QCD at the Tevatron

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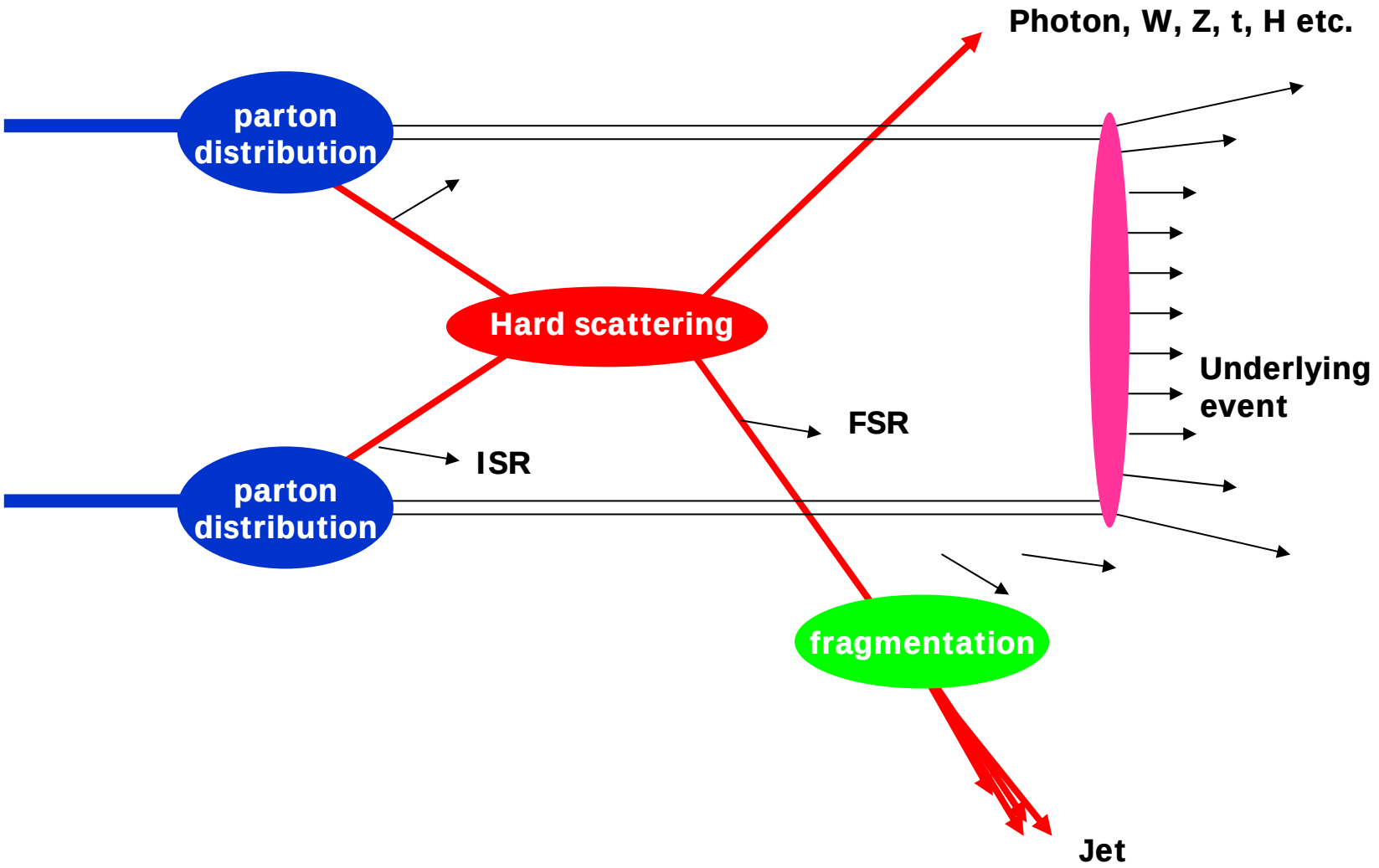
21 September 2005/ IOP Half Day

QCD at the Tevatron

- QCD is the theory of string interactions
  - Testing the quality of the predictions/calculations
  - Searching for Phenomena beyond the SM
- The Tevatron is a proton-antiproton collider
  - Everything is QCD!!
  - Complex laboratory to study all aspects of the theory
  - Testing models of:
    Total Cross Sections; Parton density functions; Diffractive processes and rapidity gaps; Underlying events .
- Talk Covers
  - Photons
  - Jets, Heavy Flavour
  - W/Z+Jets
  - Diffraction and Underlying Event

Hadron-Hadron Collisions

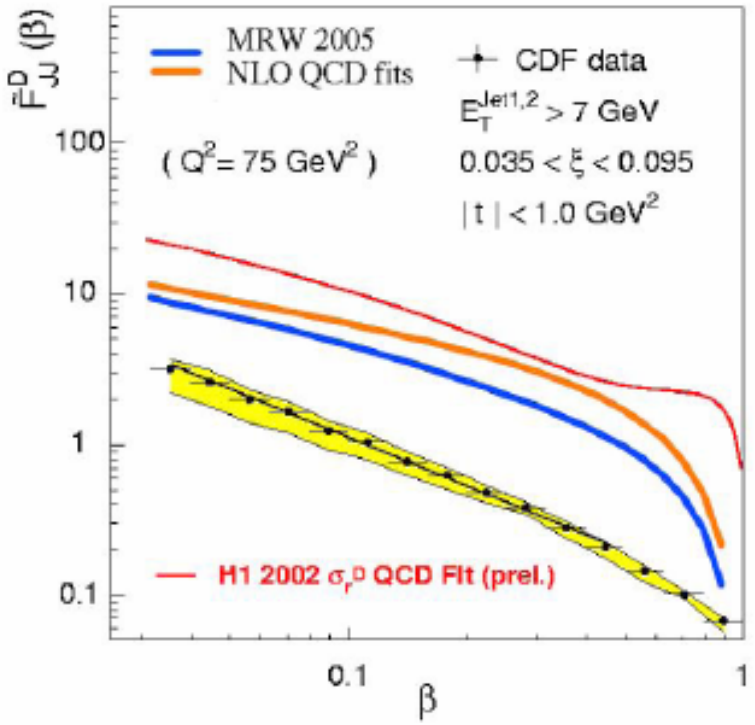


Diffraction

- Run I revealed discrepancies between HERA and Tevatron Results:

$$R_{\rm hard} = \frac{1}{\sigma^{\rm tot}_{\rm hard}} \int_{x_{F\,\rm min}}^{1} dx_F \frac{d\sigma_{\rm hard}}{dx_F}$$

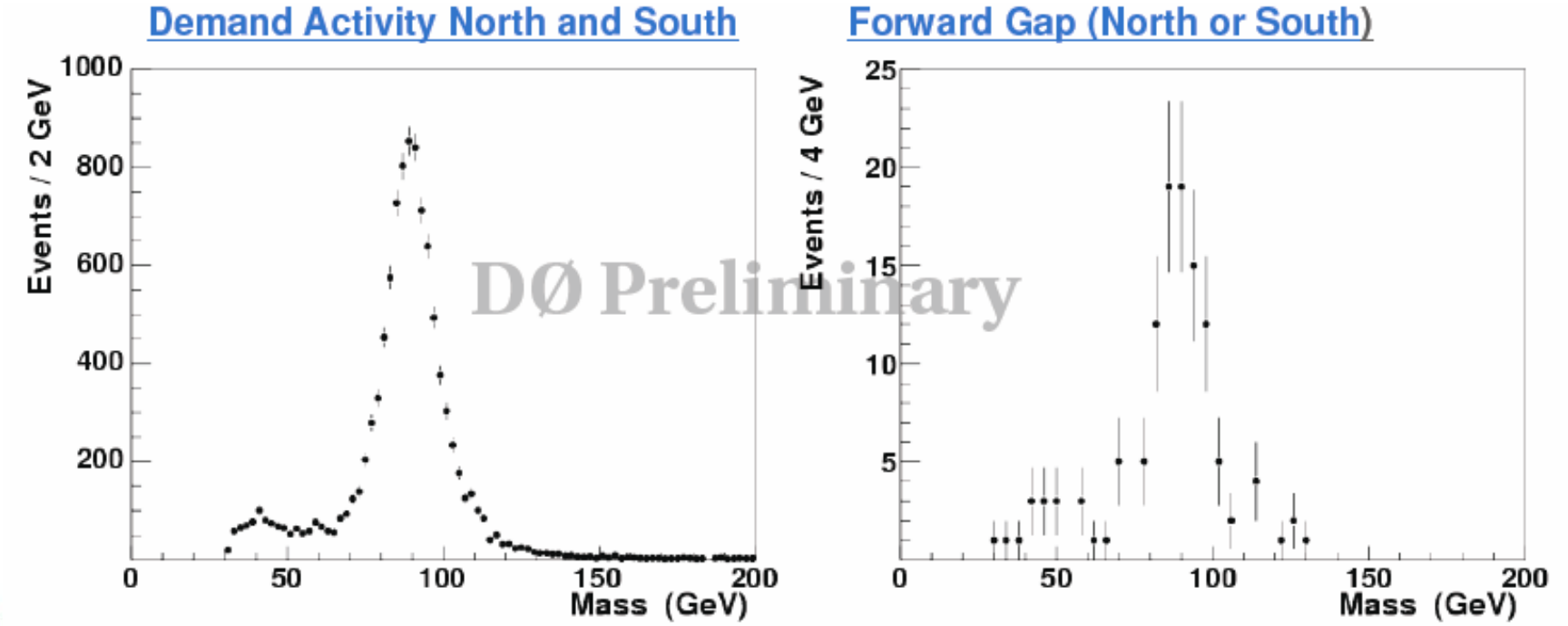
$R_{\rm hard}[\%]$	Exp.	observed
dijets	CDF	0.75 ± 0.10
W	CDF	1.15 ± 0.55
W	DØ	$1.08\ ^{+0.21}_{-0.19}$
$b\bar{b}$	CDF	0.62 ± 0.25
Z	DØ	$1.44\ ^{+0.62}_{-0.54}$
J/ψ	CDF	1.45 ± 0.25



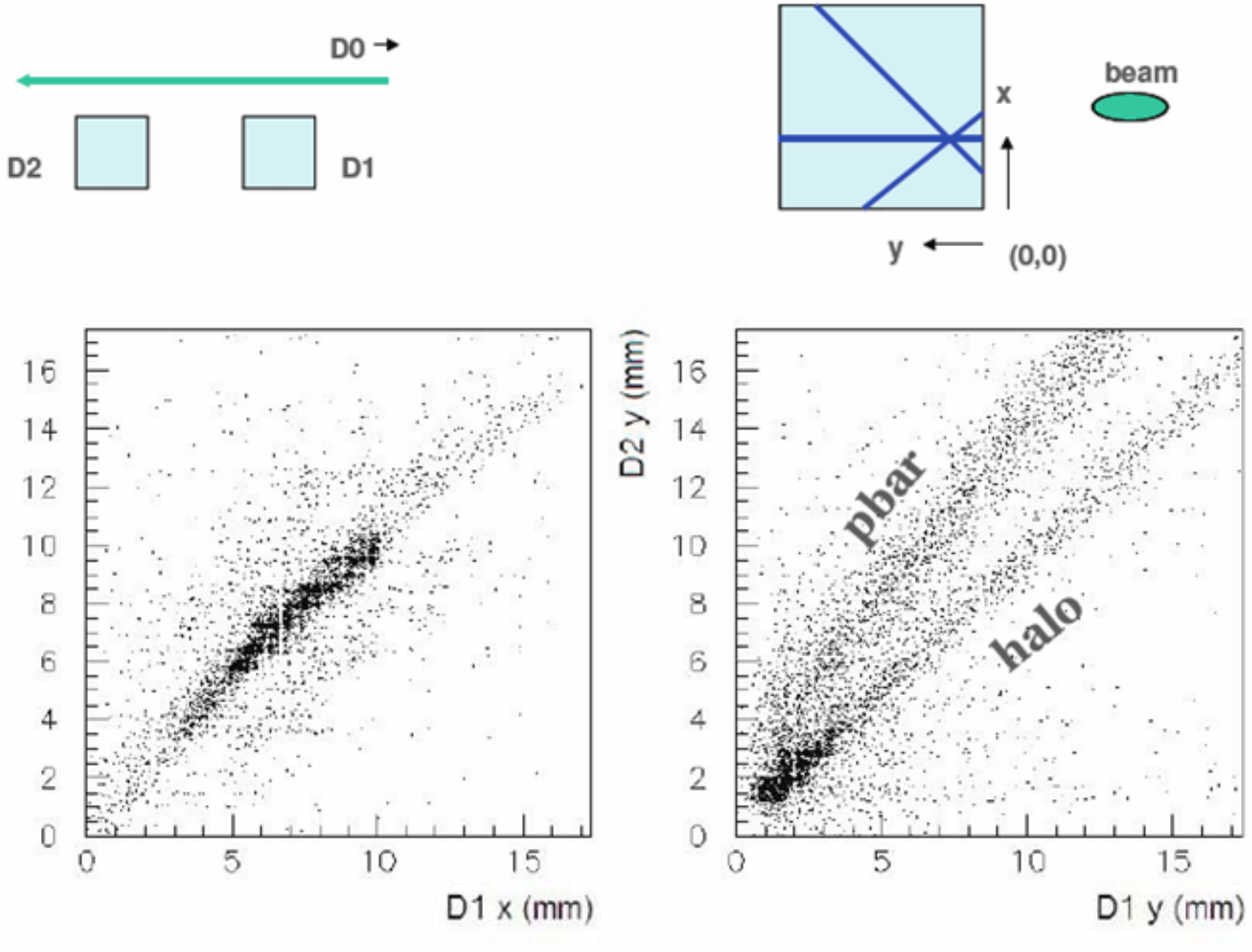
- Run II
  - Upgraded detectors at DØ and CDF
  - More luminosity
  - Higher Inst. Luminosity

DØ Diffractive Z?

- Standard Z selection
  - Require a rapidity gap (possibly a diffractive event)
  - Analysis continuing

