



Latest QCD results from the Tevatron

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On behalf of the DZero and CDF Collaborations

(Thanks to all my Tevatron colleagues)

Aspen 2008

Overview

- Tevatron collider
- DZero & CDF QCD results (2006-2007):
 - Inclusive jets (Cone & kT algos)
 - Di-jet inclusive production
 - b-bbar di-jet production
 - Di-jet and di-photon exclusive productions
 - Inclusive photons
 - Photon+jet events
 - W+c-jet
 - W/Z + (b)jets

The measurements are done at $L = 0.3 - 1.8 \text{ fb}^{-1}$

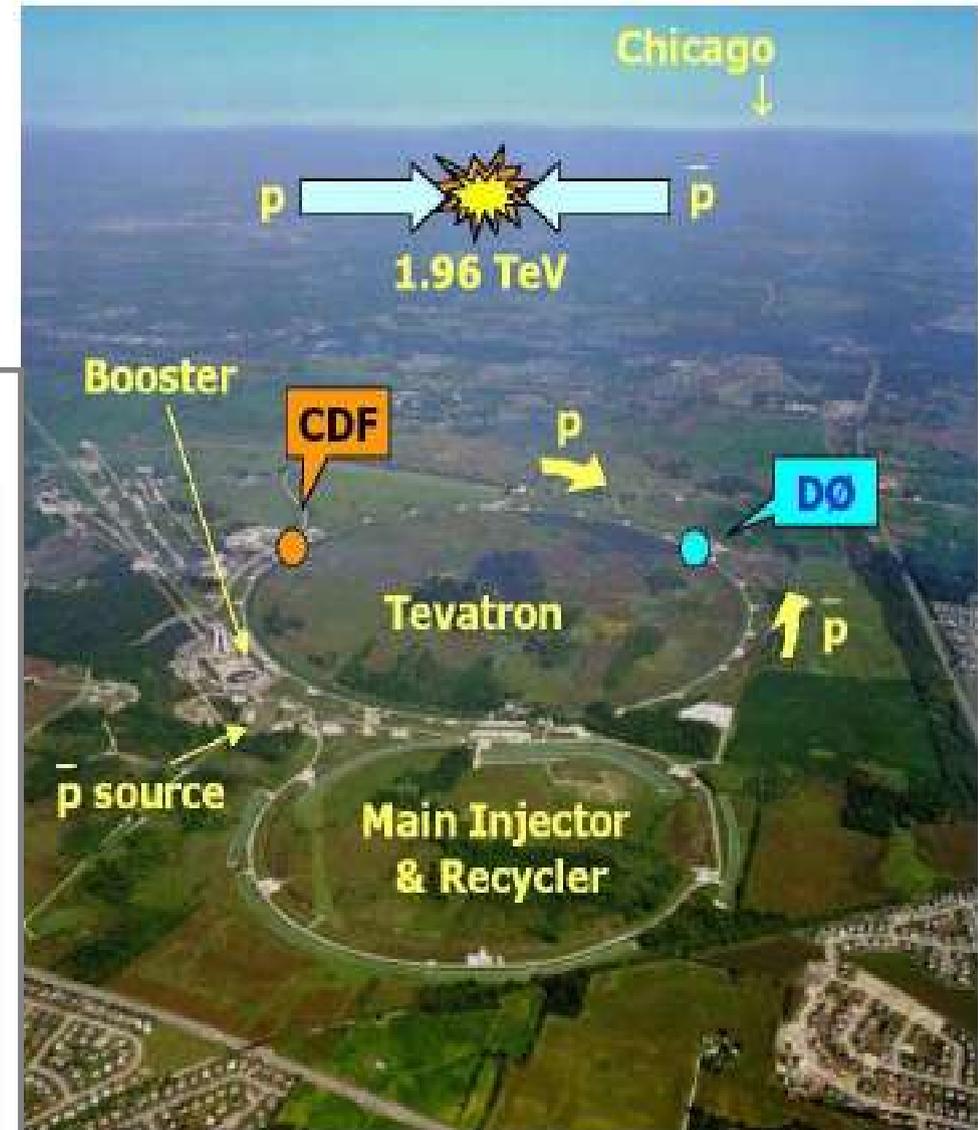
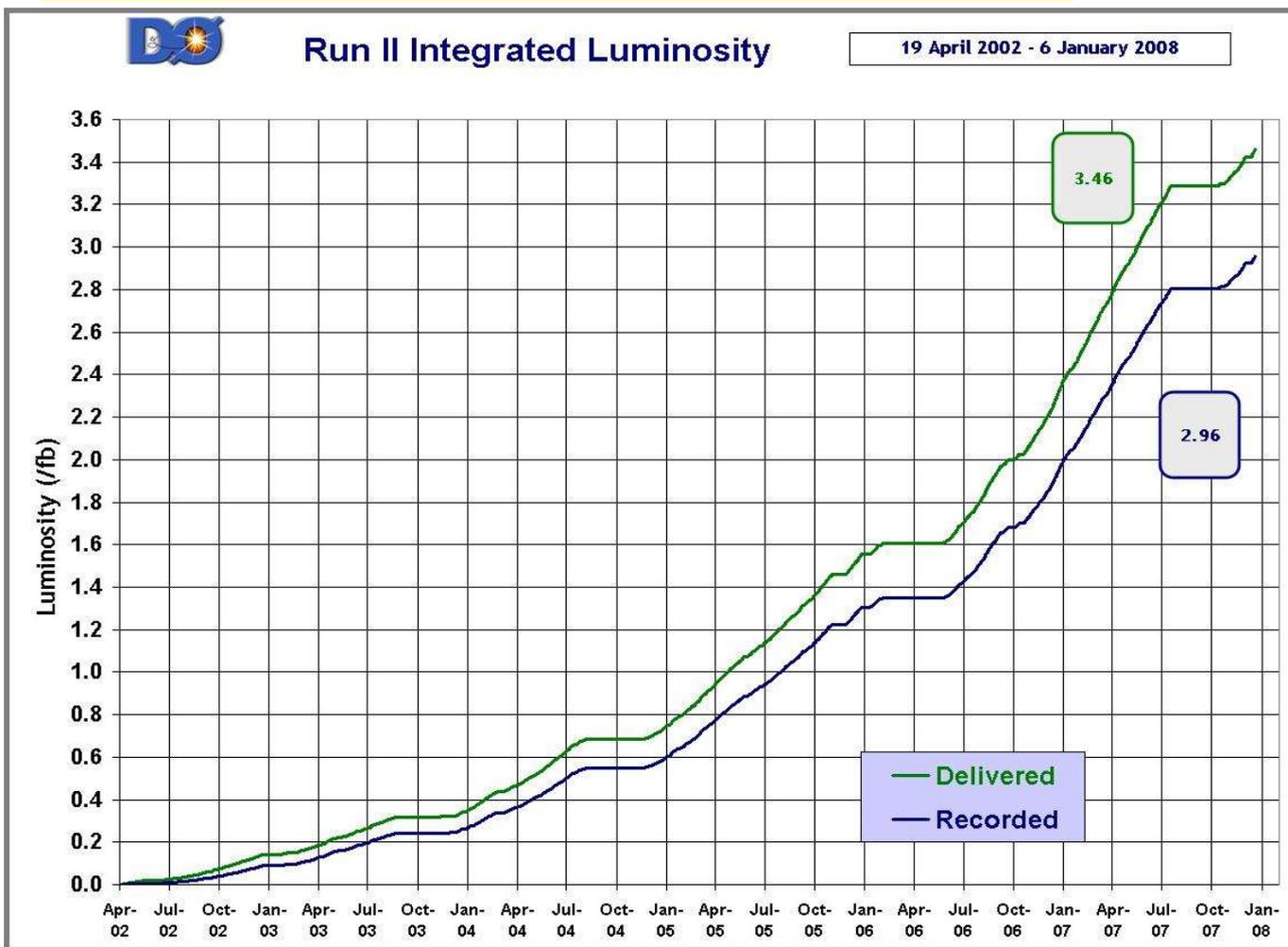
- Summary

Tevatron p-pbar collider

Run II (March 2001 → now) $\sqrt{s} = 1.96$ TeV

Excellent Tevatron performance!

- ▶ Over 3 fb^{-1} delivered to each experiment.
Goal: 8 fb^{-1} by 2009.
- ▶ Peak luminosity is $3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

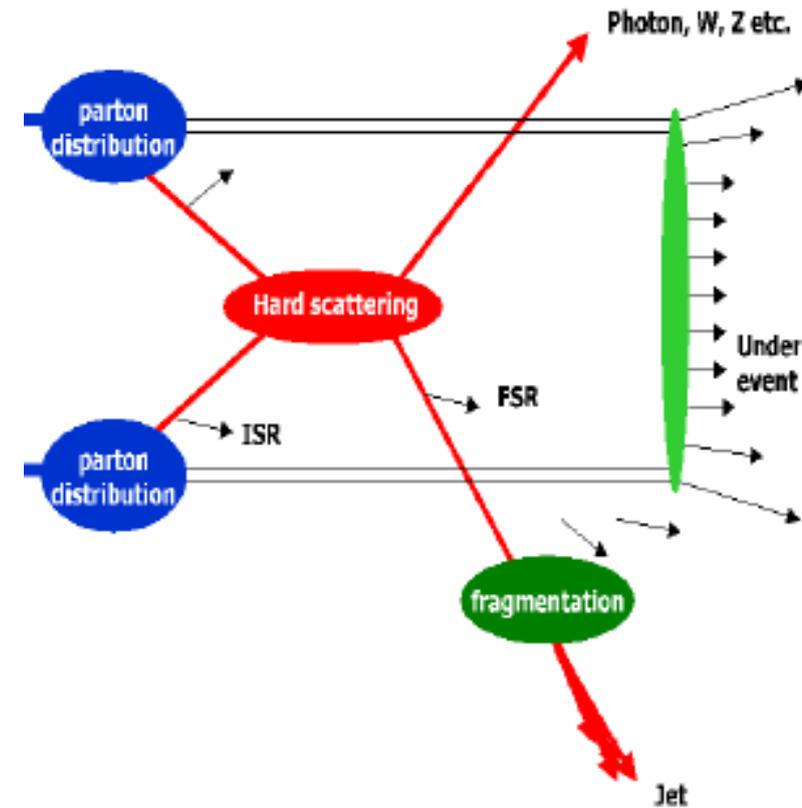


QCD at the Tevatron

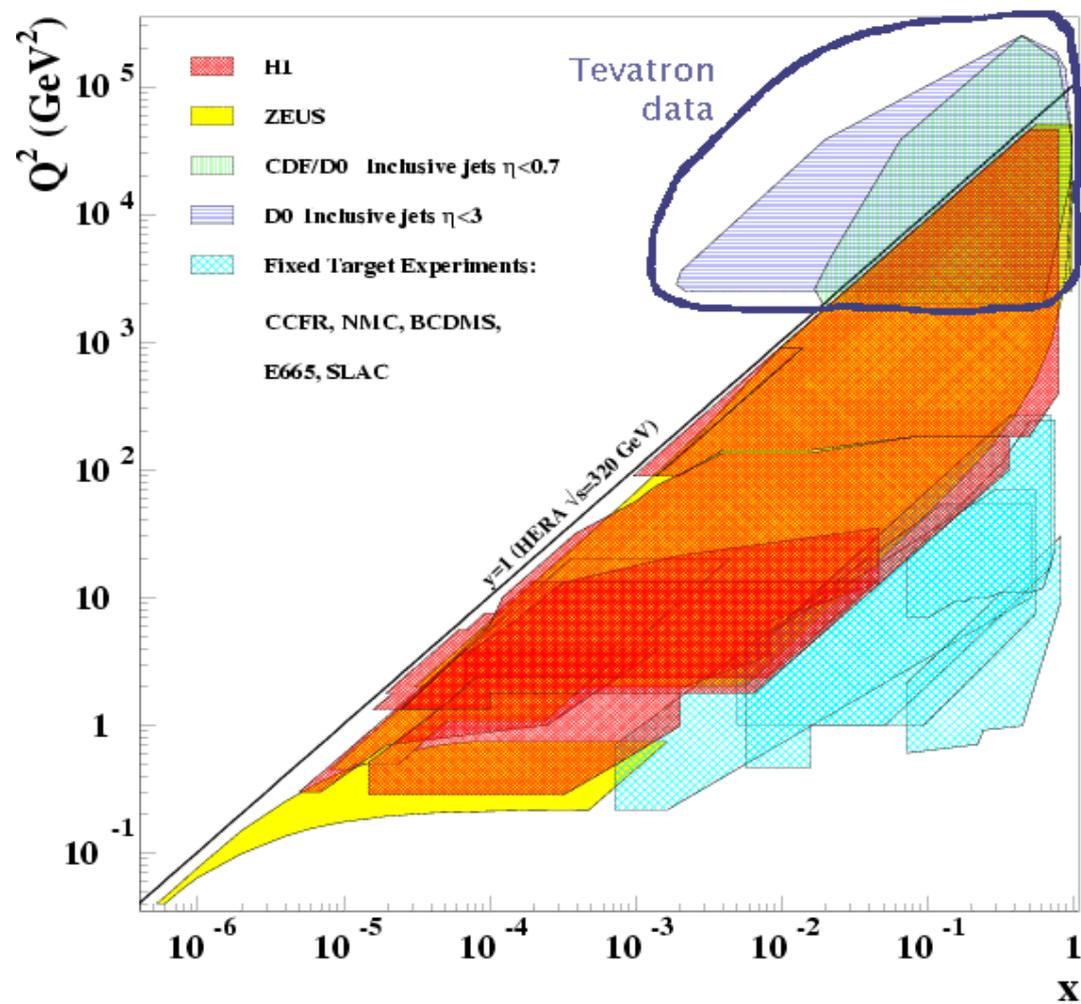
- Better determination of proton structure, especially at large x .
- Testing pQCD at a new level:
NLO + Higher Order corrections, resummations, fragmentation and ISR/FSR models, multi-jet event generators, etc.
- Final states considered include:
jet+X, (HF) di-jets, V-boson +X, V + (HF)jets.

→ *Sensitivity to new physics while probing very high energy regimes.*

- Correction of theoretical predictions for hadronization/UE effects.

