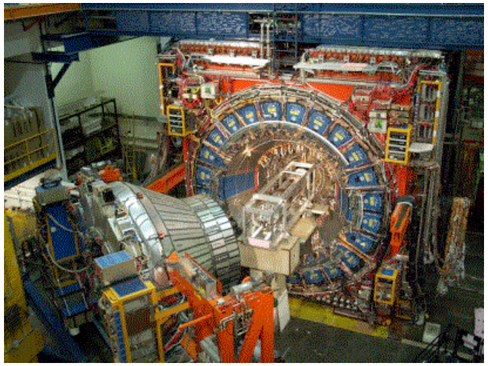
Photon and Jet Physics at CDF



Jay R. Dittmann

Fermi National Accelerator Laboratory

(For the CDF Collaboration)

31st International Conference on High Energy Physics

Amsterdam, The Netherlands, 2002

QCD Physics at the Fermilab Tevatron

- The Fermilab Tevatron Collider serves as an arena for precision tests of QCD with photons, W/Z's, and jets
  - Highest Q^2 scales currently achievable (searches for new physics at small distance scales)
  - Sensitivity to parton distributions over broad kinematic range
- Data are compared to a variety of QCD calculations (NLO, resummed, leading log Monte Carlo…)
- Dynamics of any new physics will be from QCD; backgrounds to any new physics will be from QCD processes!

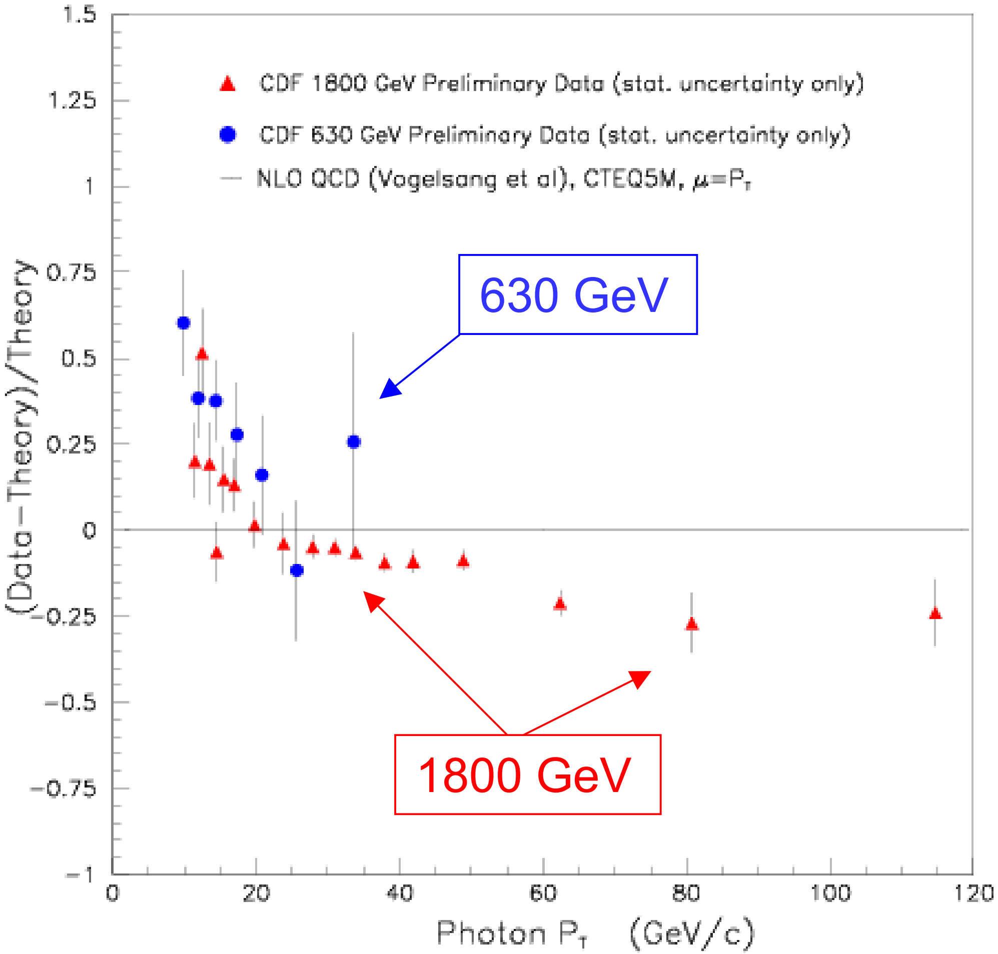
QCD Physics at the Fermilab Tevatron

- Overall, CDF and D0 data agree well with NLO QCD
- Some puzzles have been resolved:
  - W + jets: $\sigma(W + \geq 1 \text{ jet}) / \sigma(W)$ ratio
- Some puzzles remain:
  - Jet excess at high E_T (and high mass)
  - 630 GeV jet cross section and x_T scaling
  - Heavy flavor cross sections (see C. Paus talk)
  - Comparison of k_T inclusive jet cross section and NLO theory
- Improved theoretical predictions are being developed:
  - Inclusive photon cross section
- And searches still continue:
  - BFKL effects

CDF Photons in Run 1B

Inclusive photon cross section

- Deviations from NLO QCD predictions are observed at two different center of mass energies: 1800 GeV and 630 GeV
  - steeper slope at low p_T
  - normalization problem at high p_T (1800 GeV)

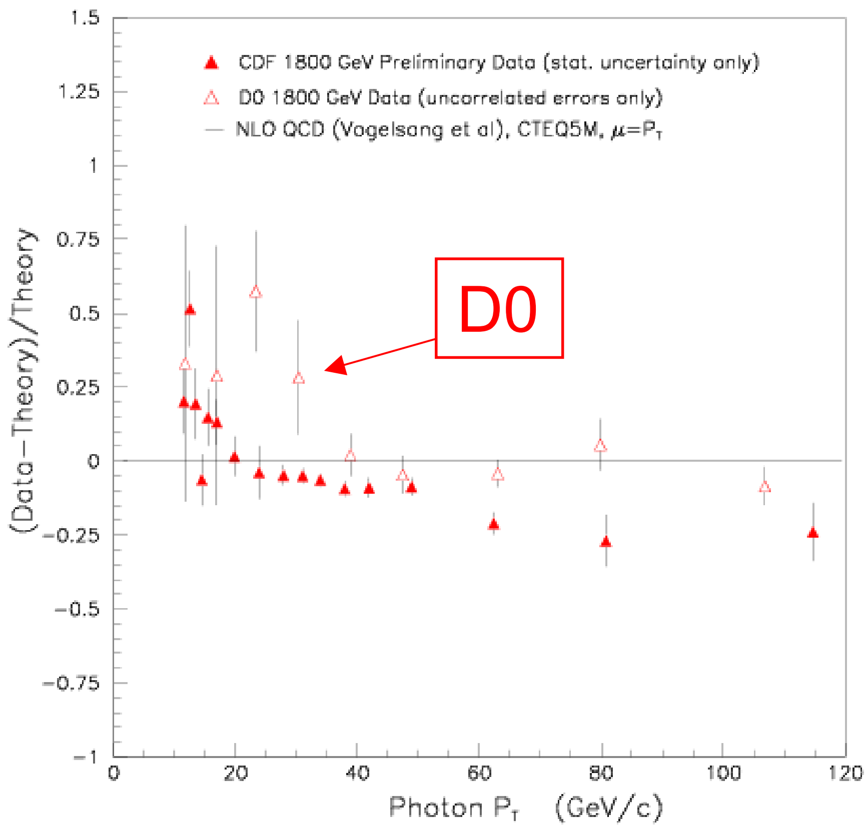


Data: Phys. Rev. D 65 112003 (2002)

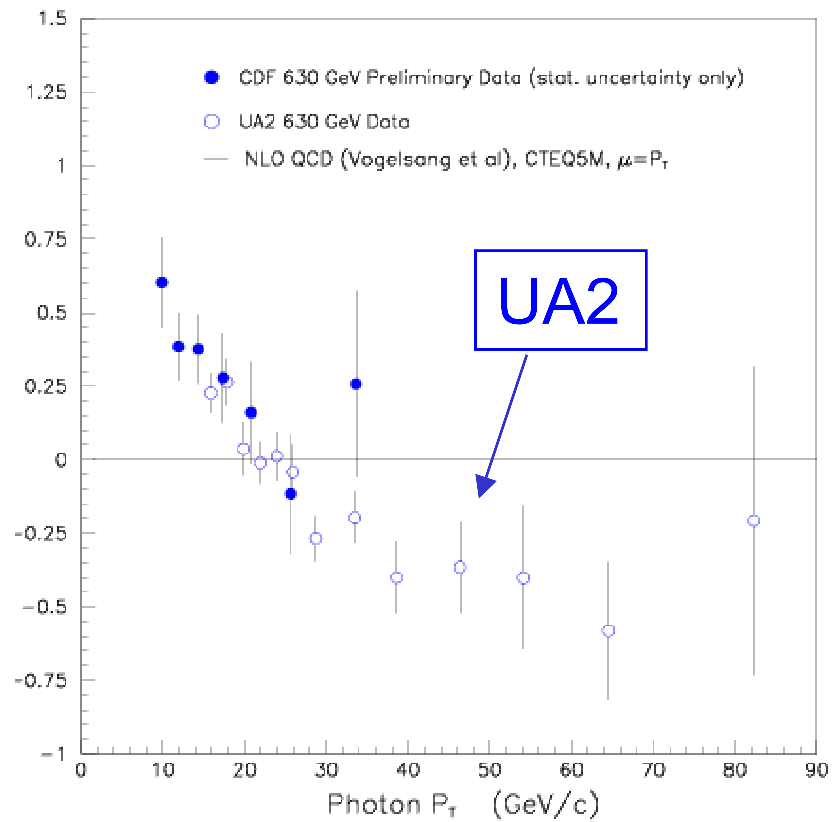
Theory: Phys. Rev. Lett. 73, 388 (1994)
Nucl. Phys. B453, 334 (1995)

CDF Photons in Run 1B

- CDF's results are consistent with those from D0 and UA2:



