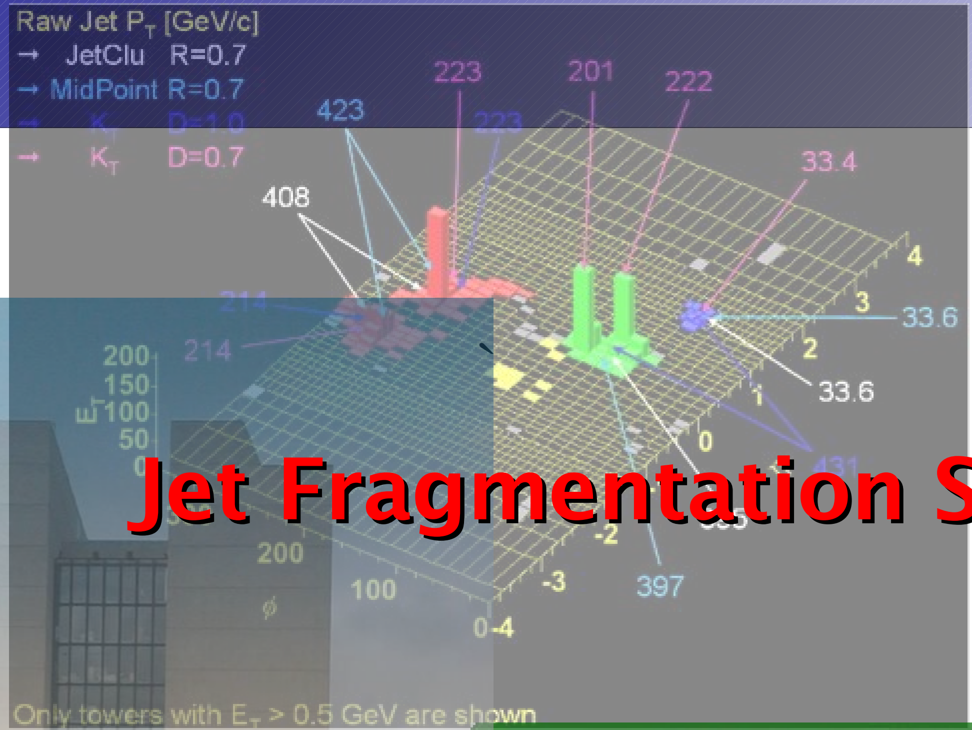


Jet Fragmentation Studies at CDF

Sergo Jindariani
(University of Florida)

July 17–18, 2007, Fermilab, Batavia, IL

Outline

Jet Fragmentation–what are we studying?

- Motivation
- Phenomenology
- Older CDF results

Two-particle momentum correlations in jets

- Why?
- Predictions
- Measurement
- Results

k_T distributions of particles in jets

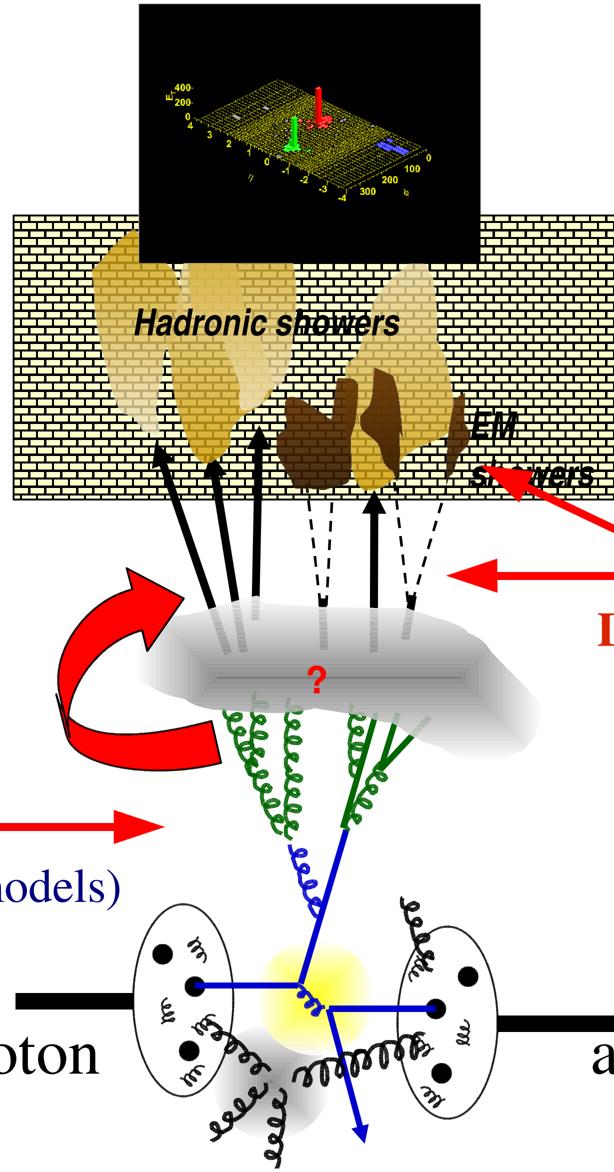
Summary and Conclusions!

Tevatron

Tevatron:

- **Worlds highest energy collider**
- **Collides protons and antiprotons**
- **Center-of-mass energy1.96 TeV**
- **Radius ~1km**

Partons, Hadrons… Jets



Data: - tracks and calorimeter towers;

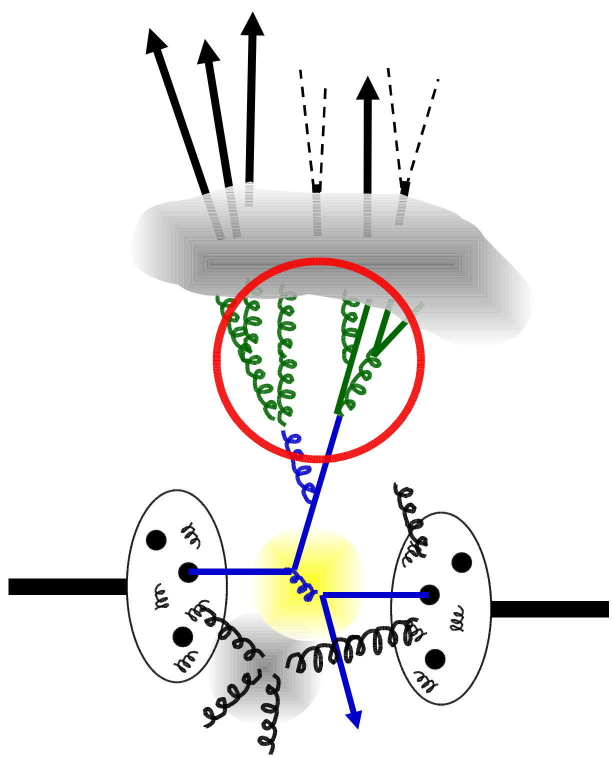
Theory: -
partons (+ hadronization models)

proton

antiproton

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

little bit of... Theory



"Soft gluon resummation" recipe:

- Set transverse momentum cutoff ($k_T > Q_{cut}$)
- Calculate soft gluon emission diagrams at all orders of α_s but with some precision (LLA, NLLA, ...)
- At the end Q_{cut} can be lowered all the way to Λ_{QCD}
- Phenomenological scale replacing Q_{cut} and Λ_{QCD} is called Q_{eff}

$$A\alpha_s = a_1\alpha_s \ln^2(Q/Q_{cut}) + a_2\alpha_s \ln(Q/Q_{cut}) + a_3\alpha_s \ldots$$

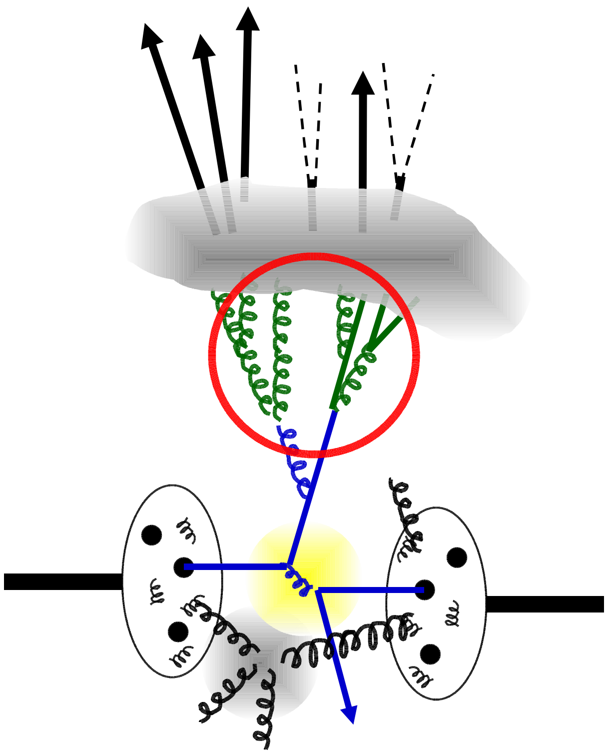
$$B\alpha_s^2 = b_1\alpha_s^2 \ln^4(Q/Q_{cut}) + b_2\alpha_s^2 \ln^3(Q/Q_{cut}) + \ldots$$

$$C\alpha_s^3 = c_1\alpha_s^3 \ln^6(Q/Q_{cut}) + c_2\alpha_s^3 \ln^5(Q/Q_{cut}) + \ldots$$

....

Leading Log Approximation (LLA)

little bit of... Theory



"Soft gluon resummation" recipe:

- **Set transverse momentum cutoff ($k_T > Q_{cut}$)**
- **Calculate soft gluon emission diagrams at all orders of α_s but with some precision (LLA, NLLA, ...)**
- **At the end Q_{cut} can be lowered all the way to Λ_{QCD}**
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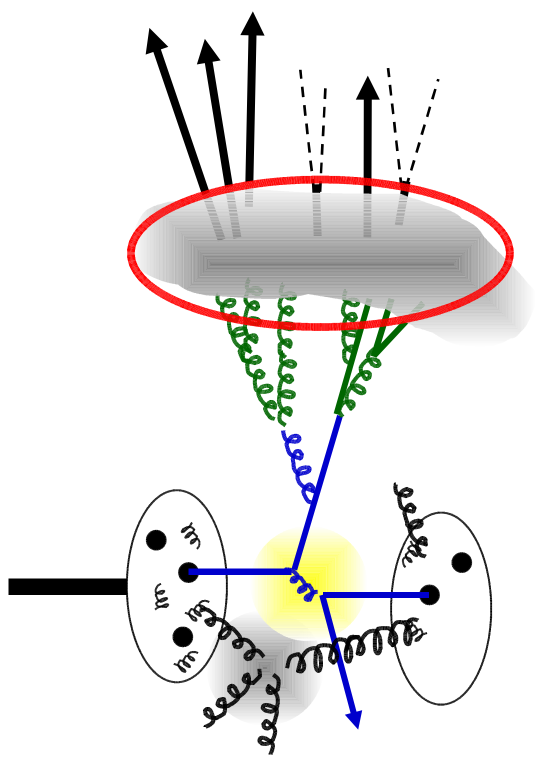
....

Next-to-Leading Log Approximation (NLLA)

little bit of... Theory

Local Parton Hadron Duality (LPHD):



- It's a hypothesis, allowing to link theoretical parton level calculations to experimental hadron level measurement
- **LPHD** suggests that conversion of partons to hadrons is independent of the scale of primary hard process
- At the end of a parton shower, hadron distributions are different from parton distributions by a constant factor $K_{LPHD} \sim 1$, for example:

$$N_{hadrons} = K_{LPHD} \cdot N_{partons}$$

- Let's see if it's true...

look to the Past

Run I CDF analysis :

- **Particle multiplicity in jets (A. Korytov, A. Safonov)**
Phys. Rev. Lett. 87:211804, 2001.

- **Particle momentum distributions in jets (A. Korytov, A. Safonov)**
Phys. Rev. D 68:012003, 2003.

- **Quark/Gluon jet differences (A. Korytov, A. Pronko)**
Phys. Rev. Lett. 94:171802, 2005.

look to the Past

Inclusive particle momentum distributions:

- **Charged hadrons in a cone with small opening angle around jet axis**
- **Defined in terms of:**

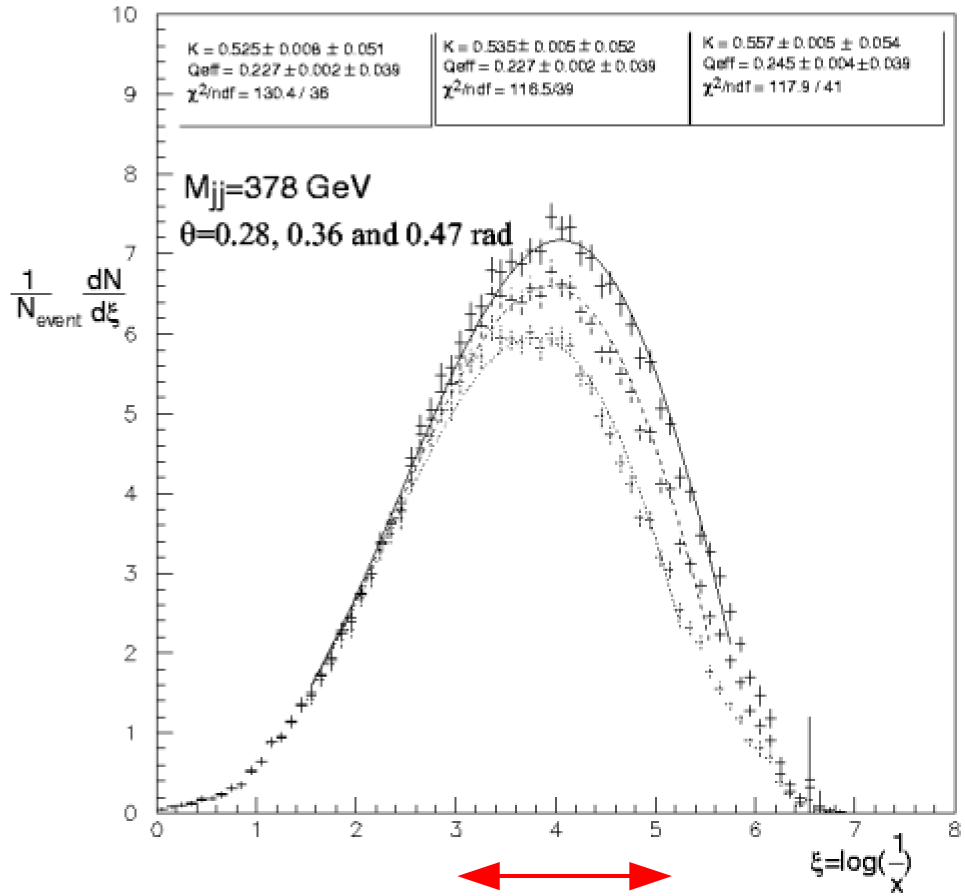
$$x = \frac{P_{hadron}}{E_{jet}} \qquad \xi = \ln\frac{1}{x} = \ln\frac{E_{jet}}{P_{hadron}}$$

- **Perform 2-parameter fit to the Modified Leading-Log (MLLA) function:**

MLLA Q_{eff} = 230±40 MeV

$K_{LPHD}^{charged}$=0.56±0.10

→ **$N_{hadrons} \cong N_{partons}$**



predictions valid around the peak typically few GeV particles

look to the Past

What are the relative roles of perturbative and non-perturbative QCD ?

