Jet Fragmentation Studies at CDF

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Soft QCD Studies at CDF

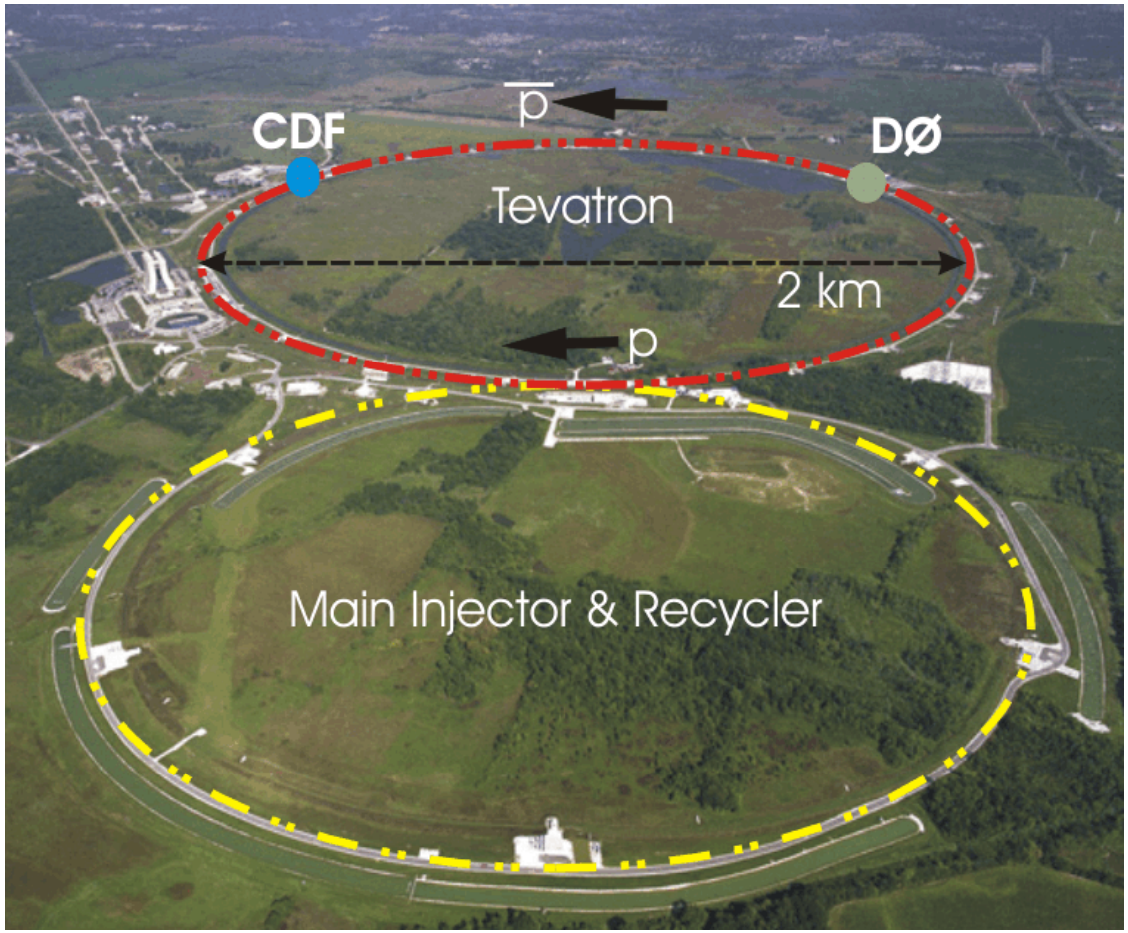
- In this talk
  - Jet Fragmentation
    - Inclusive particle momentum distribution
    - Particle multiplicities in Quark & Gluon jets
    - Two-particle momentum correlations
    - k_T distribution of particles

Data compared to Theory & MC

- Not covered in this talk
  - Jet & Event Shapes
    - Inclusive jet shapes
    - B-jet shapes
    - Event shapes (coming soon)
  - Underlying Event
    - Underlying event in dijets
    - Underlying event in Drell-Yan (coming soon)

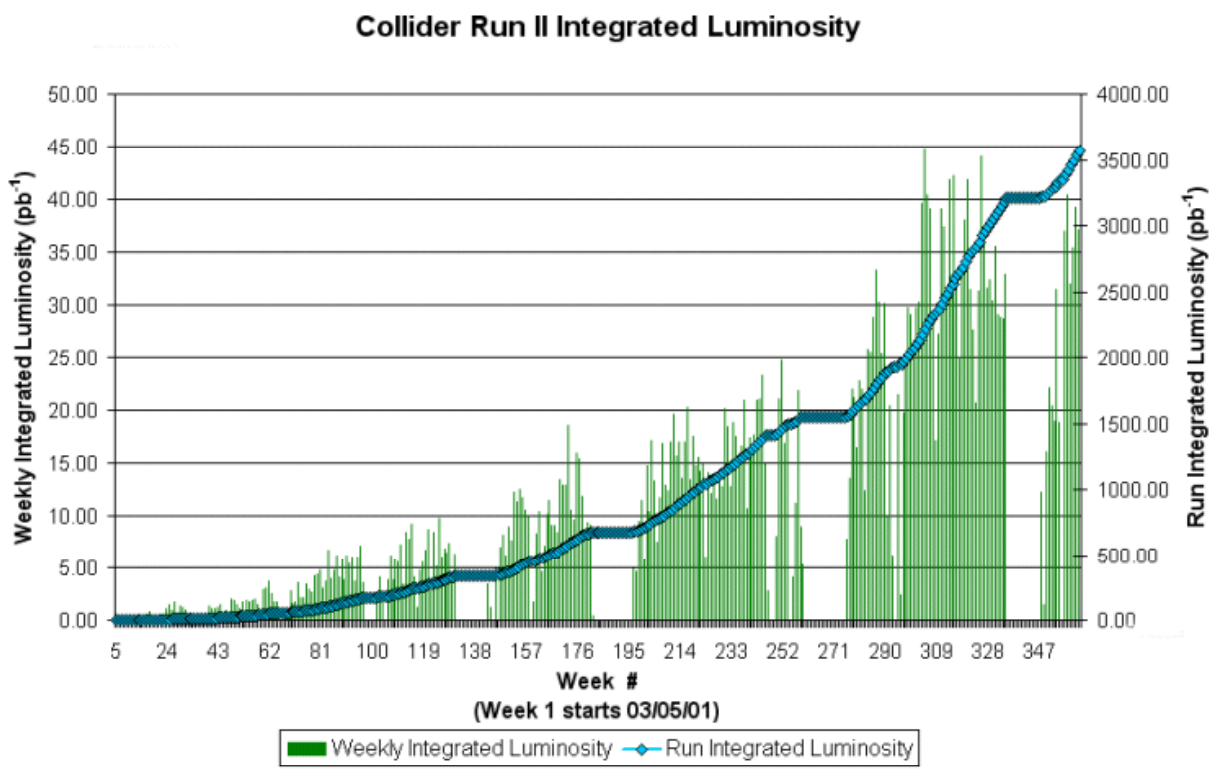
Data compared to MC Pythia tuning

Tevatron in Run II



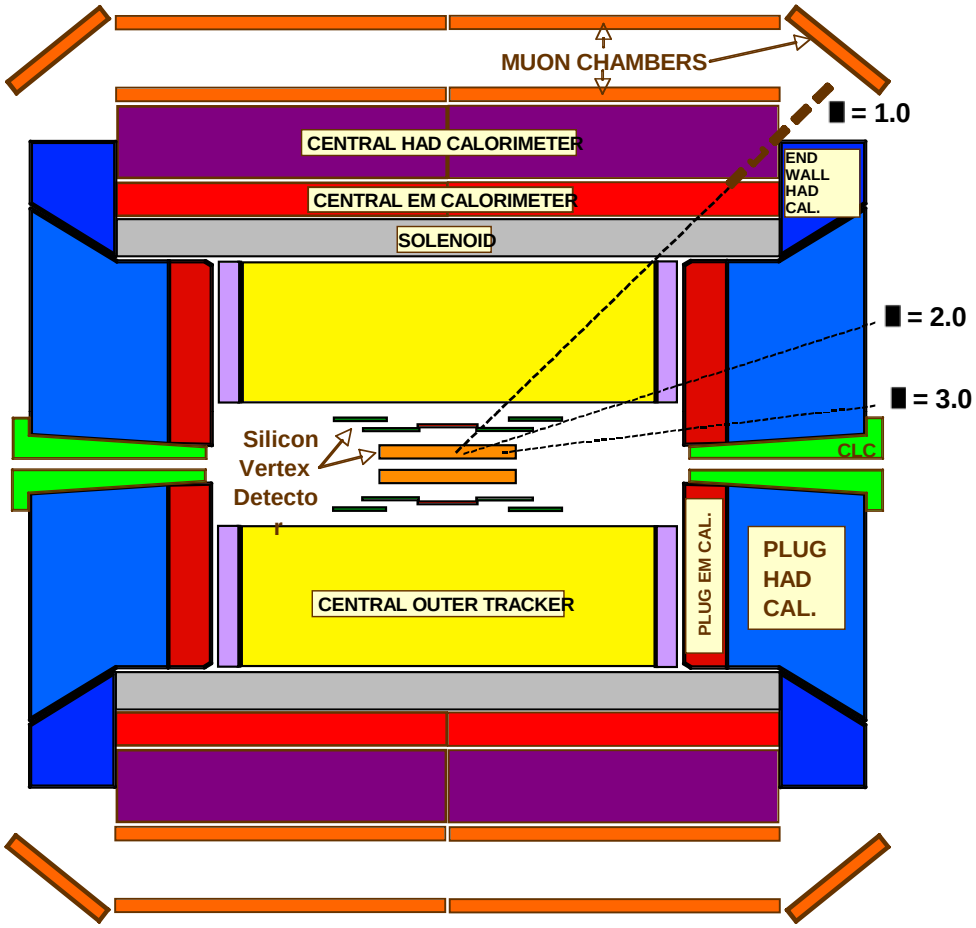
- Proton-antiproton collisions at $\sqrt{s}=1.96$ TeV
- 36×36 bunches
- Collisions every 396 ns
- Peak luminosity $298*10^{30}$ $cm^{-2}s^{-1}$
- Two experiments: CDF & DØ

Tevatron Performance



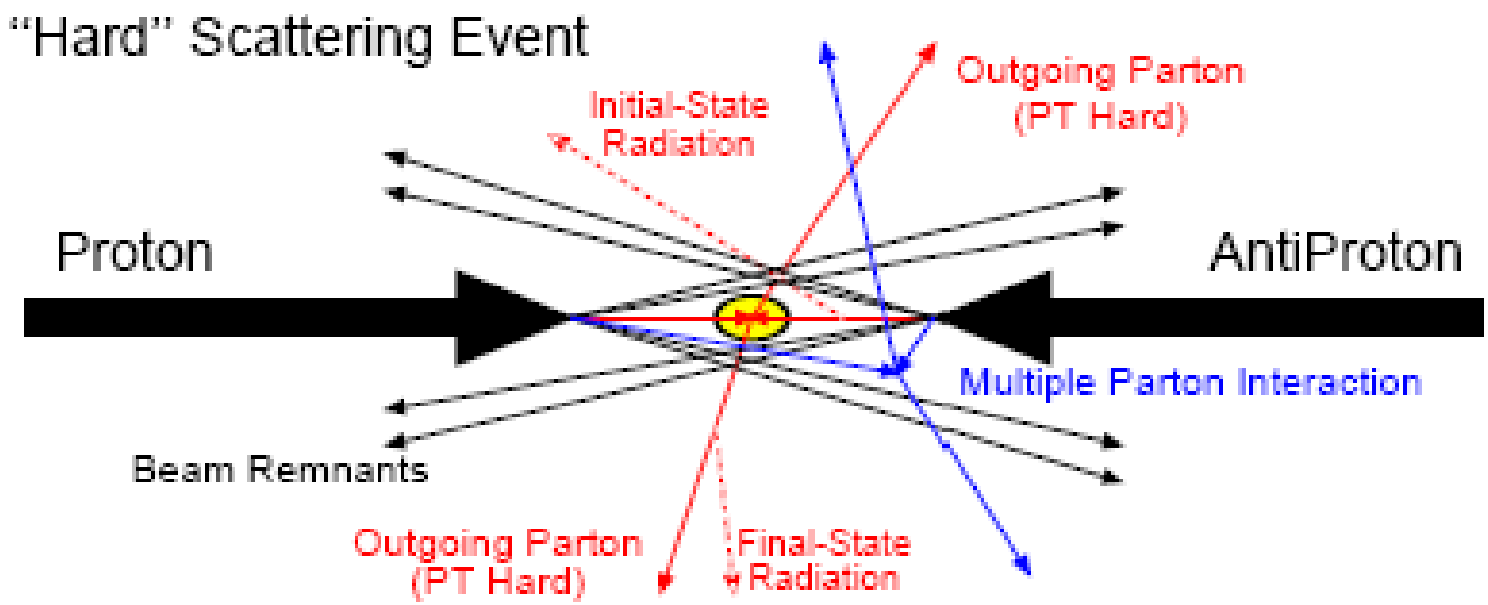
- Delivered luminosity
  - Current: 3.7 fb^{-1} per experiment
  - Goal by 2009: 5-8 fb^{-1}

