Selected QCD Results from Tevatron

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Representing
DØ and CDF

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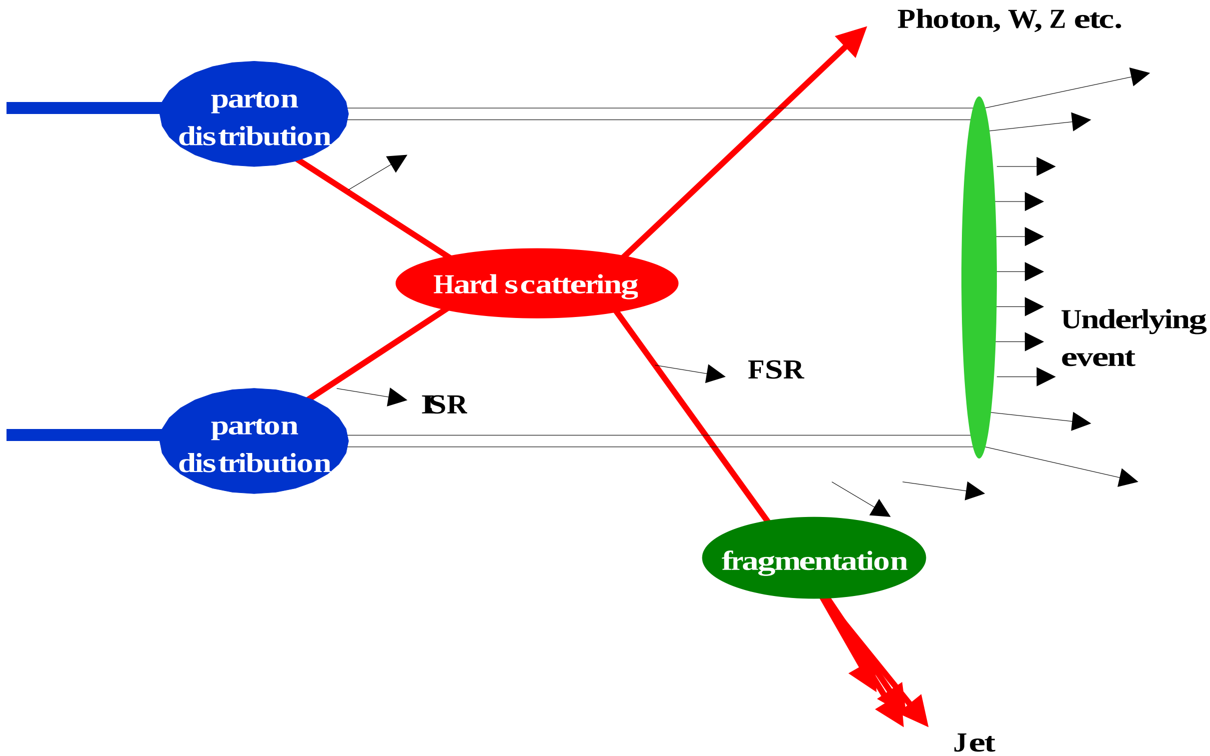
- multiple jet production
  - ▷ ratios of multijet inclusive cross–sections
  - ▷ studies of E_T and relative azimuthal angles
- jet structure
  - ▷ transverse energy distributions within jets
  - ▷ subjet/charged particle multiplicities

Topics in QCD at Tevatron

Generic hadron-hadron collision:



QCD topics in Run I:

- inclusive jet cross-sections and dijet mass distributions
- direct photon production
- vector boson production
- $b\bar{b}$ production
- hard diffraction, BFKL studies
- multiple jet production (covered here)
- jet structure, multiplicities (covered here)

Data Sets and Event Kinematics

Data sets:

- $p\bar{p}$ collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$ (and $\sqrt{s} = 630\,\mathrm{GeV}$) collected by DØ and CDF
- Run I (1992-95): $\sim 110\,\mathrm{pb}^{-1}$ (each experiment) ($\sim 0.5\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 630\,\mathrm{GeV}$)
- Run II (since 3/2001, not yet fully operational): $\sim (2 - 15)\,\mathrm{fb}^{-1}$ (each experiment)