- Particle multiplicities $N_{hadrons}$ vs. $N_{partons}$ **OK**
- Momentum spectra of partons vs hadrons **OK**

} Experimentally checked (LEP, CDF)

→ role of perturbative QCD (pQCD) seems to be dominant

How about more subtle effects?

- Parton-parton vs hadron-hadron correlations **?**
- Transverse momenta with respect to jet axis (k_T) **?**

Correlations

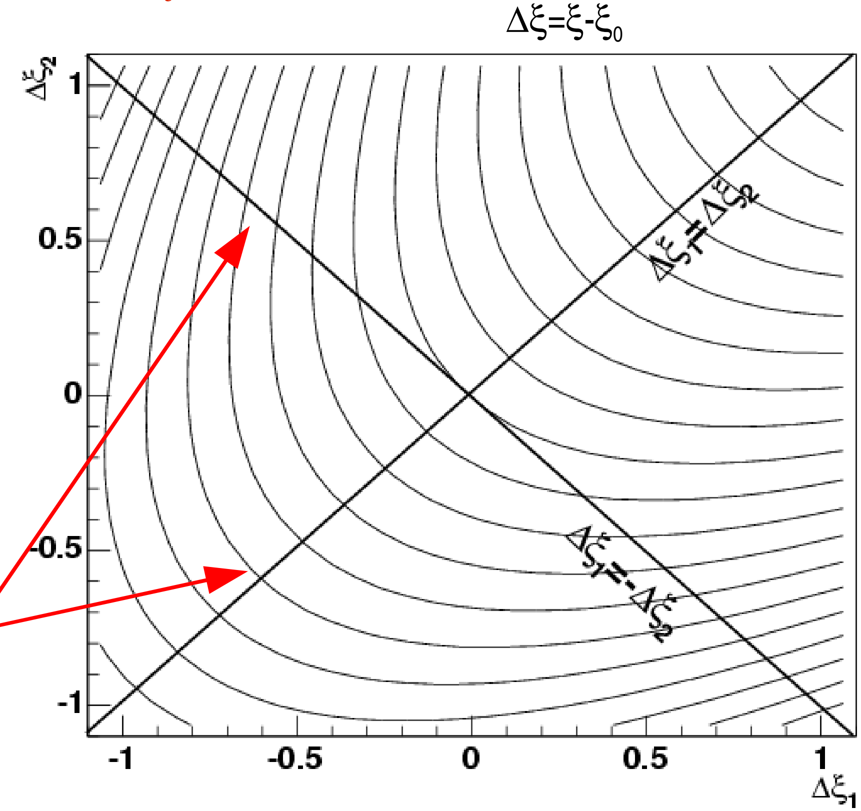
Theory: C.Fong, B.Webber (1990) **Phys.Lett. B241:255 (1990)**

$$R(\xi_1,\xi_2)=\frac{\frac{d^2N}{d\xi_1 d\xi_2}}{\left(\frac{dN}{d\xi_1}\right)\left(\frac{dN}{\xi_2}\right)}=R_0+R_1(\Delta\xi_1+\Delta\xi_2)+R_2(\Delta\xi_1-\Delta\xi_2)^2$$

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

- R_0, R_1 and R_2 depend on $Y=\ln(E_{jet}\theta_c/Q_{eff})$

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



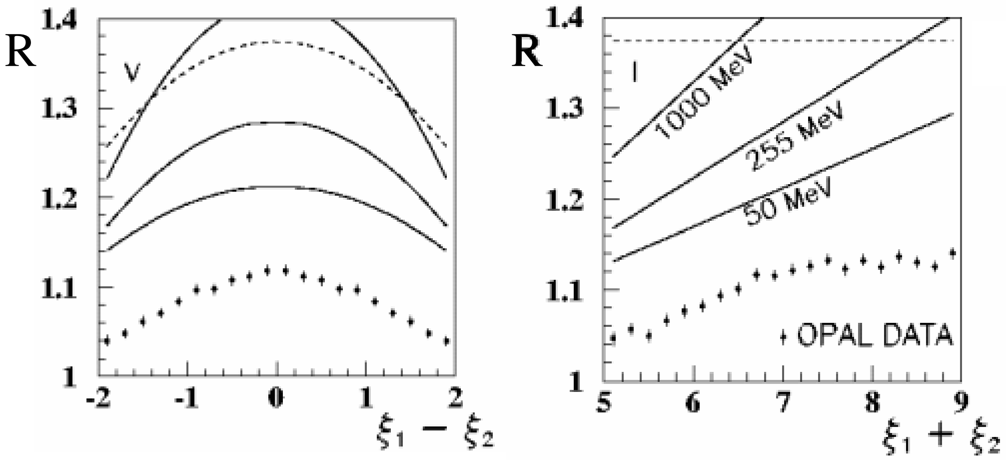
Ridge-like structure:

- **Particles with like momenta correlate**
- **Correlation is stronger for softer particles**

will plot central diagonal profiles

Correlations

OPAL measurement:



- Z-peak data, E_{jet}=45 GeV, only quark jets
- Trends with energy not studied
- Large angles considered ($\theta_c=\pi/2$)

- not controlled by theory

Results:

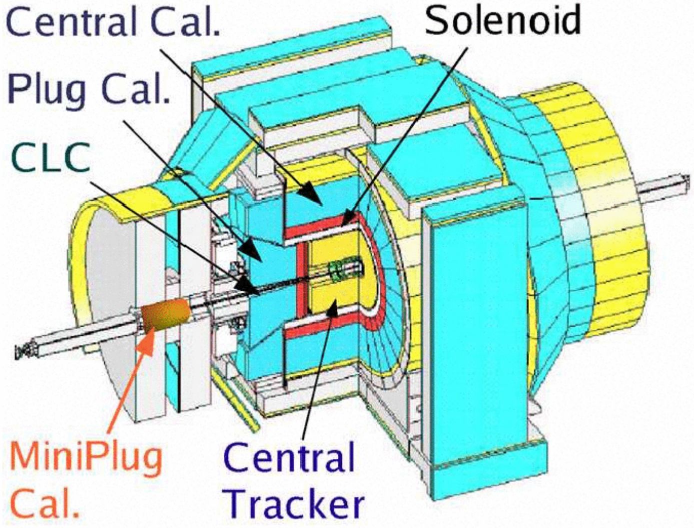
R_0=1.108±0.002 Q_{eff}=32±2 MeV

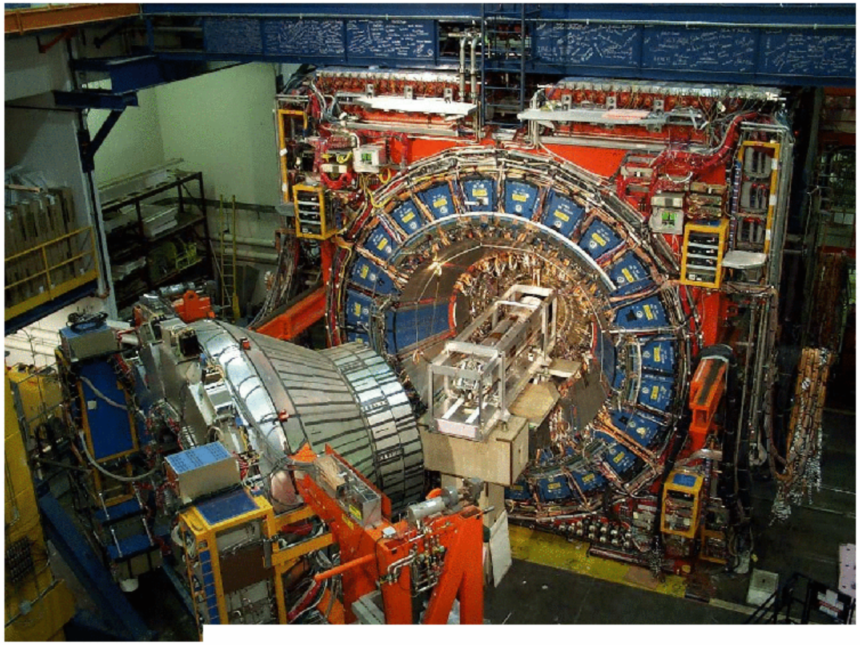
R_1=0.025±0.003 Q_{eff}=2±1 MeV

R_2=−0.021±0.003 Q_{eff}=60±38MeV

OPAL data cannot be described by the NLLA calculations with reasonable value of Q_{eff}

CDF II detector





Measurements rely on several detector components:
COT+SVX – track and vertex reconstruction;
Electromagnetic and hadronic calorimeters – jets

We do:

- **include gluon jets;**
- **study trends with energy;**
- **use small opening angles;**

Correlations

Normalization:

- **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

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

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

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

$$C(\xi_1,\xi_2)=\frac{\left(\frac{d^2n}{d\xi_1 d\xi_2}\right)}{\left(\frac{dn}{d\xi_1}\right)\left(\frac{dn}{\xi_2}\right)}=\frac{\langle N\rangle^2}{\langle N(N-1)\rangle}R(\xi_1,\xi_2)=\frac{1}{F}R(\xi_1,\xi_2)=C_0+C_1(\Delta\xi_1+\Delta\xi_2)+C_2(\Delta\xi_1-\Delta\xi_2)^2$$

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

Correlations

Mixing:

- Theoretical calculations are done for quark and gluon jets separately
- At the Tevatron we have a mixture ... so we need to mix theoretical predictions for q/g jets to compare to data:

$$C(\xi_1,\xi_2)=A(F_g,f_g,r)C_g(\xi_1,\xi_2)+B(F_q,f_q,r)C_q(\xi_1,\xi_2)$$

→ f_g – fraction of gluon jets, get from Pythia Tune A (CTEQ5L)

→ F_q and F_g - binomial moments for quark and gluon jets, get from theory

→ $r = D_g(\xi)/D_q(\xi) = 9/4 = 2.25$ from theory

Correlations

Analysis Strategy:

- ~400 pb^{-1} of data
- Well balanced di-jet events with Mjj ranging ~60-600 GeV (divided in 7 dijet mass bins);
- Jet axis in the central region $|\eta|<0.9$;
- Events with only one vertex;
- Cone jet algorithm with R=1.0;

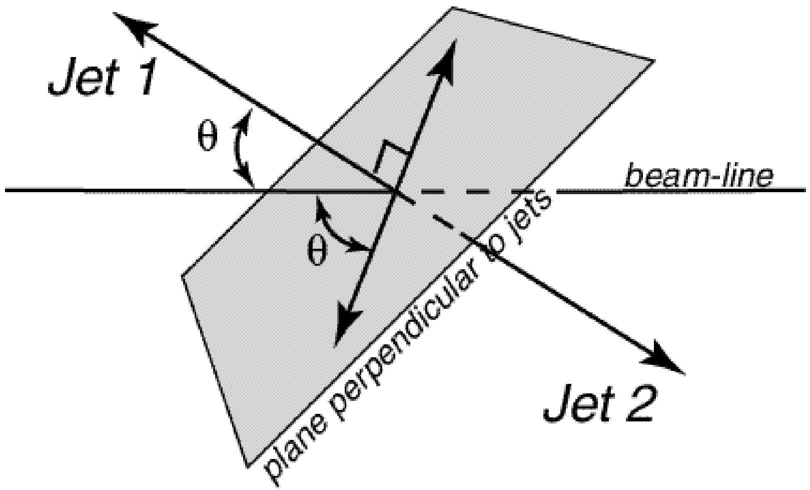
- Measurement done in the dijet center-of-mass frame;
- Charged particles in the cone with θ_c=0.5 rad.;
- Unfold the underlying event contribution;
- Remove secondaries (conversions, ...);
- Evaluate all systematic uncertainties;

- Measure correlation parameters C_0, C_1 and C_2 in all 7 dijet mass bins;
- Use evolution of these parameters with energy to obtain Qeff;
- Propagate all uncertainties to obtain an uncertainty on Qeff;

Correlations

Background subtraction:

- underlying event;
- not reconstructed second vertex;
- ...