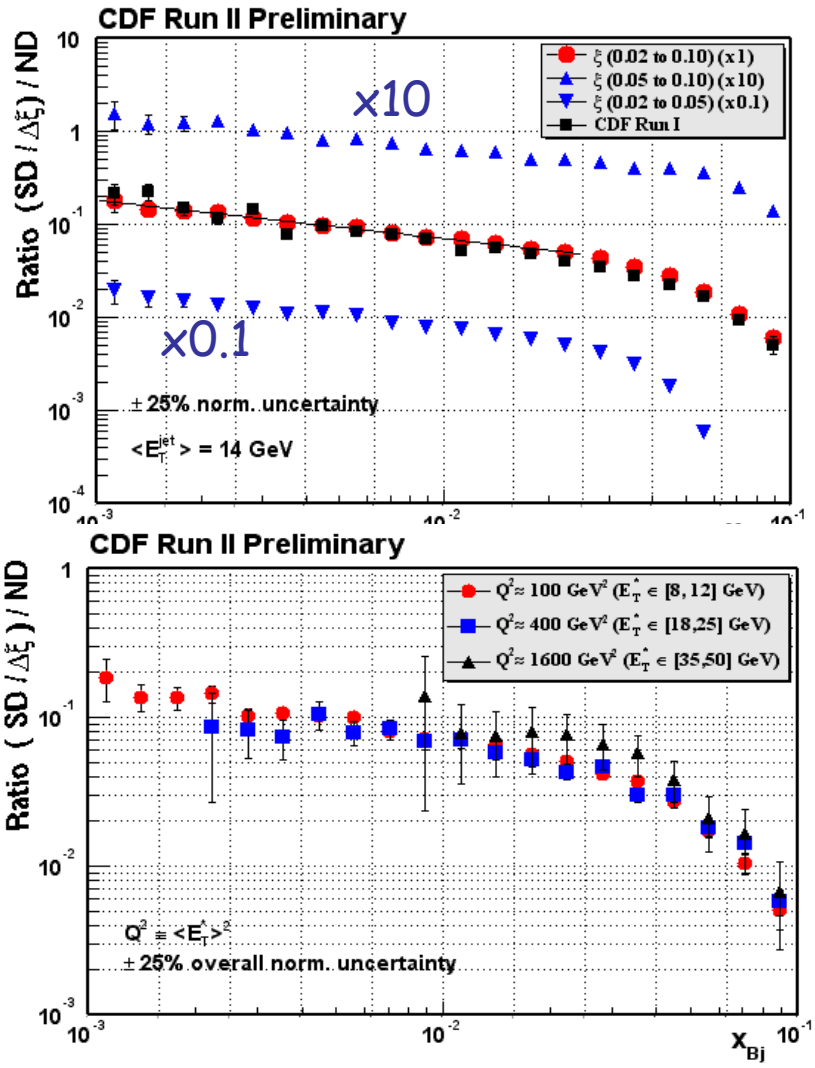


DØ FPD Preliminary Data



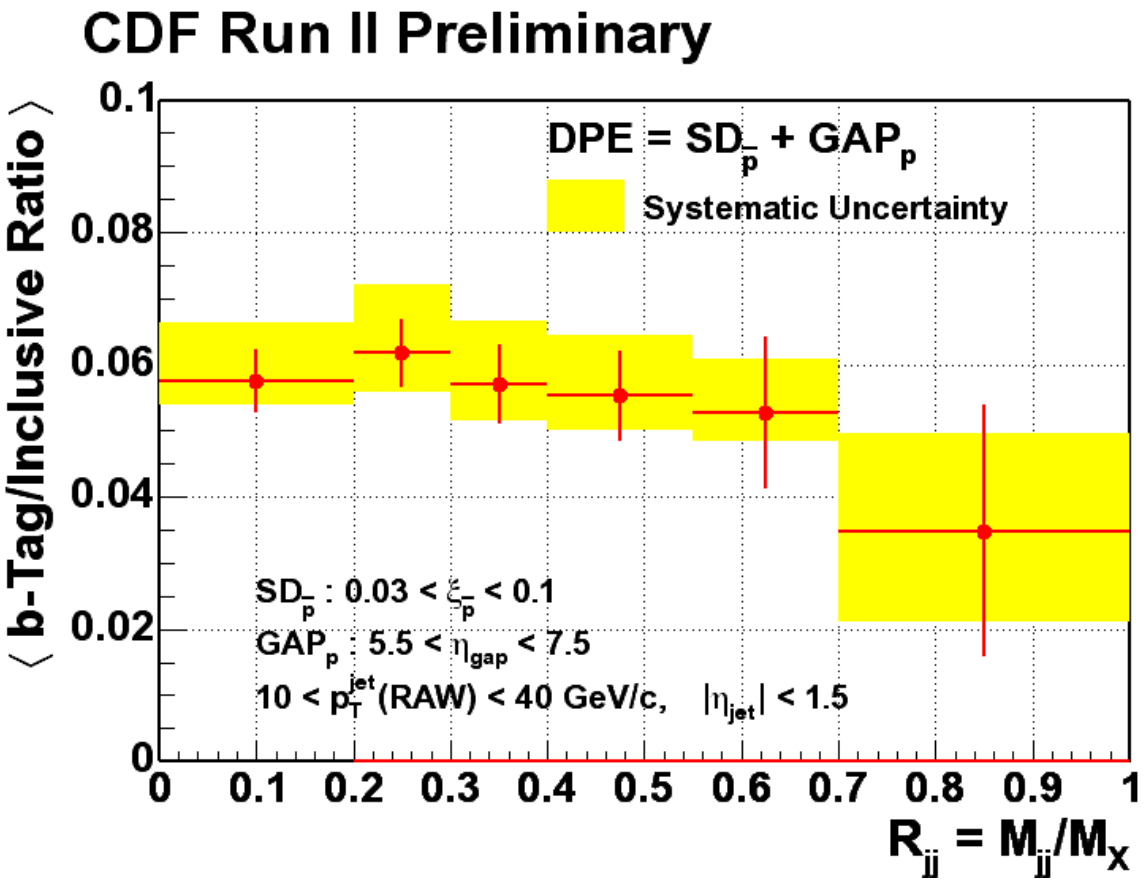
CDF Diffractive Dijets

- Ratio of SD/ND dijet event rates
  - agreement with Run 1 result
  - no x dependence in 0.03<x<0.1
  - confirms Run I results
- No appreciable Q2 dependence
  - in region $100 < Q^2 < 1{,}600$ GeV^2

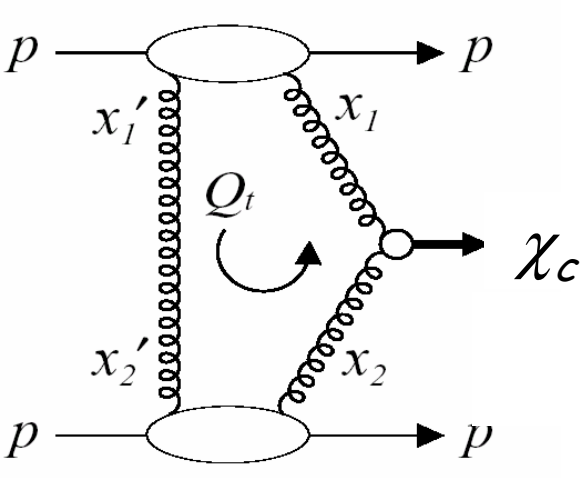


CDF Heavy Flavour Dijet

- Possible Higgs Channel
  - Colourless exchange
  - Small background
  - ???



CDF Exclusive χ_C Production



$$p\bar{p} \rightarrow p\,\chi_c\bar{p}$$

$$\chi_c \rightarrow J/\Psi + \gamma \rightarrow \mu^+\mu^- + \gamma$$

- From inclusive J/y data:
  - Cross section upper limit: $\sigma\,(J/\Psi+\gamma) = 49 \pm 18(stat) \pm 39(syst)$ pb
  - Khoze, Martin, Ryskin, and Stirling ~ 70 pb [Eur. Phys. J. C 35, 211 (2004)]

Photons

- In Principal a simple final state
  - Photon is colourless and electromagnetic
  - Accurate energy scale
  - Minimal fragmentation
- In actuality
  - Purity problems due to presence of π^0 in jets
  - Effects of underlying event and smearing on cross sections

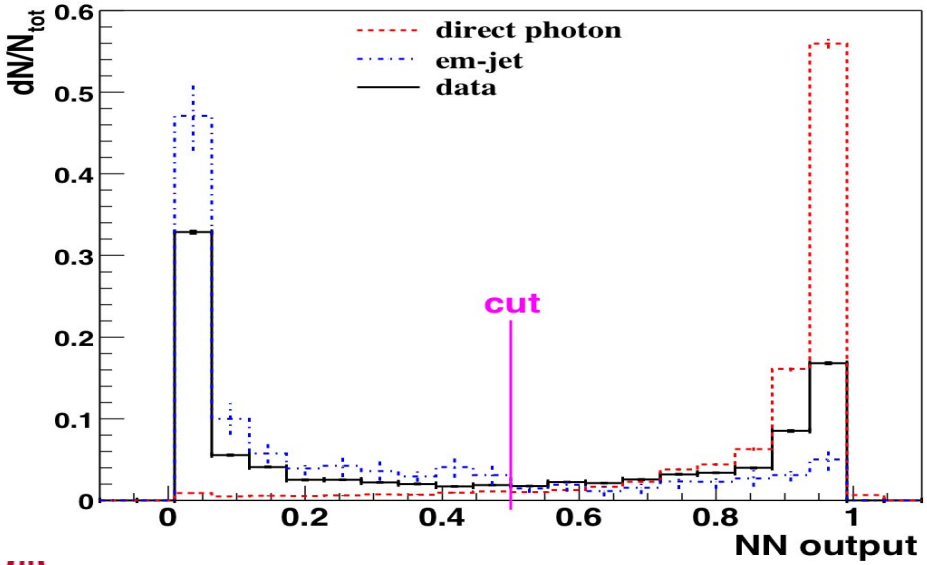
Isolated Photon Cross Section at DØ

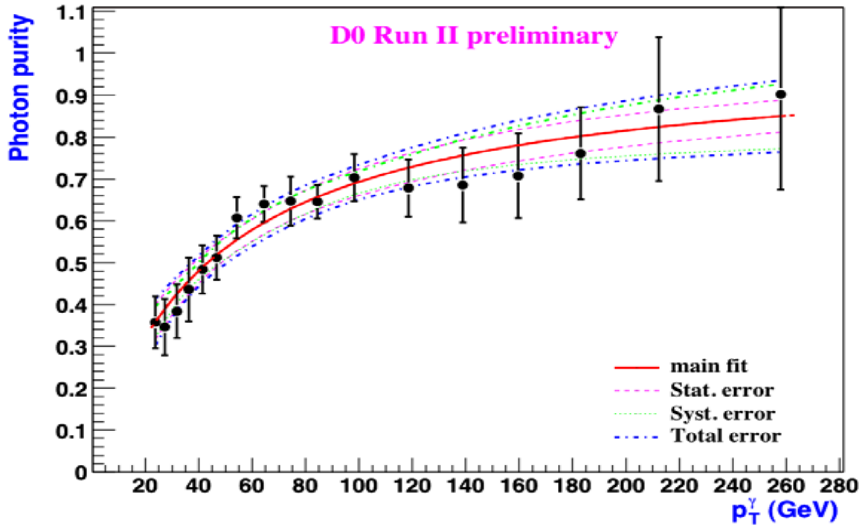
- Data set of 326 pb^{-1}
- EM cluster satisfying
  - $|\eta| < 0.9$,
  - $R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)} < 0.2$
  - $z_{vtx} < 50$ cm
  - EM fraction < 0.95
  - Isolated (no calorimeter energy in cone from R=0.2-0.4)

- Purity Estimation

$$P = \frac{N^{\gamma}}{N^{\text{total}}}$$

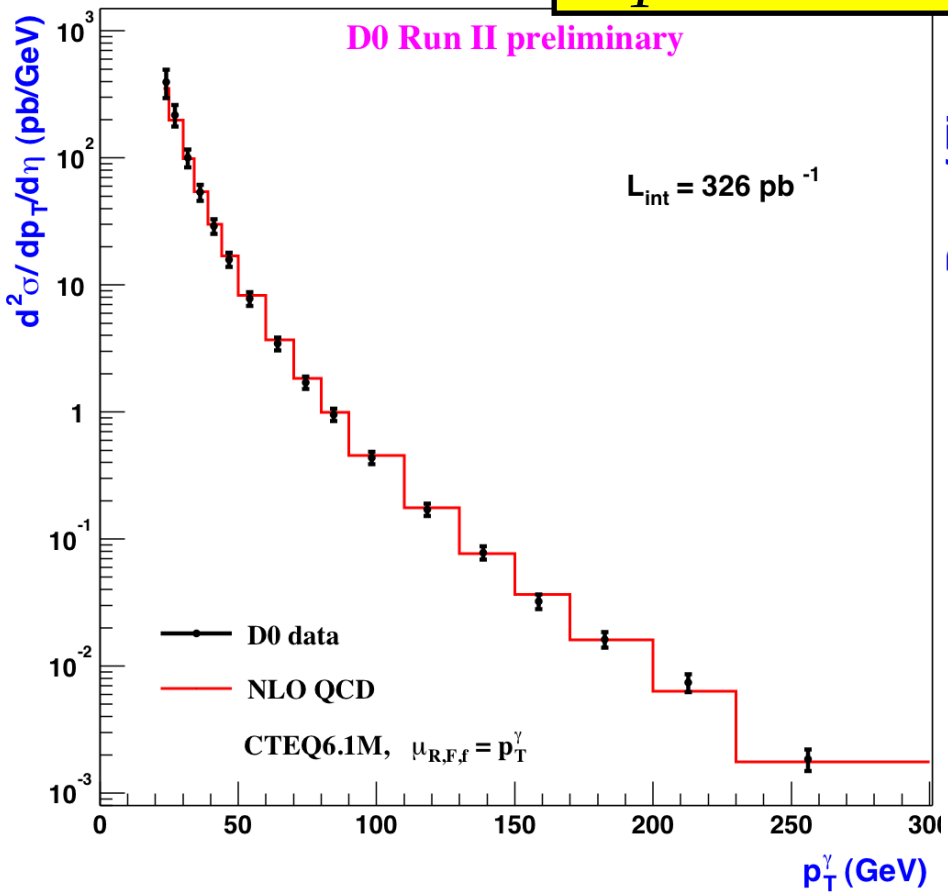
  - NN with four input variables
  - Related to energy deposition in EM calorimeter and properties of nearby tracks

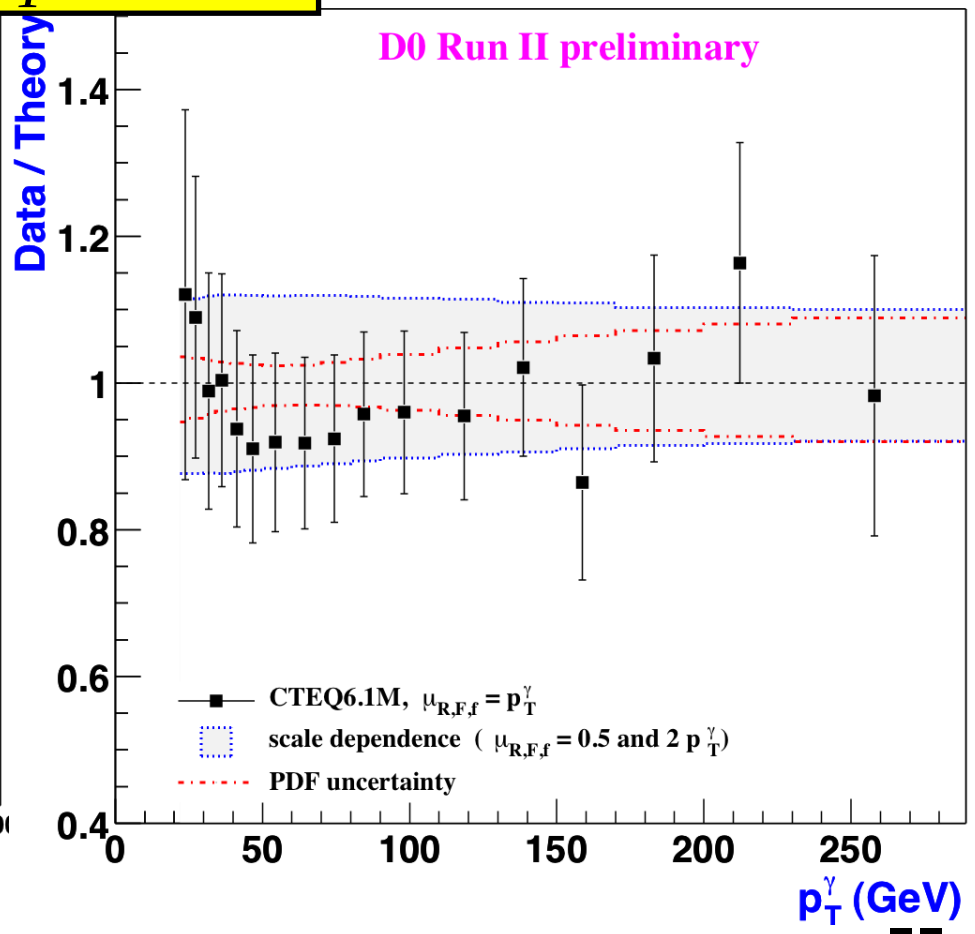




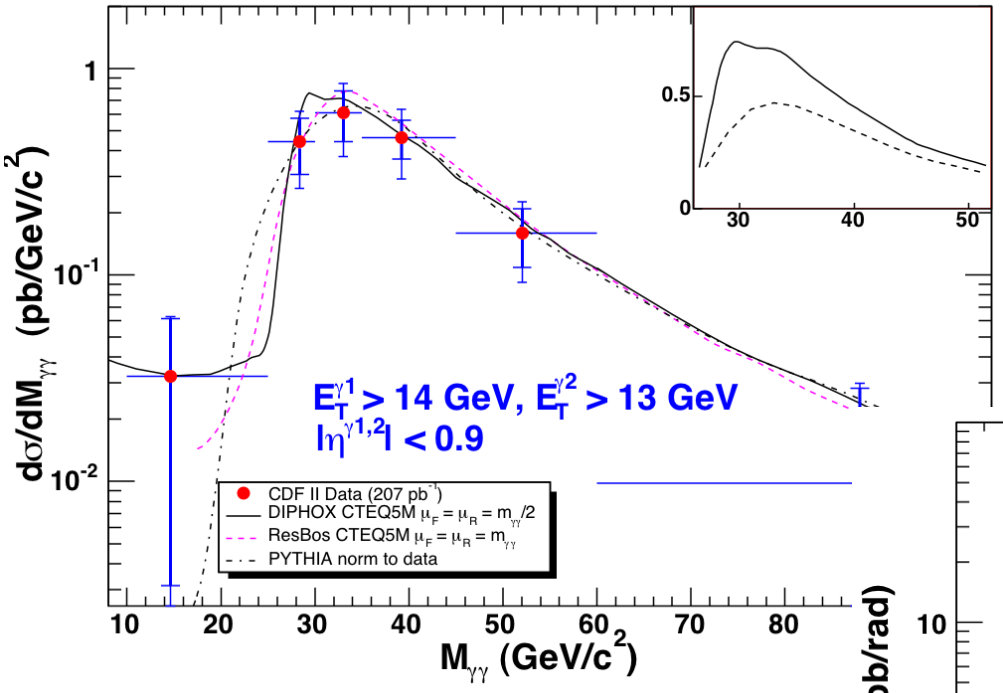
DØ Photon Cross Section

$$\frac{d^2\sigma}{dp_T^\gamma d\eta^\gamma} = \frac{NPf_{\text{unsm}}}{L\Delta p_T^\gamma \Delta\eta^\gamma A\varepsilon_t\varepsilon_s}$$

