Jet and Photon Production at the Tevatron

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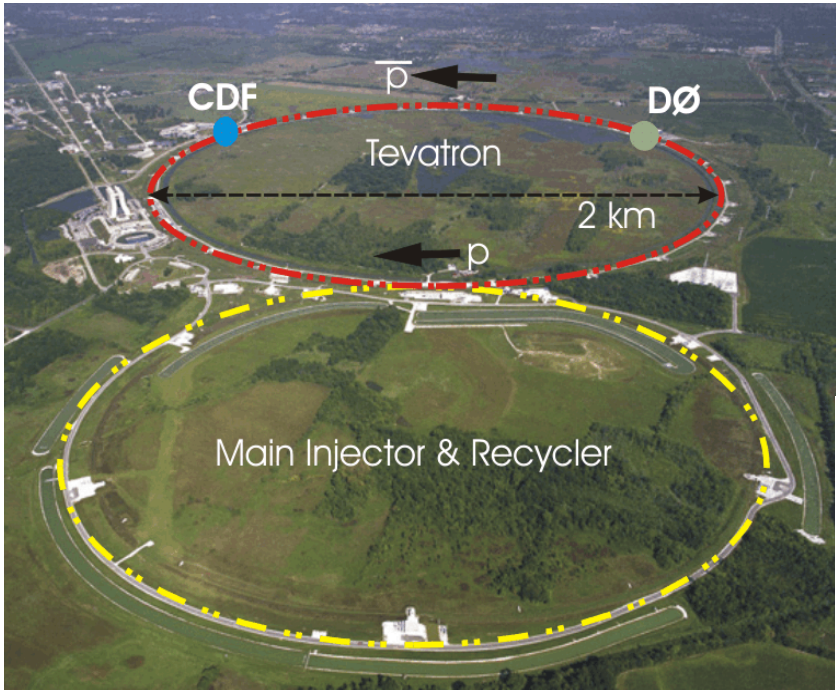
Fermilab

For CDF and DØ Collaborations

Talk Outline

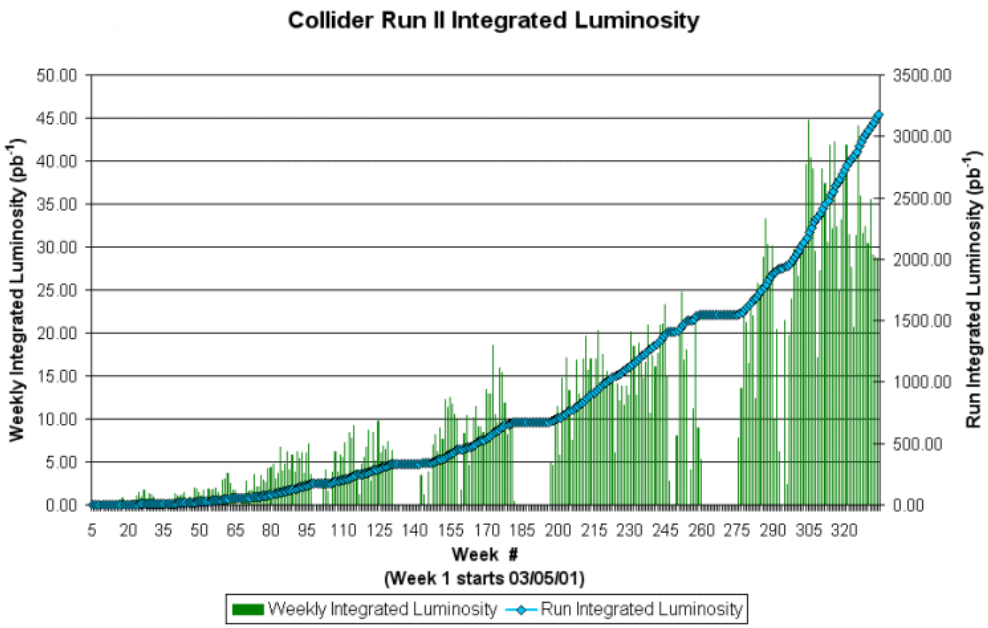
- In this talk
  - New results since summer 06 based on $\int\mathcal{L} \geq 1\ fb^{-1}$ of data
    - Inclusive jet production
    - Dijet production (jj, b-bbar)
    - γ+jet triple differential cross section
    - Inclusive Z+jets and Z+b-jet production
    - W+c-jet production
- Other results (not in this talk)
  - There are many more interesting analyses…
    - Jet fragmentation, underlying event, etc.

Tevatron in Run II

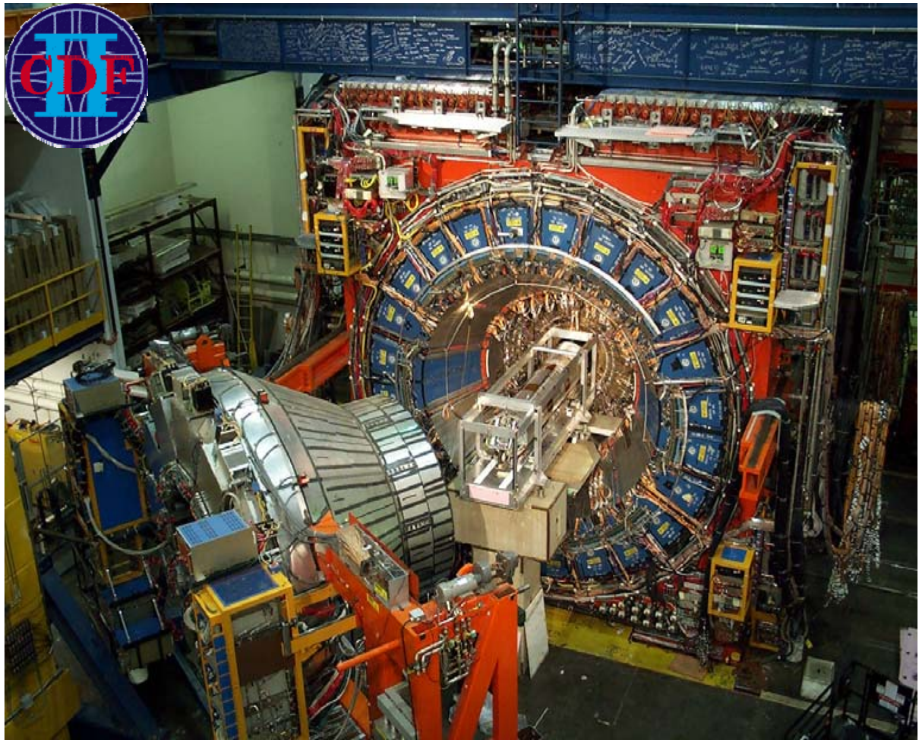


- 36×36 bunches
- Collisions every 396 ns
- Two experiments: CDF & DØ

- Proton-antiproton collisions at $\sqrt{s}=1.96$ TeV
- Delivered luminosity
  - Current: 3.3 fb^{-1} per experiment
  - Goal by 2009: 5-8 fb^{-1}

