Soft QCD and the underlying event

Sergo Jindariani

for CDF collaboration

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Outline

→ **Recent jet fragmentation studies:**

Jet shapes and b-jet shapes

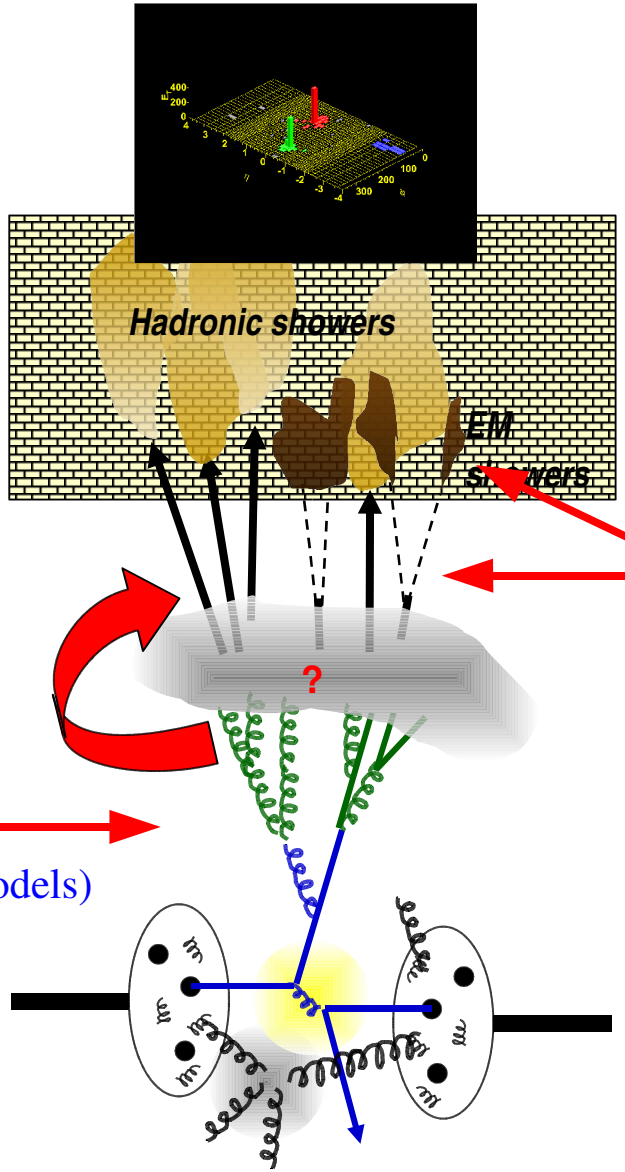
Two-particle momentum correlation of particles in jets

k_T-distributions of particles in jets

Global event shapes (analysis in progress)

→ **Underlying event studies**

Partons, Hadrons, Jets



Data:
- tracks and calorimeter towers;

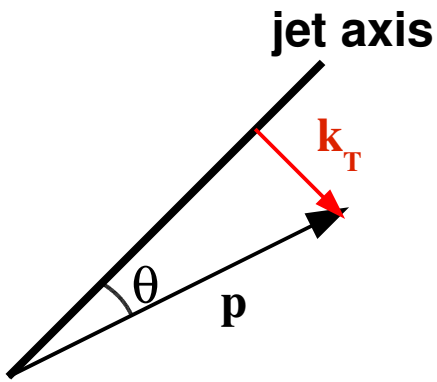
Theory: -
partons (+ hadronization models)

Monte-Carlo: - all levels
(partons, hadrons, detector simulation)

K_T distributions

MLLA: R.Perez-Ramos & B.Machet (2006)
JHEP 04 (2006) 043

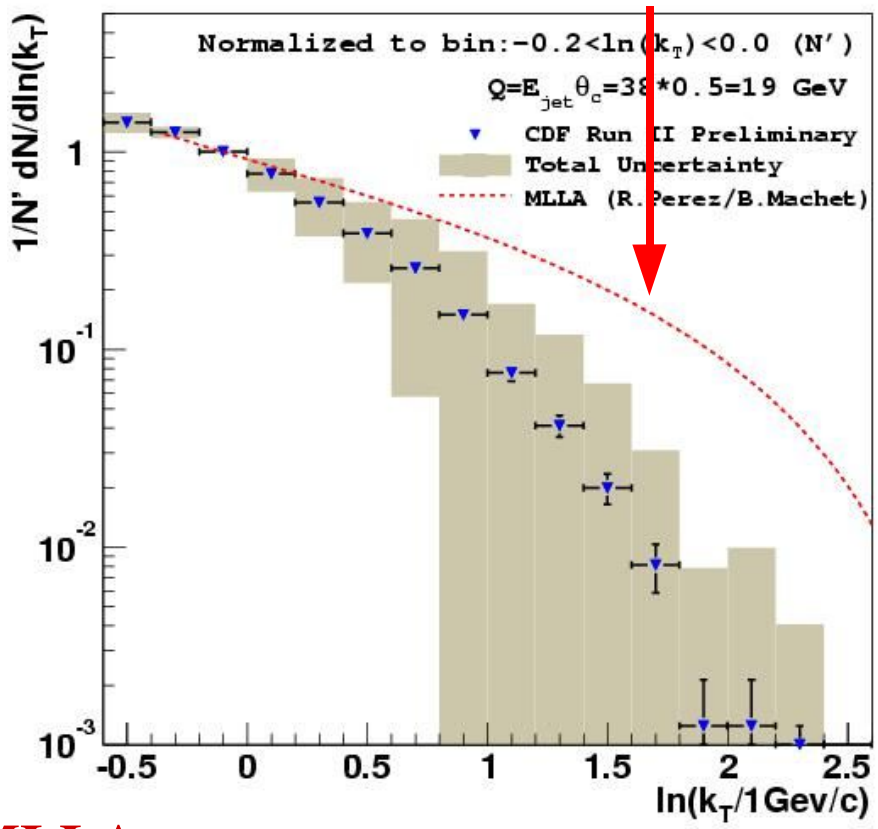
- recent theoretical work;
- allows to probe soft particle spectra;



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

➢ **In data particles in small angle θ_c=0.5 rad around jet axis are counted**

parameter free (no dep. on Qeff, q/g,...)



MLLA:

→ data indicates fewer particles with large k_T

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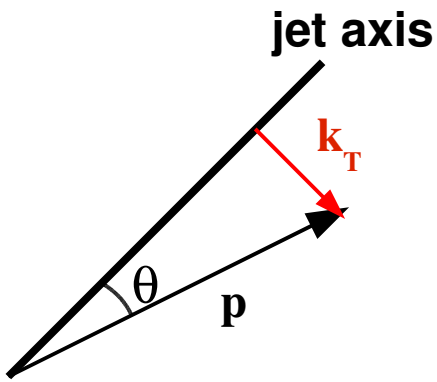

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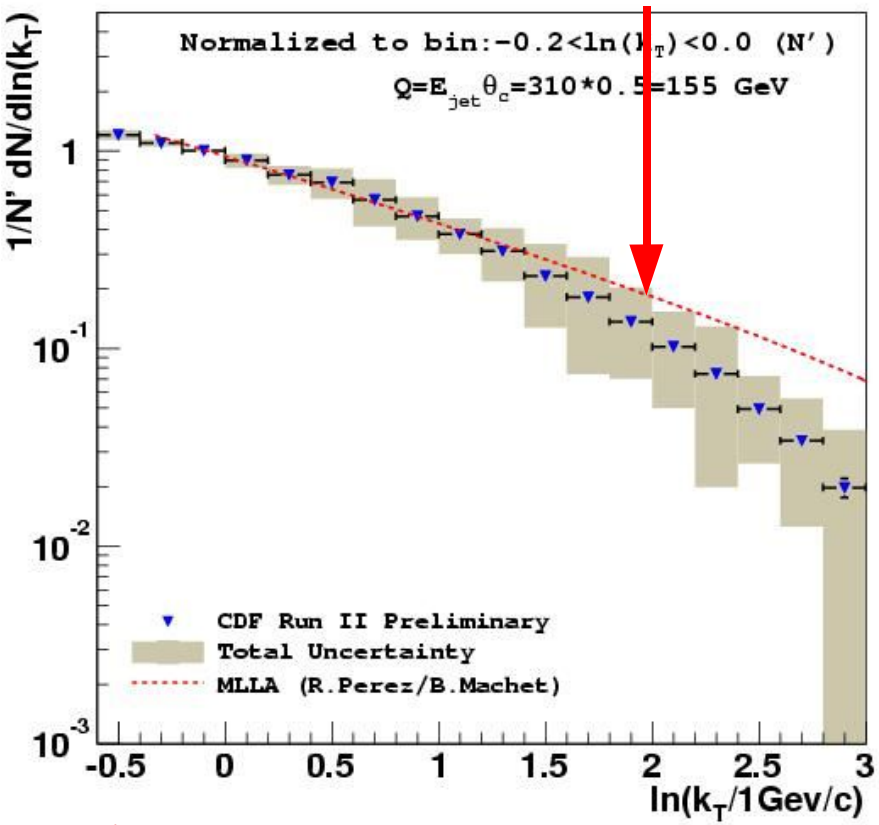

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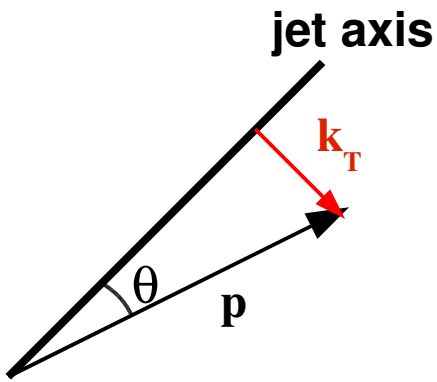

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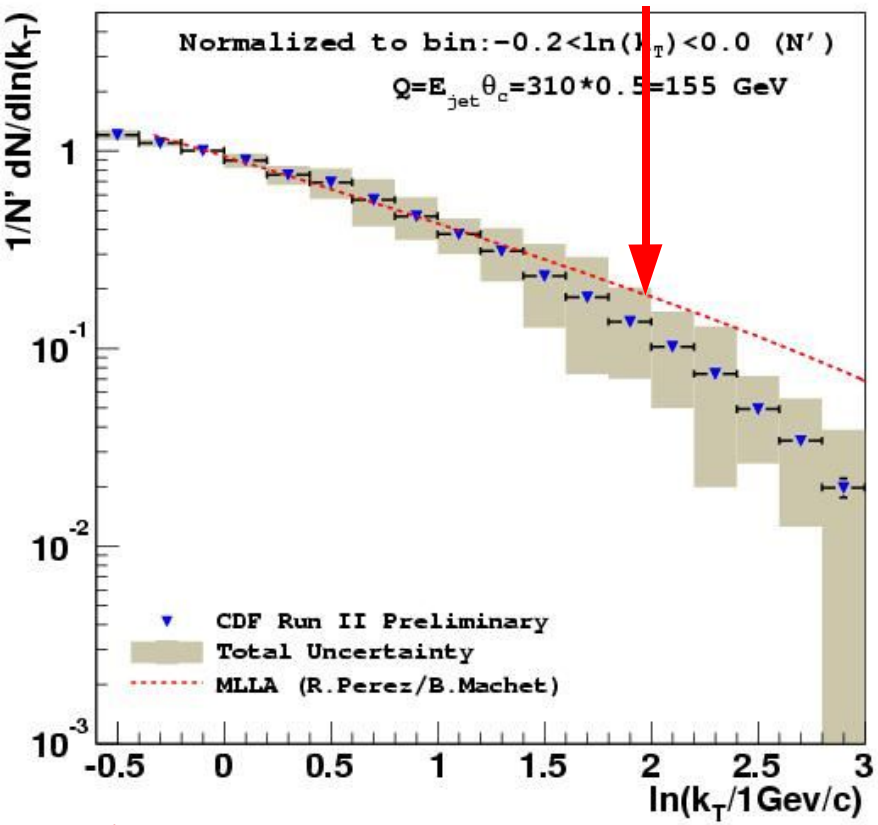

