Measurements of Jet and Multijet Cross Sections with the CDF Detector

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(On behalf of the CDF collaboration)

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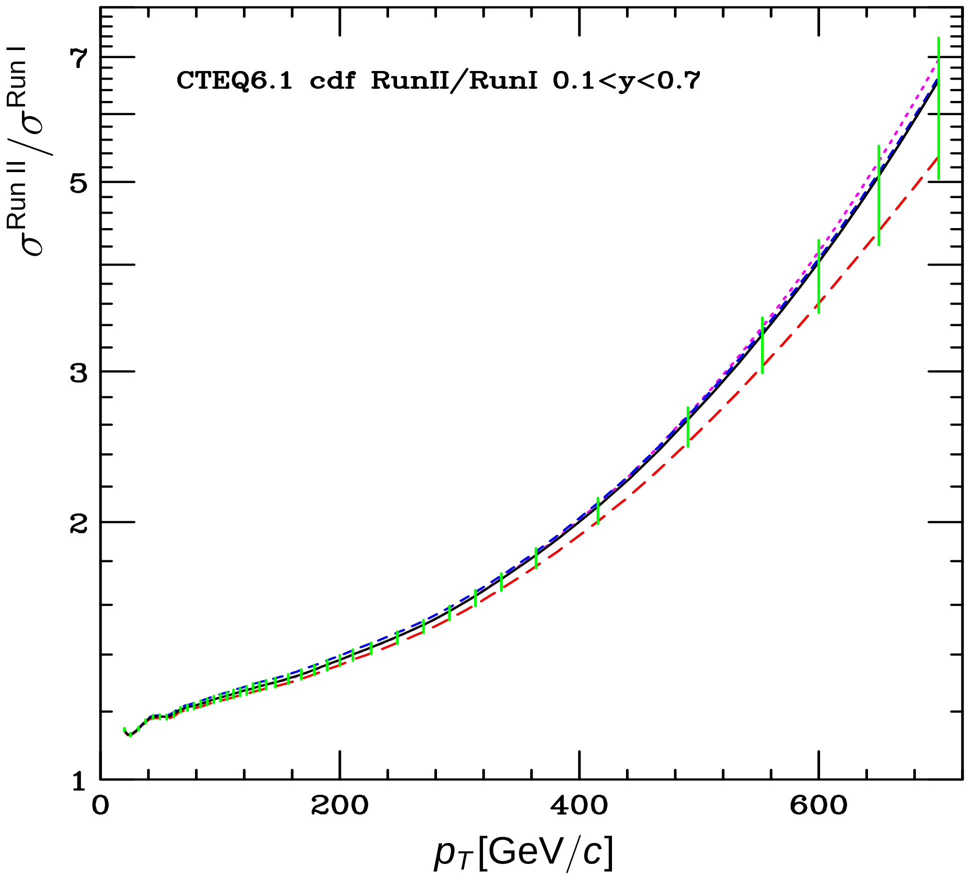
Outline:

1. Run II Inclusive Jet Cross Section
   – Status
   – Prospects
2. Run I Inclusive 3-Jet Cross Section vs. NLO QCD

Inclusive Jet Cross Section — Motivation

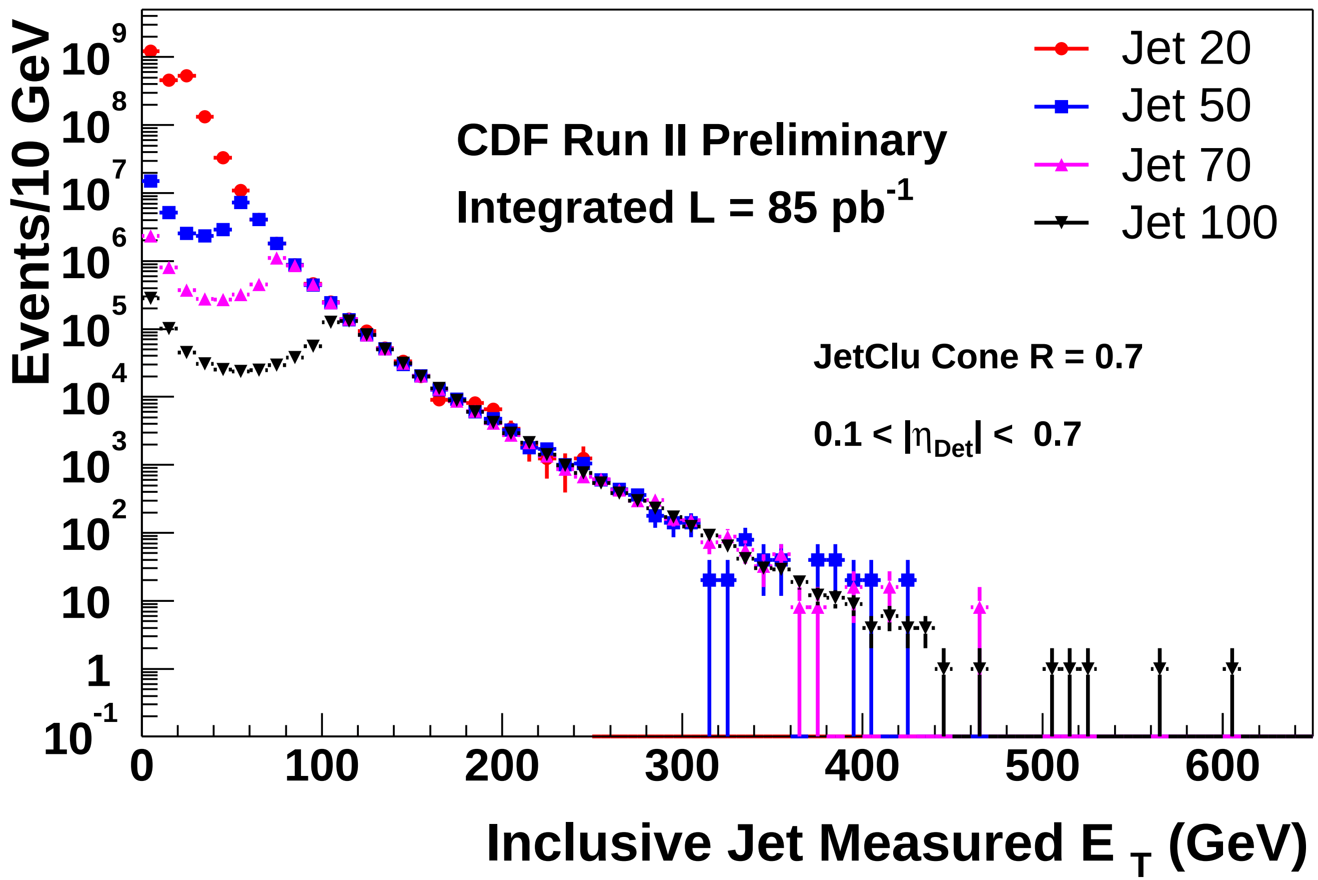
- Measure fundamental input ingredients of QCD:
  - parton distribution functions: Excess at high E_T in CDF Run I data.
    Gluon distribution not constrained at high x.
    CTEQ 6.1: Good agreement with Run I data within uncertainty.
  - strong coupling constant α_s
- Probe small distances and look for deviations from QCD predictions. (New physics?)
- Extend measured E_T spectrum to > 600 GeV:
  - integrated luminosity goal (Run IIa): 2 fb^{-1}.
  - higher $\sqrt{s}$: 1.8 $\rightarrow$ 1.96 TeV:
    cross section $\times 2$ @ E_T = 400 GeV
    $\times 4$ @ E_T = 600 GeV
- Run II so far:
  - Feb. 2002 - Jan. 2003: $\mathcal{L}_{\text{int}}$ = 85 pb^{-1}
    $\longrightarrow$ corrected cross section:
    Repeat Run I analysis (fixed cone jet algorithm JetClu, R_{cone} = 0.7; Run I corrections).
  - Feb. 2002 - July 2003: $\mathcal{L}_{\text{int}}$ = 146 pb^{-1}
    $\longrightarrow$ raw distributions



