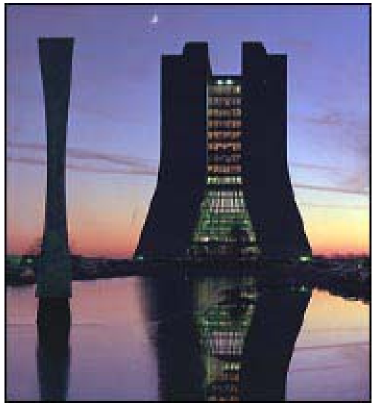
QCD at the Tevatron

Marek Zielinski
University of Rochester

Physics at LHC, Vienna, 16 July 2004



Outline

- Introduction
- From hard to soft QCD studies:
  - ➔ Cone and kT jets
  - ➔ Dijets

hard ME
pdfs

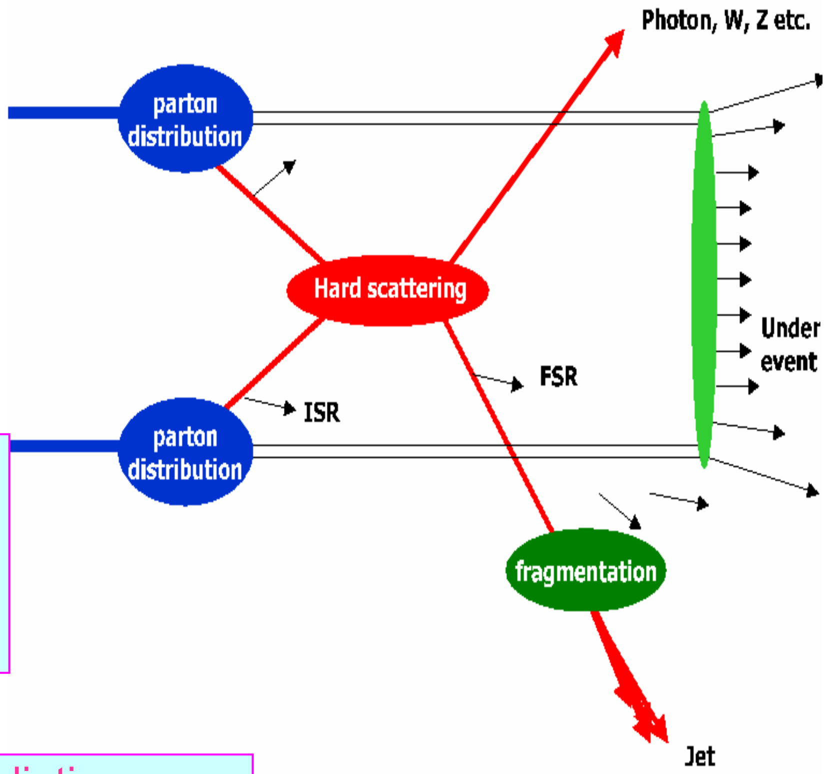
  - ➔ W + jets production
  - ➔ W/Z + b
  - ➔ Diphotons

ME + PS
hard radiation
fragmentation to HF
resummation

  - ➔ Dijet decorrelations
  - ➔ Jet shapes
  - ➔ Underlying event studies

soft radiation
multiple parton scattering
life at high luminosities…

- Summary



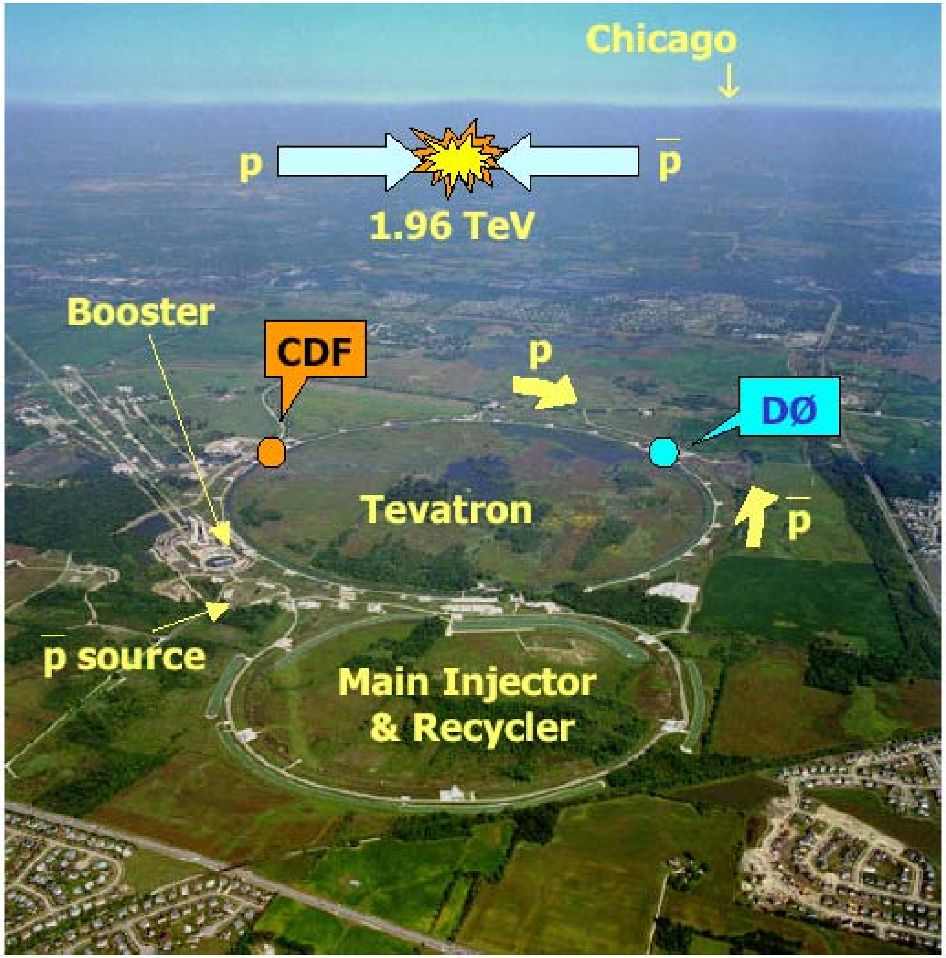
Not covered: B production, diffraction…
strong efforts exist at both CDF and DØ

The Fermilab Tevatron Collider

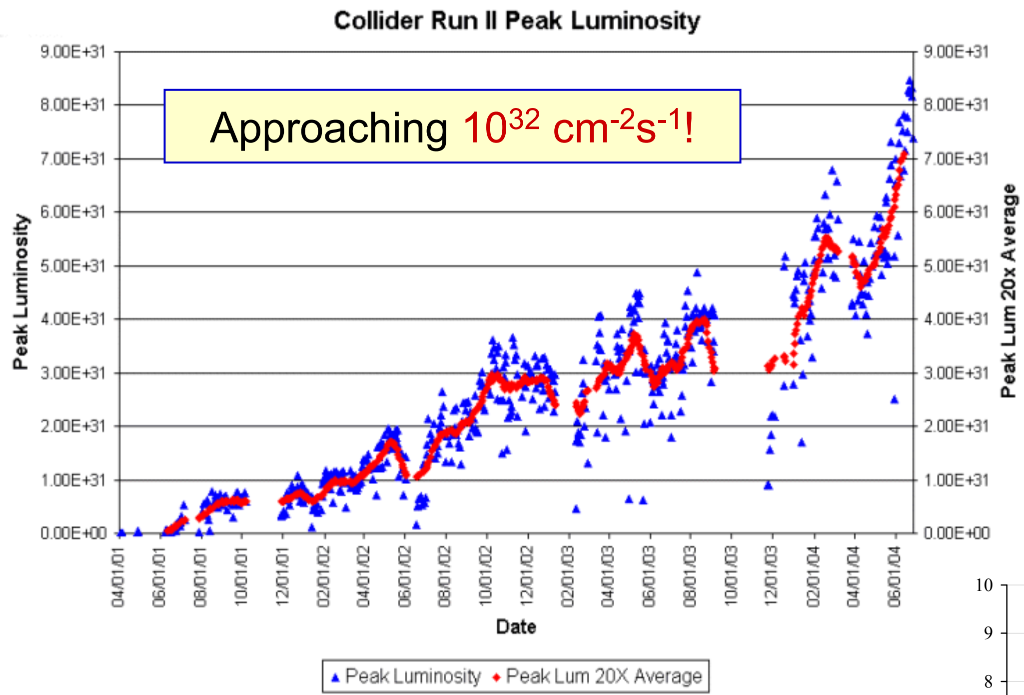
- The Tevatron is:
  - ➔ the highest-energy collider till LHC

$$\sqrt{s} = 1.96 \text{ TeV in Run II}$$
$$(1.8 \text{ TeV Run I})$$

- Increasing luminosity:
  - ➔ Run I (1992-95) ~0.1 fb^{-1}
  - ➔ Run IIa (2001~2005) ~1 fb^{-1}
  - ➔ Run IIb (2006-2009) ~4-8 fb^{-1}
- Studies of QCD at highest Q^2
  - ➔ Precision tests of pQCD
  - ➔ Phenomenological models for "soft" aspects of QCD
  - ➔ Tuning of Monte Carlo generators
  - ➔ Probing for new physics
  - ➔ Understanding backgrounds to many processes of interest

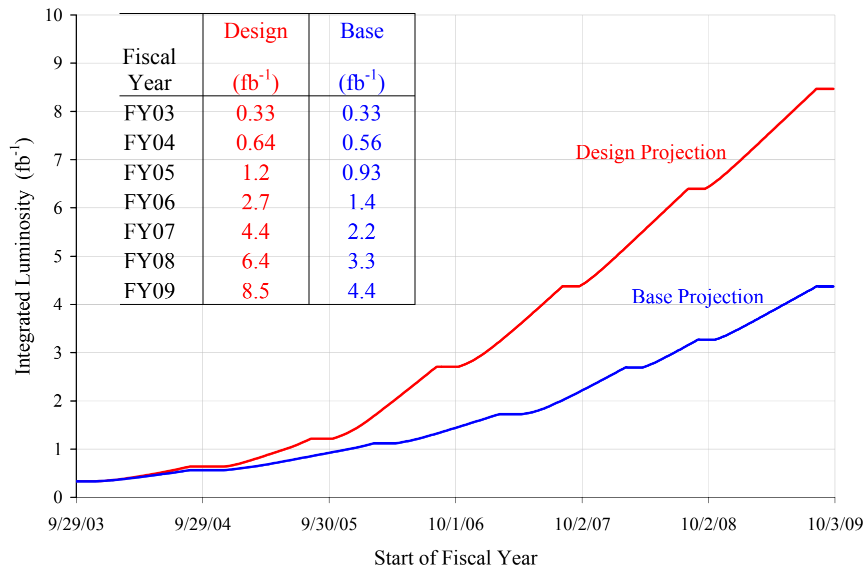


Tevatron Luminosity: Current and Future



- Tevatron has operated well in 2004
- Already have >400 pb^{-1} of data on tape per experiment
  - Recent data taking rate ~10 pb^{-1} per week
  - Data taking efficiency 80-90%

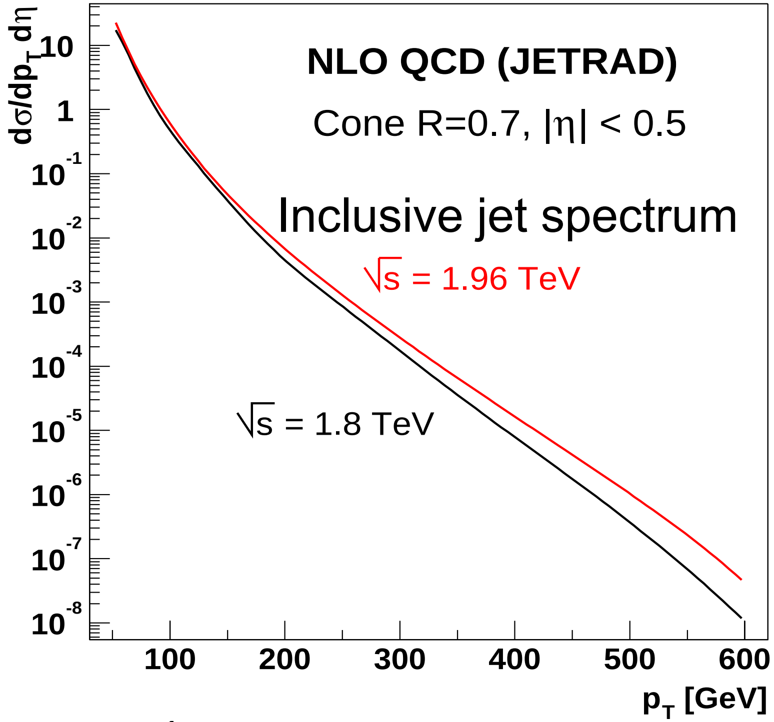
- Most results presented today are from first 130-210 pb^{-1}
- Much more to come by the time of LHC

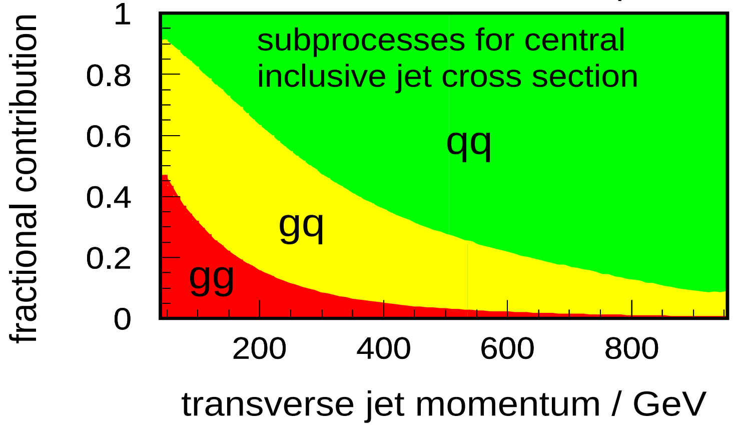


Fiscal Year	Design (fb^{-1})	Base (fb^{-1})
FY03	0.33	0.33
FY04	0.64	0.56
FY05	1.2	0.93
FY06	2.7	1.4
FY07	4.4	2.2
FY08	6.4	3.3
FY09	8.5	4.4

Jet Physics at Tevatron

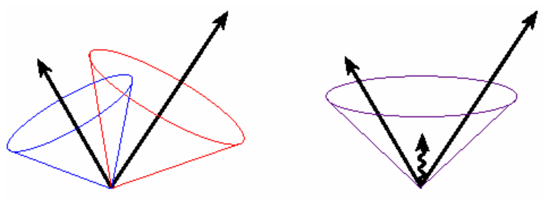
- At √s=1.96 TeV, cross section ~5x larger compared to Run I for jets with p_T > 600 GeV
  - ➔ A jet factory…
- Higher statistics important for:
  - ➔ better determination of proton structure at large x
  - ➔ testing pQCD at a new level (resummation, NNLO theory, NLO event generators)
  - ➔ continued searches for new physics while testing distances ~10^{-19} m
    - ❖ compositeness, W', Z', extra dimensions etc…
- New algorithms:
  - ➔ midpoints
  - ➔ massive jets, using jet p_T



