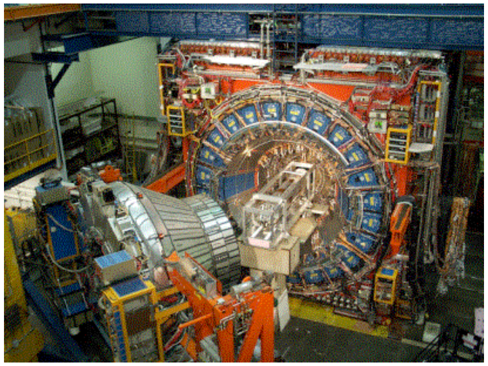
Studies of Jet Production at CDF



Jay R. Dittmann

Baylor University

(For the CDF Collaboration)

Frontiers in Contemporary Physics III — May 2005
Vanderbilt University, Nashville, Tennessee

VANDERBILT UNIVERSITY

QCD Physics at the Fermilab Tevatron

- The Fermilab Tevatron Collider serves as an arena for precision tests of QCD with jets, W/Z bosons, and photons
  - Highest Q^2 scales currently achievable (searches for new physics at small distance scales)
  - Sensitivity to parton distributions over a 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.

- Many puzzles seem to be resolved:
  - Jet excess at high E_T (and high mass)
  - Heavy flavor cross sections
  - Comparison of k_T inclusive jet cross section and NLO theory

- But the work continues...
  - Studies on soft-gluon radiation are crucial
  - Measurements of the UE in different final states are mandatory
  - Continue to contrain PDFs

pushing toward precision QCD...

The Fermilab Tevatron

Proton-Antiproton Collisions

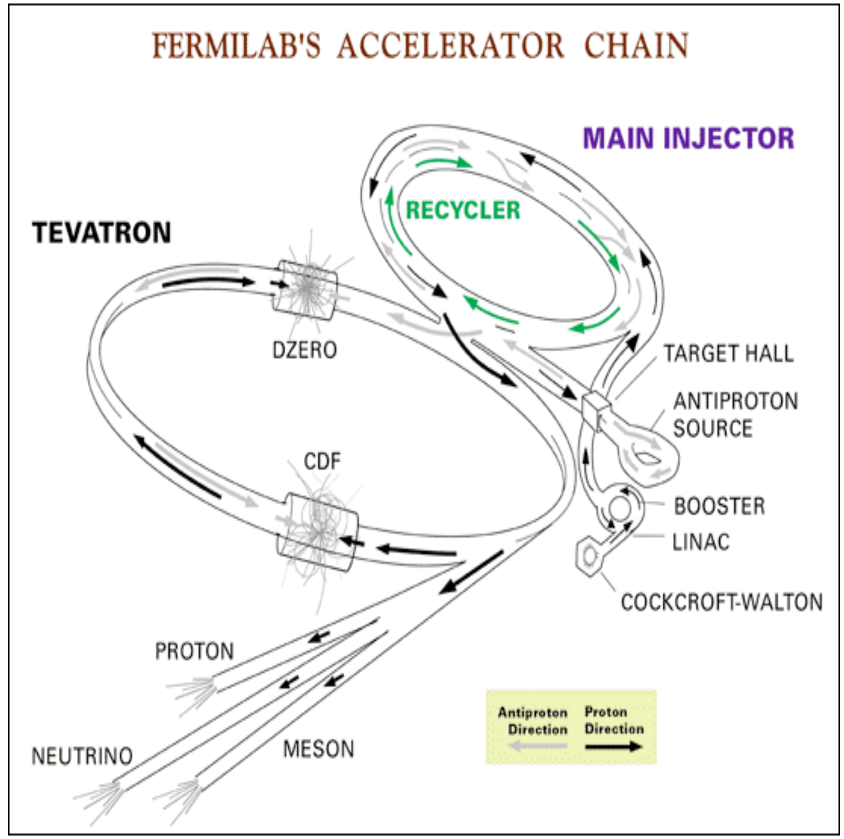
$\sqrt{s} = 1.96$ TeV

Main Injector
(150 GeV proton storage ring)

Antiproton Recycler
(commissioning)

- Electron cooling this year
- Operational by summer '05
- 40% increase in luminosity!

36 proton bunches x
36 antiproton bunches
(396 ns crossing time)

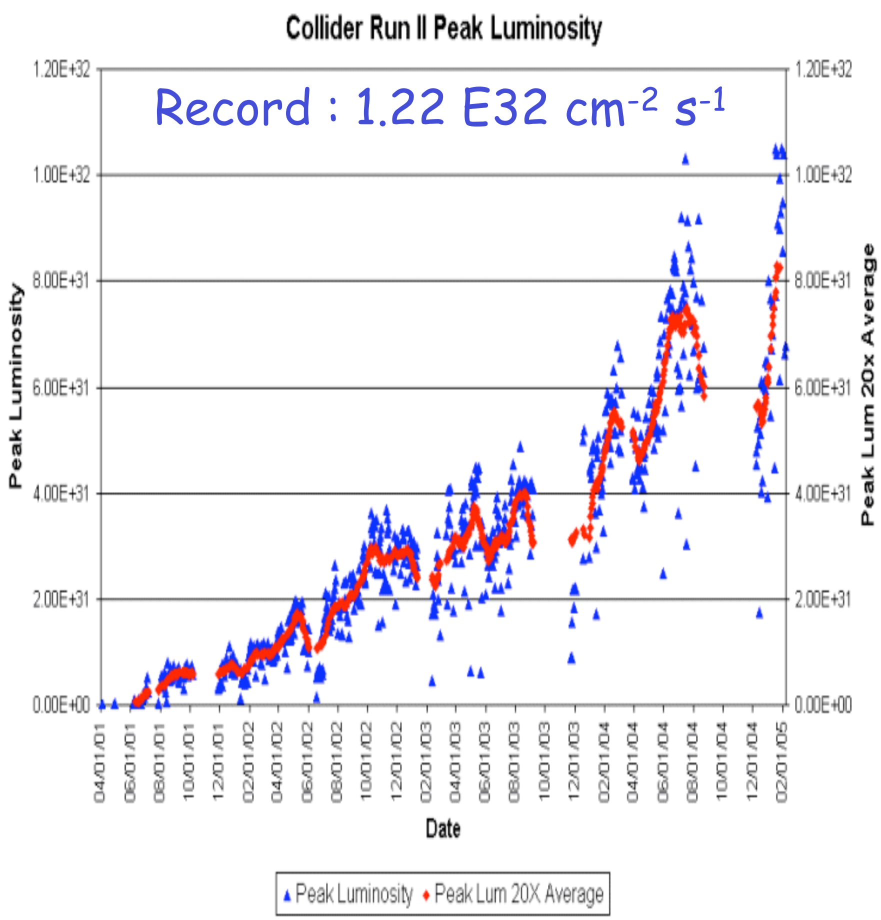


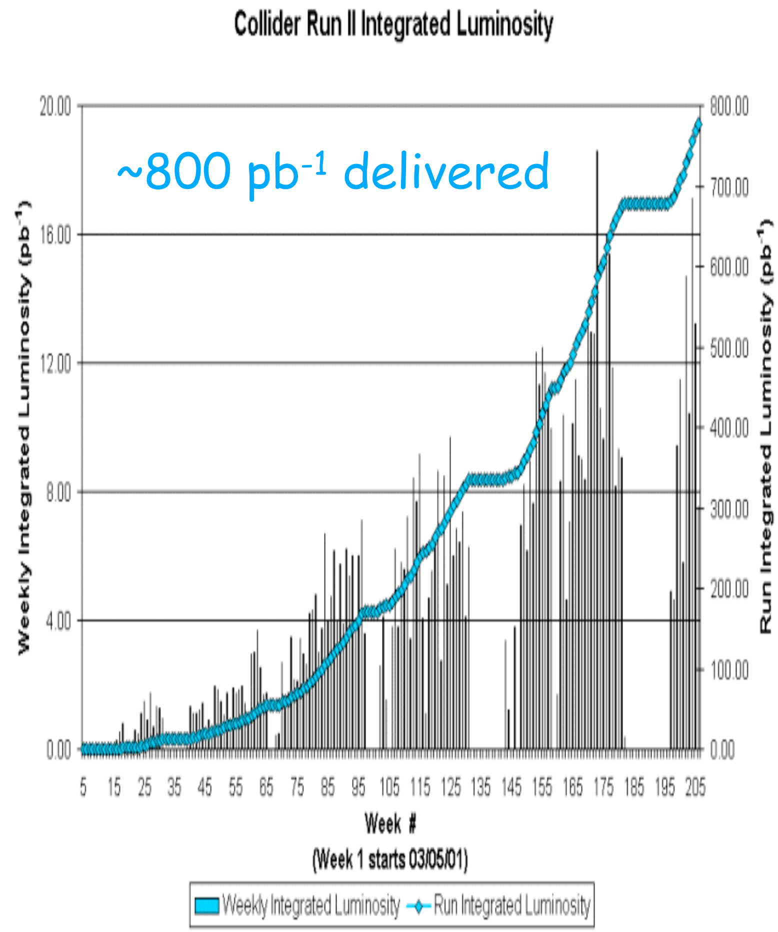
Long Term Luminosity Projection
(by the end of FY2009)

- Base Goal $\Rightarrow$ 4.4 fb^{-1}
- Design $\Rightarrow$ 8.5 fb^{-1}

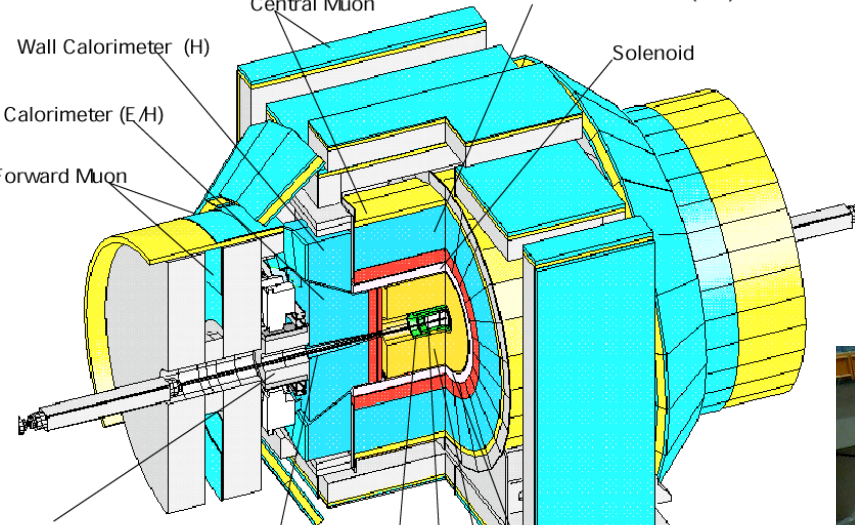
The Fermilab Tevatron

Tevatron Performance



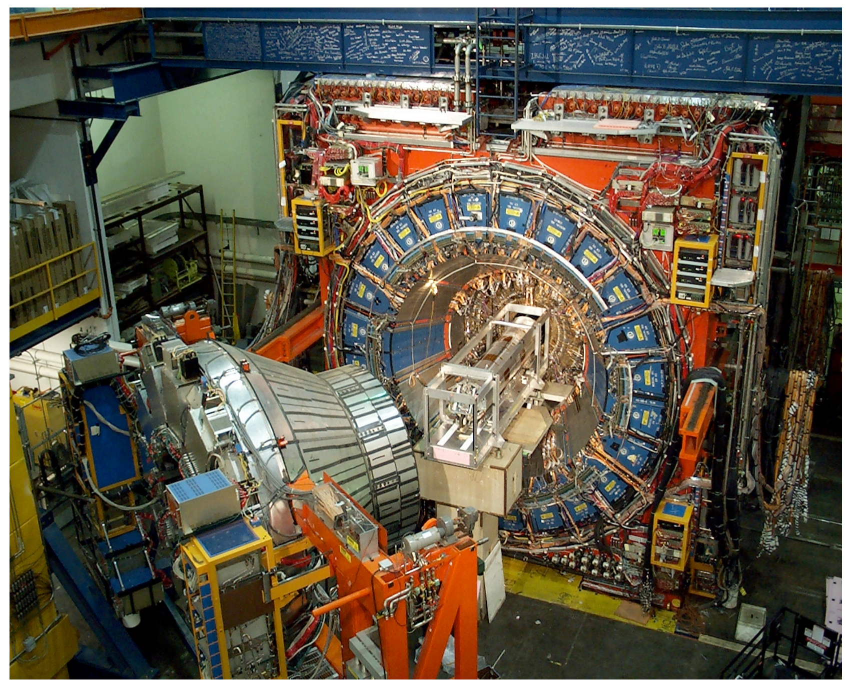


The Collider Detector at Fermilab (CDF)



