Jet Properties at the Tevatron

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On behalf of the D0 & CDF collaborations

XX Rencontres de Physique de la Vallee D'Aoste

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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 (Single Diffraction, Double-Pomeron-Exchange, Exclusive Productions)

The Tevatron

Highest-energy accelerator currently operational

Peak luminosity

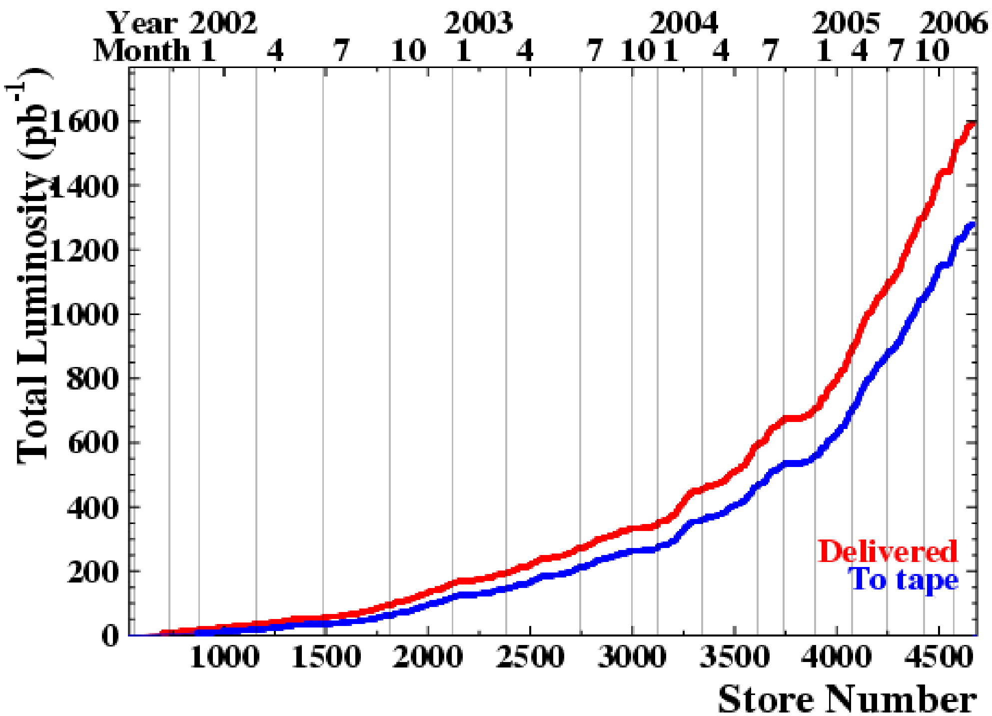
→ **1.8 $*10^{32}$ cm^{-2} s^{-1}**

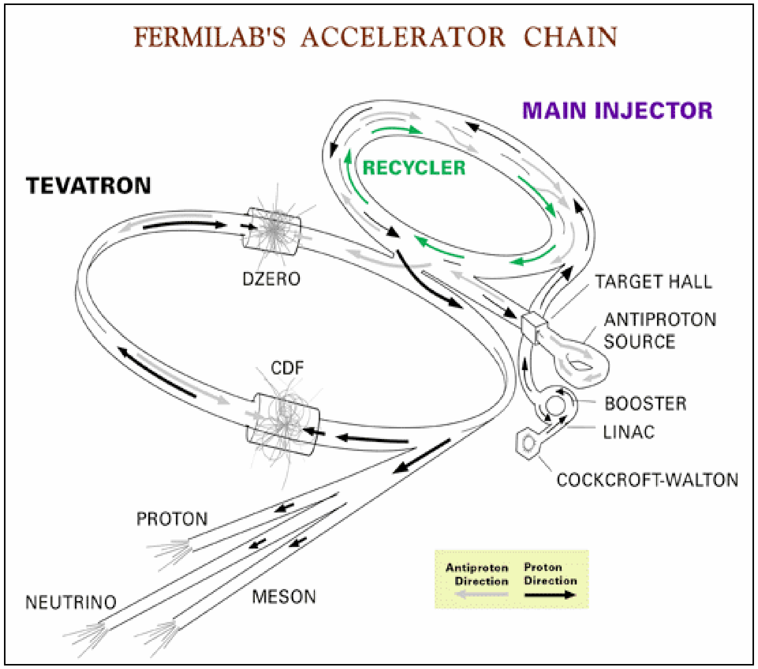
Integrated luminosity/week

→ **about 25 pb^{-1}**

CDF and D0:

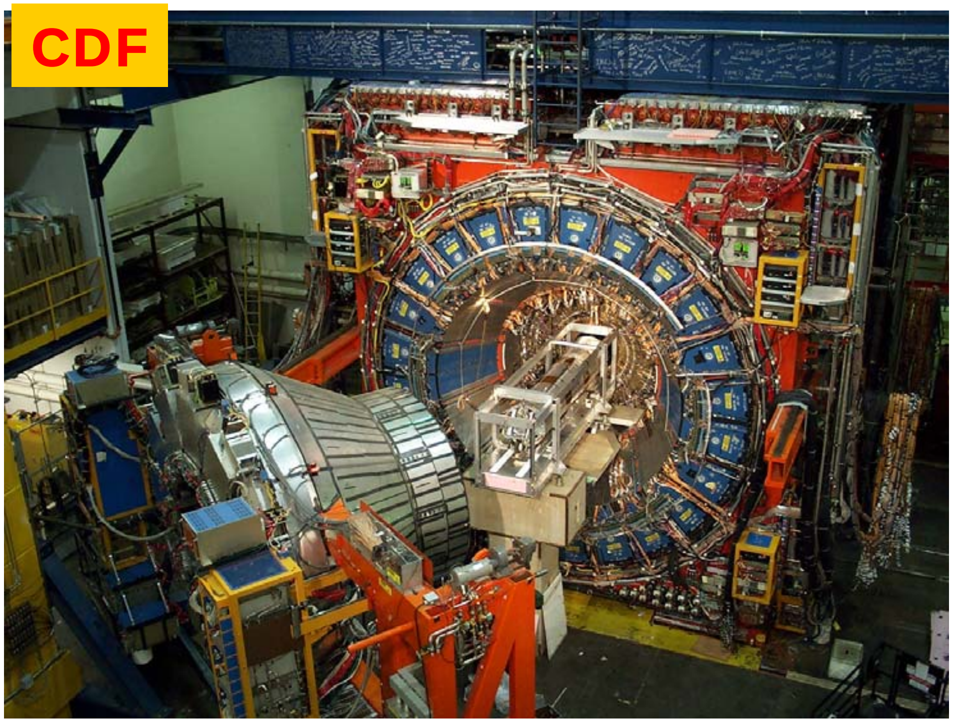
→~**1.2 fb^{-1}** on tape





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

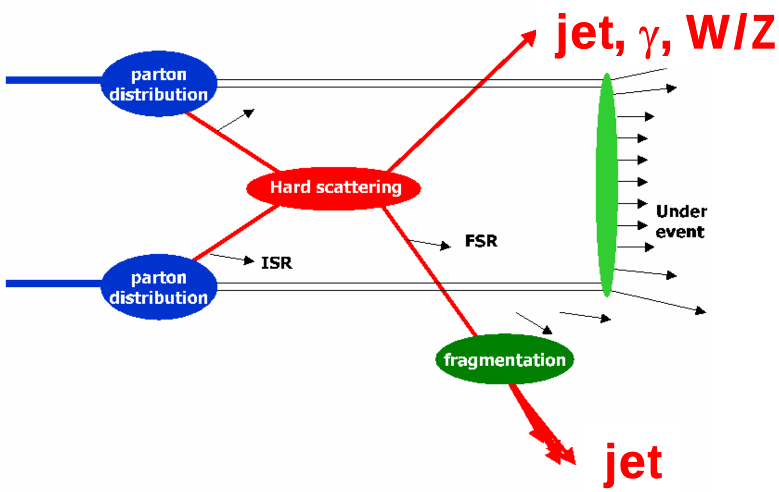
L2 trigger on displaced vertices
Excellent tracking resolution

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

Jet physics @ Tevatron

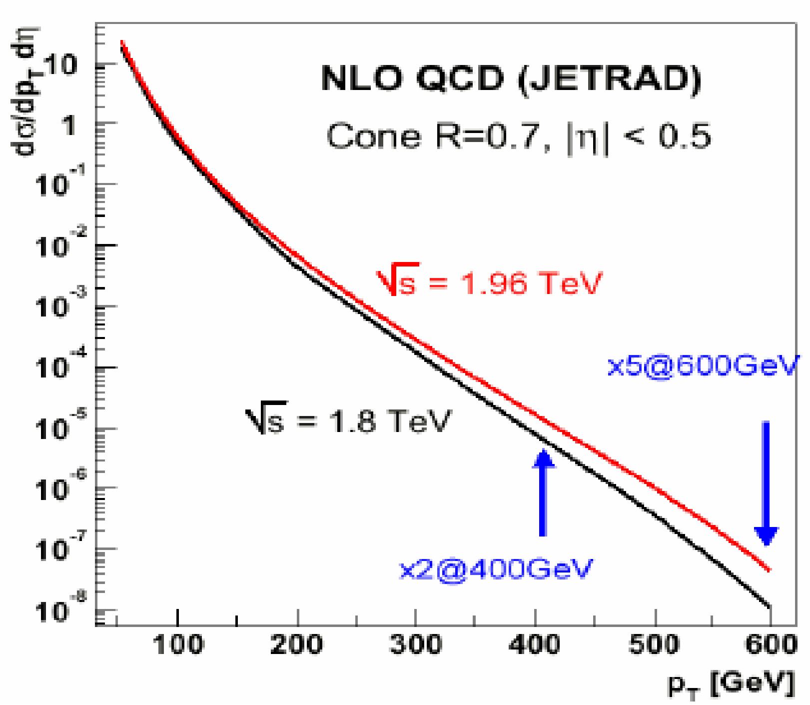
All production processes → QCD related

- 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 σ_{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**