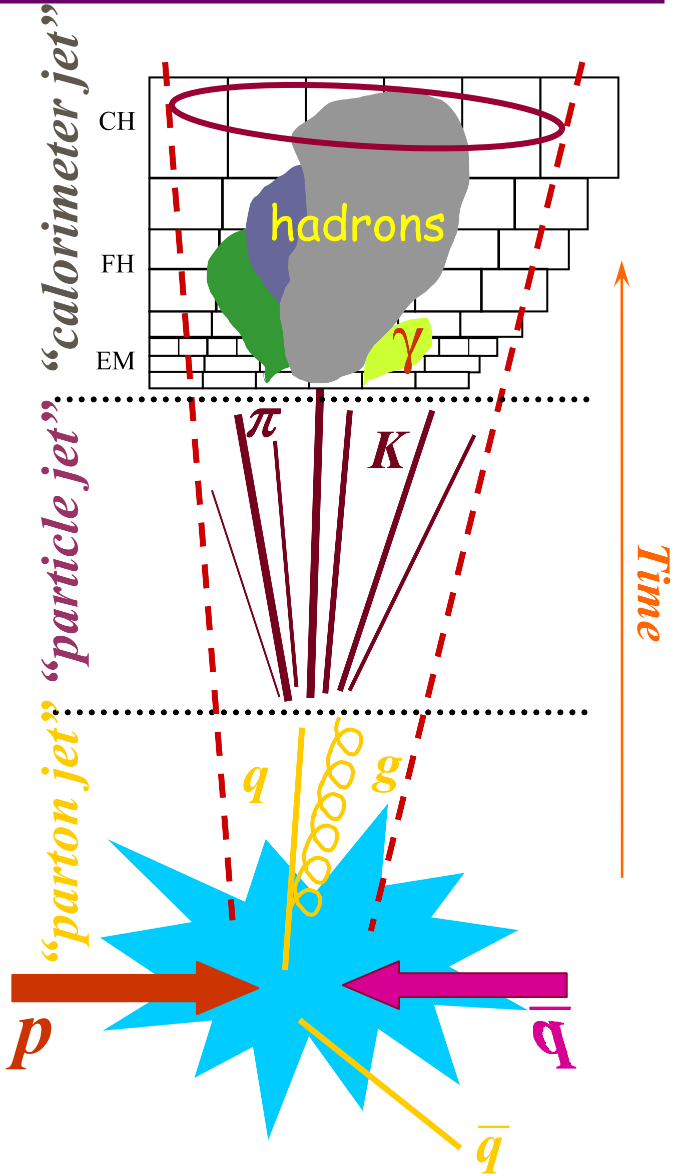


Jet Definitions in Run II

- Run I cone algorithm:
  - ➔ Add up towers around a “seed”
  - ➔ Iterate until stable
  - ➔ Jet quantities: E_T, η, ϕ
- Modifications for Run II:
  - ➔ Use 4-vector scheme, p_T instead of E_T
  - ➔ Add midpoints of jets as additional starting seeds
  - ➔ Infrared safe

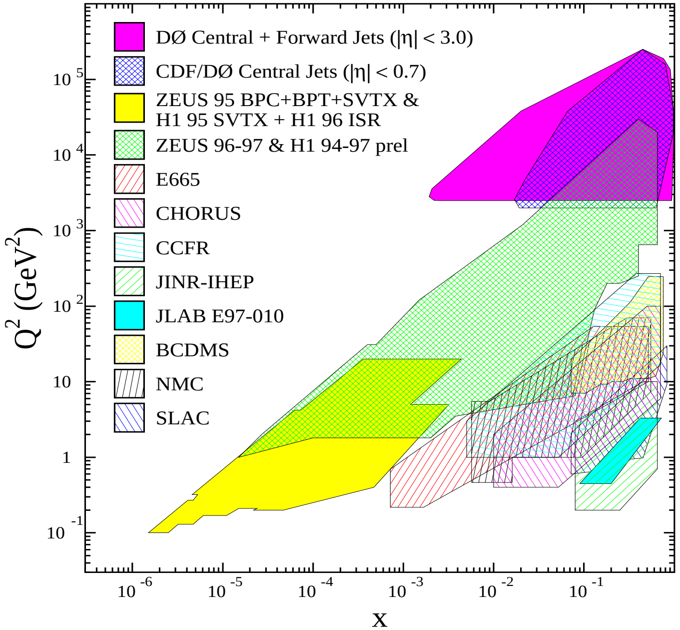


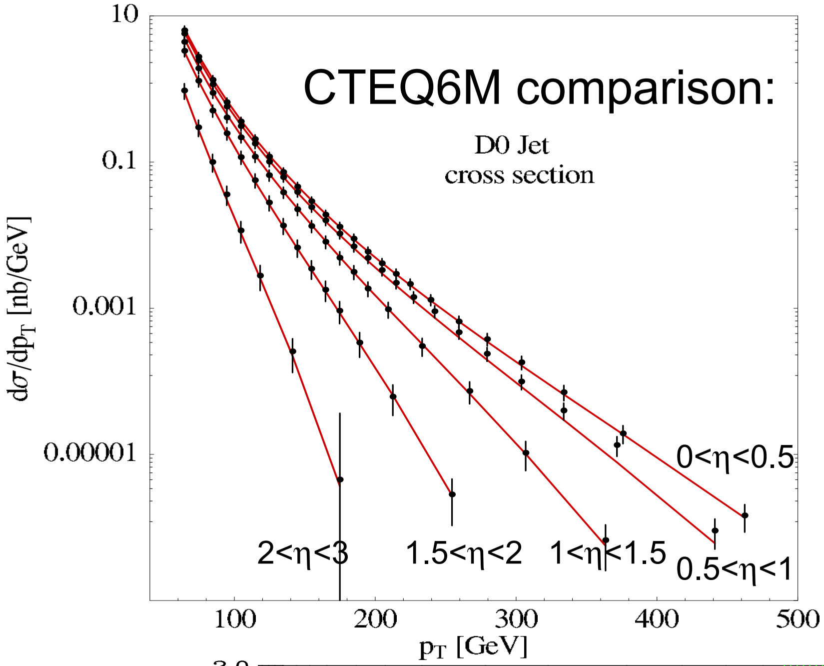
- Correct to particles
  - ➔ Underlying event, previous/extra _interactions, energy loss out of cone due to showering in the calorimeter, detector response, resolution
- CDF using the Run I JETCLU algorithm for some results, in the process of switching to midpoint
- kT algorithm also used – see later



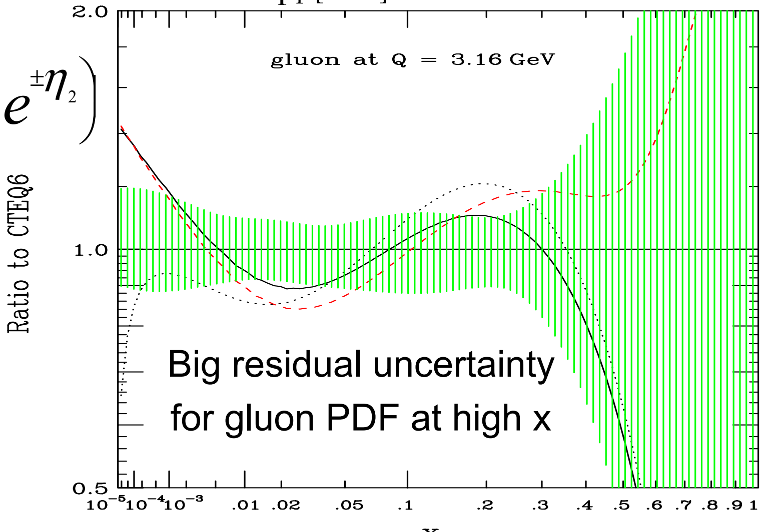
x-Q^2 Reach in Run I

- DØ's most complete jet cross section measurement in Run I
  - ➔ covers |η| < 3.0
  - ➔ complements HERA x-Q^2 range



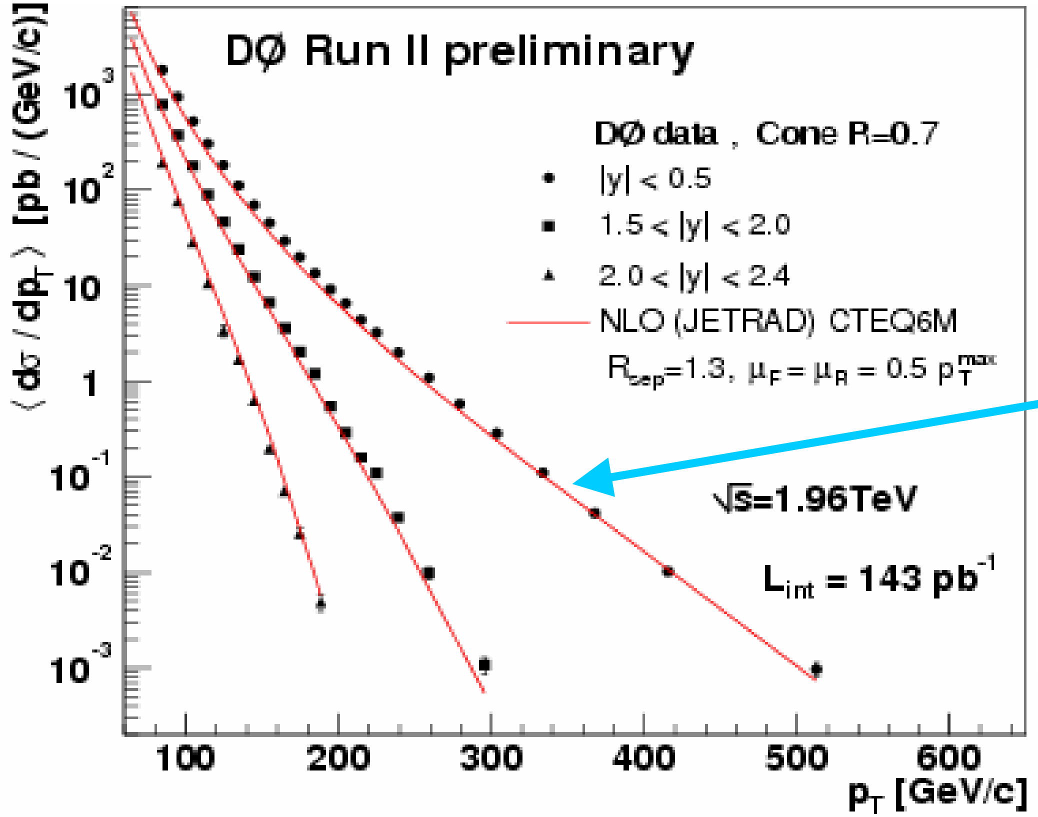


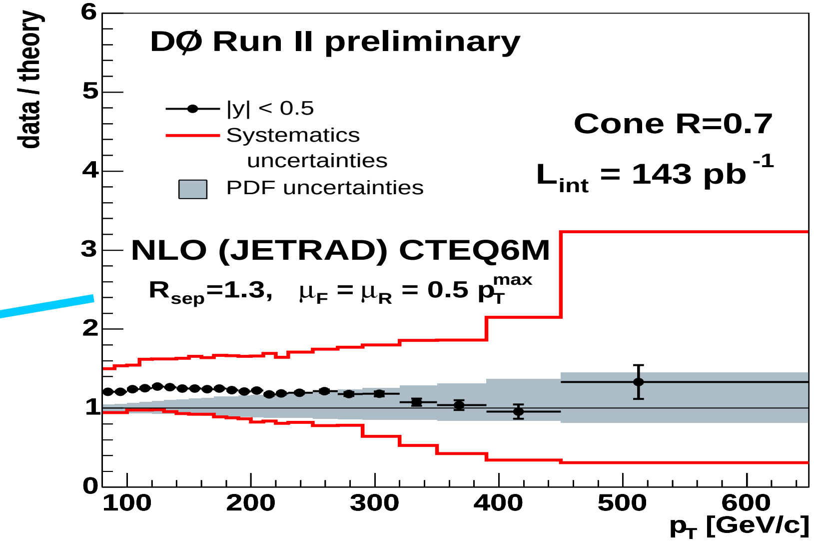
$$x_{1,2} = \frac{E_T}{\sqrt{s}} \cdot \left(e^{\pm\eta_1} + e^{\pm\eta_2}\right)$$



- Used in CTEQ6 and MRST2001 fits to determine gluon at large x
  - ➔ Enhanced gluon at large x compared to previous fits

Inclusive Jet Cross Section: Run II Midpoint

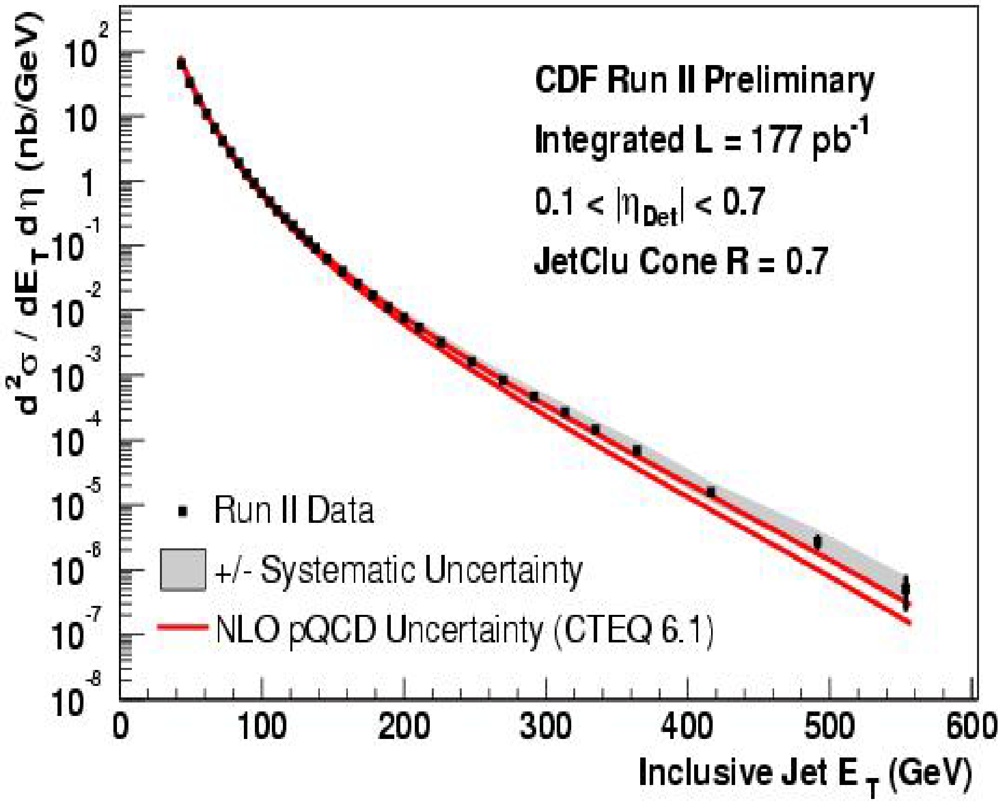


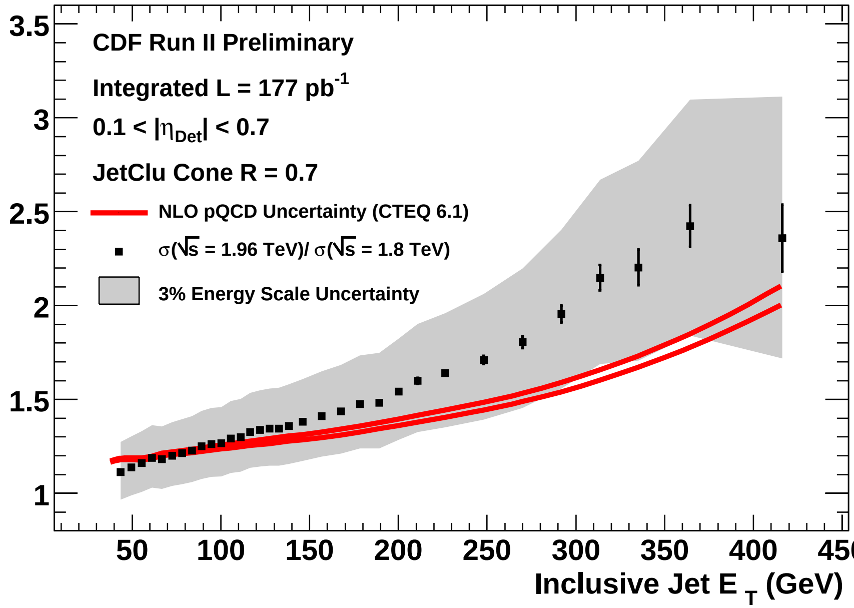


- First corrected Run II cross section for forward jets
- Important PDF information in cross section vs. rapidity
- Good agreement between data and theory
- Large uncertainties due to jet energy scale
  - ➔ Big improvements already on the way

