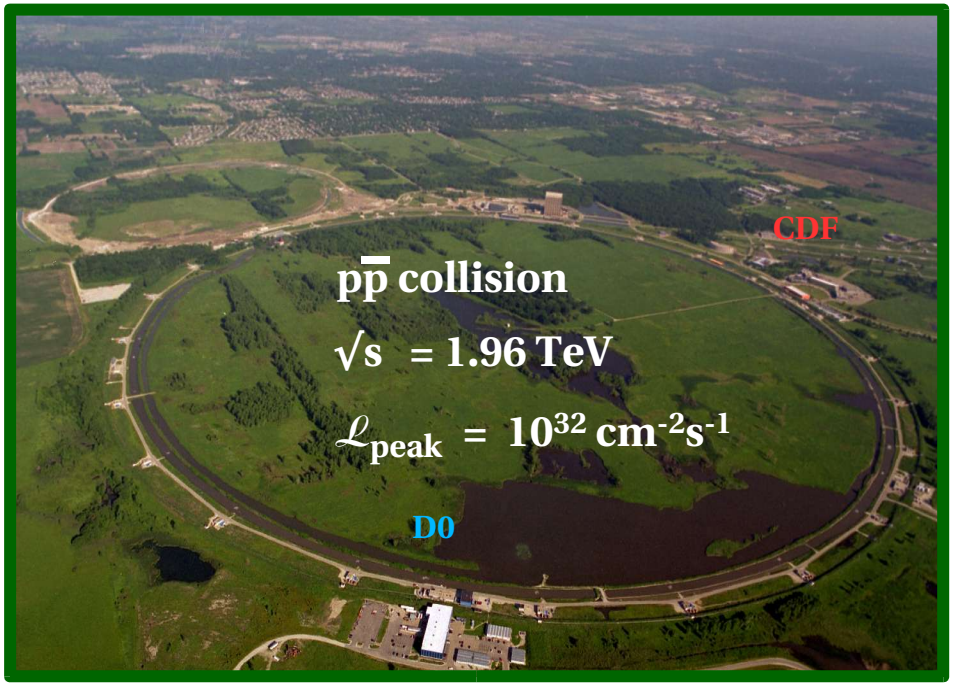
Jet Fragmentation Studies at CDF



Lester Pinera

UNIVERSITY OF FLORIDA

for CDF Collaboration

Overview

Momentum distributions of particles in jets

- PRD 68 (2003) 12003

Multiplicity of particles in jets (including g/q-jet differences)

- PRL 94 (2005) 17802
- PRL V87 No.21 (2001) 211804

Momentum correlations of particles in jets

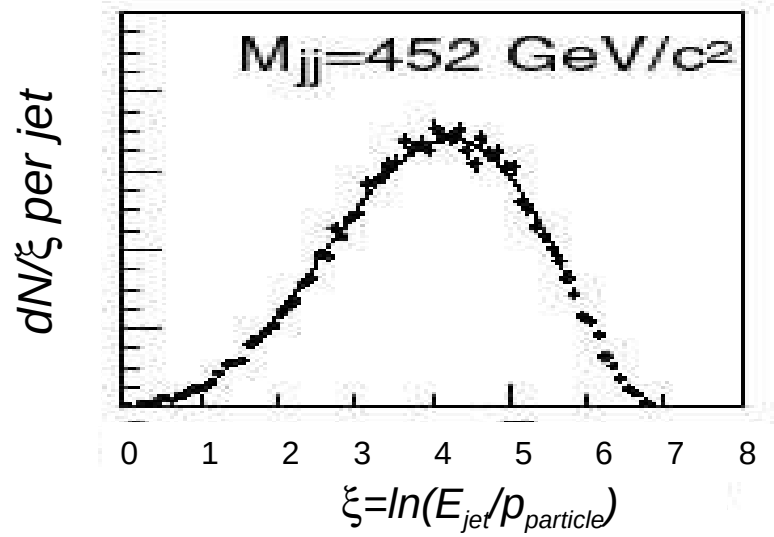
k_T-distribution of particles in jets (k_T with respect to jet axis)

Indirectly Global Event Shapes

Past CDF Results

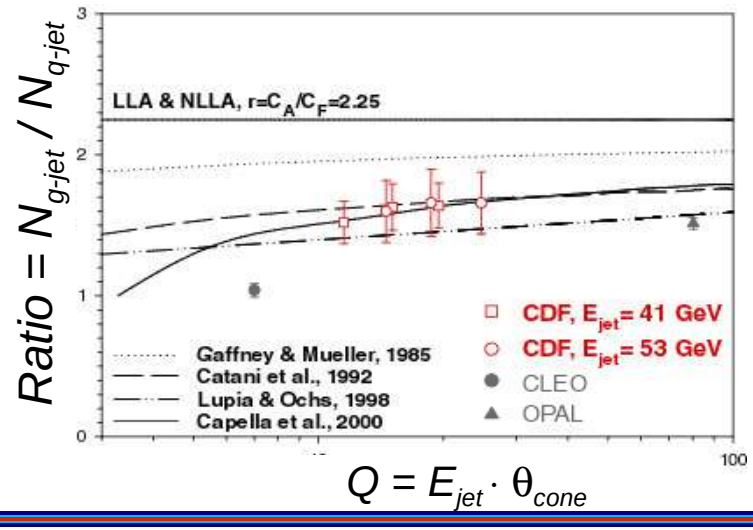
Momentum distribution of charged hadrons in jets:

- Well described by MLLA
  - dijet mass range 80-600GeV
  - cutoff $Q_{eff} = 230 \pm 40$ MeV
  - $N_{(\pm)Hadrons} / N_{Partons} = 0.56 \pm 0.10$



Ratio of charged hadron multiplicities in gluon & quark jets:

- Agrees with NNLLA
  - r = 1.6 (measured)



Implications:

- pQCD calculations carried out down to scale $Q \sim \Lambda_{QCD} \sim 200$MeV
- Local Parton-Hadron Duality

Momentum Correlations in Jets

Theory: C.Fong & B. Webber
(1990) Phys.Lett. B241:255

→ Consider all particle pairs in a small cone around jet axis

$$R(\xi_1,\xi_2) = \frac{\left(\frac{dN}{d\xi_1 d\xi_2}\right)}{\left(\frac{dN}{d\xi_1}\right)\left(\frac{dN}{d\xi_2}\right)} \quad \text{where} \quad \xi = \ln\left(\frac{E_{jet}}{p_{particle}}\right)$$

mixes together momentum correlations and multiplicity fluctuations

Effects are decoupled using binomial moments from theory

Independant of Multiplicity Fluctuations →

$$C(\xi_1,\xi_2) = \frac{\left(\frac{dn}{d\xi_1 d\xi_2}\right)}{\left(\frac{dn}{d\xi_1}\right)\left(\frac{dn}{d\xi_2}\right)} = R(\xi_1,\xi_2)\frac{\langle N\rangle^2}{\langle N(N-1)\rangle}$$