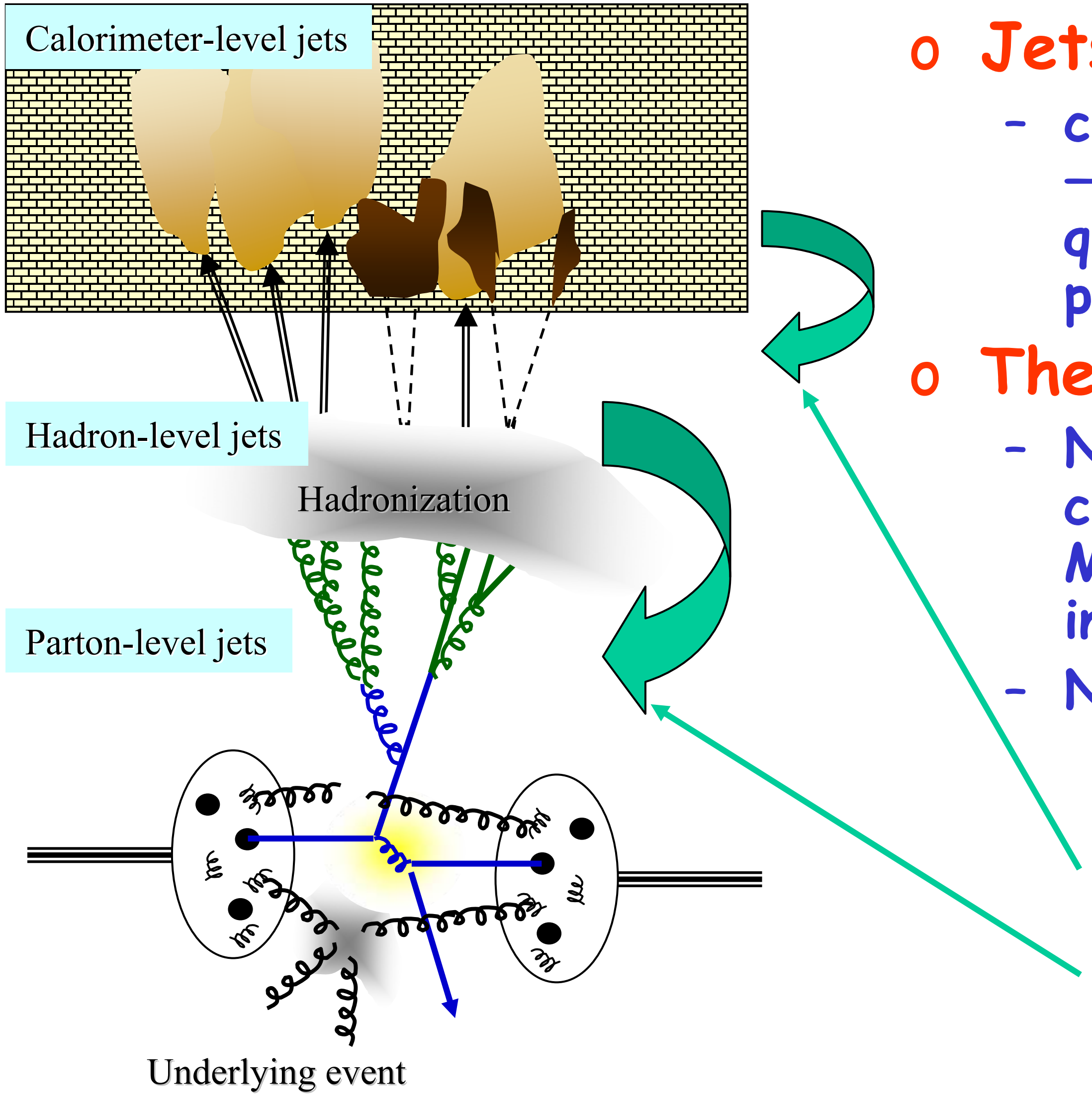


CDF and DØ Experiments



- Multipurpose detectors — classic design
  - "silicon", central tracker, solenoid, calorimeter, muon chambers
- Operating well: 80-90% efficiency
- Broad physics program
  - QCD, EWK, top, B-physics, Higgs searches, searches for new physics

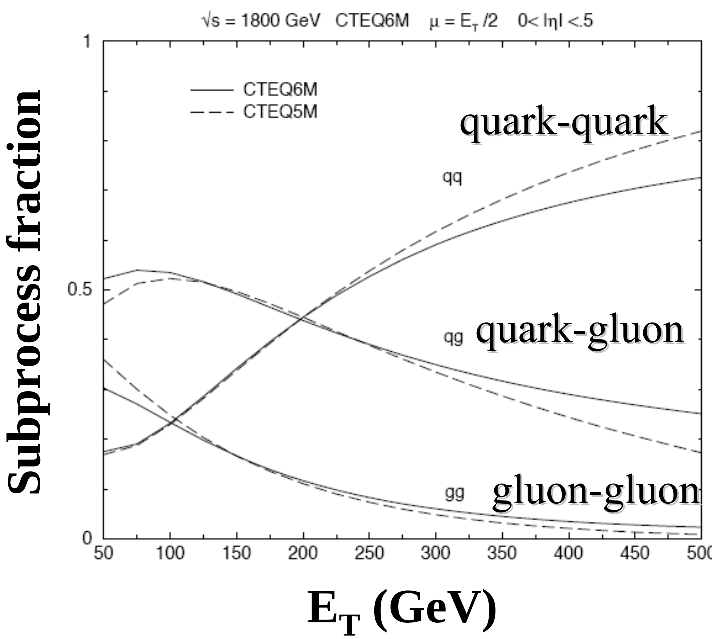
Jet Production at Hadron Collider

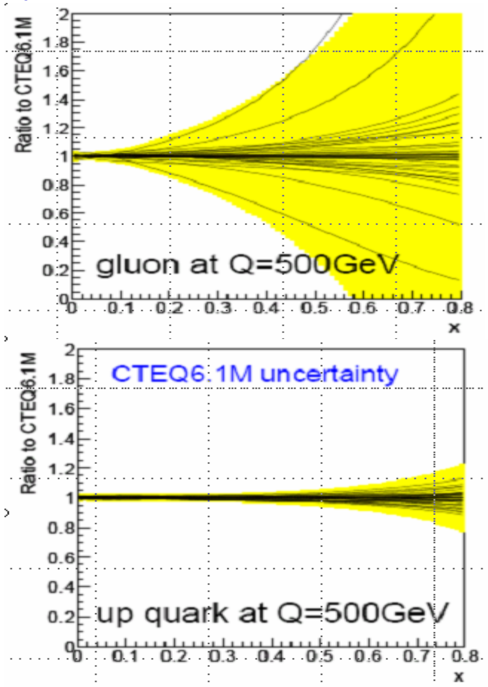


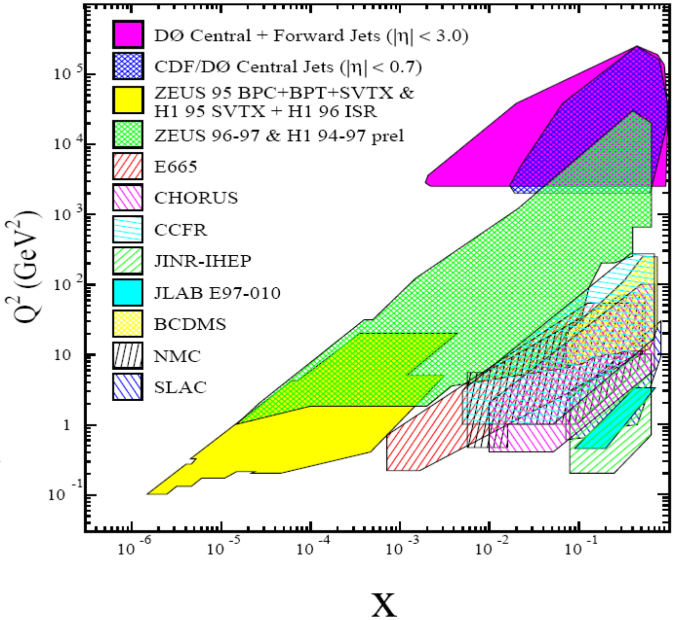
- Jets
  - collimated sprays of particles — experimental signatures of quarks and gluons from hard processes
- Theory deals with partons
  - Need well defined jet clustering algorithm (e.g., MidPoint cone or k_T — infrared & collinear safe)
  - Need set of corrections for
    - Underlying event & multiple interaction
    - Detector effects (Jet Energy Scale):dector→hadron
    - Hadronization effects: hadron→parton

Measurements with Jets

- Test pQCD predictions
- Sensitive to new physics
- Constrain α_s and PDFs
  - Sizable contribution from gq (~30% even at 500 GeV)
  - Gluon PDF not well known

