PDF constraints from W/Z- and Jet Production at the Tevatron

on behalf of the CDF and DØ Collaborations

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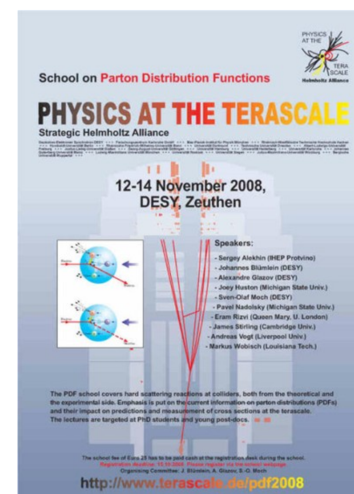
DESY, Zeuthen

Physics at the Terascale
PDF School



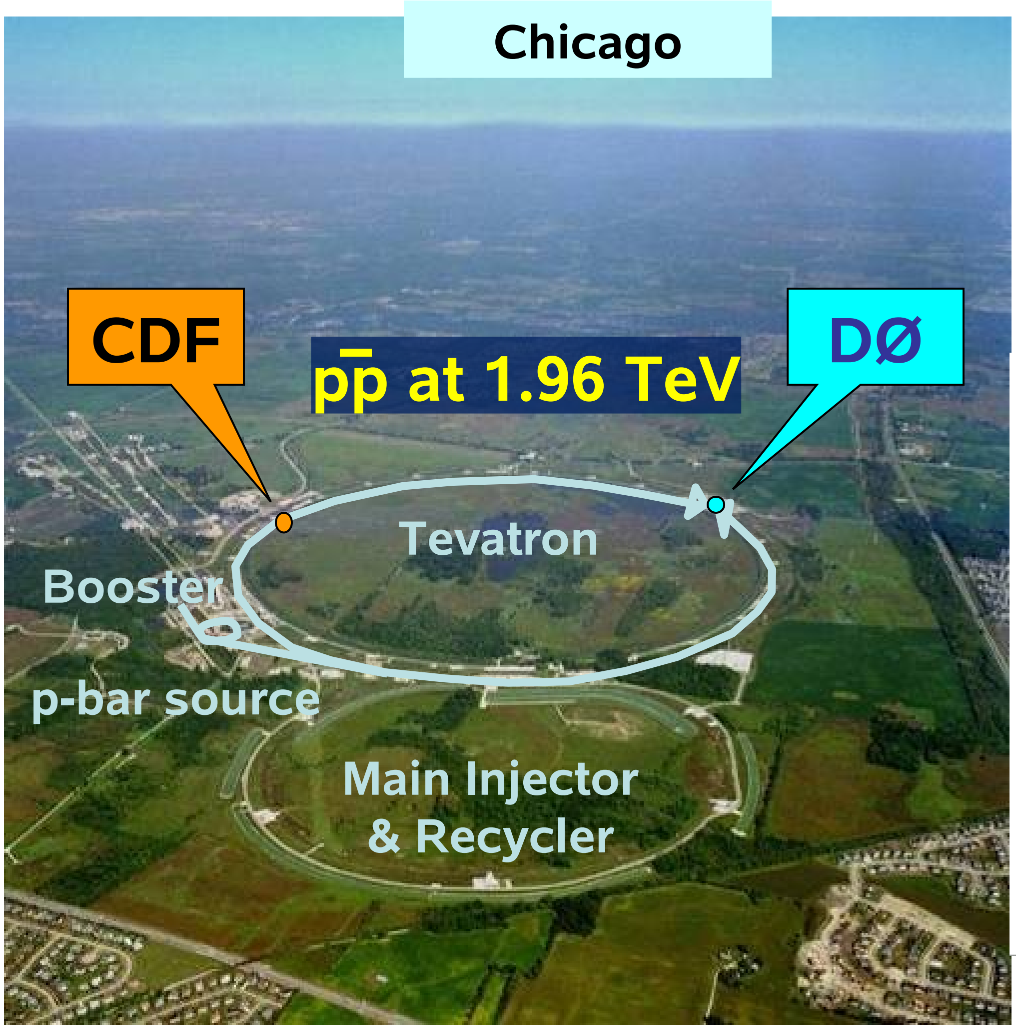
Reminder

Difference: PDFs <- -> Structure Functions

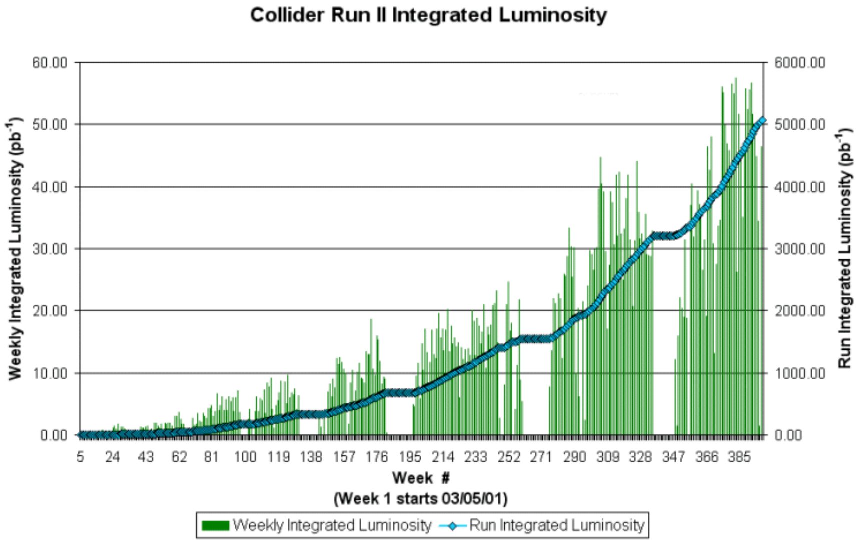
- Structure Functions are observables
  → they can be **measured**

- PDFs are **not** observables
  - they can **not** be measured
- PDFs are parameters
  - defined in a given theoretical framework (factorization scheme)
  - they can be **extracted**/determined in a theory fit to data
- PDFs are universal
  - process independent
  - determined from one data set → predictions for other data sets

Fermilab Tevatron - Run II



- 36x36 bunches
- bunch crossing 396ns
- Run II started in March 2001
- Peak Luminosity:
  2.85E32 cm^{-2} sec^{-1}

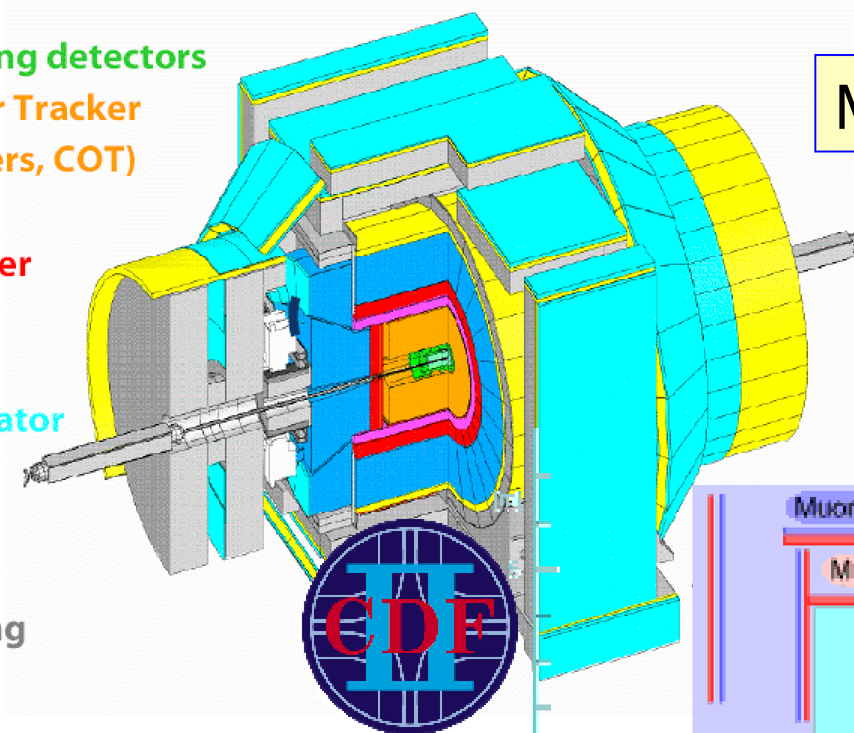


presented results 0.2-2.0 fb-1

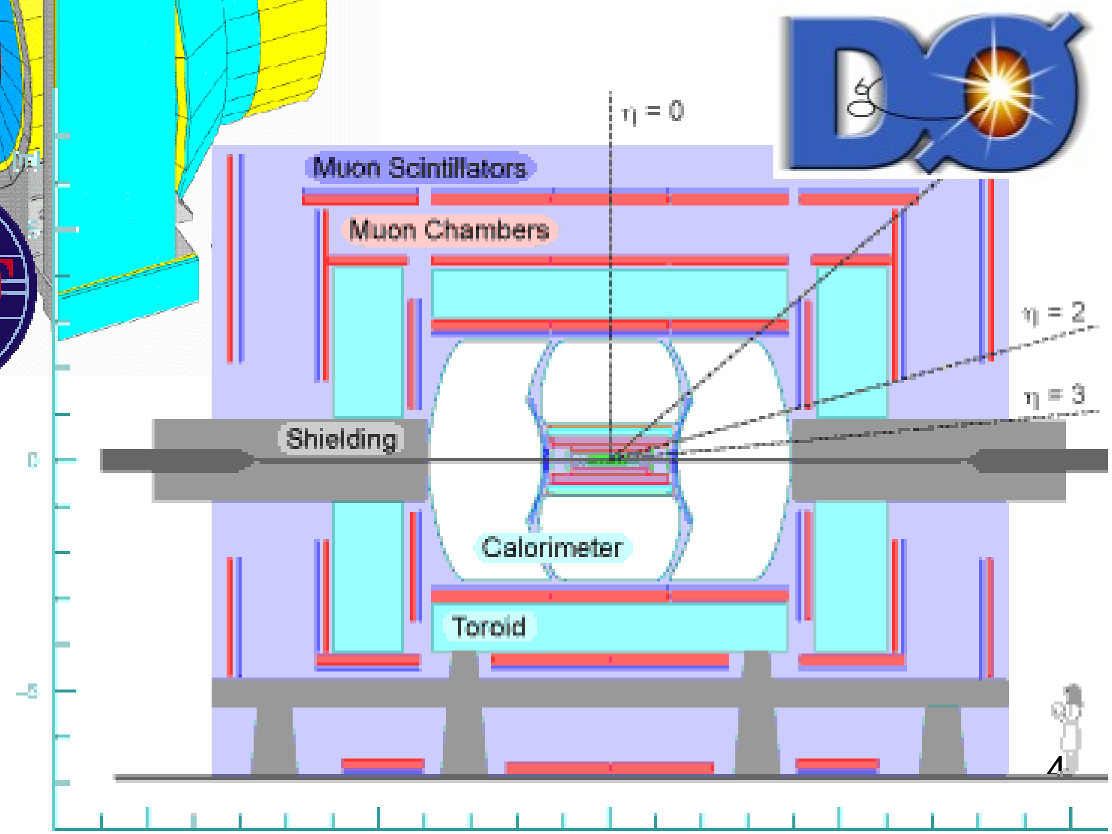
- Run II Goal: 8 fb^{-1} end of FY2010

Run II Detectors

- Silicon tracking detectors
- Central Outer Tracker (drift chambers, COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding



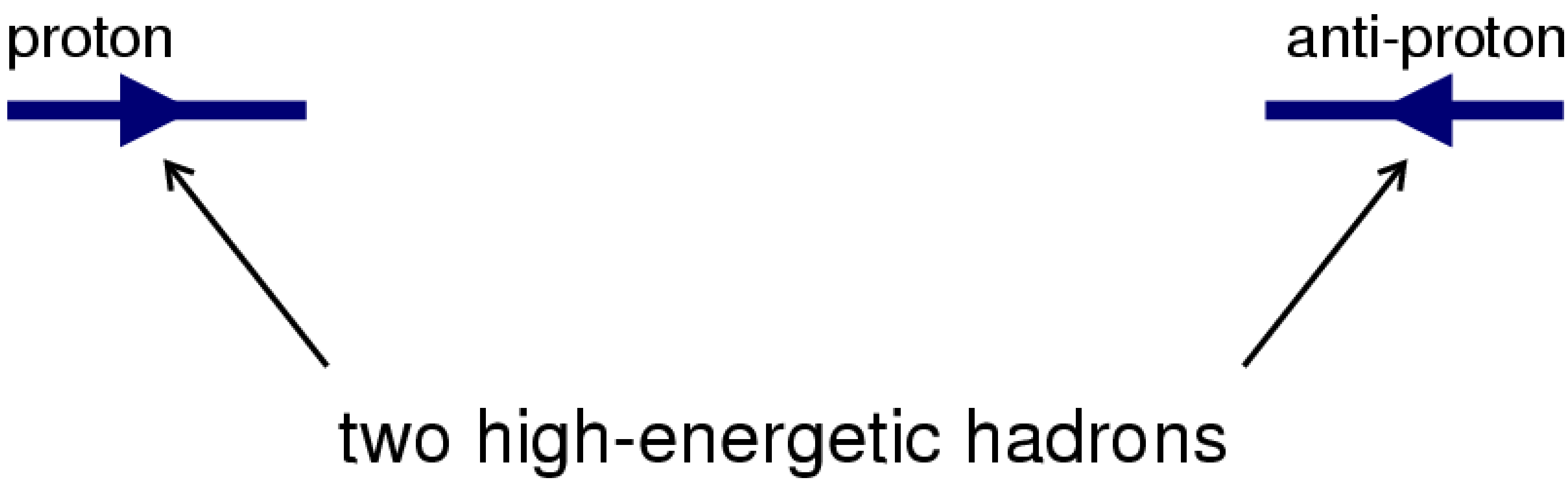
Multi-purpose Detectors



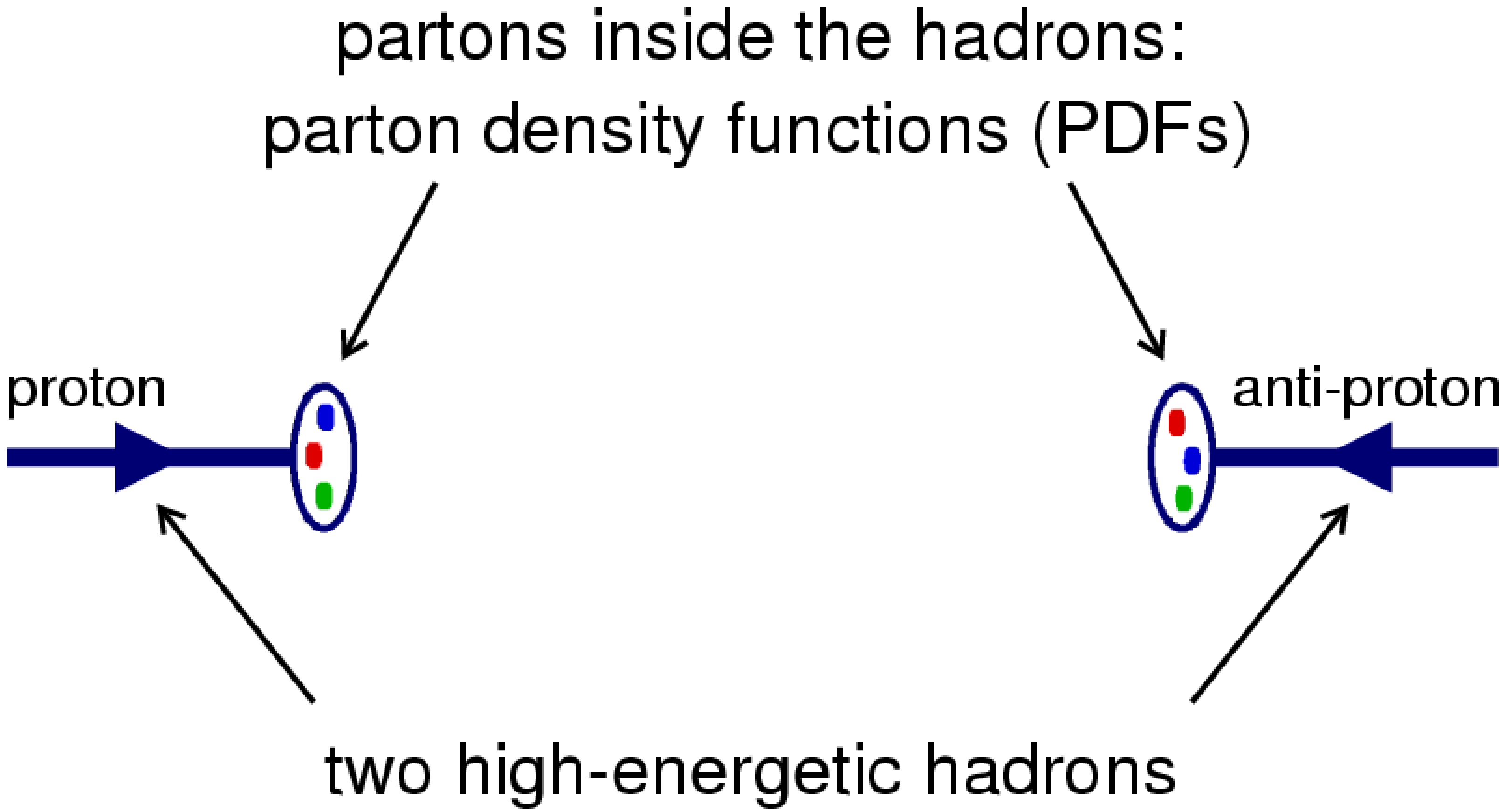
- vertexing
- precision tracking
- calorimetry
- muon system
- (hermitic → missing ET)

Hadron-Hadron Collisions

Hadron-Hadron Collisions

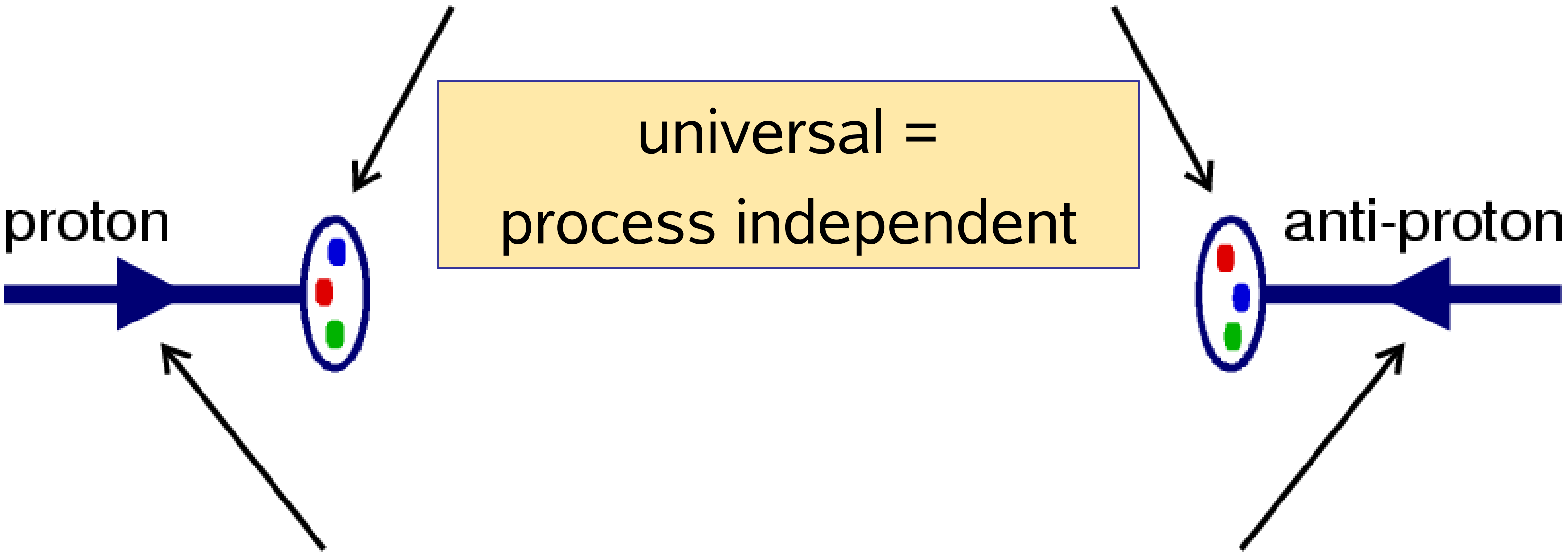


Hadron-Hadron Collisions



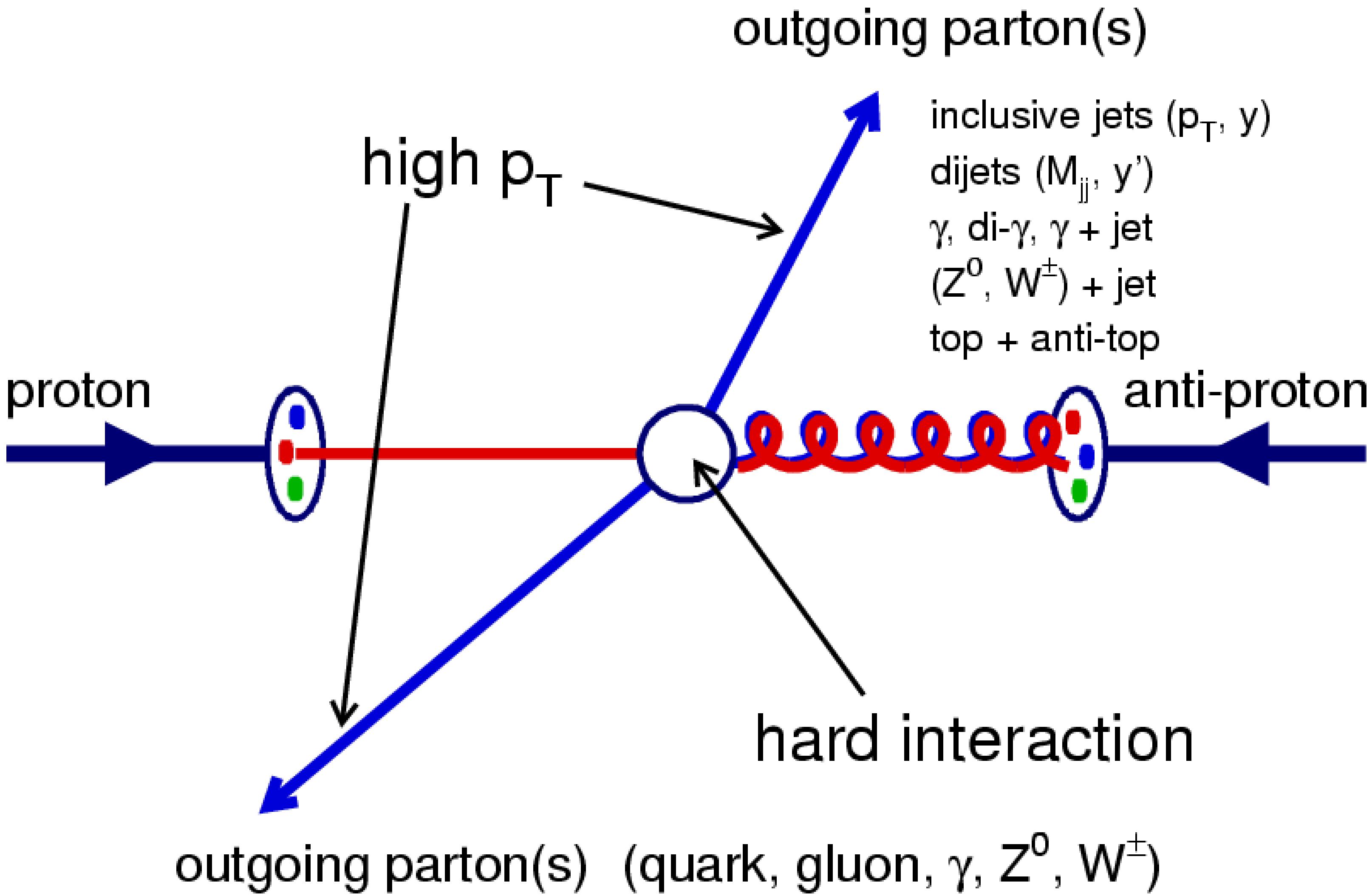
Hadron-Hadron Collisions

partons inside the hadrons:
parton density functions (PDFs)

