# *Jet Properties at the Tevatron*


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On behalf of the D0 & CDF collaborations

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# Outline

- The Tevatron, CDF and D0 experiments
- Jet physics @ Tevatron
- Jet definition and reconstruction algorithms
- New Run II results:
  - Inclusive Jet Cross section
  - Inclusive photon Cross section
  - Beauty production: inclusive b-jet and Z+bjet cross sections
  - Jet production in association to W/Z bosons
- Summary & Conclusions

Not included in this talk:

- Study on fragmentation functions
- Underlying event
- Diffractive physics

# The Tevatron

**Highest-energy accelerator currently operational**

Peak luminosity

→ **1.8 *$10^{32}$ $cm^{-2}$ $s^{-1}$**

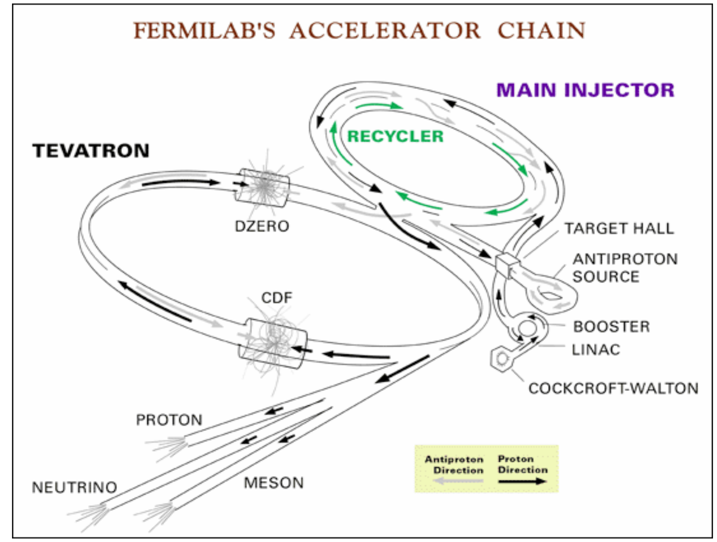
Integrated luminosity/week

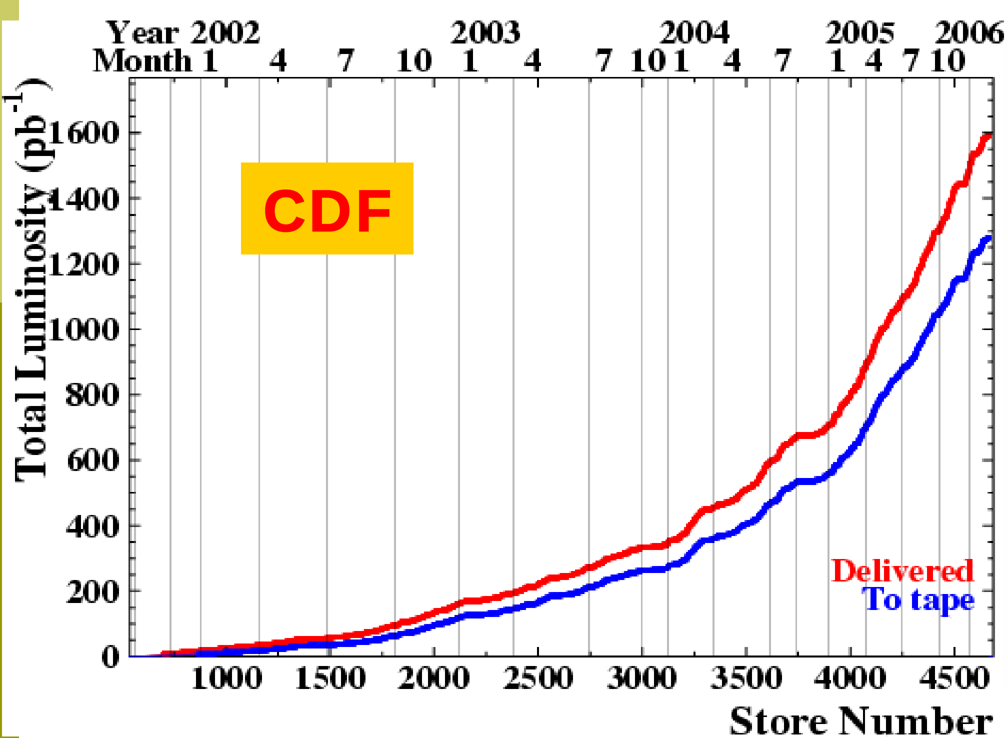
→ **about 25 $pb^{-1}$**

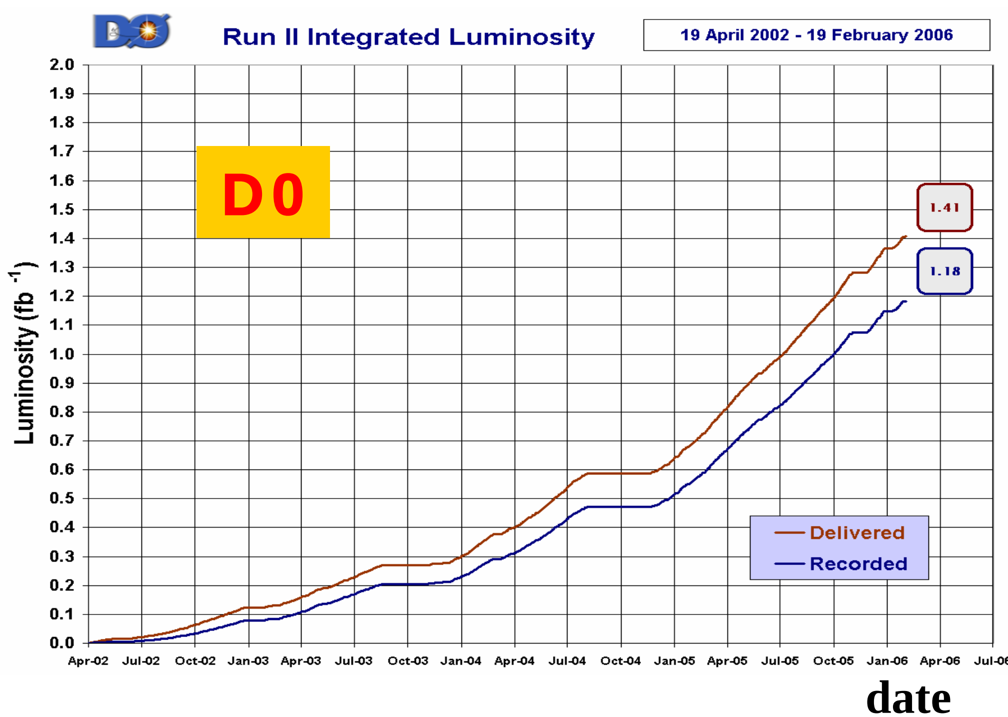
CDF and D0:

→~**1.2 $fb^{-1}$** on tape

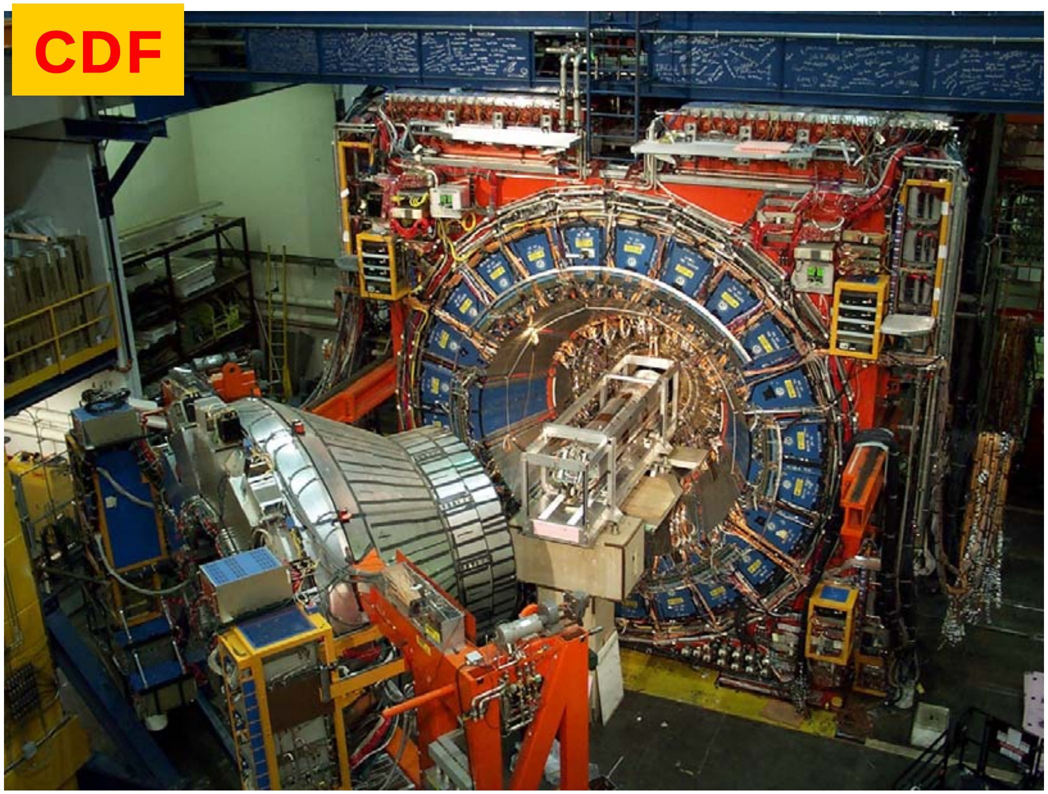
Analyses shown here use:
**0.3 – 1.0 fb $^{-1}$**



# CDF and D0 in RunII




## Both detectors

- Silicon microvertex tracker
- solenoid
- High rate trigger/DAQ
- Calorimeters and muons

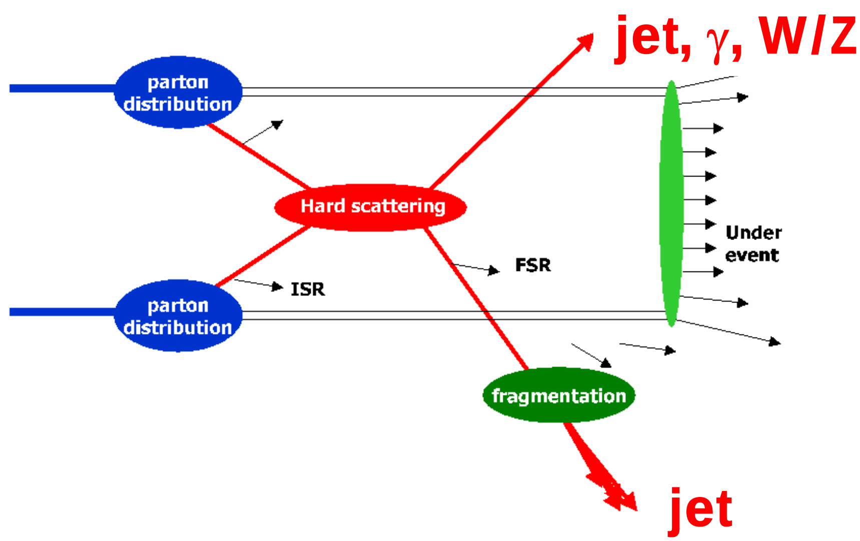
L2 trigger on displaced vertices
Excellent tracking resolution