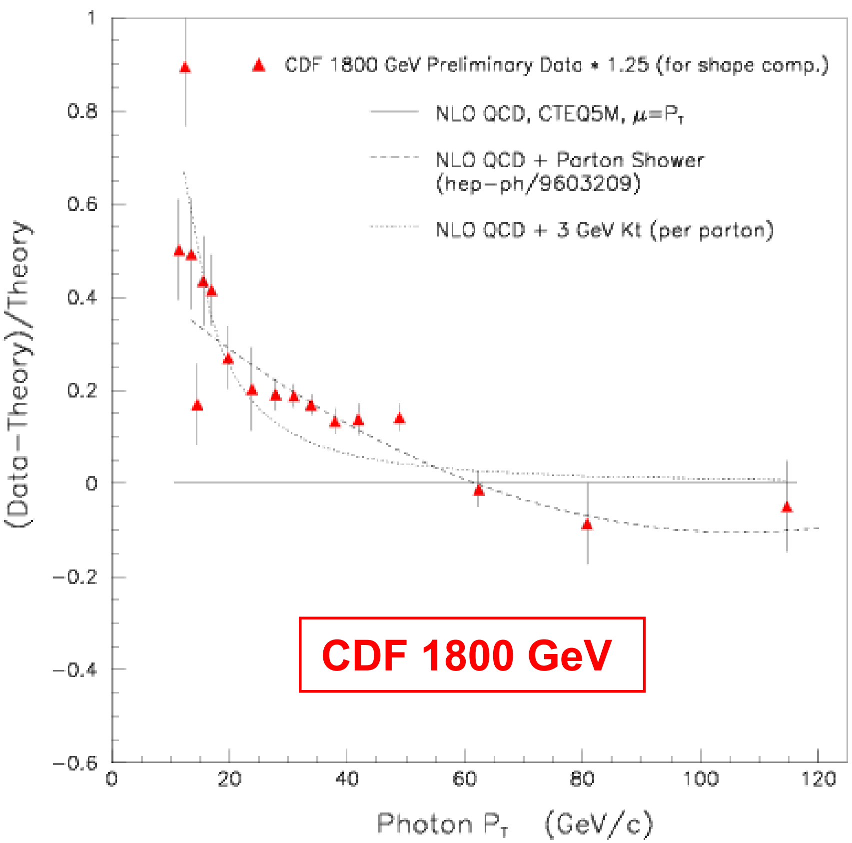
Phys. Rev. Lett. 84, 2786 (2000)

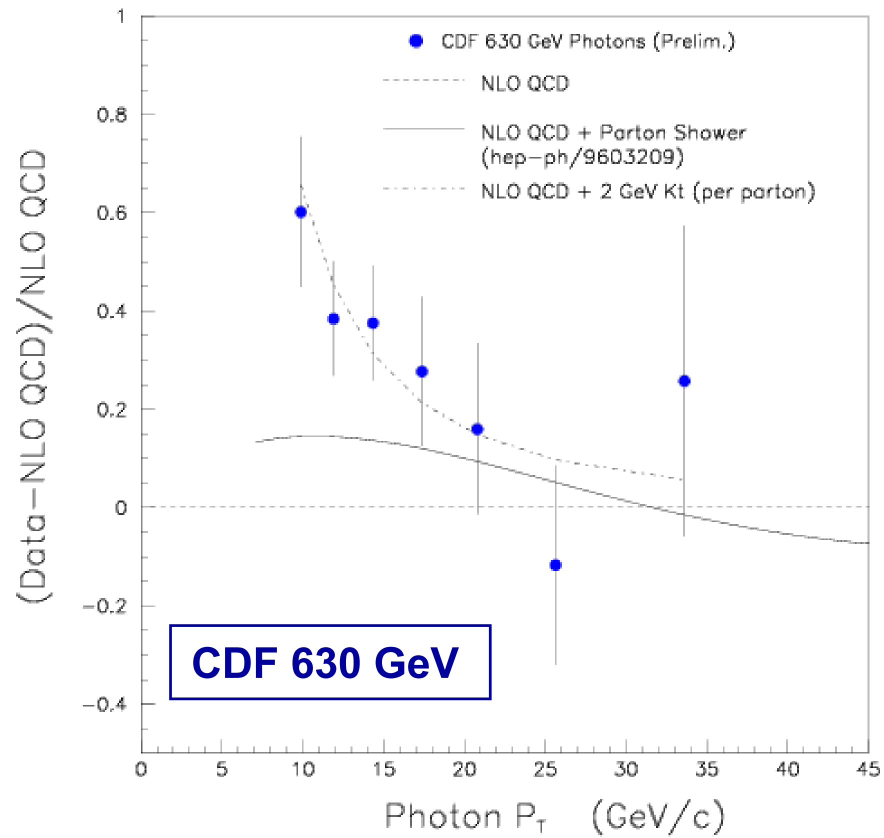


Phys. Lett. B 263, 544 (1991)

CDF Photons in Run 1B

- What is the cause? One possibility is the effect of soft gluon initial state radiation. See k_T Effects in Direct-Photon Production, PRD 59 074007 (1999)





CDF Run 2 Inclusive Photon Production

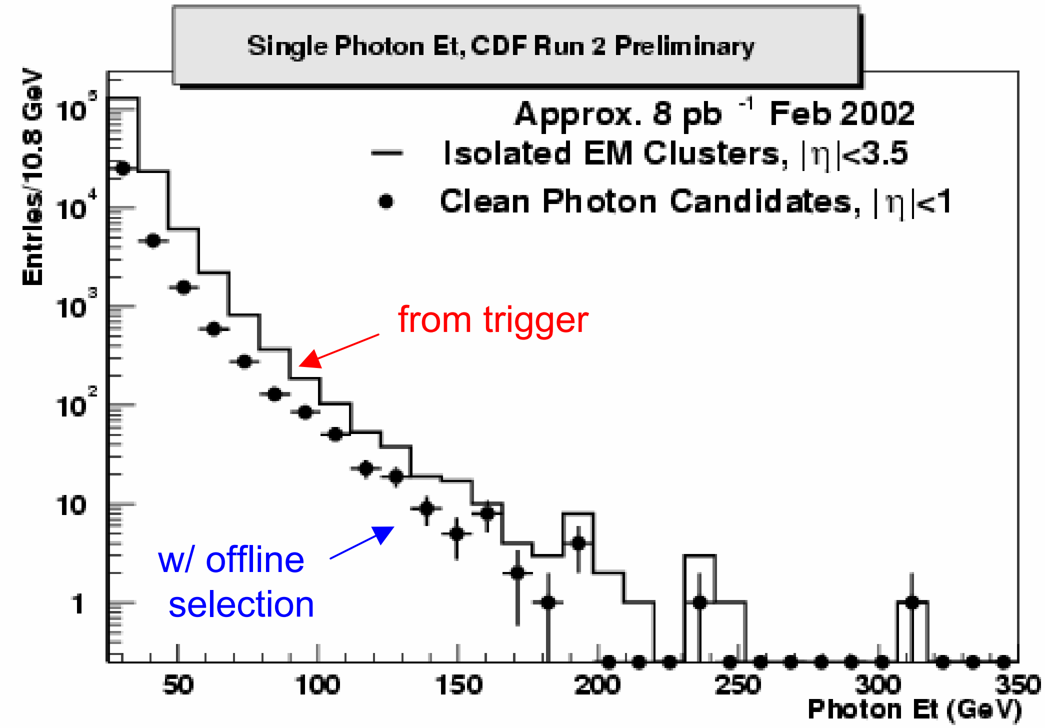
- CDF Run 2 data (Aug 2001 – Feb 2002) 8 pb^{-1}

Inclusive photon trigger:

- $E_T > 25$ GeV
- $|\eta| < 3.6$
- Isolated energy in calorimeter
- Had/EM requirement
- Require central strip chamber (CES) for $|\eta| < 1.0$

Offline selection:

- Require $|\eta| < 1.0$
- Tracking isolation
- Additional quality requirements

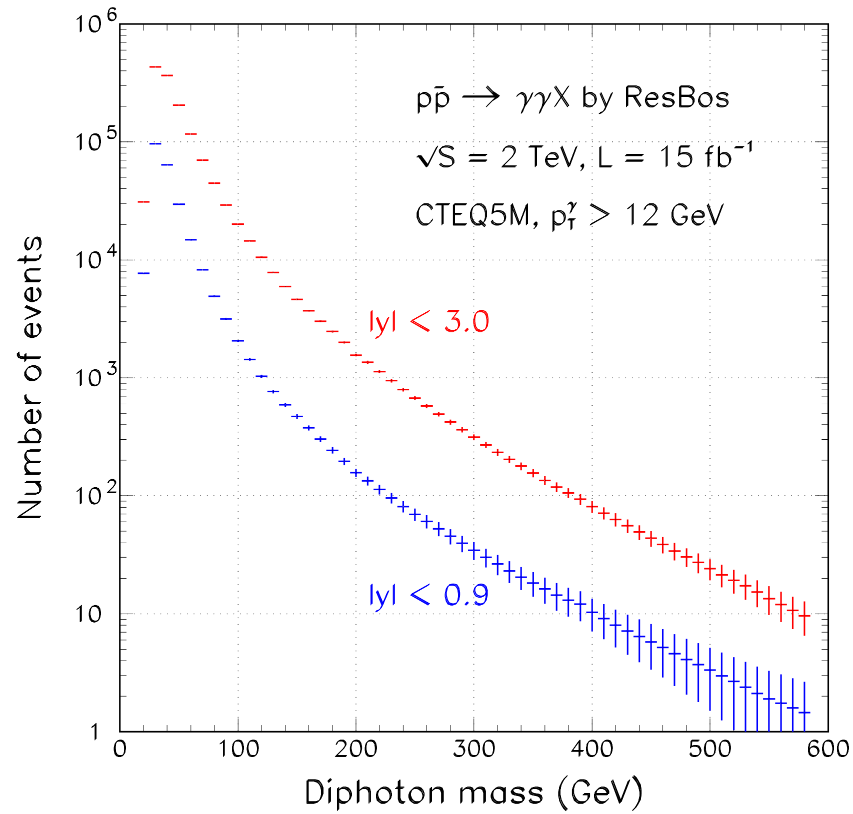


CDF Run 2 Diphoton Production

Diphoton production is interesting both for tests of QCD and searches for new phenomena!