Central Inclusive Jet Cross Section: JETCLU

- Run I reach extended by 150 GeV
- Data agree with NLO prediction within errors (Run I JETCLU used)
  - Need to be corrected for hadronization/underlying event
  - Watch the high p_T-tail…

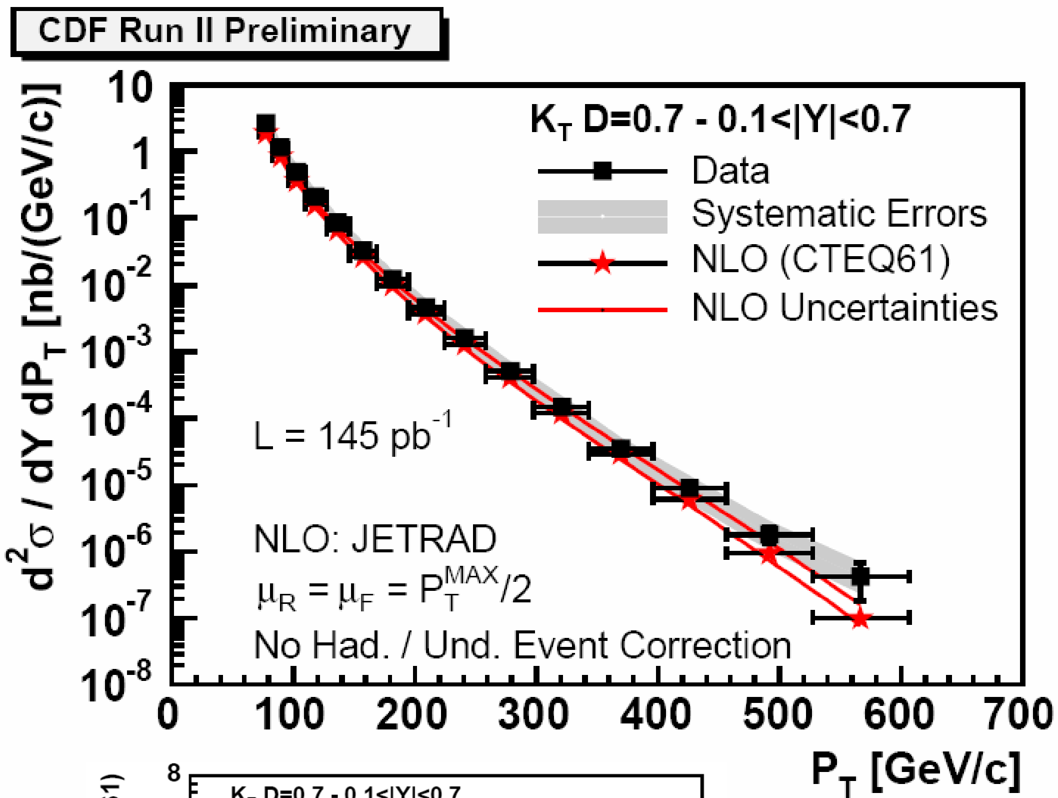


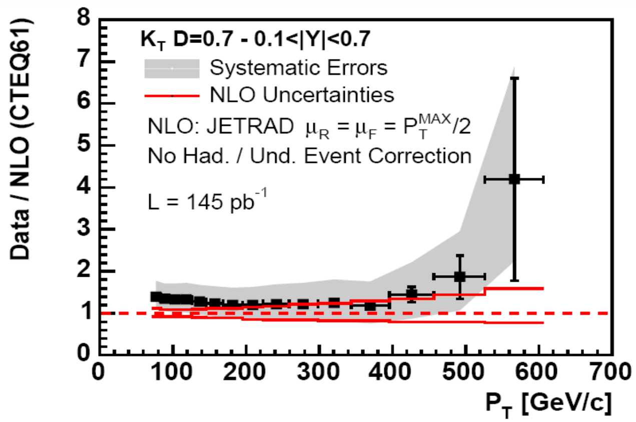


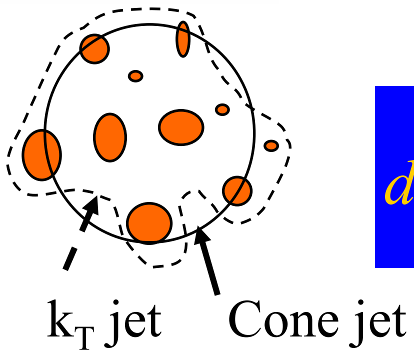
Run II/Run I

- Rapidity-dependent measurement in the works

Central Inclusive Jet Cross Section: kT





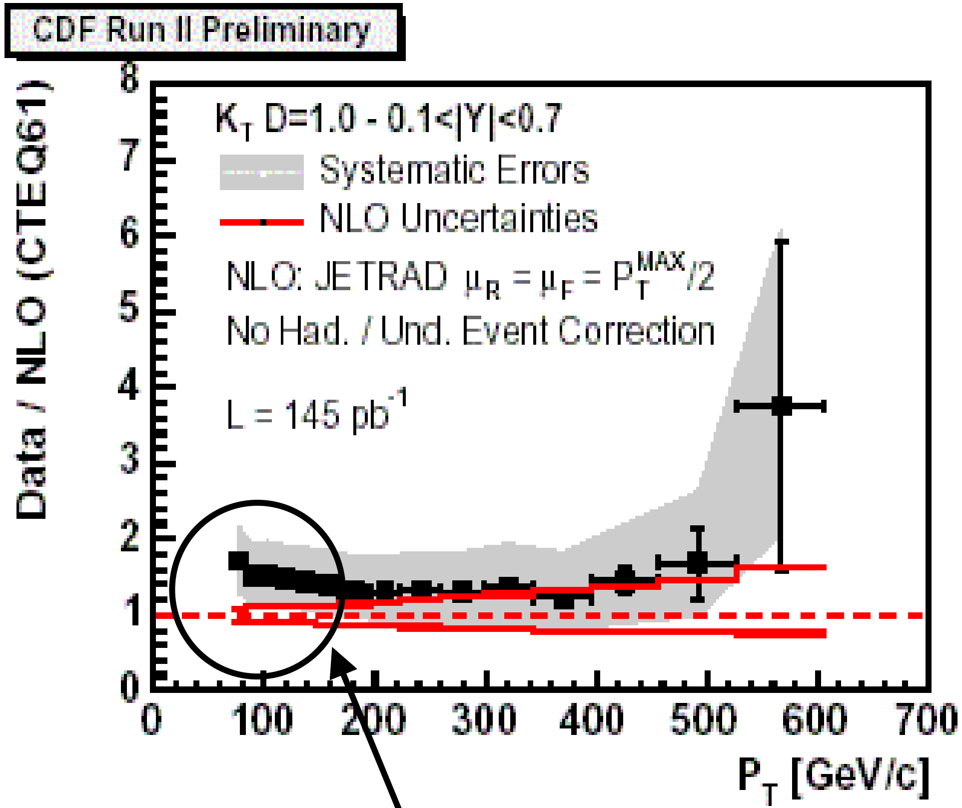


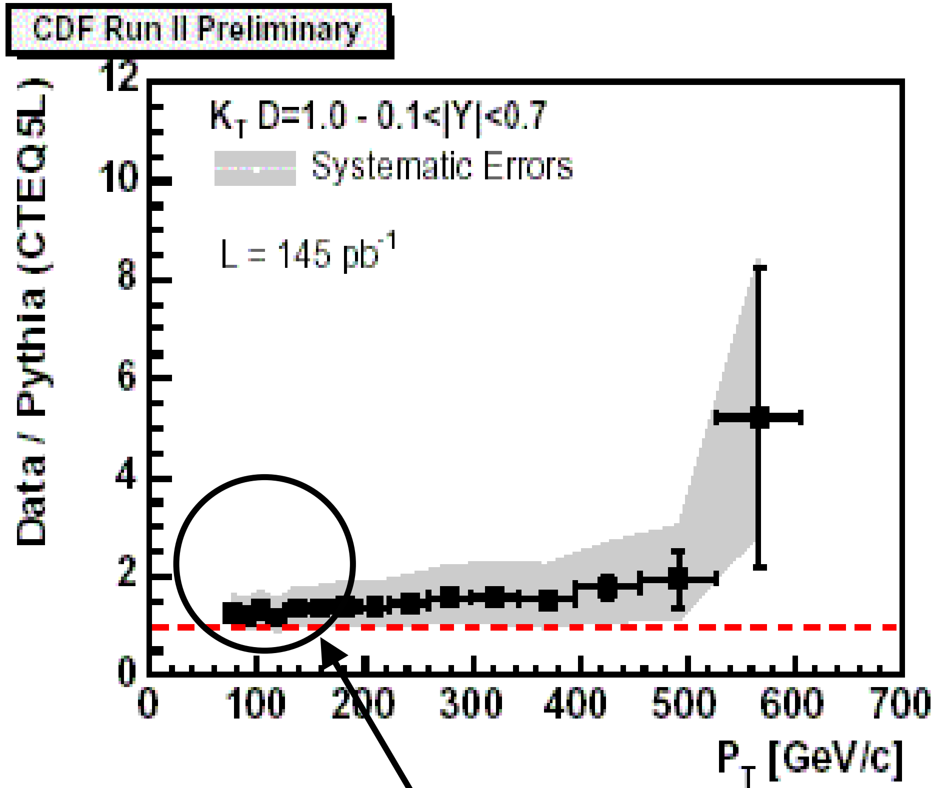
- Inclusive Jet Cross Section using kT algorithm
  - ➔ Uses relative momentum of particles
  - ➔ No split/merge ambiguities
  - ➔ Infrared and collinear safe
- Reasonable agreement between theory and data
  - ➔ NLO still needs to be corrected for hadronization and Underlying Event

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

D = Jet Size Parameter

kT-Jet Cross Section – Sensitive to UE?



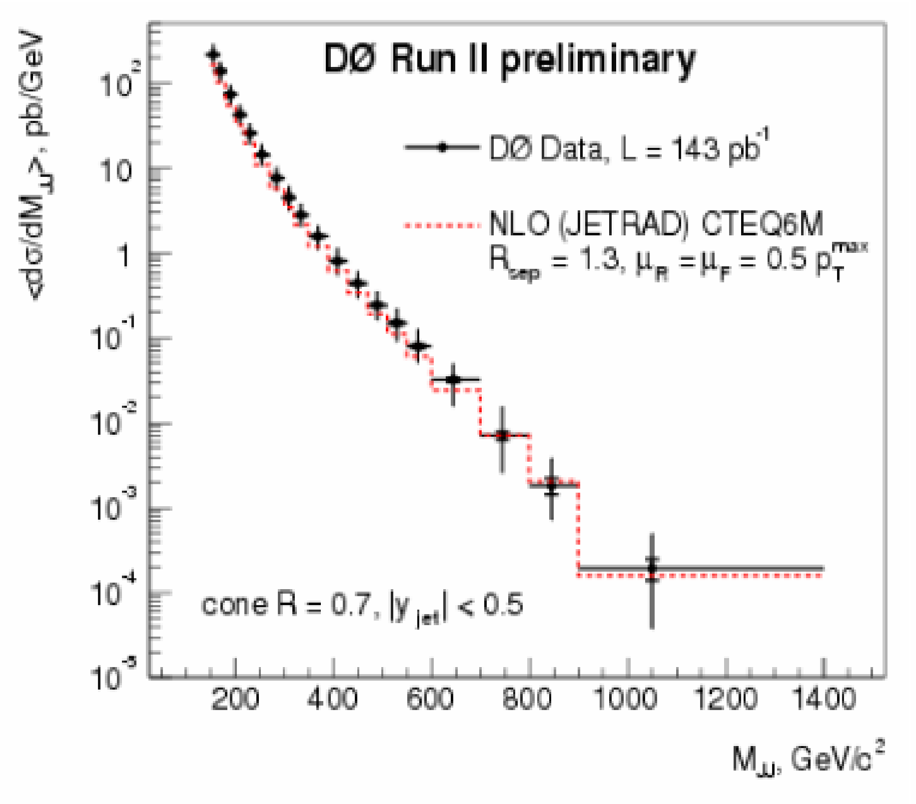


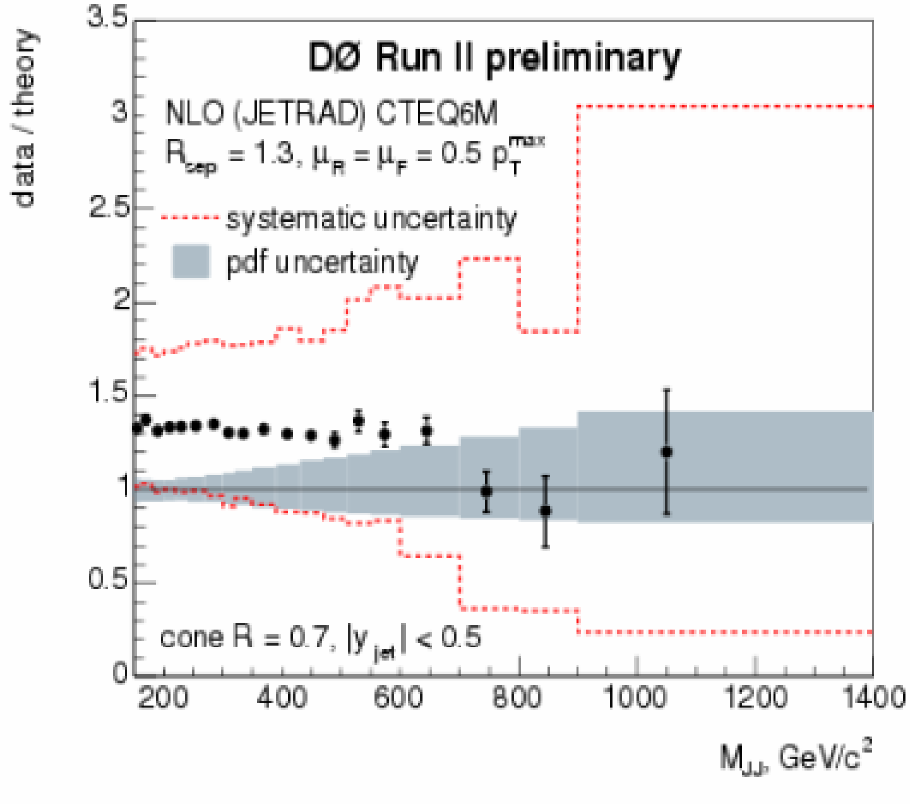
D = 1.0

Effect increases with increasing D
Picking up Underlying Event?
Not well modeled by NLO pQCD

Pythia tuned to CDF Run I data
(Pythia Tune A – see later)
Good modeling of UE important