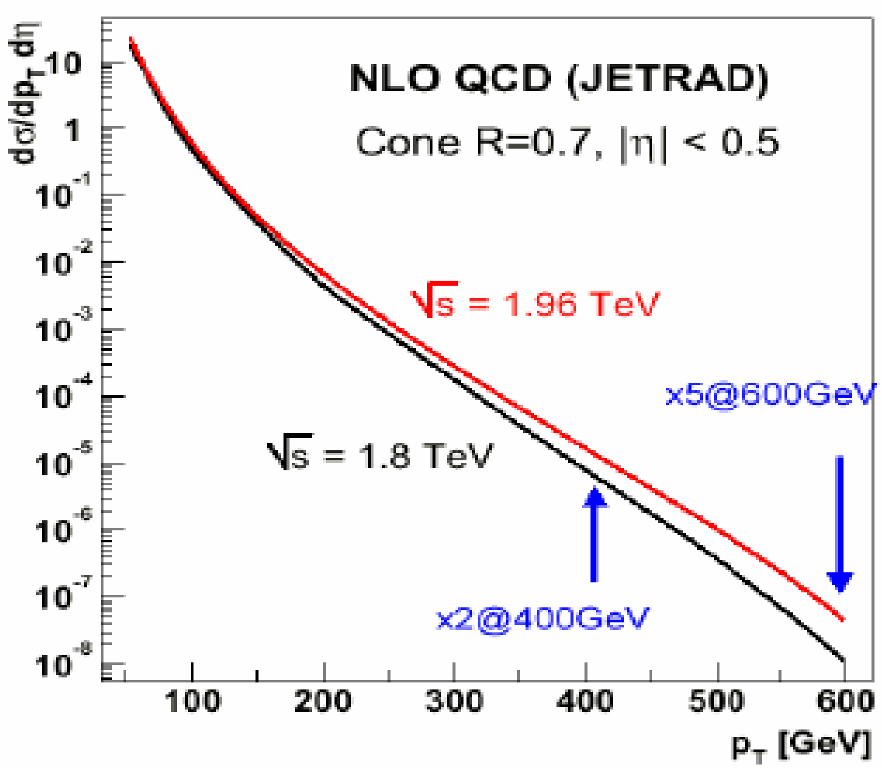
Excellent muon ID and acceptance
Excellent tracking acceptance $|\eta| < 2\text{-}3$

# Jet physics @ Tevatron

All production processes → QCD related

- ❖ Fundamental parameter
- ❖ Background for many physics channels (*e.g.* W/Z + jets production)
- ❖ Phenomenology of non-perturbative regime




Highest $Q^2$ probed
→ Precise test of pQCD at NLO

For jet production:

- Higher $\sigma_{jet}$ with respect to RunI
- Increased $p_T$ range: tails sensitive to new physics and PDF

# Jet reconstruction

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

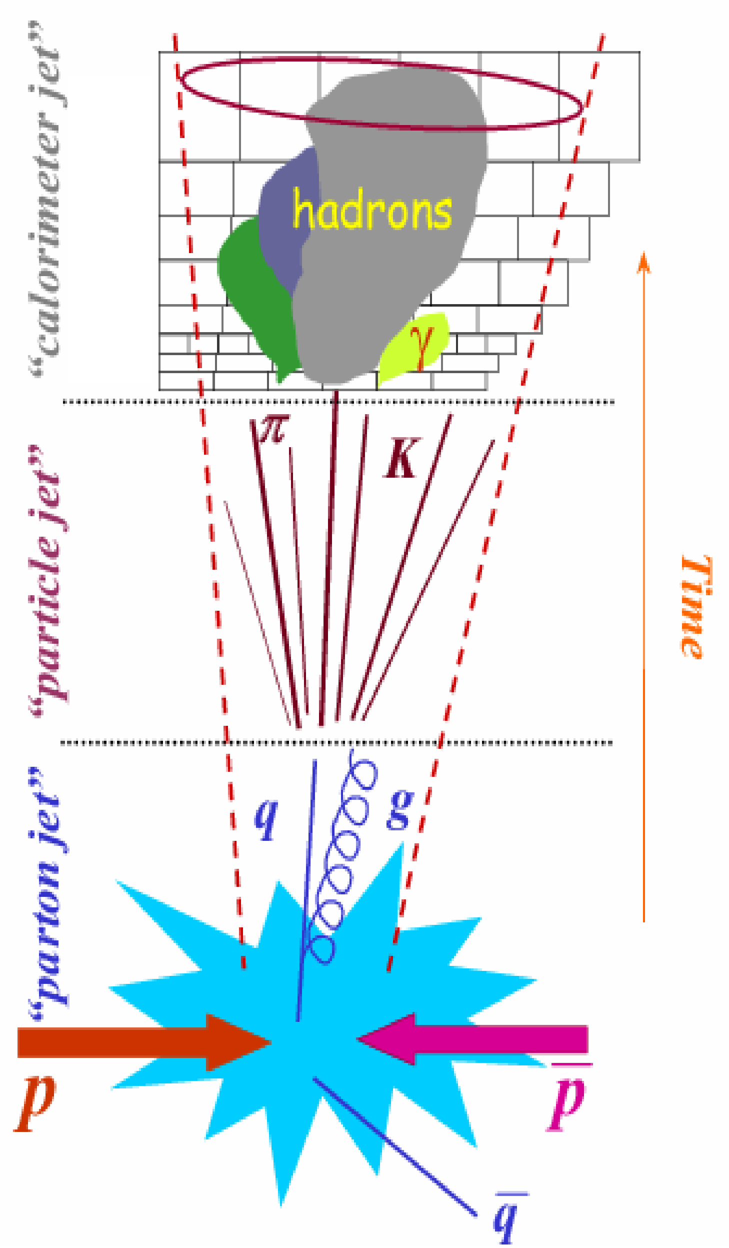
Measurements → at hadron level
Theory prediction → parton level

Need to have common and unambiguous definition used for theory and experiments.

→ **Jet reconstruction algorithms:**

- infrared and collinear safe
- jet direction = parent parton direction

Two main type of jet algorithms:
- Cone Algorithm
  → JETCLU (Run I like) and MIDPOINT
- $K_T$ algorithm

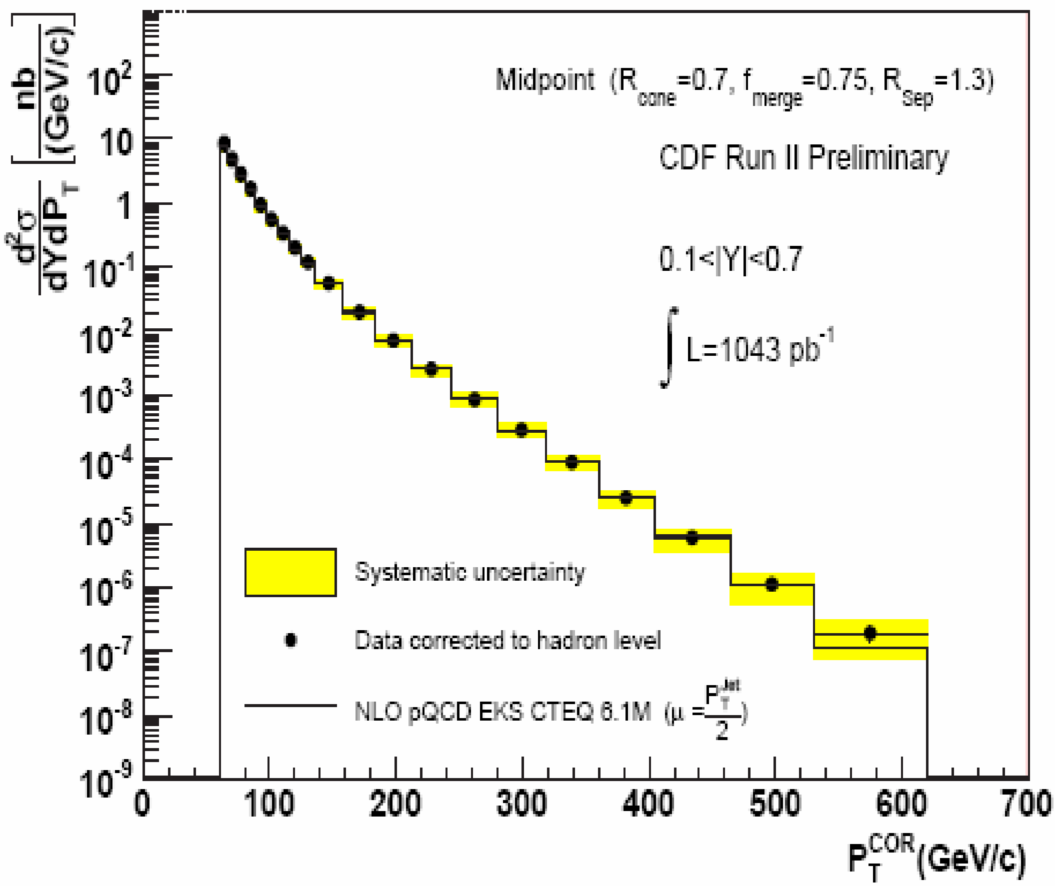


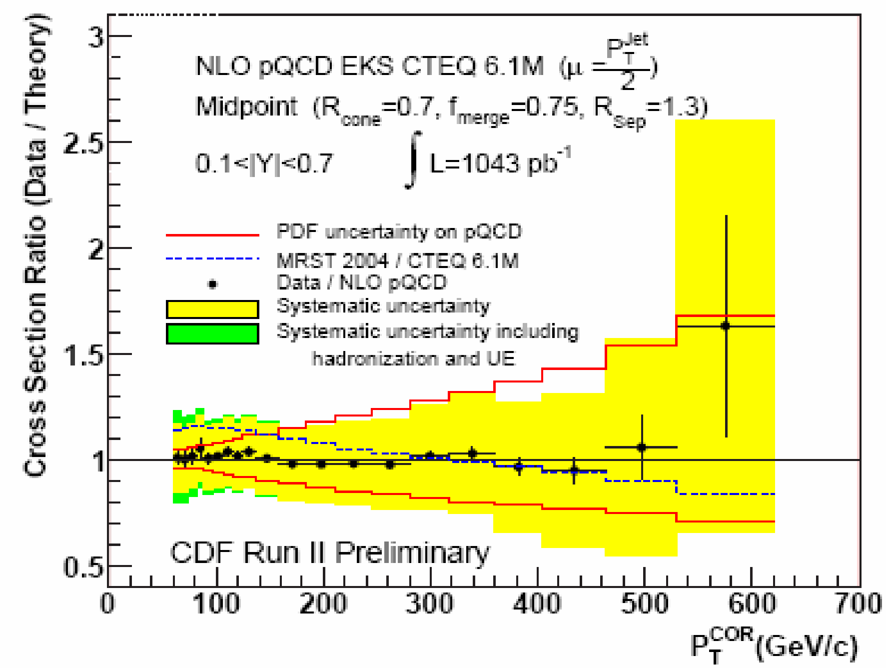
# Inclusive Jet Cross Section (CDF)

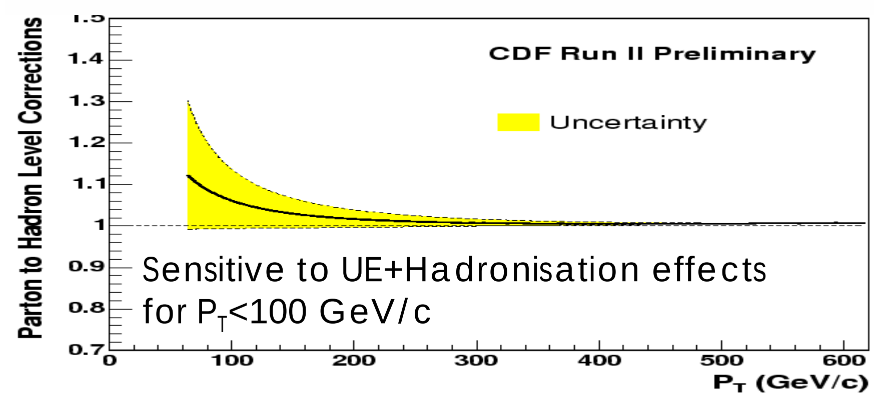
- MidPoint algorithm R = 0.7
- Central jets: $0.1 < |y^{jet}| < 0.7$
- More than 9 orders of magnitude covered