The diphoton mass reach for Run 2 extends out to nearly 600 GeV/c^2

Dominant mechanism at low mass is gg scattering; $q\bar{q}$ at higher masses



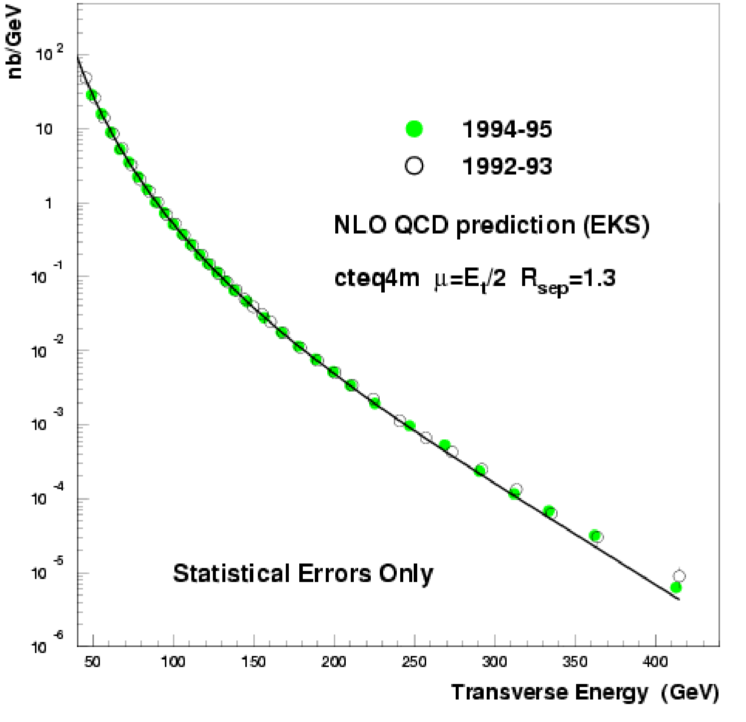
Inclusive Jet Cross Section at the Tevatron

- Data Samples:
  - Run 1A (1992-93)
    CDF: 19.5 ± 0.7 pb^{-1}
  - Run 1B (1994-95)
    CDF: 87 ± 9 pb^{-1} D0: 92 ± 6 pb^{-1}
- Event and Jet Selection:
  - Cone algorithm (R = 0.7) for jet reconstruction
    - $|z_{vert}|$ < 50 cm (D0), < 60 cm (CDF)
    - Eliminate events with large missing E_T (D0 and CDF)
    - Energy timing (CDF)
    - Jet quality cuts (D0)
  - Uncertainty ~0.5% (CDF); ~1% (D0)

In Run 1, CDF observes an excess in the jet cross section at large jet E_T, outside the range of the theoretical uncertainties

CDF: PRD 64, 032001 (2001), D0: PRL 82, 2451 (1999)

- Both experiments compare to NLO QCD calculations
  - D0: JETRAD, modified Snowmass clustering (R_{sep}=1.3, $\mu_F=\mu_R=E_{Tmax}/2$)
  - CDF: EKS, Snowmass clustering (R_{sep}=1.3, $\mu_F=\mu_R=E_{Tjet}/2$)

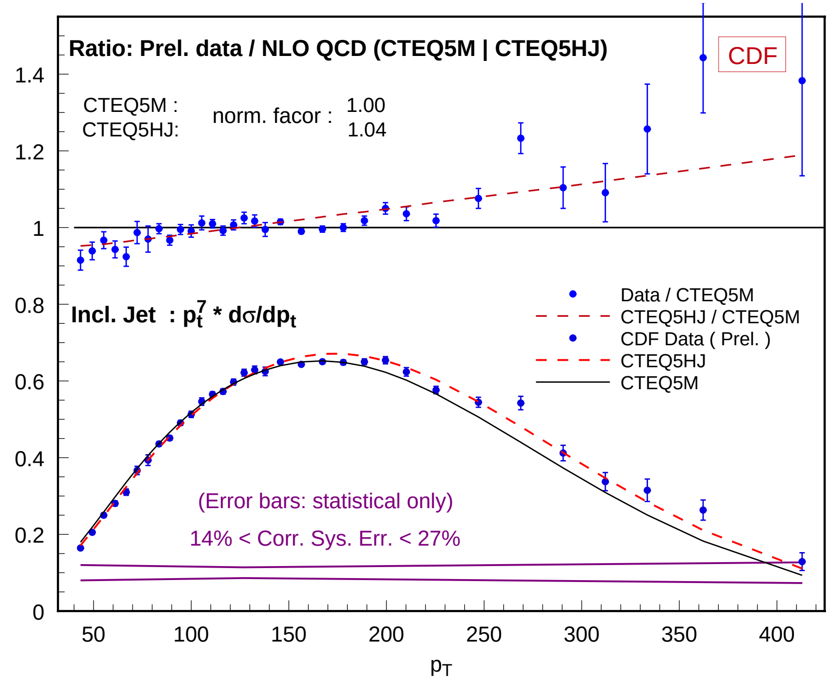


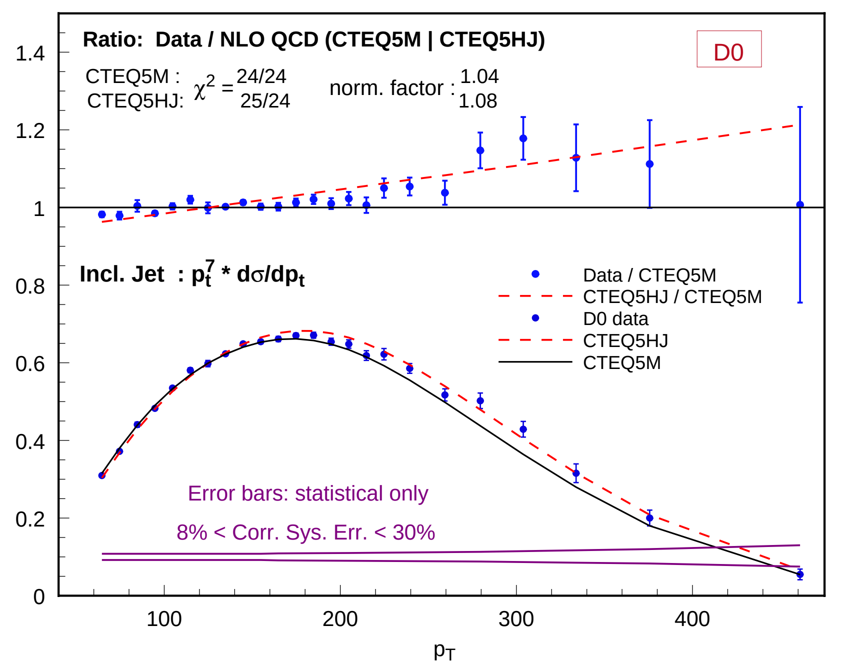
Inclusive Jet Cross Section at the Tevatron

Tevatron jets and the high-x gluon

- Best fit to CDF and D0 central jet cross sections provided by CTEQ5HJ PDFs
- But this is not the central fit – extra weight given to high E_T data points.

The central fit for CTEQ6 is more "HJ"-like, but…
We need a more powerful data sample!

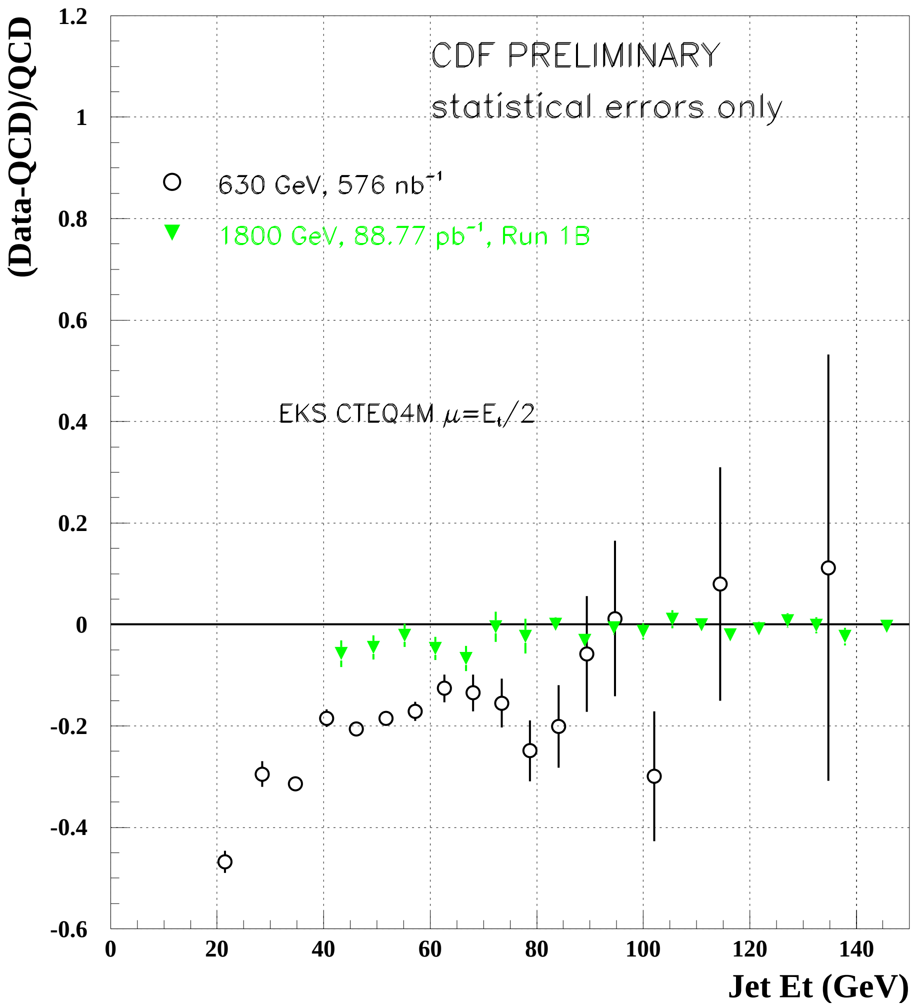




Inclusive Jet Cross Section at the Tevatron

Jets at 630 GeV

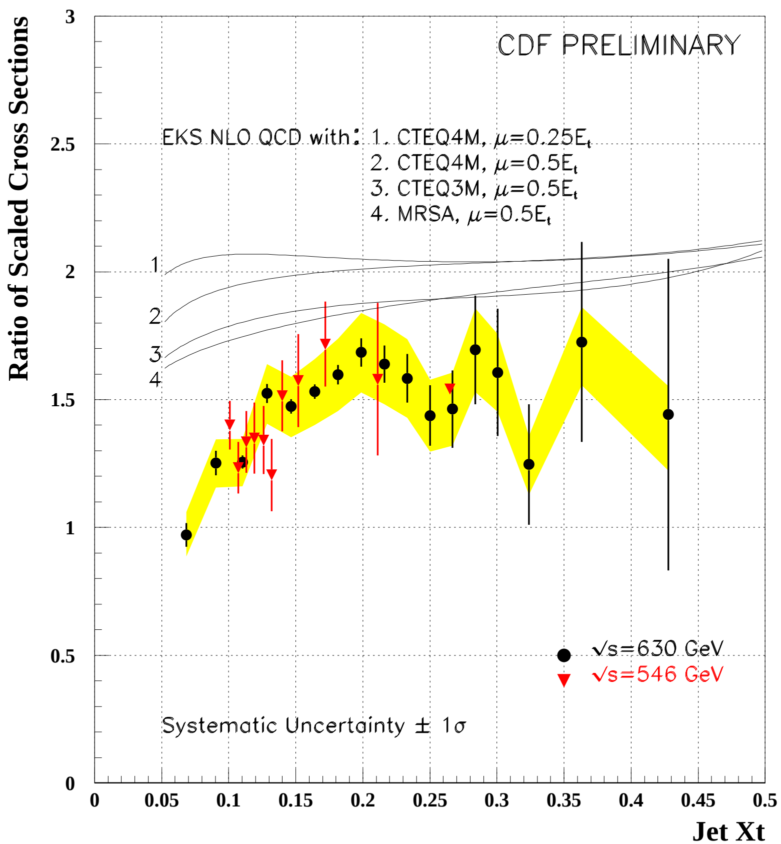
- Jet measurements at 630 GeV don't agree well with NLO QCD predictions!