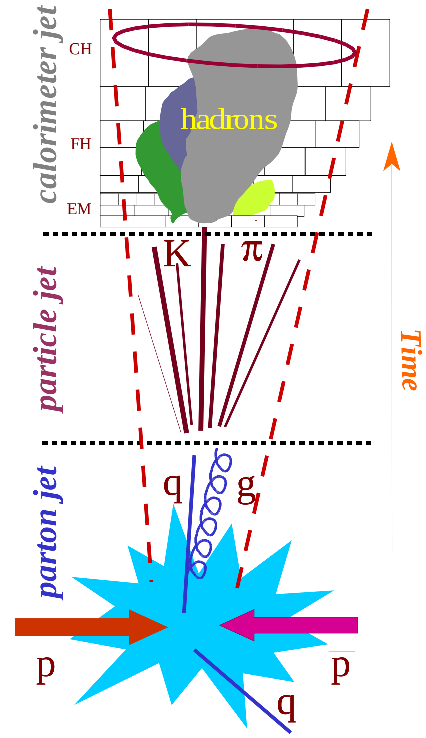
Measured event variables:

- transverse momentum: E_T
- azimuthal angle: ϕ
- pseudo-rapidity: $\eta = -\ln(\tan(\theta/2))$ with polar angle: θ

Jets at the Tevatron

Jet algorithms:

- fixed cone size (most common)
  ▷ clustering of calorimeter cells within $R = \sqrt{\eta^2 + \phi^2} \leq R_0$ (usually $R_0 = 0.7$)
- k_T algorithm
  ▷ successive combination algorithm based on relative transverse momenta of cells (particles)



Correction to particle level:

- correct for finite energy resolution
- subtract underlying event (modeled by minimum bias data)

⇒ 'hermetic' calorimeter with fine segmentation and excellent energy resolution

DØ: ▷ coverage: $|\eta| < 4.1$
▷ segmentation: $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
($\Delta\eta \times \Delta\phi = 0.05 \times 0.05$ in EM shower maximum)
▷ single particle energy resolution:
electromagnetic: $\Delta E/E \sim 15\%/\sqrt{E[\mathrm{GeV}]}$
hadronic: $\Delta E/E \sim 50\%/\sqrt{E[\mathrm{GeV}]}$

Ratios of Multijet Cross Sections (I)

Measurement of the ratio of inclusive three-jet to inclusive two-jet cross section:

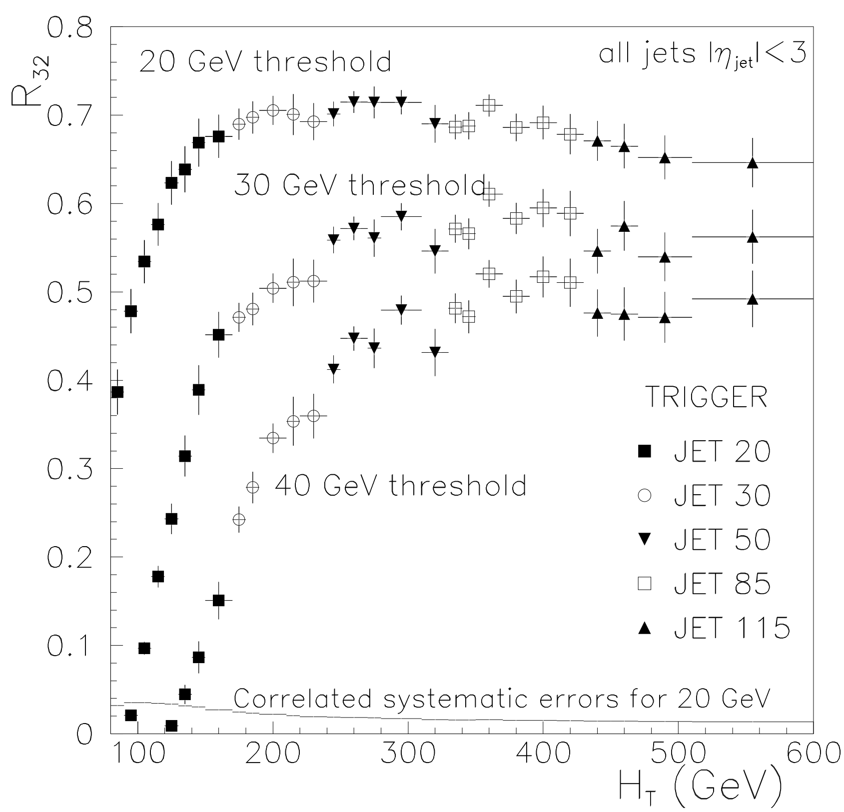
$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(p\bar{p} \to \geq 3 jets + X)}{\sigma(p\bar{p} \to \geq 2 jets + X)}$$

as a function of scalar sum of transv. energies $H_T = \sum E_T^{\text{jet}}$
DØ: PRL **86, 1955 (2001)**