L = 1 $fb^{-1}$

- Data dominated by Jet Energy Scale (JES) uncertainties (3%)
- NLO uncertainty due to high x gluon PDF



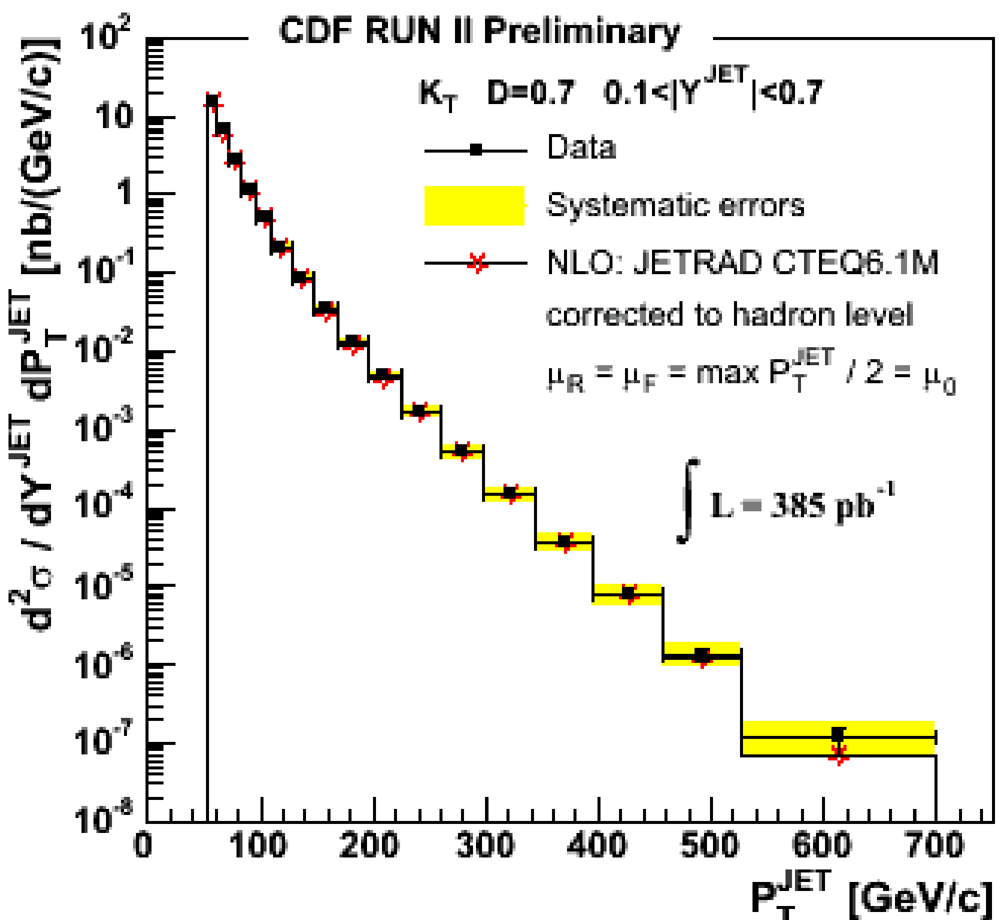

Good agreement with NLO predictions

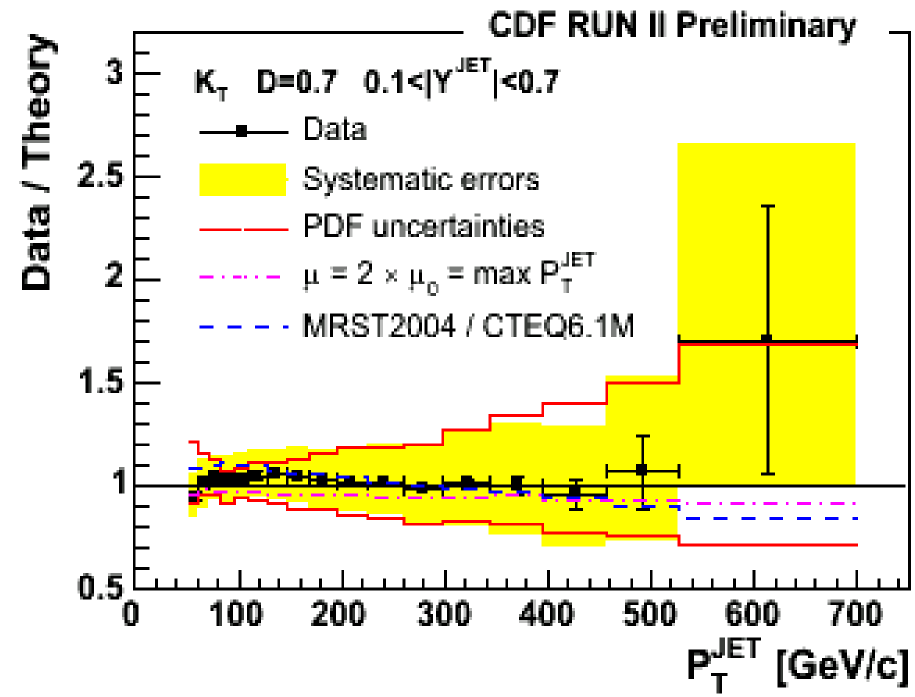
# *Inclusive Jet Cross Section (CDF)*

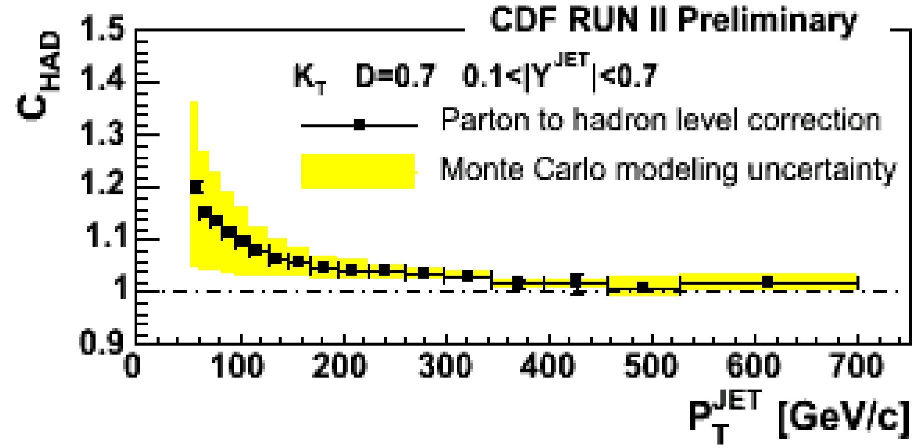
- $K_T$ algorithm (D = 0.7)

L = 385 pb$^{-1}$

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



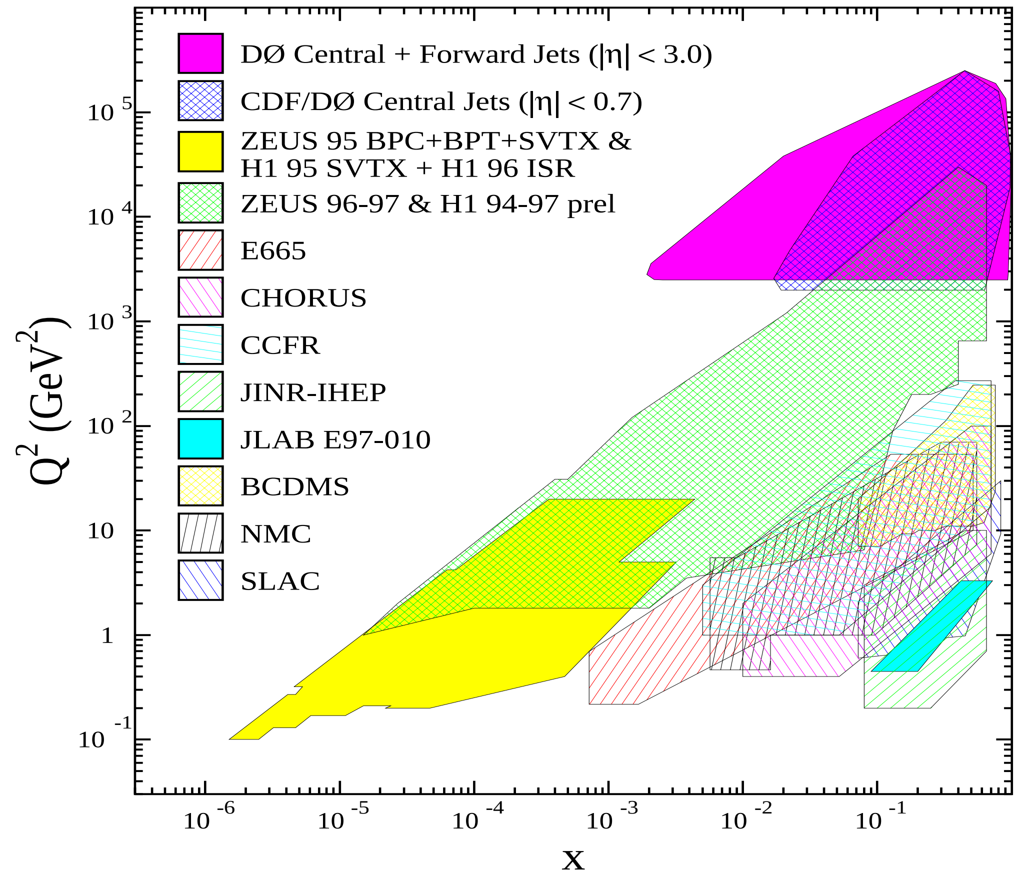



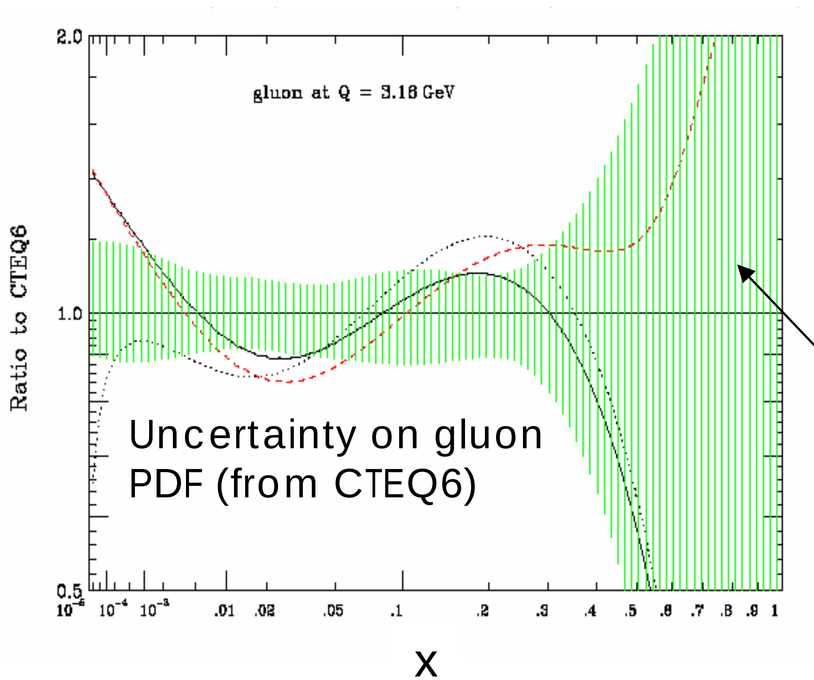

$K_T$ performs well in hadron collisions
Good agreement with NLO pQCD

# *Gluon PDF at high-x*

from Run I

E.g. Forward jets measurements help to distinguish between new physics and PDF if any excess in the central region