MLLA:

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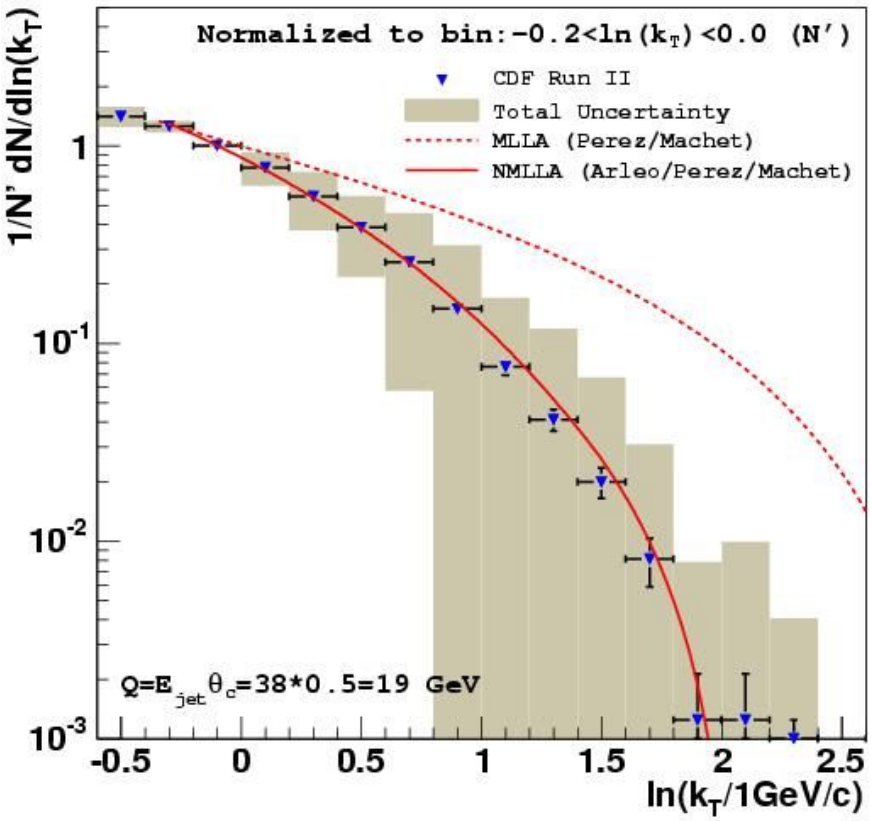
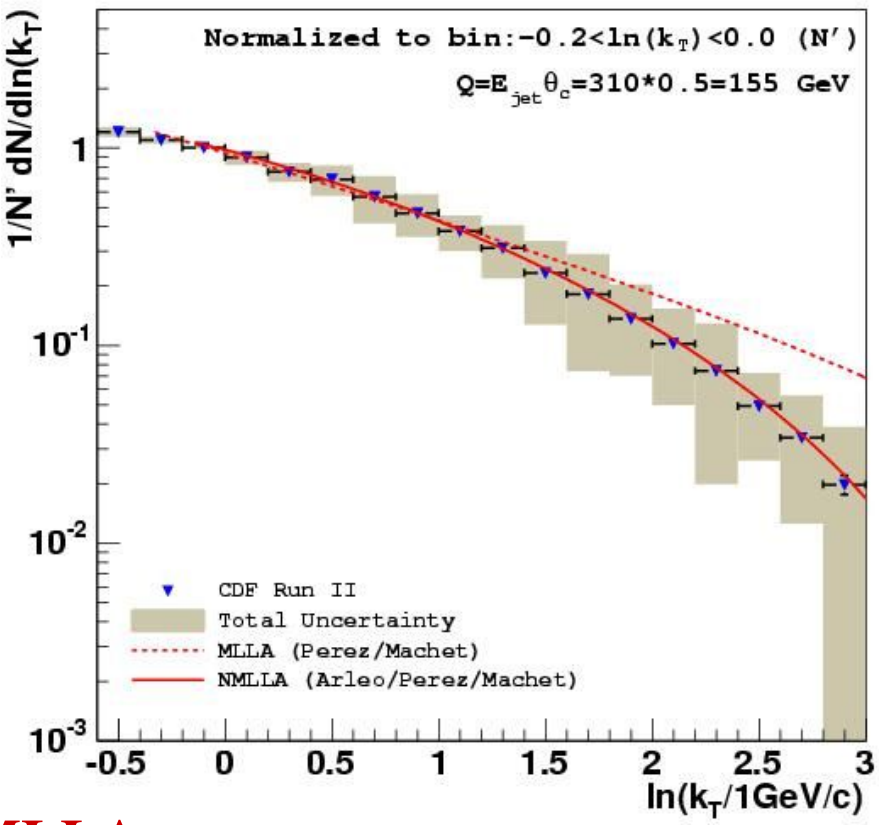
Let's bring NMLLA

K_T distributions

NMLLA: Arleo/Perez-Ramos/Machet(2007) **In preparation for publication**





MLLA:

→ data indicates fewer particles with large k_T

→ better agreement with increasing Energy scale Q

NMLLA:

→ very good agreement with the data at all Q's

K_T distributions

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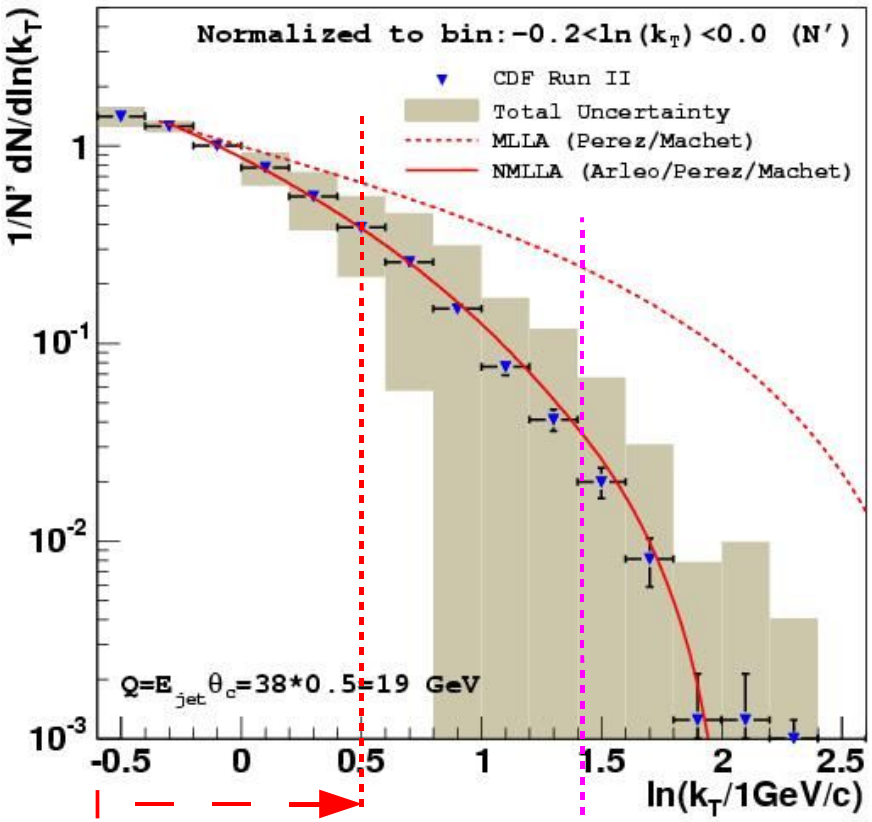
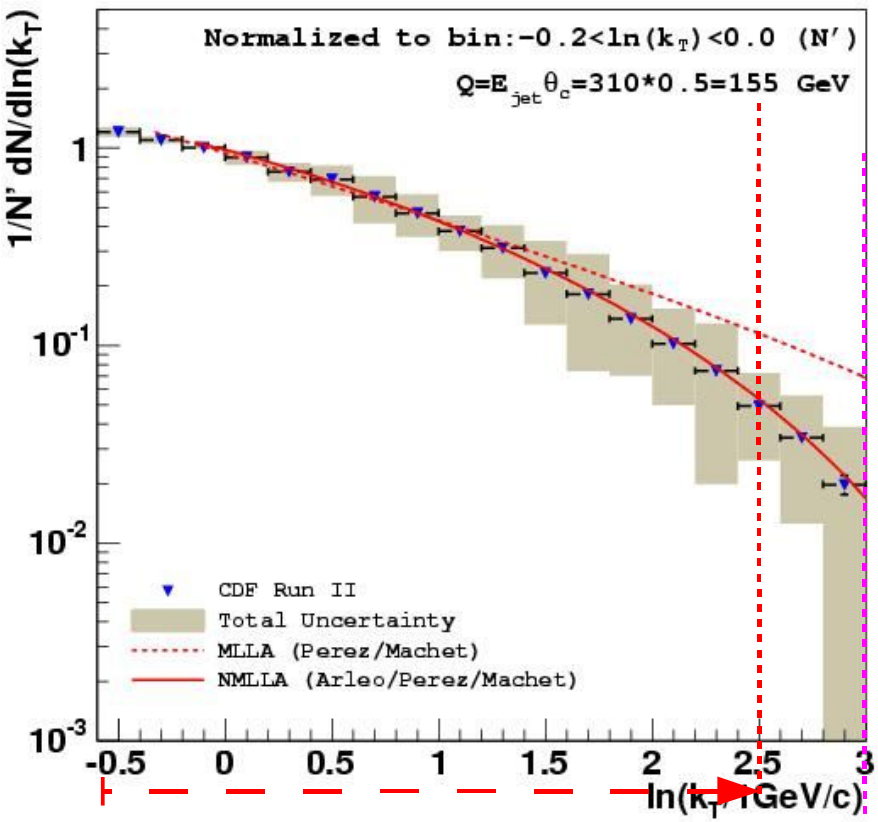




MLLA

NMLLA

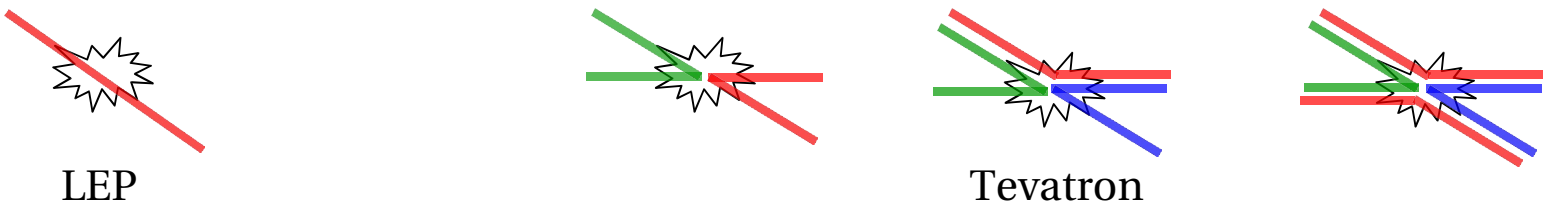
reminder: $Y=\ln(E_{jet}\theta_c/Q_{eff})$