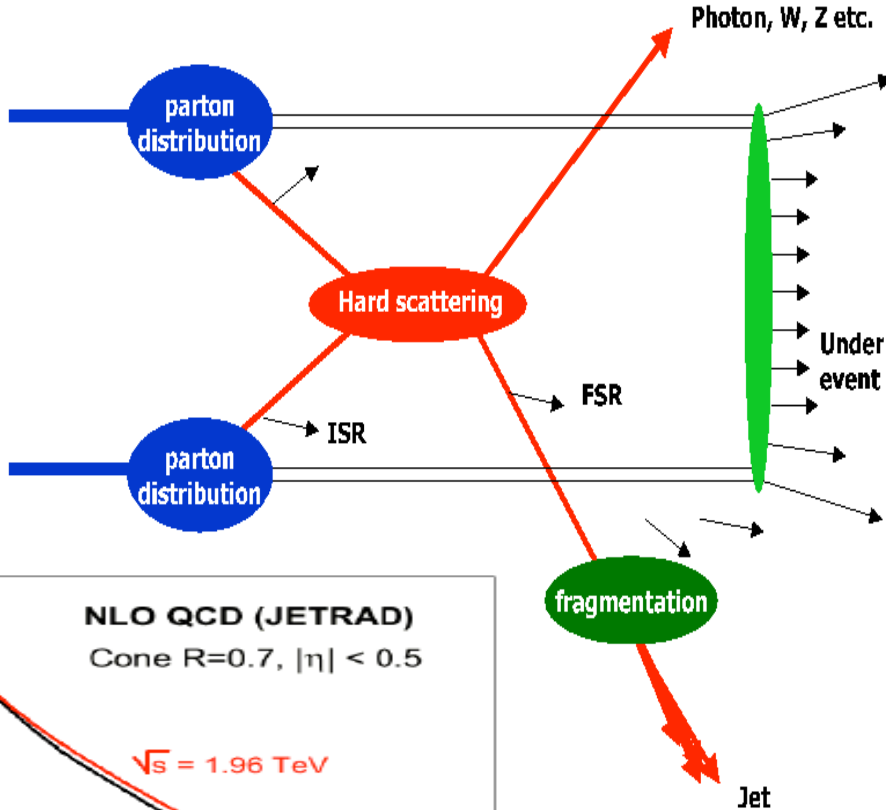
The CDF Detector is operating quite well.

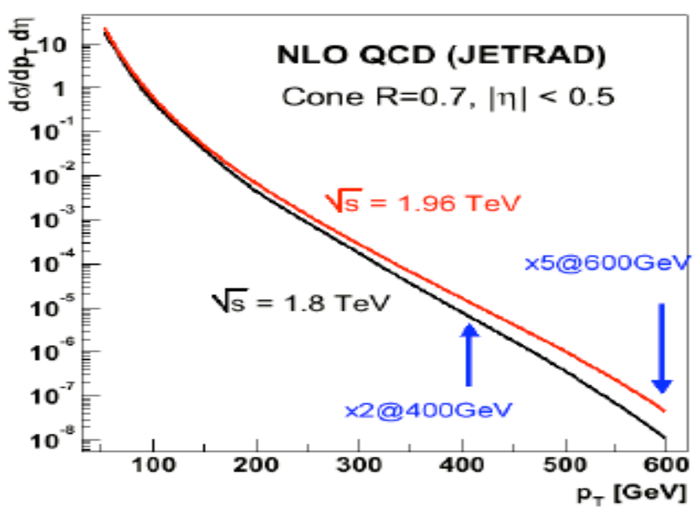
The experiment is recording physics-quality data with very high efficiency (80-85%)



CDF has collected over 600 pb^{-1} of data.

Jet Physics at 2 TeV





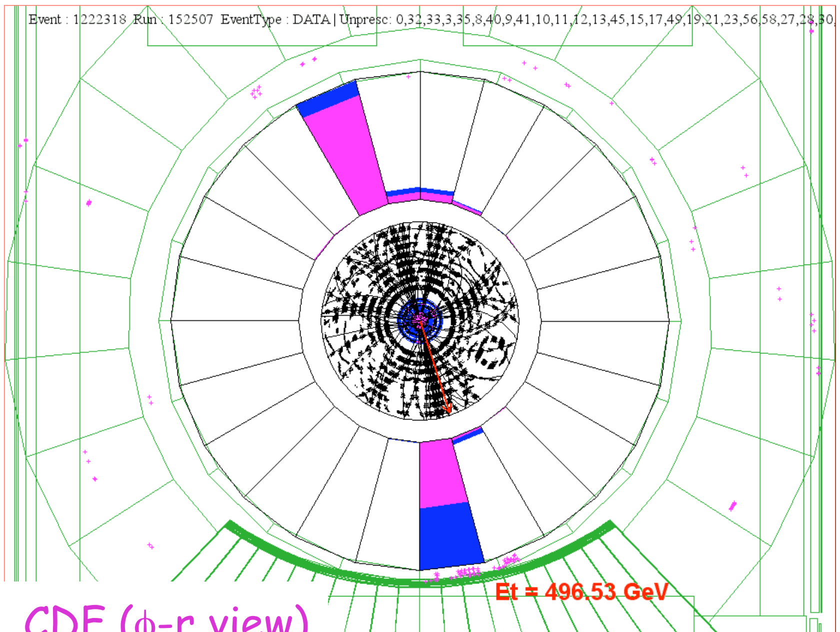
**Big increase in cross section thanks to the higher center-of-mass energy!

- Jet Cross Sections**
  - Jet algorithms
  - Data vs NLO pQCD
  - PDF uncertainties
  - Soft contributions
- B-jet Production
- $b\bar{b}$ Dijet Production
- Underlying Event
- Hard Diffraction
- ....
- ....
- Jet Shapes
- W/Z+Jet(s) Production
- γ+Heavy Quark
- Diphoton Production

Highest-Mass Dijet Event at CDF

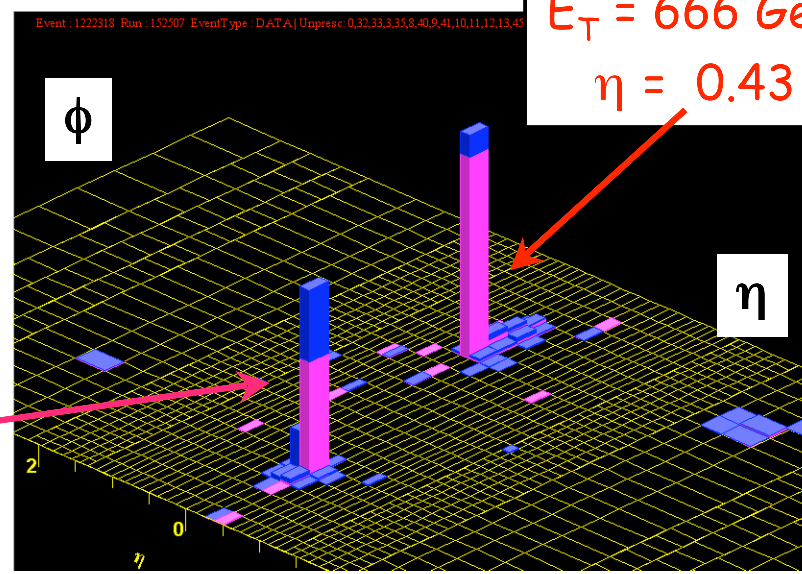
Dijet Mass = 1.36 TeV

(probing distance ~10^{-19} m)



CDF (ϕ-r view)

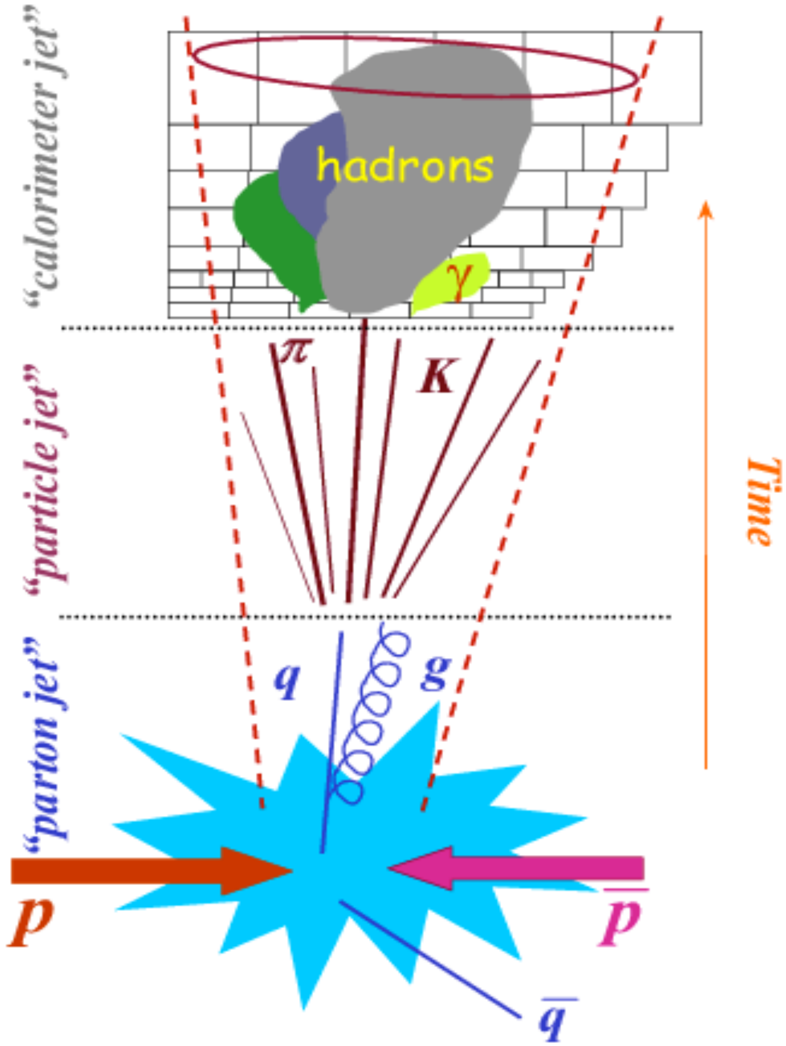
E_T = 666 GeV
η = 0.43



E_T = 633 GeV
η = -0.19

We are looking for a possible quark substructure….