CDF Detector in Run II



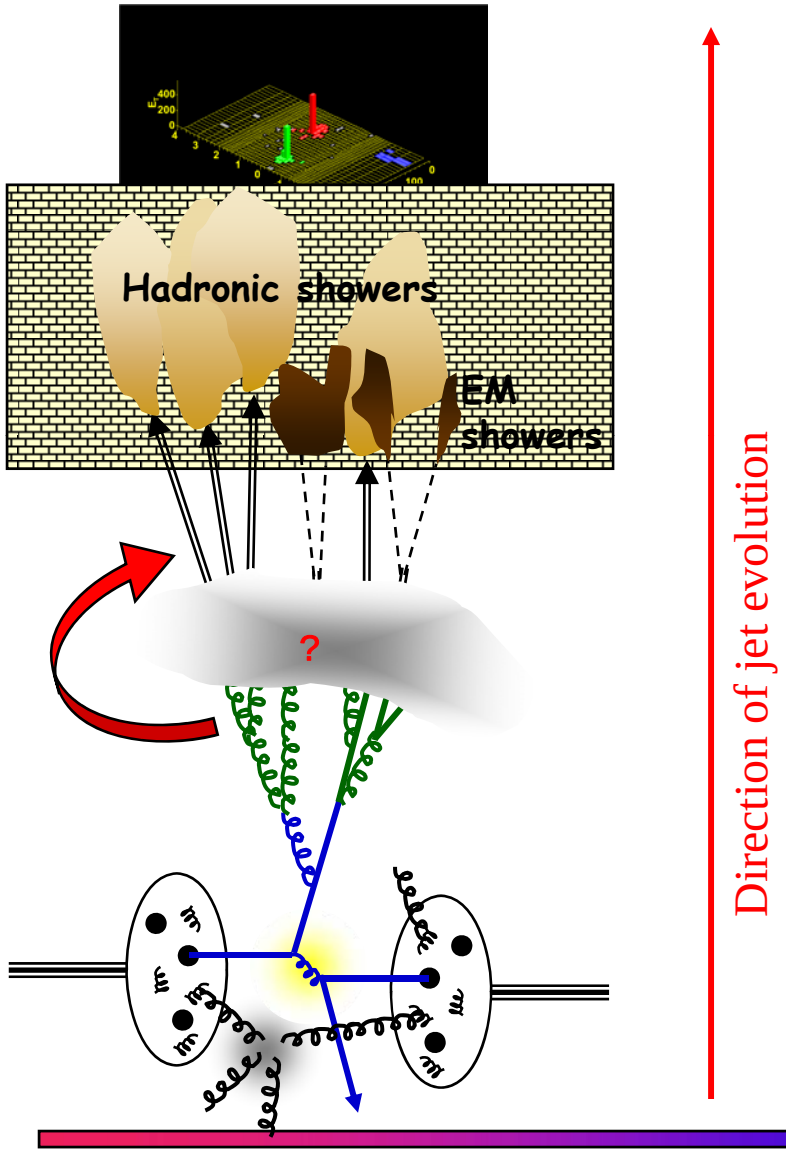
- Multipurpose detector, classic design
  - Silicon Vertex Detector
  - Wire tracker
  - Solenoid
  - Pre-shower detector & TOF
  - EM Calorimeter
  - HAD Calorimeter
  - Muon chambers
- Broad Physics program
  - QCD
  - EWK
  - Top
  - B-physics
  - Higgs & New Physics searches

Hadron Collider Environment



- Hahdron-hadron collisions is a complex environment for jet fragmentation studies
  - Need to deal with <u>underlying event</u>
    - Multiple parton interactions
    - Beam remnants
    - Initial state radiation

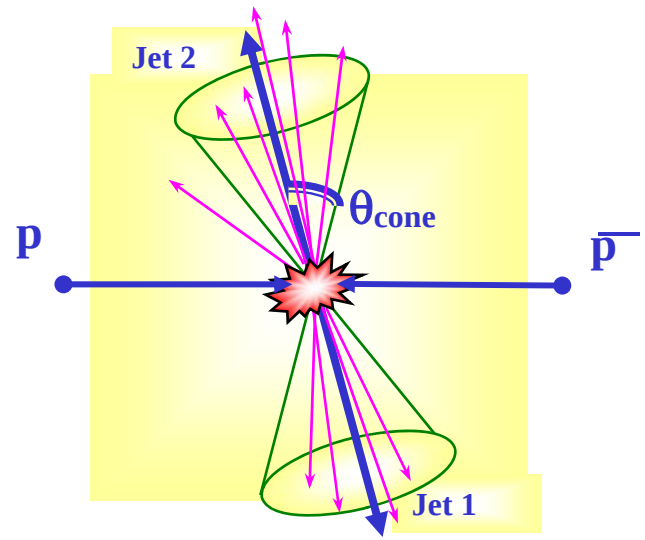
Partons, Hadrons, Jets…



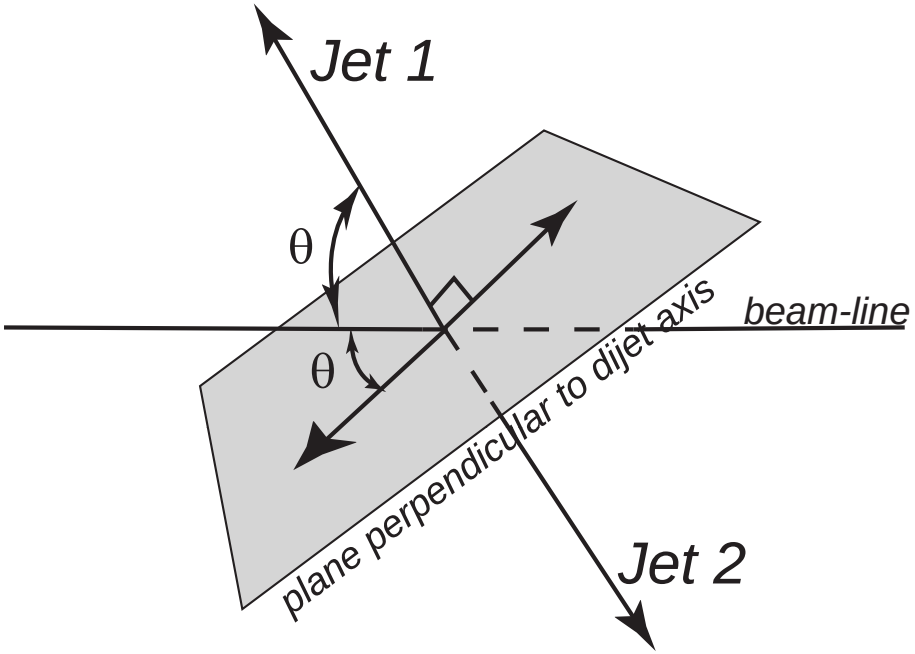
- Jet identification
  - Jet clustering algorithms
- Hadronization
  - Phenomenalogical models
- Soft final state radiation
  - pQCD approximation in all orders
- Hard scattering: 2→X
  - pQCD exact matrix element at LO, sometimes NLO
- Pick two partons and their momenta
  - Parton distribution functions (PDF's)

Jet Fragmentation Analysis at CDF

- Theoretical framework
  - Partons: MLLA & extensions
  - Local Parton Hadron Duality (LPHD) hypothesis
    - connects partons with hadrons: $N_{hadron}=K_{LPHD}*N_{parton}$
    - Naïve picture: parton~hadron (if $p>m_{\pi}$)
- Select two well-balanced jets (or γ+jet)
  - Need to know fraction of gluon jets
    - PDF+Pythia/Herwig
- Do analysis in dijet (or γ+jet) rest frame
  - $E_{jet}=1/2M_{jj}$ (or $1/2M_{\gamma j}$)
- Do analysis for small opening angles
  - θ_C~0.3-0.5 rad
  - Theory is (strictly speaking) valid for soft and collinear partons
  - Limits contribution from underlying event
- Energy scale is $Q = 2E_{jet}\tan(\theta/2) \approx E_{jet}\theta_C$
- Subtract contribution from underlying event and secondary interactions



Subtracting Underlying Event



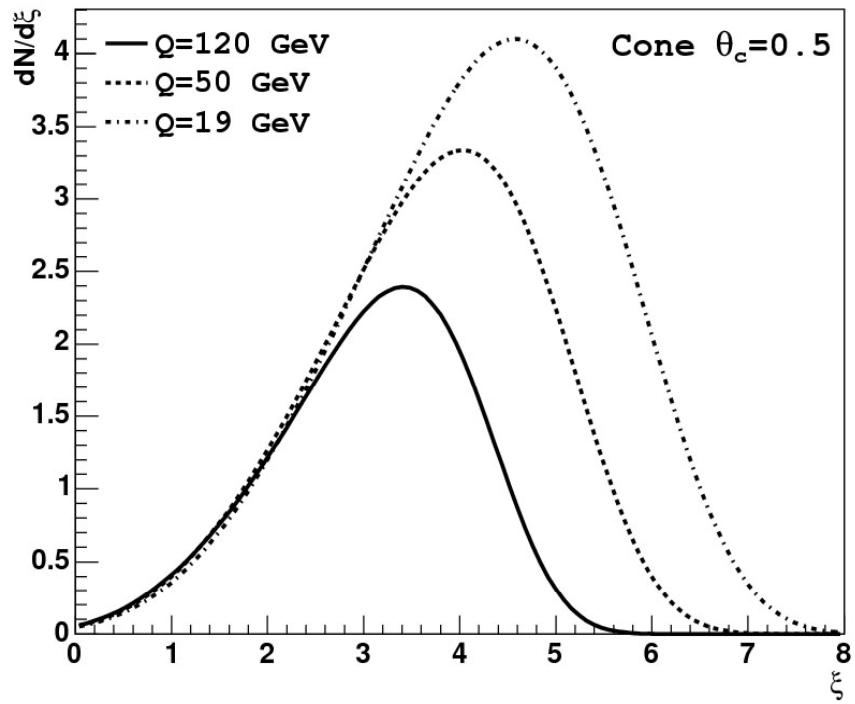
- Dijet rest frame
- Two complementary cones
  - 90° away from dijet axis
  - Same polar angle θ as dijet axis with respect to beam line
  - Statistically collect same contribution from underlying event and secondary interactions as cones around jets