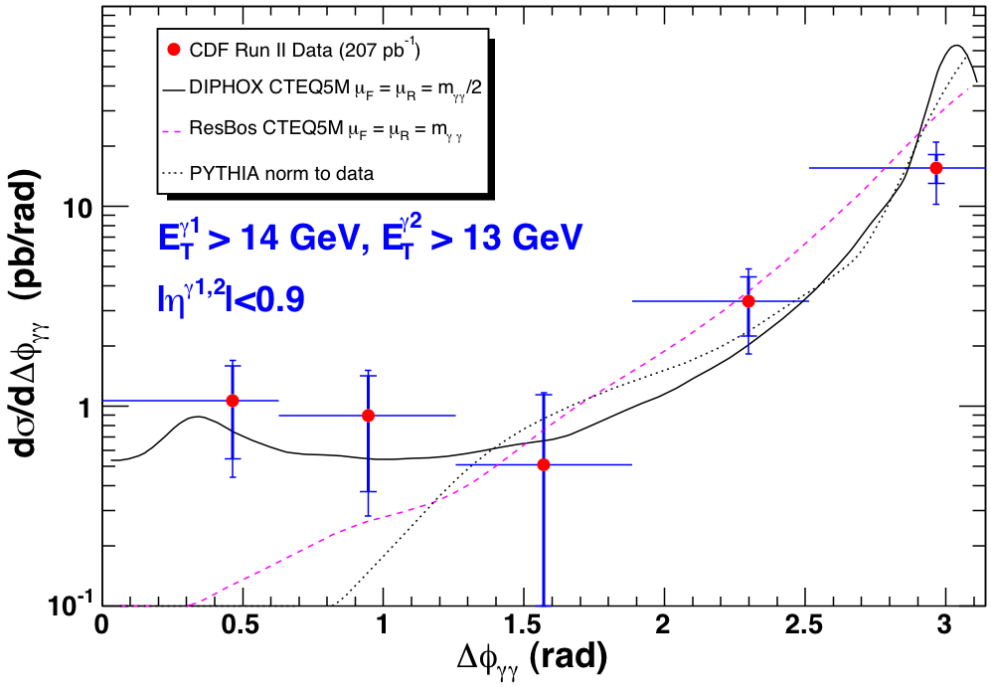




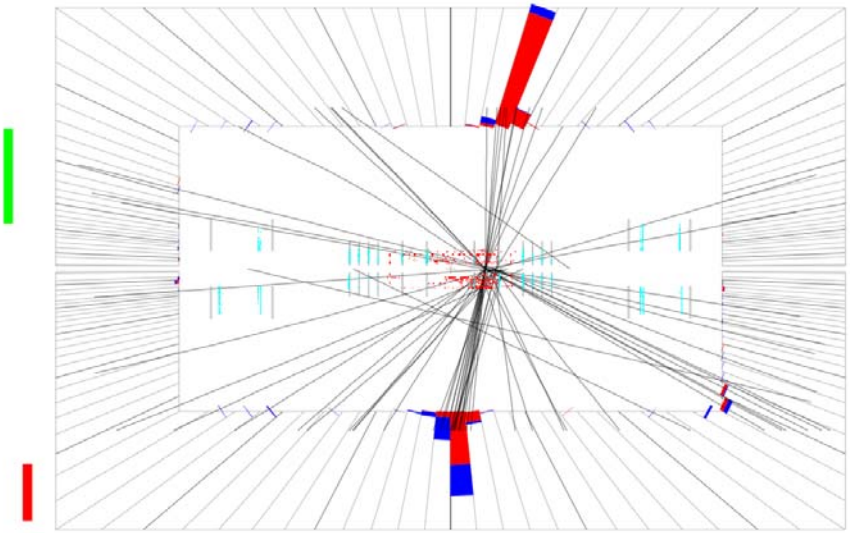
CDF Di-Photons

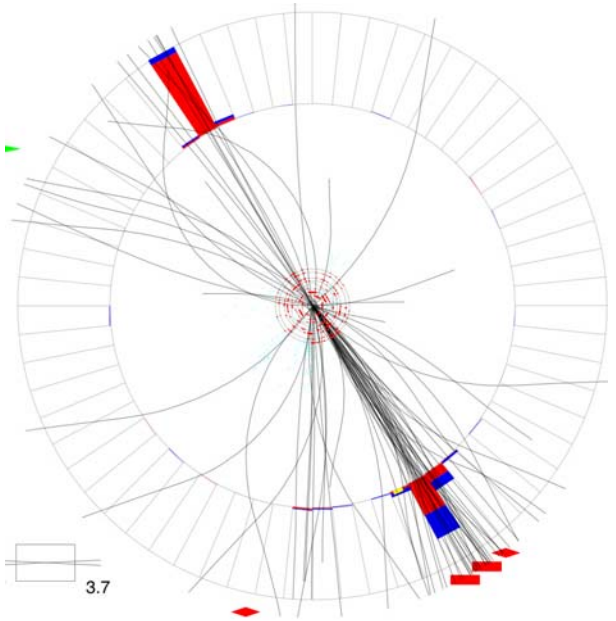


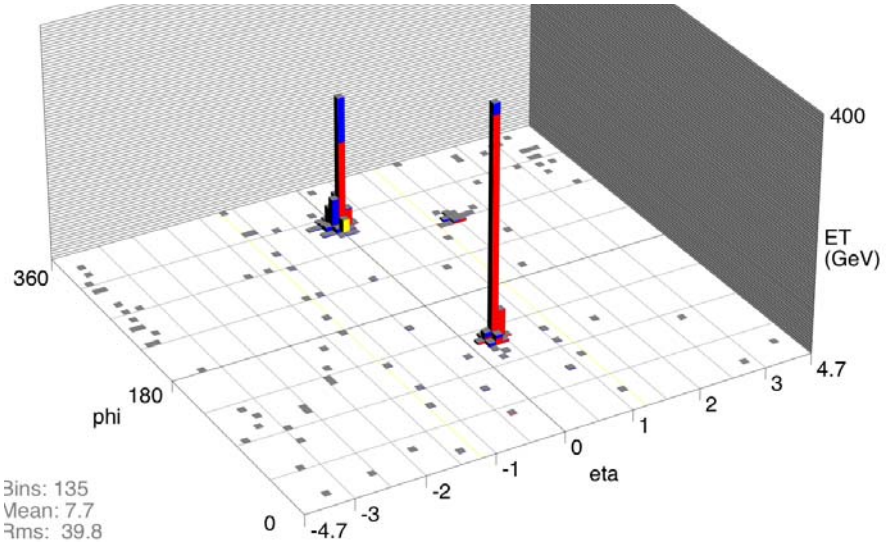
- L = 207 pb-1
- Mass and Angular Distributions
- Good Agreement with NLO predictions
- DiPHOX gives best agreement



Jets





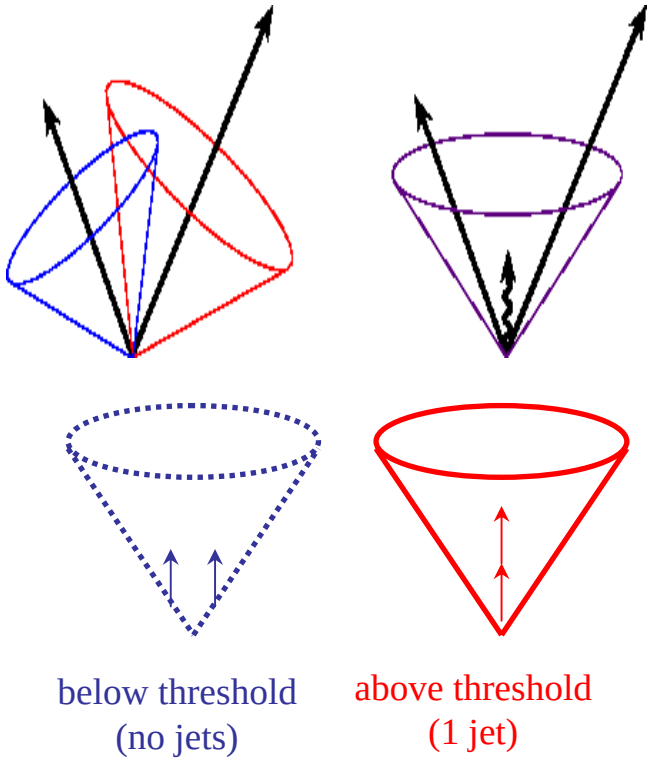


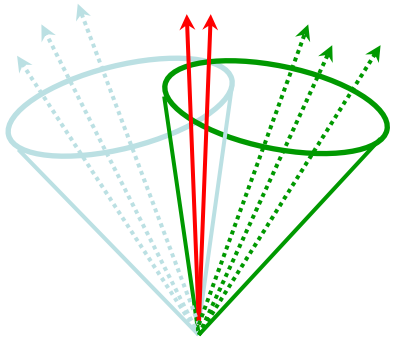
	Jet 1	Jet 2	
pT =	631	560	GeV
y =	0.14	-0.17	
ϕ=	2.1	5.3	

Mass = 1208 GeV

Cone Jet Algorithms and pQCD

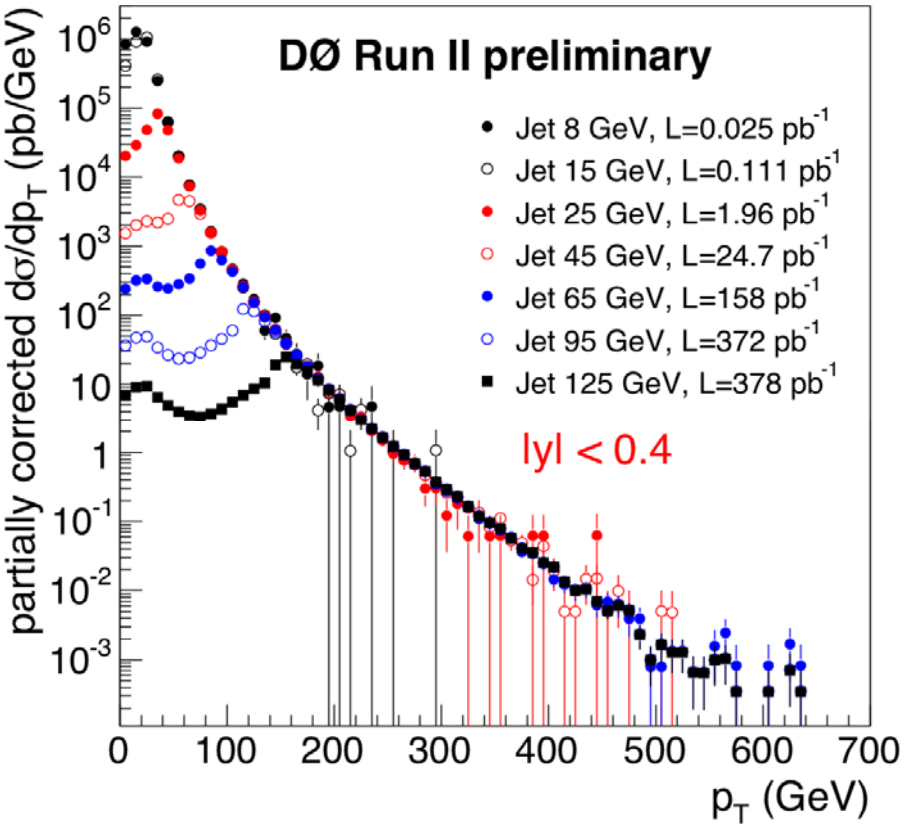
- Infrared and Collinear Safety
  - Modified Cone Algorithm!
    - Midpoint seeds
    - Massive jets and rapidity
    - aka: Improved Legacy Cone Algorithm
- Infra-red safe at NNLO
  - Split Merge
    - DØ if share > 0.5 Jet energy
    - CDF if share > 0.75 Jet energy



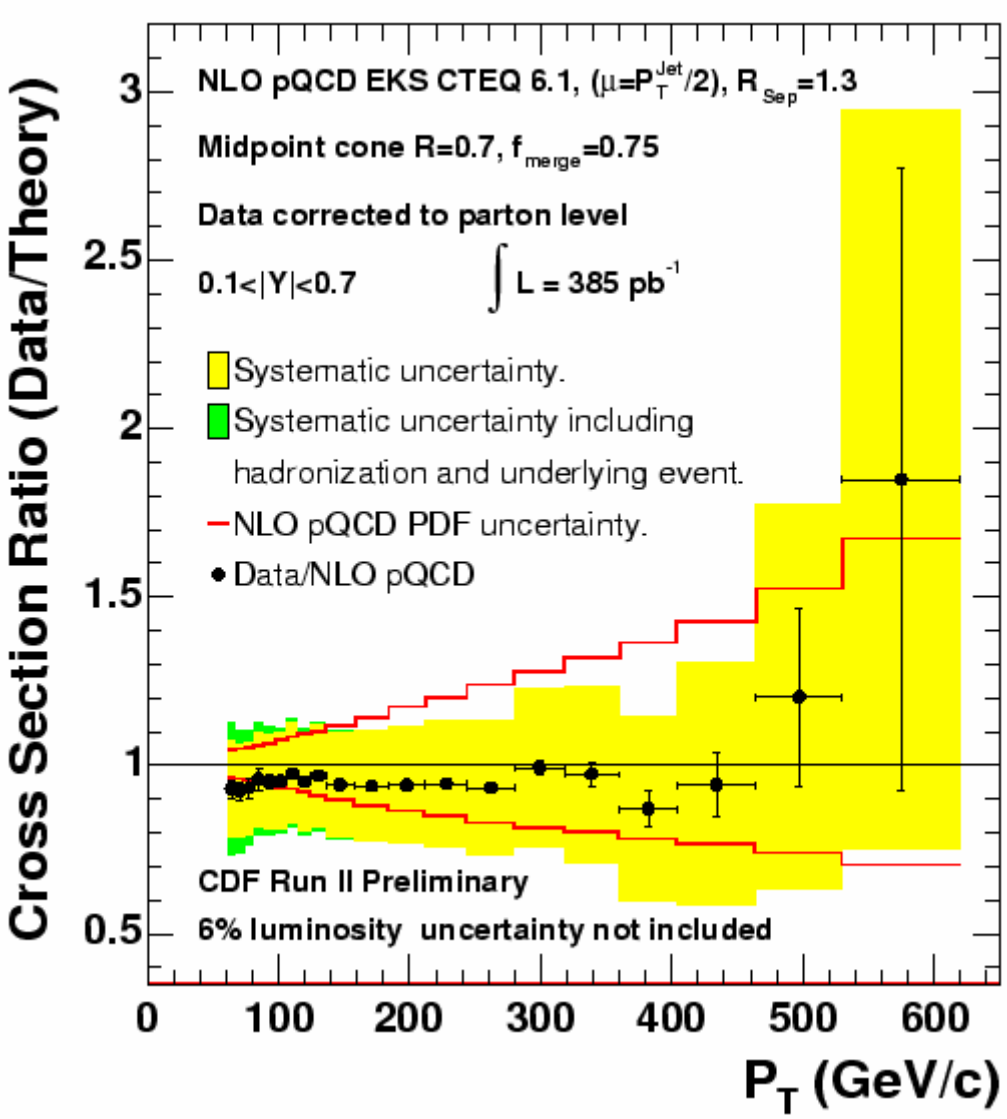


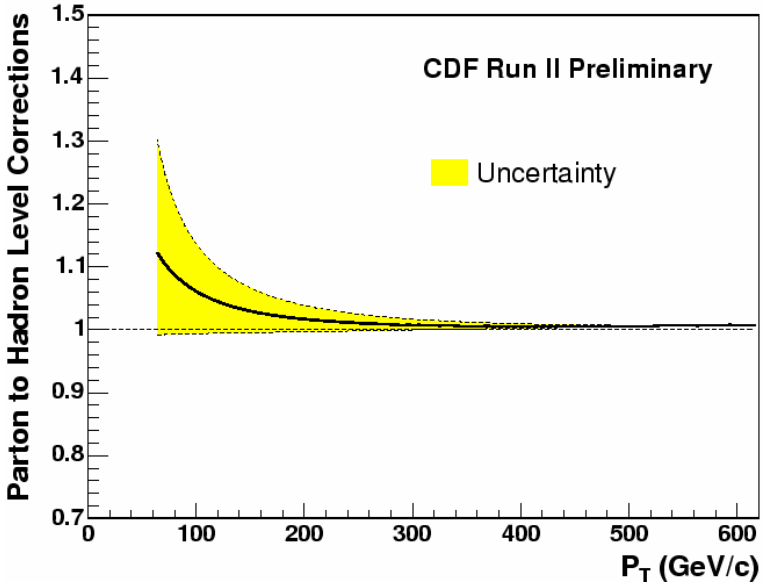
Data Samples

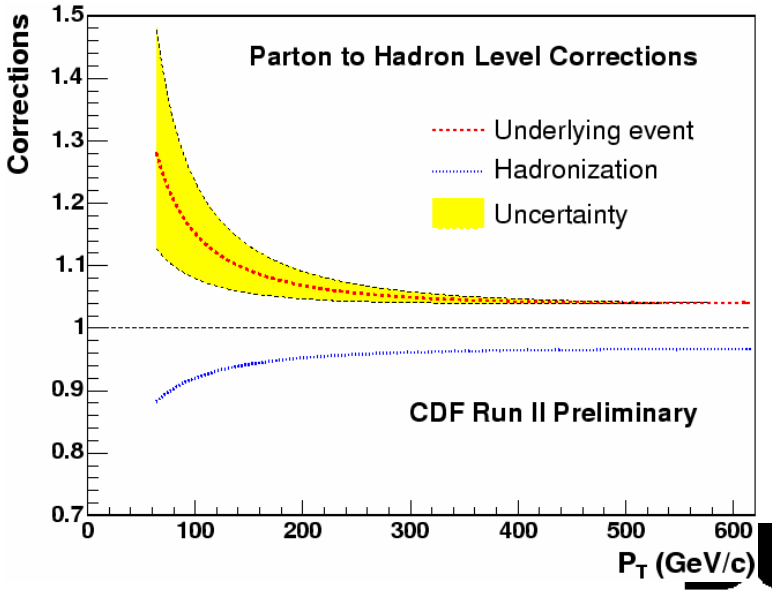
- CDF
  - 385 pb-1
  - Rapidity: 0.1 < |y| < 0.7
  - Event Vertex
    |z| < 60 cm
  - Clean-up using missing ET
  - 4 Triggers
- DØ
  - 378 pb-1
  - Rapidity: |y| < 0.4,
    0.4 < |y| < 0.7
  - Event Vertex
    |z| < 50 cm
  - Clean-up using missing ET
  - 8 Triggers