Inclusive Jet Cross Section — Event selection

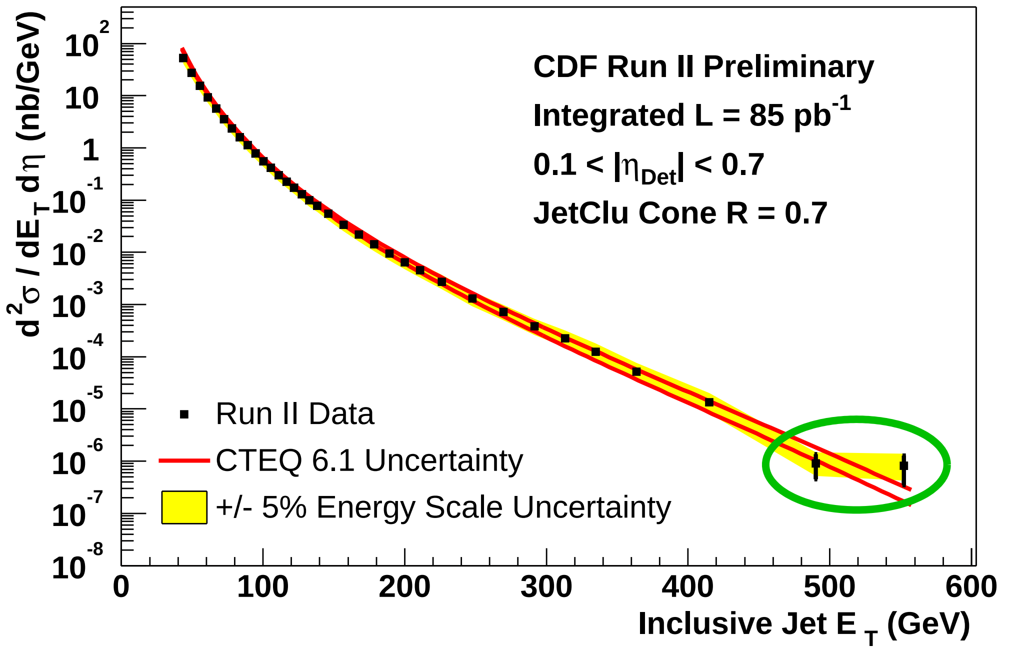
- 4 Triggers: Jet20, Jet50, Jet70, Jet100. Use where $> 99\,\%$ efficient.
- $\not{E}_T / \sqrt{\sum E_T} < 3.5 \ldots 7\,\sqrt{\text{GeV}}$.
- $|z_{\text{vertex}}| < 60\,\text{cm}$.
- $\sum E_T < 1500\,\text{GeV}$.

- Raw distributions $(0.1 < |\eta_{\text{Det}}| < 0.7)$:



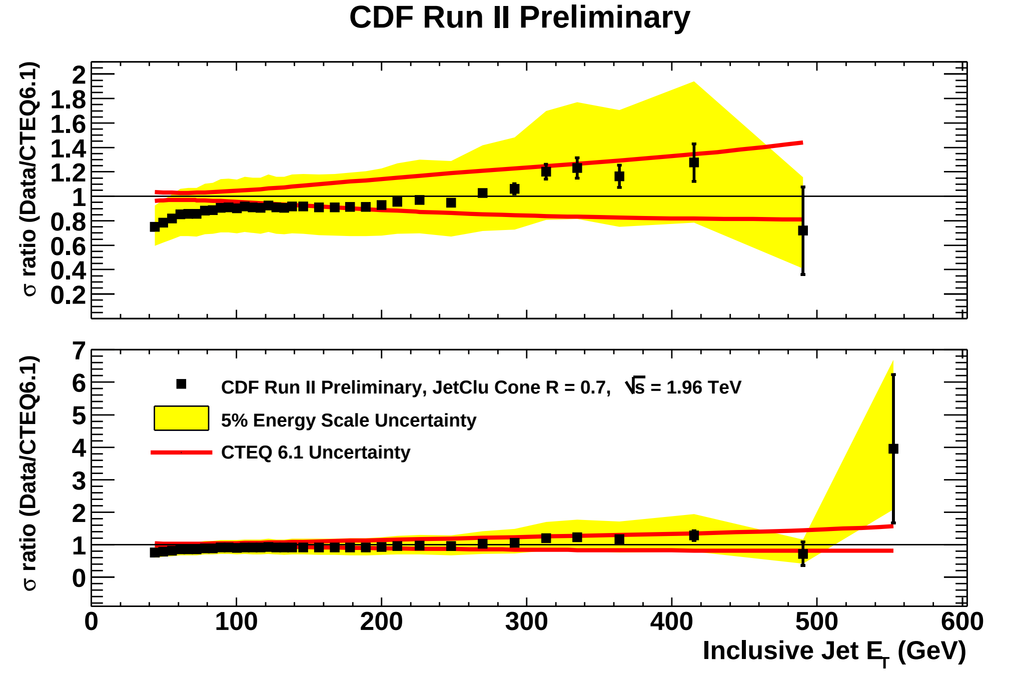
Inclusive Jet Cross Section — Corrections and Results

- Correct jet energies back to hadron level.
- Calorimeter energy scale set to Run I scale.
  $\longrightarrow$ Apply $(5 \pm 5)\,\%$ correction to raw energy.
  $\longrightarrow$ largest source of systematic uncertainty.
- Apply Run I corrections for:
  - calorimeter non-linearity
  - smearing due to resolution
  - underlying event and multiple interactions



- Two data points added w.r.t. Run I.
  E_T range extended by 150 GeV.

