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

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for CDF collaboration

Introduction & Motivation

- **Jets as a subject of studies:**

  $\rightarrow$ jet fragmentation/structure is driven by very soft QCD

  * borderline between pQCD and non-pQCD

- **Jets as a tool in high P_T physics:**

  $\rightarrow$ better understanding of jet fragmentation is important for many analyses

  * *t tbar* $\rightarrow$ *all jets* (signal: q-jets, background: lots of g-jets)

- **Jets in Monte Carlo event generators:**

  $\rightarrow$ many analyses rely on simulation of jet fragmentation

  ***** test of fragmentation models of Monte Carlo event generators

- **Jets in different collider environments:**

  $\rightarrow$ data from Tevatron will complement e^+e^- and *ep* measurements:

  * test of universality of jets

Studying Jet Fragmentation…

- **Examples of Jet Fragmentation measurements:**

CDF results in this talk

- → **mean multiplicities of particles in gluon/quark jets, N_g & N_q**
- → **momentum distributions of particles in gluon/quark jets**
- → **jet shapes**

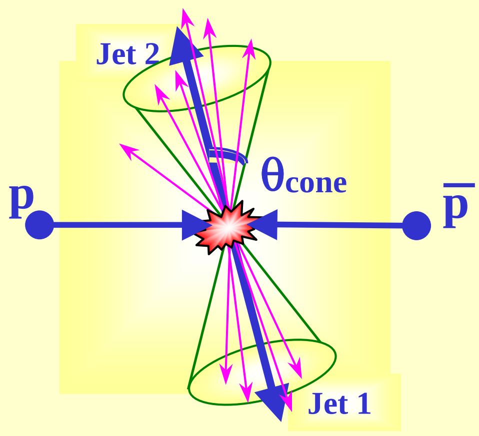
- → multiplicity distributions and their moments
- → fragmentation functions
- → correlation of particles in jets
- → particle species production rates

Quark and Gluon Jets

Jet Fragmentation: analytical approach

Parton shower development

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



Phenomenological hadronization

- **Local Parton Hadron Duality hypothesis:**
  - $\rightarrow$ link between partons and hadrons: $\mathbf{N_{hadrons} = K_{LPHD}\, N_{part}}$

Ratio of multiplicities in quark & gluon jets: History of measurements

Theory:

- Next-to-Leading-Log extensions + LPHD
- $r = N_{ch}^{G\ jet}/N_{ch}^{Q\ jet} = 1.4\text{-}1.8$, Q=10-100 GeV

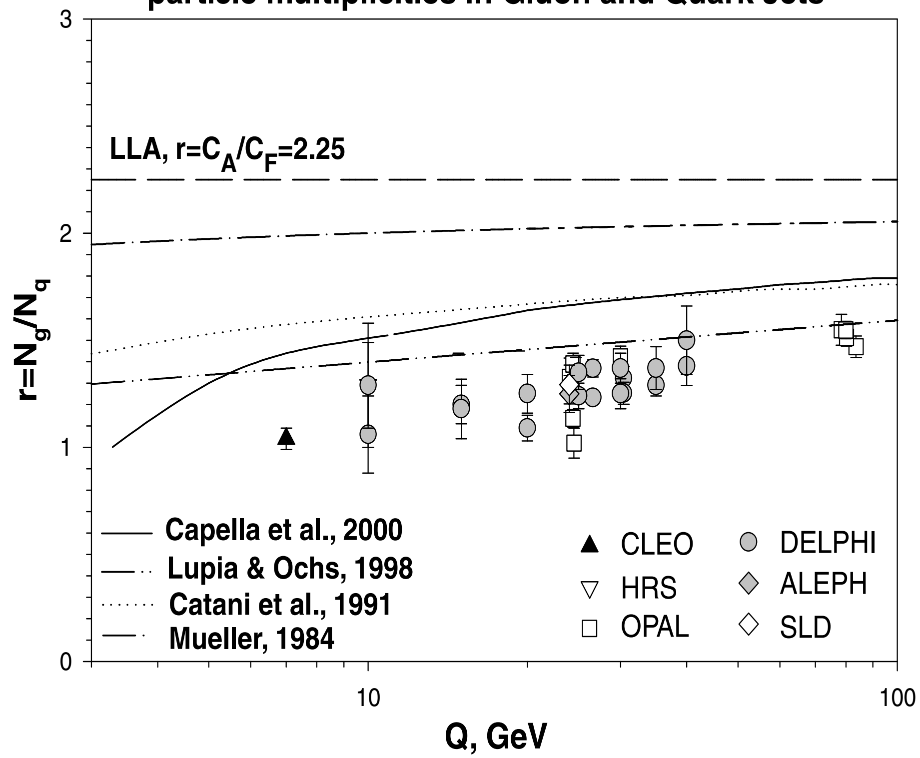
e^+e^- colliders:

- 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 $r = 1.7 \pm 0.3$

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



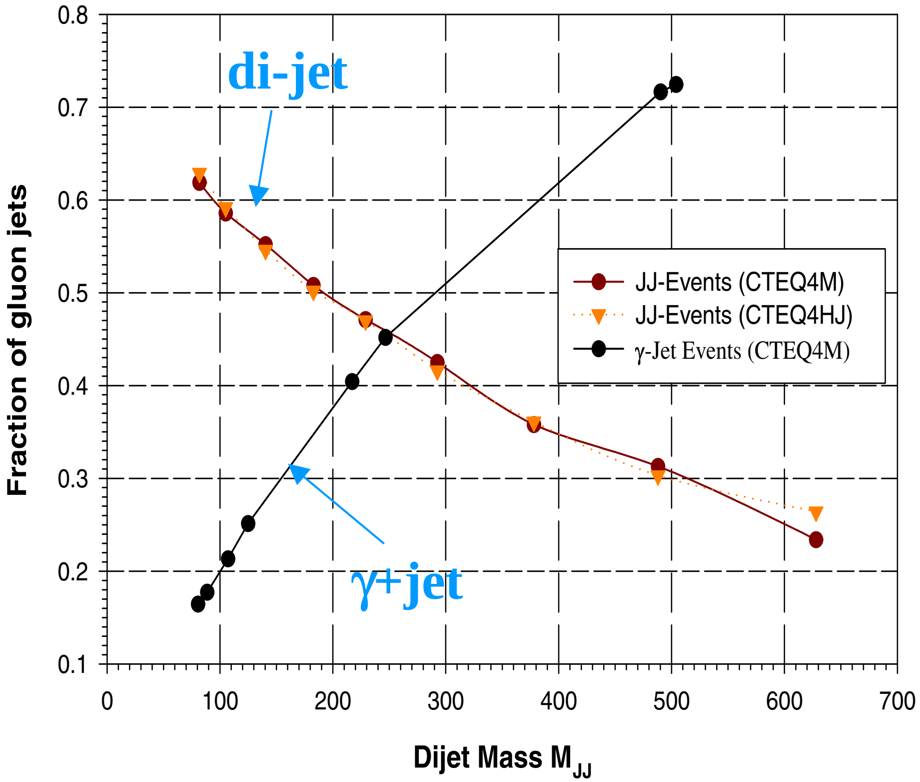
How can one study quark & gluon jets at Tevatron?

