New Results on Jet Fragmentation at CDF

Sergo Jindariani

for CDF collaboration

ISMD'2006
September 02 – 08, 2006, Paraty, State of Rio de Janeiro, Brazil

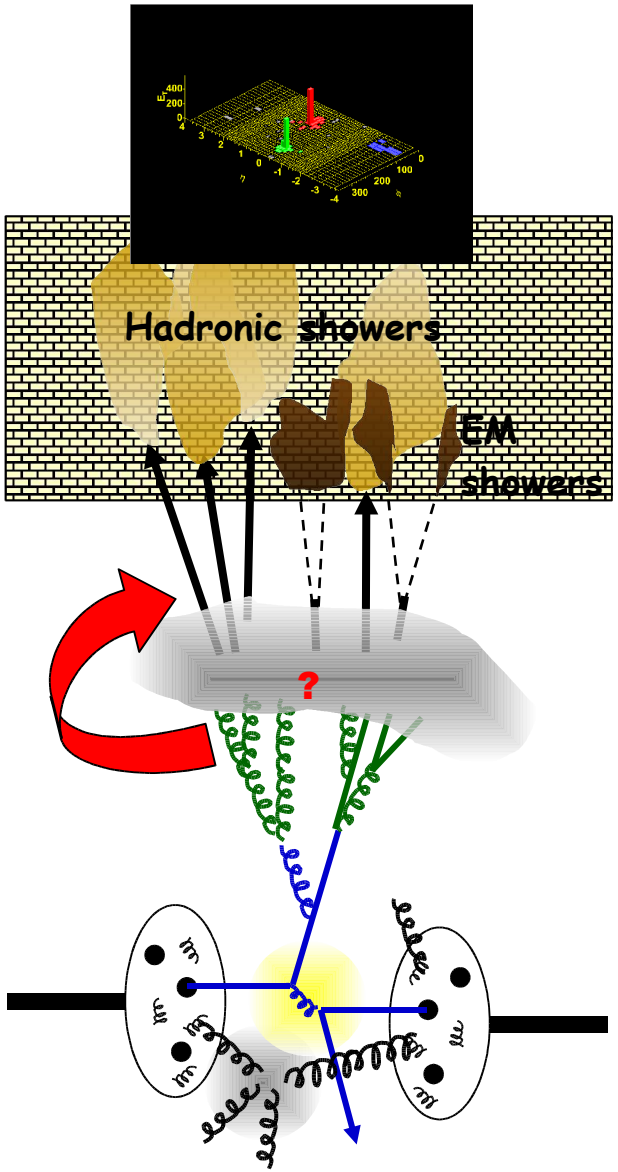
Jet fragmentation vs analytical pQCD

- Momentum distribution of particles in jets;
- Multiplicity of charged particles in jets;
  including g/q jet differences

New results:

- Momentum correlation of particles in jets;
- k_T-distributions of particles in jets;
  (k_T-transverse momentum with respect to jet axis)
- Global Event Shapes;

Partons, Hadrons, Jets



Pick two partons and their momenta:
- -phenomenological parton density functions, PDF

Hard Scattering:
- -pQCD exact matrix element at LO, some at NLO,...

Soft final state radiation:
- -pQCD approximate resummation in all orders: LLA (leading log approximation), NLLA

Underlying event:
- -phenomenological models

Hadronization:
- -phenomenological models

Calorimeter response:
- -electromagnetic shower for photons
- -hadronic shower for “stable” hadrons

Jet identification:
- -jet finding algorithms

Particle momenta and average multiplicity

Partons: NLLA resummation

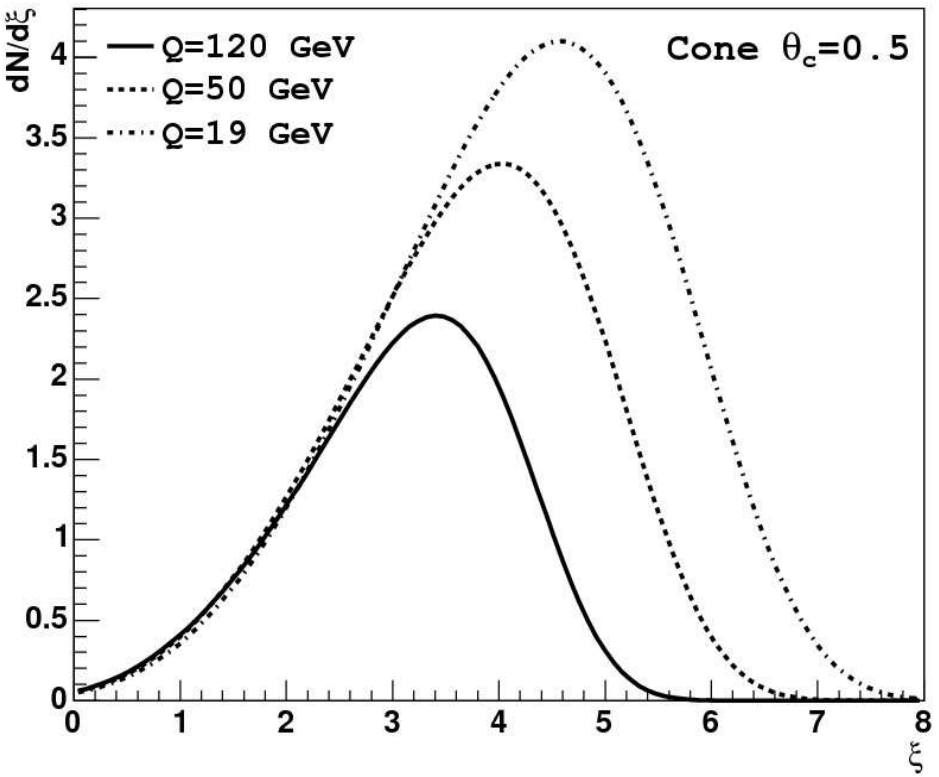
- Mueller (1983)
- Dokshitzer, Troyan (1984)
- Malaza, Webber (1984)
- plus subsequent corrections

$dN/d\xi = D(Y, \xi)$

$\xi = \ln(1/x) = \ln(E_{jet}/p_{parton})$

$Y = \ln(Q/Q_{eff})$, $\quad Q = E_{jet}\theta_{cone}$

$Q_{eff} = Q_{cutoff} = \Lambda_{QCD}$



From partons to hadrons: Local Parton-Hadron Duality

- Azimov, Dokshitzer, Khoze, Troyan (1985)

Hadron observables follow patterns predicted for partons

- $N_{hadrons} \sim N_{partons}$?
- Momentum distributions?
- Momentum correlations?
- ...

Particle momenta and average multiplicity

Momentum distribution of charged particles in jets:

- dijet events with well-balanced E_T
- 15-30° cone around dijet axis

Two parameter fit (MLLA+LPHD):

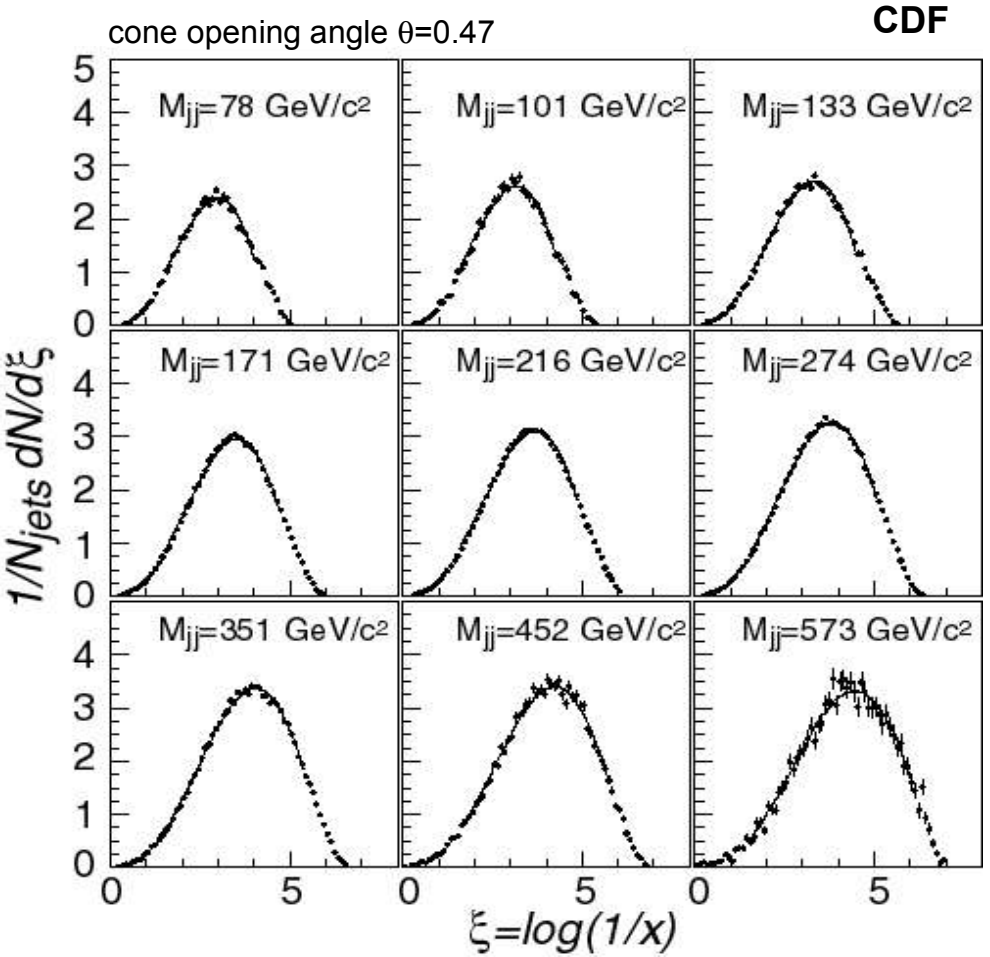
- works surprisingly well in wide range of dijet masses