Jet Algorithms



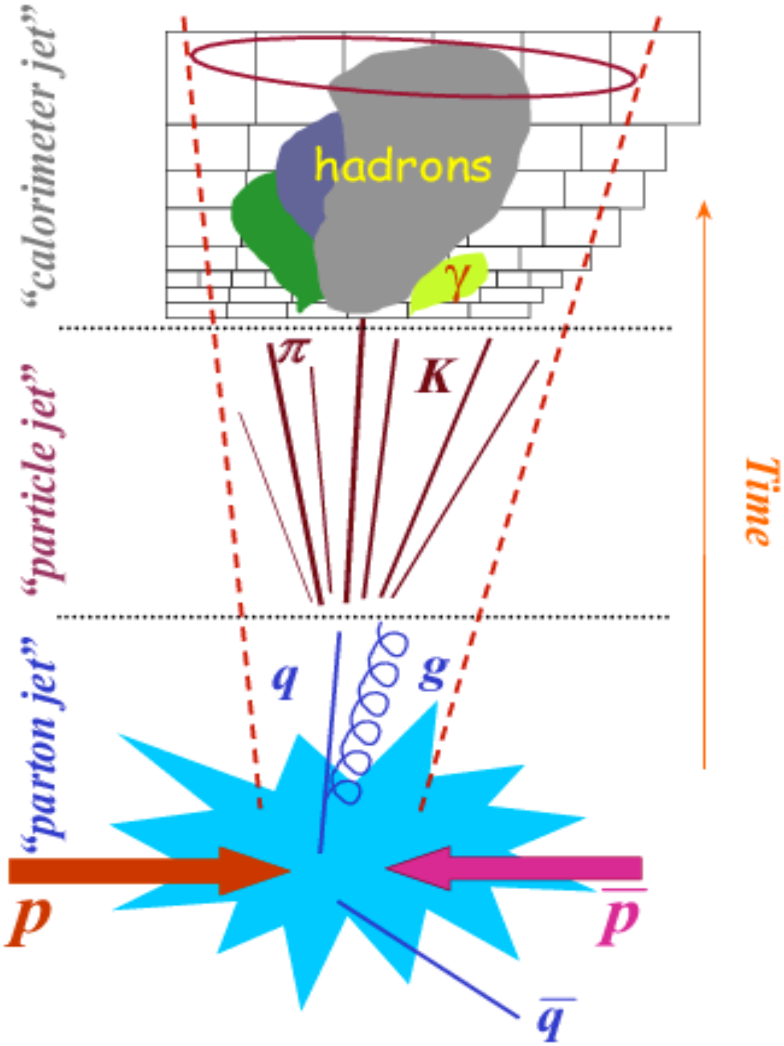
Calorimeter level:
calorimeter towers lumped together according to an experimentalist's favored algorithm

Hadron level:
sprays of long lived observable particles

Parton level 2 (resummed pQCD):
outgoing parton accompanied by a few soft QCD bremsstrahlung

Parton level 1 (NLO pQCD at Tevatron):
outgoing 1 parton or 2 partons lumped together to mimic a particular experimental jet finding algorithm

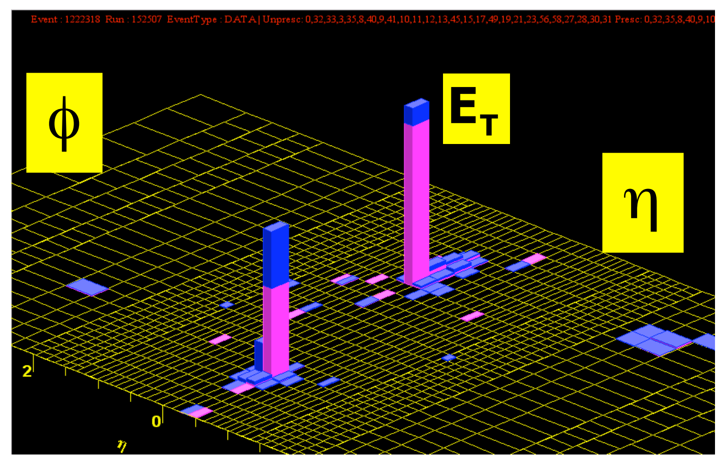
Jet Algorithms



Final state partons are revealed through collimated flows of hadrons called jets

Measurements are performed at hadron level & theory is parton level (hadron → parton transition will depend on model for gluon shower and fragmentation)

Precise jet search algorithms necessary to compare with theory and to define hard physics (cone in η – φ space ?)



Run 1 CDF Jet Algorithm — JetClu

1. Seeds with $E_T > 1$ GeV
2. Draw a cone around each seed and reconstruct the "proto-jet"

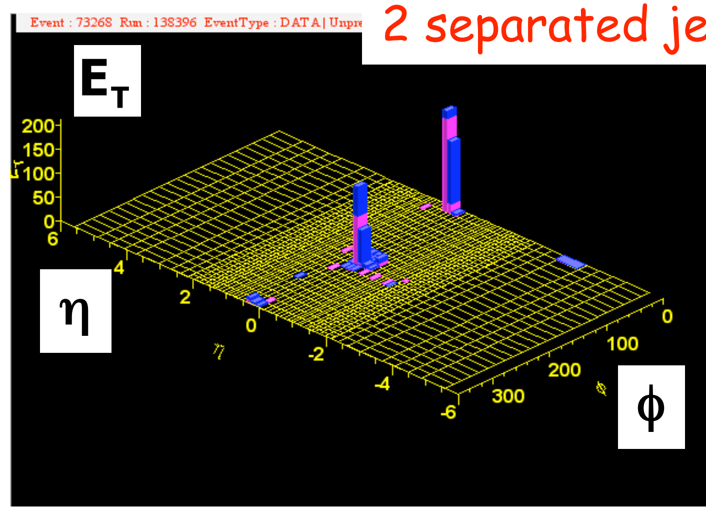
$$E_T^{jet} = \sum_k E_T^k,$$

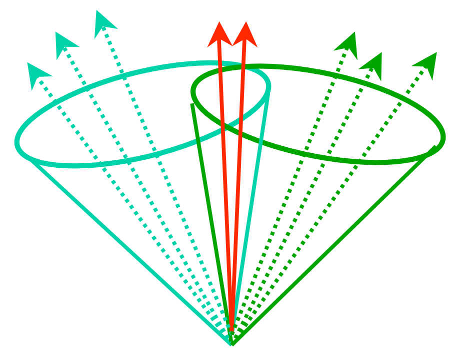
$$\eta^{jet} = \frac{\sum_k E_T^k \cdot \eta_k}{E_T^{jet}}, \quad \phi^{jet} = \frac{\sum_k E_T^k \cdot \phi_k}{E_T^{jet}}$$

3. Draw new cones around "proto-jets" and iterate until stability is achieved (Cone Radius R)

4. Look for possible overlaps

2 separated jets





merged if common E_T is more than 75 % of smallest jet

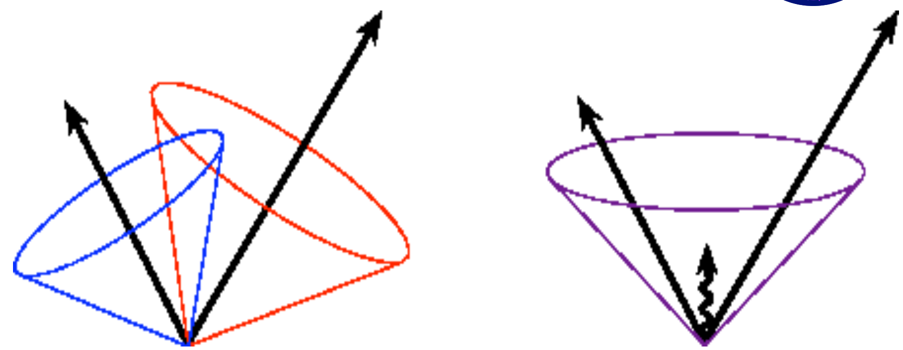
pQCD NLO uses larger cone R' = R_{sep} x R to emulate experimental procedure

⇒ arbitrary parameter in calculation

Comments on the Run 1 Cone Algorithm

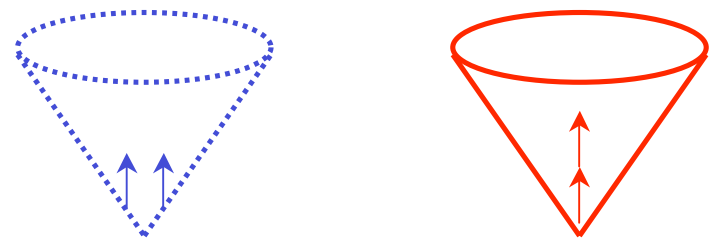
Cone algorithm not infrared safe:

The jet multiplicity changed
after emission of a soft parton



Cone algorithm not collinear safe:

Replacing a massless parton by
the sum of two collinear particles
the jet multiplicity changes



below threshold
(no jets)

above threshold
(1 jet)

Fixed-order pQCD calculations will contain not fully cancelled infrared divergences:

-> Inclusive jet cross section at NNLO
-> Three jet production at NLO
-> Jet Shapes at NLO

} three partons inside a cone

Run II Midpoint Algorithm

1. Define a list of seeds using CAL towers with $E_T > 1$ GeV

2. Draw a cone of radius R around each seed and form "proto-jet"

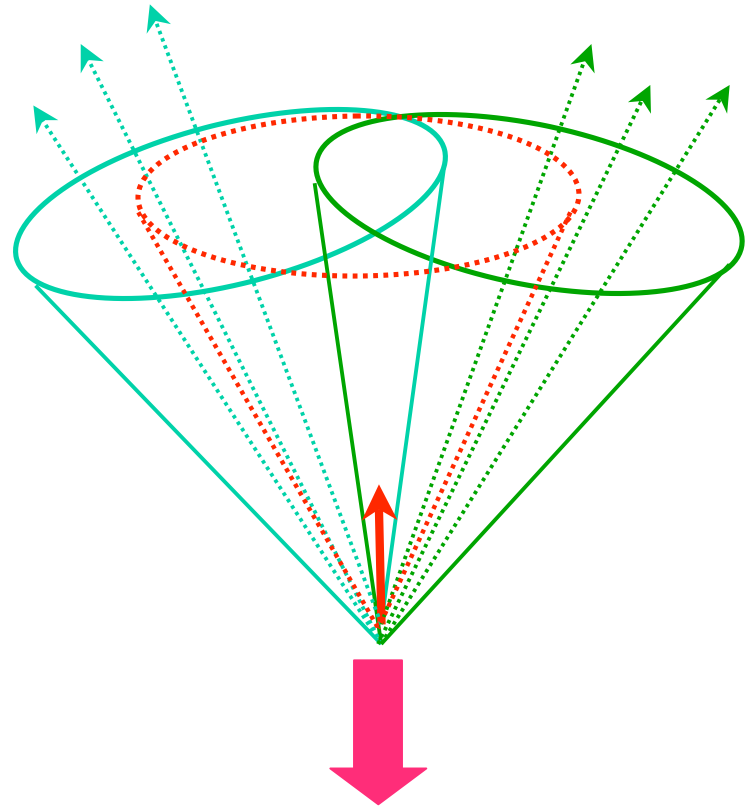
$$E^{jet} = \sum_k E^K, \quad P_i^{jet} = \sum_k P_i^K$$

$$(\text{massive jets}: P_T^{jet}, y^{jet})$$

3. Draw new cones around "proto-jets" and iterate until stable cones

4. Put seed in Midpoint ($\eta-\phi$) for each pair of proto-jets **separated by less than 2R** and iterate for stable jets