Gluon jets are produced in plenty at Tevatron:

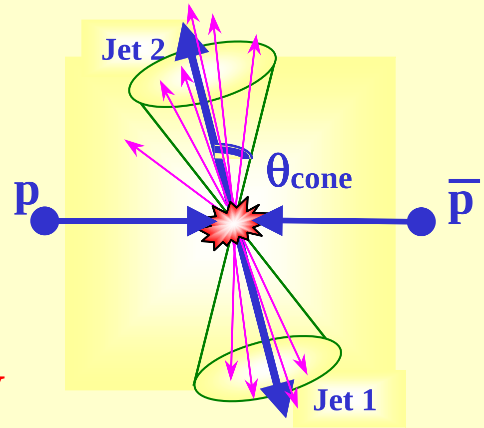
- advantage of trivial event topology of di-jet and V+jet events

Comparing data samples with very different fractions of gluon jets:

- **<u>di-jet vs. γ+jet (this analysis)</u>**
- 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**
  → 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: $E_{jet}=1/2M_{jj}$ or $1/2M_{\gamma j}$**
- **Fraction of gluon jets: <u>di-jet events</u> — ~60%, <u>γ+jet events</u> — ~20%**
  → extracted using CTEQ4M+Herwig 5.6 (cross-checks: Pythia, CTEQ4A2, & CTEQ4A4)
- **Multiplicity in cones with opening angle θ_C=0.28, 0.36, and 0.47 rad**
  → subtract contribution due underlying event & secondary interactions
- **Energy scale $Q = 2E_{jet}\tan(\theta/2) \approx E_{jet}\theta_C$**
- **Results obtained for $\langle E_{jet}\rangle$=41 and 53 GeV**

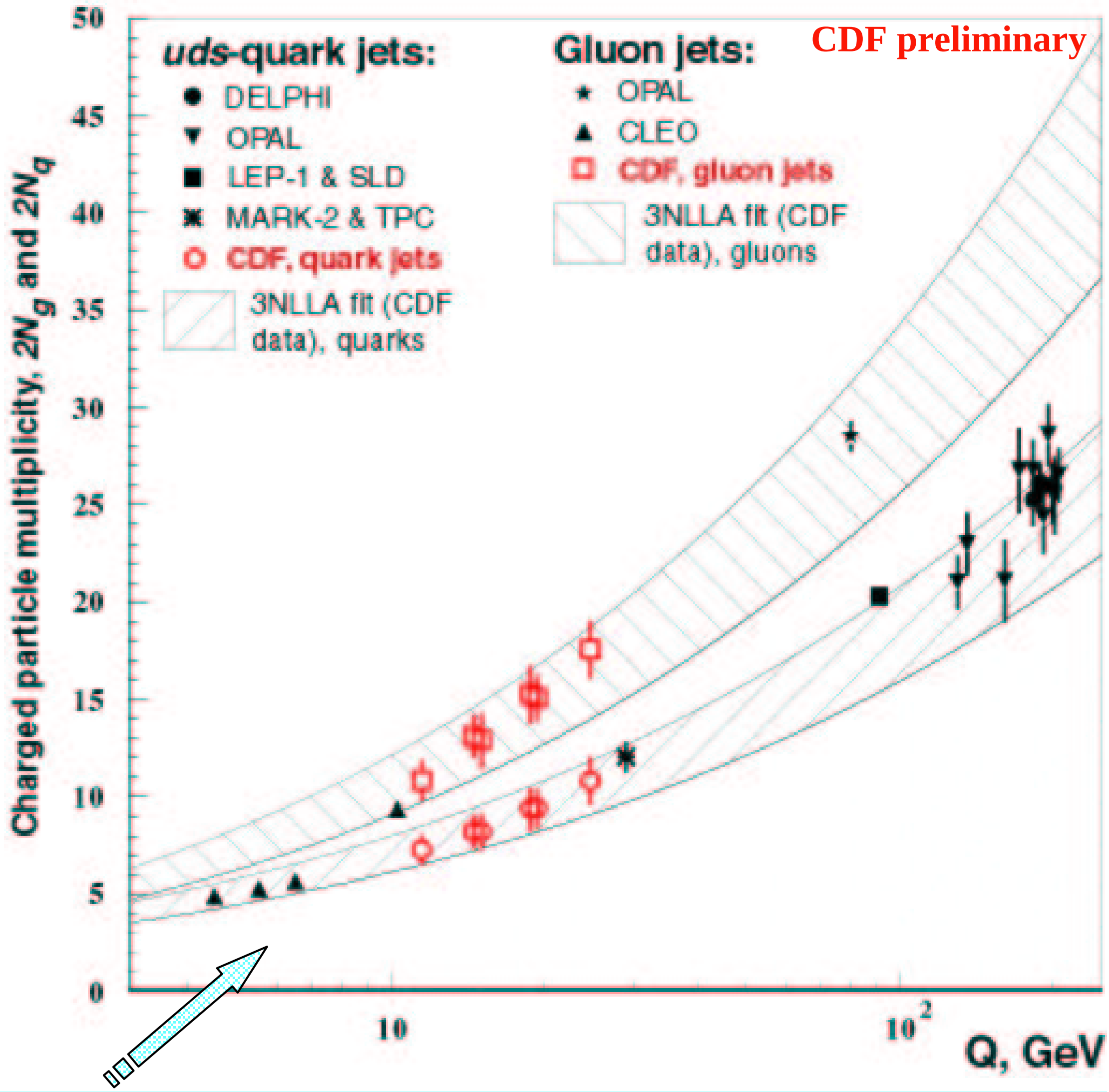
Multiplicity in quark and gluon jets

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

ü **CDF and e^+e^- data agree**
(except for CLEO at <7 GeV)

ü **CDF and e^+e^- data follow 3NLLA trends**
(except for CLEO at <7 GeV)

ü **CDF data confirm $Q \approx E_{jet}\theta_C$ scaling**
→ results obtained for different E_{jet} and θ_C but the same $Q \approx E_{jet}\theta_C$ are equal within stat. uncertainties



3NLLA curves: use Q_{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:

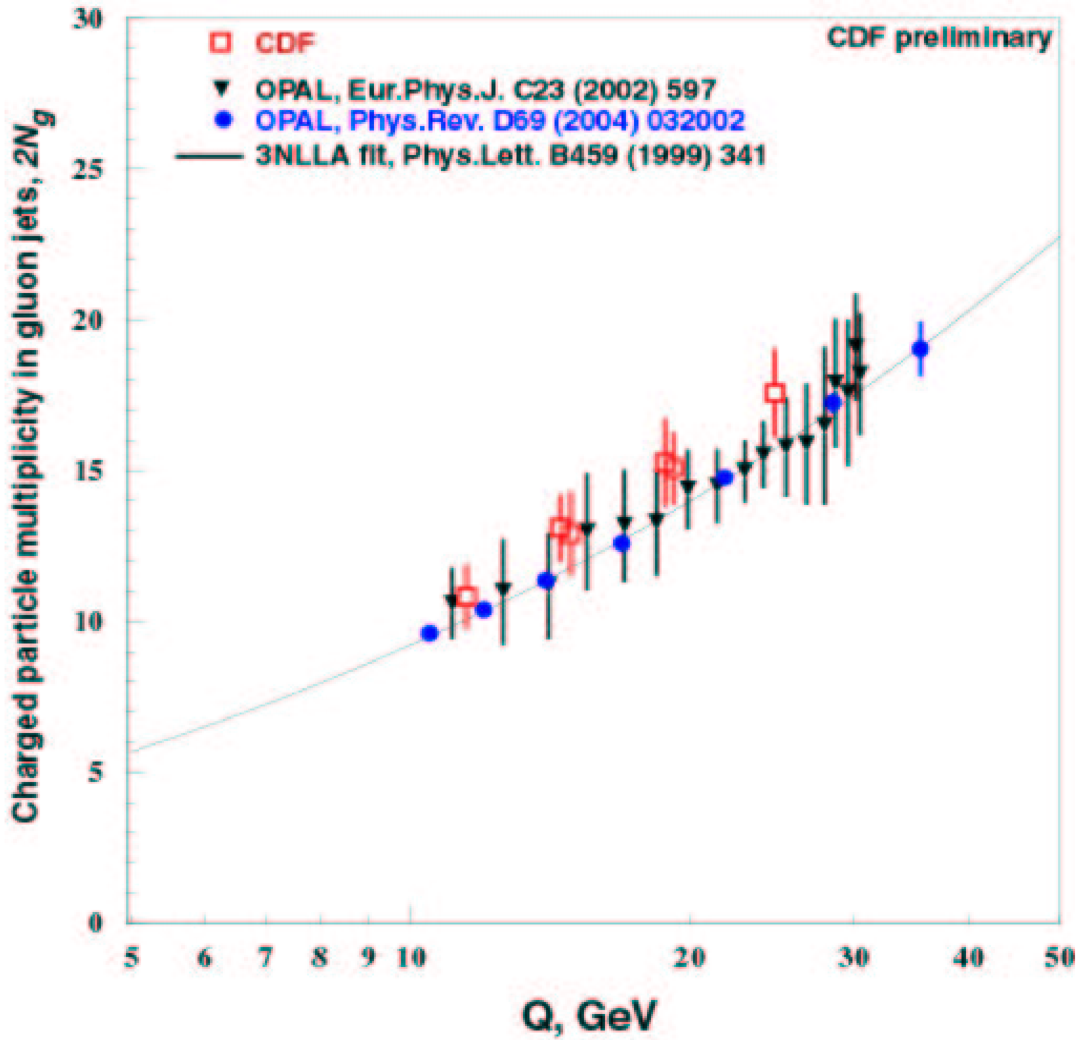
→ based on theoretical formalism

→ 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

Ratio of multiplicities in quark & gluon jets

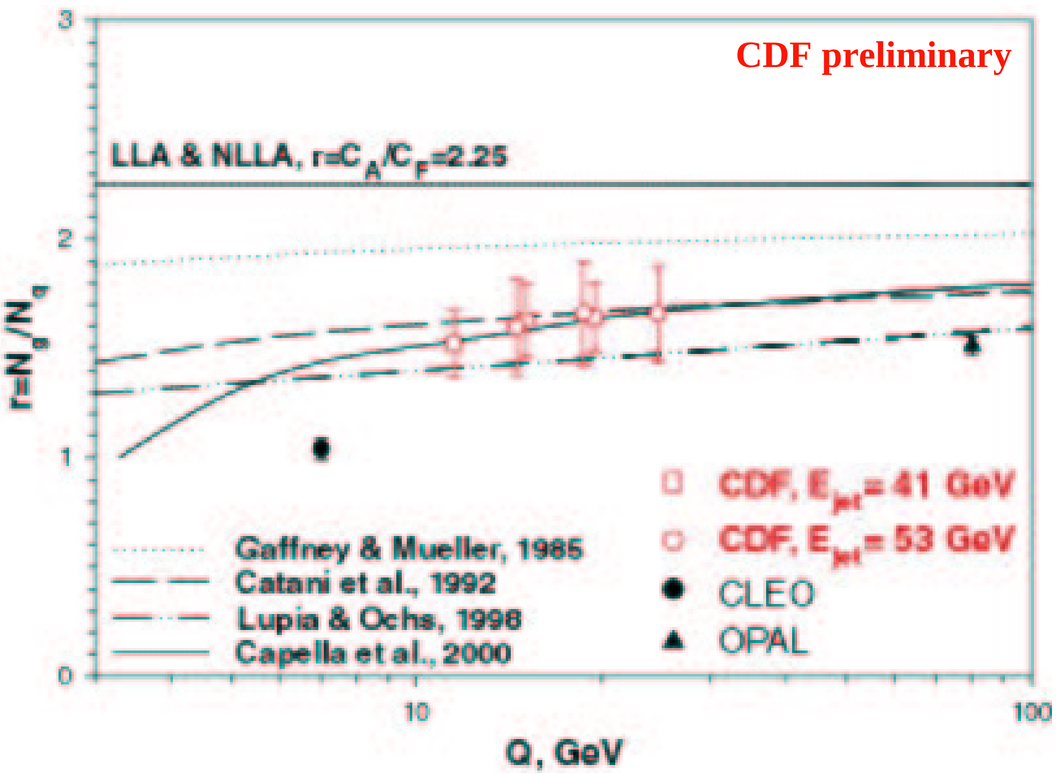
- **CDF result:**
  $r=1.64\pm0.17$ at $Q=19$ GeV

- **CDF and OPAL data agree**
  ($r=1.51\pm0.04$ at $Q=80$ GeV)

- **CDF data follow trends of the recent NLLA extensions:**

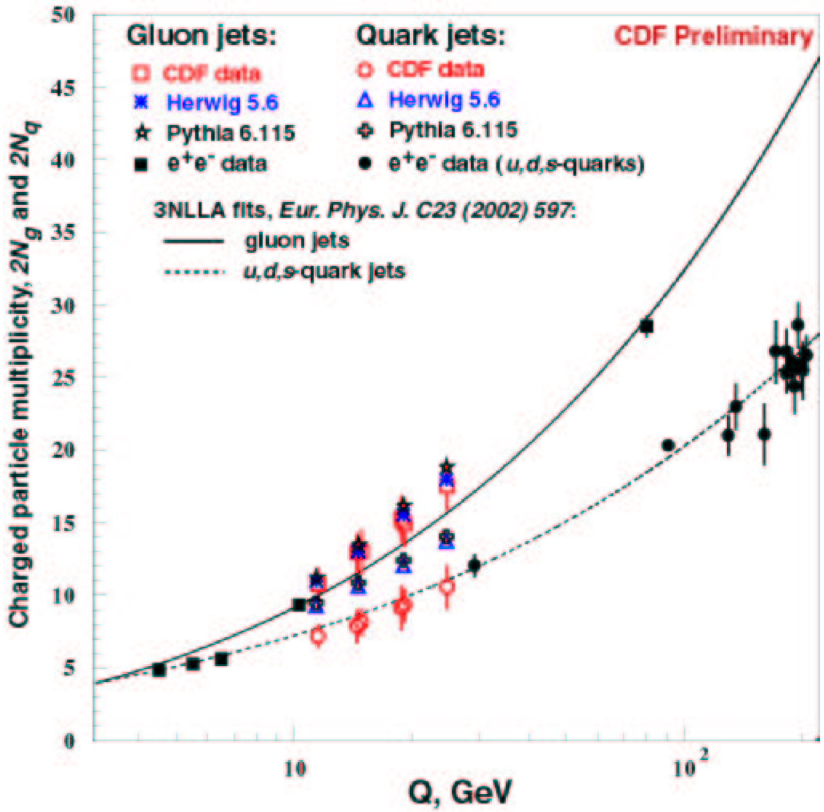
→ $Q_1=41$ GeV * 0.47 rad $=19.2$ GeV
→ $Q_2=41$ GeV * 0.28 rad $=11.5$ GeV
→ **$\Delta r=r(Q_1)-r(Q_2)=0.12\pm0.02\pm0.05$**