Dijet Production

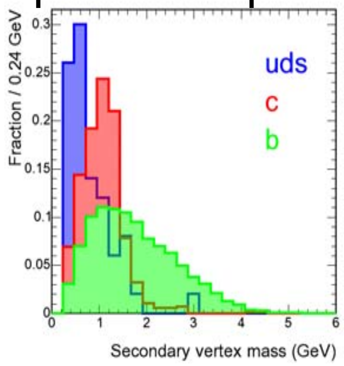




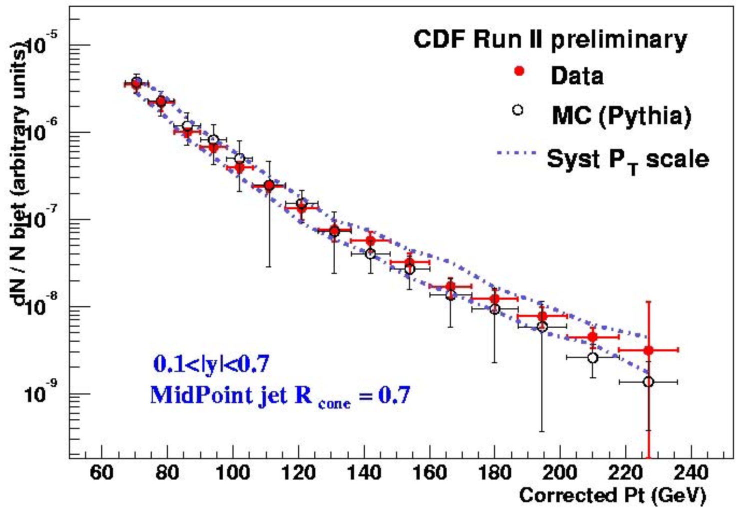
- Central region $|y_{jet}| < 0.5$, data sample ~143 pb^{-1}
- Run II midpoint algorithm
- Agrees within uncertainties with NLO/CTEQ6M
- Jet Energy Scale (<7%) -- dominant error on the measurement

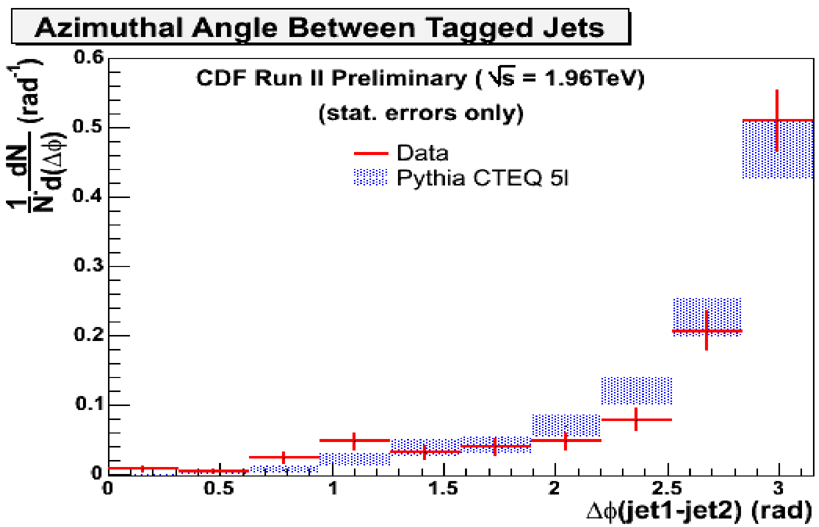
b-Jet and b$\underline{b}$ Dijet Production

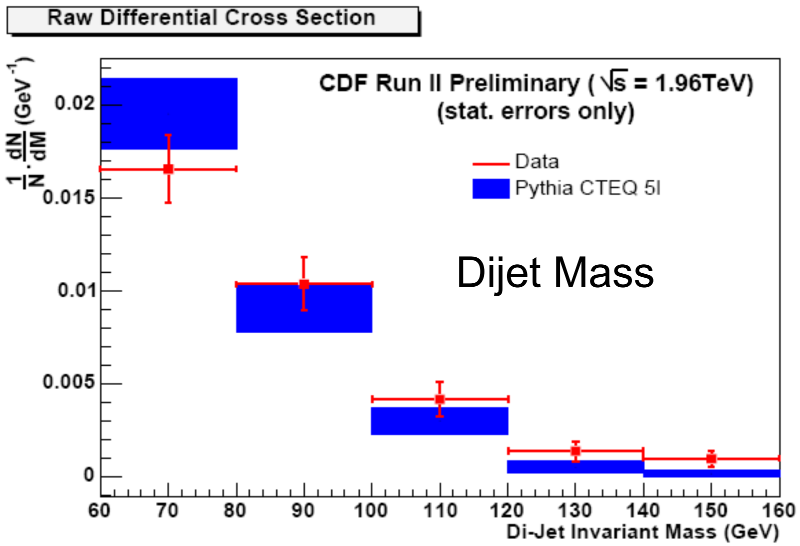
- Test heavy-flavor production in QCD
  - ➔ Probe HF content of protons, g→b$\underline{b}$ splitting, flavor creation (back-to-back)
  - ➔ New Physics may show up as "bumps" in b$\underline{b}$ mass spectrum
- 1 or 2 central tagged jets
  - ➔ Fit mass distribution in the secondary vertex to b, c, uds templates
- Ongoing work, expect more to come



Inclusive b-jet spectrum, 150 pb^{-1}

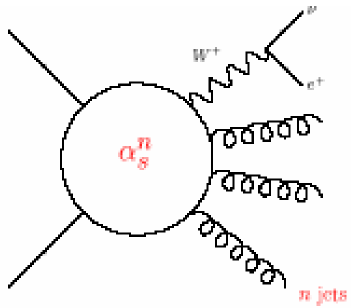




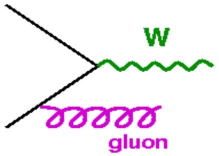


Electro-Weak Bosons + Jets

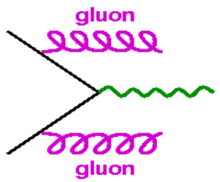
- A good testing ground for QCD
  - ➔ W/Z+n jets ~α_s^n in lowest order
  - ➔ Perturbation theory should be reliable
    - ❖ heavy boson ↔ large scale



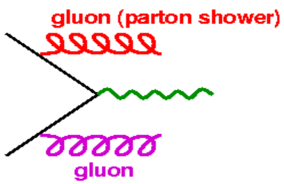
  - ➔ NLO calculations available for up to 2 jets



- W+jets, Z+jets
  - ➔ Important backgrounds for other physics channels
    - ❖ Top, Higgs,…



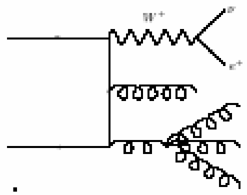
- $\gamma\gamma$, γ+jet, W/Z p_T
  - ➔ Testing resummation techniques
  - ➔ Background to Higgs→$\gamma\gamma$ discovery channel at LHC

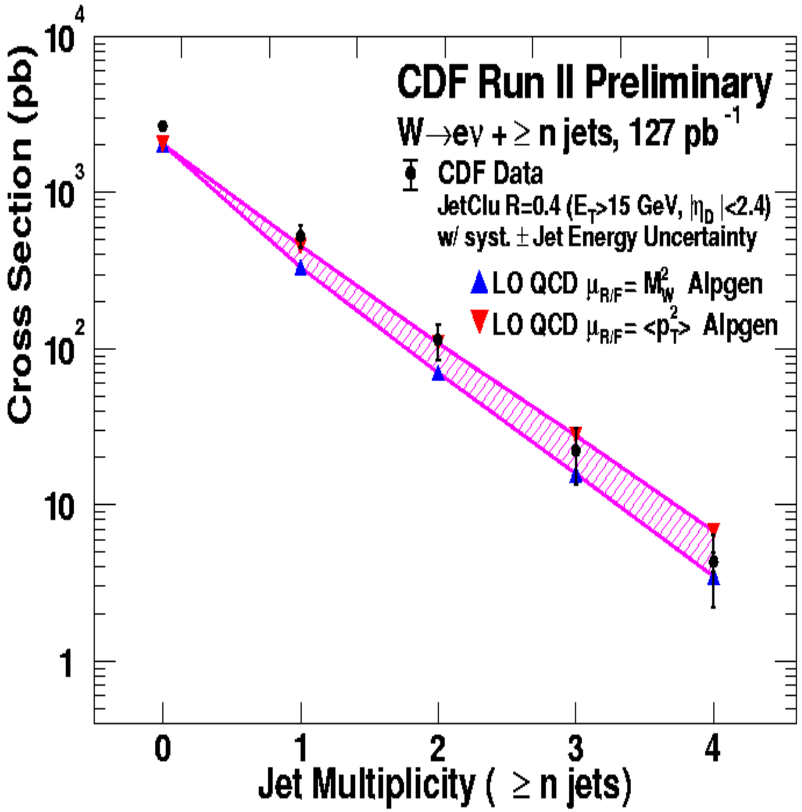


- Testing ground for Monte Carlo tools required for precision measurements and searches for new physics
  - ➔ Multi-parton generators
    - ❖ Alpgen, MadGraph,…
  - ➔ NLO generators
    - ❖ MCFM, MC@NLO,...
  - ➔ Combining Parton-Shower and Matrix Element techniques to avoid “double counting”
    - ❖ MLM, CKKW,… prescriptions
  - ➔ Tuning of ISR/FSR/MPI and soft Underlying Event important for comparisons to data
- All these aspects are being exercised/studied at the Tevatron, will benefit LHC physics

W + n Jets Cross Section vs n

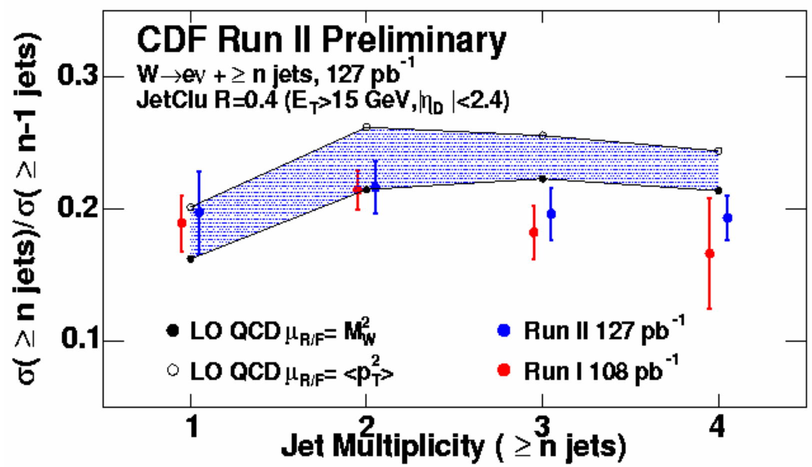
- Test of QCD predictions at large $Q^2 \sim M_W^2$
  - ➔ fundamental channel for Top/Higgs/SUSY serches
  - ➔ Compared to LO Alpgen + Herwig + detector simulation
- One energetic and isolated electron + high E_T jets
- Backgrounds: Top dominates for 4-jet bin, QCD contributes to all jet bins





Systematic uncertainty (10% in σ_1 to 40% in σ_4) limits the measurement sensitivity

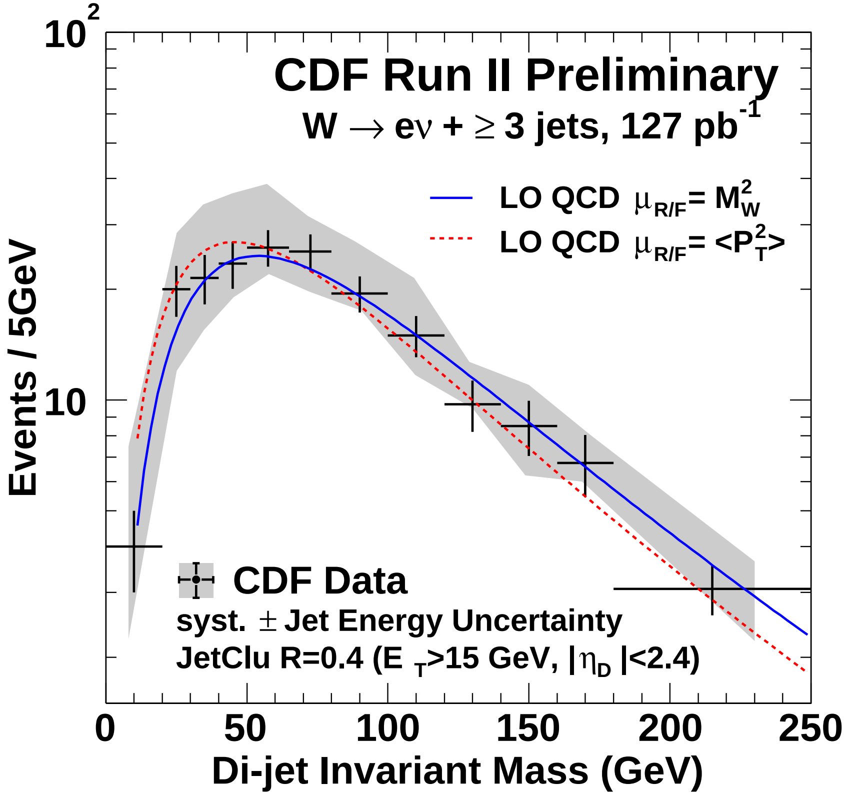
Results agree with LO QCD predictions within uncertainties

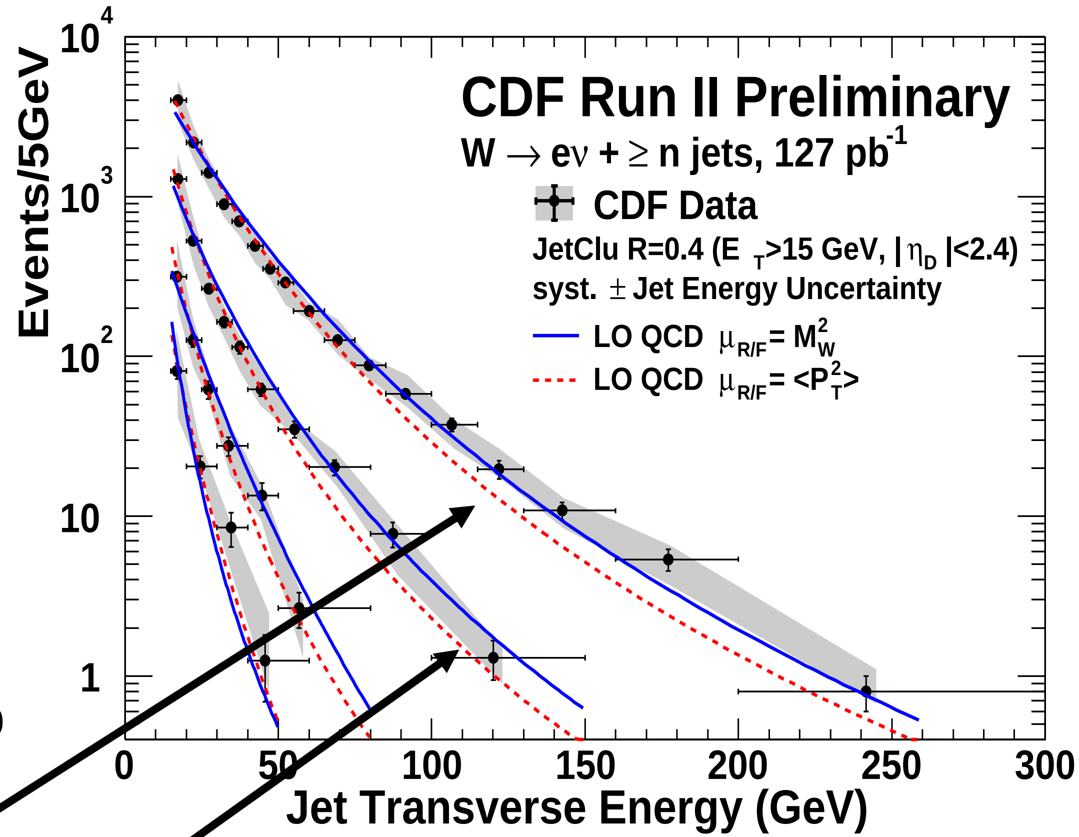


The ratio $R_{n/(n-1)}$ measures the decrease in the cross section with the addition of one jet.
It depends on α_s