- MLLA Q_{eff} = 230±40 MeV

k_T-cutoff can be set as low as Λ_{QCD}

- $K_{LPHD(\pm)}$ = 0.56 ± 0.10

$N_{hadrons} \approx N_{partons}$



$$x = \frac{p_{particle}}{E_{jet}} \qquad \xi = \ln(1/x) = \ln\left(\frac{E_{jet}}{p_{particle}}\right)$$

Gluon/Quark Jet Differences

Charged particle multiplicities in gluon and quark jets:

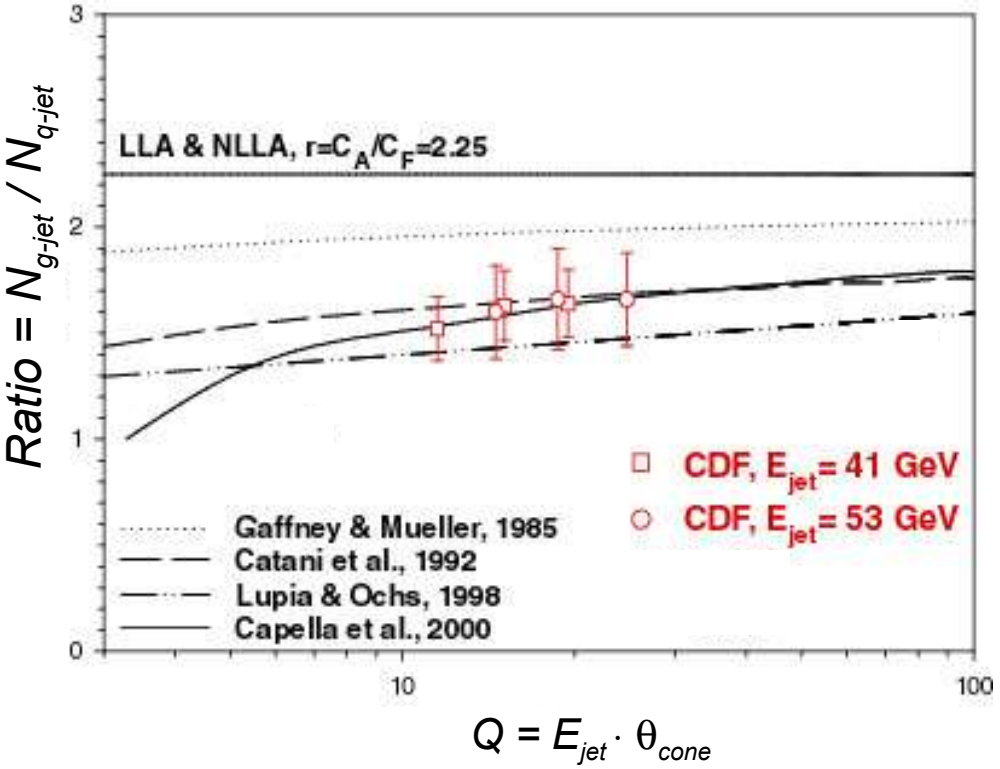
- **Measured multiplicities in di-jet and γ-jet events can be resolved for multiplicities in quark and gluon jets;**

Results agree with NNLLA:

r=1.64±0.17 at Q=20 GeV

Most recent LEP result (OPAL):

r=1.51±0.04 at Q=90 GeV



Momentum Correlations

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

(a recent update by R.Perez-Ramos just became available)

- Consider all particle pairs in a small cone around jet axis:

$$R(\xi_1,\xi_2)=\frac{\left(\frac{d^2N}{d\xi_1 d\xi_2}\right)}{\left(\frac{dN}{d\xi_1}\right)\left(\frac{dN}{\xi_2}\right)}$$

} mixes together:
- momentum correlations
- multiplicity fluctuations

$\int(dN/d\xi)d\xi=N$

$\int d^2N/(d\xi_1 d\xi_2)d\xi_1 d\xi_2=N(N-1)$

- To decouple momentum correlations and multiplicity fluctuations effects we used distributions normalized to unity:

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

where $F=\frac{\langle N(N-1)\rangle}{\langle N\rangle^2}$ - binomial moments taken from theory

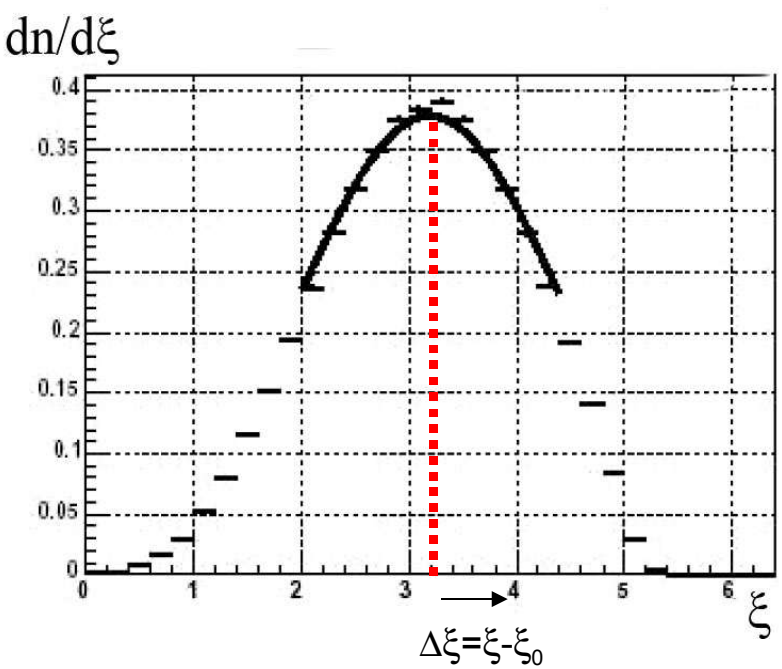
Momentum Correlations

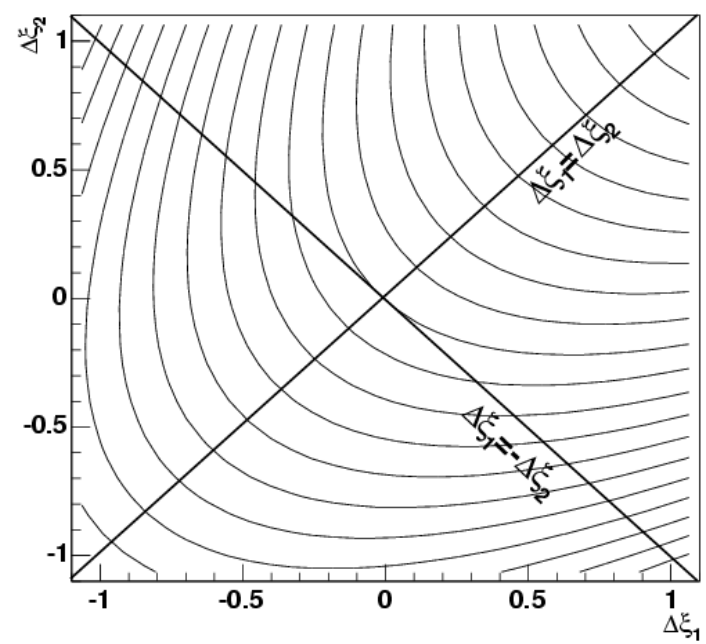
- Consider all particle pairs in a small cone around jet axis:

For particles with momenta around the peak of (dN/dξ) distribution, $C(\xi_1,\xi_2)$ is predicted by NLLA:

$$C(\xi_1,\xi_2)=\frac{\left(\frac{dn}{d\xi_1 d\xi_2}\right)}{\left(\frac{dn}{d\xi_1}\right)\left(\frac{dn}{d\xi_2}\right)}=c_0(E_{jet})+c_1(E_{jet})\cdot(\Delta\xi_1+\Delta\xi_2)+c_2(E_{jet})\cdot(\Delta\xi_1-\Delta\xi_2)^2$$

- C_0, C_1 and C_2 depend on $Y=\ln(E_{jet}\theta_c/Q_{eff})$





Momentum Correlations

- Consider all particle pairs in a small cone around jet axis:

For particles with momenta around the peak of (dN/dξ) distribution, $C(\xi_1,\xi_2)$ is predicted by NLLA:

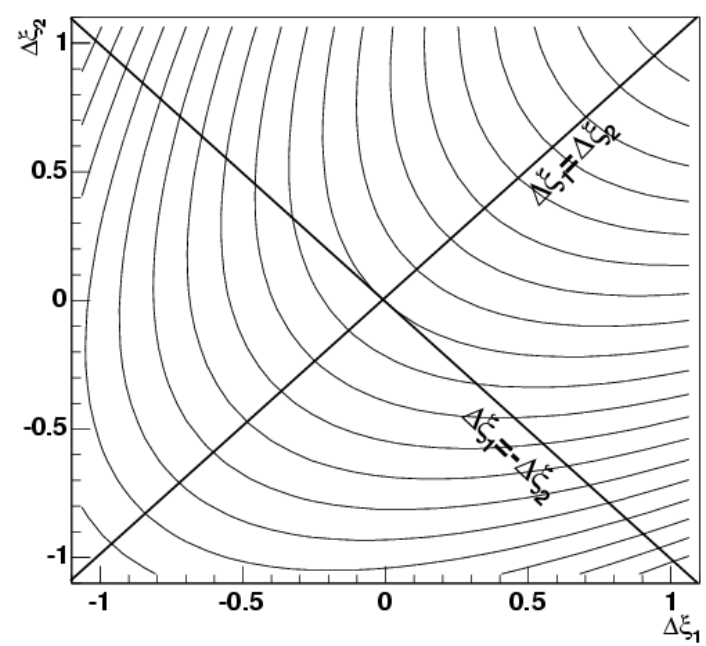
$$C(\xi_1,\xi_2)=\frac{\left(\frac{dn}{d\xi_1 d\xi_2}\right)}{\left(\frac{dn}{d\xi_1}\right)\left(\frac{dn}{d\xi_2}\right)}=c_0(E_{jet})+c_1(E_{jet})\cdot(\Delta\xi_1+\Delta\xi_2)+c_2(E_{jet})\cdot(\Delta\xi_1-\Delta\xi_2)^2$$