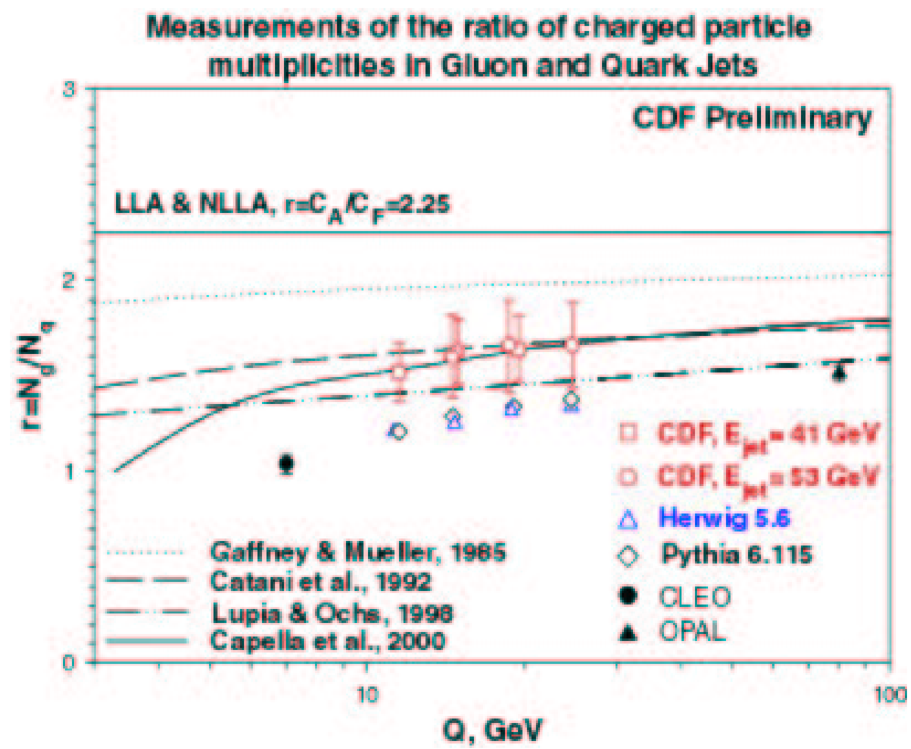
- **CLEO point at Q~7 GeV fall out…**



e^+e^- data: only unbiased/model-independent results are presented on the plot

Comparison with Monte Carlo





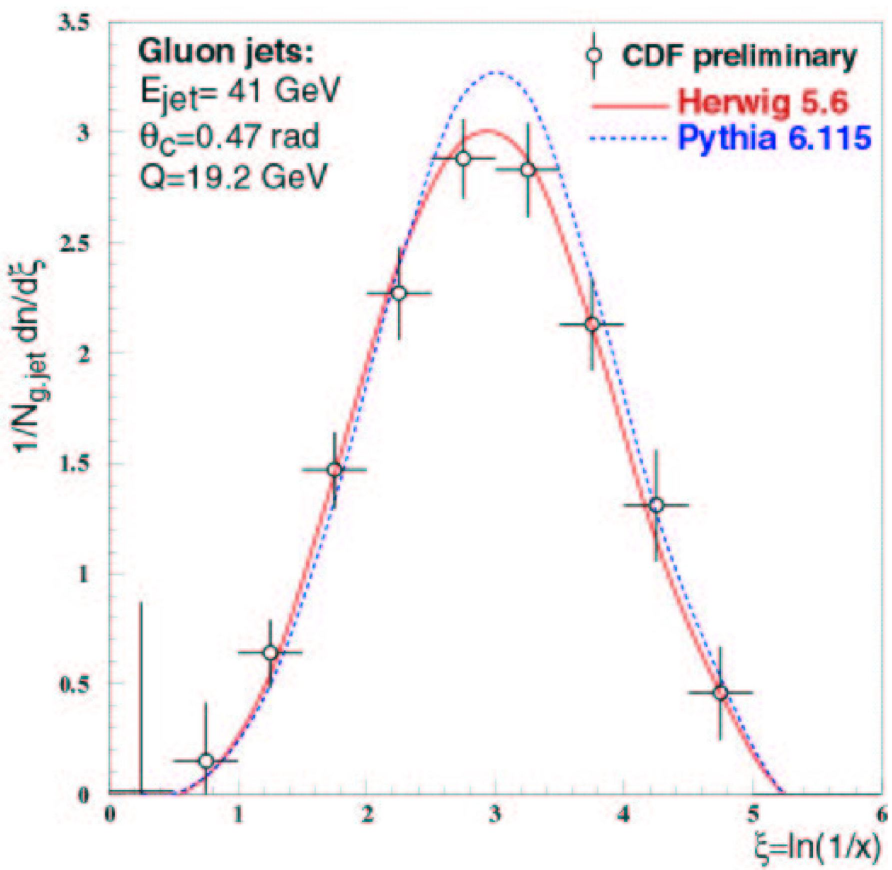
- Herwig 5.6 & Pythia 6.115 reproduce gluon jets fairly well
- Herwig 5.6 & Pythia 6.115 over-estimate multiplicity in quark jets by ~30%
- Pythia gives ~3-4% higher multiplicity than does Herwig

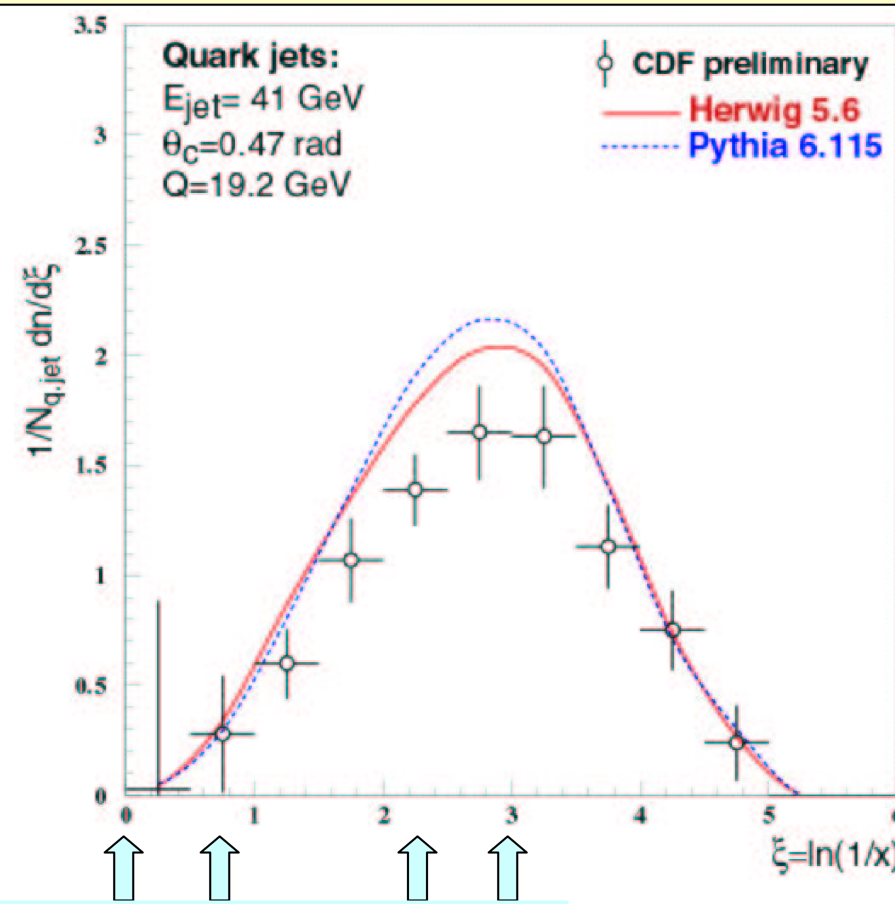
- Herwig & Pythia are below CDF data
- Herwig & Pythia are smaller than NLL predictions

