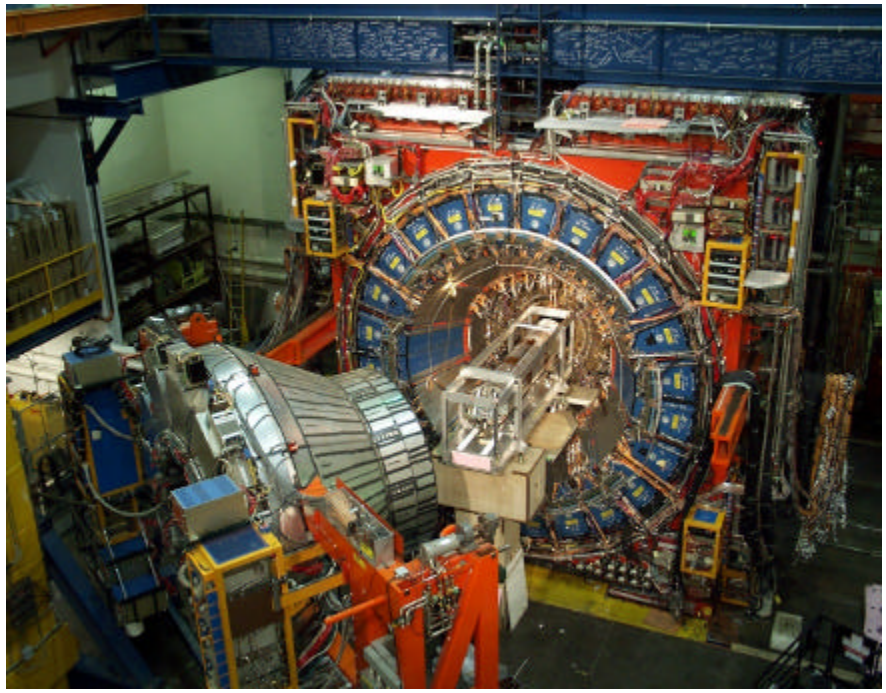
Recent QCD Results From Run II



CDF

DØ

Vivian O'Dell

for the

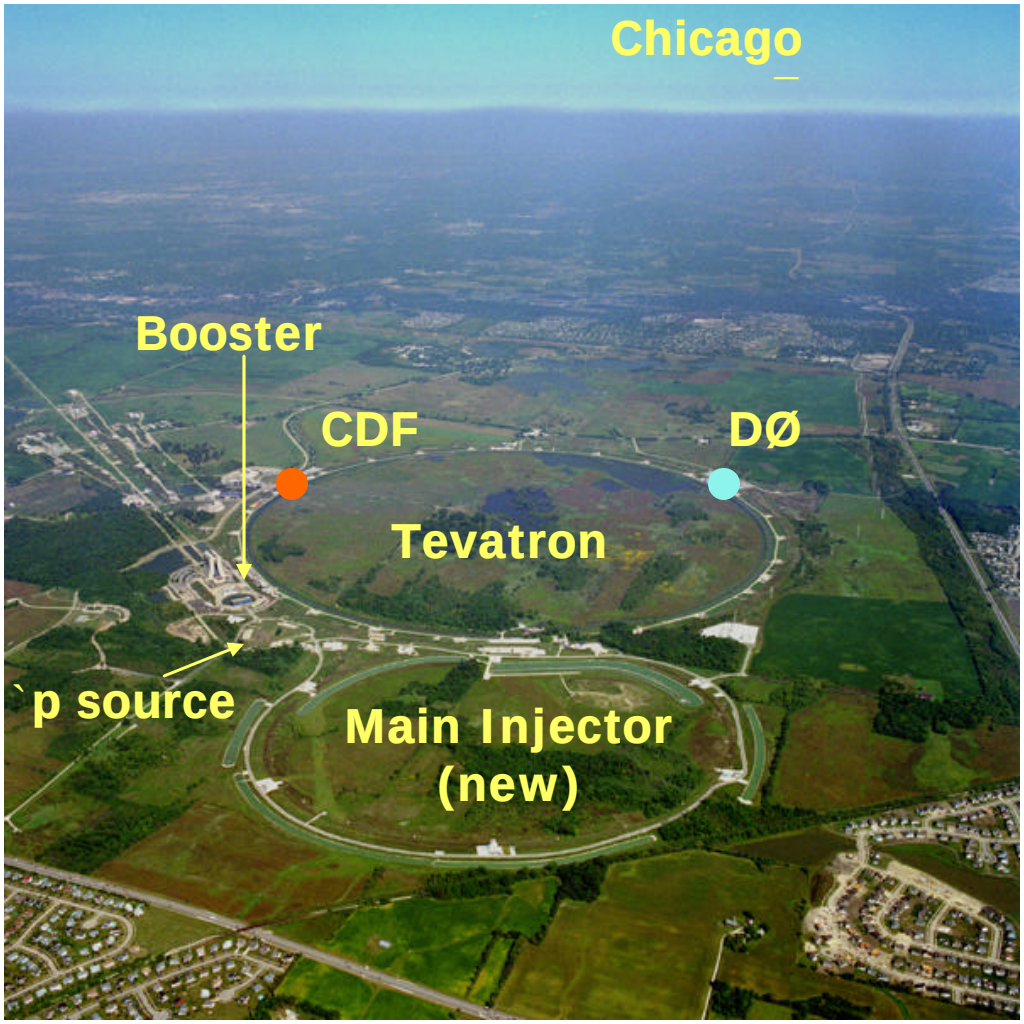
CDF and DØ collaborations

Recent QCD Results From Run II

- **What I will talk about:**
  - Jet physics including
    - **Inclusive jet cross sections**
    - **Dijet mass cross sections**
    - **Underlying event studies**
    - **Df between jets**
    - **m tagged jets**

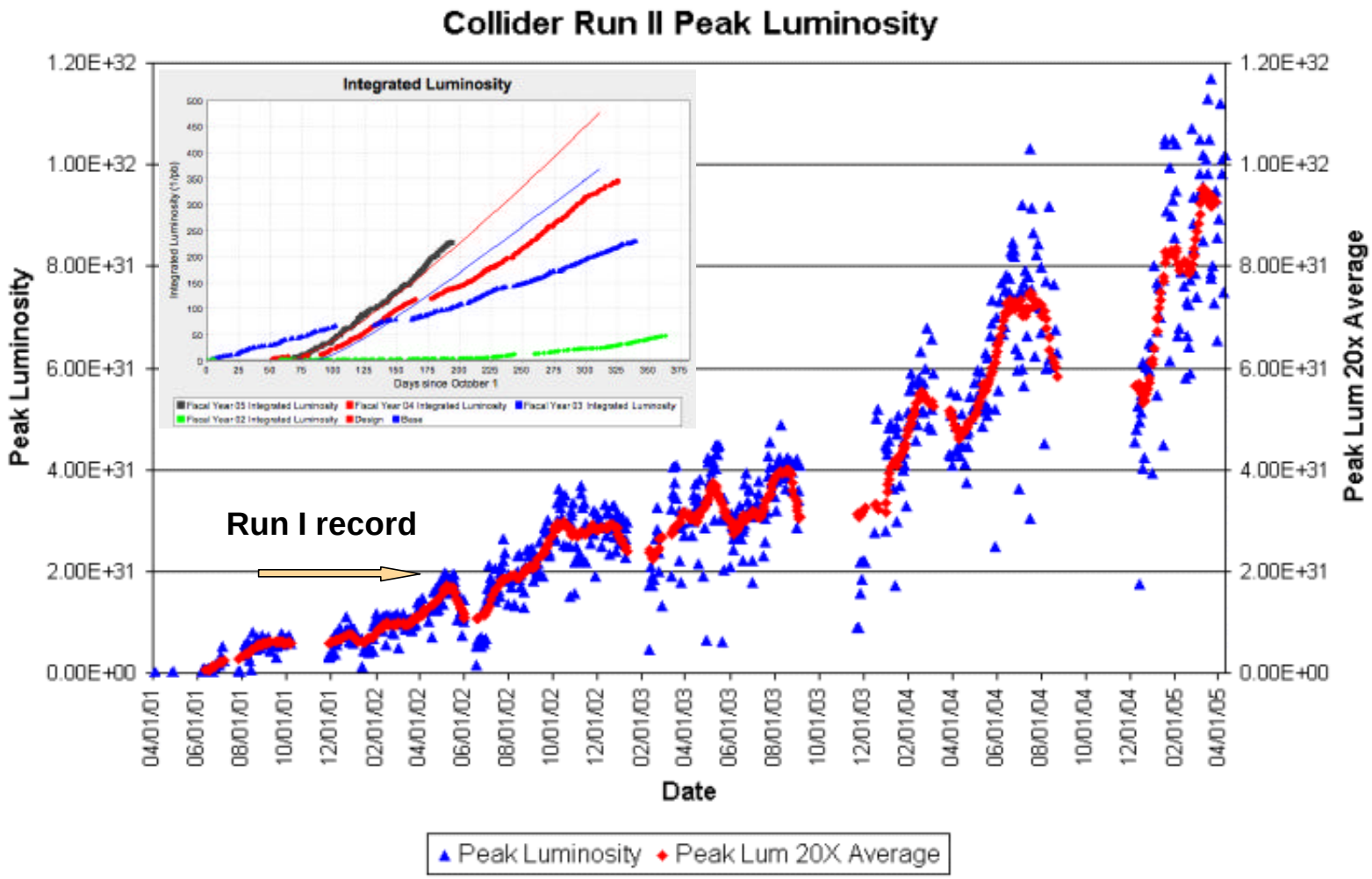
- **What I *won't* talk about (sorry!)**
  - Diffractive physics
  - Direct photon production
  - Special topics (Higgs, Top, B physics, etc) covered in other talks

The Fermilab Tevatron



- Run I (1992-95) ~100 pb^{-1} recorded
- Run IIa (2001-05) ~1 fb^{-1}
- Run IIb (2006-09) ~ 4-8 fb^{-1}
- Note the energy in Run II is also slightly boosted
  - Run I CM energy was 1.8 TeV
  - Run II CM energy is 1.96 TeV

Tevatron


Collider Run II Peak Luminosity
Integrated Luminosity
Days since October 1
Run I record
Peak Luminosity
Peak Lum 20x Average
Date
1.20E+32
1.00E+32
8.00E+31
6.00E+31
4.00E+31
2.00E+31
0.00E+00
04/01/01
06/01/01
08/01/01
10/01/01
12/01/01
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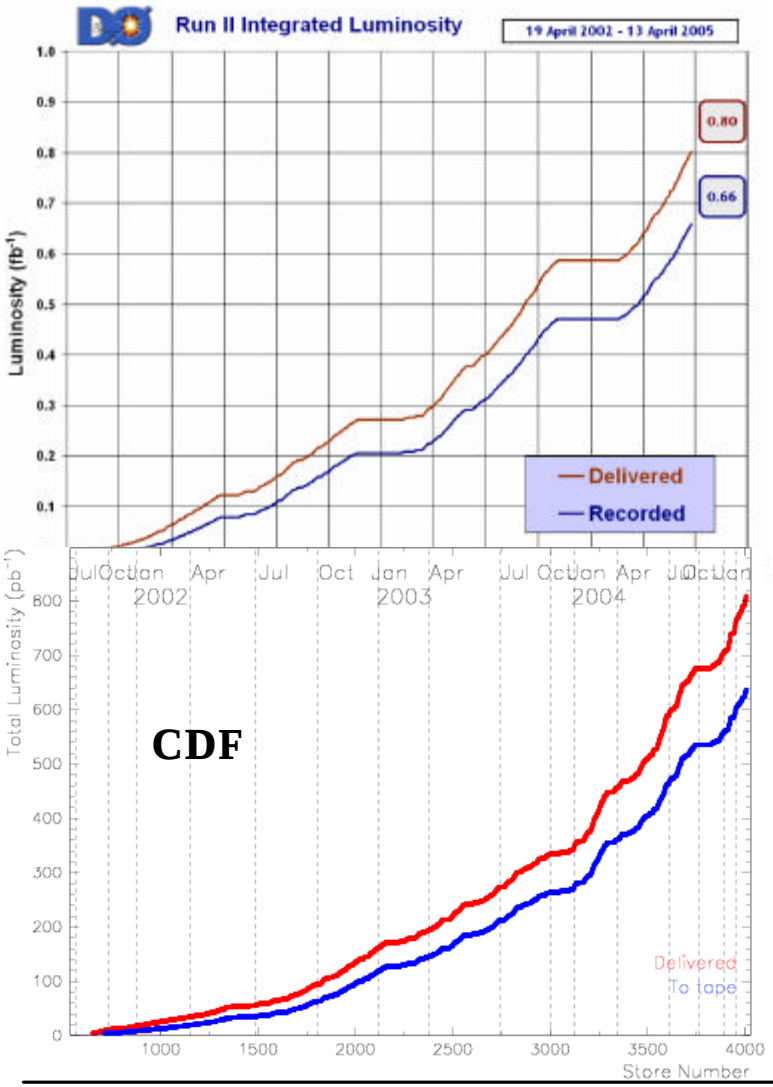
Peak Luminosity
Peak Lum 20X Average