- C_0, C_1 and C_2 depend on $Y=\ln(E_{jet}\theta_c/Q_{eff})$

$C_0 > 1$
C_1 always positive
C_2 always negative

↓

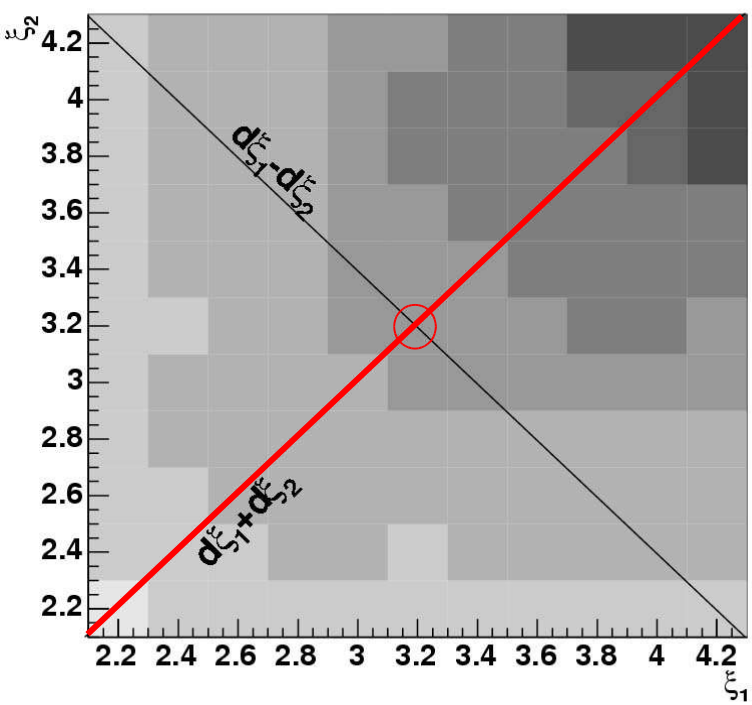
Ridge-like structure:
- Particles with like momenta correlate
- Correlation is stronger for soft particles

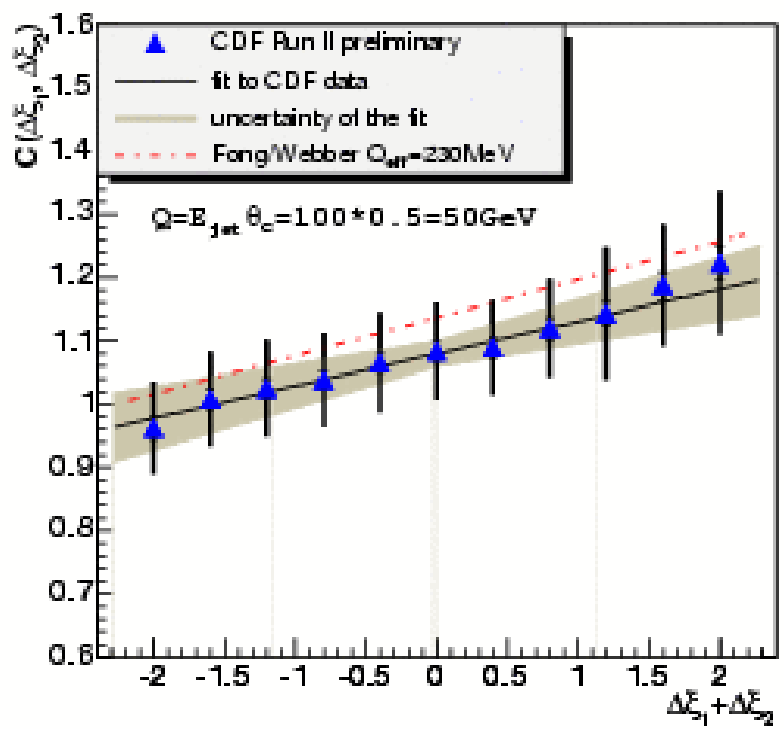


Momentum Correlations

- Hadron correlations follow the pattern expected for partons;

$$C(\xi_1,\xi_2) = c_0(E_{jet}) + c_1(E_{jet})\cdot(\Delta\xi_1 + \Delta\xi_2) + \cancel{c_2(E_{jet})\cdot(\Delta\xi_1 - \Delta\xi_2)^2}$$

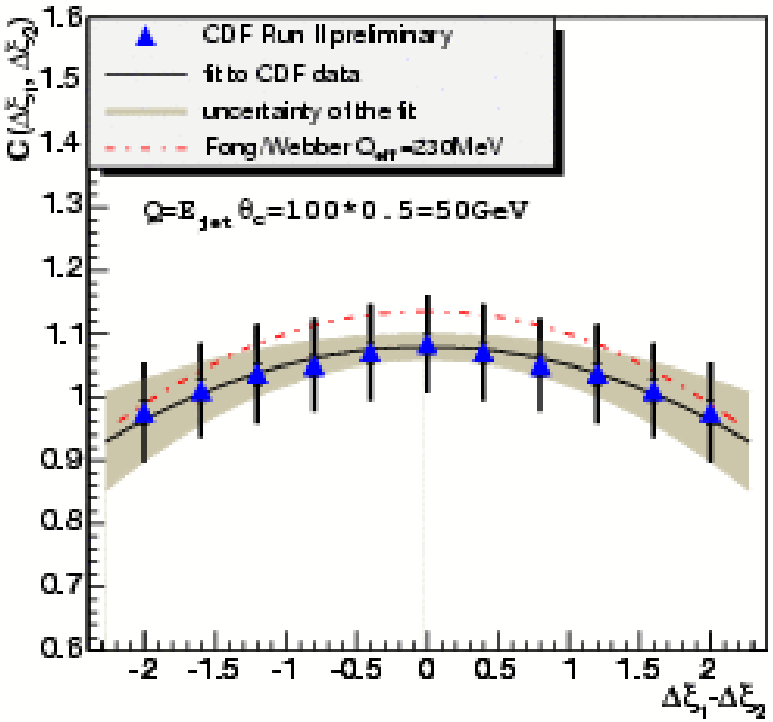


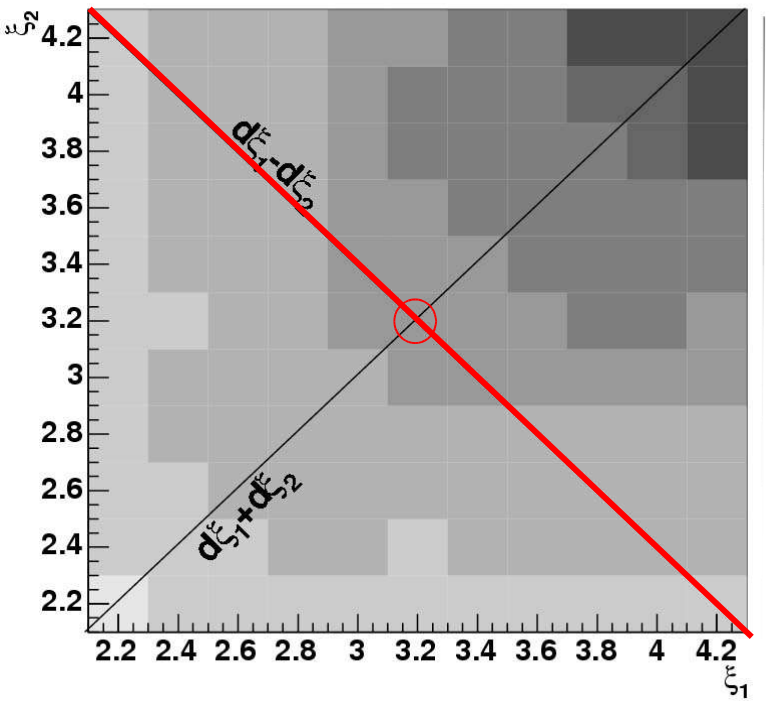


Momentum Correlations

- Hadron correlations follow the pattern expected for partons;

$$C(\xi_1,\xi_2) = c_0(E_{jet}) + \cancel{c_1(E_{jet})\cdot(\Delta\xi_1 + \Delta\xi_2)} + c_2(E_{jet})\cdot(\Delta\xi_1 - \Delta\xi_2)^2$$



