\rm T}$ spectra in Fig. 1 with the systematic uncertainties, arrising from uncertainties in jet-energy calibration and resolution. The theory is in agreement with the data for the single-inclusive jet sample in the entire $E_{\rm T}$ interval, and with the two-jet sample for most of the energy interval (some excess of data is observed at low $E_{\rm T}$). However, for the three and four-jet samples, there is large excess relative to theory at low $E_{\rm T}$ and a deficit near 75 GeV. The shapes of the experimental and theoretical spectra are clearly different, and not reconcilable through re-normalization.

The systematic uncertainty on the cross section is due primarily to the uncertainty in the energy calibration. The uncertainty from energy resolution represents the main uncertainty in the MC. The uncertainty from the energy calibration can be estimated by considering spectra with ±1 standard-deviation corrections to jet $E_{\rm T}$. The same procedure can be used to derive the uncertainty due to jet resolution in the MC. At 25 GeV uncertainty in the three-jet cross section due to calibration is 36%, and the uncertainty in the MC due to resolution is 17%. In Fig. 2, the relative systematic uncertainties corresponding to the energy calibration added to a 15% uncertainty in luminosity are shown (in quadrature) by the solid lines centered about zero. The uncertainties from energy smearing are shown by the dashed lines near the data points. The total systematic uncertainties on the ratio are shown by the dotted lines. Because the systematic uncertainties are highly correlated in $E_{\rm T}$ (a change of the cross section in one bin is accompanied by a corresponding change in neighboring bins), the departure of the ratio from zero cannot be explained solely by systematic uncertainties.

To explore the discrepancies in three and four-jet production, we turn to observations of azimuthal distributions, distributions in summed transverse momenta, and three-jet studies. In Fig. 3(a) we plot the azimuthal difference between the leading two jets in events with two or more jets. Figures 3(b)-3(d) show the azimuthal difference between the first and second, first and third, and second and third highest-$E_{\rm T}$ jets in a three-jet event. In Fig. 3(a) we see the strong anticorrelation (in the transverse plane) expected of two-jet events. The distribution widens substantially in the three-jet sample (Fig. 3(b)-3(d)). The peaks correspond to the kinematic constraint of transverse momentum conservation for jets produced in hard QCD subprocesses. Altough, in general, PYTHIA reproduces the observed shapes, there is a large excess of events in the three-jet sample not consistent with expectation. In particular, there is a significant contribution to three-jet events with two jets back-to-back in the transverse plane near ($\Phi = \pi$).

Distributions in the square of the summed vector transverse momenta of jets $Q_T^2 = (\mathbf{E}_{T1} + \mathbf{E}_{T2} + \cdots + \mathbf{E}_{Tn})^2$ shown in Fig. 4(a-c) indicate that the excess corresponds to events with a large imbalance. In fact, when these events are removed (with a requirement of a good balance in transverse momentum), the three-jet data and theory come into better agreement at small $E_{\rm T}$. The shoulder at $Q_T^2 \sim 1600$ GeV^2 in Fig. 4(a) is eliminated when the event sample is restricted to just two jets with $E_{\rm T}$ above 20 GeV, and no other jets between 8 and 20 GeV. This shoulder can consequently be associated with higher-order radiation.