5. Merging/Splitting



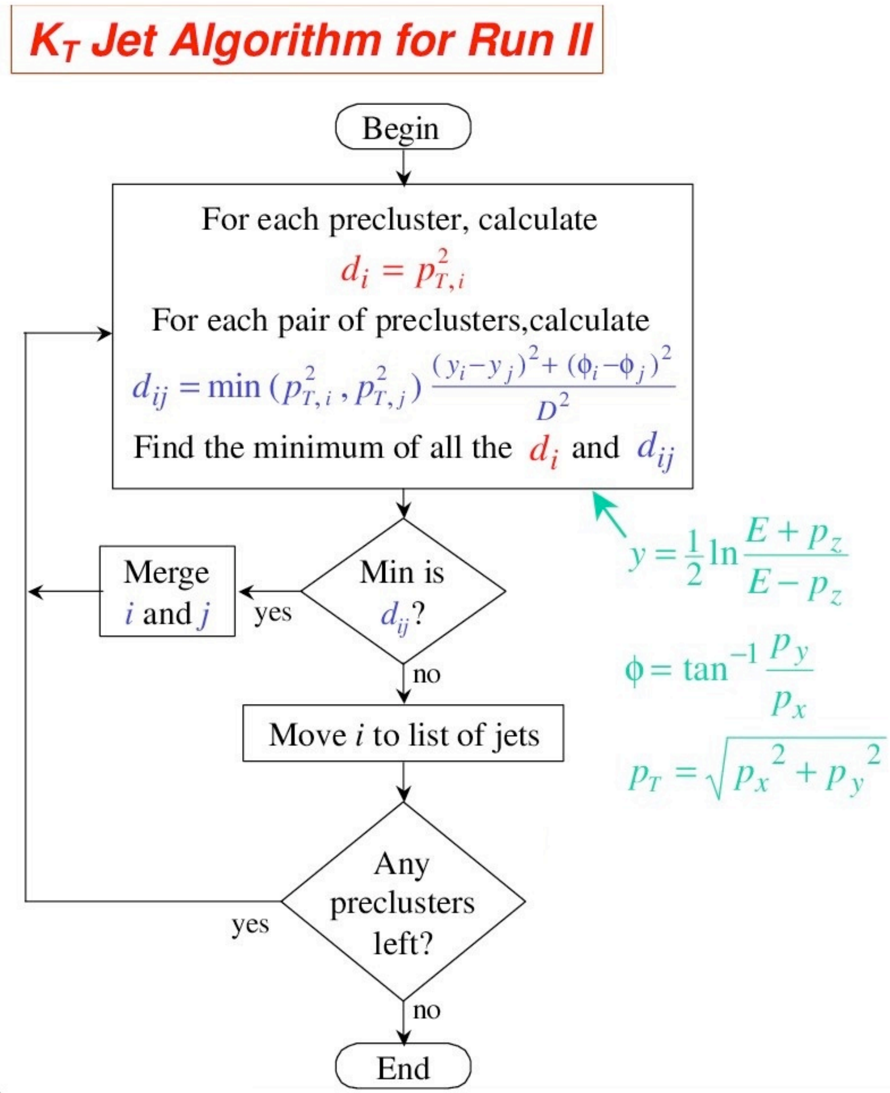
Cross section calculable in pQCD

Run 2 K_T Jet Algorithm — Motivation

QCD seems to prefer to separate partons into jets according to their relative transverse momentum

K_T algorithm preferred by theory!

- infrared stable (no splitting/merging)
- no clusters left out
- favored choice at e^+e^- colliders



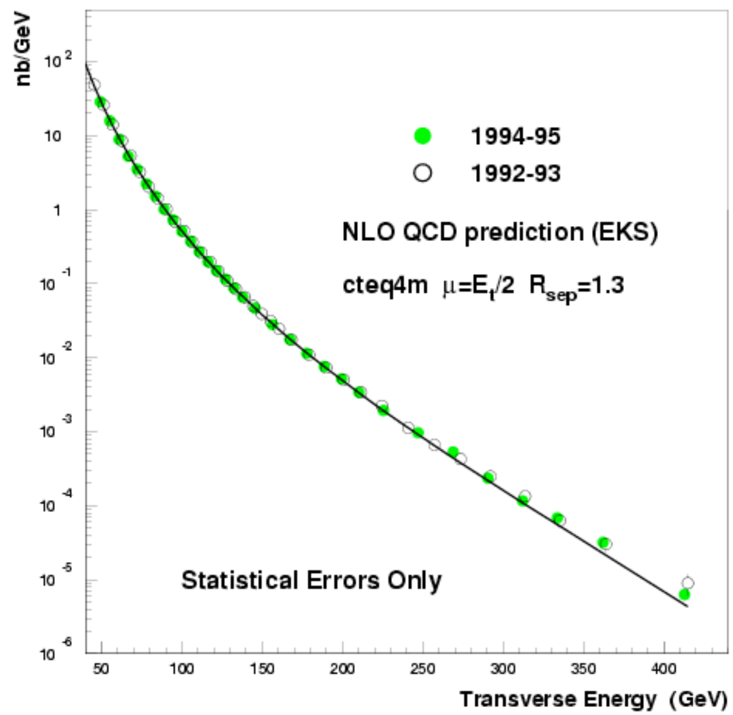
Run 1 Inclusive Jet Cross Section at the Tevatron

- 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 observed 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, $\mu_F=\mu_R=E_{Tjet}/2$)

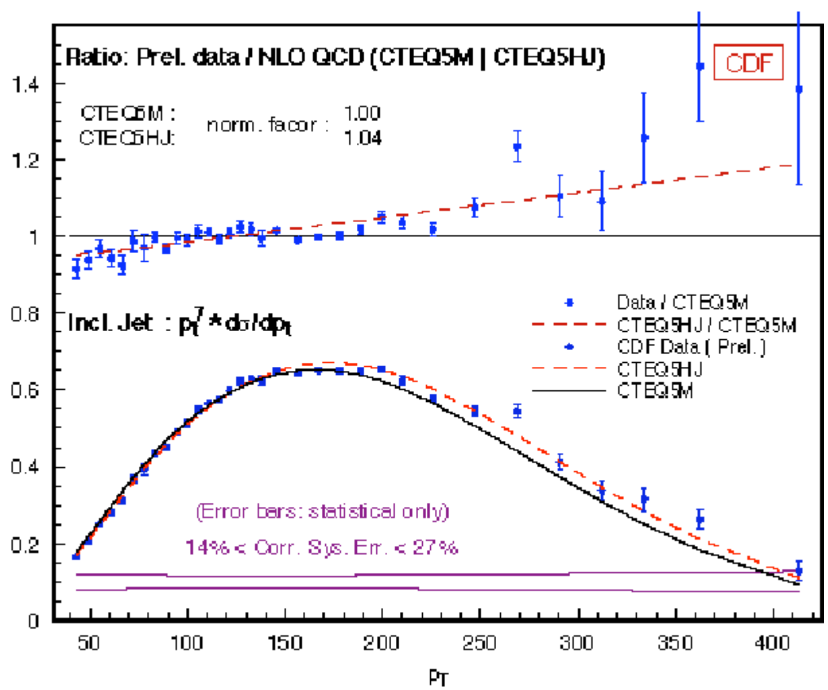


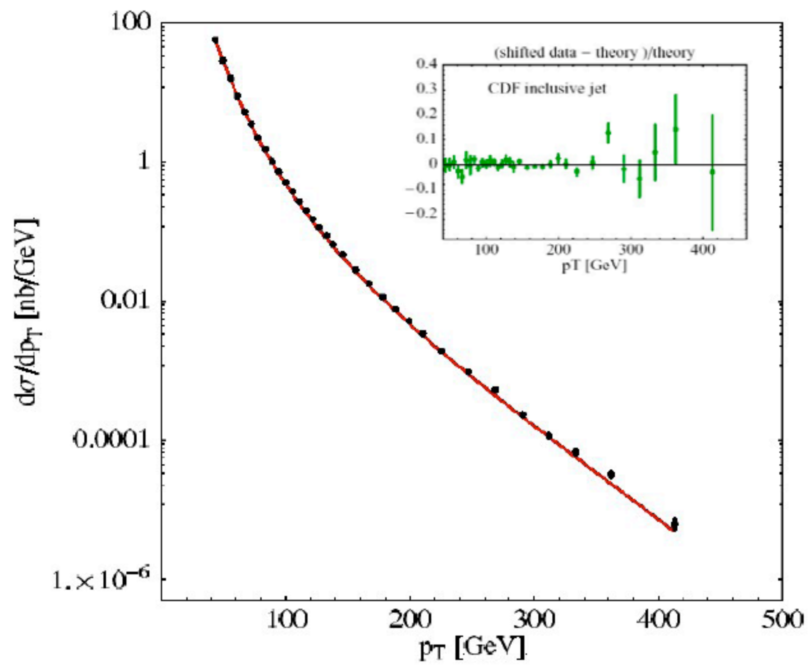
Run 1 Inclusive Jet Cross Section at the Tevatron

Tevatron jets and the high-x gluon uncertainty...

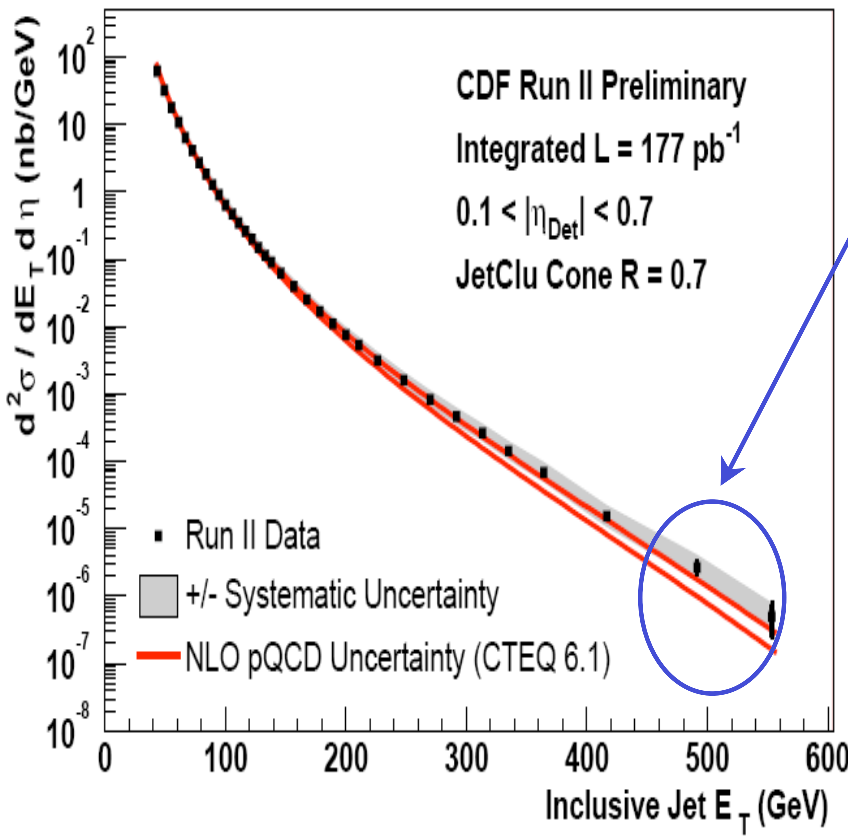
- Best fit to CDF and D0 central jet cross sections provided by CTEQ5HJ PDFs

The central fit for CTEQ6 is more “HJ”-like, and the discrepancy *vanishes*.