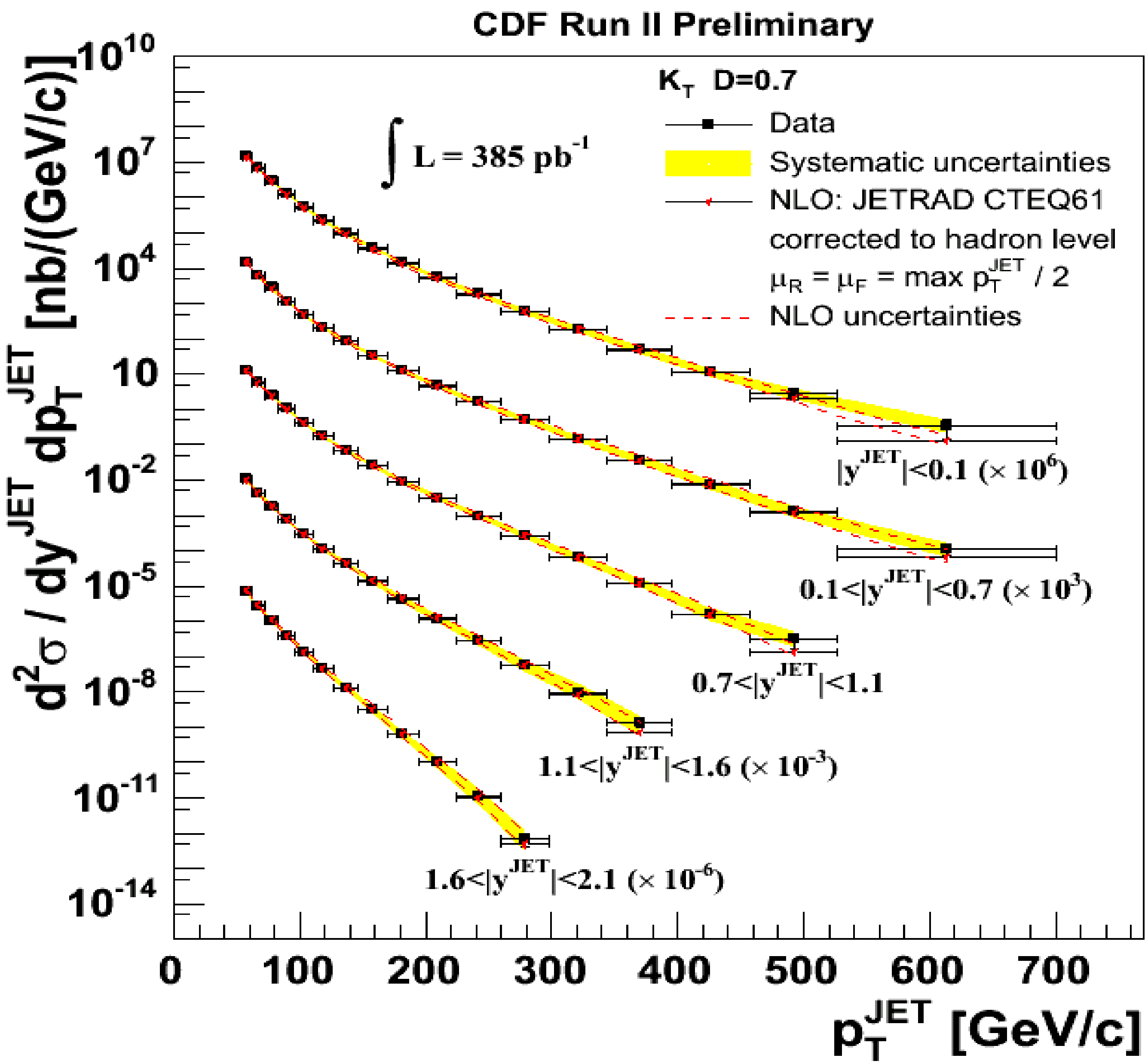



Uncertainty on gluon PDF (from CTEQ6)

Big uncertainty for high-x gluon PDF

# *Forward jets ($k_T$ algorithm ,CDF)*

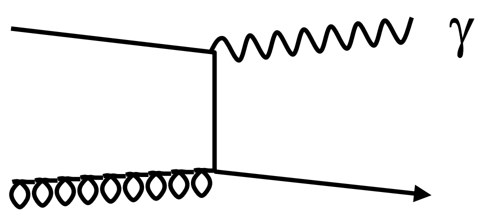



Five regions in jet rapidity explored (D=0.7):

- $|y^{jet}|<0.1$
- $0.1<|y^{jet}|<0.7$
- $0.7<|y^{jet}|<1.1$
- $1.1<|y^{jet}|<1.6$
- $1.6<|y^{jet}|<2.1$

Good agreement with the NLO pQCD for jets up to $|Y|<2.1$

# Inclusive γ cross section (D0)

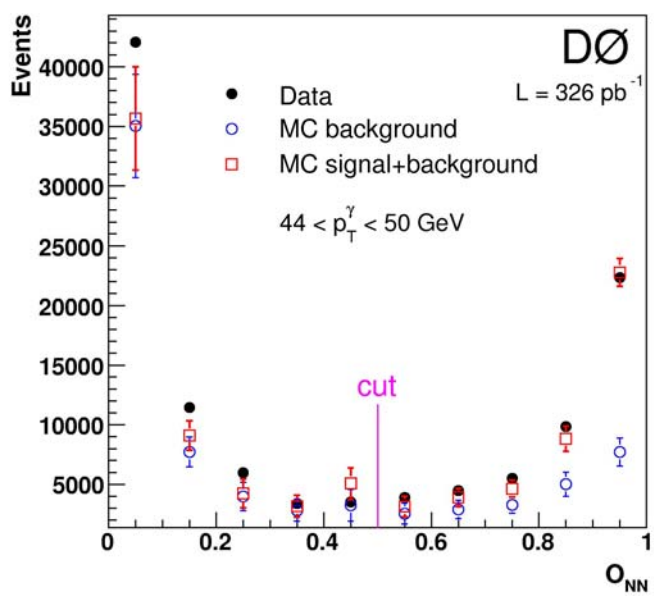


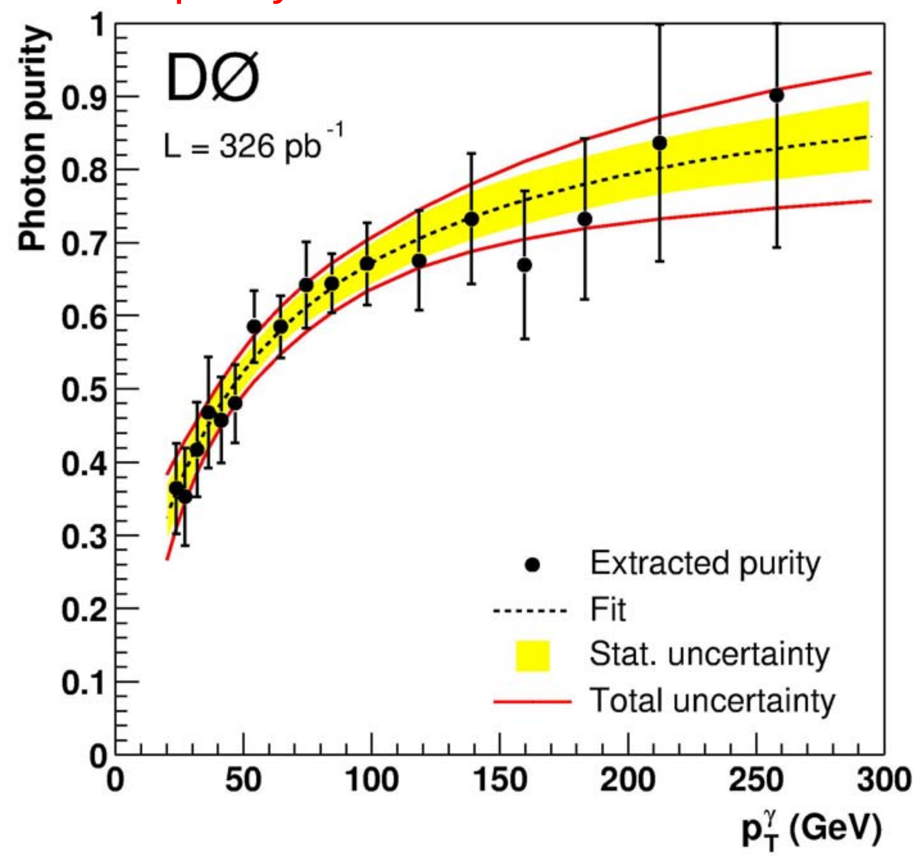

L = 330 $pb^{-1}$

- Sensitive to gluon PDF and hard scatter dynamics: no need to define "jets"
- Performed for central photons, $|y^\gamma| < 0.9$

No Jet Energy Scale error, good understanding of γ E-scale
→ purity uncertainties dominates