Inclusive Momentum Distribution

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

$$\xi = \ln(\frac{1}{x}), \quad x = \frac{p}{E_{jet}}$$

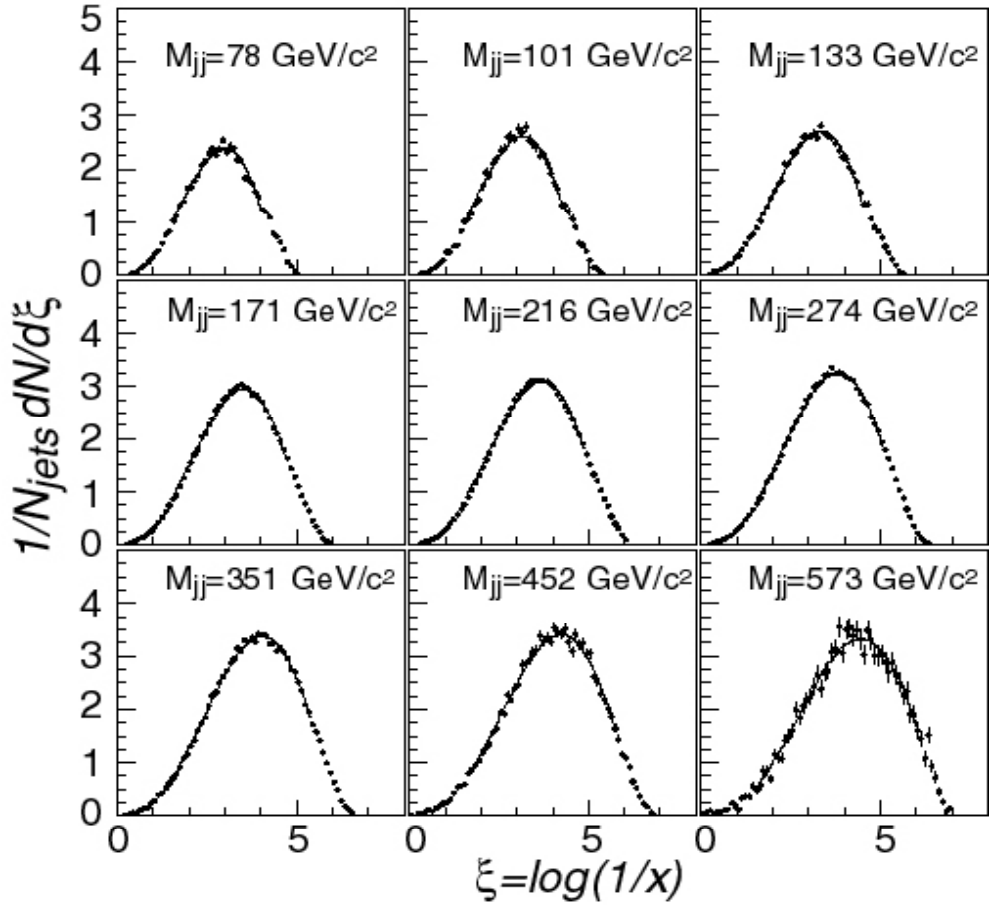
$$Y = \ln(\frac{Q}{Q_{eff}}), \quad Q = E_{jet}\theta_c, \quad Q_{eff} = Q_{cutoff} \sim \Lambda_{QCD}$$



- Previous measurements
  - Extensive studies at e^+e^- and e^+p
  - Limited to quark jets only
  - Very good agreement with MLLA
- CDF
  - Never done in hadron-hadron collisions before…

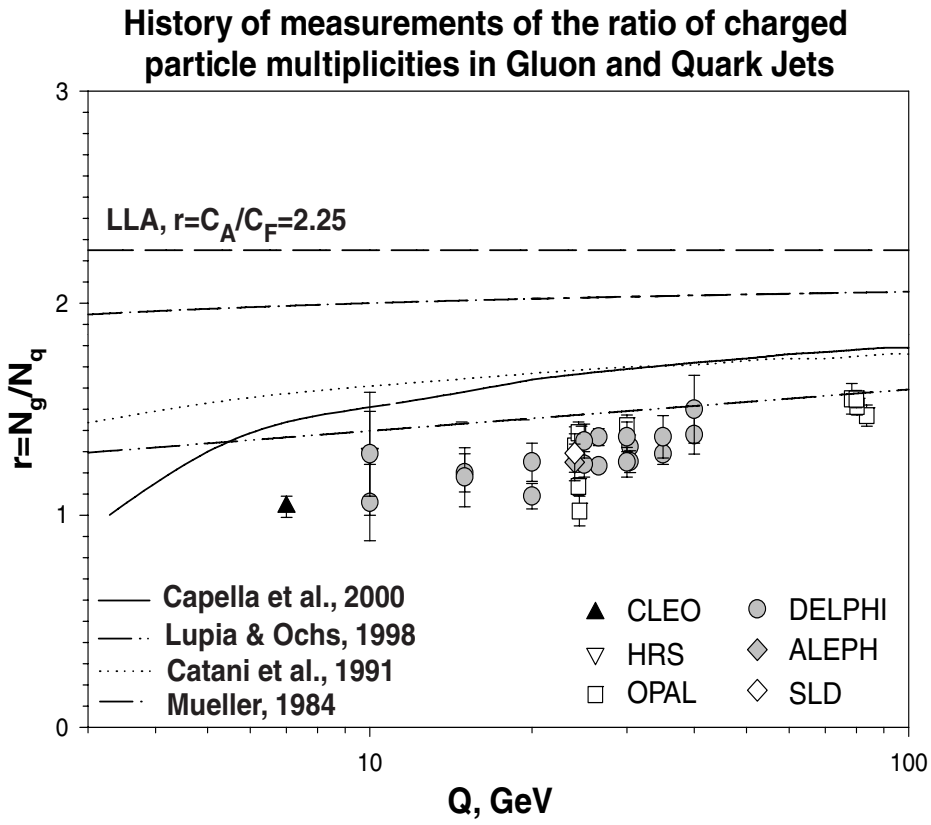
Inclusive Momentum Distribution at CDF

- CDF analysis
  - θ_c~0.3-0.5 rad
  - 9 M_{jj} bins
    - 78 GeV/c^2<$|M_{jj}|$<573 GeV/c^2
  - Fractions of gluon jets
    - From 65% ($|M_{jj}|$~70 GeV/c^2) to ~20% ($|M_{jj}|$~600 GeV/c^2)
- CDF results
  - Two parameter MLLA fit:
    - Q_{eff}=230±40 MeV
    - K_{LPHD}=0.56±0.10
  - Works surprisingly well for wide range of dijet masses
  - Evolution of peak position with Q agrees with e^+e^- and e^+p very well



Fit range:
$1.6<\xi<\ln(Q/Q_{eff})\sim\ln(Q/0.25)$

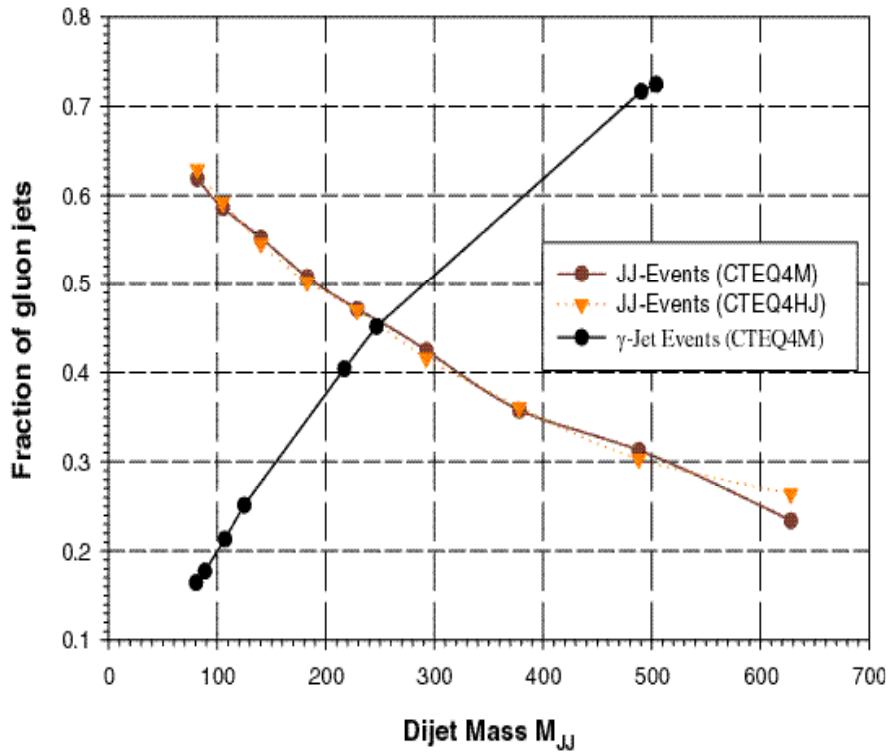
Quark vs Gluon Jets



- Theory
  - From r=2.25 (LLA, $E_{jet} \to \infty$)
  - To r~1.3-1.8 (3NLLA)
- Experiment (e^+e^-)
  - 1991: r=1.02±0.07 (OPAL)
  - 2001: r=1.42±0.05 (OPAL)
  - Illustrates evolution of our understanding of gluon jets
    - 3-jet events
    - choice of correct energy scale is non-trivial
- CDF
  - Gluon jets are copiously produced
  - Can we do it?

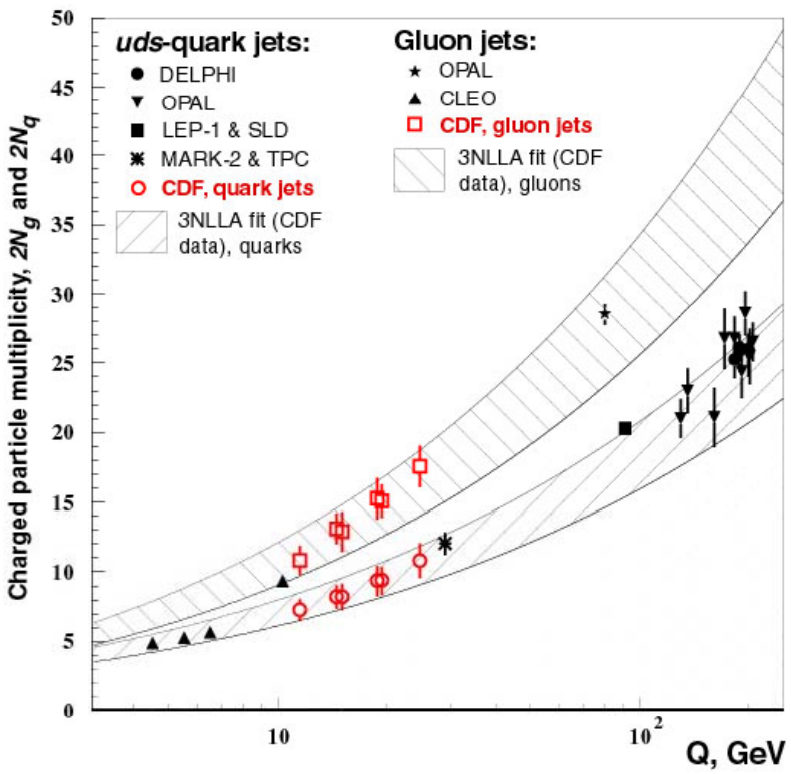
Particle Multiplicities in Quark and Gluon Jets