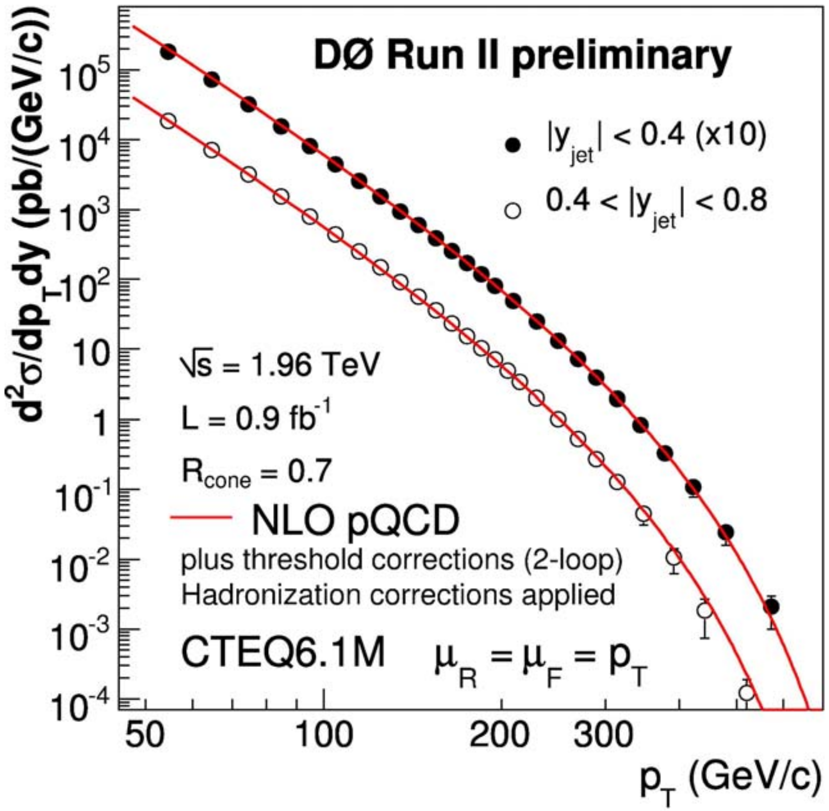


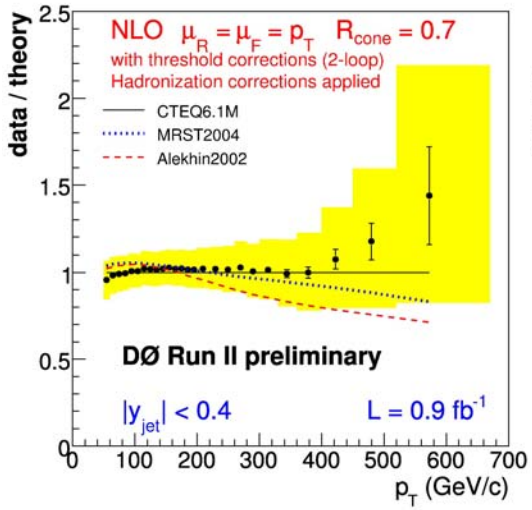


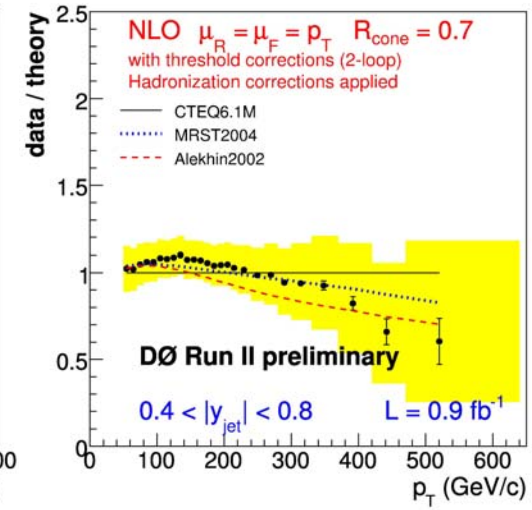


- Forward jets
  - Probe higher x at lower Q^2 than central jets
  - Extend sensitivity at lower x

Inclusive Jet Production (DØ)







L=0.9 fb^{-1}

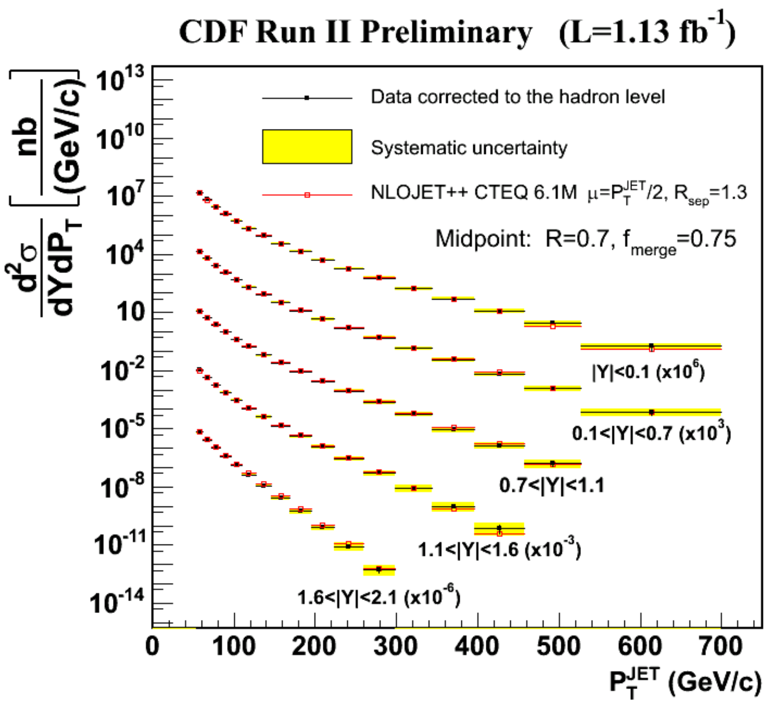
- MidPoint cone algorithm
  - ΔR=0.7, f_{merge}=0.5
- Two central rapidity regions
  - $|y_{jet}|<0.4$; $0.4<|y_{jet}|<0.8$
- Comparison to NLO predictions after unsmearing
  - PDF uncertainty ≈ syst. uncertainty
  - Experimental uncertainty dominated by uncertainty on jet energy scale (JES)

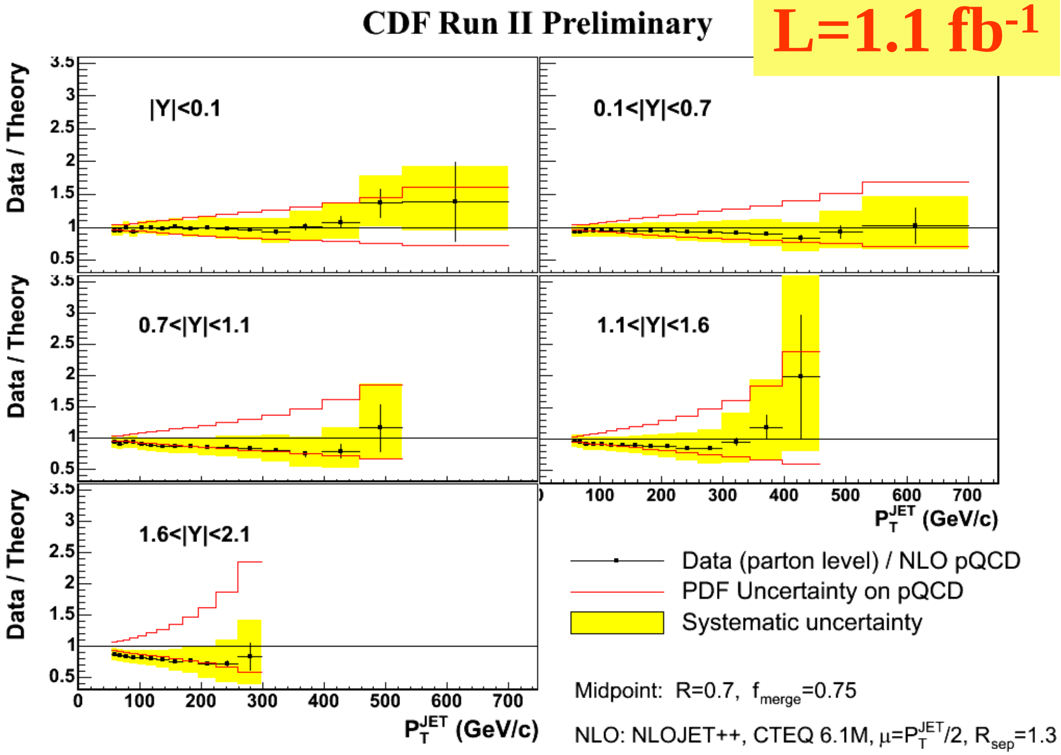
Inclusive Jet Production (CDF)

- MidPoint cone algorithm: $\Delta R=0.7$, $f_{merge}=0.75$
- 5 rapidity bins: 0.1,0.7,1.1,1.6,2.1
- Consistent with NLO predictions after unsmearing
  - Experimental uncertainty dominated by JES
  - Theory uncertainty mainly from PDFs

Experimental uncertainty in forward region smaller than PDF uncertainty!!

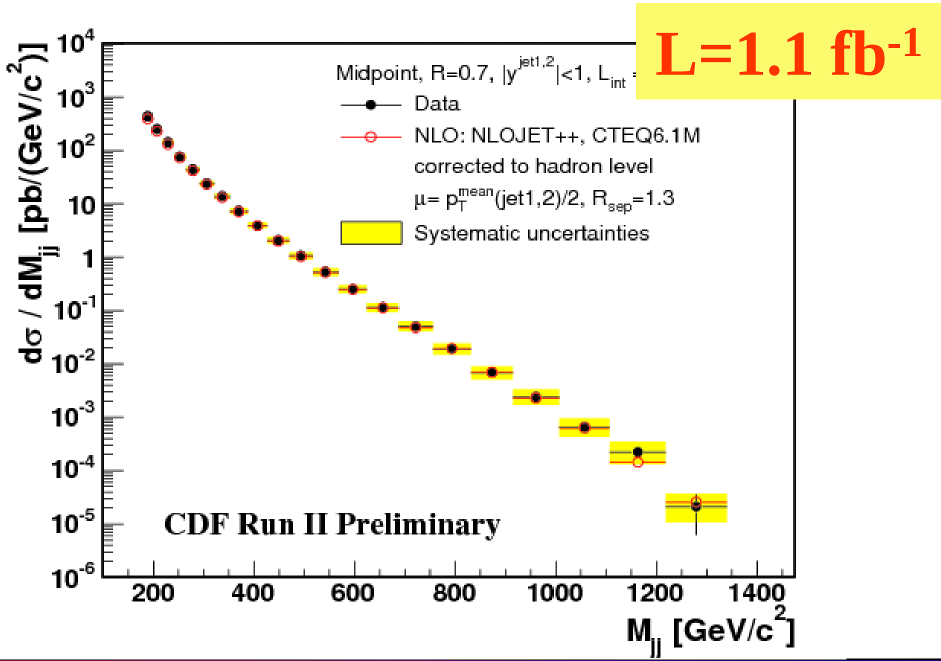
$L=1.1\ fb^{-1}$

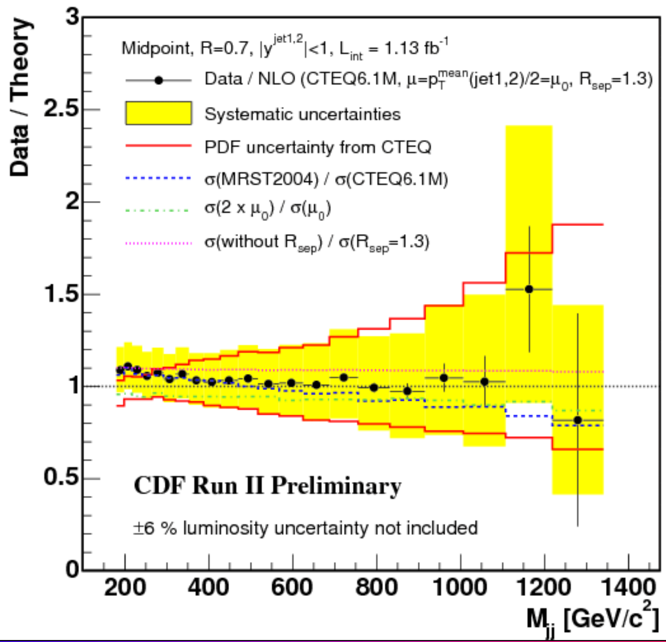




Inclusive Dijet Production (CDF)

