Fermilab FERMILAB-Pub-01/106-E CDF July 2001

# Charged Particle Multiplicity in Jets in $p\bar{p}$ collisions at $\sqrt{s}$=1.8 TeV

T. Affolder,[23] H. Akimoto,[45] A. Akopian,[37] M. G. Albrow,[11] P. Amaral,[8] D. Amidei,[25] K. Anikeev,[24] J. Antos,[1] G. Apollinari,[11] T. Arisawa,[45] A. Artikov,[9] T. Asakawa,[43] W. Ashmanskas,[8] F. Azfar,[30] P. Azzi-Bacchetta,[31] N. Bacchetta,[31] H. Bachacou,[23] S. Bailey,[16] P. de Barbaro,[36] A. Barbaro-Galtieri,[23] V. E. Barnes,[35] B. A. Barnett,[19] S. Baroiant,[5] M. Barone,[13] G. Bauer,[24] F. Bedeschi,[33] S. Belforte,[42] W. H. Bell,[15] G. Bellettini,[33] J. Bellinger,[46] D. Benjamin,[10] J. Bensinger,[4] A. Beretvas,[11] J. P. Berge,[11] J. Berryhill,[8] A. Bhatti,[37] M. Binkley,[11] D. Bisello,[31] M. Bishai,[11] R. E. Blair,[2] C. Blocker,[4] K. Bloom,[25] B. Blumenfeld,[19] S. R. Blusk,[36] A. Bocci,[37] A. Bodek,[36] W. Bokhari,[32] G. Bolla,[35] Y. Bonushkin,[6] D. Bortoletto,[35] J. Boudreau,[34] A. Brandl,[27] S. van den Brink,[19] C. Bromberg,[26] M. Brozovic,[10] E. Brubaker,[23] N. Bruner,[27] E. Buckley-Geer,[11] J. Budagov,[9] H. S. Budd,[36] K. Burkett,[16] G. Busetto,[31] A. Byon-Wagner,[11] K. L. Byrum,[2] S. Cabrera,[10] P. Calafiura,[23] M. Campbell,[25] W. Carithers,[23] J. Carlson,[25] D. Carlsmith,[46] W. Caskey,[5] A. Castro,[3] D. Cauz,[42] A. Cerri,[33] A. W. Chan,[1] P. S. Chang,[1] P. T. Chang,[1] J. Chapman,[25] C. Chen,[32] Y. C. Chen,[1] M. -T. Cheng,[1] M. Chertok,[5] G. Chiarelli,[33] I. Chirikov-Zorin,[9] G. Chlachidze,[9] F. Chlebana,[11] L. Christofek,[18] M. L. Chu,[1] Y. S. Chung,[36] C. I. Ciobanu,[28] A. G. Clark,[14] A. Connolly,[23] J. Conway,[38] M. Cordelli,[13] J. Cranshaw,[40] R. Cropp,[41] R. Culbertson,[11] D. Dagenhart,[44] S. D'Auria,[15] F. DeJongh,[11] S. Dell'Agnello,[13] M. Dell'Orso,[33] L. Demortier,[37] M. Deninno,[3] P. F. Derwent,[11] T. Devlin,[38] J. R. Dittmann,[11] A. Dominguez,[23] S. Donati,[33] J. Done,[39] M. D'Onofrio,[33] T. Dorigo,[16] N. Eddy,[18] K. Einsweiler,[23] J. E. Elias,[11] E. Engels, Jr.,[34] R. Erbacher,[11] D. Errede,[18] S. Errede,[18] Q. Fan,[36] R. G. Feild,[47] J. P. Fernandez,[11] C. Ferretti,[33] R. D. Field,[12] I. Fiori,[3] B. Flaugher,[11] G. W. Foster,[11] M. Franklin,[16] J. Freeman,[11] J. Friedman,[24] Y. Fukui,[22] I. Furic,[24] S. Galeotti,[33] A. Gallas,[(**) 16] M. Gallinaro,[37] T. Gao,[32] M. Garcia-Sciveres,[23] A. F. Garfinkel,[35] P. Gatti,[31] C. Gay,[47] D. W. Gerdes,[25] P. Giannetti,[33] P. Giromini,[13] V. Glagolev,[9] D. Glenzinski,[11] M. Gold,[27] J. Goldstein,[11] I. Gorelov,[27] A. T. Goshaw,[10] Y. Gotra,[34] K. Goulianos,[37] C. Green,[35] G. Grim,[5] P. Gris,[11] L. Groer,[38] C. Grosso-Pilcher,[8] M. Guenther,[35] G. Guillian,[25] J. Guimaraes da Costa,[16] R. M. Haas,[12] C. Haber,[23] S. R. Hahn,[11] C. Hall,[16] T. Handa,[17] R. Handler,[46] W. Hao,[40] F. Happacher,[13] K. Hara,[43] A. D. Hardman,[35] R. M. Harris,[11] F. Hartmann,[20] K. Hatakeyama,[37] J. Hauser,[6] J. Heinrich,[32] A. Heiss,[20] M. Herndon,[19] C. Hill,[5] K. D. Hoffman,[35] C. Holck,[32] R. Hollebeek,[32] L. Holloway,[18] R. Hughes,[28] J. Huston,[26] J. Huth,[16] H. Ikeda,[43] J. Incandela,[11] G. Introzzi,[33] J. Iwai,[45] Y. Iwata,[17] E. James,[25] M. Jones,[32] U. Joshi,[11] H. Kambara,[14] T. Kamon,[39] T. Kaneko,[43] K. Karr,[44] H. Kasha,[47] Y. Kato,[29] T. A. Keaffaber,[35] K. Kelley,[24] M. Kelly,[25] R. D. Kennedy,[11] R. Kephart,[11] D. Khazins,[10] T. Kikuchi,[43] B. Kilminster,[36] B. J. Kim,[21] D. H. Kim,[21] H. S. Kim,[18] M. J. Kim,[21] S. B. Kim,[21] S. H. Kim,[43] Y. K. Kim,[23] M. Kirby,[10] M. Kirk,[4] L. Kirsch,[4] S. Klimenko,[12] P. Koehn,[28] K. Kondo,[45] J. Konigsberg,[12] A. Korn,[24] A. Korytov,[12] E. Kovacs,[2] J. Kroll,[32] M. Kruse,[10] S. E. Kuhlmann,[2] K. Kurino,[17] T. Kuwabara,[43] A. T. Laasanen,[35] N. Lai,[8] S. Lami,[37] S. Lammel,[11] J. Lancaster,[10] M. Lancaster,[23] R. Lander,[5] A. Lath,[38] G. Latino,[33] T. LeCompte,[2] A. M. Lee