Fermi National Accelerator Laboratory

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Jet Fragmentation Properties of $\bar{p}p$ Collisions at $\sqrt{s}$ = 1.8 TeV*

F. Abe[16], D. Amidei[3], G. Apollinari[11], G. Ascoli[7], M. Atac[4], P. Auchincloss[14], A. R. Baden[6], A. Barbaro-Galtieri[9], V. E. Barnes[12], F. Bedeschi[11], S. Behrends[12], S. Belforte[11], G. Bellettini[11], J. Bellinger[17], J. Bensinger[2], A. Beretvas[14], P. Berge[4], S. Bertolucci[5], S. Bhadra[7], M. Binkley[4], R. Blair[1], C. Blocker[2], J. Bofill[4], A. W. Booth[4], G. Brandenburg[6] D. Brown[6], A. Byon[12], K. L. Byrum[17], M. Campbell[3], R. Carey[6], W. Carithers[9], D. Carlsmith[17], J. T. Carroll[4], R. Cashmore[4], F. Cervelli[11], K. Chadwick[4,12], T. Chapin[13], G. Chiarelli[11], W. Chinowsky[9], S. Cihangir[15], D. Cline[17], D. Connor[10], M. Contreras[2], J. Cooper[4], M. Cordelli[5], M. Curatolo[5], C. Day[4], R. DelFabbro[11], S. Dell'Agnello[11], M. Dell'Orso[11], L. DeMortier[2], T. Devlin[14], D. DiBitonto[15], R. Diebold[1], F. Dittus[4], A. DiVirgilio[11], J. E. Elias[4], R. Ely[9], S. Errede[7], B. Esposito[5], B. Flaugher[14], E. Focardi[11], G. W. Foster[4], M. Franklin[6,7], J. Freeman[4], H. Frisch[3], Y. Fukui[8], A. F. Garfinkel[12], P. Giannetti[11], N. Giokaris[13], P. Giromini[5], L. Gladney[10], M. Gold[9], K. Goulianos[13], C. Grosso-Pilcher[3], C. Haber[9], S. R. Hahn[10], R. Handler[17], R. M. Harris[9], J. Hauser[3], T. Hessing[15], R. Hollebeek[10], P. Hu[14], B. Hubbard[9], P. Hurst[7], J. Huth[4], H. Jensen[4], R. P. Johnson[4], U. Joshi[14], R. W. Kadel[4], T. Kamon[15], S. Kanda[16], D. A. Kardelis[7] I. Karliner[7], E. Kearns[6], R. Kephart[4], P. Kesten[2], H. Keutelian[7], S. Kim[16], L. Kirsch[2], K. Kondo[16], U. Kruse[7], S. E. Kuhnmann[12], A. T. Laasanen[12], W. Li[1], T. Liss[3], N. Lockyer[10], F. Marchetto[15], R. Markeloff[17], L. A. Markosky[17], P. McIntyre[15], A. Menzione[11], T. Meyer[15], S. Mikamo[8], M. Miller[10], T. Mimashi[16], S. Miscetti[5], M. Mishina[8], S. Miyashita[16], N. Mondel[17], S. Mori[16], Y. Morita[16], A. Mukherjee[4], C. Newman-Holmes[4], L. Nodulman[1], R. Paoletti[11], A. Para[4], J. Patrick[4], T. J. Phillips[6], H. Piekarz[2], R. Plunkett[13], L. Pondrom[17], J. Proudfoot[1], G. Punzi[11], D. Quarrie[4], K. Ragan[10], C. Redlinger[3], J. Rhoades[17], F. Rimondi[4], L. Ristori[11], T. Rohaly[10], A. Roodman[3], A. Sansoni[5], R. Sard[7], V. Scarpine[7], P. Schlabach[7], E. E. Schmidt[4], P. Schoessow[1], M. H. Schub[12], R. Schwitters[6] A. Scribano[11], S. Segler[4], M. Sekiguchi[16], P. Sestini[11], M. Shapiro[6], M. Sheaff[17], M. Shibata[16], M. Shochet[3], J. Siegrist[9], P. Sinervo[10], J. Skarha[17], D. A. Smith[7], F. D. Snider[3], R. St. Denis[6], A. Stefanini[11], Y. Takaiwa[16], K. Takikawa[16], S. Tarem[2], D. Theriot[4], A. Tollestrup[4], G. Tonelli[11], Y. Tsay[3], F. Ukegawa[16], D. Underwood[1], R. Vidal[4], R. G. Wagner[1], R. L. Wagner[4] J. Walsh[10], T. Watts[14], R. Webb[15], T. Westhusing[7], S. White[13], A. Wicklund[1], H. H. Williams[10], T. Yamanouchi[4], A. Yamashita[16], K. Yasuoka[16], G. P. Yeh[4], J. Yoh[4], F. Zetti[11],