Experimental Performance

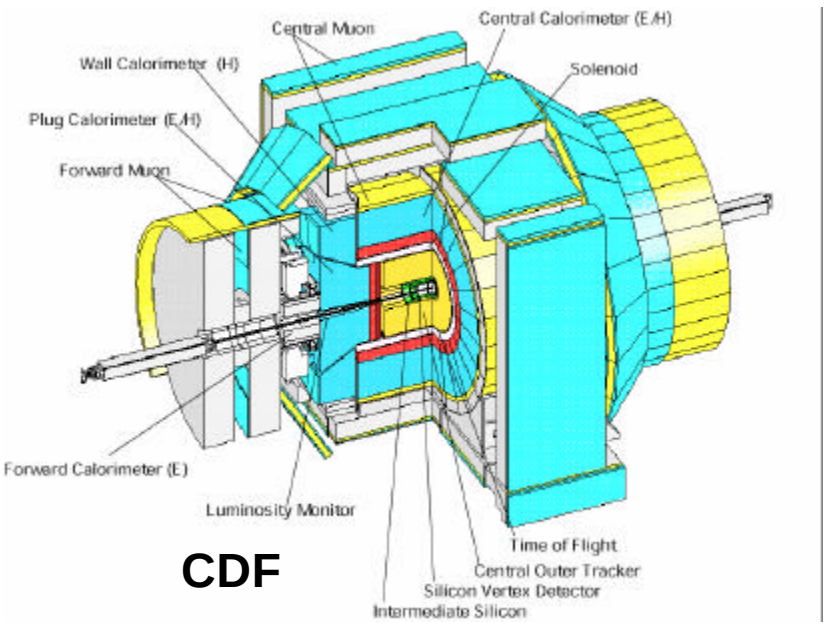


- Tevatron has delivered ~0.8 fb^{-1}
- Both experiments have collected more than 0.6 fb^{-1}
- Analyses presented here use from 150 to 400 pb^{-1}

CDF/D0 detectors

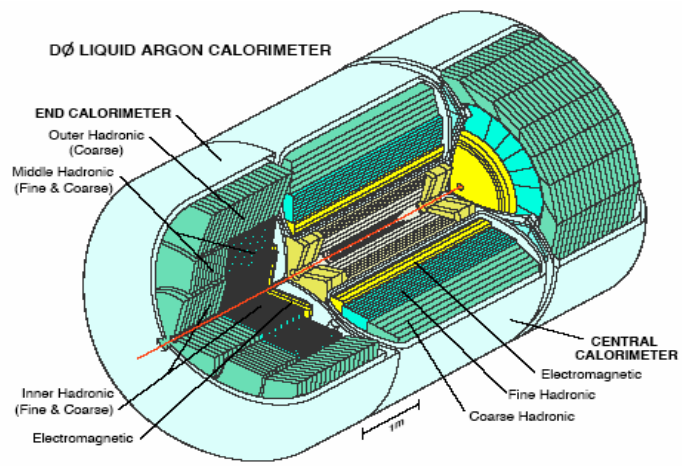
Calorimetry is at the heart of these measurements

Lead/Iron + Scintillator



CDF

Uranium + Liquid Argon



DØ

Electrons: $s_E / E = 13.5\% /ÖE$ **(central)**

$s_E / E = 16\% /ÖE$ **(plug)**

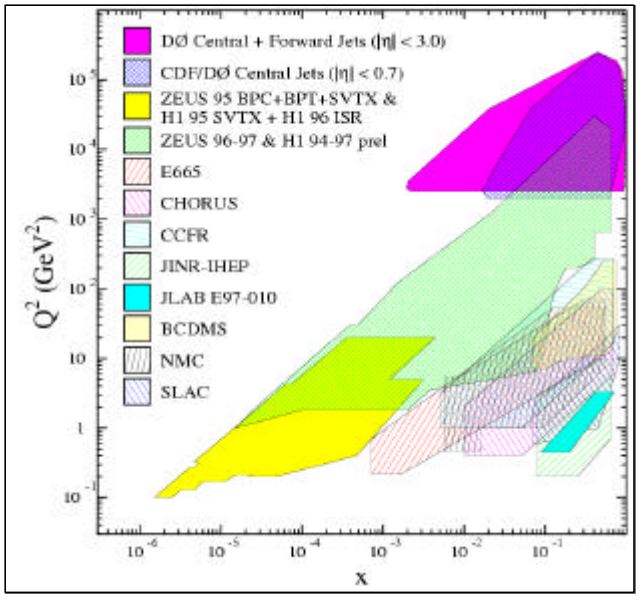
Jets: $s_E / E \sim 80\% /ÖE$

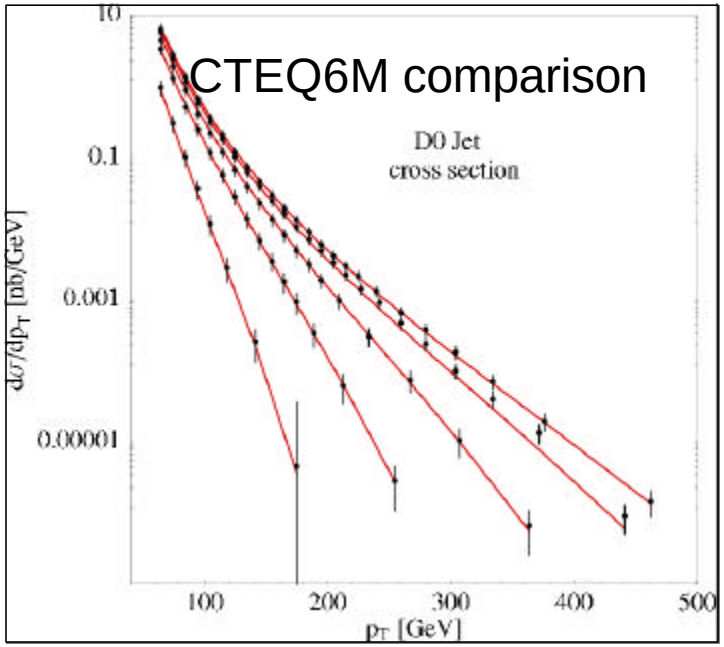
Electrons: $s_E / E = 15\% /ÖE$ Å 0.3%

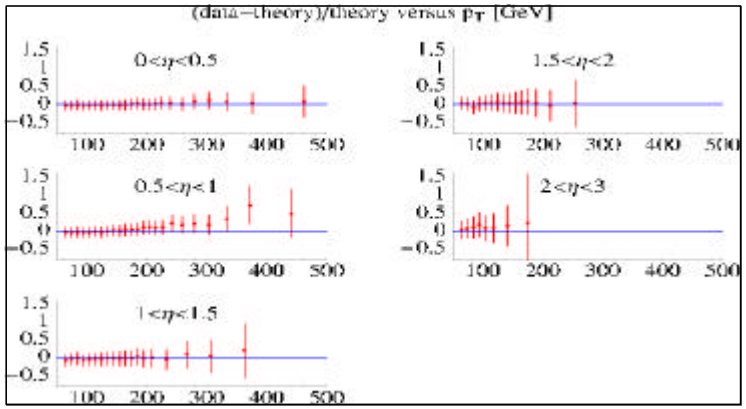
Jets: $s_E / E \sim 80\% /ÖE$

x-Q^2 Reach at the Tevatron

- **DØ's most complete cross section measurement extends over |h| < 3.0**
  - **compliments HERA x-Q^2 range**

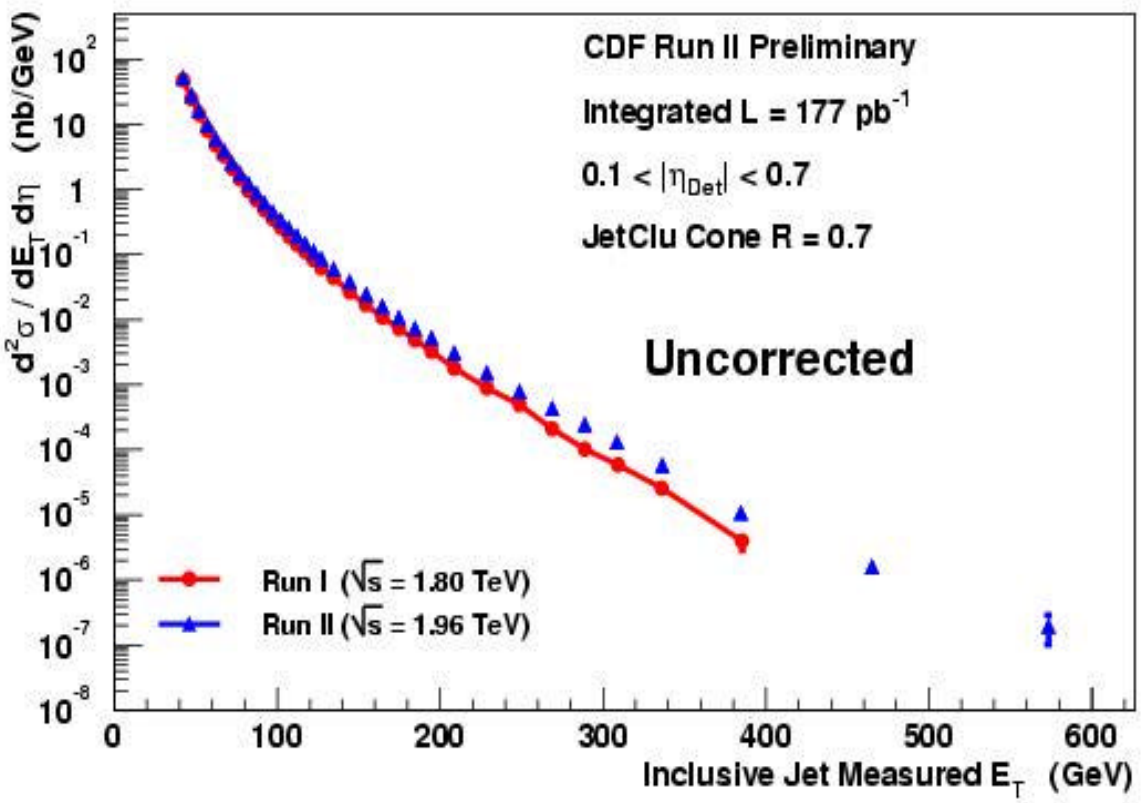






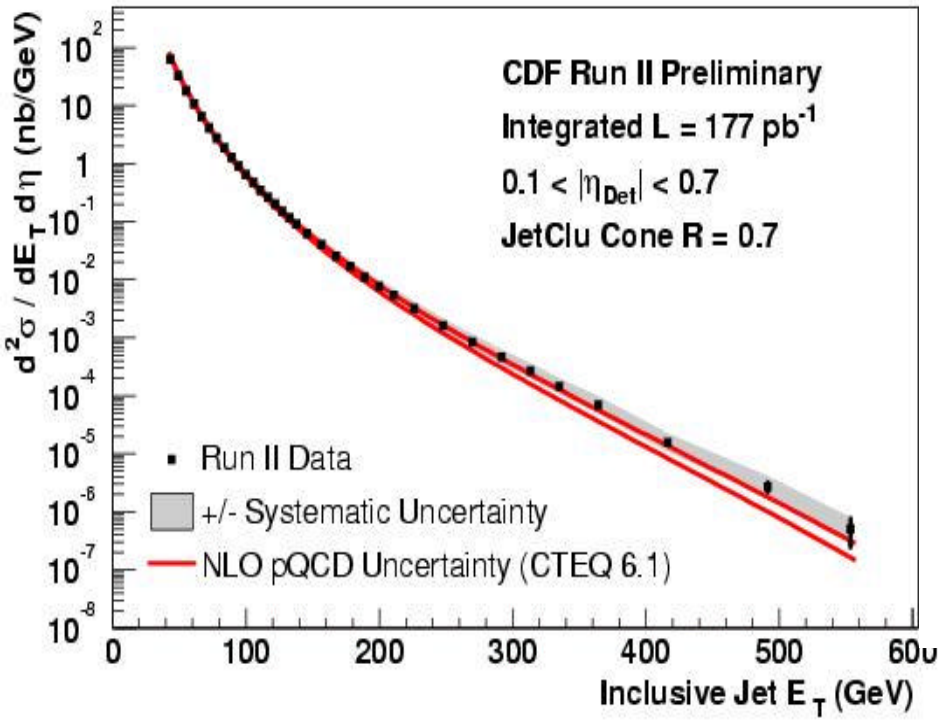
- **Used in CTEQ6 and MRST2001 fits to determine gluon at large x**
  - **Enhanced gluon at large x**

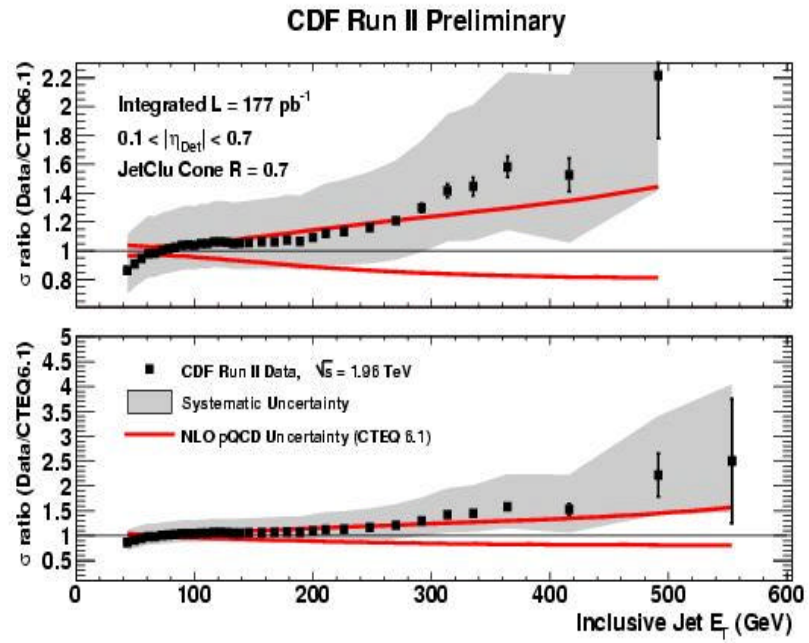
Run I vs. Run II



- Entering an era of precision QCD measurements at Tevatron/LHC
- Studying `QCD backgrounds' for more speculative phenomena
- High statistics at CM Energy 1.96 TeV
  - 5 times higher cross section for jet E_T>600 GeV!