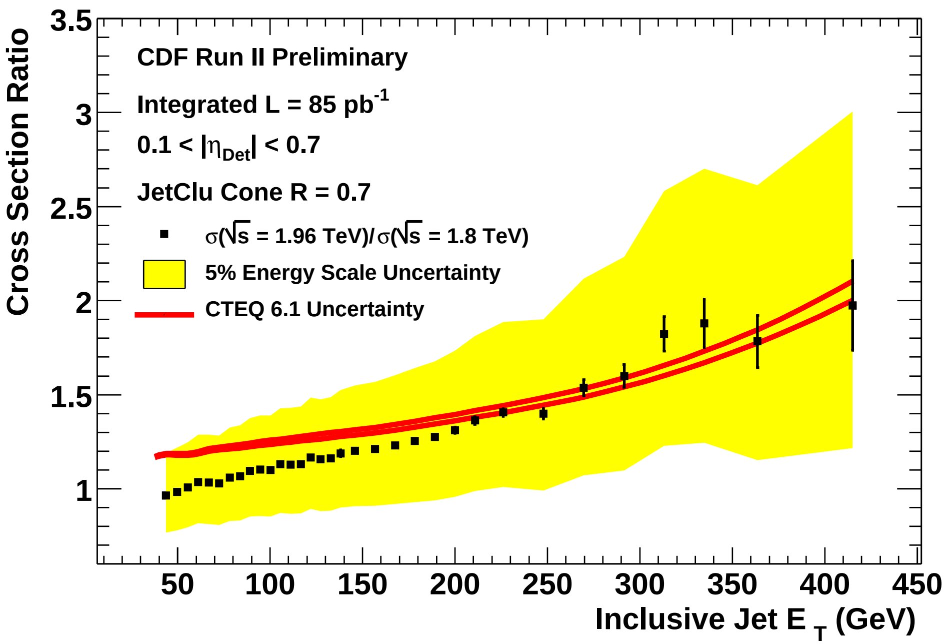
- Measured cross section agrees with prediction within uncertainties.
- Largest upward deviation in CTEQ 6.1 band:
  increased gluon content at high x.

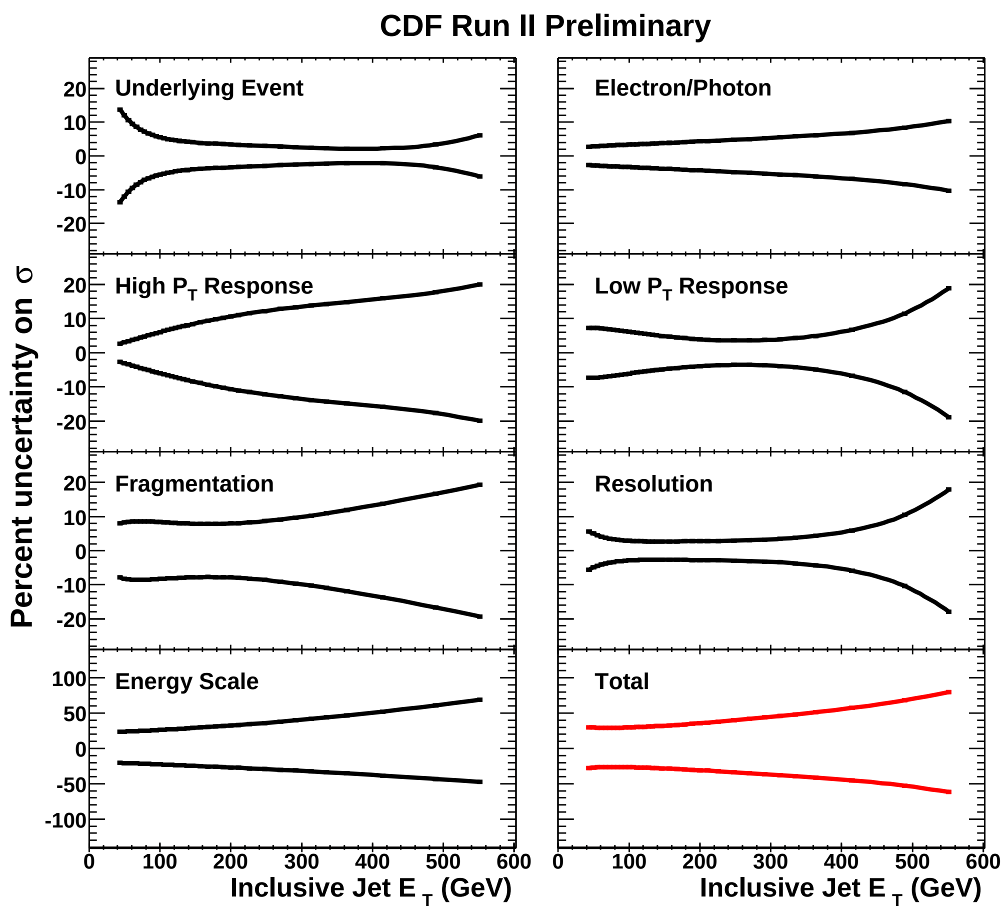


Inclusive Jet Cross Section — Run II vs. Run I and Systematics

Comparison with Run I

- $\sigma^{\text{Run II}}/\sigma^{\text{Run I}}$: Systematic errors mostly cancel, but Run II jet energy scale is dominant.
- Reasonable agreement, but more work needed to understand the details.
- $\times 2$ @ $E_T = 400\,\text{GeV}$ confirmed.