Distributions normalized to unity

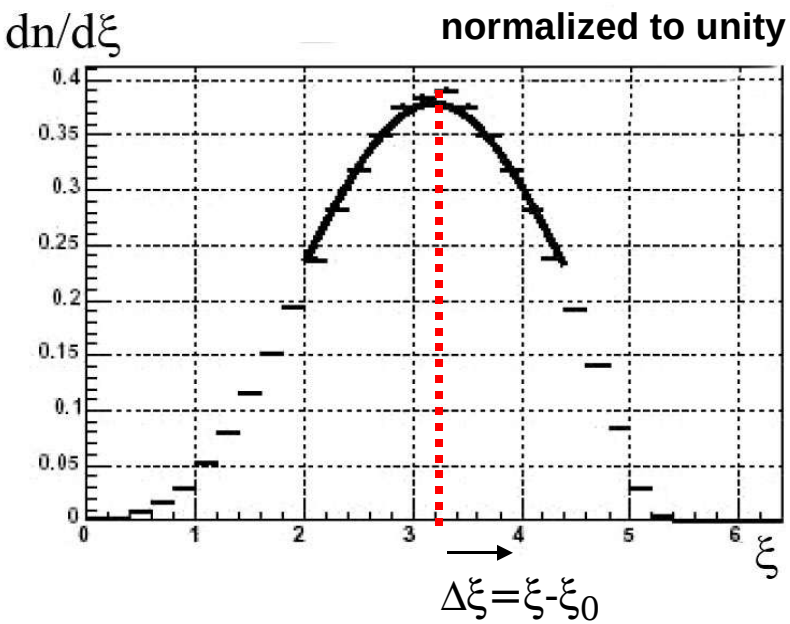
Momentum Correlations: Theory

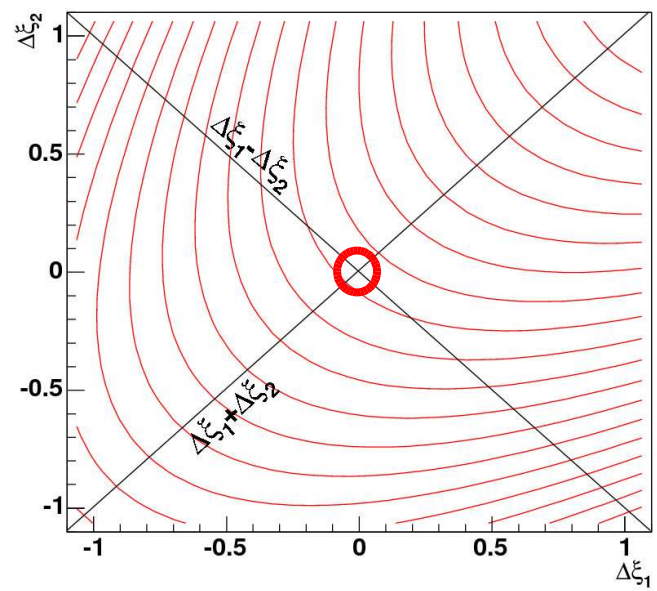
Around the peak of the inclusive momentum distribution, theory (MLLA) predicts:

$$C(\xi_1,\xi_2) = C_0(E_{jet}) + C_1(E_{jet})\cdot(\Delta\xi_1+\Delta\xi_2) + C_2(E_{jet})\cdot(\Delta\xi_1-\Delta\xi_2)^2$$

→ C_0 & C_1 always positive
→ C_2 always negative

Ridge-like structure:
- Particles with like momenta correlate
- Correlation is stronger for soft particles

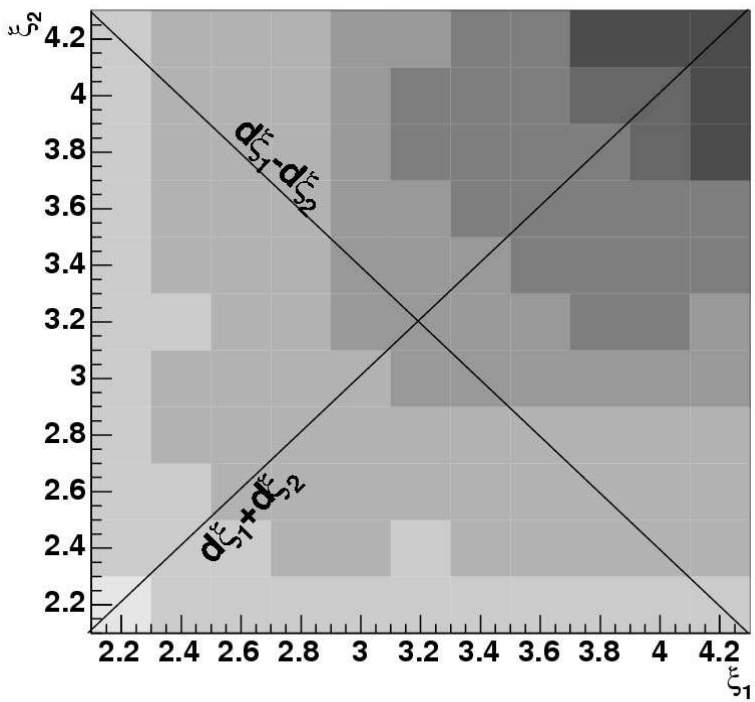




Momentum Correlations: Data (1)

Hadron Correlations follow the pattern predicted for partons!

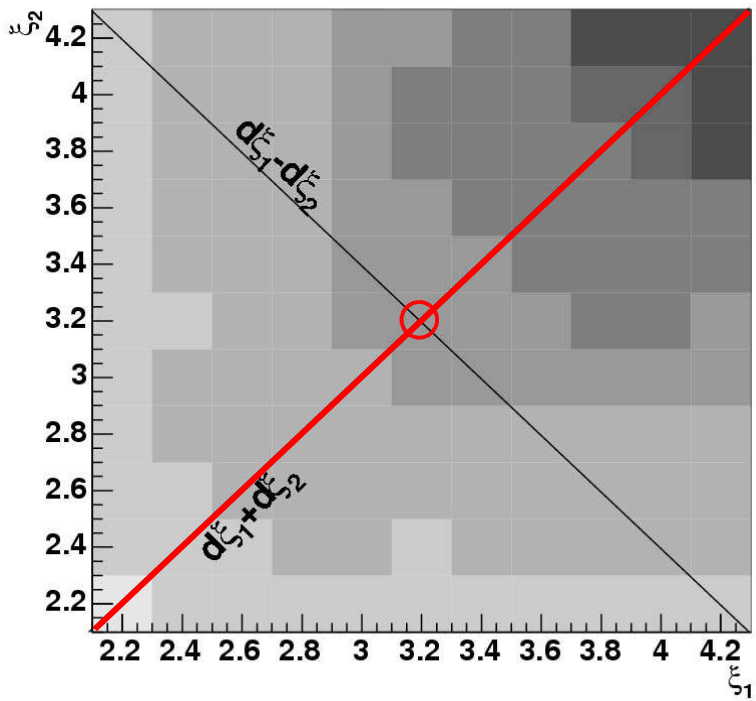
$$C(\xi_1,\xi_2) = C_0(E_{jet}) + C_1(E_{jet})\cdot(\Delta\xi_1+\Delta\xi_2) + C_2(E_{jet})\cdot(\Delta\xi_1-\Delta\xi_2)^2$$