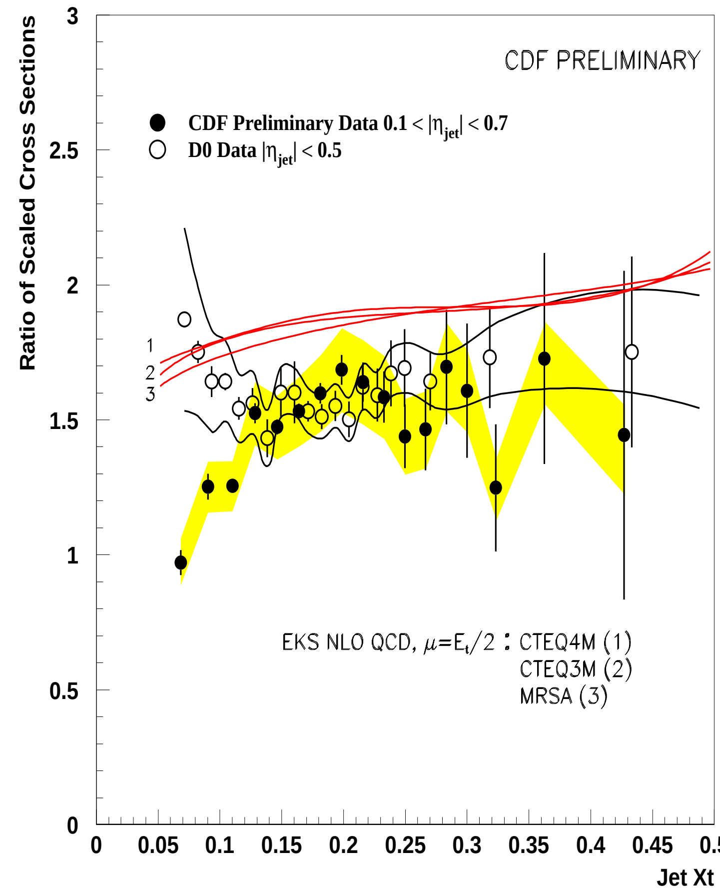
Inclusive Jet Cross Section at the Tevatron

x_T scaling

- x_T scaling ratio of 1800 to 630 GeV jet cross sections doesn't agree with NLO QCD either…



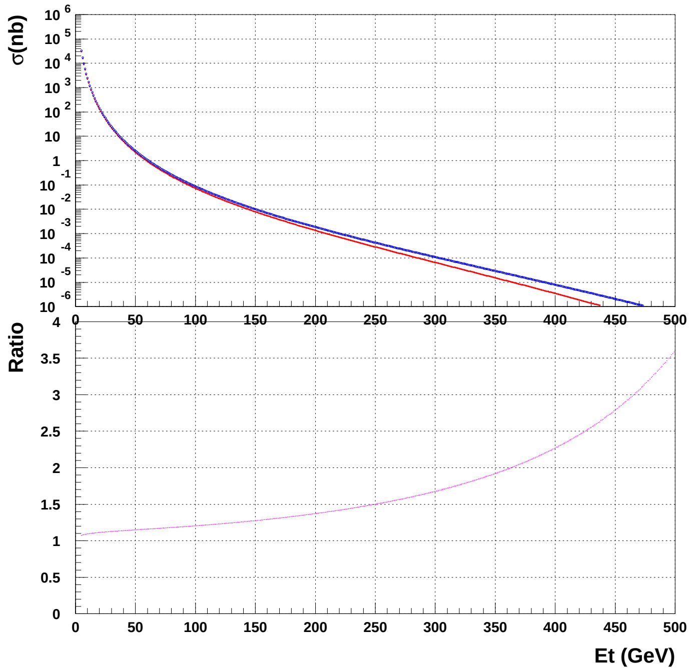
- D0 sees a similar disagreement (but different behavior at low E_T?)



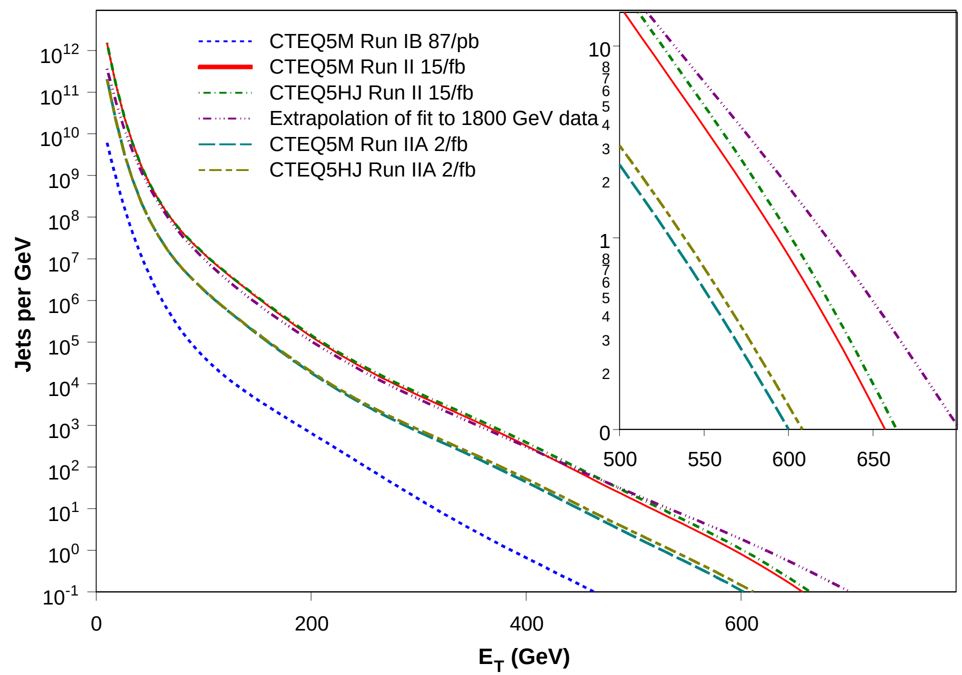
Jet Production in Run 2

The increase in the center-of-mass energy from 1.8 to 1.96 TeV has a large effect on the high E_T jet rate.

Inclusive jet cross section at 1.8 and 2.0 TeV (CTEQ4HJ)



Jet Yields Bin 1 - 0.1 < |y| < 0.7



For the full Run IIa sample the number of jets above 400 GeV will increase from 11 to $\sim$ 500.

$\sim$ 18 events by June

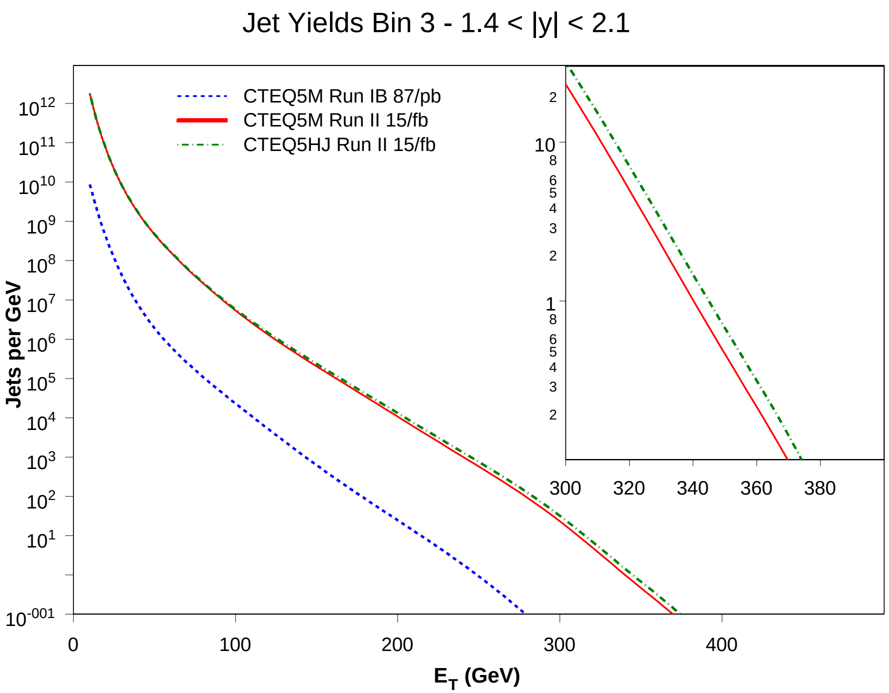
$\sim$ 75 events by end of year

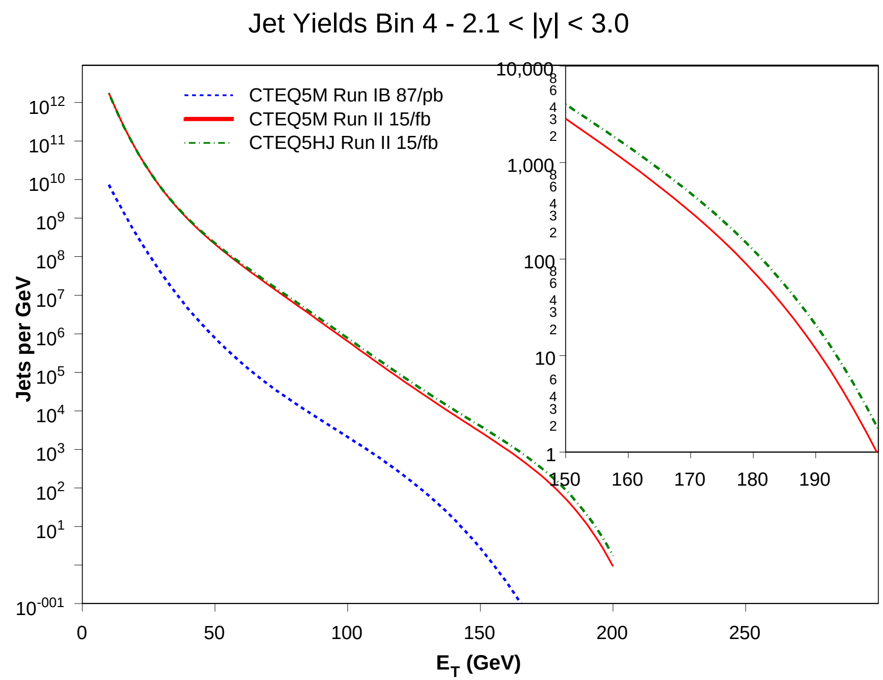
Jets will be measured with the k_T clustering algorithm as well as with improved cone algorithms.