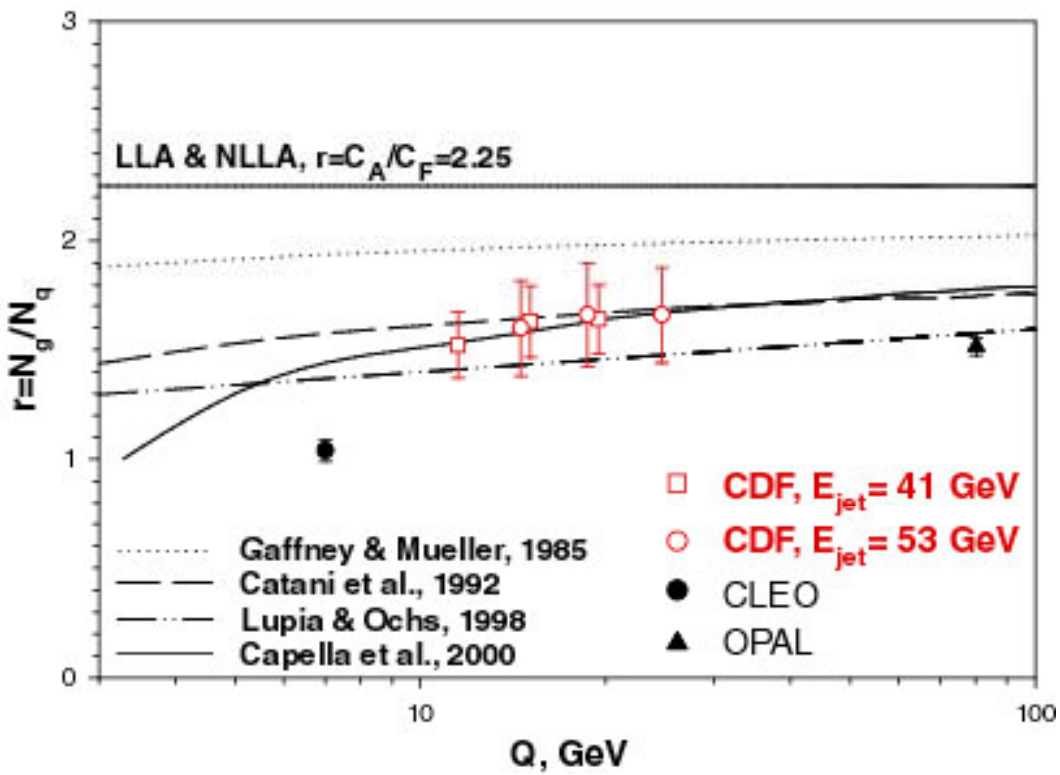
- How can we do that CDF?
  - Compare di-jet and γ+jet
  - Extract properties of Q & G jets
    - Two equations & two unknowns
    - Obtain fraction of gluon jets from PDF+MC



Particle Multiplicities in Quark and Gluon Jets

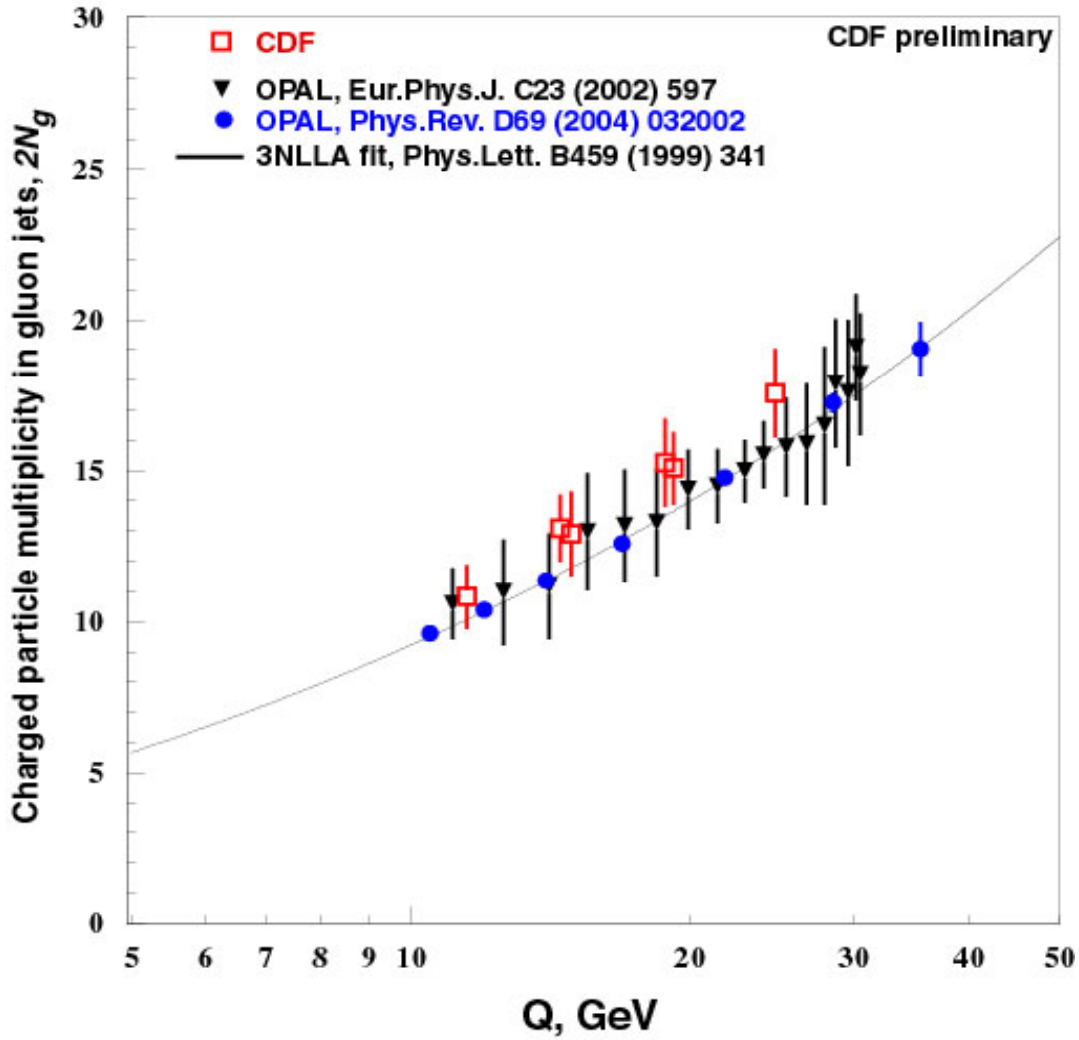
- CDF data agree well with 3NLLA & LEP (model-independent results)
  - $r=1.64\pm0.17$ at $Q=19$ GeV
  - Confirms $Q\approx E_{jet}\theta_C$ scaling:
    - $E_{jet1}\neq E_{jet2}$ and $\theta_1\neq\theta_2$, but $E_{jet1}\theta_1=E_{jet2}\theta_2 \Rightarrow N_1(E_{jet1}\theta_1)=N_2(E_{jet2}\theta_2)$





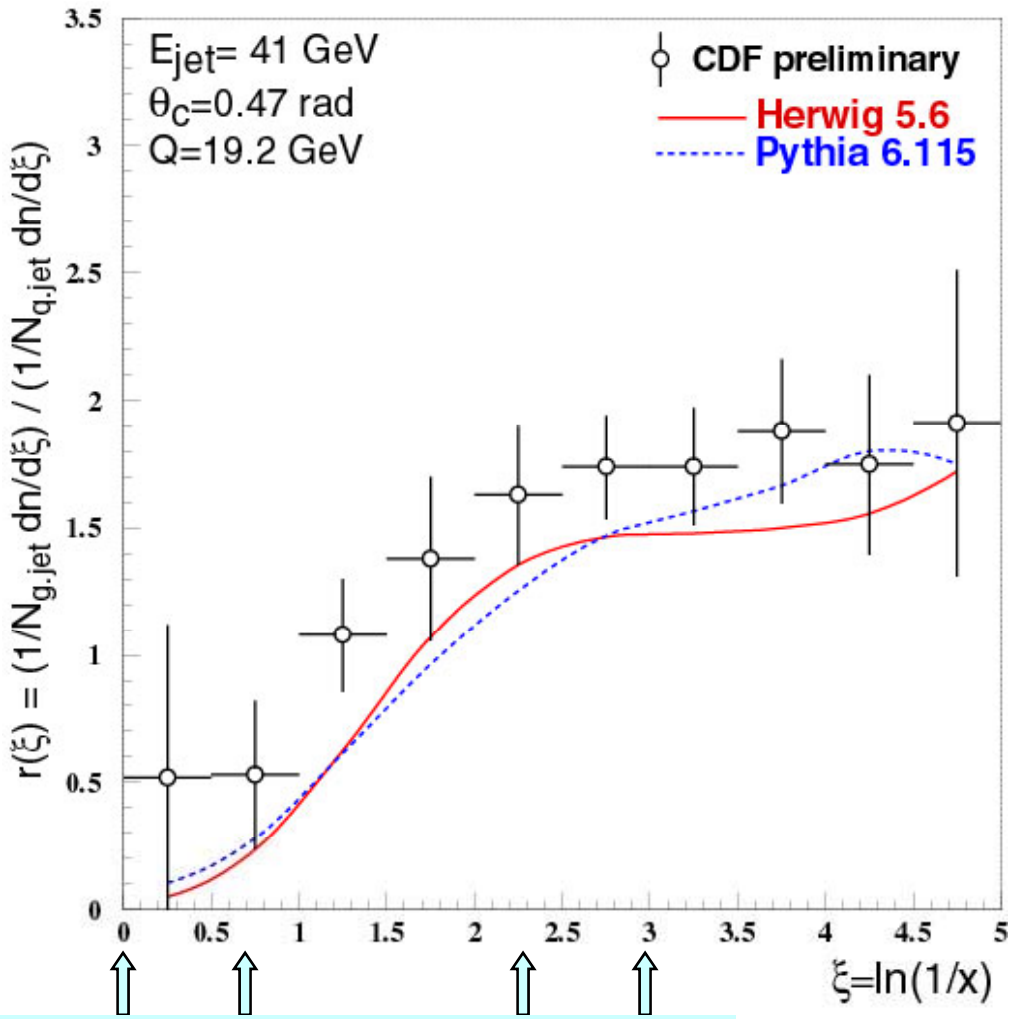
Particle Multiplicity Gluon Jets

- CDF data for gluon jets agree with model-dependent results from OPAL



Ratio of Inclusive Momentum Distributions

- r(ξ)~1.8 for soft particles (large ξ)
  - Expected from theory
- Data vs MC
  - MC qualitatively reproduces data



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

Two-particle Momentum Correlations

- Theory
  - Fong & Webber, Phys.Lett. B241:255 (1990)
  - R.Perez-Ramos, JHEP 0606, 019 (2006)

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

$$Y=\ln(\frac{Q}{Q_{eff}})=\ln(\frac{E_{jet}\theta_c}{Q_{eff}})$$

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

  - $R(\xi_1,\xi_2)$ mixes together <u>momentum correlations</u> and <u>multiplicity fluctuations</u>

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

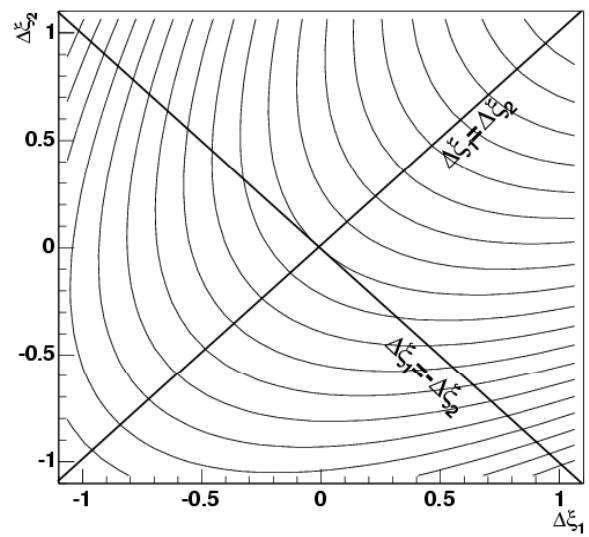
  - To de-couple momentum correlations and multiplicity fluctuations we use distributions normalized to unity (F is taken from theory):