Complementary cone:

- collects the same background as jet cones ;
- can be done when $45° < \theta_{jet} < 135°$;

$$R(\xi_1, \xi_2) = \frac{D(\xi_1, \xi_2)}{D(\xi_1) D(\xi_2)}$$

Have cross terms, subtraction is not trivial

$$D'(\xi) = D_{jet}(\xi) - D_{compl}(\xi)$$

$$D'(\xi_1, \xi_2) \approx 2 D_{jet}(\xi_1, \xi_2) - D_{jet+compl}(\xi_1, \xi_2) + 2 D_{compl}(\xi_1, \xi_2)$$

Correlations

Sources of evaluated systematic uncertainties:

- Effect of non-reconstructed vertexes;
- Jet energy scale;
- Extra jet requirements;
- Jet direction mis-measurement;
- Track quality cuts (remaining background tracks) - dominant;
- UE subtraction method;
- Tracking inefficiency;
- Neutral particles;

Correlations

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

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

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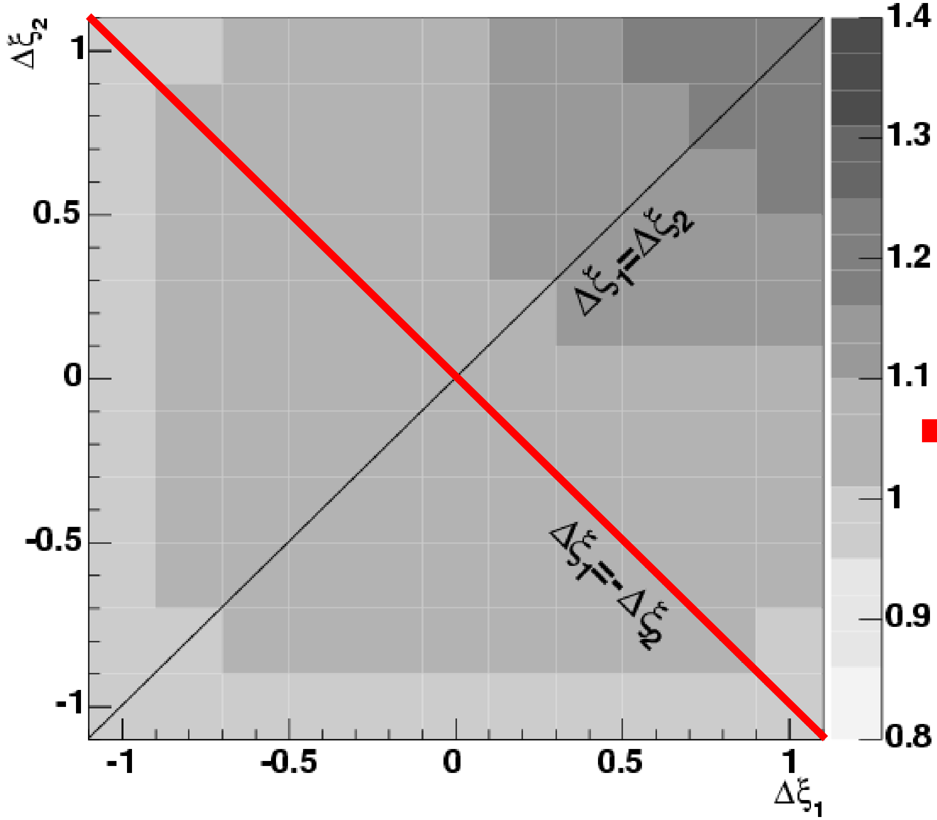
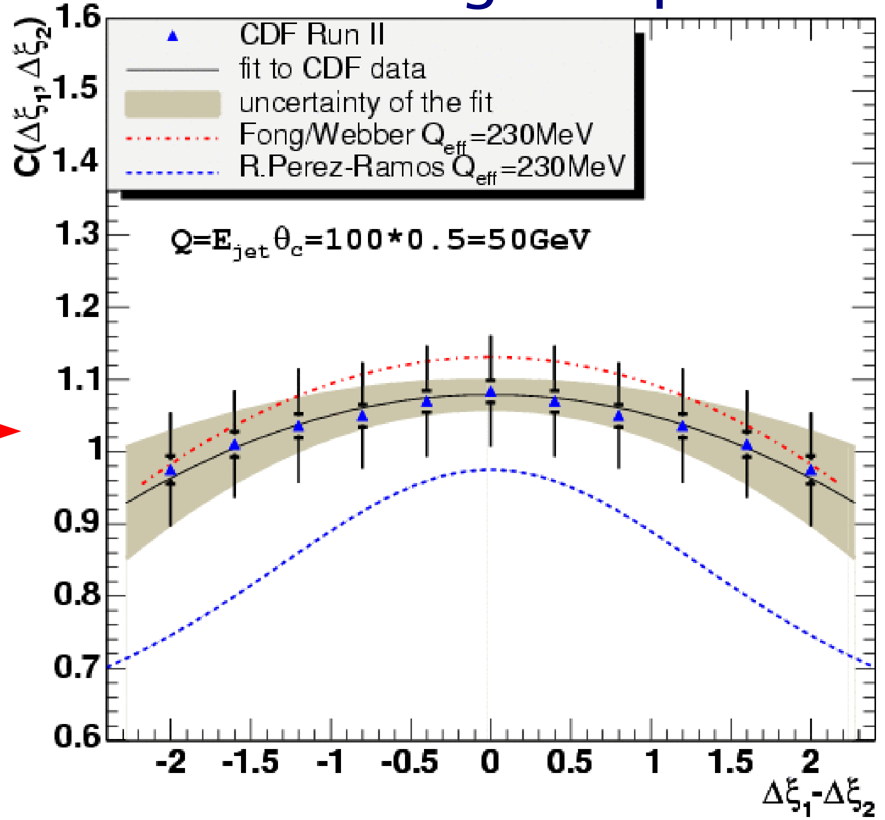


central diagonal profile



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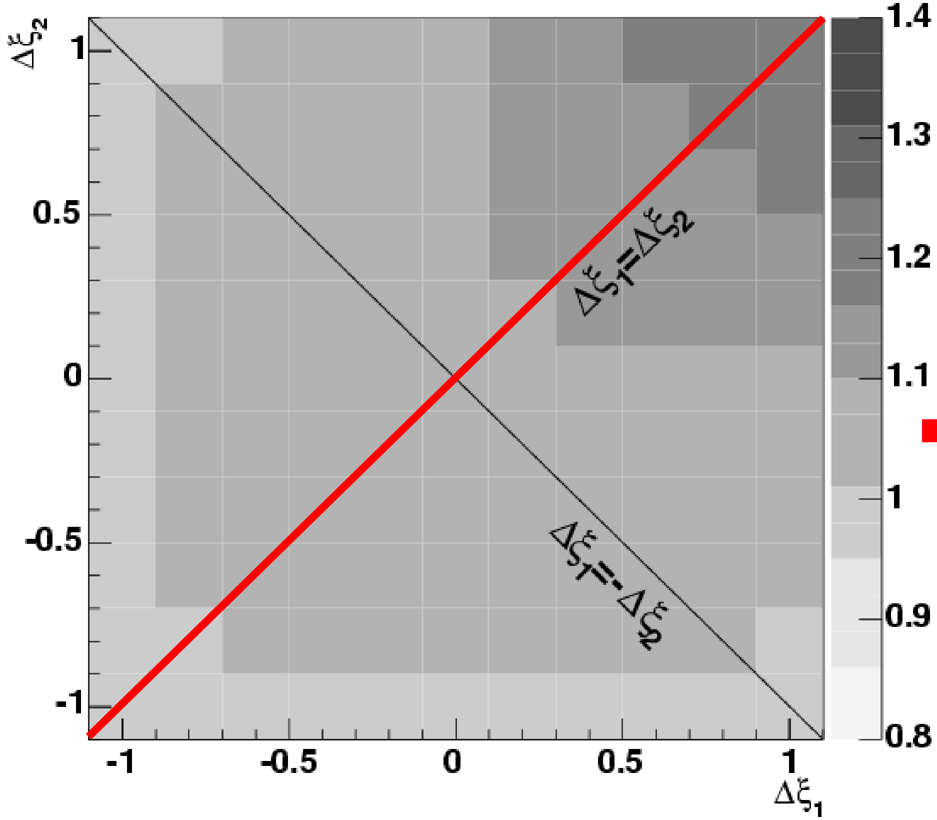

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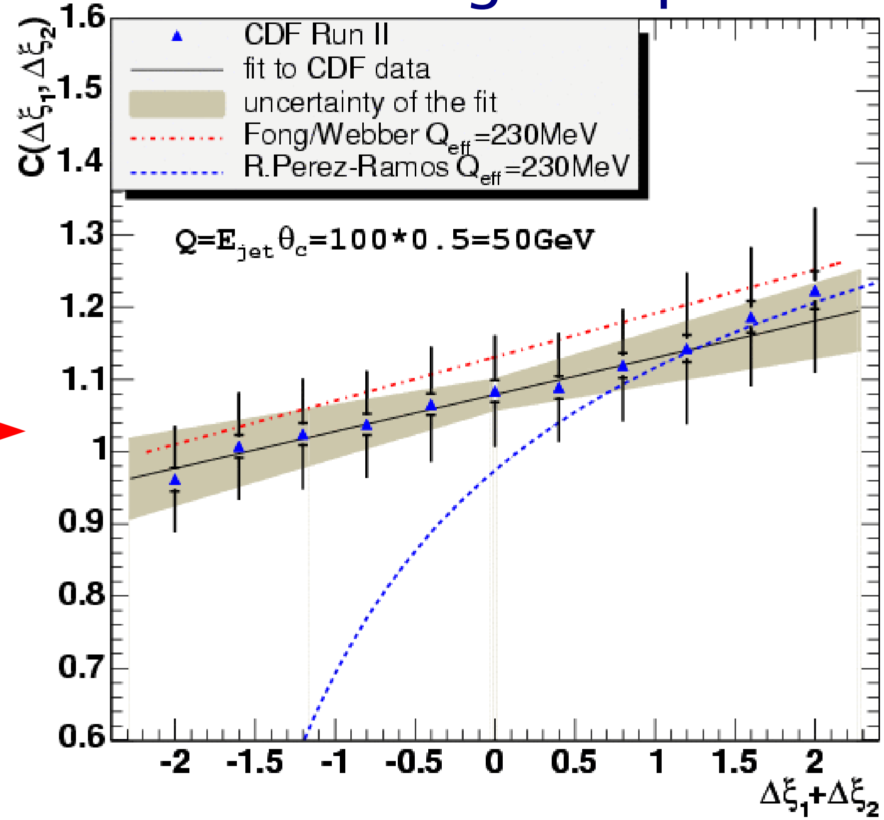
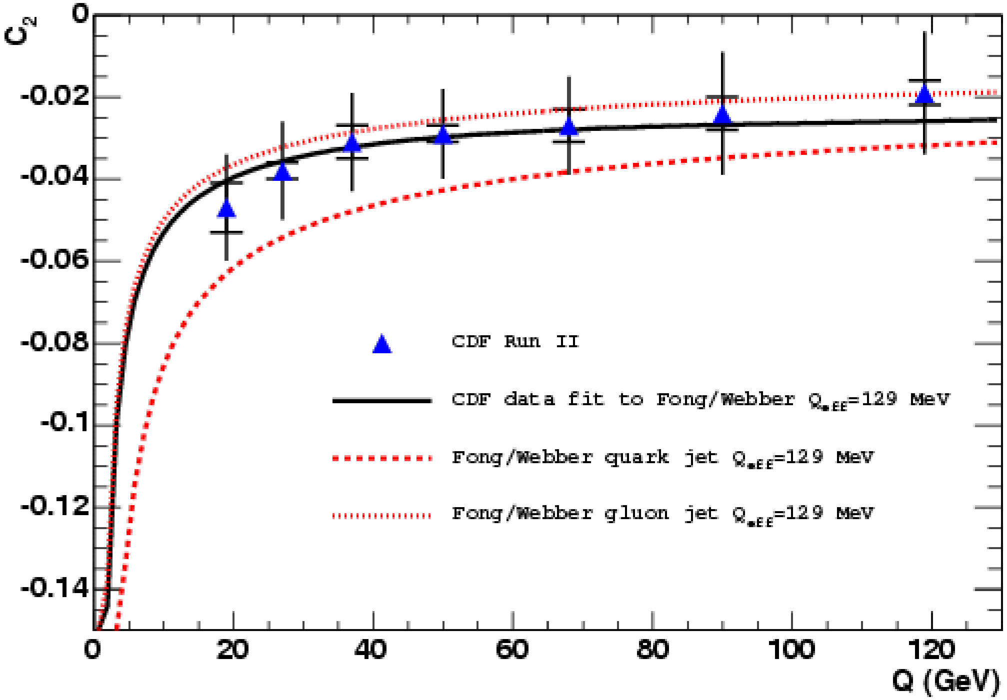
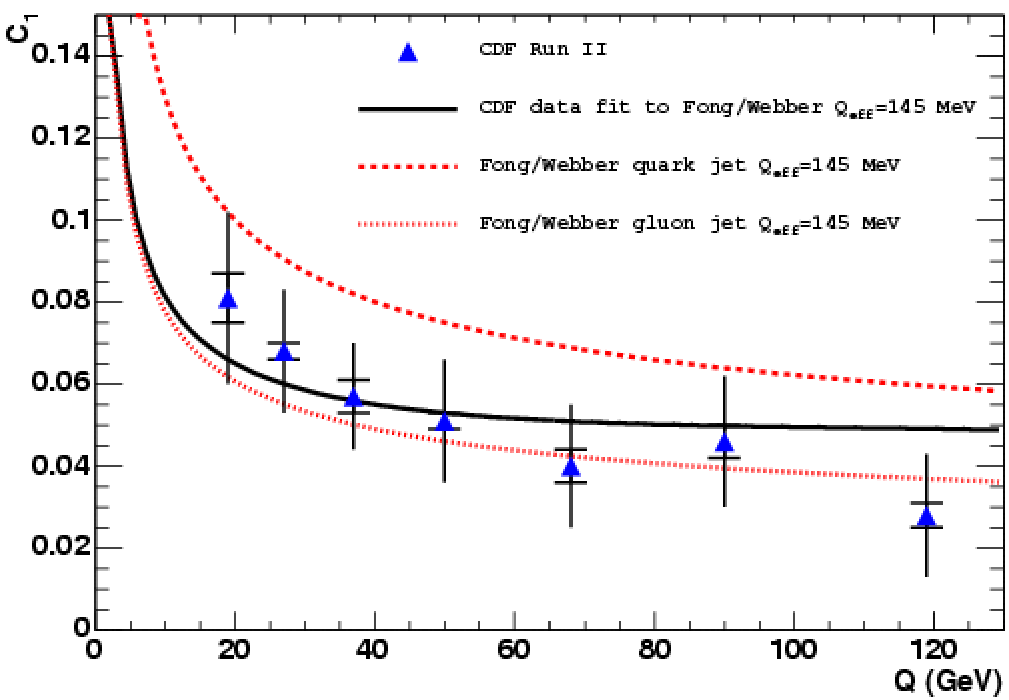