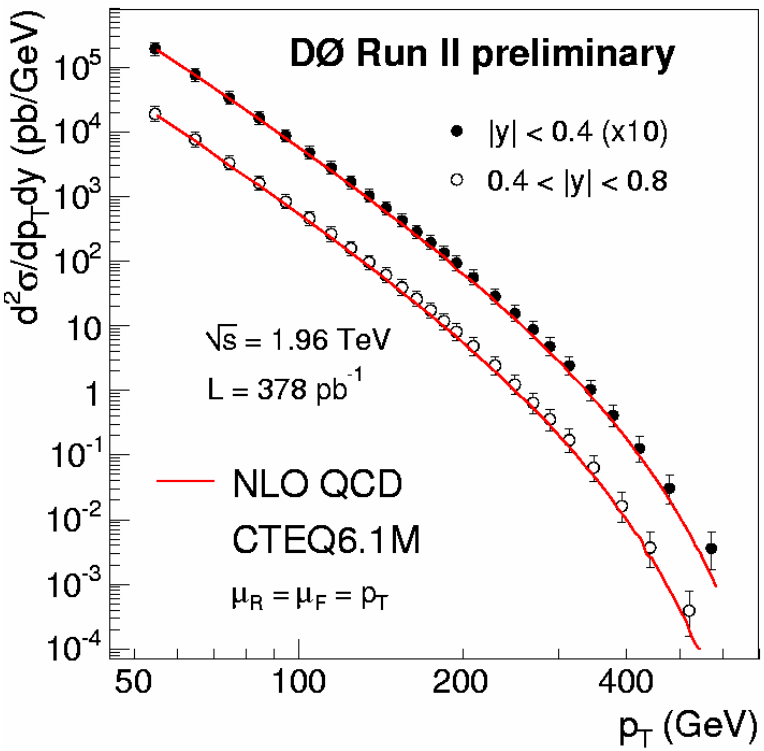
Central Inclusive Jet Cross Section at CDF

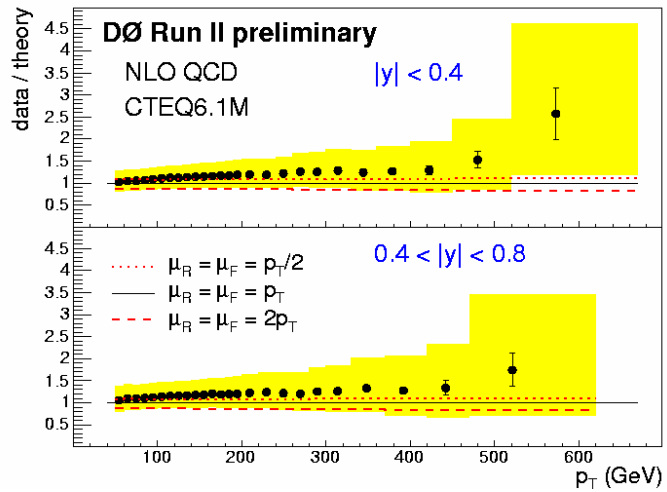


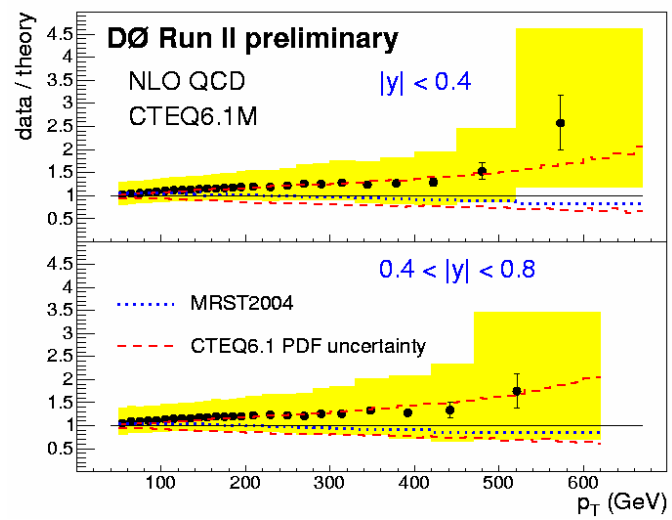


- Data currently agree with NLO prediction within errors
- Dominant uncertainty – Jet Energy Scale ~3%

Central Inclusive Jet Cross Section at D0

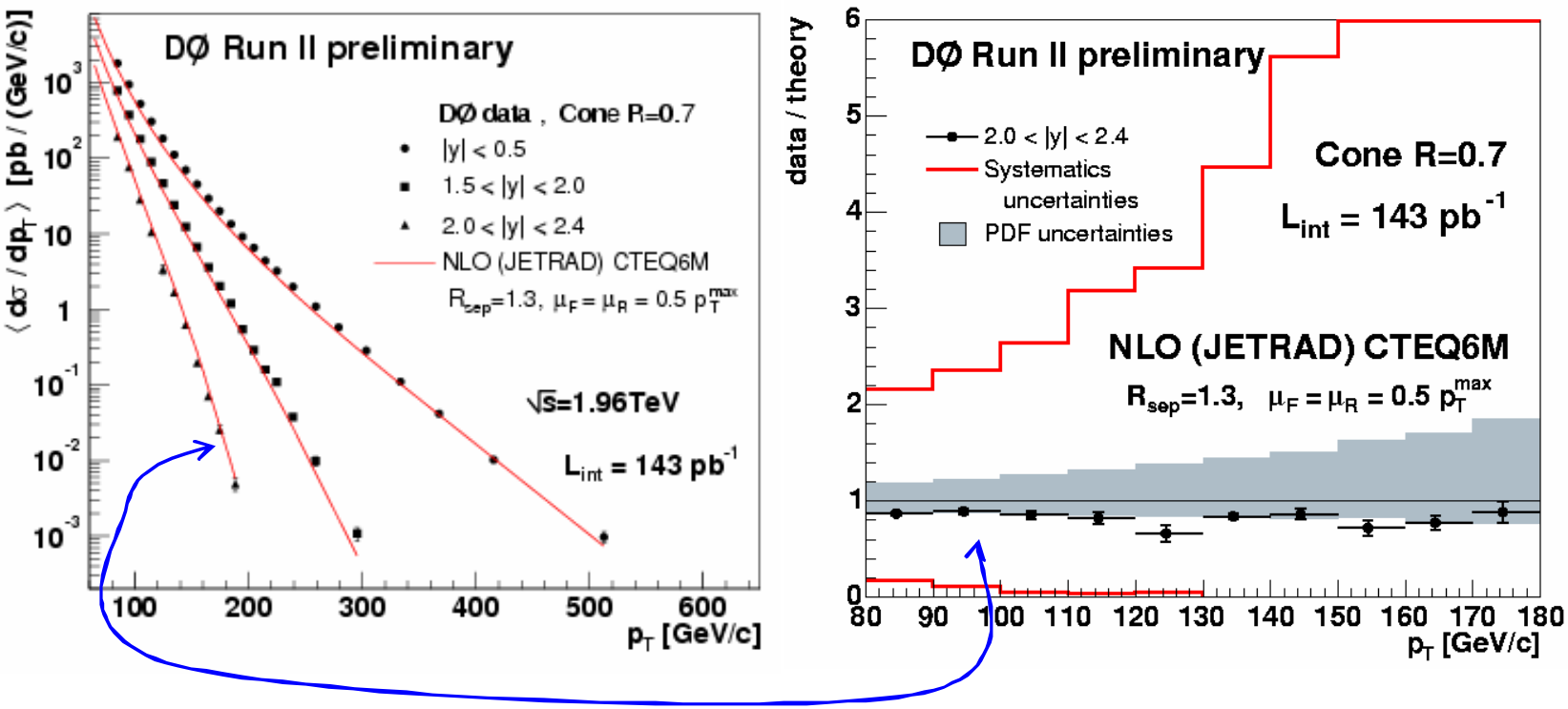






- Data agree with NLO within errors
- Dominant uncertainty:
  - Jet Energy Scale ~5%

Inclusive DØ Single Jet Cross Section vs. y

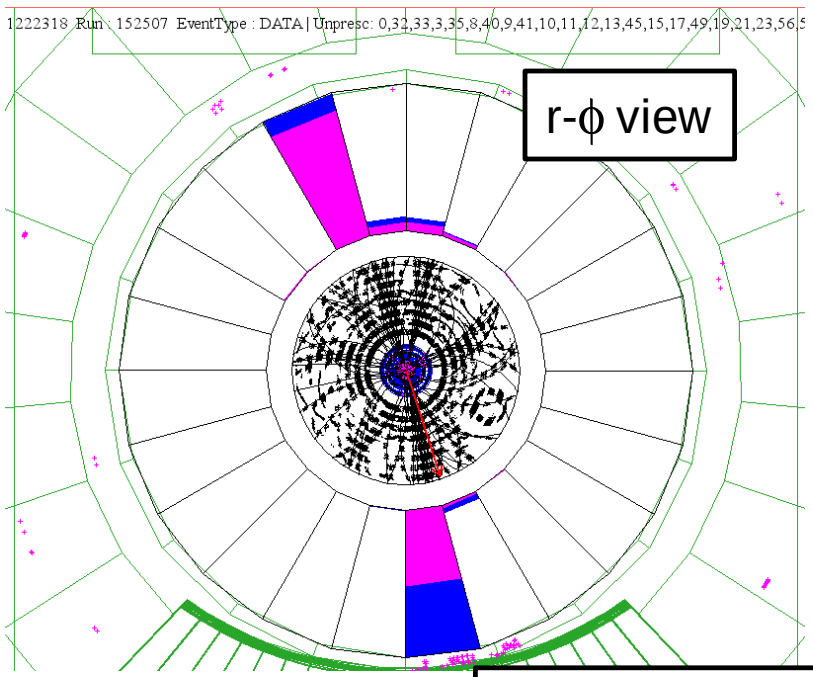


- First corrected Run II cross section for forward jets
- Important PDF information in cross section vs. rapidity
- Jet Energy Scale uncertainties dominate – need to beat these down!