Motivation:

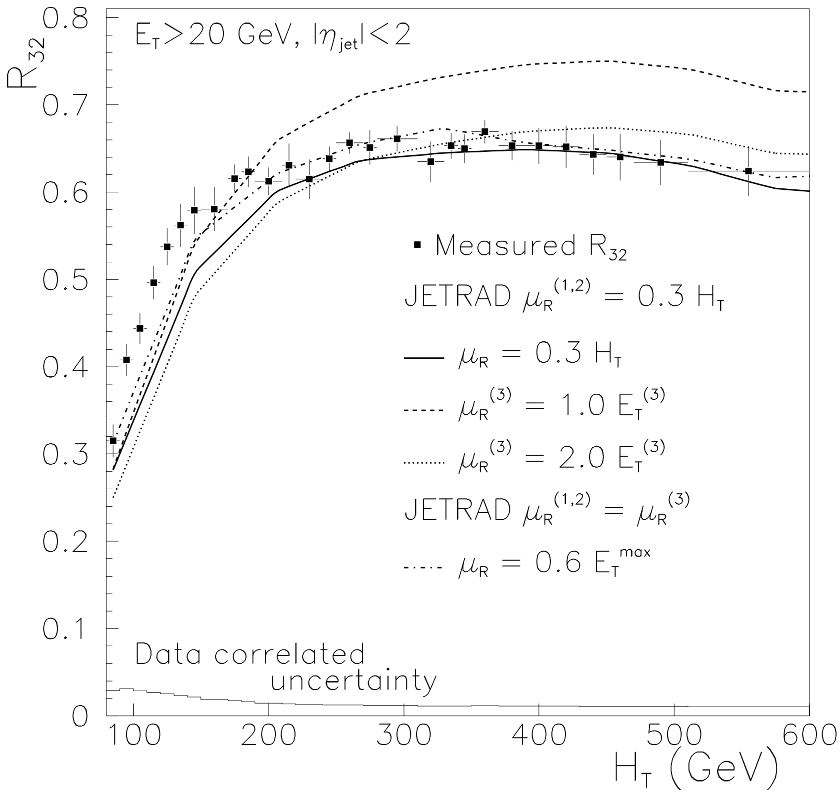
- probing the rate of gluon emission in QCD ($R_{32} \sim \alpha_s$, c.f. measurements at PETRA)
- prediction is sensitive to choice of renormalization scales

DØ



Ratios of Multijet Cross Sections (II)

DØ



- Jetrad: MC simulation of parton-level jets in NLO
- factorization scale μ_F set equal to renormal. scale μ_R
- a. choose $\mu_R^{(1,2)}$ for two leading jets proportional to H_T, vary $\mu_R^{(3)}$ of $3^{\rm rd}$ jet (same as $\mu_R^{(1,2)}$, proportional to $E_T^{(3)}$)
  b. choose all μ_R proportional to $E_T^{\rm max}$
- $\Rightarrow$ within errors (correlated) data can be described by:
  a. $\mu_R^{(1,2,3)} \sim 0.3\,H_T$
  b. $\mu_R^{(1,2,3)} \sim 0.6\,E_T^{\rm max}$