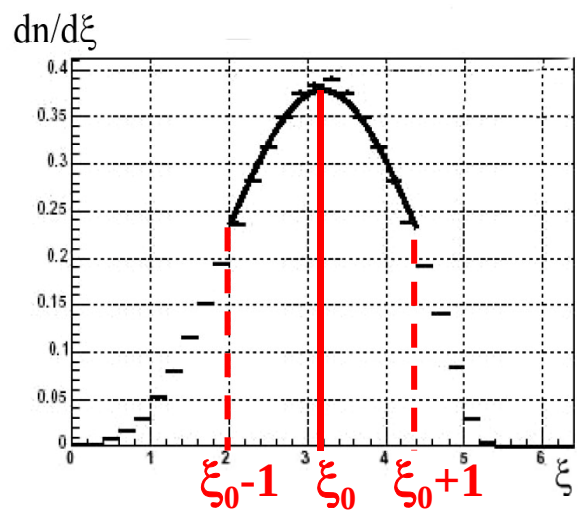
$$C(\xi_1,\xi_2)=\frac{\frac{d^2n}{d\xi_1 d\xi_2}}{\frac{dn}{d\xi_1}*\frac{dn}{d\xi_2}}=\frac{\langle N\rangle^2 R(\xi_1,\xi_2)}{\langle N(N-1)\rangle}=\frac{R(\xi_1,\xi_2)}{F}=C_0(Y)+C_1(Y,\Delta\xi_1+\Delta\xi_2)+C_2(Y,\Delta\xi_1-\Delta\xi_2)$$

Two-particle Momentum Correlations

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

- Ridge-like structure
  - Particles with like momenta correlate
  - Correlation is stronger for soft particles
- OPAL measurement (Phys.Lett.B287,401)
  - Only quark jets
  - Trends with energy not studied
  - Large angles considered ($\theta_c=\pi/2$)
  - OPAL data can't be described by NLLA with reasonable choice of Q_{eff}
- CDF measurement
  - θ_c=0.5, 66 GeV/c^2<M_{jj}<563 GeV/c^2

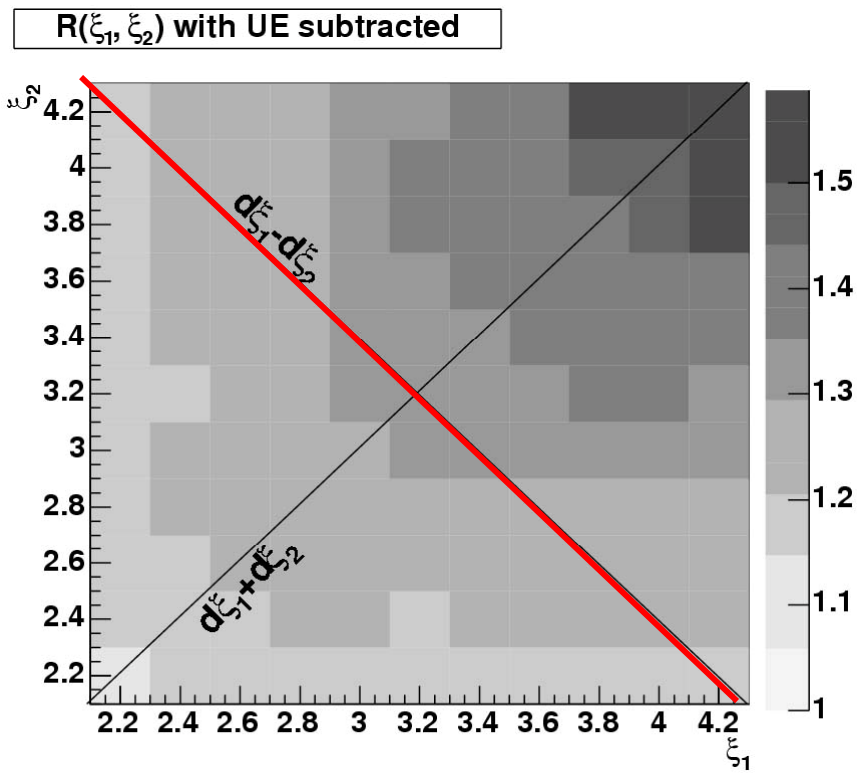


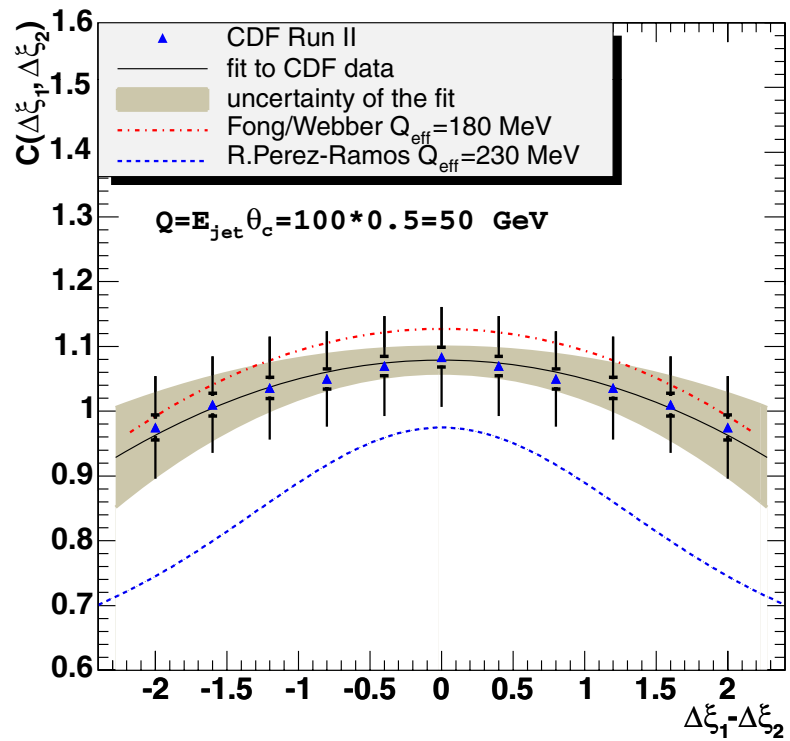


Two-particle Momentum Correlations

- Hadron correlations follow pattern predicted by Fong/Webber

$$C(\xi_1,\xi_2) = C_0(Y) + \cancel{C_1(Y,\Delta\xi_1+\Delta\xi_2)} + C_2(Y,\Delta\xi_1-\Delta\xi_2)$$

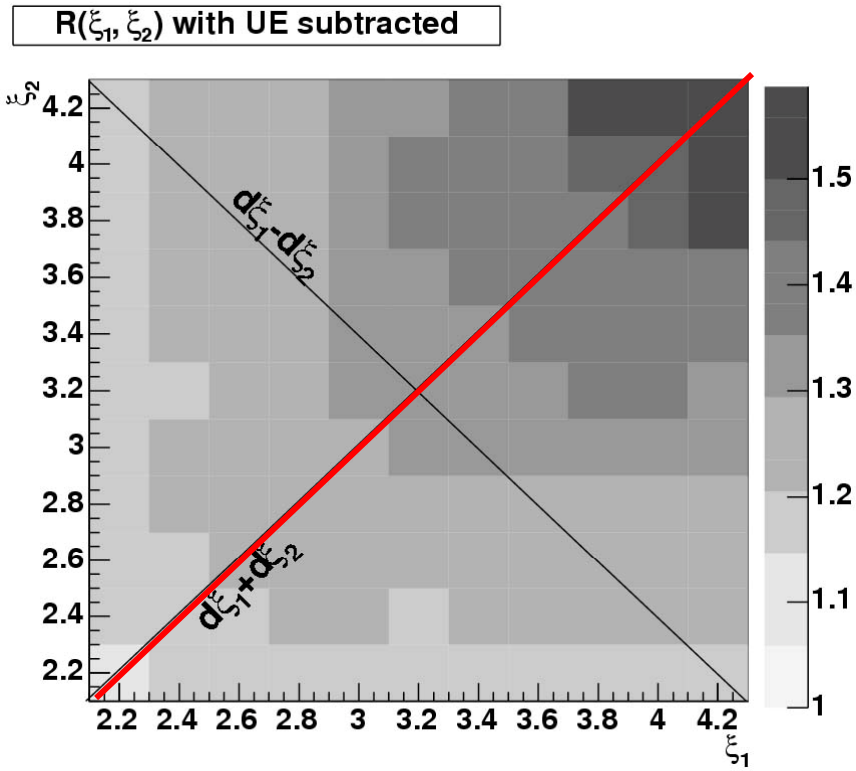


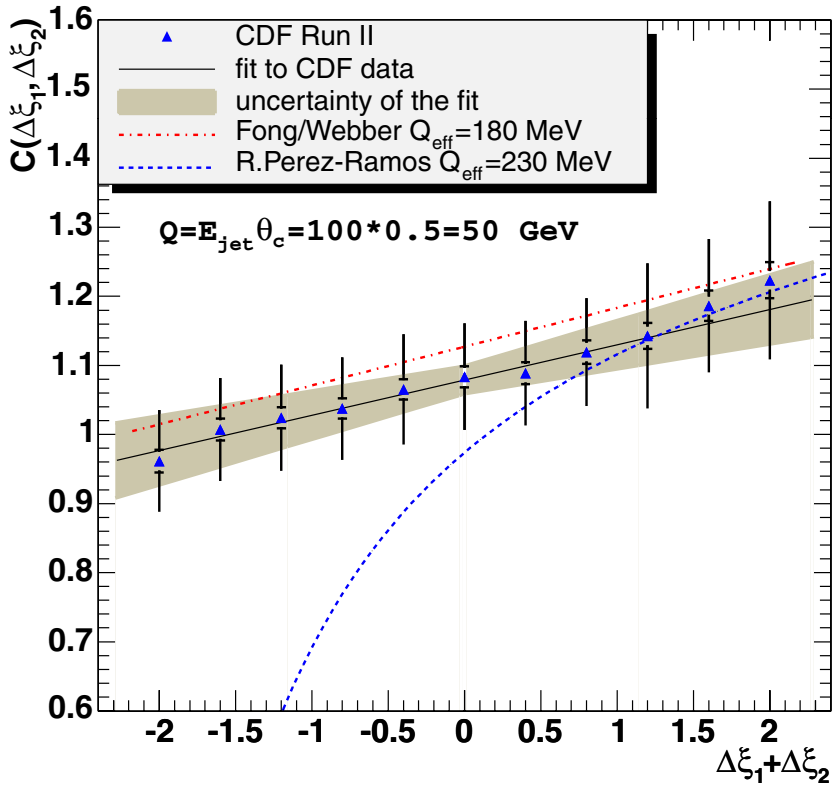


Two-particle Momentum Correlations

- Hadron correlations follow pattern predicted by Fong/Webber

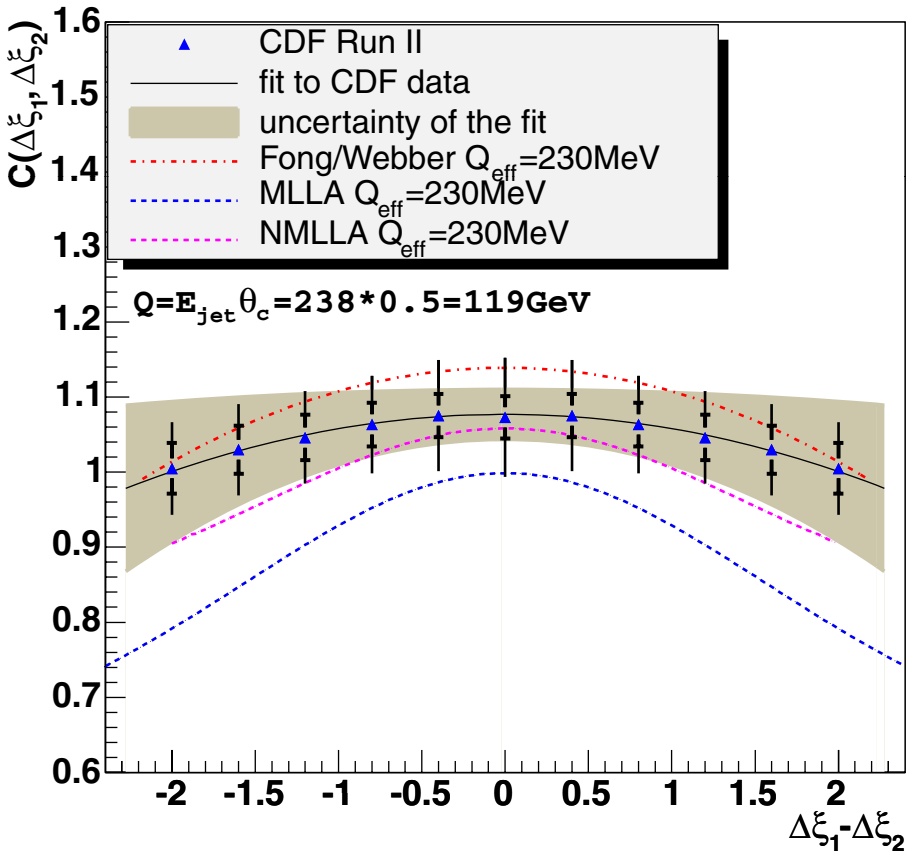
$$C(\xi_1,\xi_2) = C_0(Y) + C_1(Y,\Delta\xi_1+\Delta\xi_2) + \cancel{C_2(Y,\Delta\xi_1 - \Delta\xi_2)}$$