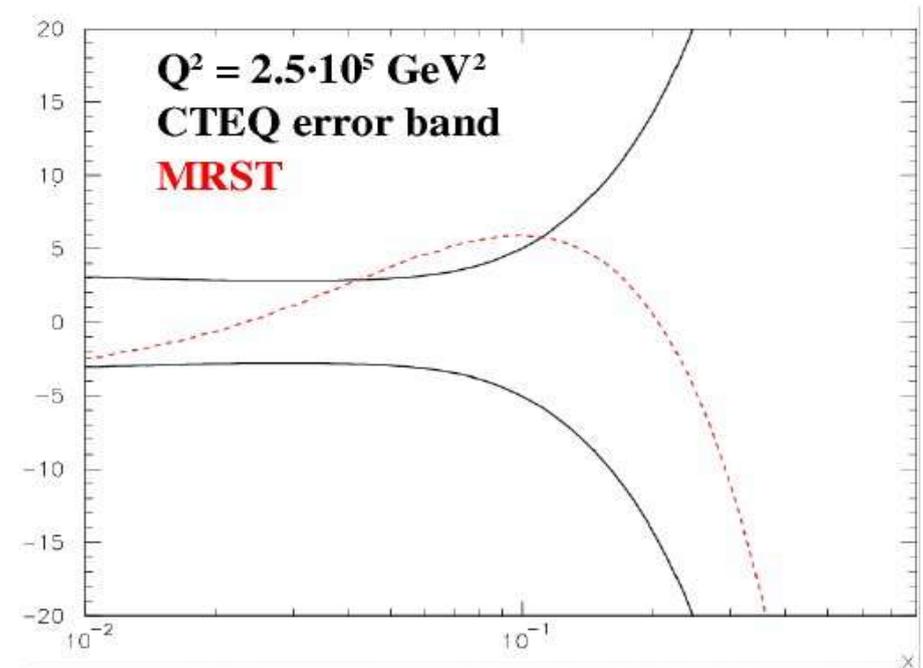


Jet inclusive p_T cross section: Motivation

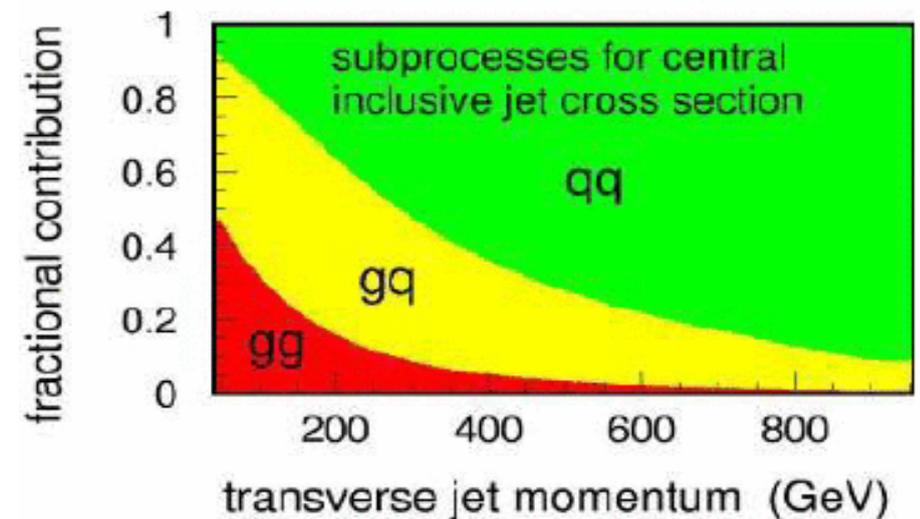


(x, Q^2) kinematic plane for HERA,
fixed target and Tevatron experiments.

High p_T cross section is dominated by qq scattering, but
 qg process still contributes $\sim 30\%$ at $p_T=500$ GeV
(\rightarrow sensitivity to high x gluons).



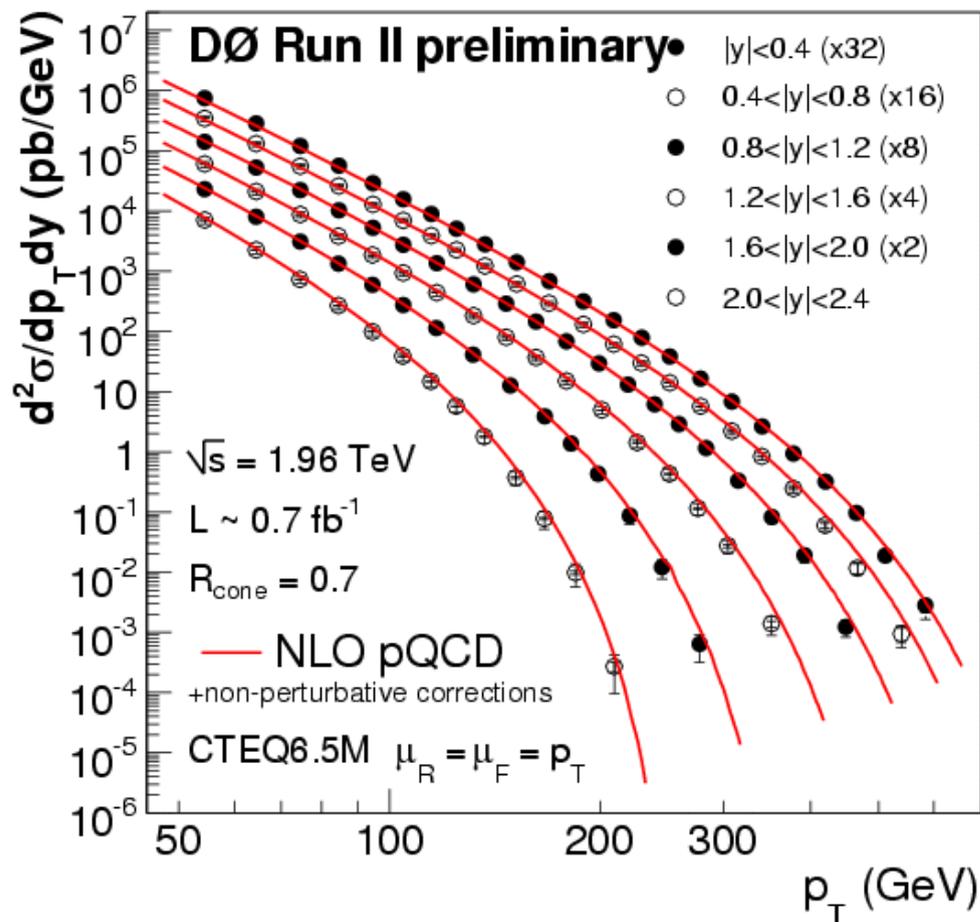
Uncertainty on *gluon PDF* from 40 CTEQ6.1 sets
and difference with MRST.



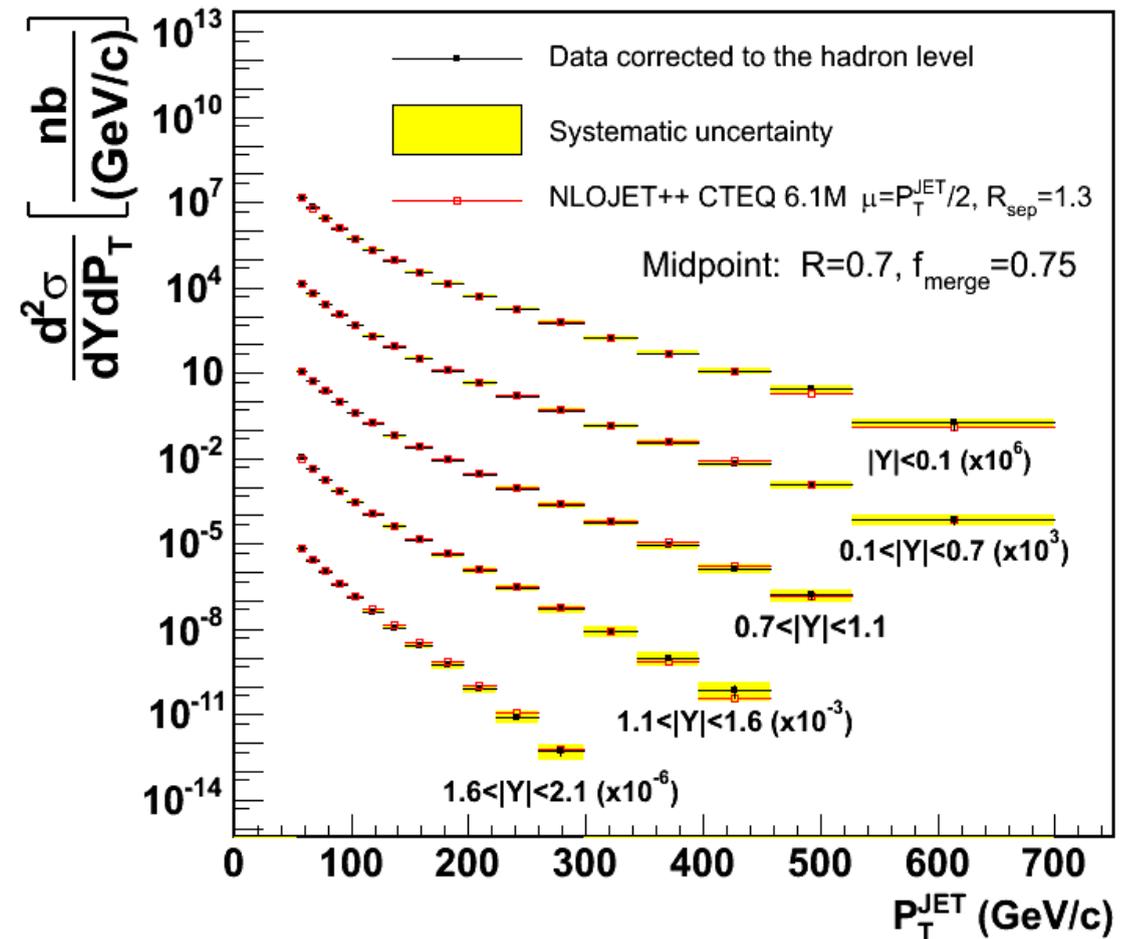
Jet inclusive p_T cross sections: D0 and CDF

Preliminary

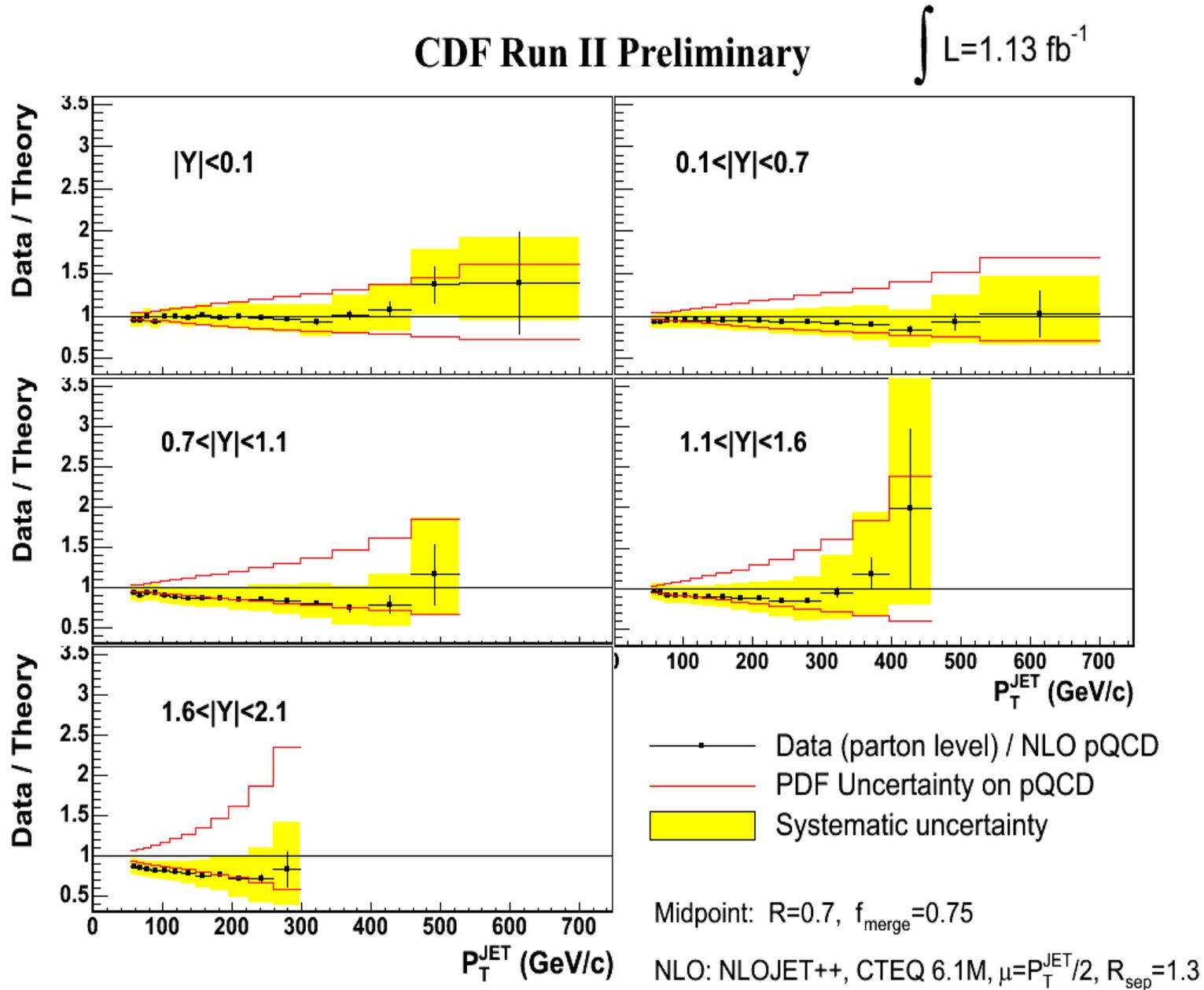
- Midpoint cone algorithm of $R=0.7$, theory correction for non-perturbative effects.
- Largest uncertainties are from JES.
- Data compared to NLO pQCD with CTEQ6.5M and MRST2004 PDFs in D0 and with CTEQ6.1M in CDF.
- Measurements cover large ranges in rapidity.