IV,[10] K. Lee,[40] S. Leone,[33] J. D. Lewis,[11] M. Lindgren,[6] T. M. Liss,[18] J. B. Liu,[36] Y. C. Liu,[1] D. O. Litvintsev,[11] O. Lobban,[40] N. Lockyer,[32] J. Loken,[30] M. Loreti,[31] D. Lucchesi,[31] P. Lukens,[11] S. Lusin,[46] L. Lyons,[30] J. Lys,[23] R. Madrak,[16] K. Maeshima,[11] P. Maksimovic,[16] L. Malferrari,[3] M. Mangano,[33] M. Mariotti,[31] G. Martignon,[31] A. Martin,[47] J. A. J. Matthews,[27] J. Mayer,[41] P. Mazzanti,[3] K. S. McFarland,[36] P. McIntyre,[39] E. McKigney,[32] M. Menguzzato,[31] A. Menzione,[33] C. Mesropian,[37] A. Meyer,[11] T. Miao,[11] R. Miller,[26] J. S. Miller,[25] H. Minato,[43] S. Miscetti,[13] M. Mishina,[22] G. Mitselmakher,[12] N. Moggi,[3] E. Moore,[27] R. Moore,[25] Y. Morita,[22] T. Moulik,[35] M. Mulhearn,[24] A. Mukherjee,[11] T. Muller,[20] A. Munar,[33] P. Murat,[11] S. Murgia,[26] J. Nachtman,[6] V. Nagaslaev,[40] S. Nahn,[47] H. Nakada,[43] I. Nakano,[17] C. Nelson,[11] T. Nelson,[11] C. Neu,[28] D. Neuberger,[20] C. Newman-Holmes,[11] C.-Y. P. Ngan,[24] H. Niu,[4] L. Nodulman,[2] A. Nomerotski,[12] S. H. Oh,[10] Y. D. Oh,[21] T. Ohmoto,[17] T. Ohsugi,[17] R. Oishi,[43] T. Okusawa,[29] J. Olsen,[46] W. Orejudos,[23] C. Pagliarone,[33] F. Palmonari,[33] R. Paoletti,[33] V. Papadimitriou,[40] D. Partos,[4] J. Patrick,[11] G. Pauletta,[42] M. Paulini,[(*) 23] C. Paus,[24] L. Pescara,[31] T. J. Phillips,[10] G. Piacentino,[33] K. T. Pitts,[18] A. Pompos,[35] L. Pondrom,[46] G. Pope,[34] M. Popovic,[41] F. Prokoshin,[9] J. Proudfoot,[2] F. Ptohos,[13] O. Pukhov,[9] G. Punzi,[33] A. Rakitine,[24] F. Ratnikov,[38] D. Reher,[23] A. Reichold,[30] A. Ribon,[31] W. Riegler,[16] F. Rimondi,[3] L. Ristori,[33] M. Riveline,[41] W. J. Robertson,[10] A. Robinson,[41] T. Rodrigo,[7] S. Rolli,[44] L. Rosenson,[24] R. Roser,[11] R. Rossin,[31] A. Roy,[35] A. Ruiz,[7] A. Safonov,[5] R. St. Denis,[15] W. K. Sakumoto,[36] D. Saltzberg,[6] C. Sanchez,[28] A. Sansoni,[13] L. Santi,[42] H. Sato,[43] P. Savard,[41] P. Schlabach,[11] E. E. Schmidt,[11] M. P. Schmidt,[47] M. Schmitt,[(**) 16] L. Scodellaro,[31] A. Scott,[6] A. Scribano,[33] S. Segler,[11] S. Seidel,[27] Y. Seiya,[43] A. Semenov,[9] F. Semeria,[3] T. Shah,[24] M. D. Shapiro,[23] P. F. Shepard,[34] T. Shibayama,[43] M. Shimojima,[43] M. Shochet,[8] A. Sidoti,[31] J. Siegrist,[23] A. Sill,[40] P. Sinervo,[41] P. Singh,[18] A. J. Slaughter,[47] K. Sliwa,[44] C. Smith,[19] F. D. Snider,[11] A. Solodsky,[37] J. Spalding,[11] T. Speer,[14] P. Sphicas,[24] F. Spinella,[33] M. Spiropulu,[16] L. Spiegel,[11] J. Steele,[46] A. Stefanini,[33] J. Strologas,[18] F. Strumia, [14] D. Stuart,[11] K. Sumorok,[24] T. Suzuki,[43] T. Takano,[29] R. Takashima,[17] K. Takikawa,[43] P. Tamburello,[10] M. Tanaka,[43] B. Tannenbaum,[6] M. Tecchio,[25] R. Tesarek,[11] P. K. Teng,[1] K. Terashi,[37] S. Tether,[24] A. S. Thompson,[15] R. Thurman-Keup,[2] P. Tipton,[36] S. Tkaczyk,[11] D. Toback,[39] K. Tollefson,[36] A. Tollestrup,[11] D. Tonelli,[33] H. Toyoda,[29] W. Trischuk,[41] J. F. de Troconiz,[16] J. Tseng,[24] N. Turini,[33] F. Ukegawa,[43] T. Vaiciulis,[36]