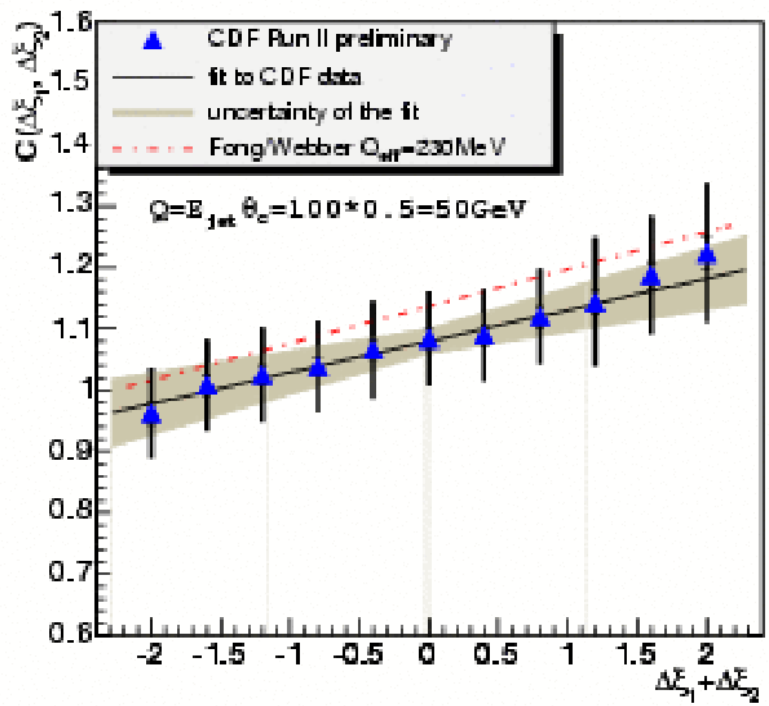


Momentum Correlations: Data (2)

Hadron Correlations follow the pattern predicted for partons!

$$C(\xi_1,\xi_2) = C_0(E_{jet}) + C_1(E_{jet})\cdot(\Delta\xi_1+\Delta\xi_2) \cancel{+ C_2(E_{jet})(\Delta\xi_1 - \Delta\xi_2)^2}$$

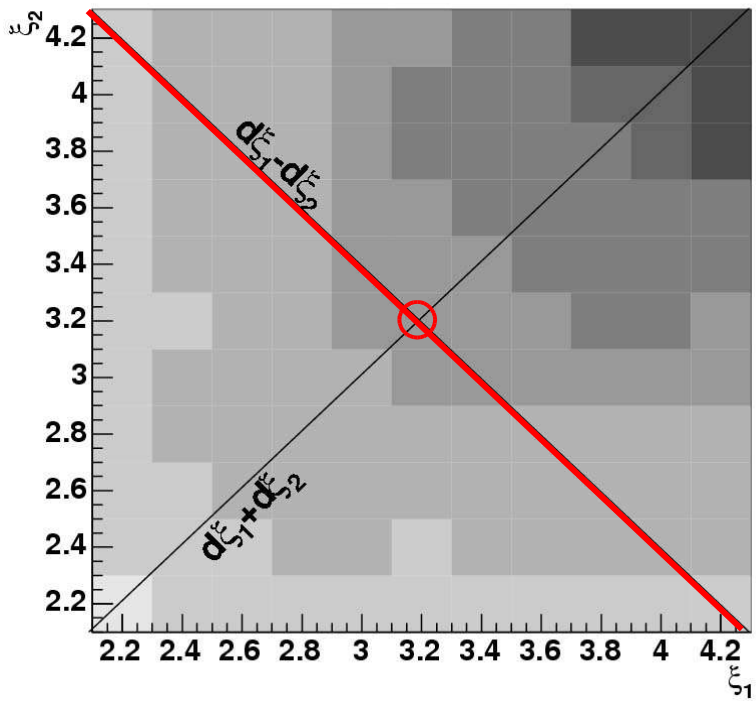


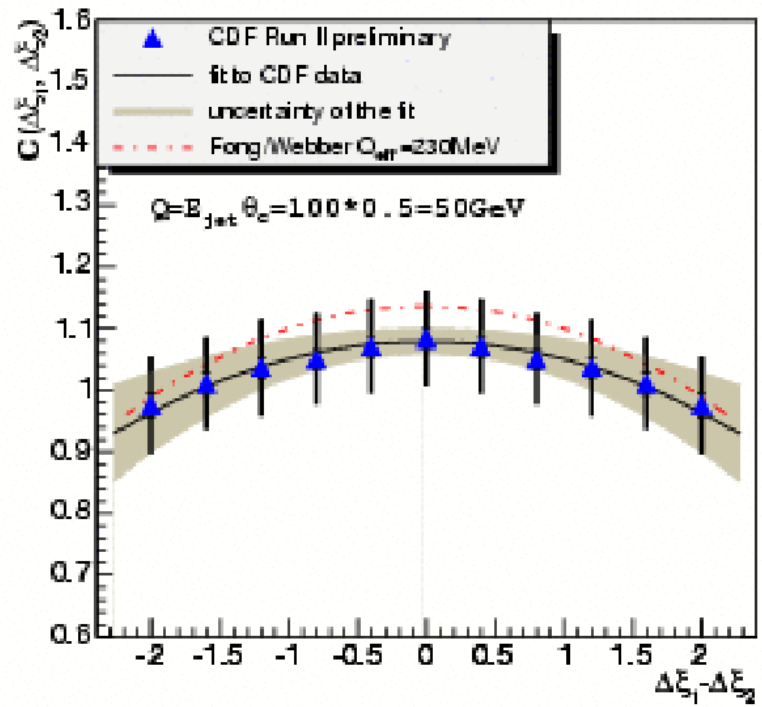


Momentum Correlations: Data (3)

Hadron Correlations follow the pattern predicted for partons!

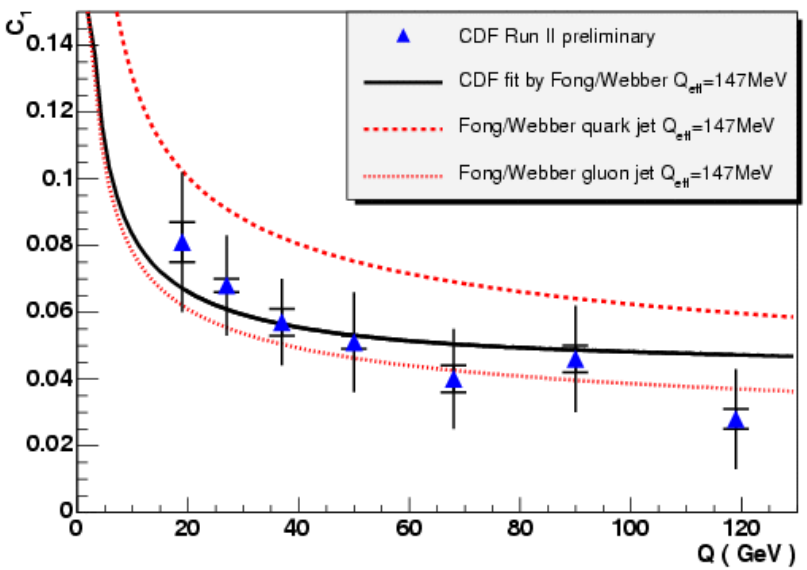
$$C(\xi_1,\xi_2) = C_0(E_{jet}) \cancel{+ C_1(E_{jet})(\Delta\xi_1+\Delta\xi_2)} + C_2(E_{jet})\cdot(\Delta\xi_1-\Delta\xi_2)^2$$