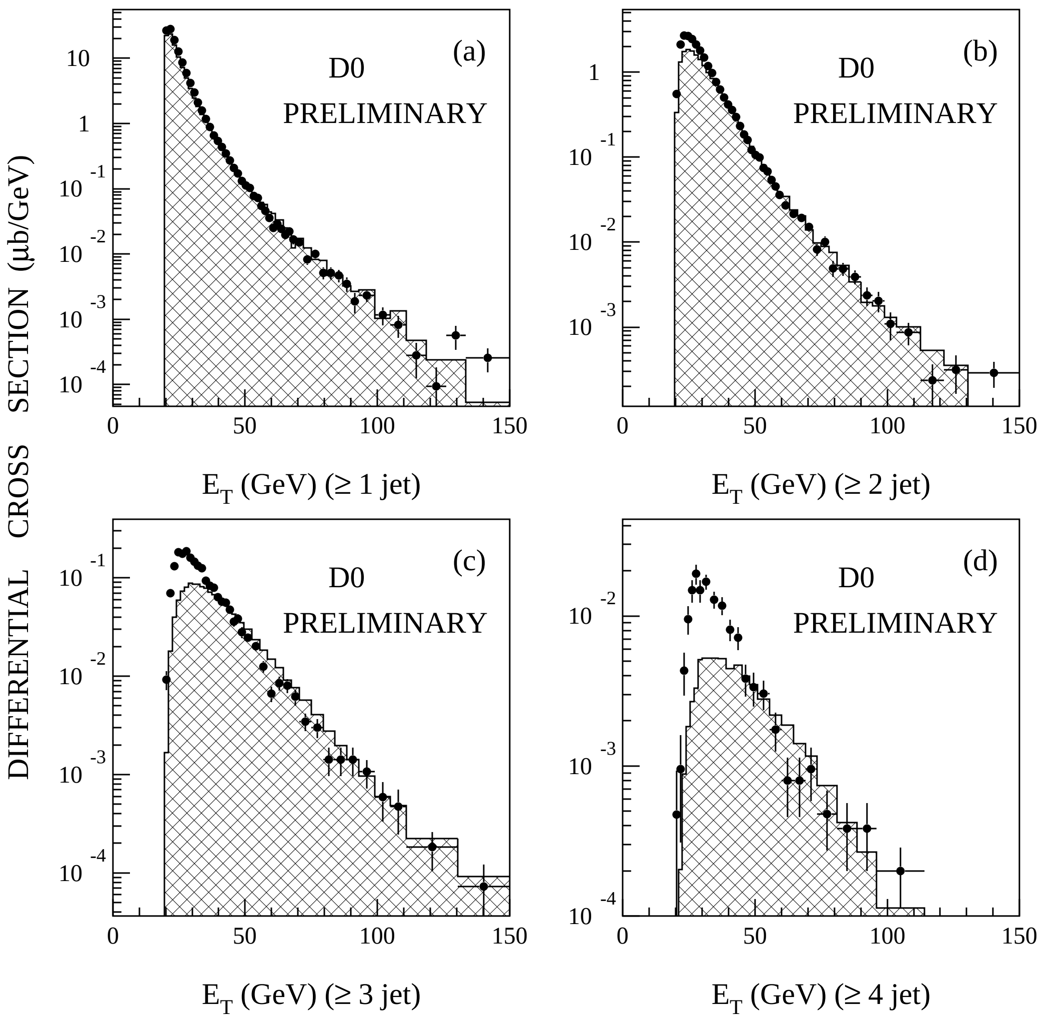

FIG. 1. Distributions in the transverse energy of the leading jet for (a) single-inclusive, (b) two-jet inclusive, (c) three-jet inclusive and (d) four-jet inclusive events. Histograms show the PYTHIA simulation normalized (increased by a factor of 1.3) to the inclusive two-jet sample at $E_{\rm T} > 40$ GeV.

To find the pair of jets $\{i, j\}$ most likely to originate from the hard interaction (rather then from gluon Brehmsshtrahlung), we define the scaled summed dijet vector transverse momenta: $\mathbf{q}_{ij} = (\mathbf{E}_{Ti} + \mathbf{E}_{Tj})/(E_{Ti} + E_{Tj})$. We choose the pair with the smallest magnitude of this vector and plot the distribution of the relative azimuthal angle Φ_c between the jets in that pair Fig. 5(a). The data lie above theory in the region where two jets, reflecting a hard scatter, appears back-to-back ($\Phi_c = \pi$). PYTHIA shows a broader distribution, and the prediction from JETRAD is peaked away from $\Phi_c = \pi$ due to the presence of the third (radiated) jet.