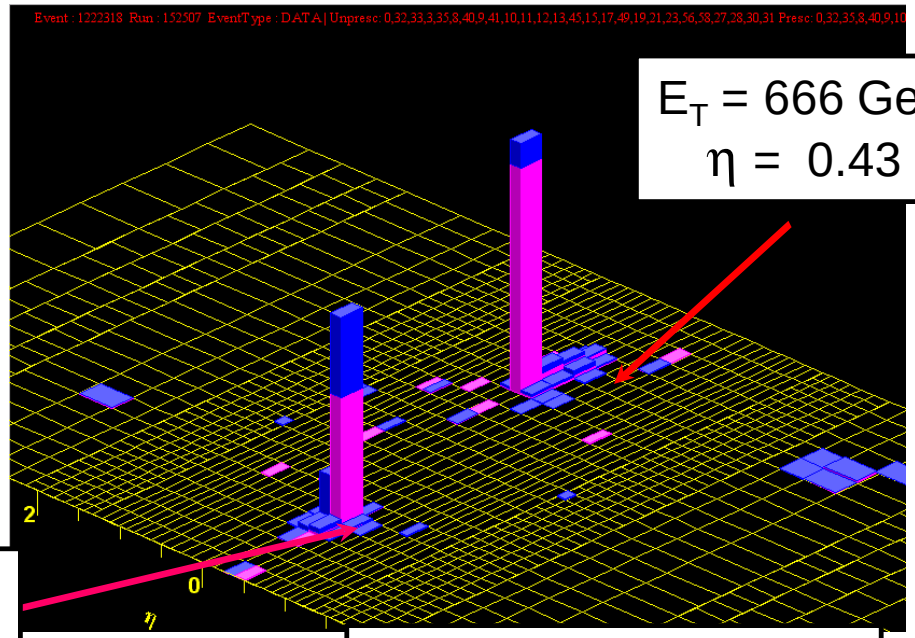
Run II
Dijet Production vs. M_{jj}

Highest mass di-jet event so far: M_{jj} = 1364 GeV/c^2

CDF



E_T = 633 GeV
η = -0.19

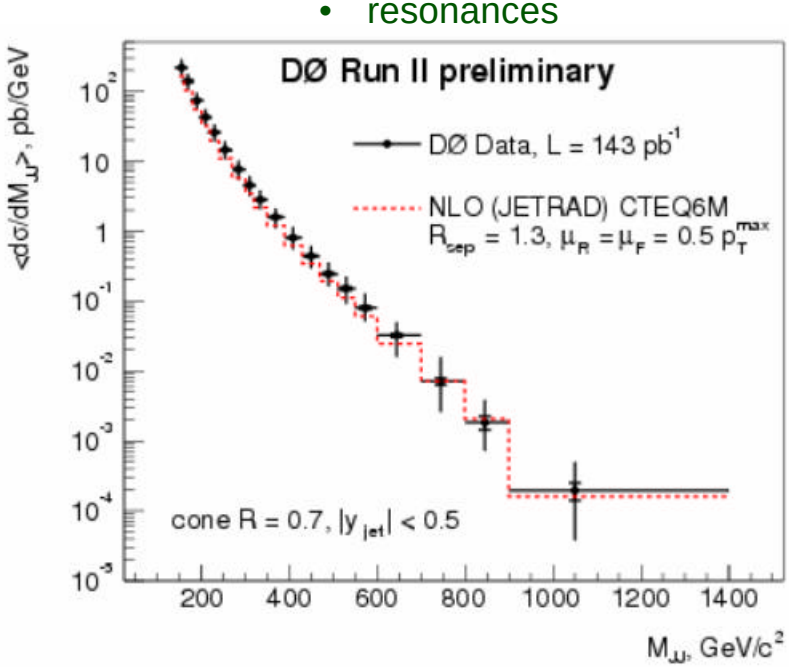


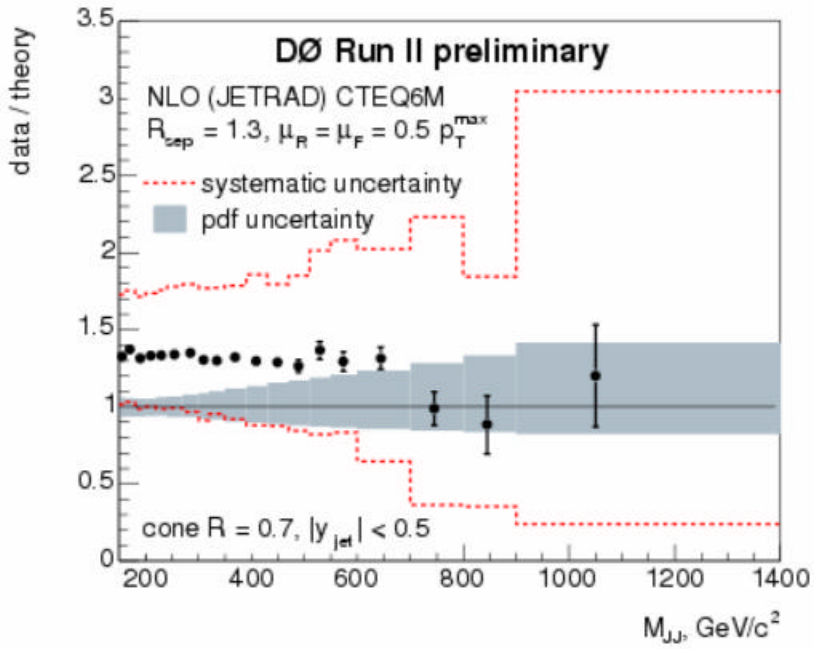
E_T = 666 GeV
η = 0.43

Calorimeter LEGO Plot

Inclusive Dijet Cross Section at DØ

- **Good probe of PDF's**
- **Place to look for new physics**
  - Compositeness (high M_{jj} excess)
  - resonances

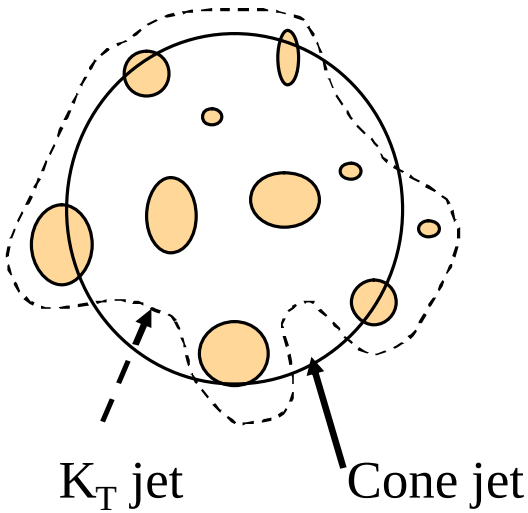




- **Agrees within uncertainties with NLO/CTEQ6M**
- **Jet Energy Scale dominant error on measurement**
- **Adding luminosity/improving Jet Energy Scale**

Quick aside on jet algorithms

- **So far we have been using only cone algorithms**
  - **Improvements over time make them more stable against soft radiation/collinear partons**
    - Still, ambiguity when 2 cone jets overlap
      - **Experimental prescription for "split/merge"**
      - **In theory, arbitrary parameter introduced to handle this**
        - Not ideal
- **Combining particles by their relative transverse momentum (k_T) is much more robust between data and theory**

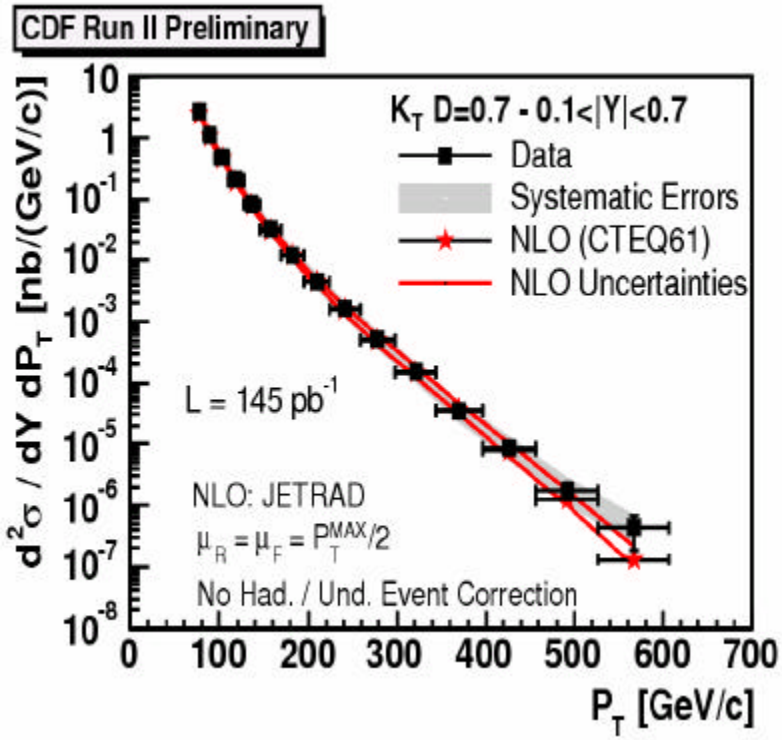


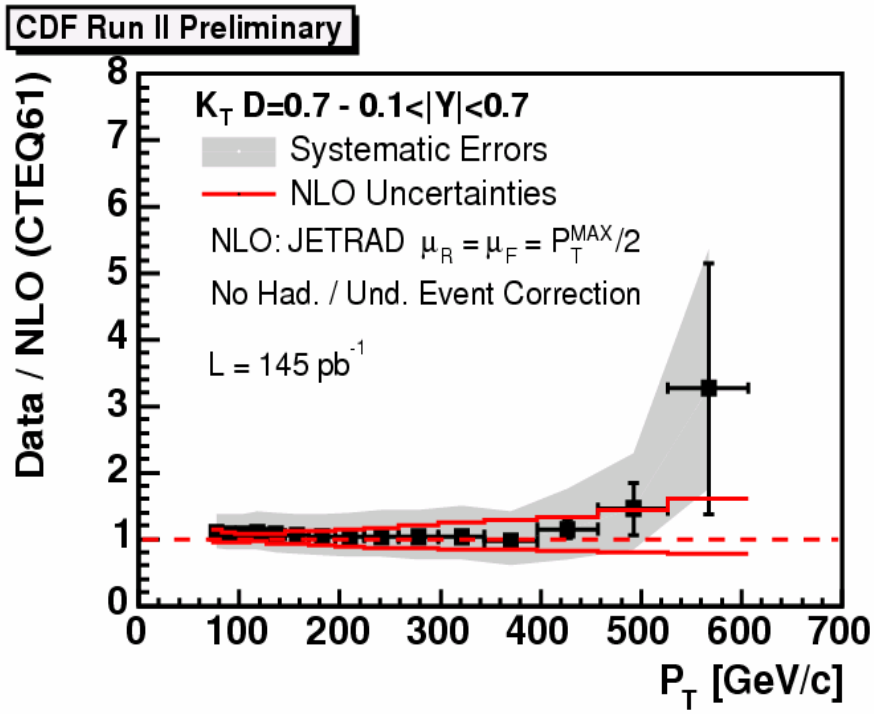
$$d_{ij} = \min(P_{T,i}^2, P_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2}$$

$$R_{ij} = \sqrt{\Delta h_{ij}^2 + \Delta j_{ij}^2}$$

(*D* is a "distance" parameter)

Inclusive CDF K_T Jet Cross Section





NLO not corrected for Hadronization & Underlying Event (important at low Pt)

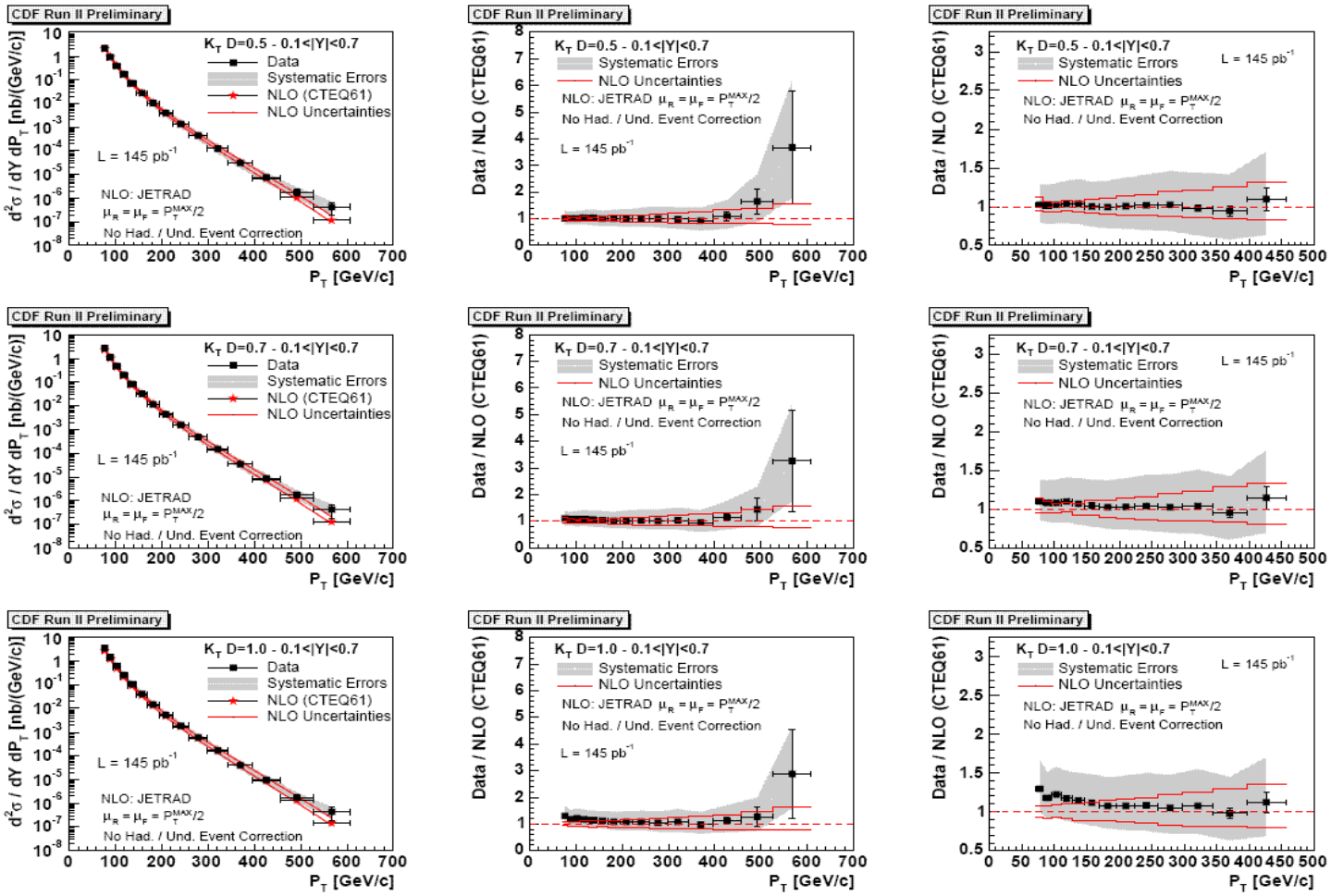
- Good agreement Data vs Theory
- High-Pt tail?