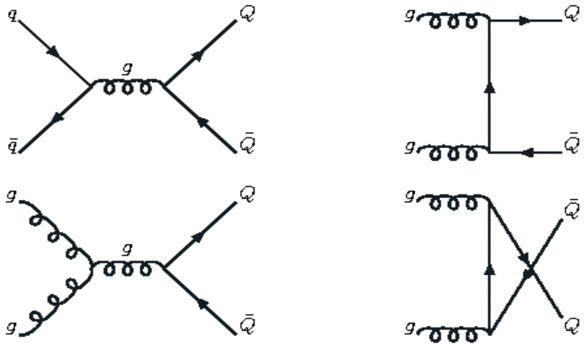
- Test of pQCD
- Sensitive to new physics: massive particles, compositeness
- MidPoint cone algorithm: $\Delta R=0.7$, $f_{merge}=0.75$
- Two central jets: $|y_{jet1,2}|<1.0$
- Consistent with NLO predictions after unsmearing
  - Experimental uncertainty (mostly JES) ~ PDF uncertainty





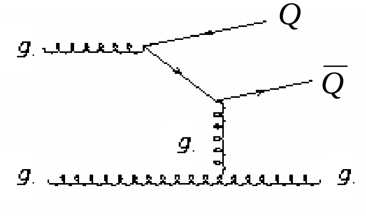
$b\bar{b}$ Dijet Production (CDF)

Flavor creation

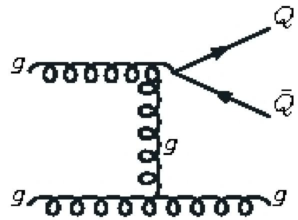


Leading order processes

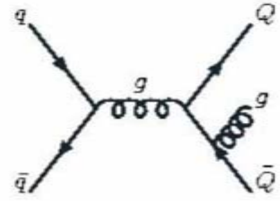
Flavor excitation



Gluon splitting



Gluon radiation

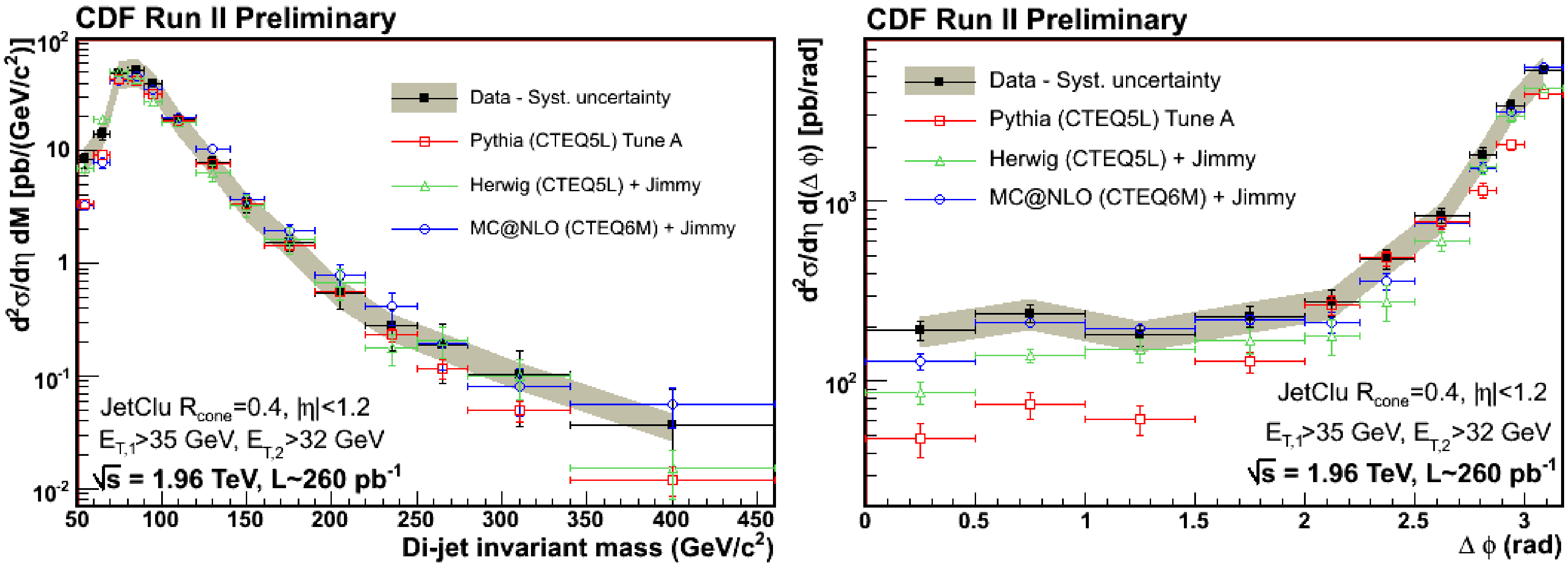


Next-to-Leading order processes

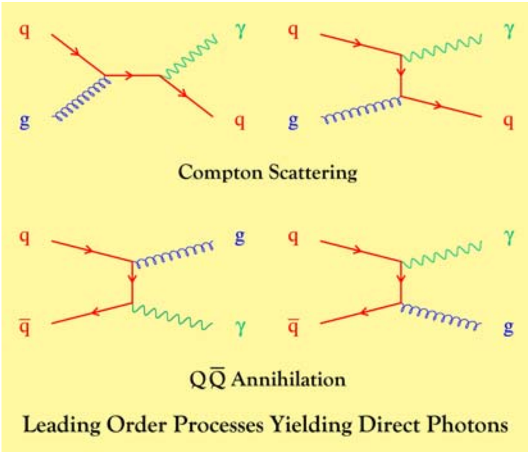
- ***b*-jet production**
  - Signature of many important EWK and new physics processes
  - Understanding b-jet production proved to be a challenge in QCD
  - Sensitivity to different production mechanisms:
    - LO processes at large $\Delta\varphi$; NLO processes at small $\Delta\varphi$
- **CDF analysis based on $\int\mathcal{L}=260\ pb^{-1}$ of data**
  - 2 jets (cone algorithm, R=0.4) with $E_{T,1}>35$ and $E_{T,2}>32$; $|\eta|<1.2$
  - Both jets b-tagged by displaced secondary vertex on L2 trigger and offline (sample purity is 85%)

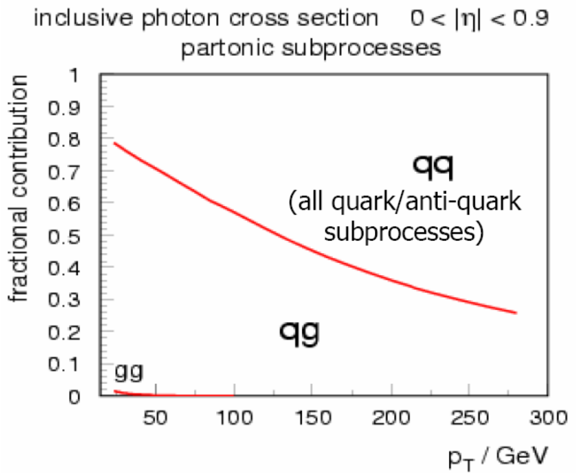
$b\bar{b}$ Dijet Production (CDF)

- differential dijet cross sections vs. $E_{T,1}$, M_{jj}, $\Delta\varphi$
- $\Delta\varphi$ very sensitive to NLO contributions
- LO predictions (using CTEQ5L): Pythia Tune A, Herwig+Jimmy
  - Fails to describe small $\Delta\varphi$
- NLO predictions: MC@NLO(CTEQ6M)+Jimmy
  - describes data well in almost entire phase space