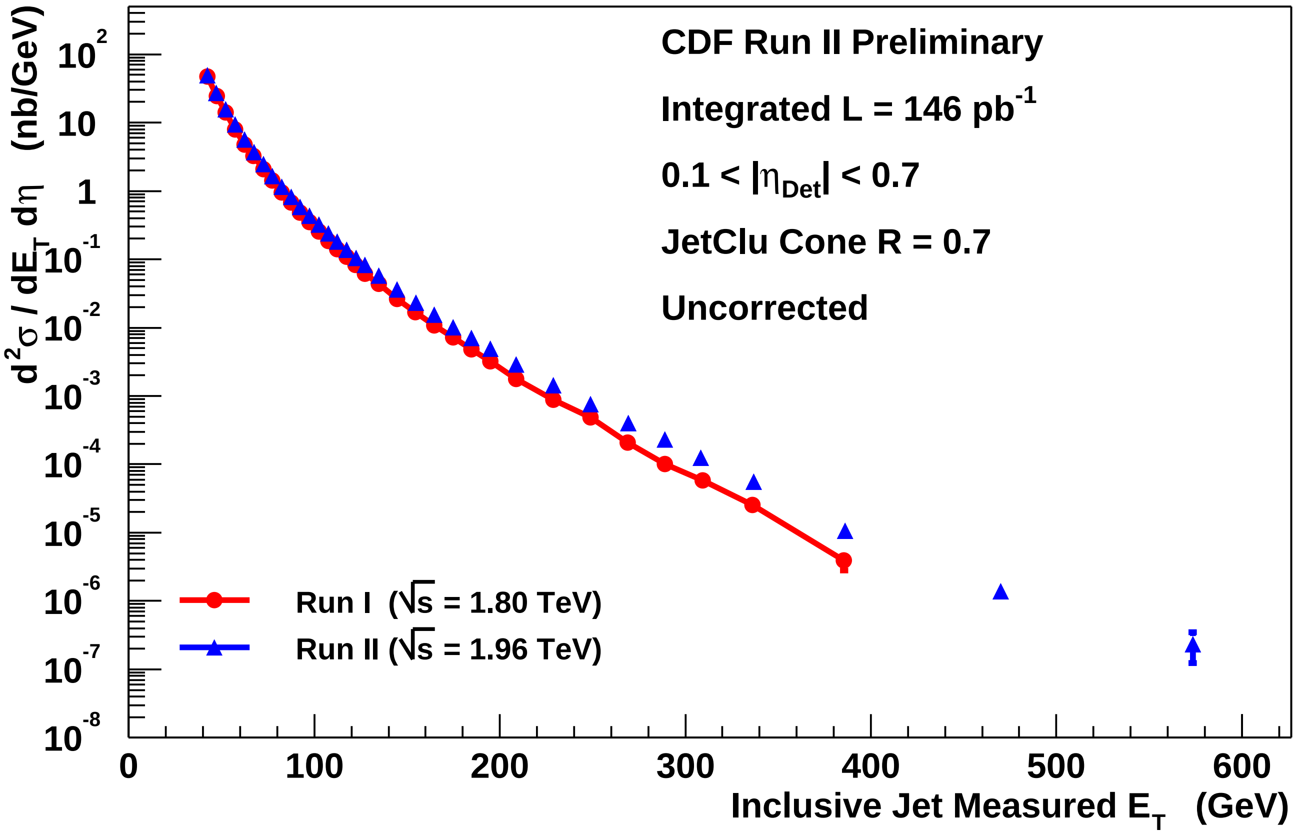
Systematic uncertainties

- dominant source: energy scale (under study).
- luminosity: $\pm 5.8\,\%$.

Inclusive Jet Cross Section — Next Steps

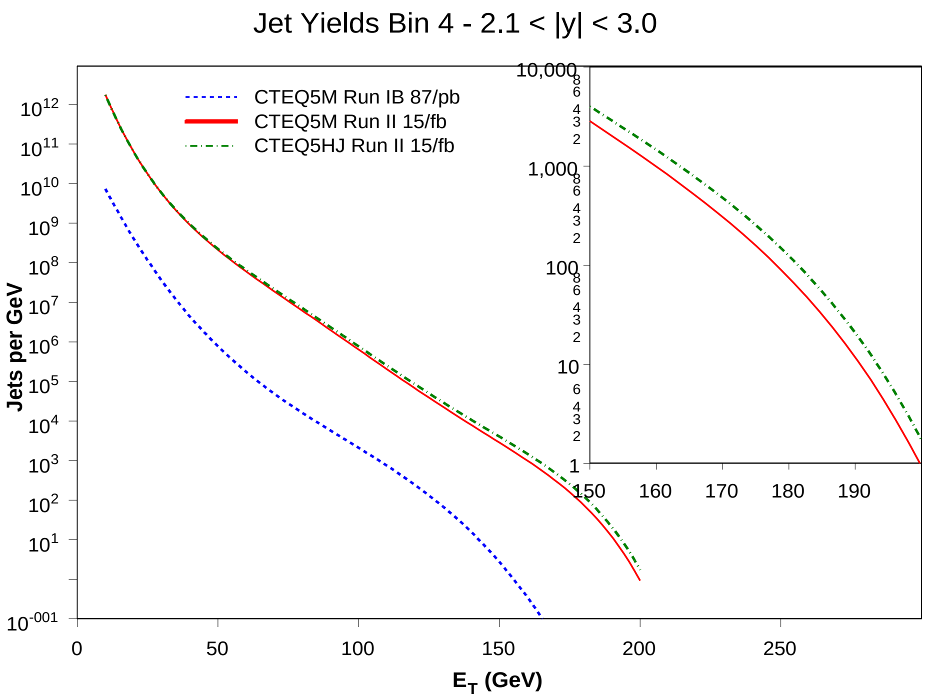
- Better understanding of calorimeter response. $\longrightarrow$ Reduce systematic uncertainty.
- Collect more data. $\longrightarrow$ Reduce statistical uncertainty.

- $\mathcal{L}_{\text{int}} = 146\,\text{pb}^{-1}$:



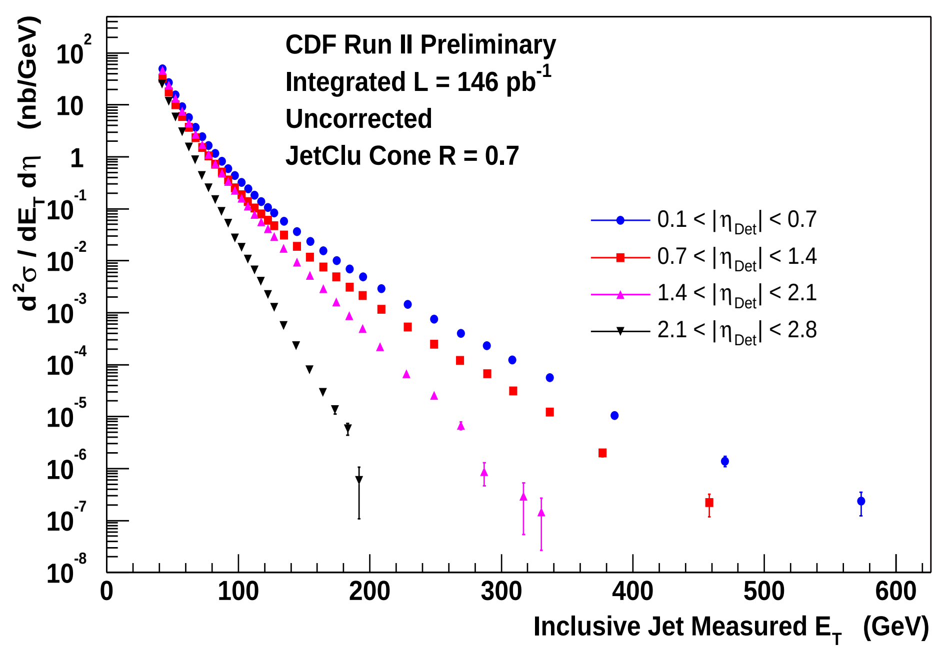
Inclusive Jet Cross Section — Forward Region

- New CDF plug calorimeter: $1.1 < |\eta_{\rm Det}| < 3.6$.



Theory:

- Sensitivity to high x gluon at high rapidities.
- Constraint on parton distribution functions.



CDF measurement:

- Only raw distributions so far.
- To be done: Study calorimeter response (calibration, jet energy scale → response function) and systematic uncertainties in the forward region.