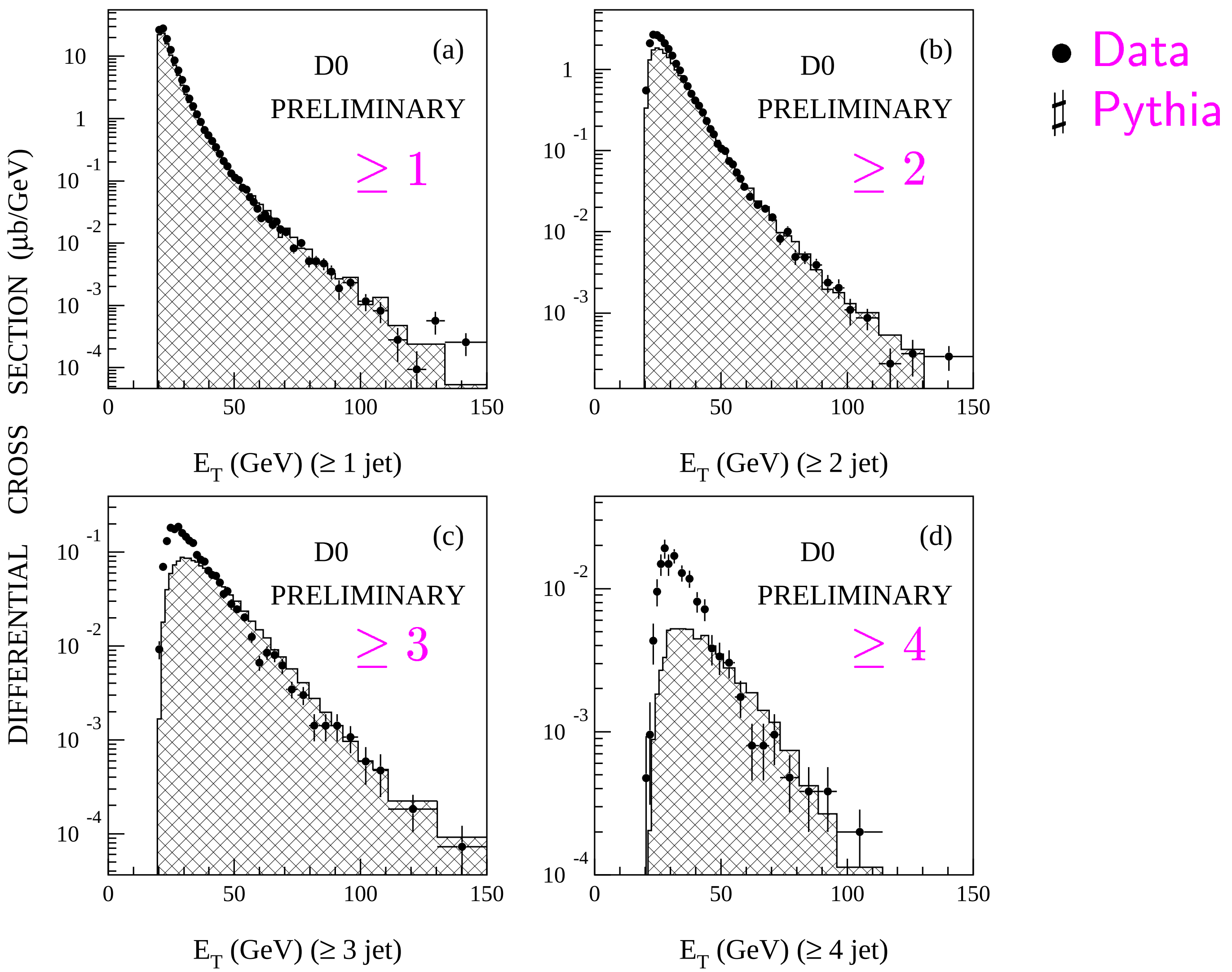
  $\hookrightarrow$ need for different scale for $3^{\rm rd}$ jet not supported

Multiple Jet Production at low E_T (I)

Study of transverse momentum distributions and relative azimuthal angles in multiple jet production with $E_T > 20\,\mathrm{GeV}$