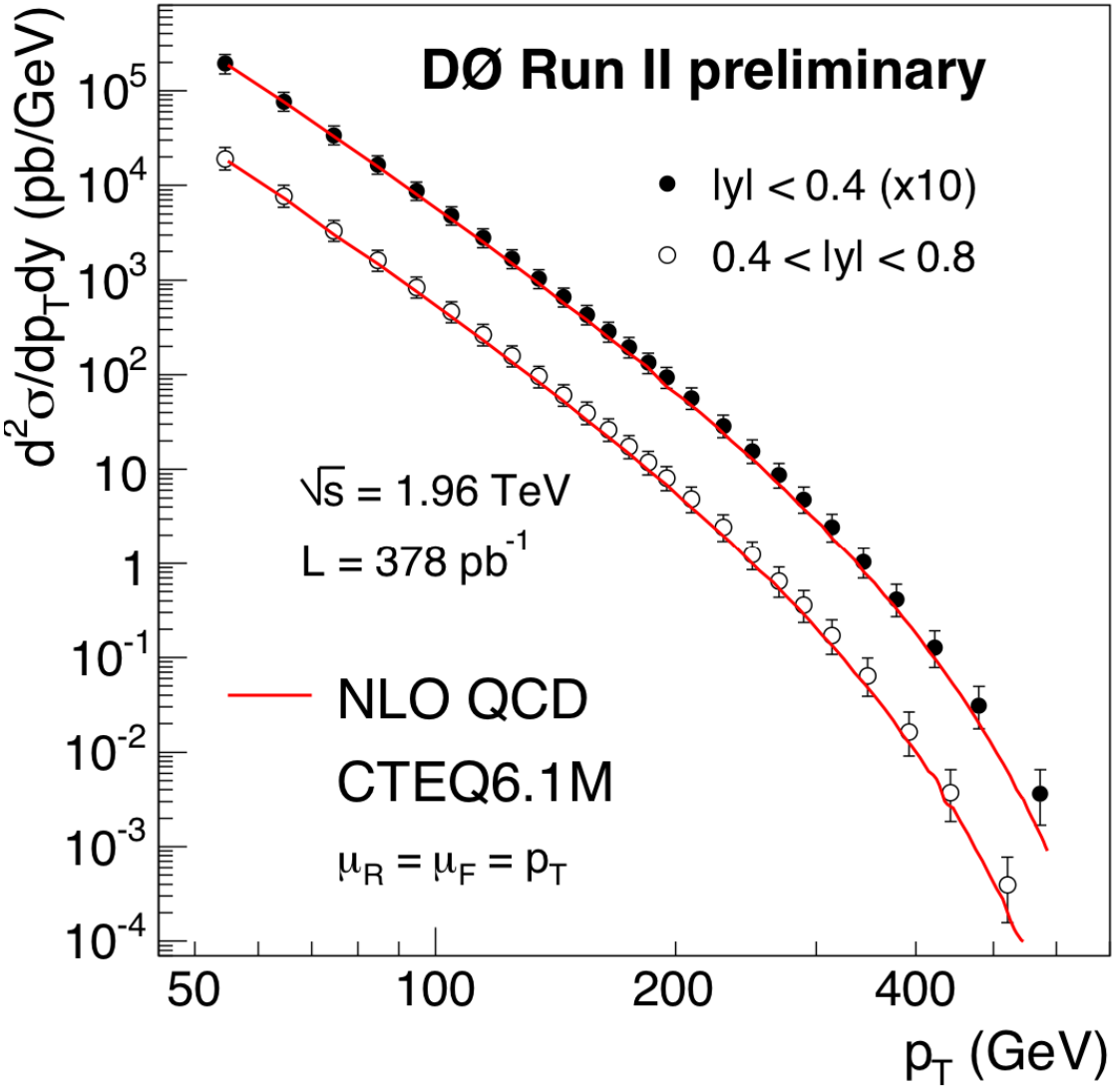
CDF Inclusive Jet



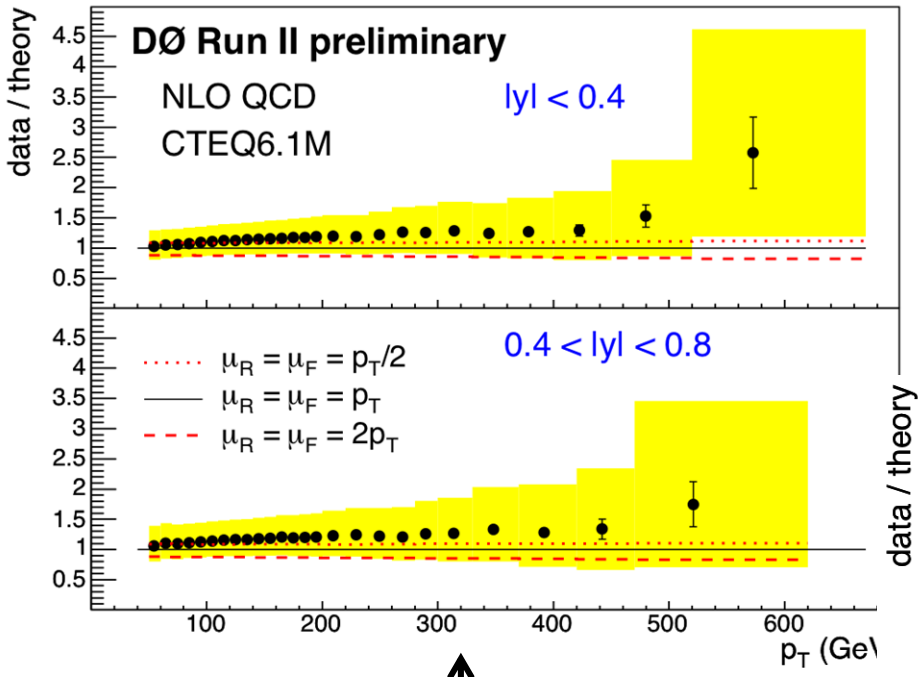




DØ Inclusive Jet

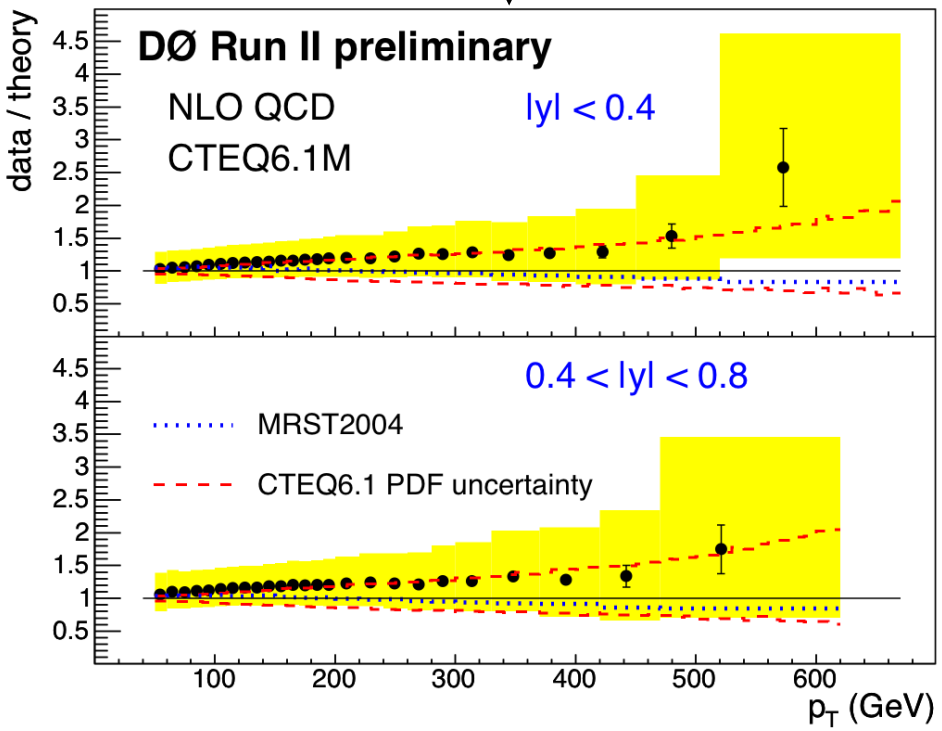


DØ Inclusive Jet II



Effect of Renormalization and Factorization Scales

Effect pdf uncertainty



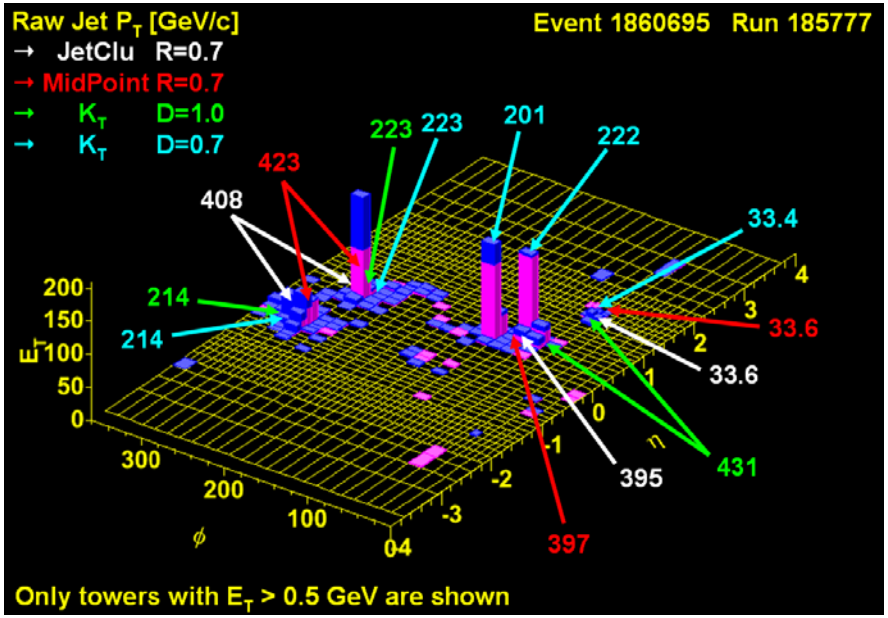
KT Algorithm

- Inclusive KT algorithm
  - Merging pairs of nearby particles in order of increasing relative pT

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

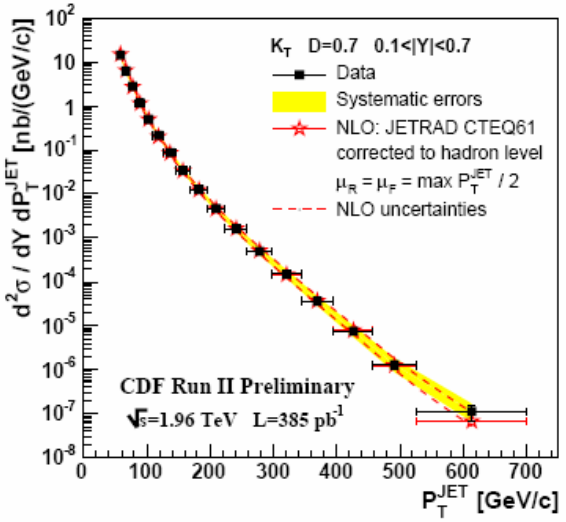
$$d_{ii} = p_{T,i}^2$$

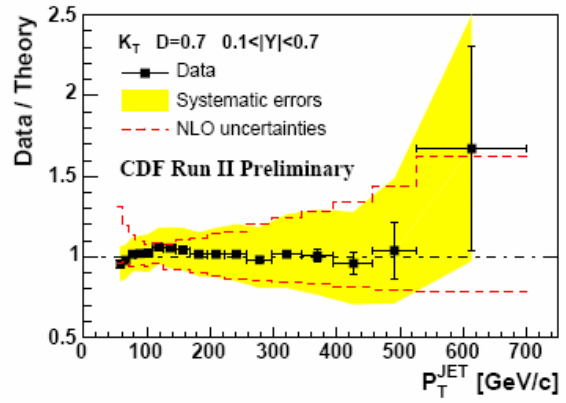
  - D parameter controls merging termination and characterizes size of resulting jets
- PT classification inspired by pQCD gluon emissions
  - Infrared and Collinear safe to all orders in pQCD
  - No merging/splitting

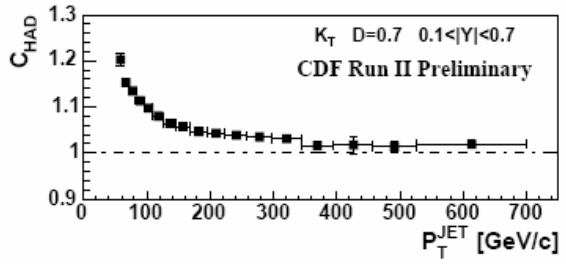


CDF Jet Production with KT

- NLO pQCD corrected to hadron level using PYTHIA-Tune A
- Good data-theory agreement
  - Over ~ 8 orders of magnitude
  - PT reach extended by ~ 150 GeV/c with respect to Run I
- Experimental uncertainty dominated by jet energy scale
  - ±6% luminosity uncertainty not included in the plots
- Theoretical error dominated by PDFs
  - Gluon at high x