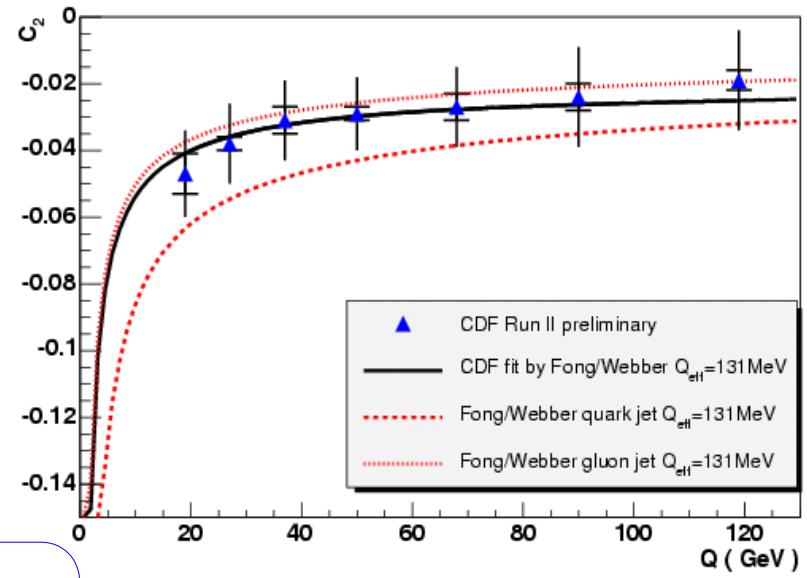




Momentum Correlations: Data (4)

Plotting the energy dependence of the coefficients we are able to extract Q_{eff}





$$C_1(E_{jet}) = +\frac{a_1}{Y^{1.5}} + \cdots$$

$$Y = \ln\left(\frac{E_{jet}\theta_{cone}}{Q_{eff}}\right)$$

$$C_2(E_{jet}) = -\frac{a_2}{Y^2} + \cdots$$

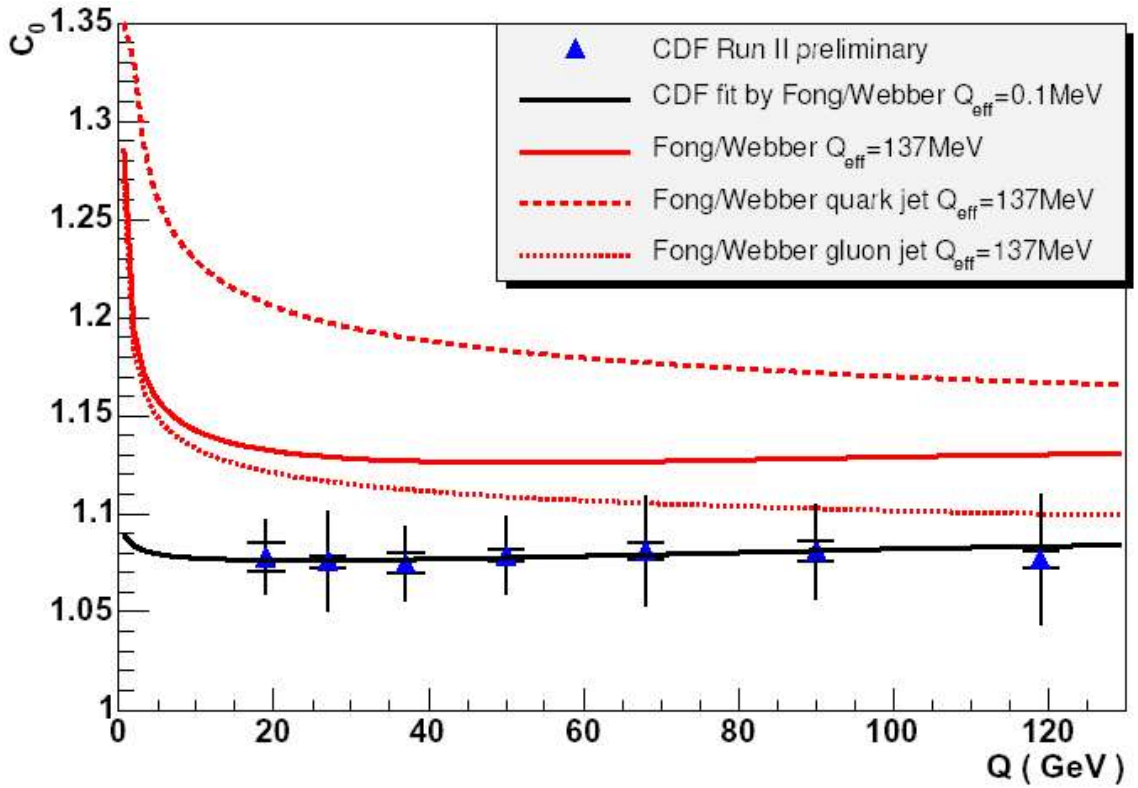
$Q_{eff} = 150 \pm 80$ MeV

$Q_{eff} = 130 \pm 80$ MeV

Theory reproduces trends seen in data

Momentum Correlations: Data (5)

- C_0 smaller than theory predicts
- However, it's independent of energy (as expected)
- Theoretically this parameter has some issues: Sensitive to expansion point