J. Valls,[38] S. Vejcik III,[11] G. Velev,[11] G. Veramendi,[23] R. Vidal,[11] I. Vila,[7] R. Vilar,[7] I. Volobouev,[23] M. von der Mey,[6] D. Vucinic,[24] R. G. Wagner,[2] R. L. Wagner,[11] N. B. Wallace,[38] Z. Wan,[38] C. Wang,[10] M. J. Wang,[1] B. Ward,[15] S. Waschke,[15] T. Watanabe,[43] D. Waters,[30] T. Watts,[38] R. Webb,[39] H. Wenzel,[20] W. C. Wester III,[11] A. B. Wicklund,[2] E. Wicklund,[11] T. Wilkes,[5] H. H. Williams,[32] P. Wilson,[11] B. L. Winer,[28] D. Winn,[25] S. Wolbers,[11] D. Wolinski,[25] J. Wolinski,[26] S. Wolinski,[25] S. Worm,[27] X. Wu,[14] J. Wyss,[33] W. Yao,[23] G. P. Yeh,[11] P. Yeh,[1] J. Yoh,[11] C. Yosef,[26] T. Yoshida,[29] I. Yu,[21] S. Yu,[32] Z. Yu,[47] A. Zanetti,[42] F. Zetti,[23] and S. Zucchelli[3]

(CDF Collaboration)

[1] *Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2] *Argonne National Laboratory, Argonne, Illinois 60439*
[3] *Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[4] *Brandeis University, Waltham, Massachusetts 02254*
[5] *University of California at Davis, Davis, California 95616*
[6] *University of California at Los Angeles, Los Angeles, California 90024*
[7] *Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[8] *Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[9] *Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[10] *Duke University, Durham, North Carolina 27708*
[11] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[12] *University of Florida, Gainesville, Florida 32611*
[13] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[14] *University of Geneva, CH-1211 Geneva 4, Switzerland*
[15] *Glasgow University, Glasgow G12 8QQ, United Kingdom*
[16] *Harvard University, Cambridge, Massachusetts 02138*
[17] *Hiroshima University, Higashi-Hiroshima 724, Japan*
[18] *University of Illinois, Urbana, Illinois 61801*
[19] *The Johns Hopkins University, Baltimore, Maryland 21218*
[20] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[21] *Center for High Energy Physics: Kyungpook National University, Taegu 702-701; Seoul National University, Seoul 151-742; and SungKyunKwan University, Suwon 440-746; Korea*
[22] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan*
[23] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[24] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[25] *University of Michigan, Ann Arbor, Michigan 48109*
[26] *Michigan State University, East Lansing, Michigan 48824*
[27] *University of New Mexico, Albuquerque, New Mexico 87131*
[28] *The Ohio State University, Columbus, Ohio 43210*
[29] *Osaka City University, Osaka 588, Japan*
[30] *University of Oxford, Oxford OX1 3RH, United Kingdom*
[31] *Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*
[32] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[33] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[34] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[35] *Purdue University, West Lafayette, Indiana 47907*
[36] *University of Rochester, Rochester, New York 14627*
[37] *Rockefeller University, New York, New York 10021*
[38] *Rutgers University, Piscataway, New Jersey 08855*
[39] *Texas A&M University, College Station, Texas 77843*
[40] *Texas Tech University, Lubbock, Texas 79409*
[41] *Institute of Particle Physics, University of Toronto, Toronto M5S 1A7, Canada*
[42] *Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy*
[43] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[44] *Tufts University, Medford, Massachusetts 02155*
[45] *Waseda University, Tokyo 169, Japan*
[46] *University of Wisconsin, Madison, Wisconsin 53706*
[47] *Yale University, New Haven, Connecticut 06520*

(*) *Now at Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
(**) *Now at Northwestern University, Evanston, Illinois 60208*