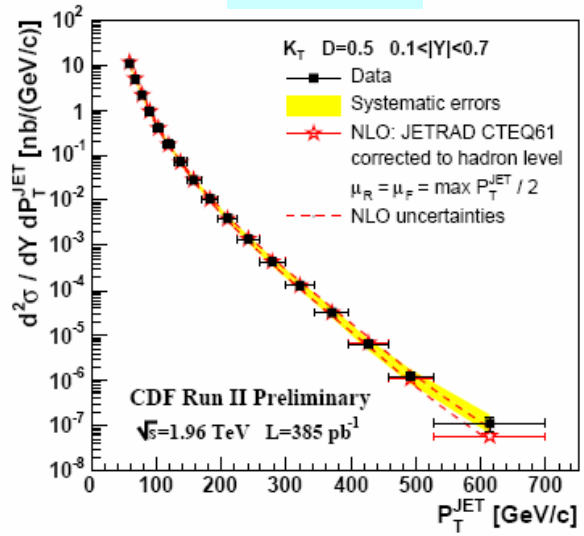


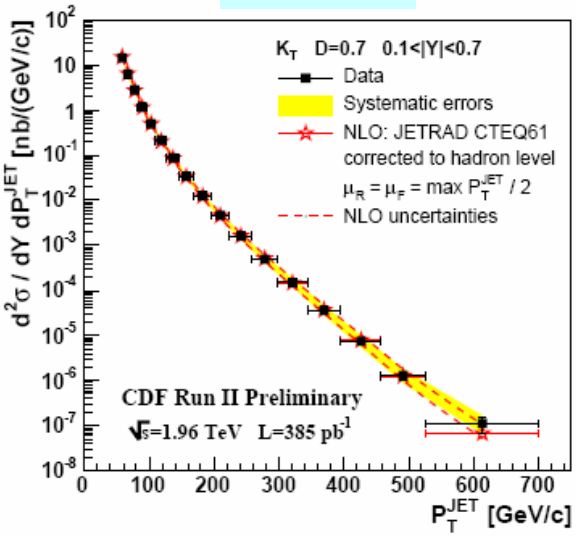


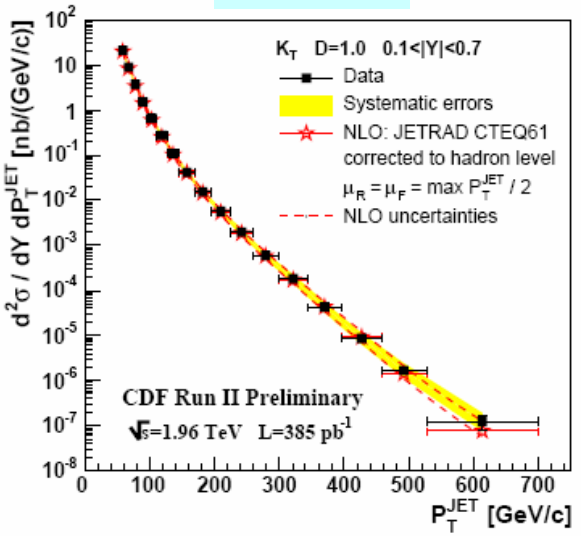


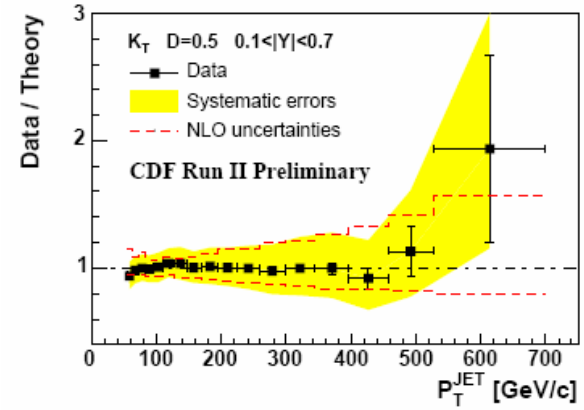
CDF K_T jets versus D

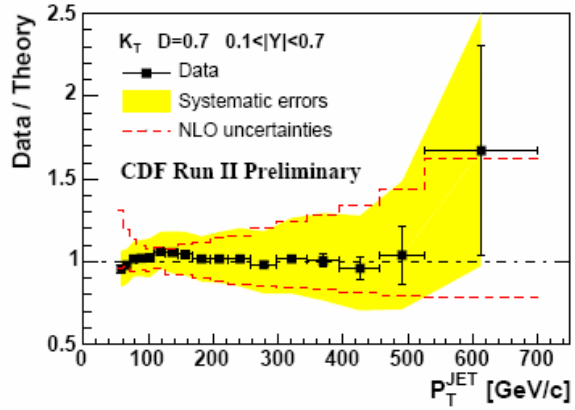
D = 0.5 | D = 0.7 | D = 1.0

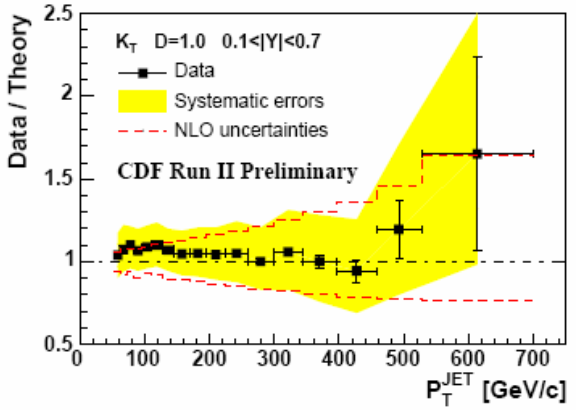


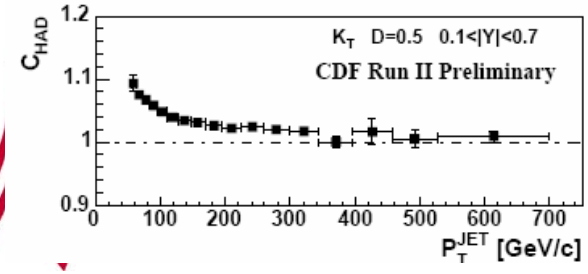


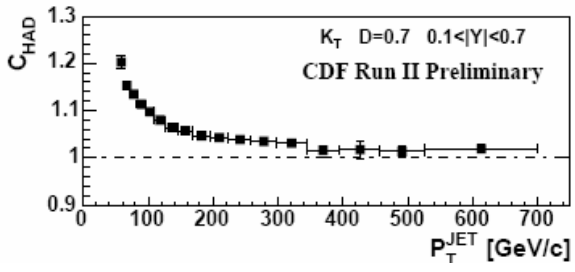


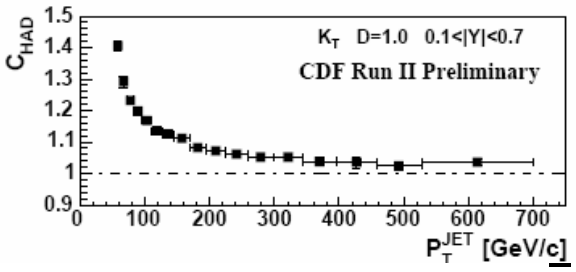






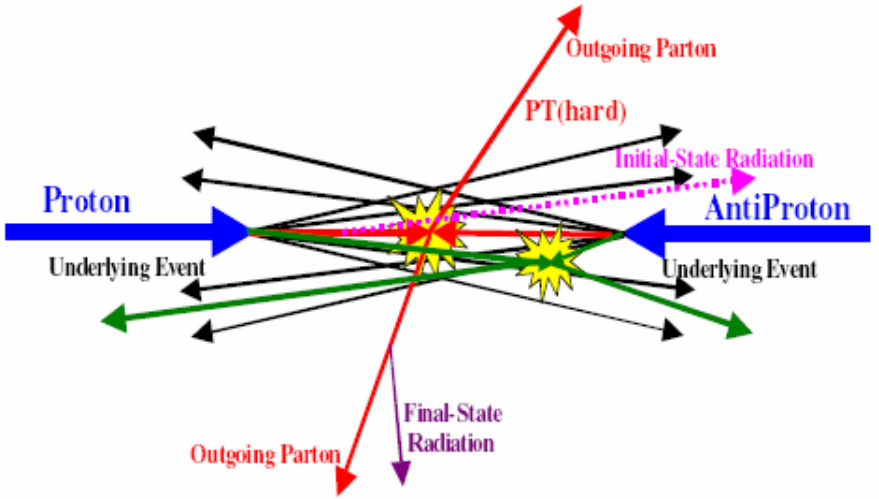


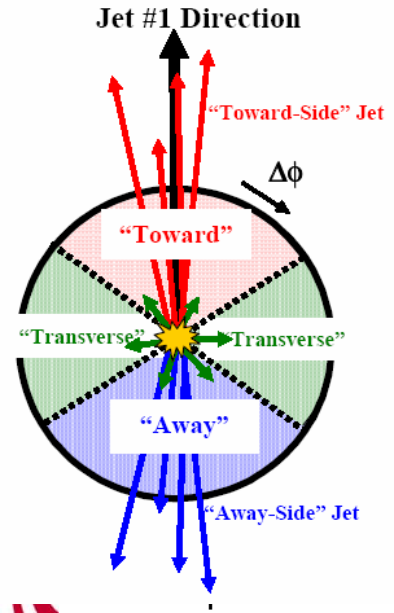


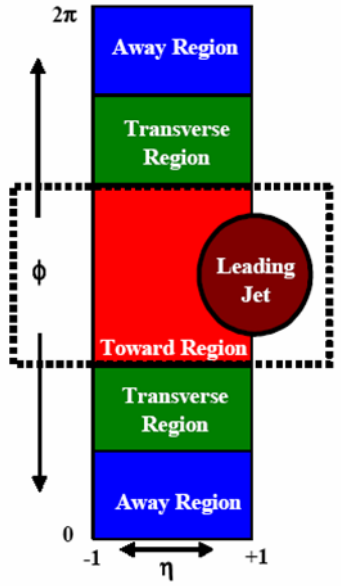


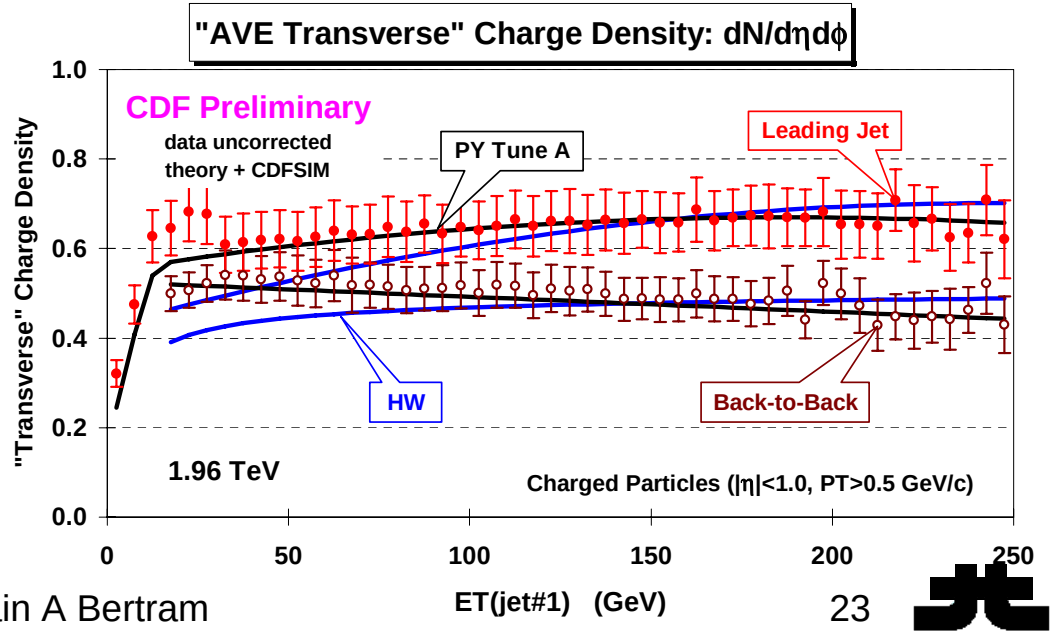
CDF Underlying Event

- Everything but the hard scattering process
  - Initial state soft radiations
  - Beam-beam remnants
  - Multiple Parton Interactions (MPI)
- Studied in the transverse region
  - Leading jet sample
  - Back-to-back sample



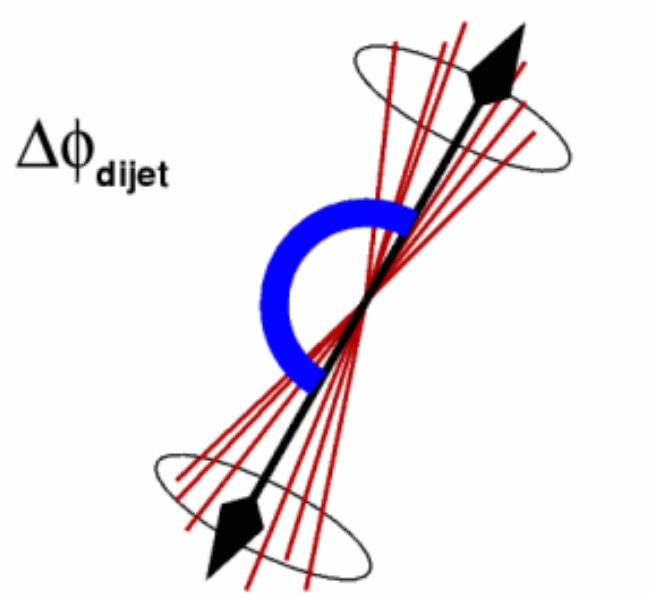






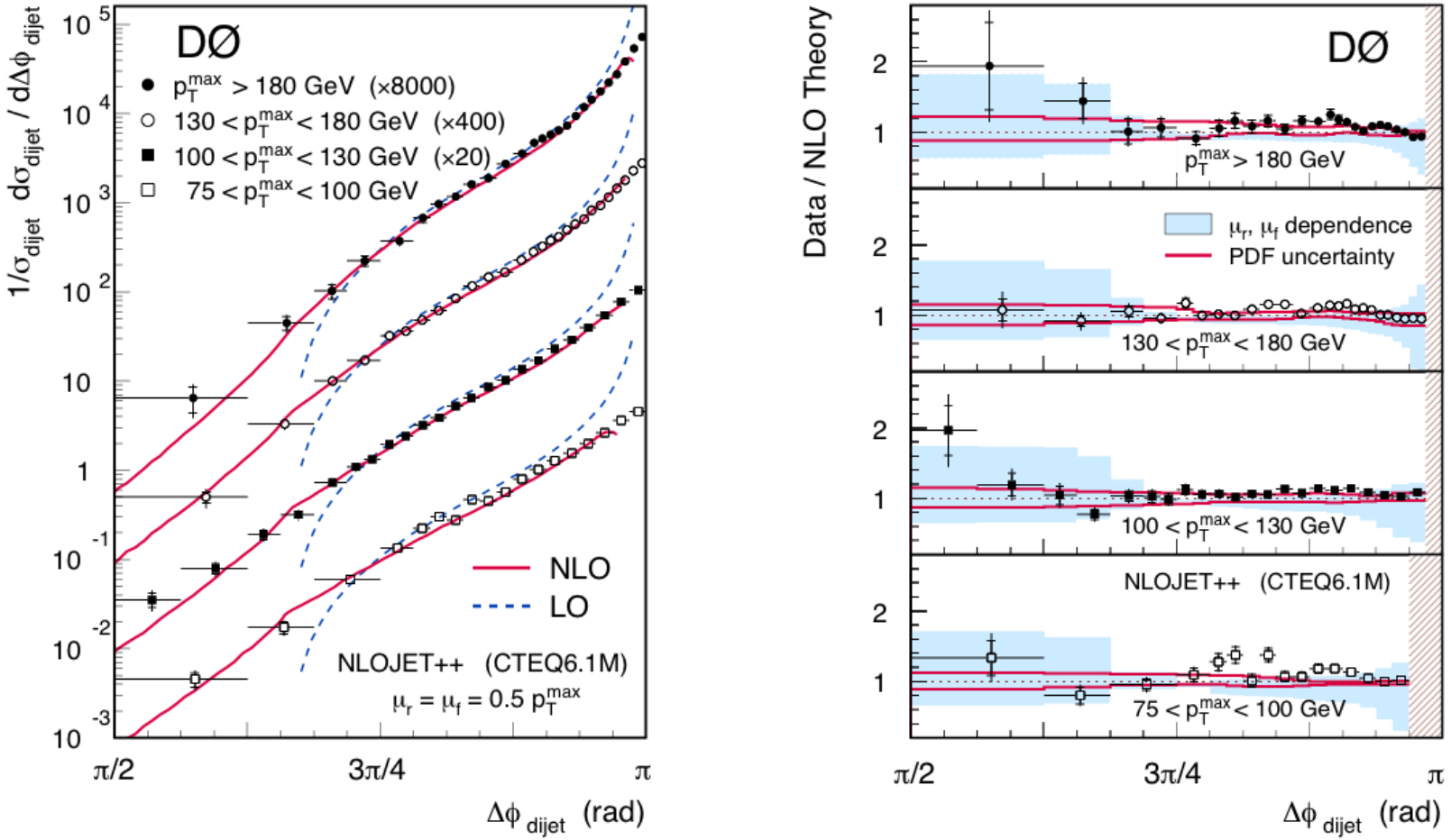
DØ Dijet azimuthal decorrelations

- Test of higher order QCD effects in two jet events without explicitly requiring additional jets.
  - additional radiation causes deviation of $\Delta\phi$ from π
  - Phys. Rev. Lett. 94 221801 (2005)



  - Data Sample
    - 150 pb^{-1}
    - 2 Jets $P_T > 40$ GeV, $|y| < 0.5$
    - Standard Jet quality criterea

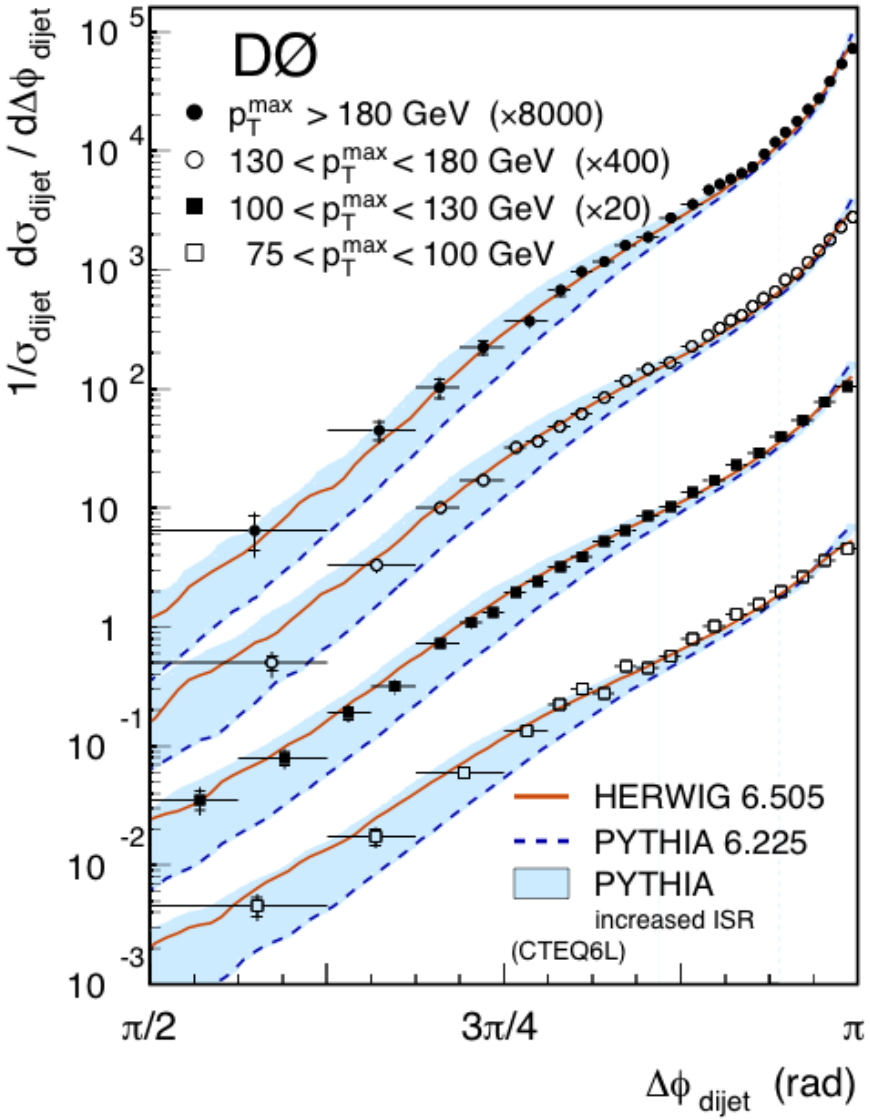
DØ Dijet azimuthal decorrelations



LO QCD fails for $\Delta\phi \approx \pi$, and $\Delta\phi \leq 2/3\pi$.
Require NLO, to describe data.