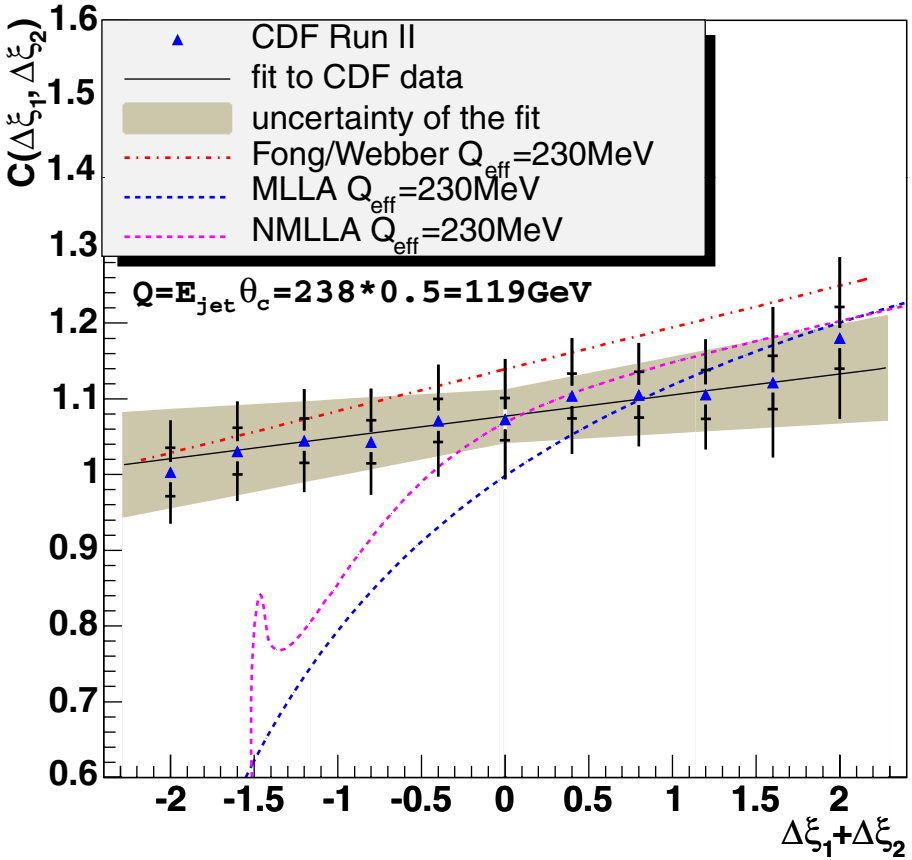




Two-particle Momentum Correlations

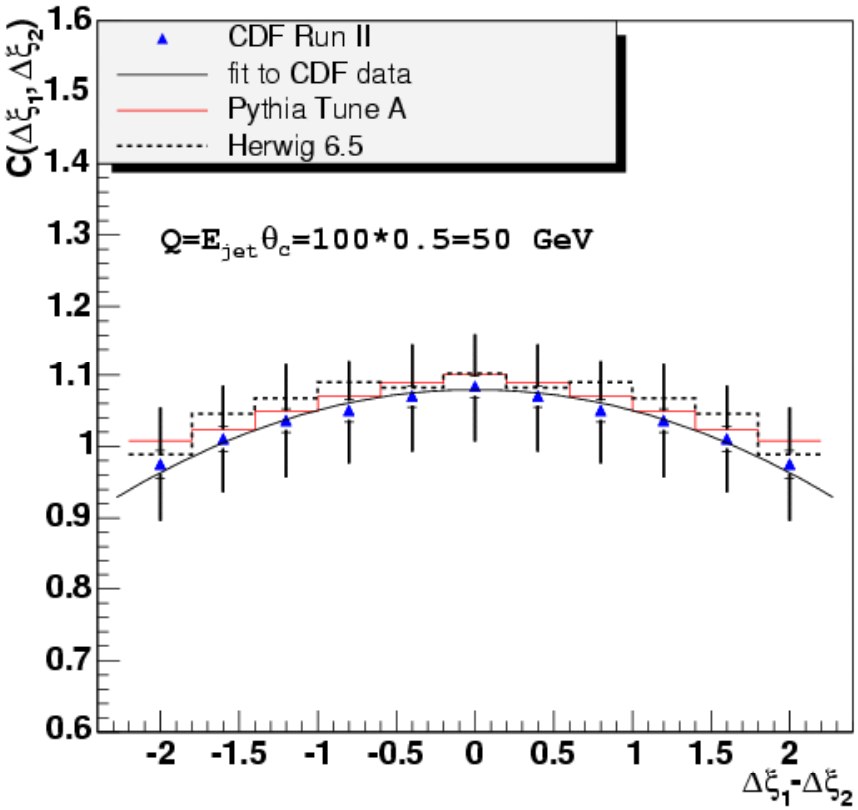
- Fong/Webber and MLLA/NMLLA predictions by Perez-Ramos have different range of applicability
- NMLLA predictions agree with data better than MLLA

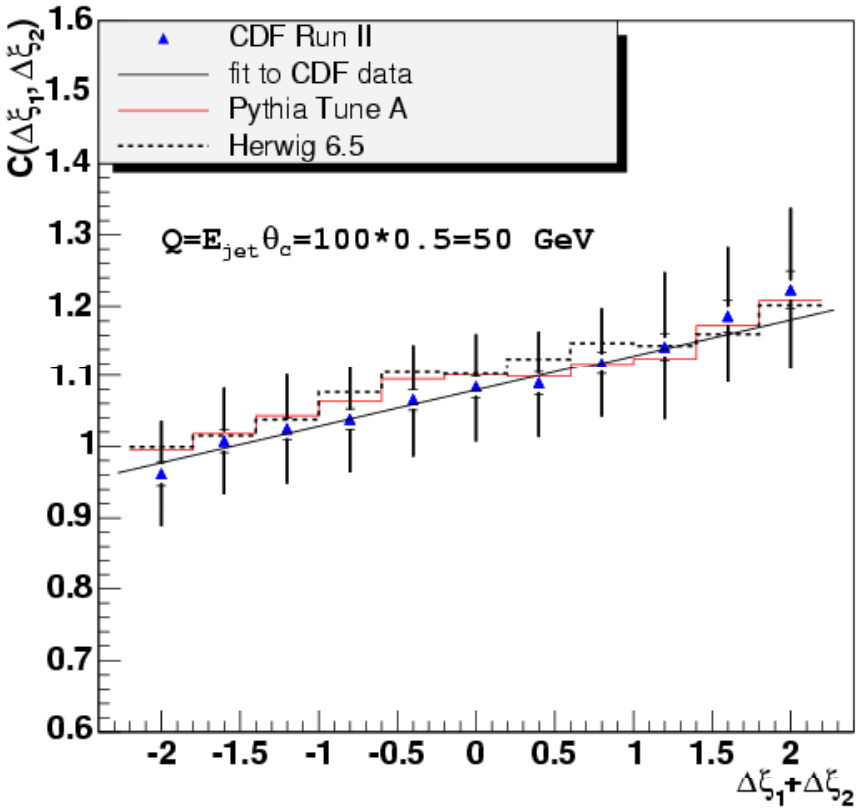




Two-particle Momentum Correlations

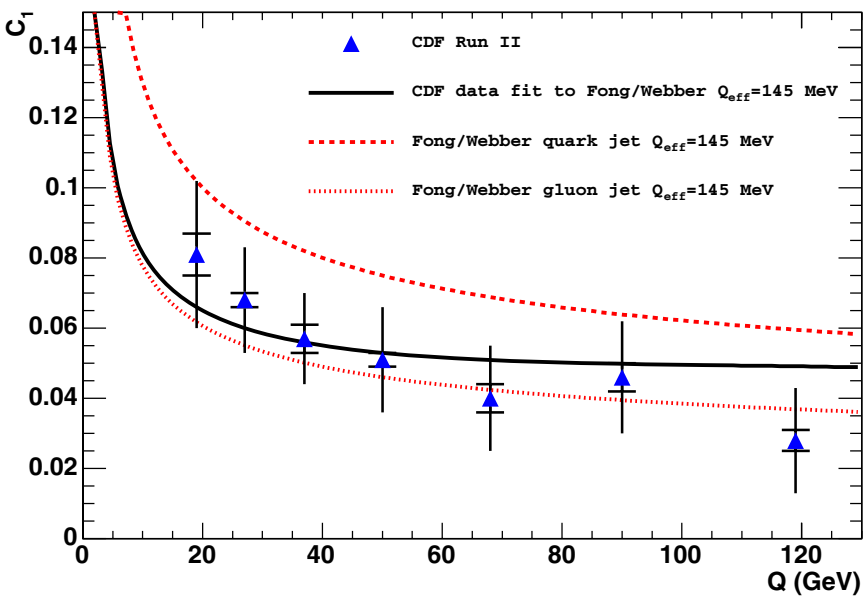
- Pythia and Herwig predictions agree with data in entire jet energy range

