Jet Fragmentation in $p\bar{p}$ collisions

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**Introduction & Motivation**

- **Jets as a subject of studies:**
  → jet fragmentation/structure is driven by very soft QCD
    * borderline between pQCD and non-pQCD

- **Jets as a tool in high $P_T$ physics:**
  → better understanding of jet fragmentation is important for many analyses
    * $t\bar{t}$ → all jets (signal: q-jets, background: lots of g-jets)

- **Jets in Monte Carlo event generators:**
  → many analyses rely on simulation of jet fragmentation
    * test of fragmentation models of Monte Carlo event generators

- **Jets in different collider environments:**
  → data from Tevatron will complement $e^+e^-$ and $ep$ measurements:
    * test of universality of jets
Examples of Jet Fragmentation measurements:

- mean multiplicities of particles in gluon/quark jets, \( N_g \) & \( N_q \)
- momentum distributions of particles in gluon/quark jets
- jet shapes
- multiplicity distributions and their moments
- fragmentation functions
- correlation of particles in jets
- particle species production rates
Quark and Gluon Jets
Jet Fragmentation: analytical approach

Parton shower development
- Modified Leading Log Approximation (MLLA or NLLA) and its extensions:
  - multiplicity of partons and their momentum distributions in quark & gluon jets
  - one $k_T$-cutoff parameter: $k_T > Q_{cutoff} = Q_{eff} \sim \Lambda_{QCD}$
  - energy scale $Q \approx E_{jet} \theta$ where $\theta$ is small

Phenomenological hadronization
- Local Parton Hadron Duality hypothesis:
  - link between partons and hadrons: $N_{hadrons} = K_{LPHD} N_{part}$
**Ratio of multiplicities in quark & gluon jets:**

**History of measurements**

**Theory:**
- Next-to-Leading-Log extensions + LPHD
- \( r = \frac{N_{ch}^{G \text{ jet}}}{N_{ch}^{Q \text{ jet}}} = 1.4 - 1.8 \), \( Q = 10 - 100 \text{ GeV} \)

**e^+e^- colliders:**
- Challenging measurement
- ~15 papers in last 10 years
- Results range from 1.0 to 1.5
- Diversity of results:
  - non-trivial 3-jet event topology
  - energy scale confusion
  - model-dependent analyses
  - 2 unbiased/model-independent results

**Tevatron:**
- D0 → ratio of sub-jet multiplicities
  \( r = 1.84^{+0.27}_{-0.23} \)
- CDF → two model-dependent studies
  \( r = 1.7 \pm 0.3 \)

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**History of measurements of the ratio of charged particle multiplicities in Gluon and Quark Jets**

- **LLA**, \( r = \frac{C_A}{C_F} = 2.25 \)
- **Capella et al., 2000**
- **Lupia & Ochs, 1998**
- **Catani et al., 1991**
- **Mueller, 1984**
- **CLEO**
- **DELPHI**
- **HRS**
- **ALEPH**
- **OPAL**
- **SLD**

**Q, GeV**

**r = \( N_{g}/N_{q} \)**
Gluon jets are produced in plenty at Tevatron:

- advantage of trivial event topology of di-jet and V+jet events

Comparing data samples with very different fractions of gluon jets:

- **di-jet vs. γ+jet (this analysis)**
- di-jet vs. W+jet (have to deal with ν)
- di-jet vs. Z+jet (clean, but small statistics)
**Quark & Gluon jets: Analysis at CDF**

- Run1 data
- Cone jet finder (R=0.7), energy corrected to parton level
  \[ \rightarrow \text{systematics check using R=0.4 \& R=1.0} \]
- Central di-jet & γ+jet events with \( M_{jj} \) or \( M_{\gamma j} \) ~72-120 GeV
- di-jet or γ+jet center of mass frame: \( E_{\text{jet}} = 1/2M_{jj} \) or \( 1/2M_{\gamma j} \)
- Fraction of gluon jets: \textbf{di-jet events} — ~60\%, \textbf{γ+jet events} — ~20\%
  \[ \rightarrow \text{extracted using CTEQ4M+Herwig 5.6 (cross-checks: Pythia, CTEQ4A2, \& CTEQ4A4)} \]
- Multiplicity in cones with opening angle \( \theta_C = 0.28, 0.36, \text{and 0.47 rad} \)
  \[ \rightarrow \text{subtract contribution due underlying event \& secondary interactions} \]
- Energy scale \( Q = 2E_{\text{jet}}\tan(\theta/2) \approx E_{\text{jet}}\theta_C \)
- Results obtained for \( \langle E_{\text{jet}} \rangle = 41 \text{ and 53 GeV} \)
Multiplicity in quark and gluon jets

- **e⁺e⁻ data**: unbiased, model-independent results
- **theory**: 3NLLA expressions (PRD61 (2000) 074009)

CDF and e⁺e⁻ data agree
(except for CLEO at <7 GeV)

CDF and e⁺e⁻ data follow 3NLLA trends
(except for CLEO at <7 GeV)

CDF data confirm

$Q \approx E_{\text{jet}} \theta_C \text{ scaling}$

→ results obtained for different $E_{\text{jet}}$ and $\theta_C$ but the same $Q \approx E_{\text{jet}} \theta_C$ are equal within stat. uncertainties

**3NLLA curves**: use $Q_{\text{eff}} = 230$ MeV from previous CDF study, with normalization fitted to CDF gluon & quark data separately; width of band corresponds to uncertainties in normalization
Multiplicities in gluon jets: comparison of CDF and OPAL results