Correlations

- Evolution of the parameters with energy allows us to extract the value of Q_{eff}



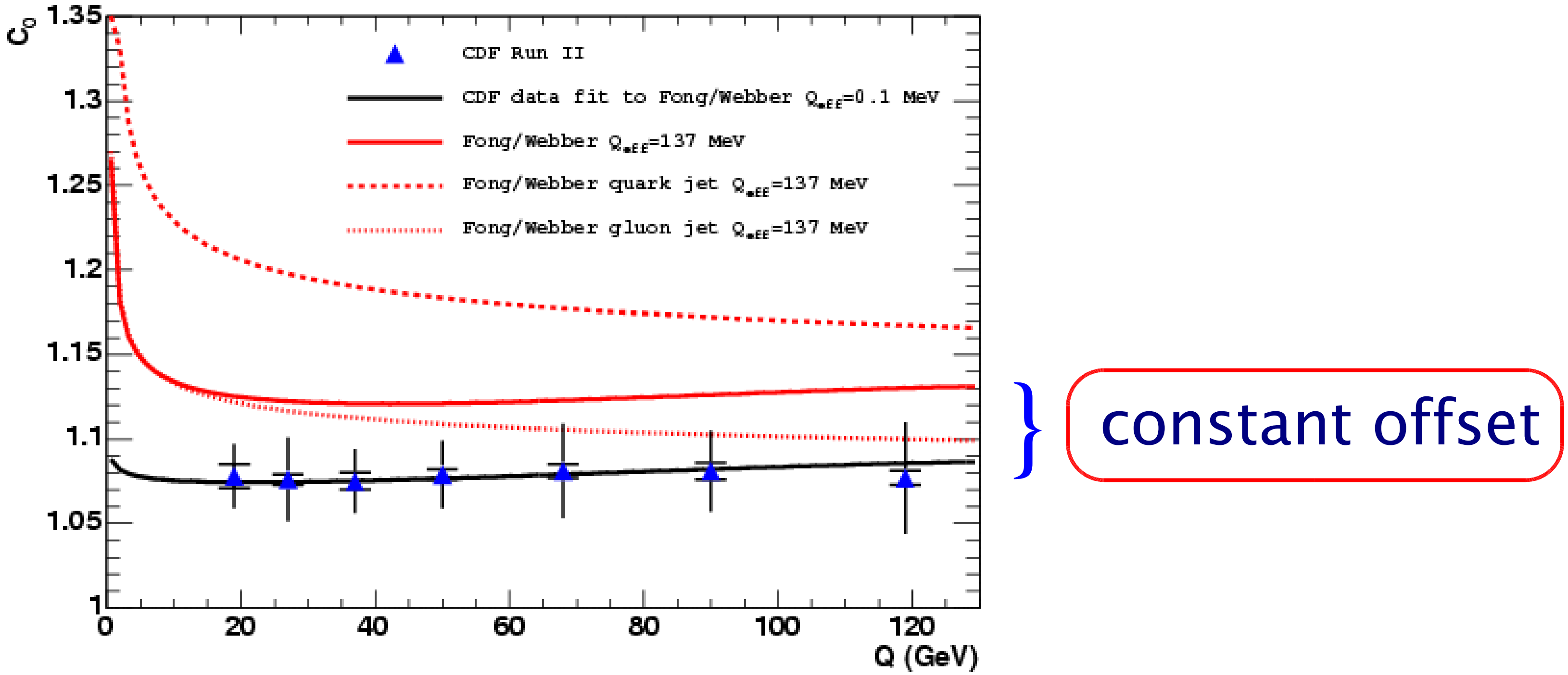
- Theory reproduces trends seen in data



- The extracted: $Q_{eff}=137^{+85}_{-69}$ MeV

Correlations

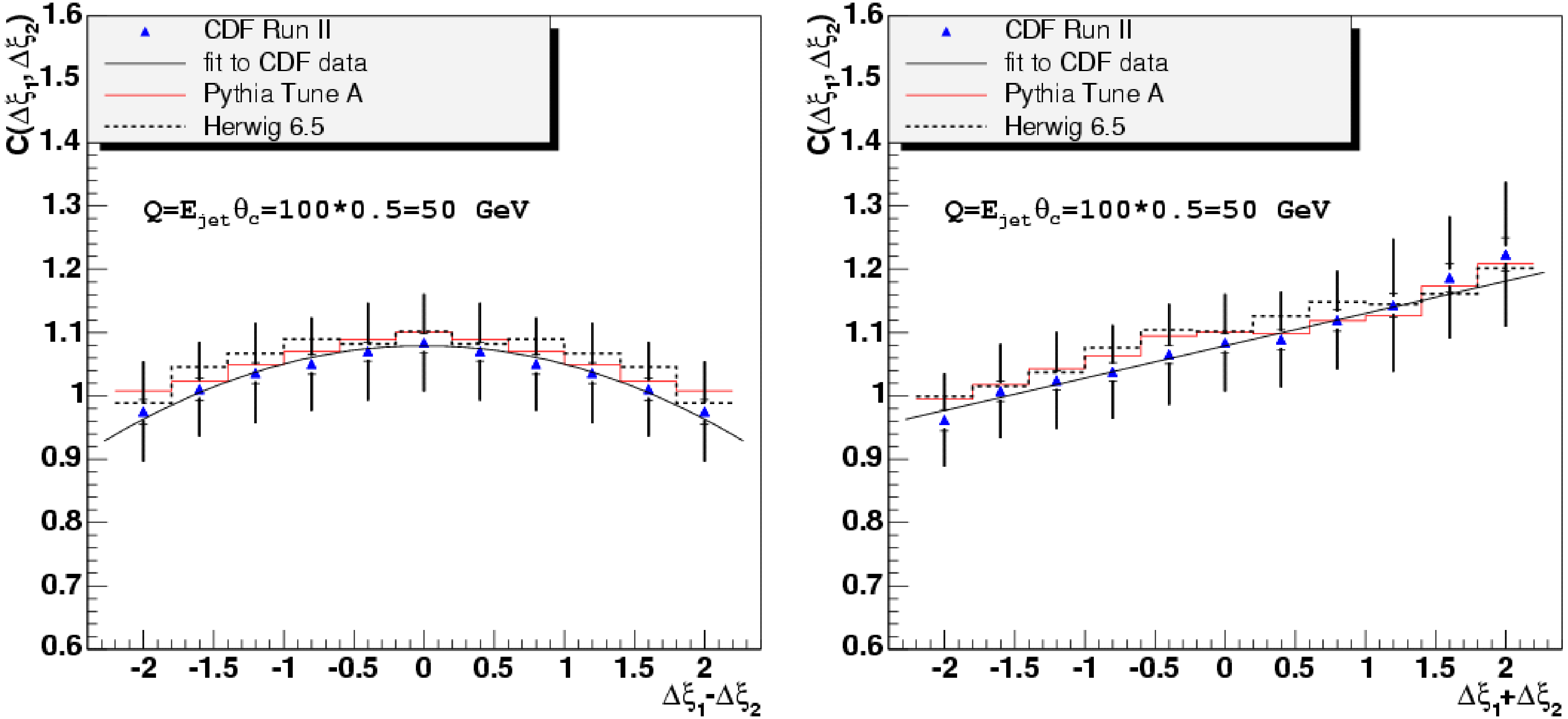
- Evolution of the parameters with energy allows us to extract the value of Q_{eff}



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

Correlations

Comparison to Monte Carlo:

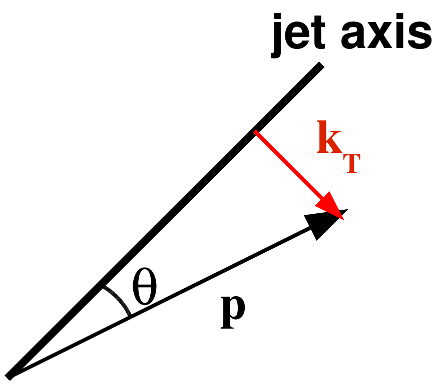


- **Both MC generators reproduce correlation in data fairly well**

K_T distributions

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

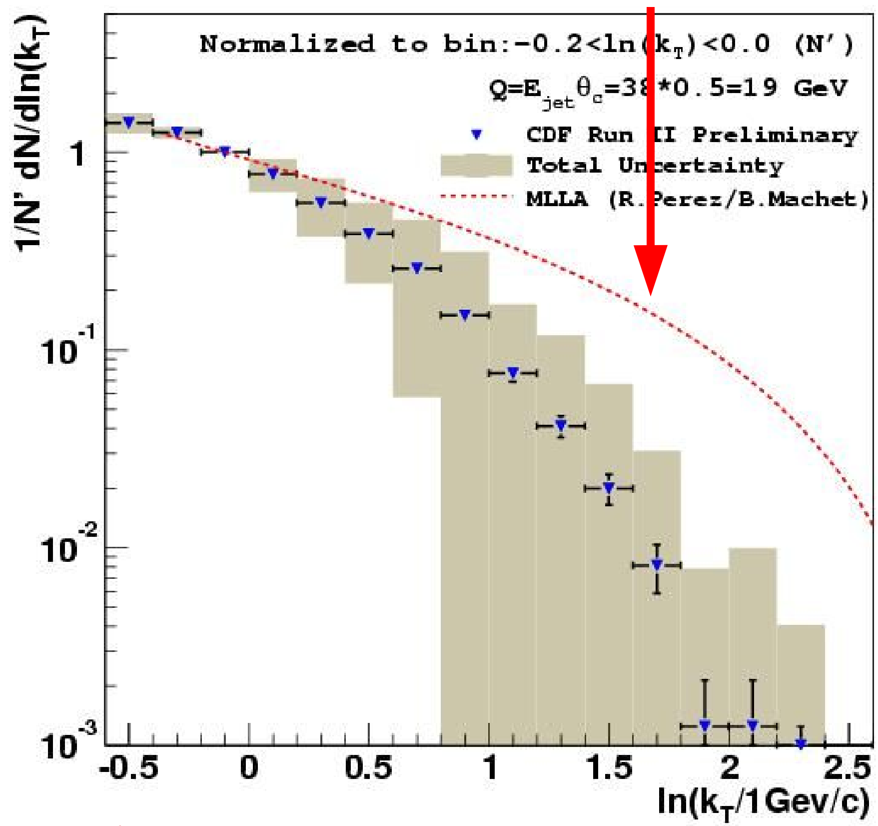
- **Recent theoretical work**
- **Allows to probe soft particle spectra**



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

- ~ 1 fb^{-1} of data
- In data particles in small angle θ_c=0.5 rad around jet axis are counted

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



MLLA:
→ data indicates fewer particles with large k_T

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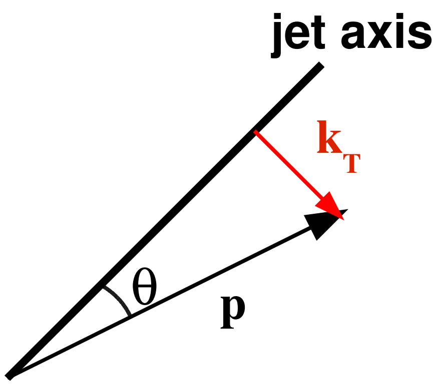

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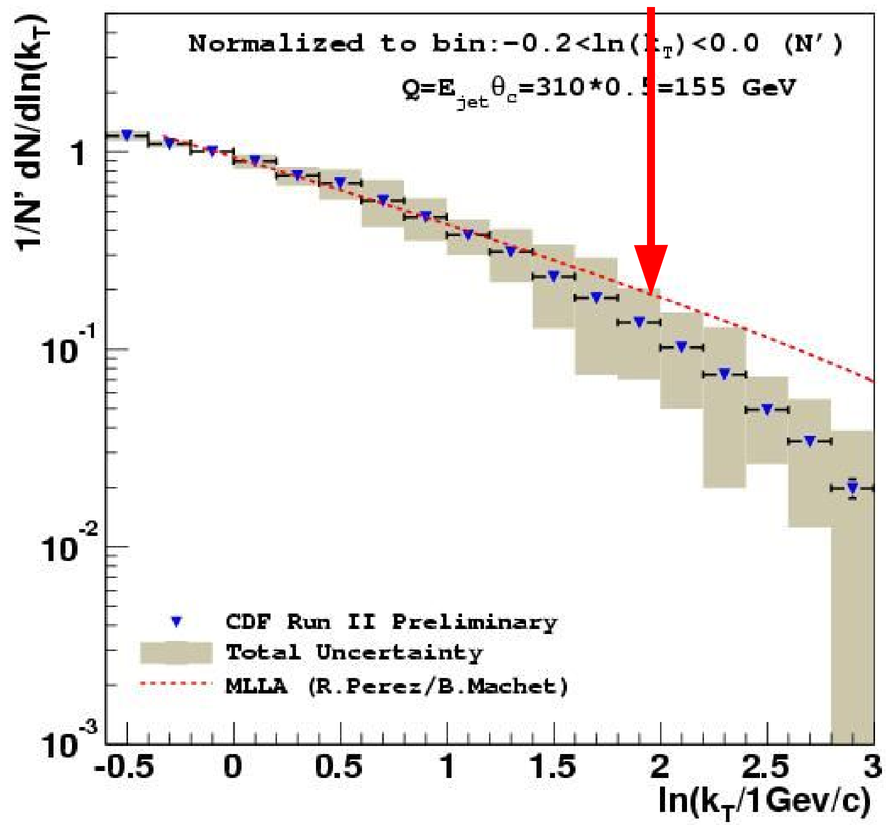

MLLA:

→ data indicates fewer particles with large k_T

→ better agreement with increasing Energy scale Q

K_T distributions

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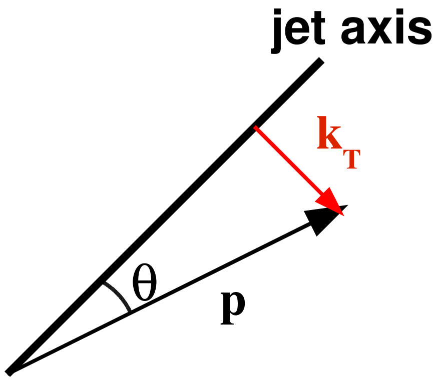
- **Allows to probe soft particle spectra**



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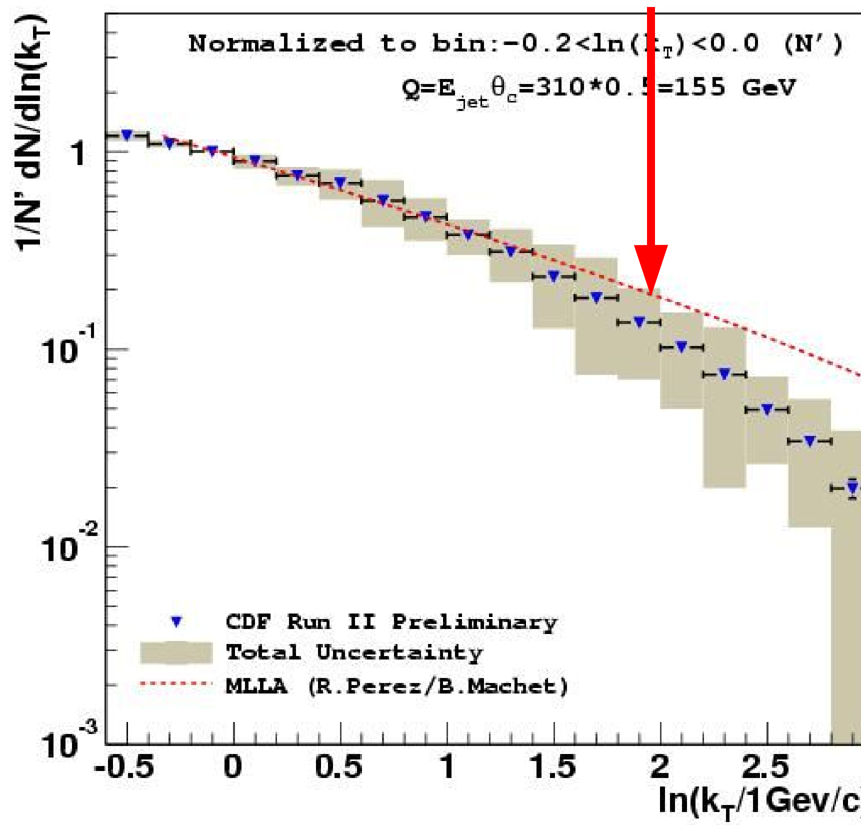


MLLA:

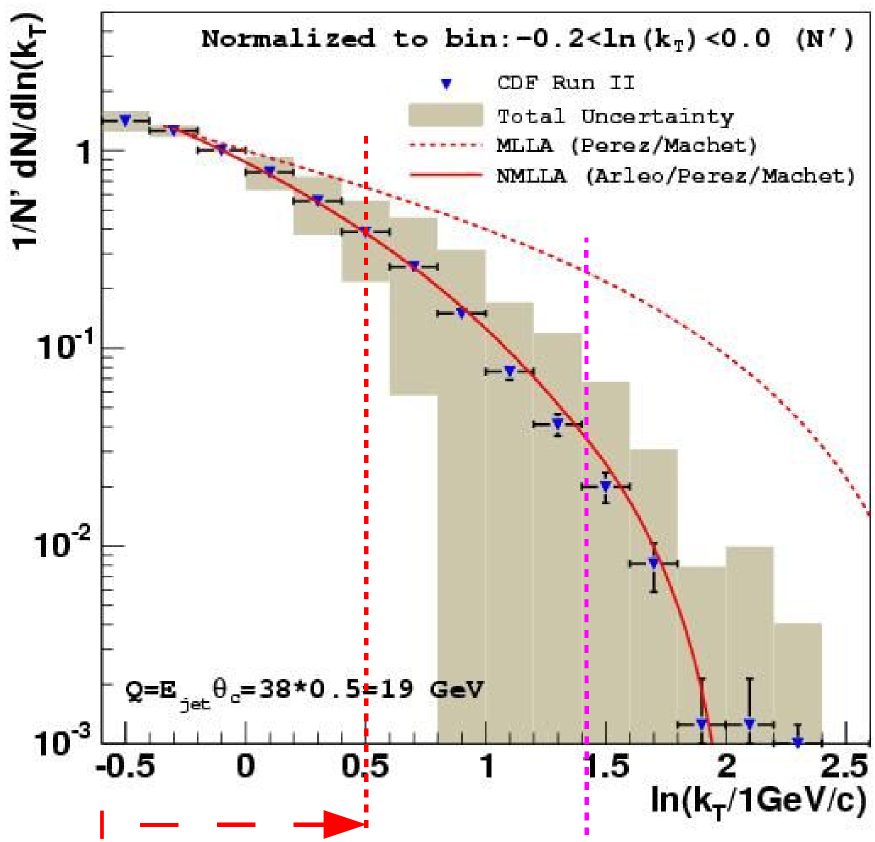
→ data indicates fewer particles with large k_T

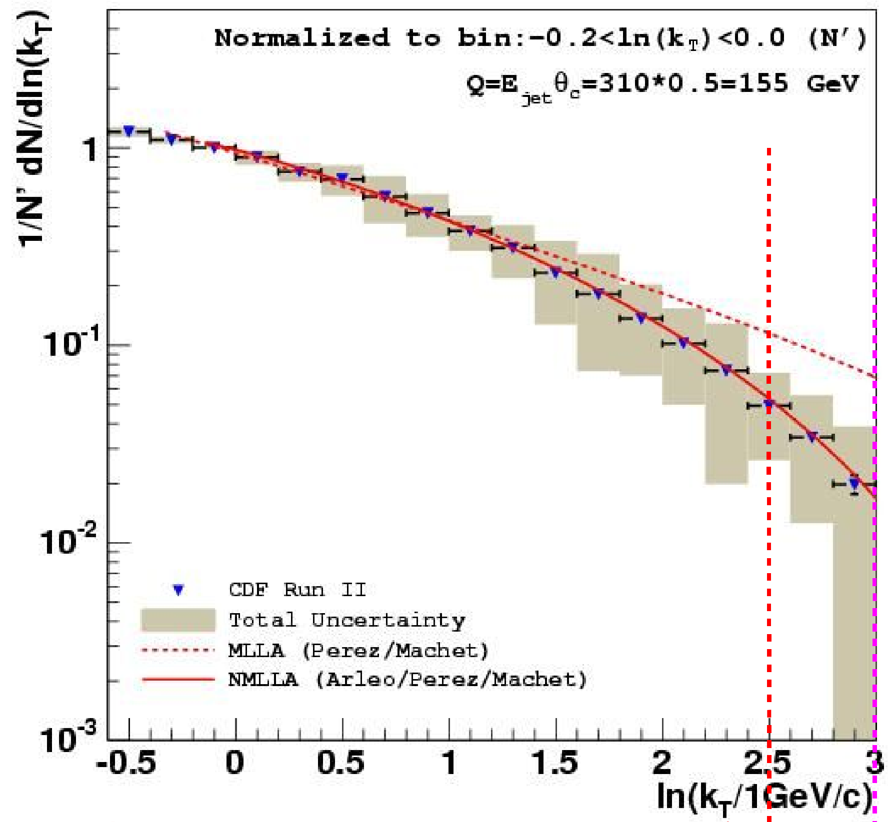
→ better agreement with increasing Energy scale Q

Let's bring NMLLA

K_T distributions

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





MLLA

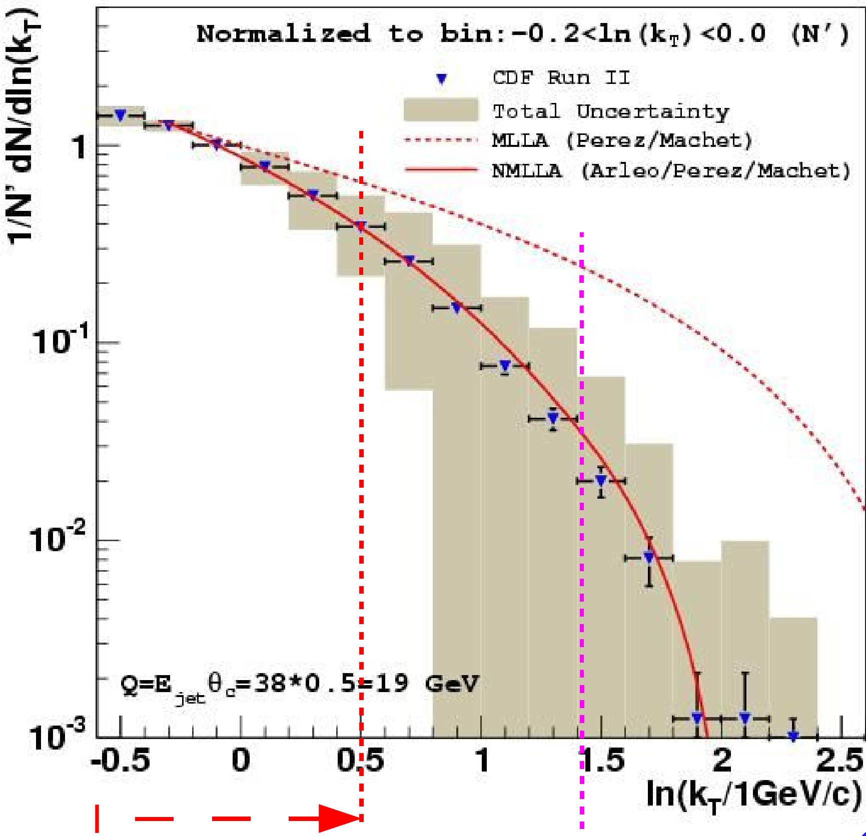
NMLLA

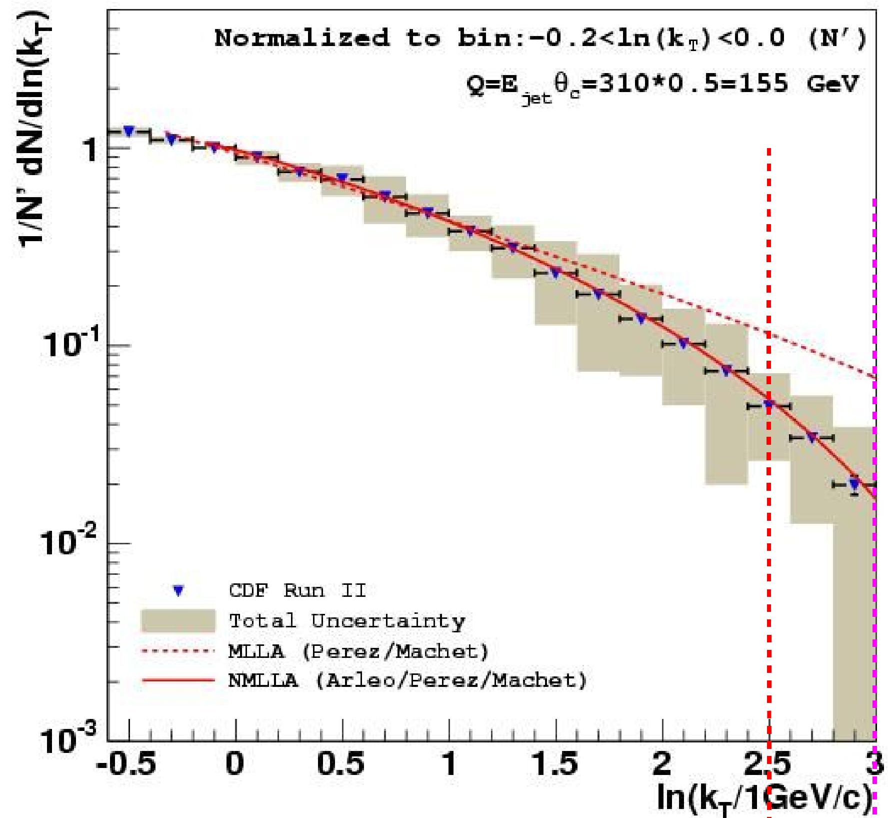
→ **NMLLA:**

very good agreement with the data at all Q's

K_T distributions

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





MLLA

NMLLA

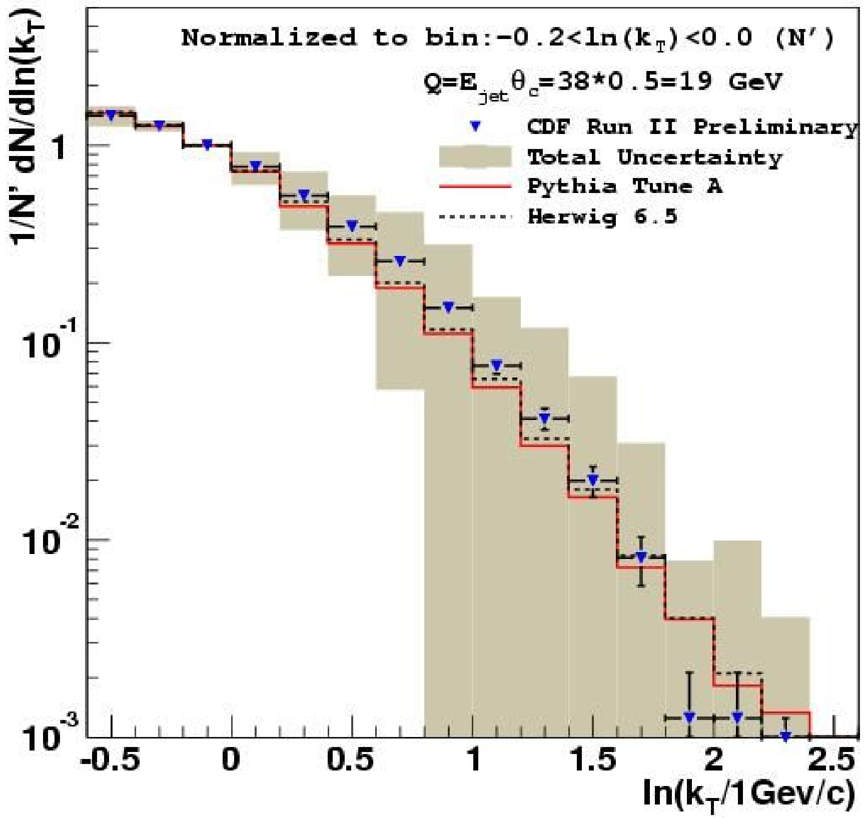
reminder: $Y=\ln(E_{jet}\theta_c/Q_{eff})$