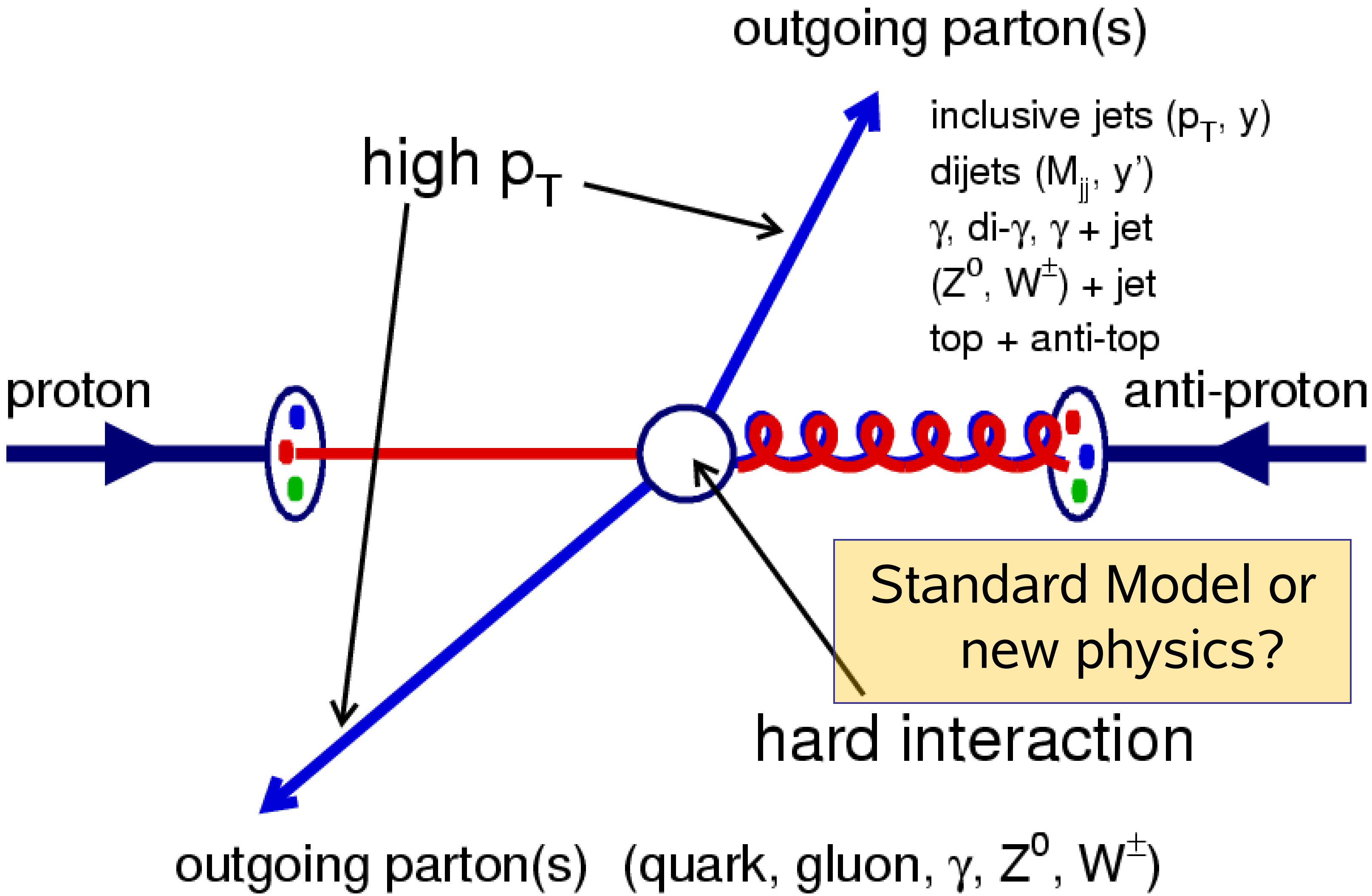


two high-energetic hadrons

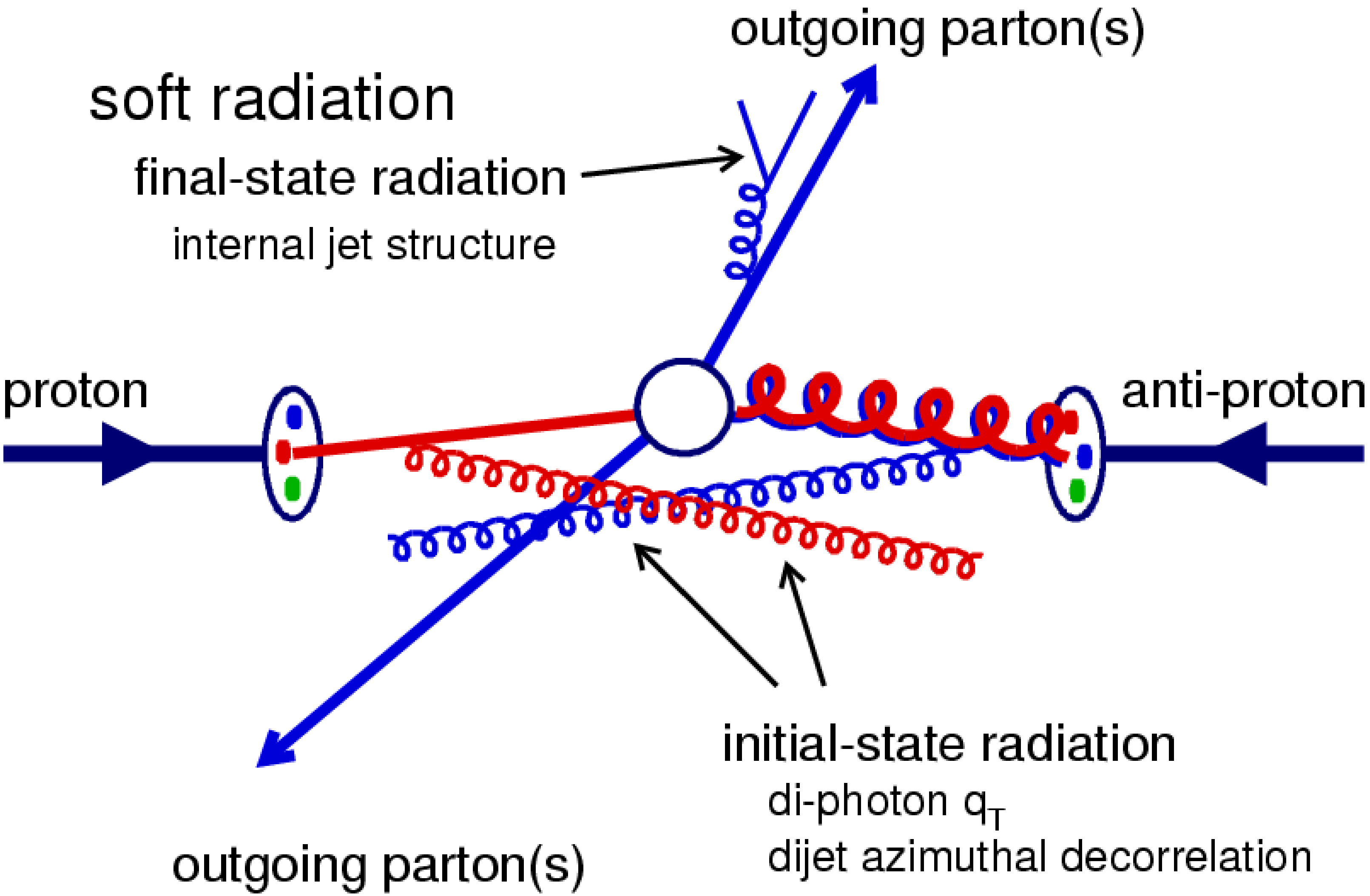
Hadron-Hadron Collisions



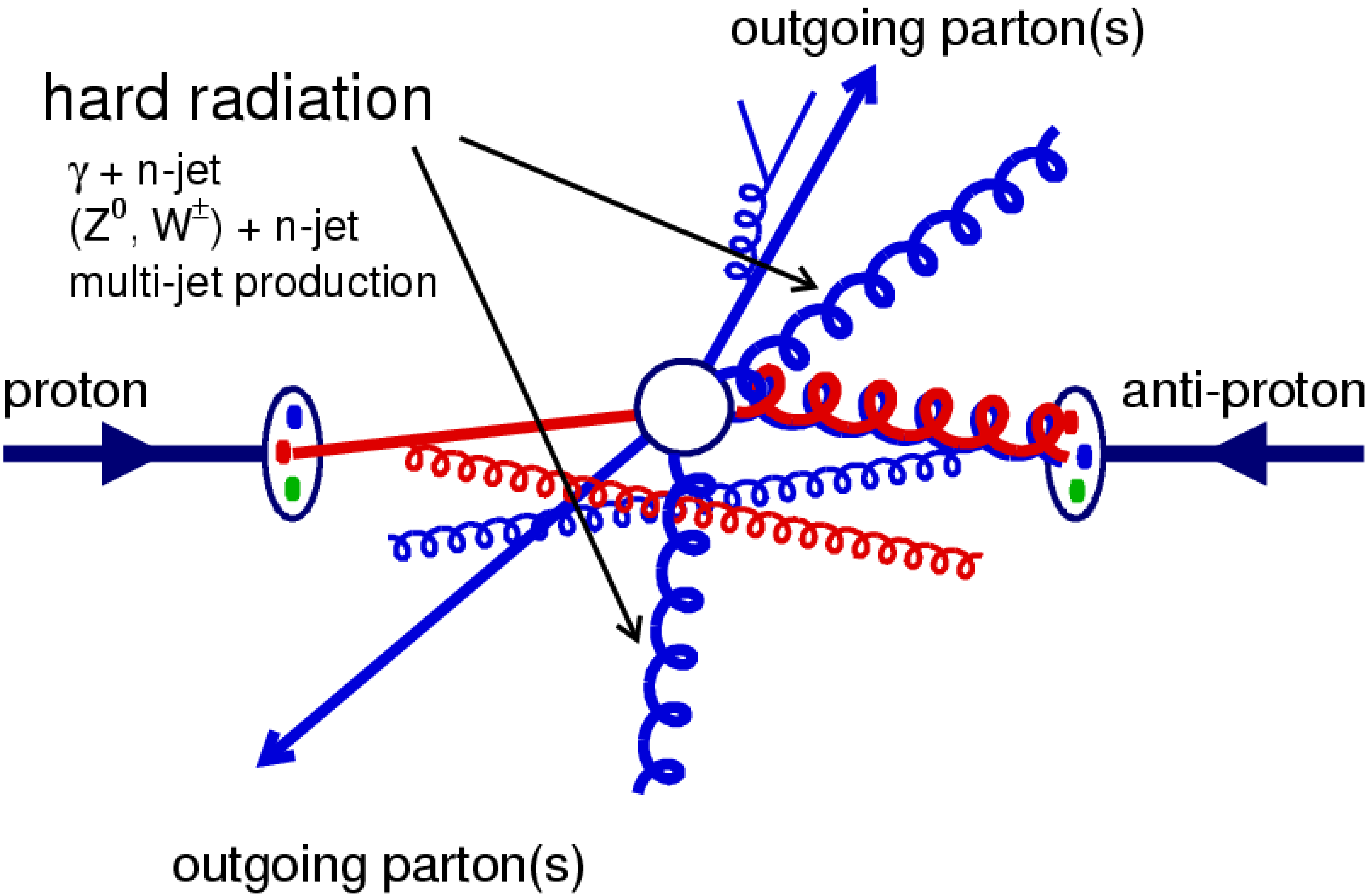
Hadron-Hadron Collisions



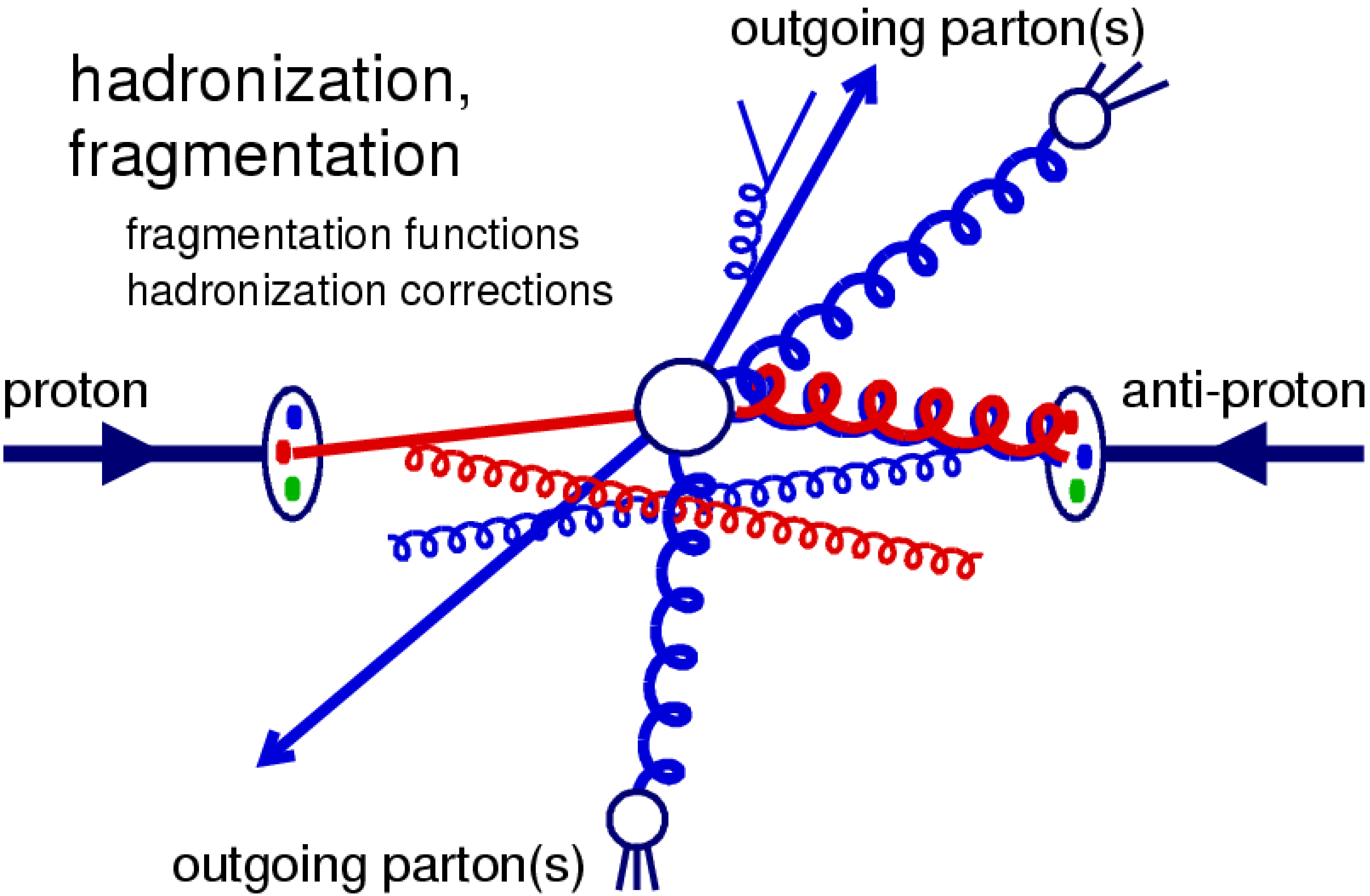
Hadron-Hadron Collisions



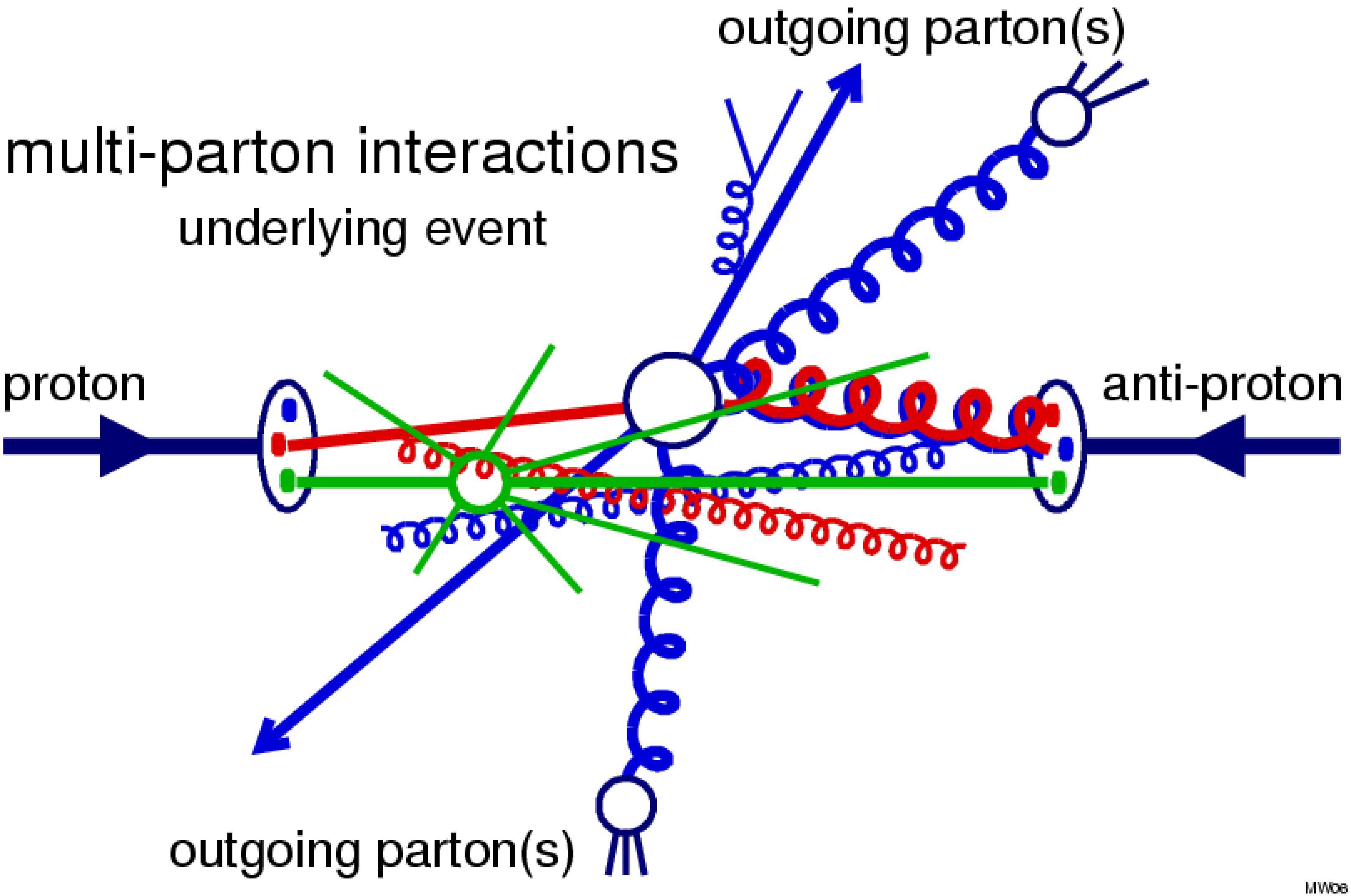
Hadron-Hadron Collisions



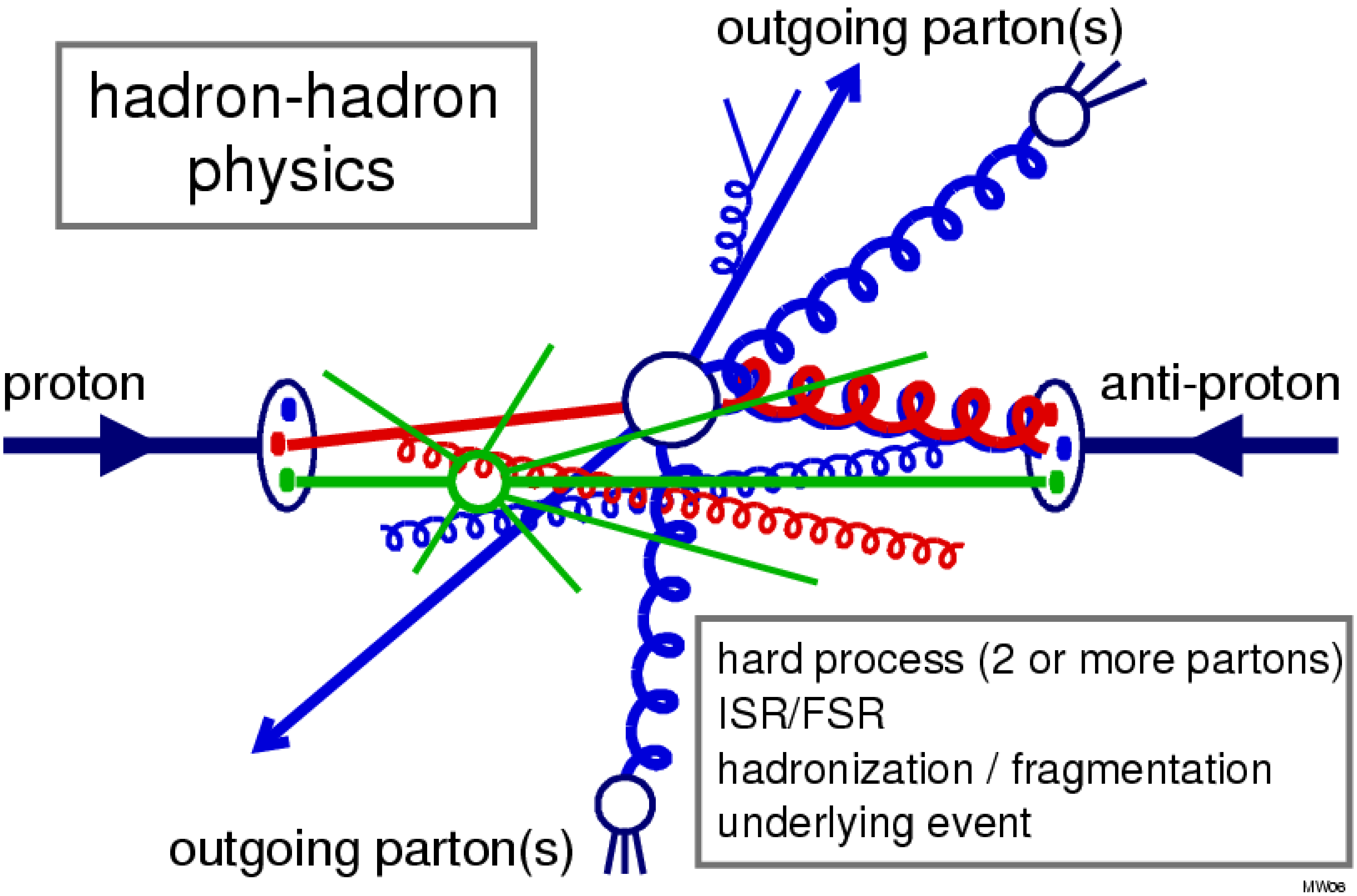
Hadron-Hadron Collisions



Hadron-Hadron Collisions



Hadron-Hadron Collisions



PDF sensitivity

Cross Sections in Hadron-Hadron Collisions

$$\sigma_{\mathrm{hh}} = \sum_n \alpha_s^n(\mu_r) \sum_{\text{PDFflavors } a} \sum_{\text{PDFflavors } b} c_{a,b,n}(\mu_r, \mu_f) \otimes f_a(x_1, \mu_f) \otimes f_b(x_2, \mu_f)$$

- Perturbative Coefficients c (include all information on observable)
- Strong coupling constant: alpha-s
- PDFs of the two hadrons: f-a(x1), f-b(x2)

PDF sensitivity

At a hadron collider:

In principle: every process is sensitive to PDFs

In practice: "When is a process sensitive to PDFs?"

related to ability of data to constrain PDFs beyond present knowledge

Sensitivity:

- If experimental + theoretical (pQCD) uncertainties are smaller than present PDF uncertainties

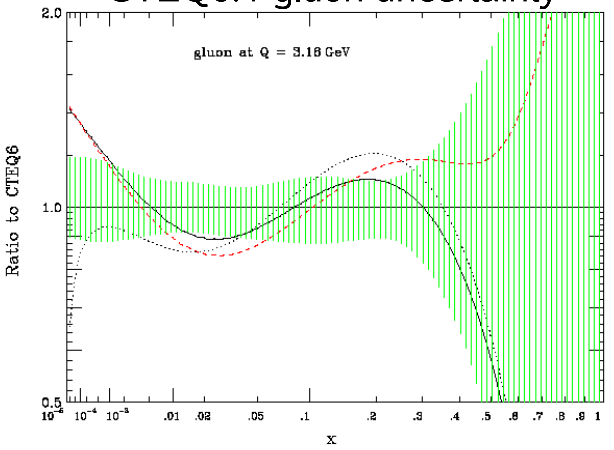
Hard QCD Processes

high pT / high mass

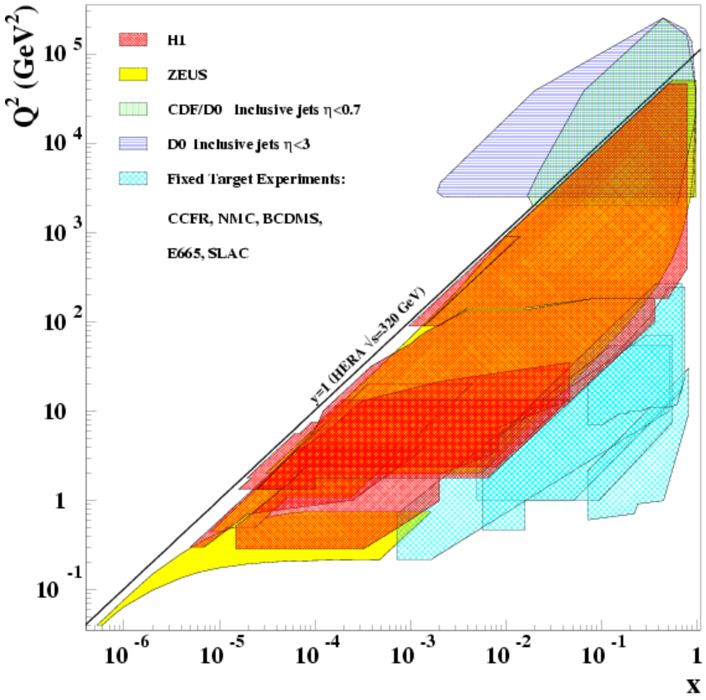
→ hard **partonic** scattering

→ perturbative predictions

CTEQ6.1 gluon uncertainty



kinematic plane



sensitive:

- strong coupling constant
- proton's parton content
- dynamics of interaction
  - validity of approximations (NLO, LLA, …)
  - QCD vs. new physical phenomena

→ still: unique pT reach at Tevatron

Comment

PDFs are strongly constrained by high precision DIS structure function data (huge kinematic range of HERA)

- strong direct constraints on quark densities
- strong indirect constraints on low-x gluon density

Tevatron ppbar data → important **additional** information

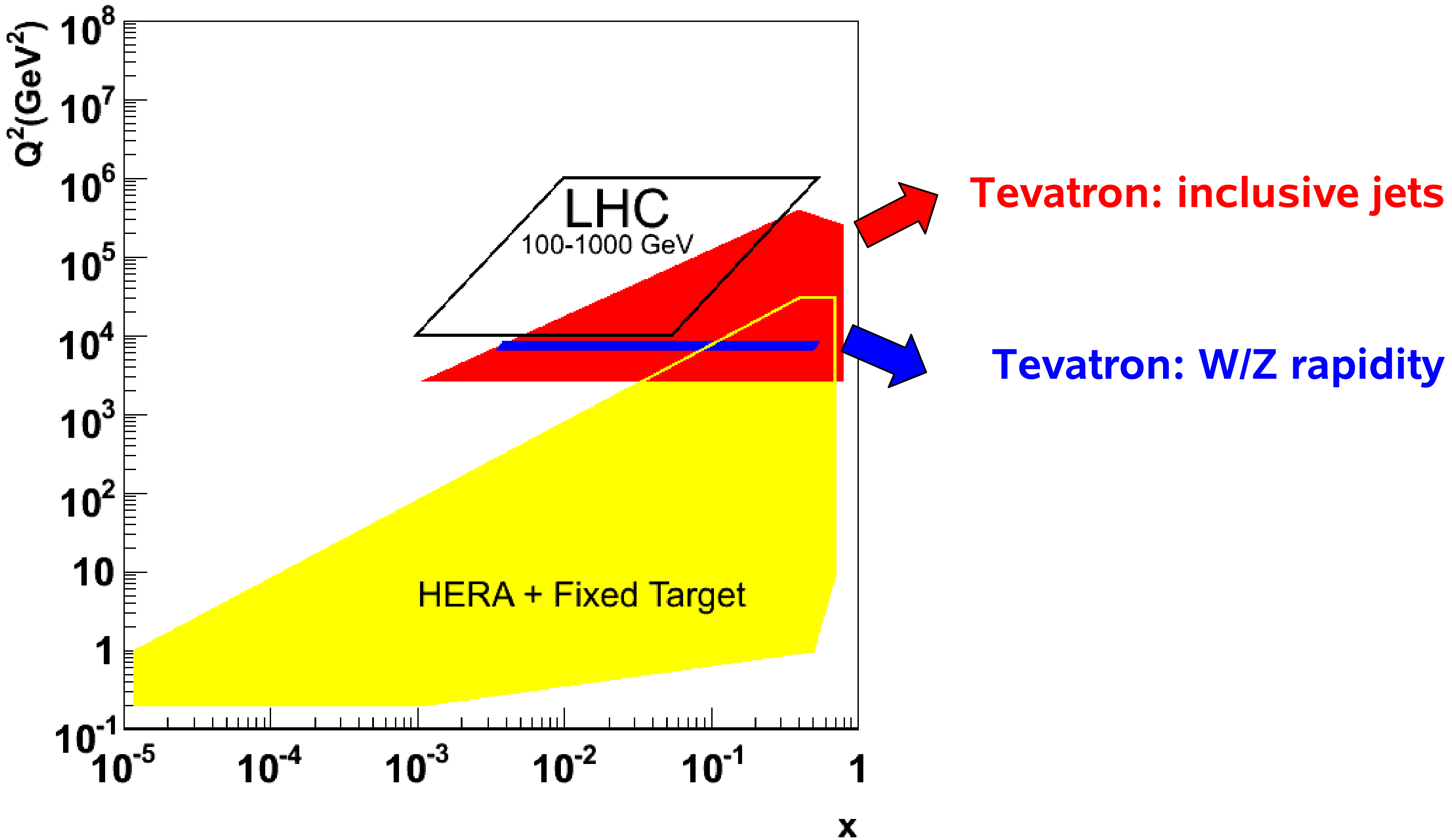
- direct constraints on high-x gluon density
- constraints on up/down quark densities