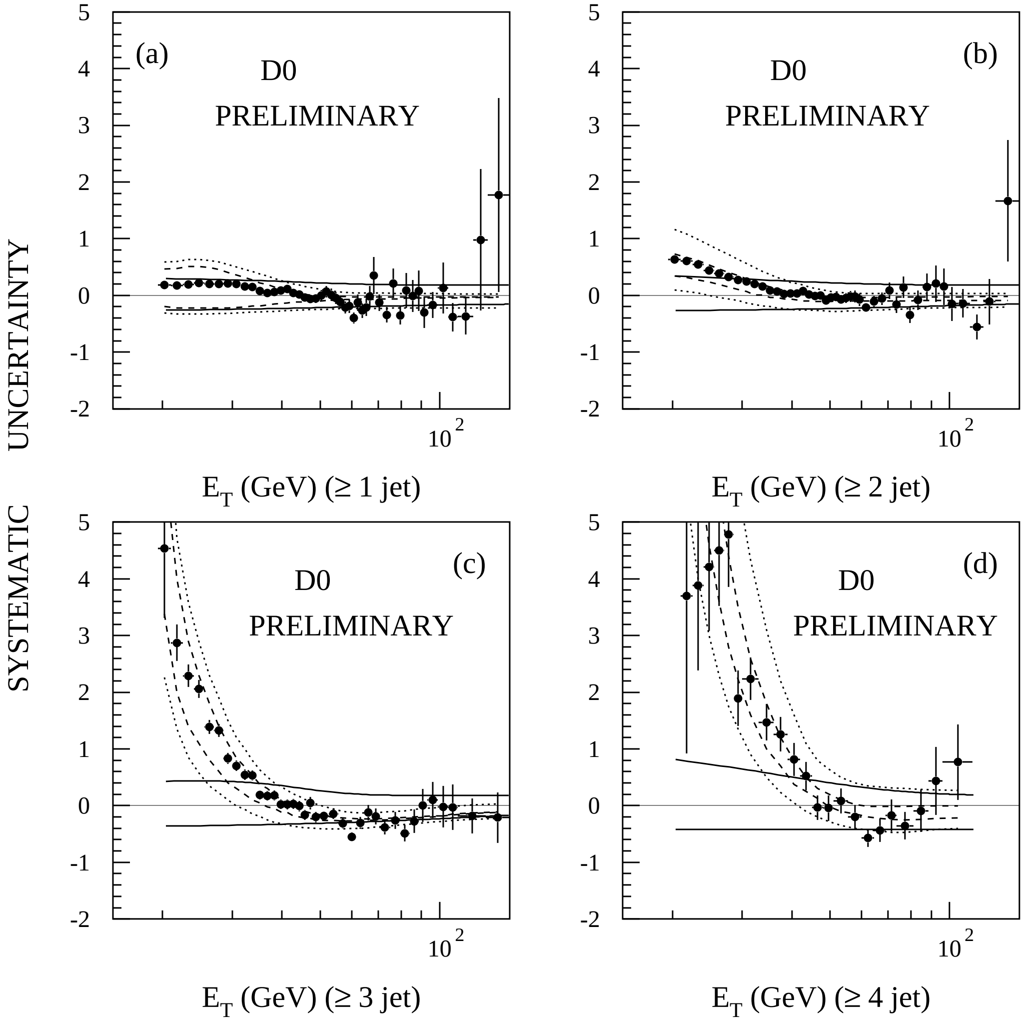

FIG. 2. (Data - Theory)/Theory as a function of the transverse energy of the leading jet for (a) single-jet inclusive, (b) two-jet inclusive, (c) three-jet inclusive and (d) four-jet inclusive event samples.

Figures 5(b) and Fig. 5(c) show the azimuthal separation of the third jet from each of the two jets that correspond to the minimum q_{ij}^2. These distributions contain events only for $\pi - \Phi_c \leq 0.4$; that is, events in which the balanced jets are essentially back-to-back. When the third jet is correlated with the balanced jets, it will be expected to be emitted along or opposite to the balanced jets. The uncertainties from the energy calibration and luminosity are shown by the solid lines, and from the energy resolution by dashed lines. We see that the data has a wider distribution than PYTHIA, and much wider distribution than JETRAD. The third jet appeares to be uncorrelated with the balanced jets, and is emitted at all angles. Our studies indicate that the observed differences in shape are not sensitive to modeling of the underlying event or contributions from multiple-parton scattering.