[1] Argonne National Laboratory, Argonne, Illinois 60439 - [2] Brandeis University, Waltham, Massachusetts 02254 - [3] University of Chicago, Chicago, Illinois 60637 - [4] Fermi National Accelerator Laboratory, Batavia, Illinois 60510 - [5] Laboratori Nazionali di Frascati, Instituto Nazionale di Fiscia Nucleare, I-00044, Frascati, Italy - [6] Harvard University, Cambridge, Massachusetts 02138 - [7] University of Illinois, Urbana, Illinois 61801 - [8] National Laboratory for High Energy Physics (KEK), Tsukuba-gun, Ibaraki-ken 305, Japan - [9] Lawrence Berkeley Laboratory, Berkeley, California 94720 - 10 University of Pennsylvania, Philadelphia, Pennsylvania 19104 - [11] INFN, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy - [12] Purdue University, West Lafayette, Indiana 47907 - [13] Rockefeller University, New York, New York 10021 - [14] Rutgers University, Piscataway, New Jersey 08854 - [15] Texas A&M University, College Station, Texas 77843 - [16] University of Tsukuba, Tsukuba, Ibaraki 305, Japan - [17] University of Wisconsin, Madison, Wisconsin 53706

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F.Abe,[16] D.Amidei,[3] G.Apollinari,[11] G.Ascoli,[7] M.Atac,[4] P.Auchincloss,[14] A.R.Baden,[6] A.Barbaro-Galtieri,[9] V.E.Barnes,[12] F.Bedeschi,[11] S.Behrends,[12] S.Belforte,[11] G.Bellettini,[11] J.Bellinger,[17] J.Bensinger,[2] A.Beretvas,[14] P.Berge,[4] S.Bertolucci,[5] S.Bhadra,[7] M.Binkley,[4] R.Blair,[1] C.Blocker,[2] J.Bofill,[4] A.W.Booth,[4] G.Brandenburg,[6] D.Brown,[6] A.Byon,[12] K.L.Byrum,[17] M.Campbell,[3] R.Carey,[6] W.Carithers,[9] D.Carlsmith,[17] J.T.Carroll,[4] R.Cashmore,[4] F.Cervelli,[11] K.Chadwick,[4,12] T.Chapin,[13] G.Chiarelli,[11] W.Chinowsky,[9] S.Cihangir,[15] D.Cline,[17] D.Connor,[10] M.Contreras,[2] J.Cooper,[4] M.Cordelli,[5] M.Curatolo,[5] C.Day,[4] R.DelFabbro,[11] S.Dell'Agnello,[11] M.Dell'Orso,[11] L.DeMortier,[2] T.Devlin,[14] D.DiBitonto,[15] R.Diebold,[1] F.Dittus,[4] A.DiVirgilio,[11] J.E.Elias,[4] R.Ely,[9] S.Errede,[7] B.Esposito,[5] B.Flaugher,[14] E.Focardi,[11] G.W.Foster,[4] M.Franklin,[6,7] J.Freeman,[4] H.Frisch,[3] Y.Fukui,[8] A.F.Garfinkel,[12] P.Giannetti,[11] N.Giokaris,[13] P.Giromini,[5] L.Gladney,[10] M.Gold,[9] K.Goulianos,[13] C.Grosso-Pilcher,[3] C.Haber,[9] S.R.Hahn,[10] R.Handler,[17] R.M.Harris,[9] J.Hauser,[3] T.Hessing,[15] R.Hollebeek,[10] P.Hu,[14] B.Hubbard,[9] P.Hurst,[7] J.Huth,[4] H.Jensen,[4] R.P.Johnson,[4] U.Joshi,[14] R.W.Kadel,[4] T.Kamon,[15] S.Kanda,[16] D.A.Kardelis,[7] I.Karliner,[7] E.Kearns,[6] R.Kephart,[4] P.Kesten,[2] H.Keutelian,[7] S.Kim,[16] L.Kirsch,[2] K.Kondo,[16] U.Kruse,[7] S.E.Kuhlmann,[12] A.T.Laasanen,[12] W.Li,[1] T.Liss,[3] N.Lockyer,[10] F.Marchetto,[15] R.Markeloff,[17] L.A.Markosky,[17] P.McIntyre,[15] A.Menzione,[11] T.Meyer,[15] S.Mikamo,[8] M.Miller,[10] T.Mimashi,[16] S.Miscetti,[5] M.Mishina,[8] S.Miyashita,[16] N.Mondal,[17] S.Mori,[16] Y.Morita,[16] A.Mukherjee,[4] C.Newman-Holmes,[4] L.Nodulman,[1] R.Paoletti,[11] A.Para,[4] J.Patrick,[4] T.J.Phillips,[6] H.Piekarz,[2] R.Plunkett,[13] L.Pondrom,[17] J.Proudfoot,[1] G.Punzi,[11] D.Quarrie,[4] K.Ragan,[10] G.Redlinger,[3] J.Rhoades,[17] F.Rimondi,[4] L.Ristori,[11] T.Rohaly,[10] A.Roodman,[3] A.Sansoni,[5] R.Sard,[7] V.Scarpine,[7] P.Schlabach,[7] E.E.Schmidt,[4] P.Schoessow,[1] M.H.Schub,[12] R.Schwitters,[6] A.Scribano,[11]