→ No Tevatron-only PDFs

→ Tevatron Data are input for global fits

Tevatron kinematic region

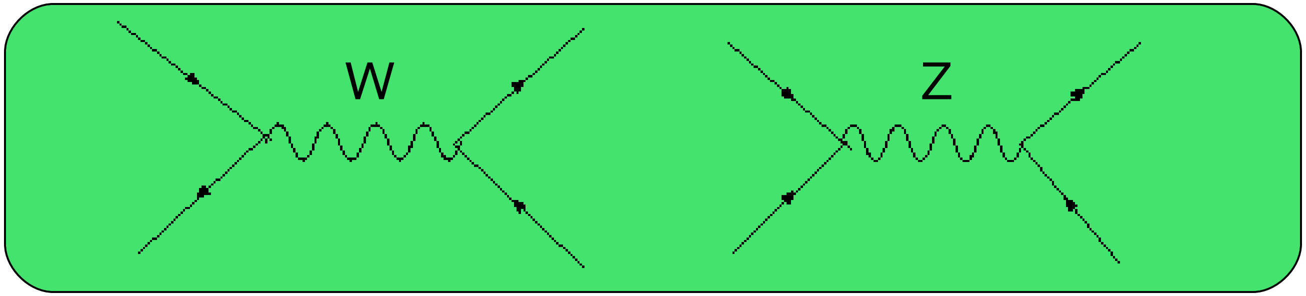
- Tevatron data provide 10% of the data-points in the PDF fits
- Complement HERA and fixed-target data providing constraints at high-Q^2



Outline

- **W/Z Production**
  - Z rapidity
  - W asymmetry
- **Jets Production**
  - inclusive jets
  - sensitivity to new physics
- **Other processes**
  - prompt photon production
  - W+c jet production

W/Z-Production



W & Z rapidity

Data presently being used in global fits:

- 0.4 fb^{-1} D0 Z-ee rapidity – Phys. Rev D 76 012003 (2007)
- 2.0 fb^{-1} CDF Z-ee rapidity http://www-cdf.fnal.gov/physics/ewk/2008/dszdy
- 0.3 fb^{-1} D0 W-μν charge asymmetry – Phys. Rev. D 77 011106(R) (2008).
- 0.2 fb^{-1} CDF W-eν - Phys. Rev. D71 051104 (2005).

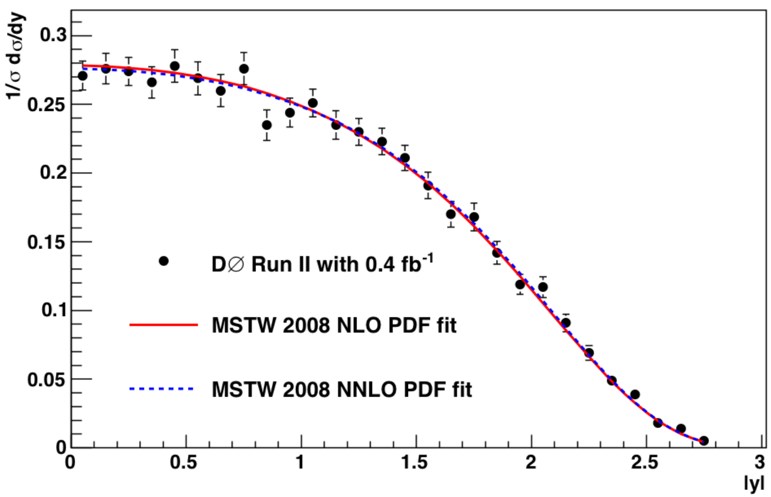
Latest CDF/D0 W charge asymmetry not included due to inconsistencies

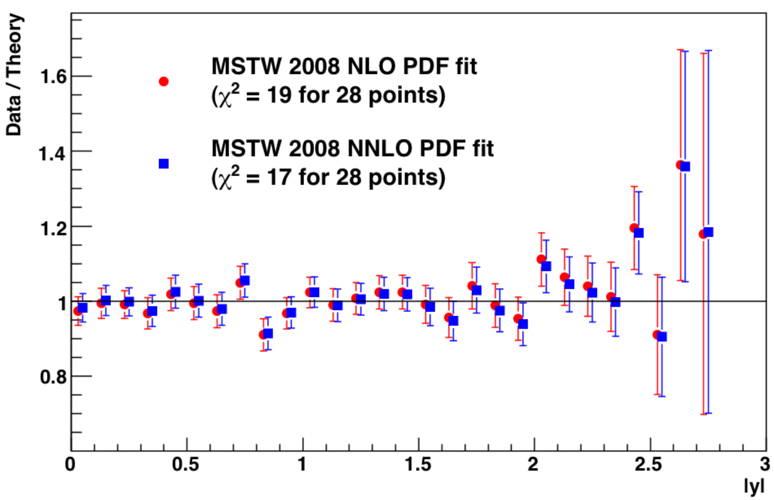
Mainly sensitive to up- and down-quark distributions
but up-quark already well constrained by F_2 (e_Q^2 weighted quark sum)

→ Tevatron W/Z data help to constrain down quark

Z rapidity

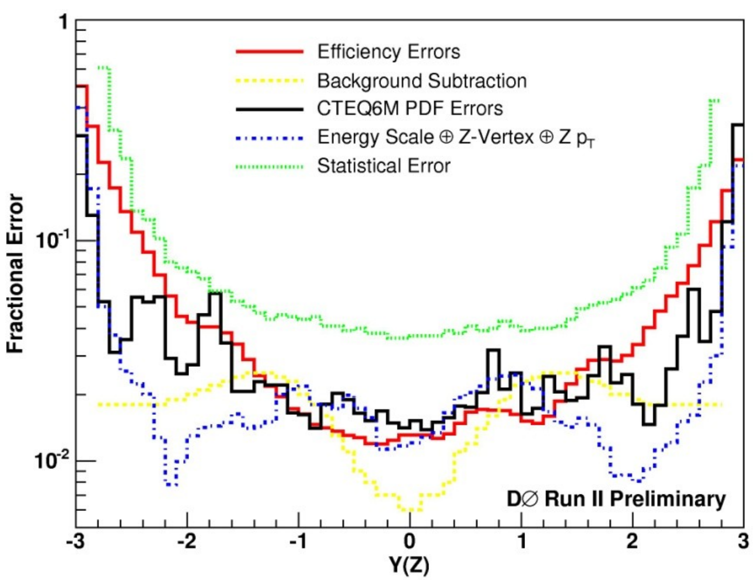
Z/γ* rapidity shape distribution from D∅





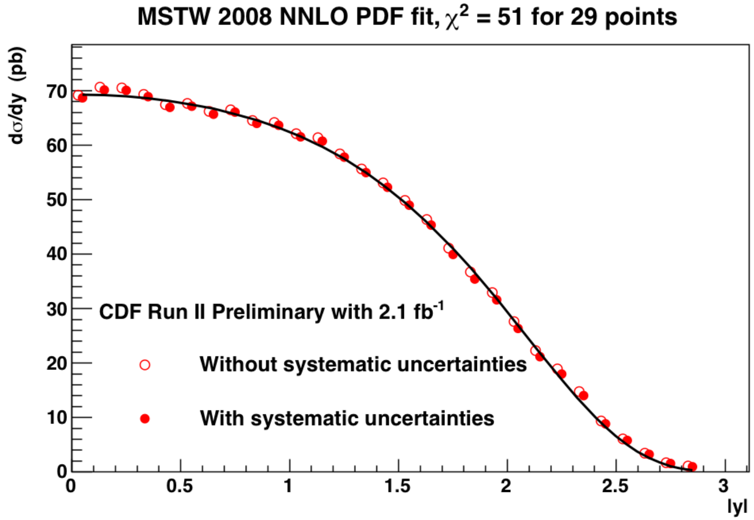
$$Y_Z = 0.5 \ln \left(\frac{x_p}{x_{\bar{p}}} \right)$$

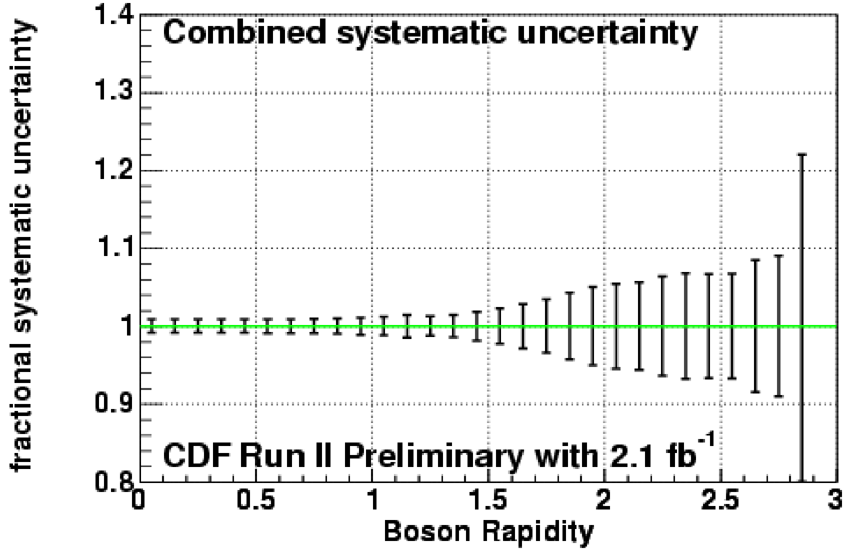
large Y_Z region
probes one high *x*
+ one low *x* parton

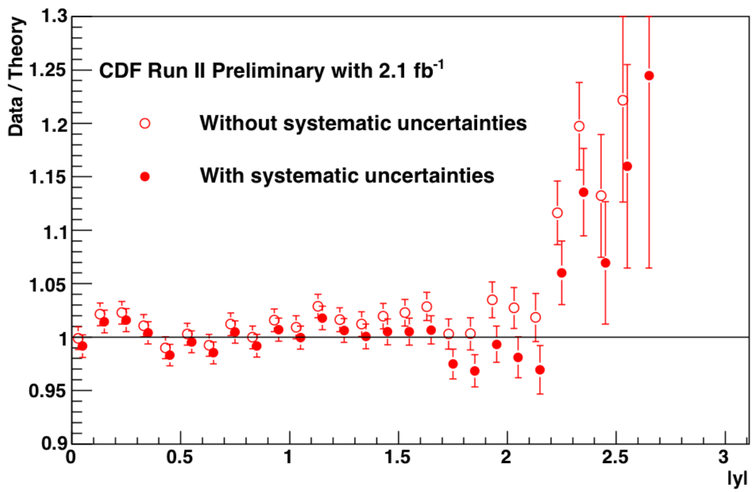


Z rapidity

Z/γ* rapidity distribution from CDF

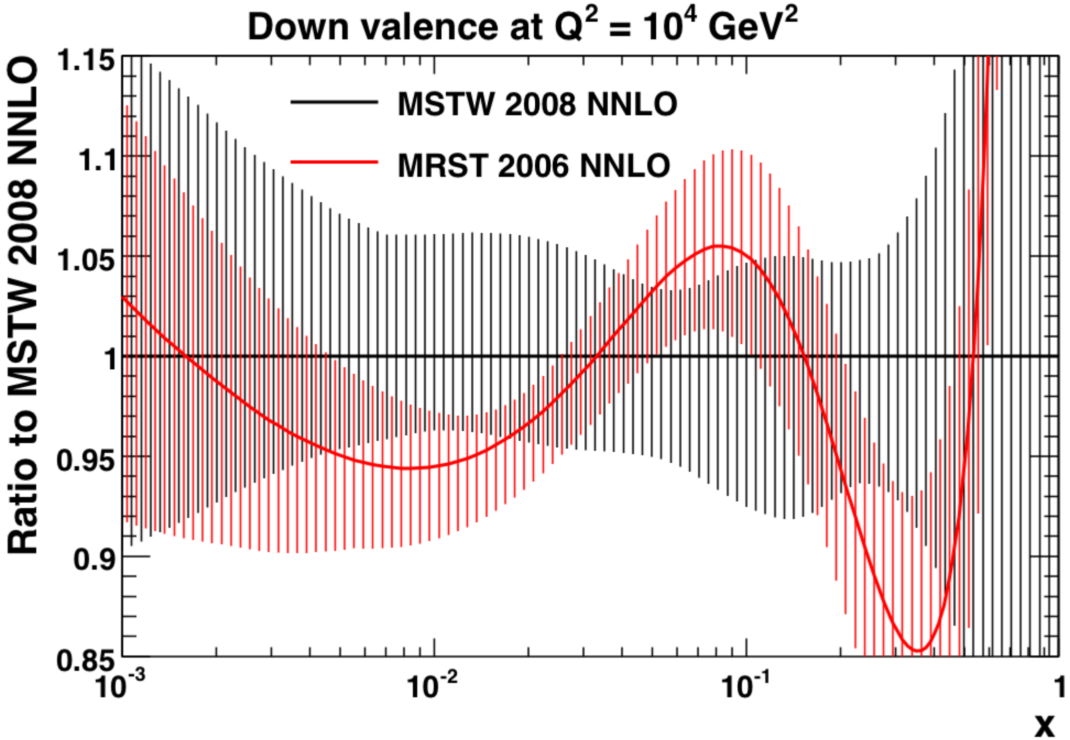






PDF	χ^2/df
CTEQ 6.1M NLO	39/29
MRST NNLO	56/29
MSTW NNLO (2008)	51/29

Z rapidity

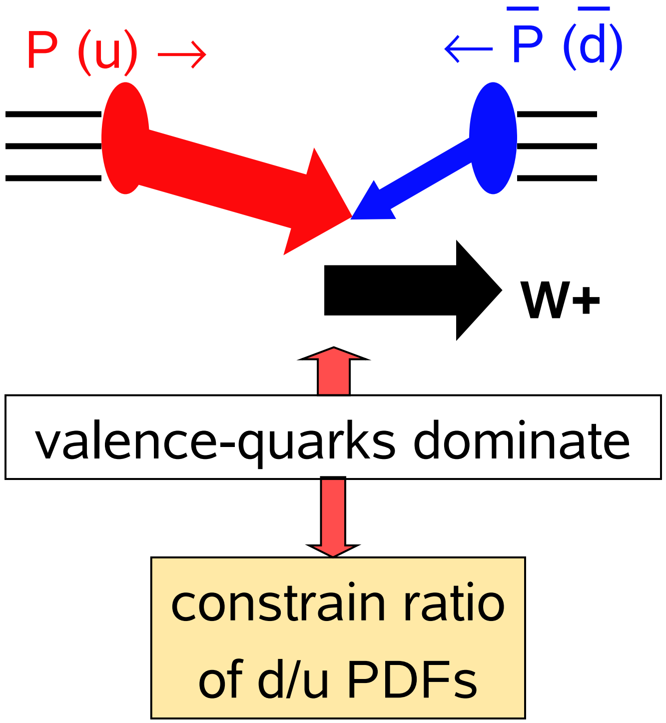


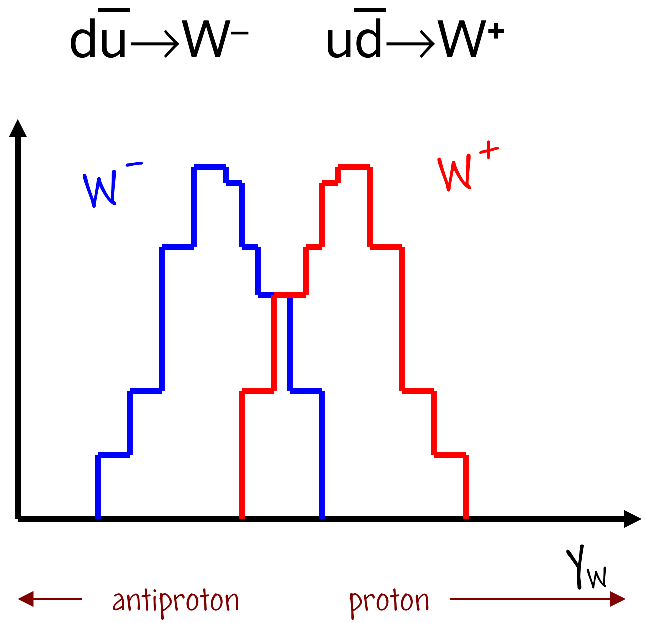
More d_V parameters in new fit as compared to previous fits

→ despite better constraining data, the variance in d_V is now larger !!!

→ reminder: some PDF constraints can be due to fit restrictions

W-Asymmetry





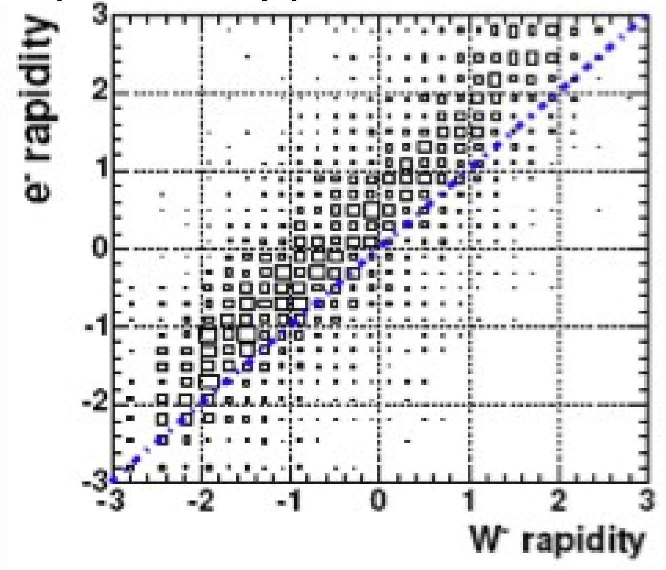
$$A = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W} \approx \frac{d}{u}$$

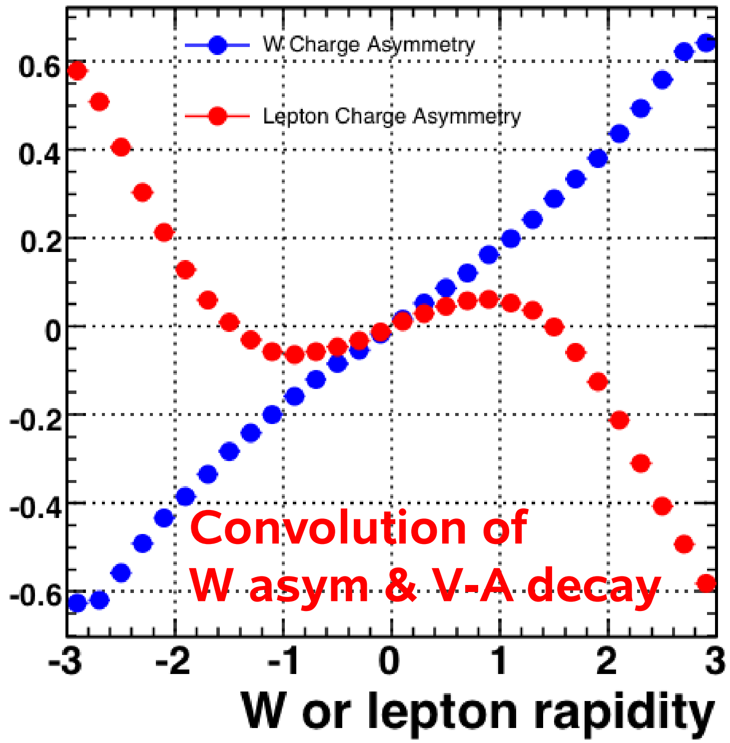
W decay: longitudinal neutrino momentum not measured

→ can't reconstruct W rapidity → measure lepton charge asymmetry

Lepton Charge Asymmetry

V-A structure of W decay favors lepton in opposite direction





Lepton Charge Asymmetry

W-Asymmetry

Lepton Charge Asymmetry

$$A_l(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \simeq \frac{\mathrm{d(x)}}{\mathrm{u(x)}}$$

$$\cos\theta^* = \sqrt{1 - 4E_T^2/M_W^2}$$

Angle between lepton and proton in W rest frame

$$y_l = y_W \pm \frac{1}{2}\ln\left(\frac{1+\cos\theta^*}{1-\cos\theta^*}\right)$$

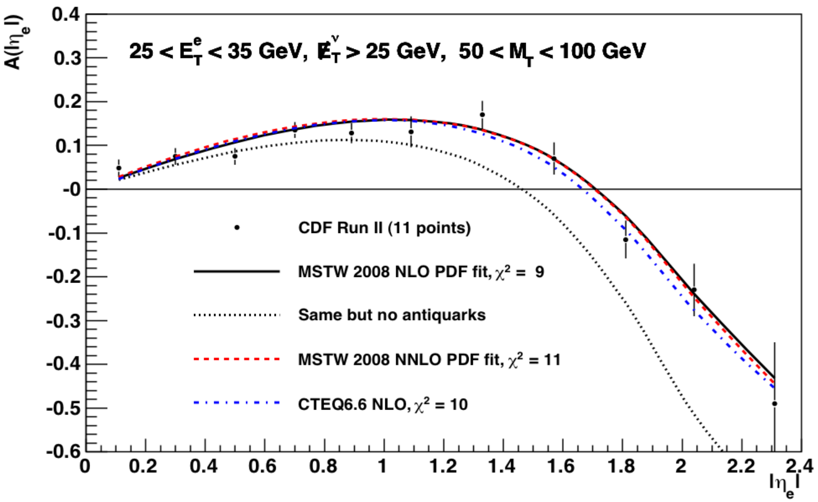
$$d\sigma(l^+)/d\eta_l - d\sigma(l^-)/d\eta_l \approx u(x_1)d(x_2)(1-\cos\theta^*)^2 + \underline{\bar{d}(x_1)\bar{u}(x_2)(1+\cos\theta^*)^2} - d(x_1)u(x_2)(1+\cos\theta^*)^2$$