DØ: hep-ex/0106072

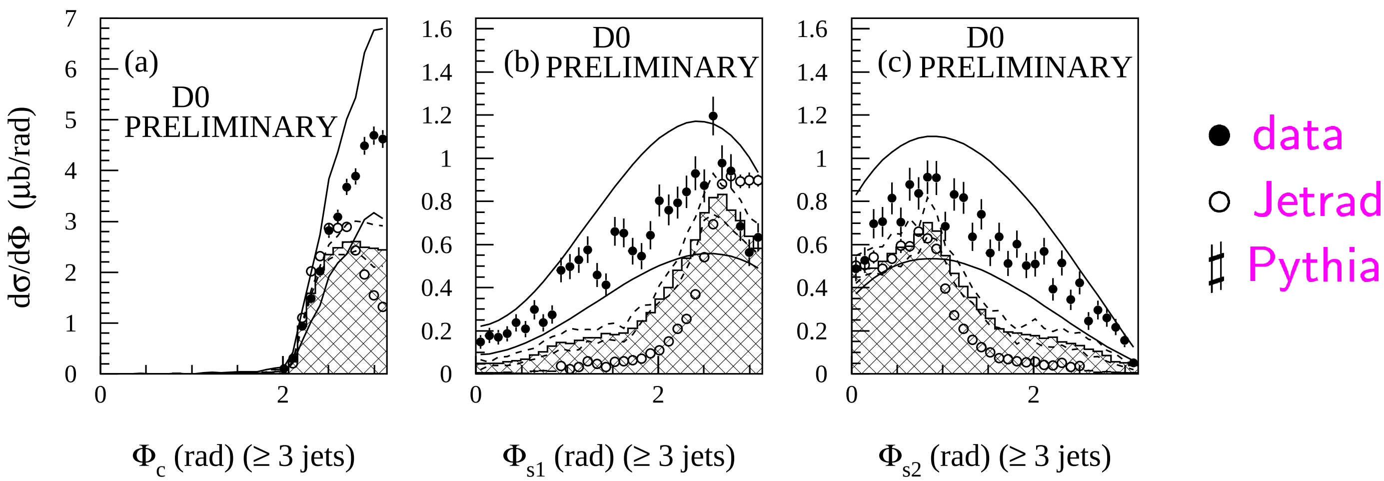
Large discrepancies between data and Pythia for 3 and 4 jet production for E_T of leading jet below $\sim (30-40)\,\mathrm{GeV}$



Multiple Jet Production at low E_T (II)

Relative azimuthal angle in $\geq$ 3–jet events:

- a. between pair with minimal
  $\mathbf{q_{ij}} = (\mathbf{E_{T_i}} + \mathbf{E_{T_j}})/(E_{T_i} + E_{T_j})$ $(\Phi_c = \Phi_{ij})$
- b.+c. between $3^{\rm rd}$ jet and the $1^{\rm st}$ and $2^{\rm nd}$ leading jet in pair (cut on $\pi - \Phi_c < 0.4$)