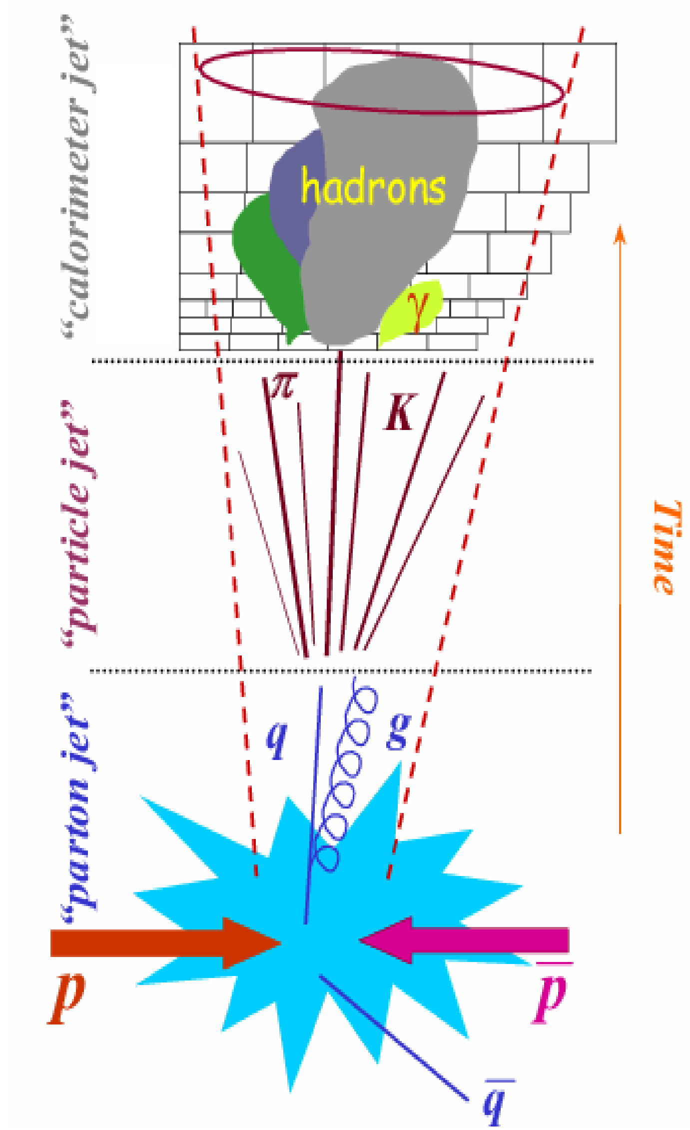
Measurements → at hadron level
Theory prediction → parton level

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 types of jet algorithms:
- Cone Algorithm
  → JETCLU (Run I like) and MIDPOINT
- K_T algorithm

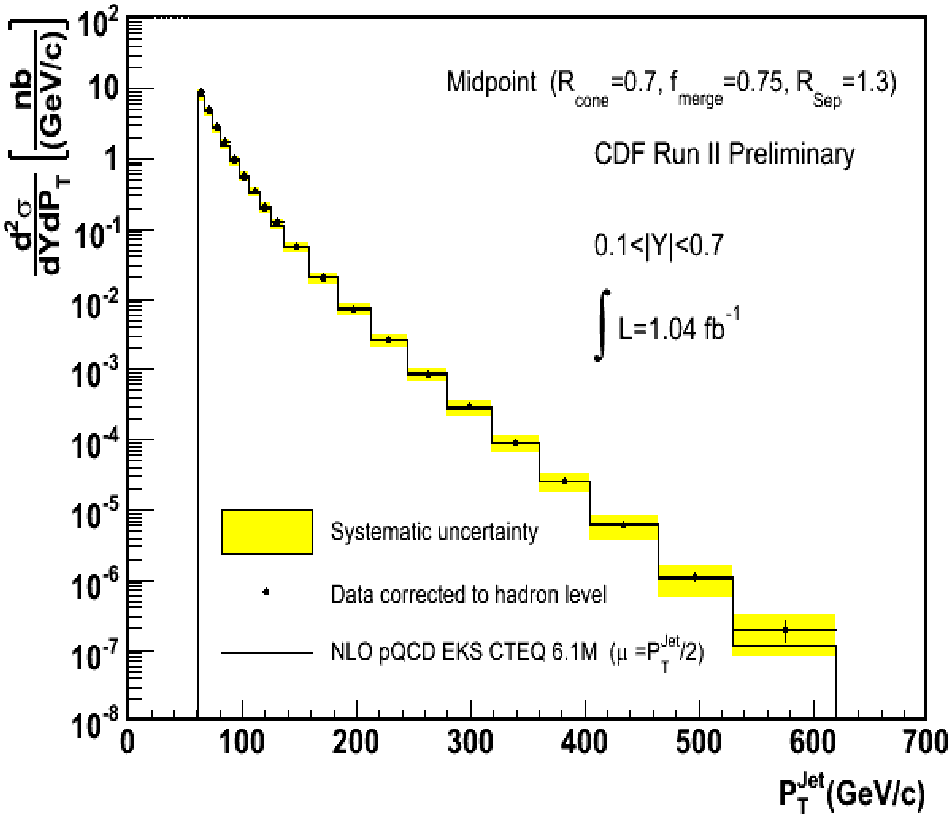


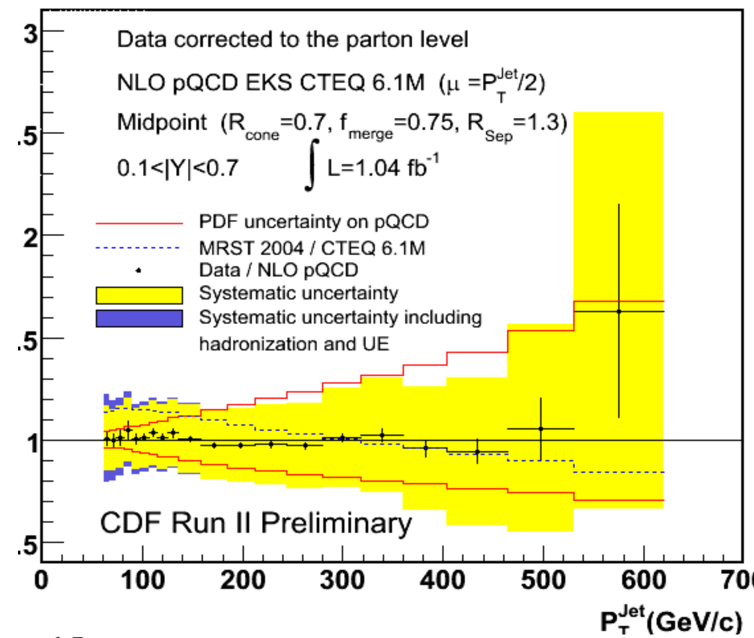
Inclusive Jet Cross Section (CDF)

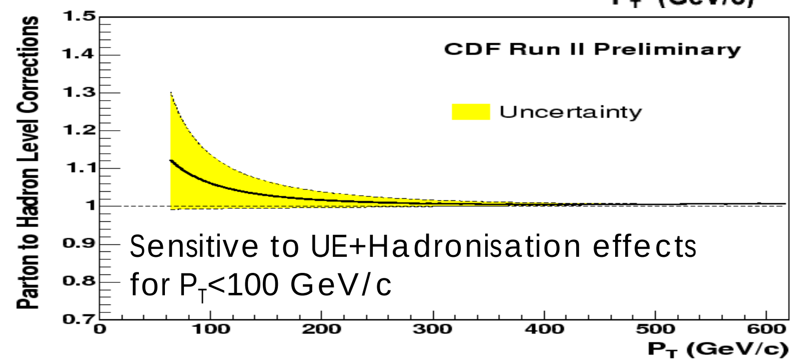
- MidPoint algorithm R = 0.7
- Central jets: $0.1 < |y^{jet}| < 0.7$
- More than 8 orders of magnitude covered

L = 1 fb^{-1}

- Data dominated by Jet Energy Scale (JES) uncertainties (2-3%)
- NLO uncertainty due to high x gluon PDF