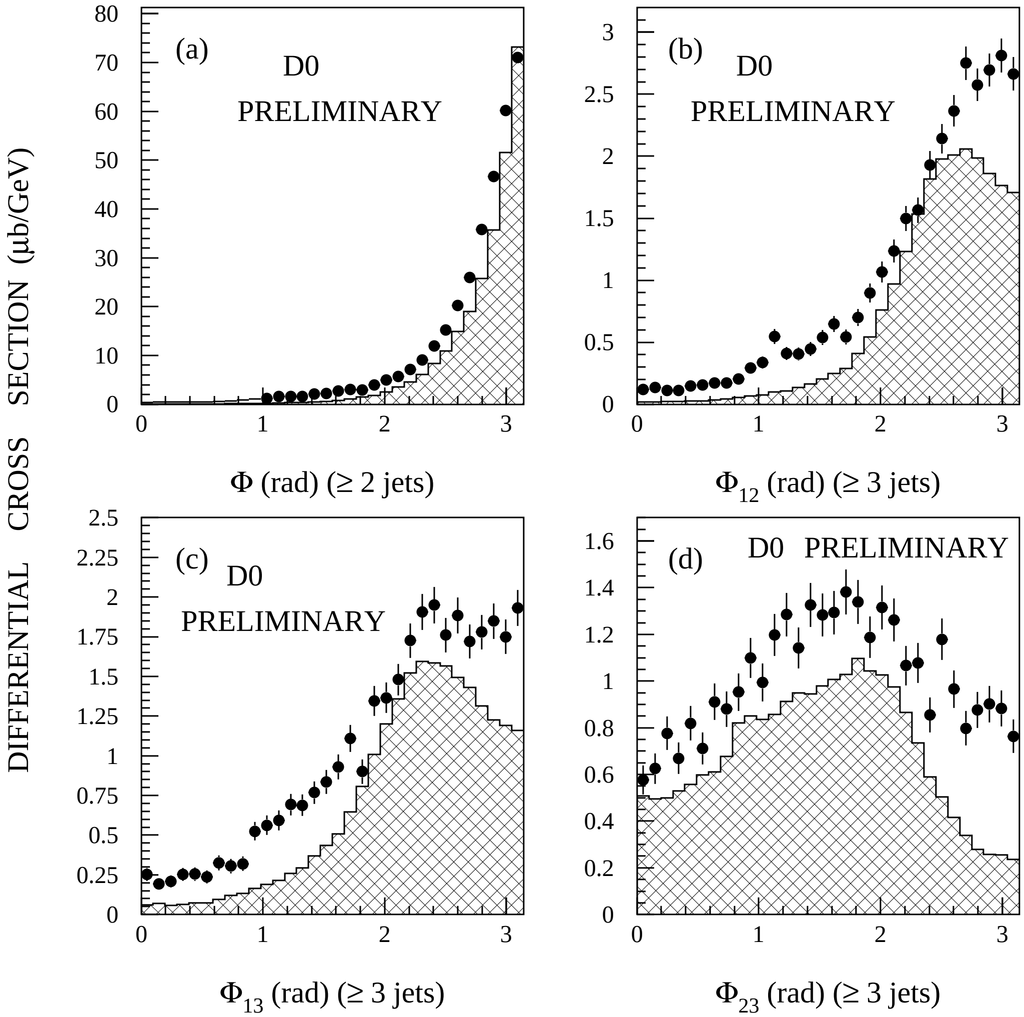

FIG. 3. Distributions of the relative azimuthal angle between two jets in (a) two-jet events and in three-jet events (b-d). Jets are ordered by their transverse energies. Histograms are from a PYTHIA simulation of such events.

In summary, our data on multiple-jet production at low E_{T} show significant discrepancies with PYTHIA and JETRAD. This is observed in the distributions of the transverse energy of the leading jets (Fig. 1), in the square of the summed vector transverse momenta Q_T^2 (Fig. 4), and in the three-jet angular distributions that suggest the presence of an uncorrelated jet (Fig. 5). Additional corrections to QCD calculations are therefore required to accommodate these results; higher-order or BFKL processes are possible candidates.