CDF Run II Preliminary ($L=1.13$ fb $^{-1}$)

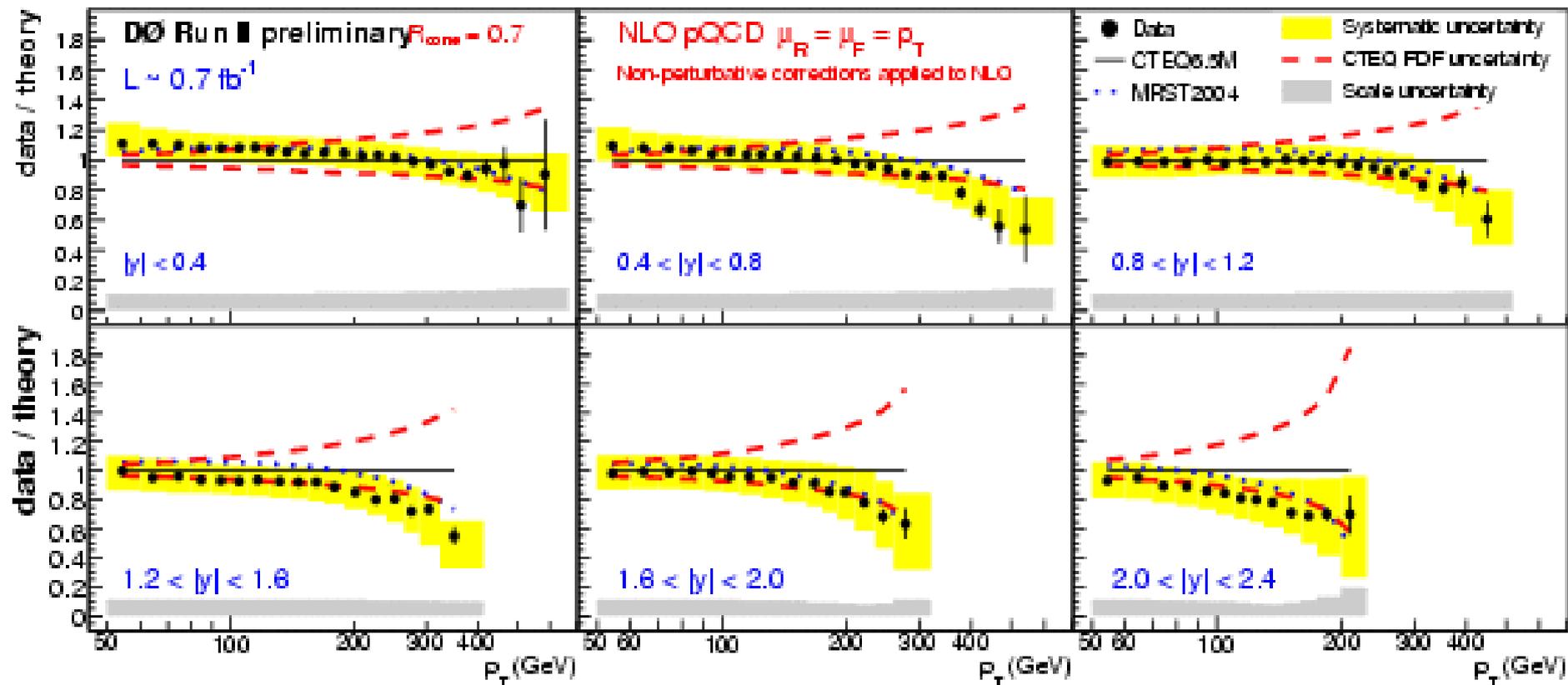


(continued)



→ *Data uncertainties are smaller than CTEQ6.1M uncertainties, so the measurement should contribute to reduce PDF uncertainties*

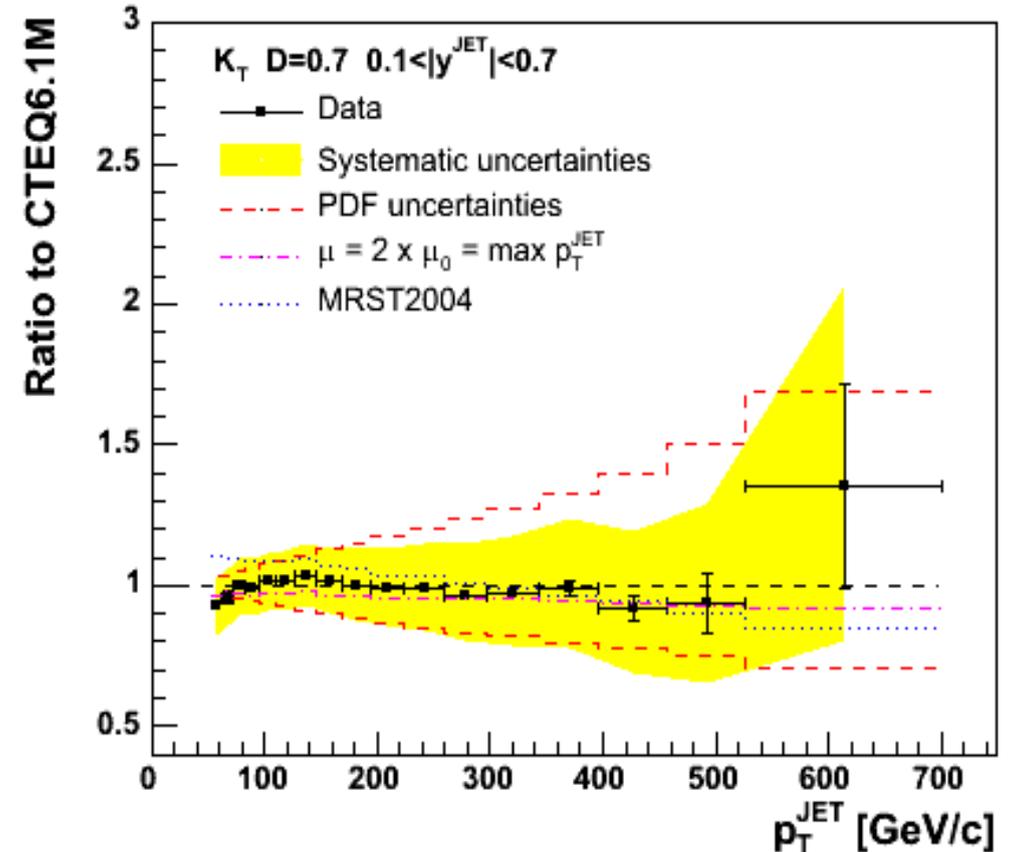
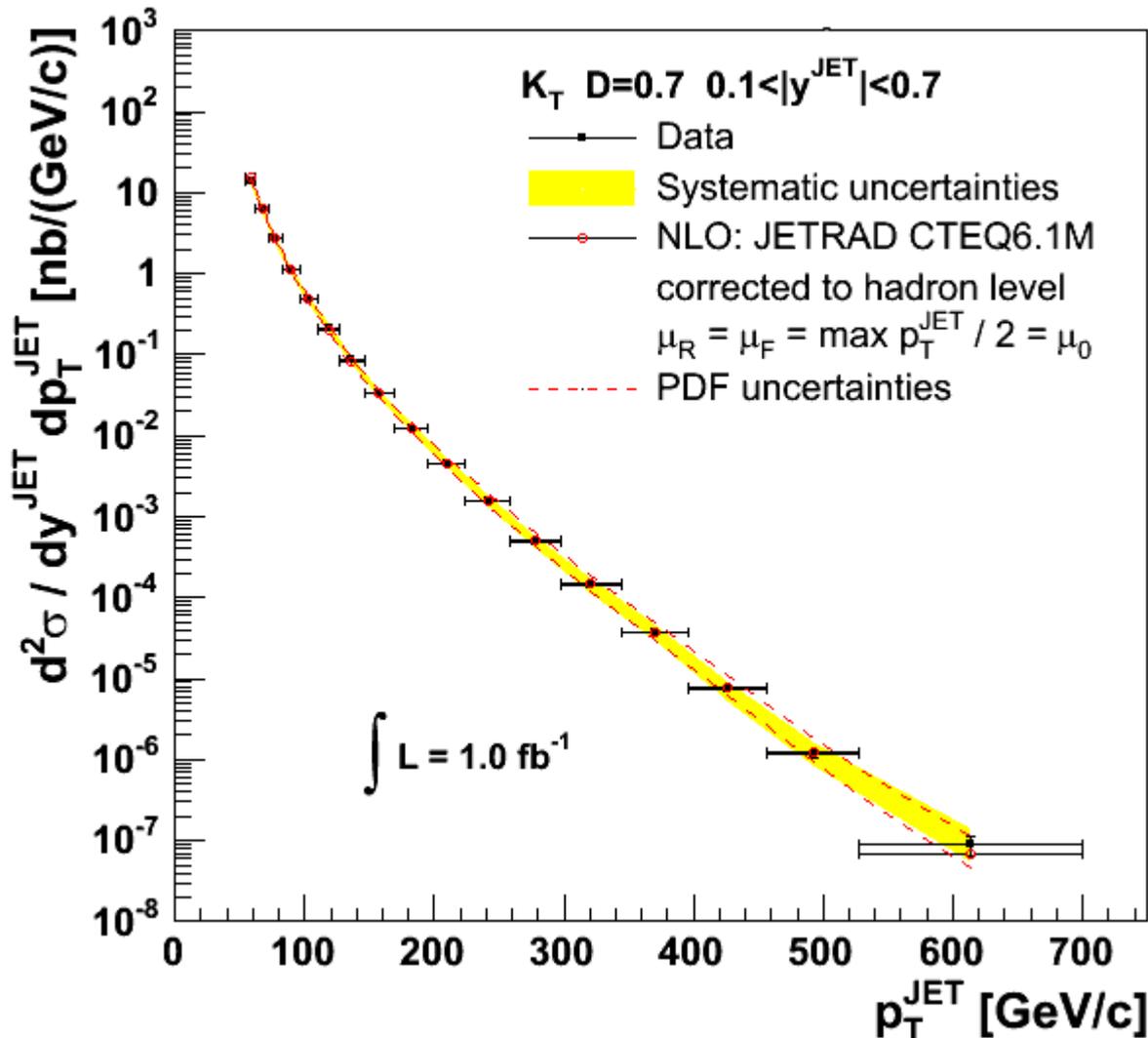
- Data agree with theory predictions and favor the lower edge of PDF error band at large p_T for CTEQ6.5M and shape of p_T dependence for MRST2004.
- Uncertainties on data of the same order as uncertainties from CTEQ6.5M PDF, so data will allow to further constrain PDF.



- Correlations are studied to make further data interpretations (global PDF fits).

Jet inclusive p_T cross section using k_T algo (CDF)

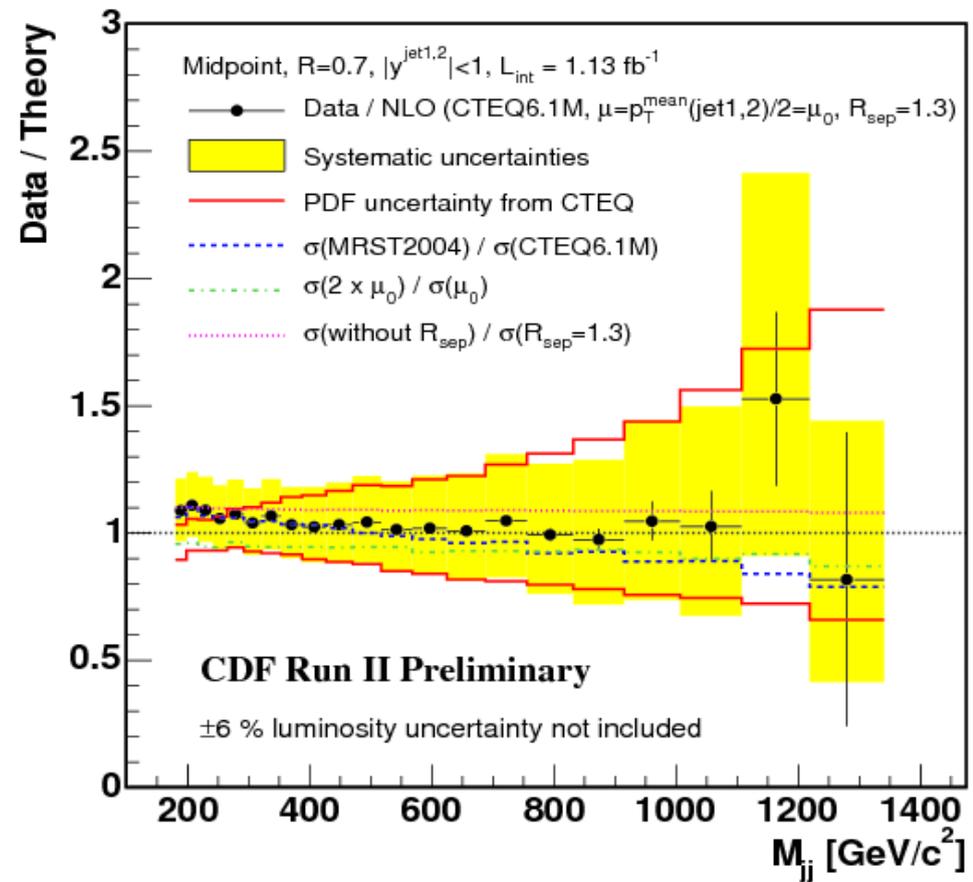
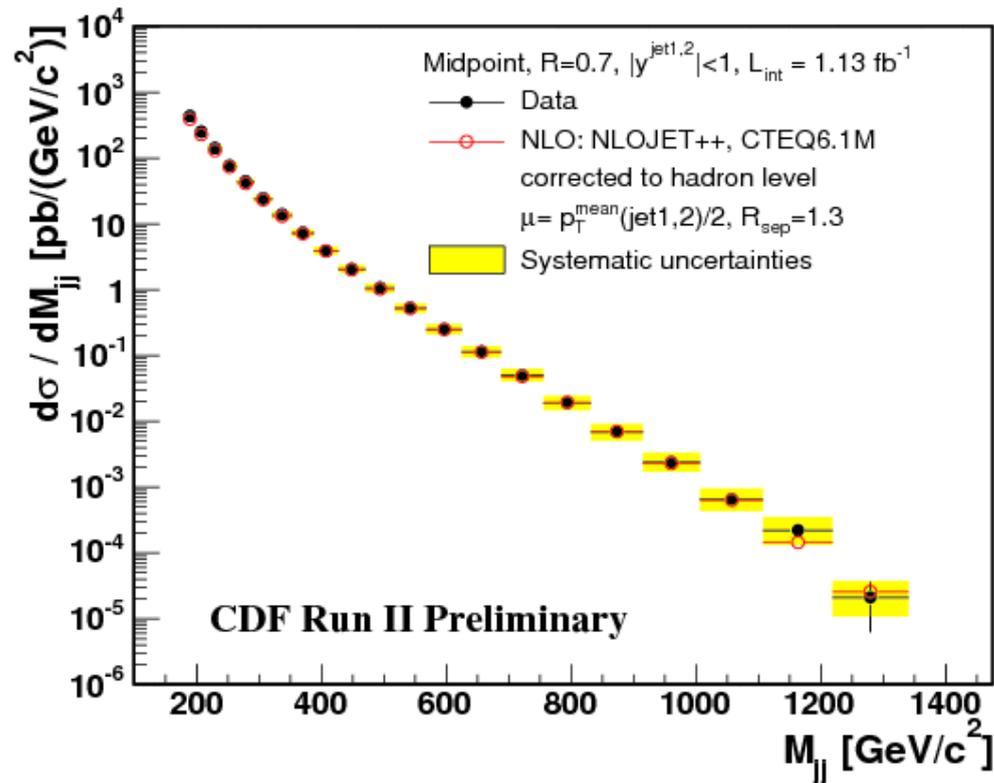
- $L = 1 \text{ fb}^{-1}$ (Phys. Rev. D 75, 092006 (2007)).
- $p_T > 54 \text{ GeV}$, five rapidity bins up to $|y^{\text{jet}}| < 2.1$.
- NLO QCD calculations (JETRAD) corrected for hadronization and underlying events.
- The measured cross section is in a good agreement with NLO pQCD predictions for all considered distances: $D=0.5, 0.7$ and 1.0 .