Inclusive Jet Cross Section — KtClus algorithm

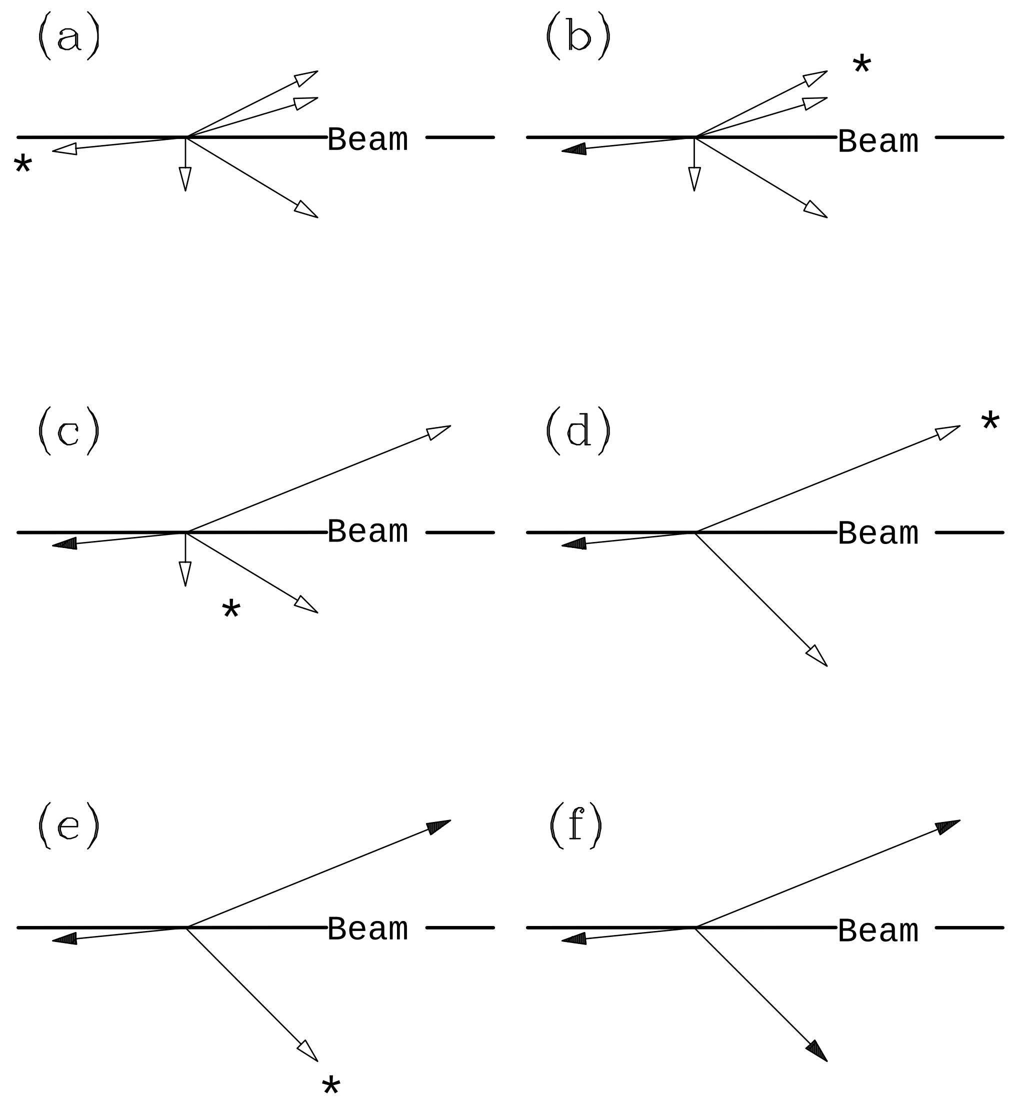
- KtClus combines particles based on relative transverse momentum:

$$d_{ij} = \frac{\min(E_{T,i}^2, E_{T,j}^2) \cdot (\Delta R)^2}{D^2}, \quad d_i = E_{T,i}^2.$$

$\min(d_{ij}, d_i) = d_{ij} \quad \rightarrow$ merge i and j.
$\min(d_{ij}, d_i) = d_i \quad \rightarrow$ promote i to a jet.

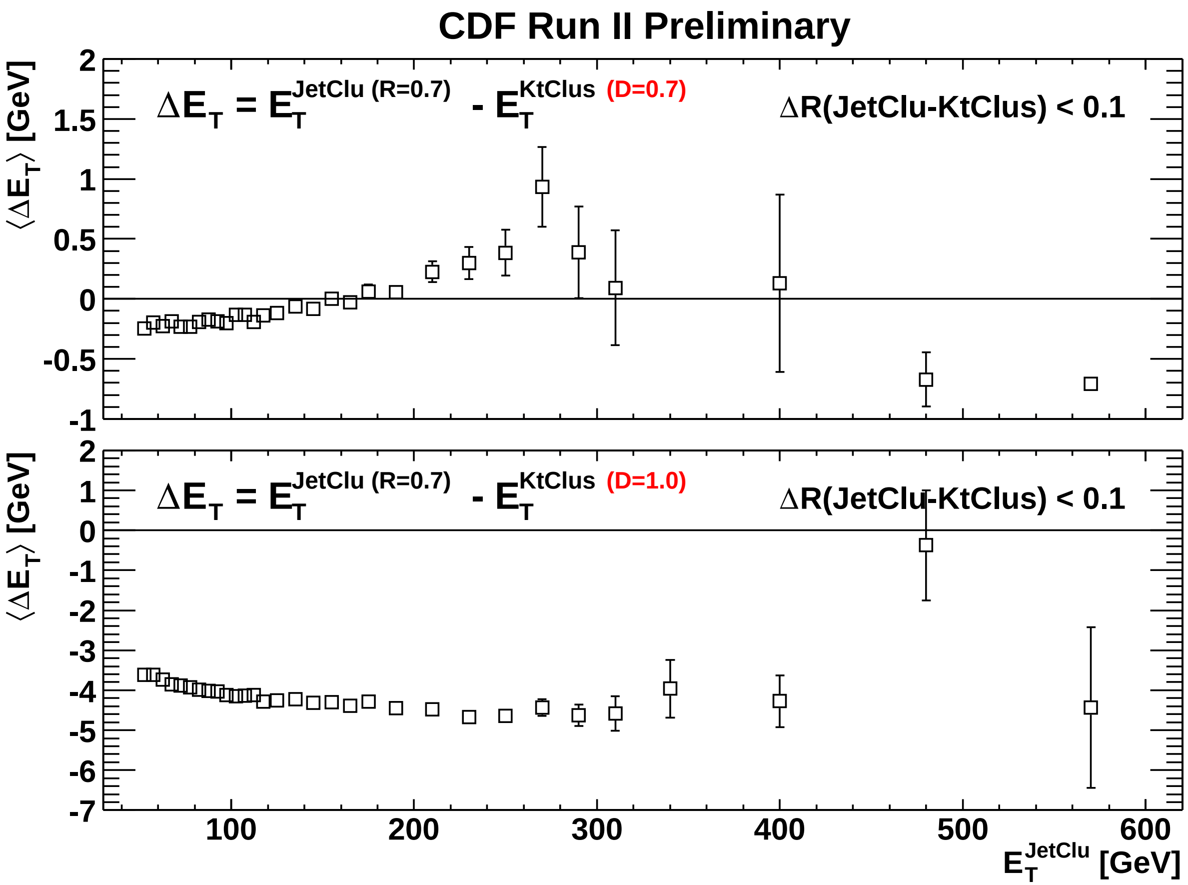
D controls the size of the jets.