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S.Segler,[4] M.Sekiguchi,[16] P.Sestini,[11] M.Shapiro,[6] M.Sheaff,[17] M.Shibata,[16] M.Shochet,[3]
J.Siegrist,[9] P.Sinervo,[10] J.Skarha,[17] D.A.Smith,[7] F.D.Snider,[3] R.St.Denis,[6] A.Stefanini,[11]
Y.Takaiwa,[16] K.Takikawa,[16] S.Tarem,[2] D.Theriot,[4] A.Tollestrup,[4] G.Tonelli,[11] Y.Tsay,[3]
F.Ukegawa,[16] D.Underwood,[1] R.Vidal,[4] R.G.Wagner,[1] R.L.Wagner,[4] J.Walsh,[10]
T.Watts,[14] R.Webb,[15] T.Westhusing,[7] S.White,[13] A.Wicklund,[1] H.H.Williams,[10]
T.Yamanouchi,[4] A.Yamashita,[16] K.Yasuoka,[16] G.P.Yeh,[4] J.Yoh,[4] F.Zetti[11]

[1] Argonne National Laboratory, Argonne, Illinois 60439

[2] Brandeis University, Waltham, Massachusetts 02254

[3] University of Chicago, Chicago, Illinois 60637

[4] Fermi National Accelerator Laboratory, Batavia, Illinois 60510

[5] Laboratori Nazionali di Frascati of the Istituto Nazionale di Fisica Nucleare, Italy

[6] Harvard University, Cambridge, Massachusetts 02138

[7] University of Illinois, Urbana, Illinois 61801

[8] National Laboratory for High Energy Physics (KEK), Tsukuba-gun, Ibaraki-ken 305, Japan

[9] Lawrence Berkeley Laboratory, Berkeley, California

[10] University of Pennsylvania, Philadelphia, Pennsylvania 19104

[11] Istituto Nazionale de Fisica Nucleare, University and Scuola Normale Superiore, Pisa, Italy

[12] Purdue University, West Lafayette, Indiana 47907

[13] Rockefeller University, New York, New York 10021

[14] Rutgers University, Piscataway, New Jersey 08854

[15] Texas A&M University, College Station, Texas 77843

[16] University of Tsukuba, Ibaraki 305, Japan

[17] University of Wisconsin, Madison, Wisconsin 53706

Abstract

The charged particle fractional momentum distribution within jets, $D(z)$, has been measured in dijet events from 1.8 TeV $\bar{p}p$ collisions in the Collider Detector at Fermilab (CDF). As expected from scale breaking in Quantum Chromodynamics (QCD), the fragmentation function $D(z)$ falls more steeply as dijet invariant mass increases from 60 to 200 GeV/c^2. The average fraction of the jet momentum carried by charged particles is $0.65 \pm 0.02(\text{stat}) \pm 0.08(\text{sys})$.