→ The validity range of the pQCD predictions increases from MLLA to NMLLA :

- MLLA works for $y=\ln(k_T/Q_{eff})$ in the range $y<Y-2.5$
- NMLLA works for $y=\ln(k_T/Q_{eff})$ in the range $y<Y-1.6$

Event Shapes

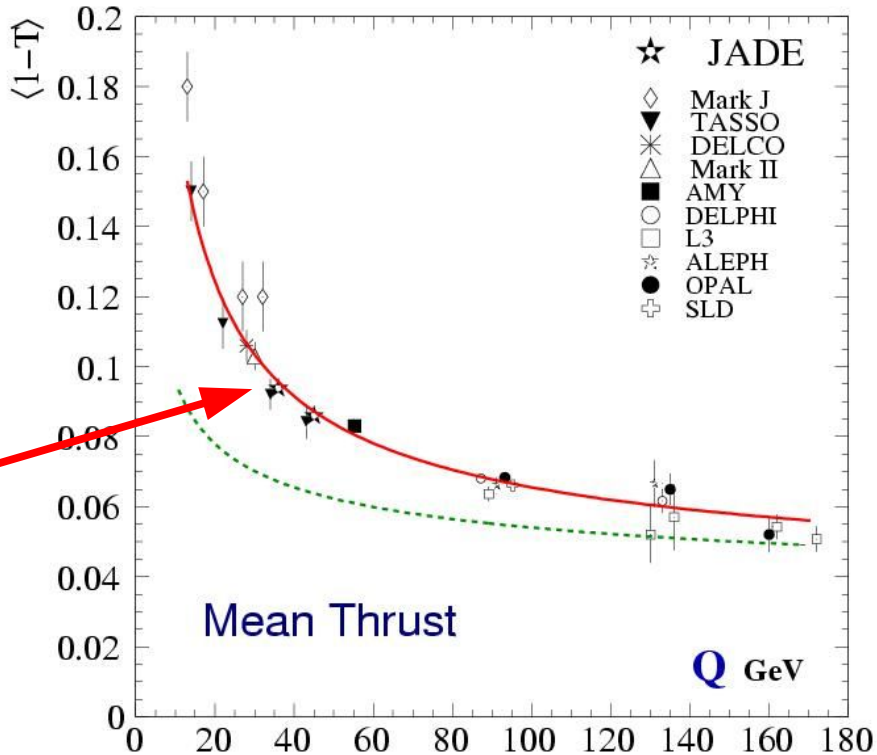
Event grows from a much richer color structure:



Event shapes describe the energy flow in the event.

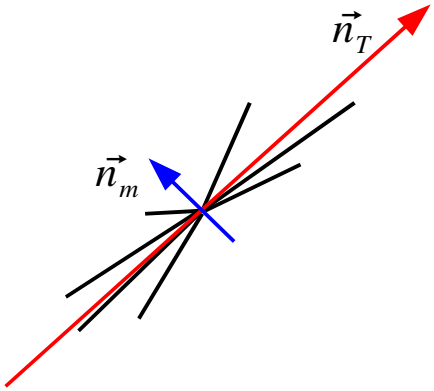
Allow to study:

- soft pQCD;
- analytical non-pQCD corrections;
- underlying event;



Event Shapes

Theory: A.Banfi, G. Salam, G. Zanderighi JHEP 0408:062 (2004)



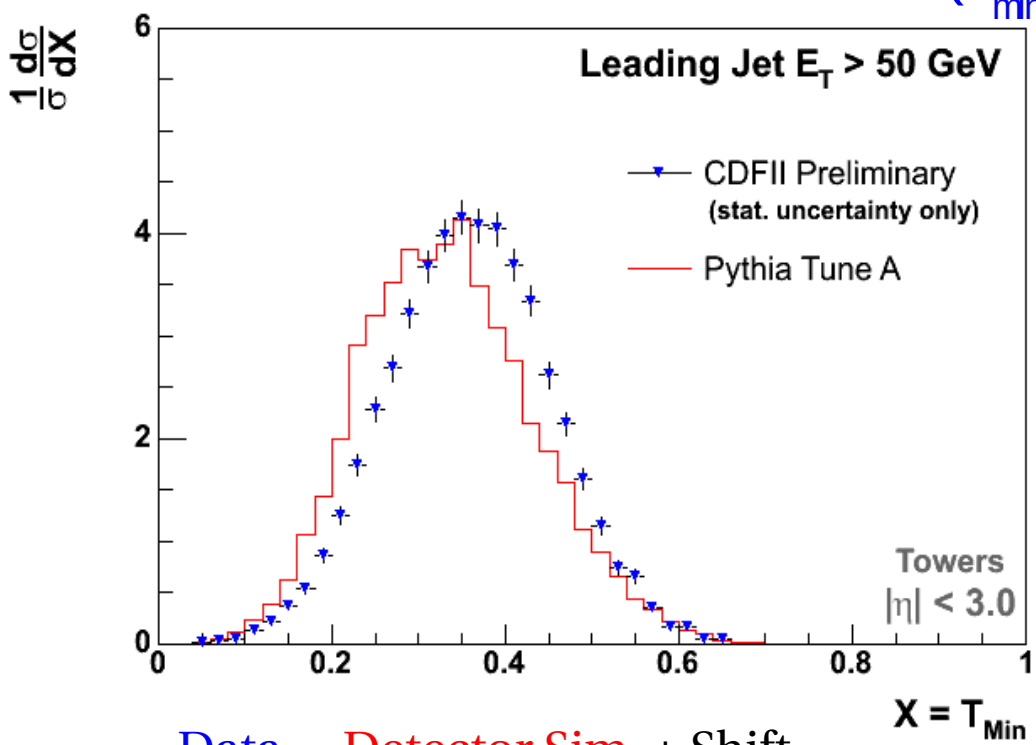
Transverse Thrust

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

Transverse Thrust Minor

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

Thrust Minor (T_{min}):



Data ≈ Detector Sim. + Shift

Is this real or due to some instrumental effects?

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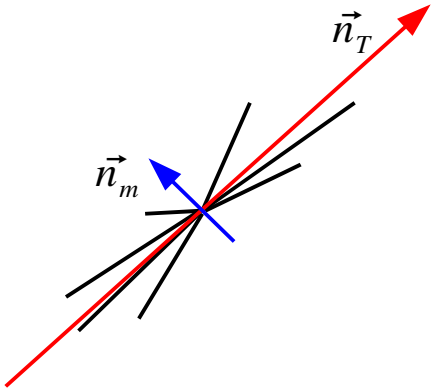

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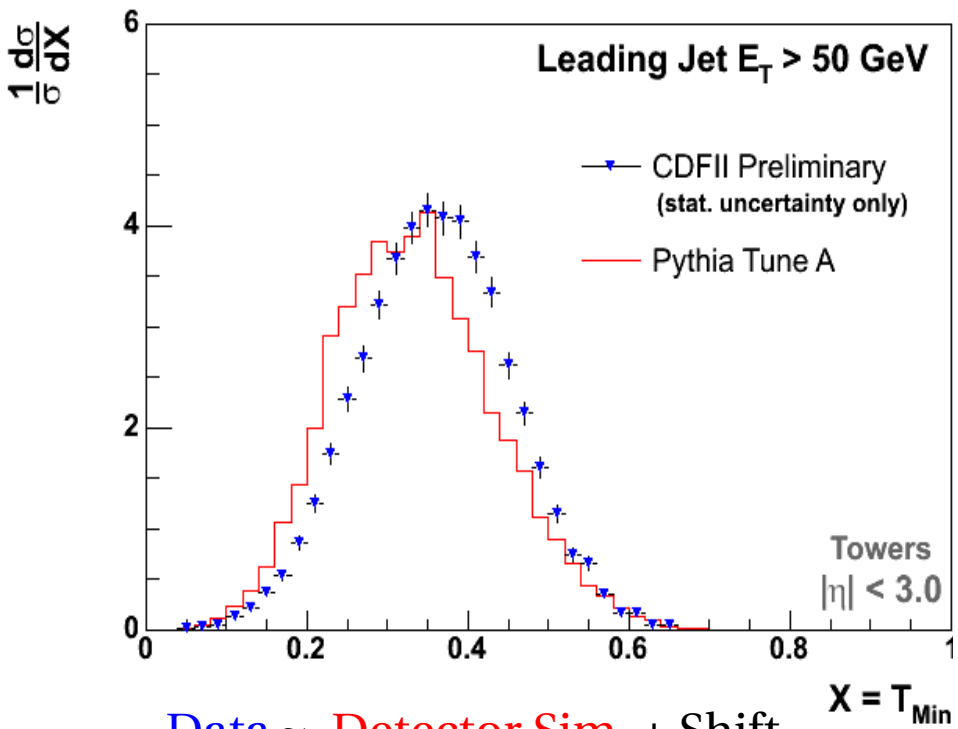

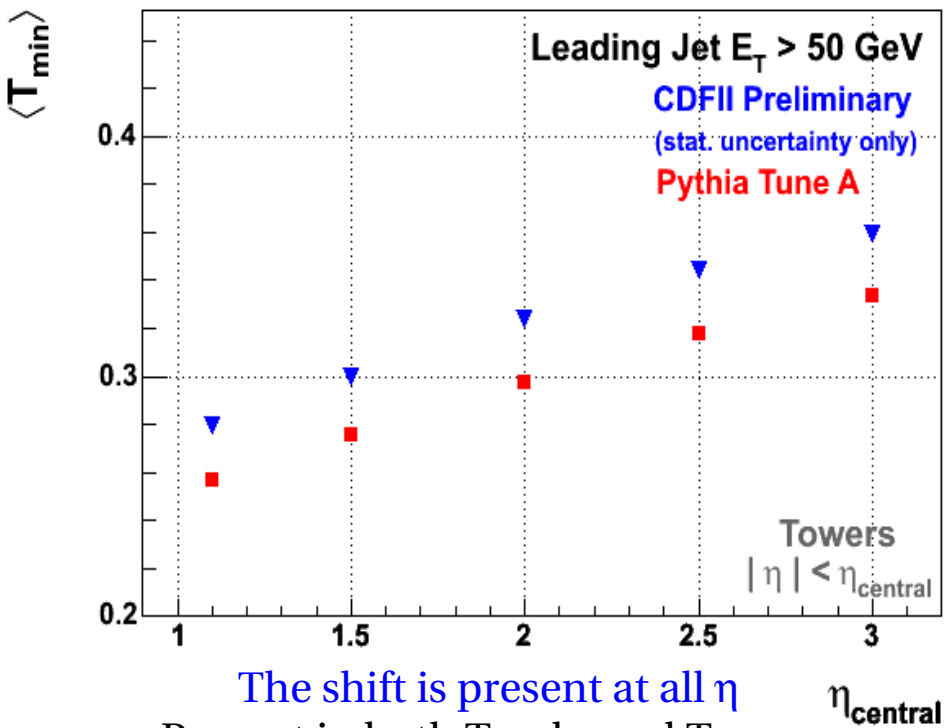

Data ≈ Detector Sim. + Shift

The shift is present at all η

Present in both Tracks and Towers.