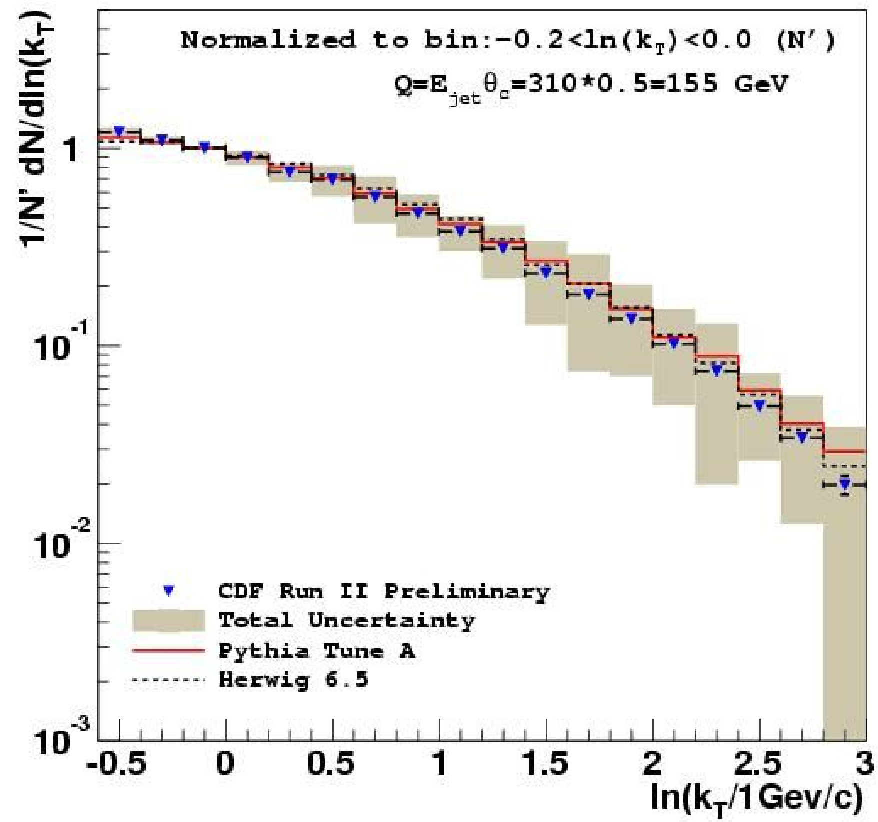
→ The validity range of the pQCD predictions increases from MLLA to NMLLA :

- 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 $y<Y-1.6$

K_T distributions

Data vs LLA Monte Carlo:





- Very good agreement between data and MC hadron level
- MC tuned to reproduce data ?

Summary & Conclusions

Momentum correlations:

- First measurement in the hadron collider environment, wide range of dijet masses
- Data follows trends of the theoretical calculations
- $Q_{eff}=137^{+85}_{-69}$ MeV extracted from the fits of the parabolic and linear terms.

An offset in the constant term observed at all energies

- Correlation clearly survives the hadronization

Kt distributions:

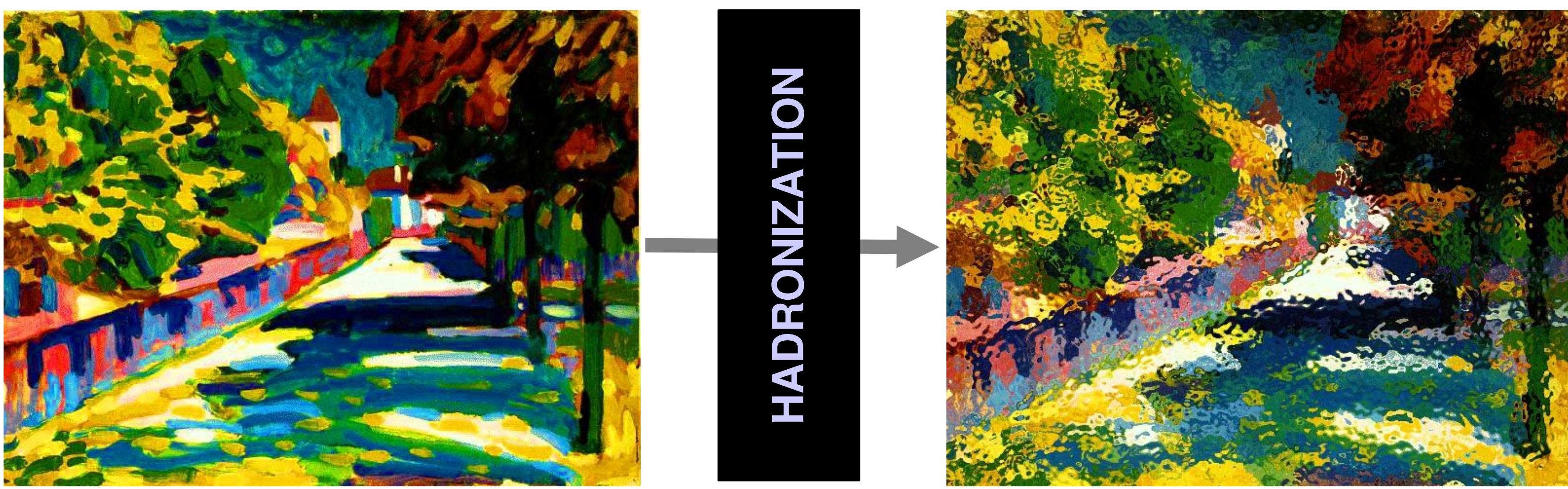
- First comparison of k_T distributions to the results of pQCD calculations
- Good agreement between data and MLLA in the soft region, excellent agreement between data and NMLLA in the entire range of kt

Overall:

- Results of both analysis indicate that the pQCD stage of the jet formation is dominant thus giving further support to the hypothesis of LPHD!
- Both analysis are in preparation for PRD

Summary & Conclusions

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



Other…

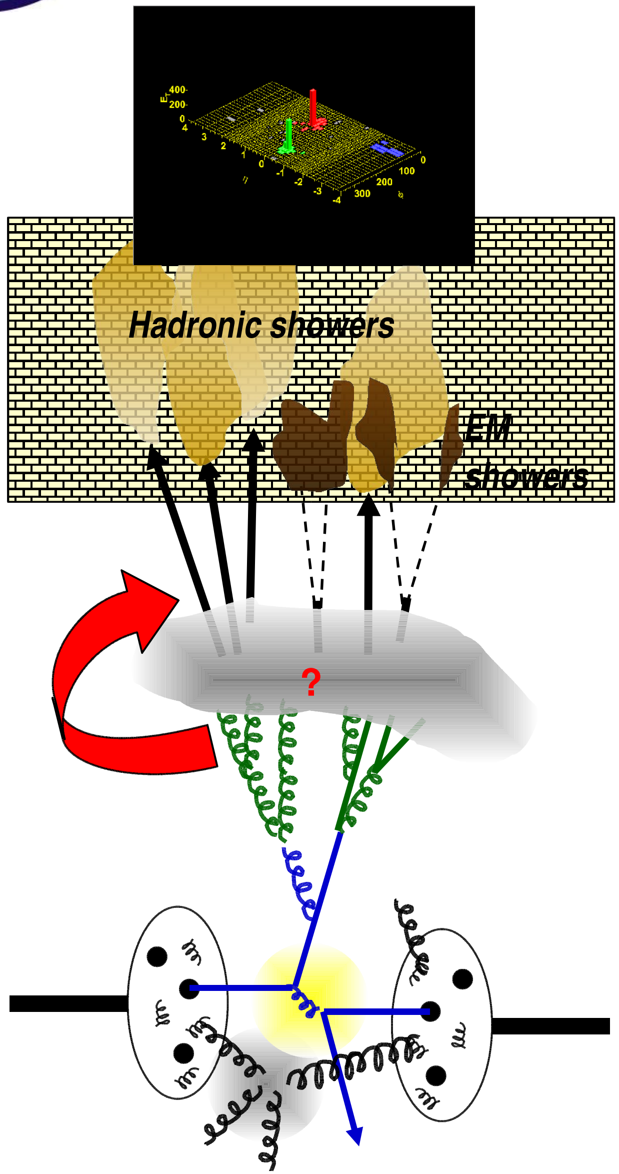
Other research and service activities:

- Event Shapes at CDF;
- Inclusive momentum distributions of tracks in jets in Run II;
- Operations of the Cherenkov Luminosity Counter (CLC);
- Developed offline software for the CLC calibration;
- Performed store-by-store CLC calibration;
- Developed tools to monitor stability of the luminosity measurement and the aging of the detector components;

More details can be found at:

www-cdf.fnal.gov/~sergo/

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

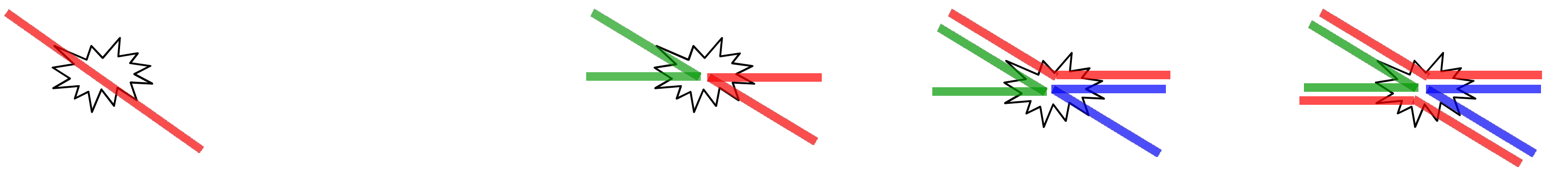
-hadronic shower for "stable" hadrons

Jet identification:

-jet finding algorithms

Event Shapes

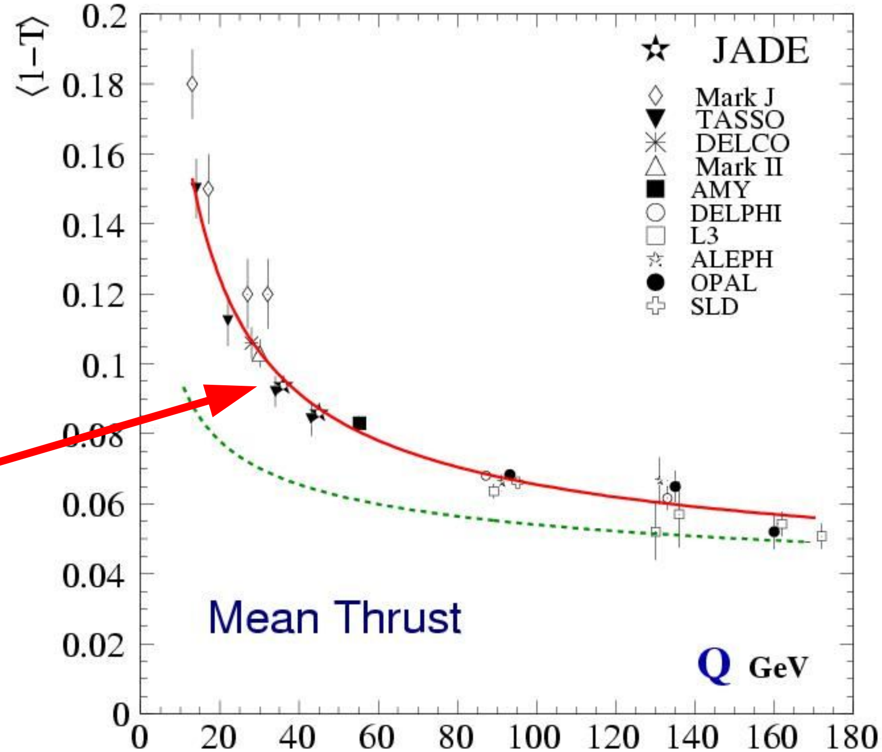
Event grows from a much richer color structure:



LEP

Tevatron

Event shapes describe the energy flow in the event.