Jet Production in Run 2

- Measurements in Run 2 will extend to forward regions!

It’s crucial to measure jet cross sections over a large rapidity range



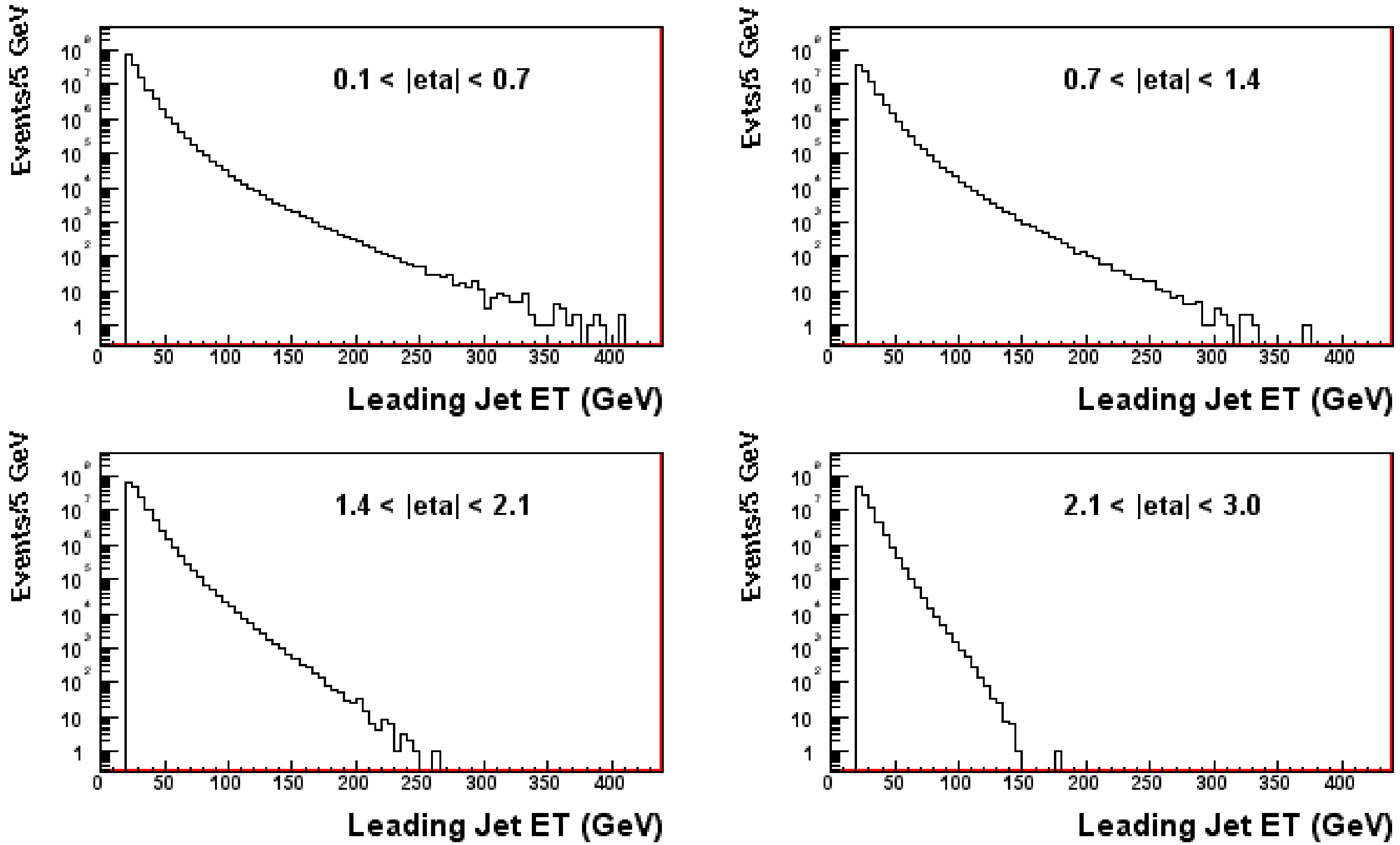


First Look at Run 2 Jet Data

Leading Jet ET in CDF Jet Events

CDF Run 2 Preliminary (12/14/2001 - 6/2/2002) 25.6 pb-1

(Raw E_T values!)

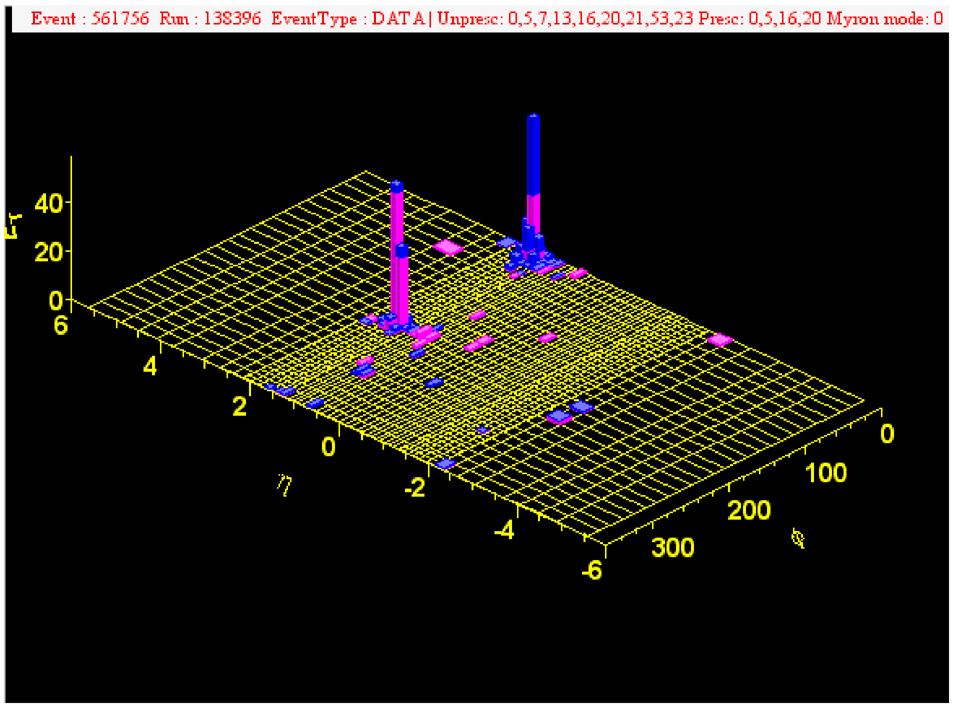


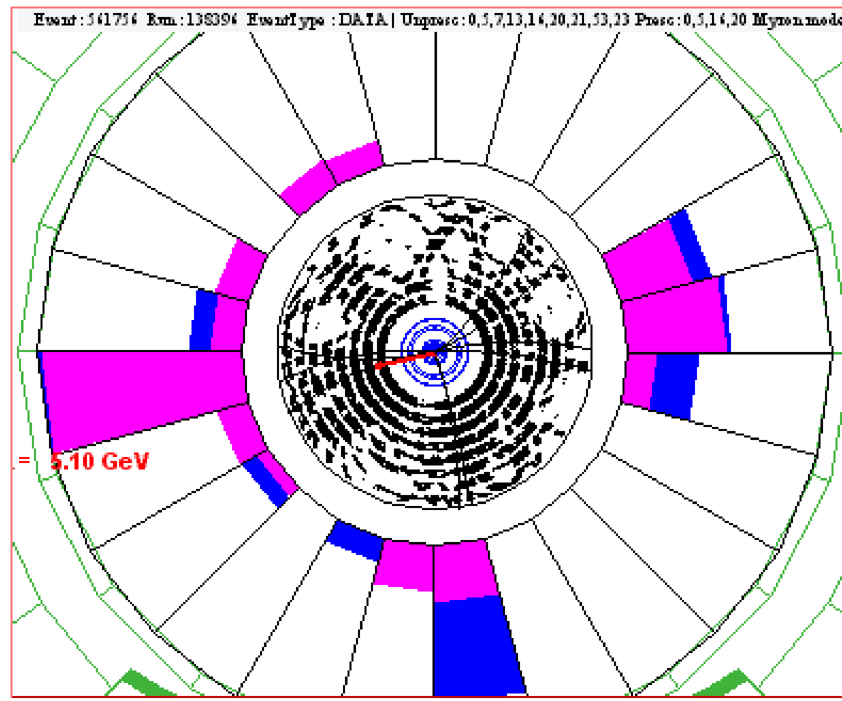
First Look at Run 2 Jet Data

A Run 2 Dijet Event… both jets in plug calorimeter

E_T^{jet1} = 154 GeV
E_T^{jet2} = 147 GeV

Raw jet E_T!!





CDF Three-Jet Production Cross Section

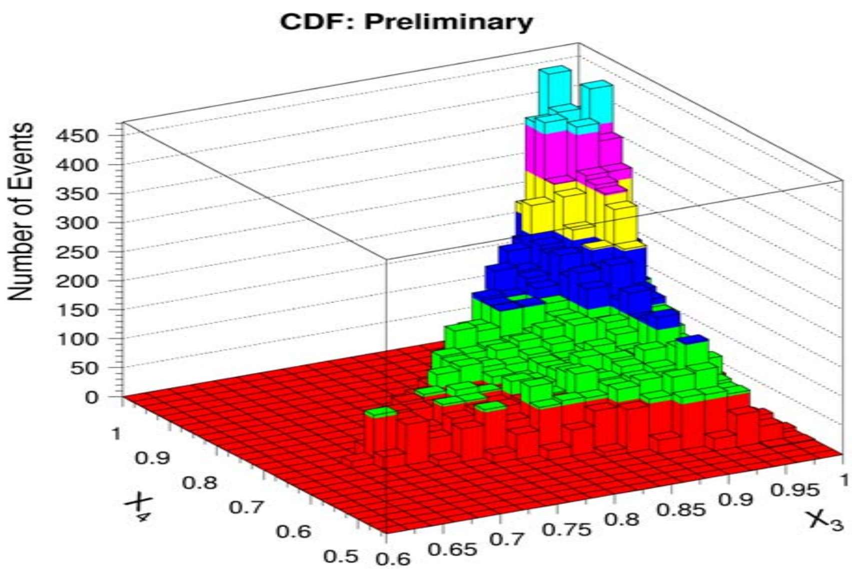
- Features of CDF Run 1B inclusive three-jet events are compared to NLO QCD predictions (Kilgore & Giele, hep-ph/0009193)

These are the first comparisons of 3-jet production to a NLO QCD prediction at a hadron collider!