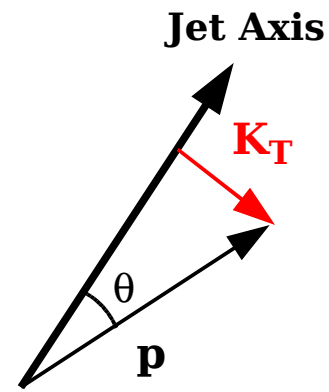


K_T Distribution of Particles in Jets

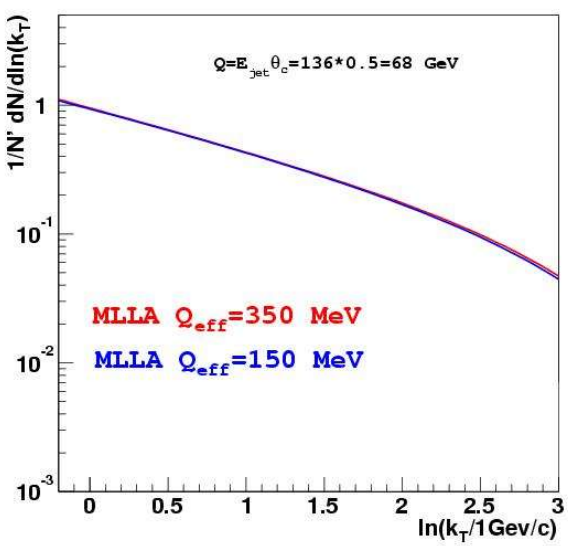
Theory: R. Perez-Ramos & B. Machet

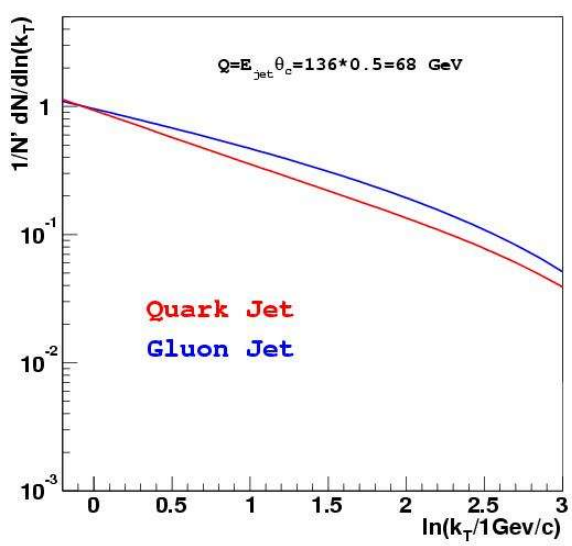
JHEP04 (2006) 043

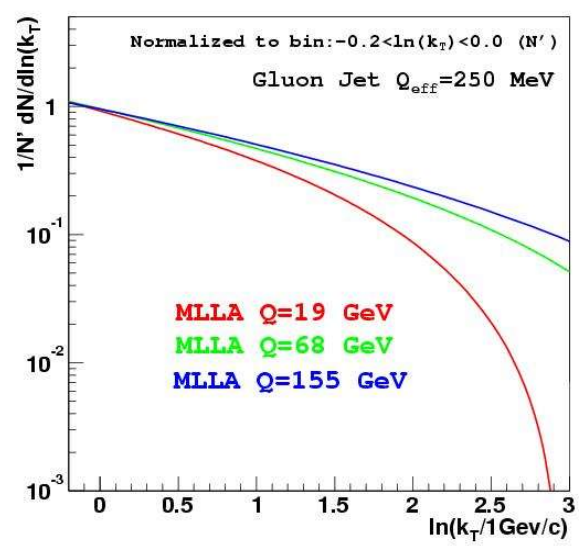
- Nearly no dependence on Q_{eff}
- Weak dependence on jet origin (q or g)
- Energy scale $Q = E_{jet}\theta$ defines k_T cutoff



$K_T = |p| \cdot \sin(\theta)$





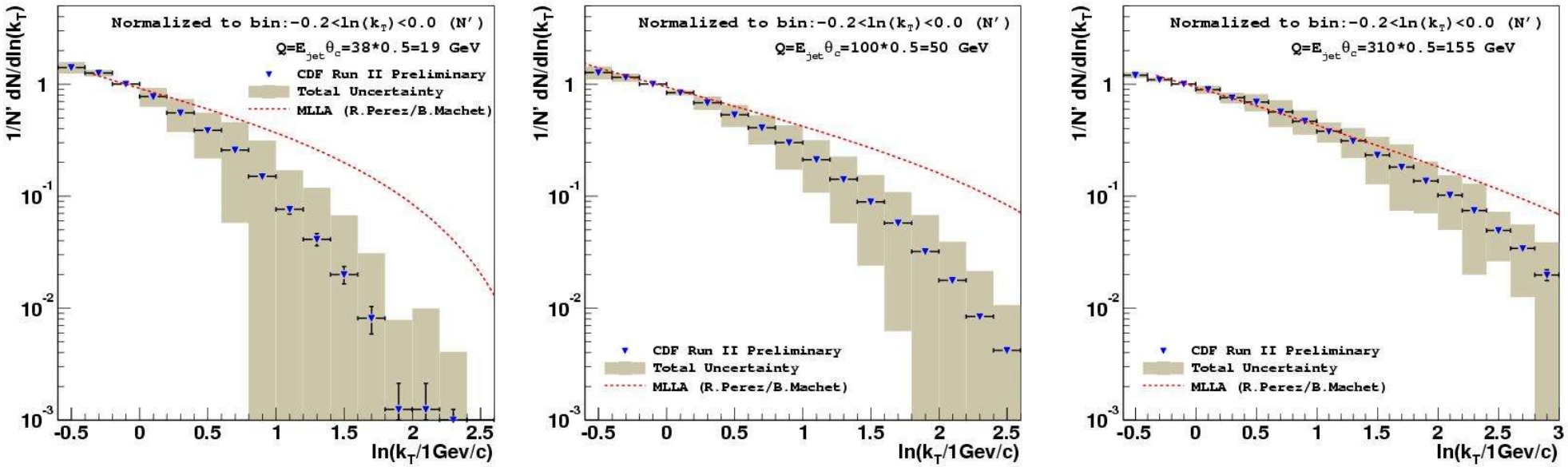


K_T Distribution: Data vs. Theory

→ Data indicates fewer particles with large k_T

→ Better agreement with increasing Energy scale Q

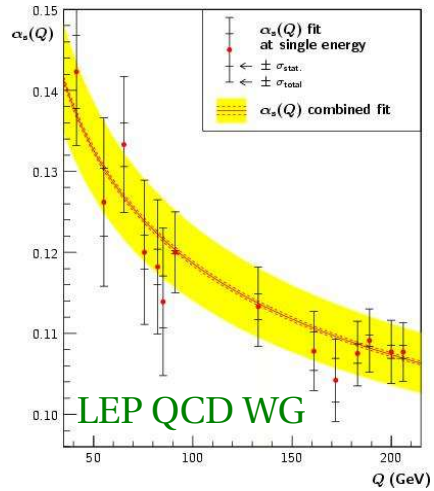
Is this due to an incomplete pQCD or the intervention of Hadronization?

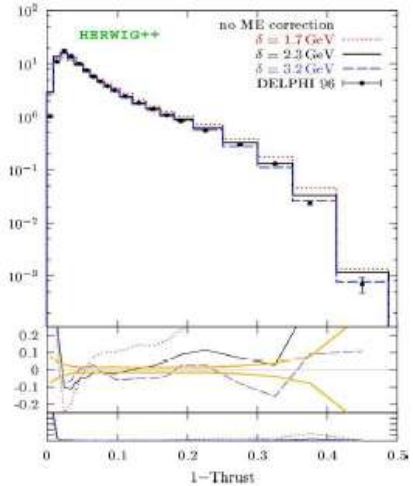


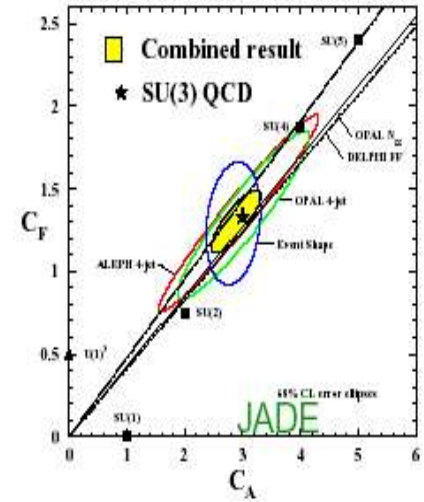
Event Shapes : e^+e^- & DIS

Studied extensively in the context of e+e- and DIS experiments:

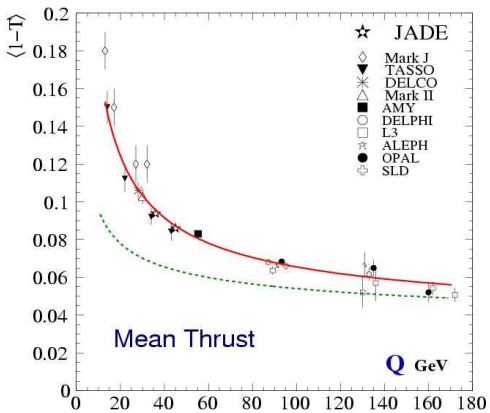
- Measurements of α_s
- Means of tuning MC
- Color Factor Fits