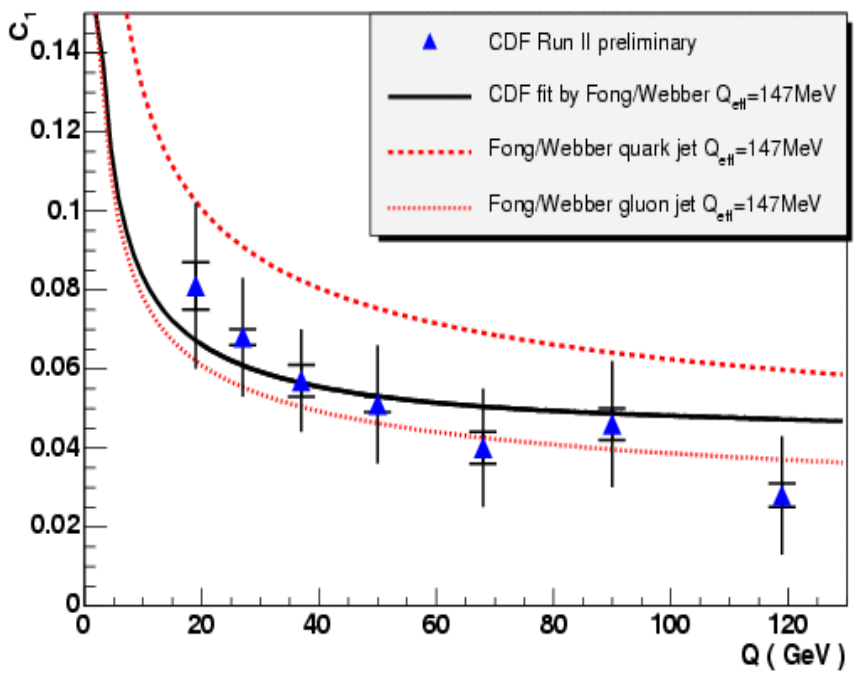


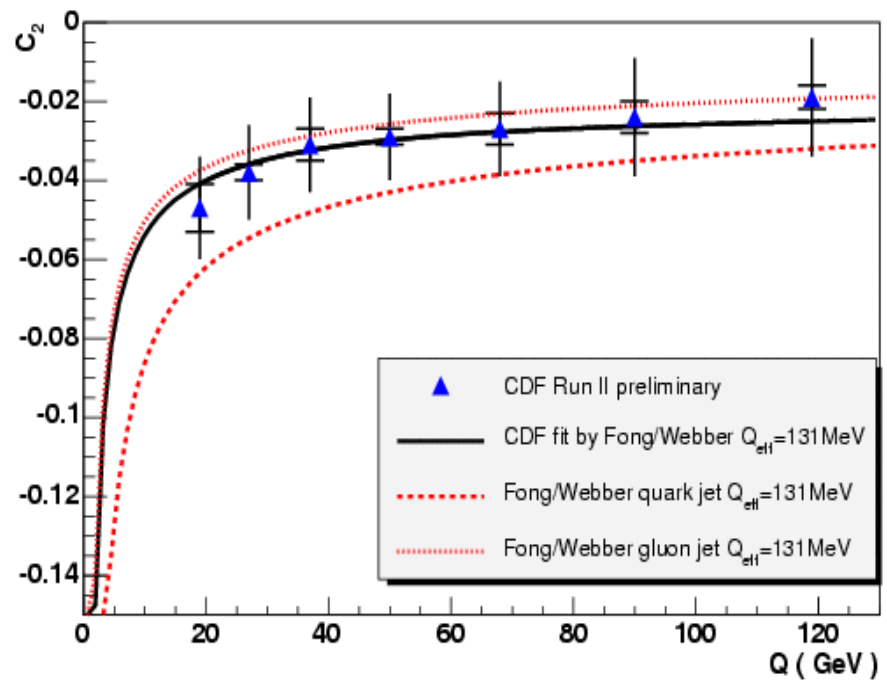
Momentum Correlations

Plotting the energy dependence of the coefficients allows us to extract Q_{eff}

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

$$C_1(Y) = +\frac{a_1}{Y^{1.5}} + \cdots \qquad C_2(Y) = -\frac{a_2}{Y^{2}} + \cdots$$





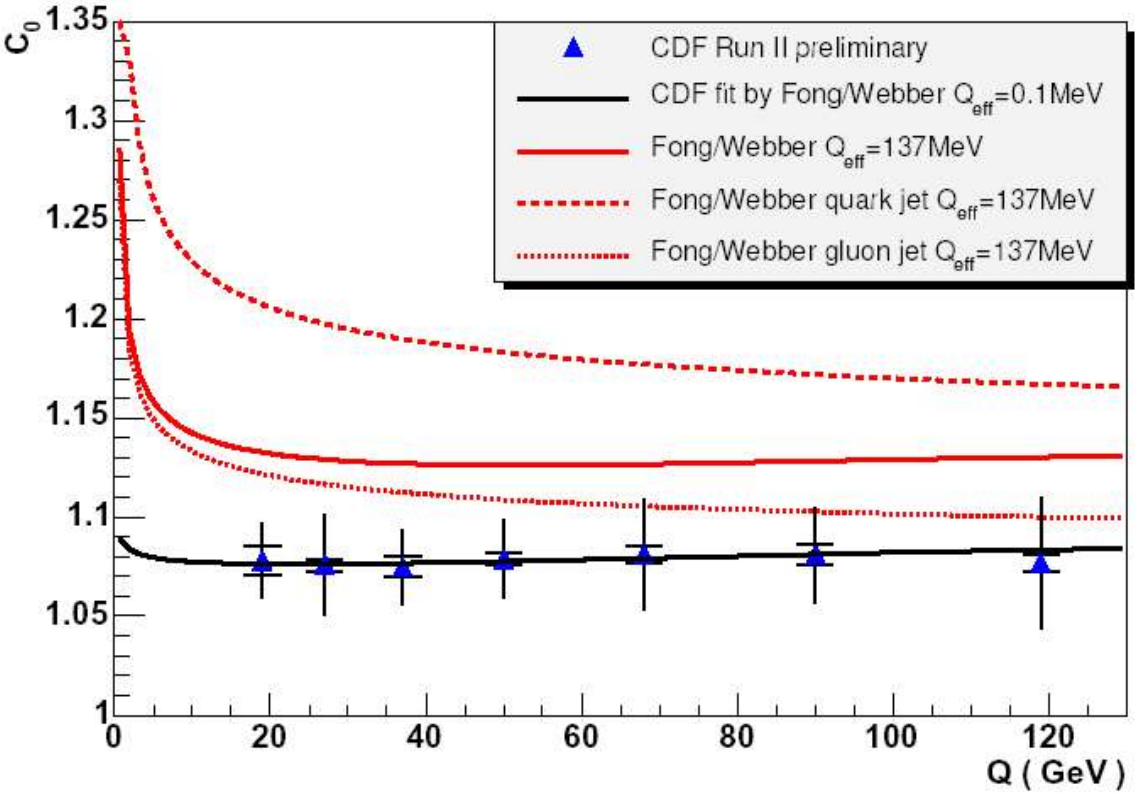
$Q_{eff} = 150 \pm 80$ MeV

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

Theory reproduces trends seen in data

Momentum Correlations

- C_0 is too small if compared to theory;
- However, it's almost independent of energy, as expected;
- Theoretically, this parameter has some issues...



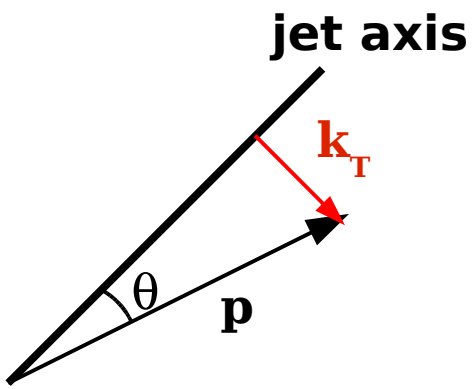
$$Y = \ln\left(\frac{E_{jet}\,\theta_{cone}}{Q_{eff}}\right) = \ln\frac{Q}{Q_{e}}$$

$$C_0(Y) = 1 + \Delta + \ldots$$

} constant offset

Kt distributions

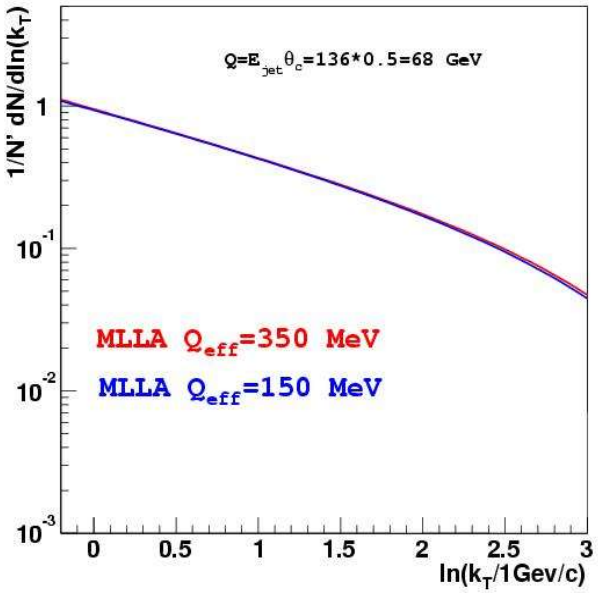
R.Perez-Ramoz & B.Machet (2006)
JHEP 04 (2006) 043

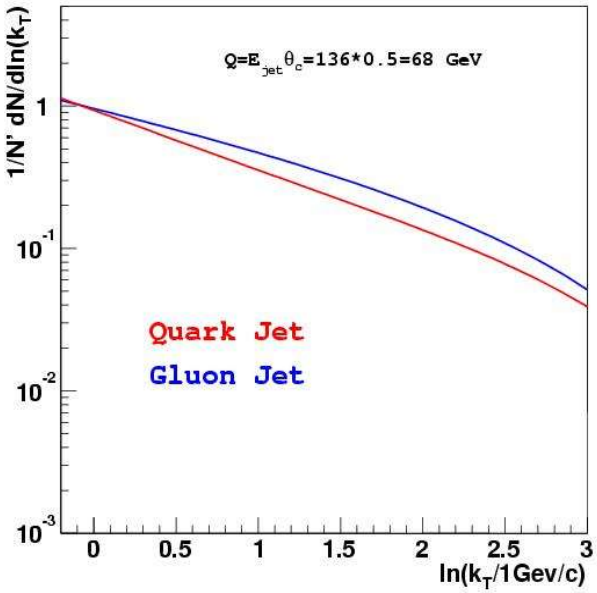


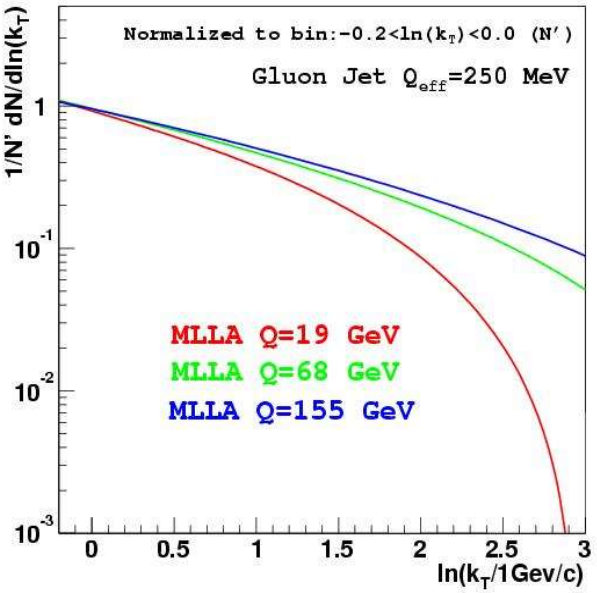
- allows to probe softer particle spectra