Event Shapes

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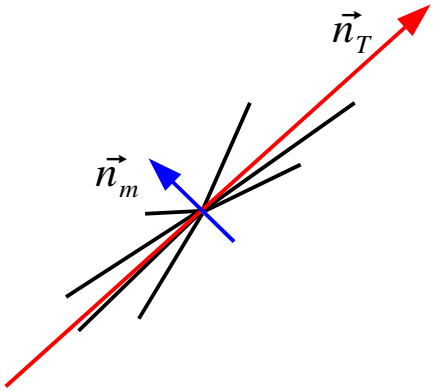

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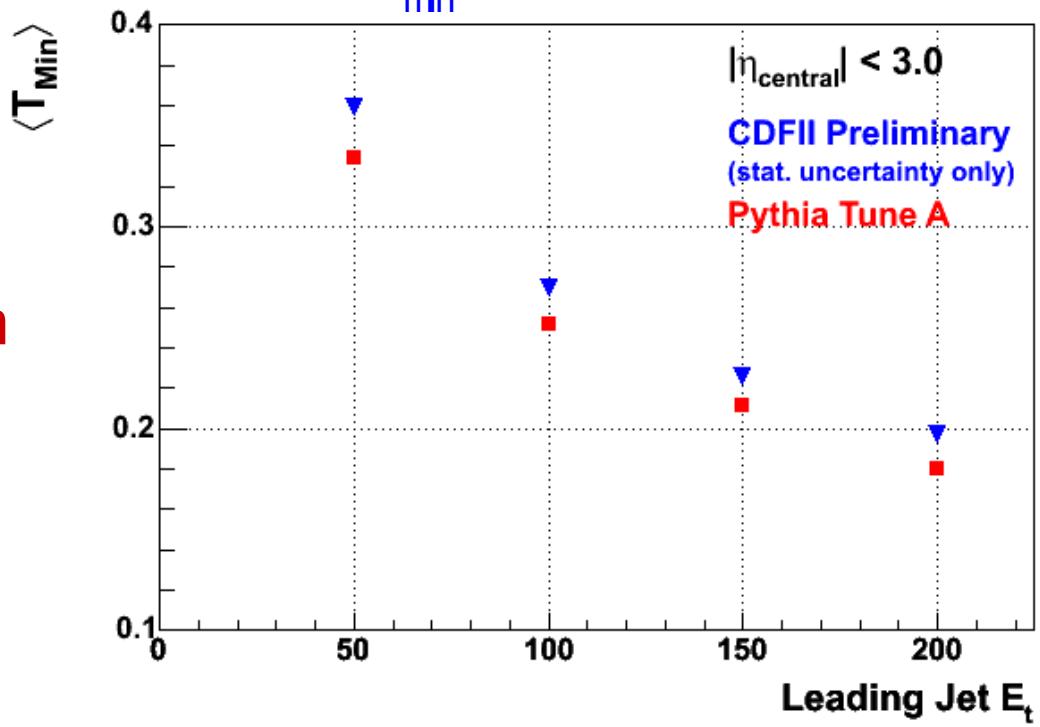
Thrust Minor (T_{min}):

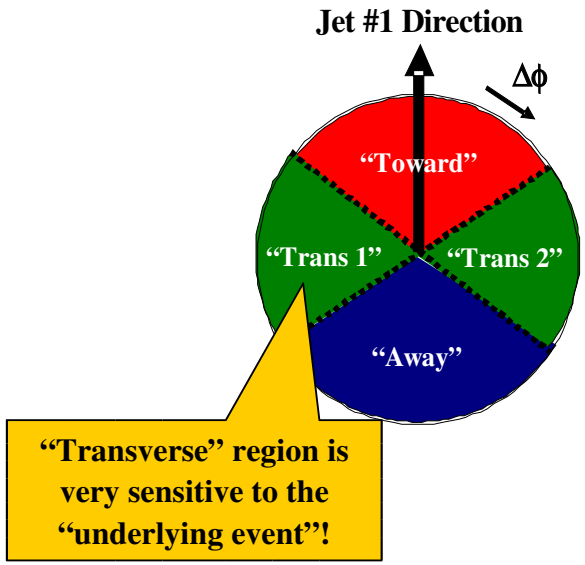
How does T_{min} scale with energy?

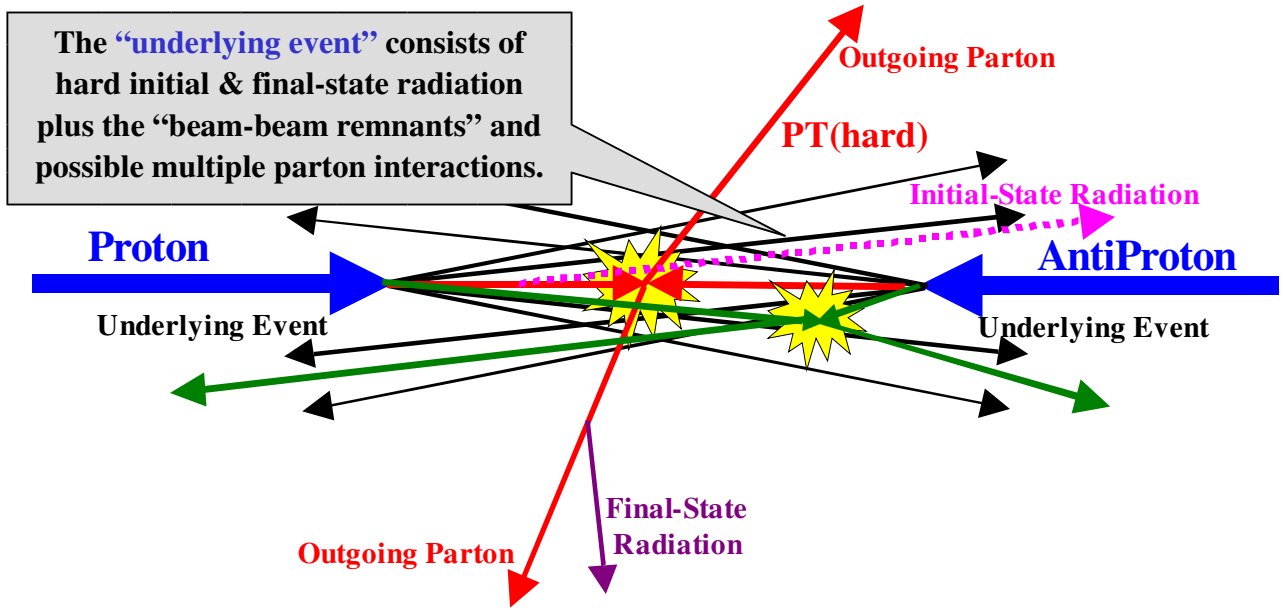


Is this non-pQCD? ...Still awaiting theoretical predictions!

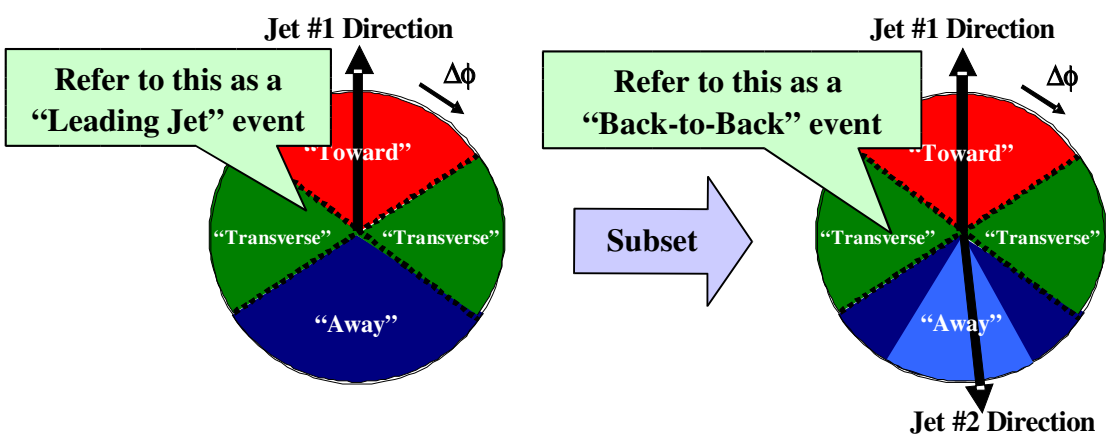
Underlying Event

- Construct observables sensitive to the "underlying event" and compare CDF data to Monte Carlo with different tunings.





→ **Two Classes of Events:** "Leading Jet" and "Back-to-Back"



- Look at charged particle correlations in the azimuthal angle $\Delta\phi$ relative to the leading calorimeter jet.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < -\Delta\phi < 120^o$ and $60^o < \Delta\phi < 120^o$ as "Transverse 1" and "Transverse 2", and $|\Delta\phi| > 120^o$ as "Away".
- Data Corrected to the Particle Level