Measurement of the di-jet mass cross section (CDF)

Preliminary

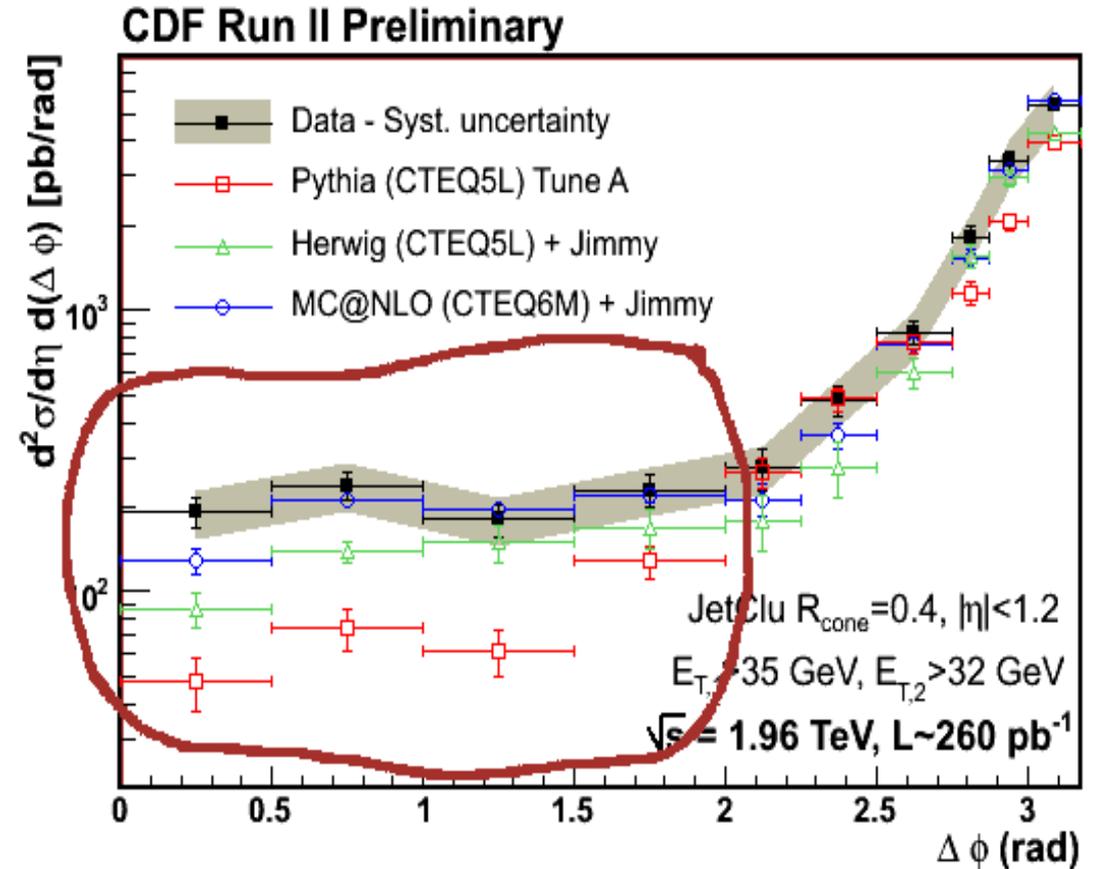
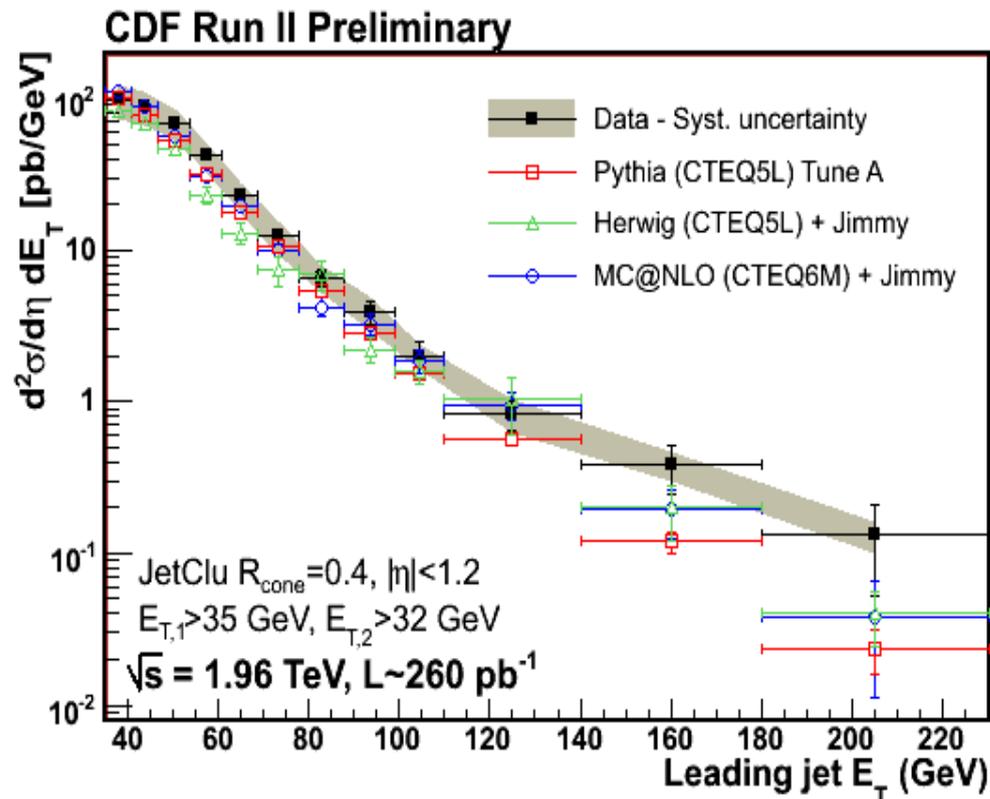
- $L = 1.13 \text{ fb}^{-1}$.
 - Midpoint cone algorithm ($R=0.7$), $M_{jj} > 180 \text{ GeV}/c^2$ and $|y^{\text{jet}1,2}| < 1.0$.
 - Sensitivity to compositeness and di-jet mass resonances (excited quarks, Z' , W' , etc)
- new exclusion limits are expected soon.



b-bbar Dijet Production using SVT (CDF)

Preliminary

- $L = 260 \text{ pb}^{-1}$
- Cone algo ($R=0.4$), jets $p_T > 20 \text{ GeV}$, $|\eta| < 1.2$ and are associated to two displaced tracks.
- Measured: $d\sigma / dp_T$, $d\sigma / dM_{jj}$, $d\sigma / d\Delta\phi$
- Compared to LO Monte Carlo's (Pythia Tune A and Herwig) and to MC@NLO.



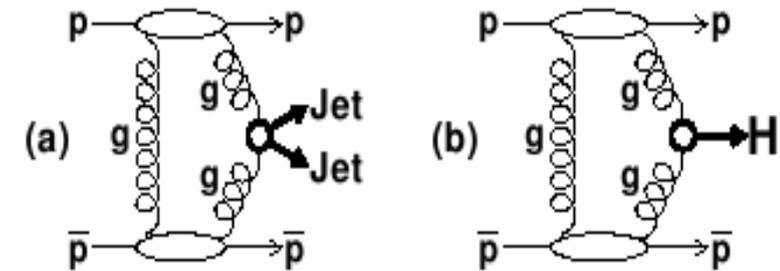
- *MC@NLO reproduces the data within uncertainties (UE correction is needed for a better description), while PYTHIA is far off the systematic error band.*

Exclusive di-jet & di-photon production (CDF)

$$p+pbar \rightarrow p' + \text{di-jet (di-photon)} + pbar'$$

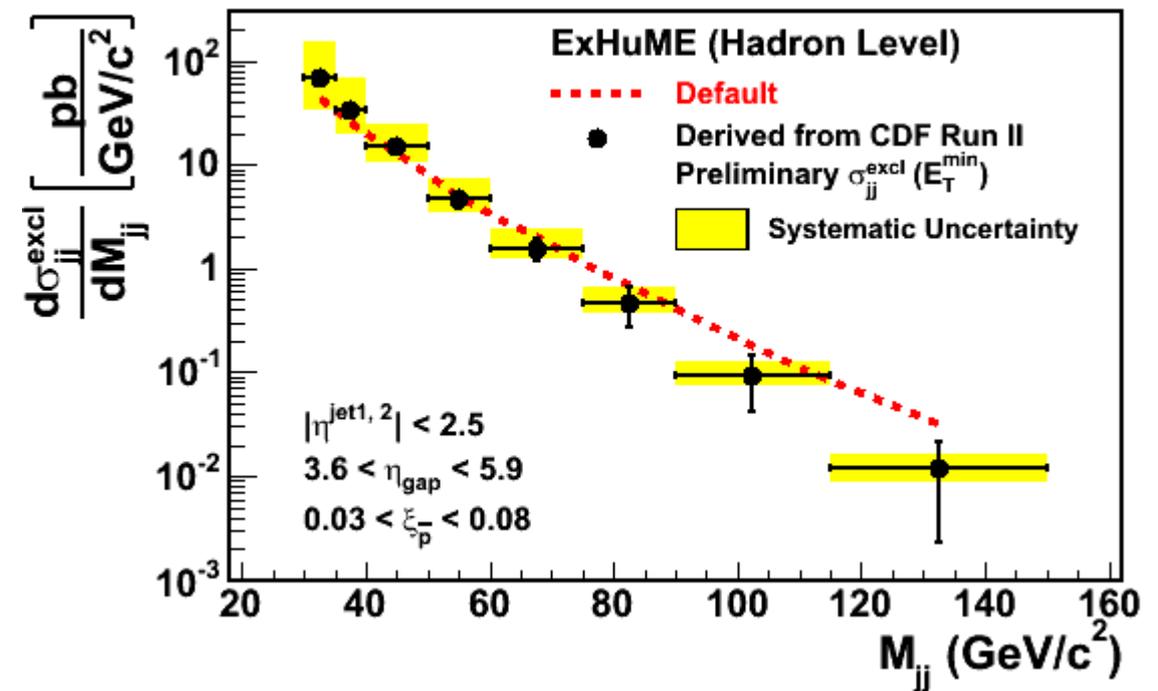
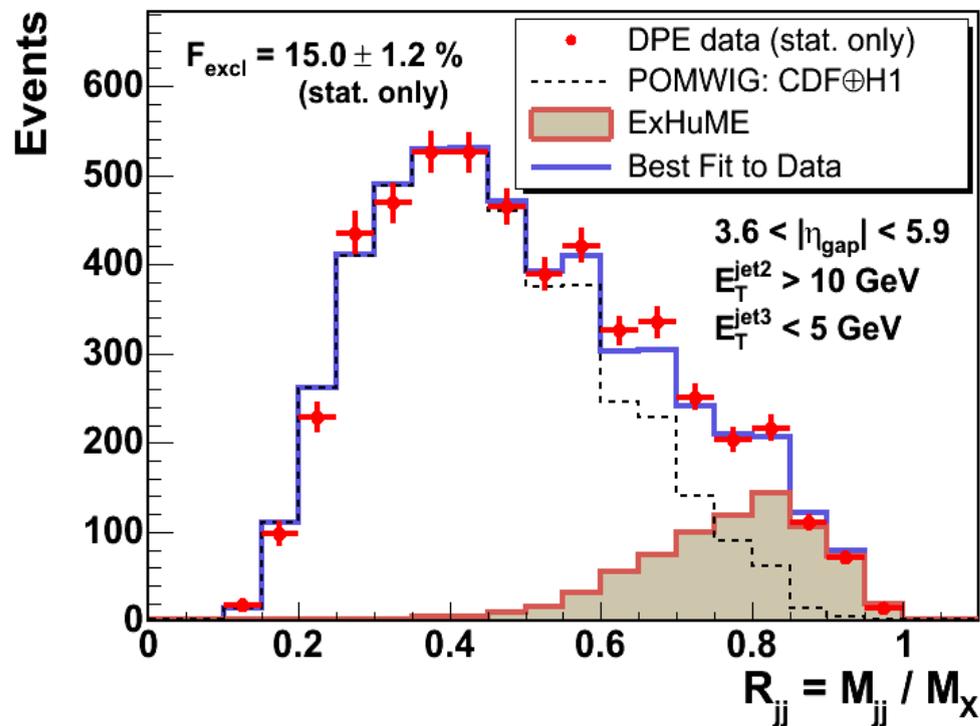
Submitted to Phys.Rev.D

- Measurement of exclusive di-jet (and $\gamma\gamma$) production at the Tevatron to calibrate calculations for exclusive Higgs production at the LHC.
- $L = 310 \text{ pb}^{-1}$: $p+pbar \rightarrow pbar' + X(\text{incl. } 2\text{jets}) + \text{rapidity gap}$
- Reconstruction of di-jet mass fraction: $R_{jj} = M_{jj} / M_X$
- An excess in data observed at high R_{jj} over inclusive prediction (Pomwig MC) and is in agreement with exclusive di-jet signal done by ExHuME and DPEMC MCs.



Exclusive di-jet and Higgs production

First observation of exclusive dijet production at the Tevatron



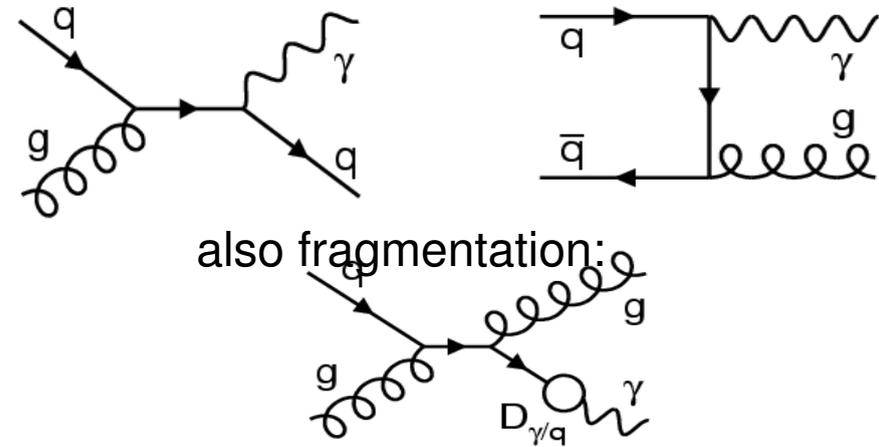
- Exclusive di-photons (PRL 99, 242002 (2007)) : 3 events observed at $L=510 \text{ fb}^{-1}$, $\sigma_{\text{excl.}\gamma\gamma} < 410 \text{ fb}$ (95% CL) with prediction: $\sim 40 \text{ fb}$ (factor 3 uncertainty).

Inclusive photon cross section (D0): Motivation

Direct photons emerge unaltered from the parton hard interaction processes.