Sensitive to UE+Hadronisation effects for P_T<100 GeV/c

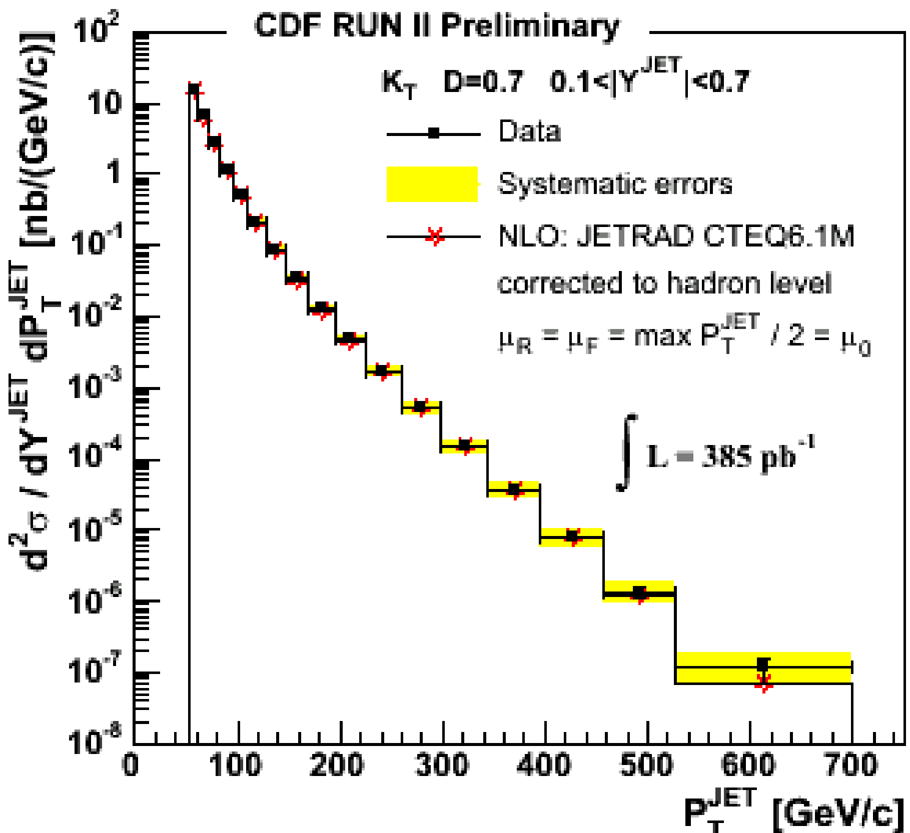
Good agreement with NLO predictions

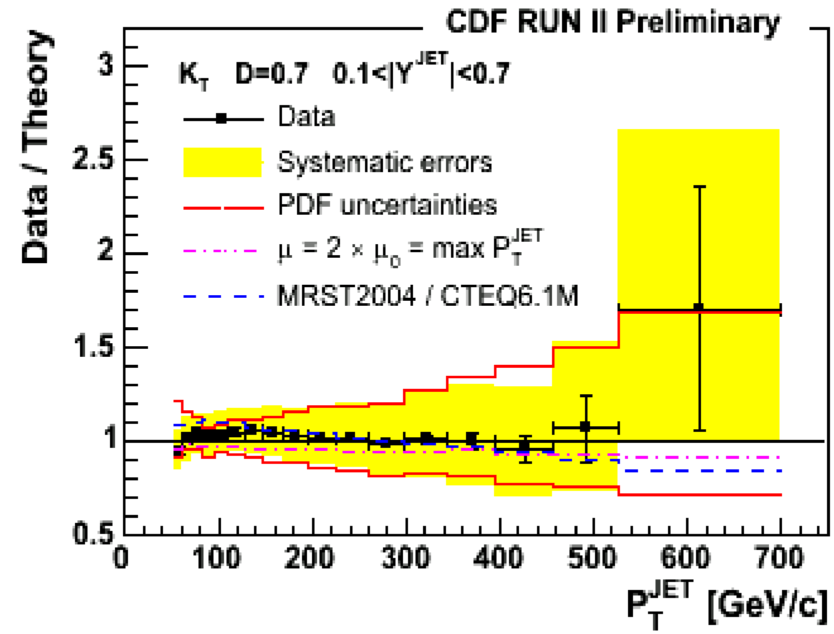
Inclusive Jet Cross Section (CDF)

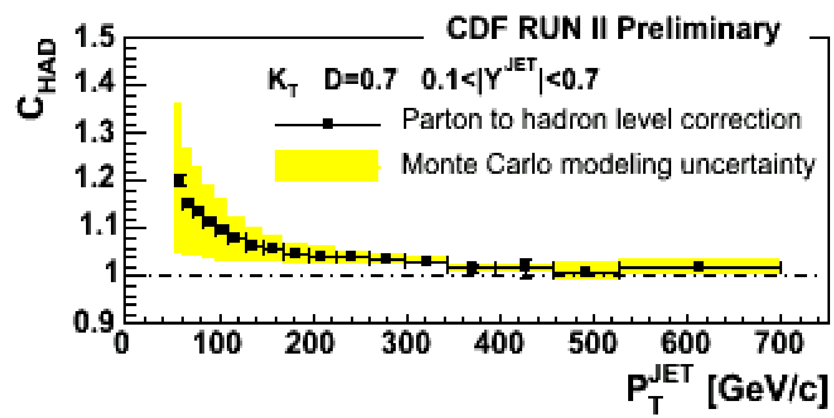
- K_T algorithm (D = 0.7)

L = 385 pb^{-1}

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





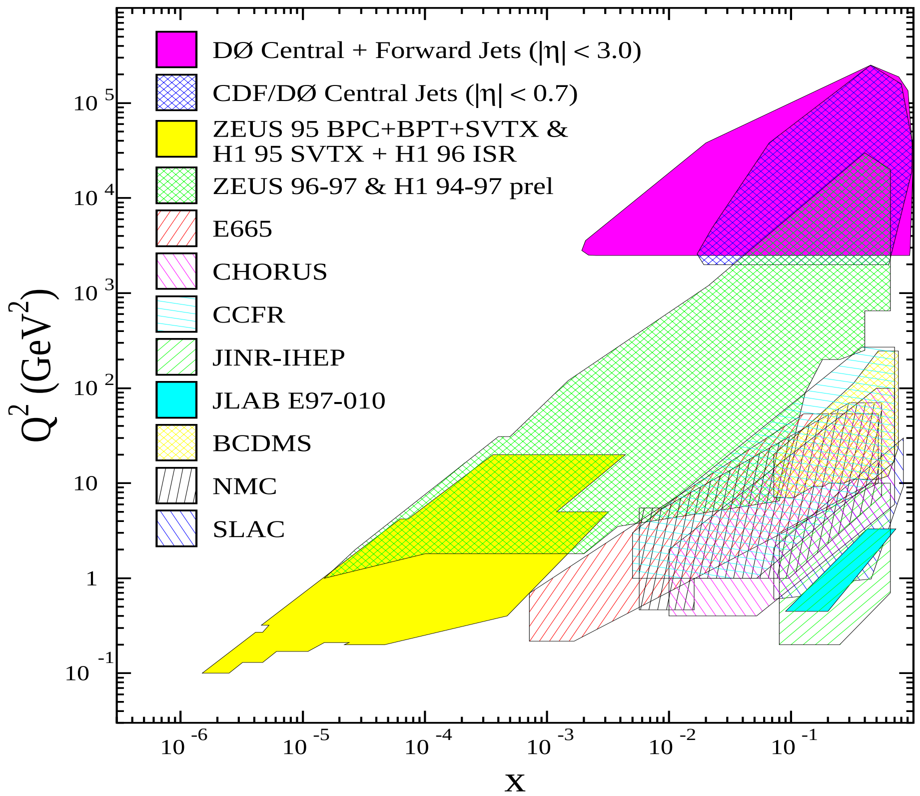


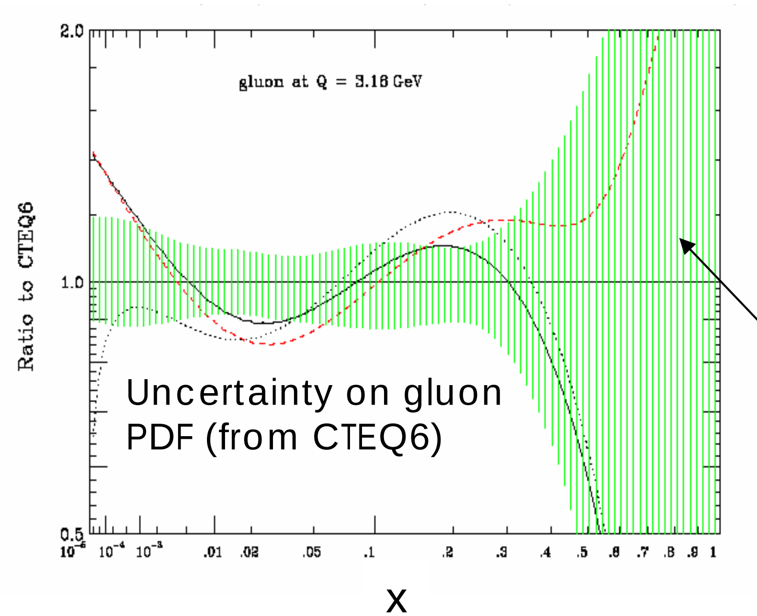
K_T performs well in hadron collisions
Good agreement with NLO pQCD

