



## MEASUREMENTS OF HIGHER ORDER EFFECTS IN QCD FROM THE TEVATRON COLLIDER

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Quantum Chromodynamics has been studied extensively at Fermilab's Tevatron collider. Between 1992 and 1996 the DØ and CDF experiments, each accumulated approximately  $100 \text{ pb}^{-1}$  of proton-antiproton collisions at a center-of-mass energy  $\sqrt{s} = 1800 \text{ GeV}$  and  $\sim 0.5 \text{ pb}^{-1}$  at  $\sqrt{s} = 630 \text{ GeV}$ . In this paper, we present selected recent measurements of higher order effects in QCD: multiple jet production and subjet and charged particle multiplicities in quark and gluon jets.

### 1 Introduction

Within the framework of Quantum Chromodynamics (QCD) the inelastic scattering between a proton and an antiproton can be described as a hard interaction between their partons, namely quarks and gluons. After the collision, the outgoing partons fragment and hadronize in streams of particles called jets. Whereas lowest order perturbative QCD only predicts the production of two partons, which are emitted at opposite transverse momentum, higher order effects account for the production of multiple jets and the internal structure of jets. In this paper, we summarize recent measurements by the DØ and CDF collaborations based on approximately  $100 \text{ pb}^{-1}$  of proton-antiproton collision data at a center-of-mass energy  $\sqrt{s} = 1800 \text{ GeV}$  and  $\sim 0.5 \text{ pb}^{-1}$  at  $\sqrt{s} = 630 \text{ GeV}$  obtained between 1992 and 1996: ratios of inclusive multijet cross sections,<sup>1</sup> as well as subjet and charged particle multiplicities in quark and gluon initiated jets.<sup>2,3</sup>

#### 1.1 Jet Reconstruction

Jets are commonly defined by their energy deposition in multiple calorimeter towers. For the reconstruction of jets, most of the analyses presented here use an iterative fixed cone algorithm with a cone radius of typically  $R = 0.7$  in  $\eta - \phi$  space (pseudo-rapidity is defined as  $\eta = \ln(\tan \frac{\theta}{2})$ ).<sup>4</sup> The DØ subjet multiplicity measurement applies a successive combination algorithm based on relative transverse momenta, the  $k_T$  algorithm with a clustering parameter  $\mathcal{D} = 0.5$ .<sup>2</sup> CDF exploits tracks reconstructed within fixed cone sizes for their analysis of charged particle multiplicities.

## 2 Ratios of Multijet Cross Section

Three-jet production probes the rate of gluon emission, thus the fundamental coupling of QCD:  $\alpha_s$ . In addition its study allows to investigate possible scale differences for the secondary gluon vertex as compared to the initial hard interaction.

DØ measures the ratio of inclusive three-jet to two-jet production

$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(p\bar{p} \rightarrow \geq 3jets + X)}{\sigma(p\bar{p} \rightarrow \geq 2jets + X)}$$

as a function of the scalar sum of transverse energy  $H_T = \sum E_T^{\text{jet}}$ .

The measurement of  $R_{32}$  as a function of  $H_T$  is performed for different jet  $E_T$  thresholds of 20, 30, and 40 GeV and within the ranges  $|\eta_{\text{jet}}| < 3$  and  $|\eta_{\text{jet}}| < 2$ .<sup>1</sup> The results for jet  $E_T > 20$  GeV and central pseudo-rapidities are shown in Figure 1. To study the sensitivity to the choice of renormalization scale  $\mu_R$  for the production of additional jets, the data are compared to next-to-leading order (NLO) QCD predictions of JETRAD<sup>5</sup> for different assumptions for the scales  $\mu_R^{(i)}$  of the two vertices. For all JETRAD predictions the factorization scale  $\mu_F$  has been chosen to be identical to  $\mu_R$ . The scale  $\mu_R^{(3)}$  for the third jet has been varied proportionally to  $H_T$ , the transverse energy of the third jet  $E_T^{(3)}$  and the maximum jet transverse energy  $E_T^{\text{max}}$ , while the scale for the two leading jets  $\mu_R^{(1,2)}$  has been set either proportional to  $H_T$  or  $E_T^{\text{max}}$ . A fair description of the data is obtained for the choices  $\mu_R^{(1,2,3)} \sim 0.3 H_T$  and  $\mu_R^{(1,2,3)} \sim 0.6 E_T^{\text{max}}$ . The result does not indicate a need for a significantly different scale for the secondary gluon vertex from that of the primary hard interaction.

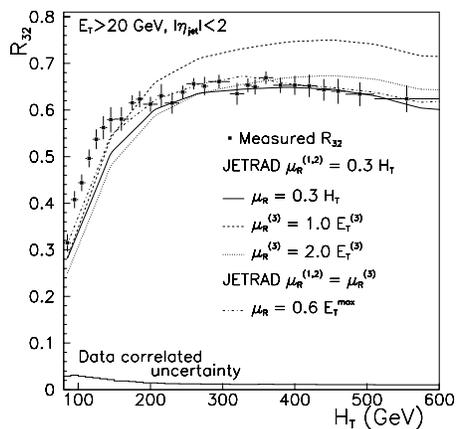


Figure 1. DØ measurement of the ratio of inclusive three-jet to inclusive two-jet cross section  $R_{32}$  as a function of the scalar sum of jet transverse energies  $H_T$ . The four smoothed distributions show the JETRAD prediction for the renormalization scales indicated in the legend.

### 3 Subjet and Charged Particle Multiplicities in Quark and Gluon Jets

Asymptotically, the ratio of the number of particles within gluon initiated jets to that in quark jets is expected to be in the ratio of their color charges  $C_A/C_F = 9/4$ . Corrections to this estimate are given by perturbative QCD calculations within the framework of the Modified Leading Log Approximation.<sup>3</sup> Measurements of charged particle and subjet multiplicities not only allow to test the applicability of perturbative QCD calculations to the description of the soft process of jet fragmentation, but might also provide a method of jet tagging in other analyses.