- Separating photons from jet backgrounds is challenging

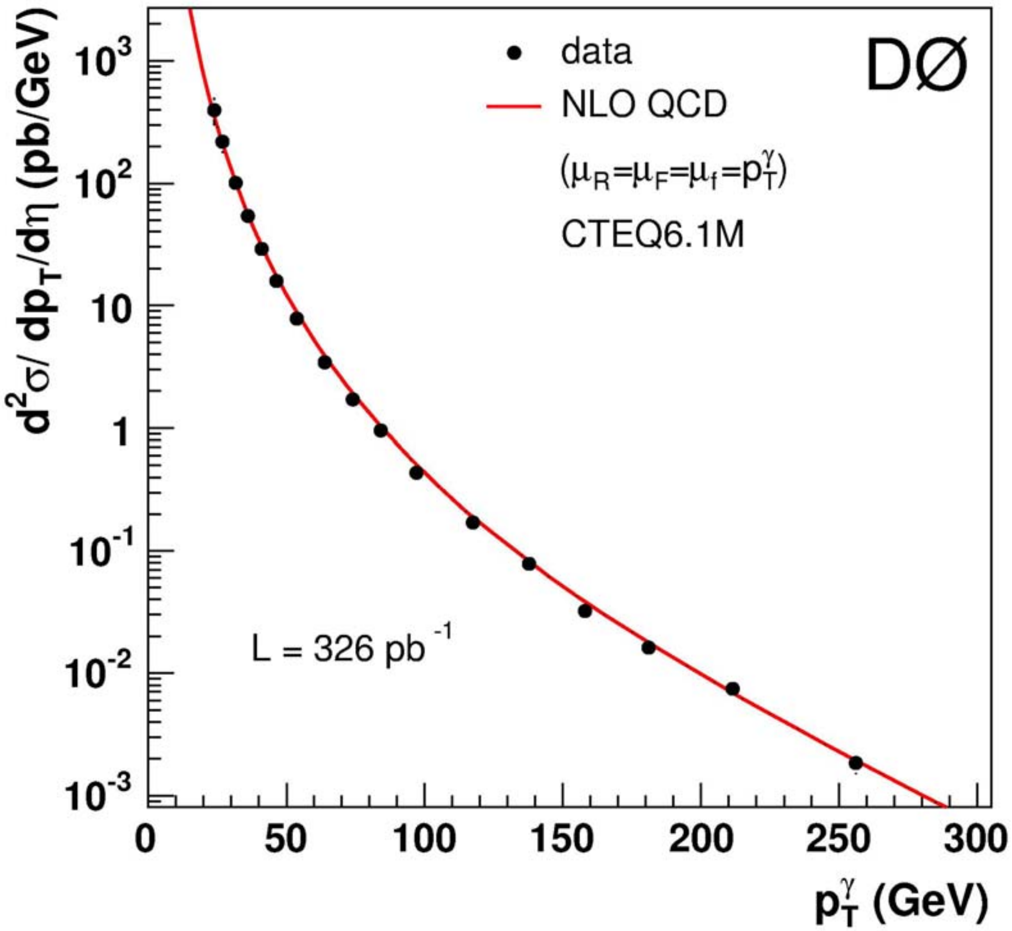


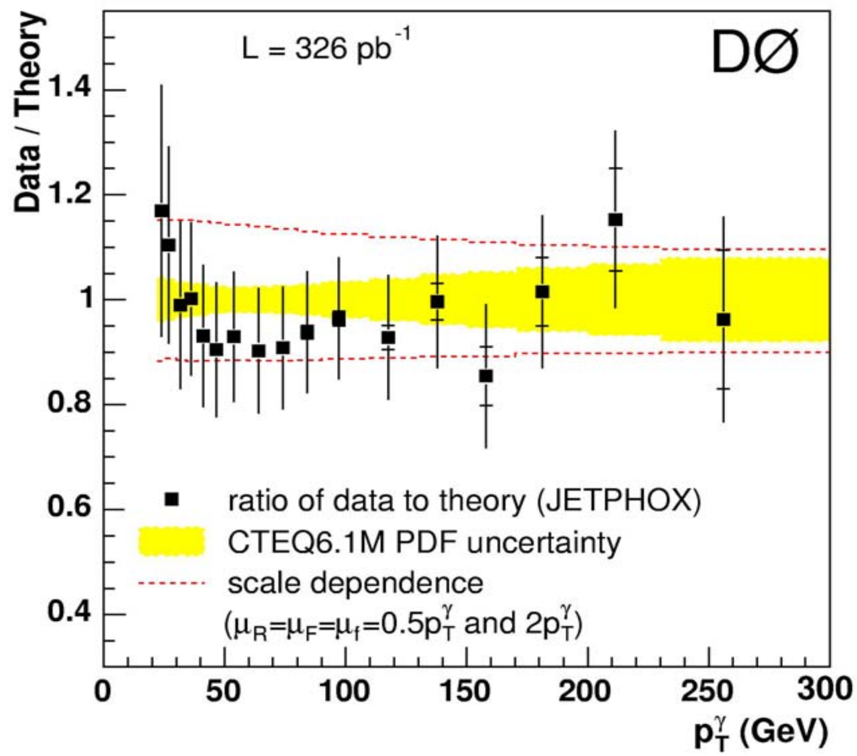




- Use neural network (NN)
  - Track isolation and calorimeter shower shape variables

# *Inclusive γ cross section (D0)*

- Highest $p_T(\gamma)$ is 442 GeV/c
  - 3 events above 300 GeV/c not displayed



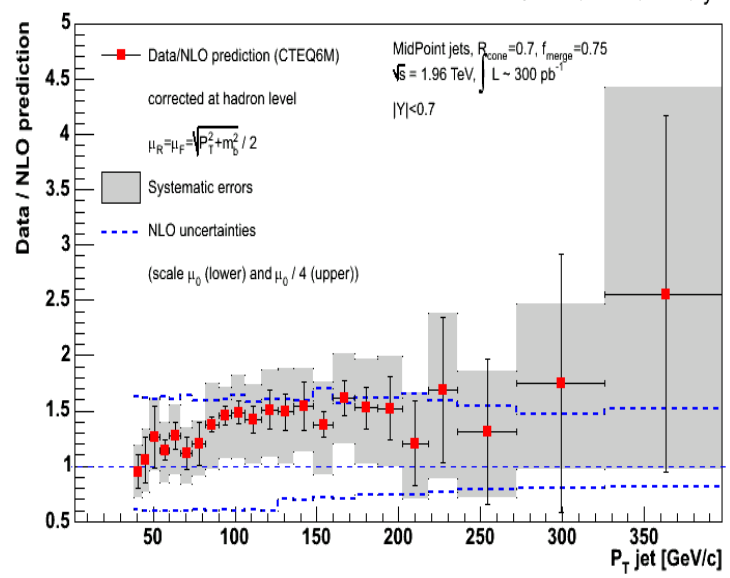

- Errors ~20%
- Very promising at the $fb^{-1}$ to constrain gluon PDF at high x

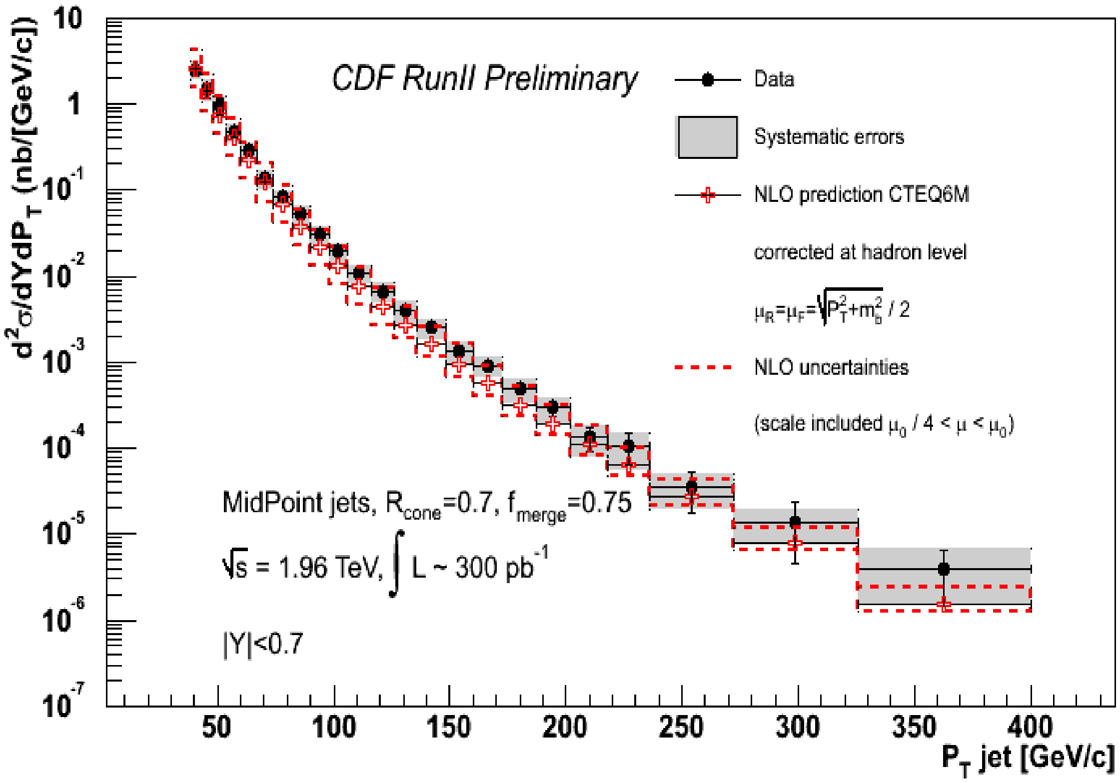
Good agreement with pQCD NLO

# High $P_T$ b-jet cross section (CDF)

- Beauty production → Test of pQCD
- MidPoint jets: R = 0.7, $|y^{jet}| < 0.7$
- Reconstruct secondary vertex from B hadron decays (b-tagging)
- Shape of secondary vertex mass used to extract b-fraction from data

L = 300 pb$^{-1}$

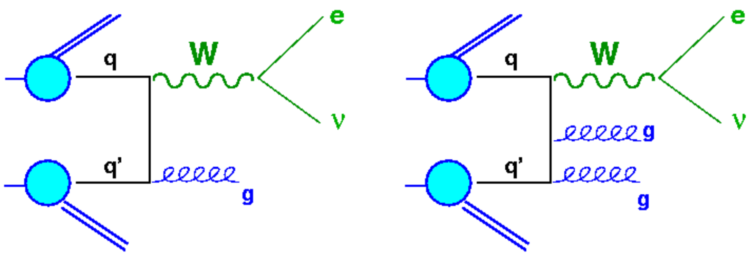



- More than 6 orders of magnitude covered
- Data dominated by Jet Energy Scale and b-fraction uncertainties
- Uncertainties on NLO due to PDF and $\mu_R/\mu_F$ scales

Agreement with pQCD NLO within systematic uncertainties
→ Sensitive to high order effect (NNLO)

# W+jets production (CDF)

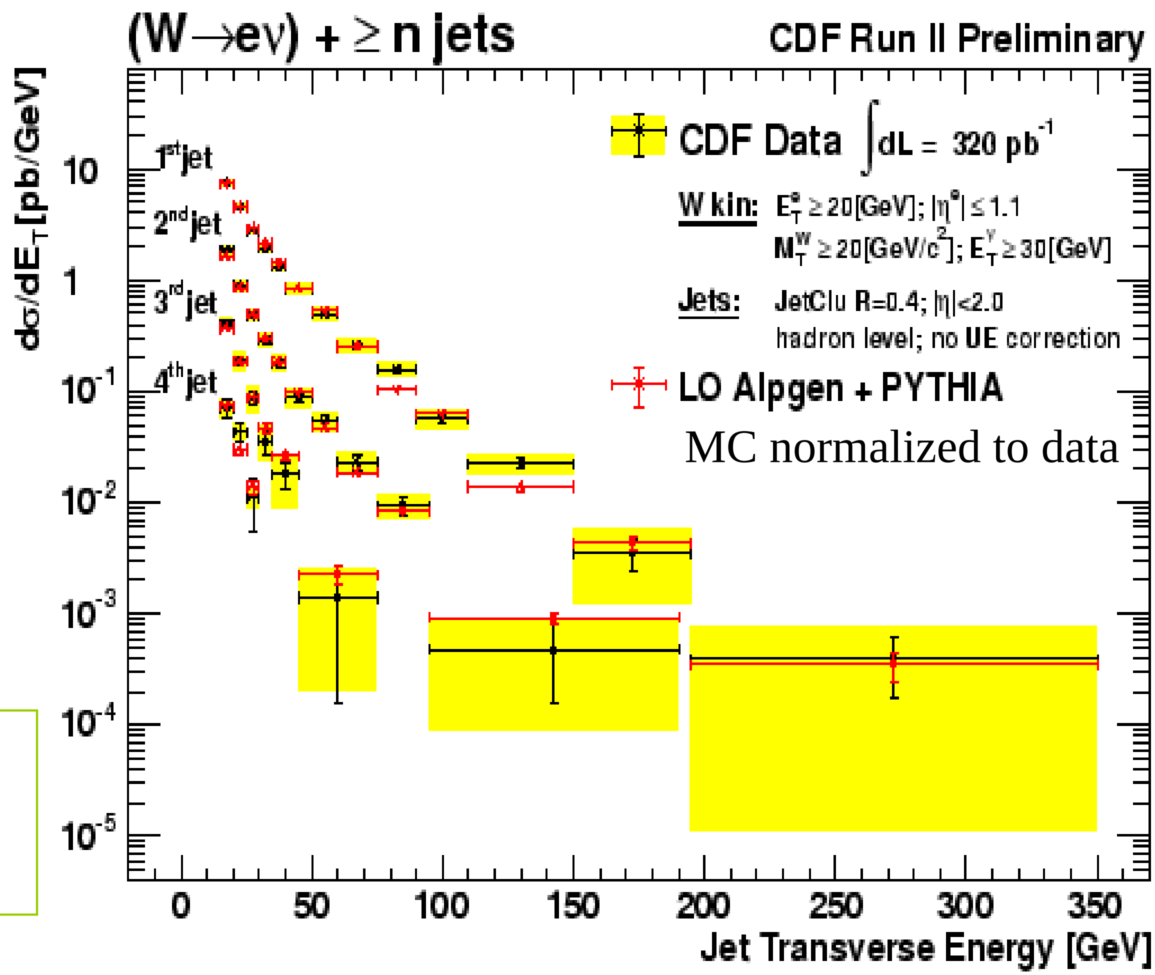



- Background to top and Higgs Physics
- Testing ground for pQCD in multijet environment
  - Key sample to test LO and NLO ME+PS predictions