W + Jets Cross Section: Kinematics

- Reasonable agreement of E_T and mass spectra with Alpgen + Herwig
  - ➔ Sensitivity to variation of renormalization scale

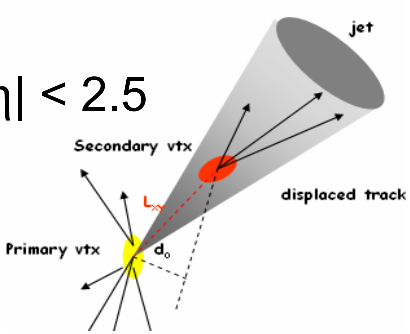




Highest E_T jet in W + ≥1 jet
Second highest E_T jet in W + ≥2 jet, etc…

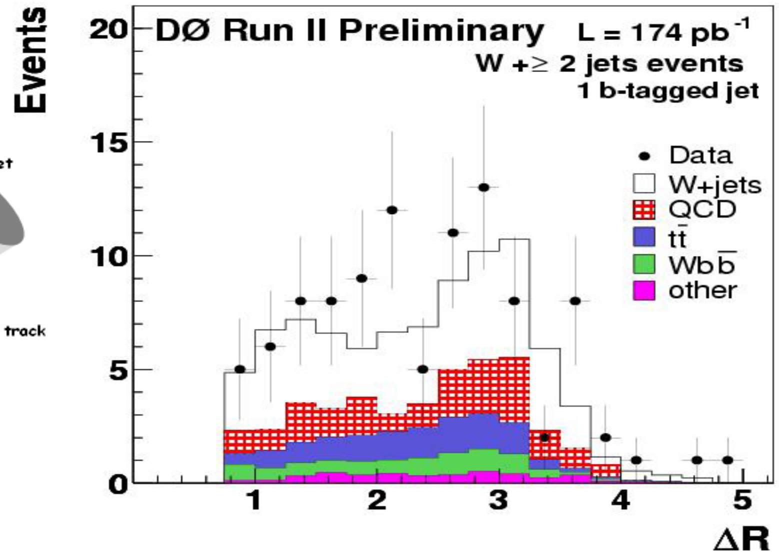
W + 2 Jets with b-tagging

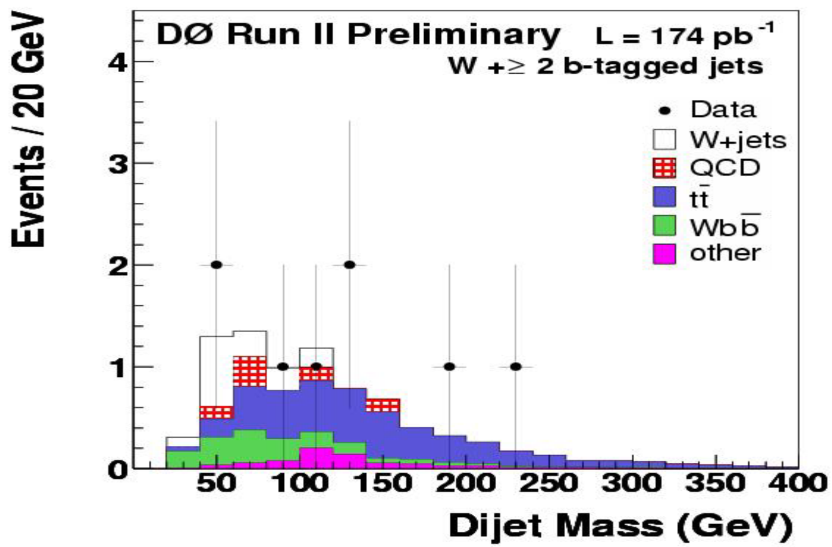
- Data sample requires
  - ➔ a central electron with p_T > 20 GeV
  - ➔ Missing E_T > 25 GeV
  - ➔ 2 jets: p_T > 20 GeV, $|\eta|$ < 2.5
  - ➔ b-tagging based on impact parameter information



- Consistent with Alpgen + Pythia
  - ➔ Several processes contribute
  - ➔ Mass and ΔR distributions are sensitive to parton radiation process
    - ❖ ΔR is a measure of jet-jet distance in $\eta - \phi$ space
- Towards the measurement of Wb$\bar{b}$ cross section and Higgs searches!

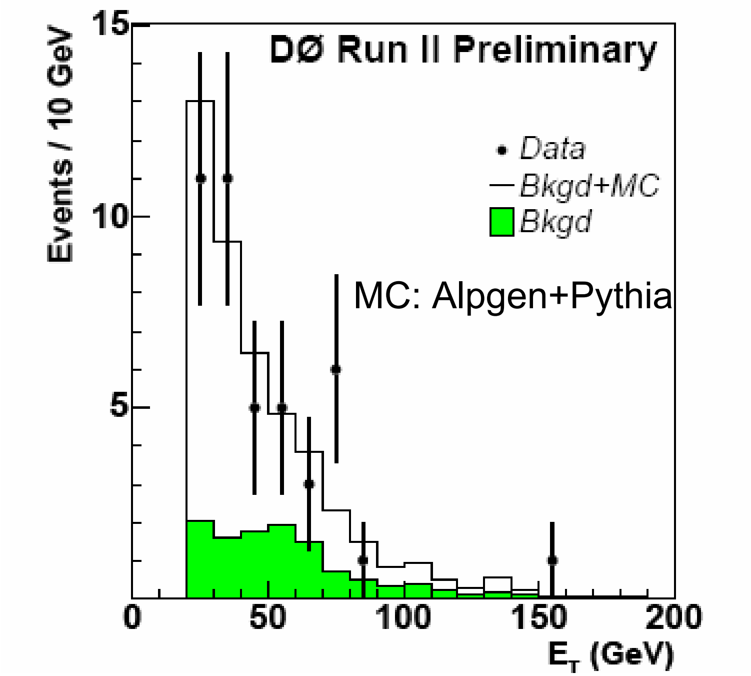
MC: Alpgen+Pythia

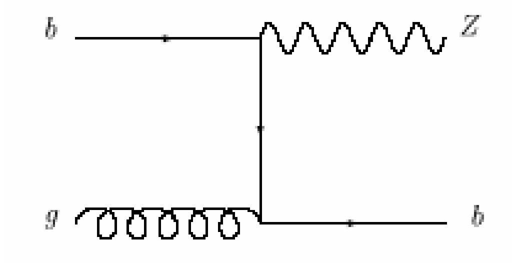




Z + b Production

- Z+b signal observed at DØ
  - ➔ Main background to search for associated HZ production
- Data 152 ($\mu\mu$), 184 (ee) pb^{-1} :
  - ➔ p_{Tjet}>20 GeV, $|\eta|$<2.5
  - ➔ Secondary vertex tag
- Ratio (Z+b)/(Z+j)=0.024±0.007 consistent with NLO calculation



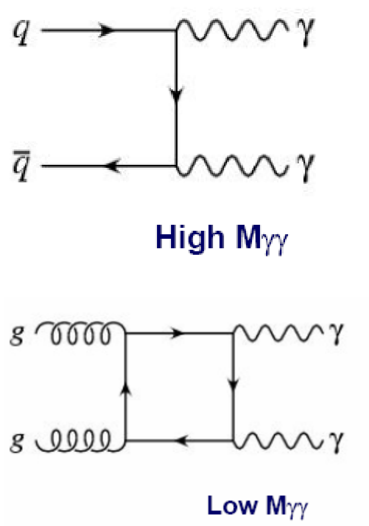


Campbell et al.
p_{Tjet} > 15 GeV

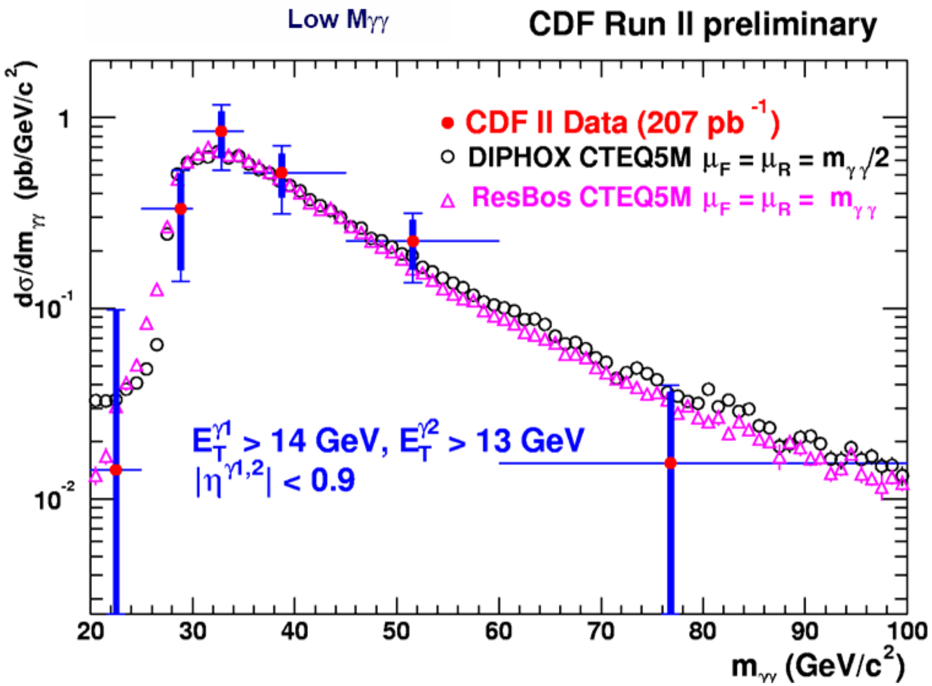
44% at Tevatron
83% at LHC

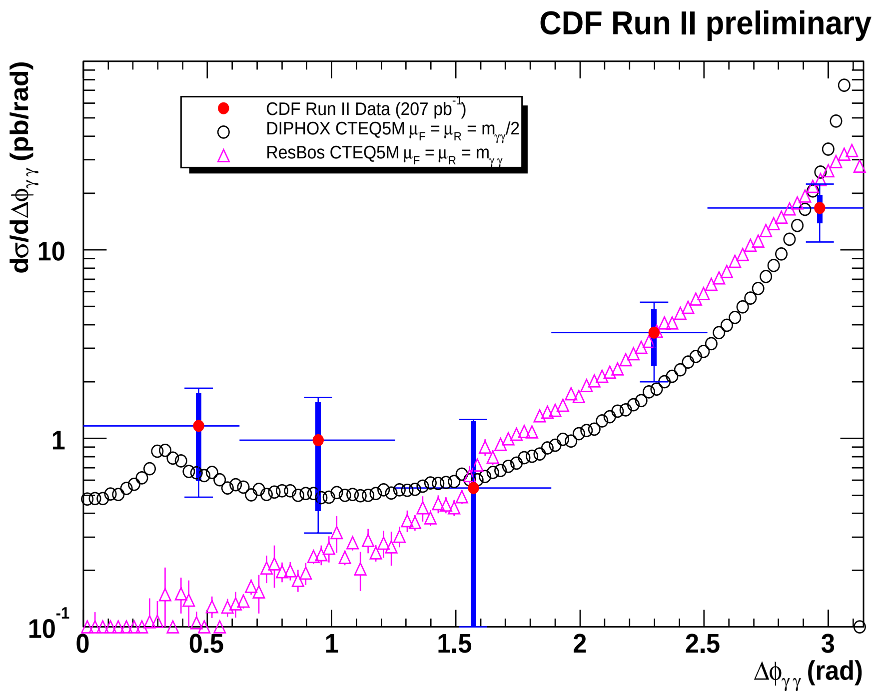
- Clean measurement of b-pdf at LHC?
  Useful for
  - ➔ Single top: qb→qtW
  - ➔ Single top: gb→tW
  - ➔ (charged) Higgs+b: gb→Hb, H^-t
  - ➔ Inclusive Higgs: bb→H

Diphoton Production



- Testing NLO pQCD and resummation methods
- Signature of interesting physics
  - ➔ One of main Higgs discovery channels at LHC
  - ➔ Possible signature of GMSB SUSY
- Data: 2 isolated γs in central region, $E_{T1,2}$ > 13, 14 GeV
- General agreement with NLO predictions, except
  - ➔ Low mass and high ΔΦ in DIPHOX (no resummation)
  - ➔ Low ΔΦ in RESBOS (resummation helps at large ΔΦ)
  - ➔ LO Pythia low by a factor ~2.2, but reasonable mass shape

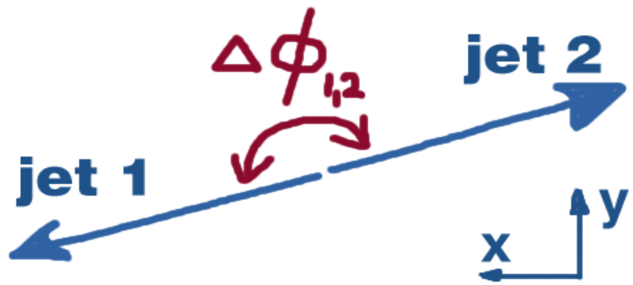




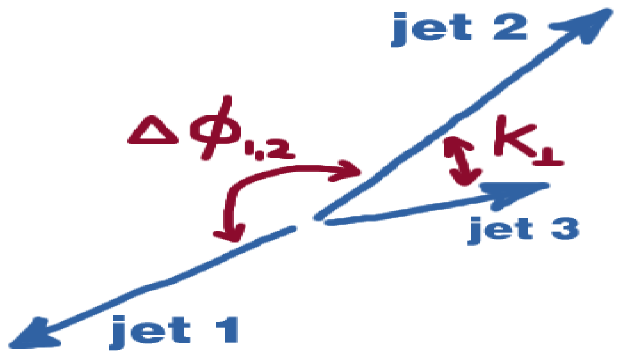
Dijets: Azimuthal Decorrelations

- In 2→2 scattering, partons emerge back-to-back ➞ additional radiation introduces decorrelation in ΔΦ between the two leading partons/jets
  - ➔ Soft radiation: ΔΦ ~ π
  - ➔ Hard radiation: ΔΦ < π
- ΔΦ distribution is directly sensitive to higher-order QCD radiation
- Testing fixed-order pQCD and parton-shower models across ΔΦ:
  - ➔ ΔΦ~π:
    - ❖ Fixed-Order calculations unstable
    - ❖ Parton-Shower Monte Carlo's applicable
  - ➔ 2π/3 < ΔΦ < π:
    - ❖ First non-trivial description by 2→3 tree-level ME
    - ❖ 2→3 NLO ME calculations became available recently (NLOJET++)
  - ➔ ΔΦ < 2π/3 (3-jet "Mercedes")
    - ❖ 2→4 processes and higher