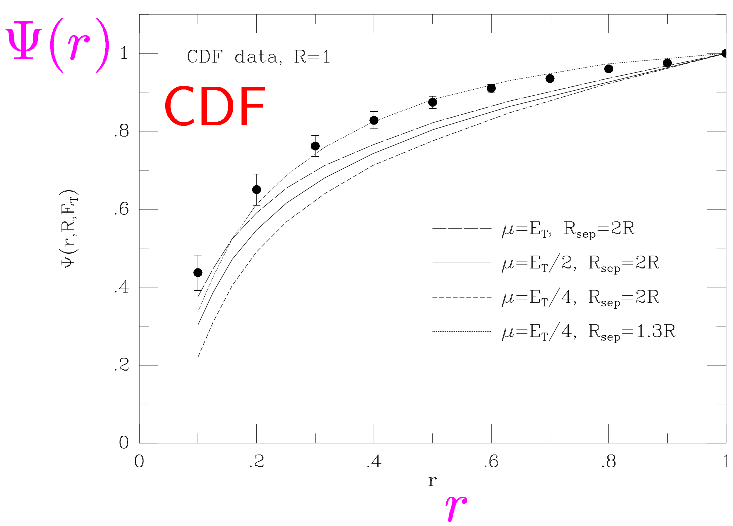


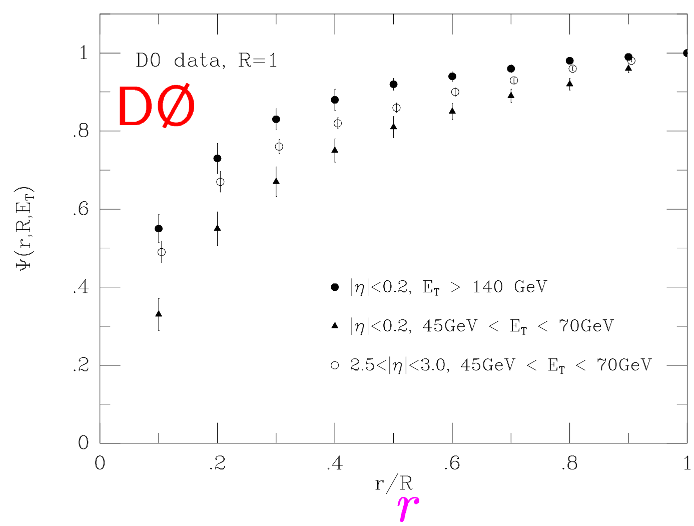
- Leading jets are more back-to-back in data.
- Correlation of $3^{\rm rd}$ jet with axis of $2^{\rm nd}$ jet much less pronounced in data.
- c.f. good description of angular distributions for $E_T > 50\mathrm{GeV}$, DØ: PRD **53, 6000 (1996)**
- Observed differences cannot be explained by variations in the modeling of underlying event or multiple-parton scattering.
- BFKL dynamics in low Q^2/s regime?

Jet Profiles, Transverse Energy Distributions

Early studies by CDF and DØ of jet profiles as measured by the transverse energy flow within the cone
CDF: PRL **70, 713 (1993); DØ: PL B357, 500 (1995); (now textbook knowledge)**

$\Psi(r)$: average fraction of the jet E_T in a sub–cone of radius $r \leq R = 1$





Learned:

- Large scale dependence in $\mathcal{O}(\alpha_s^3)$.
- Jets become narrower with increasing E_T
- Jets have narrower profile in forward region (high x: larger quark contribution in hard scattering)

Multiplicities in Quark and Gluon Jets

Motivation:

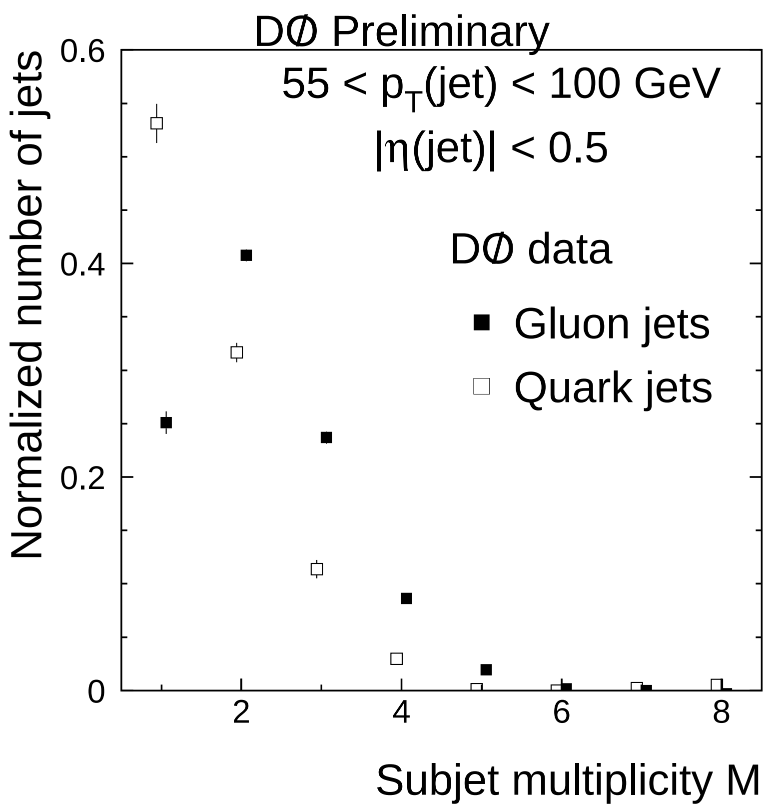
- test of QCD: ratio of number of particles within gluon jets to quark jets expected to be approximately ratio of color charges: $C_A/C_F = 9/4$
- separation of q and g jets (e.g. for top, W + jet)

Method:

- select quark and gluon enriched jet samples using average momentum fraction of parton x
  - ▷ low x: gluon dominance
  - ▷ high x: valence quarks
- DØ: compare jets at same (E_T, η) produced at different $\sqrt{s}$
- CDF: study dependence of multiplicity on dijet mass $(\sim x_1 x_2)$ at fixed $\sqrt{s}$
- both experiments: obtain relative q/g content from MC simulations (Herwig) and parton distribution functions (PDFs, based on DIS and other data)