Gluon PDF at high-x

from Run I

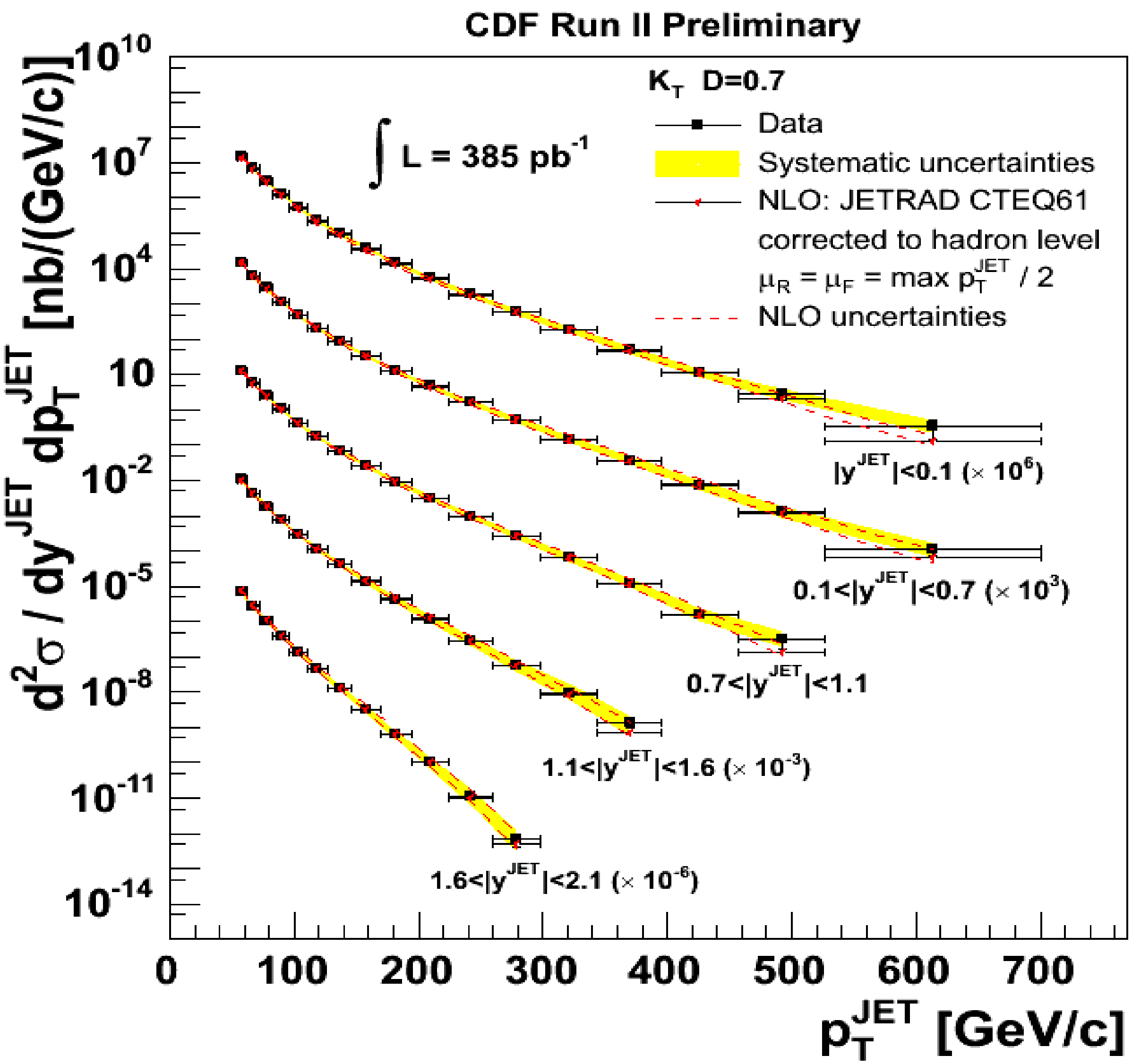
E.g. Forward jets measurements help to distinguish between new physics and PDF if any excess in the central region





Big uncertainty for high-x gluon PDF

Forward jets (k_T algorithm ,CDF)

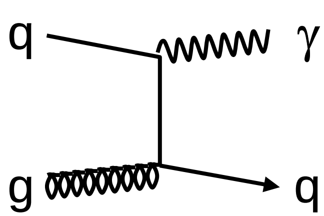


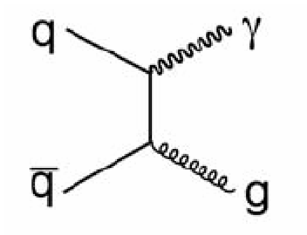
Five regions in jet rapidity explored (D=0.7):

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

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

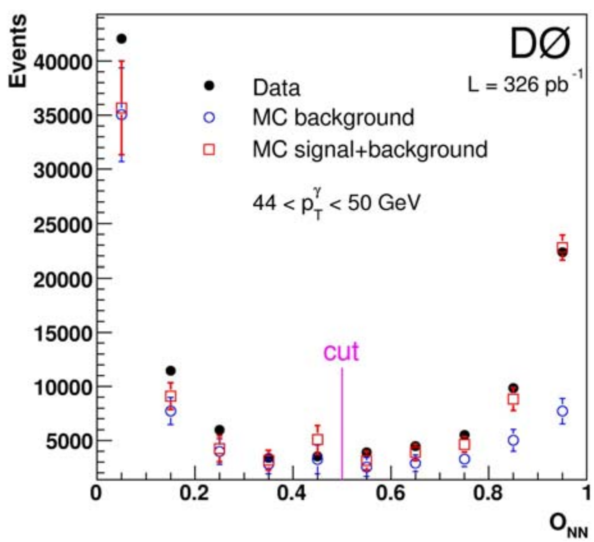
Inclusive γ cross section (D0)





L = 330 pb^{-1}

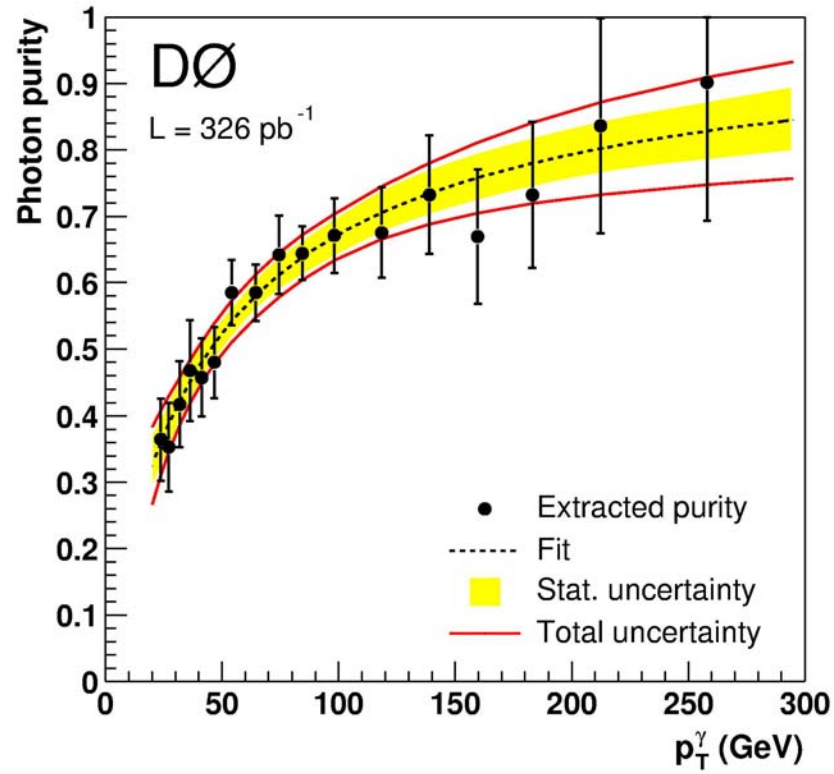
- Separating photons from jet backgrounds is challenging



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

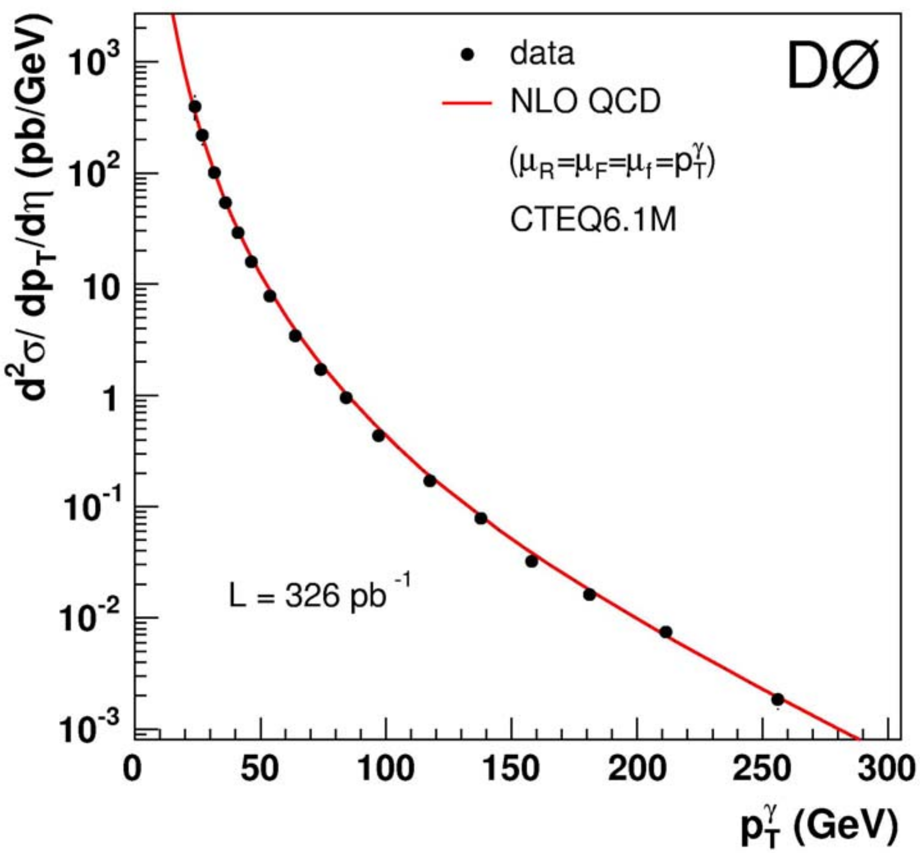
- Sensitive to PDF and hard scatter dynamics: no need to define "jets"
- Performed for central photons, $|y^{\gamma}| < 0.9$