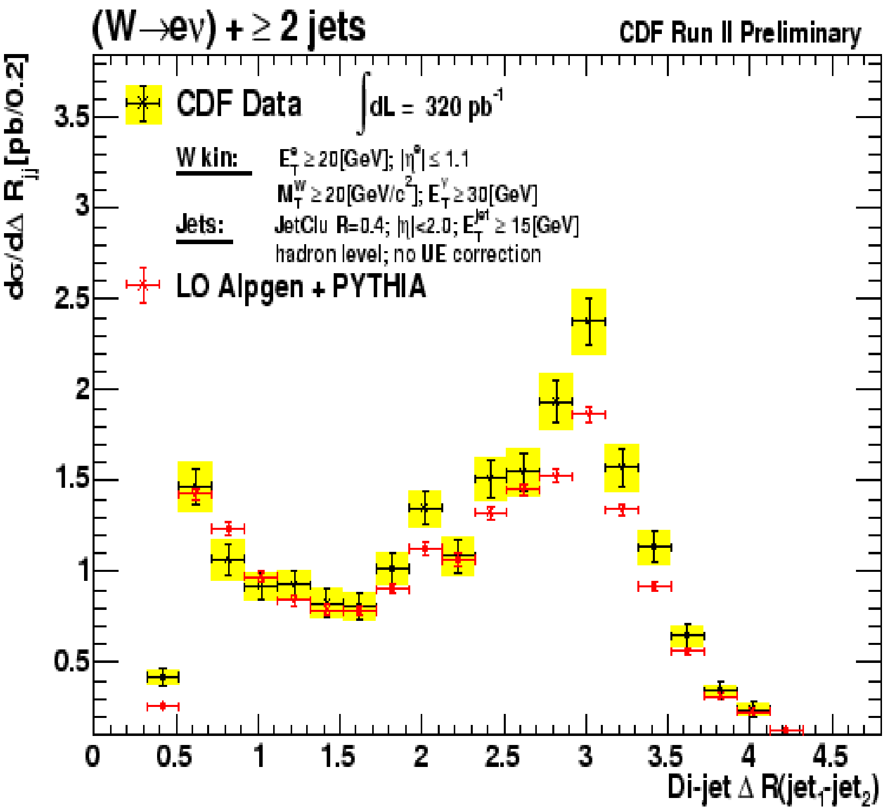
L = 320 pb$^{-1}$

- Restrict $\sigma_W$:
  - W → e ν, $|\eta^e| < 1.1$
- JETCLU jets (R=0.4):
  - $E_T^{jets}$>15 GeV, $|\eta^{jet}| < 2.$
- Uncertainties dominated by background subtraction and Jet Energy Scale

LO predictions normalized to data integrated cross sections
→ **Shape comparison only**

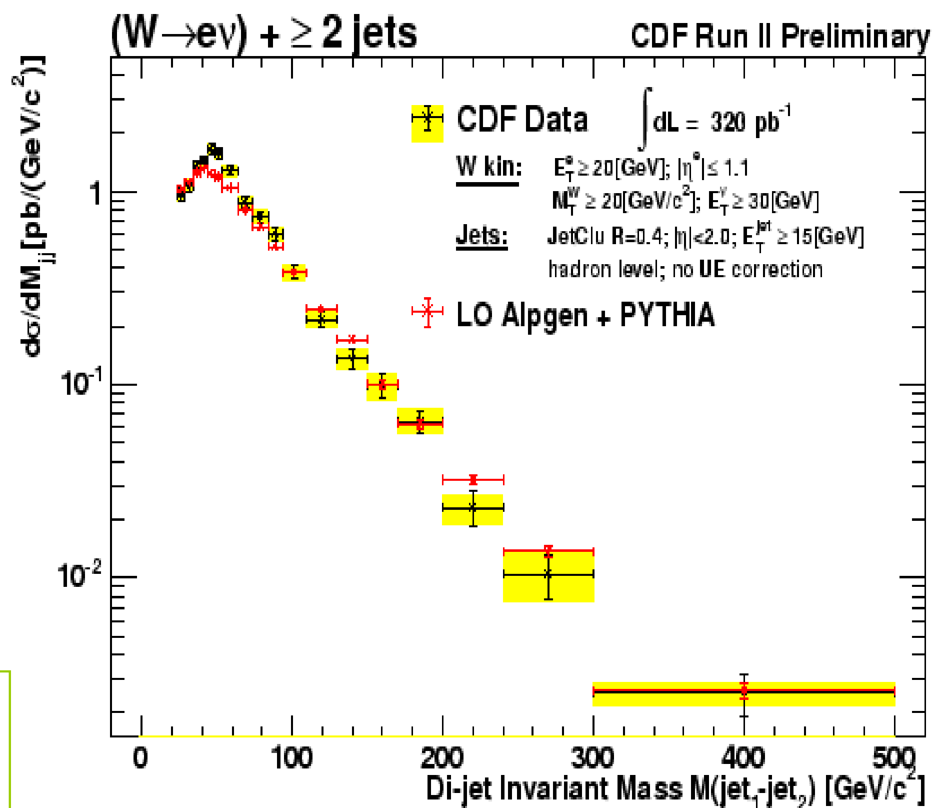


# *W+jets production (CDF)*




Differential cross section w.r.t. di-jet ΔR in the W+2 jet inclusive sample

Differential cross section w.r.t. di-jet invariant mass in the W+2 jet inclusive sample




LO predictions normalized to data integrated cross sections

→ **Shape comparison only**

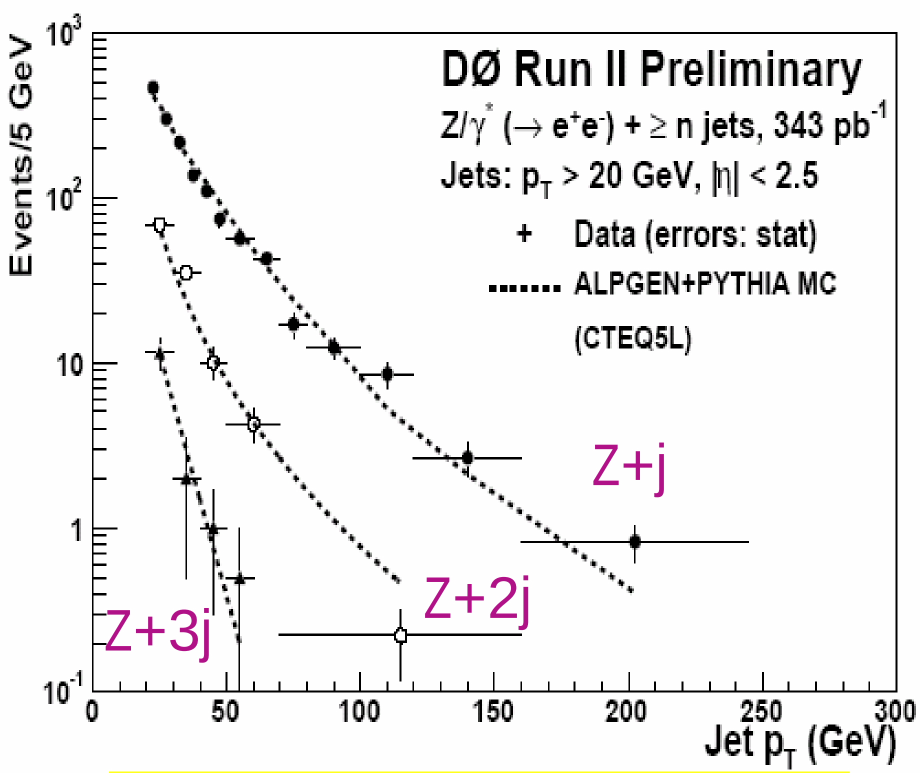
More exhaustive comparisons expected soon!!!

# Z+jets production (D0)

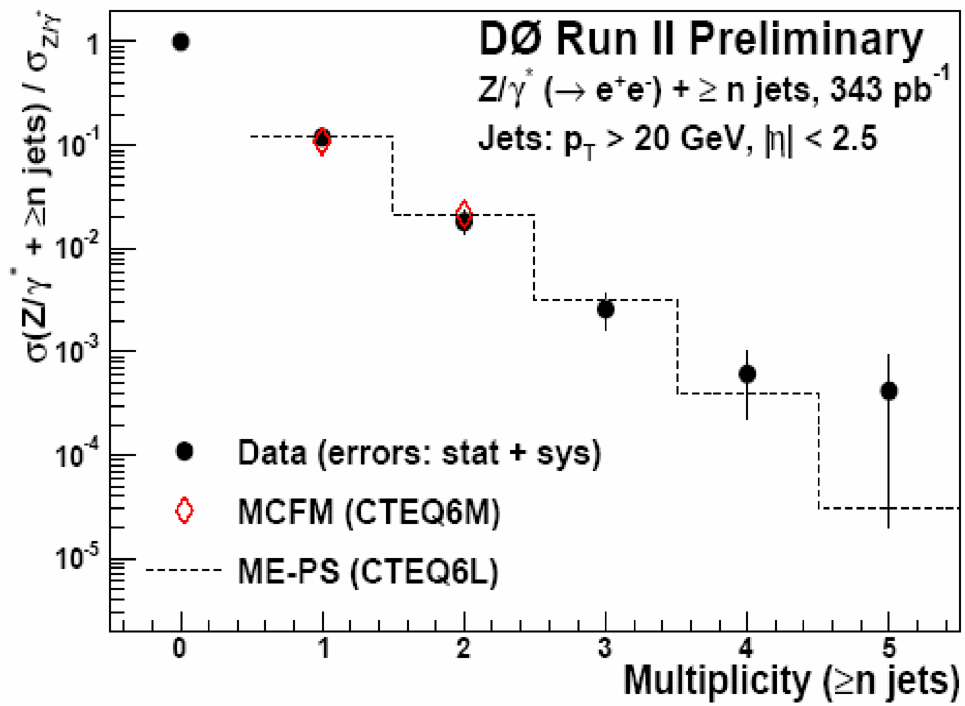
L = 343 pb$^{-1}$

- Same motivations as W + jets
  - $\sigma(Z) \sim \sigma(W)$ / 10, but Z→e$^+$e$^-$ cleaner
- Central electrons ( | η | <1.1)
- MidPoint jets:
  - R = 0.5, $p_T$ > 20 GeV/c, | $y^{jet}$ | <2.5

$$R_n = \frac{\sigma_n}{\sigma_0} = \frac{\sigma[Z/\gamma^*(\to e^+e^-) + \geq njets]}{\sigma[Z/\gamma^*(\to e^+e^-)]}$$




$p_T$ spectra of n$^{th}$ jet distribution

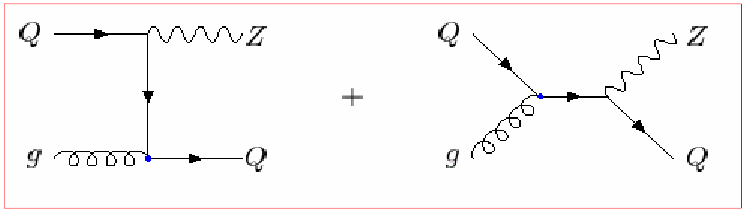



**MCFM**: NLO for Z+1p or Z+2p → good description of the measured cross sections

**ME + PS**: with MADGRAPH tree level process up to 3 partons → reproduce shape of $N_{jet}$ distributions (Pythia used for PS)

# Z+b jets production (CDF & D0)

→ Important background for new physics




Test for pQCD:
→ Important to probe heavy flavour content in the proton

- Leptonic decays for Z:
  $Z \rightarrow e^+e^-, \mu^+\mu^-$
- Z associated with jets

(CDF: JETCLU, D0: MidPoint):
R = 0.7, $|\eta^{jet}|<1.5$, $E_T$ ($p_T$) >20 GeV

- Look for tagged jets in Z events

Both CDF and D0:

Data systematic uncertainty:
→ B-fraction for jet events with 2 heavy quarks.
→ Jet Energy Scale

**CDF**

L = 335 pb$^{-1}$

Extract fraction of b-tagged jets from secondary vertex Mass: no assumption on the charm content