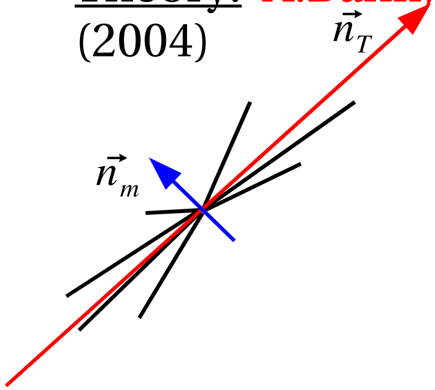


Allow to study:

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

Event Shapes

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



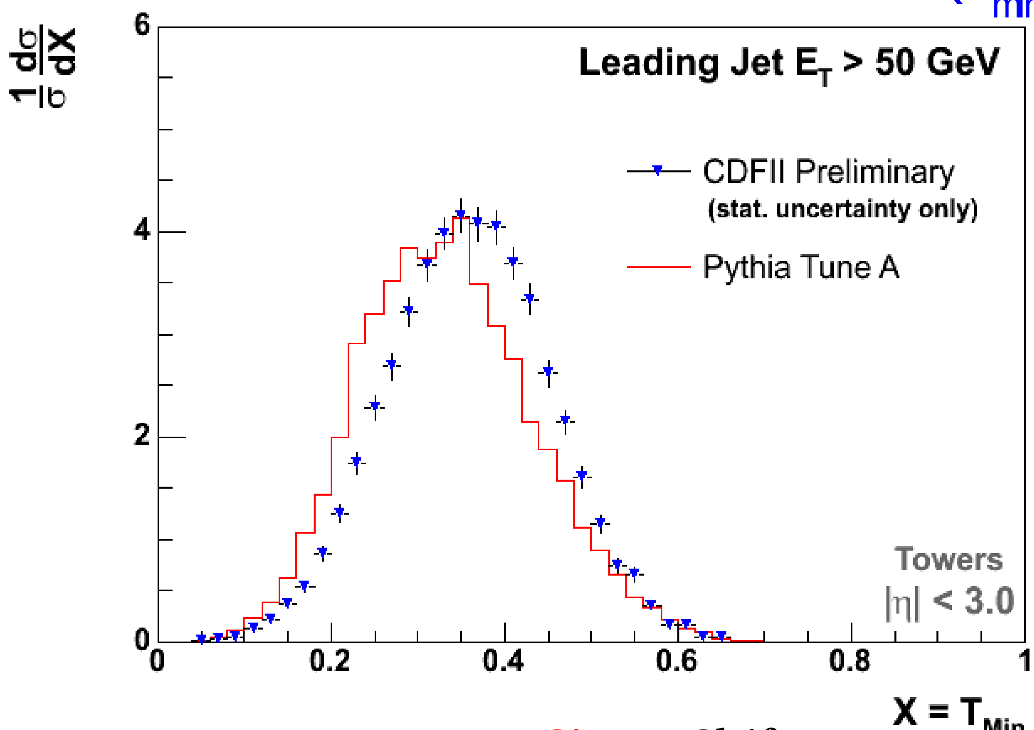
Transverse Thrust

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

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}):

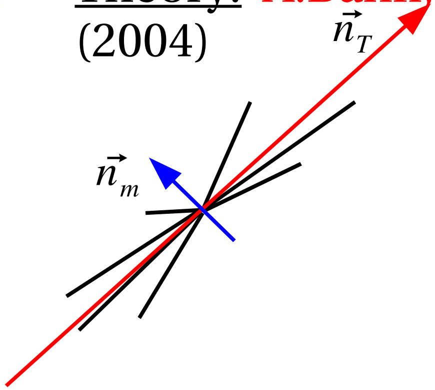


Is this real or due to some instrumental effects?

Data ≈ Detector Sim. + Shift

Event Shapes

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



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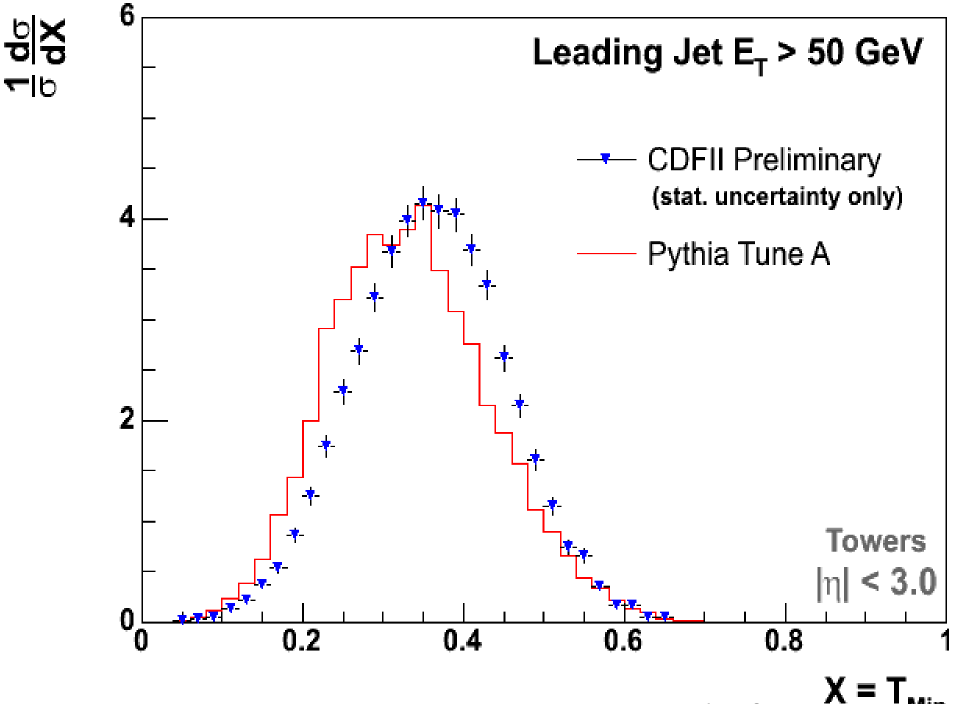
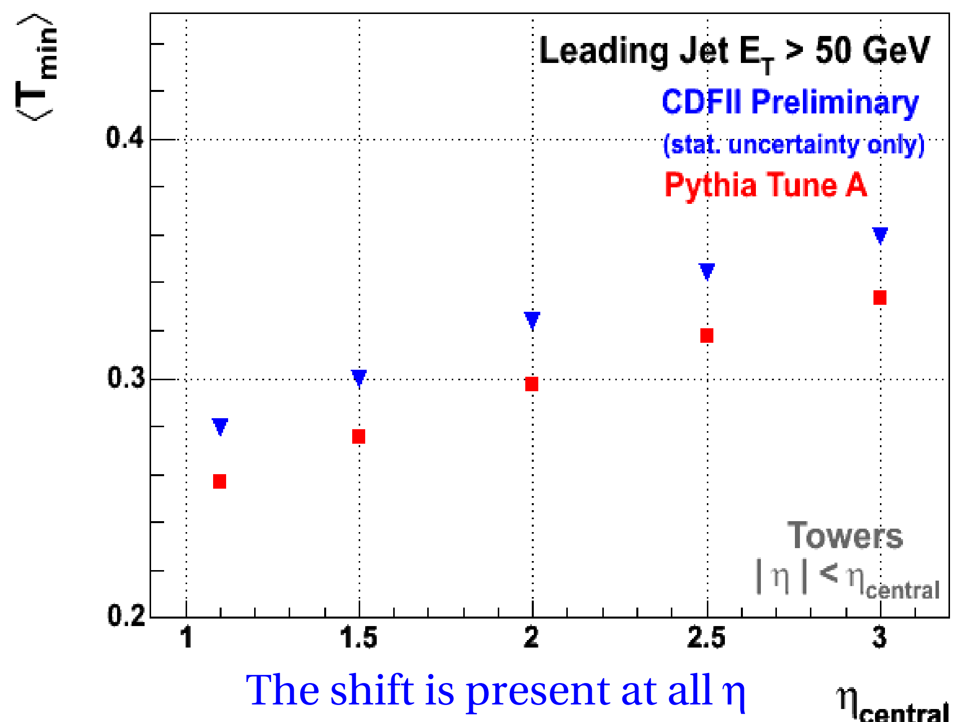


Data ≈ Detector Sim. + Shift

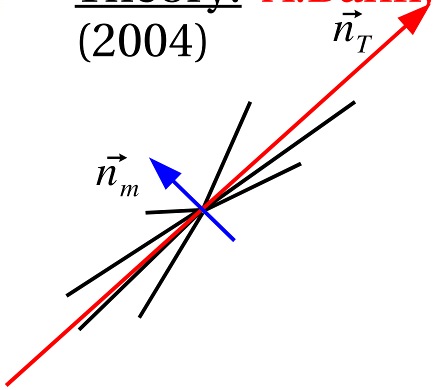


The shift is present at all η

Present in both Tracks and Towers.

Event Shapes

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



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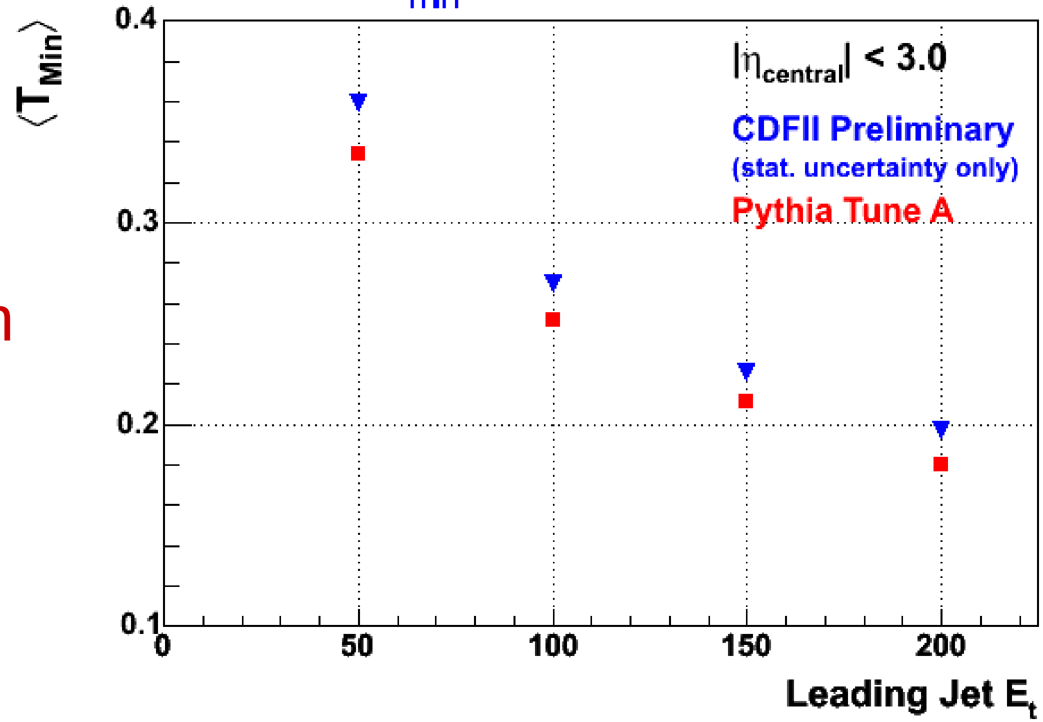
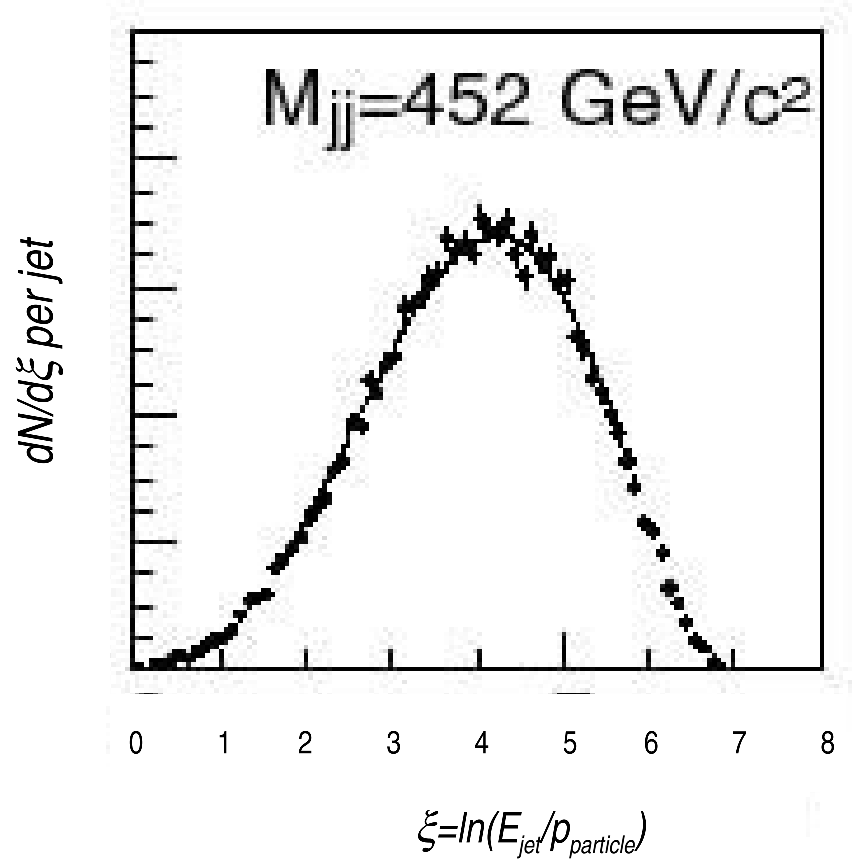
Thrust Minor (T_{min}):

How does T_{min} scale with energy?



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

- 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.