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 <u>disagree</u> with data





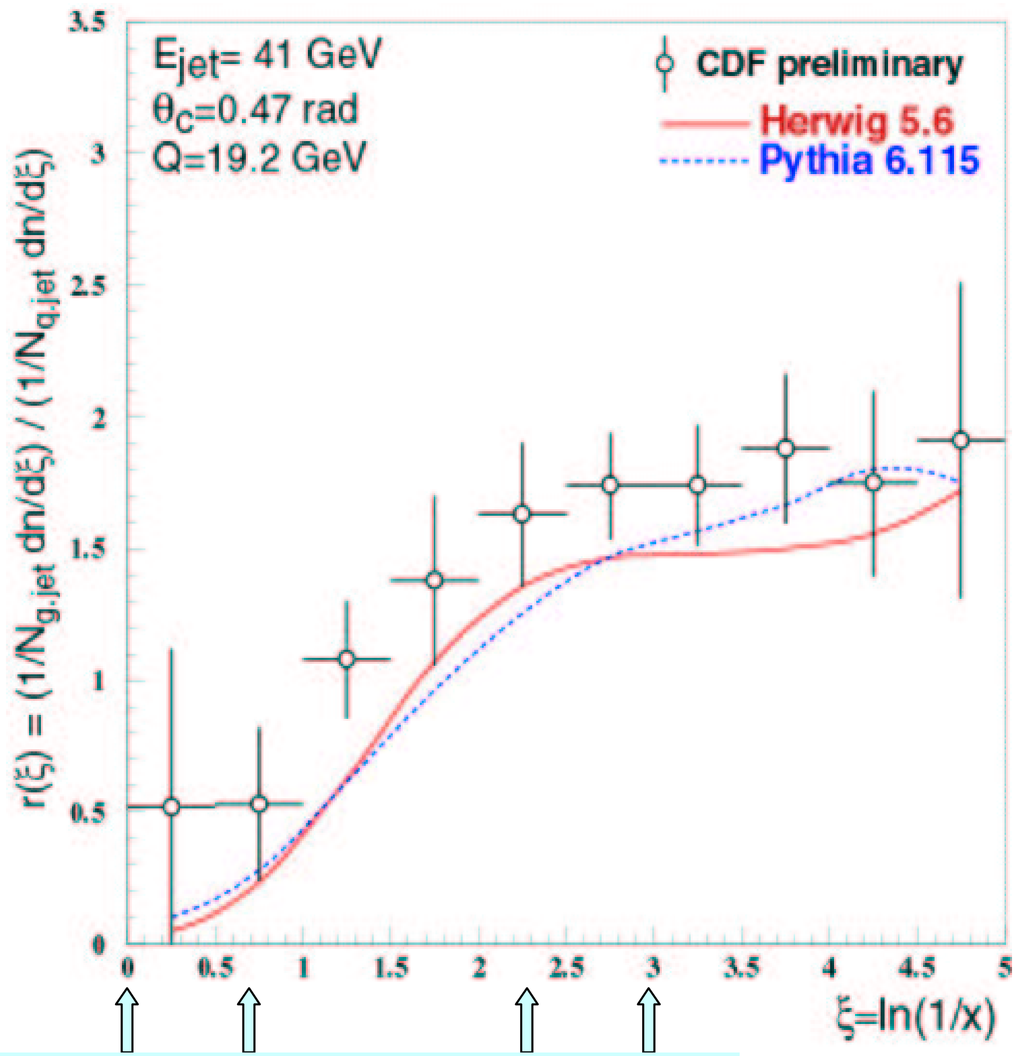
$x = p/E_{jet} = 1$ 0.5 0.1 0.05

Ratio of momentum distribution of charged particles in quark & gluon jets

CDF data vs. MC:

→ Monte Carlo qualitatively reproduces shape of r(ξ)

→ Monte Carlo predicts lower ratio



$x = p/E_{jet}$ = 1 0.5 0.1 0.05

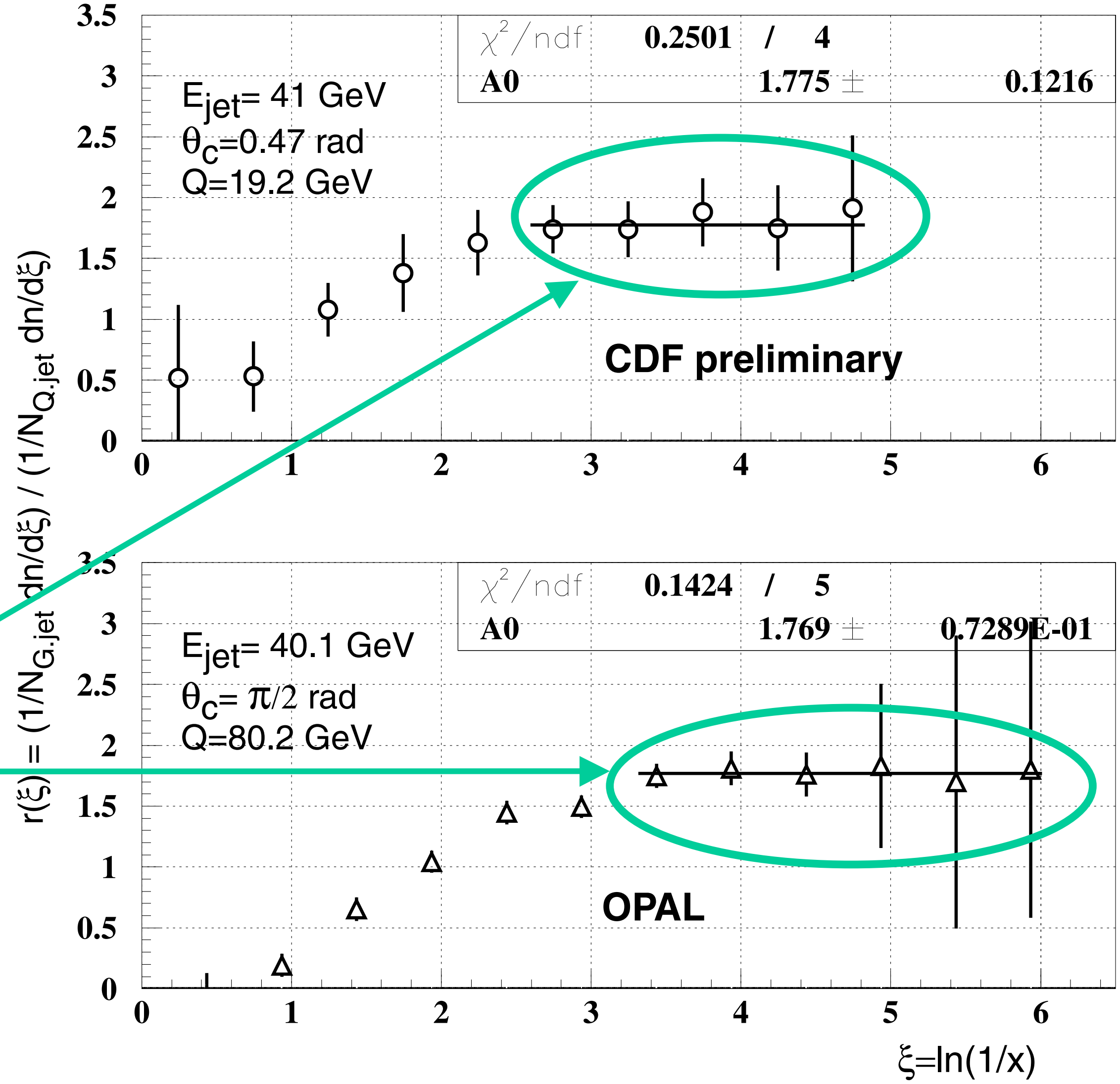
Ratio of momentum distribution of charged particles in quark & gluon jets, *cont.*