Dijet production in lowest-order pQCD

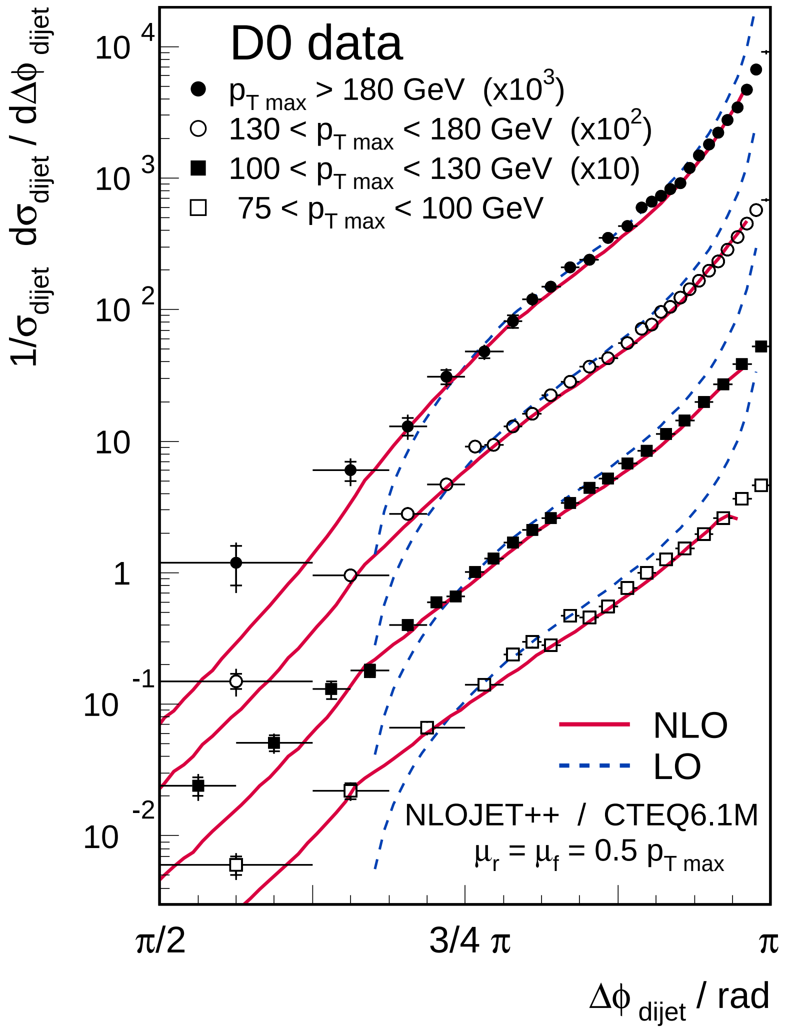


3-jet production in lowest-order pQCD



ΔΦ: Comparison to Fixed-Order pQCD

$$\frac{1}{\sigma_{\text{dijet}}} \cdot \frac{d\sigma_{\text{dijet}}}{d\Delta\Phi}$$

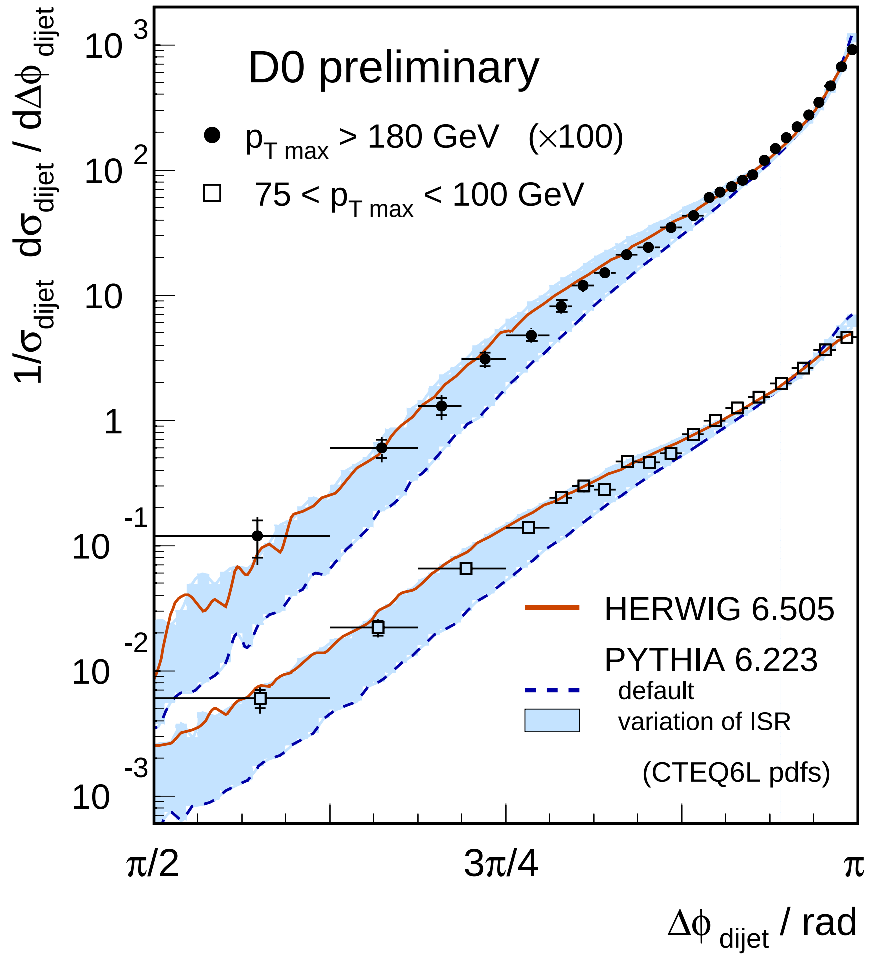


- ΔΦ distribution:
  - ➔ Sensitive to QCD radiation
  - ➔ No need to reconstruct any other jets
  - ➔ Reduced sensitivity to jet energy scale
- Data set ~150 pb^{-1}
  - ➔ Central jets |y| < 0.5
  - ➔ Second-leading p_T > 40 GeV
- Towards larger p_T, ΔΦ spectra more strongly peaked at ~π
  - ➔ Increased correlation in ΔΦ
- Distributions extend into the "4 final-state parton regime", ΔΦ<2π/3

- Leading order (dashed blue curve)
  - ➔ Divergence at ΔΦ = π (need soft processes)
  - ➔ No phase-space at ΔΦ<2π/3 (only three partons)
- Next-to-leading order (red curve)
  - ➔ Good description by NLOJET++ over the whole range, except in extreme ΔΦ regions

ΔΦ: Comparison to Parton-Shower Monte Carlo's

- Testing the radiation process:
  - ➔ 3rd and 4th jets generated by parton showers
- Herwig 6.505 (default)
  - ➔ Good overall description!
  - ➔ Slightly too high in mid-range
- Pythia 6.223 (default)
  - ➔ Very different shape
  - ➔ Too steep dependence
  - ➔ Underestimates low ΔΦ
- ΔΦ distributions are sensitive to the amount of initial-state radiation
  - ➔ Plot shows variation of PARP(67) from 1.0 (current default) to 4.0 (previous default, Tune A)
    - ❖ controls the scale of parton showers
  - ➔ Intermediate value suggested
- More Pythia tuning possible!

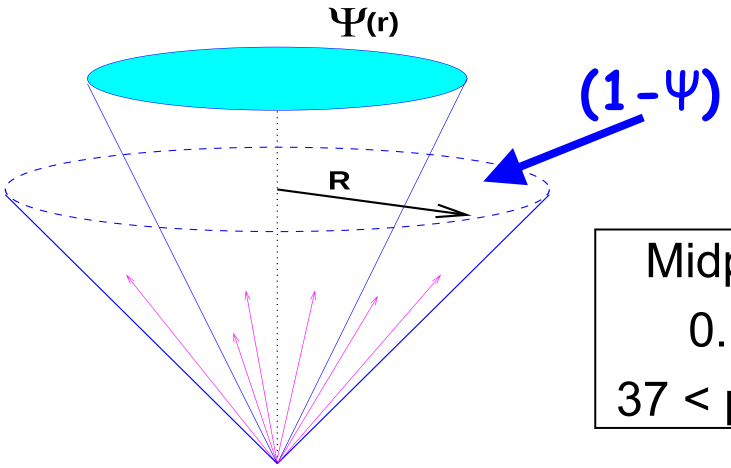


CTEQ6L

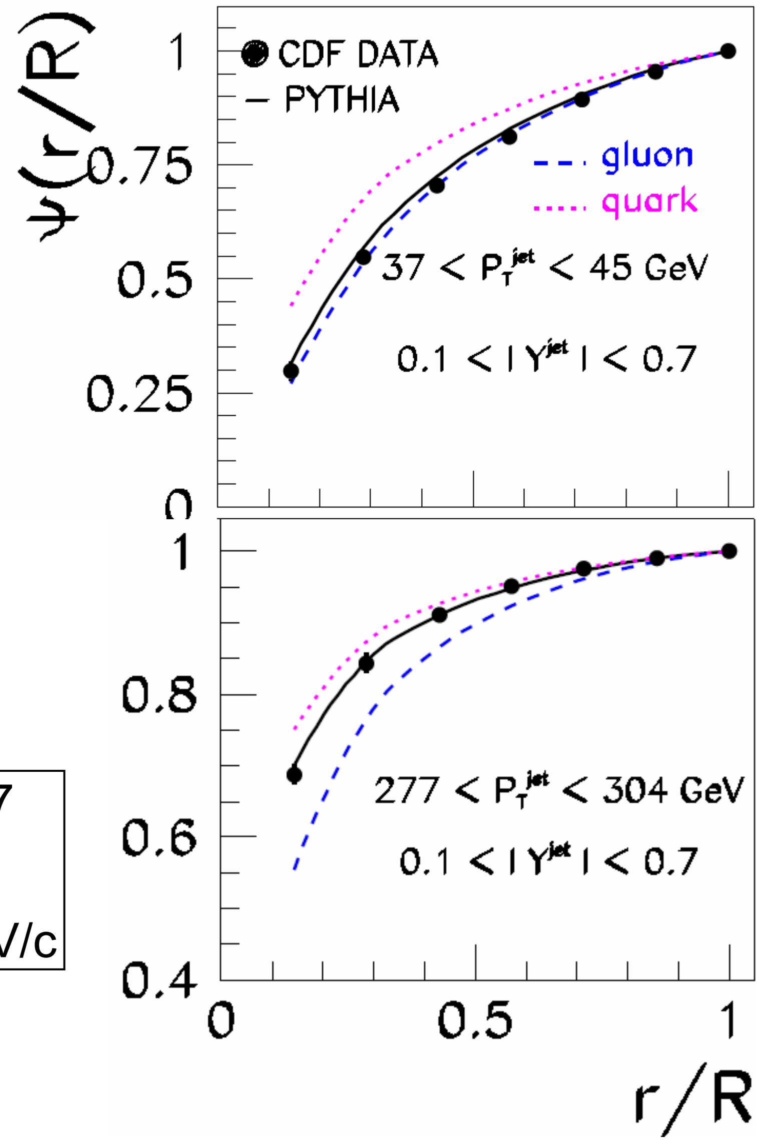
Jet Shapes

- Jet shape: fractional energy flow

  $\Psi(r) = E_T(r) / E_T(R)$
- Governed by multi-gluon emissions from the primary parton
  - ➔ Test of parton-shower model
  - ➔ Sensitive to quark/gluon composition of final state
  - ➔ Sensitive to underlying event



Midpoint: R = 0.7
0.1 < |y| < 0.7
37 < p_T < 380 GeV/c



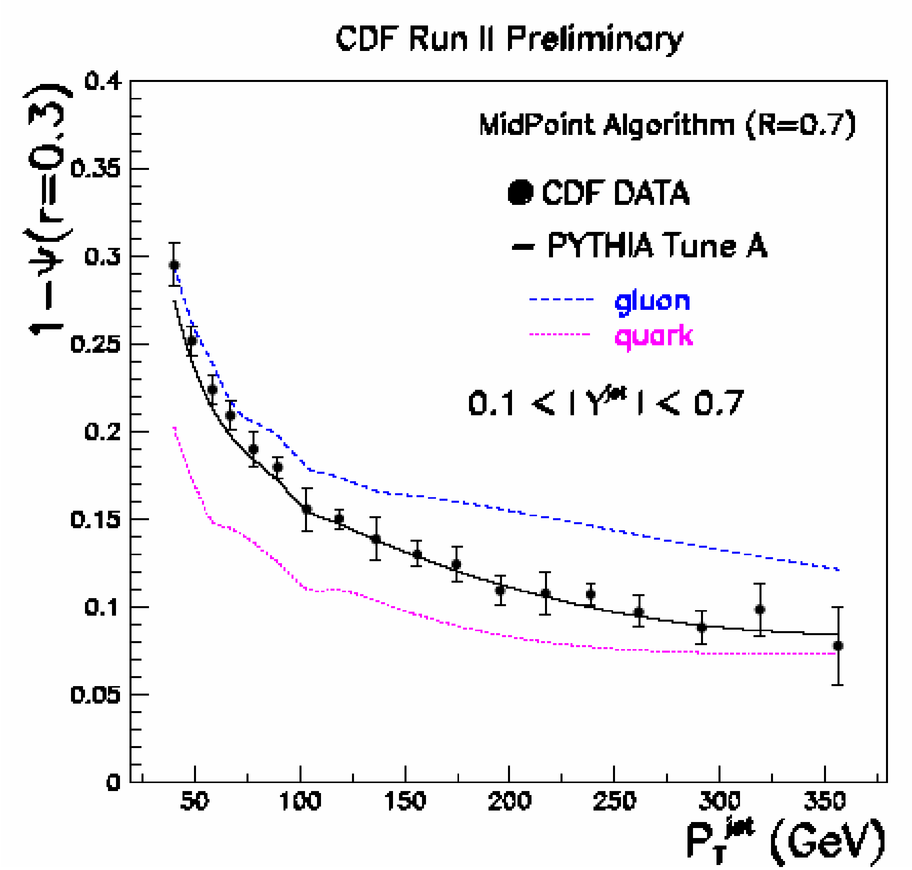
- Shapes are nearly identical for calorimeter towers and charged tracks

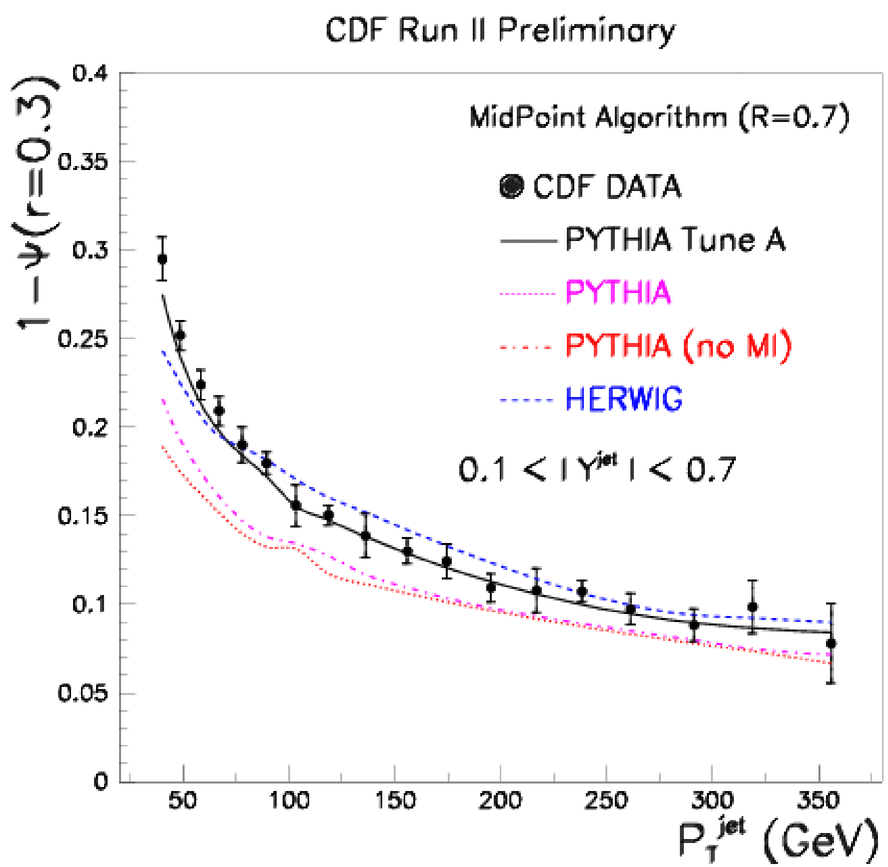
Jet Shapes vs p_T

- p_T fraction in outer part of cone $(0.3 < R < 0.7)$ vs p_T
  - ➔ Jet shapes evolve from gluon to quark dominated profiles