We report on a measurement of the mean charged particle multiplicity of jets in dijet events with dijet masses in the range 80 to 630 GeV/$c^2$, produced at the Tevatron in $p\bar{p}$ collisions with $\sqrt{s}$=1.8 TeV and recorded by the Collider Detector at Fermilab. The data are fit to perturbative QCD calculations carried out in the framework of the Modified Leading Log Approximation and the hypothesis of Local Parton-Hadron Duality. The fit yields values for two parameters in that framework: the ratio of parton multiplicities in gluon and quark jets, $r \equiv N^{g-jet}_{partons}/N^{q-jet}_{partons} = 1.7 \pm 0.3$, and the ratio of the number of charged hadrons to the number of partons in a jet, $K^{charged}_{LPHD} \equiv N^{charged}_{hadrons}/N_{partons} = 0.57 \pm 0.11$.

Measurement of inclusive charged particle multiplicities in jets allows testing of the applicability of perturbative QCD methods to the description of the soft process of jet fragmentation. We present here multiplicities measured in dijet events with dijet masses between 80 and 630 GeV/$c^2$. These results are compared with perturbative QCD calculations carried out in the framework of the Modified Leading Log Approximation, MLLA [1], and the hypothesis of Local Parton-Hadron Duality, LPHD [2]. From this comparison we extract the value of the ratio of parton multiplicities in gluon and quark jets, $r = N^{g-jet}_{partons}/N^{q-jet}_{partons}$, as well as the ratio of the number of charged hadrons to the number of partons in a jet, $K^{charged}_{LPHD} = N^{charged}_{hadrons}/N_{partons}$.

The MLLA+LPHD scheme views jet fragmentation as a predominantly perturbative QCD process. MLLA handles production of partons with $k_T$ down to some effective cut-off scale $Q_{eff}$ ($k_T > Q_{eff}$), where $k_T$ is the transverse momentum with respect to the jet direction. MLLA calculations stay infrared-stable with $Q_{eff}$ as low as $\Lambda_{QCD}$. $Q_{eff}$ is the only MLLA parameter and has to be determined experimentally. The LPHD hypothesis assumes that hadronization is local and occurs at the end of the parton shower development, so that properties of hadrons are closely related to those of partons. In particular, the number of hadrons is related to the number of partons via an energy-independent constant $K_{LPHD}$:

$$N_{hadrons} = K_{LPHD} \times N_{partons}. \quad (1)$$

A simple interpretation of Eq. 1 is that each parton produced during the perturbative QCD stage picks up a color partner from the vacuum sea at the end of parton branching and turns into a hadron, so that $K_{LPHD} = N_{hadrons}/N_{partons} \sim 1$. Then, for charged particles only, one expects from simple isospin counting that the constant $K^{charged}_{LPHD} = N^{charged}_{hadrons}/N_{partons}$ should be approximately 2/3 (e.g. $\sim 0.60$ as suggested by [3]). In MLLA, the multiplicity $N^{g-jet}_{partons}$ of partons in a gluon jet of energy $E_{jet}$, and within an opening angle $\theta_c$, is a function of $E_{jet}\sin\theta_c/Q_{eff}$ [1]. The multiplicity of partons in a quark jet has exactly the same energy dependence and differs from a gluon jet only by the factor $r$, predicted to be the ratio of color charges $C_A/C_F = 9/4$ [4].

Recent and more accurate solutions [5, 6, 7] of the same primary set of QCD evolution equations that forms the basis of the MLLA have resulted in corrections to both $N^{g-jet}_{partons}$ and $r$. Reported results for the next-to-MLLA correction factor for $N^{g-jet}_{partons}$ are $F_{nMLLA}$=1.13±0.02 [5], 1.50±0.08 [6], and 1.40± 0.01 [7]. The parameter $r$ takes the values 1.75±0.05, 1.60±0.05, and 1.79±0.07, respectively. For all three calculations, both $F_{nMLLA}$ and $r$ show little energy dependence and were treated as constants in this analysis. The uncertainties in the numbers quoted above correspond to the range of dijet masses in our sample.

Experimentally, early measurements of $r$ were consistent with 1.0 [8]. More recent results from LEP and SLAC range from 1.0 to 1.5 with typically quite small errors [9]. The spread of the results motivates an independent measurement performed by different methods and in a different environment. Analyses of charged particle momentum spectra at LEP yield $K^{charged}_{LPHD}$=1.28±0.01 [10] (about twice the expected value). These measurements are obtained assuming $F_{nMLLA}$=1 and $r$=9/4. If one uses $F_{nMLLA}$=1.3 ± 0.2 (the range suggested by [5, 6, 7]) and $r$=1.5 (the most recent measurements from LEP, [9]), one arrives at $K^{charged}_{LPHD} \sim 0.67$.

At the Tevatron, dijet events are a mixture of gluon and quark jets. Denoting the fractions of gluon and quark jets as $\epsilon_g$ and $\epsilon_q = (1-\epsilon_g)$, one can derive an expression for the multiplicity of charged particles in the mixed jets:

$$N^{charged}_{hadrons} = K^{charged}_{LPHD}(\epsilon_g + (1-\epsilon_g)\frac{1}{r})F_{nMLLA}N^{g-jet}_{partons}. \quad (2)$$

The current analysis is based on 95 pb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s}$=1.8 TeV recorded by the Collider Detector at Fermilab (CDF). The CDF detector is described in detail in [11] and references therein. Here, we will focus on those elements of the detector that are directly related to this analysis: the vertex detector (VTX), the Central Tracking Chamber (CTC) and the full set of electromagnetic and hadronic calorimeters.