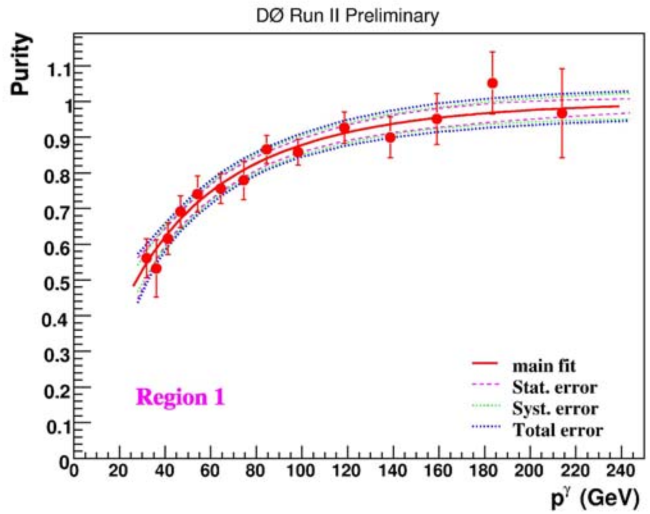


Inclusive γ+jet Production (DØ)





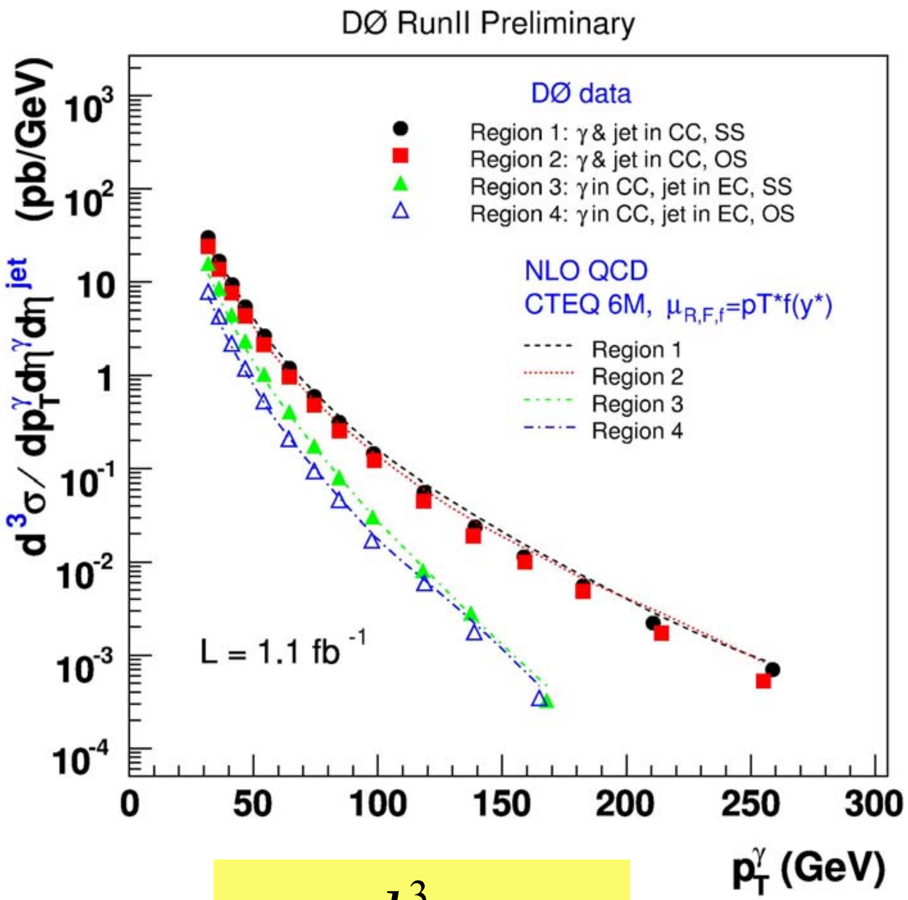
- $\sigma(\gamma)/\sigma(\text{jets}) \sim 10^{-3} \rightarrow$ challenging measurement
  - Main background: π^0/η from jets
  - Isolation to reduce background due to jets
  - Dominant experimental uncertainty: photon purity



- Direct isolated γ's come unaltered (by fragmentation/hadronization) from hard scattering
- Well known coupling to quarks
- Well measured (unlike jets) P_T^{γ}
- qg dominates at P_T^{γ}<150 GeV
  - Constrain gluon PDFs?
    - Requires improved theory (resummation & NNLO)

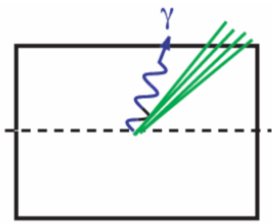
Inclusive γ+jet Production (DØ)

- Central isolated photon
  - $P_T>30$ GeV; $|\eta_\gamma|<0.8$
- Leading jet with $P_T>15$ GeV
  - Central $|\eta_{jet}|<0.8$; forward $1.5<|\eta_{jet}|<2.5$
- 4 regions
  - Central-central (CC) & central-forward (CF) of 2 kinds
    - Same sign (SS): $\eta_{jet}*\eta_\gamma>0$
    - Opposite sign (OS): $\eta_{jet}*\eta_\gamma<0$
  - Different sensitivity to Compton and annihilation contributions
- Triple differential cross section
  - First measurement of this kind
- Comparison to NLO predictions
  - JETPHOX with CTEQ6.1M PDFs and BFG fragmentation functions

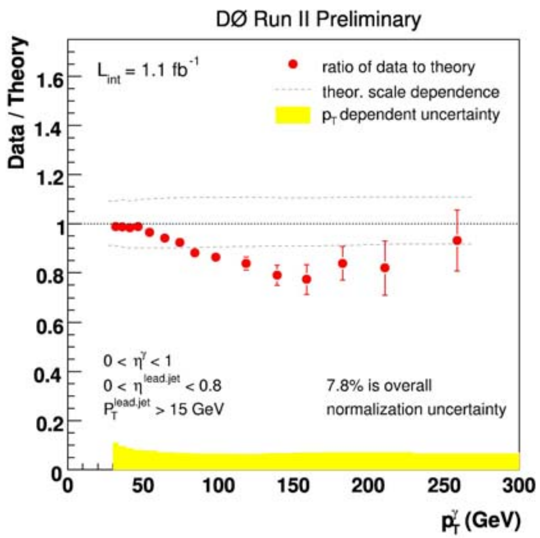


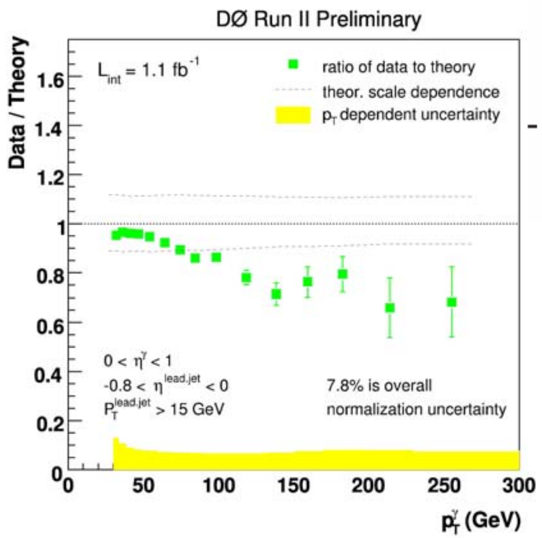
$$\frac{d^3\sigma}{dP_T^\gamma\, d\eta^\gamma\, d\eta^{jet}}$$

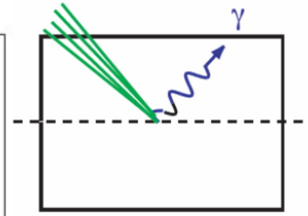
Inclusive γ+jet Production (DØ)



Region 1
CC / SS

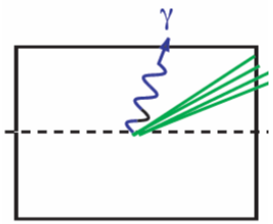




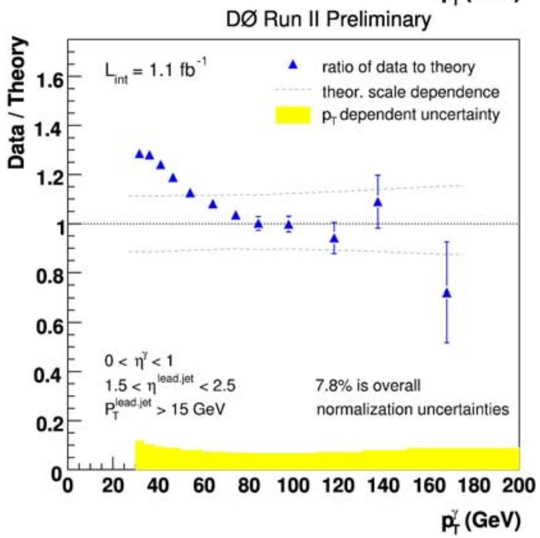


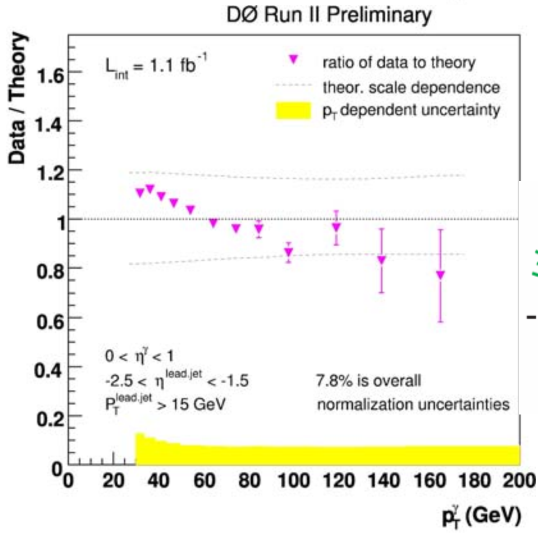
Region 2
CC / OS

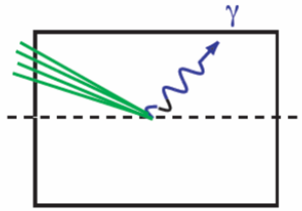
- Similar deviations seen before in other measurements (CDF,UA2,DØ)