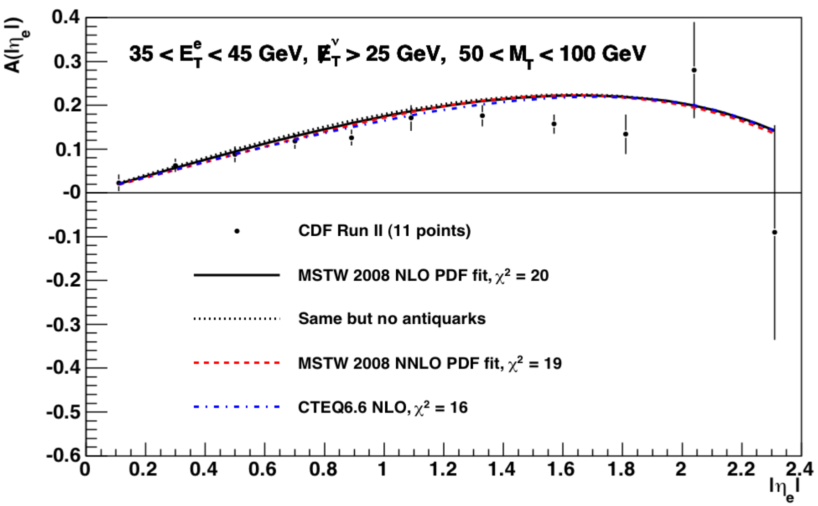
Anti-quark term enhanced at low E_T

Measurements in E_T bins provide separate information on sea & valence

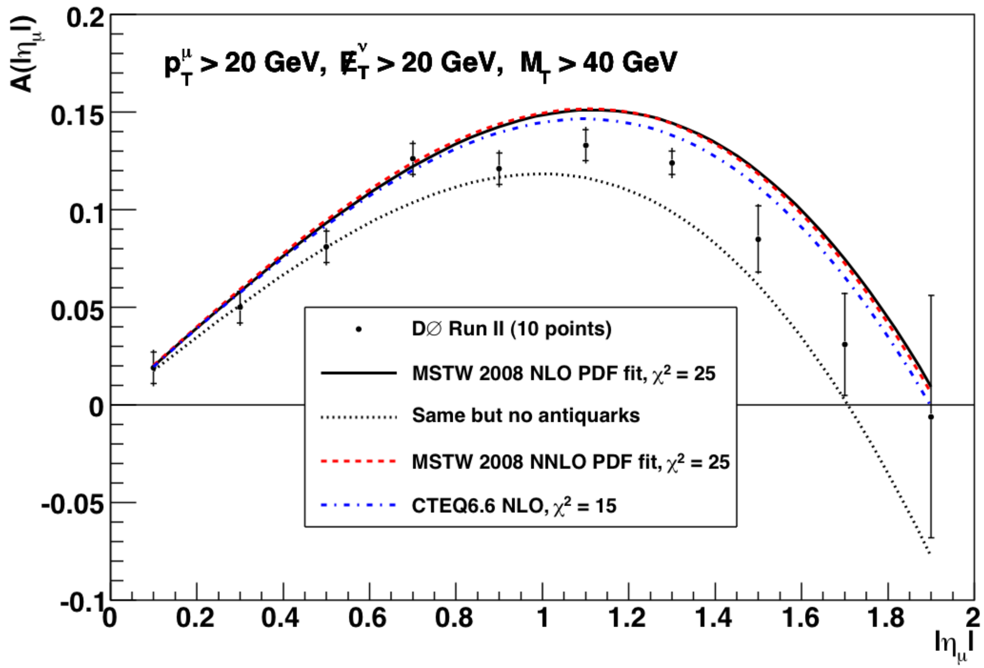
Lepton Charge Asymmetry

CDF data on lepton charge asymmetry from $W \to e\nu$ decays





DØ data on lepton charge asymmetry from $W \to \mu\nu$ decays



at low E_T →
anti-quark discriminating power

Direct Extraction of $A(y_W)$

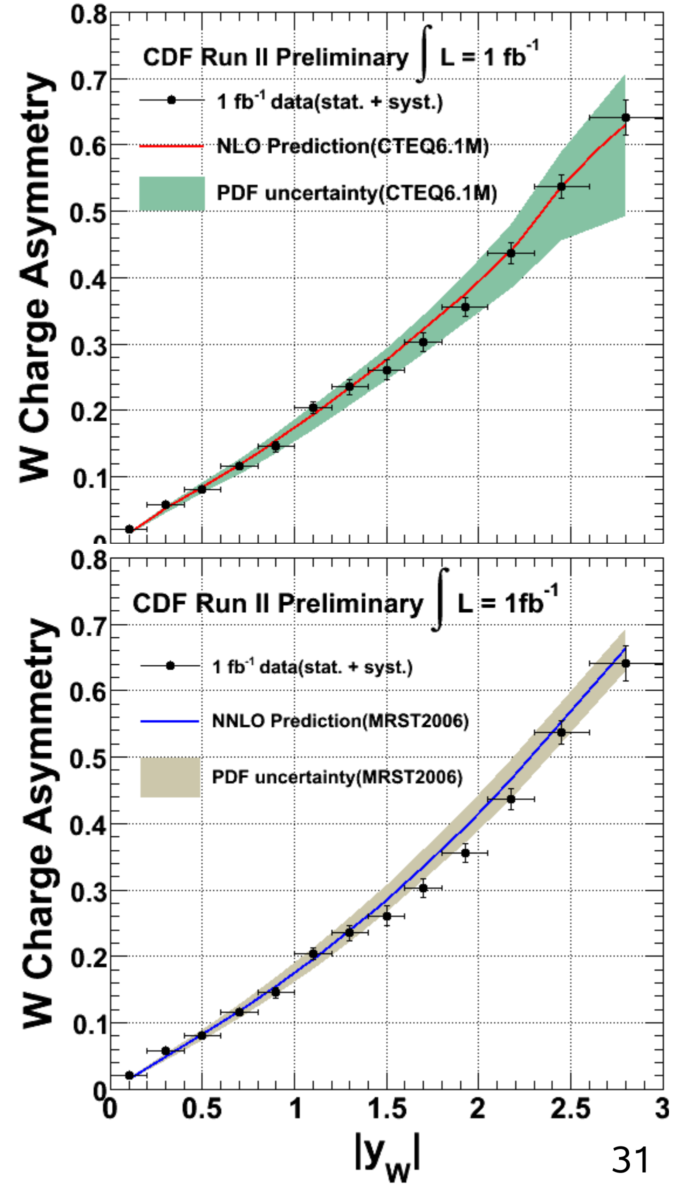
- determine p_L^{ν} by constraining M_W = 80.4 GeV
  $\rightarrow$ two possible solutions for y_W

- Each solution receives a weight probability according to:
  - V-A decay structure
  - W cross-section: $\sigma(y_W)$

- Process iterated since $\sigma(y_W)$ depends on asymmetry
  Analysis method: arXiv:hep-ph/0711.2859

- preliminary CDF measurement (1 fb^{-1}) (~715,000 $W \rightarrow e\nu$ events with $|\eta_e|<2.8$)

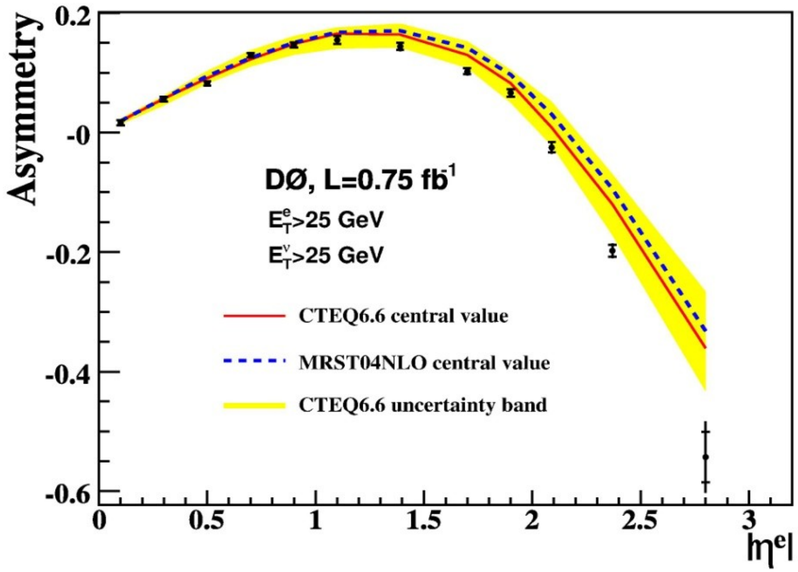
→ Compared to CTEQ6.1 and MRST2006 PDFs



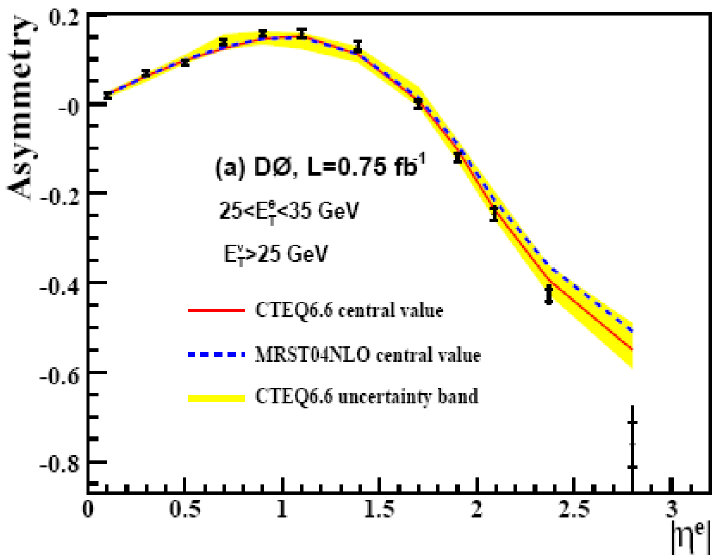
http://www...

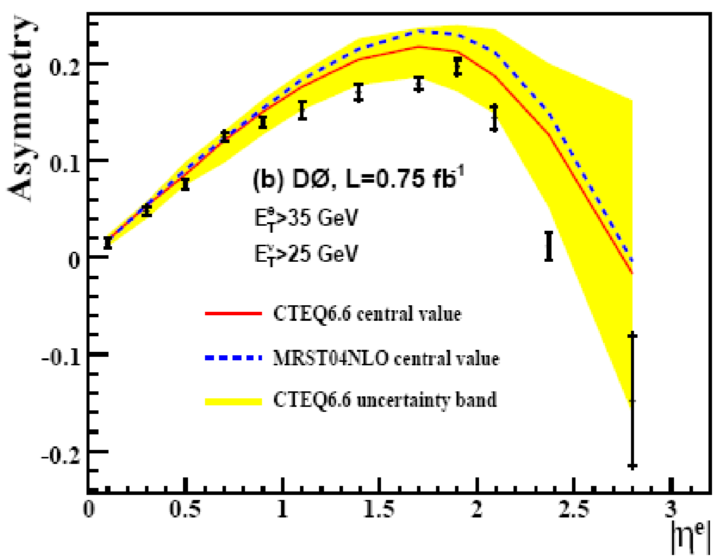
Lepton Charge Asymmetry

new D0 W-eν measurement with 0.75fb^{-1}
differential in E_T
arXiv:/0807.3367 [hep-ex]

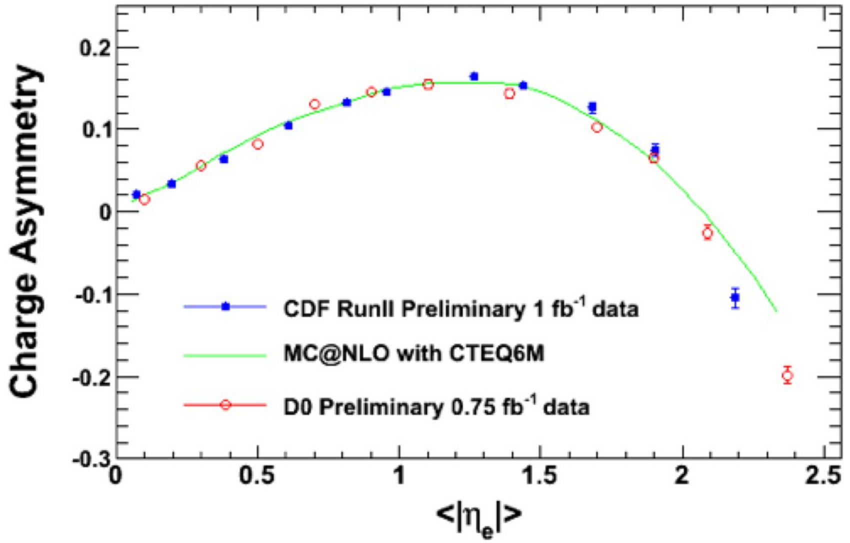


These latest CDF/D0 data should provide improved d/u constraints, but …



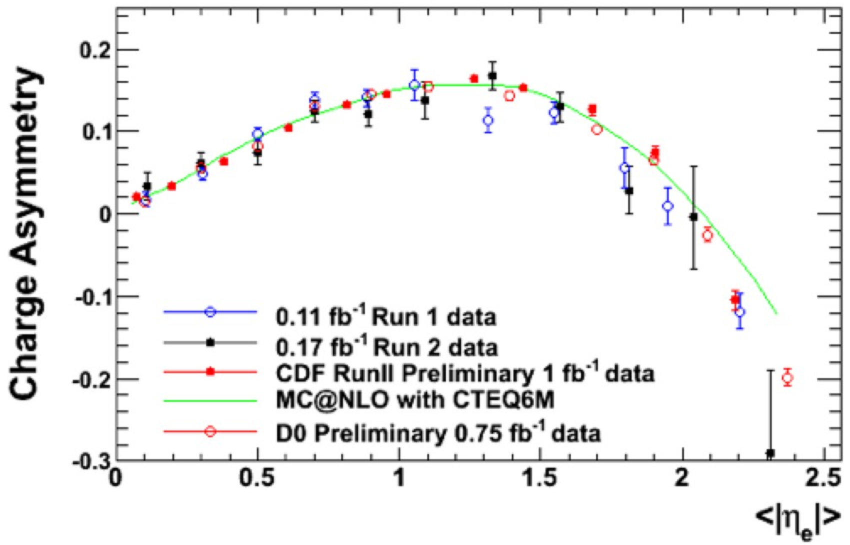


Latest W results



In addition to Y_W results

CDF provides stat. only η_l data.

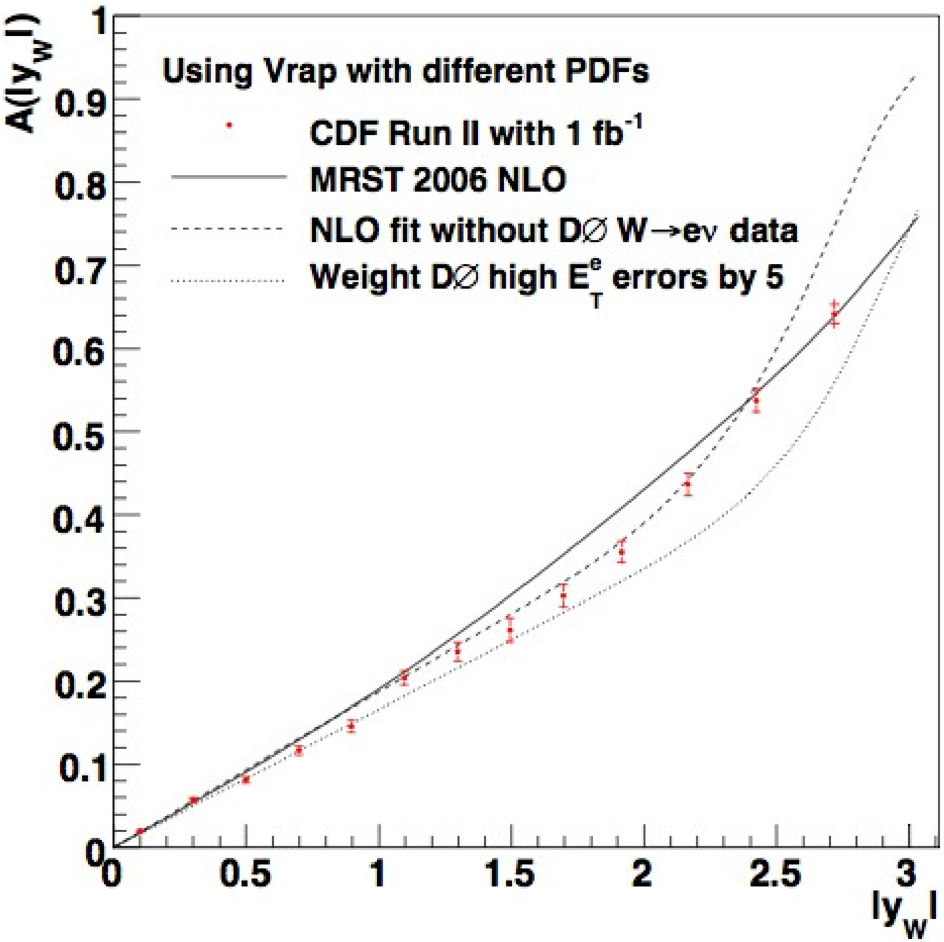


For $0.8 < \eta_l < 2.0$

D0 data below CDF

Latest W results

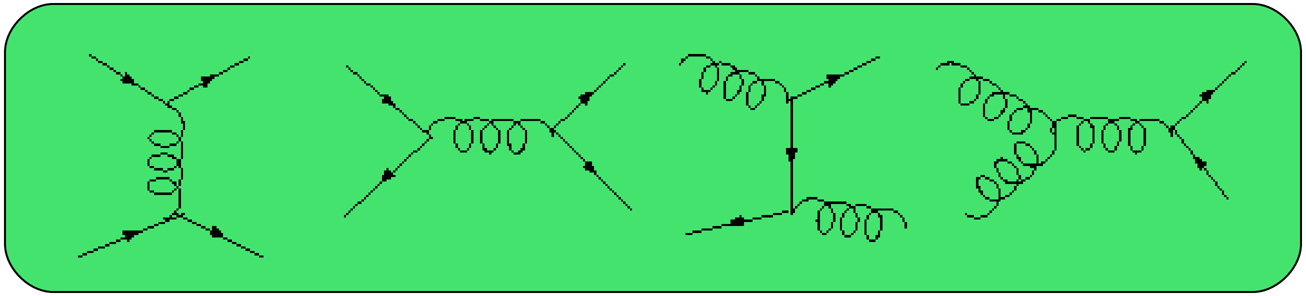
CDF/D0 inconsistency is significant



NLO fit without D0 data fits CDF o.k.
or
NLO fit to weighted D0 is below CDF

Under investigation by CDF/D0:
→ backgrounds, cut consistency, E_T scale, smearing, charge mis-id.

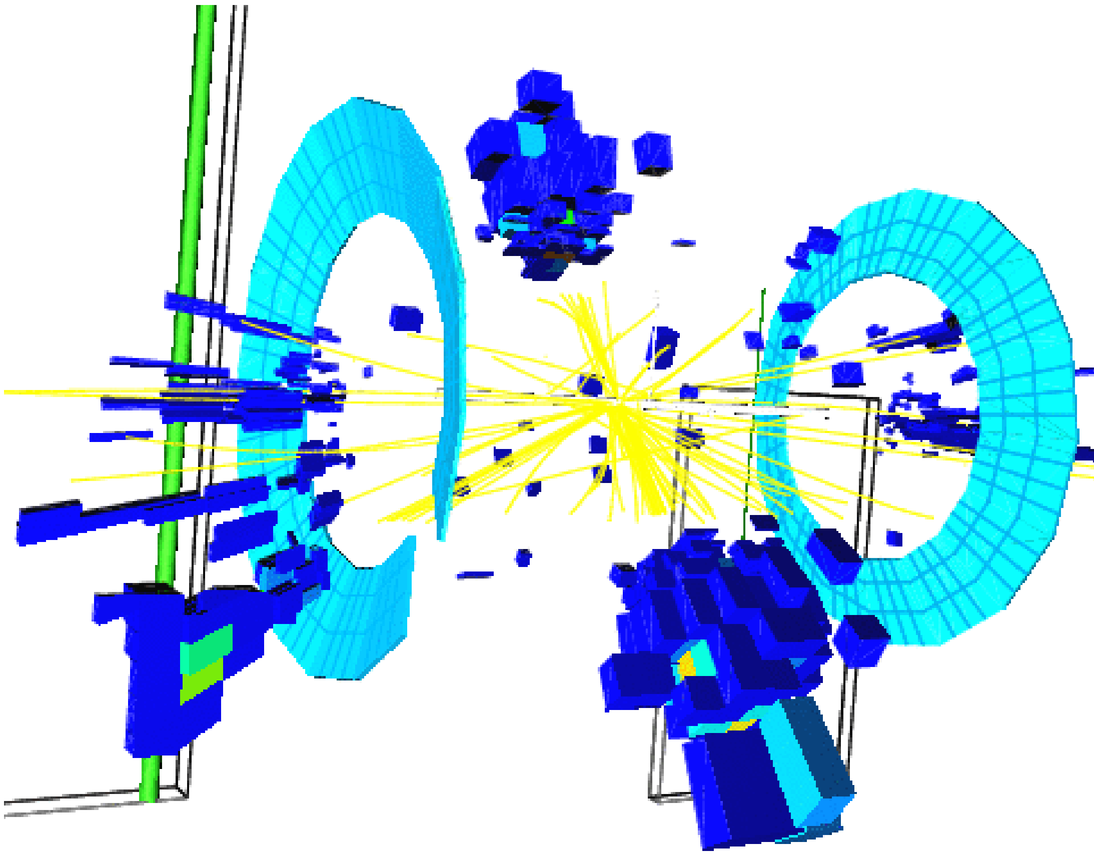
Jet Production

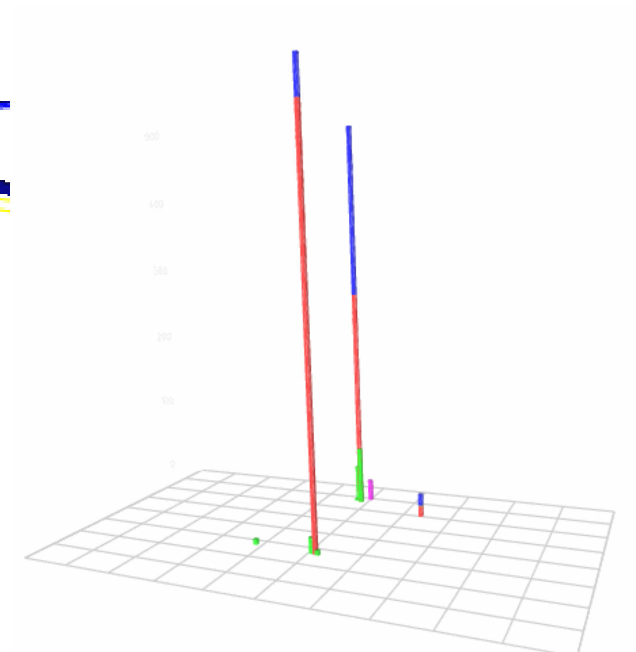


entering the TeV regime!

→ D0's highest p_T dijet in Run IIa

first jet	second jet
p_T = 624 GeV	p_T = 594 GeV
y_{jet} = 0.14	y_{jet} = -0.17
ϕ = 2.10	ϕ = 5.27
	M_{jj} = 1.22 TeV !





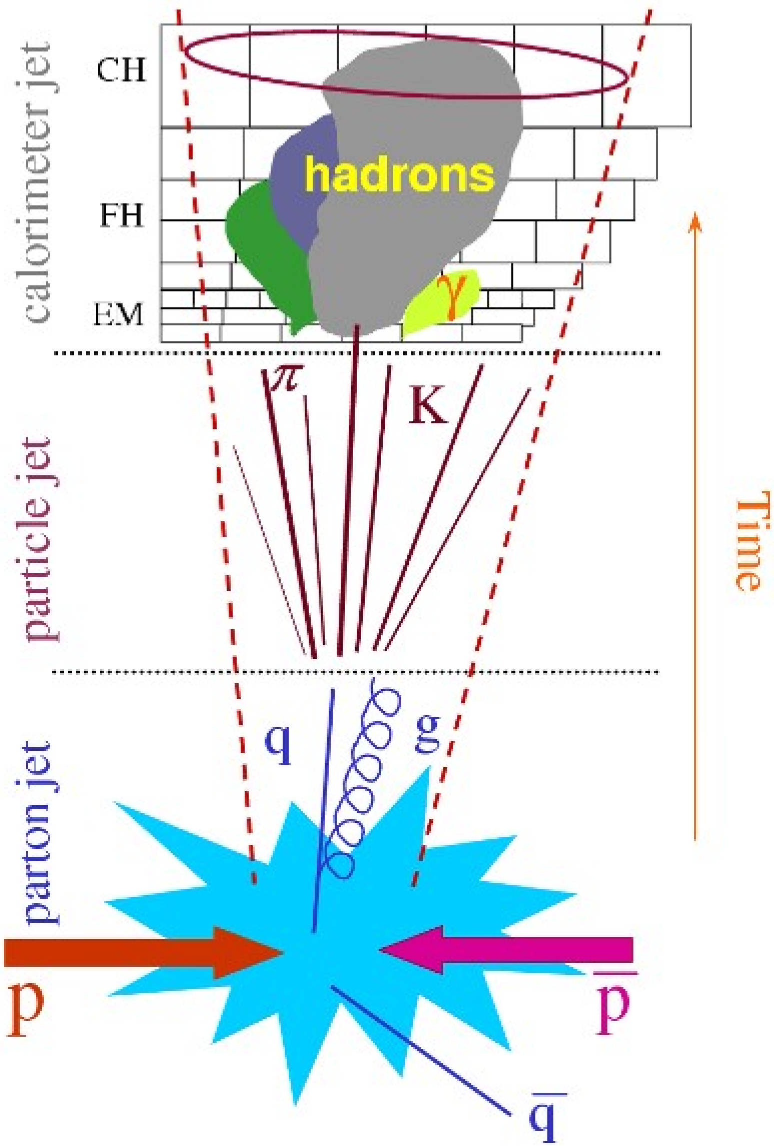
Biggest Misconception:

"A jet represents a parton
from the LO 2→ n parton process."

"The jet algorithm should find
this parton with high efficiency."

Nonsense!

Parton-, Hadron-, Detector- "Jets"



- Use Jet Definition to relate Observables defined on Partons, Particles, Detector

- Direct Observation:
  Energy Deposits / Tracks

- Stable Particles (=True Observable)

- Idealized: Parton-Jets
  no Observable (color confinement)
  only quantity to be predicted in pQCD

IR- and Collinear safe jet algorithms:
- TeV4LHC workshop
- Les Houches 2007 workshop

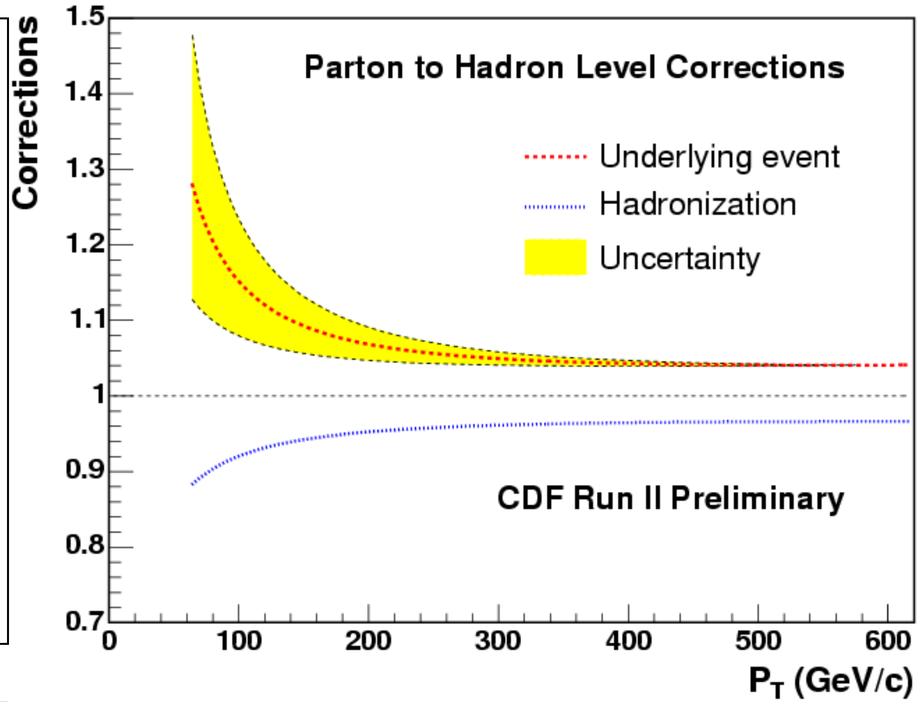
From Particle to Parton Level

- Measure cross section for pp-bar → jets (on "particle-level") corrected for experimental effects (efficiencies, resolution, …)

Use models to study effects of non-perturbative processes (PYTHIA, HERWIG)

- Hadronization correction
- Underlying event correction

CDF study for cone R=0.7 for central jet cross section

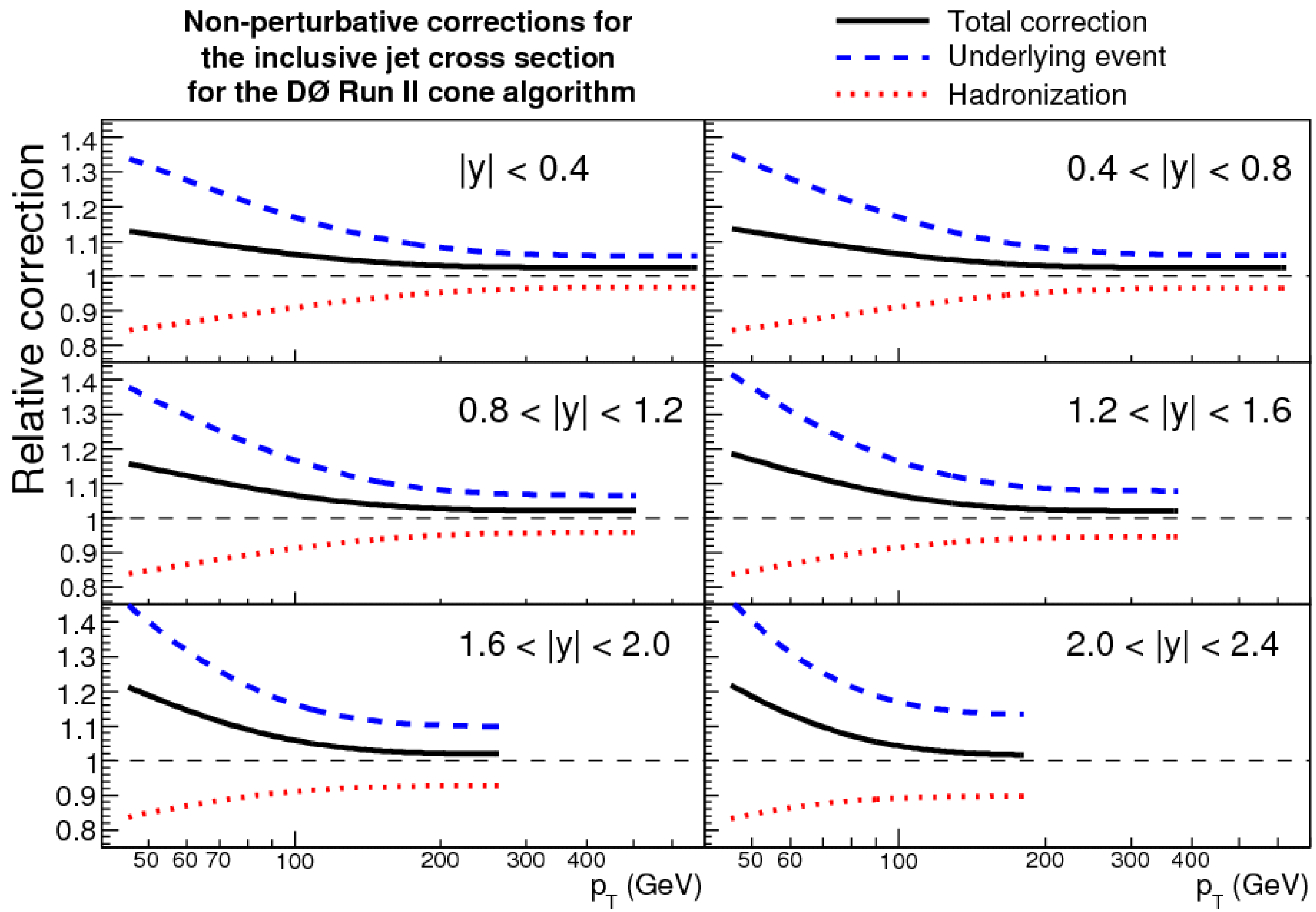


→ Apply this correction to the pQCD calculation
→ to be used for future MSTW/CTEQ PDF results
→ First time consistent theoretical treatment of jet data in PDF fits!