Leading order QCD calculations agree very well with measurements of jet production in proton-antiproton collisions over a large center-of-mass energy ($\sqrt{s}$) range[1,2]. The transformation of outgoing quarks and gluons into jets of hadrons should also be described by QCD, but the hadronization process involves non-perturbative effects which prevent quantitative predictions. The distribution of the jet momentum among charged hadrons is described phenomenologically by the fragmentation function $D(z) = (1/N_{jets})(dN_{charged}/dz)$, where we define $z = P_{\|}/|\vec{P}_{jet}|$, with $P_{\|}$ being the momentum component of a hadron along the axis of a jet with momentum $\vec{P}_{jet}$. According to the naive parton model, at high energy, where one may neglect particle masses, $D(z)$ should be independent of Q^2, where Q is the momentum transfer of the hard scattering process. Perturbative QCD calculations predict that logarithmic deviations from scaling with increasing Q^2[3], and that the fragmentation function for gluon jets should fall more steeply than that for quark jets[4,5]. At the Tevatron Collider $\sqrt{s}$ of 1.8 TeV, the ratio of gluon to quark jets is expected to be $\sim$3:1 at typical transverse momenta (P_T) of $\sim$ 50 GeV/c, and to decrease slowly with increasing P_T[6].

In this letter we present a measurement of the fragmentation function of jets into charged hadrons and its evolution with dijet invariant mass M_{JJ}. The data used here were collected with the Collider Detector at Fermilab (CDF) during the 1987 Tevatron Collider run. We briefly describe those aspects of CDF which are relevant for this analysis; the complete detector is described in [7] and references therein. The apparatus is azimuthally symmetric about the beam axis, so we utilize a coordinate system in which ϕ is the azimuthal angle, Z is the distance along the beam, and θ is the polar angle to the proton beam direction. The transverse quantities P_T and E_T are the momentum and energy multiplied by $\sin\theta$. An additional useful variable is the pseudo-rapidity η defined by the relation $\eta \equiv -\ln\tan(\theta/2)$.

Charged particle momenta are measured with the Central Tracking Chamber (CTC), a cylindrical drift chamber immersed in a 1.5 T solenoidal magnetic field parallel to the beam axis. In the pseudo-rapidity range $|\eta| < 1.2$, particle trajectories are measured in the CTC using 84 sense wire layers, with a position resolution per wire of approximately 200 microns. In this analysis, the transverse momentum resolution is $\delta P_T/P_T^2 \simeq 0.0015 GeV/c^{-1}$ for tracks constrained to the event vertex, where the collision vertex position is determined by the vertex time projection chamber. The track polar angle is measured by the CTC with an accuracy $\delta\theta$ of ± 0.02 radians by 24 stereo layers tilted at $\pm 3°$ to the axial direction.

The energy of charged and neutral particles is measured by electromagnetic and hadron calorimeters surrounding the tracking volume, covering the range $|\eta| < 4.2$ or $2° < \theta < 178°$. In the central region, where the CTC coverage is complete, the calorimeter is composed of scintillator interleaved with lead (electromagnetic compartment) or iron (hadron compartment) absorber, and is segmented into a grid of projective towers of $\Delta\phi = 15°$ by $\Delta\eta$=0.1.