Subjet Multiplicity in q and g Jets

- DØ compares 630 GeV and 1800 GeV data at same E_T and η and infers q and g jet differences using Herwig 5.9 and CTEQ4M PDF. hep-ex/0106040
- Jets and subjets are defined with k_T algorithm. Objects are merged into subjets if
  $d_{ij} = min(p^2_{T_i}, p^2_{T_j}) \cdot \frac{\Delta R^2_{ij}}{D^2} < 10^{-3} p_T^{jet}$



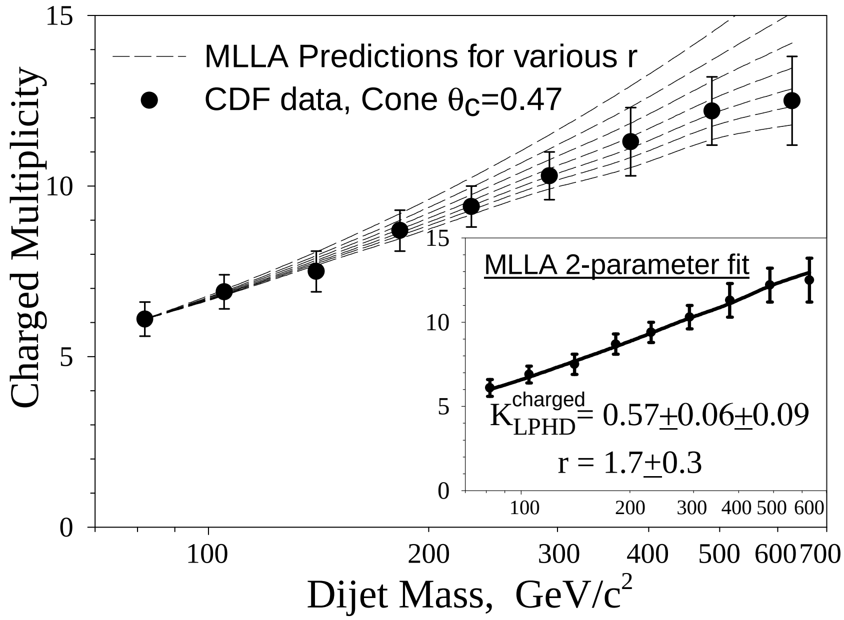
$\Rightarrow R = \frac{<M_g>-1}{<M_q>-1} = \; 1.84 \pm 0.15(\text{stat})^{+0.22}_{-0.18}(\text{sys})$

c.f. Herwig: $R = 1.91 \pm 0.16$

in accordance with naive expect. from color factors $(\frac{C_A}{C_F} = \frac{9}{4})$

Charged Particle Multiplicity in Jets

- CDF measures mean charged particle multiplicity in dijet prod. as a function of dijet masses between 80 and 630 GeV/c^2.
  FERMILAB-PUB-01-106-E
- Relative quark/gluon jet contributions are inferred from Herwig and CTEQ4M and CTEQ4HJ PDFs.
- Data are fit within framework of Modified Leading Log Approximation (MLLA) and Local Parton Hadron Duality (LPHD, $\rightarrow \sharp$ partons to $\sharp$ hadrons independent of E_T)



- Within MLLA+LPHD scheme:

$$N^{\mathrm{g-jets}}_{\mathrm{partons}} / N^{\mathrm{q-jets}}_{\mathrm{partons}} = 1.7 \pm 0.3$$
$$N^{\mathrm{charged}}_{\mathrm{hadrons}} / N_{\mathrm{partons}} = 0.57 \pm 0.11$$

▷ multiplicity ratio consistent with naive expect. and Herwig
▷ $N_{\mathrm{hadrons}} \sim N_{\mathrm{partons}}$

Summary and Outlook

- Tevatron contributes to qualitative and quantitative understanding of higher order effects in QCD.

- Parton Shower MC and NLO calculations can describe most data except in the low E_T region of multijet production.

- Additional DØ event shape study (transverse thrust) available soon.

- Run II offers good opportunities for QCD measurements, especially at large E_T.