Inclusive CDF K_T Jet Cross Section

D=0.5

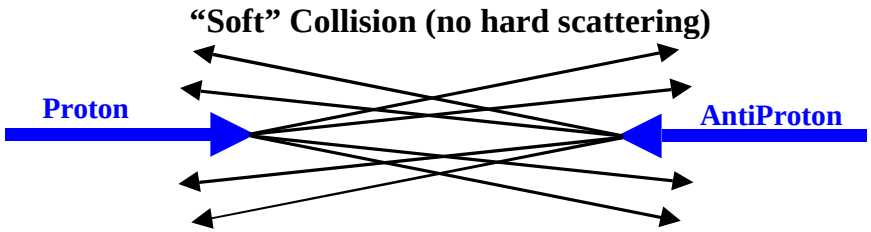
D=0.7

D=1.0

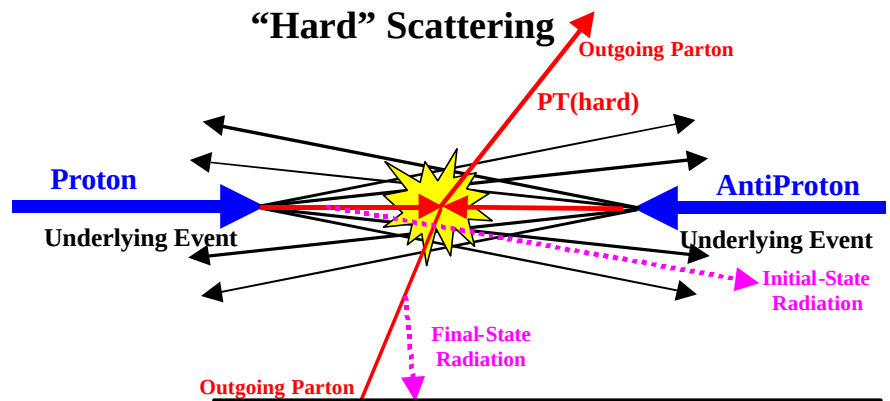


- Low P_T soft contributions increase with increasing D (underlying event)
- Deviations at high P_T a bit larger than with cone algorithms (?)

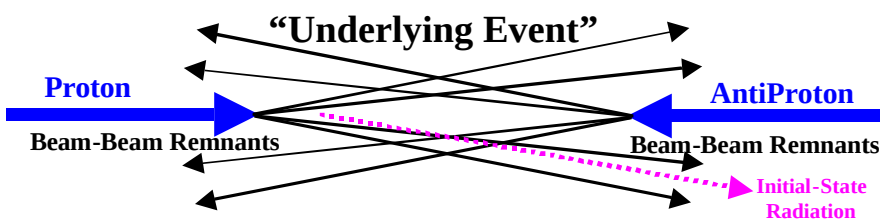
Underlying Event Studies



No hard scattering.
"Min-Bias" event.



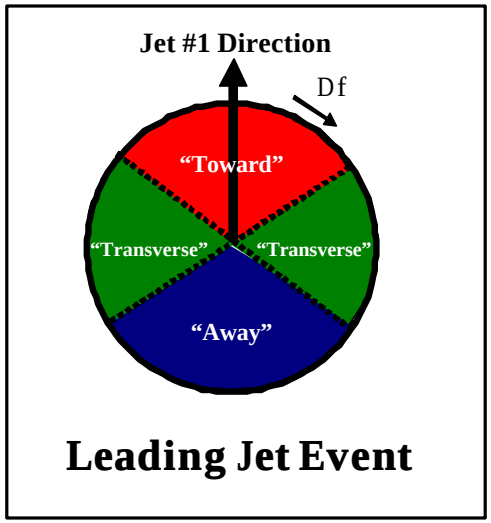
"hard" parton-parton collision : large transverse momentum outgoing jets.

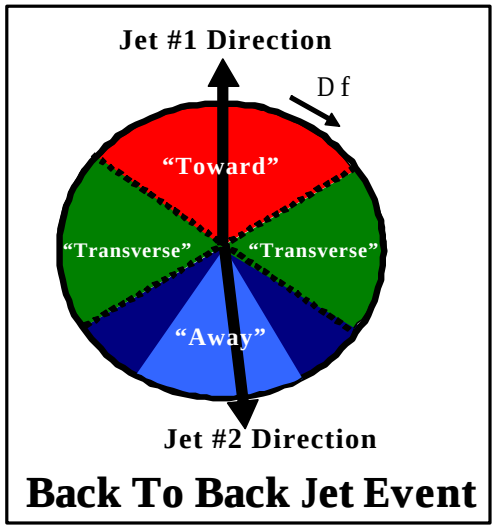


"underlying event": everything but the two outgoing hard scattered "jets".

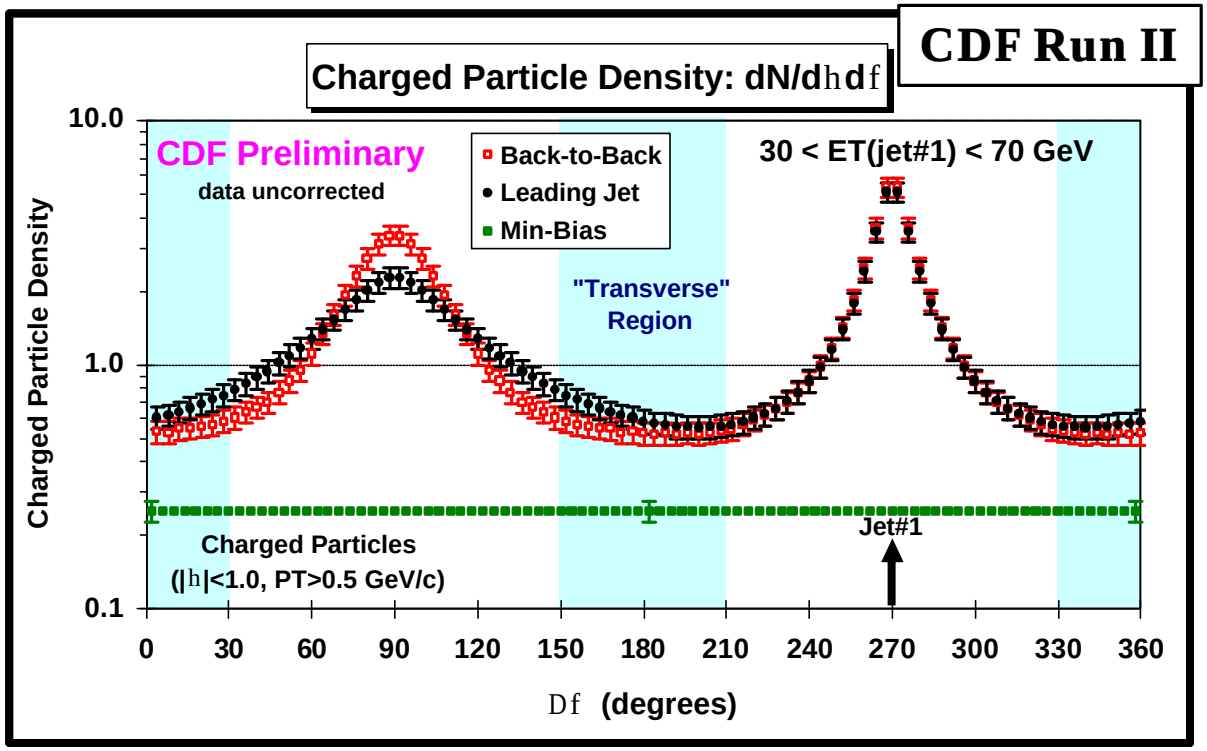
- Underlying event is not the same as a minimum bias event
- Includes ISR/FSR/MPI – not completely independent of hard scatter

Charged Particle Density Df Dependence





Transverse direction sensitive to underlying event

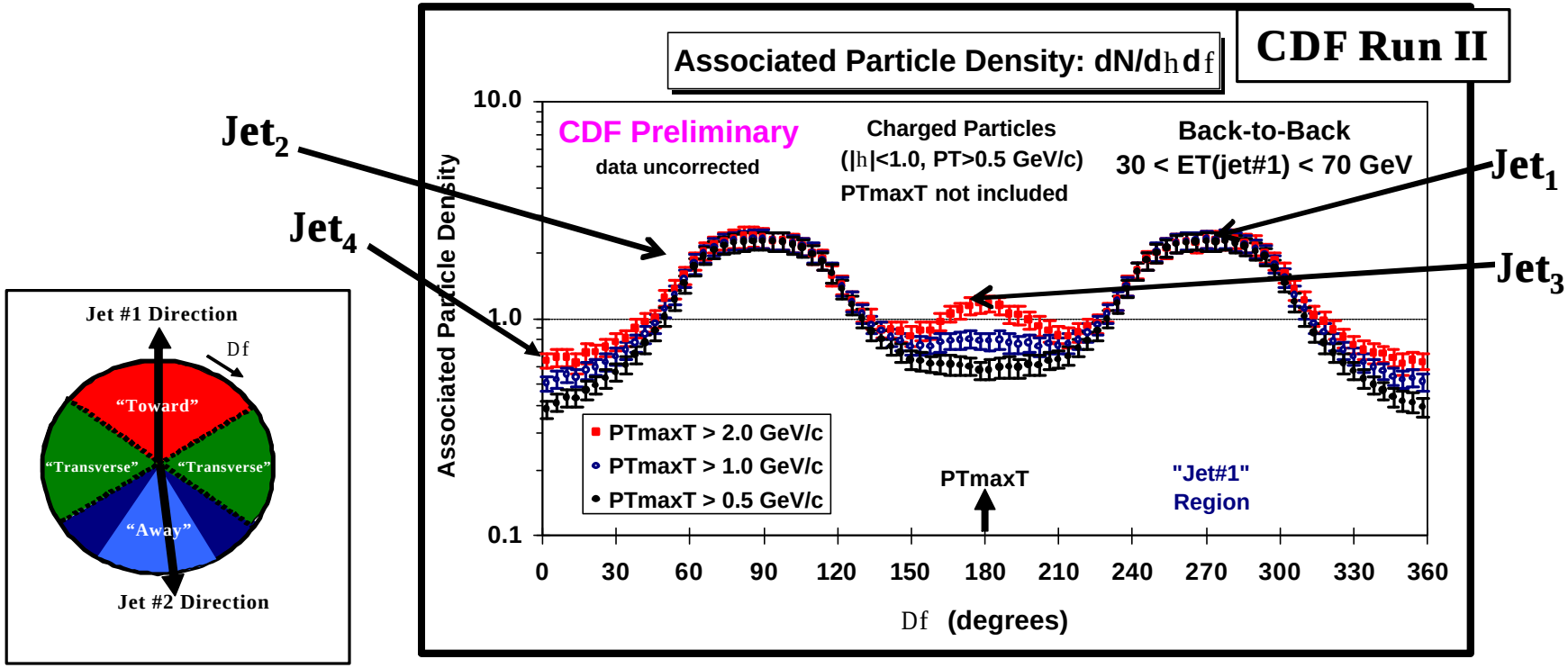


"transverse" region defined by leading jet (JetClu R = 0.7, |h| < 2) or by leading two jets (JetClu R = 0.7, |h| < 2).

"Back-to-Back" events have at least two jets nearly "back-to-back" (Df_{12} > 150°) and almost equal transverse energies ($E_T(Jet_2)/E_T(Jet_1)$ > 0.8).