The VTX is a time-projection drift chamber and determines the z-position of the primary vertex (or ver-

tices in the case of multiple $p\bar{p}$ interactions in the same bunch crossing). The CTC is an open-cell drift chamber designed for measuring particle trajectories. Determination of a particle's momentum is based on the curvature of its trajectory in the solenoidal magnetic field. In our analysis, we considered particles falling in restricted cones around the jet axis and determined the angular parameters of their trajectories with the CTC.

The jet energy and direction were measured in the central lead-scintillator electromagnetic (CEM) and iron-scintillator hadronic (CHA) calorimeters. The CEM and CHA both have $2\pi$ azimuthal coverage. In pseudorapidity [12] they cover the region $|\eta| < 1.0$. The segmentation of both detectors is $15^o$ in $\phi$ and 0.1 unit in $\eta$.

CDF defines jets using a cone algorithm; full details can be found in [13]. The algorithm searches in cones of radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$ around the calorimeter seed towers (any tower with tranverse energy $E_T$ [12] above 1 GeV) and adds towers with $E_T$ above 0.1 GeV. If two or more adjacent seed towers are found within R=0.7, they are merged. The coordinates of the jet axis are calculated as $E_{T_i}$-weighted sums of the $\phi_i$ and $\eta_i$ of towers assigned to the jet. Merging continues until a stable set of clusters is found. Corrections were applied to compensate for the non-linearity and non-uniformity of the energy response of the calorimeter, the energy deposited inside the jet cone from sources other than the parent parton, and the parent-parton energy that radiates out of the jet cone.

Approximately 100,000 dijet events were accumulated using single-jet triggers with transverse jet energy thresholds of 20, 50, 70 and 100 GeV, the first three triggers being pre-scaled by 1000, 40 and 8 respectively. To select dijet events, we required the presence of two high-$E_T$ jets, well balanced in the transverse direction: $|\vec{E}_{T_1} + \vec{E}_{T_2}|/(E_{T_1} + E_{T_2}) < 0.15$. To avoid biases, 3- and 4-jet events were allowed as well, if the non-leading extra jets were very soft, $(E_{T_3} + E_{T_4})/(E_{T_1} + E_{T_2}) < 0.05$. Only events with both leading jets in the central region of the detector ($|\eta_{1,2}| < 0.9$) were retained for the analysis to ensure that the tracks fell in the fiducial volume of the CTC. The data were further subdivided into nine bins according to dijet mass $M_{JJ}$, as measured by the calorimeters ($M_{JJ} = \sqrt{(E_1 + E_2)^2/c^4 - (\vec{P}_1 + \vec{P}_2)^2/c^2}$, where $E_i$ and $\vec{P}_i$ are the jet energies and momenta and the jets were treated as massless objects, i.e. $|\vec{P}_i| = E_i/c$). The bin width was uniform in log-scale, $\Delta \ln(M_{JJ}) = 0.3$, and was always larger than the resolution errors in the dijet mass determination, $\delta M_{JJ}/M_{JJ} \sim 7 - 11\%$. The mean values of the dijet masses for the nine bins were $M_{JJ}$= 82, 105, 140, 182, 229, 293, 378, 488, and 629 GeV/$c^2$.

Charged particle multiplicities were obtained for tracks lying in three restricted cones with $\theta_c$ =0.17, 0.28 and 0.47 rad around the jet axis, where $\theta_c$ is defined as the angle between the jet axis and the cone side. The analysis was carried out in the dijet center of mass frame, so that $E_{jet} = M_{JJ}c^2/2$. All multiplicities quoted below are per jet.

To reconstruct the true charged particle multiplicities, several cuts and corrections were applied. First, we required full 3D reconstruction in the CTC and used vertex cuts to ensure that tracks included in the analysis originated in the primary vertex and were not due to secondary interactions, $\gamma$-conversions, $K_S$ and $\Lambda$ decays, or cosmic and other backgrounds.

Second, the data were corrected for CTC track reconstruction inefficiency. To evaluate track losses, we used a procedure based on mixing real data tracks from one jet into the opposite jet in the same event. Tracks were embedded one at a time at the CTC hit level and the full CTC track reconstruction was executed. The parameters of all found tracks were compared to the original parameters of the embedded tracks in order to determine the inefficiency corrections. The average tracking efficiency with the vertex cuts chosen and within the opening angle $\theta_c$=0.47 was found to be 93% at the lowest dijet masses, decreasing to 78% for the largest dijet masses.

Third, tracks coming from the underlying event and multiple interactions in the same bunch crossing were subtracted. We defined two complementary cones positioned at the same polar angle with respect to the beamline as the original jets and rotated in $\phi$ so that they were at $90^o$ with respect to the dijet axis. These cones collected statistically the same backgrounds as the cones around jets. The absolute scale of this correction, for the largest opening angle $\theta_c$=0.47 around the jet axis, was almost independent of the jet energy and amounted to about 0.5-0.6 tracks per jet.