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

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

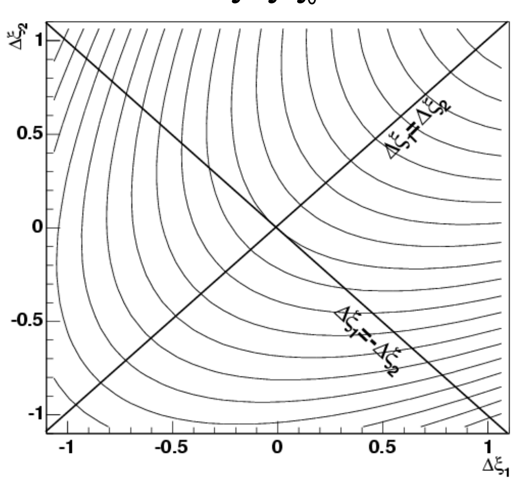
- C_0, C_1 and C_2 depend on $Y=\ln(E_{jet}\theta_c/Q_{eff})$

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

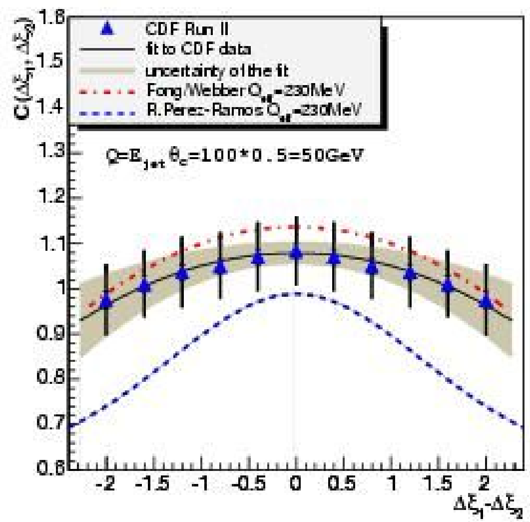
Ridge-like structure:

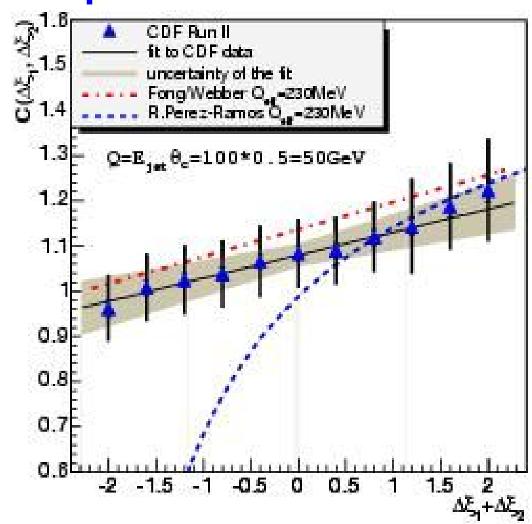
- Particles with like momenta correlate
- Correlation is stronger for soft particles

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



central diagonal profiles

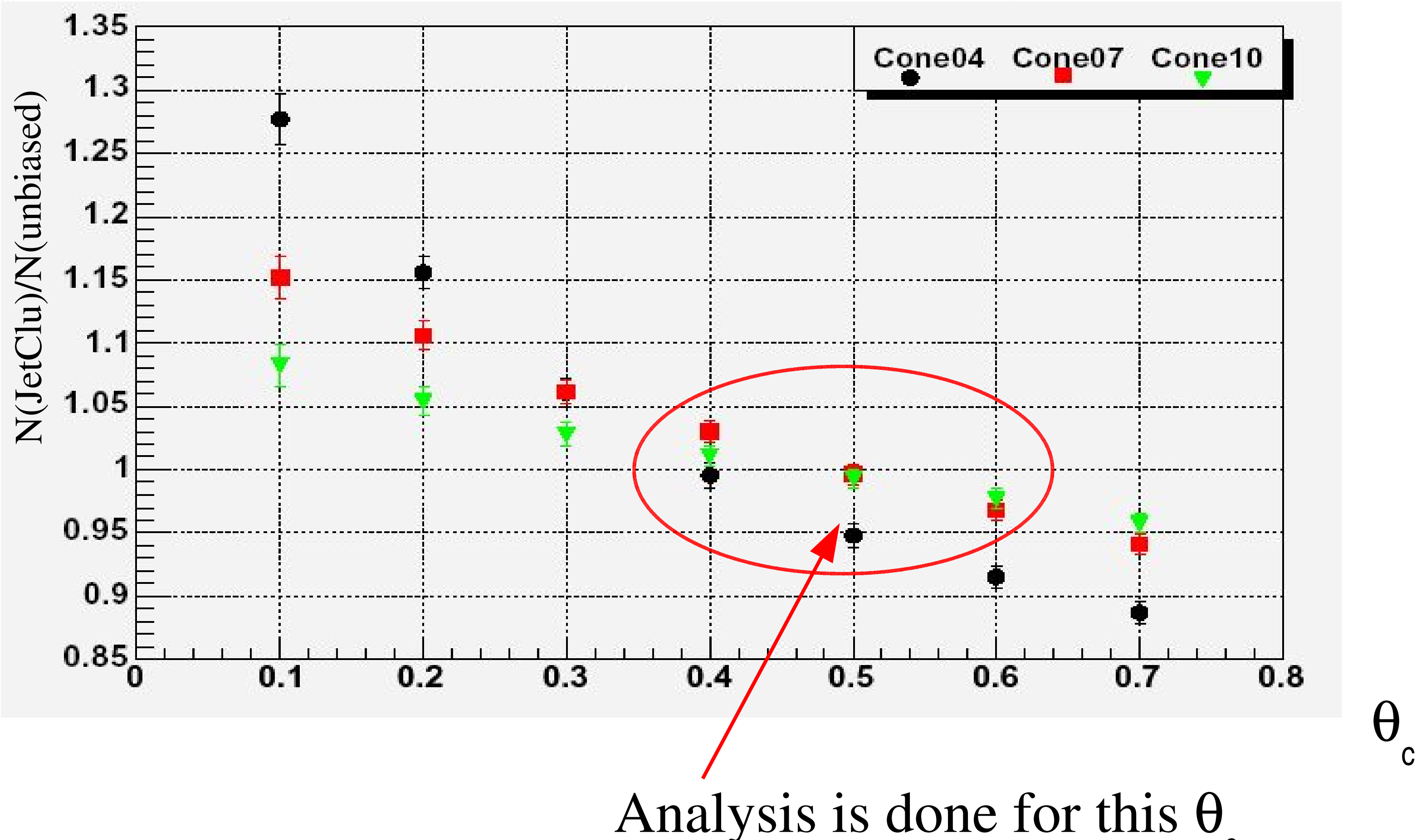




JetClu R=1.0

In MC:

- count # of particles around parton direction in unbiased sample;
- count # of particles around jet direction in sample where JetClu was used;
- compare them;

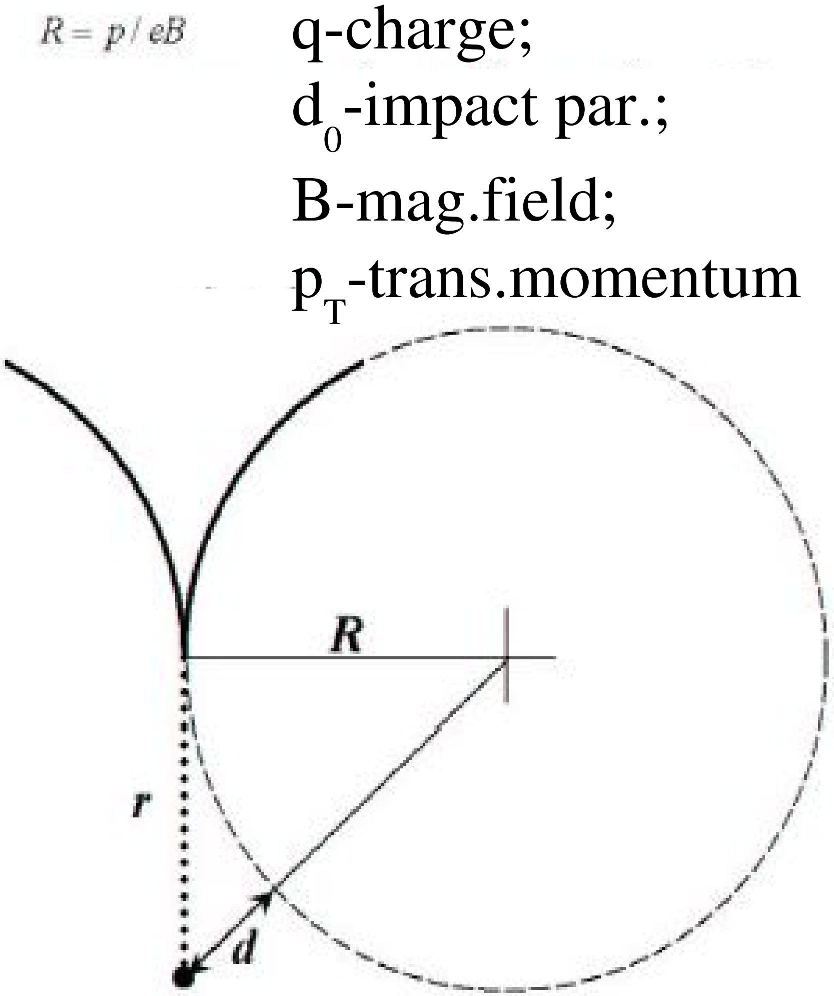


Conversions

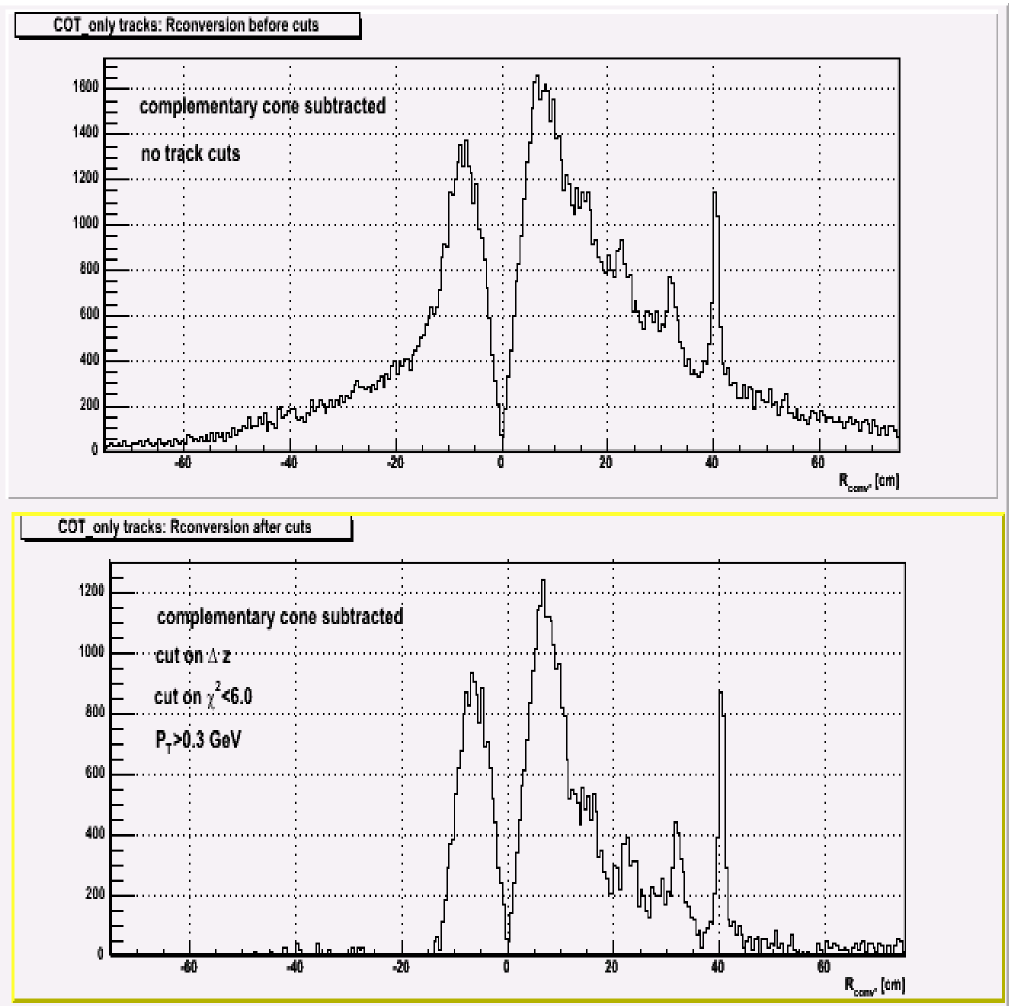
$$R_{conv}^2 = d_0^2 + \frac{d_0 q p_T}{0.15B} \approx \frac{d_0 q p_T}{0.15B}$$

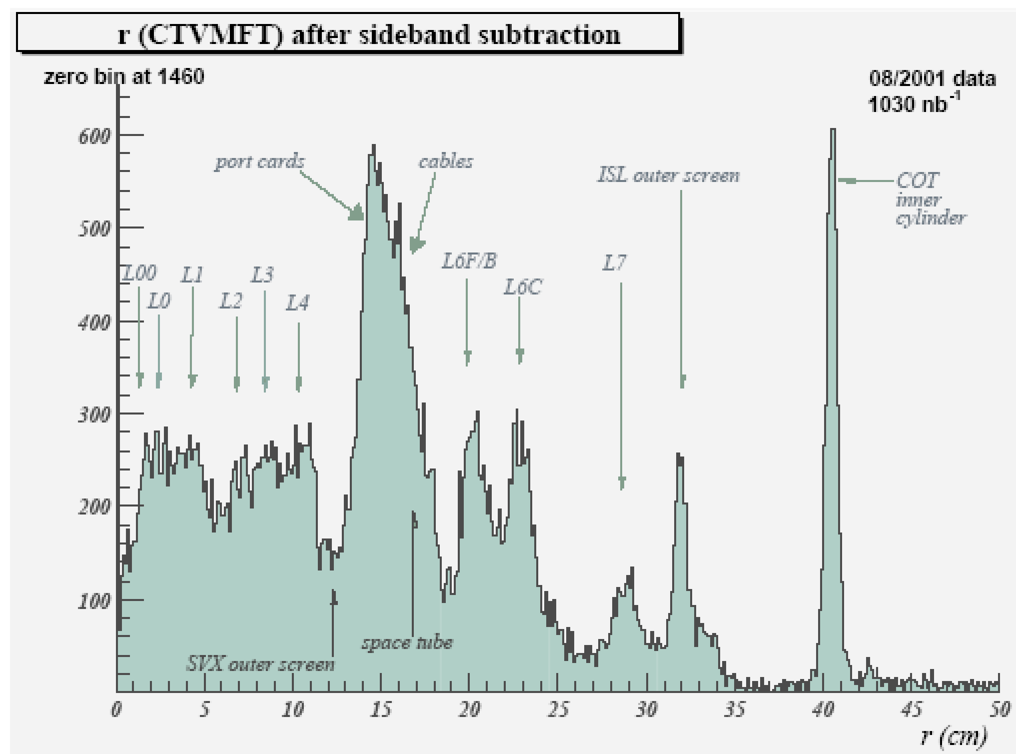
- **γ-conversions: $d_0 * q > 0$**
- **Promt tracks: $d_0 * q > 0$ or $d_0 * q < 0$ due to mismeasurement and multiple scattering**
- **Sign rule: $R_{conv} < 0$ if $d_0 * q < 0$,**
  $R_{conv} > 0$ if $d_0 * q > 0$
- **R_{conv} calculated for each track → no need to consider pairs of tracks**

q-charge;
d_0-impact par.;
B-mag.field;
p_T-trans.momentum



Conversions





Conversions reconstructed using R_{conv}

Track Cuts

Multiplicity and momentum distributions before and after track cuts. CDFSim tracks are compared to the Pythia Tune A charged hadrons