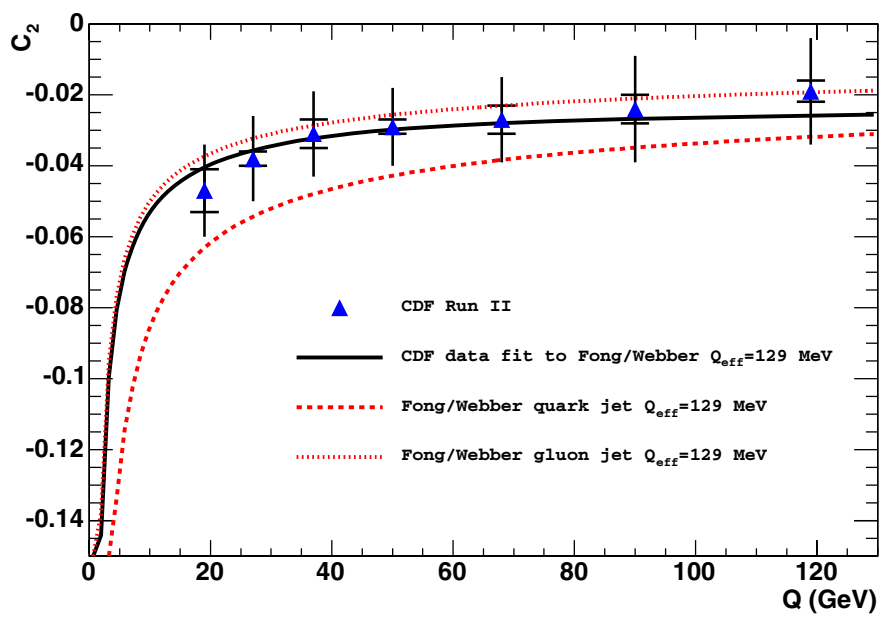




Two-particle Momentum Correlations

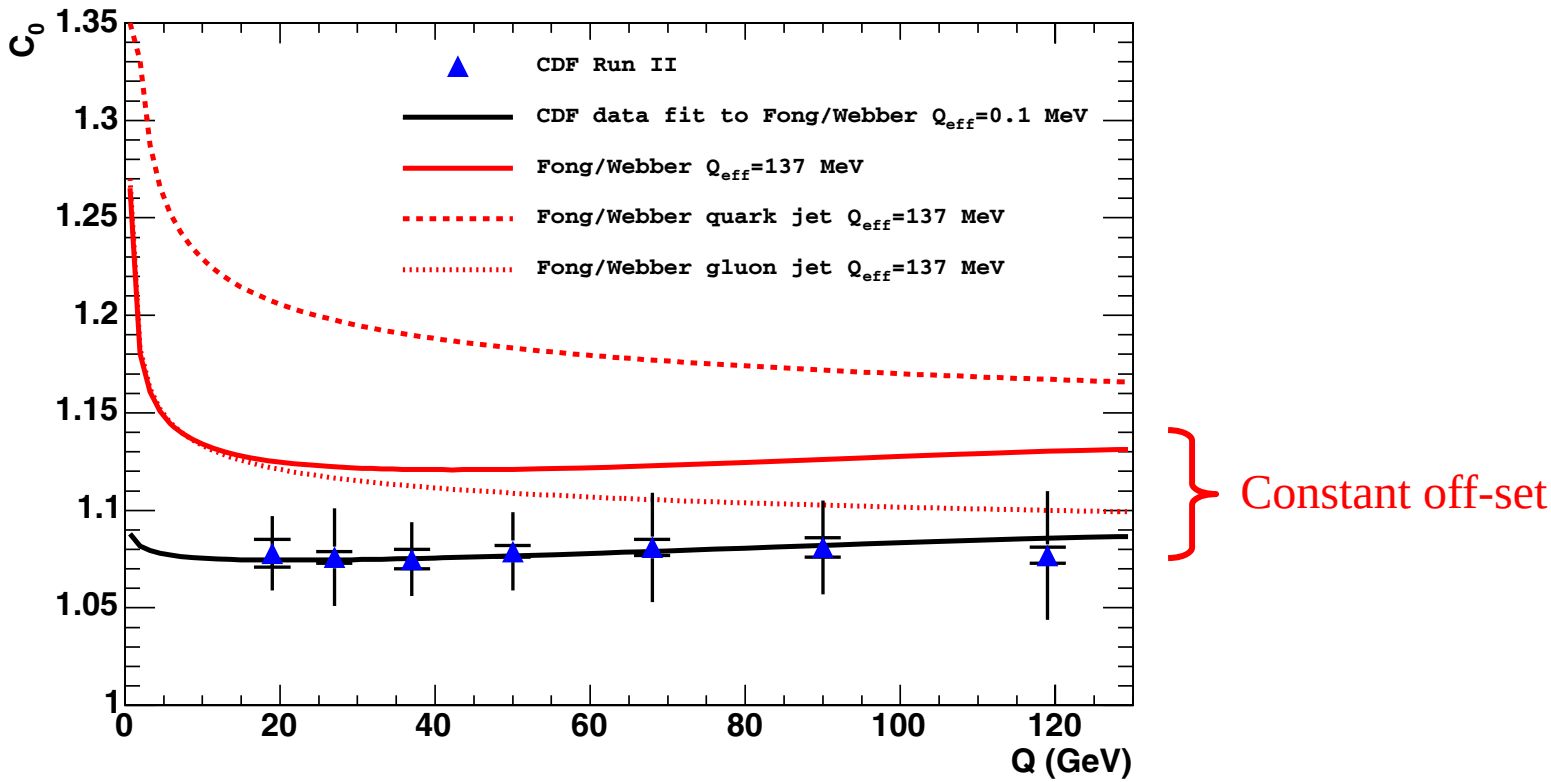
- Evolution of parameters with energy allows to extract value of Q_{eff}
- Theory reproduces trends in data
- Results
  - From fit to C_1 and C_2 give consistent results
  - Combined: $Q_{eff}=137^{+85}_{-69}$ MeV





Two-particle Momentum Correlations

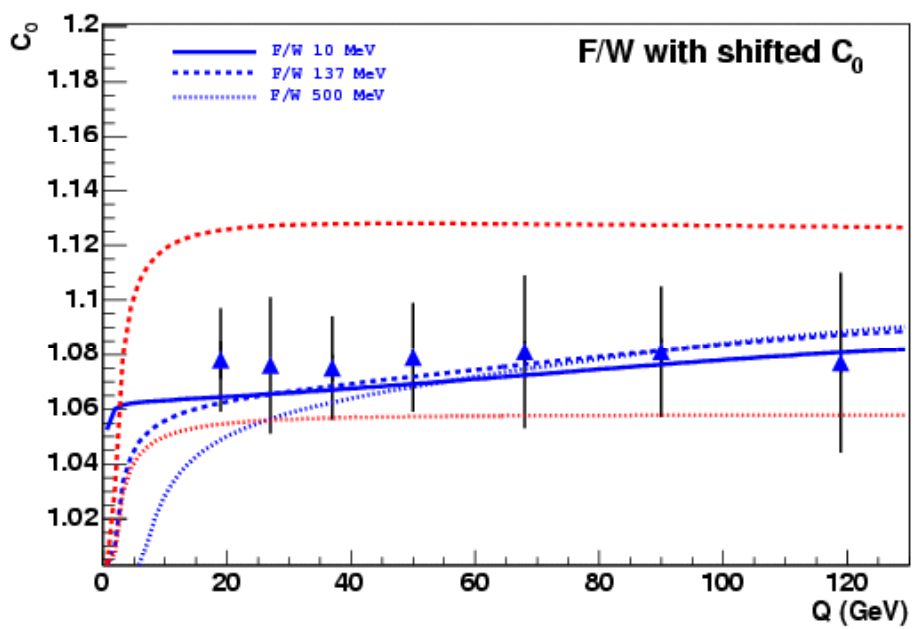
- C_0 is too small compared to theory
- Almost no energy dependence, as expected
- From theoretical point of view, C_0 has some issues…



Two-particle Momentum Correlations

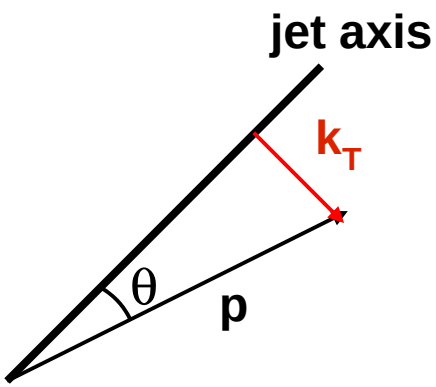
- We measure correlations around peak position, $\xi 0$
  - True peak position: $\xi_0=1/2Y+a*Y^{1/2}+O(1)$, $Y=\ln(Q/Q_{eff})$
  - Peak position in Fong/Webber: $\xi_0=1/2Y+\cancel{a*Y^{1/2}+O(1)}$, $Y=\ln(Q/Q_{eff})$
- Agreement improves if O(1)=-0.6 inserted by hand
  - O(1)=-0.6 obtained from fits of CDF data for $dN/d\xi$

Fong/Webber:
$c_0'=c_0-2c_1O(1)=c_0+1.2c_1$

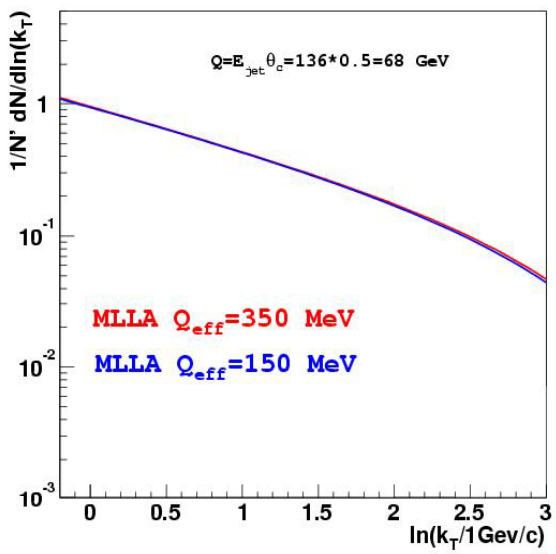


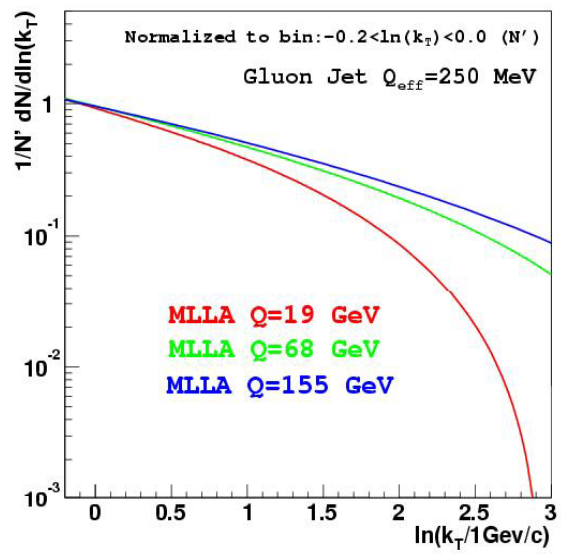
K_T distribution

- k_T studies probe softer particle spectra than $dN/d\xi$ and $C(\xi_1,\xi_2)$ studies
- First study of k_T distributions at hadron collider
  - θ_C=0.5, 66 GeV/c^2<M_{jj}<737 GeV/c^2
- Compare with recent theoretical results
  - MLLA calculations by Perez-Ramos & Machet, JHEP 04, 043 (2006)
  - NMLLA calculations by Arleo, Perez-Ramos & Machet



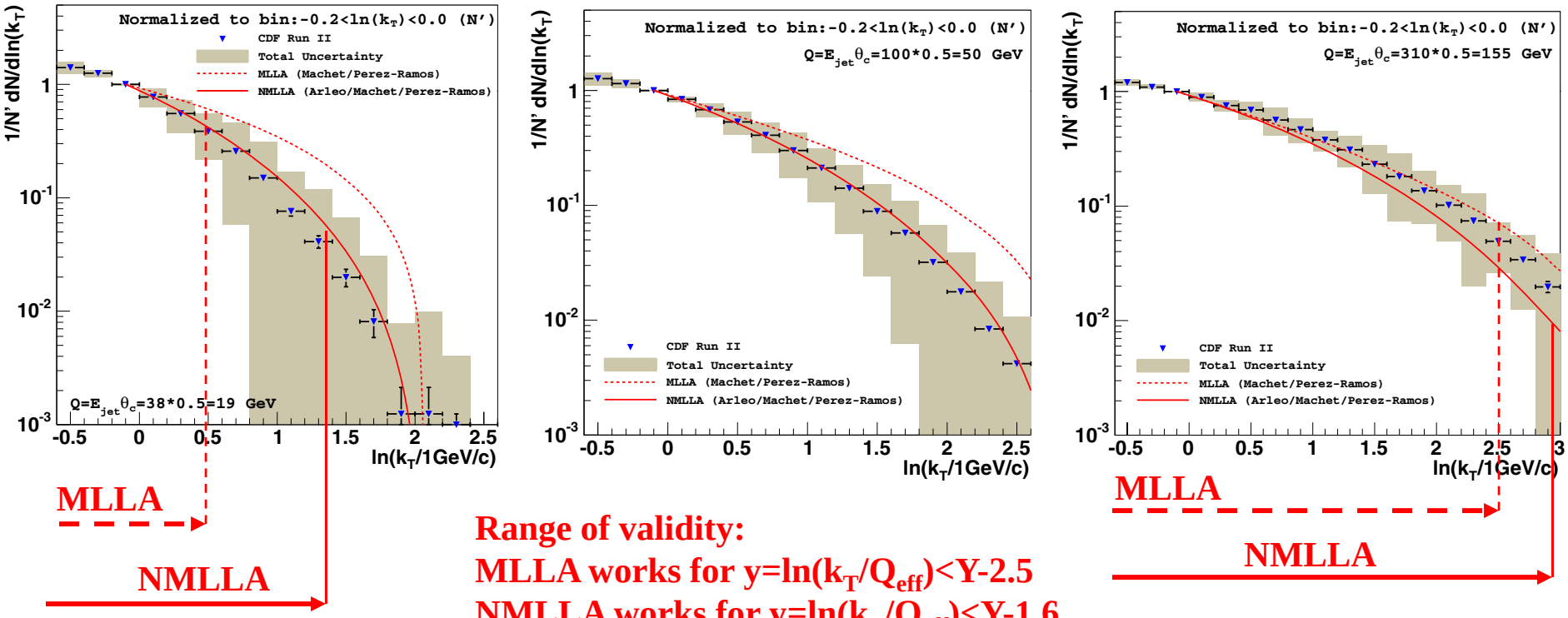
k_T=p*sin(θ)