Finally, a small fraction of tracks coming from $\gamma$-conversions that were not removed by the vertex cuts was subtracted. The Herwig Monte Carlo event generator (version 5.6) [14] was used to evaluate the number of remaining $\gamma$-conversion tracks. The scale of this correction was 0.3 (0.8) tracks per jet for the lowest (highest) dijet mass data samples (for cone size $\theta_c = 0.47$).

The major sources of systematic uncertainties were as follows (for $\theta_c$ =0.47): (a) background track removal, 6-7%, (b) uncertainties in CTC track reconstruction efficiency, 2-6%, (c) jet energy measurement errors including both resolution and overall scale errors, 0.4-3%, and (d) errors in the jet direction determination based on energy deposition in the calorimeter, 0.7-1.2%. The uncertainties from a given source are strongly correlated between different dijet mass samples. These correlations were taken into account in the data analysis.

Table 1 summarizes the multiplicities for the three jet opening angles and all dijet mass data samples. Fig. 1 shows the charged track multiplicity (per jet) in a cone $\theta_c$ =0.47 as a function of the dijet mass. To show the trends, we have also plotted curves corresponding to the function (2) with different values of the ratio $r$. Equation (2) implies knowledge of the relative fractions of quark

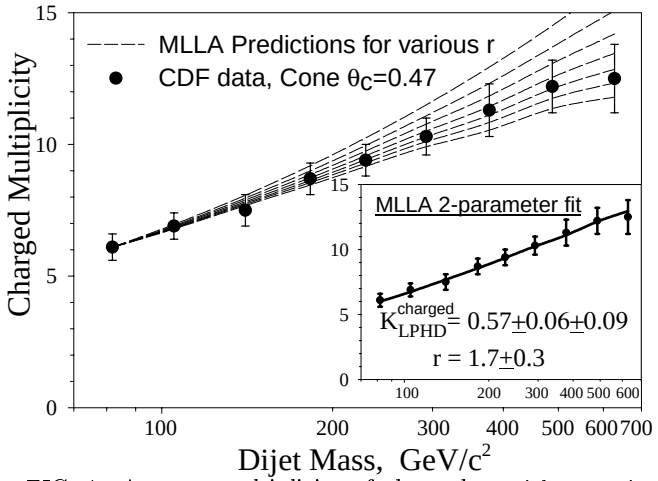


FIG. 1. Average multiplicity of charged particles per jet within a cone of size $\theta_c = 0.47$ in dijet events (points with error bars) vs. dijet mass. A set of MLLA curves (normalized to the first data point) correspond to different values of $r$ (from top to bottom $r$=1, 1.2, 1.4, 1.6, 1.8, 2.0, 2.25). The two-parameter MLLA fit is represented by the solid line in the insert.

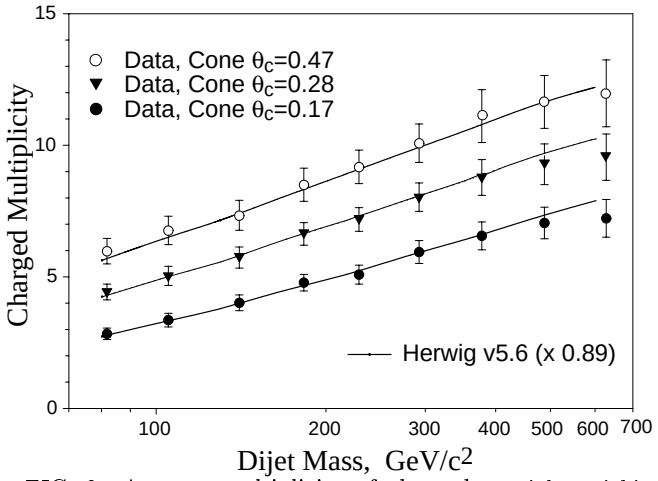


FIG. 2. Average multiplicity of charged particles within cones $\theta_c$=0.17, 0.28 and 0.47 in dijet events (symbols with error bars) compared to the Herwig predictions including detector simulation (lines), scaled by a factor of 0.89. Data errors are dominated by systematic uncertainties.

and gluon jets in our dijet samples. These fractions were extracted from the Herwig Monte Carlo with CTEQ4M[15] parton distribution functions (PDFs), as well as with CTEQ4HJ [16]. The fraction of gluon jets was found to decrease from $\epsilon_g$ ~61-63% of all jets at $M_{JJ}$=80 GeV/$c^2$ to 23-26% at 630 GeV/$c^2$ (the variations result from using different PDFs).

Due to correlations between $Q_{eff}$ and $K^{charged}_{LPHD}$, average multiplicity measurements alone do not allow the extraction of all three parameters $Q_{eff}$, $r$ and $K^{charged}_{LPHD}$. Therefore, we fixed $Q_{eff}$=240 MeV, as obtained in our studies of charged particle momentum distribution shapes [17], and fitted the data with the function (2) for two free parameters: $r$ and the combination $K^{charged}_{LPHD} \cdot F_{nMLLA}$. The fit yielded the following results: $r = 1.7 \pm 0.3 \pm 0.0 \pm 0.0$ for the ratio of multiplicities and $K^{charged}_{LPHD} \cdot F_{nMLLA} = 0.74 \pm 0.04 \pm 0.06 \pm 0.04$. The first uncertainty comes from statistical and systematic experimental errors (as discussed above and summarized in Table 1), the second one from variations of $Q_{eff}$ by ±40 MeV, and the third from using different PDFs. The choice of $Q_{eff}$ and PDFs had little effect on the measurement of $r$. This value agrees well with the three most recent theoretical predictions mentioned above.