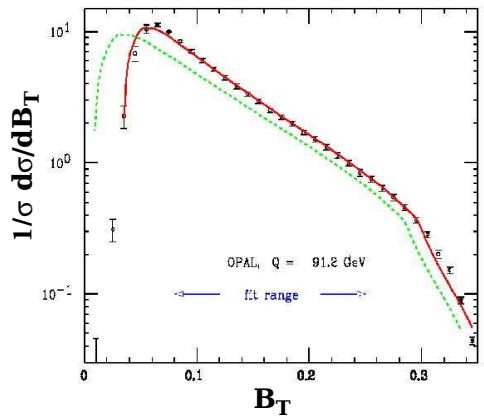


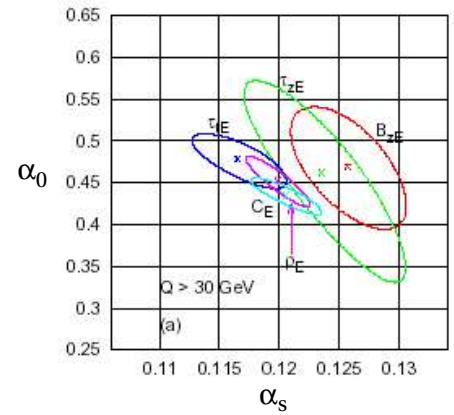




- Analytical non-perturbative QCD corrections (~1/Q)

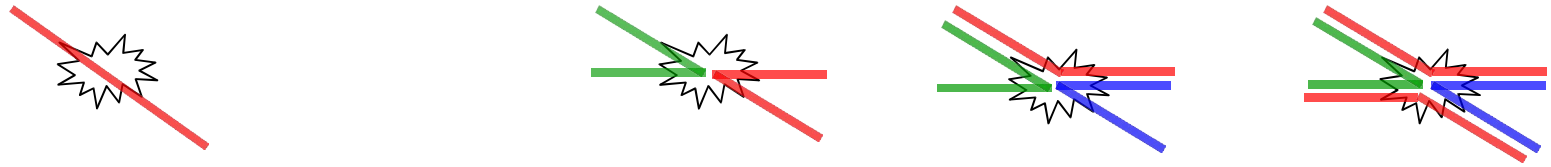






Event Shapes : Tevatron

Event grows from a much richer color structure:

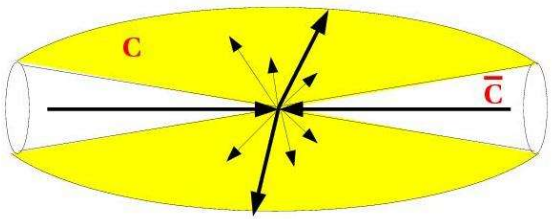


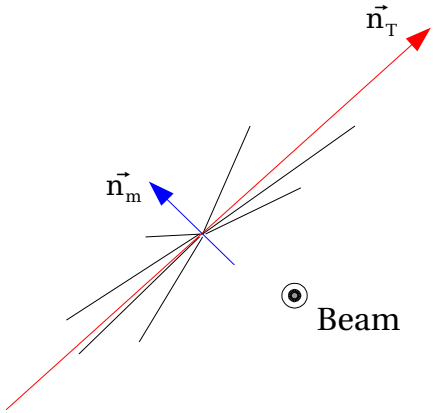
LEP Tevatron

Complication: Forward region is experimentally inaccessible. Analytical predictions require "global" observables (i.e. sensitive to emissions in <u>all</u> directions).

→ Indirectly Global Event Shapes = Central Event Shape + Recoil
(both Central ES & Recoil defined within central region C)

<u>Theory:</u> A.Banfi, G. Salam, G. Zanderighi JHEP 0408:062 (2004)





Transverse Thrust

$$T \equiv \max_{\vec{n}_T} \frac{\sum |\vec{q}_{\perp i} \cdot \vec{n}_T|}{\sum |\vec{q}_{\perp i}|}$$

Transverse Thrust Minor

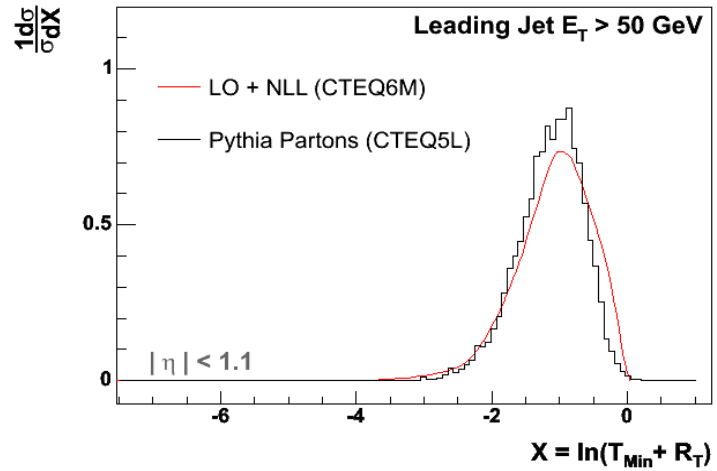
$$T_m \equiv \frac{\sum |\vec{q}_{\perp} \cdot \vec{n}_m|}{\sum |\vec{q}_{\perp}|} \qquad \vec{n}_m \equiv \vec{n}_T \times \hat{z}$$

Recoil

$$R_{\perp,C} = \frac{1}{\sum_{i \in C} |\vec{q}_{\perp i}|} \left| \sum_{i \in C} \vec{q}_{\perp i} \right|$$

Event Shapes : Theory

MC at Parton Level in agreement with preliminary analytical pQCD predictions.

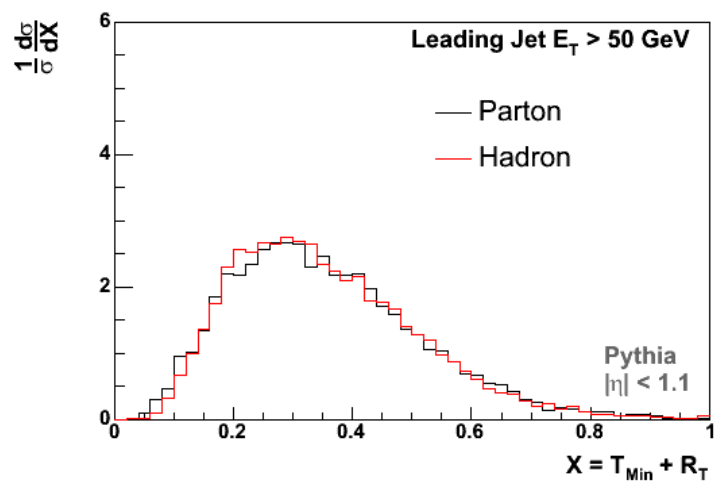


MC at Hadron Level in agreement with MC Parton Level.