Complementary to subjet multiplicity measurements at LEP<sup>6</sup> and HERA,<sup>7</sup> DØ and CDF are using two different techniques to select quark and gluon enriched samples based on the average momentum fraction  $x$  of the initial partons (low  $x$ : gluon dominance, high  $x$ : valence quarks). The relative quark and gluon content in the enriched samples is inferred from the HERWIG Monte Carlo generator<sup>8</sup> and the CTEQ4M (DØ and CDF) and CTEQ4HJ (CDF) parton distribution functions.

#### 3.1 Subjet Multiplicity at DØ

DØ measures the subjet multiplicity for center-of-mass energies  $\sqrt{s} = 1800$  GeV and 630 GeV at fixed  $E_T$  and  $\eta$ ,<sup>2</sup> effectively probing smaller values of  $x$  with increasing  $\sqrt{s}$ . Jets and subjets are defined using the  $k_T$  algorithm with a clustering parameter  $\mathcal{D} = 0.5$  and a resolution parameter  $y_{\text{cut}} = 10^{-3}$ . The unfolded subjet multiplicities for quark and gluon jets, corrected to particle level, are shown in the left panel of Figure 2. The ratio of the average multiplicities  $M_{q/g}$  (reduced by one to account for the initial parton) is measured to be  $R = (\langle M_g \rangle - 1)/(\langle M_q \rangle - 1) = 1.84 \pm 0.15$  (stat.)  $^{+0.22}_{-0.18}$  (sys.), in agreement with the HERWIG prediction of  $R = 1.91$ .

#### 3.2 Charged Particle Multiplicities at CDF

CDF measures the mean charged particle multiplicity within fixed cones of  $\theta_c = 0.17, 0.28$  and  $0.47$  in dijet events as a function of dijet mass between 80 and 630 GeV/ $c^2$ ,<sup>3</sup> which is proportional to the product of the momentum contributions of the incoming partons. A fit to the data (cf. Fig. 2, right) within the framework of the Modified Leading Log Approximation (MLLA)<sup>9</sup> and assuming Local Parton Hadron Duality (LPHD)<sup>10</sup> yields  $r = \langle M_g \rangle / \langle M_q \rangle = 1.7 \pm 0.3$  for the ratio of parton multiplicities, in agreement with perturbative QCD calculations, and for the ratio of multiplicities

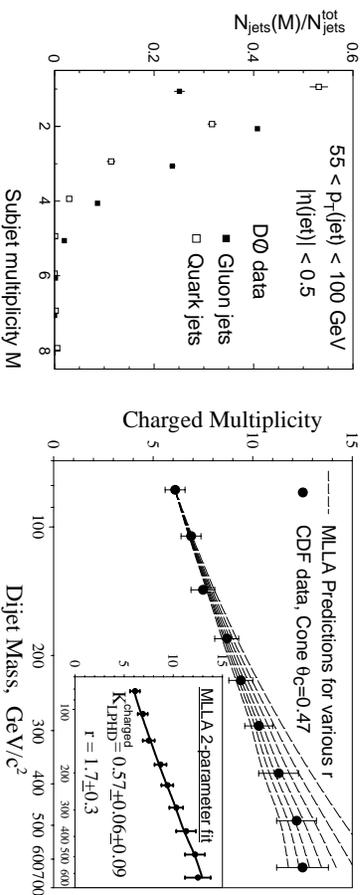


Figure 2. Left: Corrected (particle-level) subjet multiplicity for gluon and quark jets, extracted from DØ inclusive jet data at  $\sqrt{s} = 1800 \text{ GeV}$  and  $630 \text{ GeV}$ . Jets and subjets are defined with the  $k_T$  algorithm. Right: Average multiplicity of charged particles per jet vs. dijet mass. The curves show MLLA prediction for different values of  $1 < r \leq 2.25$  (increasing from top to bottom). The two-parameter MLLA fit is represented by the solid line in the insert.

of charged hadrons to partons  $K_{\text{LPHD}}^{\text{charged}} = N_{\text{hadrons}}^{\text{charged}}/N_{\text{partons}} = 0.57 \pm 0.11$ . After normalization ( $\times 0.89$ ) HERWIG gives a good description of the evolution of charged multiplicity as function of dijet mass.

## References

1. DØ Collaboration, B. Abbott *et al.*, *Phys. Rev. Lett.* **86**, 1955 (2001).
2. DØ Collaboration, V.M. Abazov *et al.*, submitted to *Phys. Rev. D*, FERMILAB-PUB-01-248-E, hep-ex/0108054, and references therein.
3. CDF Collaboration, T. Affolder *et al.*, submitted to *Phys. Rev. Lett.*, FERMILAB-PUB-01-106-E, and references therein.
4. DØ Collaboration, B. Abbott *et al.*, *Phys. Rev. D* **64**, 032003 (2001); CDF Collaboration, T. Affolder *et al.*, *Phys. Rev. D* **64**, 032001 (2001); and references therein.
5. W.T. Giele, E.W.N. Glover, and D.A. Kosower, *Nucl. Phys.* B **403**, 633 (1993).
6. W. Gary, these proceedings.
7. E. Heaphy, these proceedings.
8. G. Marchesini *et al.*, *Comp. Phys. Comm.* **67**, 465 (1992).
9. Yu.L. Dokshitzer, V.A. Khoze, and S.I. Troyan, *ZPC* **55**, 107 (1992).
10. Ya. Azimov, Yu. Dokshitzer, V. Khoze, S. Troyan, *ZPC* **31**, 213 (1986).