- No splitting/merging prescription required.
- Infrared and collinear safe.
- Theoretically preferred (and used by DØ): $D = 1.0$.
- Compare JetClu ($R_{\text{cone}} = 0.7$) to KtClus ($D = 0.7$, $D = 1.0$).



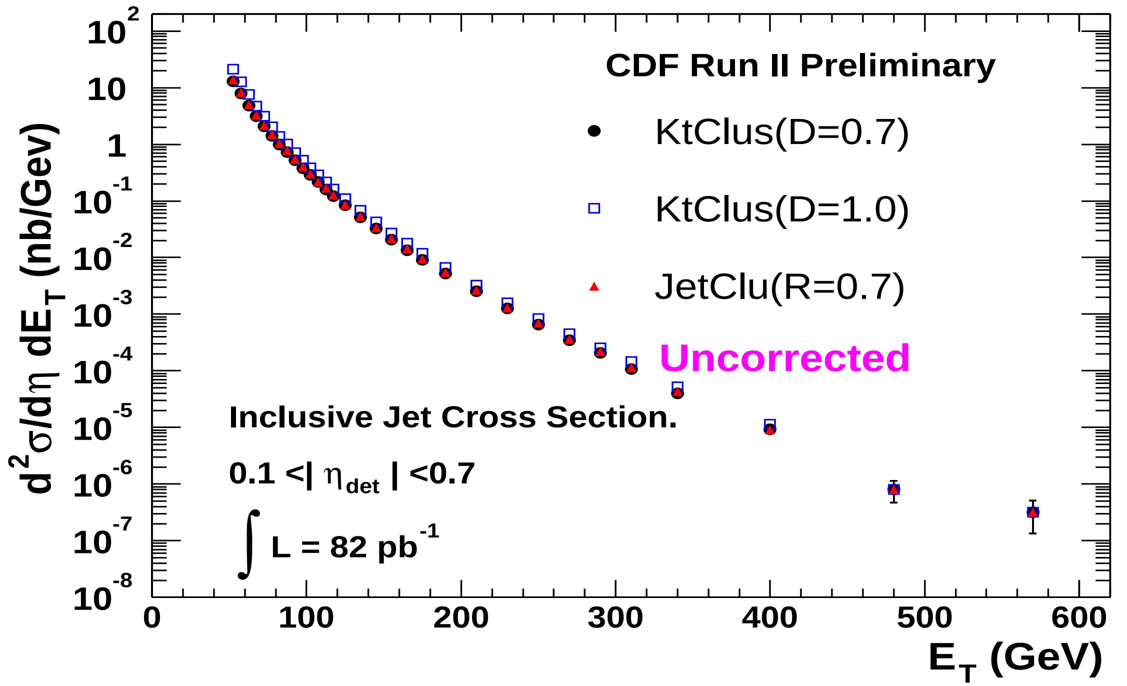
Inclusive Jet Cross Section — E_T: JetClu vs. KtClus

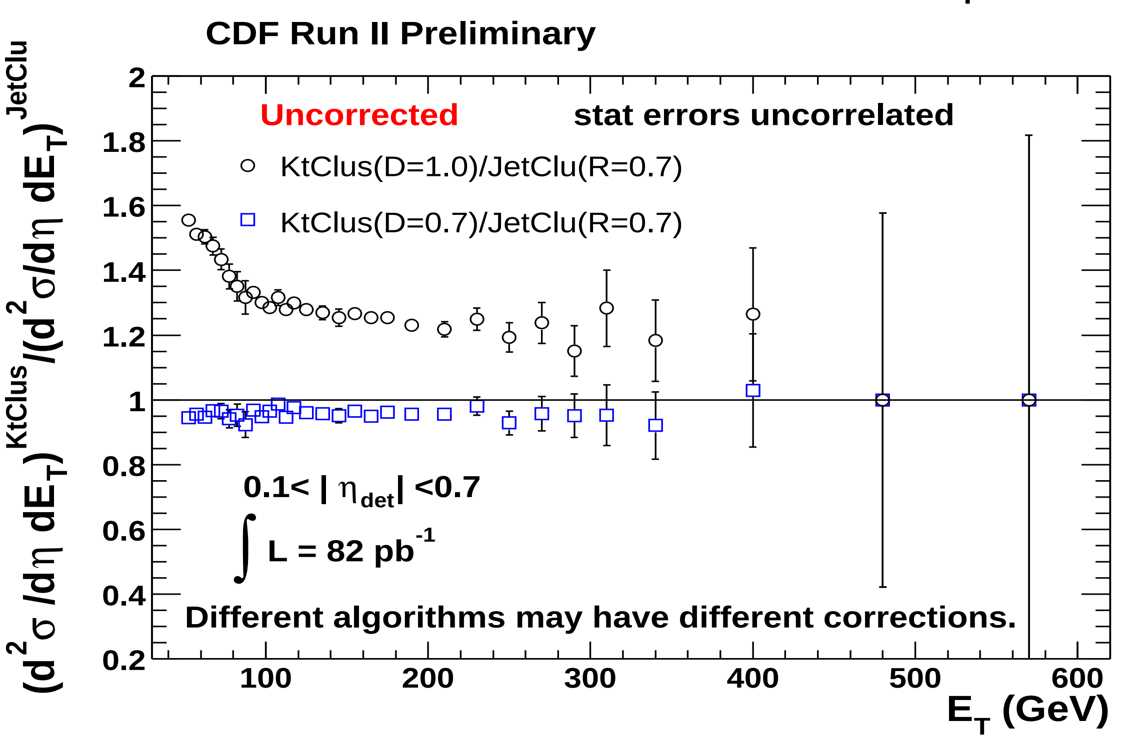
- Compare E_T of JetClu and matched KtClus jets:
  - Choose JetClu jet.
  - Find corresponding KtClus jet. Matching requirement: $\Delta R < 0.1$.
  - Plot mean ΔE_T(JetClu-KtClus) vs. E_T(JetClu).
- Dataset: $\mathcal{L}_{\text{int}} = 82\,\text{pb}^{-1}$ of CDF Run II data.
- Event selection: $\widetilde{\not\!E_T} < 6\sqrt{\text{GeV}}$, $\sum E_T < 1960\,\text{GeV}$, $|z_{\text{vertex}}| < 60\,\text{cm}$.
- $D = 0.7$: Small differences to JetClu ($R_{\text{cone}} = 0.7$). Non-constant shift.
- $D = 1.0$: Up to 4-5 GeV higher E_T in KtClus jets.
- Cannot apply JetClu jet energy corrections to KtClus jets.