⇒ **Direct probe** of the hard scattering dynamics

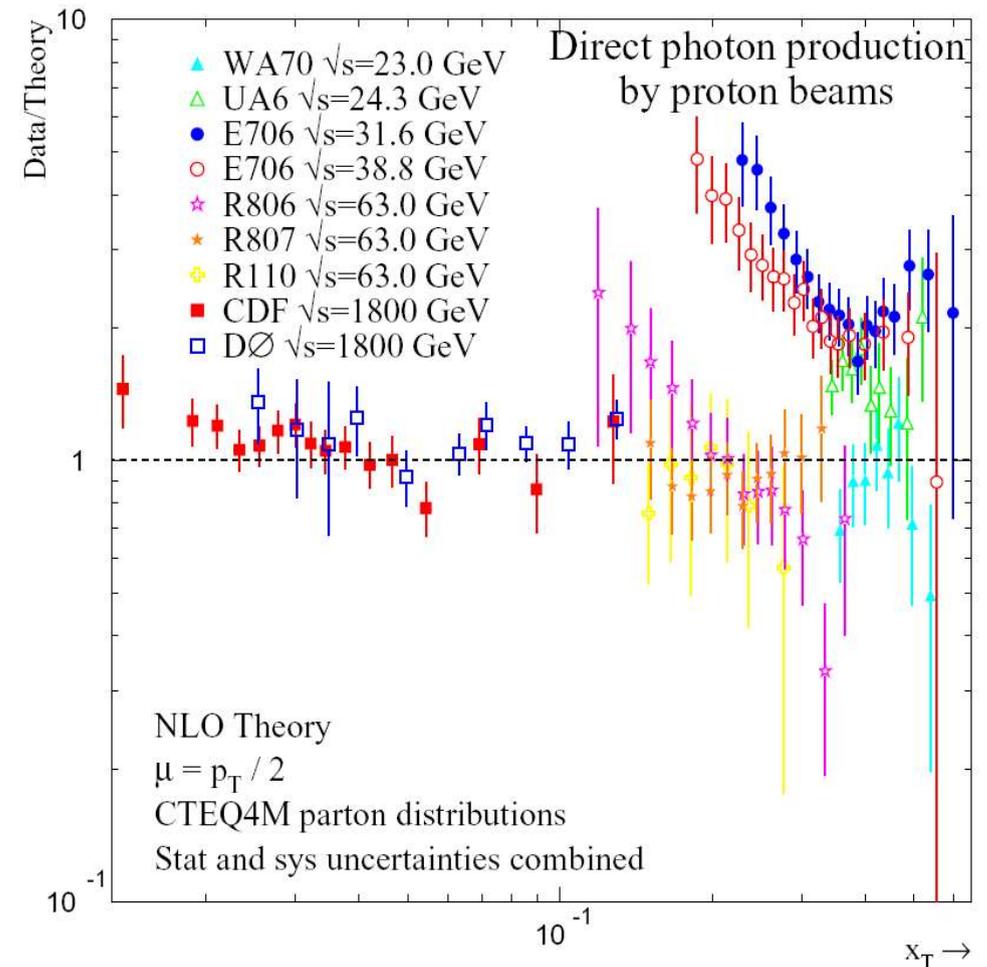
Clean probe without complications from fragmentation and systematics with jet identification and measurement.



Understanding of the QCD photon production mechanisms is prerequisite for searches for many new physics processes.

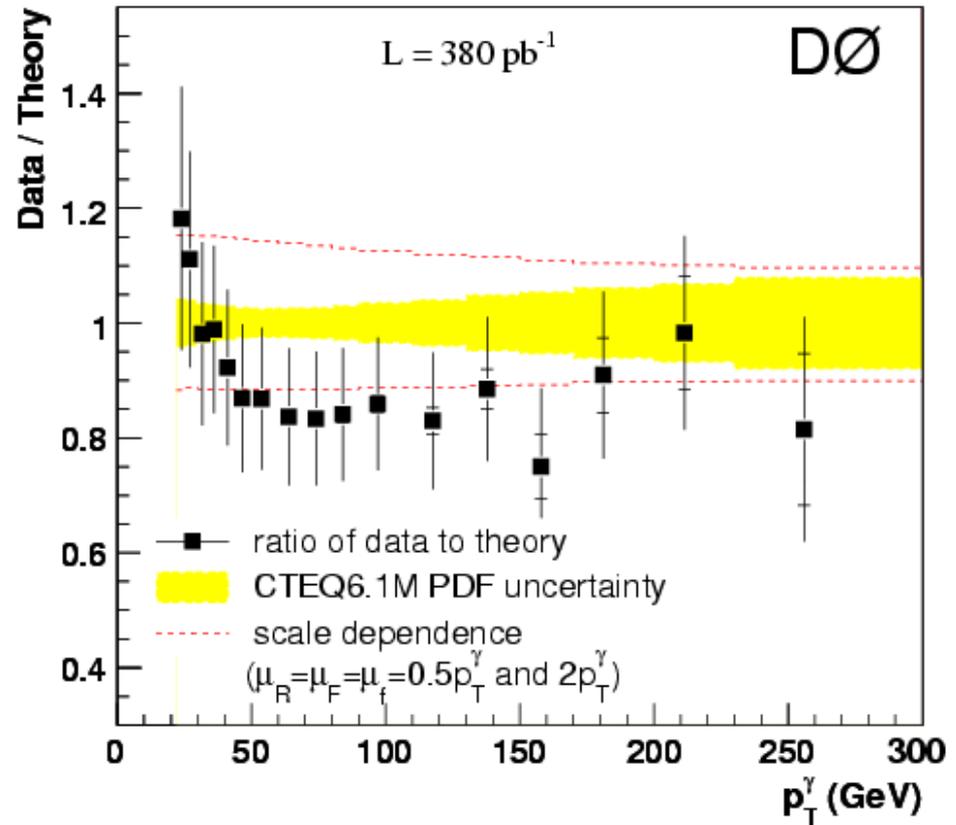
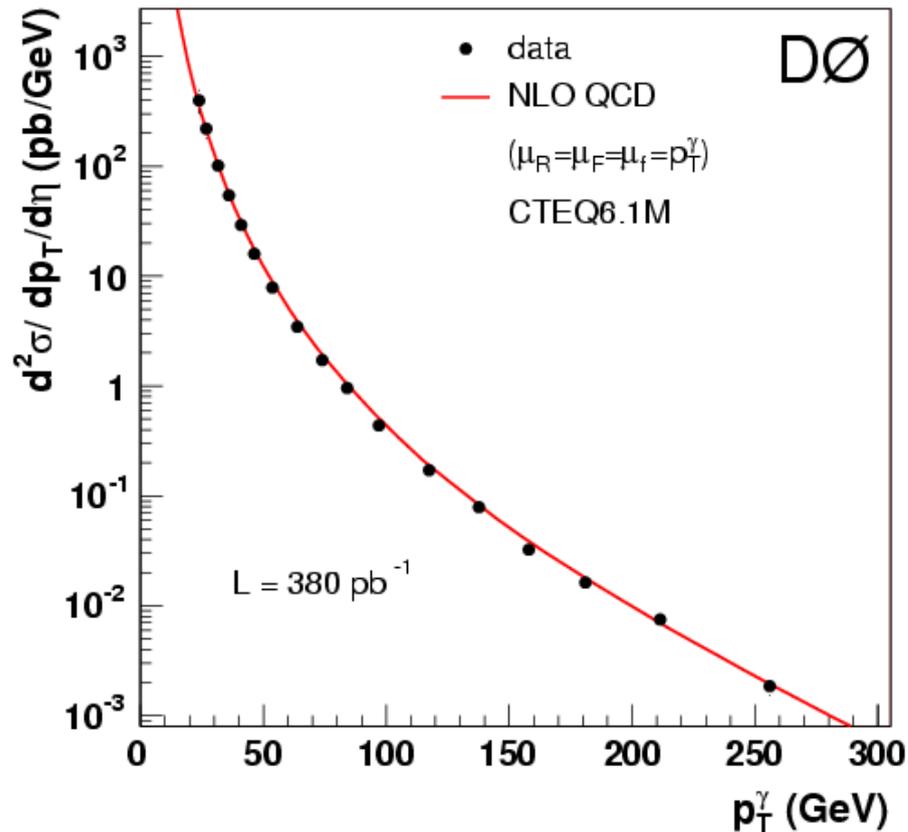
$$\sigma(\text{jet})/\sigma(\gamma) \sim 10^3$$

⇒ powerful & reliable γ ID tools required.



Inclusive photon cross section (D0)

Published: Phys.Lett. B658(2007)



- $23 < p_T < 300 \text{ GeV}$ for $|\eta| < 0.9$.
- NLO pQCD with JetPhoX / W.Vogelsang using CTEQ6.1M and MRST2004 PDFs.
- Theory agrees with data within uncertainties in the whole p_T range.
But: qualitative difference in shape, similar to that of UA2(1991) and CDF(2002).
- PDF sensitivity requires: reduced exp. uncertainty and improved theory
(resummation / NNLO ?).

Photon + jet triple differential cross section (D0)

$$\frac{d^3\sigma}{dp_T^\gamma d\eta^\gamma d\eta^{\text{jet}}}$$

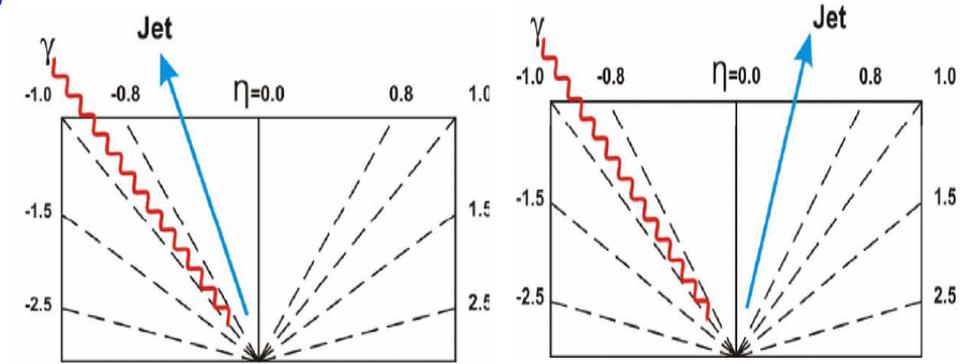
Preliminary

- Cross section is directly proportional to PDFs in a given (x, Q^2) interval with $Q^2 = (p_T^\gamma)^2$

- $30 < p_T^\gamma < 400$ (200) GeV, four photon and jet rapidity regions:

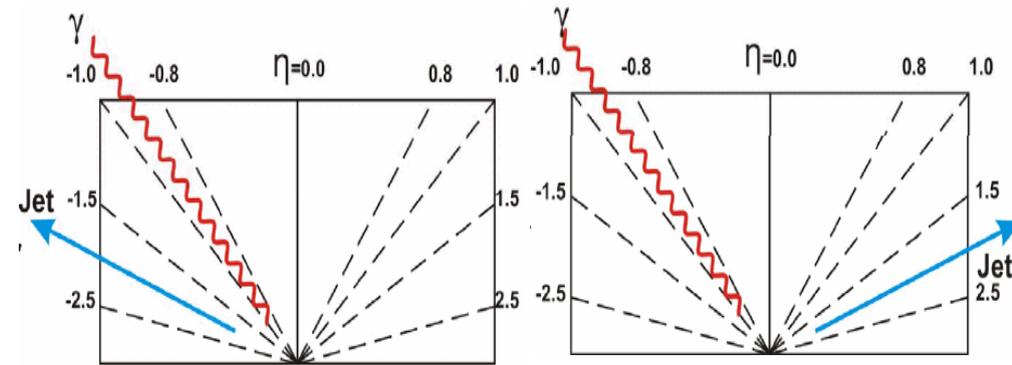
- Quantization of parton $x_{1,2}$ space: example for $p_T^\gamma \approx 35$ GeV with LO: $x_{1,2} = p_T^\gamma / \sqrt{s} [\exp(\pm y^{\text{jet}}) + \exp(\pm y^\gamma)]$

Region	x_1	\leftrightarrow	x_2
1	0.02 -- 0.04		0.05 -- 0.10
2	0.03 -- 0.07		0.03 -- 0.07
3	0.01 -- 0.03		0.14 -- 0.37
4	0.10 -- 0.26		0.02 -- 0.06



1: $|y^{\text{jet}}| < 0.8, y^{\text{jet}} \cdot y^\gamma > 0$

2: $|y^{\text{jet}}| < 0.8, y^{\text{jet}} \cdot y^\gamma < 0$



3: $1.5 < |y^{\text{jet}}| < 2.5, y^{\text{jet}} \cdot y^\gamma > 0$ 4: $1.5 < |y^{\text{jet}}| < 2.5, y^{\text{jet}} \cdot y^\gamma < 0$

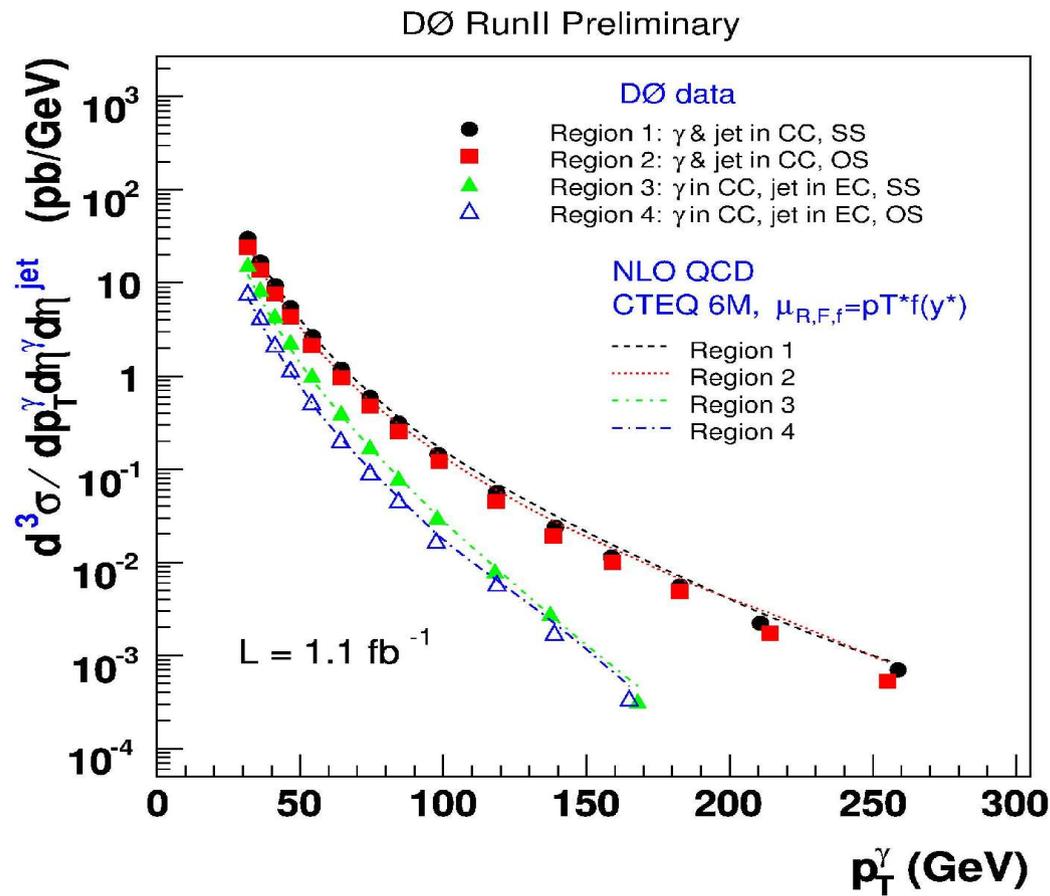
- Total covered x - Q^2 range :

$$0.007 \leq x \leq 0.7$$

$$900 \leq Q^2 \leq (0.4 - 1.0) \times 10^5 \text{ GeV}^2$$

- Significantly extends analogous measurements done by ISR-AFS, UA2 and CDF collaborations.