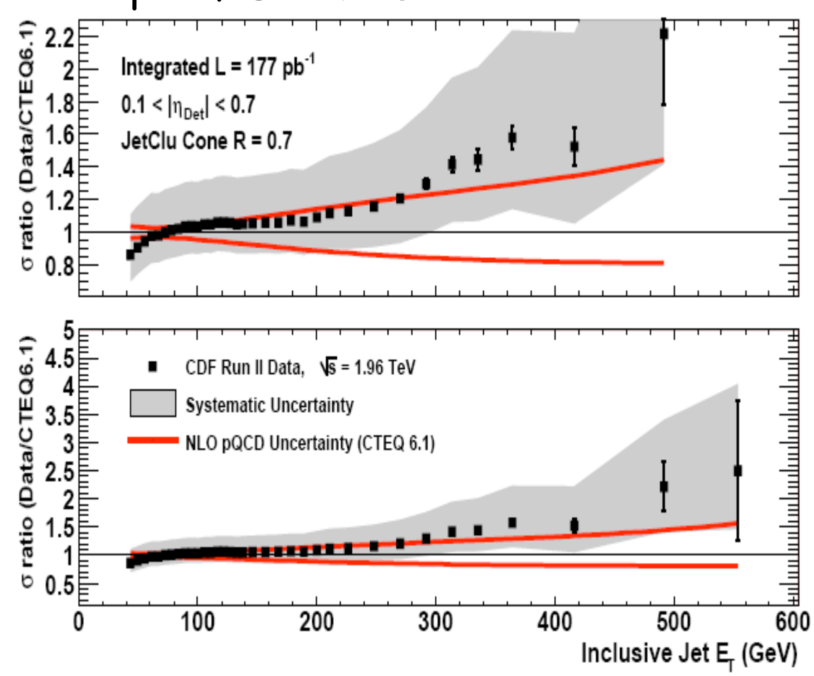


Run II Inclusive Jet Cross Section — JetClu



- Using Run I cone algorithm & unfolding E_T^{jet} range increased by ~150 GeV
- Comparison with pQCD NLO (JETRAD) (over almost nine orders of magnitude)

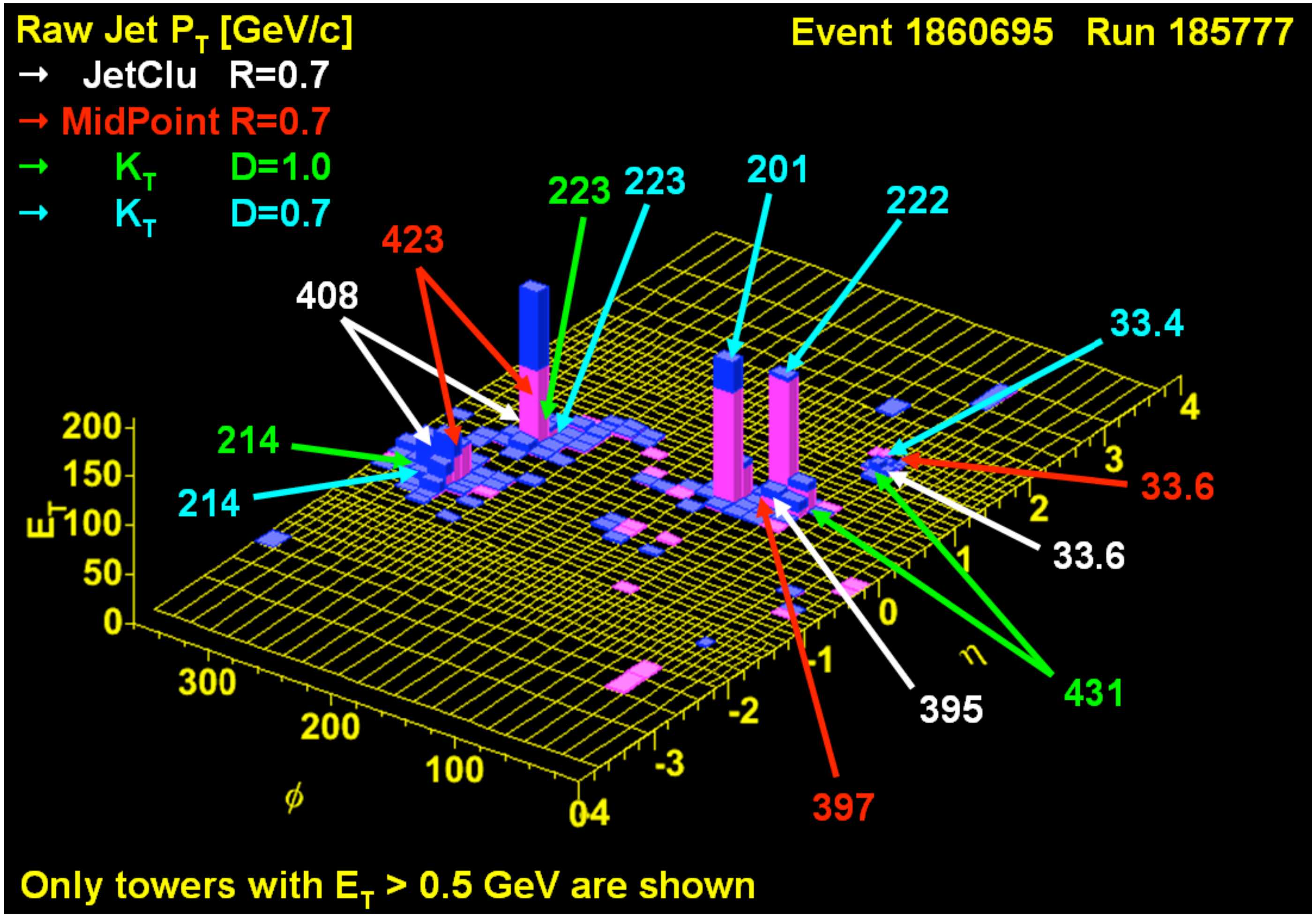
Shape of Data/NLO to be understood



Data dominated by jet energy scale
NLO error mainly from gluon at high x

No hadronization corrections applied to NLO prediction → relevant @ low jet E_T

One Event ... Different Jet Algorithms

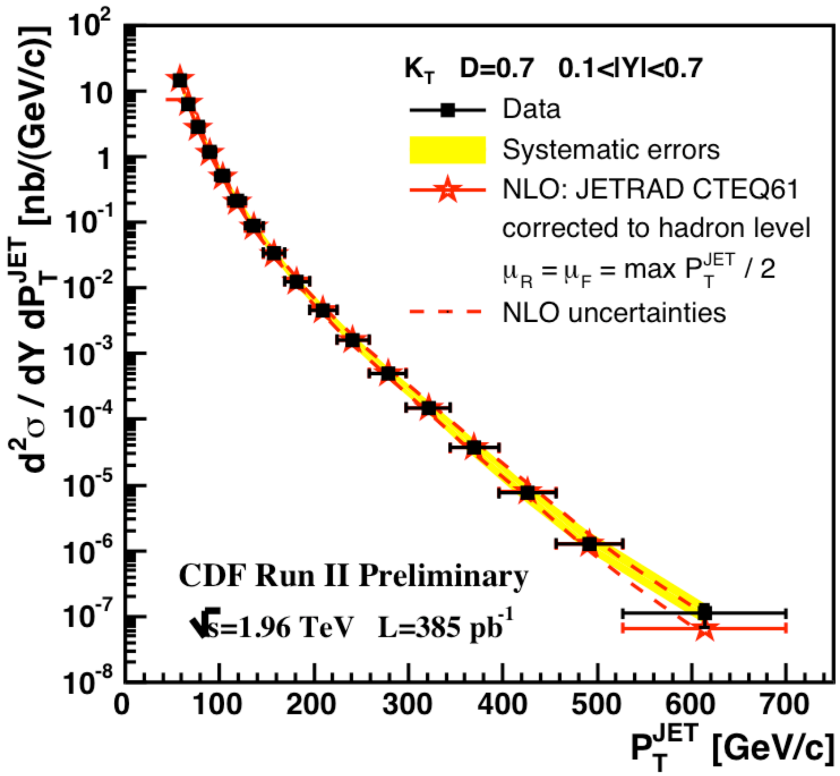


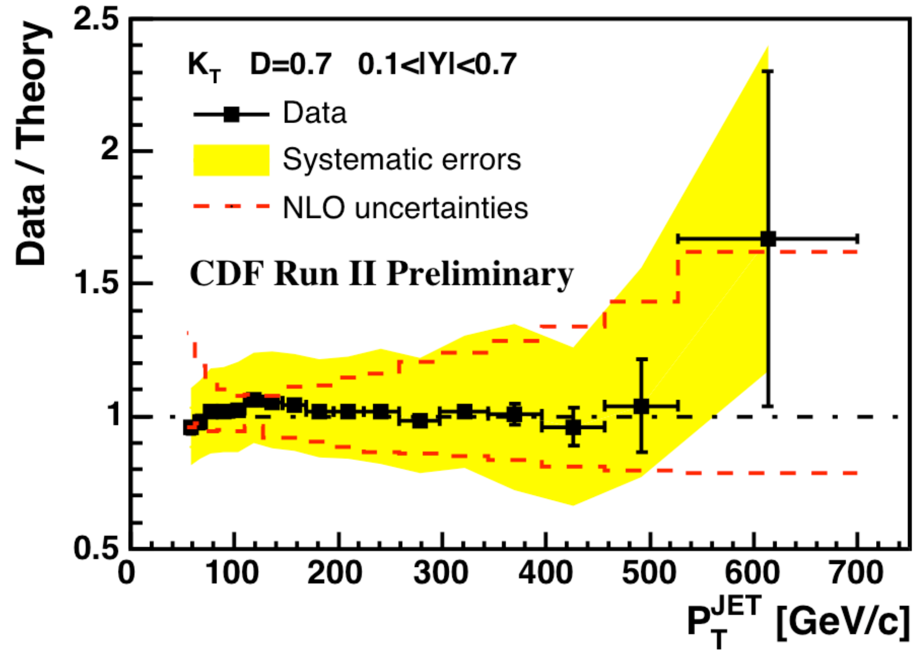
Run II Inclusive Jet Cross Section — K_T

- Inclusive K_T algorithm

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j})\frac{\Delta R^2}{D^2}$$

$$d_i = (P_{T,i})^2$$



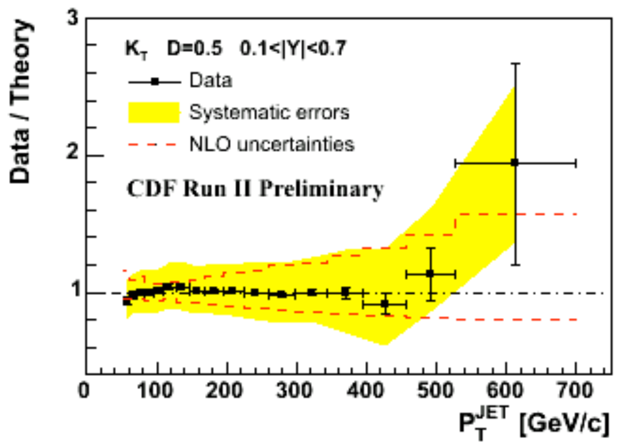


- Good agreement Data vs Theory
- High-Pt tail to be watched closely…
- K_T works in hadron collisions !