Inclusive Jet Cross Section — σ^{raw}: JetClu vs. KtClus

- Large differences between D = 0.7 and D = 1.0.
- Shape at low E_T different.
- Caveat: These are uncorrected distributions.
- Long term goal: Measure jet cross section using the Run II jet algorithms (KtClus, MidPoint):
  - Derive jet energy corrections.
  - Study jet fragmentation.
  - Study energy contributions from underlying event.
  - . . .





3-Jet Production vs. NLO QCD

- Full NLO QCD prediction for 3-jet production at hadron colliders by Kilgore & Giele: hep-ph/0009193.

  $\rightarrow$ allow for a measurement of α_s from $R_{32} = \frac{\sigma^{\text{3-jet}}}{\sigma^{\text{2-jet}}}$
  or from event shapes.

- Comparison to Run Ib data.

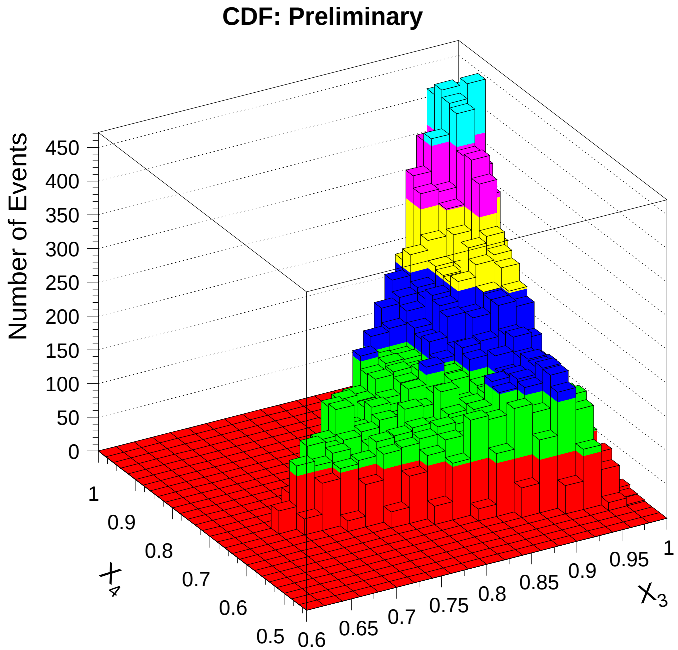
- Event selection:
  - Jet reconstruction using JetClu, $R_{\text{cone}} = 0.7$.
  - Trigger: $\sum E_T > 175\,\text{GeV}$.
  - Require ≥ 3 jets with $E_T > 20\,\text{GeV}$, $|\eta| < 2.0$.
    $\sum E_T^{\text{3 jets}} > 320\,\text{GeV}$.
    Cone separation: $\Delta R > 1.0$.
    (Reduces s_{min} dependence in NLO QCD prediction.)
  - Remove and correct for multiple interactions.

- Boost into 3-jet rest frame. Number 3 leading jets such that:
  $E_3 > E_4 > E_5 \quad (1 + 2 \rightarrow 3 + 4 + 5)$.

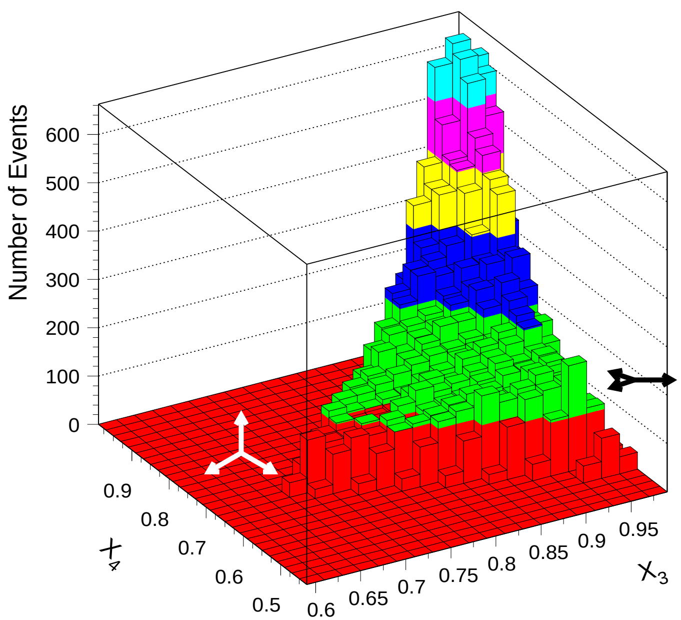
- Dalitz variables $\quad X_i = \frac{2\,E_i}{m_{\text{3 jets}}}$:

  $$X_3 + X_4 + X_5 = 2, \quad X_3 = \frac{2}{3} \ldots 1, \quad X_4 = \frac{1}{2} \ldots 1, \quad X_5 = 0 \ldots \frac{2}{3}.$$

- $\frac{d^2\sigma}{dX_3\,dX_4} \propto |\mathcal{M}|^2 \propto$ density in Dalitz plane.