DØ Dijet azimuthal decorrelations

- Shower Monte Carlo
  - Describe the $\Delta\phi \approx \pi$ region well
  - Herwig describes $\Delta\phi < 2/3\pi$
  - Standard Pythia 6.225 underestimates $\Delta\phi < 2/3\pi$
    - Tune ISR in Pythia to get good agreement
    - Change in ISR cut-off (PAR(67)) from 1 to 4 GeV



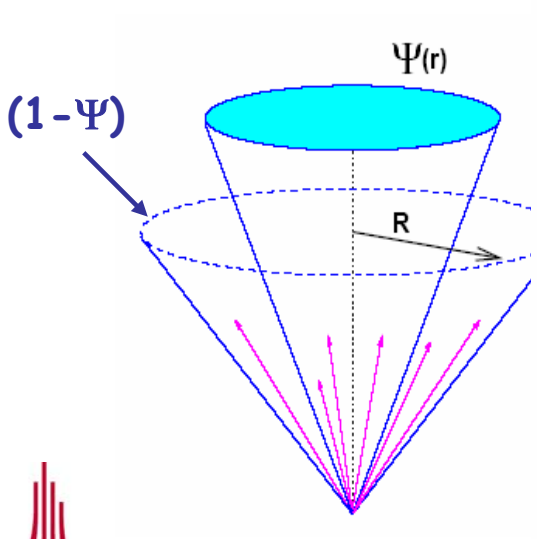
Energy Flow Inside Jets

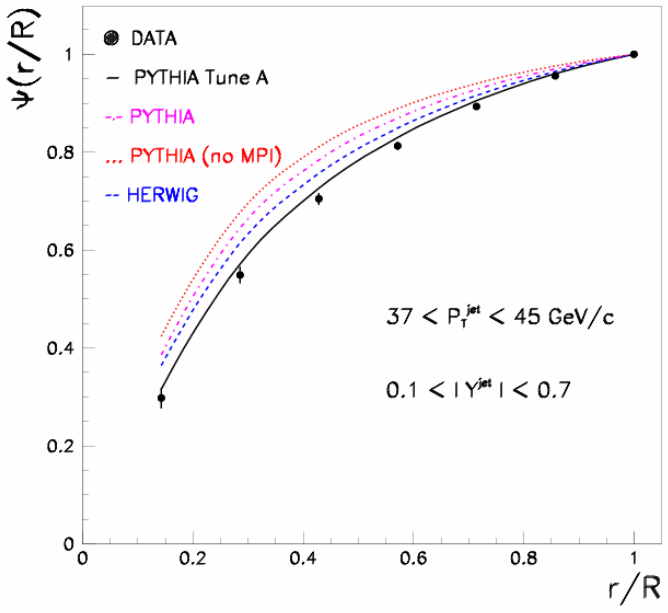
Jet shapes governed by multi-gluon emission from primary parton

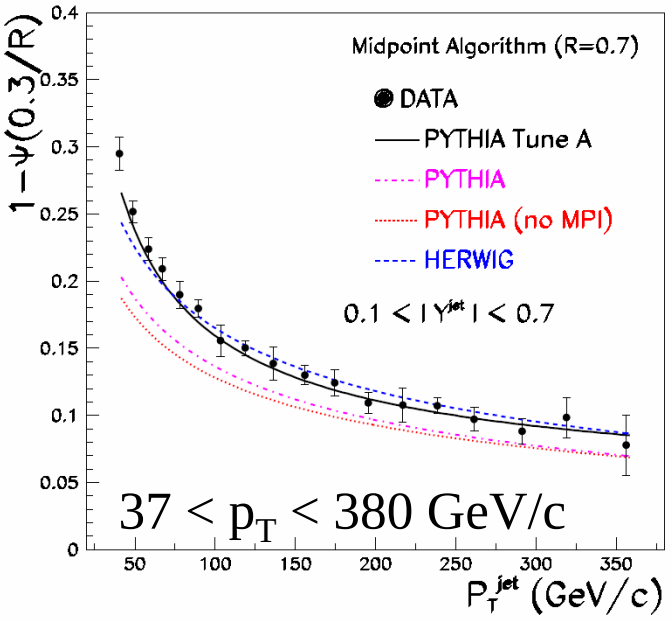
- Test of parton shower models
- Sensitive to underlying event structure
- Sensitive to quark and gluon mixture in the final state

$$\psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{P_T(0,r)}{P_T(0,R)}$$

hep-ex/0505013
(Accepted by PRD)



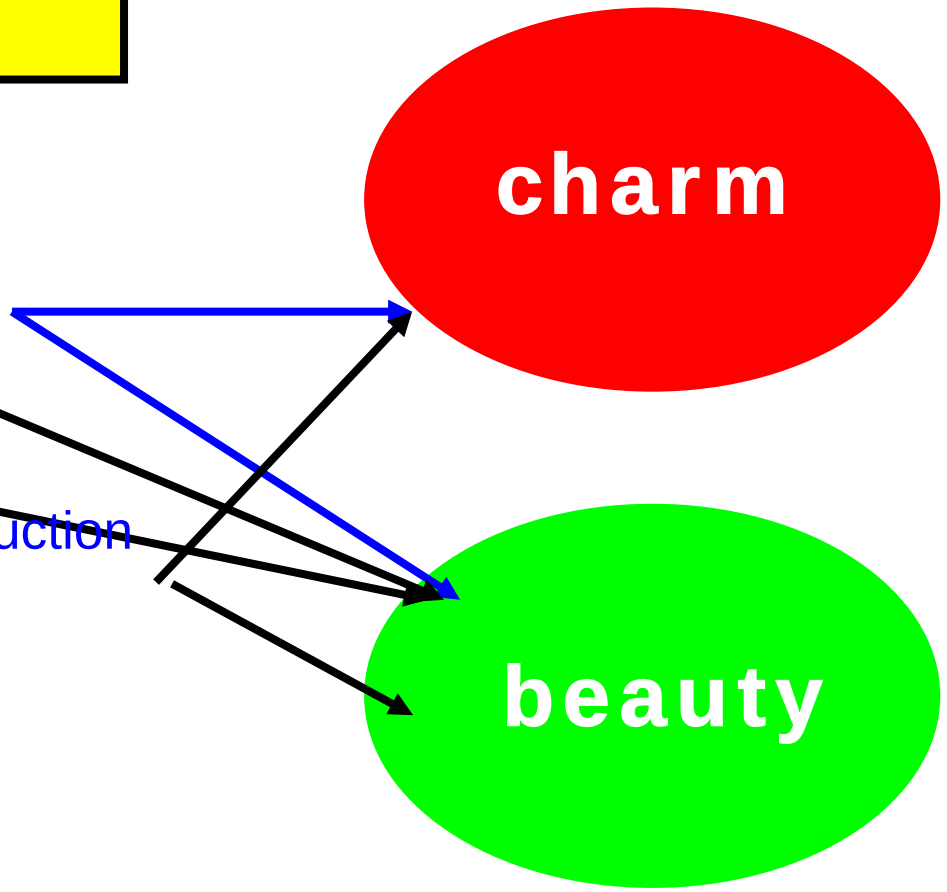




Tests of b and c production at Run 2

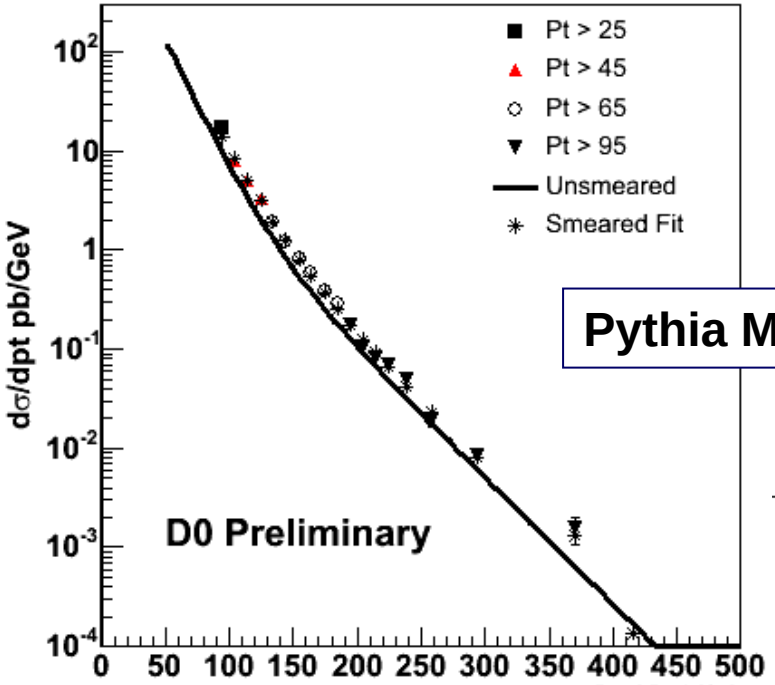
Direct and combined measurements

- 4 analyses presented:
  - Muon tagged jet production
  - Inclusive b production
  - bbbar production
  - Photon + heavy flavour production

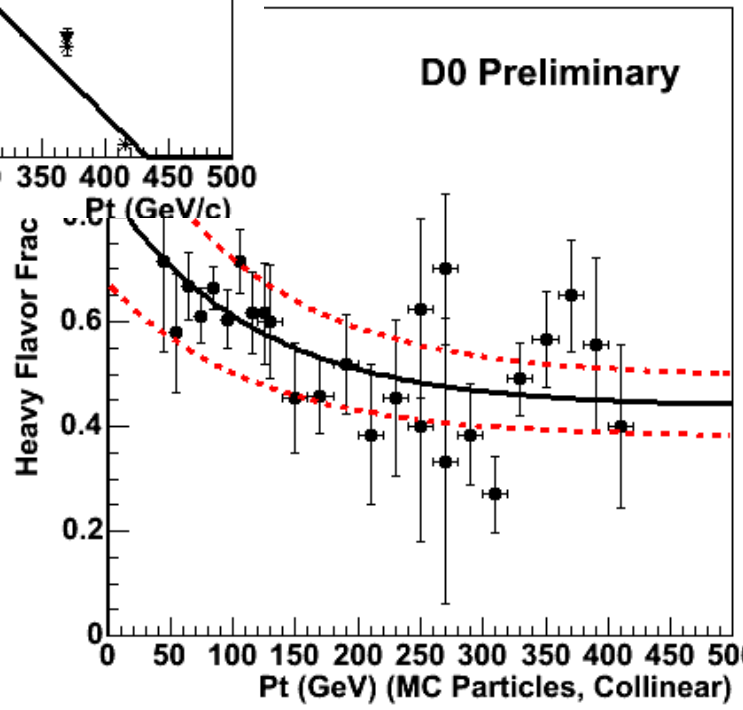


DØ μ tagged jet production

- Data Selection
  - Require events with at least 1 jet, |y|<0.5, containing a muon (pT>5 GeV)
  - Jet pT 90 – 400 GeV considered
  - 294 pb-1 data analysed
- Extract heavy flavour component from simulation
  - Measurement sensitive to b + c production

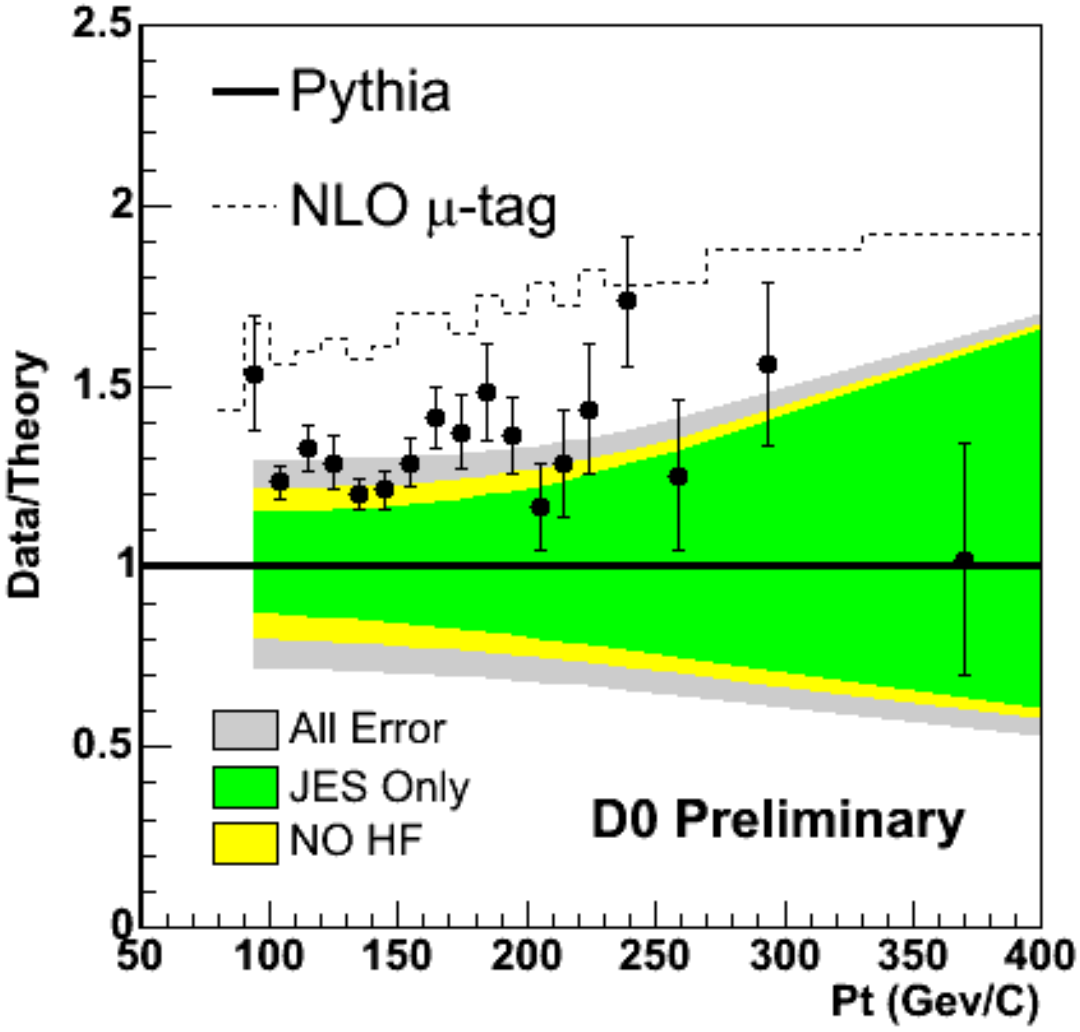


Pythia MC



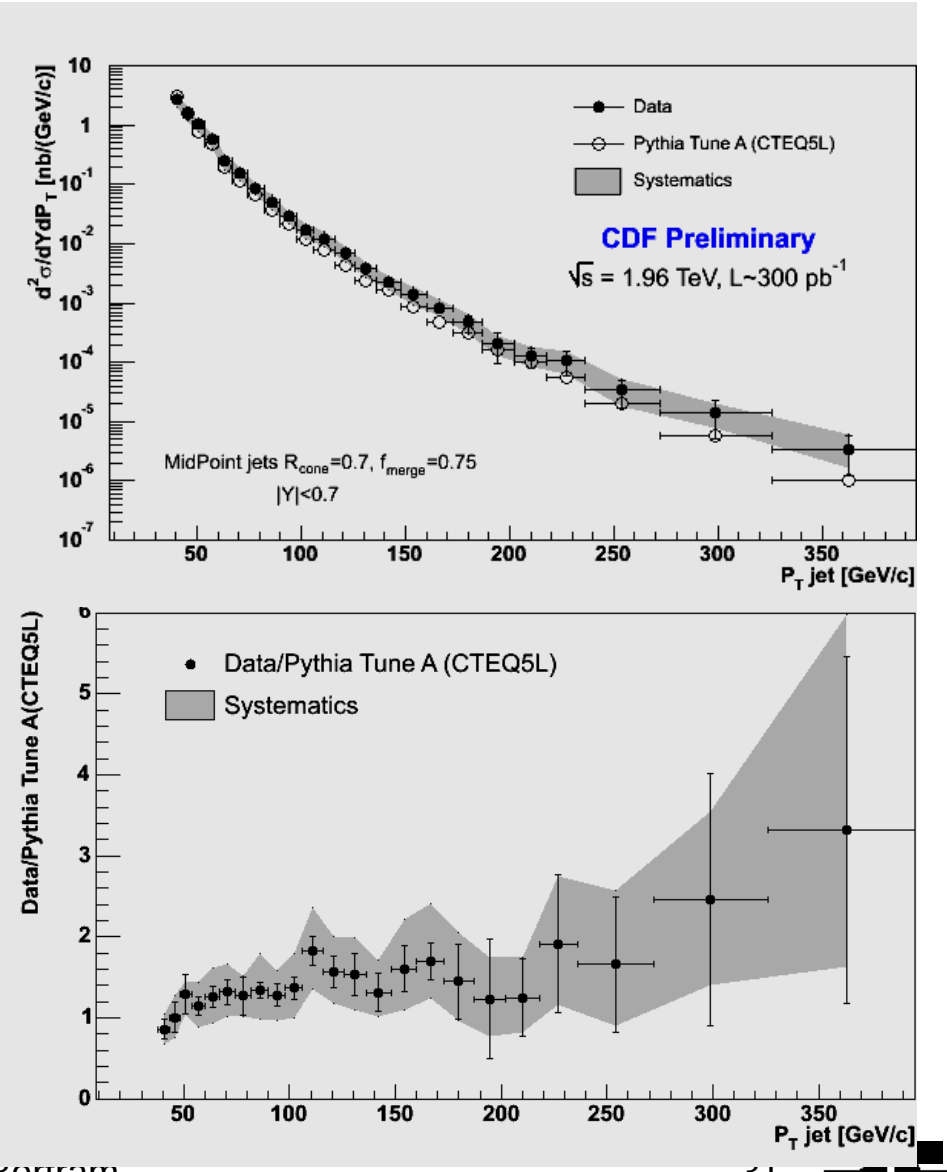
DØ μ tagged jet production

- Results consistent with LO (Pythia CTEQ 6L) and NLO (NLOJET++ CTEQ6M)
  - NLOJET++: Z. Nagy, Phys. Rev. Lett. 88 122003 (2002); Phys. Rev. D68 094002 (2003)