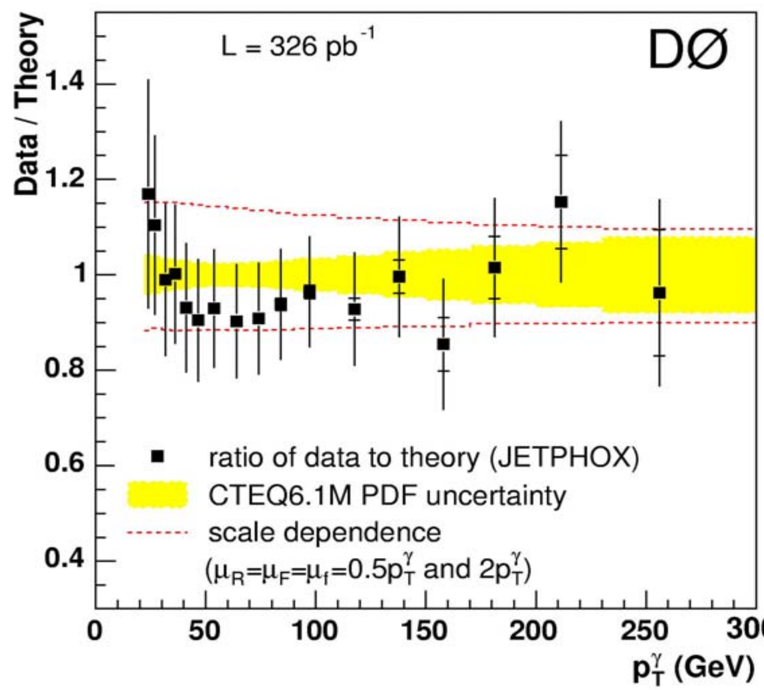
No Jet Energy Scale error, good understanding of γ E-scale
→ purity uncertainties dominates



Inclusive γ cross section (D0)

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





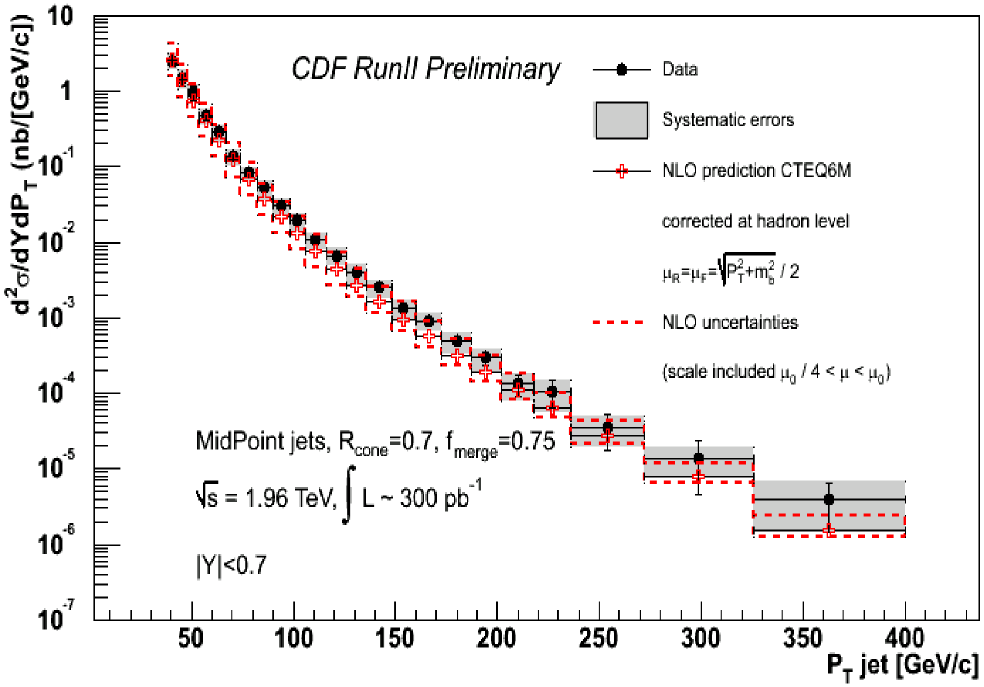
- Errors ~20%
- Very promising at the fb^{-1} to constrain gluon PDF at high x

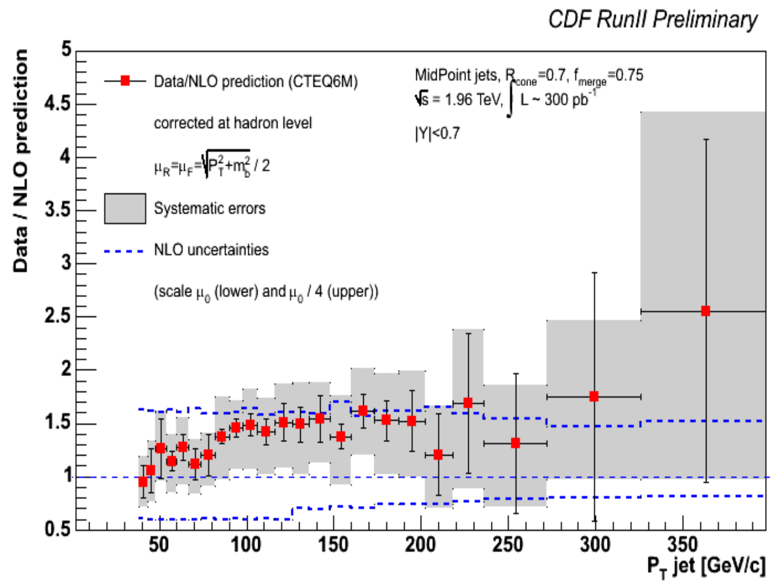
Good agreement with pQCD NLO

High P_T b-jet cross section (CDF)

L = 300 pb^{-1}

- 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

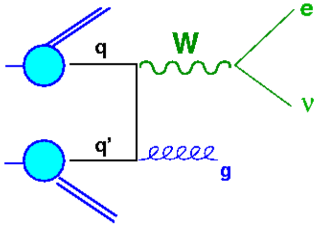


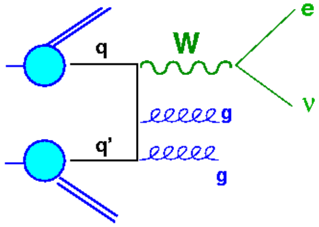


- More than 6 orders of magnitude covered
- Data systematic uncertainties dominated by Jet Energy Scale and b-fraction uncertainties
- Main uncertainties on NLO due μ_R/μ_F scales

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

W+jets production (CDF)