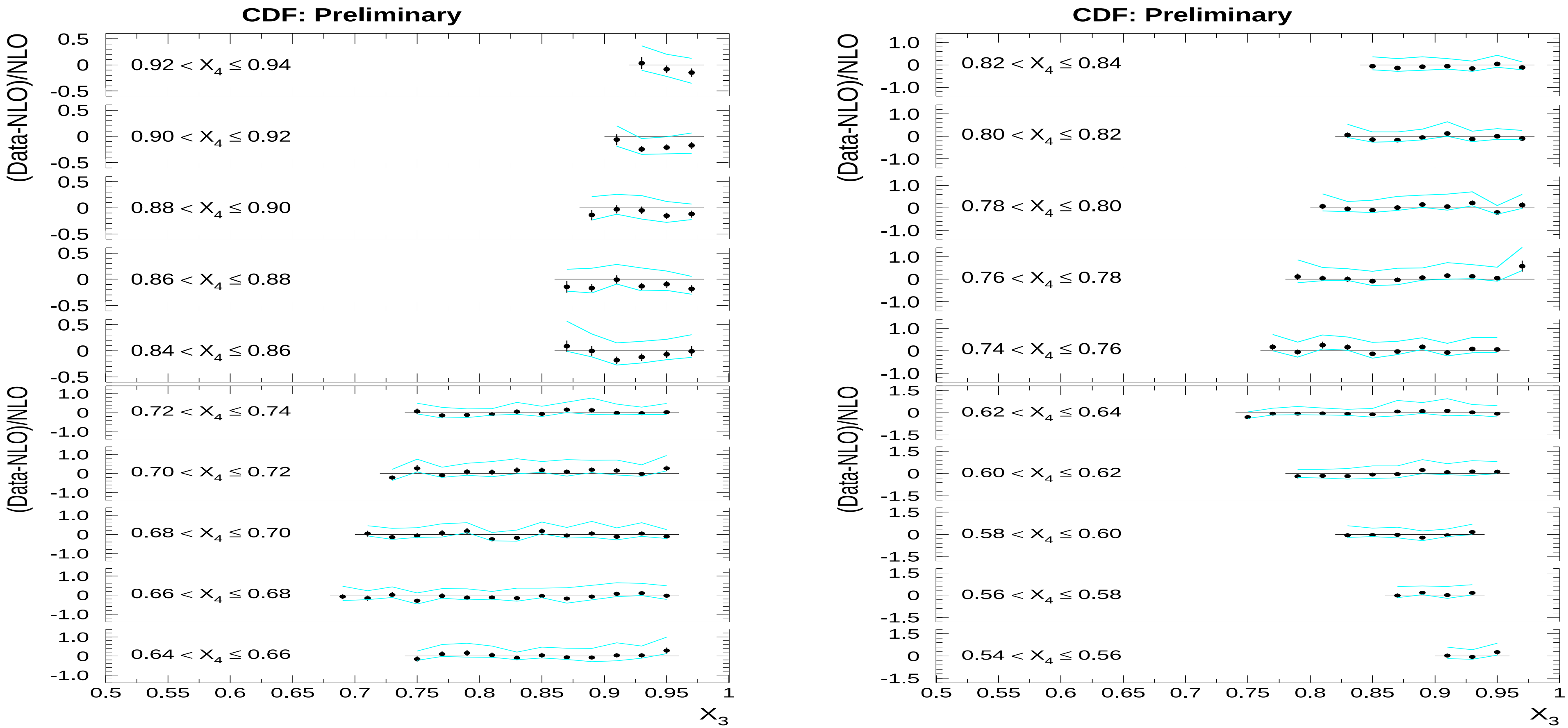
CDF Run I Data



NLO QCD + CTEQ 4M (α_s = 0.1155)

3-Jet Production vs. NLO QCD — 1d distributions

- For each bin in X_4: Plot (Data$-$NLO)/NLO as a function of X_3:



- Reasonable agreement within systematic and theoretical uncertainties.
- Dominant source of systematic uncertainty: jet energy scale.
- χ^2 analysis: no sensitivity to α_s
- 3-jet production cross section (integrated over $X_3 < 0.98$):

Data: $\sigma^{\text{3-jet}} = 456 \pm 2(\text{stat.})\,^{+202}_{-68}(\text{syst.})$ pb.   NLO: $\sigma^{\text{3-jet}} = 482 \pm 2(\text{stat.})\,^{+31}_{-72}(\text{theo.})$ pb.

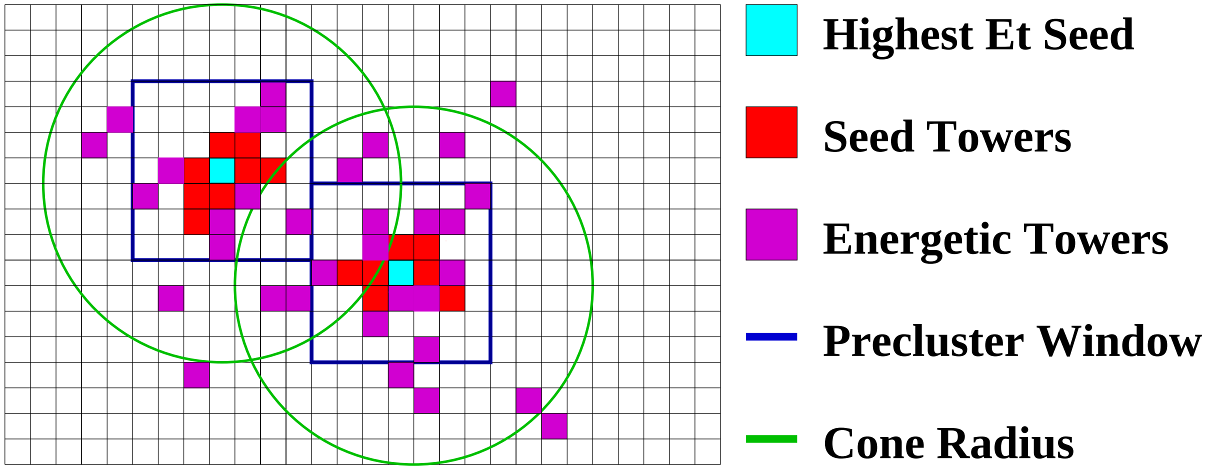
Summary and Outlook

- Inclusive Jet Cross Section (Run II):
  - Run II dataset larger than Run I.
  - Measured cross section agrees with prediction from NLO QCD (CTEQ 6.1).
  - Ratio $\sigma^{\text{Run II}}/\sigma^{\text{Run I}}$ agrees with prediction.
  - Dominant systematic uncertainty: calorimeter jet energy scale: 5 % (Run I: 1 %).
  - Measure jet cross section in forward region. $\longrightarrow$ Sensitivity to high *x* gluon.
  - Employ Run II jet algorithms: KtClus, MidPoint.

- 3-Jet Production vs. NLO QCD (Run I):
  - Reasonable agreement with predictions within systematic and theoretical uncertainties.
  - Dalitz analysis: No extraction of α_s possible.
  - Prospects for Run II:
    - higher statistics, reduced systematics, more precise QCD calculations (CPU power)
    - α_s from $R_{32} = \frac{\sigma^{\text{3-jet}}}{\sigma^{\text{2-jet}}}$ or from event shapes.

Backup Slides: JetClu Algorithm

- **JetClu:** CDF's Run I algorithm
  - Create E_T-ordered list of calorimeter towers (seed towers: $E_T > 1\,\text{GeV}$).
  - Build pre-clusters from adjacent seed towers beginning with the highest E_T tower.
  - For each pre-cluster: Calculate centroid;
    iterate cone using all towers above 100 MeV
    $(\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < R_{\text{cone}})$.
  - **"Ratcheting":** During the iteration no seed tower of the original pre-cluster ever leaves the cone! (Pre-clusters remain connected to cones.)
  - Two overlapping stable cones are merged if more than 75 % of the transverse energy of one of the cones is shared by the other one.
    Otherwise the cones are split by distributing the shared energy among the cones.
    (CDF-specific, iterative)
  - JetClu is neither infrared safe nor collinear safe.
  - Yet, JetClu is being used in CDF's Run II Level 3 trigger and for some analyses (backward compatibility).



Backup Slides: Central / Forward Region