Underlying Event

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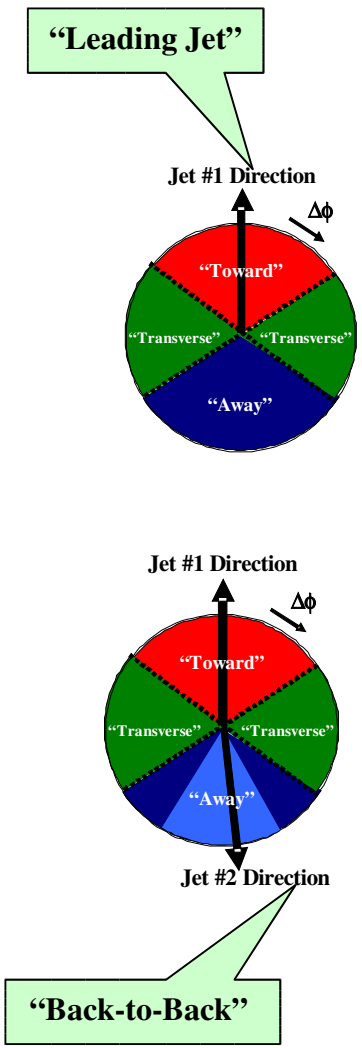
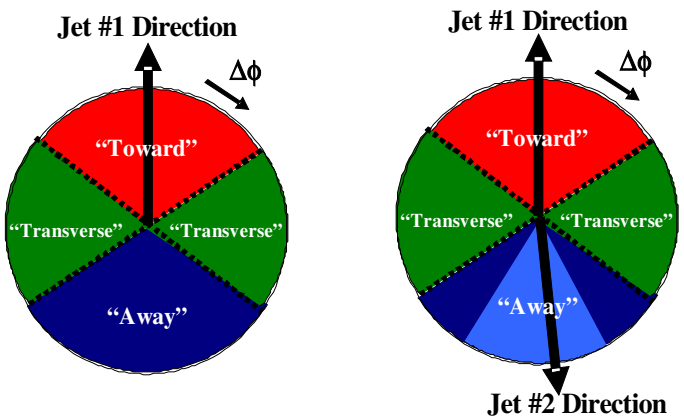
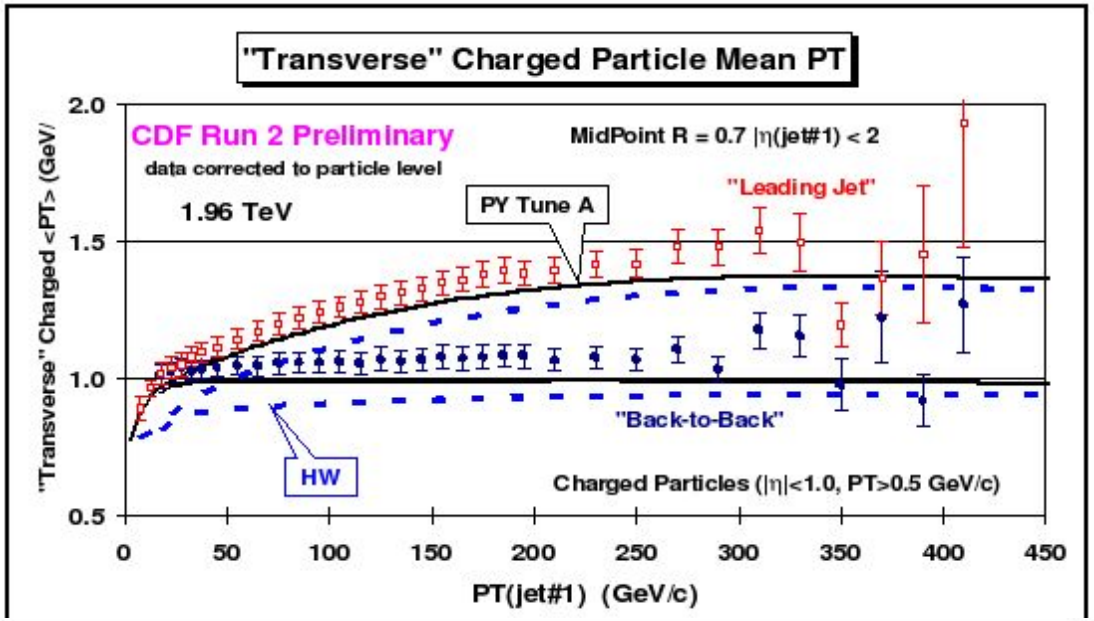
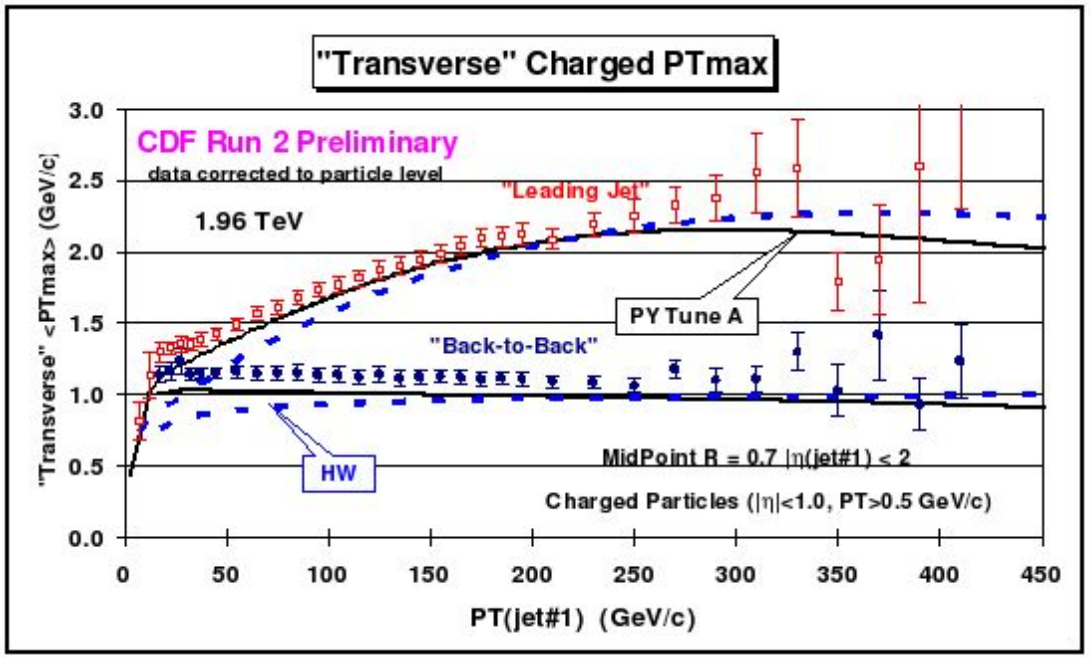


Observable	Particle Level	Detector Level
$dN_{chg}/d\eta d\phi$	Number of charged particles per unit η-ϕ ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$)	Number of "good" charged tracks per unit η-ϕ ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$)
$dPT_{sum}/d\eta d\phi$	Scalar p_T sum of charged particles per unit η-ϕ ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$)	Scalar p_T sum of "good" charged tracks per unit η-ϕ ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$)
$\langle p_T \rangle$	Average p_T of charged particles ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$)	Average p_T of "good" charged tracks ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$)
PT_{max}	Maximum p_T charged particle ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$) $PT_{max} = 0$ for no charged particle	Maximum p_T "good" charged tracks ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$) $PT_{max} = 0$ for no "good" charged track
$dET_{sum}/d\eta d\phi$	Scalar E_T sum of all particles per unit η-ϕ (all p_T, $\lvert\eta\rvert < 1$)	Scalar E_T sum of all calorimeter towers per unit η-ϕ ($E_T > 0.1$ GeV, $\lvert\eta\rvert < 1$)
PT_{sum}/ET_{sum}	Scalar p_T sum of charged particles ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$) divided by the scalar E_T sum of all particles (all p_T, $\lvert\eta\rvert < 1$)	Scalar p_T sum of "good" charged tracks ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$) divided by the scalar E_T sum of calorimeter towers ($E_T > 0.1$ GeV, $\lvert\eta\rvert < 1$)

Underlying Event



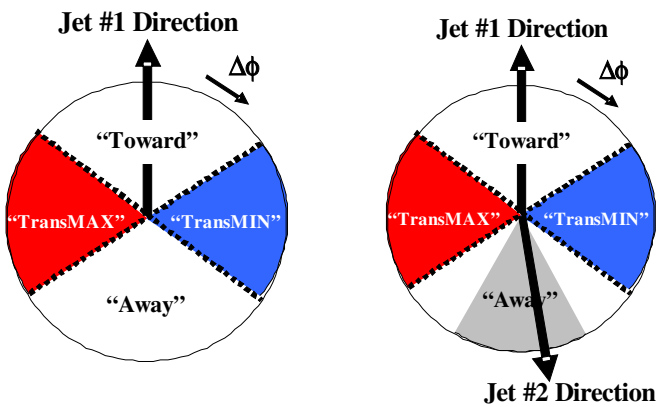


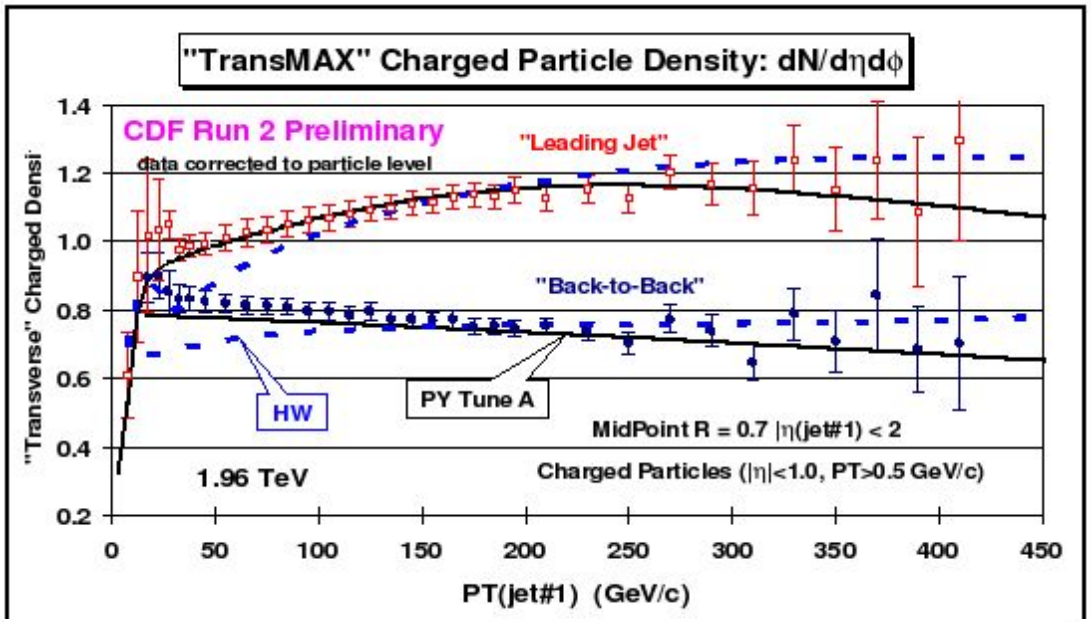


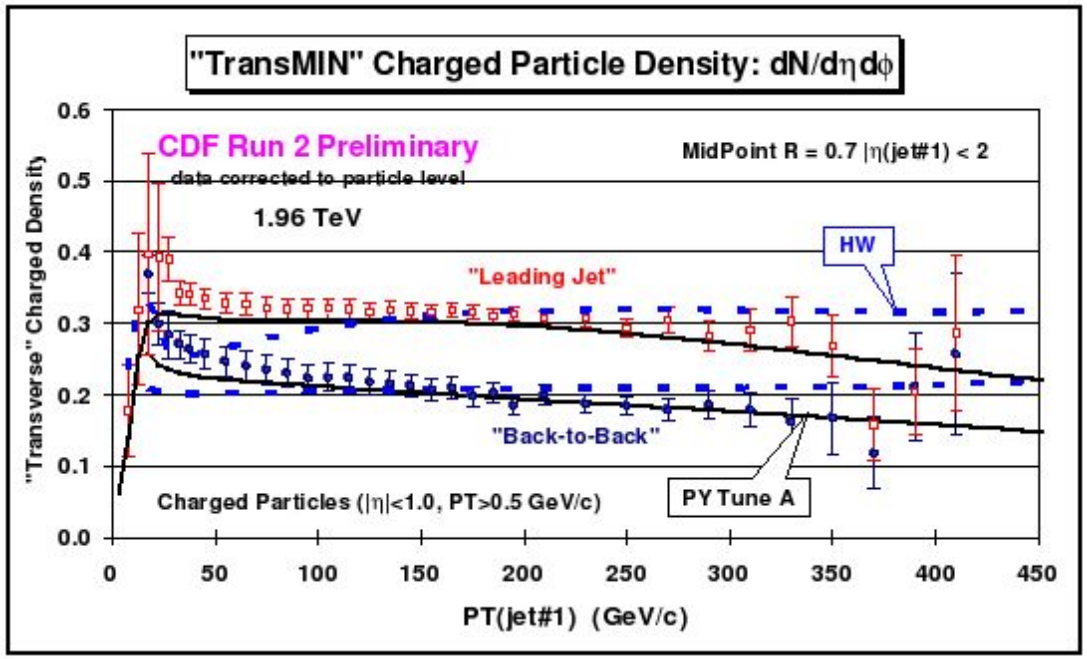
- Shows the average transverse momentum, $\langle P_T \rangle$, and $\langle PTmax \rangle$ for charged particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) and HERWIG (without MPI) at the particle level.