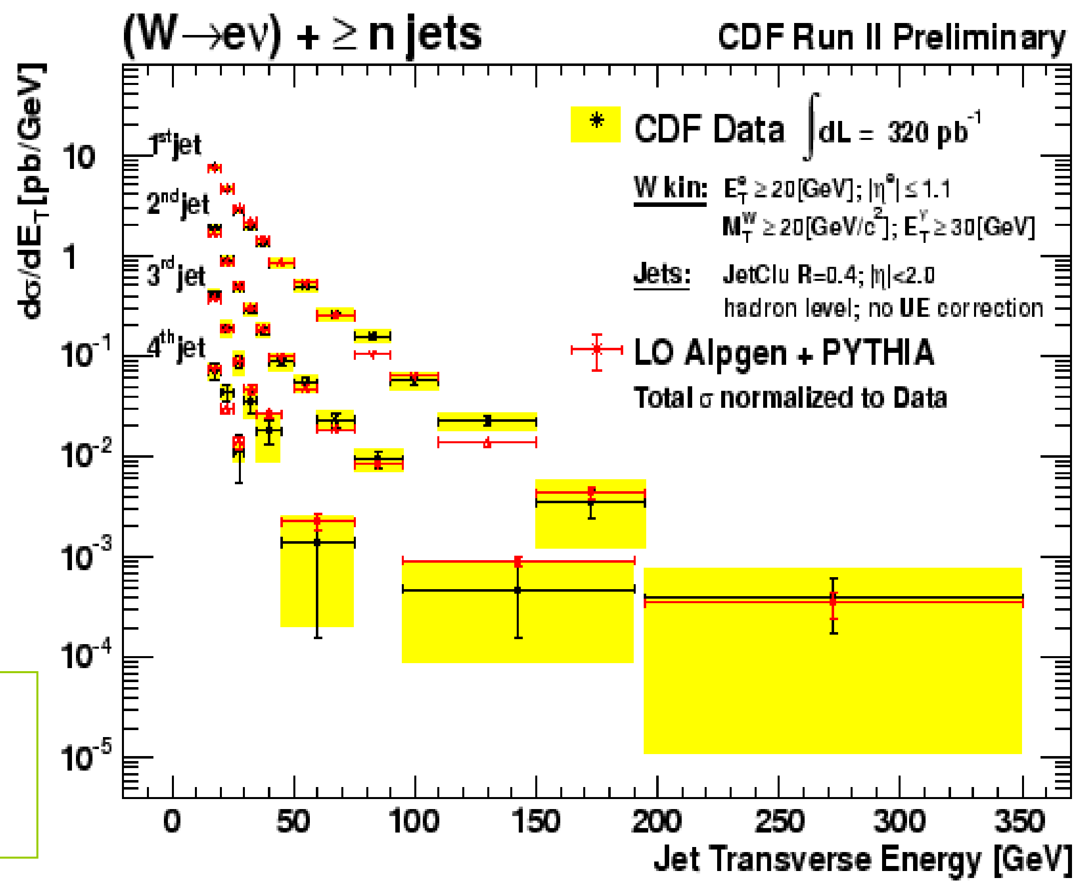




- Background to top and Higgs Physics
- Testing ground for pQCD in multijet environment
  - Key sample to test LO and NLO ME+PS predictions

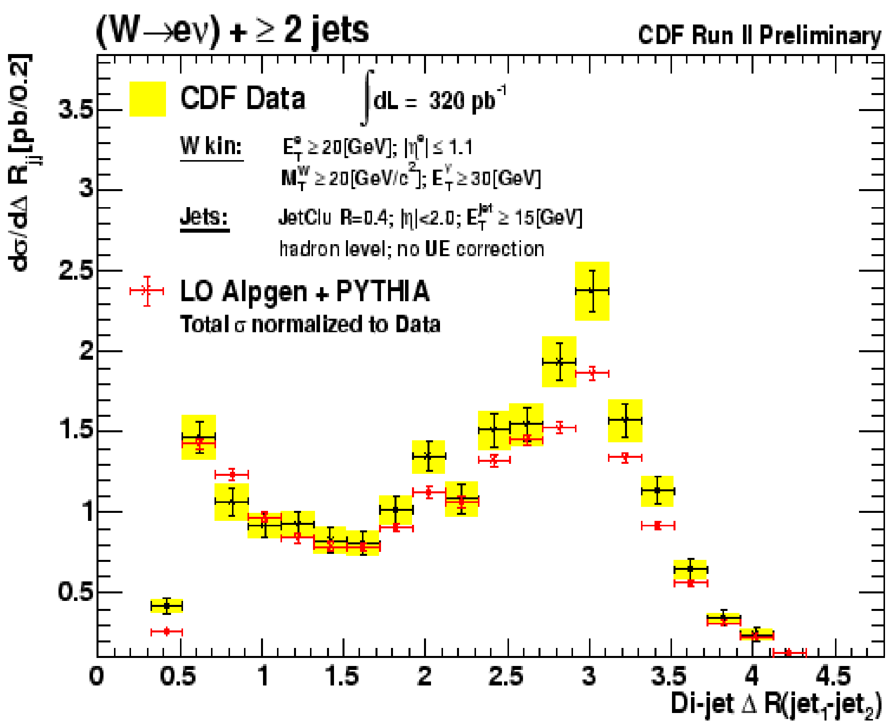
L = 320 pb^{-1}

- Restrict σ_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



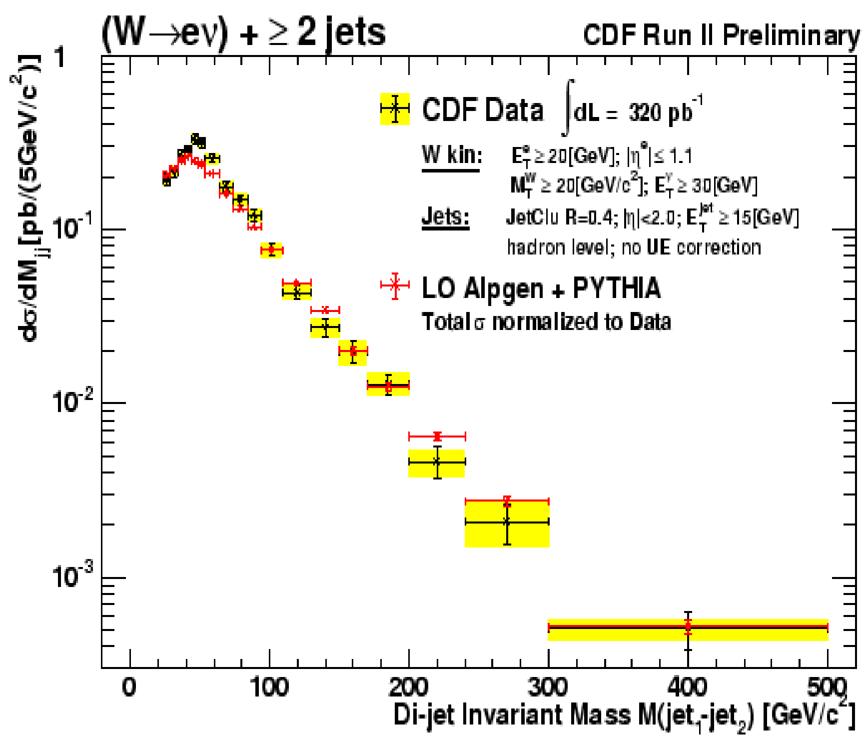
LO predictions normalized to data integrated cross sections
→ **Shape comparison only**

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**

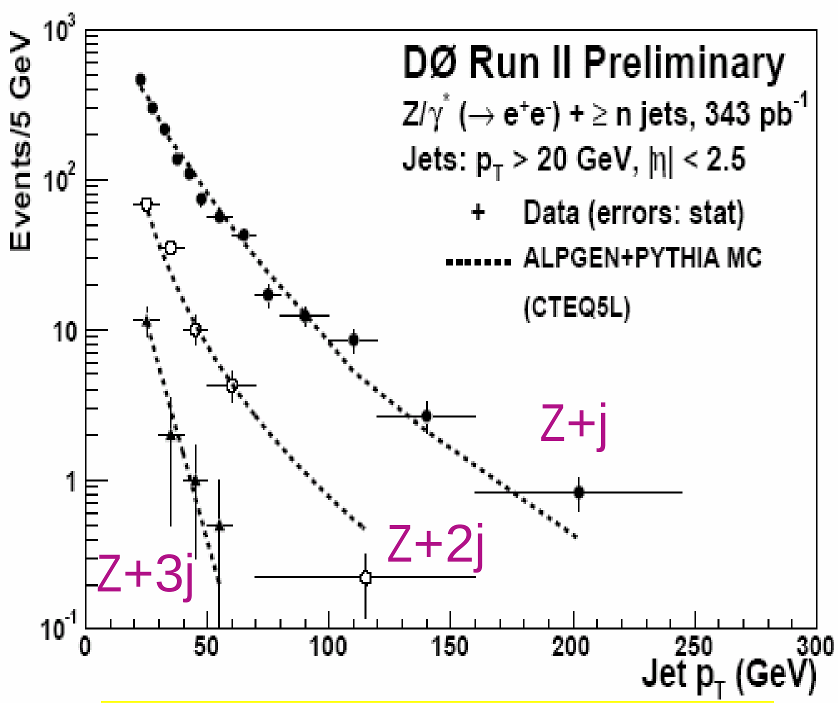
More exhaustive comparisons expected soon!!!

Z+jets production (D0)

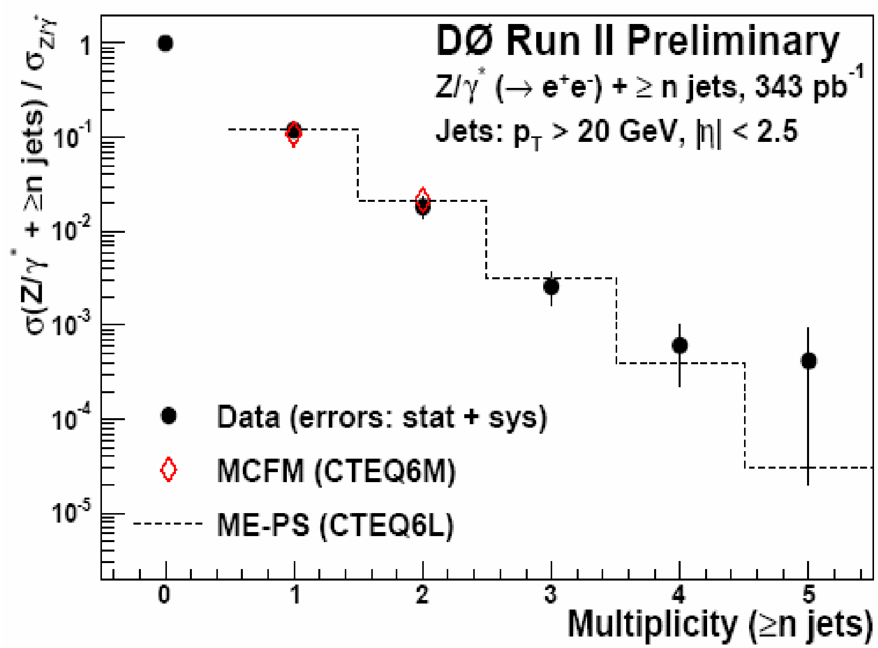
L = 343 pb^{-1}

- Same motivations as W + jets
  - $\sigma(Z) \sim \sigma(W)$ / 10, but Z→e^+e^- cleaner
- Central electrons ($|\eta|<1.1$)
- 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 nth jet distribution