→ Relevant for LHC strategies

Run II Inclusive Jet Cross Section — K_T

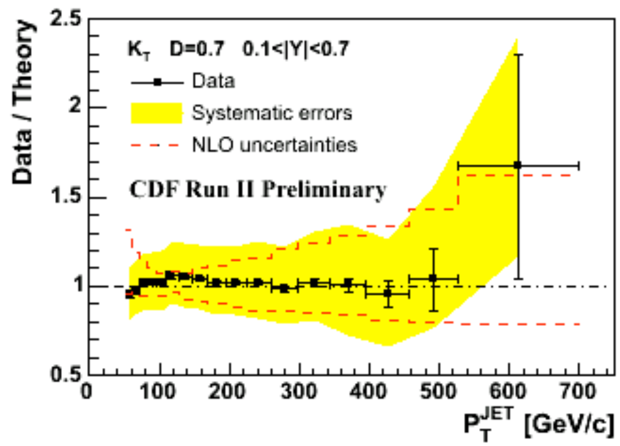
D=0.5



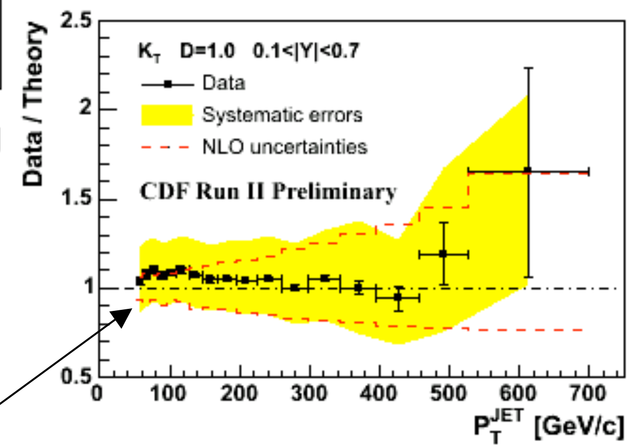
Dependence on D

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

D=0.7



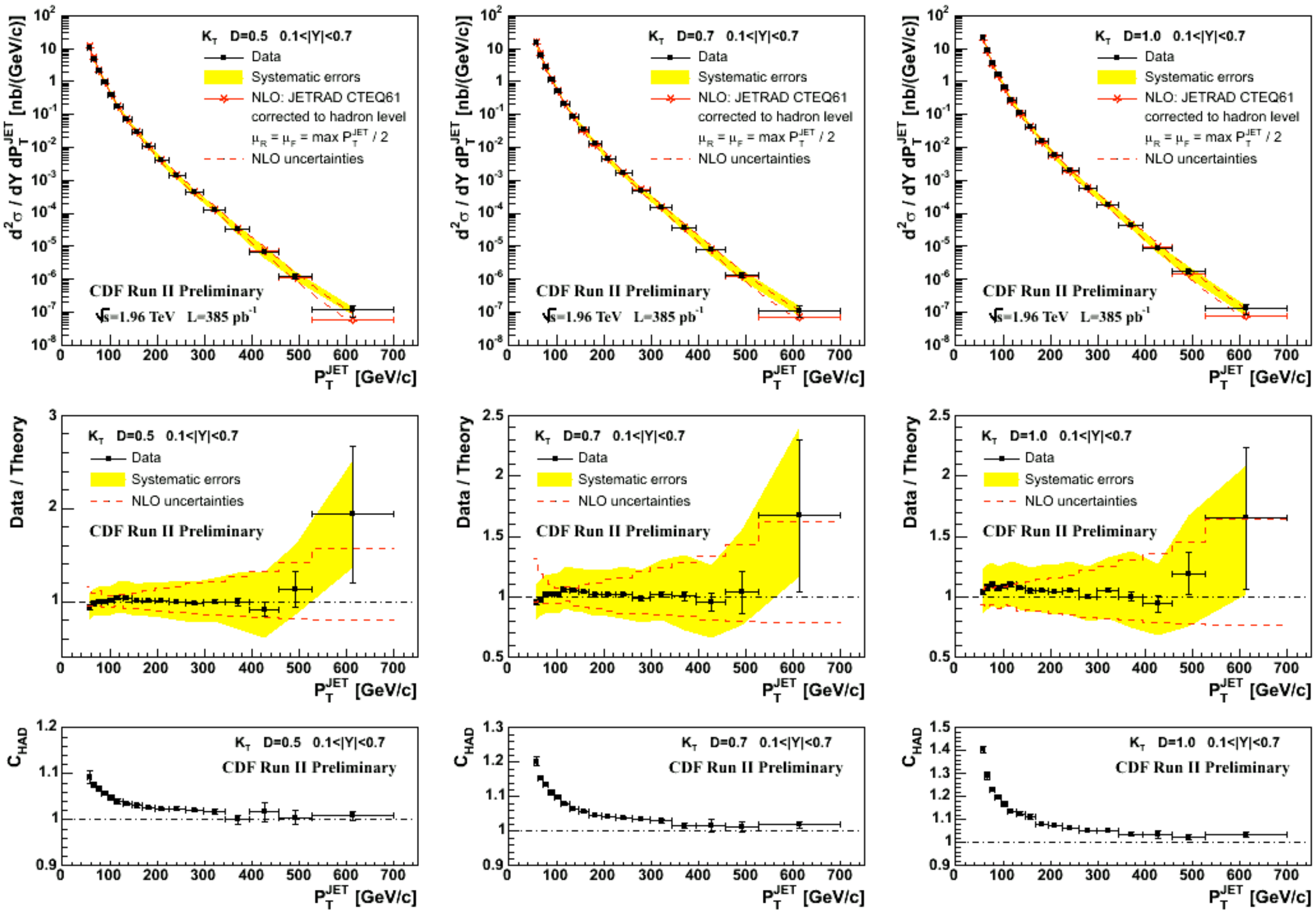
D=1.0



As D increases → more soft contributions

(we need a good UE model!)

Run II Inclusive Jet Cross Section — K_T



High P_T b-jet Cross Section

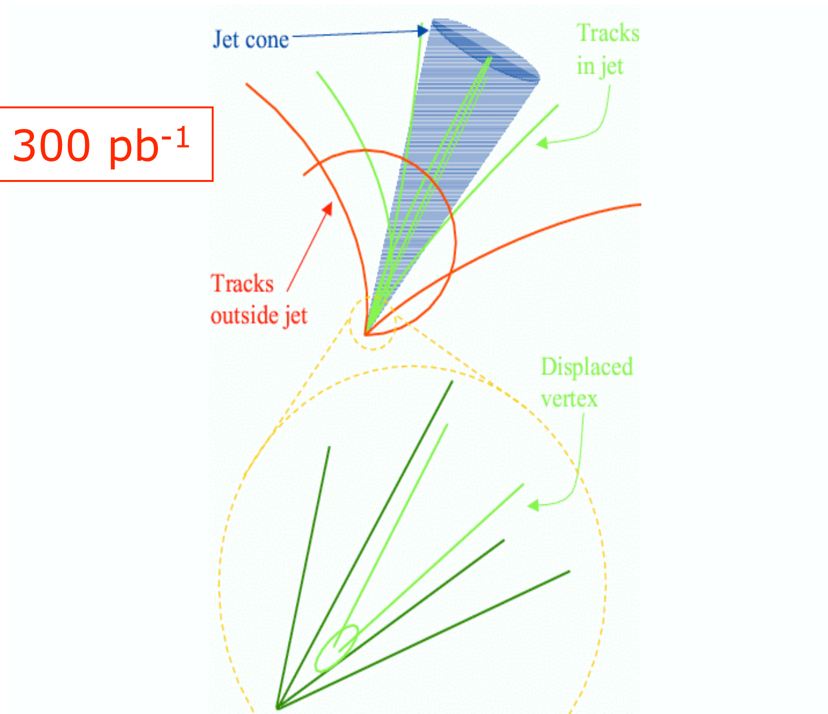
b-jets include most of quark fragmentation remnants

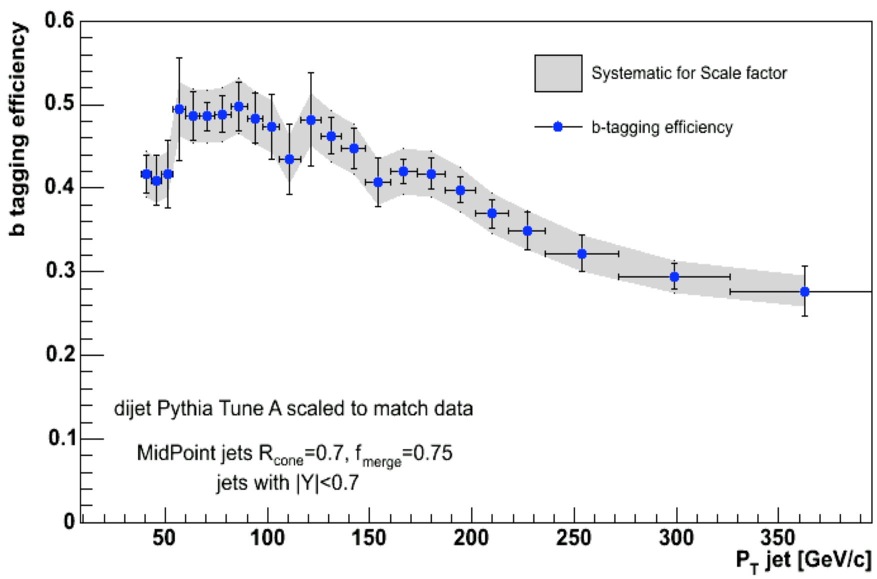
→ ***small dependence on fragmentation***

- MidPoint algorithm for jet reconstruction
- <u>kinematics:</u> jet P_T and rapidity (y)
- jet R_{cone} = 0.7, $|y_{jet}|<0.7$
- P_T range 30-360 GeV/c → 38-400 GeV/c

(Energy scale corrected for detector effects)

Lum ~ 300 pb^{-1}

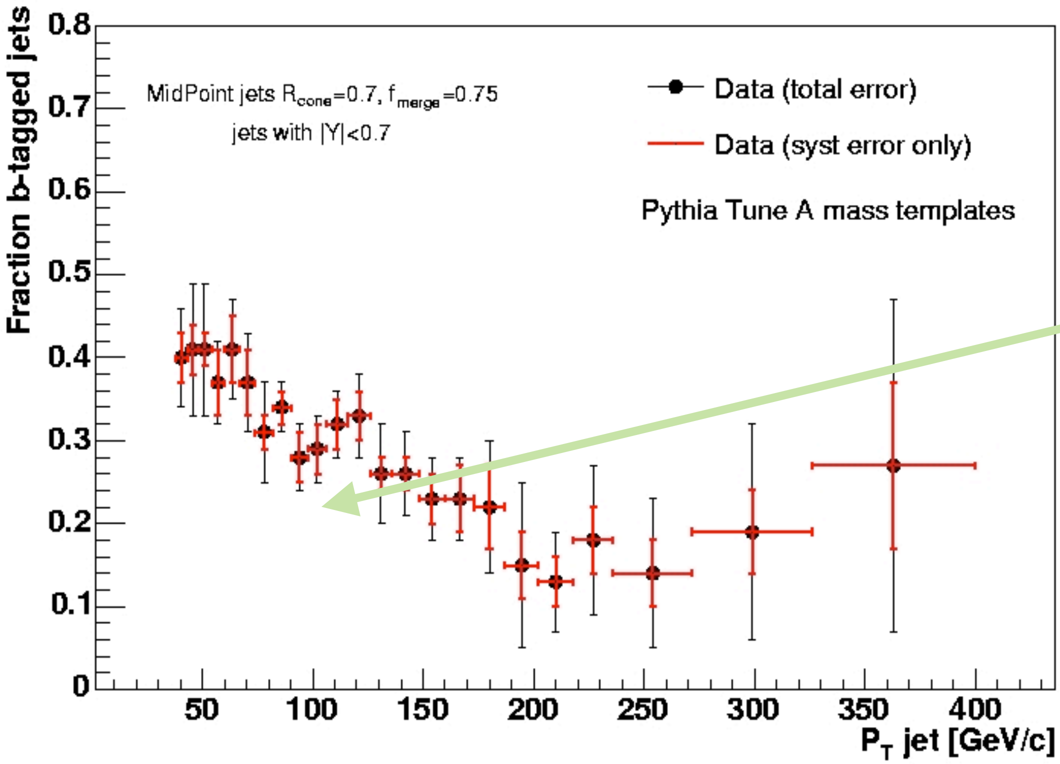


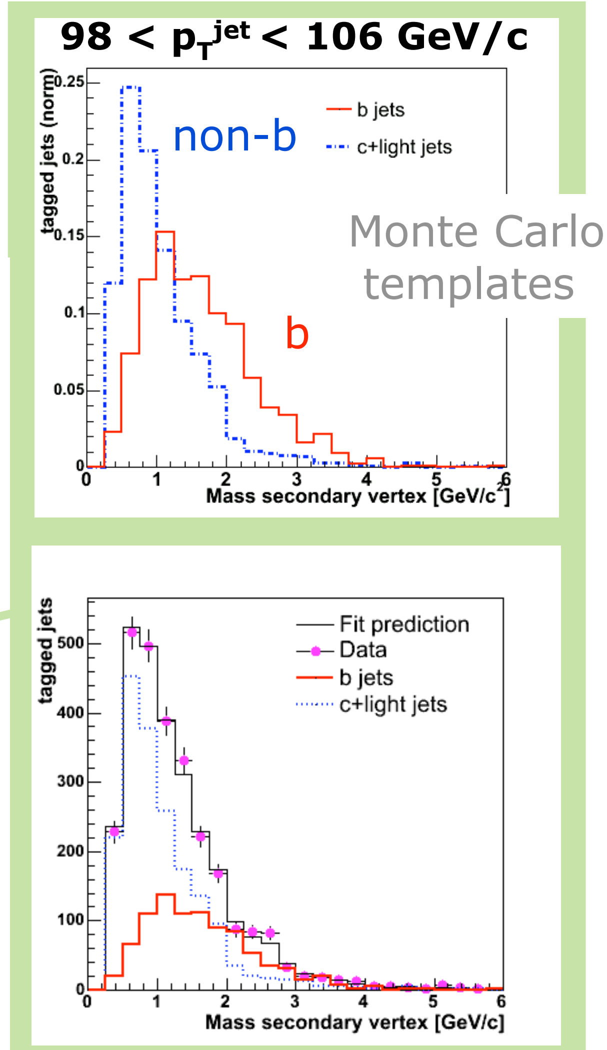


- Use displaced tracks inside jet to reconstruct the secondary vertex (b-tagging)