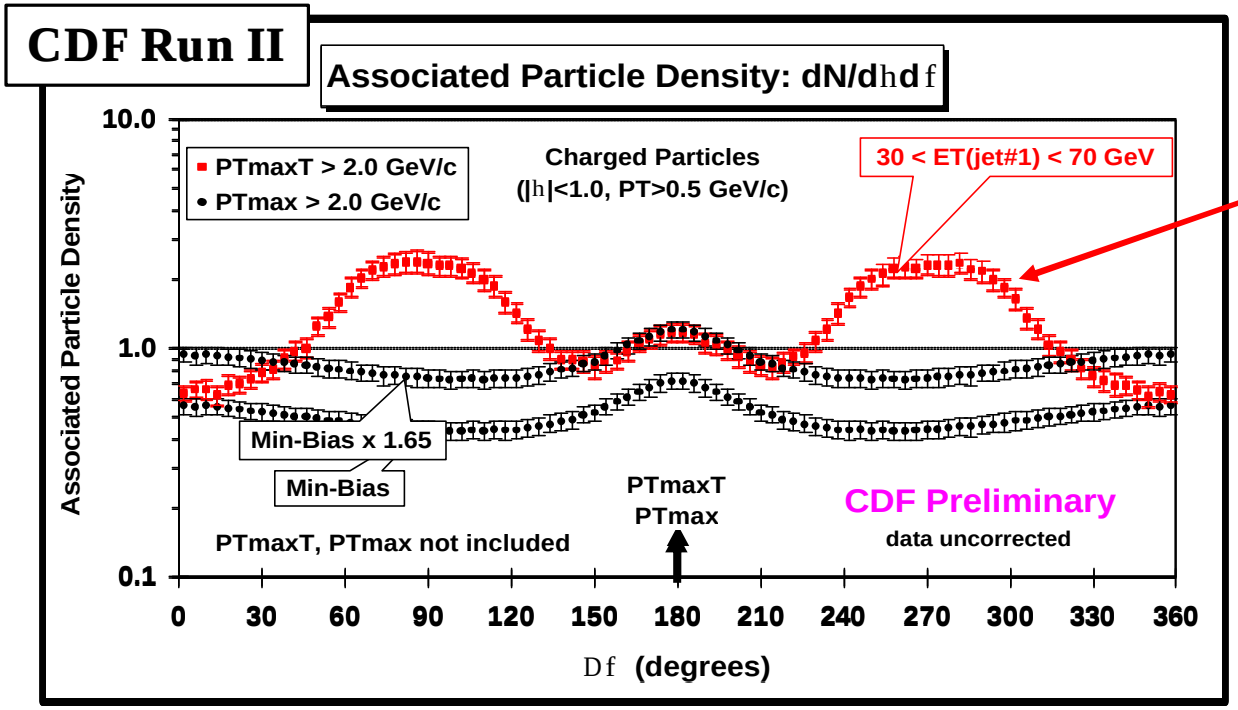
"Associated" Charged Particle Density Df Dependence

- **Associated Charged particle density in back to back jet events**
  - **30 GeV < $E_T(Jet_1)$ < 70 GeV**
  - **Find $P_T$maxT, the maximum P_T particle transverse to Jet_1**
  - **Plot charge particle density for charged particles (p_T > 0.5 GeV/c, |h| < 1, *not including $P_T$maxT*) relative to $P_T$maxT**

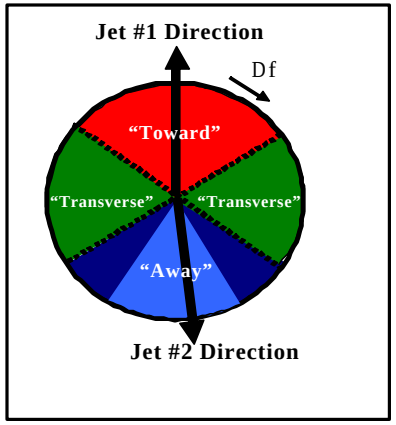


"Associated" Charged Particle Density Df Dependence

- **Associated Charged particle density in "minimum bias" data**
  - **30 GeV < $E_T(Jet_1)$ < 70 GeV**
  - **Find $P_T$maxT, the maximum P_T particle transverse to Jet_1**
  - **Plot charge particle density for charged particles (p_T > 0.5 GeV/c, |h| < 1, *not including $P_T$maxT*) relative to $P_T$maxT**



Back to Back Data

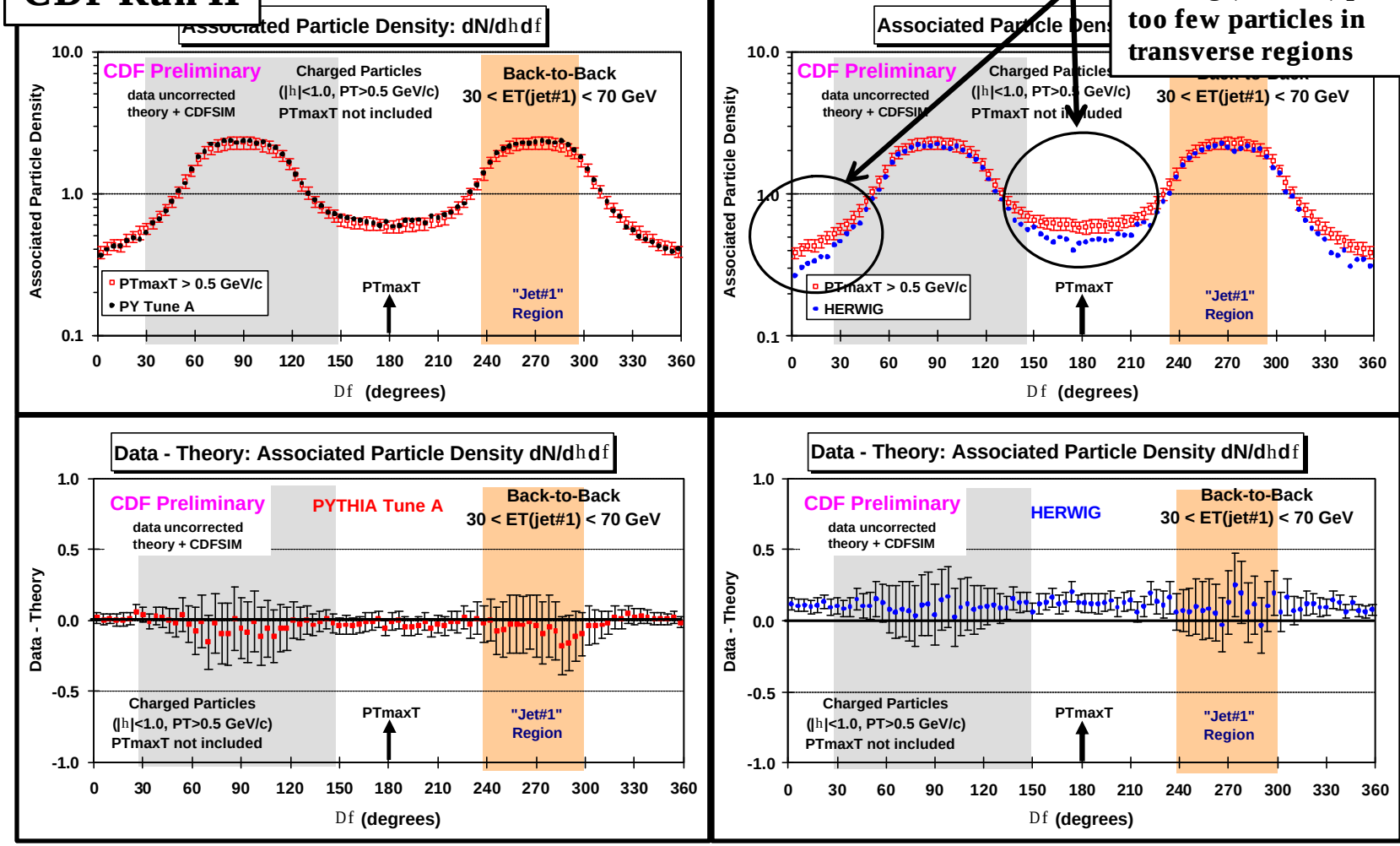


Associated Charged Particle Density

PYTHIA Tune A Vs. HERWIG (untuned)

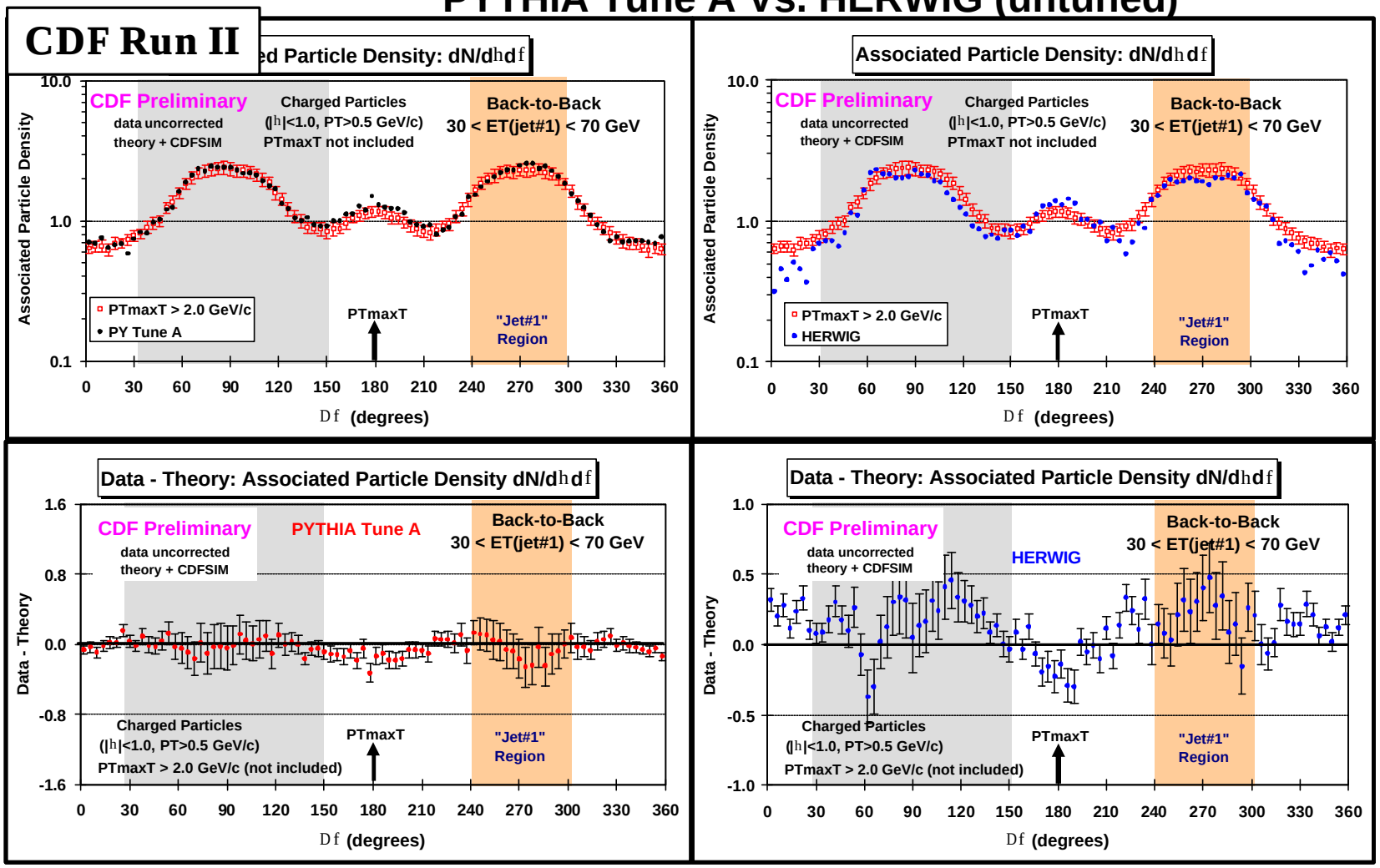
CDF Run II

Herwig (no MPI) predicts too few particles in transverse regions

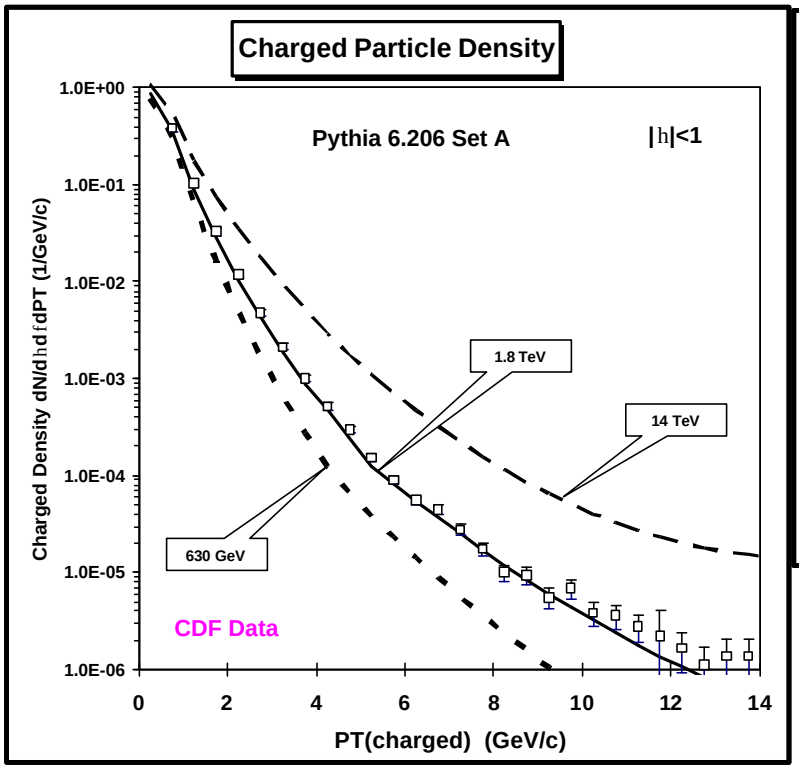


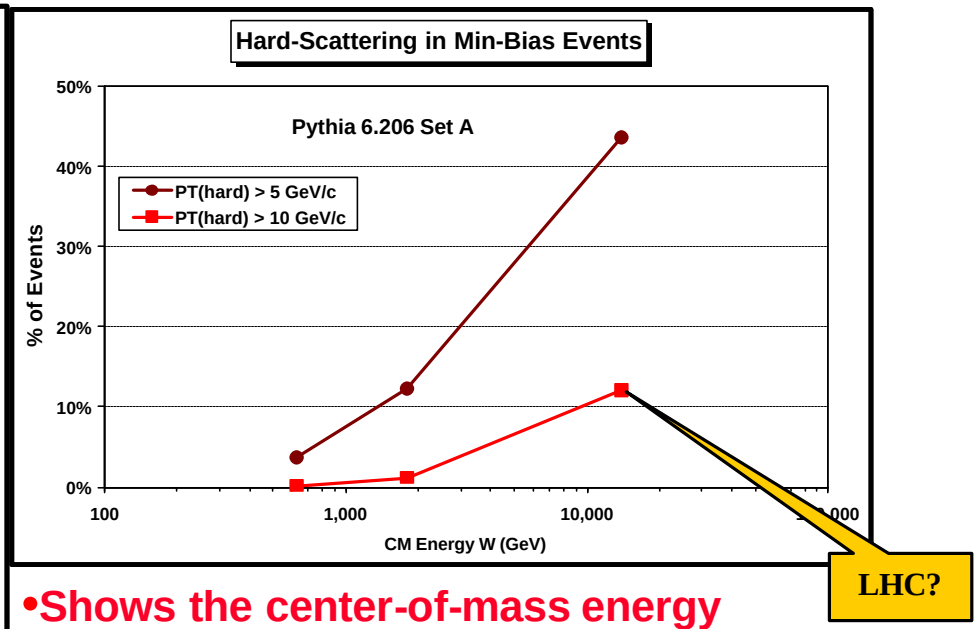
Associated Charged Particle Density

PYTHIA Tune A Vs. HERWIG (untuned)