Assuming $F_{nMLLA} = 1.30 \pm 0.20$, the data yielded $K^{charged}_{LPHD} = 0.57 \pm 0.06 \pm 0.09$. The first uncertainty includes all statistical and systematic uncertainties discussed above, while the second comes from the theoretical uncertainty in $F_{nMLLA}$. The result is consistent with the LPHD hypothesis of approximately one-to-one correspondence between final partons and observed hadrons.

Fig. 2 shows how the average charged particle multiplicity in three restricted cones changes with $M_{JJ}$ and how it compares to the Herwig Monte Carlo that uses resummed perturbative calculations similar to MLLA for parton branching and a cluster model of hadronization.The error bars are statistical and systematic uncertainties added in quadrature. Herwig was found to be above the data by approximately 11%. A fit of the data to the Herwig predictions, where the overall Herwig normalization was treated as a free parameter $N$, and which took into account all systematic errors and their correlations, resulted in $N = 0.89 \pm 0.06$ (illustrated in Fig.2).

In summary, we have measured the inclusive charged particle multiplicity in dijet events for a wide range of dijet masses 80-630 GeV/$c^2$. The data were compared to calculations carried out in the framework of the Modified Leading Log Approximation complemented with the hypothesis of Local Parton-Hadron Duality. Assuming that multiplicity evolves with energy as prescribed by MLLA, we have fit two parameters of the model and found the ratio of parton multiplicities in gluon and quark jets $r = N^{g-jet}_{partons}/N^{q-jet}_{partons} = 1.7 \pm 0.3$ and the LPHD conversion constant $K^{charged}_{LPHD} = 0.57 \pm 0.11$. The Herwig Monte Carlo was found to reflect the major trends observed in data, although an overall scaling of the Monte Carlo multiplicities by a factor of 0.89 is preferred.

We are grateful to Yu. Dokshitzer, I. Dremin, V. Khoze, A. H. Mueller, V. Nechitailo, W. Ochs, R. Peschanski, and B. Webber for a number of very fruitful discussions. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and the National Science Foundation, the Italian Istituto Nazionale di Fisica Nucleare, the Ministry of Science, Culture and Education of Japan, the Natural Sciences and Engineering Research Council of Canada, the National Science Council of the Republic of China, and the A.P. Sloan Foundation.

[1] Yu. Dokshitzer, S. Troyan, XIX Winter School of LNPI, vol. 1, p. 144; A. H. Mueller, Nucl. Phys. B **213,** 85 (1983); Erratum ibid., B **241**, 141 (1984); Yu.L.Dokshitzer, V.A.Khoze, S.I.Troyan, Int. Journ. Mod. Phys. A **7**, 1875 (1992); Z. Phys. C **55**, 107 (1992). In MLLA, the parton multiplicity in a gluon jet is given by $N_{partons}^{g-jet} = \Gamma(B)\,(z/2)^{-B+1}\,I_{B+1}(z)$, with $z = \sqrt{16N_c/b\ln(E_{jet}\sin\theta_c/Q_{eff})}$, and where $I_{B+1}(z)$ is the modified Bessel function of order $B+1$. For the number of colors $N_c$=3 and the number of flavors of light quarks $n_f$=3, used in this analysis, $B$=101/81 and $b$=9.

[2] Ya. I. Azimov, Yu. Dokshitzer, V. Khoze, S.Troyan, Z. Phys. C **27**, 65 (1985);Z. Phys. C **31**, 213 (1986).

[3] A straightforward estimate of the fraction of charged particles with respect to all particles in jets can be obtained by measuring the energy fraction carried by charged particles. It was reported to be around 0.61±0.02, e.g., see: JADE Collab.: W. Bartel et al., Z. Phys. C **9**, 315 (1981); CELLO Collab.: H. J. Behrend et al., Phys. Lett. B **113**, 427 (1982); TASSO Collab: M. Althoff et al., Z. Phys. C **22**, 307 (1984); HRS Collab.: D. Bender et al., Phys. Rev. D **31**, 1 (1985).

[4] S. J. Brodsky, J.F. Gunion, Phys. Rev. Lett. **37**, 402 (1976).

[5] S. Catani, Yu. Dokshitzer, F. Fiorani, B. R. Webber, Nucl. Phys. B **377**, 445 (1992).

[6] S. Lupia, W. Ochs, Nucl. Phys. (Proc. Suppl.) **64**, 74 (1998).

[7] I. M. Dremin, J. W. Gary, Phys. Lett. B **459**, 341 (1999).

[8] JADE Collab.: W. Bartel et al., Phys. Lett. B **123**, 460 (1983); HRS Collab.: M. Derrick et al., Phys. Lett. B **165**, 449 (1985); MARK II Collab.: A. Petersen et al., Phys. Rev. Lett. **55**, 1954 (1985); TASSO Collab.: W. Braunschweig et al., Z. Phys. C **45**, 1 (1989); AMY Collab.: Y. K. Kim et al., Phys. Rev. Lett. **63**, 1772 (1989).