**D0**

L = 180 pb$^{-1}$

Assumption on the charm content from theoretical prediction: $N_c=1.69N_b$

$$\sigma(Z+bjet) = 0.96 \pm 0.32 \pm 0.14\,pb$$

$$R = \frac{\sigma[Z+bjet]}{\sigma[Z+jet]} = 0.0237 \pm 0.0078(stat) \pm 0.0033(syst)$$

$$R = \frac{\sigma[Z+bjet]}{\sigma[Z+jet]} = 0.021 \pm 0.004(stat)^{+0.002}_{-0.003}(syst)$$

Agreement with NLO prediction: $\sigma(Z+bjet) = 0.52\,pb \quad R = 0.018 \pm 0.004$

# Conclusions

- In 2005, Tevatron achieved the 1 $fb^{-1}$ goal
- Delivered total luminosity 1.6 $fb^{-1}$
  - → 1.2 $fb^{-1}$ on tape ready for data analyses!
- Explore different jet algorithms
- Very rich QCD physics program ongoing at CDF and D0
  - Thanks to the large data sample, we can perform precision measurements to test pQCD and constrain PDF.
  - W/Z + jets production provides good feedback for MC tools (Matrix element and Parton showering)
  - Important for the LHC

# *Back up*

# Jet algorithms

## Cone algorithms:

- Seed towers
  - Only iterate over towers above certain threshold

**JETCLU:** Snowmass ($E_T$) - scheme

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

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

**MIDPOINT:** E - scheme

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

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

  - MidPoint adds extra seed in centre of each pair of seeds → Infrared and collinear safe
- Ratcheting (JetClu only)
  - All towers initially inside a cone must stay in a cone
- Jet merging/splitting is an issue:
  - Need to define a $F_{merge}$ parameter

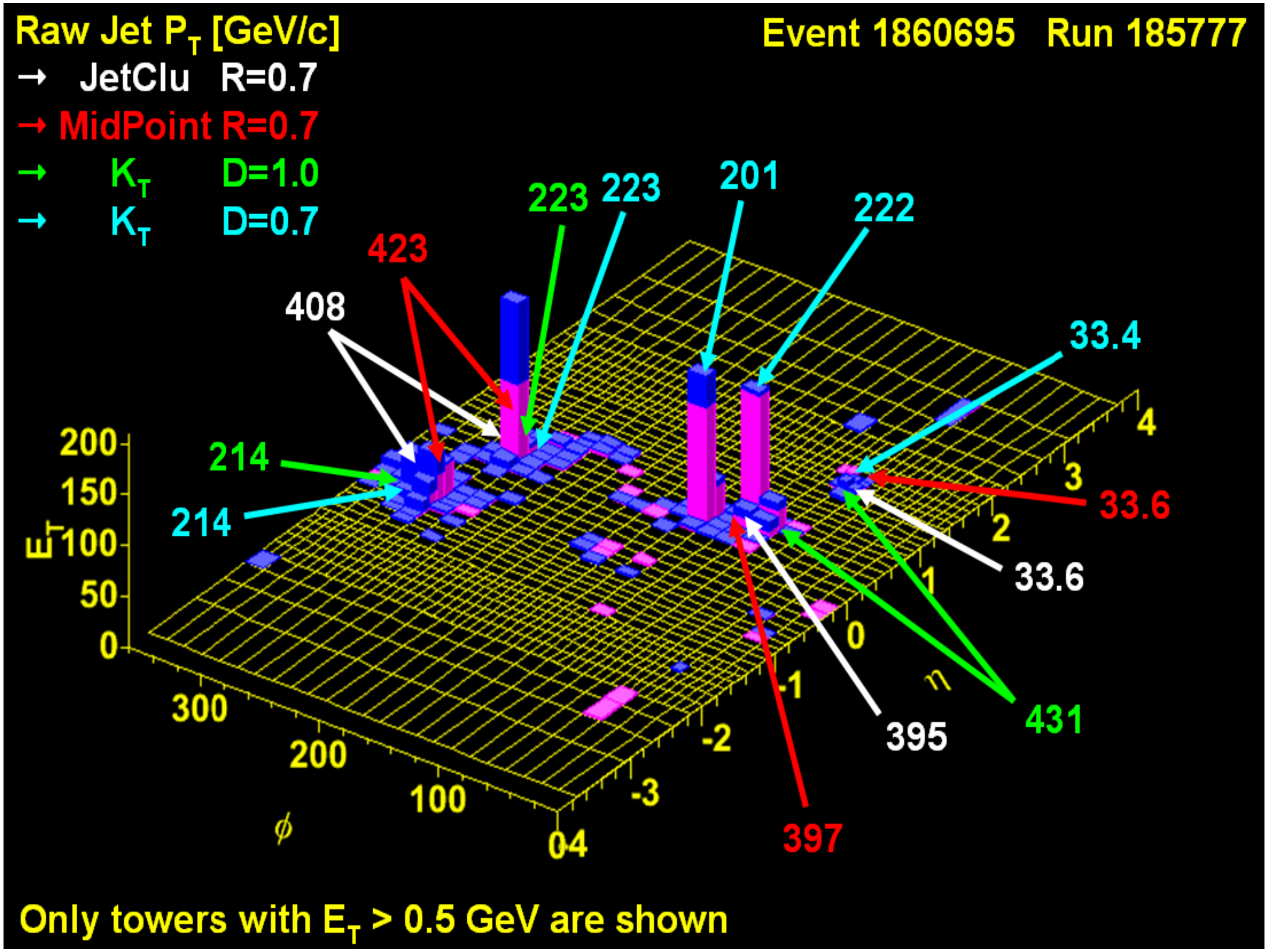
## $K_T$ algorithm:

- Preferred by theory
  - Partons are separated into jets according to their transverse momentum
- Compute for each pair (i,j) and for each particle (i) the quantities

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

  - Iteration until find stable jets
  - Use E-scheme
  - Infrared and collinear safe
- No merging/splitting parameter needed
- successfully used at LEP and HERA → relatively new in hadron colliders
- More sensitive to Underlying event and multiple interactions

# *MidPoint vs. $K_T$ algorithm*

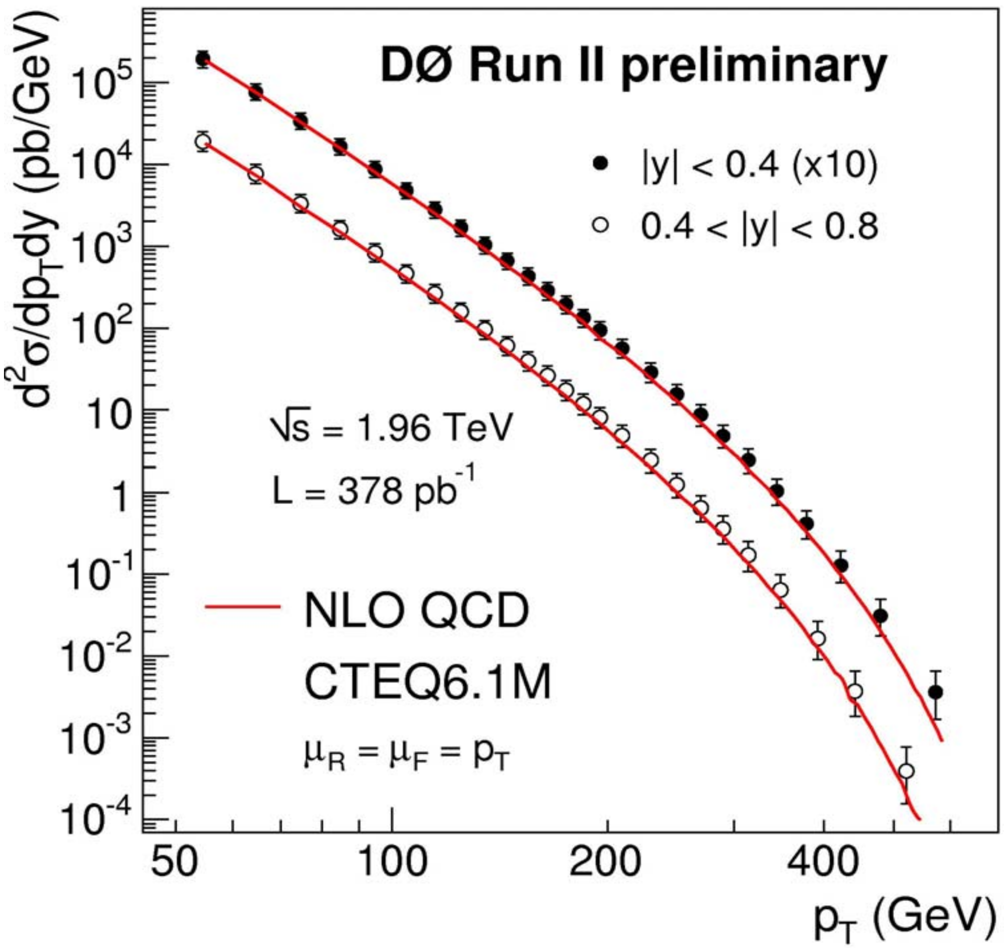



Differences in # of jets, jet $E_T$ .. → Different Cross section measurements

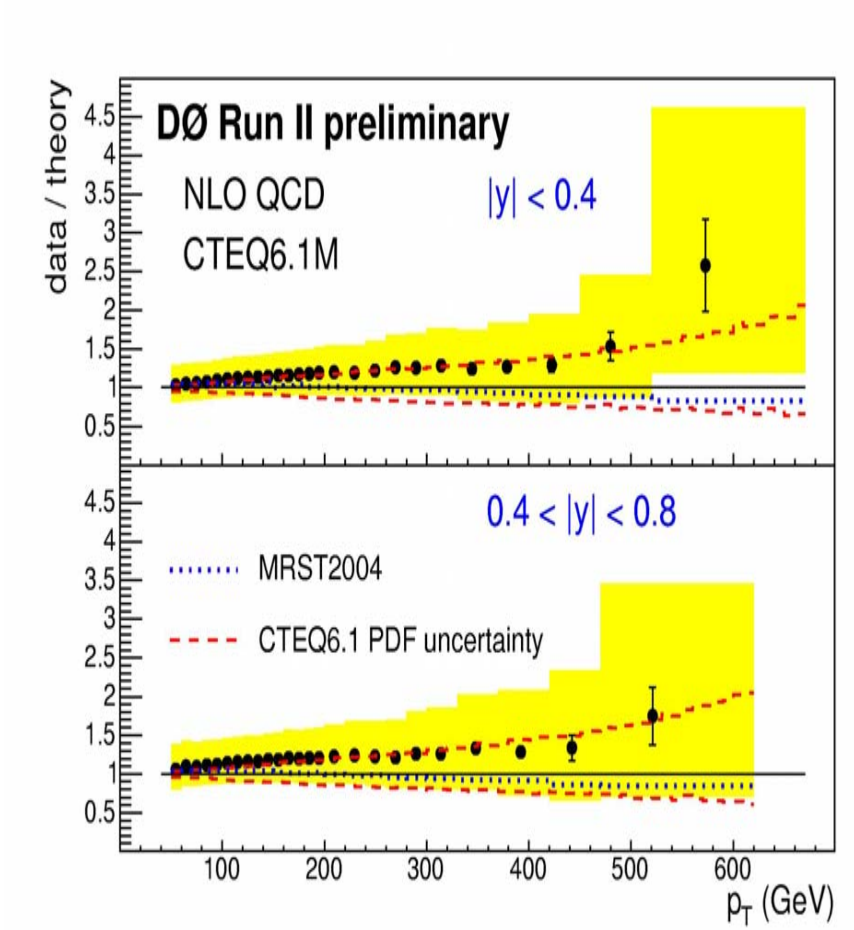
# *Inclusive jet cross section (D0)*

- MidPoint algorithm R = 0.7
- 2 regions in rapidity explored
  - $|y^{jet}| < 0.4$
  - $0.4 < |y^{jet}| < 0.8$