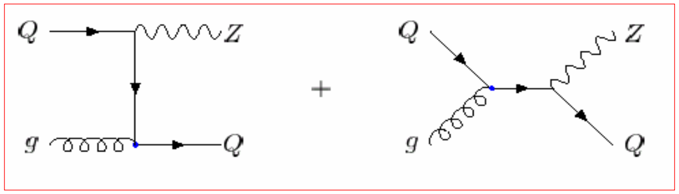


MCFM: NLO for Z+1p or Z+2p → good description of the measured cross sections

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:
  $Z \rightarrow e^+e^-, \mu^+\mu^-$

Both CDF and D0:

- 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

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

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

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

  - 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

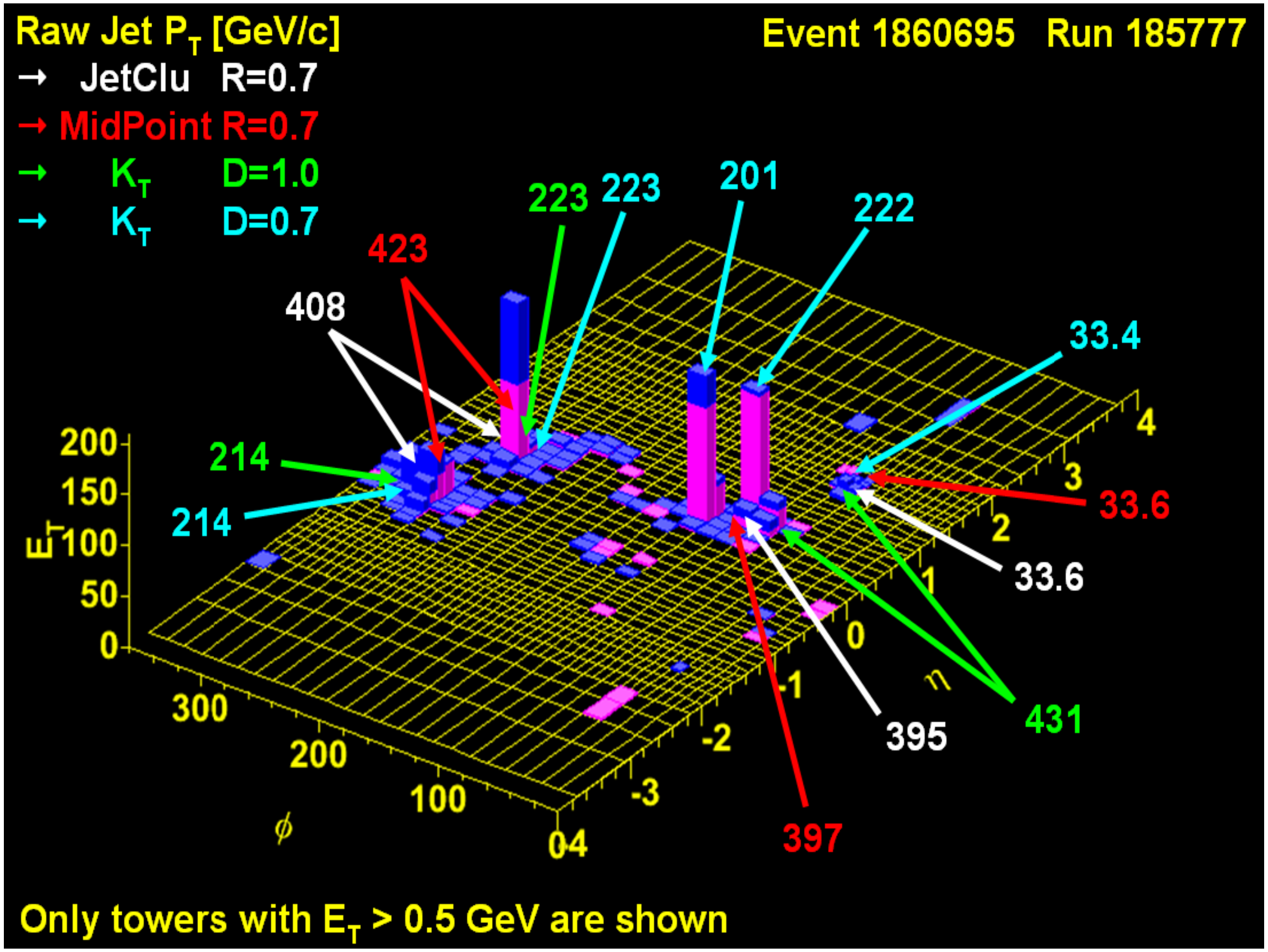
K_T algorithm:

- 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



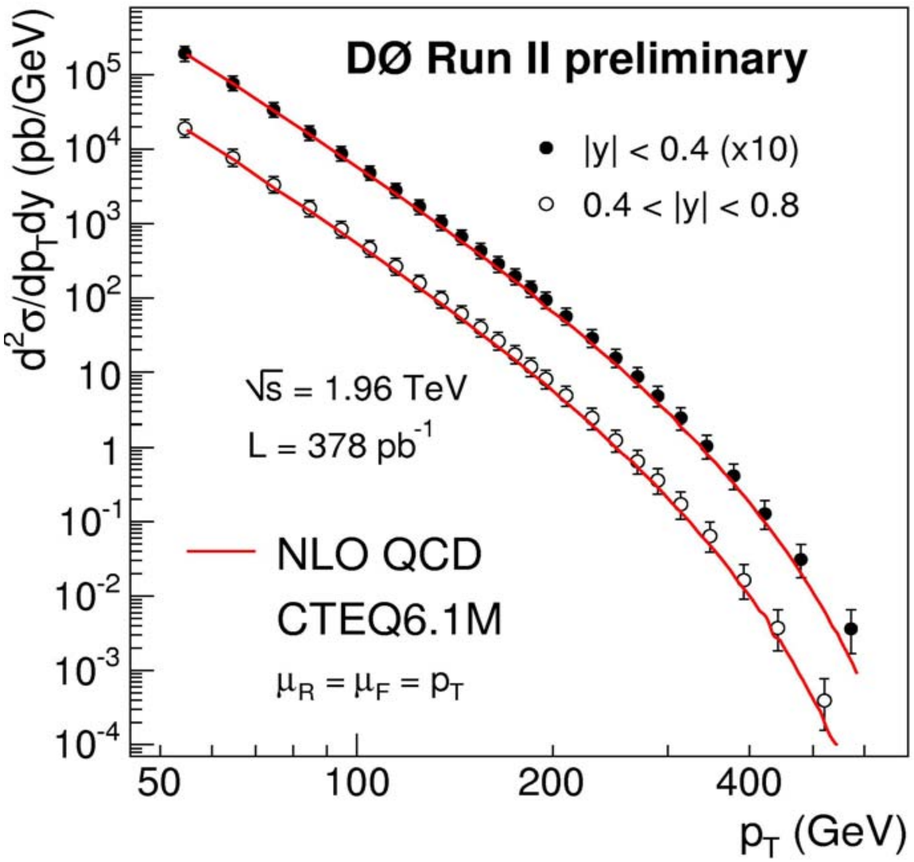
Differences in # of jets, jet E_T .. → Different Cross section measurements

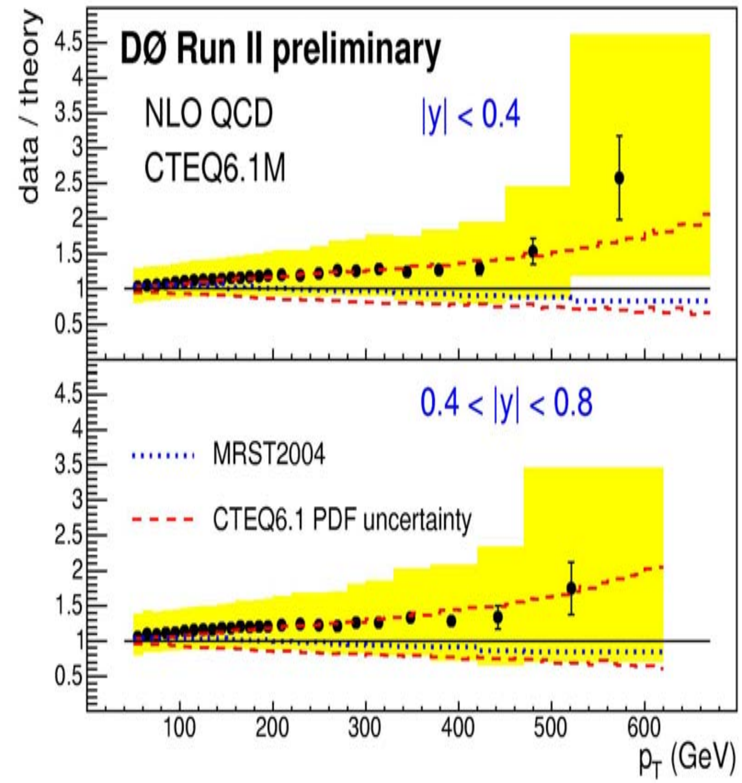
Inclusive jet cross section (D0)