➔ Data well described by Pythia Tune A and Herwig

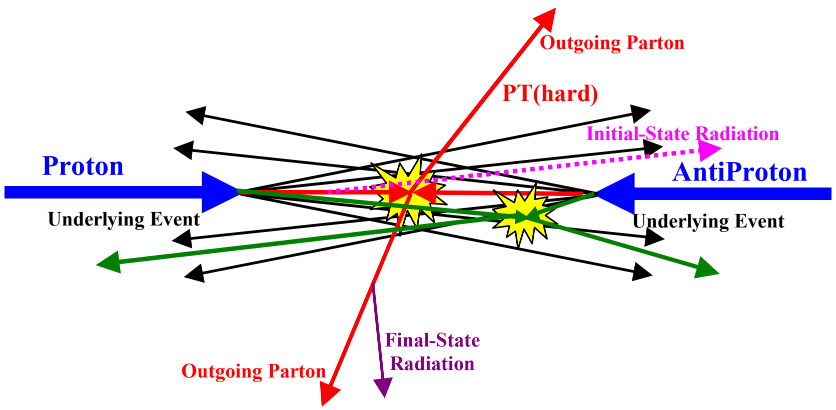
➔ Default Pythia too narrow, especially at low p_T





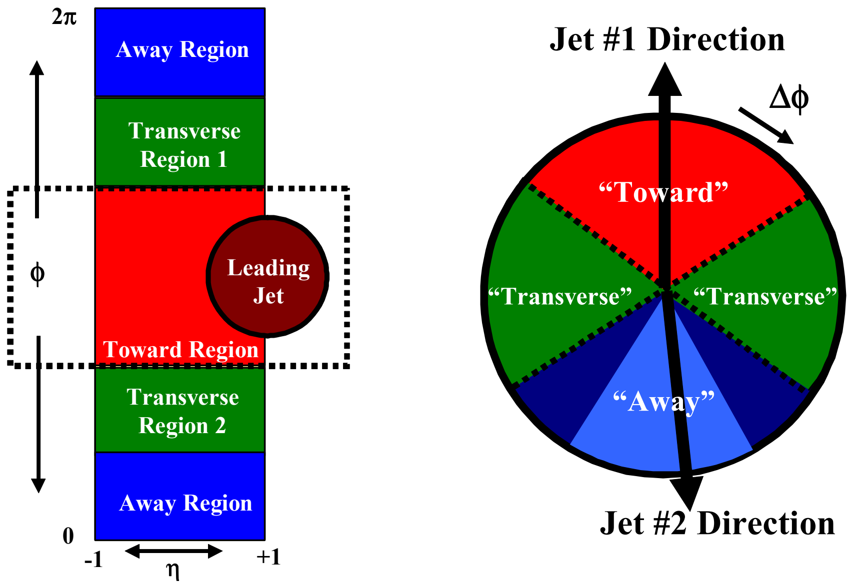
"Soft Aspects": Underlying Event

"hard" parton-parton collision:
- ➡ outgoing jets with large p_T
- ➡ but: everything color-connected



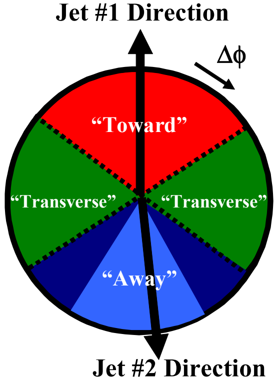
"Underlying Event": everything but the two outgoing hard scattered "jets"
- ➡ NOT the same as Min-Bias
- ➡ Not independent of hard scatter (includes ISR/FSR/MPI)

- UE contributes to hard-scatter processes
  - ➔ Not well understood theoretically
  - ➔ Good modeling essential
- The studies:
  - ➔ Look at charged particle distributions ($p_T > 0.5$ GeV, $|\eta| < 1$) relative to the leading jet ($|\eta| < 2$)
  - ➔ Focus on the region "Transverse" to the jet – high sensitivity to UE

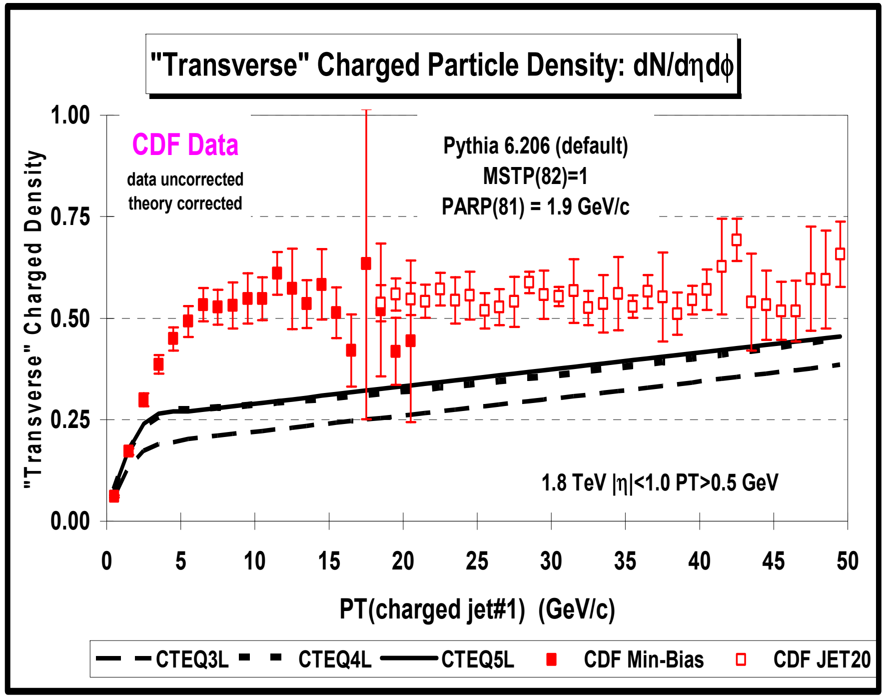


UE: Data vs Monte Carlo

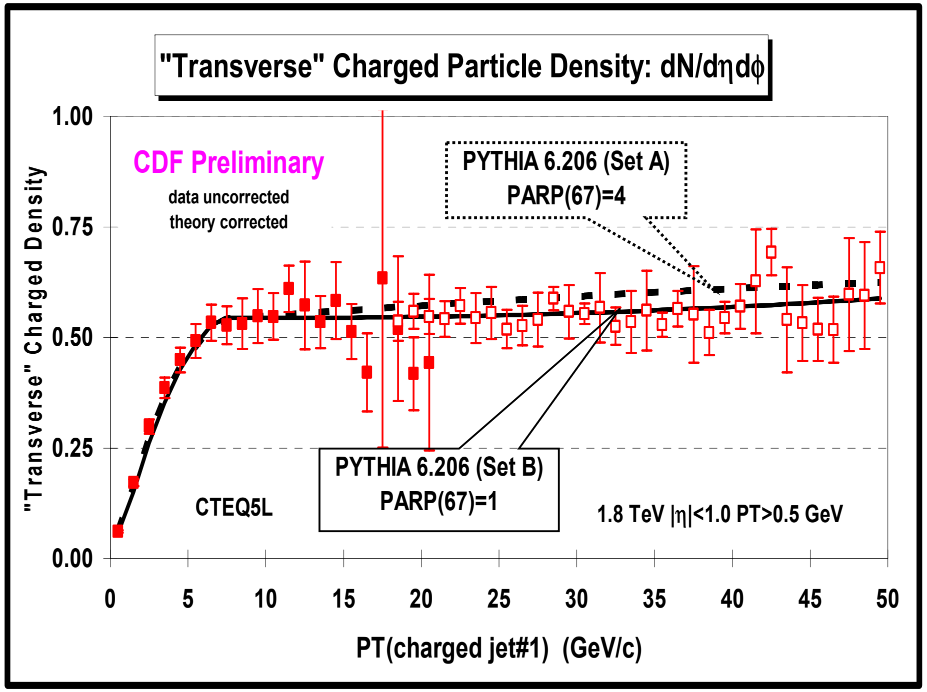
- Consider particle density in the "Transverse" region
  - ➔ Poor desription by default Pythia
  - ➔ Good description by tuned Pythia (Tune A preferred by other studies)



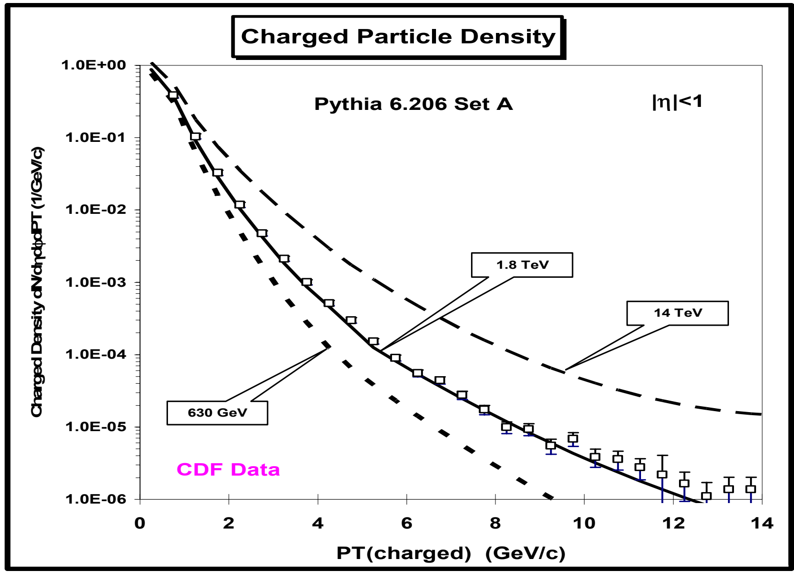
Default Pythia

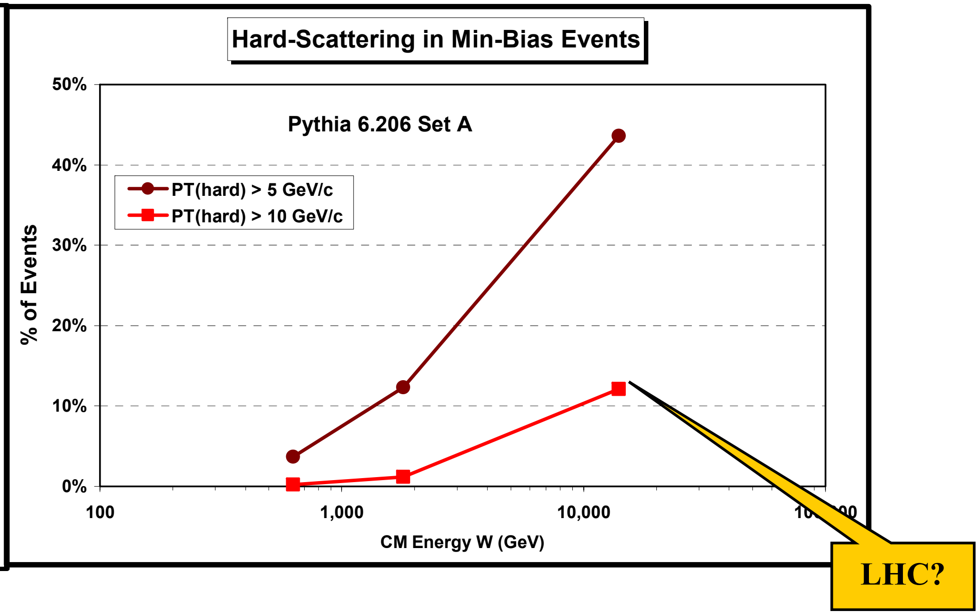


Tuned Pythia



Using Tuned Pythia to Predict LHC



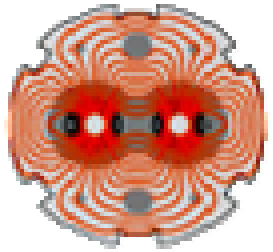


- ☛ √s dependence of the charged particle density for "Min-Bias" collisions compared with Pythia Tune A
- ☛ Fraction of MinBias events with PT(hard) > 5 and 10 GeV vs √s, expected from PYTHIA Tune A

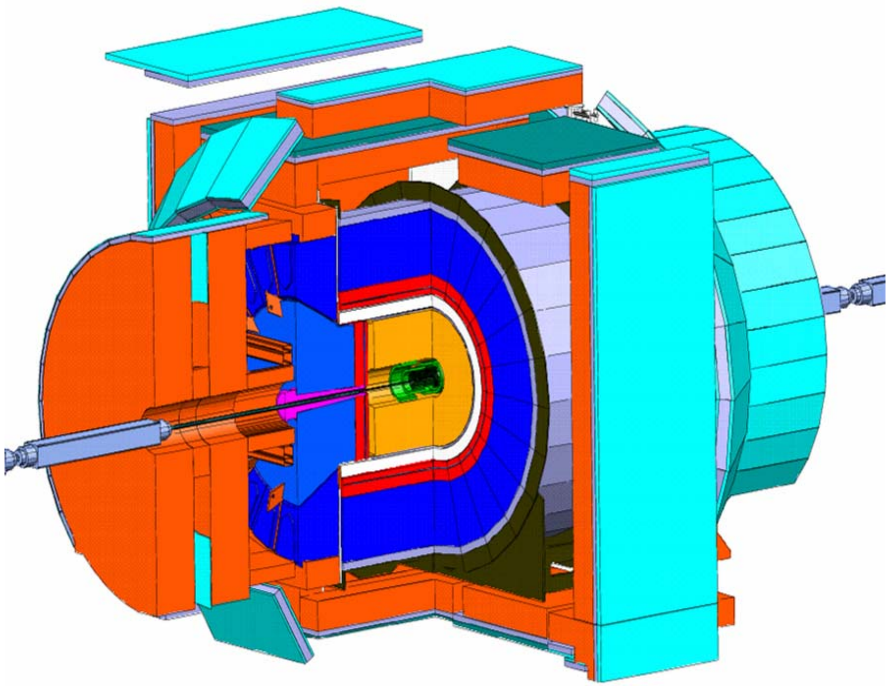
- Pythia Tune A predicts that 1% of all "Min-Bias" events at 1.8 TeV result from hard 2-to-2 parton-parton interactions with P_T(hard) > 10 GeV/c
  - ➔ increases to 12% at 14 TeV
- Work starting on "universal tuning" (Rick Field, CDF)
  - ➔ include jets, γ, Z, W, DY, HF etc…

Summary

- Tevatron, CDF and DØ are performing well
  - ➔ Data samples already significantly exceed those of Run I
  - ➔ On track for accumulating 4-8 fb^{-1} by 2009
- Robust QCD program is underway
  - ➔ Jets, photons, W/Z+jets, heavy flavors
    - ❖ Jet energy scale is the dominant systematics – improvements on the way
    - ❖ Heavy flavor identification is working well
  - ➔ Probing hard scatter Matrix Elements to 10^{-19} m, α_s, pdfs, soft and hard radiation, jet structure, Underlying and MinBias Event properties
  - ➔ Verifying and tuning tools: NLO/NNLO calculations, Monte Carlo generators, resummation techniques, combining ME with PS
    - ❖ NLO does well for hard aspects
    - ❖ LO + Pythia give reasonable description of W/Z+n jets
    - ❖ Tuned Pythia models soft aspects well
- QCD knowledge from Tevatron is essential for
  - ➔ Precision measurements and searches for New Physics
  - ➔ Expectations for LHC