$k_T = p \cdot \sin(\theta)$

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

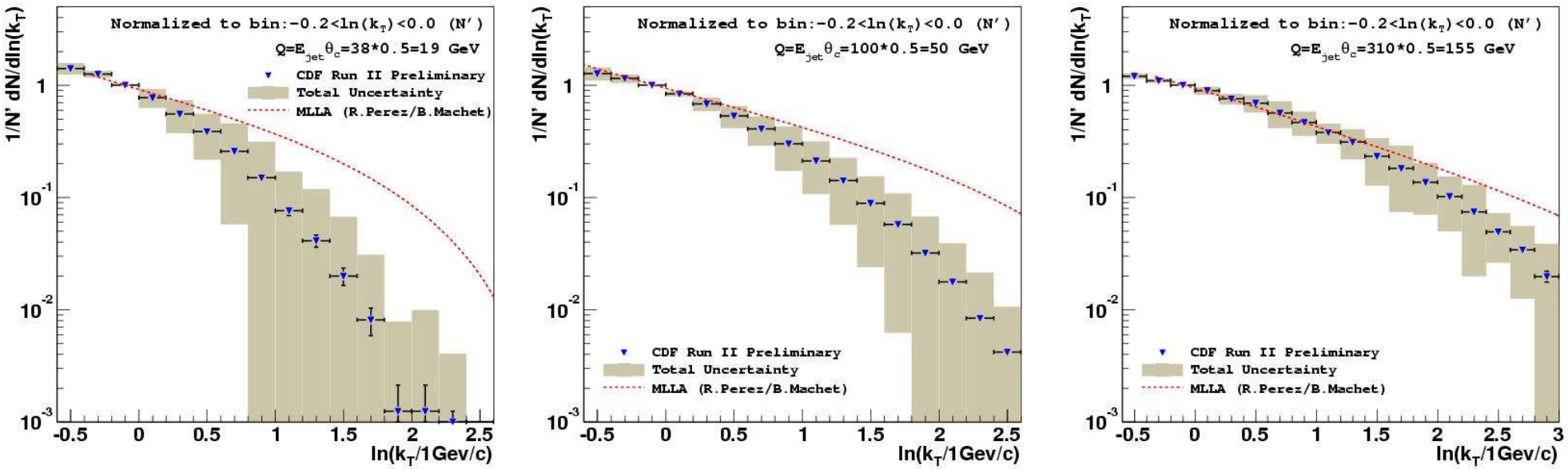






Kt distributions

R.Perez-Ramoz & B.Machet (2006)
JHEP 04 (2006) 043



Soft approximarion: $p/E_{jet} \sim 0.1$

Works well for $y=\ln(k_T/Q_{eff})$ in the range $y<Y-2.5$ → Can get Kt range

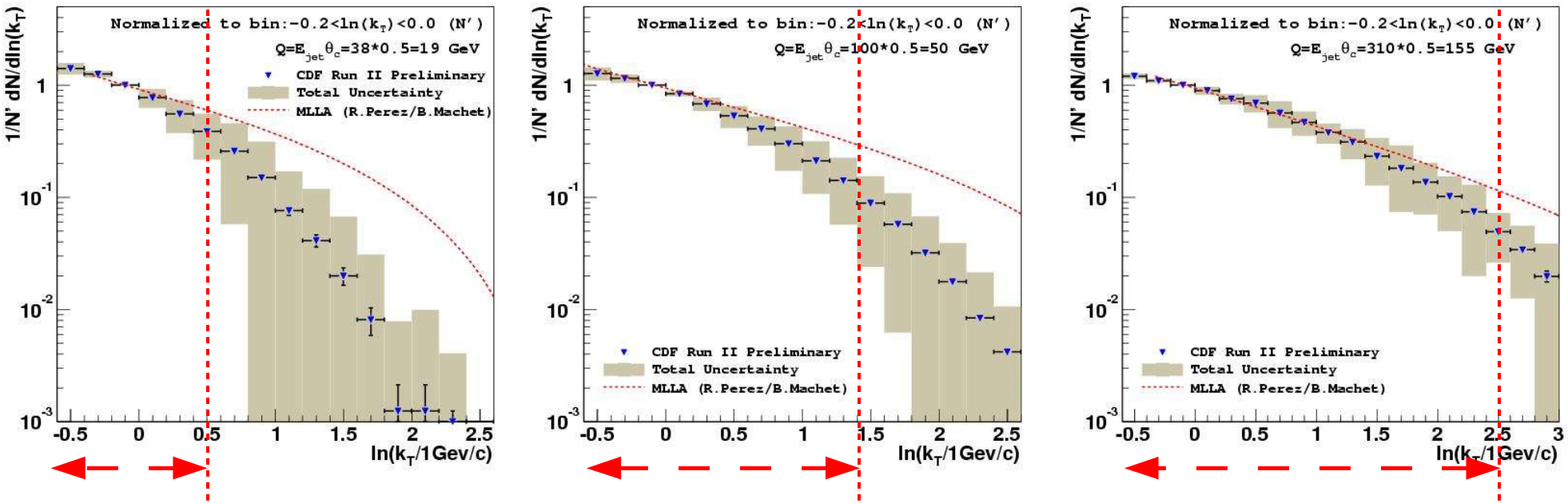
→ Data indicates fewer particles with large k_T

→ Better agreement with increasing Energy scale Q

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

Kt distributions

R.Perez-Ramoz & B.Machet (2006)
JHEP 04 (2006) 043



Soft approximarion: $p/E_{jet} \sim 0.1$

Works well for $y=\ln(k_T/Q_{eff})$ in the range $y<Y-2.5$ → Can get Kt range

→ Data indicates fewer particles with large k_T

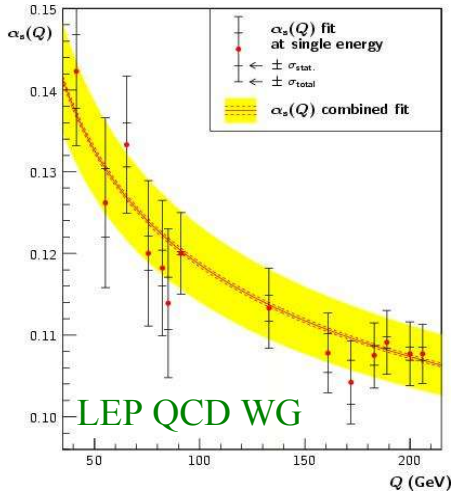
→ Better agreement with increasing Energy scale Q

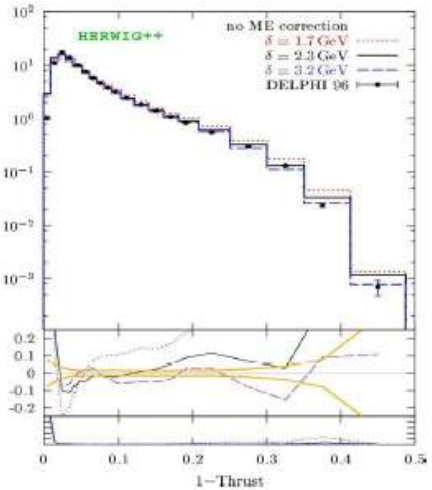
Is this due to an incomplete pQCD or the intervention of Hadronization?

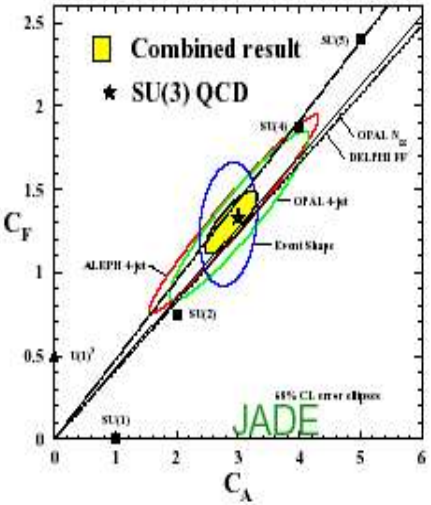
Event Shapes

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

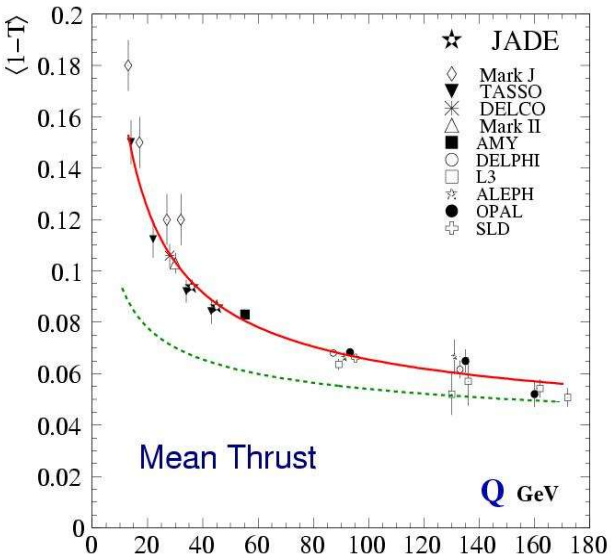
- Measurements of a_s
- Means of tuning MC
- Color Factor Fits