Jets are defined as energy clusters in the calorimeter which are found with a standard clustering algorithm[2]. The cluster energy is the sum of tower energies within a cone of radius $R \equiv (\Delta\eta^2 + \Delta\phi^2)^{\frac{1}{2}} = 1.0$ about the cluster centroid, and the momentum is defined as the vector sum of tower momenta. Two corrections were applied to obtain the jet energy and momentum from the cluster quantities. Using the tracks found in the CTC, an energy correction ranging from +10 to +30% is applied to each jet. This procedure corrects for the nonlinear calorimeter response to charged pions and the magnetic field changing the direction of low momentum particles, and is observed to improve the jet momentum resolution by $\sim$ 15%[8]. A further correction of +5% was applied to account for the effects of the underlying event and jet energy lost outside the clustering cone[2]. The uncertainty on the corrected jet momentum is typically 6 to 8% for jets with $30 < P < 100$ GeV/c and $|\eta| < 0.8$. The momentum resolution for these jets, determined empirically by studying the dijet P_T imbalance[9], is approximately $\sigma_P \simeq 1.1 \times \sqrt{P} - 1.5$ GeV/c.

The data were collected using a total transverse energy trigger described in reference [2], and corresponds to an integrated luminosity of 26 nb^{-1}. For this study, we selected events containing two jets in the range $|\eta| < 0.8$ with the sum of the transverse energy above twice the trigger threshold, in order to avoid trigger bias. The two leading jets were required to be nearly opposite in azimuth ($\Delta\phi = 180 \pm 30°$), and any additional jets had to have $E_T < 20$ GeV and $E_T < 0.2(E_T(\text{jet1}) + E_T(\text{jet2}))$. The transverse momenta of the two jets were required to balance within ~3 standard deviations $|P_T(\text{jet1}) - P_T(\text{jet2})| < 3\sqrt{P_T(\text{jet1}) + P_T(\text{jet2})}$). For acceptance considerations, events were required to have dijet boost pseudo-rapidity $|\eta_{BOOST}| \equiv |\eta(\text{jet1}) + \eta(\text{jet2})|/2 < 0.6$ along the beam direction. A total of 5541 events satisfied the above selection cuts. Furthermore, only jets within the pseudo-rapidity range $0.1 < |\eta| < 0.7$ were used in this analysis, resulting in a sample of 8609 jets.

To obtain the $D(z)$ distribution, events were Lorentz transformed along the beam axis by the boost pseudo-rapidity, to the approximate center-of-mass of the dijet system. Charged tracks consistent with the primary vertex were associated with jets if they were produced within a cone of 48° half angle about the axis of the jet, and had $P_{||}$ along the jet axis greater than 0.6 GeV/c. The efficiency of the reconstruction program for finding tracks was estimated as a function of z and M_{JJ} by merging simulated tracks into data, and by detector simulation of Monte-Carlo events. We restrict this study to $M_{JJ} < 200$ GeV/c^2 where the tracking efficiency is above 85% for all z.

Acceptance corrections were applied to account for tracks outside the CTC or jet association cone. The contribution to the fragmentation function by the underlying event was evaluated using an axis at 90° in ϕ to the two jets, and was subtracted from the distribution. The size of these two corrections is $\sim 30\%$ for $z < 0.05$ and negligible for $z > 0.1$. For $z > 0.7$, where statistics are low, two backgrounds were found to be significant. The first was hadrons that did not interact in the calorimeter or did not deposit all their energy, which can cause a jet momentum to be substantially undermeasured. The rate for this is reliably estimated from the calorimeter geometry and the measured fragmentation function at lower z values. The second was due to tracking pattern recognition errors caused by overlap of nearby tracks. A small number of tracks with $z > 1.0$ in the raw distribution were found to be due to the latter source. We estimate the contribution of these backgrounds to be less than 5% below $z = 0.7$ and $\sim 20\%$ for $0.7 < z < 1.0$; this is not subtracted from the data.

The fragmentation function was corrected for the effects of detector resolution smearing in P_{jet} and P_{track} by a deconvolution procedure[8]. For each z interval, a correction factor $D(z)/D_{meas}(z)$ is calculated, taking into account the falling jet momentum spectrum and fragmentation function[10]. The correction, shown in Figure 1, is less than 35% for all z. The separate effects of jet and track momentum resolution are also indicated, assuming perfect resolution for the other quantity. The effect of the falling spectrum is to cause a net shift of jets to higher momenta than produced, and consequently, tracks to be assigned a lower z. For this reason, the correction to $D(z)$ is greater than unity for z below 0.7. As z approaches 1.0, the shape of the fragmentation function and worsening track momentum resolution cause the correction to be less than unity.