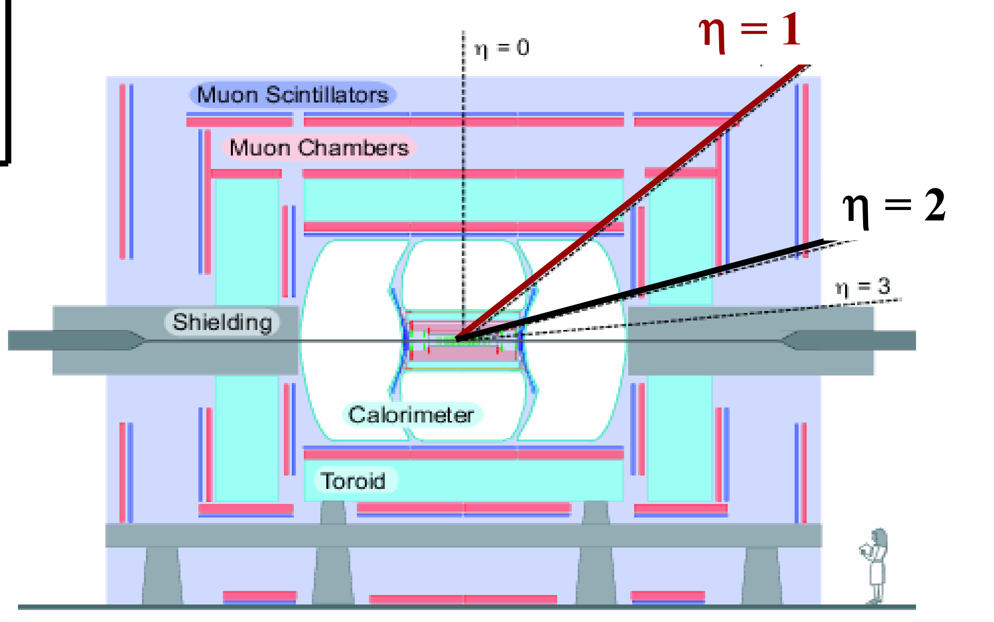


CDF and DØ Detectors



- New silicon and drift chamber
- Upgraded calorimeter and muon systems
- Upgrade of Trigger/DAQ

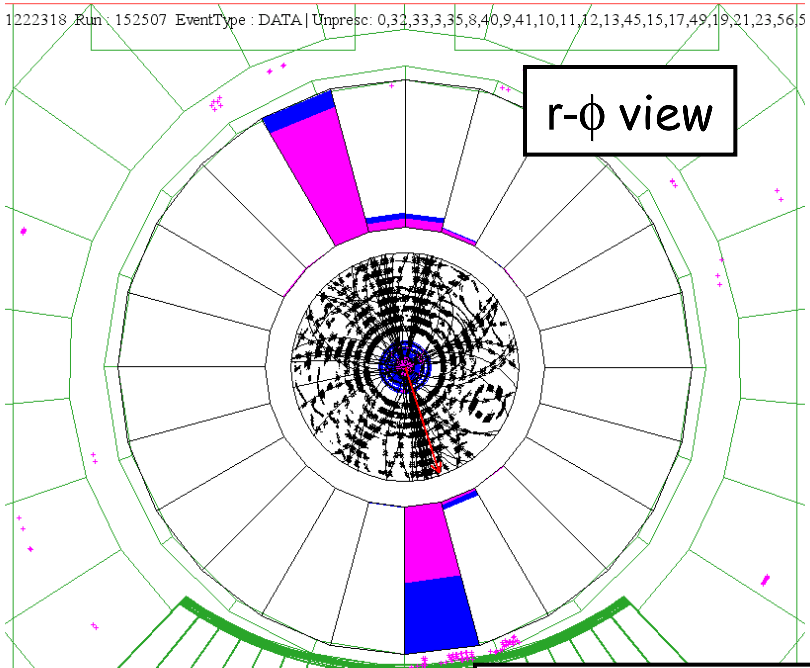
- New silicon and fiber tracker
- Solenoid (2 Tesla)
- Upgrade of muon system
- Upgrade of Trigger/DAQ

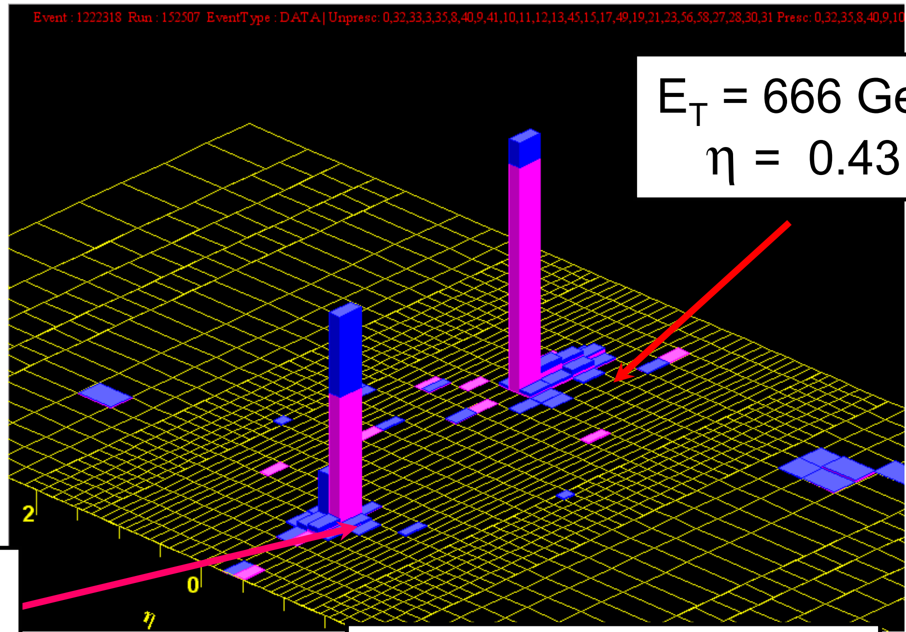


Run II High E_T Jets

A high mass di-jet event: M_{jj} = 1364 GeV/c^2

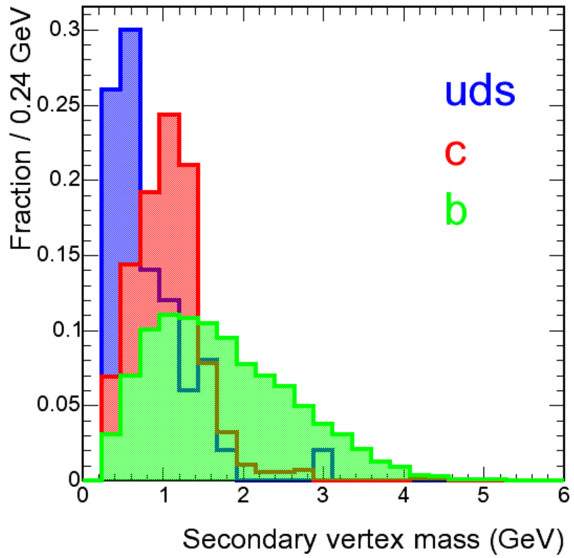
CDF

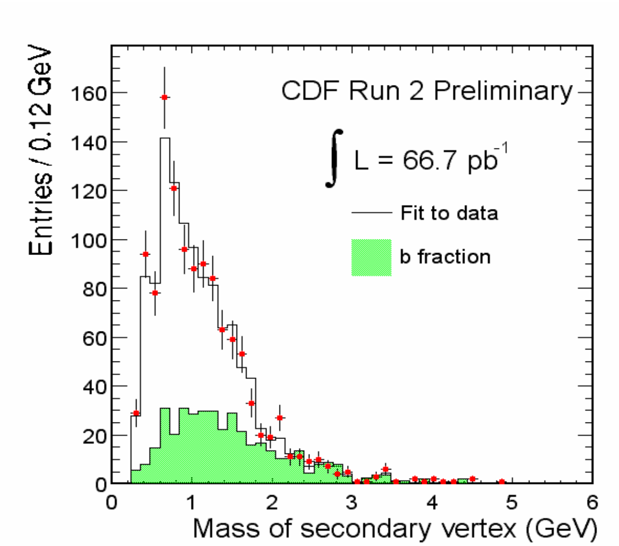


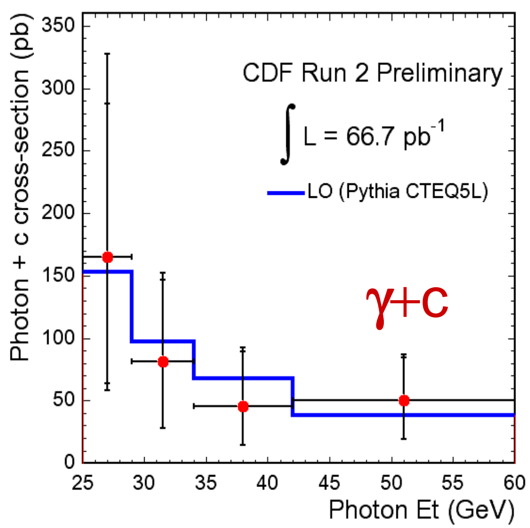


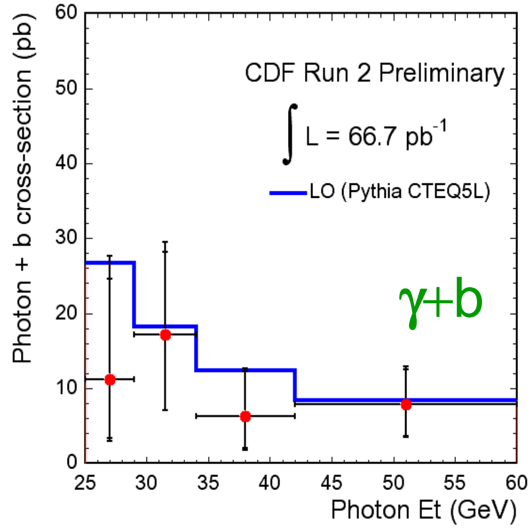
γ + b/c Cross Section

- Test heavy-flavor production in QCD
  - ➔ Probe HF content of protons, g→bb̲ splitting
  - ➔ Possible signatures of New Physics
- Data: 1 isolated γ E_T > 25 GeV,
  1 jet with secondary vertex (“b/c-like”)
  - ➔ Fit mass distribution in the secondary vertex to b, c, uds templates
- QCD consistent with data
  - ➔ Still big uncertainties
  - ➔ No new physics seen yet…



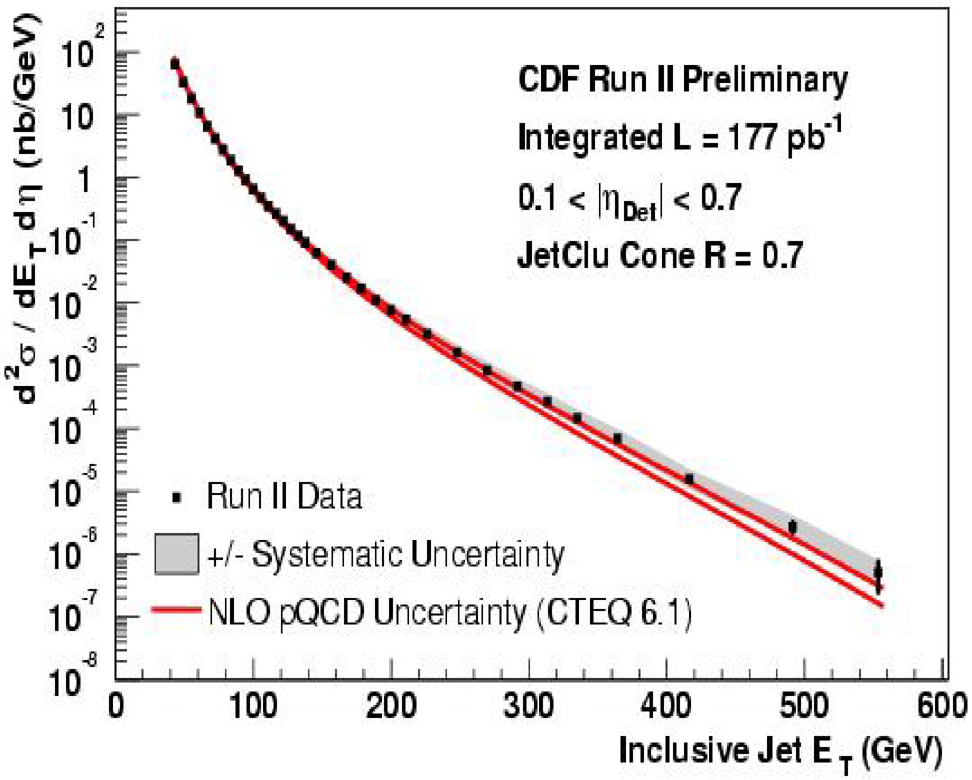


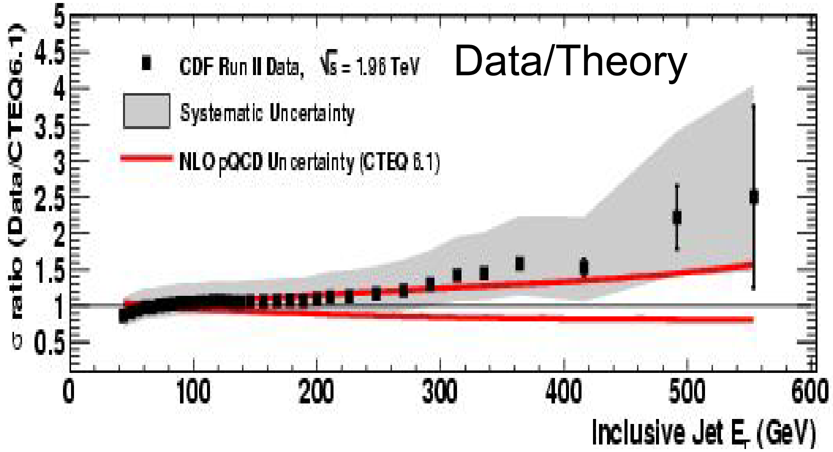


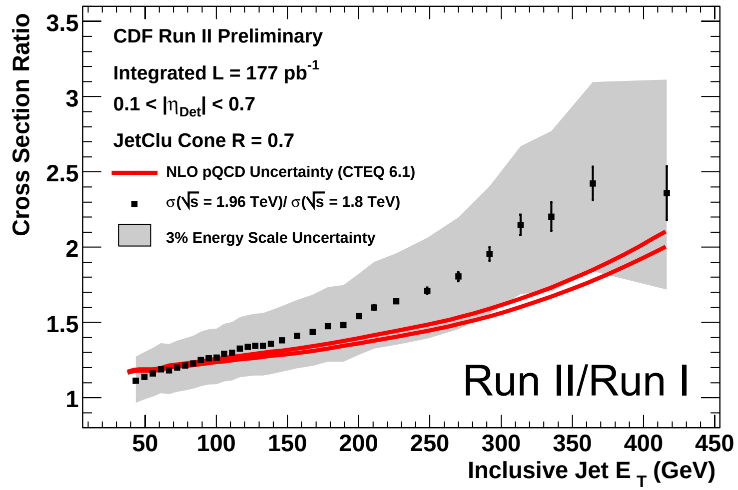


Central Inclusive Jet Cross Section: JETCLU

- Run I reach extended by 150 GeV
- Data agree with NLO prediction within errors (Run I JETCLU used)







- Rapidity-dependent measurement in the works