Using Tuned Pythia to predict LHC





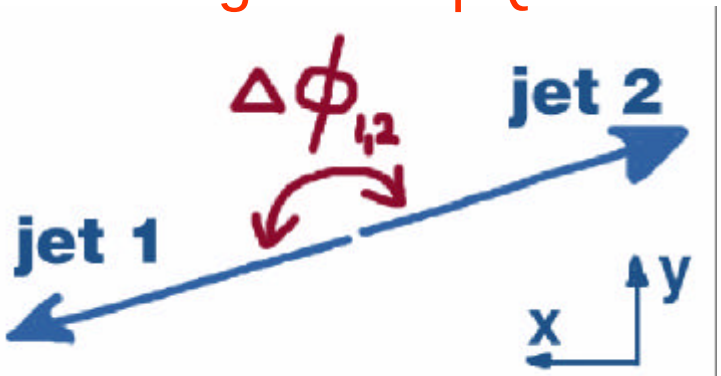
- Shows the center-of-mass energy dependence of the charged particle density, $dN_{chg}/dhdfdP_T$, for "Min-Bias" collisions compared with the a tuned version of PYTHIA 6.206 (Set A) with P_T(hard) > 0.

- PYTHIA Tune A predicts 1% of all "Min-Bias" events at 1.8 TeV are a result of a hard 2-to-2 parton-parton scattering with P_T(hard) > 10 GeV/c which increases to 12% at 14 TeV

DØ, F Decorrelation

Looking at $\Delta\phi_{12}$ between jets at DØ

Leading Order pQCD

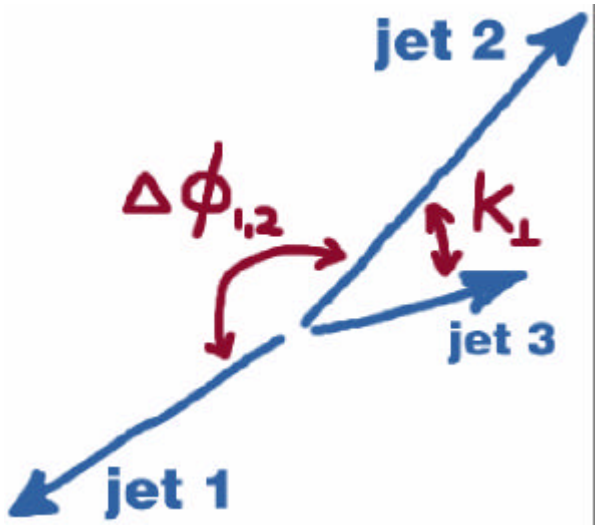


Jets are back-to-back

$\Delta\phi_{12} = \pi$

$\Delta\phi_{12}$ is sensitive to jet formation without having to measure 3rd jet directly

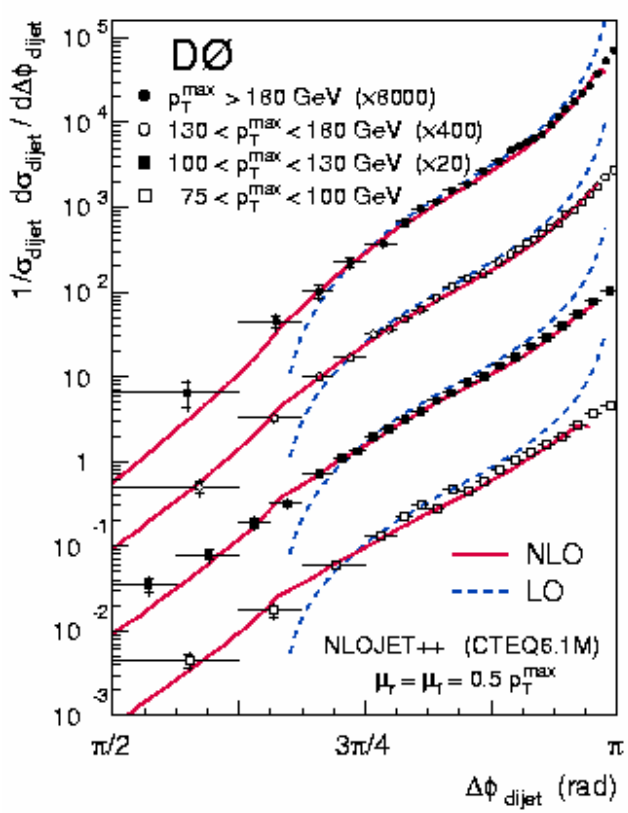
3 jets in pQCD

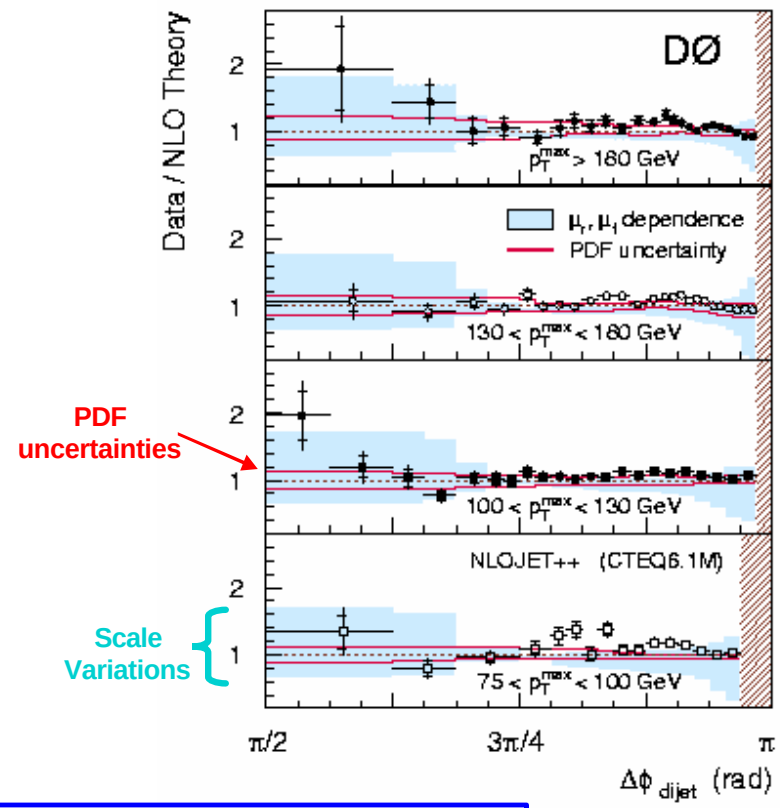


$\Delta\phi_{12} < \pi$

$$\lim_{p_{T_3}\to 0} \Delta f_{1,2} = p$$

Df between jets – Comparison with pQCD

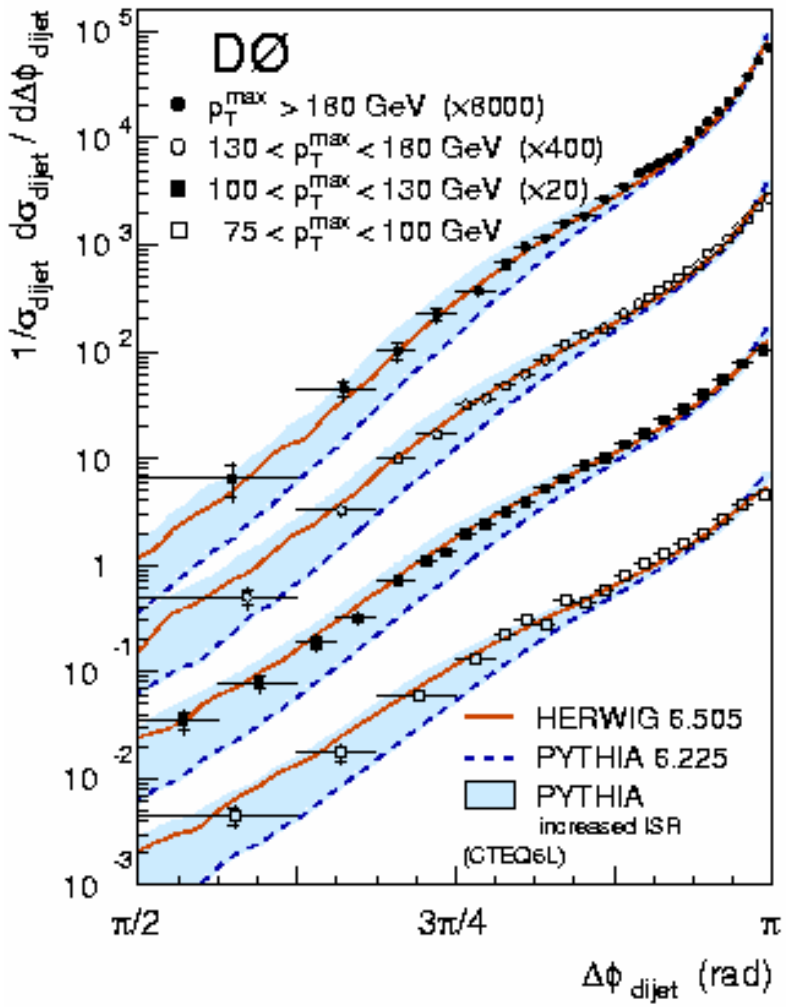




Df as function of Jet$_1$ P_T (Jet$_2$ P_T > 40 GeV/c)
Compared to LO and NLO pQCD in 3rd jet

- **NLO better than LO**
- **Both fail at soft jet limit**

Df between jets – Comparison with MC



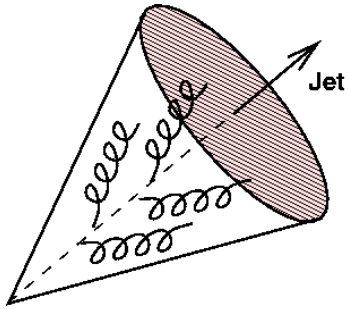
Using parton shower MC (Pythia, Herwig) gives us the soft gluon contribution missing in pQCD calculations

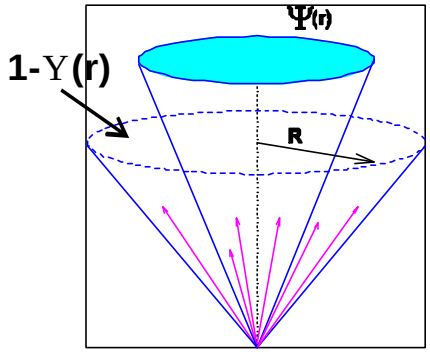
Default Herwig does a better job than default Pythia