Region 3
CF / SS



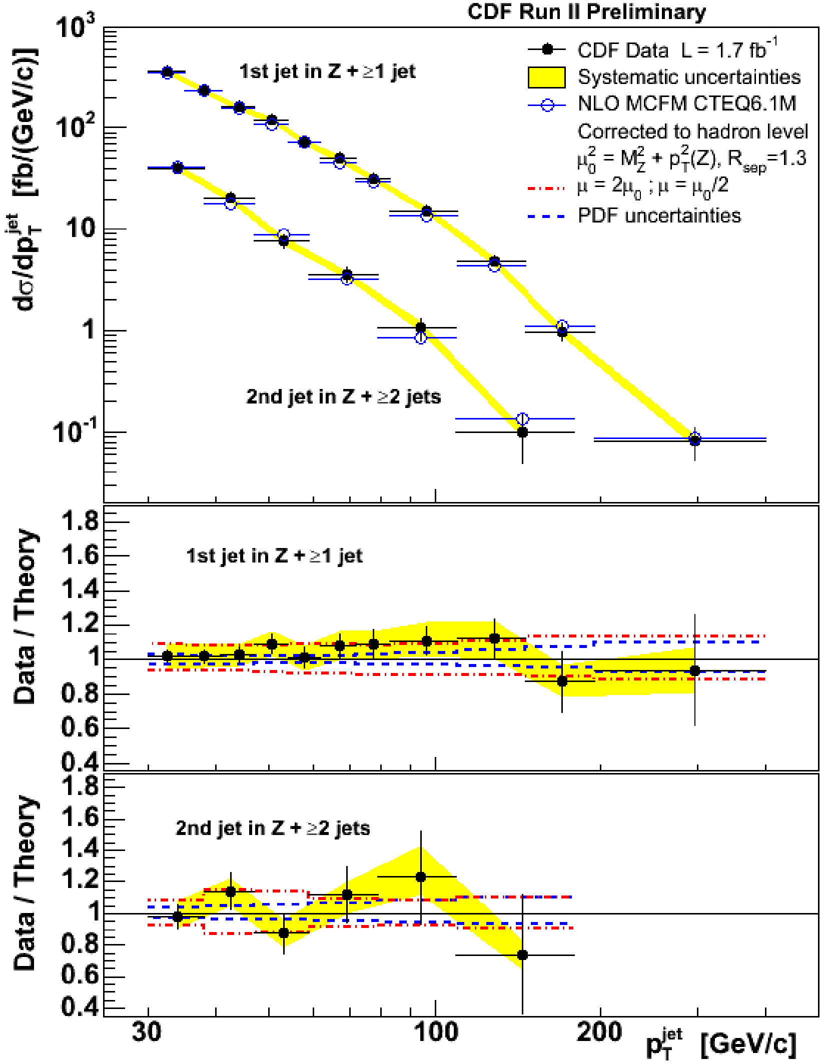




Region 4
CF / OS

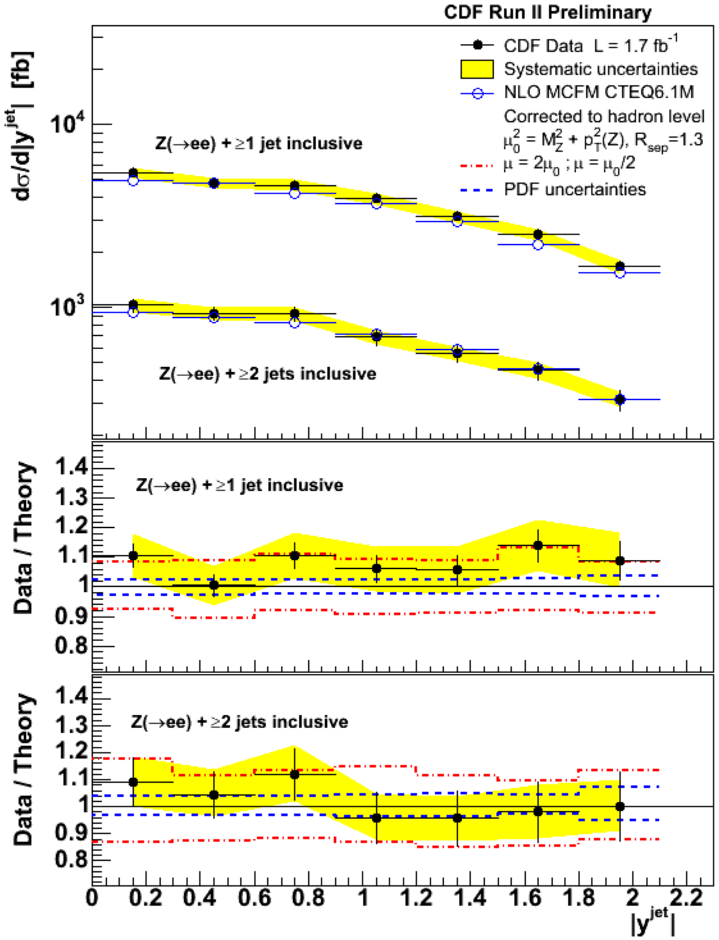
Inclusive Z+jet Production (CDF)

- Boson+jet production
  - Test of pQCD at large Q
  - Major background for many searches
- CDF analysis
  - $\int L = 1.7\ fb^{-1}$ of data
  - Two CC or CF electorns with $E_T > 25$ GeV and $66 < M_{ee} < 116$ GeV
  - Jets reconstructed with MidPoint algorithm ($R=0.7$, $f_{merge}=0.75$); $P_T^{jet} > 30$ GeV, $|y_{jet}| < 2.1$
- Good agreement with NLO predictions

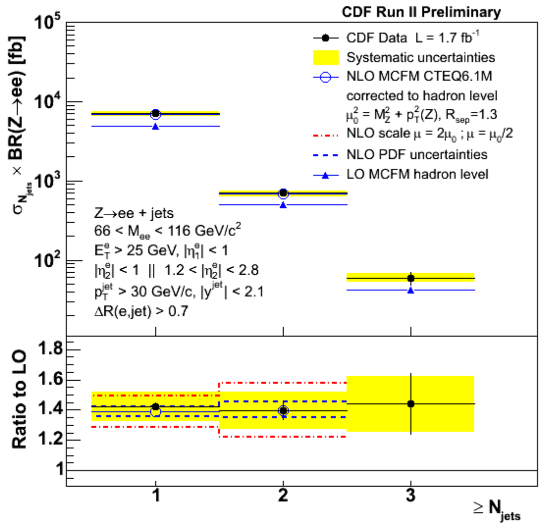


Inclusive Z+jet Production (CDF)

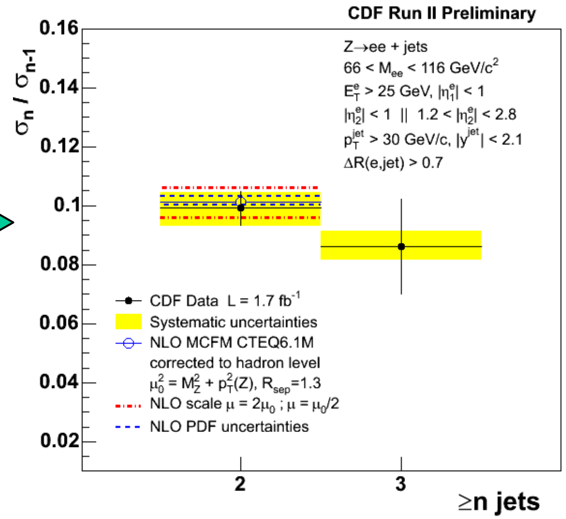
$d\sigma / dy_{jet}$



- Constant k-factor for NLO/LO with jet multiplicity

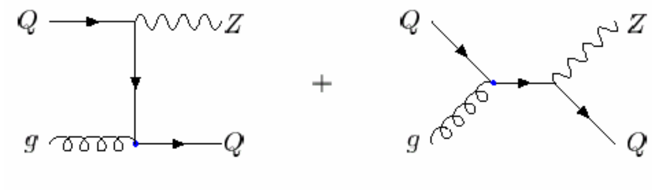


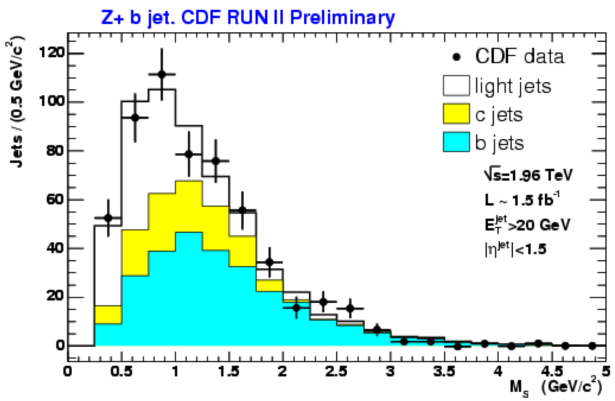
- Ratio of $\sigma(n)/\sigma(n-1) \sim \alpha_s$