CDF vs. OPAL:

→ Same E_{jet} but different θ_C and Q

→ Both CDF and OPAL see a constant ratio in the soft part of the spectrum $r(\xi_{soft}) \approx 1.8$

soft particles



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

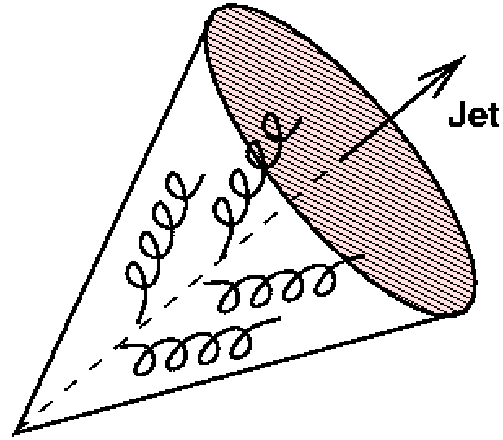
→ driven by soft gluon emission

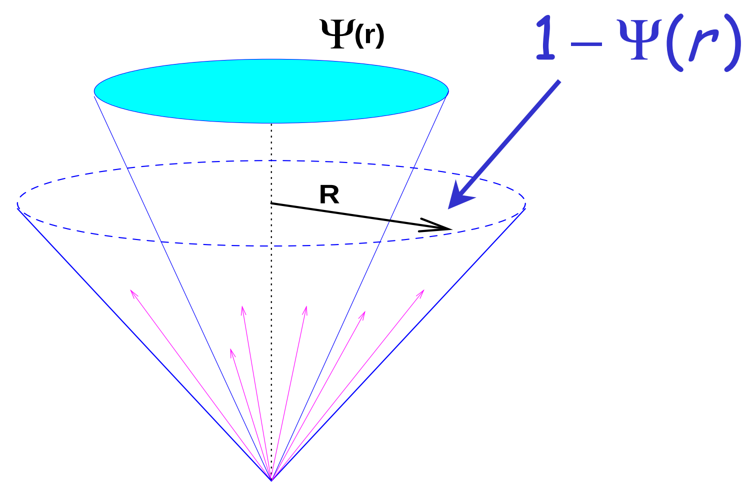
→ sensitive to quark/gluon jet mixture and running of strong coupling

→ 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



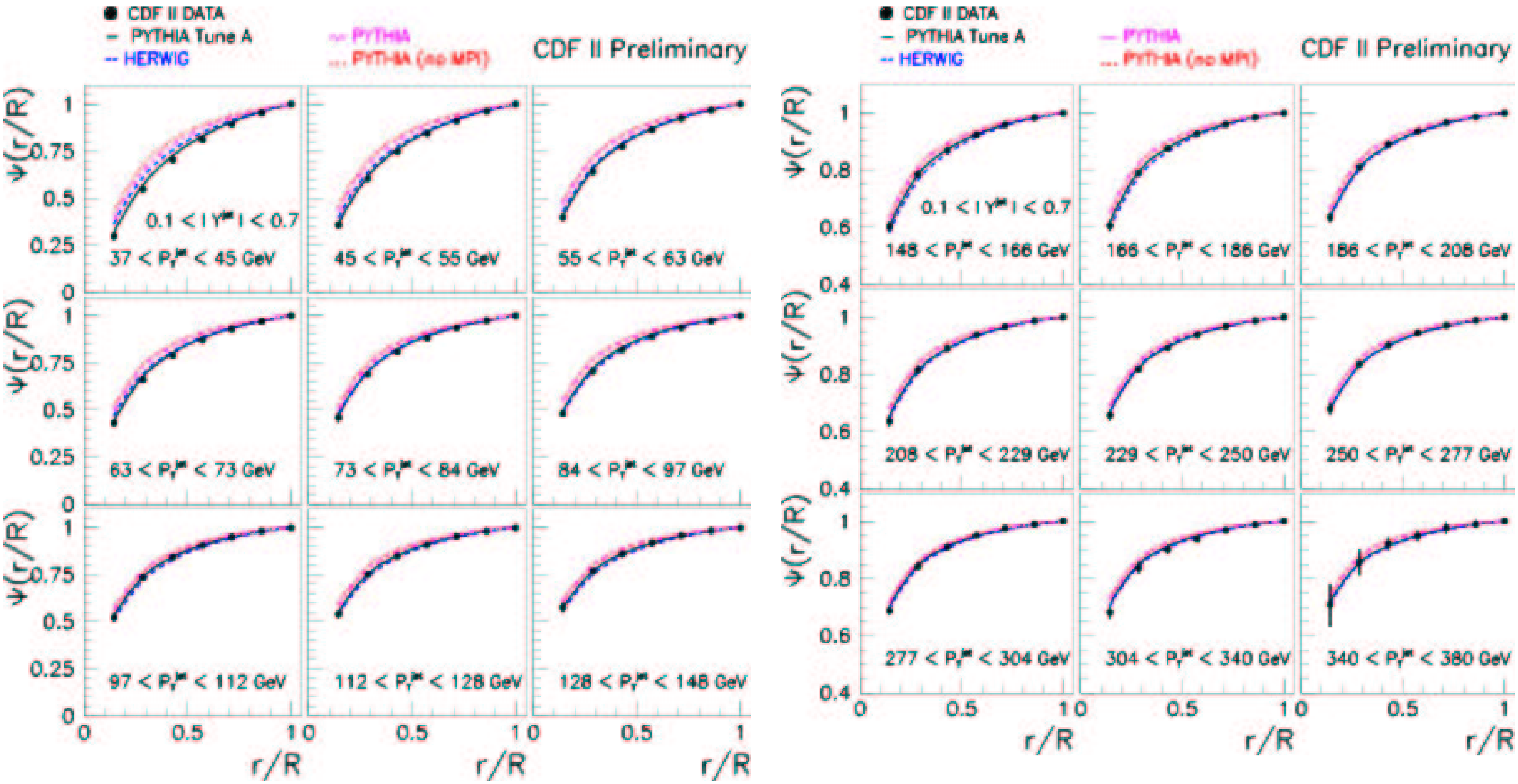


$$\Psi(r) = \frac{1}{N_{jet}} \Sigma_{jet} \frac{P_T(0,r)}{P_T^{jet}(0,R)}$$

Jet Shapes: Analysis at CDF

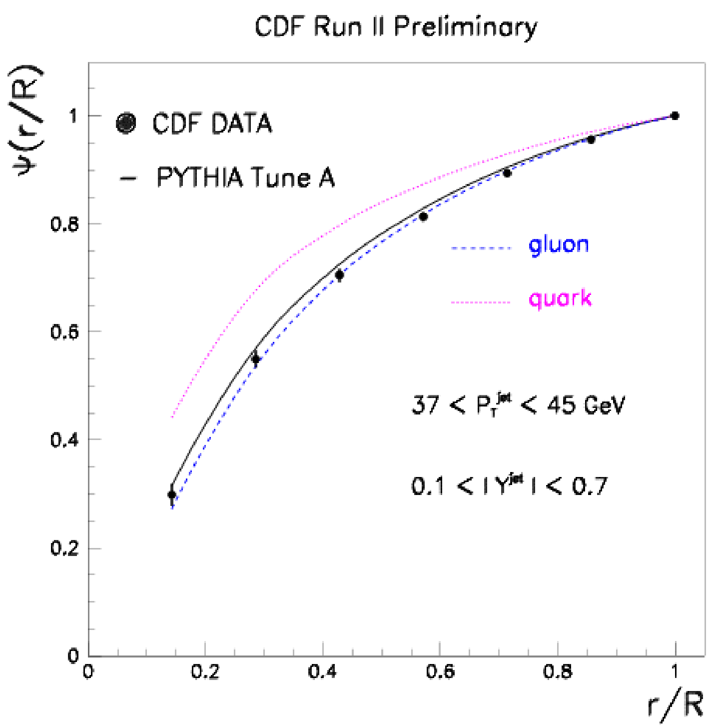
- ~170 pb^{-1} of Run2 data
- MidPoint jet finder with cone R=0.7
  $\rightarrow$ infrared safe
- Jet energy corrected for detector effects
- Only events with one primary interaction
- >=1 jet: 0.1<|Y|<0.7 and 37 GeV< P_T <380 GeV
- calorimeter towers with minimum E_T >0.1 GeV
  $\rightarrow$ cross-check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