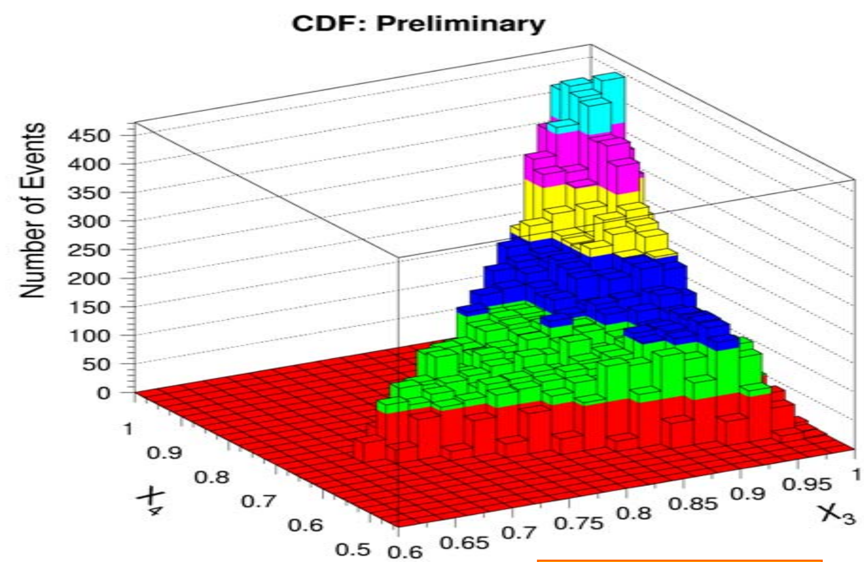
- **Event selection**
  - Calorimeter clusters are reconstructed as jets using the CDF cone algorithm with radius R = 0.7.
  - Events with ≥3 jets that pass the $\Sigma E_T > 175$ GeV trigger are boosted into the 3-jet rest frame. The energies of the 3 leading jets are corrected, unsmeared, and numbered such that $E_3 > E_4 > E_5$.
  - Require $E_T^{jet} > 20$ GeV, $|\eta| \leq 2.0$, $\Sigma E_{T3jets} > 320$ GeV, cone separation $\Delta R > 1.0$, remove and correct for multiple interactions, apply other data quality cuts.
  - Construct mass m_{3jet} of the system and Dalitz variables $X_i = 2E_i / m_{3jet}$ for the jets.

CDF Three-Jet Production Cross Section

- Bin the Dalitz plane in units of 0.02 × 0.02 and plot the data.
- Apply NLO calculation to predict the inclusive 3-jet cross section versus X_3 and X_4; convert to predicted number of events at CDF luminosity; bin in Dalitz plane.



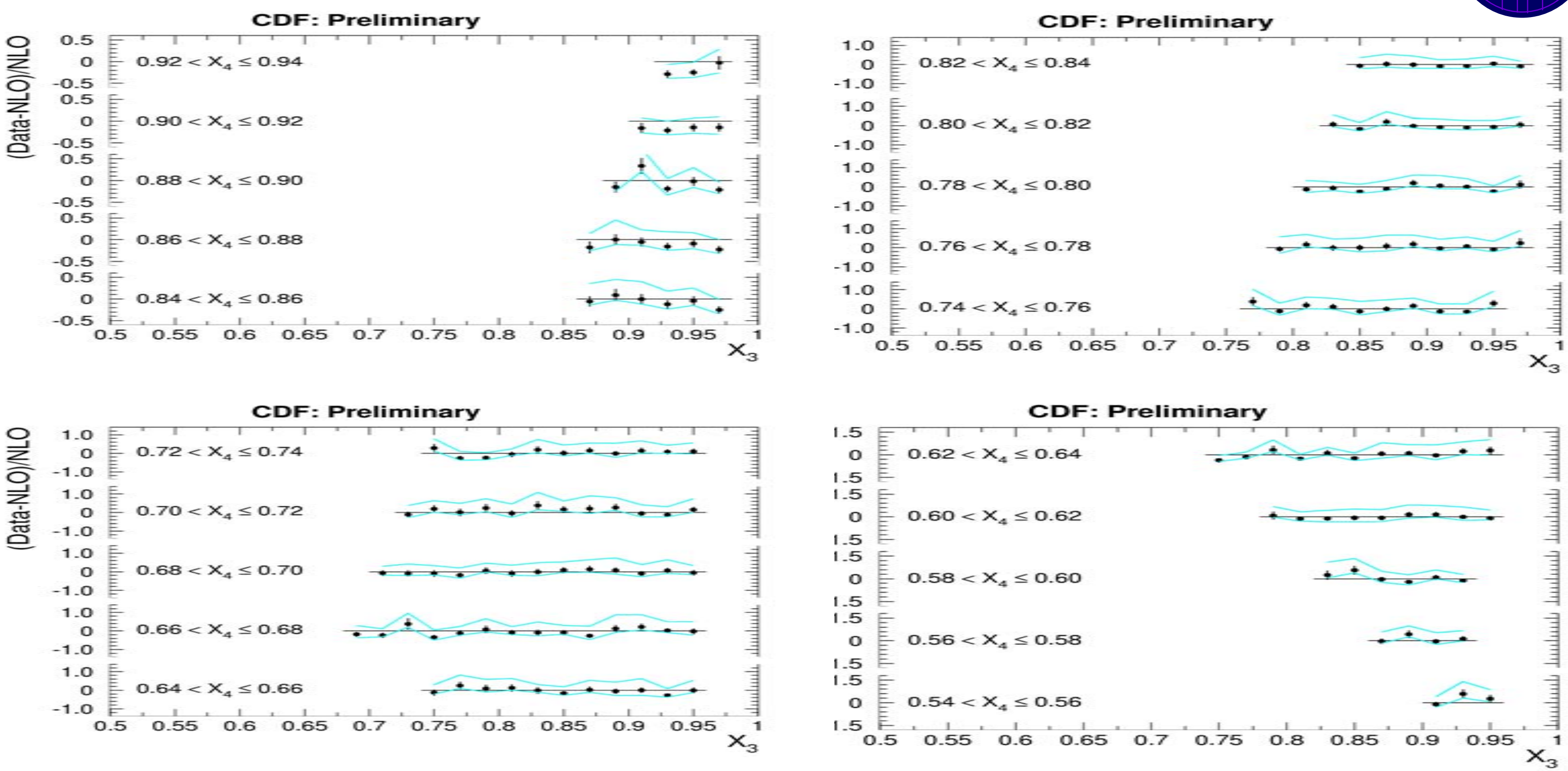
CDF Data



NLO QCD

CTEQ3, $\alpha_s = 0.1160$

CDF Three-Jet Production Cross Section



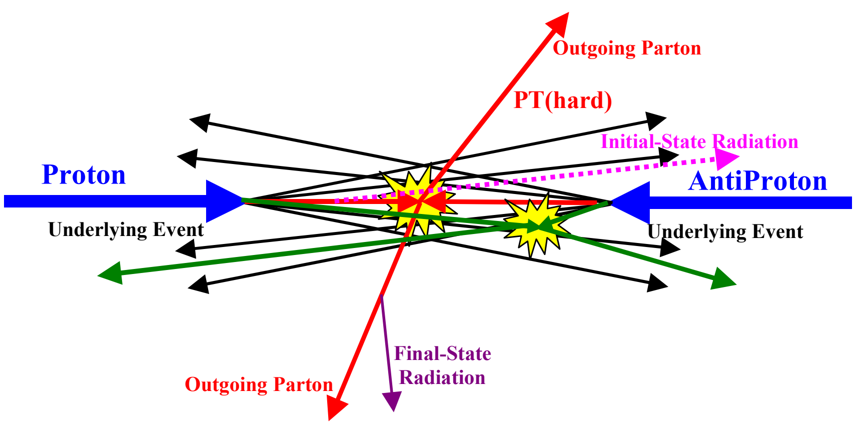
The measured total 3-jet production cross section, using the full kinematically allowed Dalitz plane:

$466 \pm 2(\text{stat})\ ^{+206}_{-71}(\text{syst})$ pb

Consistent with NLO QCD
402 ± 3 pb

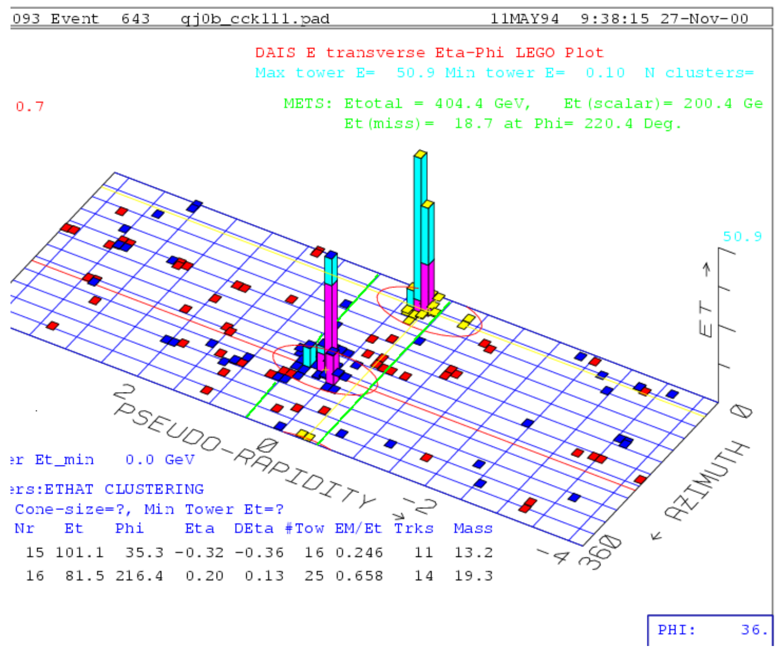
Underlying Event Studies at CDF

- Jet events at the Tevatron consist of:
  - 2->2 hard scatter
  - initial and final state radiation
  - semi-hard scatters (multiple parton scattering)
  - beam-beam remnant interactions



Underlying event energy (multiple parton scattering, beam-beam remnants, and (part of) initial and final state radiation) must be subtracted from jet energies for comparison of jet cross sections to NLO QCD predictions (largest uncertainty for low E_T)

Interesting interface between perturbative and non-perturbative physics!