K_T distribution

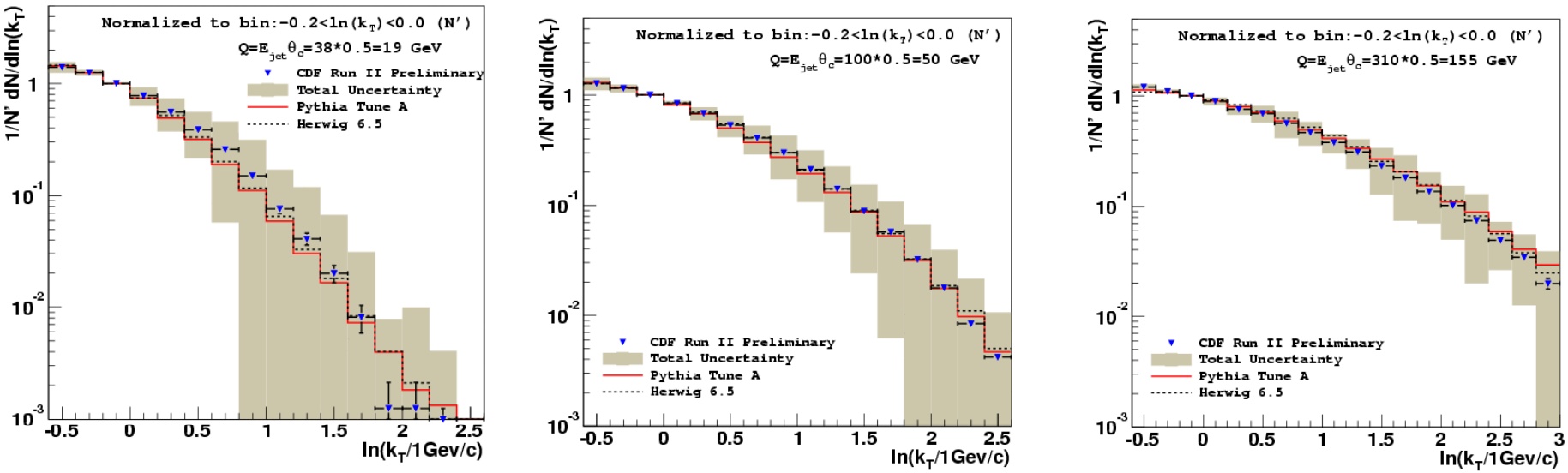
- NMLLA agrees better with data compared to MLLA
  - Indicates importance of higher level corrections
  - MLLA: agreement with data becomes better at large Q
  - NMLLA: agreement with data is good at all Q's



Range of validity:
MLLA works for $y=\ln(k_T/Q_{eff})<Y-2.5$
NMLLA works for $y=\ln(k_T/Q_{eff})<Y-1.6$

K_T distribution

- Both Herwig and Pythia agree with data in entire range of jet energies



Summary and Coclusion

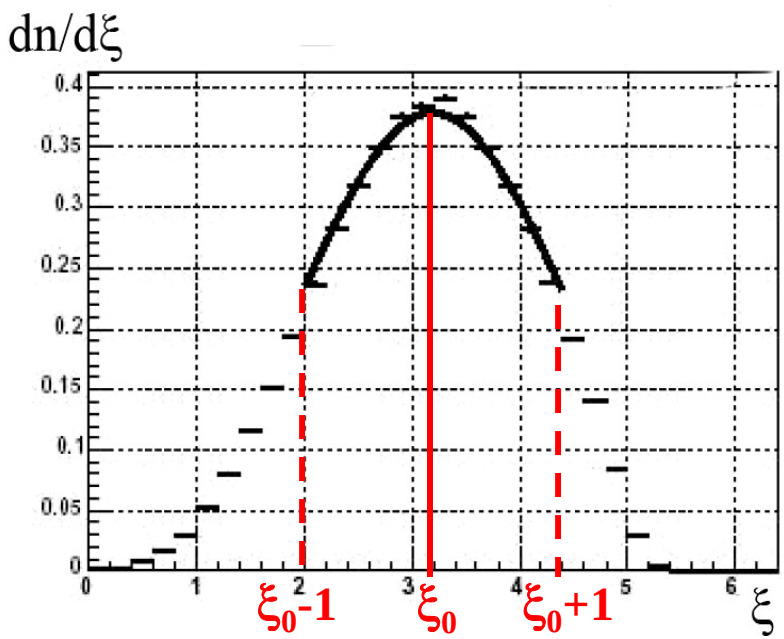
- Studies of jet fragmentation at CDF confirm that pQCD calculations can be successfully applied to describe most aspects of jet formation
  - Further support to LPHD
  - $dN/d\xi$ distribution: Phys.Rev.D 068:012003 (2003)
    - $Q_{eff}=230\pm40$ MeV; $K_{LPHD}=0.56\pm0.10$
  - Multiplicity in gluon & quark jets, N_G & N_Q: PRL94:171802 (2005)
    - $r=N_G/N_Q=1.64\pm0.17$ at Q=19 GeV
  - Two-particle momentum correlations: submitted to PRD
    - $Q_{eff}=137^{+85}_{-69}$ MeV
  - k_T distribution: to be submitted to PRL soon
    - Data agree with NMLLA at all Q's

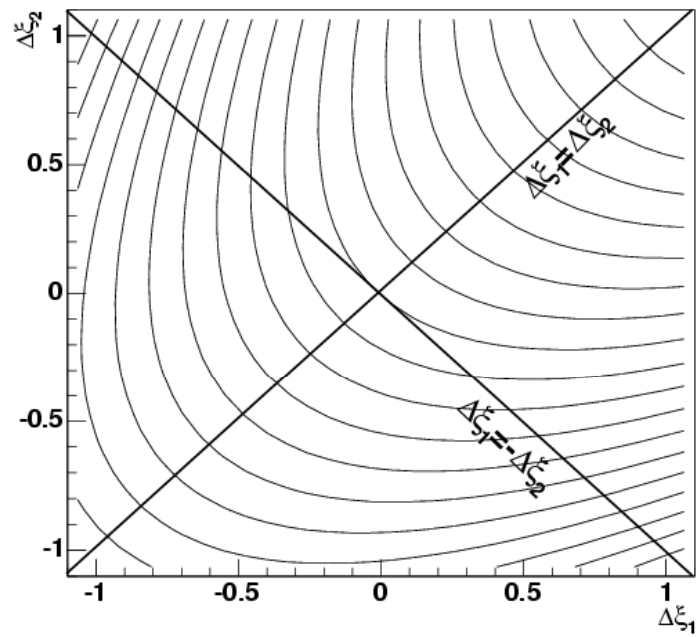
Backup

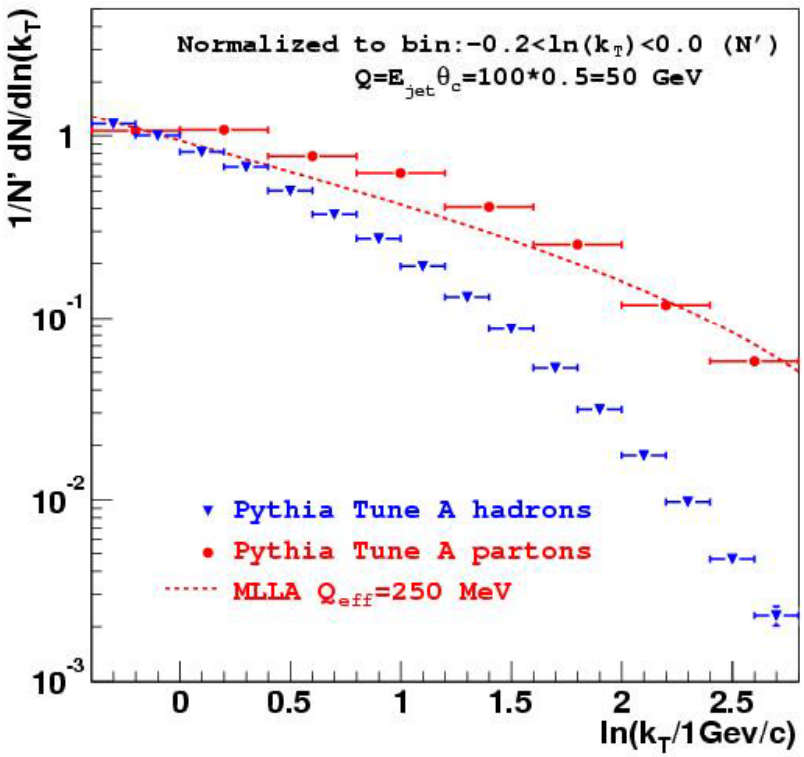
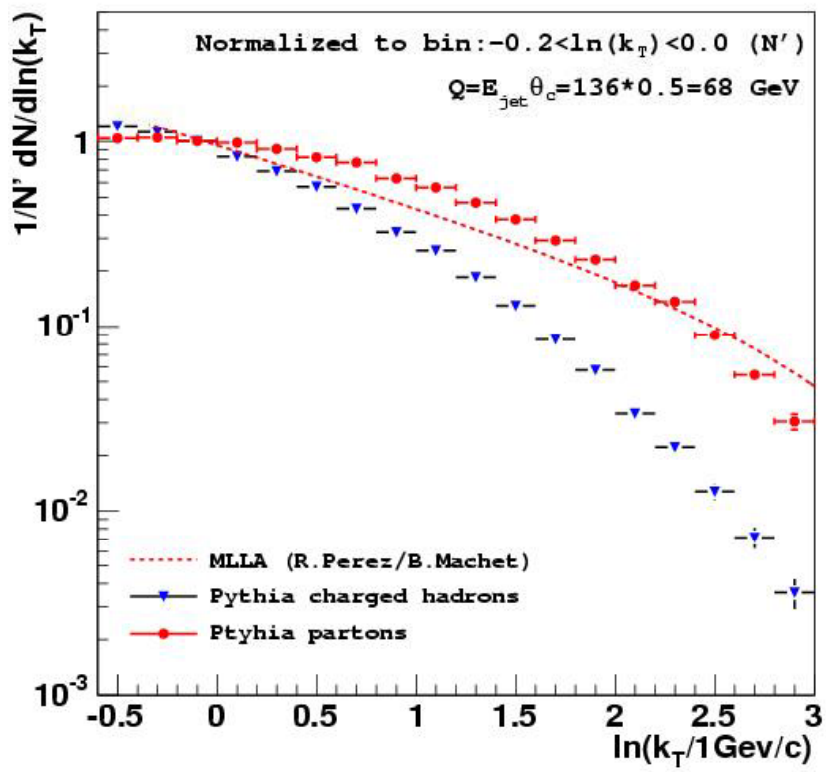
Two-particle Momentum Correlations

- Consider all pairs of particles with $\xi_0-1<\xi<\xi_0+1$ in cone $\theta_c<0.5$ around jet axis

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





K_T distribution

- MLLA seem to agree with k_T distribution of partons in Pythia