Pythia with tuned (i.e. enhanced) ISR models data extremely well

- **Another handle on MC tunes**

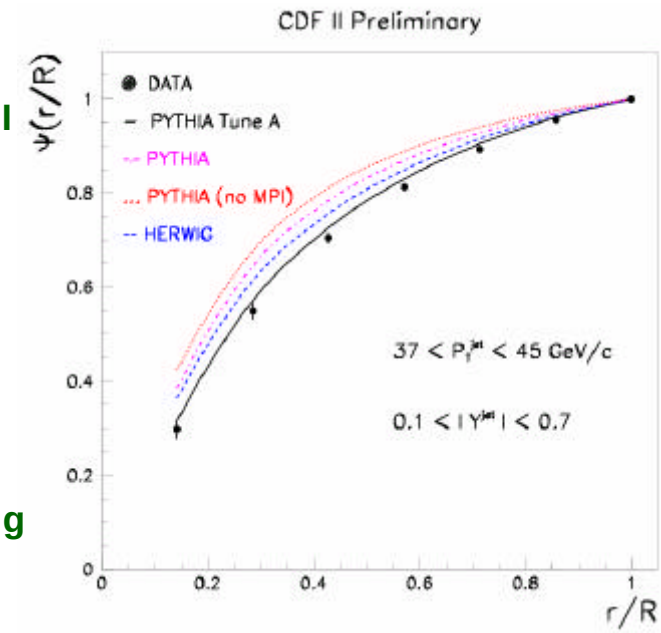
Studies of Jet Fragmentation

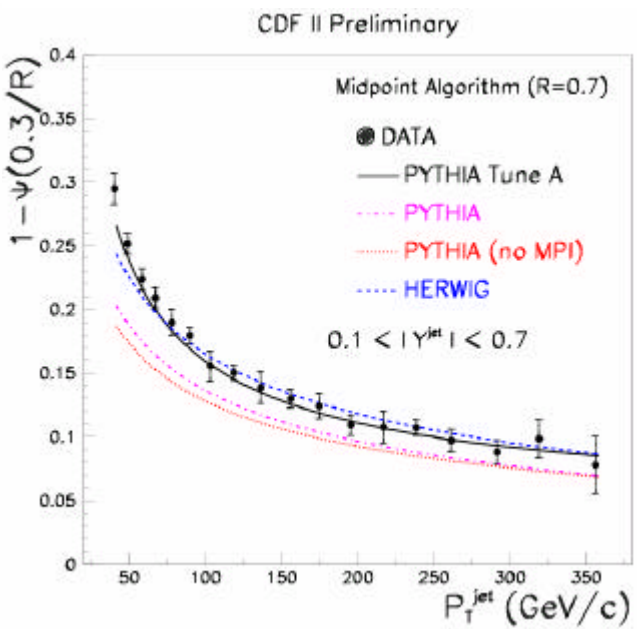




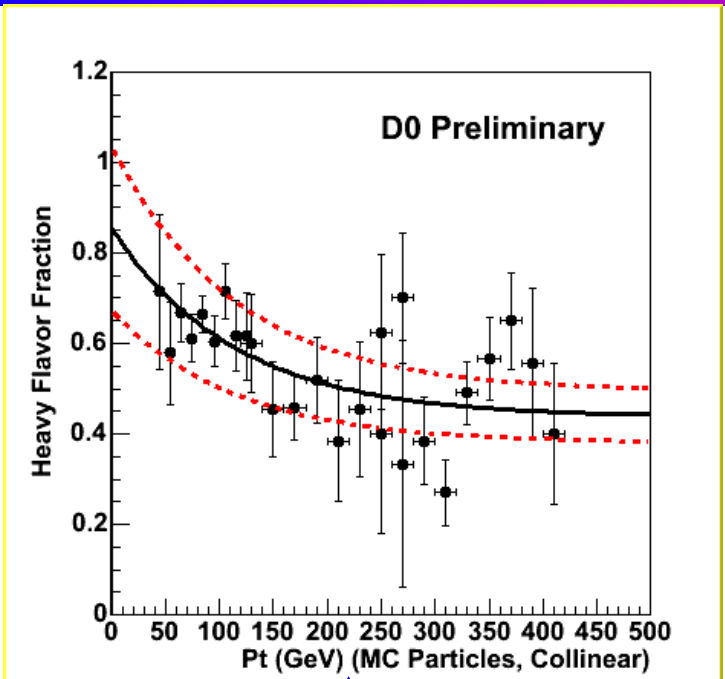
Υ(r) measures the narrowness of the jet
- Dictated by multi-gluon emission from primary parton
- Good test of parton shower models
- Also sensitive to underlying event

- Pythia without MPI tuning too narrow especially at low Pt
- Pythia Tune A describes data well (enhanced ISR+MPI tuning)
- Clearly we're doing something right!



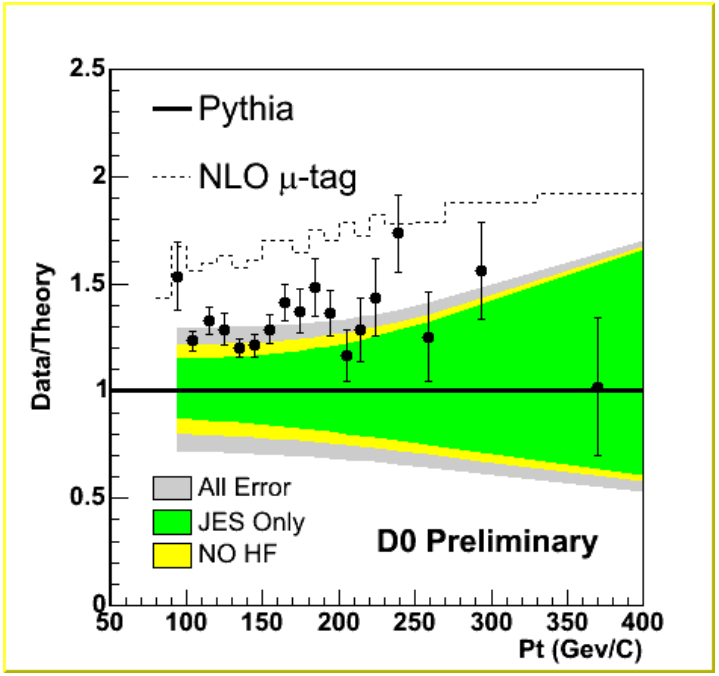


m + jets cross section



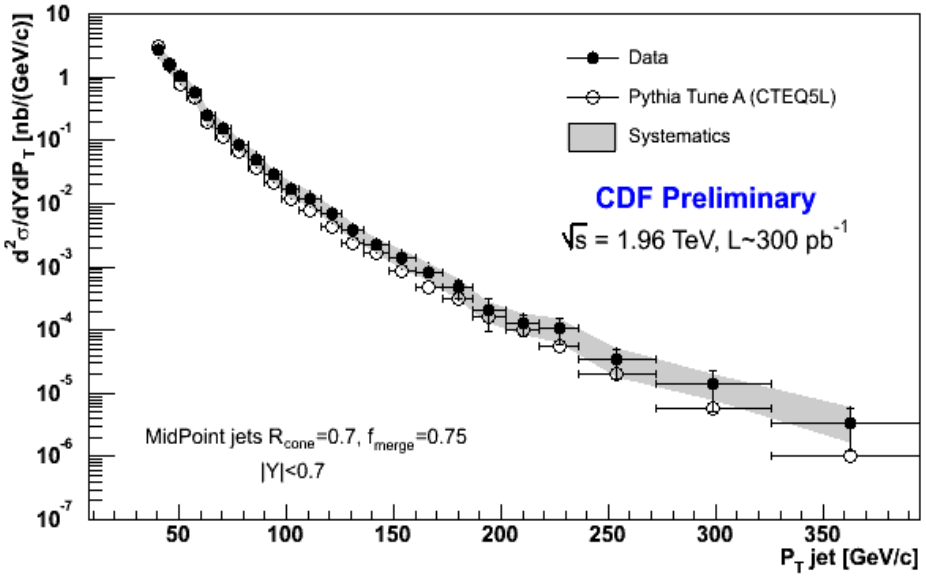
Fraction of m tagged jets coming from heavy flavor

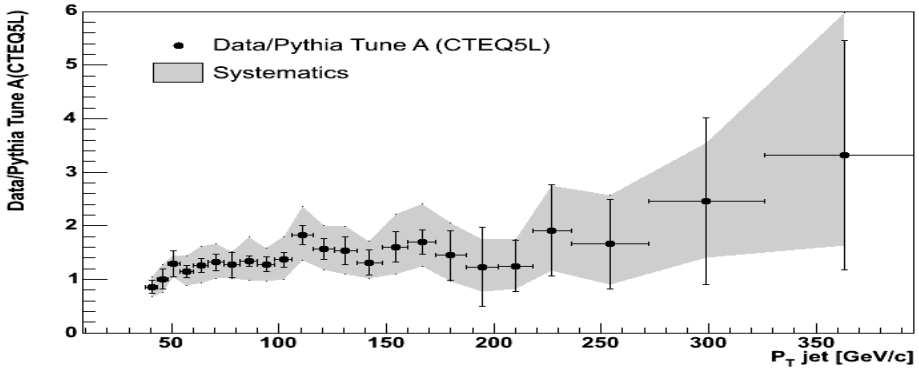
- using m tagged jets enhances heavy flavor content
- Good place to look for new physics? Compositeness?



Comparing m+jets cross section result to Pythia and NLO

b jet cross section (CDF)





Extracted b jet cross section using b tagged jets

b tagging demands displaced vertex

Compared with Pythia

- **No surprises?**

New measurement from CDF coming soon

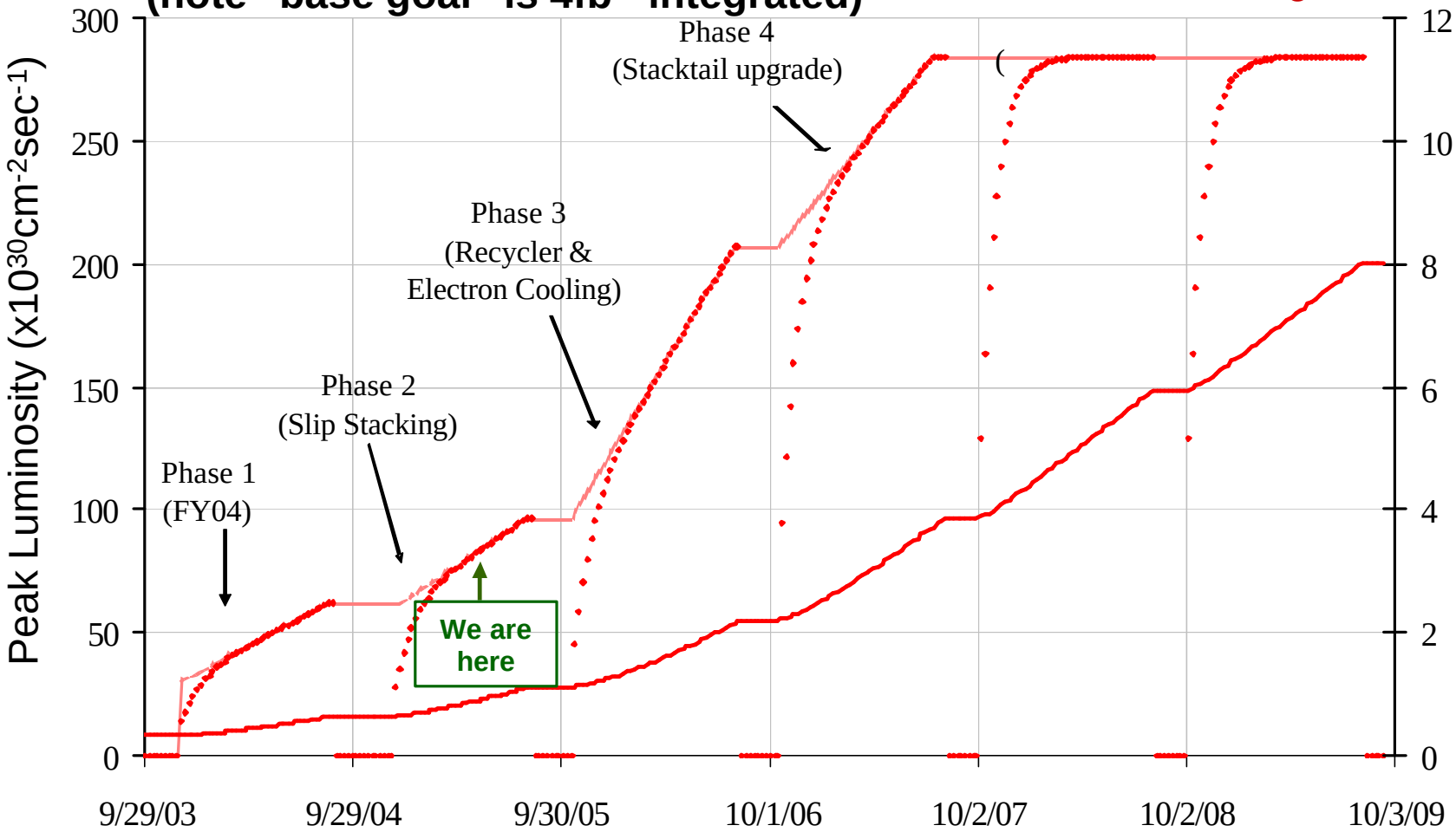
Conclusions

- New results from Run II on jet properties and cross sections
  - No real surprises
    - Expect more good input for pdf's
    - Tuned Pythia (Pythia Tune A) with enhanced ISR/FSR models data well
    - NLO does well (except in limits of soft jets)
  - Using tuned Pythia gives us some confidence in predicting LHC jet properties
- Both experiments will be measuring inclusive jet cross sections in the forward direction
  - Better understanding/constraints of pdf's/gluon contributions at high jet p_T
- Jet Energy Scale is dominant error in inclusive cross sections
  - Both experiments actively working to reduce uncertainties
  - Will improve with better understanding, more luminosity
- And for the future…

Run II Luminosity Projections

Luminosity just keeps on coming!
(note "base goal" is 4fb^{-1} integrated)

~2.8e32 peak
~8 fb^{-1} integrated



Future RunII upgrades

- **Accelerator upgrades**
  - **Electron cooling, accumulator stacktail upgrades**
    - **(basically continue to increase and use antiprotons)**
  - **Tevatron is on track for delivering 8 fb^{-1} by end of 2009**
    - Base goal 4 fb^{-1}
- **Collider experiments upgrading to take advantage of increased luminosity**
  - **CDF RunIIb**
    - **Faster readout electronics**
    - **Improved tracking triggers**
    - **Calorimeter upgrade (being commissioned now)**
  - **D0 RunIIb**
    - **New silicon Layer 0 detector**
      - **Improves impact parameter resolution**
      - **Mitigates loss of efficiency due to radiation damage of current silicon inner layer**
    - **Improved calorimeter trigger, tracking triggers, and processing triggers**