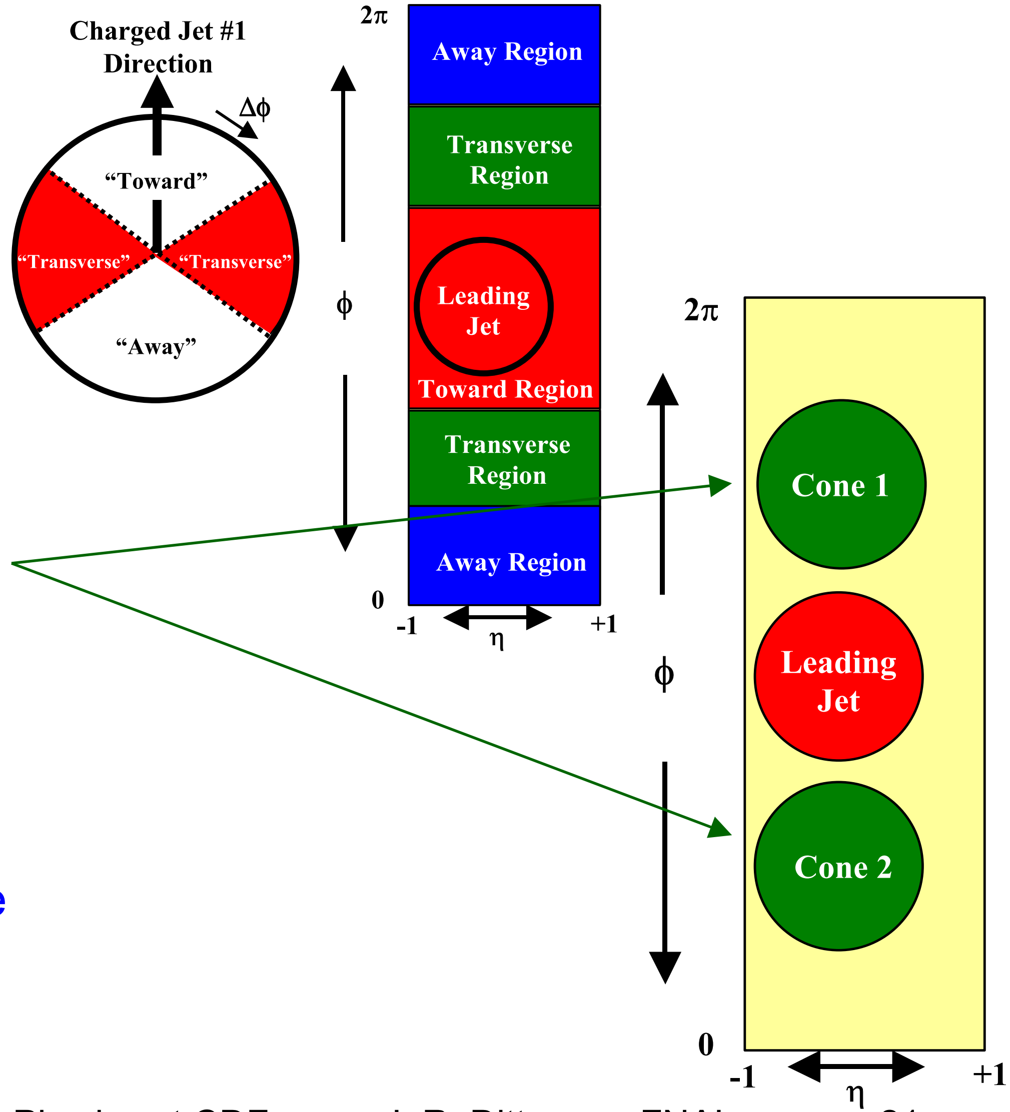
Underlying Event Studies at CDF

- Complementary analyses:

  First examines jet event structure from 1 GeV to 50 GeV looking at *towards*, *away* and *transverse* regions in phi for central rapidities

  Second examines jet events over the range from 50 GeV to ~300 GeV looking in 2 cones at same η as lead jet and at ±90 degrees in phi away, again in the central region

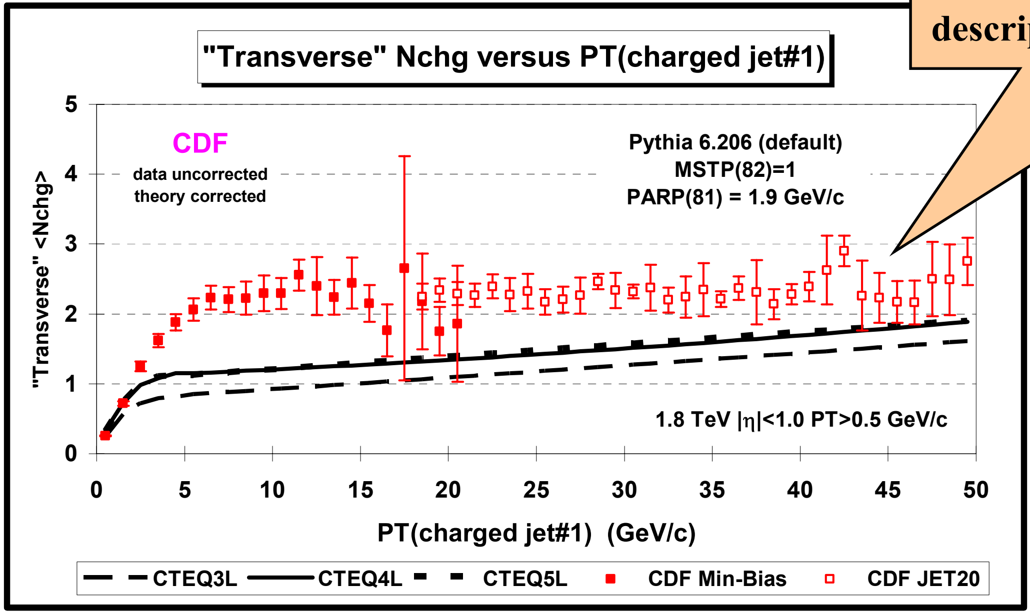
  Both analyses use charged track information ($\Sigma p_{Ttracks}$) and compare their results to predictions from leading log Monte Carlo programs



Underlying Event Studies at CDF

- PYTHIA 6.206 Defaults

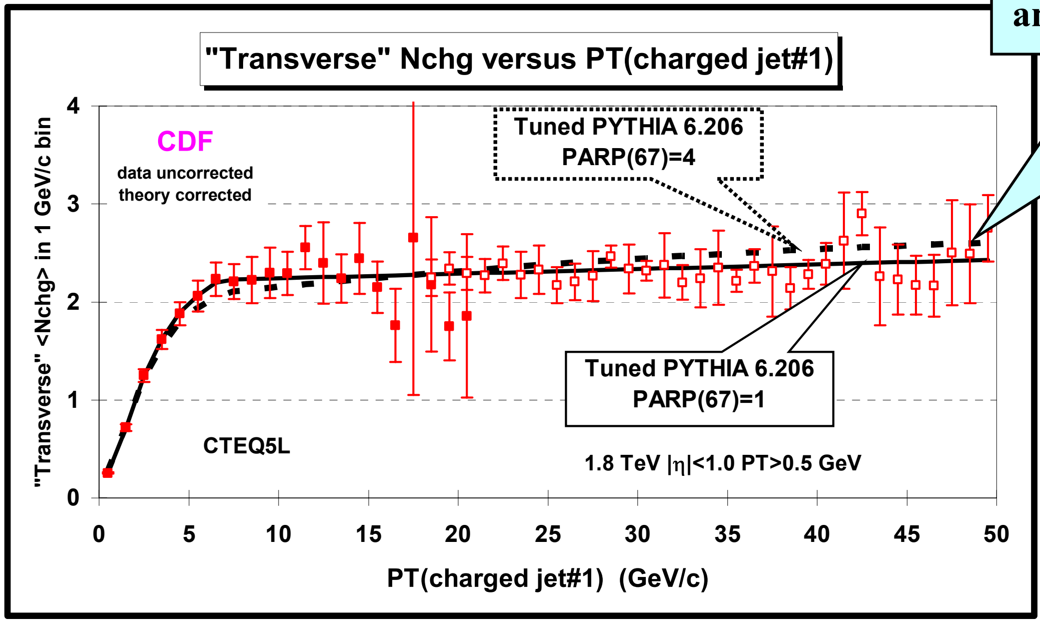
Default parameters give inadequate description of the "underlying event"!



Plot shows the mean number of charged tracks in the "Transverse" region versus P_T (leading jet), compared to the QCD hard scattering predictions of PYTHIA 6.206 (P_T(hard) > 0) using the default parameters for multiple parton interactions and CTEQ3L, CTEQ4L, and CTEQ5L.

Underlying Event Studies at CDF

- Tuned PYTHIA 6.206



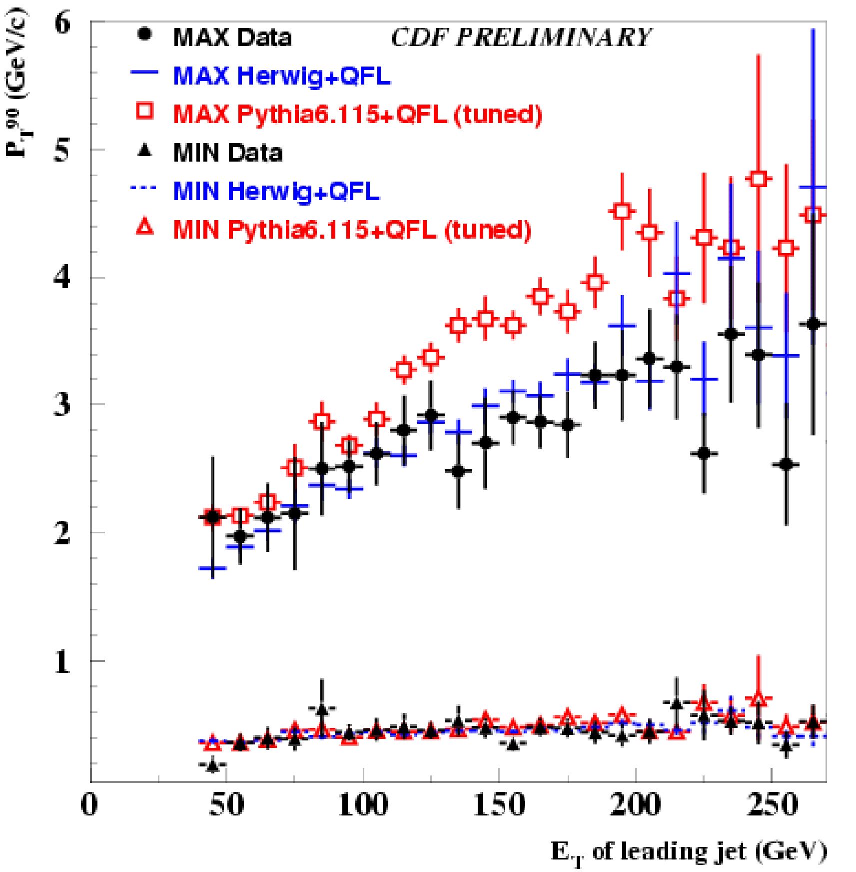
Good agreement between CDF data and tuned PYTHIA 6.206

Plot shows the mean number of charged tracks in the "Transverse" region versus P_T (leading jet), compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L).