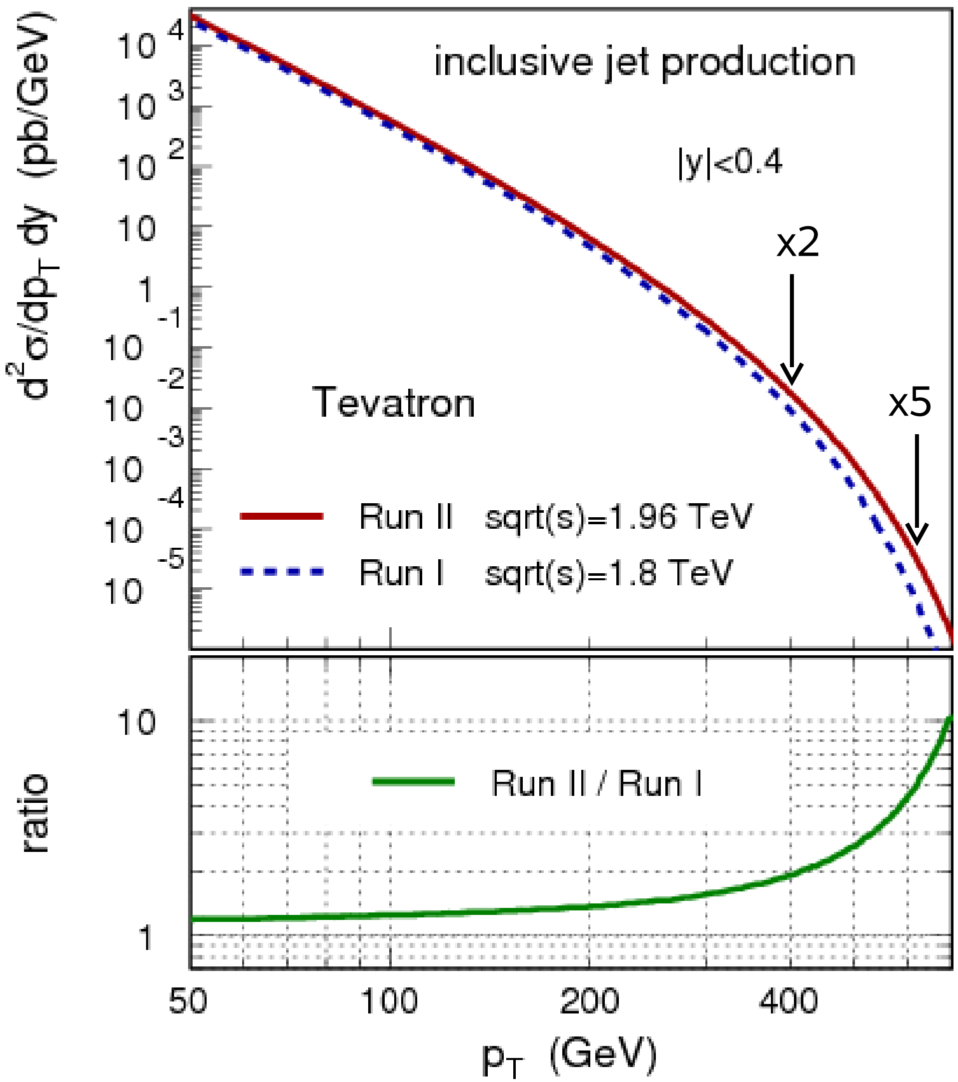
New in Run II !!!

Non-perturbative corrections

- Non-perturbative corrections from PYTHIA (tune QW) for D0's inclusive jet cross section vs. rapidity



Inclusive Jet Production



largest high pT cross section at a hadron collider
→ unique sensitivity

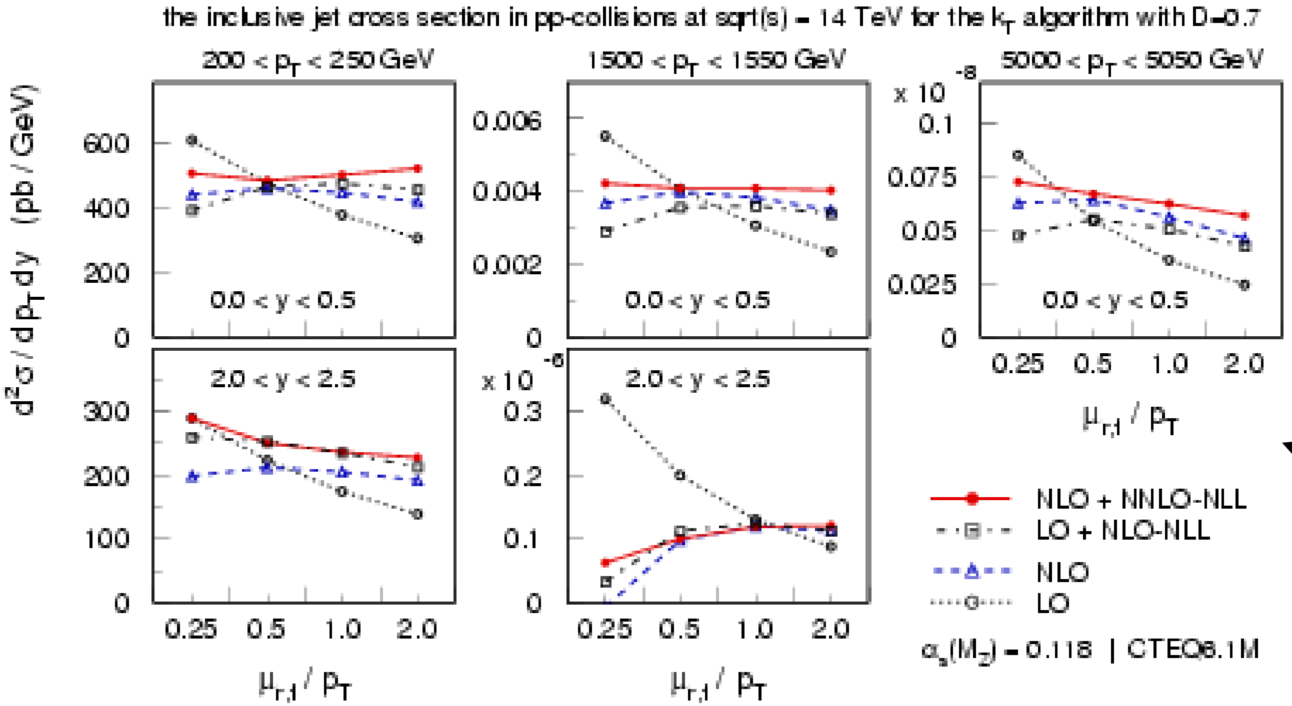
Run II: increased cross section by factor of 5 at pT=600GeV

→ sensitive to new physics:
Quark Compositeness,
Extra Dimensions,
…(?)…

Threshold Corrections

N. Kidonakis, J. Owens, Phys. Rev. D63, 054019 (2001)

- 2-loop threshold corrections to NLO calculation for inclusive jets
  → Significant Reduction of Scale Dependence

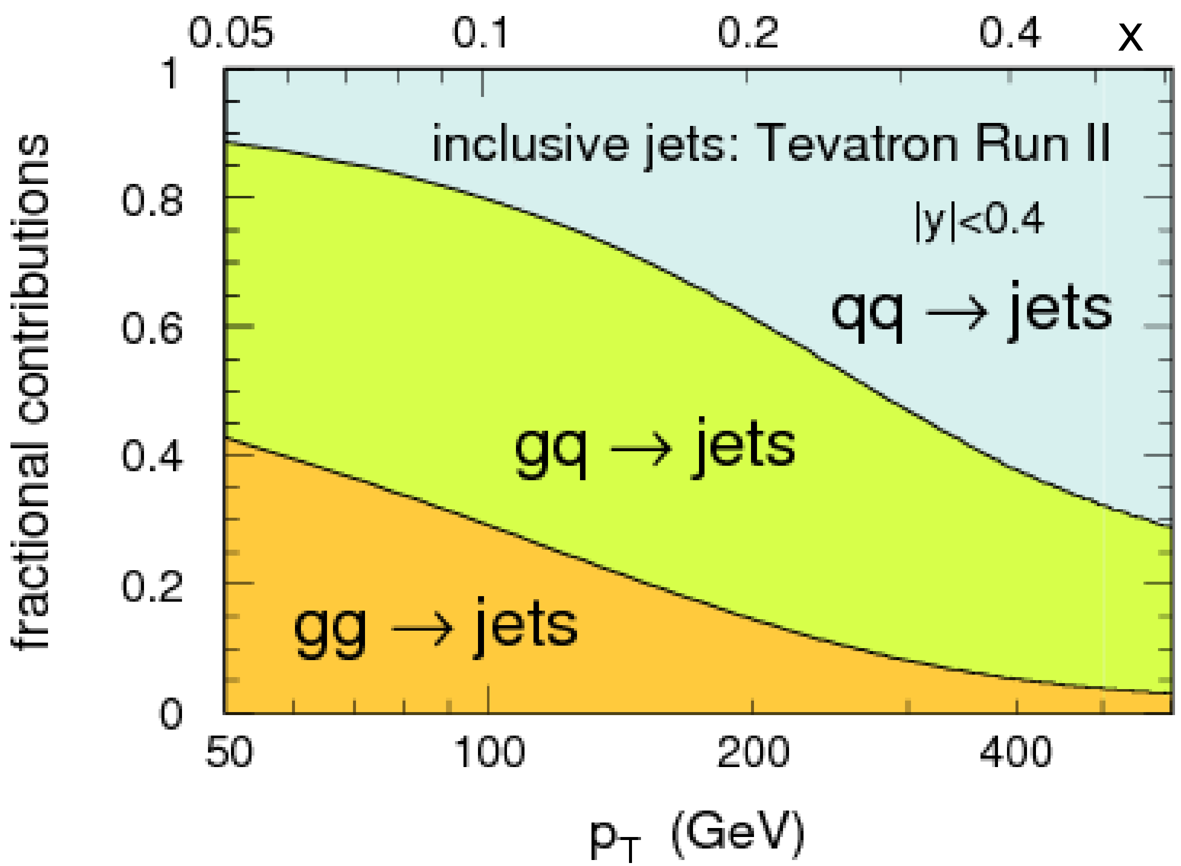


Example for Inclusive Jets at the LHC

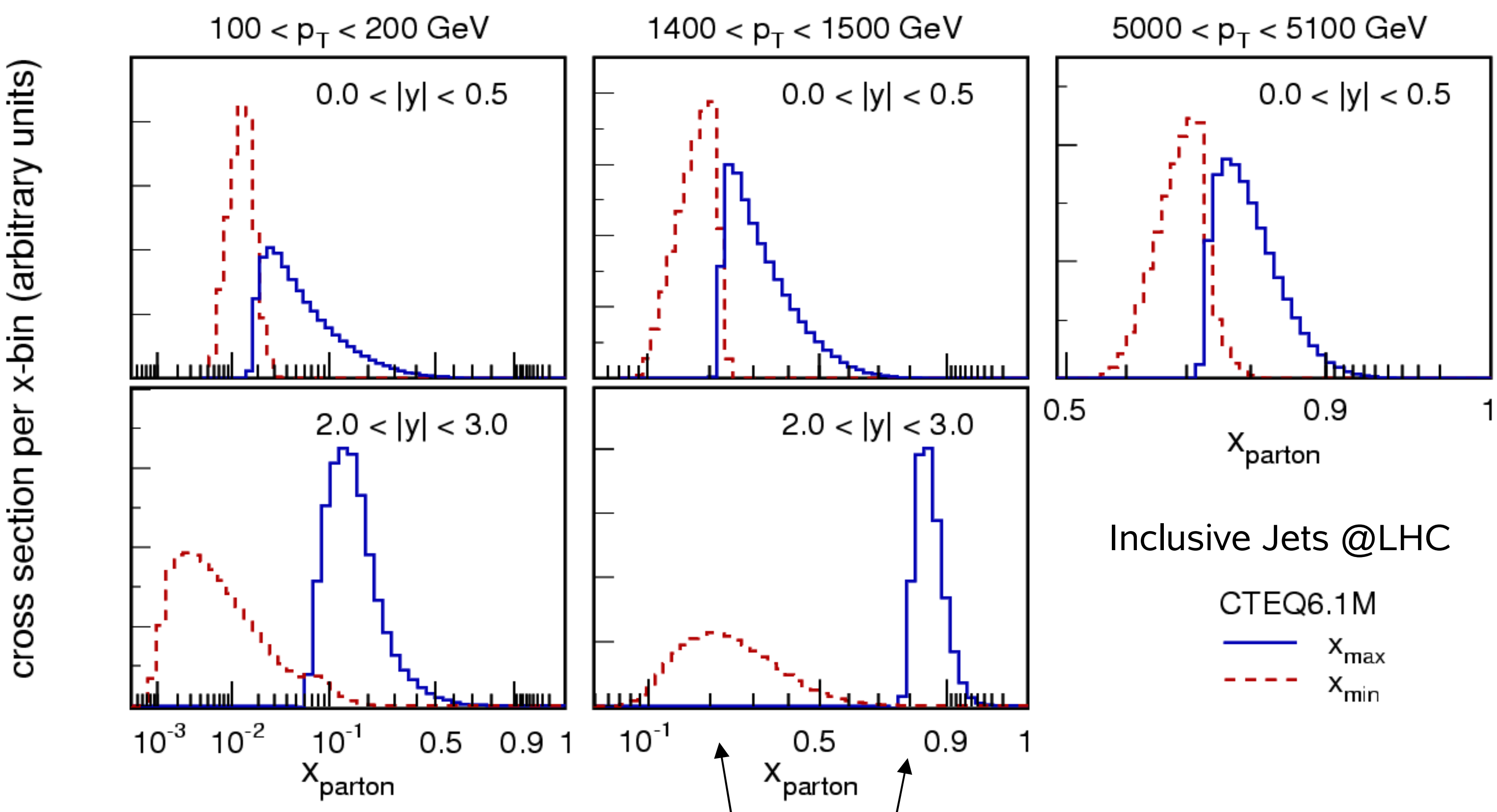
First step towards NNLO calculation
→ important for including inclusive jet data in NNLO PDF fits

Inclusive Jet Production

- theory @NLO is reliable (±10%)
  → sensitivity to PDFs
  → unique: high-x gluon



x distributions

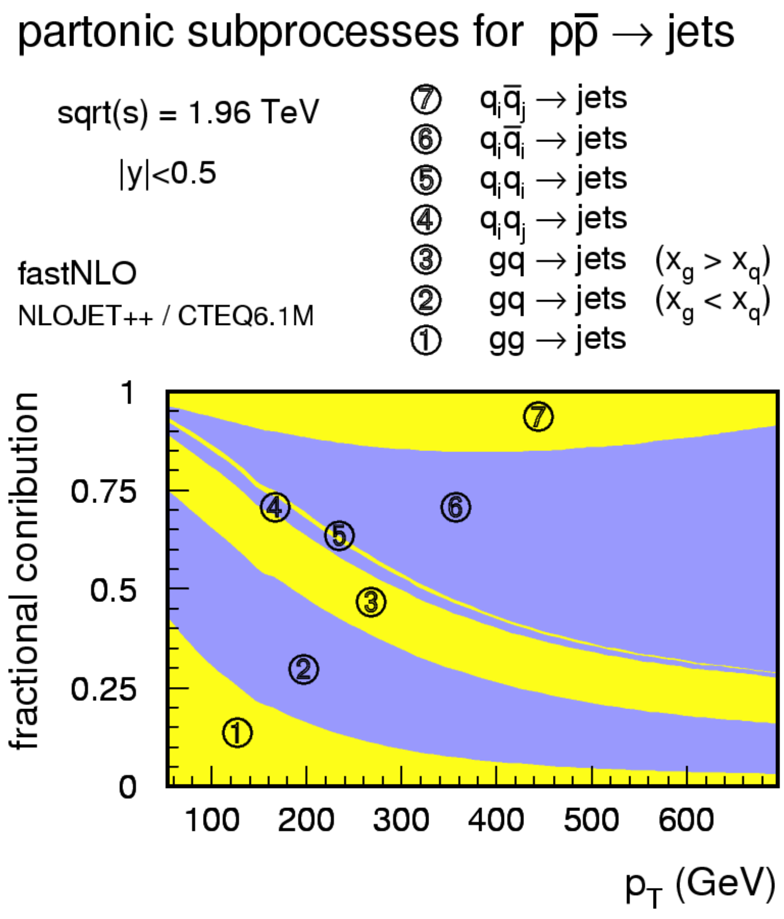


In the forward region, x1 and x2 can be very different

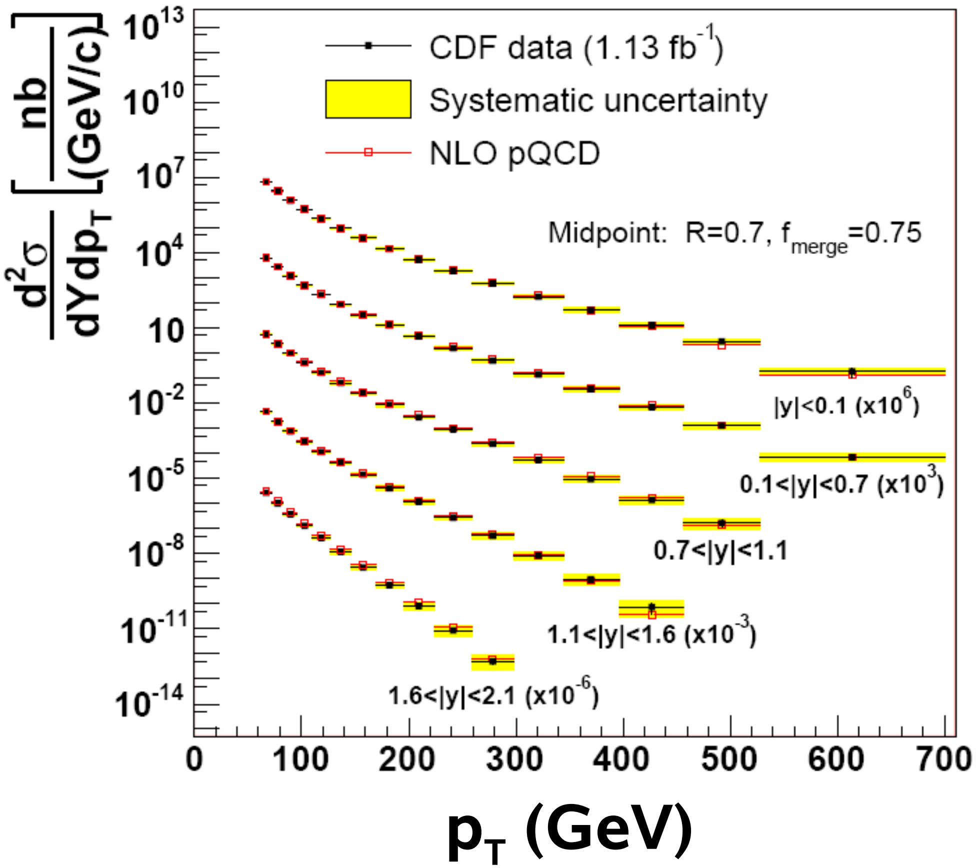
Partonic Subprocesses

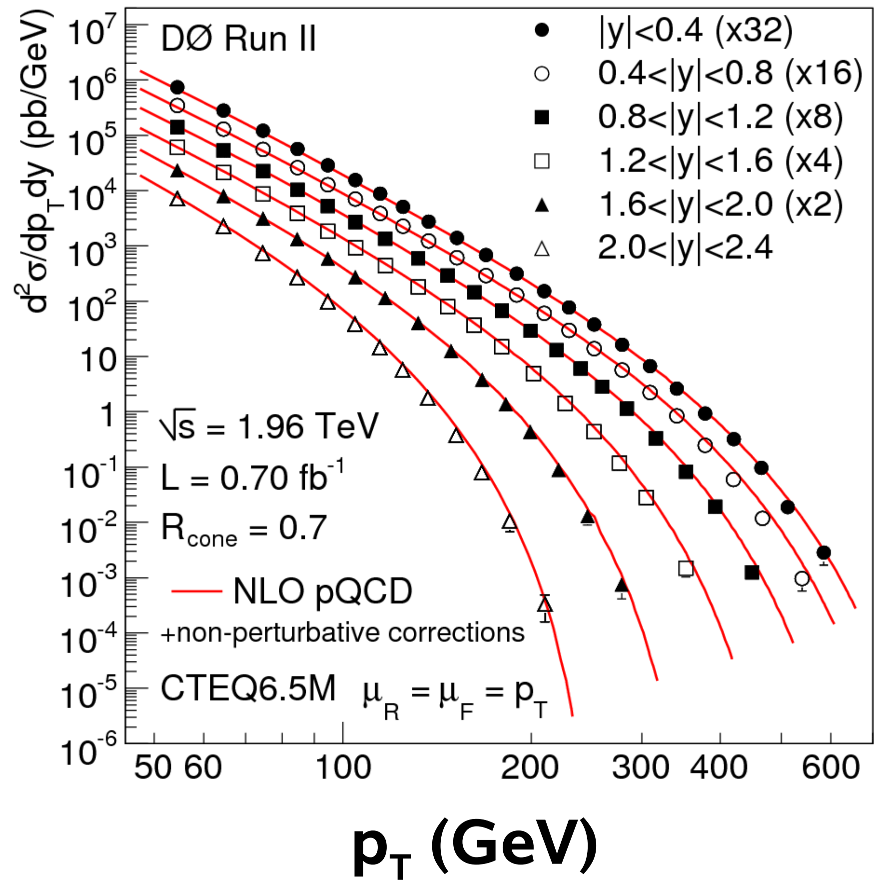
Seven Relevant Partonic Subprocesses:

$$
\begin{array}{llllll}
gg \longrightarrow \text{jets} & & & & \propto & H_1(x_1,x_2) \\
qg \longrightarrow \text{jets} & \text{plus} & \bar{q}g \longrightarrow \text{jets} & & \propto & H_2(x_1,x_2) \\
gq \longrightarrow \text{jets} & \text{plus} & g\bar{q} \longrightarrow \text{jets} & & \propto & H_3(x_1,x_2) \\
q_iq_j \longrightarrow \text{jets} & \text{plus} & \bar{q}_i\bar{q}_j \longrightarrow \text{jets} & & \propto & H_4(x_1,x_2) \\
q_iq_i \longrightarrow \text{jets} & \text{plus} & \bar{q}_i\bar{q}_i \longrightarrow \text{jets} & & \propto & H_5(x_1,x_2) \\
q_i\bar{q}_i \longrightarrow \text{jets} & \text{plus} & \bar{q}_iq_i \longrightarrow \text{jets} & & \propto & H_6(x_1,x_2) \\
q_i\bar{q}_j \longrightarrow \text{jets} & \text{plus} & \bar{q}_iq_j \longrightarrow \text{jets} & & \propto & H_7(x_1,x_2)
\end{array}
$$



Inclusive Jets





steeply falling pT spectrum:

1% error in jet energy calibration

→ 5—10% (10—25%)