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

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

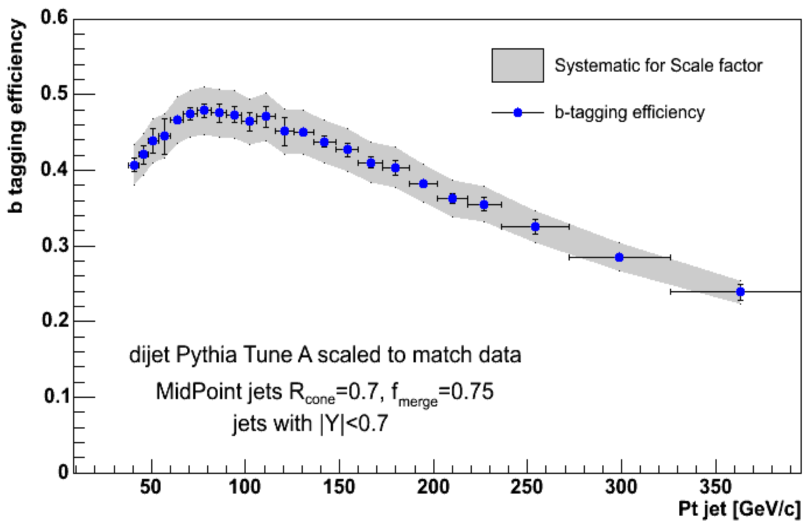
Jet energy scale uncertainty
→ dominant error



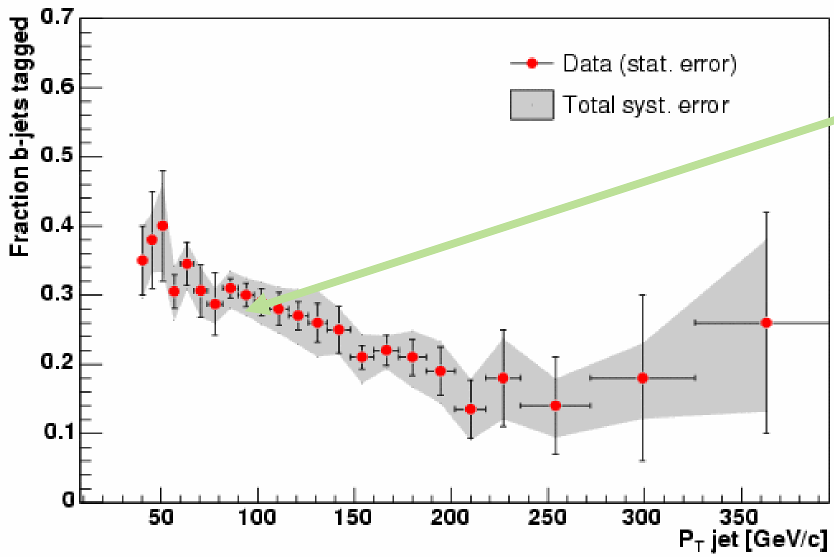


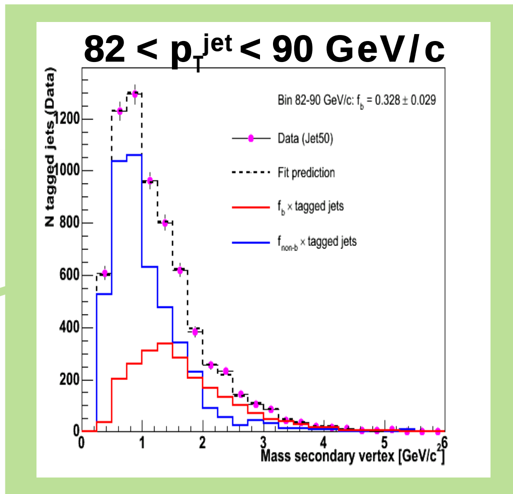
Good agreement with NLO prediction (NLOJET++)

High P_T b-jet cross section (CDF)



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

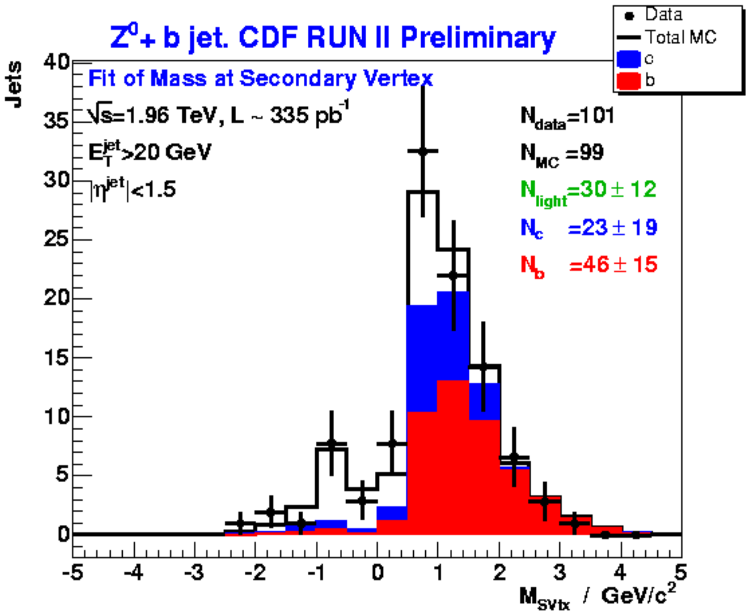




Extract fraction of b-tagged jets from data:

→ 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

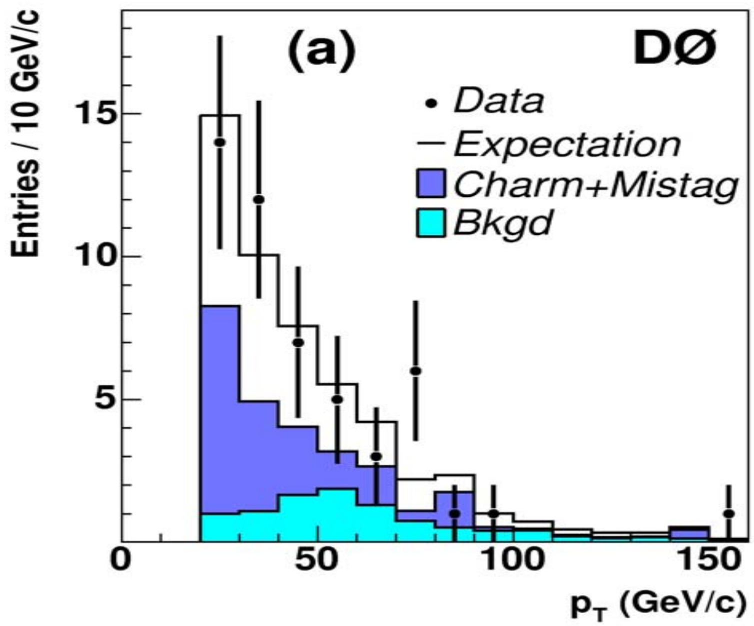
→ extract ρ_b: N^b_{Data}/N^b_{MC}

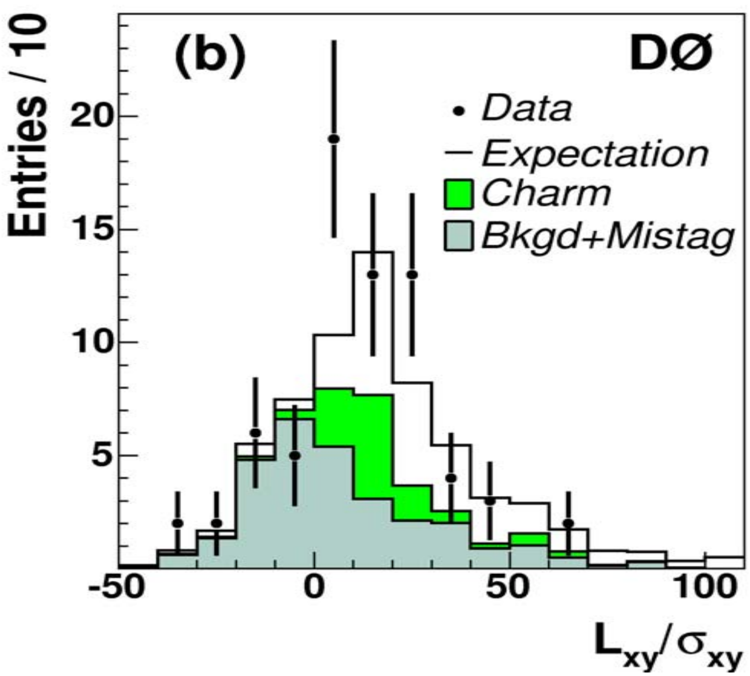
$\mu_R = \mu_F = M_Z$
Uncertainty ~10% changing scale

$E_T^{jet} > 20$ GeV, $\|\eta^{jet}\| < 1.5$	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=1.69N_b





W+jets production (CDF)

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