Underlying Event Studies at CDF

Max/Min 90° Cones

- Of the 2 cones at 90°, define the one with the greater energy as *max* and the lesser as *min*
- *Max* cone increases as lead jet E_T increases; *min* cone stays constant at a level similar to that found in minimum bias events at 1800 GeV
- HERWIG agrees well with the data without any tuning
- PYTHIA parameters can be tuned to give a better fit to jet and min bias data at 1800 GeV



p_{t0} (regularization scale for multiple parton scattering)

Varying impact parameters option for underlying event generation

Harder events ↓ smaller impact parameter

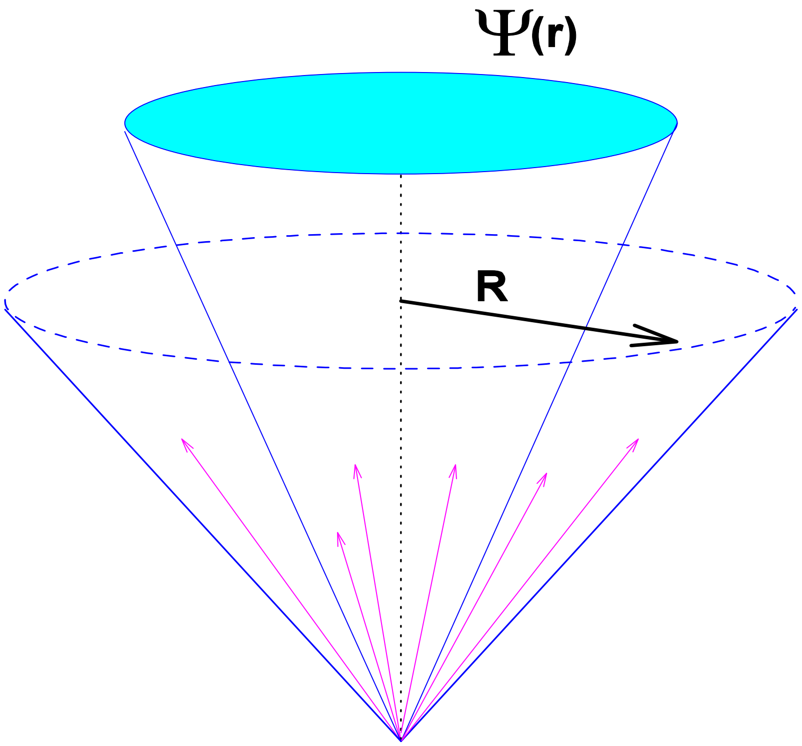
CDF Run 2 Jet Shape Analysis

Jet Shape Analysis – Method

- Select inclusive dijet events using a cone algorithm with radius
  R = 0.7

- Define $\Psi(r)$ as the fraction of the jet's E_T inside an inner cone of radius r < R

- By definition, $\Psi(r=R) = 1$



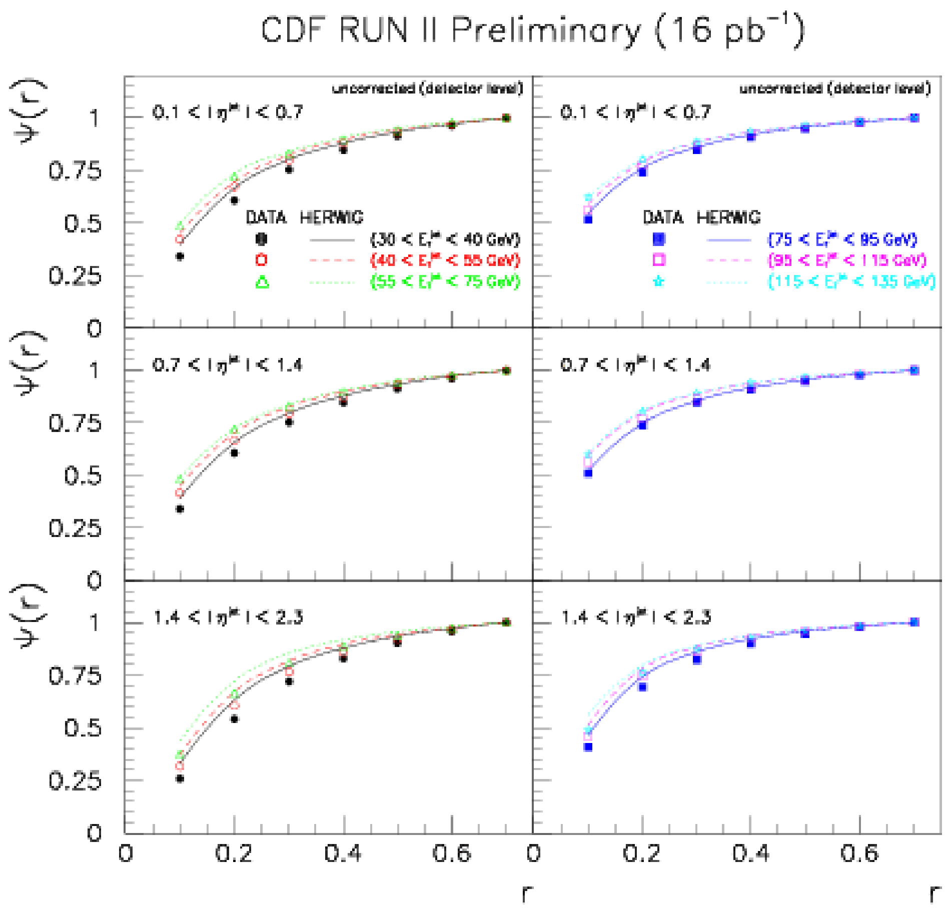
CDF Run 2 Jet Shape Analysis

Measured integrated jet shapes

- Measurements over wide range of jet E_T and η
  - 30 GeV < E_T < 135 GeV
  - $0.1 < |\eta| < 2.3$
- Measurements at the calorimeter level

Comparison to HERWIG + CDF detector simulation

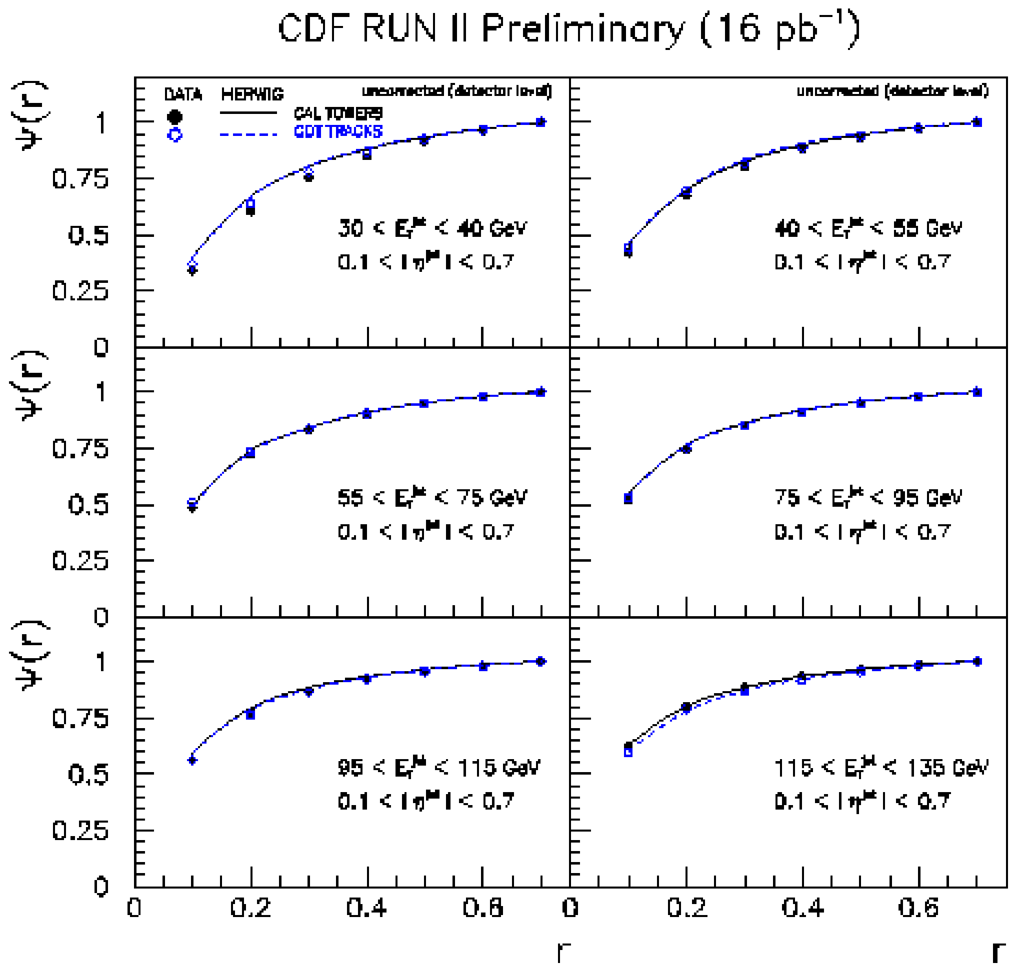
➢ HERWIG predicts jets that are too narrow at low E_T and high η $\rightarrow$ underlying event



CDF Run 2 Jet Shape Analysis

Jet shapes measured with calorimeter vs. tracks

- Measurement performed for central jets with good Central Outer Tracker (COT) coverage
- Excellent agreement between calorimeter and tracking measurements
- HERWIG slightly narrower than the data for low-E_T jets



Similar measurements needed for b-quark tagged jets

Photon and Jet Physics at CDF

Summary

- Recent Run 1 measurements of inclusive photon production indicate discrepancies with NLO QCD. A larger data sample is needed!
- The Run 2 inclusive jet cross section, extending beyond 600 GeV, is expected to settle the issue of the high-x excess seen in Run 1 data. Is the high-x gluon distribution responsible?
- New measurements of 3-jet production at CDF compare well to NLO QCD predictions.
- Studies of the underlying event at CDF have revealed inadequacies of some Monte Carlo generators and have led to improved tuning.
- New measurements of jet shapes in Run 2 dijet events generally agree well with predictions of HERWIG + detector simulation.

Run 2 analyses of photons and jets at CDF are well underway!