(continued)

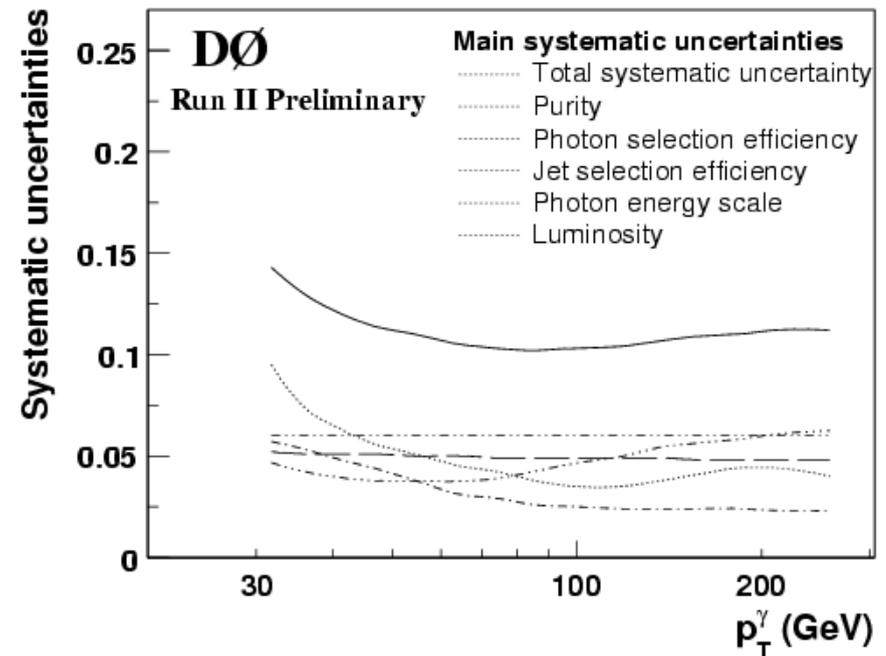


← Differential cross section as a function of p_T^γ for the four rapidity regions. Data are compared to NLO QCD

(JetPhoX) with CTEQ6.1M and all scales = p_T^γ .

● Purity of “ γ +jet” events: from ~ 0.5 ($p_T^\gamma = 30$ GeV) to > 0.90 ($p_T^\gamma > 150$ GeV)

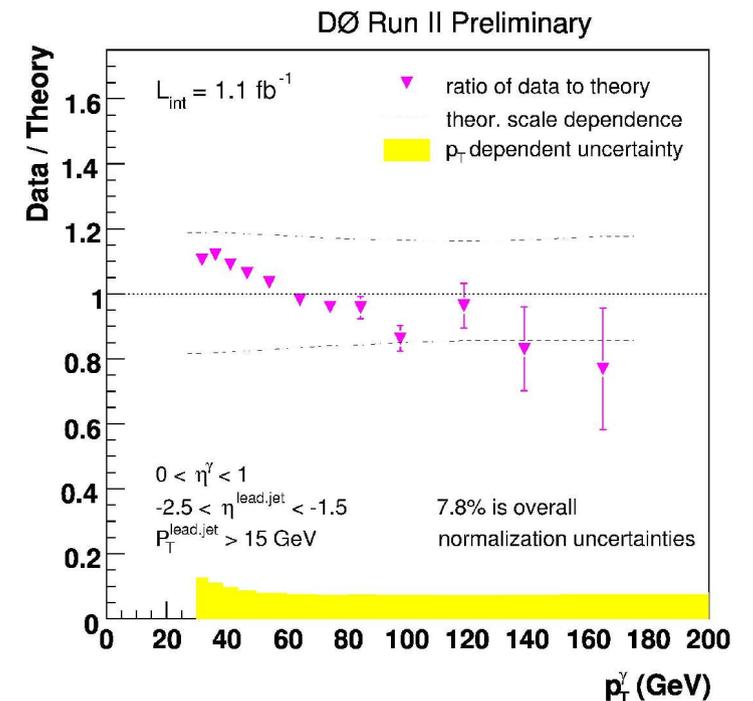
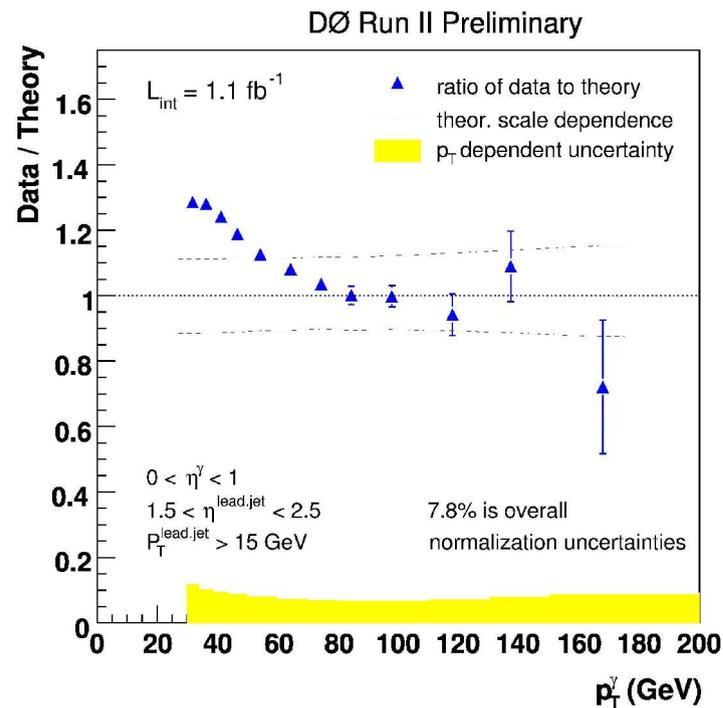
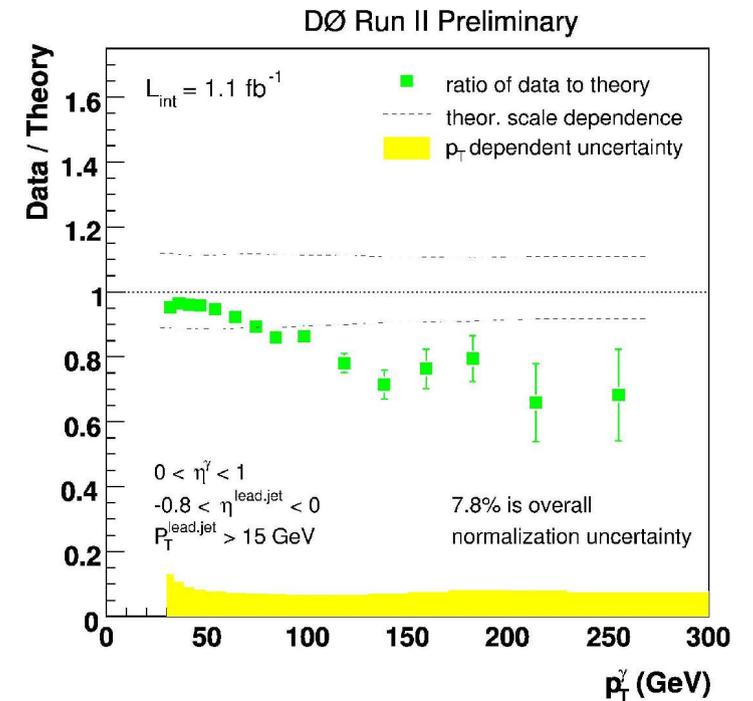
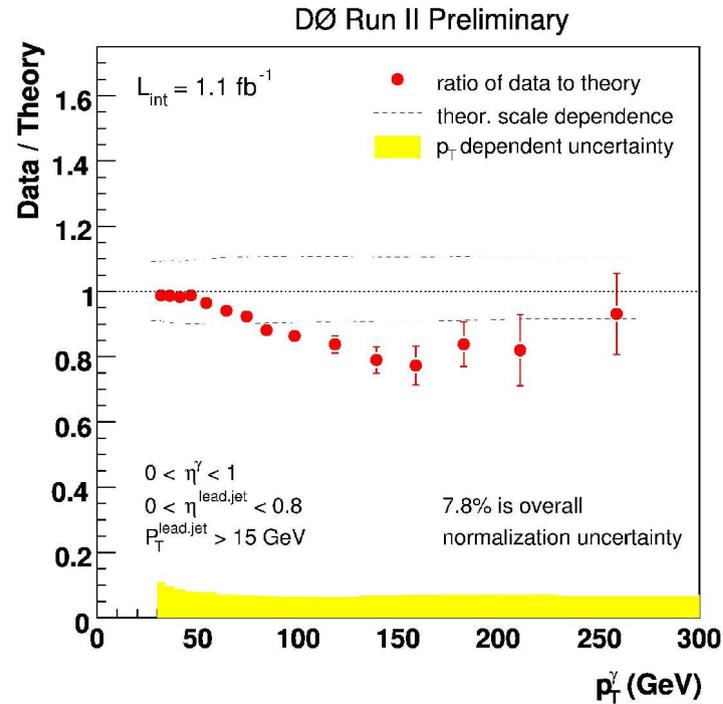
Main systematic uncertainties to the cross section for region 1 ($|\eta_{jet}| < 0.8$, same sign rapidities)



Photon + jet Cross Section: Data/Theory

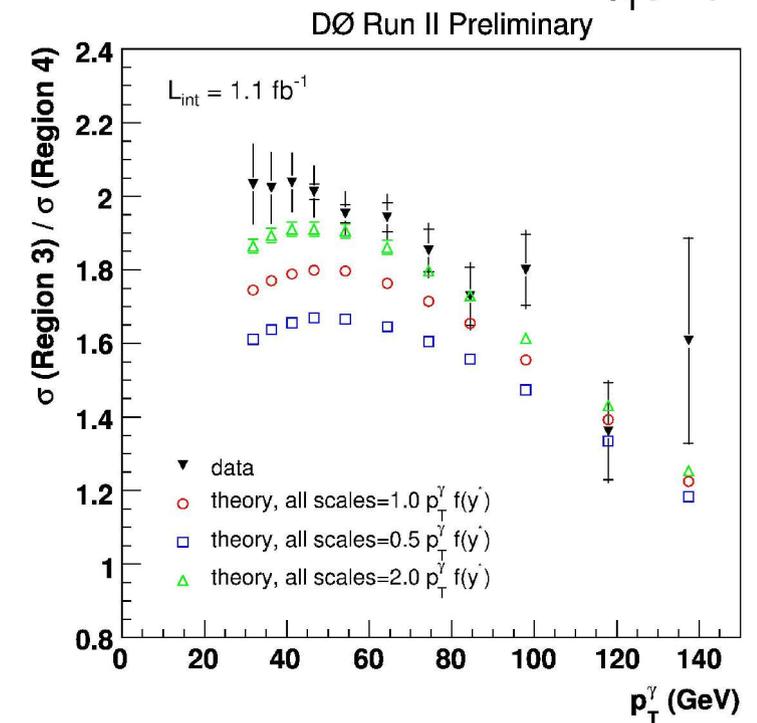
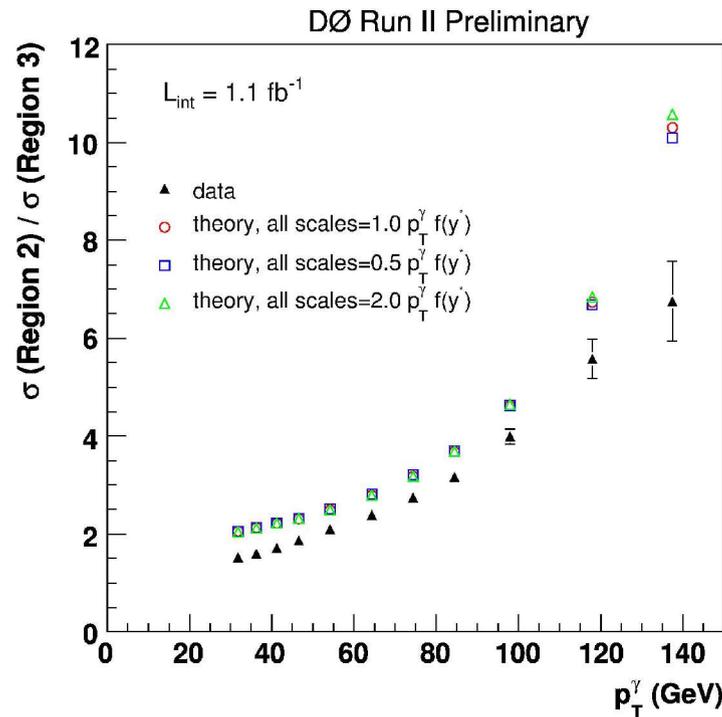
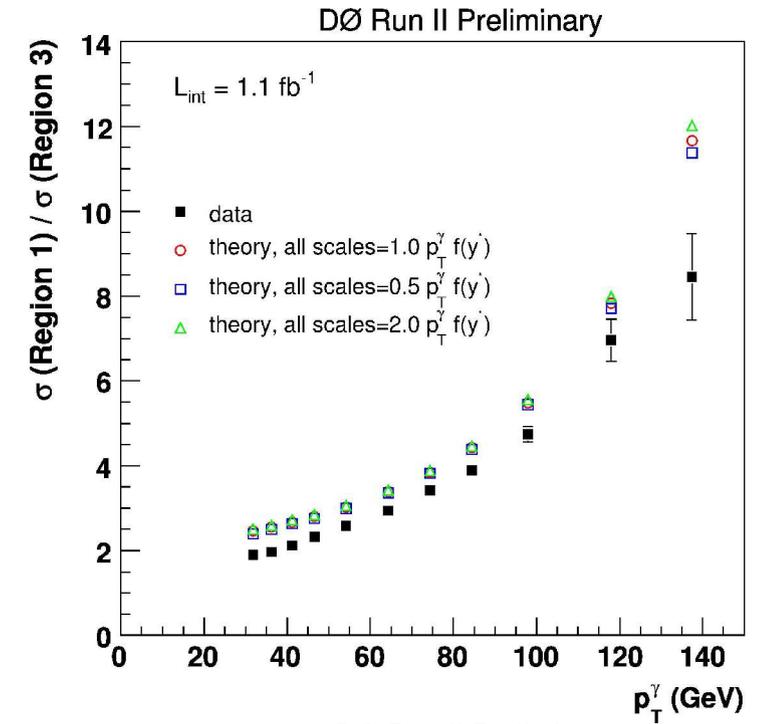
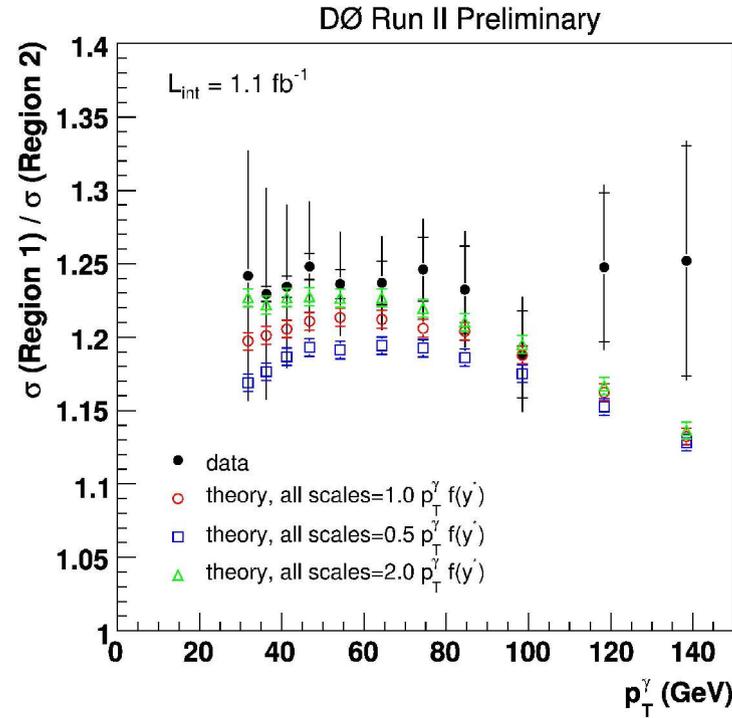
- Theoretical scale variations are unable to simultaneously describe the normalization of the data in each of the four regions.