CDF and recent OPAL results for unbiased gluon jets are in a good agreement

OPAL-2002:
→ based on theoretical formalism
→ comparison of properties two-jet & three-jet events

OPAL-2004:
→ based on jet boost algorithm
→ three-jet events

3NLLA curve: two-parameter fit to CLEO and OPAL gluon data at Q=10 & 80 GeV
CDF result:
r = 1.64 ± 0.17 at Q = 19 GeV

CDF and OPAL data agree
(r = 1.51 ± 0.04 at Q = 80 GeV)

CDF data follow trends of the recent NLLA extensions:
→ Q₁ = 41 GeV * 0.47 rad = 19.2 GeV
→ Q₂ = 41 GeV * 0.28 rad = 11.5 GeV
→ Δr = r(Q₁) - r(Q₂) = 0.12 ± 0.02 ± 0.05

CLEO point at Q ~ 7 GeV falls out...

e⁺e⁻ data: only unbiased/model-independent results are presented on the plot
**Comparison with Monte Carlo**

Herwig 5.6 & Pythia 6.115 reproduce gluon jets fairly well

**Herwig 5.6 & Pythia 6.115 over-estimate multiplicity in quark jets by ~30%**

Pythia gives ~3-4% higher multiplicity than does Herwig

Herwig & Pythia are **below** CDF data

Herwig & Pythia are **smaller** than NLL predictions
Momentum distribution of charged particles in quark & gluon jets

Gluon jets: Herwig and Pythia are in reasonable agreement with data
Quark jets: Herwig and Pythia disagree with data

\[ x = \frac{p}{E_{\text{jet}}} = 1 \quad 0.5 \quad 0.1 \quad 0.05 \]
Ratio of momentum distribution of charged particles in quark & gluon jets

CDF data vs. MC:
→ Monte Carlo qualitatively reproduces shape of $r(\xi)$
→ Monte Carlo predicts lower ratio

$x = p/E_{jet} = 1 \quad 0.5 \quad 0.1 \quad 0.05$
Ratio of momentum distribution of charged particles in quark & gluon jets, cont.

CDF vs. OPAL:
→ Same $E_{\text{jet}}$ but different $\theta_c$ and $Q$
→ Both CDF and OPAL see a constant ratio in the soft part of the spectrum $r(\xi_{\text{soft}}) \approx 1.8$
Jet shapes
Definition of Jet Shapes

“Jet Shape”—fraction of the jet’s energy within a cone of a given size around the jet direction

→ driven by soft gluon emission

→ sensitive to quark/gluon jet mixture and running of strong coupling

→ sensitive to underlying event contribution

→ can use calorimeter towers or charged tracks

→ can be used to test implementation of parton showering and underlying event in Monte Carlo

\[
\Psi(r) = \frac{1}{N_\Psi} \sum_\Psi \frac{P_T(O,r)}{P_T(O,R)}
\]
Jet Shapes: Analysis at CDF

- ~170 pb$^{-1}$ of Run2 data
- MidPoint jet finder with cone R=0.7
  - infrared safe
- Jet energy corrected for detector effects
- Only events with one primary interaction
- $\geq 1$ jet: $0.1 <|Y|< 0.7$ and $37$ GeV $< P_T < 380$ GeV
- calorimeter towers with minimum $E_T > 0.1$ GeV
  - cross-check with charged particles
- Results corrected back to the hadron level
Jet Shapes: CDF results

Jet Shapes obtained for a broad range of jet transverse momentum
Jet Shapes: Comparison to MC quark & gluon jets

Jet shapes are sensitive to quark/gluon mixture:

- **Low** $P_T$ → dominated by “wide” gluon jets
- **High** $P_T$ → dominated by “narrow” quark jets

CTEQ5L PDF set is used for all MC’s
**Jet Shapes: Comparison to various MC**

All MC’s have fairly good description of data at high $P_T$

- CTEQ5L PDF set is used for all MC’s

- Low $P_T$ region: importance of underlying event
  - Good: PYTHIA TuneA — good description of low & high $P_T$ jets
  - Default PYTHIA 6.2
  - HERWIG 6.2
  - PYTHIA 6.2 (no MPI)
**Jet Shapes: running of $\alpha_S$**

Good description of data by Pythia TuneA and Herwig 6.2 (except for two lowest $P_T$ bins)

- Default Pythia 6.2 & Pythia 6.2 (no MPI) are clearly off for all $P_T$ range

$1 - \Psi(r_0) \propto \alpha_s(P_T^{jet})$

CTEQ5L PDF set is used for all MC’s
**Summary**

**Quark and Gluon jets**
- results obtained for average multiplicities and momentum distributions
- $r = \frac{N_g}{N_q} = 1.64 \pm 0.17$ at $Q = 19$ GeV
- CDF data on gluon and quark jets follow next-to-NLLA trends
- Good agreement with $e^+e^-$ results
- Herwig 5.6 and Pythia 6.115 reproduce gluon jets fairly well, but systematically over-estimate multiplicity in quark jets by ~30%

**Jet Shapes**
- obtained for jets with $37$ GeV $< P_T < 380$ GeV and $0.1 < |Y_{jet}| < 0.7$
- Pythia TuneA and Herwig 6.2 in good agreement with data for $P_T > 55$ GeV
- Default Pythia 6.206 (with On/Off MPI) fail to describe data
  - → *indicates importance of ISR and MPI in underlying event modeling*
- Results obtained with MidPoint (infrared safe)
  - → *allows future comparison to NLO calculations*