[9] OPAL Collab.: G. Alexander et al., Phys. Lett. B **265**, 462 (1991); OPAL Collab.: P. D. Acton et al., Z. Phys. C **58**, 387 (1993); OPAL Collab.: R. Akers et al., Z. Phys. C **68**, 179 (1995); ALEPH Collab.: D. Busculic et al., Phys. Lett. B **346**, 389 (1995); OPAL Collab.: G. Alexander et al., Phys. Lett. B **388**, 659 (1996); ALEPH Collab.: D. Busculic et al., Phys. Lett. B **384**, 353 (1996); DELPHI Collab.: P. Abreu et al., Z. Phys. C **70**, 179 (1996); OPAL Collab.: K. Ackerstaff et al., Eur. Phys. J. C **1**, 479 (1998); DELPHI Collab.: P. Abreu et al., Phys. Lett. B **449**, 383 (1999); OPAL Collab.: G. Abbiendi et al., Eur. Phys. J. C **11**, 217 (1999); Y. Iwasaki, for SLD Collaboration, SLAC-PUB-6597, Aug 1994, Presented at DPF 94, Albuquerque, NM, Aug 2-6, 1994; Y. Iwasaki, for SLD Collaboration, SLAC-R-95-460, SLAC preprint, Stanford, 1995.

[10] OPAL Collab: M.Z.Akrawy et al., Phys. Lett. B **247**, 617 (1990).

[11] F. Abe et al., Nucl. Instrum. Methods Phys. Res. A **271**, 387 (1988).

[12] The pseudorapidity $\eta$ is defined as $-\ln(\tan(\theta/2))$, where $\theta$ is the polar angle measured relative to the outgoing proton beam. The transverse energy $E_T$ is defined as $E\sin\theta$.

[13] F. Abe et al., Phys. Rev. D **45**, 1448 (1992).

[14] G. Marchesini, B.R. Webber, G. Abbiendi, I.G. Knowles, M.H. Seymour, L. Stanco, Comput. Phys. Commun. **67**, 465 (1992).

[15] H.L. Lai, J. Huston, S. Kuhlmann, F. Olness, J. Owens, D. Soper, W.K. Tung, H. Weerts, Phys. Rev. D **55**, 1280 (1997).

[16] J. Huston, E. Kovacs, S. Kuhlmann, H. L. Lai, J. F. Owens, D. Soper, W. K. Tung, Phys. Rev. Lett. 77, 444 (1996).

[17] A. Korytov, for CDF Collaboration, presented at "QCD-96", Montpellier, France, July 4-12, 1996. Publ. in: Nucl. Phys. B (Proc. Suppl.) **54A**, 67 (1997).

TABLE I. Measured values of inclusive charged particle multiplicity per jet for tracks falling in restricted cones with opening angles $\theta_c$=0.17, 0.28 and 0.47. The first error is statistical and the second is total systematic uncertainty. Systematic uncertainties are strongly correlated.

| Dijet Mass | $N_{events}$ | Mean Charged Particle Multiplicity per Jet | | |
|---|---|---|---|---|
| (GeV/$c^2$) | | (Cone $\theta_c = 0.17$) | (Cone $\theta_c = 0.28$) | (Cone $\theta_c = 0.47$) |
| 82 | 4148 | $2.9 \pm 0.03 \pm 0.2$ | $4.5 \pm 0.04 \pm 0.3$ | $6.1 \pm 0.05 \pm 0.5$ |
| 105 | 1968 | $3.4 \pm 0.04 \pm 0.3$ | $5.1 \pm 0.05 \pm 0.4$ | $6.9 \pm 0.06 \pm 0.5$ |
| 140 | 3378 | $4.0 \pm 0.04 \pm 0.3$ | $5.8 \pm 0.05 \pm 0.4$ | $7.5 \pm 0.05 \pm 0.6$ |
| 182 | 12058 | $4.9 \pm 0.04 \pm 0.3$ | $6.8 \pm 0.04 \pm 0.4$ | $8.7 \pm 0.04 \pm 0.6$ |
| 229 | 31406 | $5.2 \pm 0.04 \pm 0.4$ | $7.3 \pm 0.04 \pm 0.5$ | $9.4 \pm 0.05 \pm 0.6$ |
| 293 | 23206 | $6.0 \pm 0.05 \pm 0.4$ | $8.2 \pm 0.05 \pm 0.5$ | $10.3 \pm 0.05 \pm 0.7$ |
| 378 | 7153 | $6.7 \pm 0.06 \pm 0.5$ | $8.9 \pm 0.06 \pm 0.7$ | $11.3 \pm 0.09 \pm 1.0$ |
| 488 | 1943 | $7.4 \pm 0.08 \pm 0.6$ | $9.7 \pm 0.09 \pm 0.8$ | $12.2 \pm 0.10 \pm 1.0$ |
| 629 | 416 | $7.5 \pm 0.14 \pm 0.7$ | $9.9 \pm 0.16 \pm 0.9$ | $12.5 \pm 0.18 \pm 1.3$ |