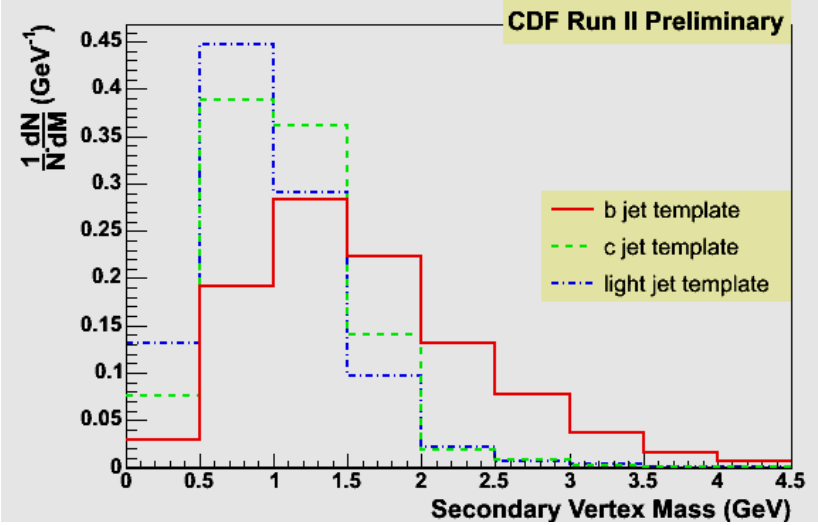
CDF Inclusive b production

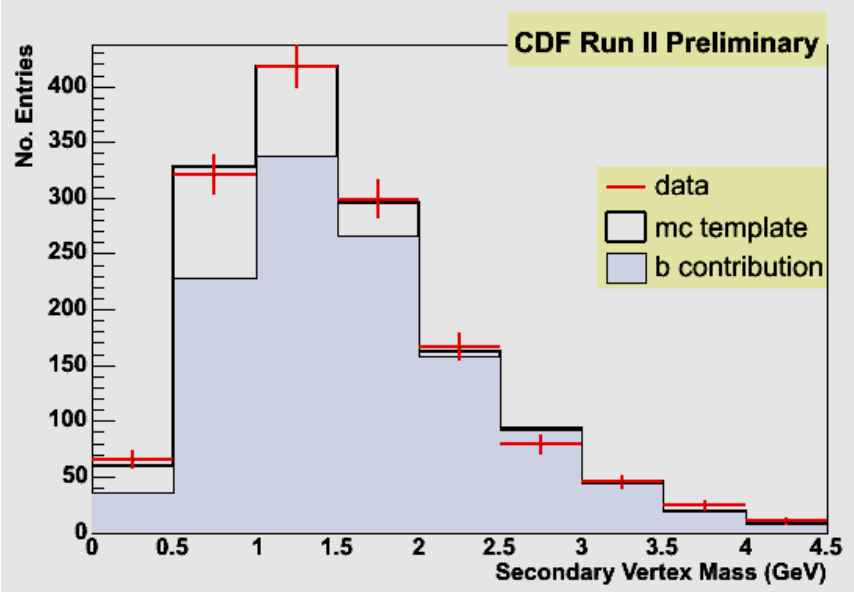
- Require 1 jet, |h|<0.7, with separated secondary vertex
  - Jet Et 38 – 400 GeV
  - 300 pb-1 data analysed
- Determine b fraction by fit to secondary vertex mass
- Results compared to LO (no NLO yet) : ratio ~1.4 as expected



bb production

- Require 2 jets, |η|<1.2, both with separated secondary vertex
  - Et 1 > 30 GeV, Et 2 > 20 GeV
  - 64.5 pb-1 data analysed
- Determine b fraction by fit to secondary vertex mass
- Calculate cross-section as fn. of :
  - Jet Et, m(bb), Δφ(b jets)



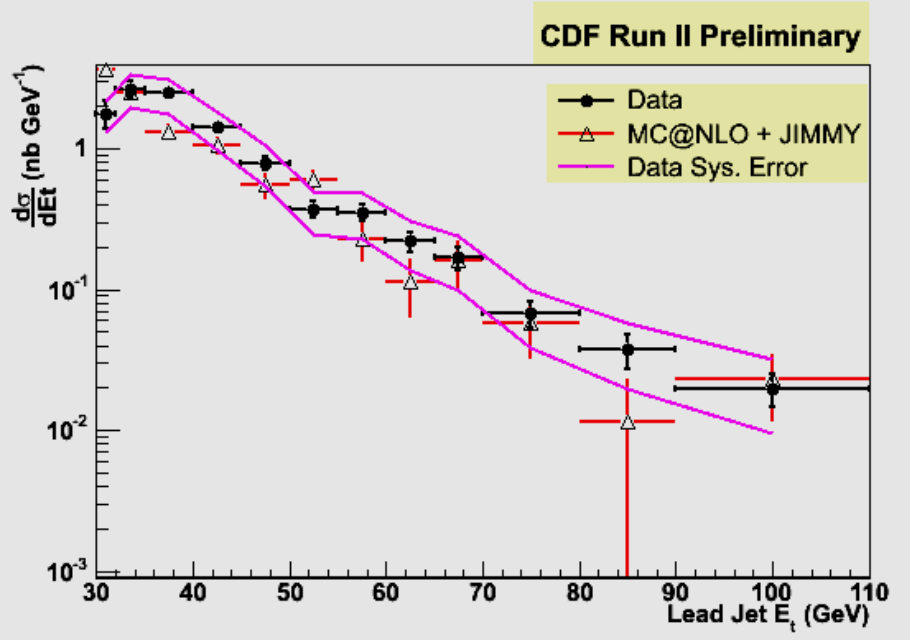


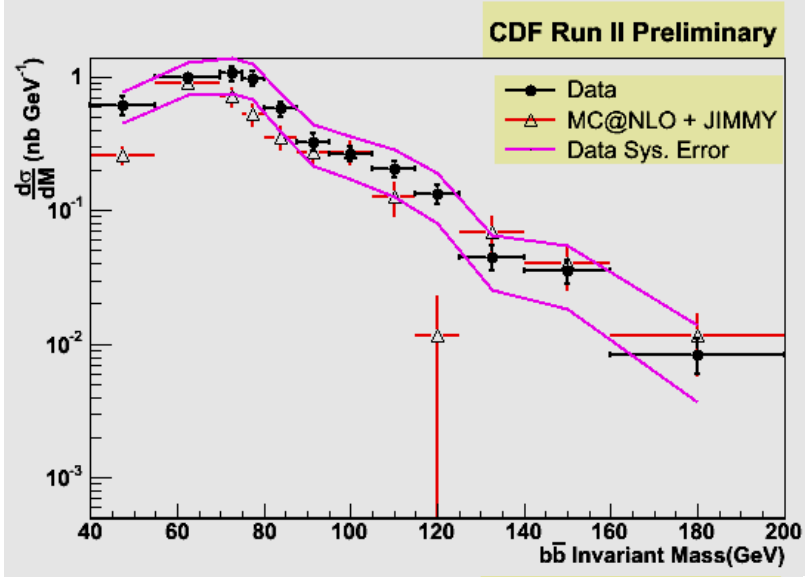
CDF bb production

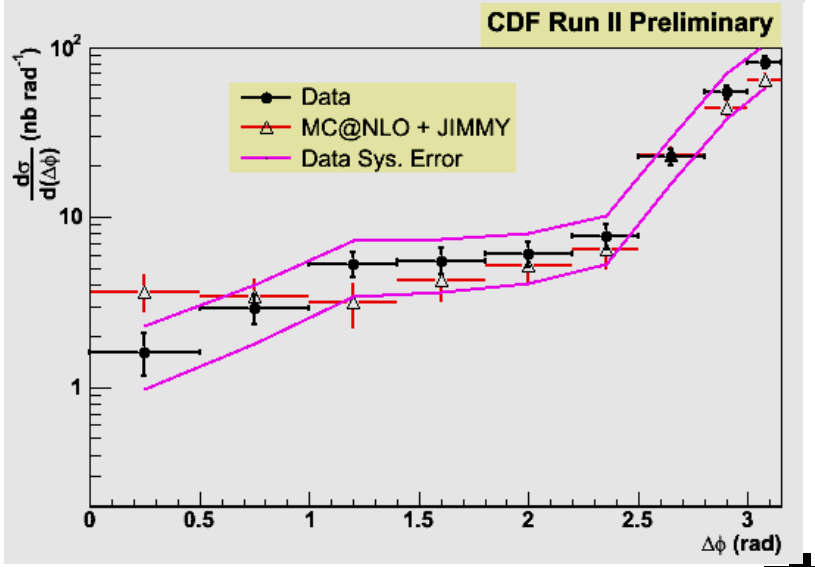
- σ (bb)(|η|<1.2, Et_1>30GeV, Et_2>20GeV) = 34.5 ± 1.8 ± 10.5 nb
  - LO: 38.7 ± 0.6 nb
  - NLO: 35.7 ± 2.0 nb

- Results consistent with LO (Pythia CTEQ5L) and NLO (MC@NLO + JIMMY U.E. simulation)
- Note: selection enhances flavour creation (LO)

bb production



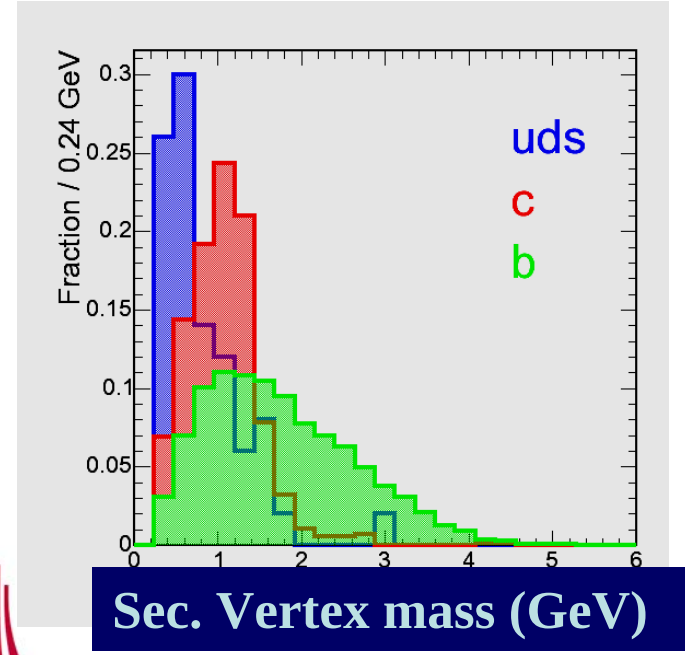


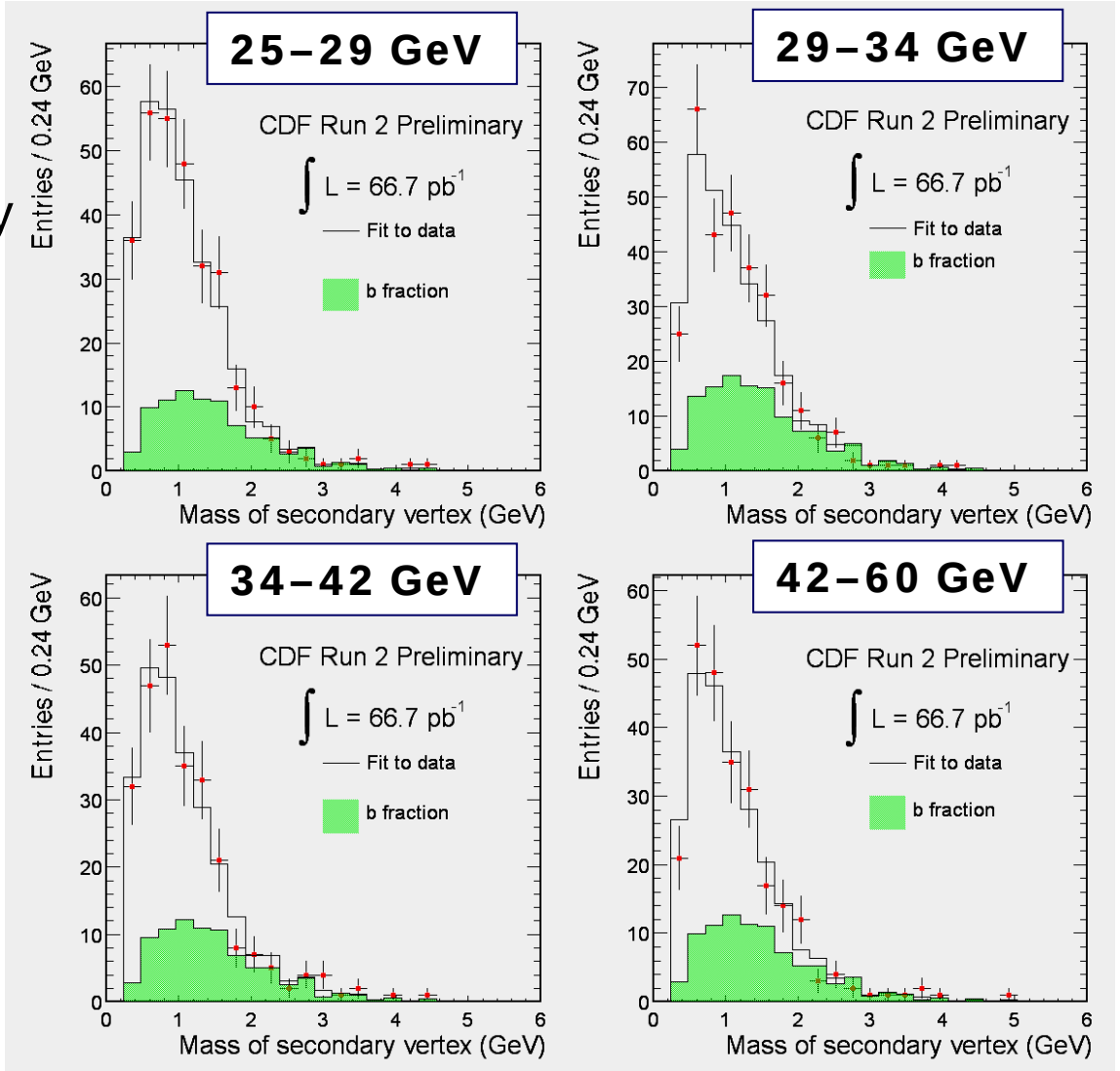


Results consistent with LO (Pythia CTEQ5L) and NLO (MC@NLO + JIMMY U.E. simulation)

CDF γ + b / γ + c production

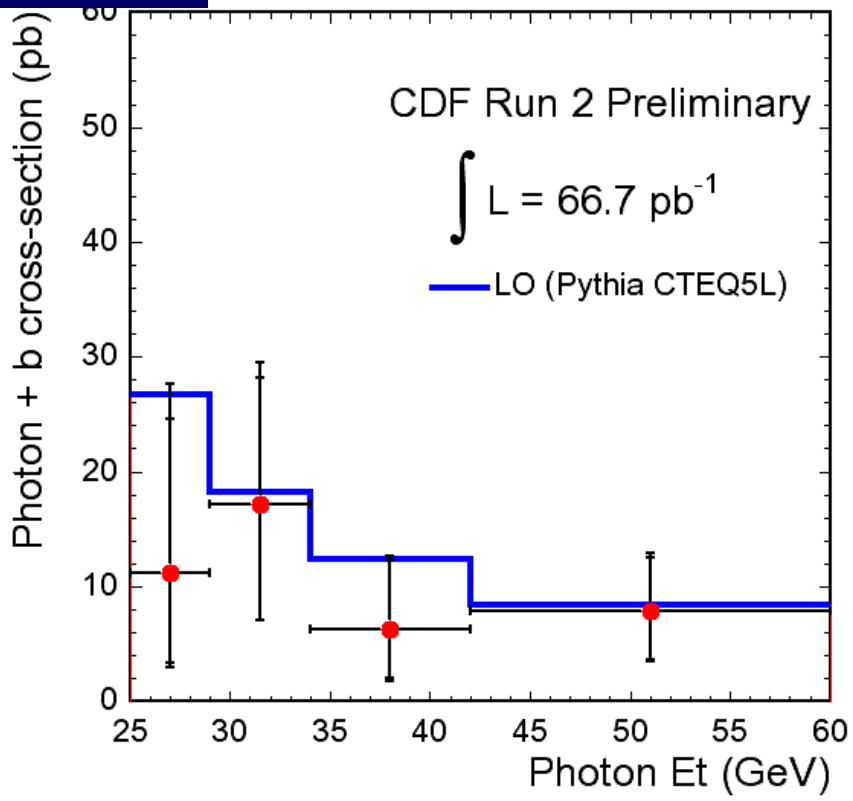
- γ Et > 25 GeV (|η|<1.0) + jet with secondary vertex
- Determine b, c, uds contributions (fit secondary vertex mass)
- Subtract bkg, find cross-section as fn. of γ Et