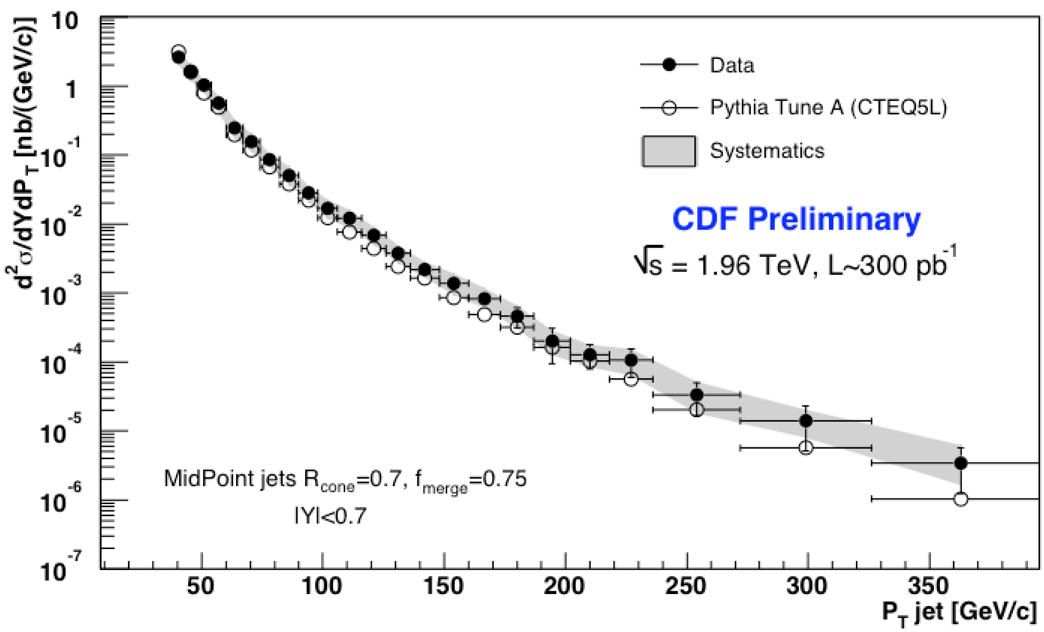
b-jet Cross Section: b-tagged jet fraction

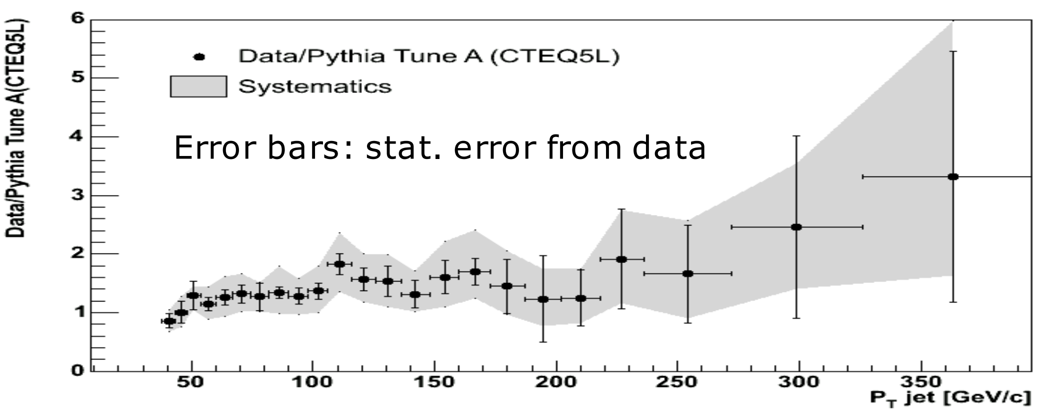
Extract fraction of b-tagged jets from data using shape of mass of secondary vertex as discriminating quantity
→ bin-by-bin as a function of jet p_T





High P_T b-jet Cross Section: Results





b-jet cross section as function of jet p_T (Range 38-400 GeV/c)

Systematic Error	low P_T	high P_T
Luminosity	6%	6%
Absolute Energy Scale	15-20%	40%
Jet energy resolution	6%	6%
B-tagging efficiency	10%	15%
B-tagged jets fraction	10-15%	40%
Unfolding	8%	8%

No comparison with NLO yet

Data/Pythia Tune A ~ 1.4
in agreement
with expectations

$b\bar{b}$ Dijet Cross Section

- Jet algorithm: JetClu with $R_{cone} = 0.7$
- Kinematical range
  - 2 b-jets within $|\eta| < 1.2$
  - $E_T^{1st\ b\text{-}jet} > 30$ GeV, $E_T^{2nd\ b\text{-}jet} > 20$ GeV
- Data sample: 65 pb^{-1}
  - Jet 20 only (prescaled trigger)

$$\sigma_{bb} = \frac{N_{ev} F_b}{\varepsilon_b^{lead}\, \varepsilon_b^{other} A \int L}$$

N_{ev} = Number of Events

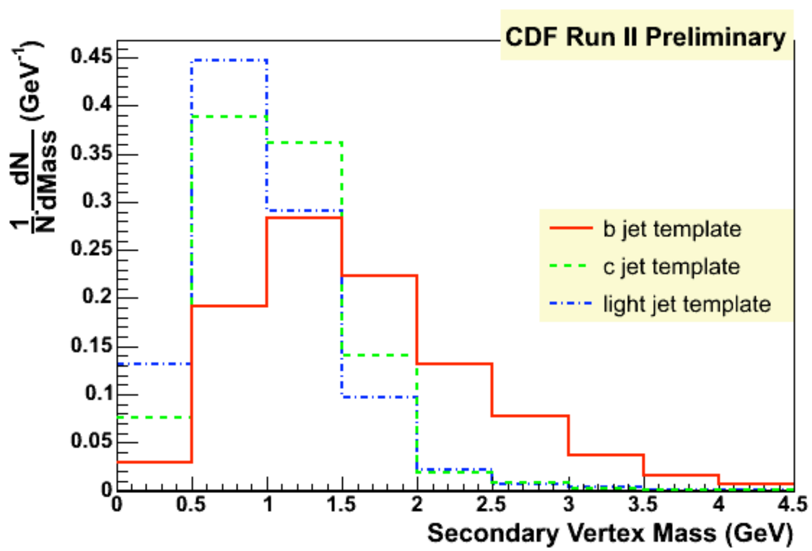
F_b = b Fraction of Events

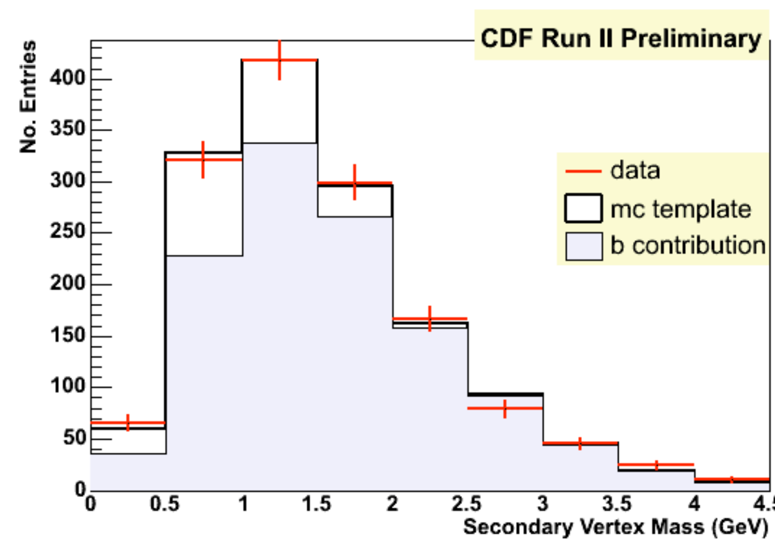
ε_b = SECVTX Tagging Efficiency

A = Acceptance (Trigger Efficiency Folded in)