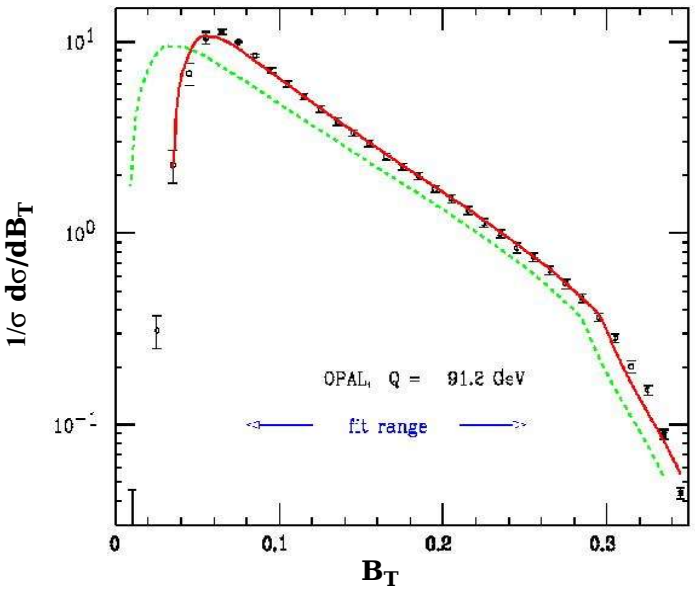


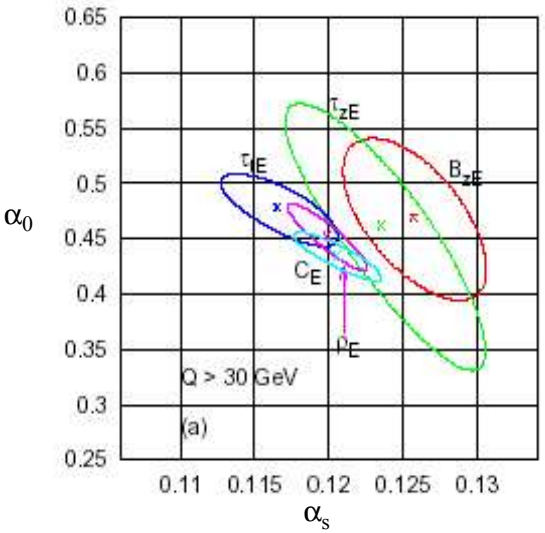




- Analytical non-perturbative QCD corrections (~1/Q)

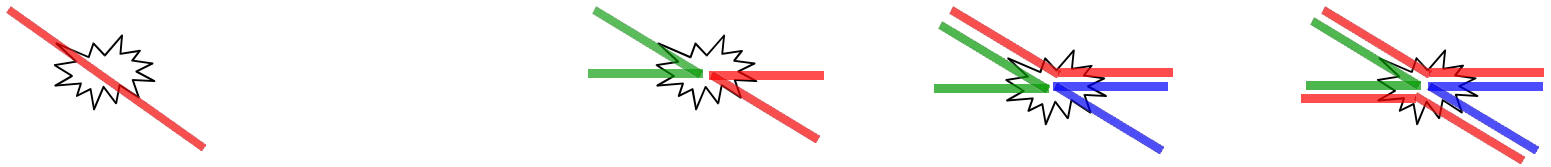






Event Shapes

Event grows from a much richer color structure:

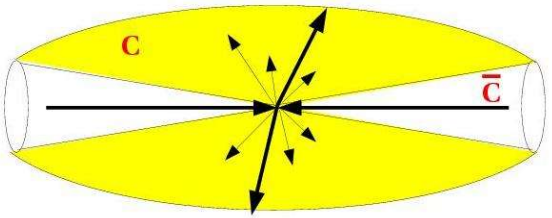


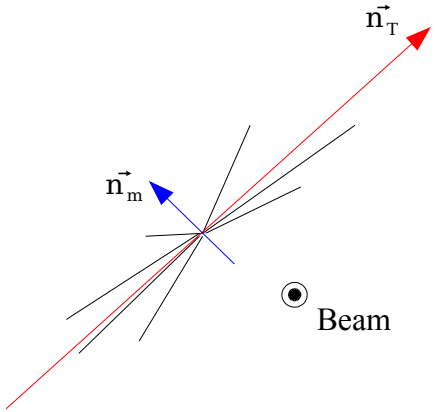
LEP Tevatron

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

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

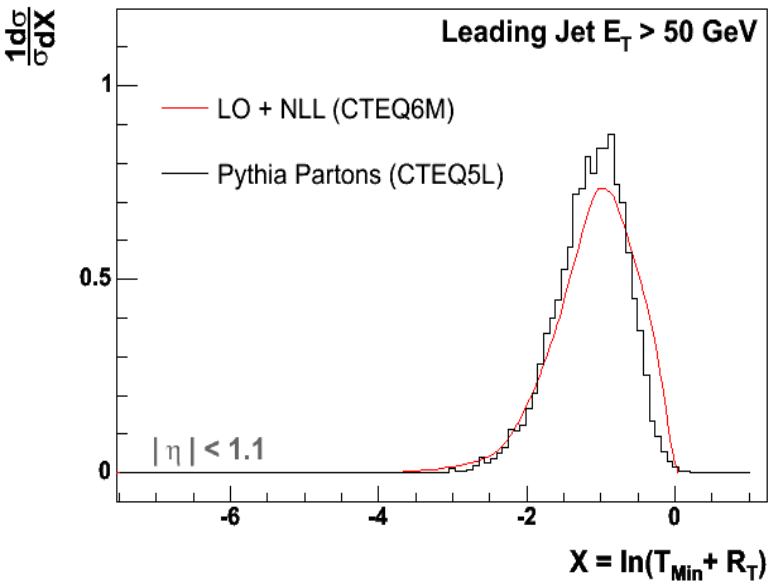
Transverse Thrust Minor

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

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



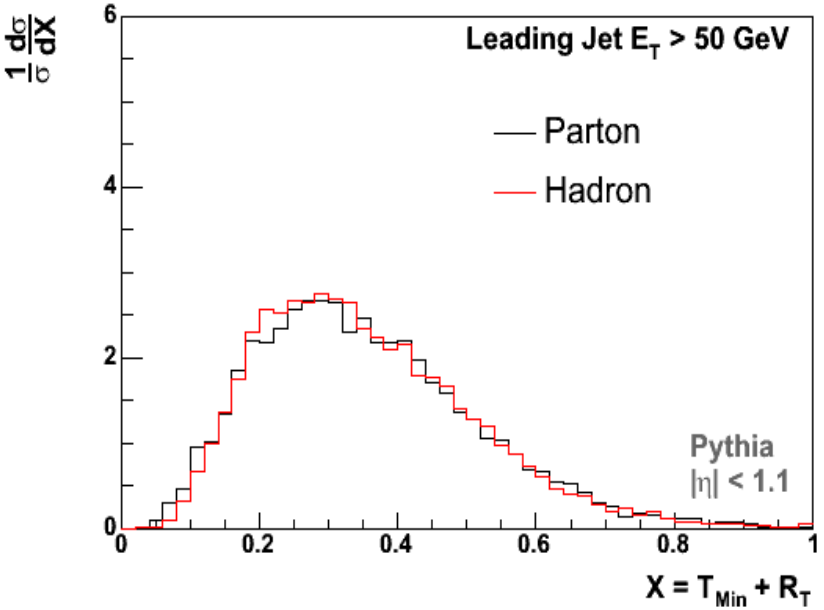
MC at Parton Level in agreement with preliminary analytical pQCD predictions.

MC at Hadron Level in agreement with MC Parton Level:

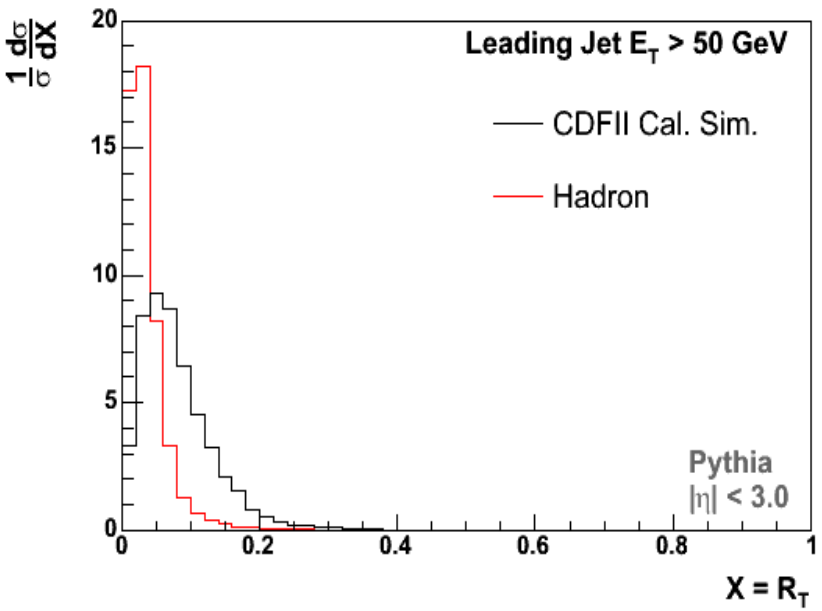
True of T_{Min} and R_T independantly

Strong Correlation between levels too

No shift due to hadronization in the MC



Event Shapes: Detector Effects

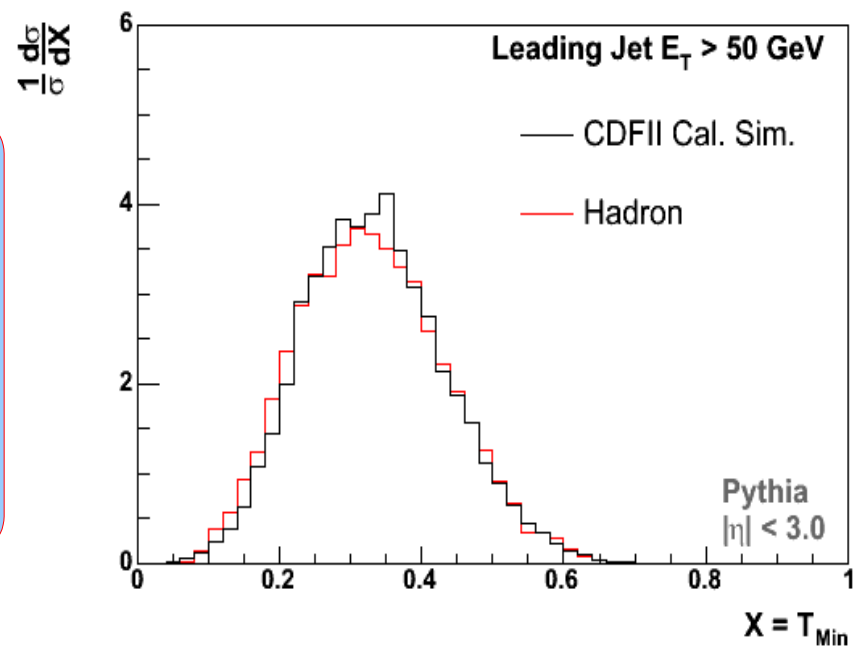


Recoil:

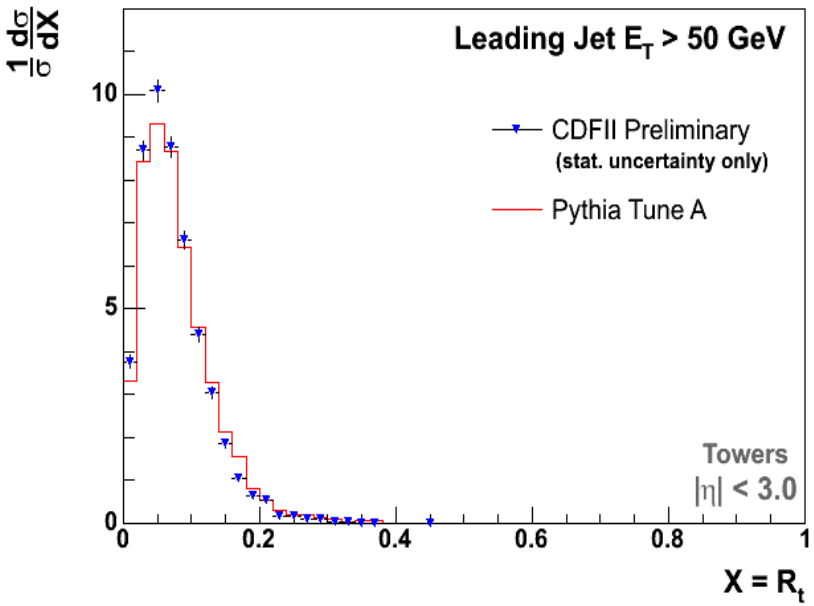
Detector Sim. ≠MC Hadron Level
(instrumental effects to be unfolded)

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

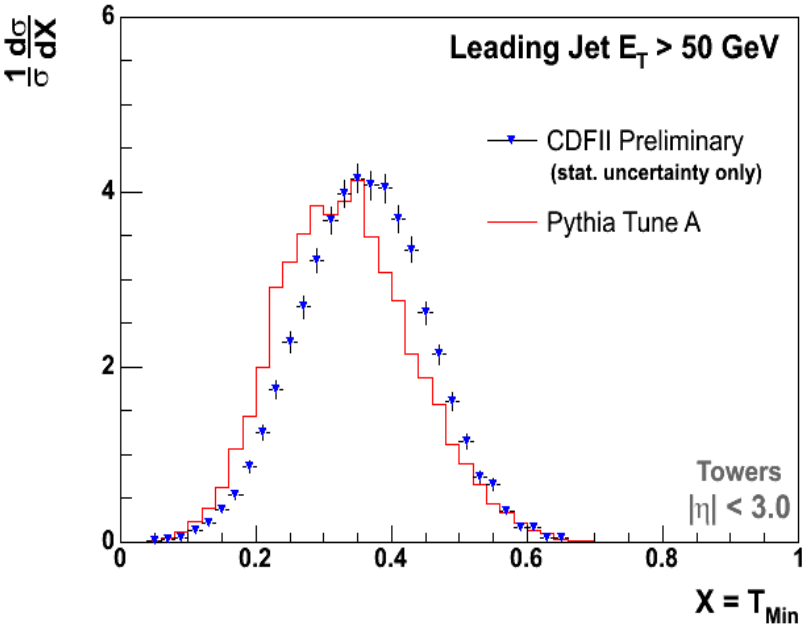


Recoil:

Data = Detector Sim.
No surprises there

Central Event Shapes:

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



Conclusions

Momentum distributions and particle multiplicity in jets:

- Consistent with parton distribution predicted by MLLA;
- Q_{eff}=240±40 MeV over the entire range of dijet masses;
- K_{LPHD}=0.56±0.10 for charged particles;
- Ratio of multiplicities in g/q jets r=1.6±0.2;

Momentum correlations:

- Hadron correlations follow the pattern expected for partons;
- The constant term is smaller than predicted by pQCD...;
- Q_{eff}=140±80 MeV from linear and parabolic terms;

Kt distributions:

- Data at low k_T agrees with theory, but seems to sag at large k_T;
- Discrepancy is smaller for larger Q;

Indirectly global event shapes:

- Data is shifted with respect to Monte Carlo;
- Awaiting theoretical predictions...;
- This branch of studies promises very interesting results;
- Stay tuned for updates;

Hadronization :)

The more we learn, the less the role of phenomenological hadronization in shaping the jet structure seems to be...

Backup

Experimental Features

Measurement:

- Well balanced di-jet events with Mjj ranging 60-600 GeV;
- Jet axis in the central region $|\eta|<0.9$;
- Events with only one vertex;
- Measurement done in the dijet center-of-mass frame;
- Cone jet algorithm with R=1.0;

- Charged particles in the cone with $\theta_c=0.5$;
- Unfold the small underlying event contribution;
- Remove secondaries (conversions, ...)

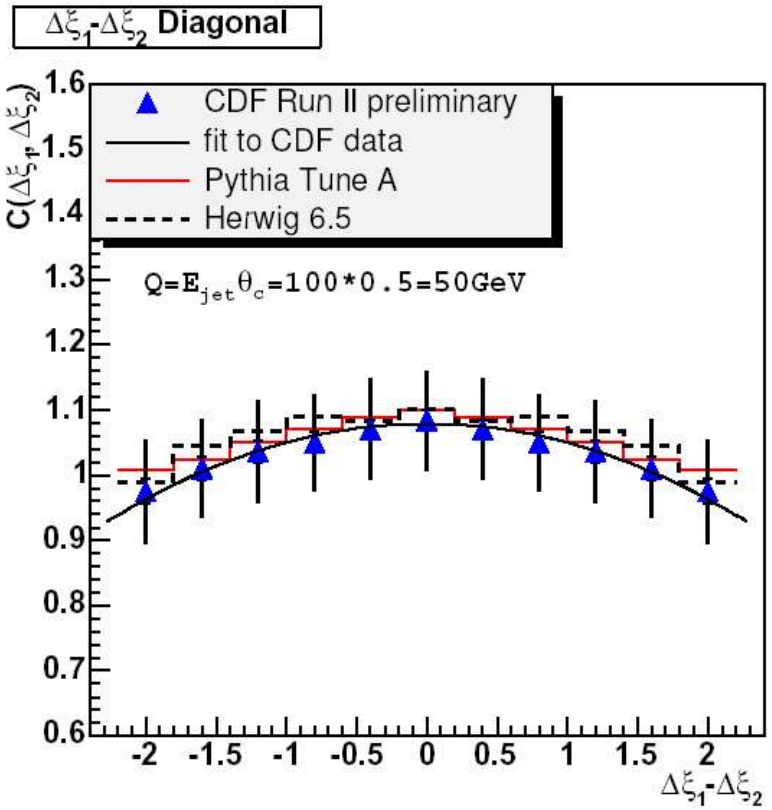
Theory(to make compare to data):

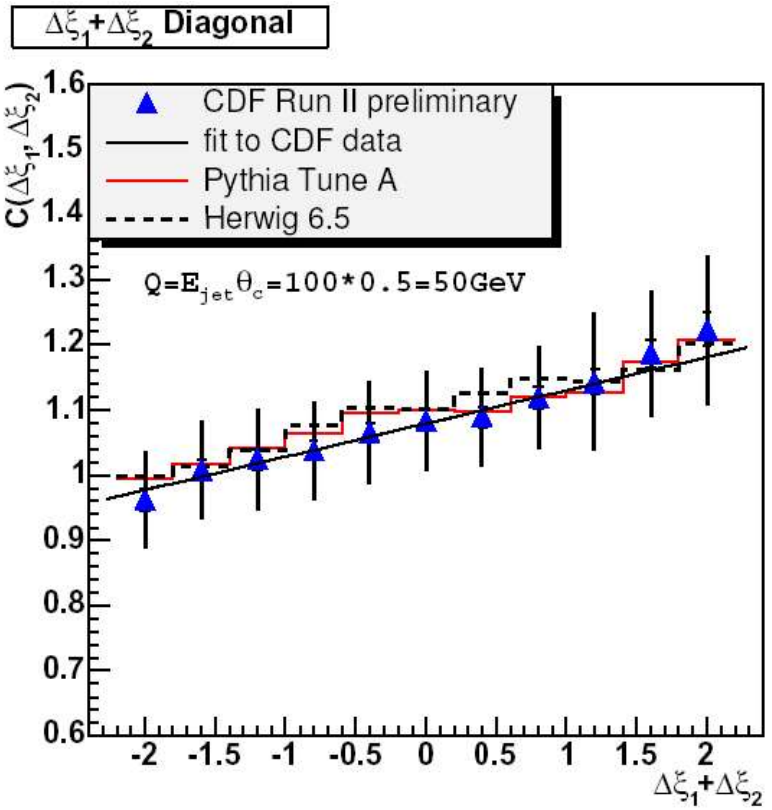
- produce correlation function for a mixture of quark and gluon jets;
- get fraction of gluon jets in the sample from Pythia Tune A Monte-Carlo;