- In most cases data are beyond CTEQ6.1M PDF uncertainties.



Photon + jet Cross Section Ratios

The ratios between different regions reduce noticeably both, experimental systematic and theoretical scale uncertainties.

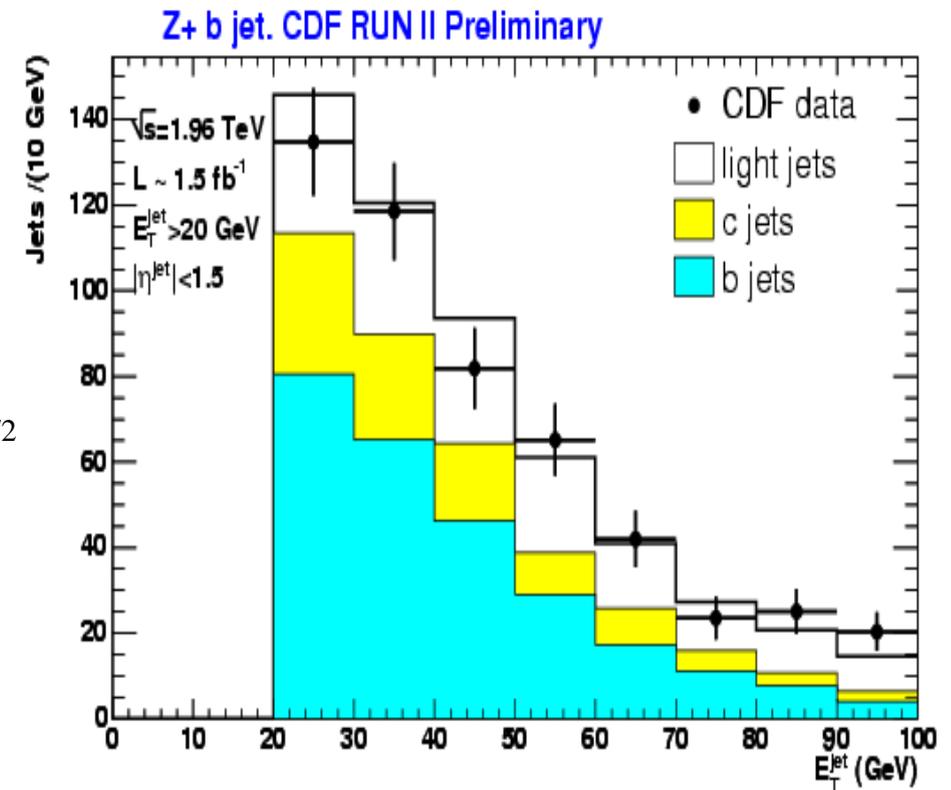


Measurement of the Z+b-jet Cross section (CDF)

Preliminary

⇒ Sensitive to *b*-quark PDF; background
to Higgs production ZH , single top: $gb \rightarrow Wt$

- $L=1.5 \text{ fb}^{-1}$
 - Cone algo ($R=0.7$), $p_T > 20 \text{ GeV}$; $Z \rightarrow ee, \mu\mu$.
 - Theory: MCFM, CTEQ6.1M PDF with $\mu_F = \mu_R = (M_Z^2 + p_T^2)^{1/2}$
- Theor. uncertainty is 15% (HO and PDFs).



The cross sections are multiplied by $\text{Br}(Z \rightarrow l+l^-)$:

	CDF Data	PYTHIA	MCFM NLO	MCFM NLO +UE+hadr.
$\sigma(Z^0 + b\text{jet})$	$0.94 \pm 0.15 \pm 0.15 \text{ pb}$	n.a.	0.51 pb	0.56 pb
$\sigma(Z^0 + b\text{jet})/\sigma(Z^0)$	$0.369 \pm 0.057 \pm 0.055\%$	0.35%	0.21%	0.23%
$\sigma(Z^0 + b\text{jet})/\sigma(Z^0 + \text{jet})$	$2.35 \pm 0.36 \pm 0.45\%$	2.18%	1.88%	1.77%

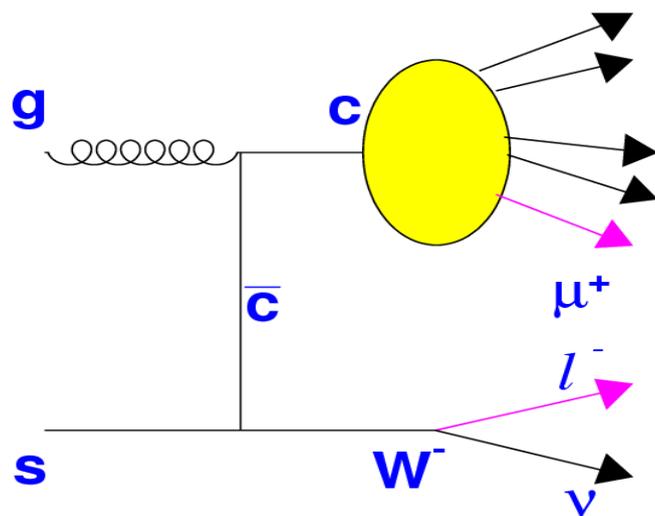
- About a factor of two difference with MCFM NLO predictions.

W+c-jets cross-sections : D0 and CDF

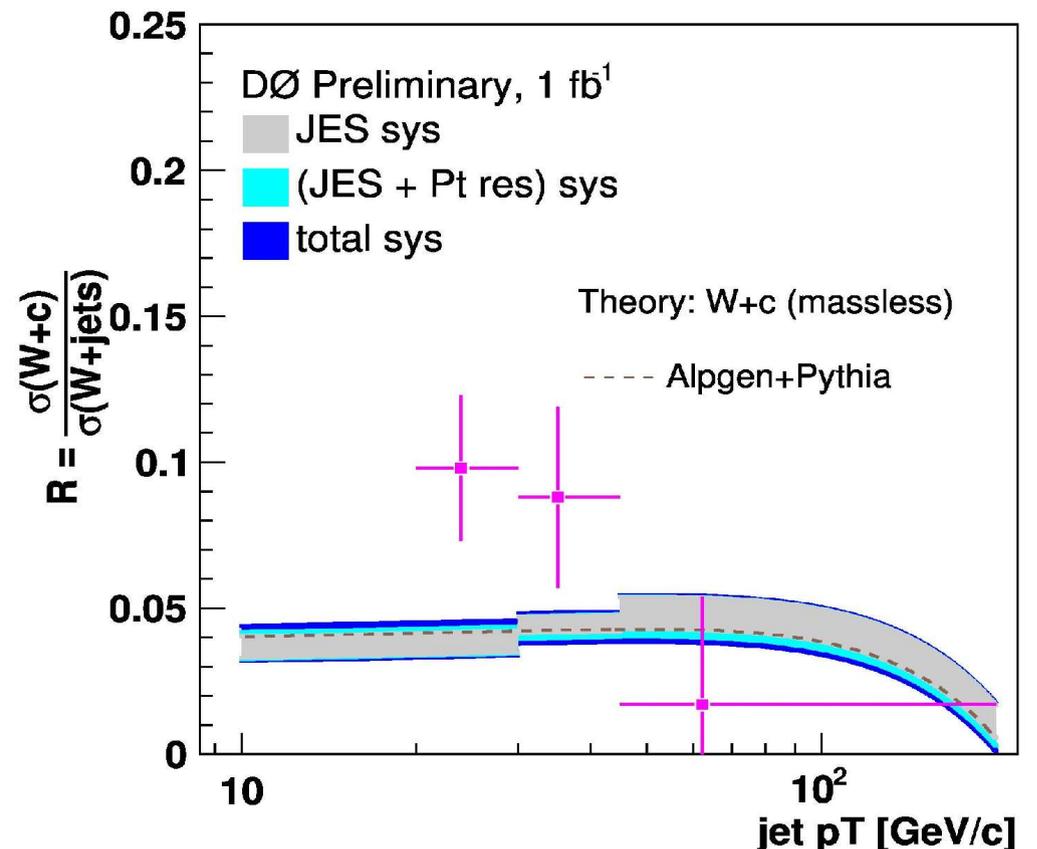
⇒ Sensitivity to *s*-quark PDF. Possible background to top-, stop- quarks and Higgs productions.

- Charge correlation is used: leptons from *c*(*c*bar)-quark and *W*⁻(*W*⁺) decays are of opposite sign.
- *W*: electron and muon channels are considered.
- CDF measured σ of inclusive production and compared with LO ALPGEN predictions
- D0 measured ratio $\sigma(W+c)/\sigma(W+jets)$ and compared with ALPGEN+PYTHIA in three *p*_T bins: ALPGEN calculates the matrix element and PYTHIA does showering and hadronization.
- Both measurements agree with the theoretical expectations.

CDF : $\sigma_{Wc}(p_T^{jet} > 20 \text{ GeV}, |y| < 1.5) * BR(W \rightarrow e \nu) =$
 $9.8 \pm 2.8(\text{stat})^{+1.4}_{-1.6}(\text{sys}) \pm 0.6(\text{lum}) \text{ pb}$



+ *s*-channel diagram

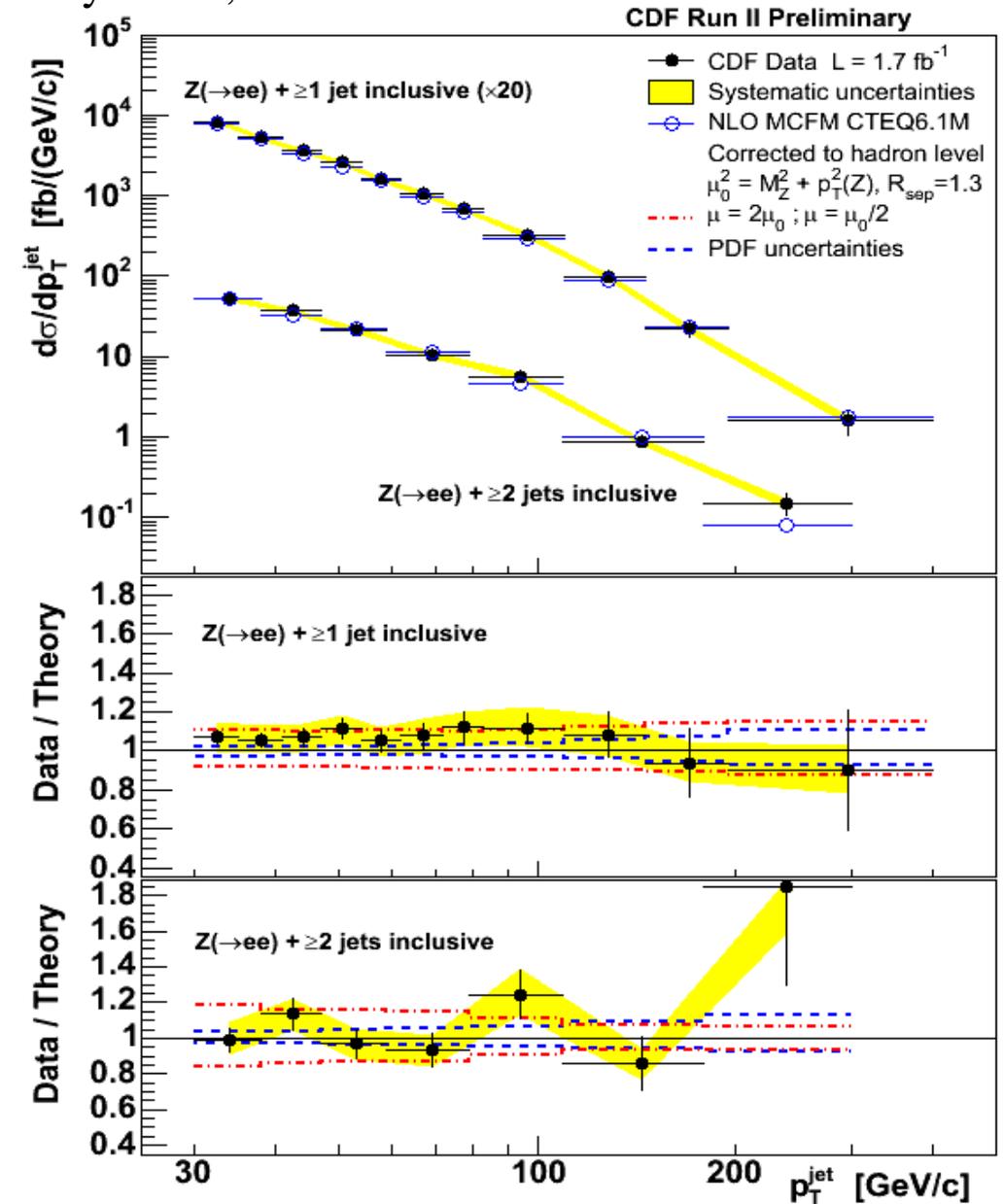
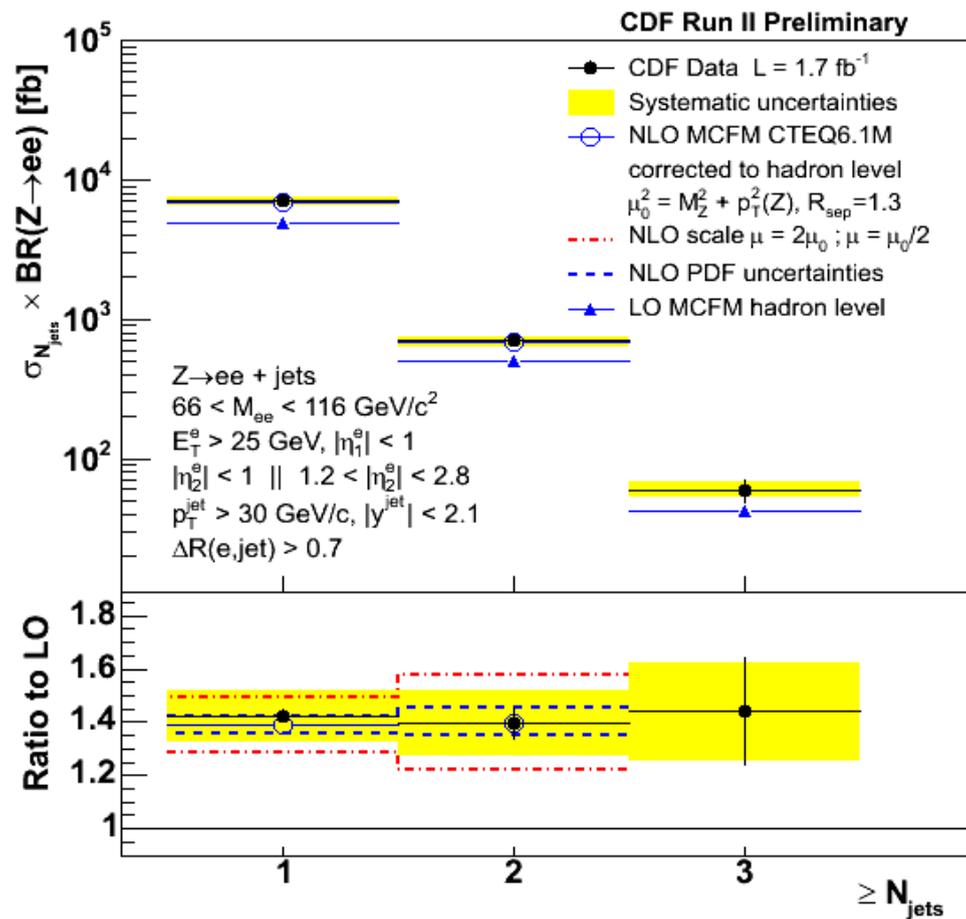