True of T_{Min} and R_T independantly

Strong Correlation between levels too

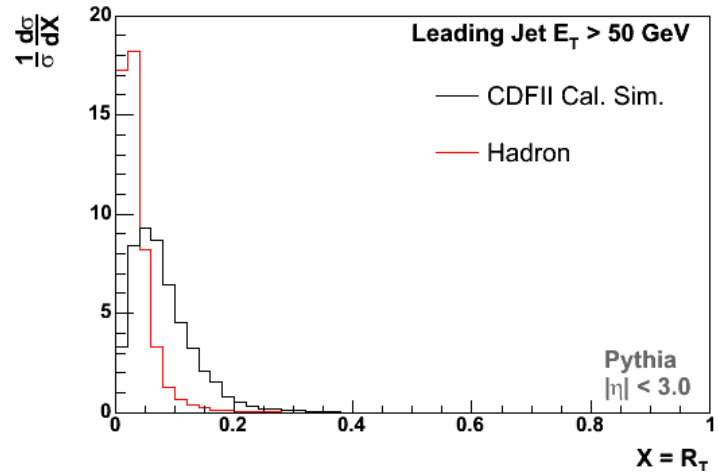
No shift due to hadronization in the MC



Event Shapes : Detector Effects

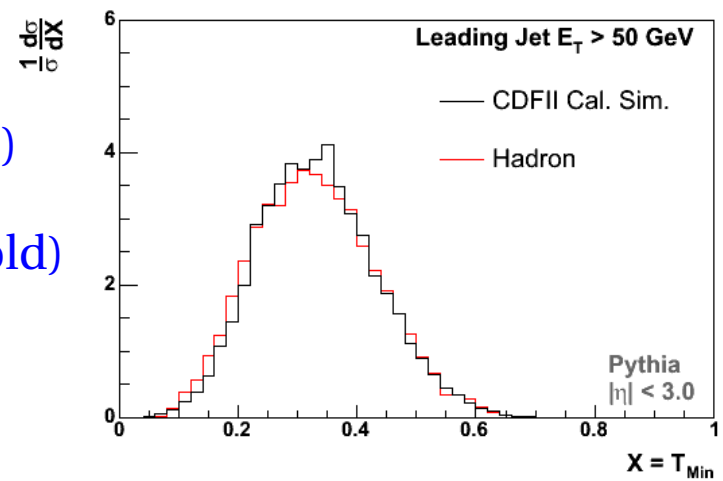
Recoil:

Detector Sim. ≠ MC Hadron Level
(instrumental effects to be unfolded)



Central Event Shapes:

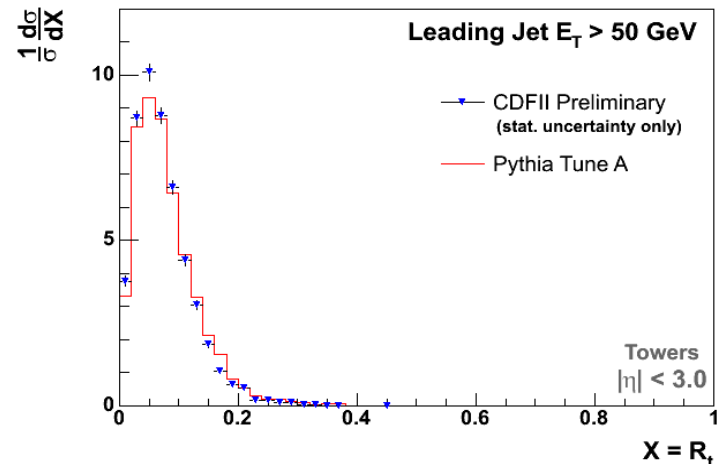
Detector Sim. = MC Hadron Level
(true of Tracks and Calorimeter Towers!)
True on an event by event basis
(approx. no instrumental effects to unfold)



Event Shapes : Data

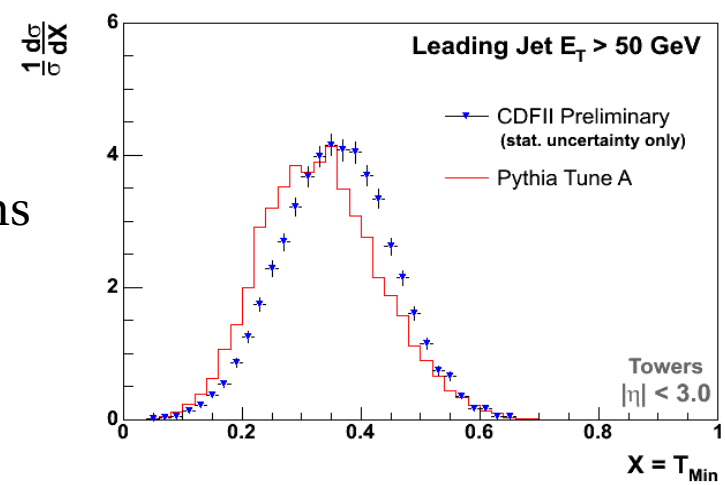
Recoil:

Data = Detector Sim.
No surprises there



Central Event Shapes:

Data ≈ Detector Sim. + Shift
Present in Tracks and Towers
Is it 1/Q? Awaiting analytical predictions



Summary

Momentum Distributions & Multiplicity of Charged Particles in Jets

- consistent with predictions from pQCD within MLLA framework
- Parton Shower cutoff $Q_{eff} \sim \Lambda_{QCD}$
- Lent support to Local Parton Hadron Duality ($N_{hadrons} = K_{LPHD} N_{partons}$) $K_{LPHD} \sim 1$
- N^{gluon} / N^{quark} consistent with NNLLA prediction

Momentum correlations of particles in jets

- follow pQCD predictions for partons
- $Q_{eff} \approx 140 \pm 80$ MeV for parabolic and linear terms
- the constant (momentum-independent) term is much smaller than predicted…

k_T-distribution of particles

- data at low k_T agrees with theory, but seems to sag at large k_T
- discrepancy gets smaller for larger Q

Indirectly Global Event Shapes

- data shifted with respect to MC!
- awaiting theoretical predictions. . . .
- this branch of studies promises very interesting result