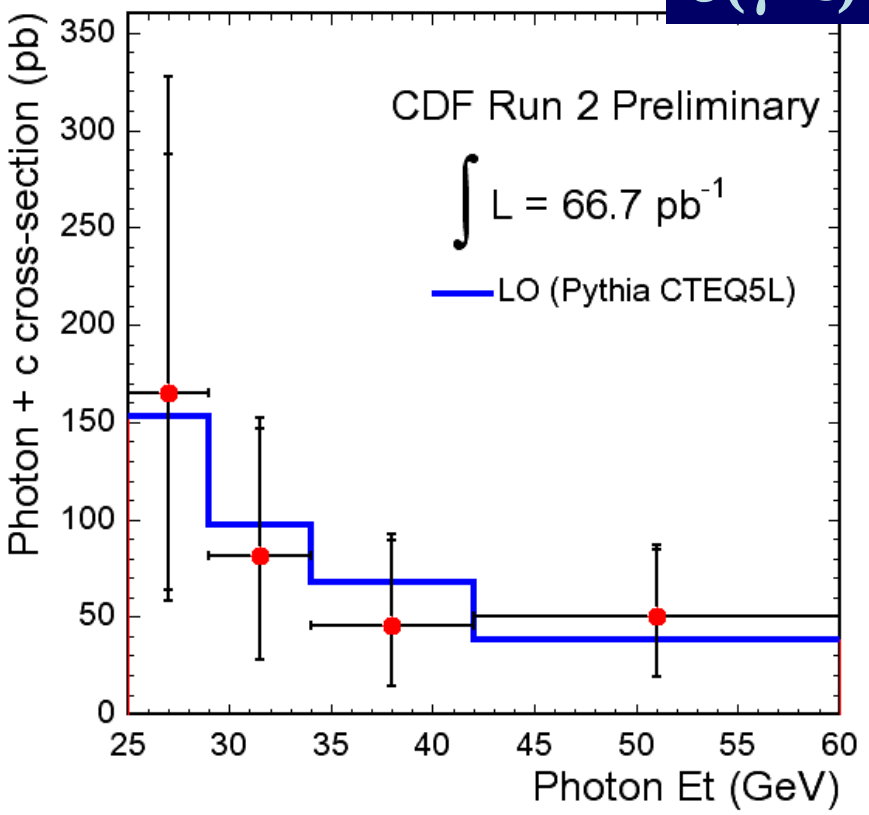


CDF γ + b / γ + c production

σ(γ+b)



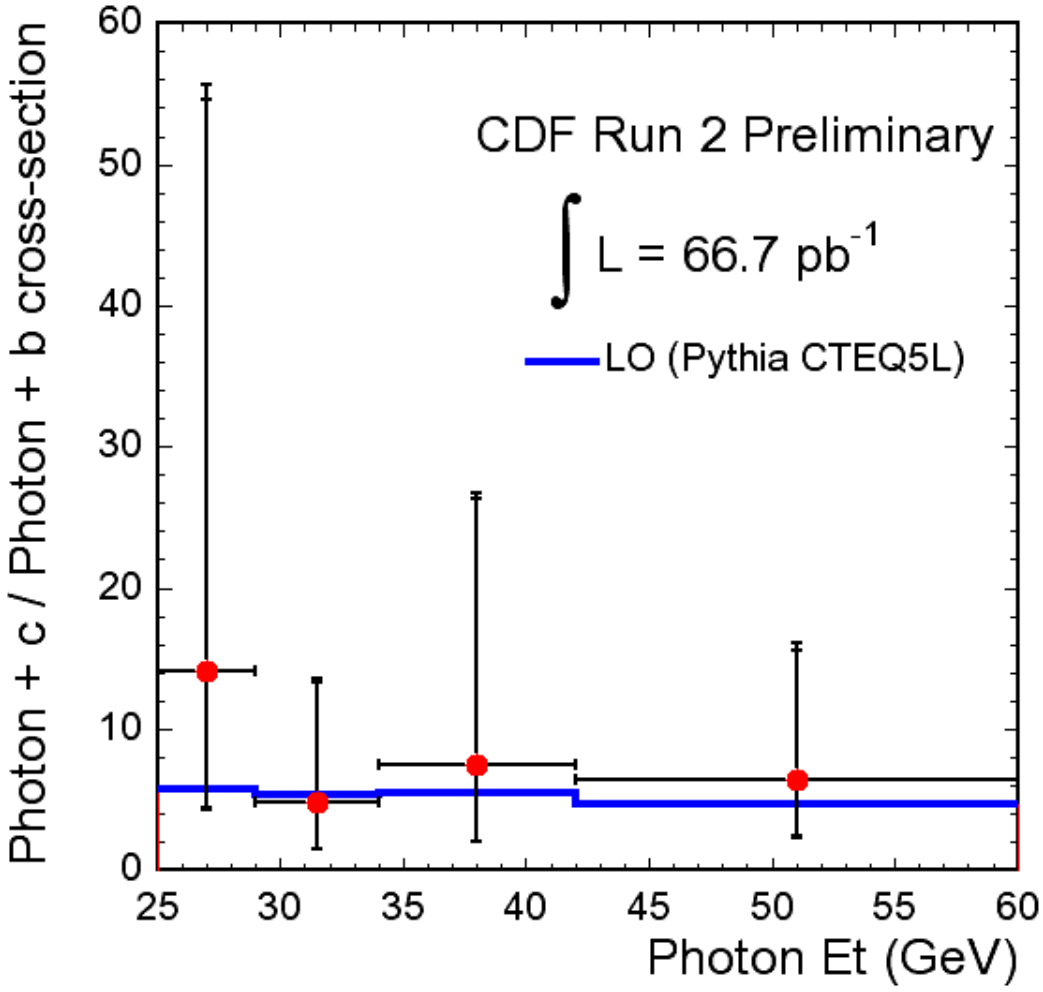
σ(γ+c)



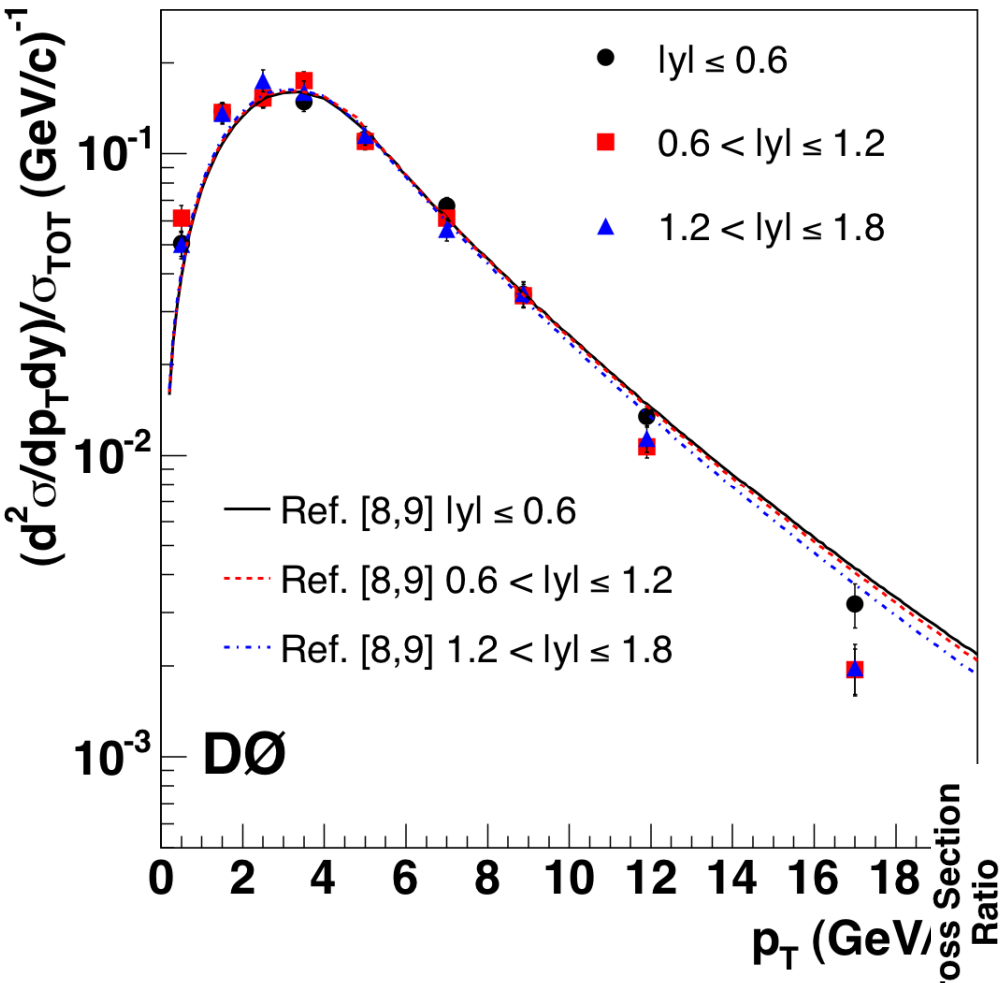
Results consistent with LO

CDF $\sigma(\gamma + c) / \sigma(\gamma + b)$

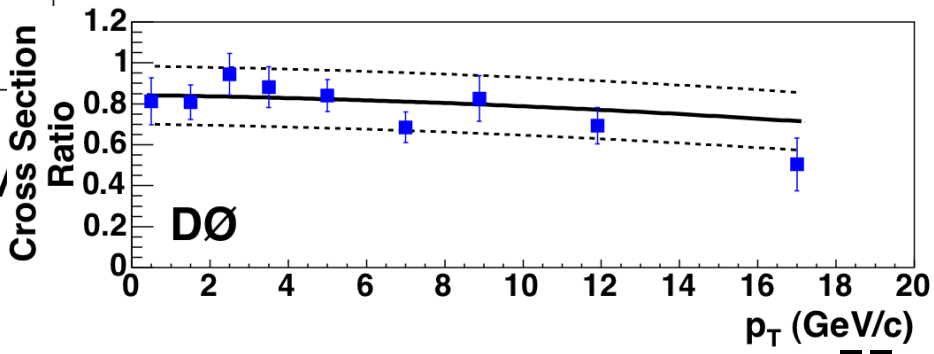
Ratio consistent with LO



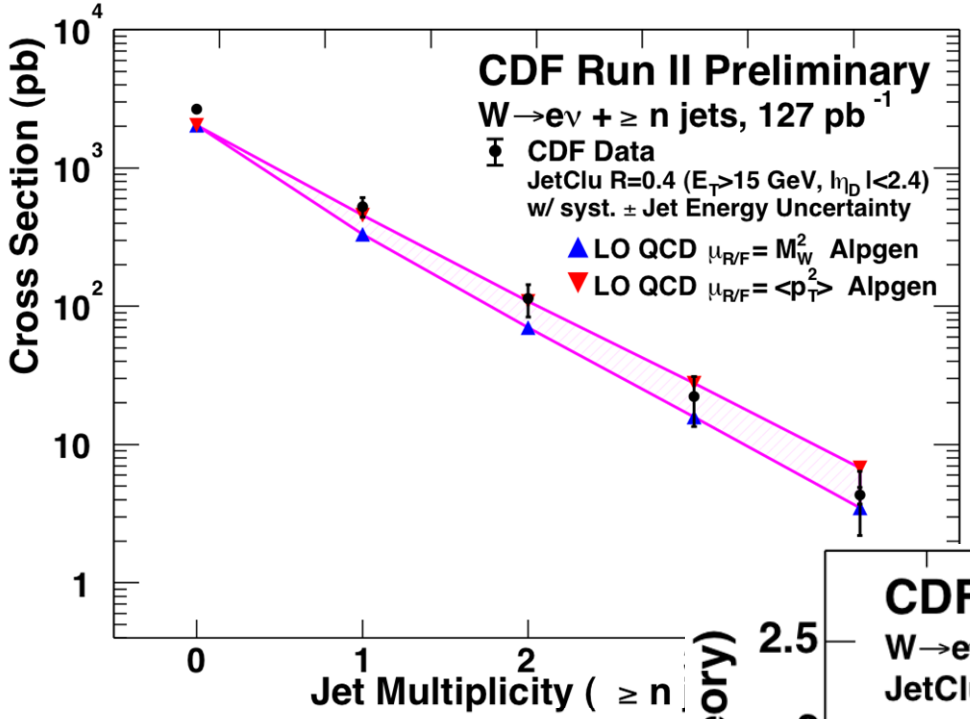
DØ Ψ(1S) Production



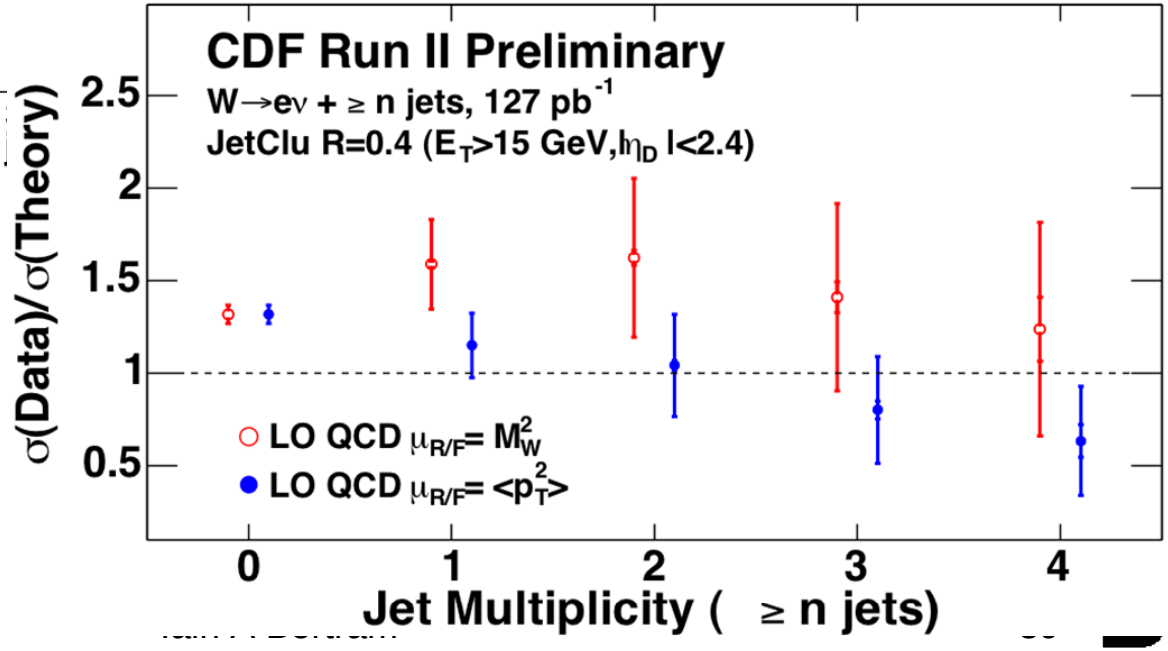
- little variation in the shape of the cross section as a function of rapidity
- reasonable agreement with calculations byBerger et al, hep-ph/0411026



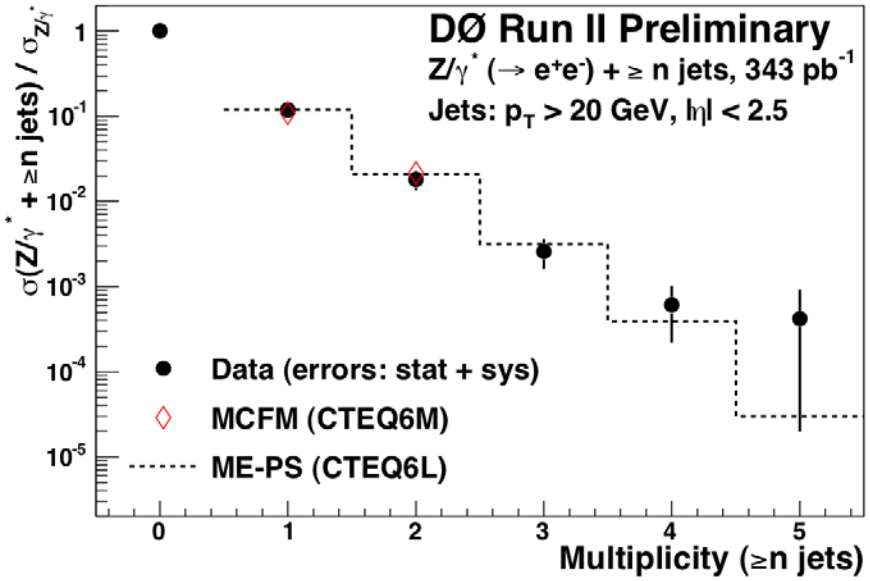
CDF W + jets

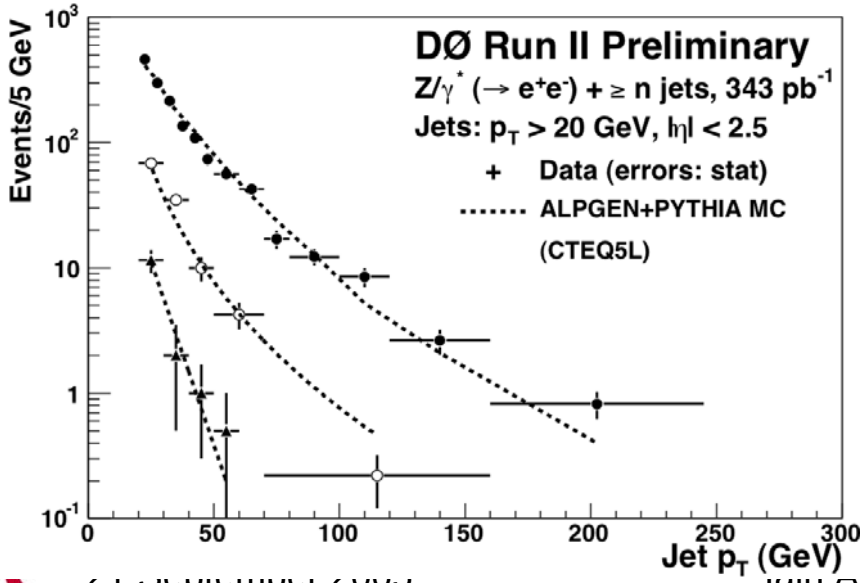


- L = 127 pb^{-1}
- Major background for top, Higgs Searches, SUSY etc.
- Alpgen and Pythia reproduce number and p_T of Jets



DØ Z (+ n jets)





- L = 343 pb^{-1}
- Major background for Higgs Searches

- Alpgen and Pythia reproduce number and p_T of Jets
- NNLO represents rapidity well

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Summary

- **Excellent Results, steady improvement over Run I**
- **Expect analyses with1 fb^{-1} of data in the new year**
- **Major improvement of Jet Energy Scales to come**