$L = 380\ pb^{-1}$

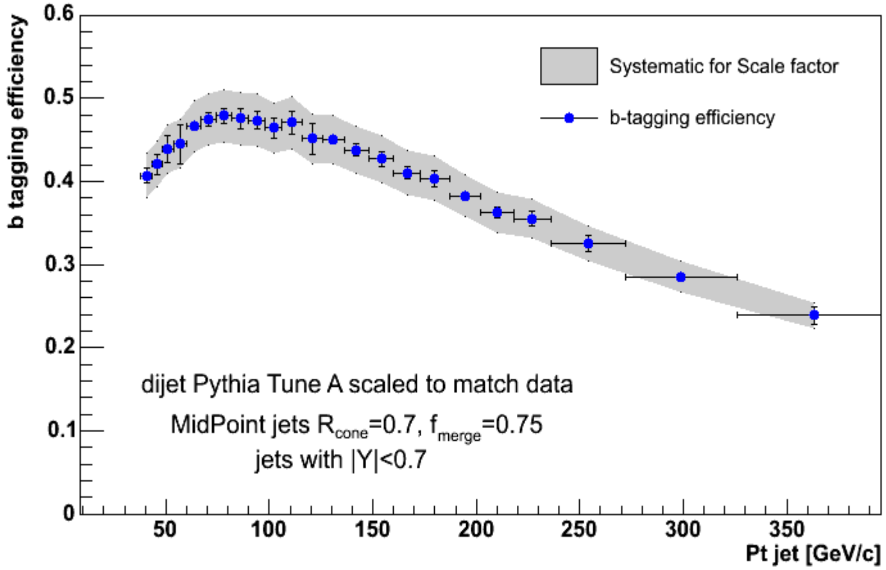



Jet energy scale uncertainty
→ dominant error

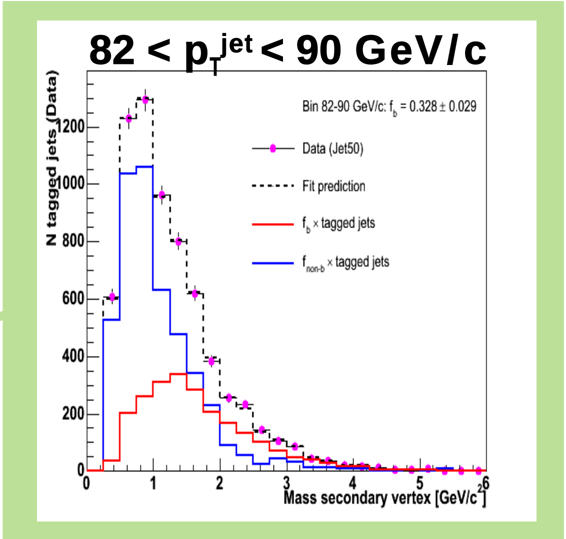



Good agreement with NLO prediction (NLOJET++)

# *High $P_T$ b-jet cross section (CDF)*

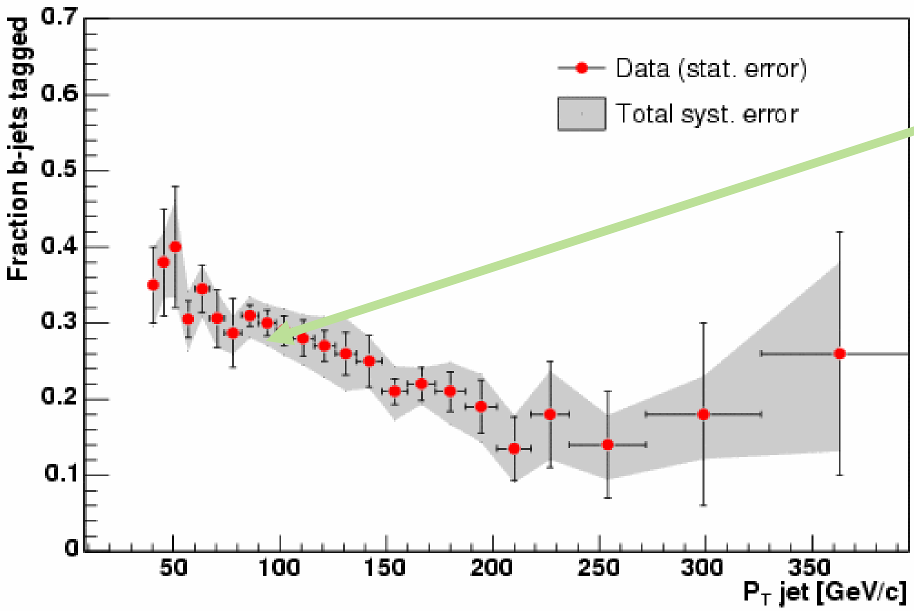



Displaced tracks inside jet used to reconstruct secondary vertex from B hadron decays (b-tagging)

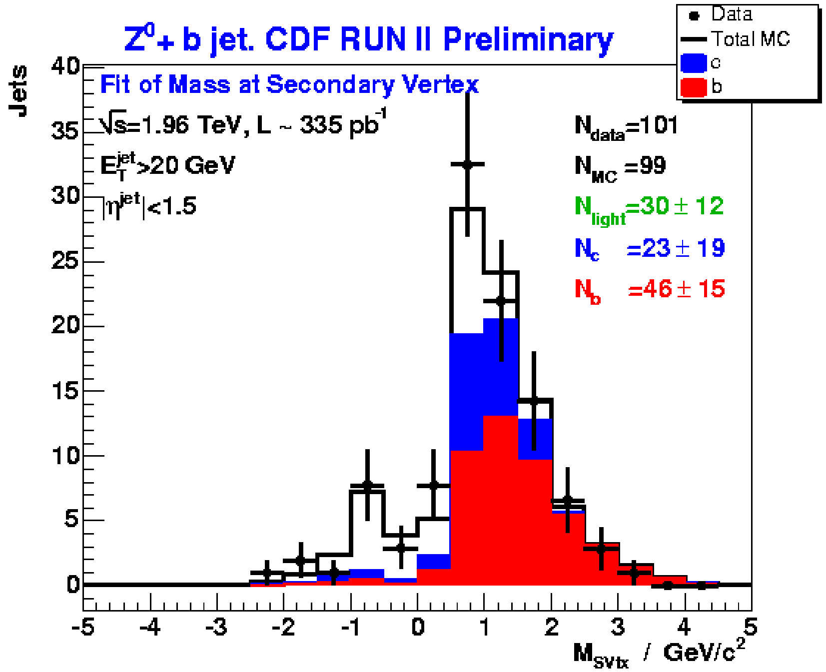



Extract fraction of b-tagged jets from data:

→ use shape of secondary vertex mass



# Z+b jets production (CDF)



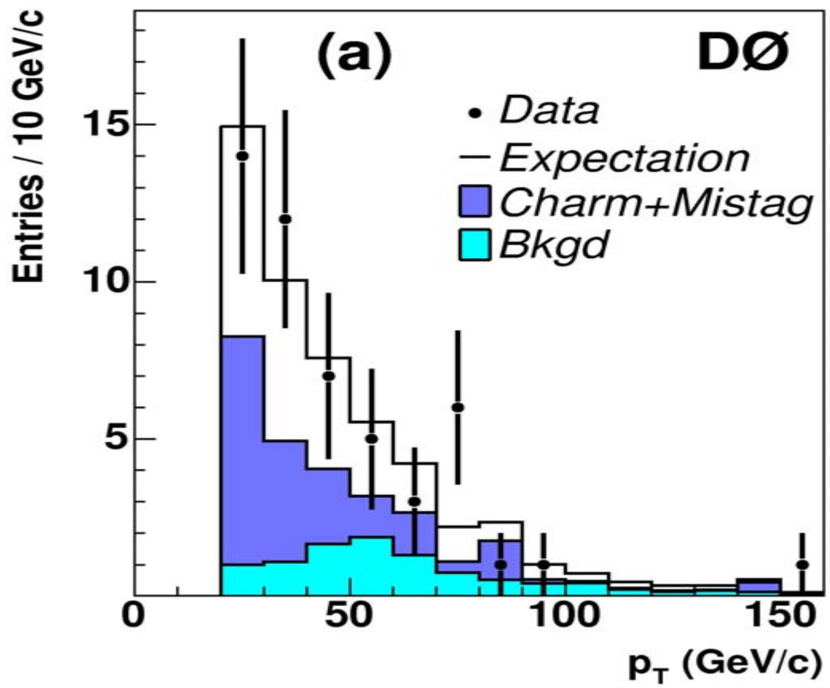

- Look for tagged jets in *Z* events
  - ✓ Same algorithm as in b-jet cross section
  - ✓ Extract fraction of b-tagged jets from secondary vertex Mass
  - ✓ Make no assumption on the charm content

→ extract $\rho_b$: $N^b_{Data}/N^b_{MC}$

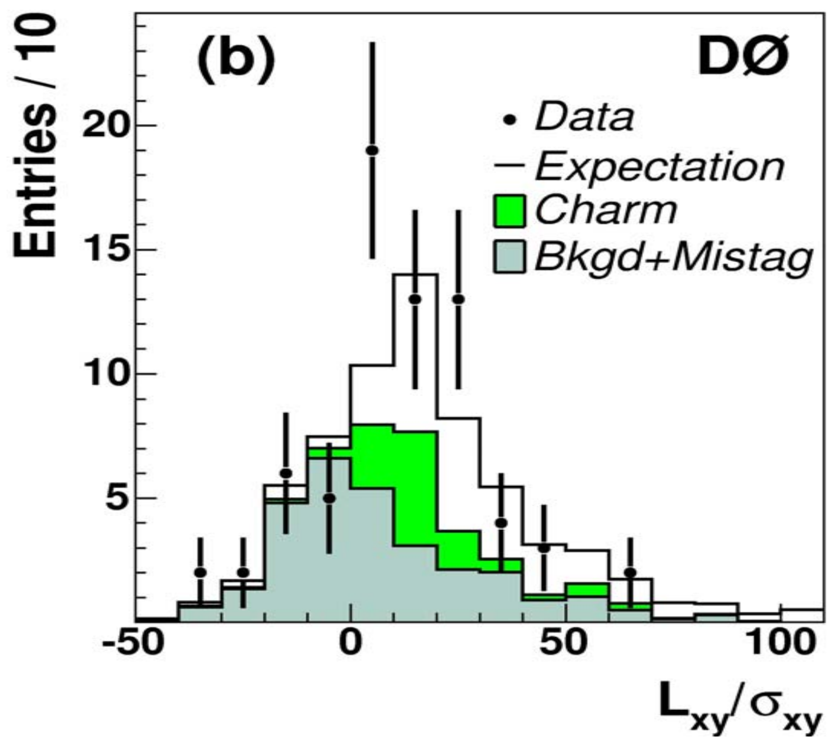
$\mu_R = \mu_F = M_Z$
Uncertainty ~10% changing scale

| $E_T^{jet} > 20$ GeV, $\lvert\eta^{jet}\rvert < 1.5$ | CDF PreliminaryData | PYTHIA TuneA(CTEQ5L) | NLO J. Campbell | NLO withHad, UE |
|---|---|---|---|---|
| $\sigma(Z^0 + b\,\text{jet})$ | $0.96 \pm 0.32 \pm 0.14$ pb | 0.83 pb | 0.48 pb | 0.52 pb |
| $\sigma(Z^0 + b\,\text{jet})/\sigma(Z^0)$ | $0.0038 \pm 0.0012 \pm 0.0005$ | 0.0034 | 0.0019 | 0.0021 |
| $\sigma(Z^0 + b\,\text{jet})/\sigma(Z^0 + \text{jet})$ | $0.0237 \pm 0.0078 \pm 0.0033$ | 0.0207 | 0.0185 | 0.0185 |

# Z+b jets production (D0)




- Look for tagged jets in *Z* events
  - B-tagging algorithms reconstruct secondary vertecis
  - Assumption on the charm content from theoretical prediction: $N_c$=1.69$N_b$



# W+jets production (CDF)

Integrated cross section w.r.t. jet $E_T$ in each of the 4 W+n jet inclusive samples