$\int L$ = Integrated Luminosity

$b\bar{b}$ Dijet Cross Section





b fraction: $F_b = 0.83 \pm 0.04$

$b\bar{b}$ Dijet Cross Section

Final Result: σ_{bb} = 34.5 ± 1.8 +10.3 −10.7 nb

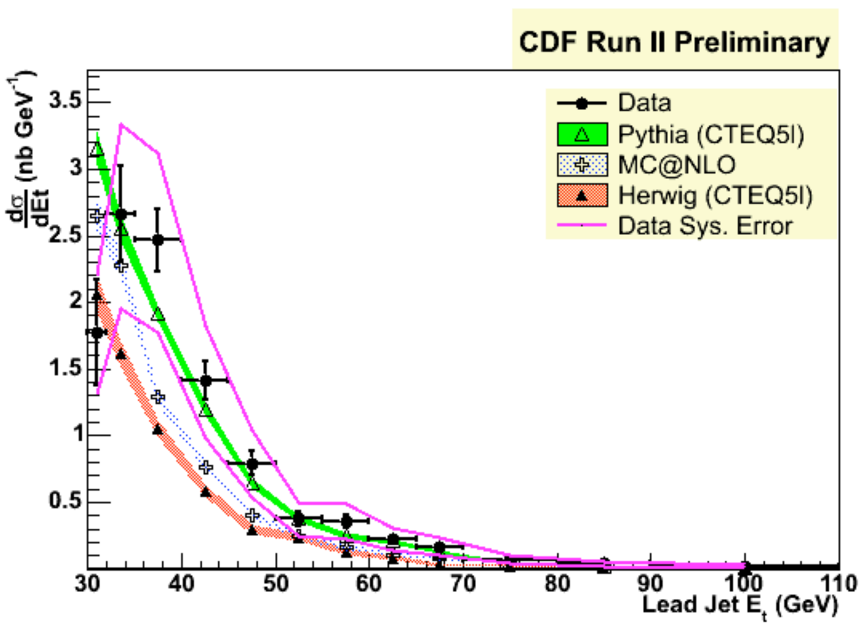
Pythia (CTEQ 5l) σ = 38.71 ± 0.62 nb

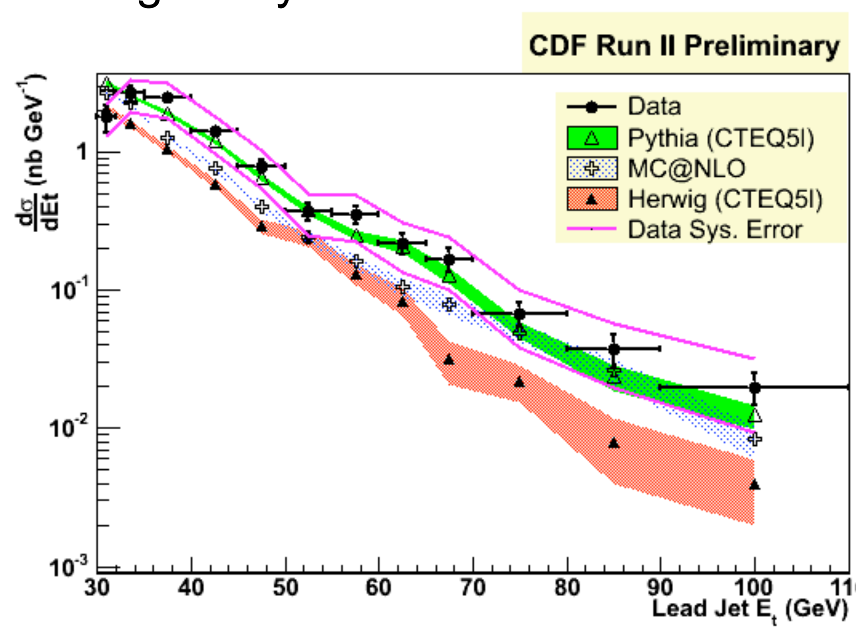
Herwig (CTEQ 5l) σ = 21.53 ± 0.66 nb

MC@NLO σ = 28.49 ± 0.58 nb

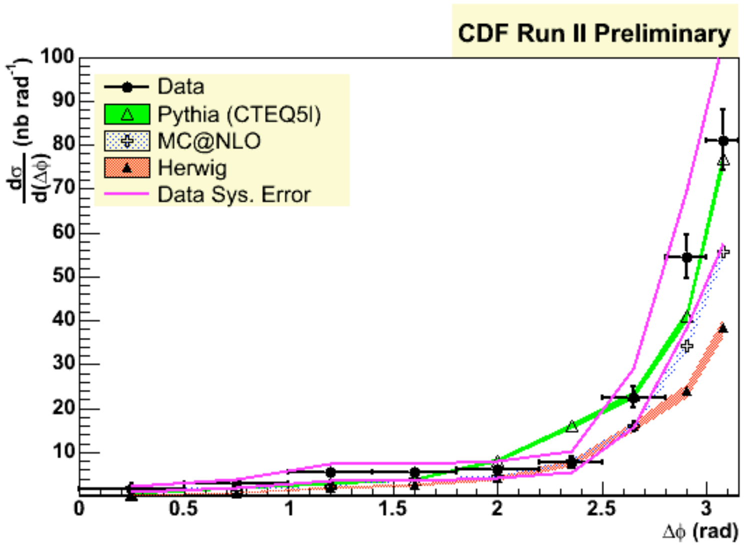
S. Frixione & B.R.Webber: JHEP 0206 (2002) 029, 0308 (2003) 007

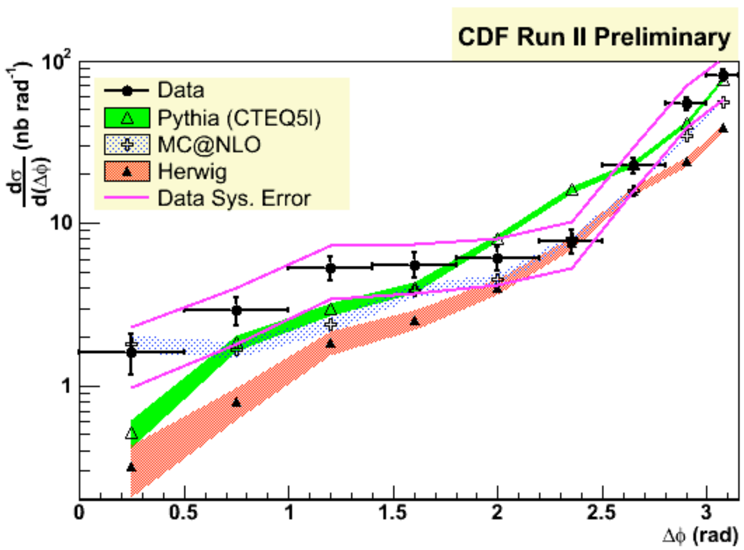
- Data agrees with Pythia
- MC@NLO in better agreement at high Et
- Herwig always low





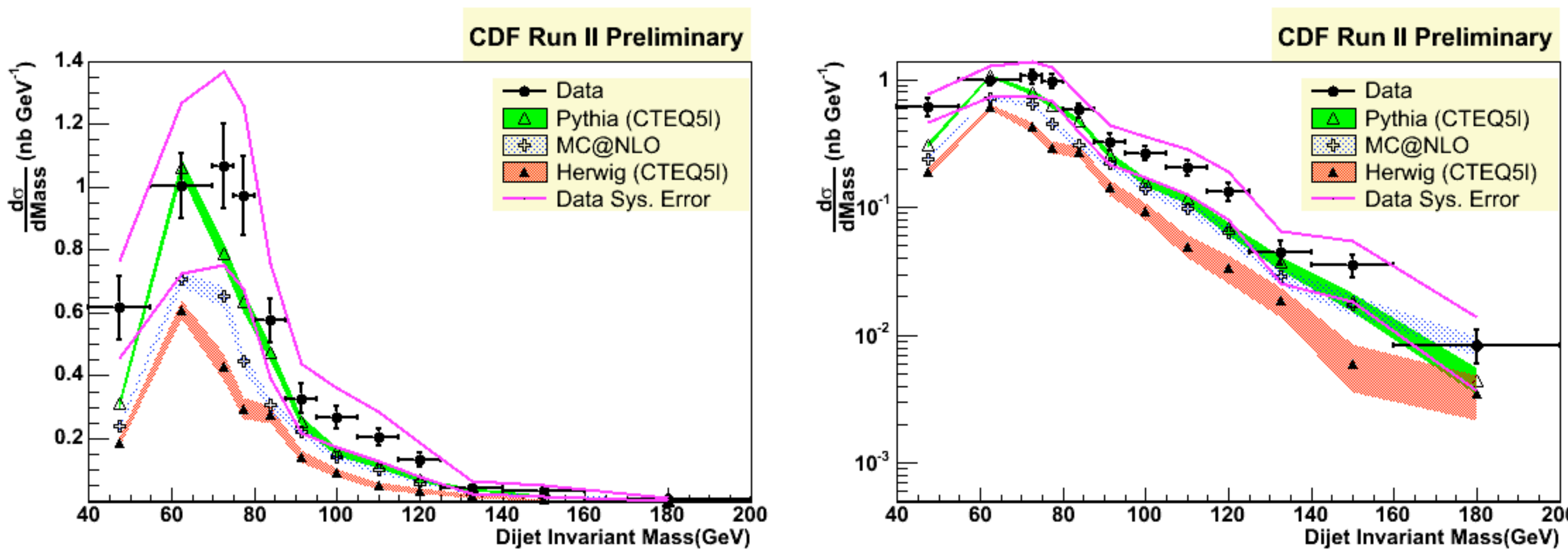
$b\bar{b}$ Dijet Cross Section





- Predominantly back to back
- Reasonable agreement with Pythia
  - Deviates away at low $\Delta\phi$

$b\bar{b}$ Dijet Cross Section

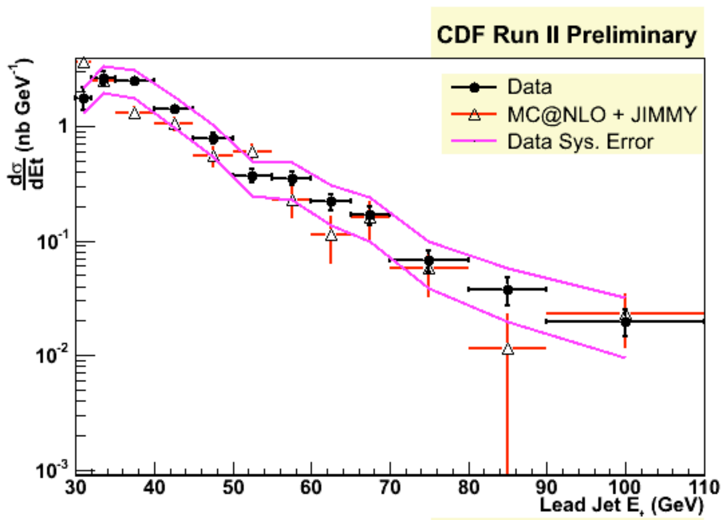


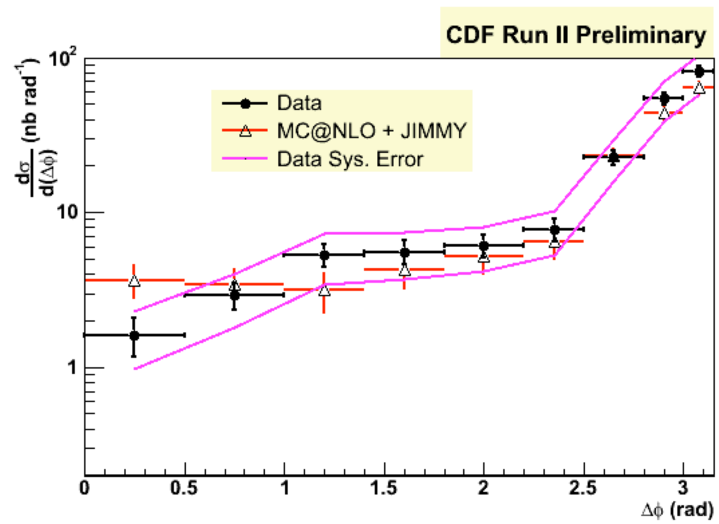
- Reasonable agreement with Pythia
- MC@NLO in better agreement at high Mass
- Herwig always low

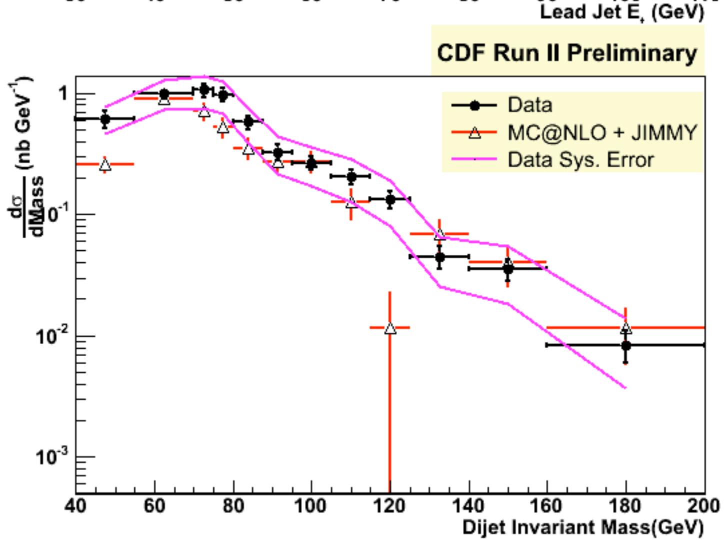
$b\bar{b}$ Dijet Cross Section

MC@NLO+JIMMY (Generator for multiparton interactions)

Butterworth, Forshaw, Seymour







- $\sigma_{bb} = 35.7 \pm 2.0$ nb
- Good agreement with DATA
- $\Delta\phi$ distribution in better agreement than Pythia

$b\bar{b}$ Dijet Cross Section: Summary

- Cross section calculated to be
  - 34.5 ± 1.8 + 10.3 – 10.7 nb
- Agreement with LO Pythia
- MC@NLO and Herwig both low
- Difference between Pythia and MC@NLO due to underlying event contributions to jet
- When JIMMY is used MC@NLO agrees with data and LO order Pythia predictions
- $d\sigma/d\Delta\phi$ shows event selection enhances LO contributions
  - Hence agreement between MC@NLO and Pythia
  - MC@NLO appears to predict this better than Pythia

Jet Physics at CDF

Summary

- The Fermilab Tevatron is actively producing great numbers of proton-antiproton collisions ⇒ excellent recent performance!

  sizable datasets (>600 pb^{-1}) for high-p_T QCD analyses!

- The Run 2 inclusive jet cross section, extending beyond 600 GeV, allows us to reinvestigate the issue of the high-x excess seen in Run 1 data. Is the high-x gluon distribution responsible ... or?

  Run 2 explores different jet algorithms

  K_T works in hadron collisions ⇒ relevant for LHC strategies

  New b-jets analyses considerably extend range in p_T of cross section: for CDF, NLO (and beyond) comparison expected soon, LO comparison agrees as expected!

Thank you!

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