The corrected fragmentation function $D(z)$ for charged tracks is plotted in Figure 2 and listed in Table 1, for dijet events with M_{JJ} in the range 80 to 200 GeV/c^2. Due to the steeply falling $D(z)$ spectrum, the uncertainty on the jet momentum scale is the dominant systematic uncertainty in $D(z)$, except for $z < 0.05$ where the acceptance and underlying event corrections are substantial. Above $z = 0.8$, uncertainties from the resolution smearing and backgrounds are large; the data above $z = 0.8$ should be considered an upper limit. The prediction of the HERWIG Monte-Carlo program[11] is also shown.

In Figure 3, the fragmentation function is shown vs. M^2_{JJ} (our estimator of Q^2) for six intervals in z, along with data from the e^+e^- experiment TASSO (plotted vs s, the c.m.s. energy squared) [12]. The two experiments show the same trend. As Q^2 increases, more particles are observed at low z values per jet, and fewer for $z > 0.1$, indicating a steepening of the fragmentation function with Q^2. Also shown are independent fits for each z interval to the form:

$$D(z, Q^2) = \gamma(z) + \delta(z)\ln(Q^2). \qquad (1)$$

The CDF slopes $\delta(z)$ agree qualitatively with predicted Altarelli-Parisi evolution[3], and are statistically inconsistent ($\chi^2/DOF = 116/30$) with the assumption of perfect scaling. Quantitative comparison of the experiments is difficult due to theoretical uncertainty in the Q^2 definition between the two, differences in the definition of the variable z, and differences in the ratios of quark to gluon jets.

We extract the average charged momentum fraction $< f_{ch} >$ using the sum rule:

$$< f_{ch} > = \int_0^1 z\,D(z)\,dz \simeq \sum_i z_i D_i(z)\Delta z + \int_{0.0}^{0.02} zD(z)dz \qquad (2)$$

The contribution below $z = 0.02$ is estimated to be 0.09±0.03, determined using the fit parametrization to $D(z)$[10]. The CDF value of $< f_{ch} >$, 0.65±0.02(stat)±0.08(sys), is consistent, within systematic uncertainty, with the TASSO result of 0.58 ± 0.02[12], and is higher than the UA1 result of 0.47±0.02(stat)±0.05(sys)[13].

In summary we have measured the charged fragmentation function of predominantly gluon jets in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. A QCD Monte Carlo model shows qualitative agreement with the data. Significant scaling violations are observed in the $D(z)$ distribution with increasing dijet invariant mass between 60 and 200 GeV/c^2. Detailed comparison between these results and those of e^+e^- experiments is made difficult by Q^2 scale definition uncertainties and different definitions of the fragmentation variable used.

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Table 1: Charged fragmentation function $D(Z)$ for $80 < M_{JJ} < 140$ GeV/c^2. Statistical and systematic errors are listed separately. The systematic uncertainty is partially correlated from point to point.