Z+≥n jets differential cross sections (CDF)

→ Test HO QCD corrections, ISR/FSR radiation models.

Essential for many new physics searches, irreducible background in SUSY squark/gluino searches.

- $L = 1.7 \text{ fb}^{-1}$ (*Submitted* to Phys.Rev.Lett.).
- $Z/\gamma^* \rightarrow ee$ with electron $p_T > 25 \text{ GeV}$ and with one central electron $|\eta| < 1.0$;
- jet $p_T > 30 \text{ GeV}$ and $|\eta| < 2.1$.
- *NLO pQCD is in good agreement with data.*

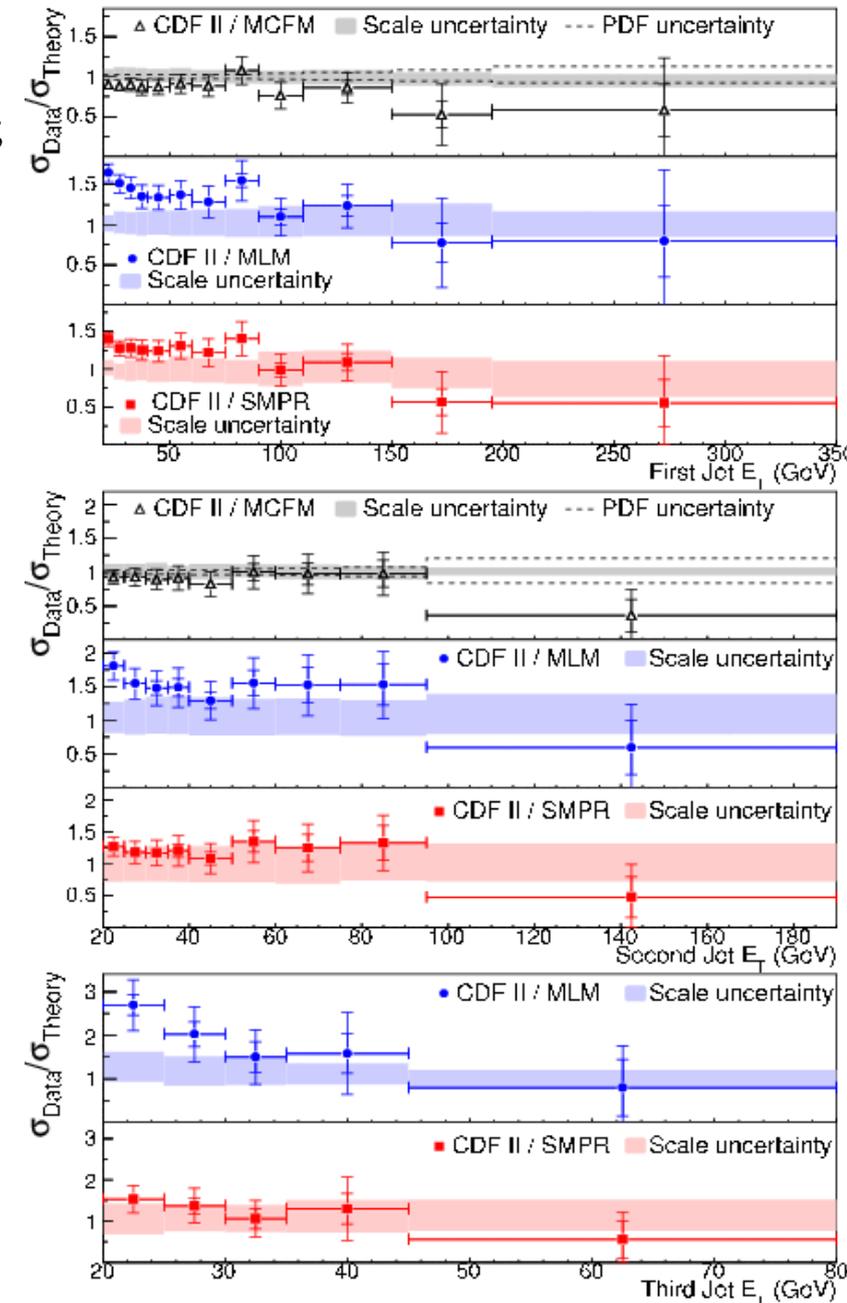
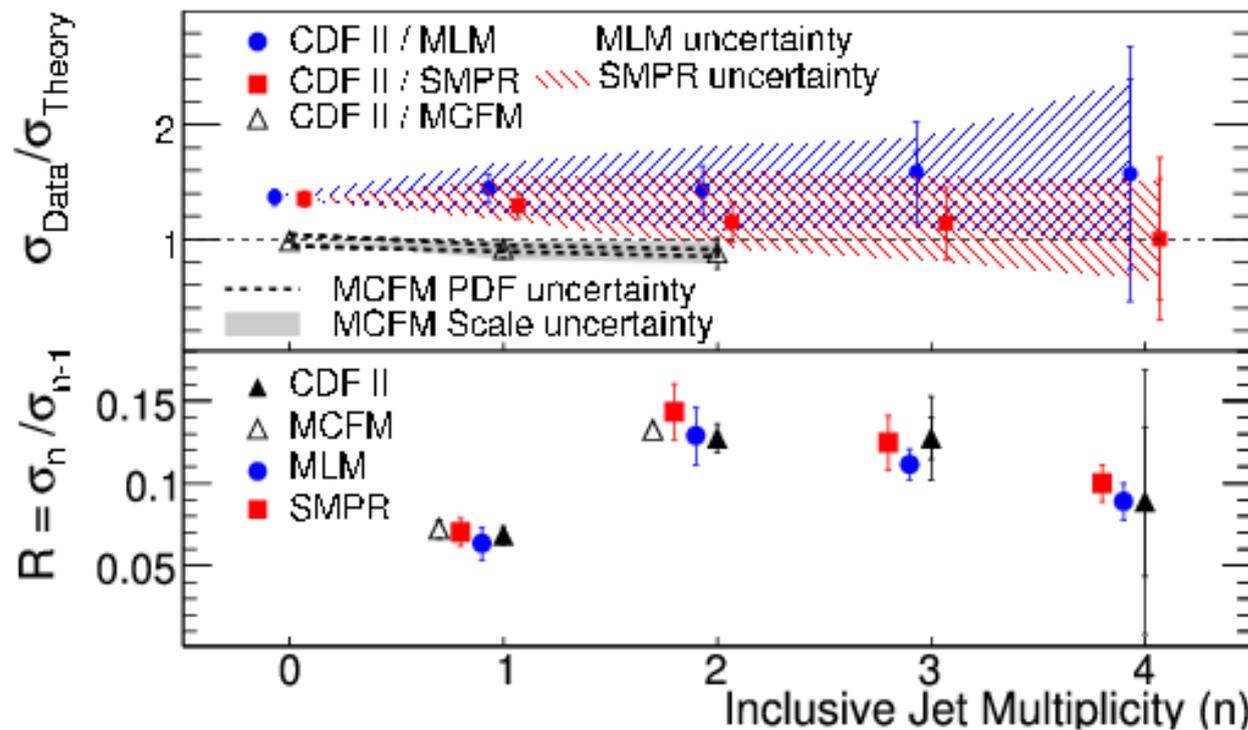


W+n jets differential cross sections (CDF)

- Good understanding of W+jets production is essential for (single)top, Higgs and SUSY
- Good test ground of matrix element + parton shower (ME+PS) techniques

- $L = 320 \text{ pb}^{-1}$ (*Submitted* to Phys.Rev.D).
- Measured p_T cross sections for 1-3 jets and jet multiplicities. Compared to:
LO ME+PS: SMPR and MLM (differ by a treatment of multi-jet phase space);
SMPR: Madgraph (ME)+Pythia+CTEQ6L;
MLM: Alpgen+Herwig+CTEQ5L
NLO : MCFM (with $\mu_F = \mu_R = (M_Z^2 + p_T^2)^{1/2}$ and CTEQ6.1M)

- *Jet p_T dependence is better described by SMPR.*
- *QCD NLO is in good agreement with all measurements.*

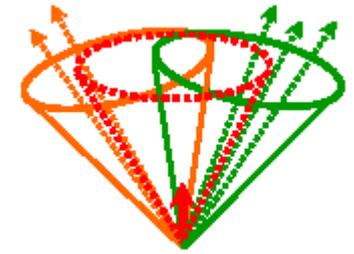


Summary

- High Q^2 QCD studies at Tevatron are essential in Run II physics programs: better understanding of all QCD mechanisms will be beneficial to all physics analyses, including any searches for new physics.
Better knowledge of QCD is crucial for Tevatron and also for the coming LHC data.
- QCD analyses give stringent test of QCD calculations and new constraints on proton PDFs, NLO + HO corrections, resummations, fragmentation effects and ISR models.
Most of QCD channels are directly sensitive to new physics.
- In general, QCD results are in good agreement with theory predictions.
But some results (e.g. inclusive photons, photon/W + jet production) still require a further theory tuning.
- A lot of exciting work still in progress. Stay tuned!

BACKUP SLIDES

DZero Run II Cone Algorithm



- Preclustering similar to RunI except:
 - seeds = p_T ordered list of particles with $p_T > 500$ MeV
 - precluster = all particles in a cone of $r=0.3$ around seed for Cone Jets with $R \geq 0.5$
 - precluster 4-momentum calculated using the E -scheme
- Clustering
 - seeds = p_T ordered list of preclusters with $p_T > 1$ GeV
except those close to already found proto-jets: $\Delta R(\text{precluster}, \text{proto-jet}) < 0.5 R_{\text{cone}}$
 - cone drifting until
 - > cone axis coincides with jet direction
 - > $p_T < 0.5 \text{ Jet } p_T^{\text{min}}$
 - > # iterations = 50 (to avoid ∞ cycles)
 - remove duplicates
 - repeat same clustering for midpoints*
 - > no condition on close proto-jet
 - * for pairs only, calculated using p_T -weighted mean
 - > no removal of duplicates
- Merging/splitting similar to RunI except:
 - use p_T ordered list of proto-jets (from seeds and midpoints)
 - at each merging/splitting
 - > recalculate 4-momenta of merged/splitted jets
 - > re-order list of merged/splitted jets

CDF Midpoint Algorithm with smaller Search Cone Option

- Jets might be missed by RunII Cone Algorithm (S.D. Ellis *et al.*, hep-ph/0111434)
 - low p_T jets
 - too close to high p_T jet to form a stable cone (cone will drift towards high p_T jet)
 - too far away from high p_T jet to be part of the high p_T jet stable cone
- Proposed solution
 - remove stability requirement of cone
 - run cone algorithm with smaller cone radius to limit cone drifting
($R_{search} = R_{cone} / \sqrt{2}$)
 - form cone jets of radius R_{cone} around proto-jets found with radius R_{search}

Remarks

- Problem of lost jets seen by CDF, not seen by DØ
 - A physics or an experimental problem?
 - Proposed solution unsatisfactory w.r.t. cone jet definition
- ⇒ DØ prefers using RunII Cone without Smaller Search Cone

k_T Algorithm

Description of inclusive k_{\perp} algorithm (Ellis&Soper, PRD48, 3160, (1993))

- $D\emptyset$: geometrical 2x2 preclustering, remove preclusters with $E < 0$
- p_T ordered list of particles \rightarrow form the list of $d_i = (p_T^i)^2$
- calculate for all pairs of particles, $d_{ij} = \text{Min}((p_T^i)^2, (p_T^j)^2) \Delta R/D$
- find the minimum of all d_i and d_{ij}
 - if it is a d_i , form a jet candidate with particle i and remove i from the list
 - if not, combine i and j according to the E -scheme
 - use combined particle $i + j$ as a new particle in next iteration
 - need to reorder list at each iteration \rightarrow computing time $\propto O(N^3)$ (N particles)
- proceed until the list of preclusters is exhausted

Remarks

- originally proposed for e^+e^- colliders, then adapted to hadron colliders
(S. Catani *et al.*, NPB406,187 (1993))
- universal factorisation of initial-state collinear singularities
- infrared safe: soft partons are combined first with harder partons
- collinear safe: two collinear partons are combined first in the original parton
- no issue with merging/splitting
 - resolution
 - Correct data by ratio of original to smeared ansatz function
 - Cross check with Pythia