Underlying Event

Pythia Tune A vs. Herwig







- Shows the charged particle density, $dN_{chg}/d\eta d\phi$, in the "transMAX" and "transMIN" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
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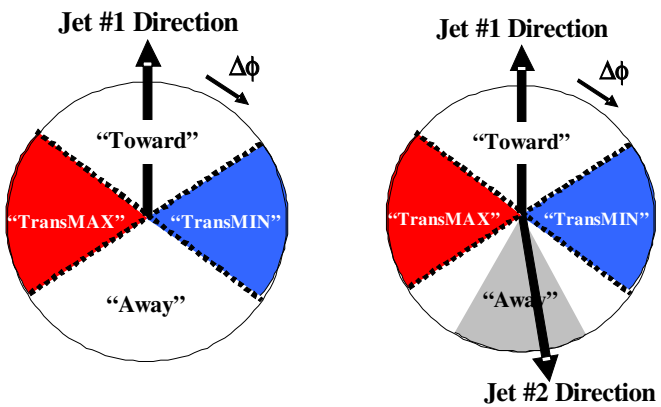
Underlying Event

Pythia Tune A vs. JIMMY



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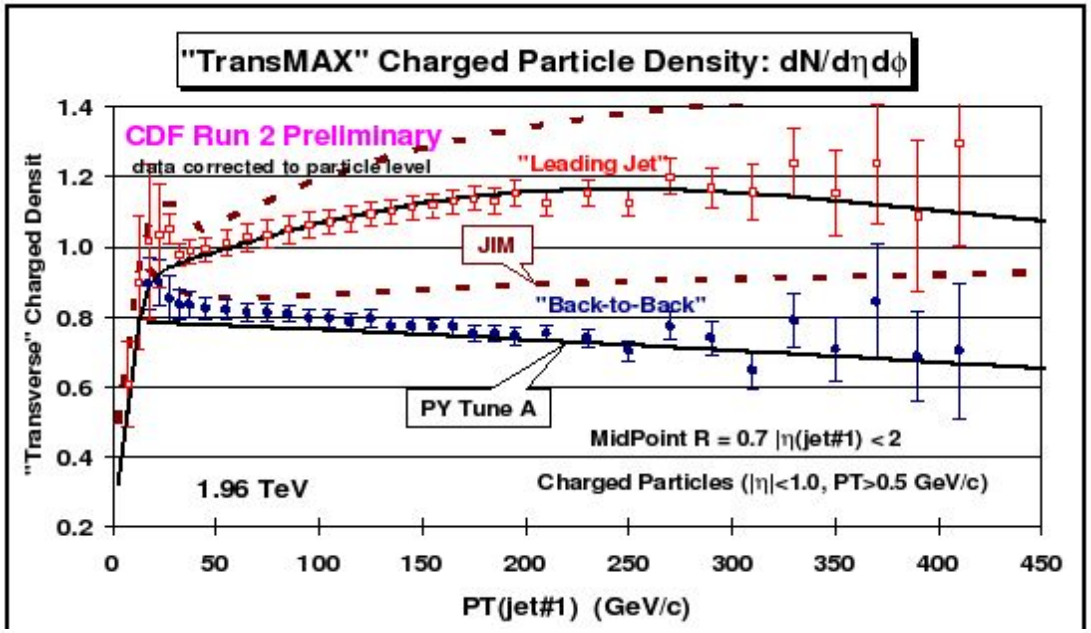
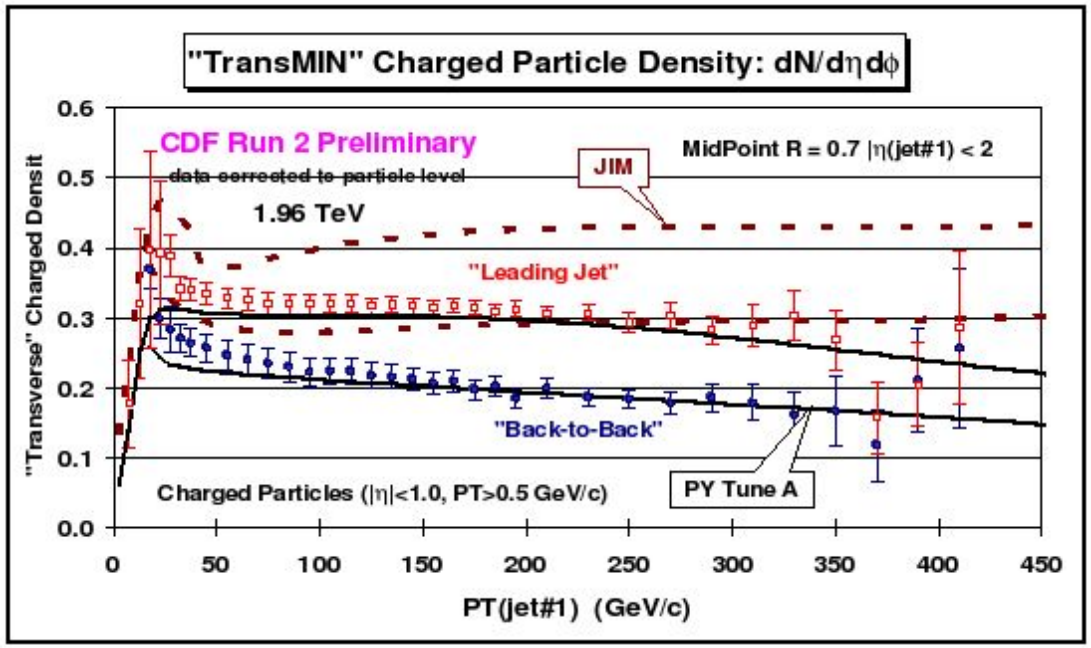
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) and a tuned version of JIMMY (with MPI, PTJIM = 3.25 GeV/c) at the particle level.



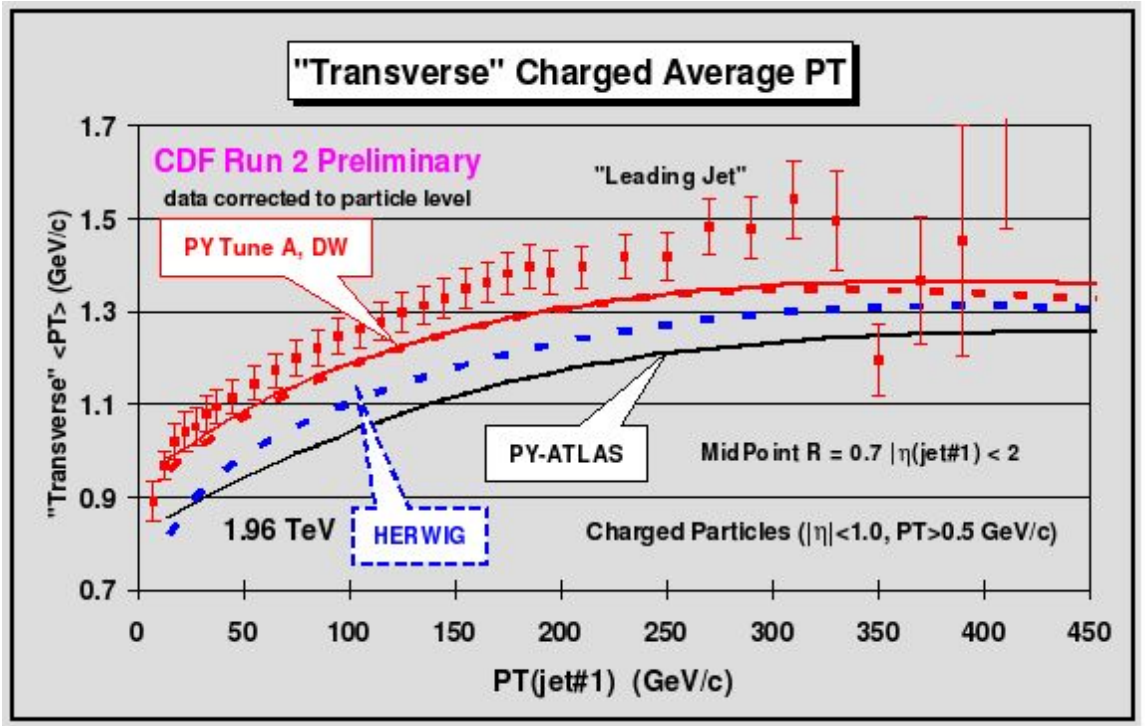


Underlying Event

PYTHIA 6.2 CTEQ5L

Parameter	Tune A	Tune DW	Tune DWT	ATLAS
MSTP(81)	1	1	1	1
MSTP(82)	4	4	4	4
PARP(82)	2.0 GeV	1.9 GeV	1.9409 GeV	1.8 GeV
PARP(83)	0.5	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.4	0.5
PARP(85)	0.9	1.0	1.0	0.33
PARP(86)	0.95	1.0	1.0	0.66
PARP(89)	1.8 TeV	1.8 TeV	1.96 TeV	1.0 TeV
PARP(90)	0.25	0.25	0.16	0.16
PARP(62)	1.0	1.25	1.25	1.0
PARP(64)	1.0	0.2	0.2	1.0
PARP(67)	4.0	2.5	2.5	1.0
MSTP(91)	1	1	1	1
PARP(91)	1.0	2.1	2.1	1.0
PARP(93)	5.0	15	15.0	5.0

Identical to DW at 1.96 TeV but uses ATLAS extrapolation to the LHC!



- The "transverse" charged average p_T, versus P_T (jet#1) for "leading jet" events at 1.96 TeV for Tune A, DW, ATLAS, and HERWIG (without MPI).

Conclusions

- Nice agreement b/w k_T distributions in data and theory gives further support to the idea that the pQCD stage of jet formation is dominant (earlier this was observed for the particle multiplicities, momentum distributions and momentum correlations).