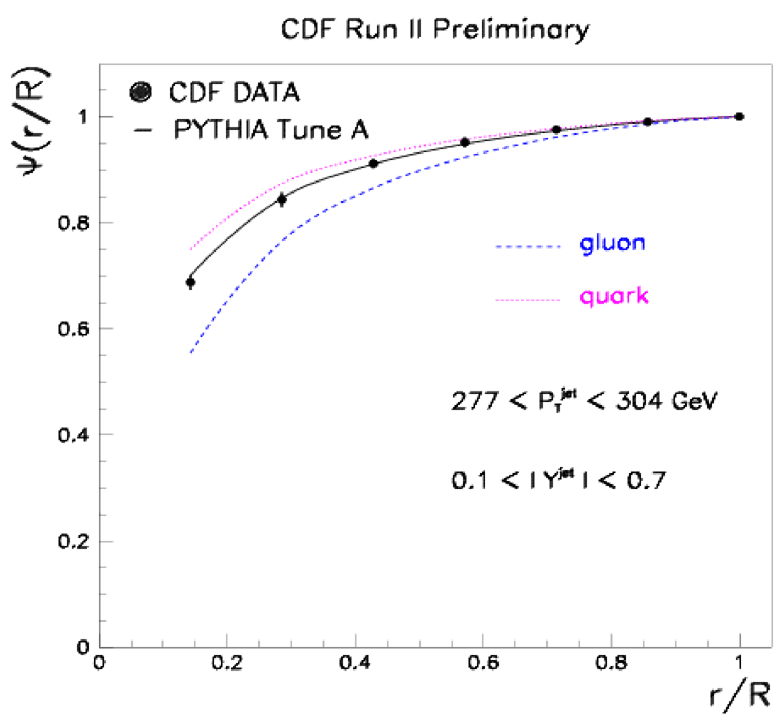
Jet Shapes: CDF results



- ü **Jet Shapes obtained for a broad range of jet transverse momentum**

Jet Shapes: Comparison to MC quark & gluon jets



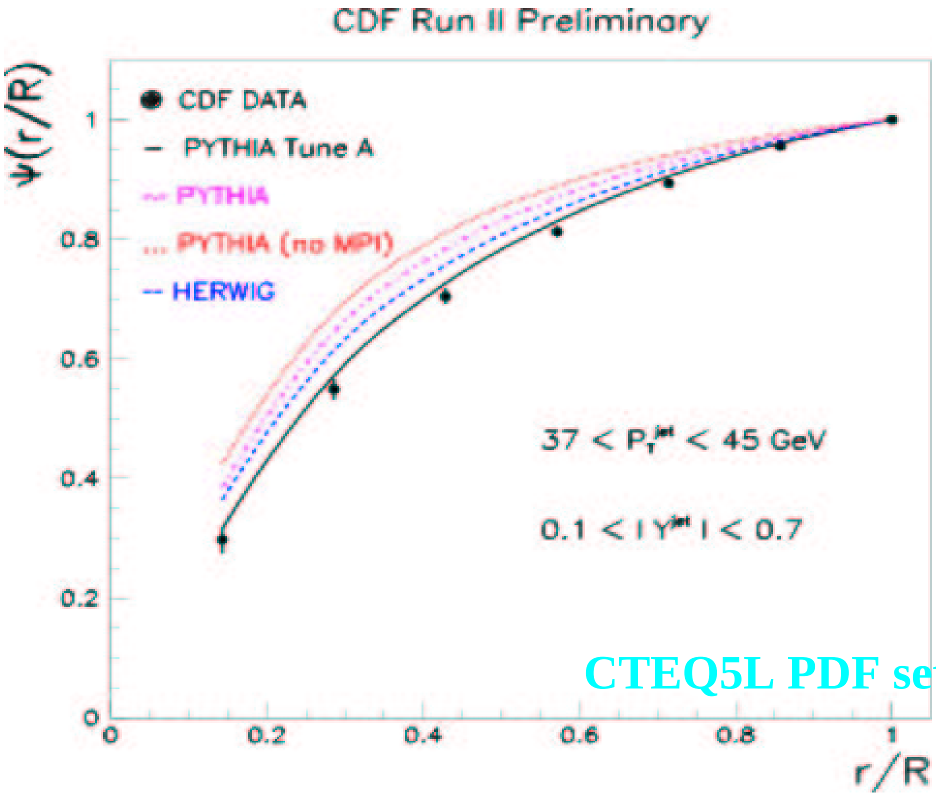


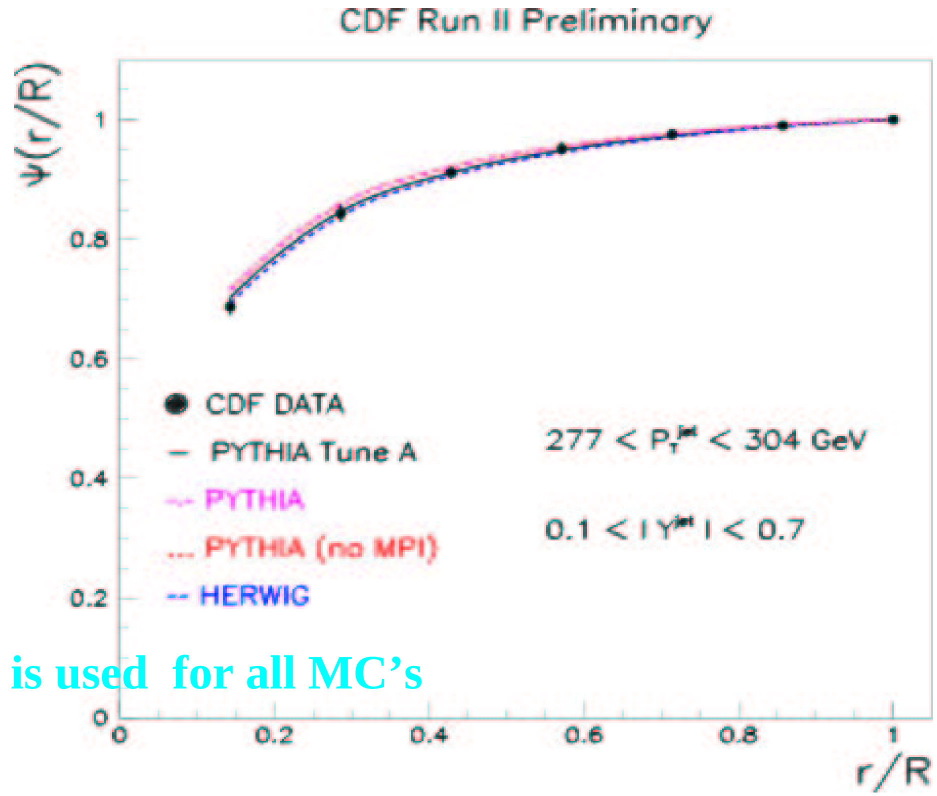
CTEQ5L PDF set is used for all MC's

Jet shapes are sensitive to quark/gluon mixture:

- **Low $P_T \rightarrow$ dominated by "wide" gluon jets**
- **High $P_T \rightarrow$ dominated by "narrow" quark jets**

Jet Shapes: Comparison to various MC





CTEQ5L PDF set is used for all MC's

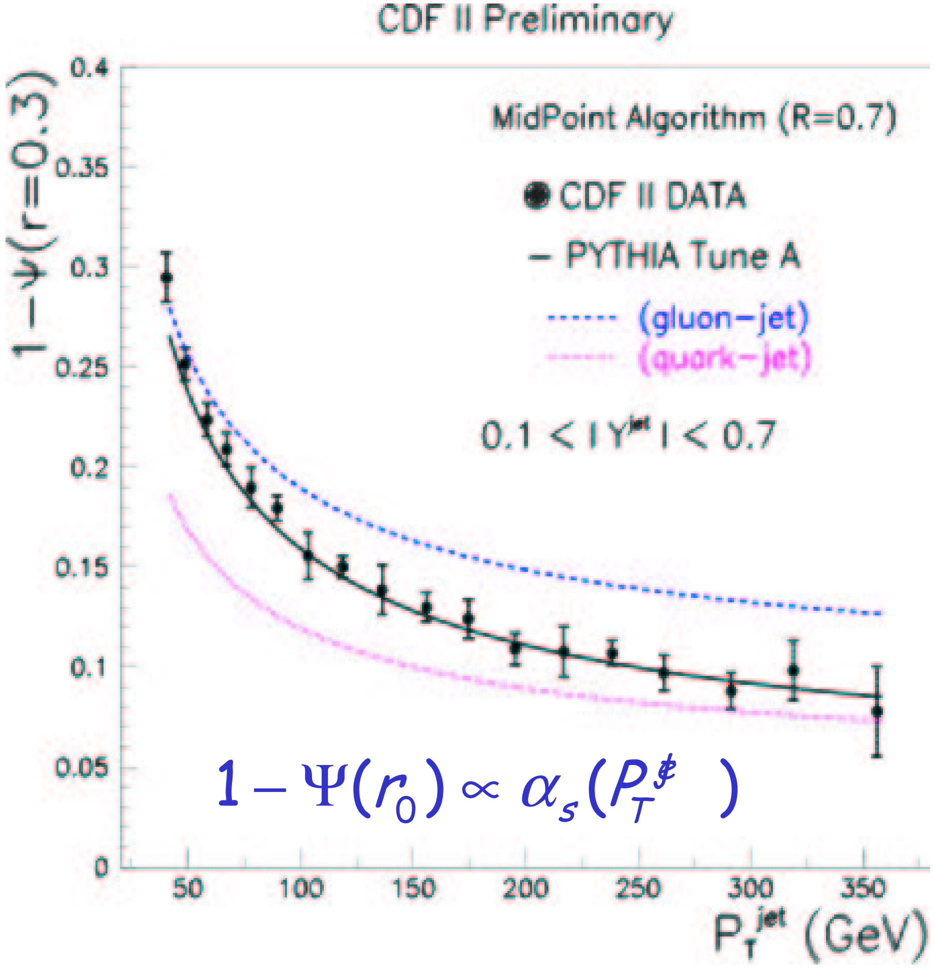
All MC's have fairly good description of data at high P_T

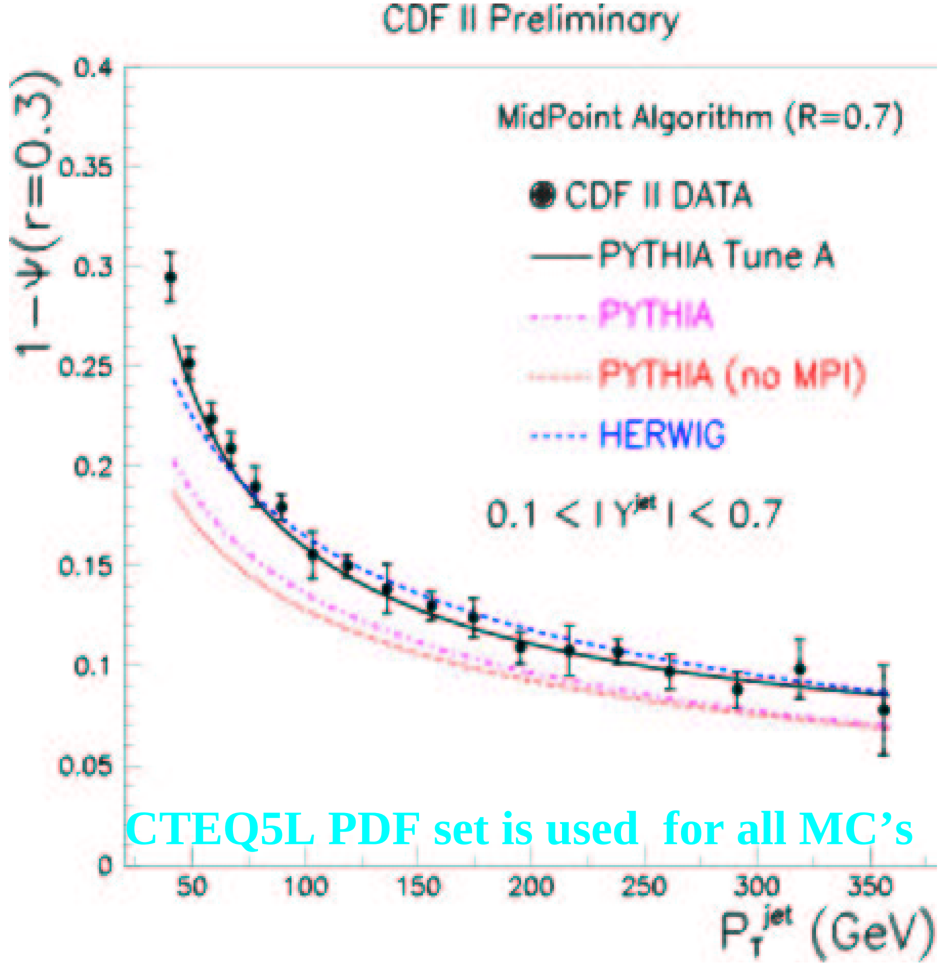
low P_T region:
importance of
underlying event

good
↓
bad

PYTHIA TuneA — good description of low & high P_T jets
HERWIG 6.2
Default PYTHIA 6.2
PYTHIA 6.2 (no MPI)

Jet Shapes: running of α_S





ü 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

Summary

Quark and Gluon jets

- ü results obtained for average multiplicities and momentum distributions
- ü $r=Ng/Nq=1.64\pm0.17$ at $Q=19$ GeV
- ü CDF data on gluon and quark jets follow next-to-NLLA trends
- ü Good agreement with e^+e^- results
- ü Herwig 5.6 and Pythia 6.115 reproduce gluon jets fairly well, but systematically over-estimate multiplicity in quark jets by ~30%

Jet Shapes

- ü obtained for jets with 37 GeV $<P_T<$ 380 GeV and $0.1<|Y_{jet}|<0.7$
- ü Pythia TuneA and Herwig 6.2 in good agreement with data for $P_T>55$ GeV
- ü Default Pythia 6.206 (with On/Off MPI) fail to describe data

  → *indicates importance of ISR and MPI in underlying event modeling*
- ü Results obtained with MidPoint (infrared safe)

  → *allows future comparison to NLO calculations*