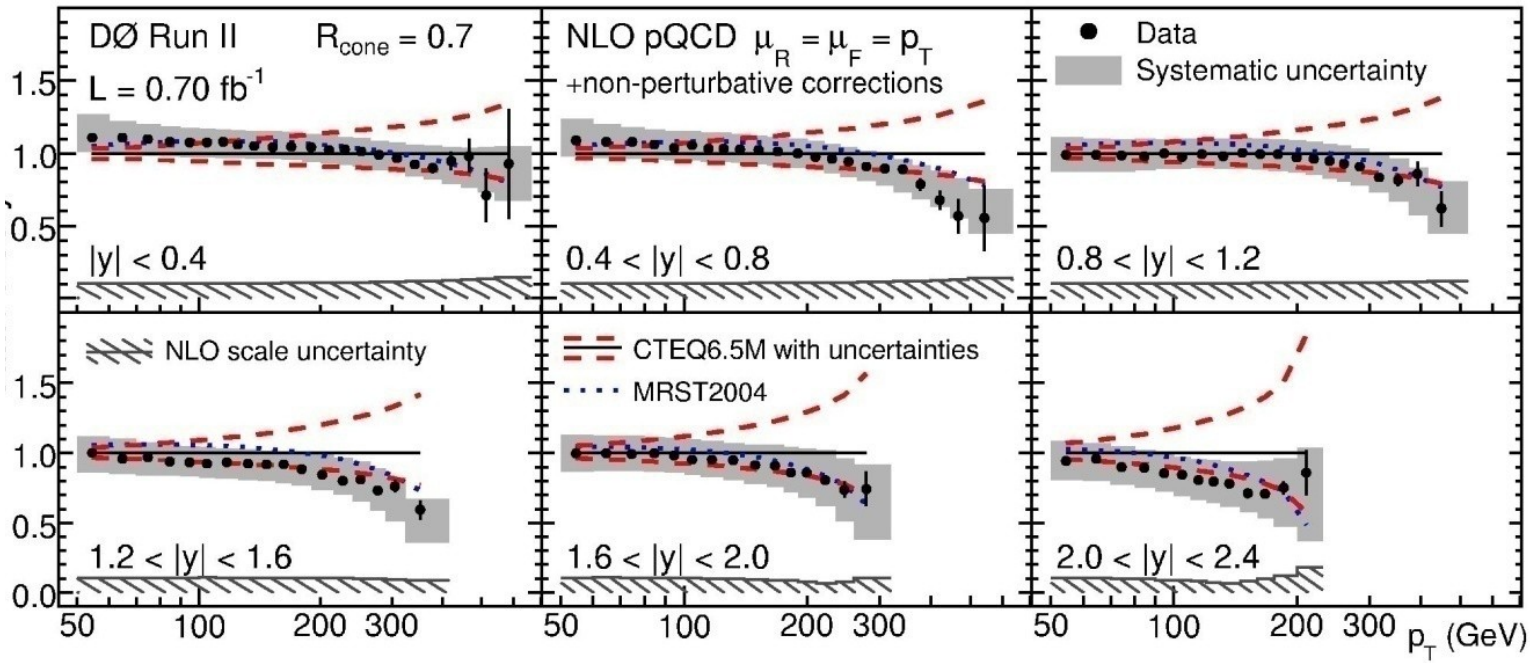
central (forward) x-section

benefit from:

- high luminosity in Run II
- increased Run II cm energy → high pT
- hard work on jet energy calibration

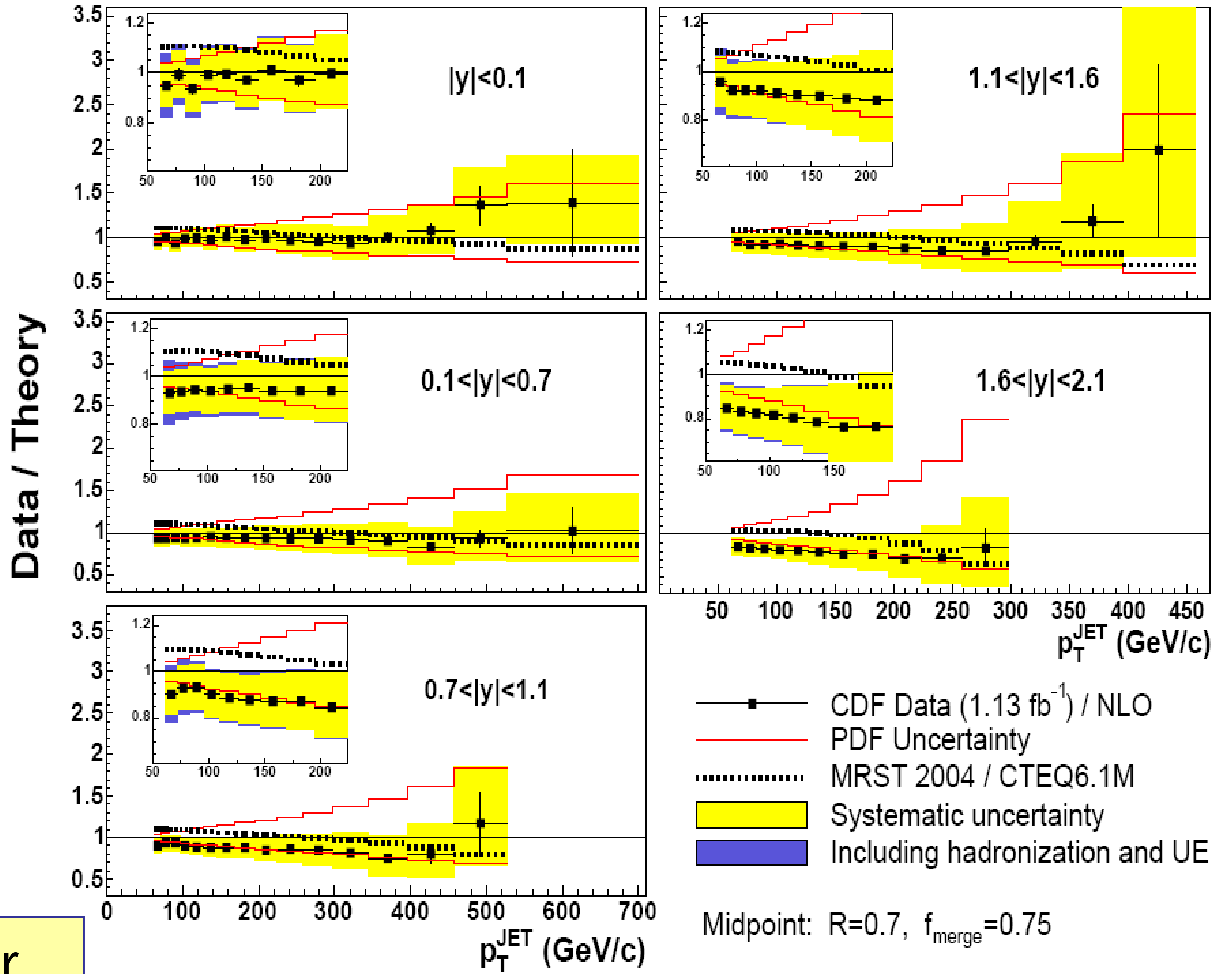
Inclusive Jets

D0 data / theory



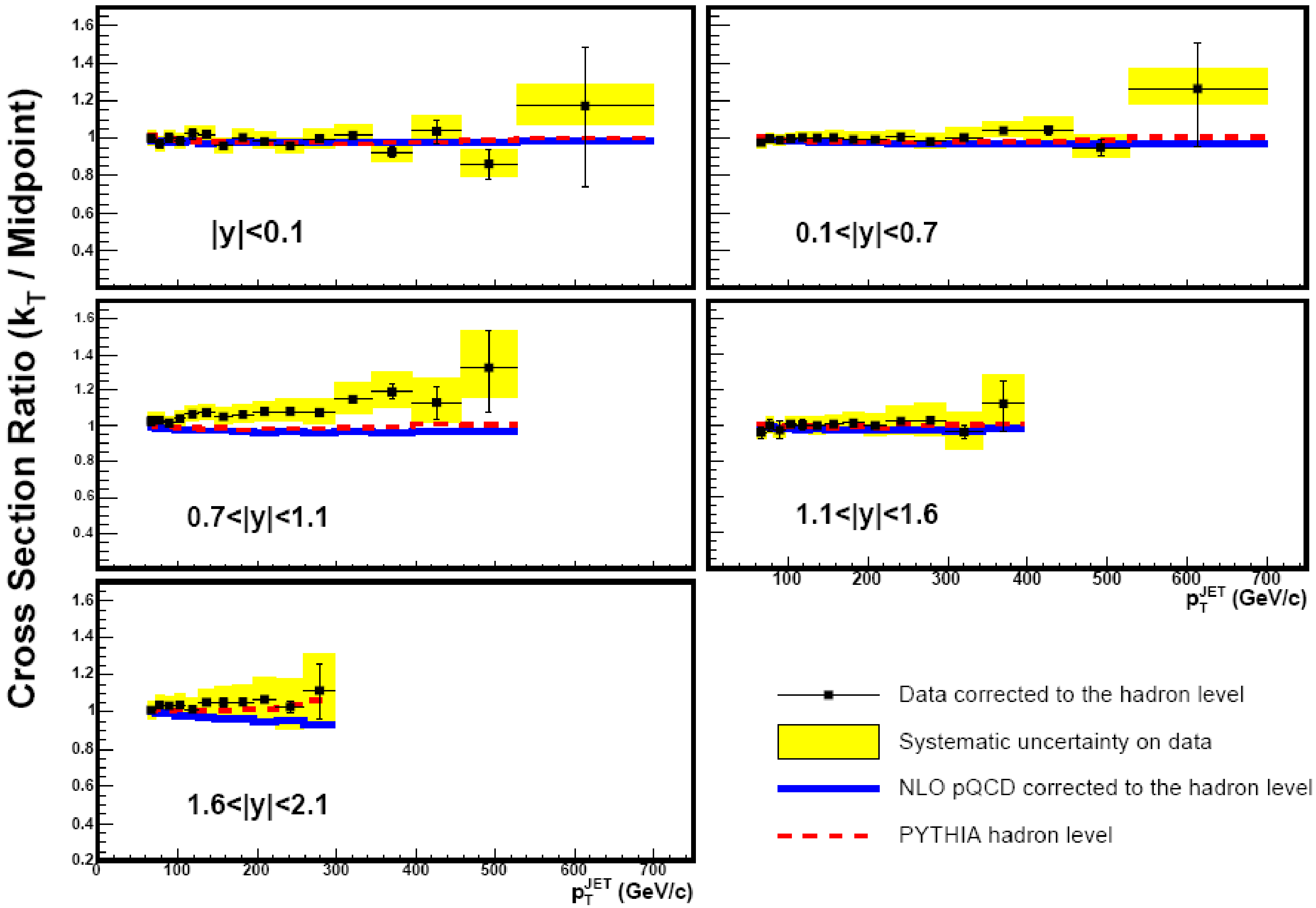
- consistent with NLO pQCD theory
- experimental uncertainties: smaller than PDF uncertainties!
- data favor lower edge of CTEQ6.5
  PDF uncertainties at high p_T
- shape well described by

Inclusive Jets



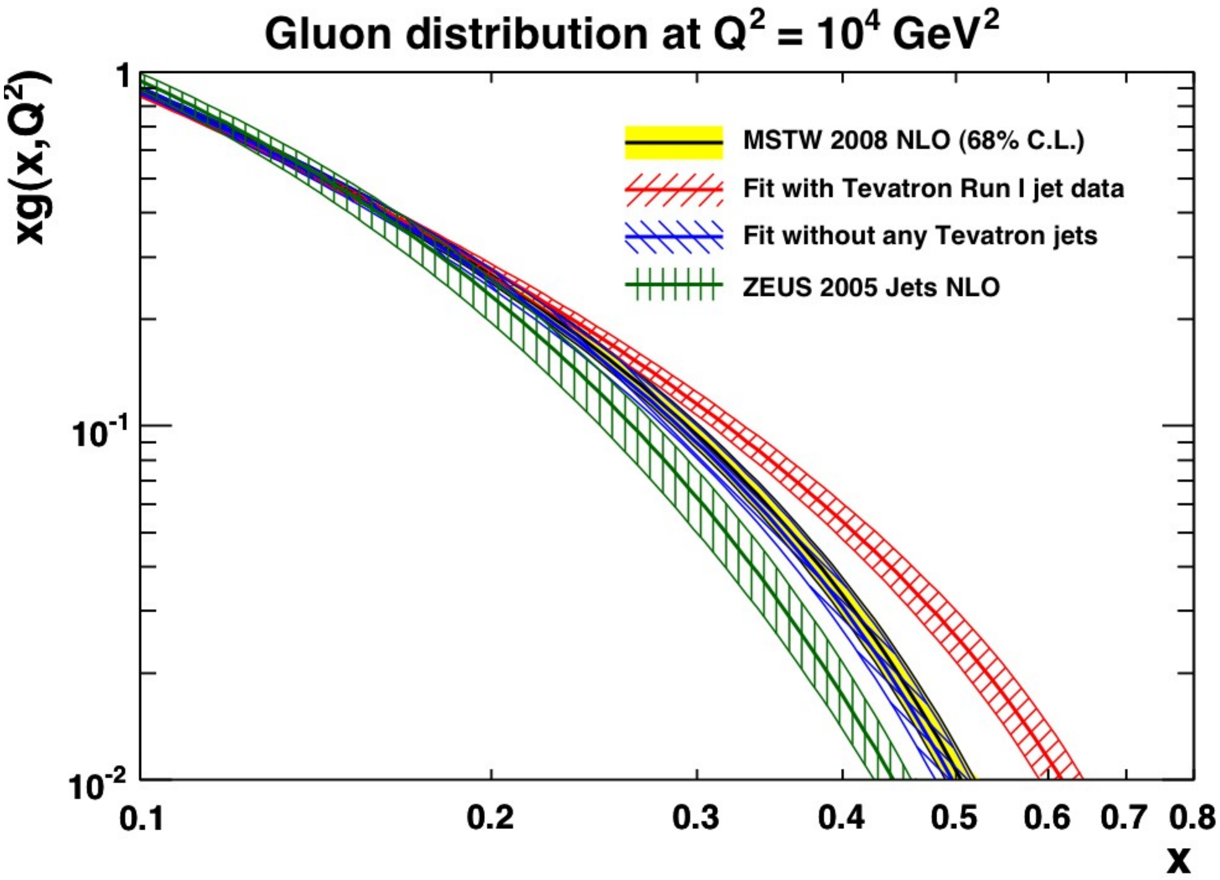
- CDF/D0 data have similar experimental uncertainties
- CDF/D0 data are consistent

Inclusive Jets: Cone vs. kT Algorithms



CDF result for cone algorithm
is consistent with CDF kT result

Impact of Jet Data on Gluon

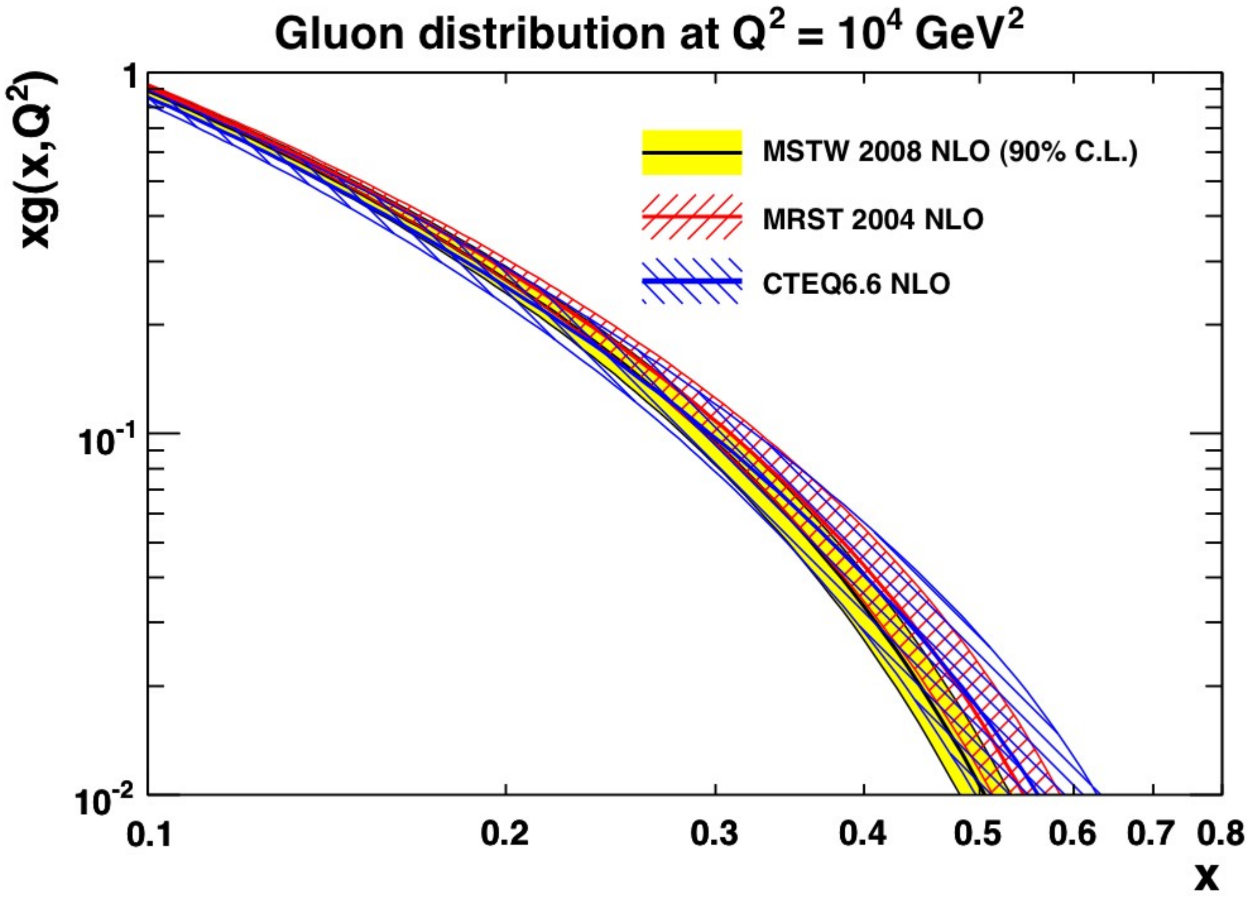


New jet data prefer a lower high-x gluon as compared to previous fits (and data)

Consistent with fit without jet data

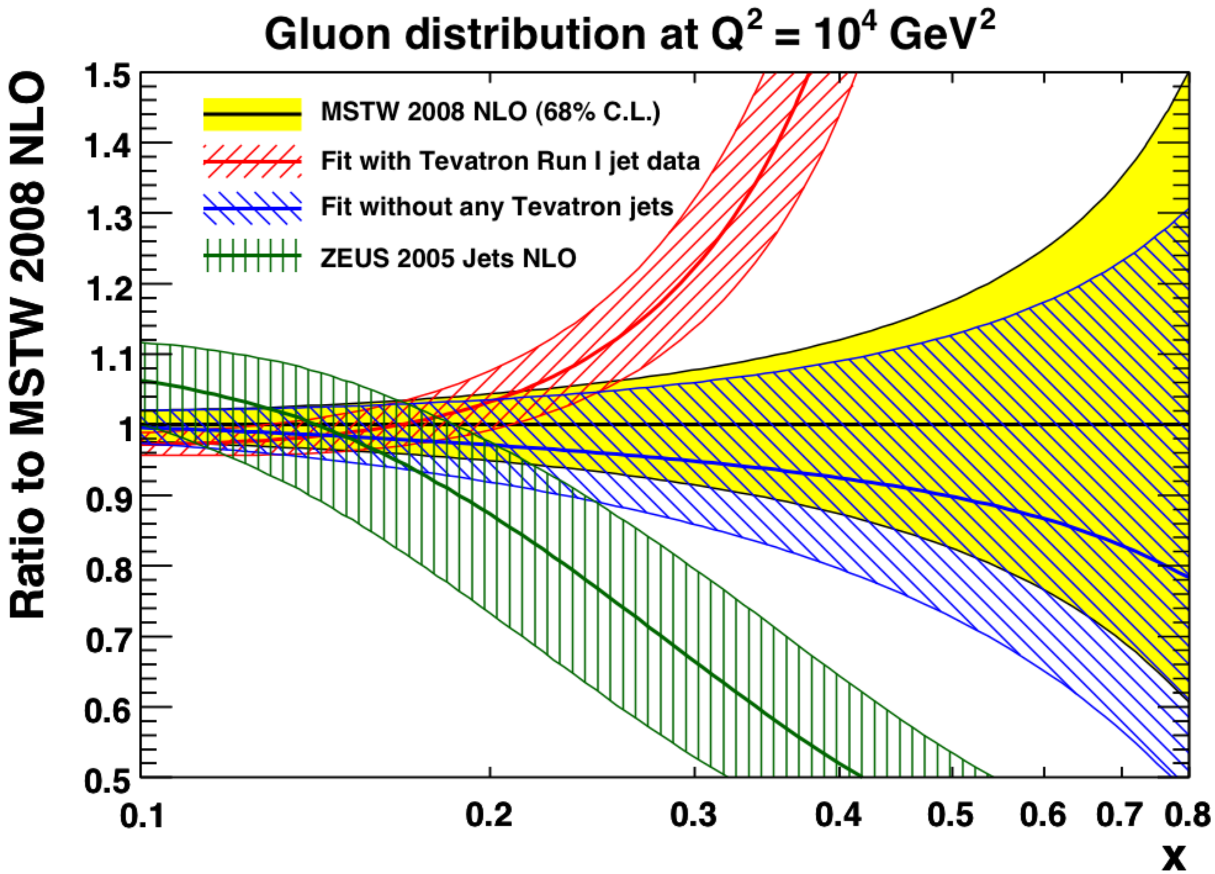
ZEUS-fit is still softer

Impact of Jet Data on Gluon



→ Differences between MSTW2008 NLO and CTEQ6.6 NLO

Impact of Jet Data on Gluon



Differences at x>0.3

Fit to Run I data gave higher gluon

Uncertainty still large
→ No significant improvements

- Still expect factor 8 more luminosity → reduce statistical errors at high pT
- Don't expect significant improvements in systematics (high lumi running)

Question

What if there was new physics at high pT?

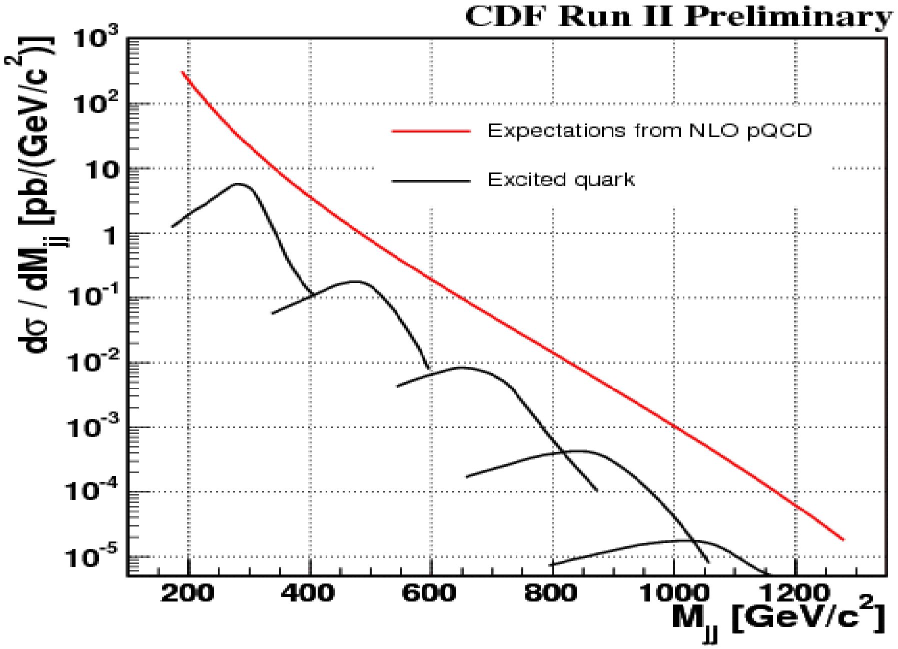
Important to check, otherwise we may absorb these contributions into the high-x PDFs!

study further dijet properties:
→ mass and scattering angle

Dijet Mass Distribution

central dijet production |y|<1

- test pQCD predictions
- sensitive to new particles decaying into dijets: excited quarks, Z', W', Randall-Sundrum gravitons, color-octet technirho, axigluons, colorons