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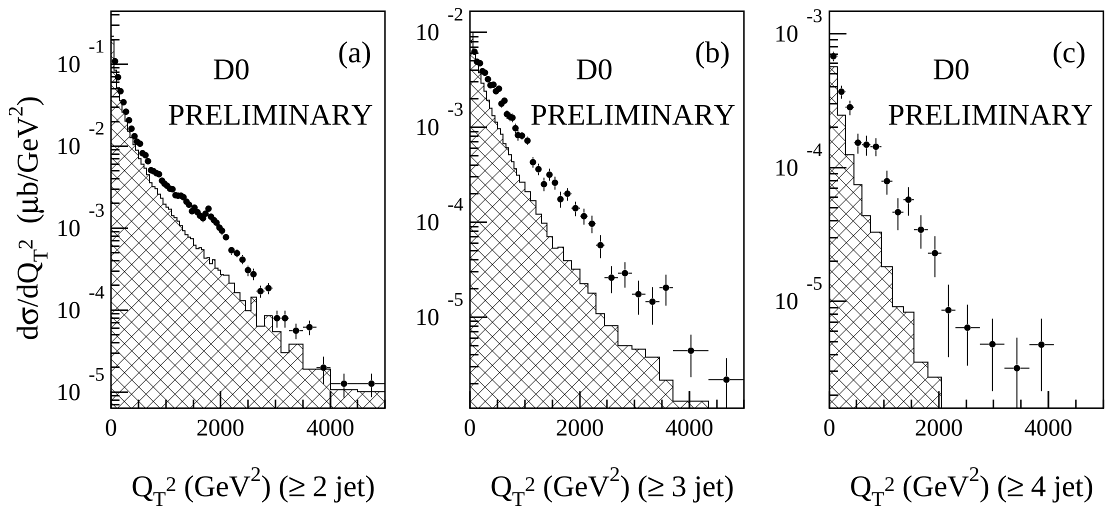

FIG. 4. Distributions in the square of the summed vector transverse momenta Q_T^2, for two-jet inclusive, three-jet inclusive and four-jet inclusive event samples (a-c). Histograms show the PYTHIA simulation.

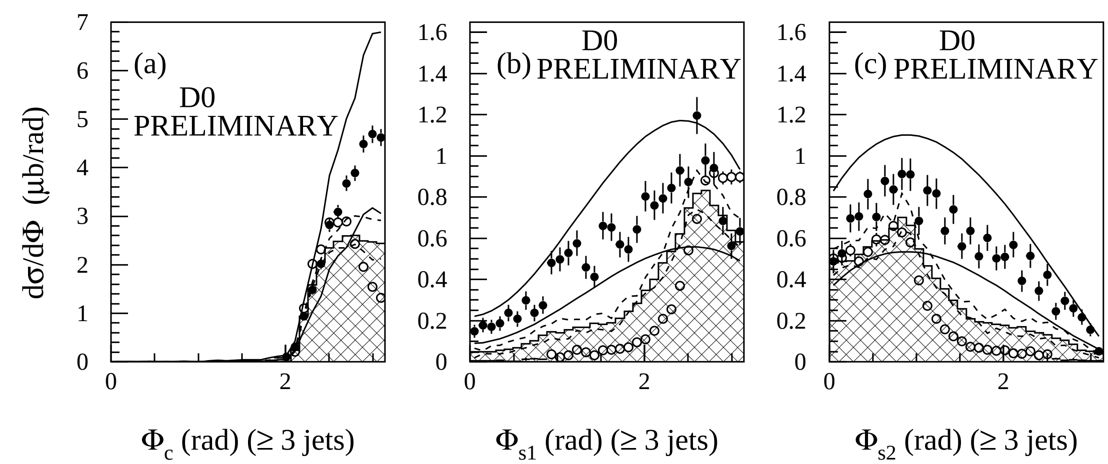

FIG. 5. The distribution of the relative azimuthal angle in three-jet events, between the jets in the pair with the minimal scaled summed transverse momentum (a), and between the third jet and the other two leading E_{T} jets in the pair (b-c). Histograms show the PYTHIA simulation, and the open symbols the JETRAD simulation.

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