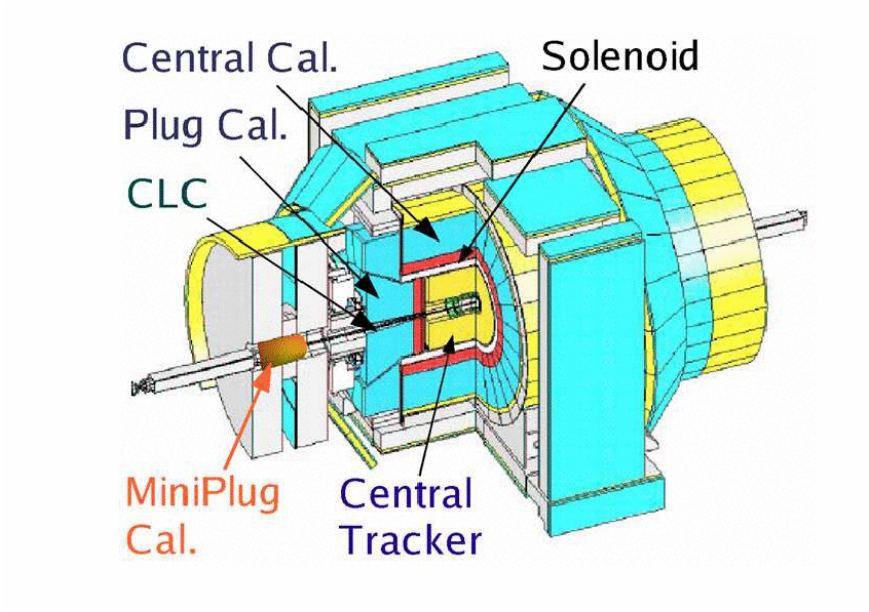
- The "Event Shapes and CDF" analysis is in progress and we expect to see very interesting results. Awaiting theoretical predictions to make comparison of data to the results of NLO+NLLA calculations.

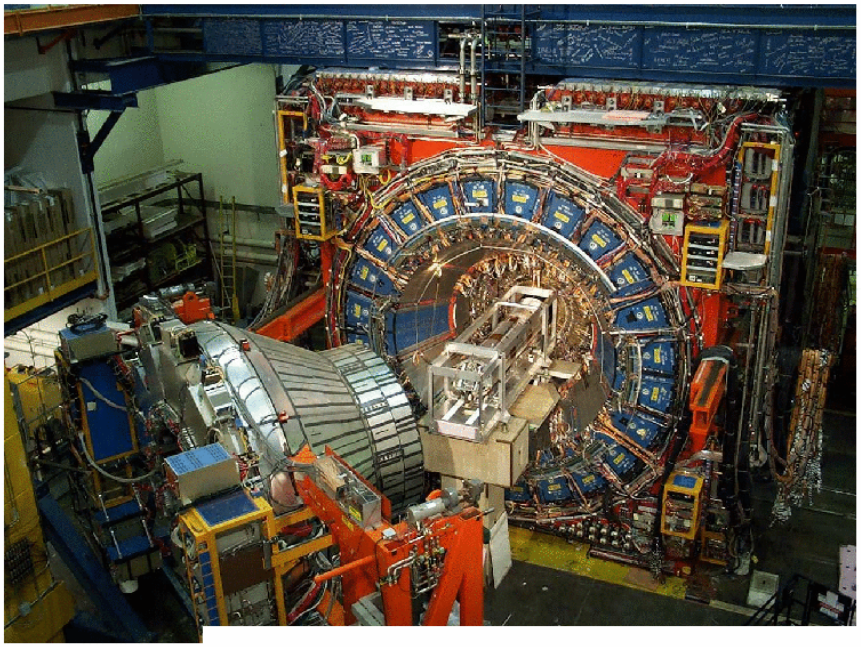
- We are making good progress in understanding and modeling the "underlying event". However, we do not yet have a perfect fit to all the features of the CDF underlying event data. So far Pythia Tune DW seems to be the best.

- It will be important to measure the "underlying event" at the LHC, tune the Monte Carlo models and compare to CDF.

Backup

CDF detector





Measurements rely on several detector components:

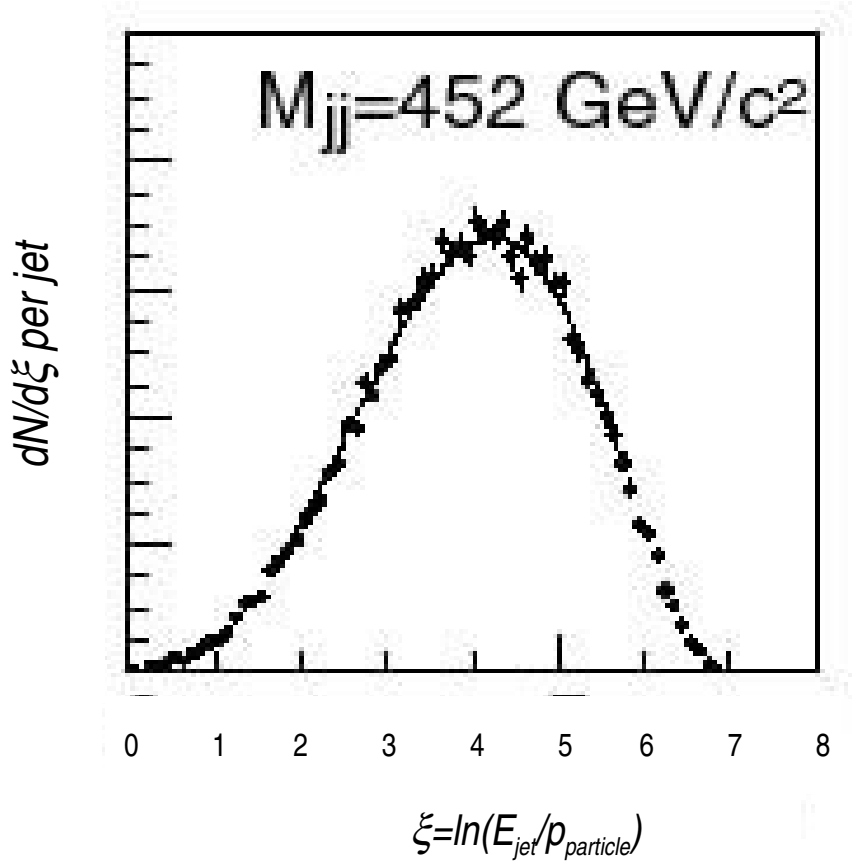
COT+SVX – track and vertex reconstruction

Electromagnetic calorimeters – Jets, e^{+-}, γ

Hadronic calorimeters - Jets

Particle Momentum Distributions

- Particles in small angle θ_c=0.5 rad arond jet axis are counted
- In theory are defined in terms of variable $\xi = \ln\left(\frac{E_{jet}}{P_{hadron}}\right)$



- Sensitive to soft and hard particles.
- Low p ⇔ high ξ and vice versa.
- The peak position depends on $Q=E_{jet}\theta_c$ and corresponds to particles with p ~ several GeV.

It has been shown in Run I that theory describes data very well.
Parton shower cut-off extracted from the fits - Qeff~230 MeV.

Momentum Correlations

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

$$C(\xi_1,\xi_2)=\frac{\frac{d^2 n}{d\xi_1 d\xi_2}}{(\frac{dn}{d\xi_1})(\frac{dn}{\xi_2})}=C_0+C_1(\Delta\xi_1+\Delta\xi_2)+C_2(\Delta\xi_1-\Delta\xi_2)^2$$

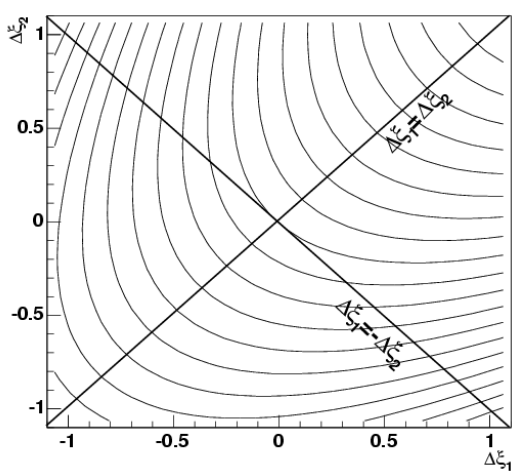
- C_0, C_1 and C_2 depend on $Y=\ln(E_{jet}\theta_c/Q_{eff})$

MLLA: R.Perez-Ramos (2006) JHEP 0606, 019 (2006)

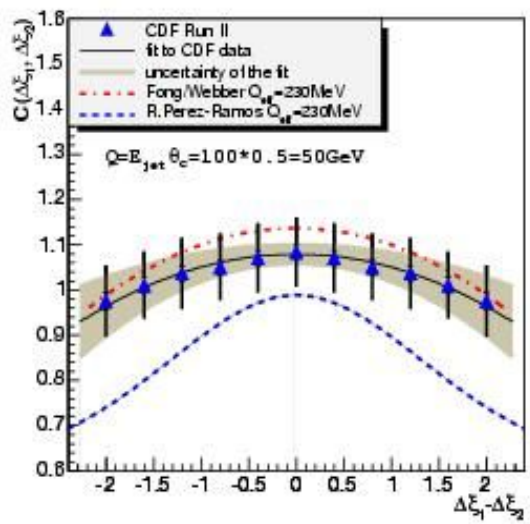
Ridge-like structure:

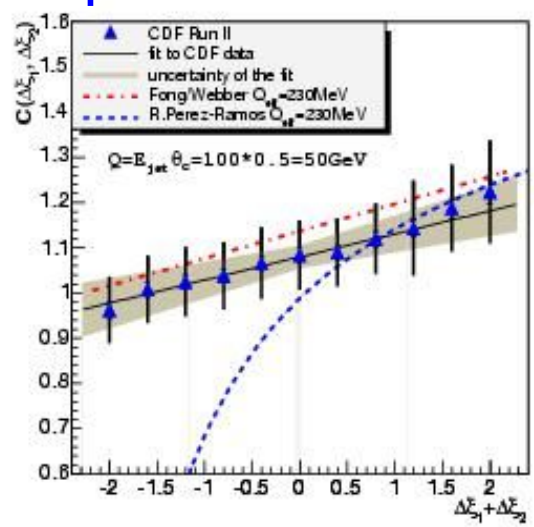
- Particles with like momenta correlate
- Correlation is stronger for soft particles

$\Delta\xi=\xi-\xi_0$



central diagonal profiles



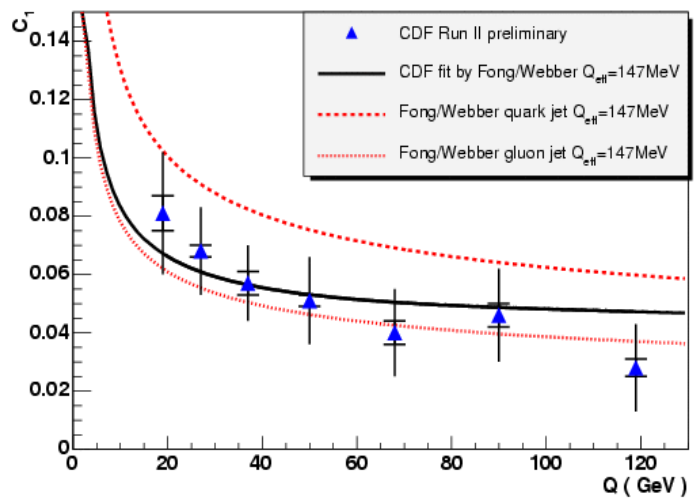


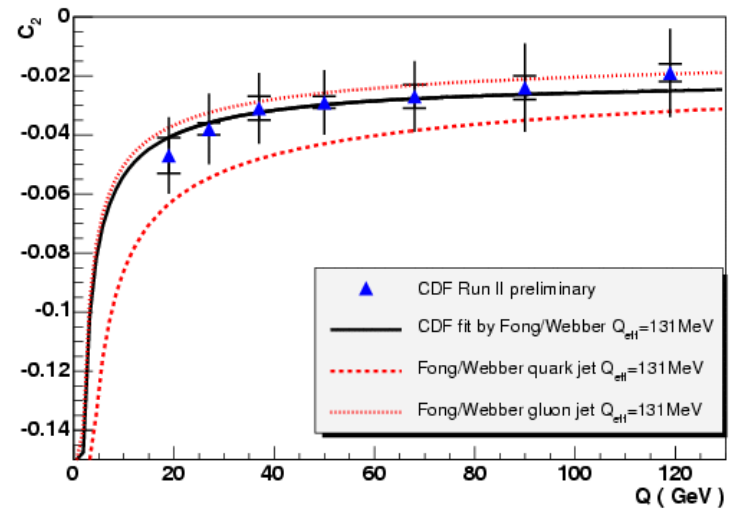
Momentum Correlations

$$C(\xi_1,\xi_2)=\frac{\frac{d^2 n}{d\xi_1 d\xi_2}}{(\frac{dn}{d\xi_1})(\frac{dn}{\xi_2})}=C_0+C_1(\Delta\xi_1+\Delta\xi_2)+C_2(\Delta\xi_1-\Delta\xi_2)^2$$