Z+b-jet Production (CDF)

- Probes heavy flavor content of proton
- Major background for many searches (e.g., ZH, $H \to bb$)
- CDF analysis based on $\int L = 1.5\ fb^{-1}$:
  - $Z \to ee$ or $\mu\mu$; 66 GeV $< M_Z <$ 116 GeV
  - Jets reconstructed with cone algorithm (R=0.7); $E_T^{jet} > 20$ GeV, $|\eta^{jet}| < 1.5$
  - B-jet identification: secondary vertex tagging
  - Data is somewhat higher that NLO predictions





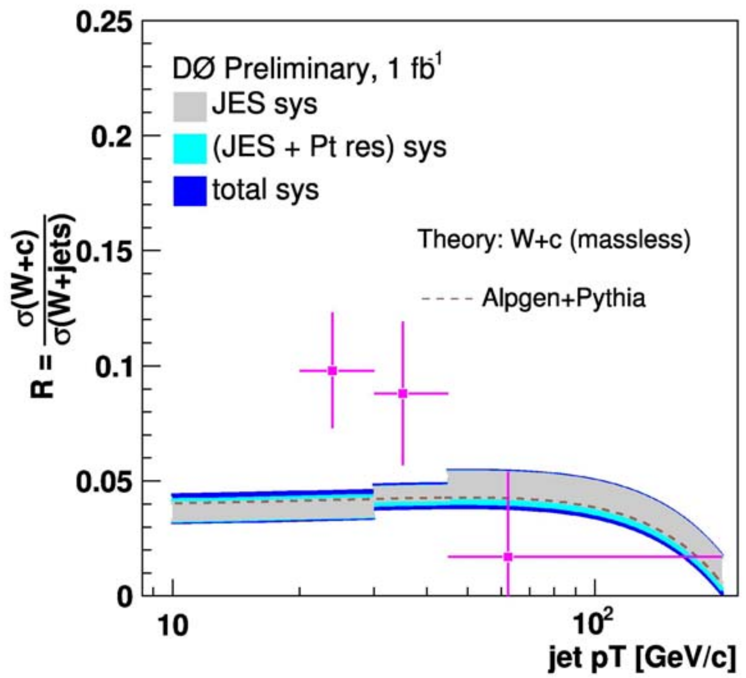
$E_T^{jet} > 20$ GeV, $\|\eta^{jet}\| < 1.5$ $R_{jet} = 0.7$	CDF Run II Preliminary measurement	PYTHIA	MCFM NLO	MCFM NLO + UE + hadr.
$\sigma(Z+b\text{-jet})$	$0.94 \pm 0.15 \pm 0.15$ (pb)		0.51 pb	0.56(pb)
$\sigma(Z+b\text{-jet})/\ \sigma(Z)$	0. $369 \pm 0.057 \pm 0.055\%$	0.35 %	0.21 %	0.23 %
$\sigma(Z+b\text{-jet})/\ \sigma(Z+\text{jet})$	$2.35 \pm 0.36 \pm 0.45$ %	2.18 %	1.88 %	1.77 %

W+c-jet Production (DØ)

- W+c/b production
  - Signature of many new physics processes
  - No measurements for W+c
  - Direct sensitivity s-quark PDFs
- DØ analysis
  - $W \to l\nu$: μ/e with $P_T>20$ GeV; MET>20 Gev
  - Jets: MidPoint (R=0.5); $P_T>20$ GeV; $|\eta|<2.5$
  - c-jet: "μ-tagged" jet; $P_T^{\mu}>4$ GeV; $|\eta|<2.0$; $\Delta R(\mu,jet)<0.5$; $q_c q_W<0$ (OppositeSign=signal, SameSign used for background)

$$\frac{\sigma(W+c)}{\sigma(W+jets)} = 0.071 \pm 0.017$$

In agreement with Alpgen+Pythia: 0.040±0.003



Summary

- Improved theoretical predictions (NLO calculations, ME-PS matching, PDFs) provide good description of data in wider P_T and rapidity range than before

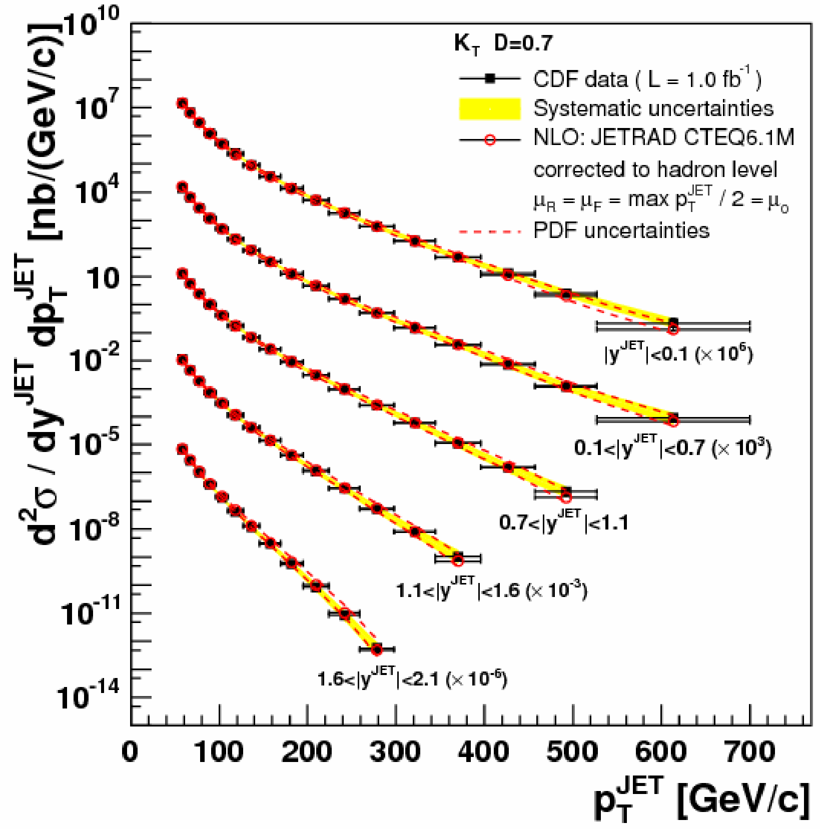
- With ~2.7 fb^{-1} on tape and 2-5 fb^{-1} still to come, expect more exciting results
  - Already at 1 fb^{-1}: experimental uncertainties ~ PDF uncertainties
  - Extended reach in P_T and rapidity
  - Small x-section processes (heavy flavor, $\gamma\gamma$, etc.)

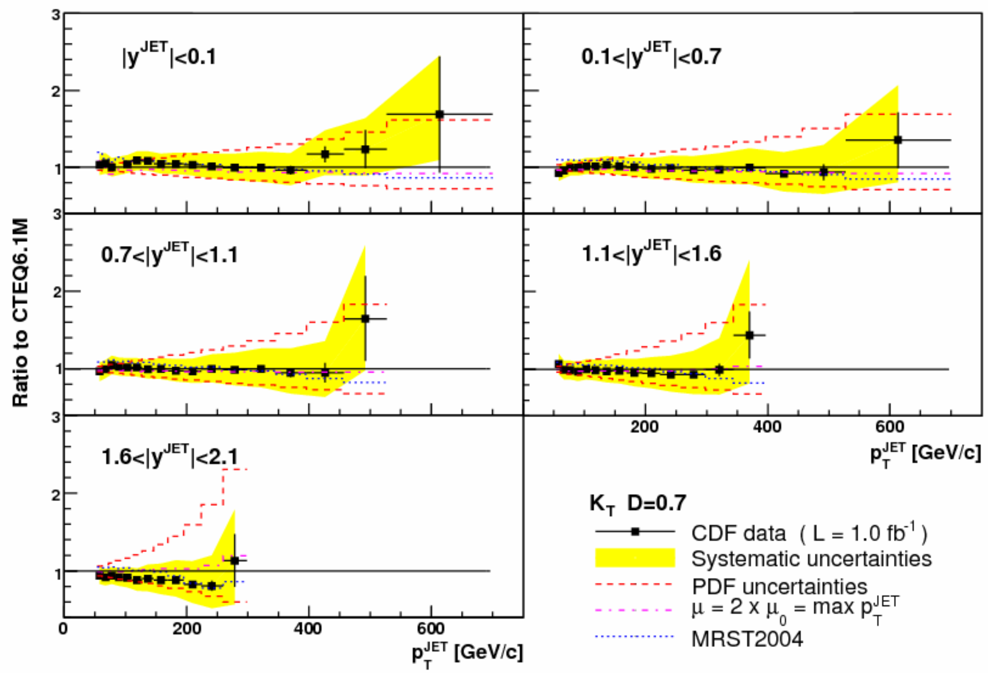
- LHC will benefit a lot from QCD studies at Tevatron
  - Better understanding of QCD backgrounds for new physics