Z	$D(Z) \pm (\text{stat}) \pm (\text{sys})$	Z	$D(Z) \pm (\text{stat}) \pm (\text{sys})$
0.02-0.03	$164. \pm 2. \pm 30.$	0.22-0.24	$3.6 \pm 0.2 \pm 0.7$
0.03-0.04	$107. \pm 2. \pm 11.$	0.24-0.26	$2.9 \pm 0.2 \pm 0.6$
0.04-0.05	$79.3 \pm 1.3 \pm 6.8$	0.26-0.28	$2.4 \pm 0.2 \pm 0.5$
0.05-0.06	$59.4 \pm 1.2 \pm 4.9$	0.28-0.32	$1.57 \pm 0.09 \pm 0.38$
0.06-0.07	$46.3 \pm 1.0 \pm 3.8$	0.32-0.36	$0.95 \pm 0.07 \pm 0.25$
0.07-0.08	$36.9 \pm 0.9 \pm 3.2$	0.36-0.40	$0.72 \pm 0.06 \pm 0.23$
0.08-0.09	$31.4 \pm 0.8 \pm 2.8$	0.40-0.44	$0.47 \pm 0.05 \pm 0.17$
0.09-0.10	$24.8 \pm 0.7 \pm 2.4$	0.44-0.50	$0.36 \pm 0.04 \pm 0.15$
0.10-0.12	$19.8 \pm 0.5 \pm 2.1$	0.50-0.60	$0.18 \pm 0.02 \pm 0.09$
0.12-0.14	$14.2 \pm 0.4 \pm 1.7$	0.60-0.70	$0.06 \pm 0.01^{+0.03}_{-0.02}$
0.14-0.16	$10.1 \pm 0.3 \pm 1.3$	0.70-0.80	$0.012^{+0.007+0.008}_{-0.005-0.006}$
0.16-0.18	$7.2 \pm 0.3 \pm 1.0$	0.80-0.90	$0.0032^{+0.0035+0.0030}_{-0.0018-0.0018}$
0.18-0.20	$5.8 \pm 0.3 \pm 0.9$	0.90-1.00	$0.0010^{+0.0020+0.0014}_{-0.0010-0.0006}$
0.20-0.22	$4.4 \pm 0.2 \pm 0.8$		

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[10] For $D(z)$, the parametrization used was:

$$D(z) = \begin{cases} \frac{\alpha}{z} \times \exp(-\beta * z) & \text{for } z < 0.24 \\ \exp(a + bz + cz^2 + dz^3 + ez^4) & \text{for } z > 0.24 \end{cases}$$

where the functions, first and second derivatives were set equal at $z = 0.24$.

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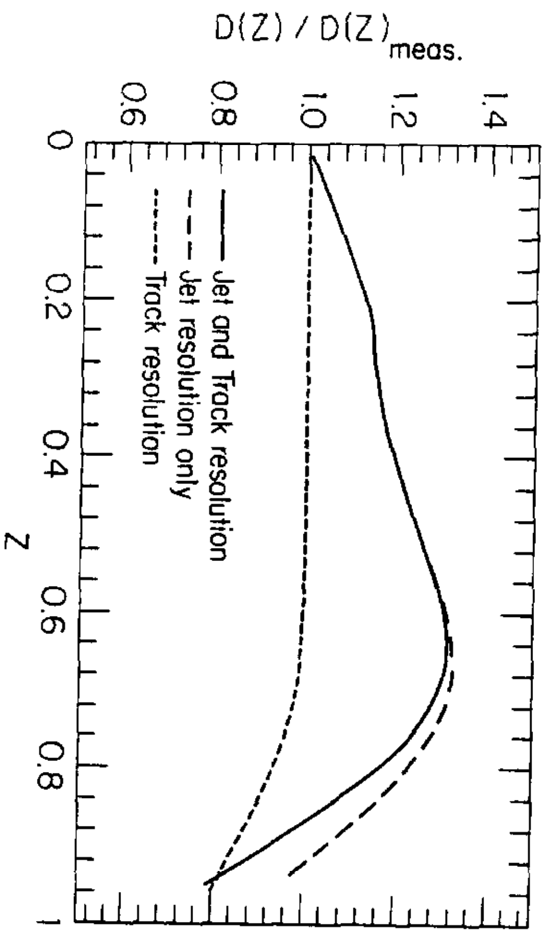
Figure Captions:

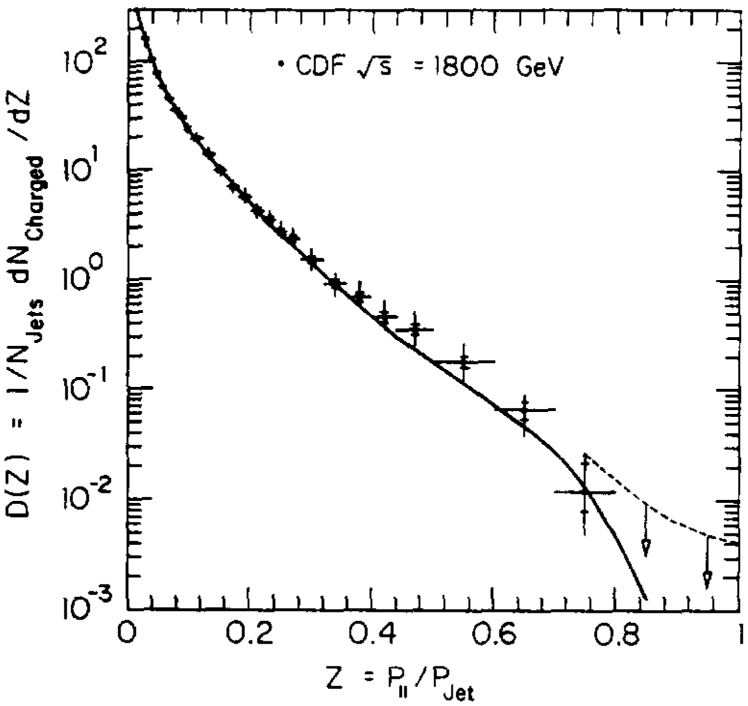
Figure 1: Correction applied to the charged fragmentation function due to jet and track momentum resolution. The two contributions are also indicated separately.

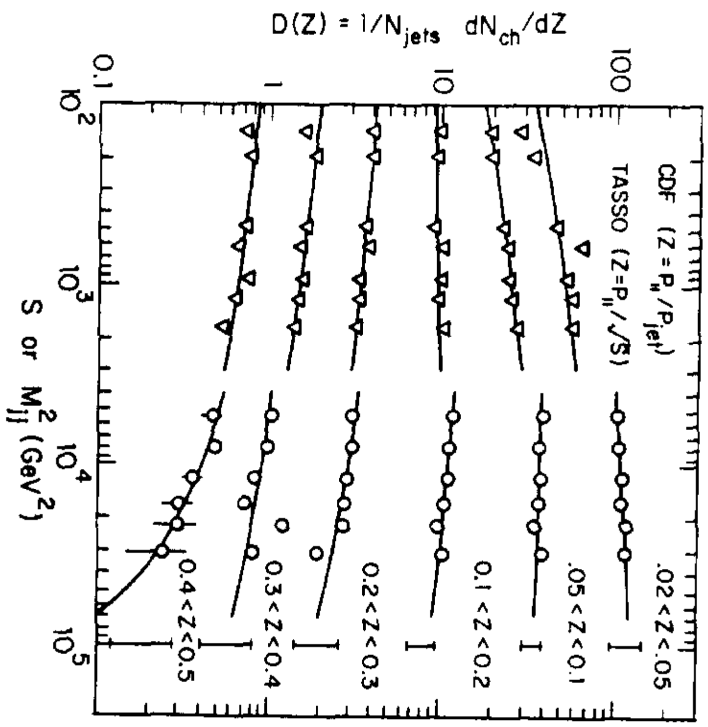
Figure 2: Charged fragmentation function $D(z)$. The error bars plotted are statistical (inner) and statistical and systematic added in quadrature (outer). The dotted curve indicates a one sigma upper limit to $D(z)$ for $z > 0.8$. The solid curve is a prediction of the HERWIG 3.2 Monte-Carlo program[11]

Figure 3: Evolution of the fragmentation function $D(z)$ vs. M_{JJ} (CDF, circles) or s (TASSO[12], triangles) for six z intervals. The CDF data have statistical errors plotted. Typical systematic errors for the CDF data are shown at the right.



D(Z) / D(Z)meas.
0.6
0.8
1.0
1.2
1.4
0
0.2
0.4
0.6
0.8
1
Z
Jet and Track resolution
Jet resolution only
Track resolution


• CDF √s = 1800 GeV
D(Z) = 1/N_Jets dN_Charged /dZ
Z = P_∥/P_Jet
10^2
10^1
10^0
10^-1
10^-2
10^-3
0
0.2
0.4
0.6
0.8
1



D(Z) = 1/N_jets dN_ch/dZ
100
10
1
0.1
CDF (Z = P_∥/P_jet)
TASSO (Z=P_∥/√S)
.02<Z<.05
.05<Z<0.1
0.1<Z<0.2
0.2<Z<0.3
0.3<Z<0.4
0.4<Z<0.5
10^2
10^3
10^4
10^5
S or M_jj^2 (GeV^2)