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

plot $C_1(Q)$ and $C_2(Q)$





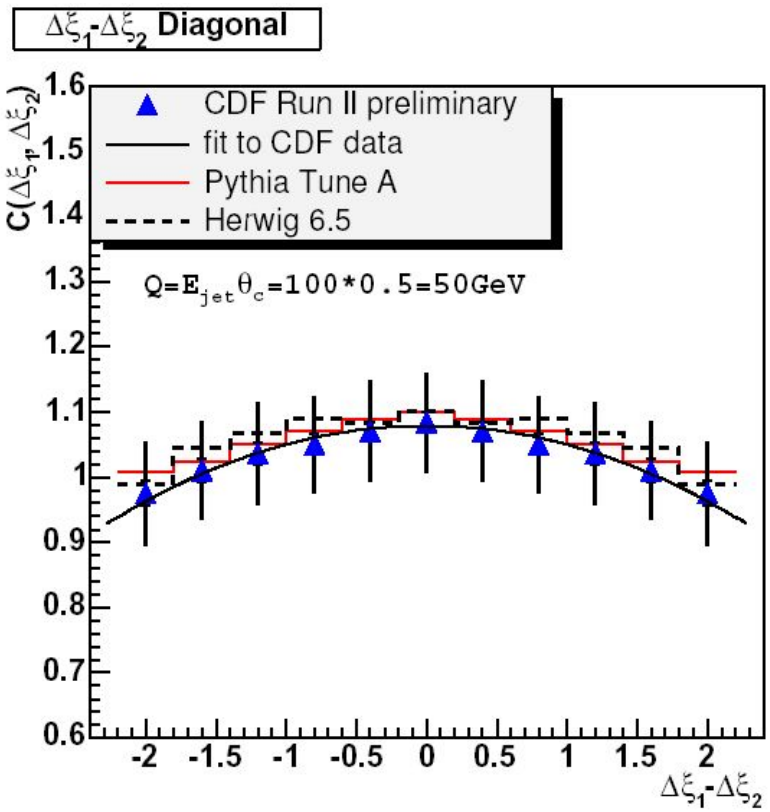
→ Hadron correlations follow the pattern expected for partons;

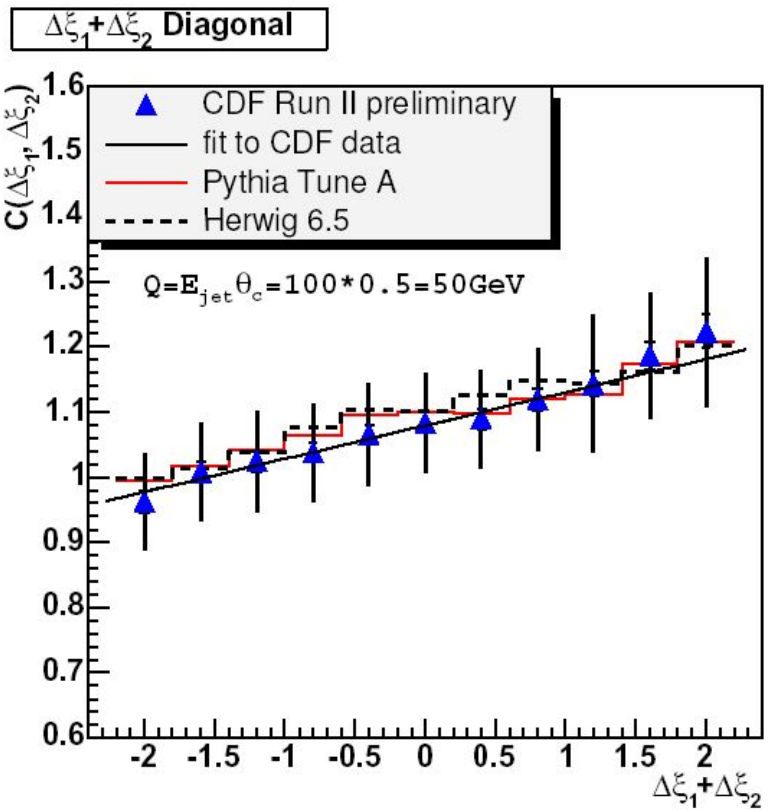
$Q_{eff} \sim 140 \pm 80$ MeV

Correlation Data-MC

Pythia Tune A and Herwig 6.5

- Both MC generators reproduce correlation in data fairly well;



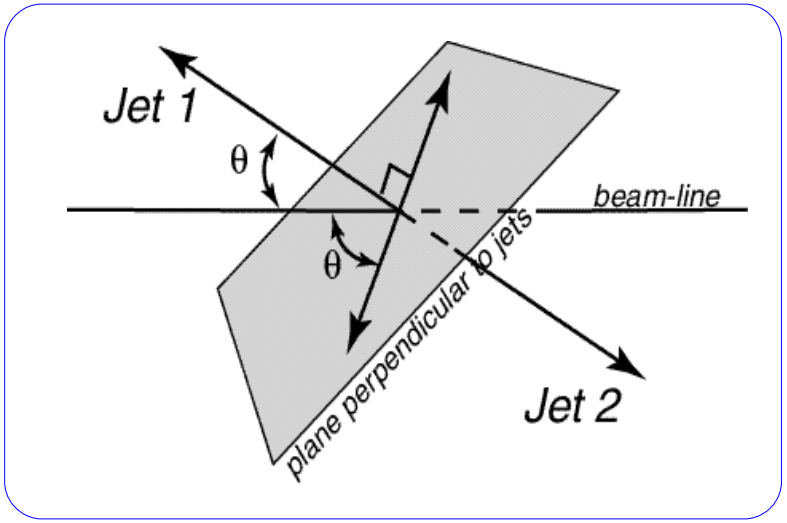


Kt distributions

Measurement:

- Well balanced di-jet events with Mjj ranging 60-600 GeV (divided in 8 dijet mass bins);
- 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 θ_c=0.5;
- Unfold the small underlying event contribution;
- Correct for tracking inefficiency;
- Remove secondaries (conversions, ...)

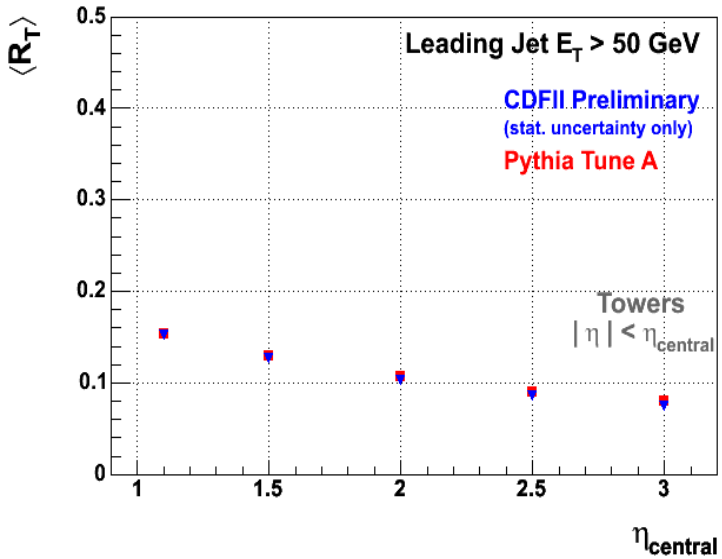


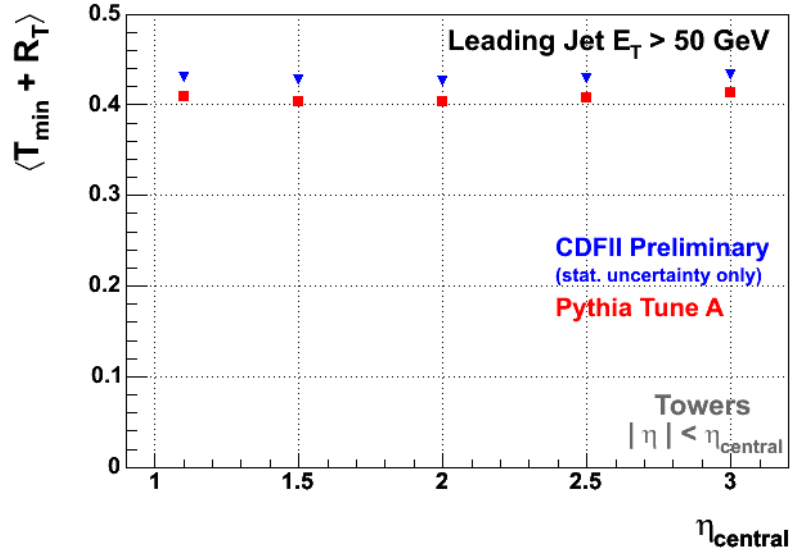
Theory(to make compare to data):

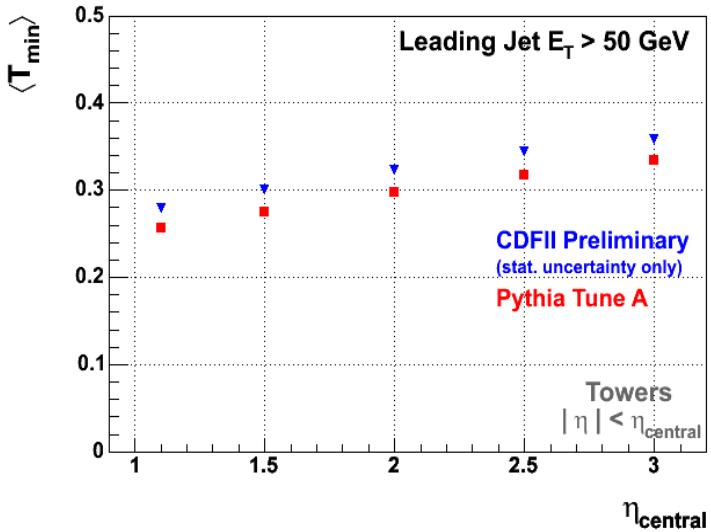
- produce curves for a mixture of quark and gluon jets;
- get fraction of gluon jets in the sample from Pythia Tune A Monte-Carlo;

- compare only shape of the distributions (not the overall normalization, which was proved to be correct earlier);

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)