Backup slides

Inclusive Jet Production with k_T (CDF)

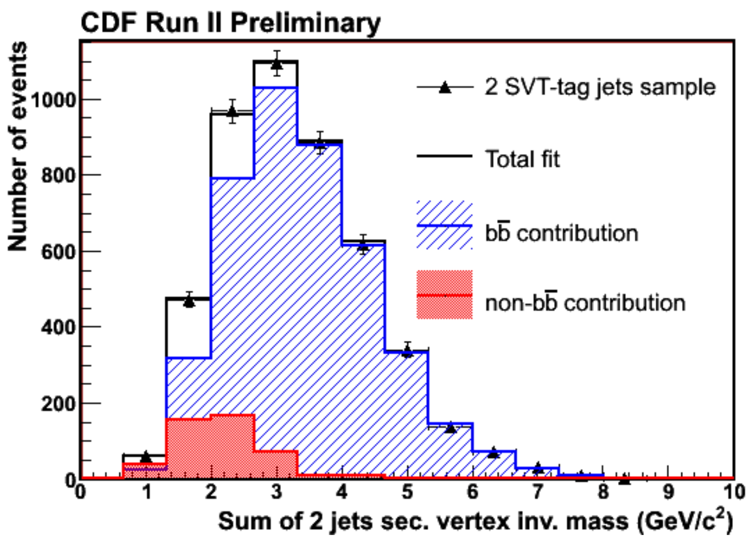
- Published in Phys. Rev. D 75, 092006 (2007)

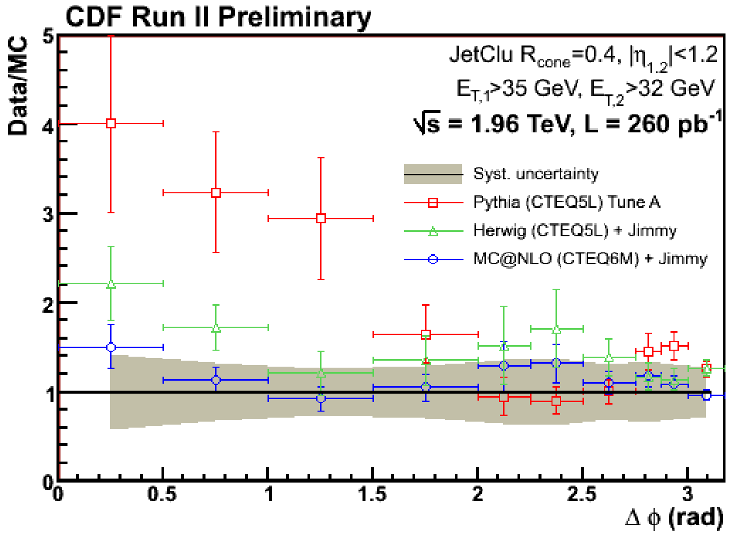




$b\bar{b}$ Dijet Production (CDF)

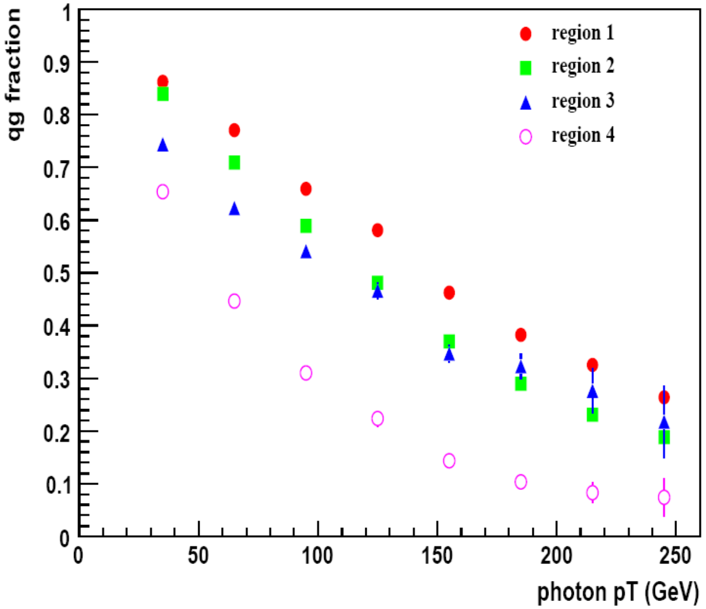
CDF Run II Preliminary	σ [pb] $\lvert\eta_{1,2}\rvert < 1.2$, $E_{T,1} > 35$ GeV, $E_{T,2} > 32$ GeV
Data	$\sigma = 5664 \pm 168$ (stat.) ± 1270 (syst.)
Pythia (CTEQ5L) Tune A	$\sigma = 5136 \pm 52$ (stat.)
Herwig (CTEQ5L) + Jimmy	$\sigma = 5296 \pm 98$ (stat.)
MC@NLO (CTEQ6M) + Jimmy	$\sigma = 5421 \pm 105$ (stat.)

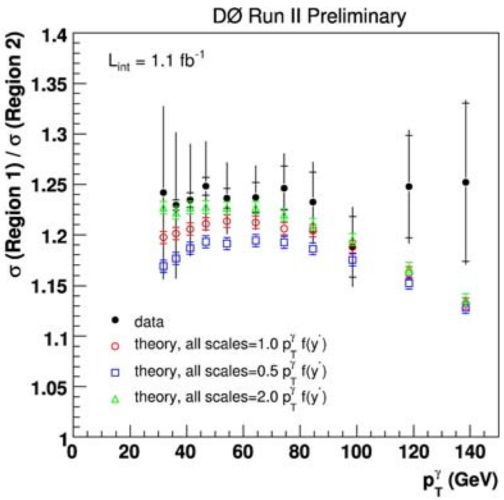


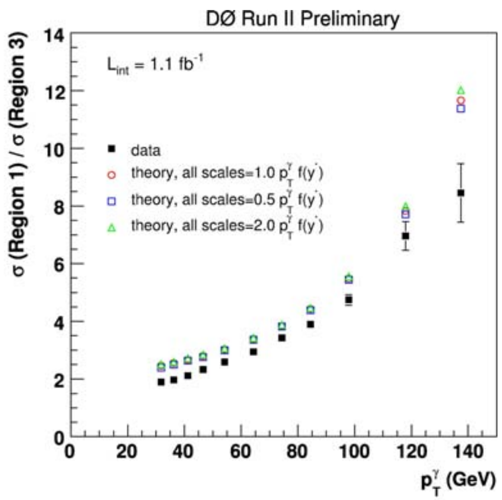


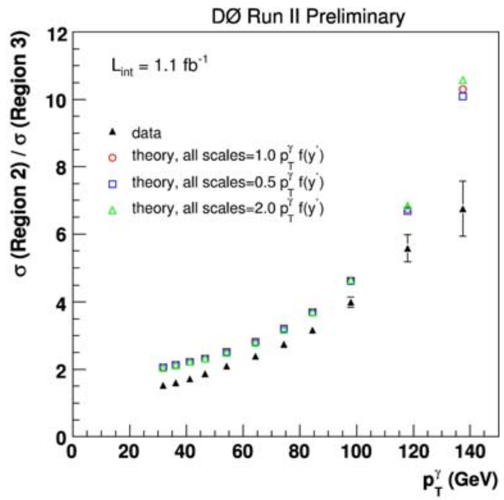
Inclusive γ+jet Production (DØ)

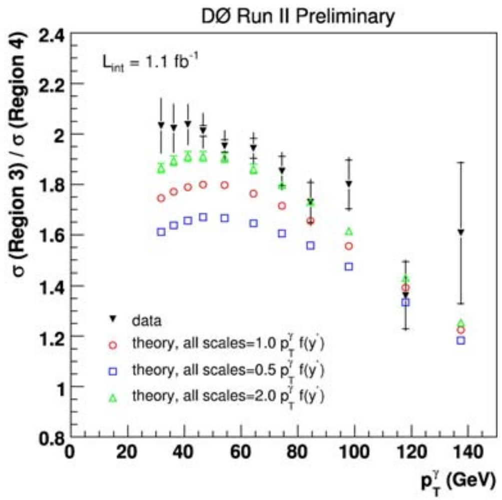
- Region 1: *CC/SS*
- Region 2: *CC/OS*
- Region 3: *CF/SS*
- Region 4: *CF/OS*











Z+b-jet Production (CDF)

- b, c and light fractions determined from the template fit of the secondary vertex mass distributions

Source of Uncertainty	Uncertainty (%)
jet energy scale	1.5
b jet energy scale	1.0
MC η^{jet} dependence	3.8
MC E_T^{jet} dependence	10
b tagging efficiency	4.1
single/double b/c quark in jet	4.6
track reconstruction efficiency	7.7
b hadron multiplicity	0.8
fake lepton background	2.4
other backgrounds	0.4
Z selection efficiency	1.8
luminosity	5.8
total	16