Correlation Data-MC

Pythia Tune A and Herwig 6.5

- Both MC generators reproduce correlation in data fairly well;





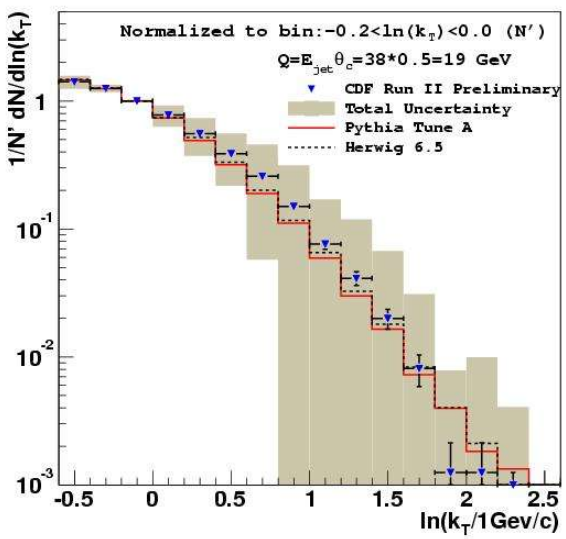
Kt Data-MC

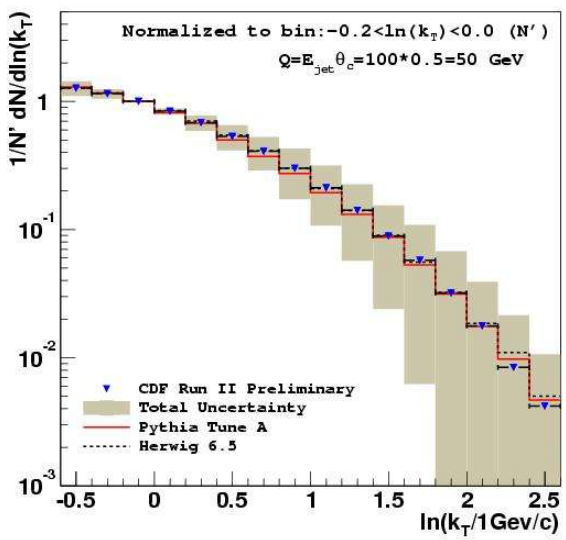
Pythia and Herwig (Hadron level) in agreement with Data over the full range of k_T

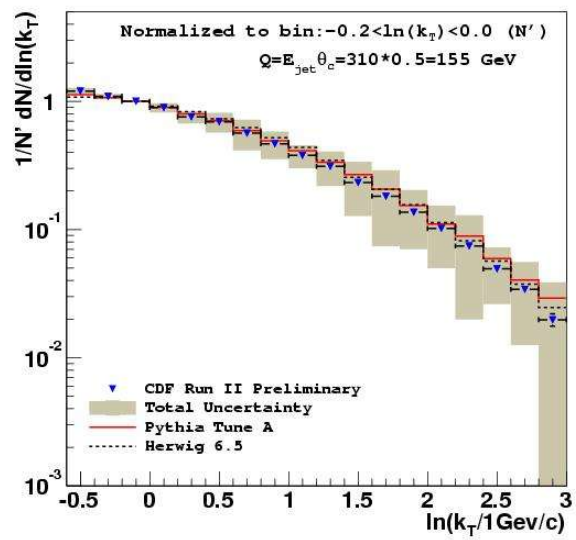
Where is the discrepancy coming from?

MLLA $\rightarrow$ Next-to-Leading Log

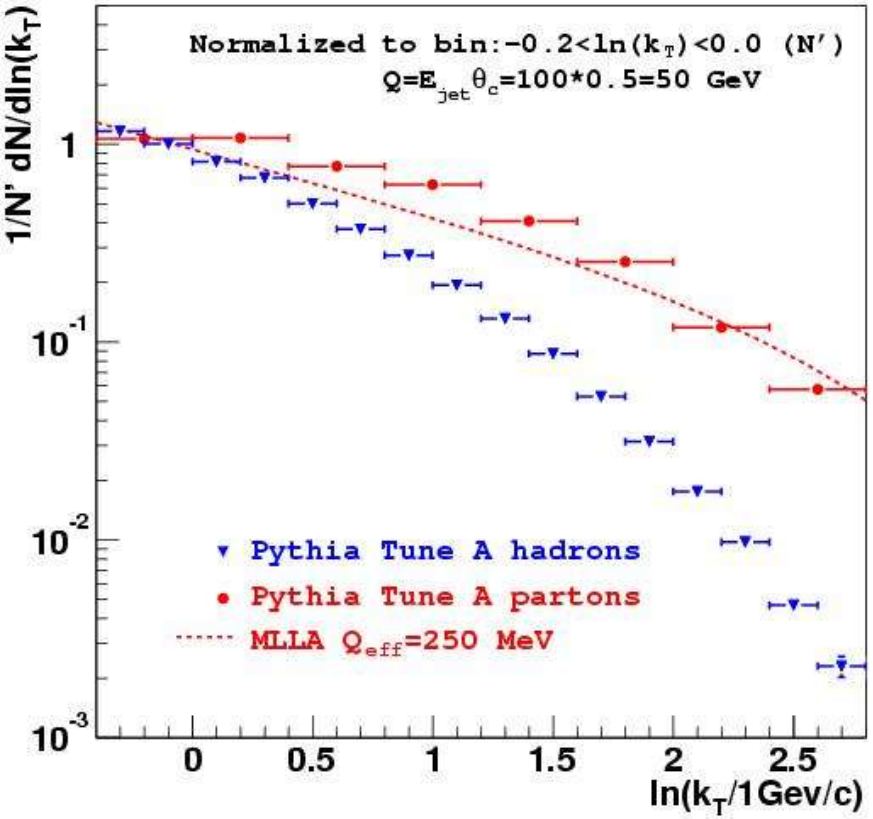
Pythia $\rightarrow$ Leading Log + Energy conservation







Kt Data-MC



Pythia Partons follow MLLA

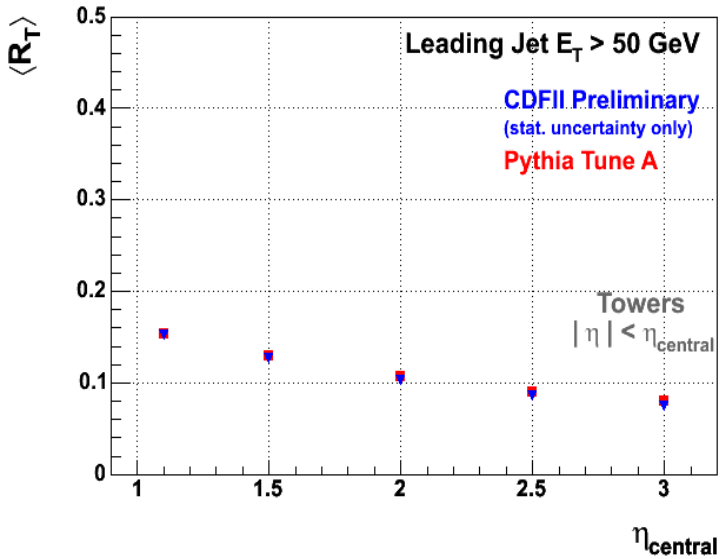
↓

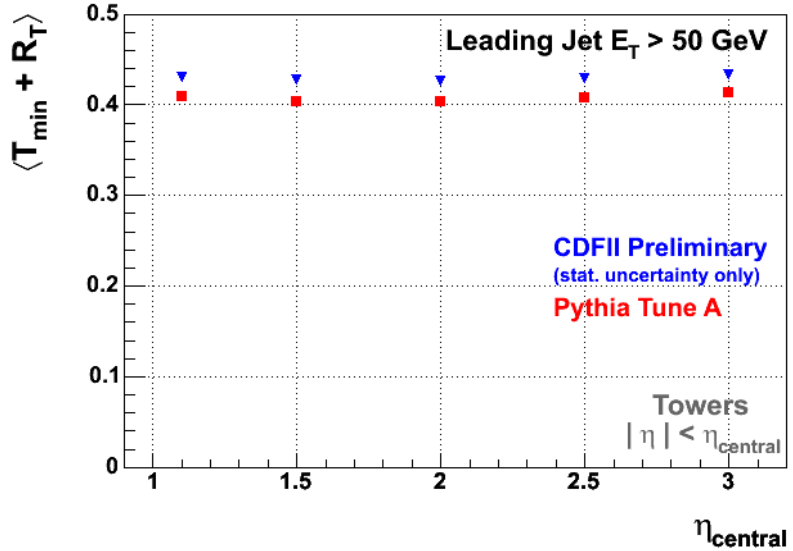
Doesn't look like it's Energy conservation

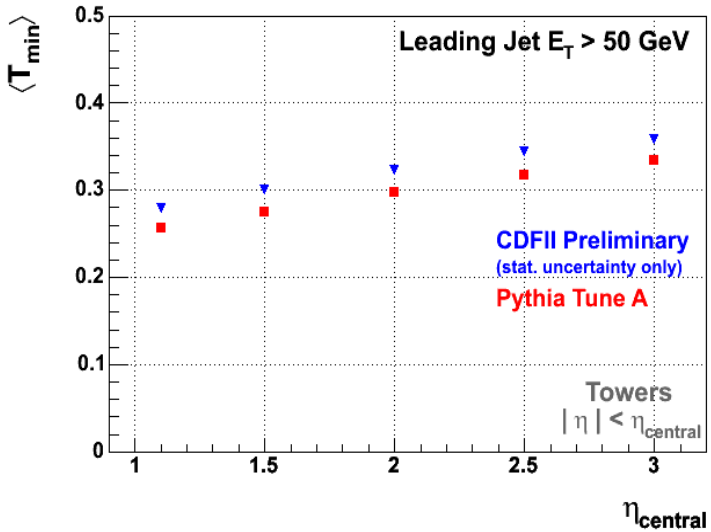
↓

Hadronization???

Event Shapes







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