Backups

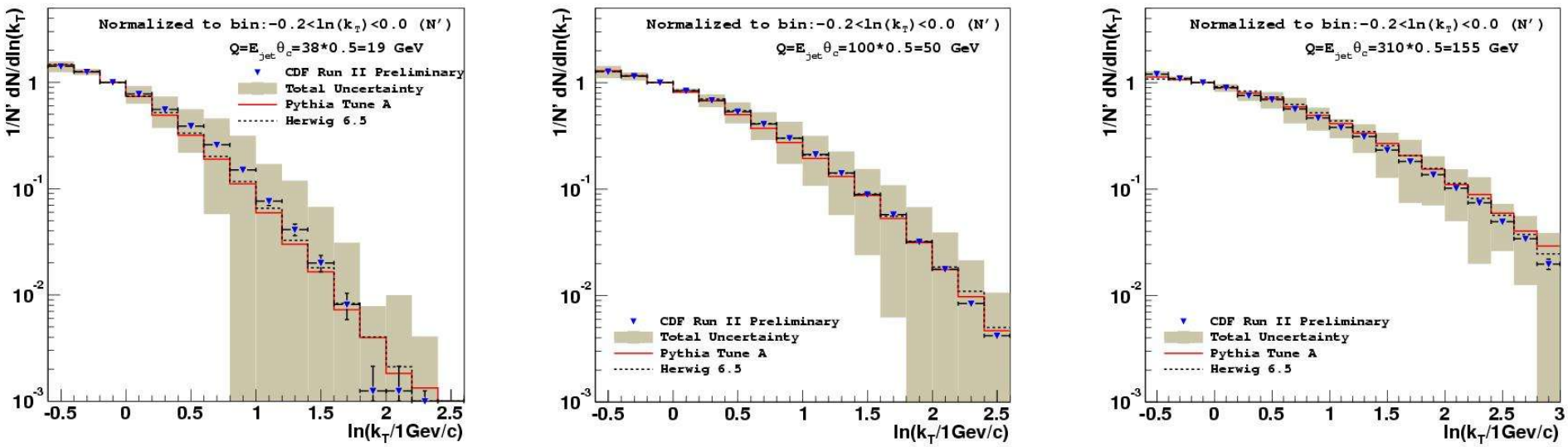
K_T Distribution: Data vs. MC

→ Pythia and Herwig (Hadron level) in agreement with Data over the full range of k_T

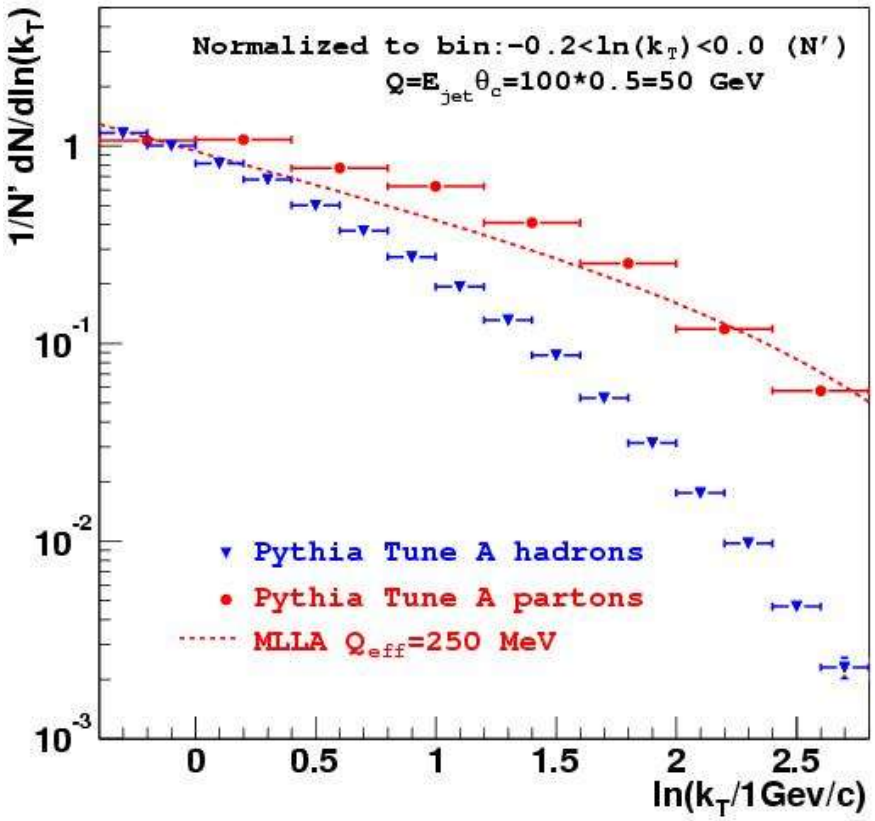
Where is the discrepancy coming from?

MLLA → Next-to-Leading Log

Pythia → Leading Log + Energy conservation



K_T Distribution: Pythia Partons



Pythia Partons follow MLLA

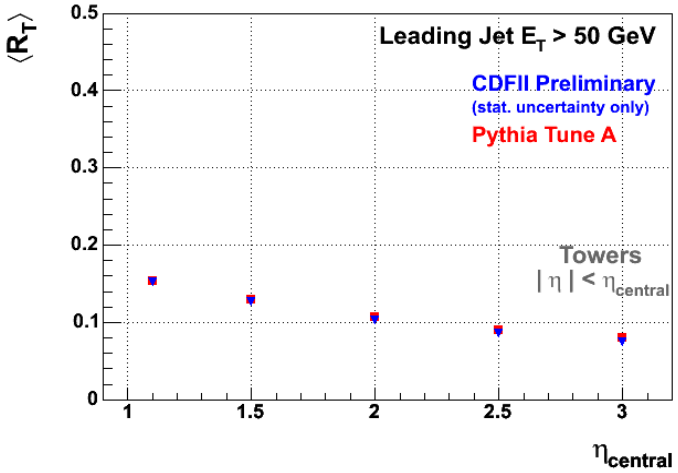
↓

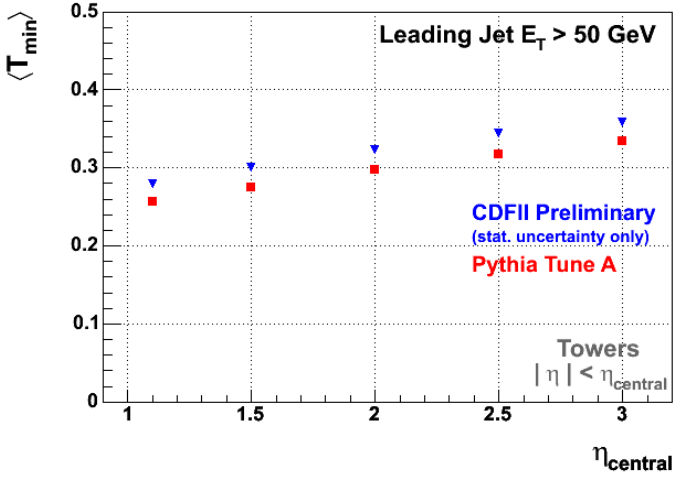
Doesn't look like it's Energy conservation

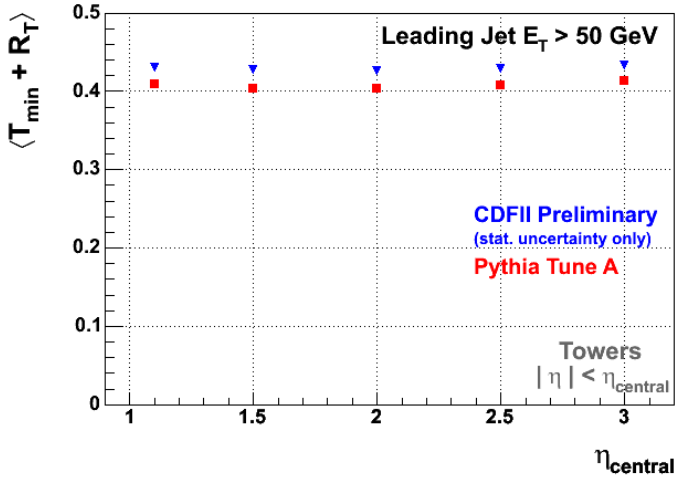
↓

Hadronization???

Event Shapes: Central Region







- Shift between <Data> & <MC> independent of how central region defined
- $\langle T_{Min}+R_T \rangle$ constant as function of $\eta_{central}$ (Thrust saturates)