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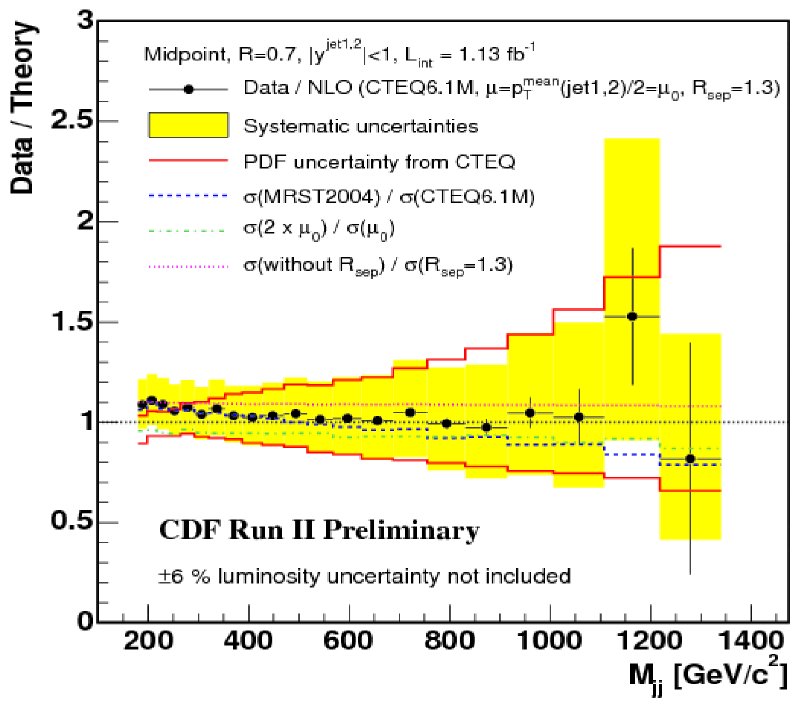
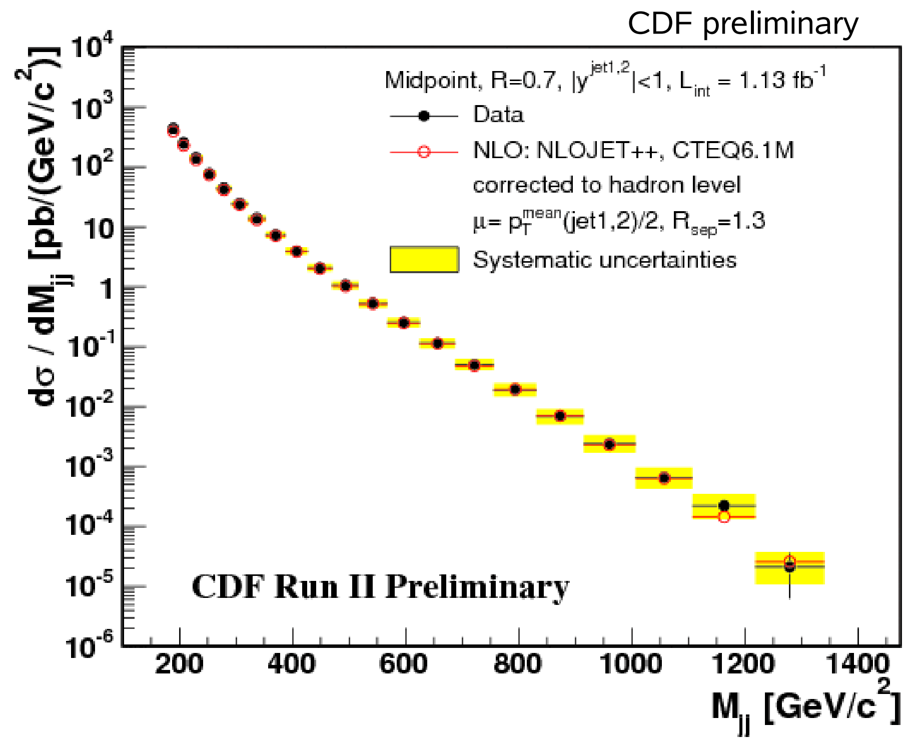
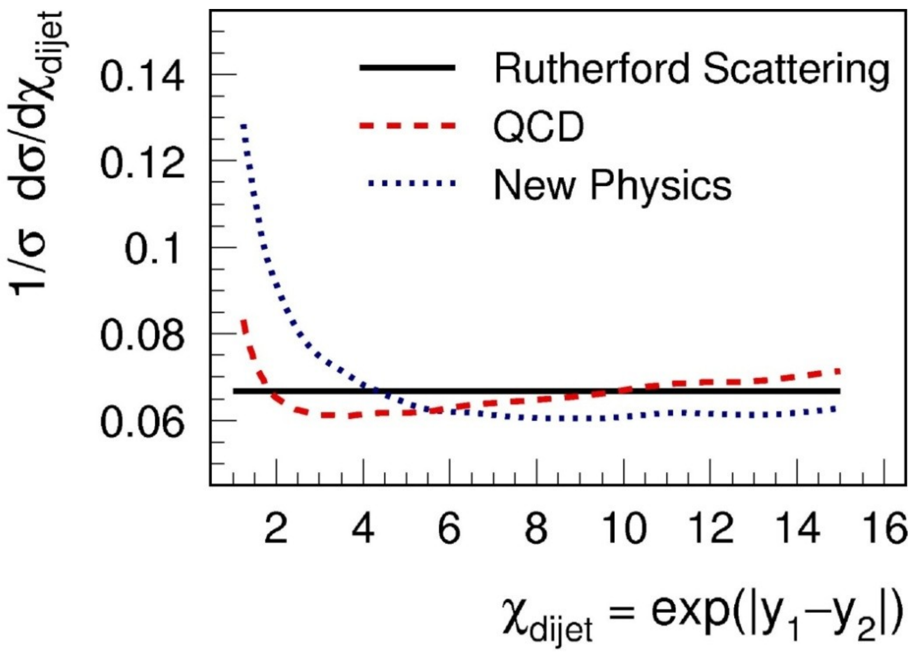




→ data with Mjj > 1.2TeV!
→ all described by NLO pQCD
→ no indications for resonances

Dijet Angular Distribution



variable: $\chi_{\mathrm{dijet}} = \exp(|y_1 - y_2|)$

at LO, related to CM scattering angle

$$\chi_{\mathrm{dijet}} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

- flat for Rutherford scattering
- slightly shaped in QCD
- enhancement at low χ_{dijet}
  → new physics, e.g.:
  - quark compositeness
  - extra spatial dimensions
- not sensitive to PDFs

→ normalized distribution $\frac{1}{\sigma}\frac{d\sigma}{d\chi_{\mathrm{dijet}}}$

→ reduced experimental and theoretical uncertainties

Dijet Angular Distribution

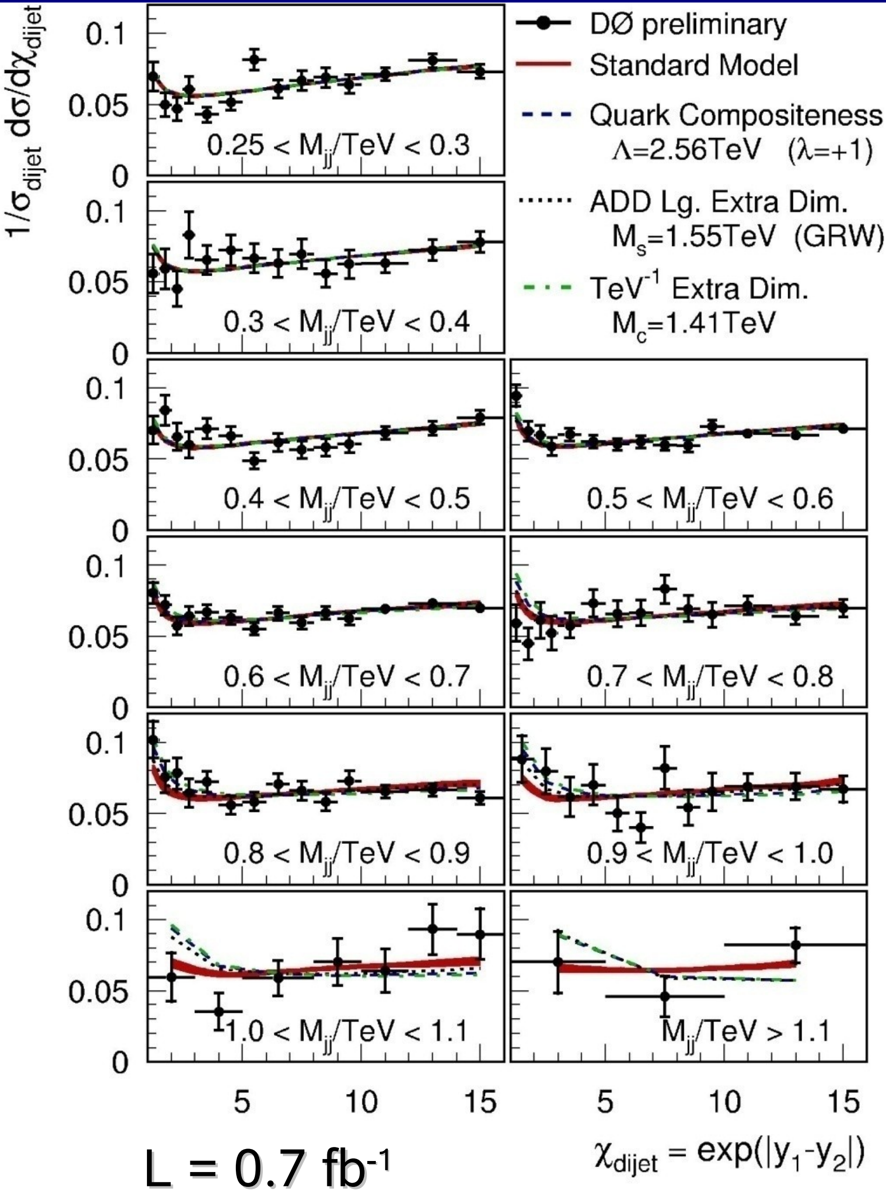
first measurement of angular distributions of a scattering process above 1 TeV

at highest dijet mass data still agree with standard model predictions

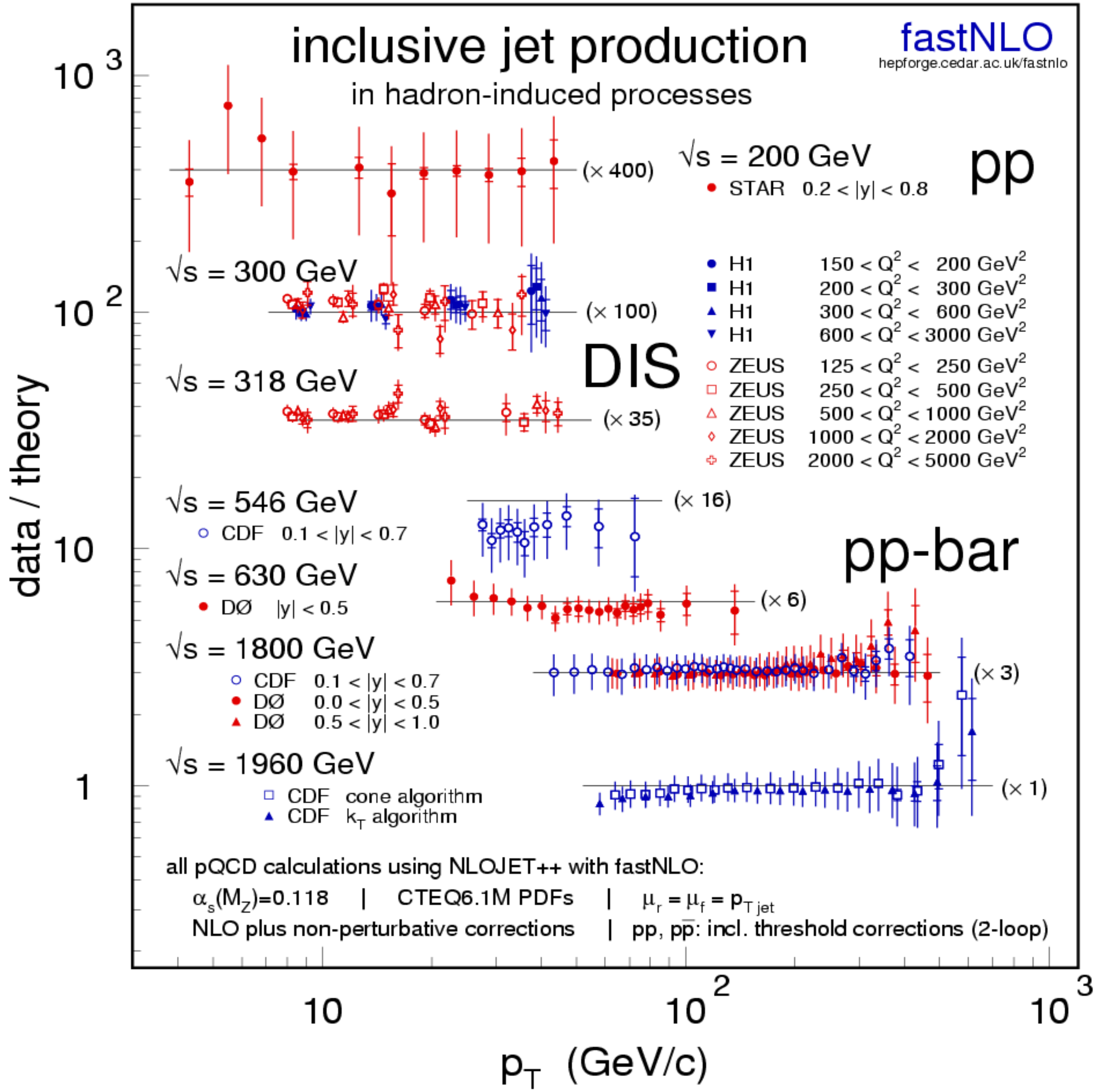
→ set limits on new phenomena:

- Quark Compositeness
- TeV-1 Extra Dimensions
- ADD Large Extra Dimensions

No indications for any deviations from the Standard Model



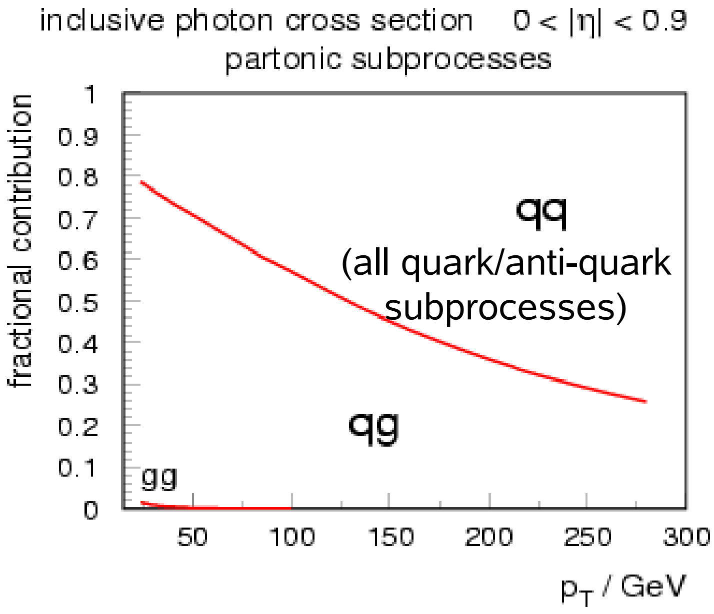
Jet world data



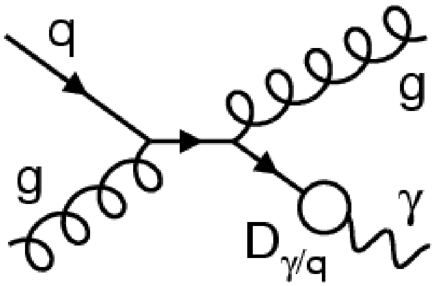
Other Processes

Direct Photon Production

direct photons come unaltered from the hard subprocess
→ direct probe of the hard scattering dynamics
→ sensitivity to PDFs (gluon!) …but only if theory works

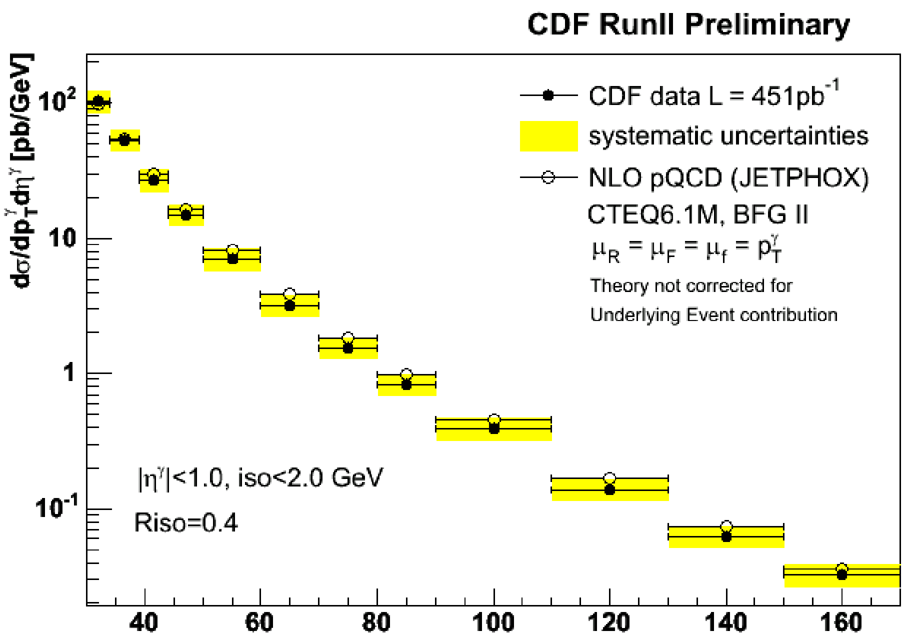


also fragmentation contributions:

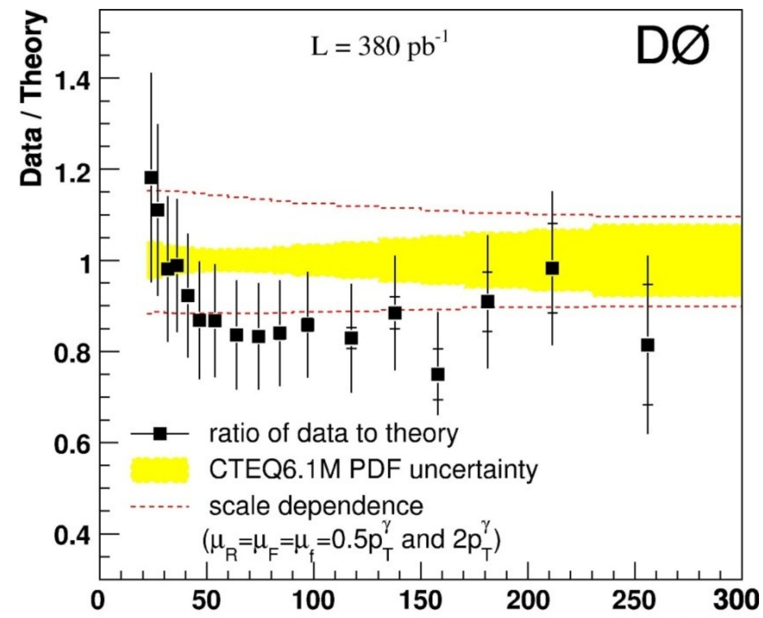


suppress by isolation criterion
→ observable: **isolated** photons

Incl. Isolated Photons



p_T^γ (GeV)



p_T^γ (GeV)

- CDF and D0 measurements: 20<pT<300GeV → agreement
- data/theory: different shape at low pT
- experimental and theory uncertainties > PDF uncertainty
  → no PDF sensitivity yet
- first: need to understand discrepancies in shape

Isolated Photon + Jet

investigate source for disagreement

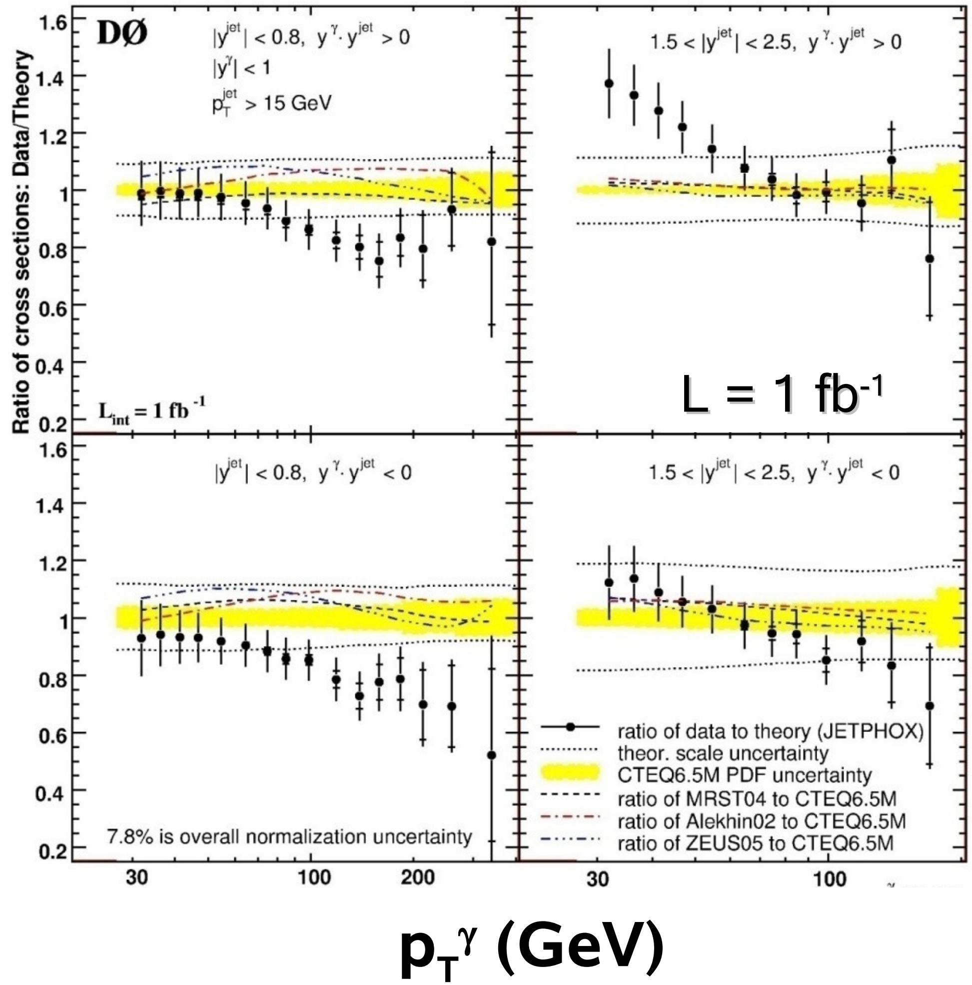
→measure more differential:

- tag **photon and jet**
  → reconstruct full event kinematics

- measure in 4 regions of y^{γ} / y^{jet}
  - photon: central
  - jet: central / forward
  - same side / opposite side

discrepancies if data/theory
→ figure out what is missing…
- higher orders?
- resummation?
- …???

DØ, arXiv: 0804.1107 [hep-ex]

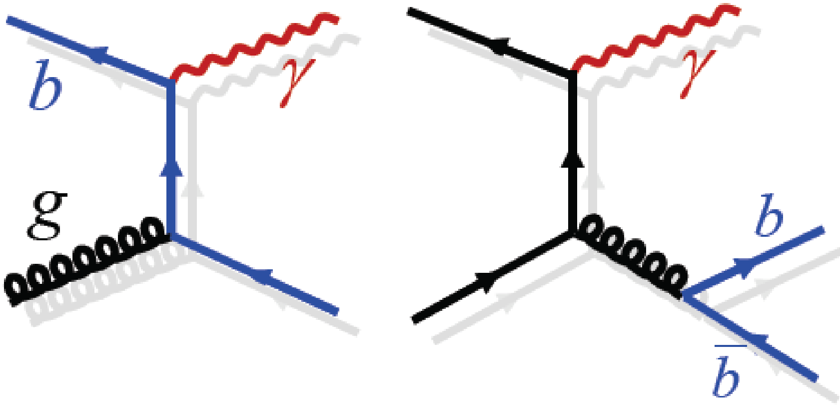


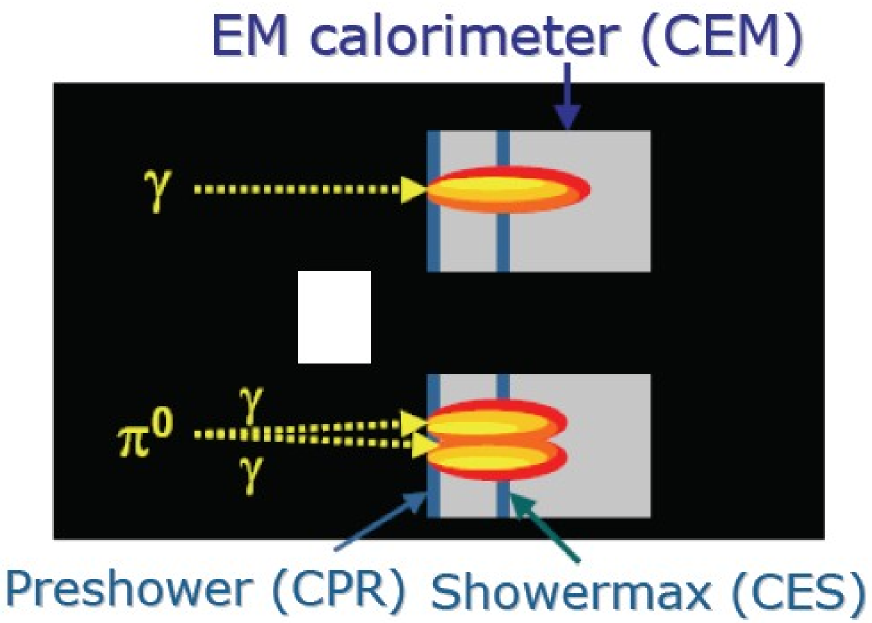
see talk by K. Hatakeyama for new D0 results on "isolated photon + heavy flavor jet production"

Isolated Photon + b-Jet

Motivation:

- Sensitive to b-quark content of proton
- Background to many new physics processes
  - Technicolor $\omega_{TC} \to \gamma\pi_{TC} \to \gamma b\bar{b}$
  - SUSY, e.g. $\tilde{\chi}_i^+ \tilde{\chi}_2^0, \tilde{\chi}_i^\pm \to \tilde{t}\, b \to bc\tilde{\chi}_1^0, \tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$
  - 4th generation, excited b-quark

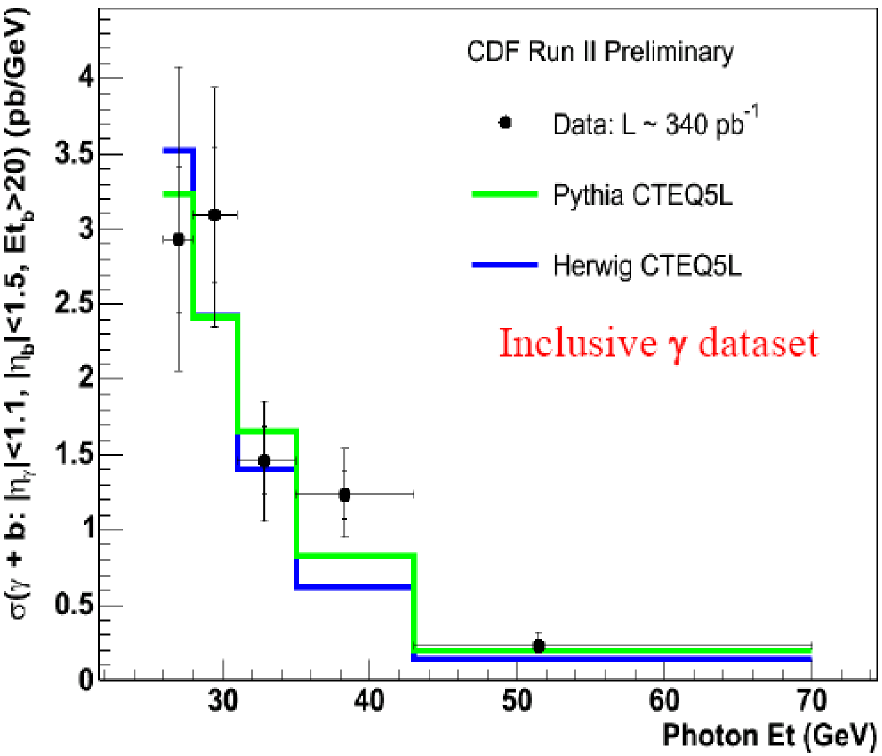


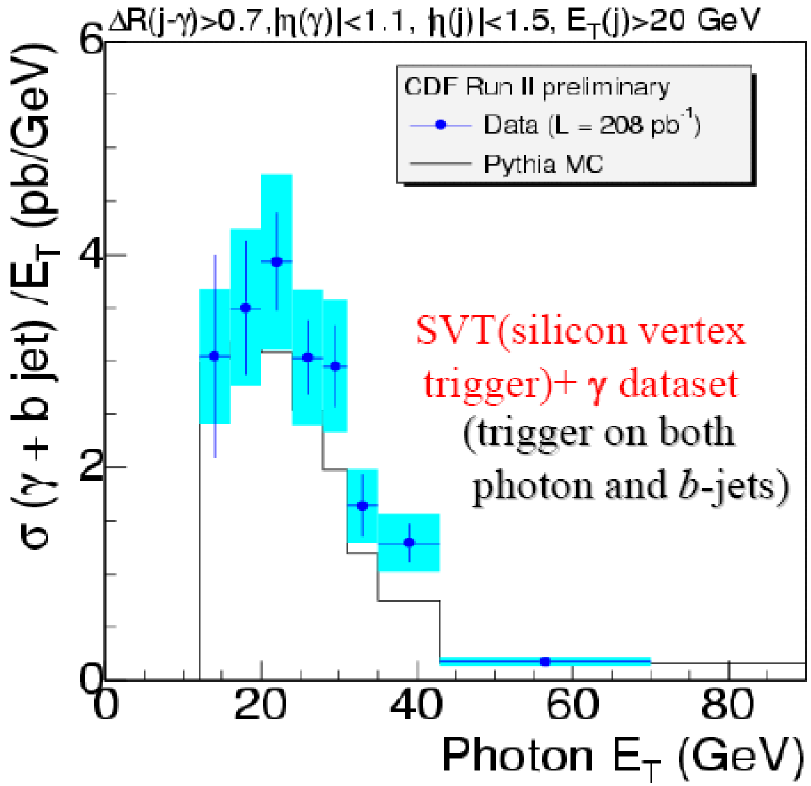


Strategy:

- Photon identification
  statistical separation from pions based on measured shower shapes
- B-jet identification
  tight secondary vertex tagging

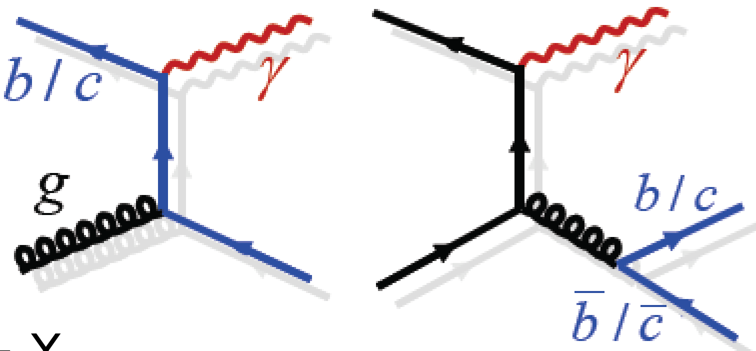
Isolated Photon + b-Jet





Reasonably well described by PYTHIA (LO)
→ Waiting for NLO pQCD result

Isolated Photon + HF Jet



Photon + (b/c) jet + X

Photon pT: 30-150 GeV

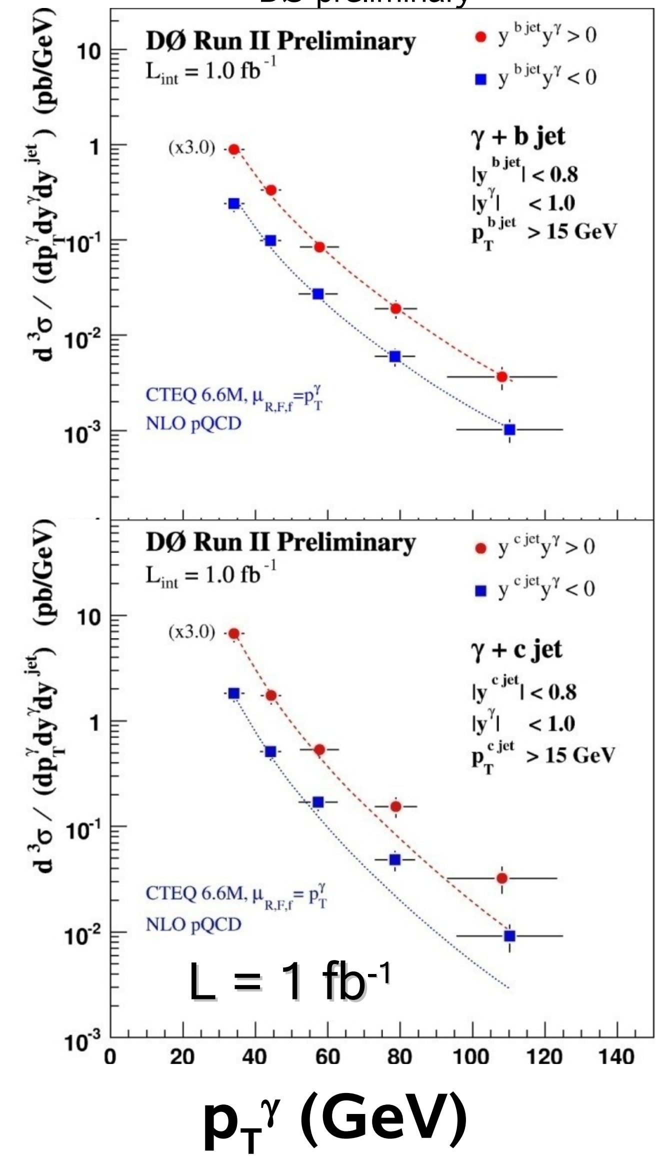
0.01<x<0.3 → b, c, gluon PDF

tag **photon and jet**

Rapidities: $|y^{\gamma}| < 1.0$ $|y^{\text{jet}}| < 0.8$

→ triple differential $\mathrm{d}^3\sigma/(\mathrm{d}p_T^{\gamma}\mathrm{d}y^{\gamma}\mathrm{d}y^{\text{jet}})$

DØ preliminary

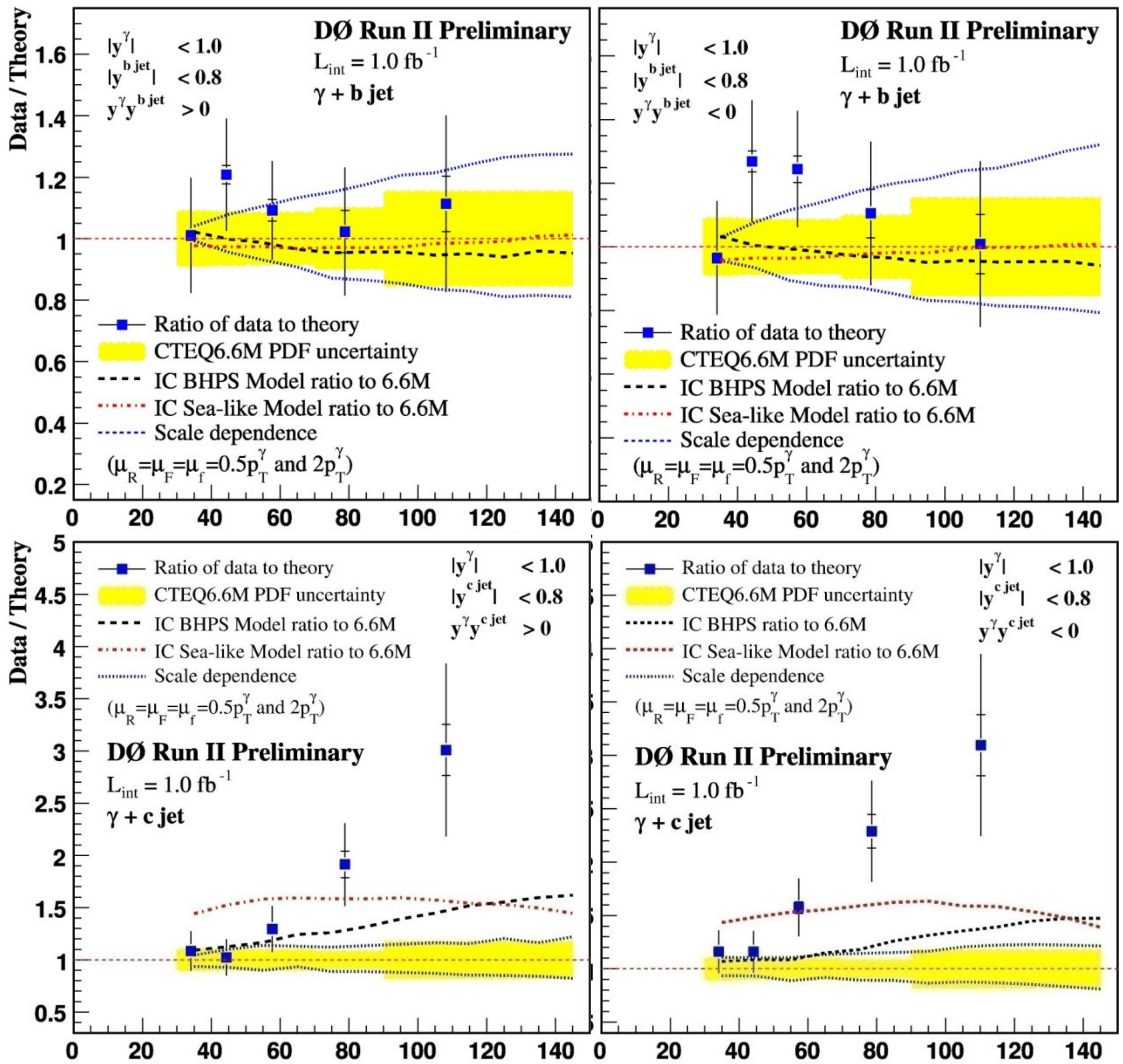


Isolated Photon + HF Jet

DØ preliminary

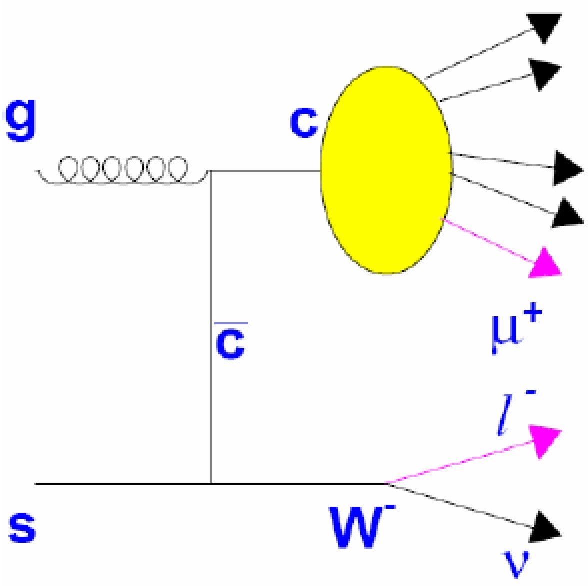
→ photon+b:
agreement over full
pT range: 30-150 GeV
→ no PDF sensitivity

→ photon+c:
- agree only at pT<50GeV
- disagreement increases with photon pT
- using PDF including intrinsic charm (IC) improves the theory pT dependence



L = 1 fb^{-1} p_T^γ (GeV)

$W^{\pm}$ + single c-jet



- strange quark PDF at rather large Q^2
  - PDF fits so far: no direct input on the strange quark density
  - strange quark-PDF errors are small because: s=(u-sea +d-sea)/2
  - this small uncertainty is fake
    → does not reflect true uncertainty
- sensitive to $|V_{cs}|$
- Part of W+jets bkgd to top, Higgs searches

Here: First Measurements of $W^{\pm}$+c

$W^{\pm}$ + single c-jet

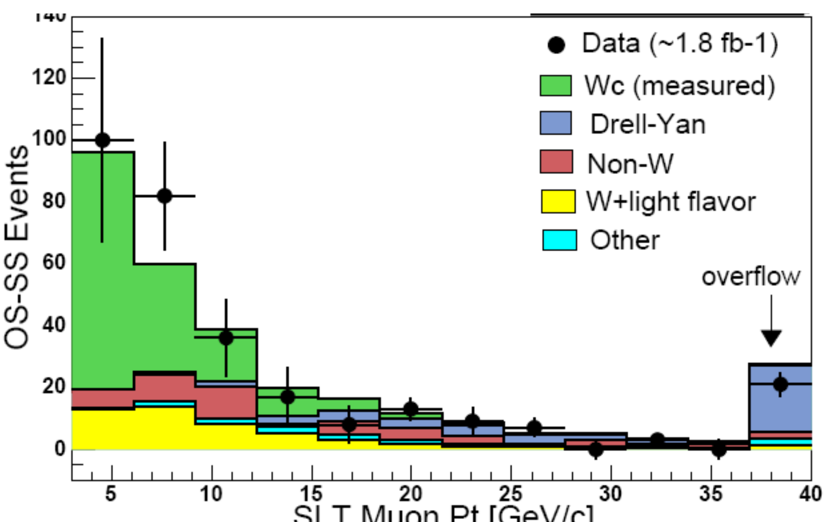
Phys. Rev. Lett. 100, 091803 (2008)

Subm. to Phys. Lett. B - arXiv:/0803.2259 [hep-ex]

$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = \frac{N^{\mathrm{OS-SS}}_{\mathrm{Tot}} - N^{\mathrm{OS-SS}}_{\mathrm{Bkg}}}{A \cdot \mathrm{L}}$$

σ x BR

- **CDF:** for $p_T^c > 20$ GeV, $|\eta^c|<1.5$
  9.8 ± 2.8 (stat) $^{+1.4}_{-1.6}$(syst) ± 0.6 (lum) pb
- NLO prediction (MCFM):
  σ x BR = 11.0 $^{+1.4}_{-3.0}$ pb

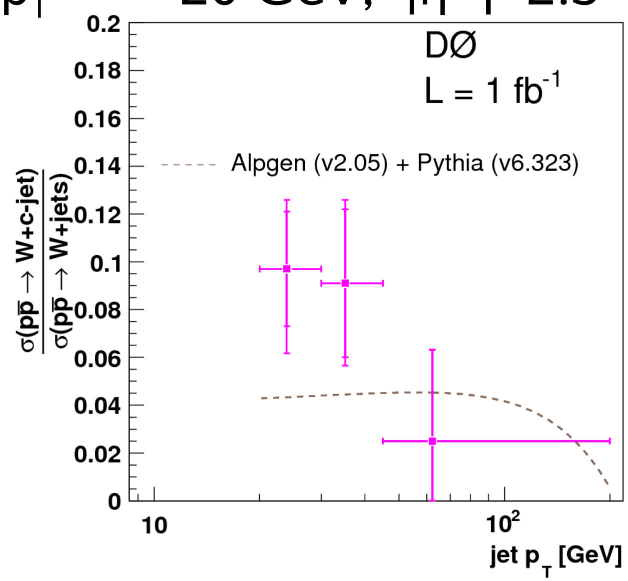


D0: measure ratio

W+c-jet / W+jet vs. jet pT

→partial cancelation of syst. uncert.

$p_T^{\mathrm{lepton}} > 20$ GeV, $|\eta^{\mathrm{jet}}|<2.5$



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

LO prediction: 0.040 ± 0.003 (PDF)

Summary

Tevatron data on inclusive jet and W/Z-production
with luminosities of 0.2-2fb-1

→ Additional PDF constraints on
- high-x gluon (incl. jets)
- down quark (W/Z rapidity distributions)

Other processes: incl. photon, photon + jet, photon+HF jet, W+c jet are either limited by statistics, systematics and/or by theory
→ hopefully progress on all sides

→ 4fb-1 already on tape and soon expect 8fb-1
→ Will lead to further progress → PDF constraints

World Jet Data vs. CTEQ6.1M

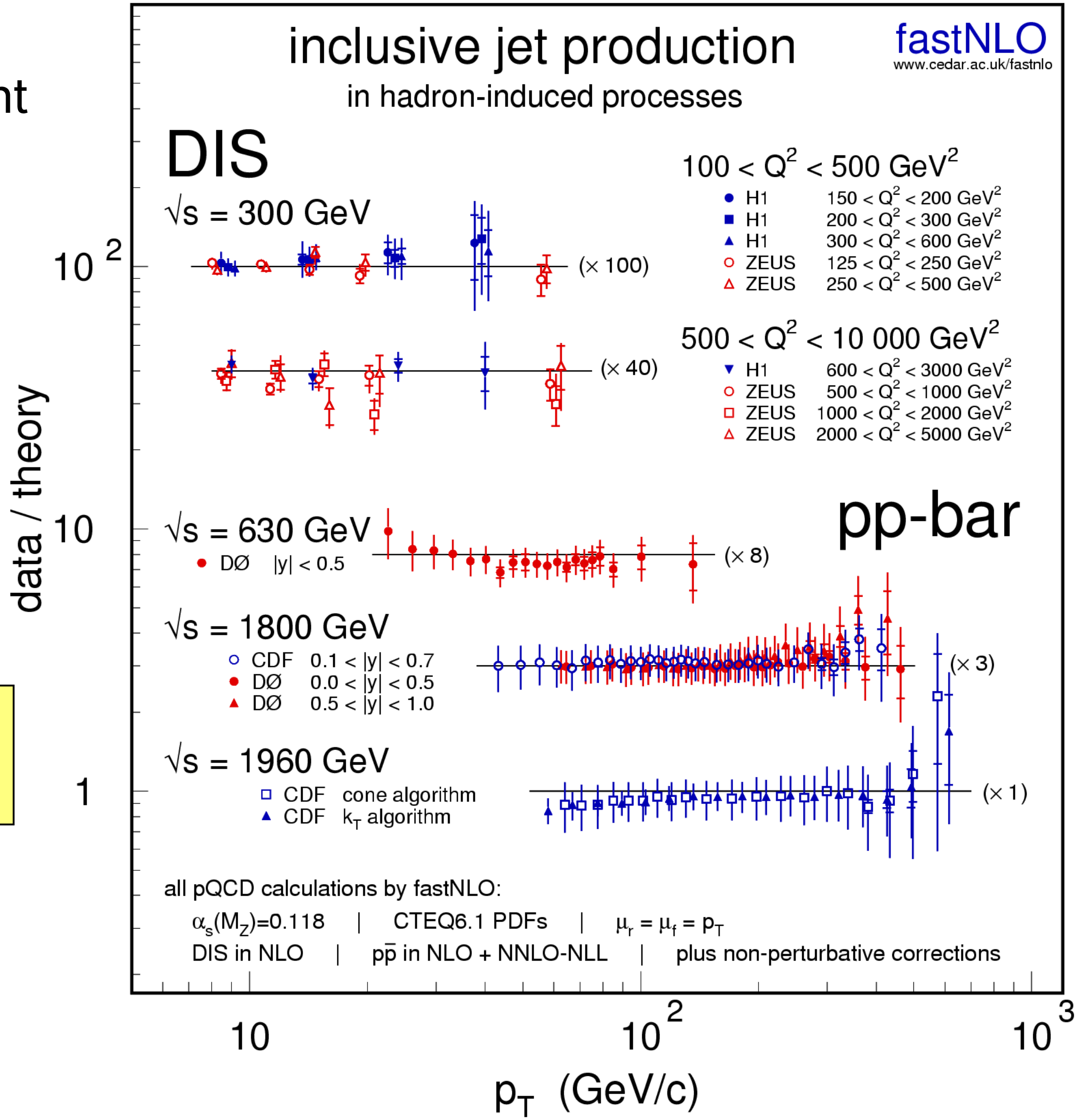
Inclusive Jet Data from different

- Experiments
- Processes
- Center-of-Mass Energies

compared to predictions

- **with CTEQ6.1M PDFs**

Good Description Everywhere



World Jet Data H1 2000 PDFs

Inclusive Jet Data from Different

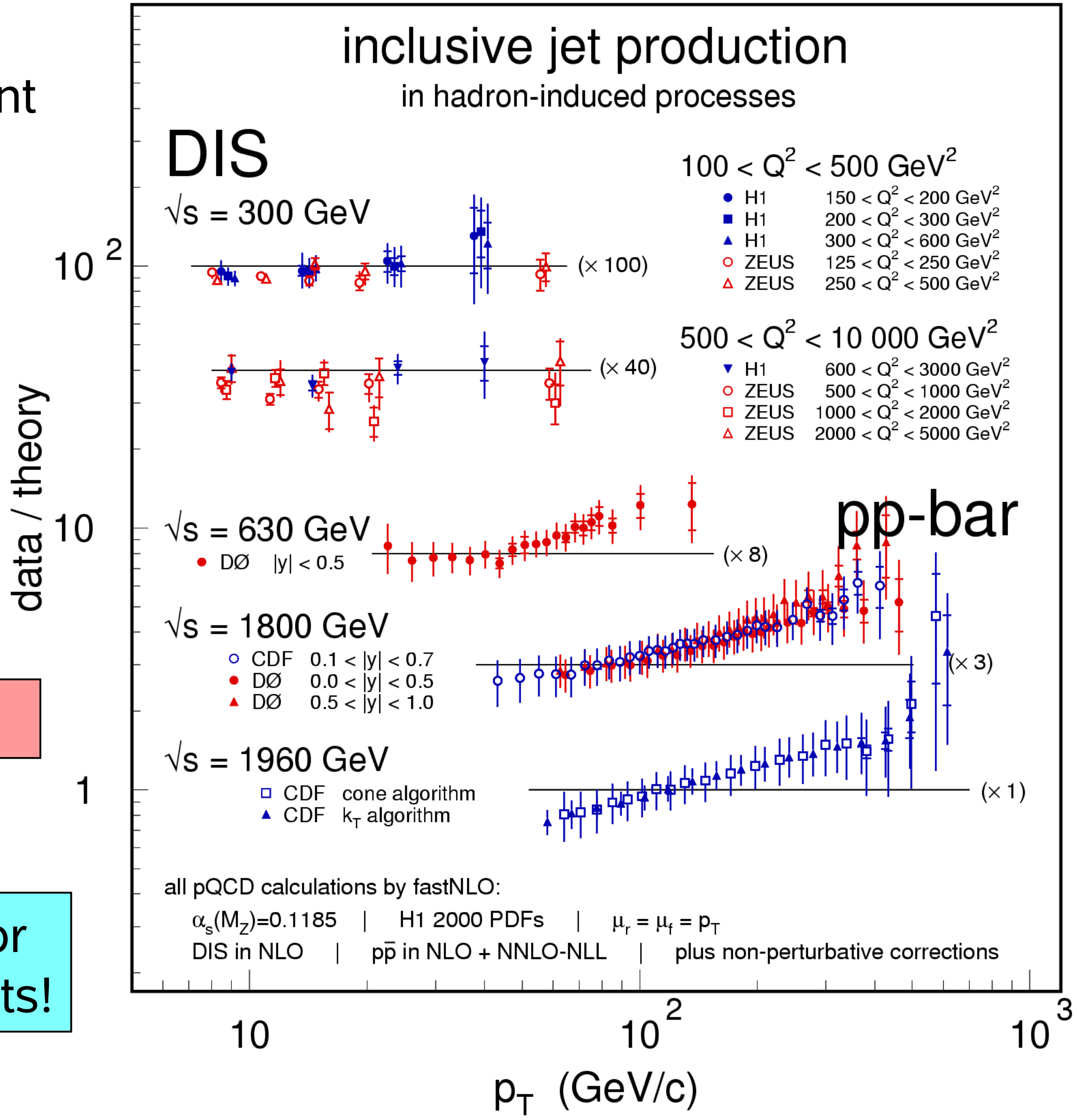
- Experiments
- Processes
- Center-of-Mass Energies

compared to predictions

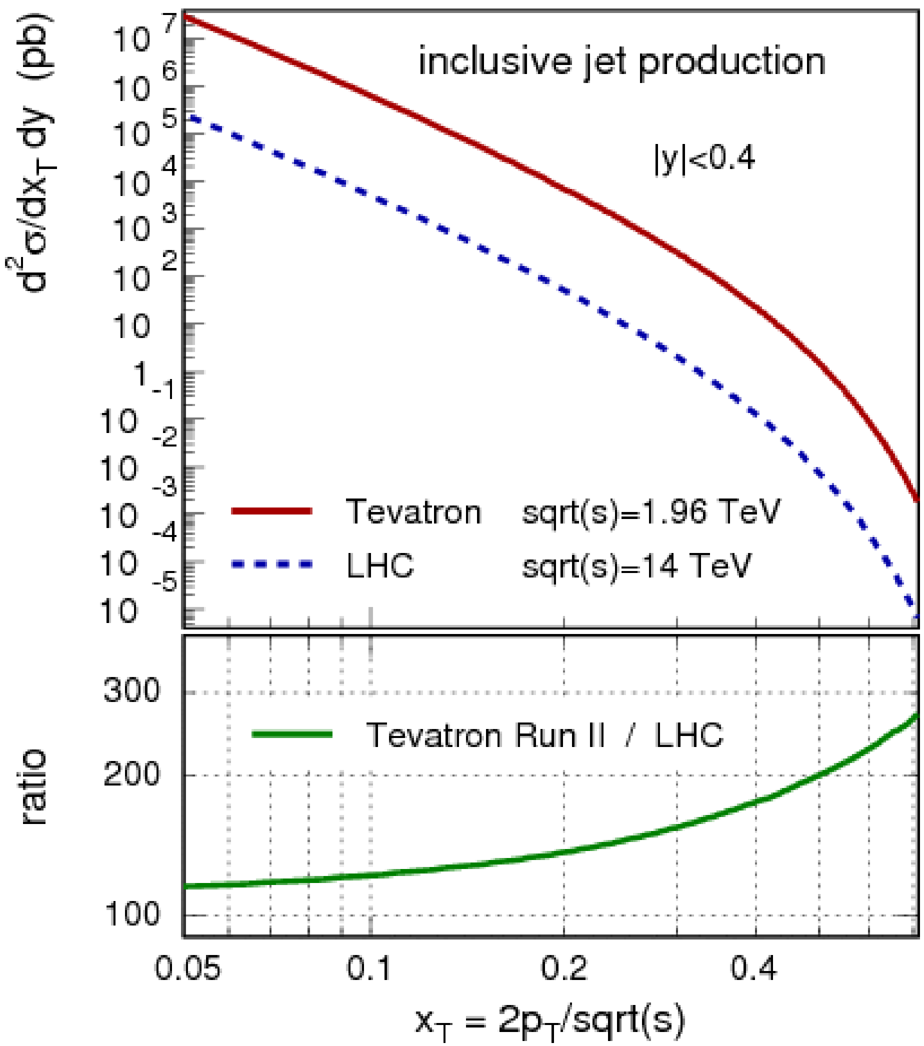
- **with "H1 2000" PDFs**

Poor Description

→ need to include Jet Data for Meaningful PDF Fits Results!



Inclusive Jets: Tevatron vs. LHC



PDF sensitivity:

→ compare jet cross section at fixed
xT = 2pT / sqrt(s)

Tevatron (ppbar)

>100x higher cross section @ all xT

>200x higher cross section @ xT>0.5

LHC (pp)

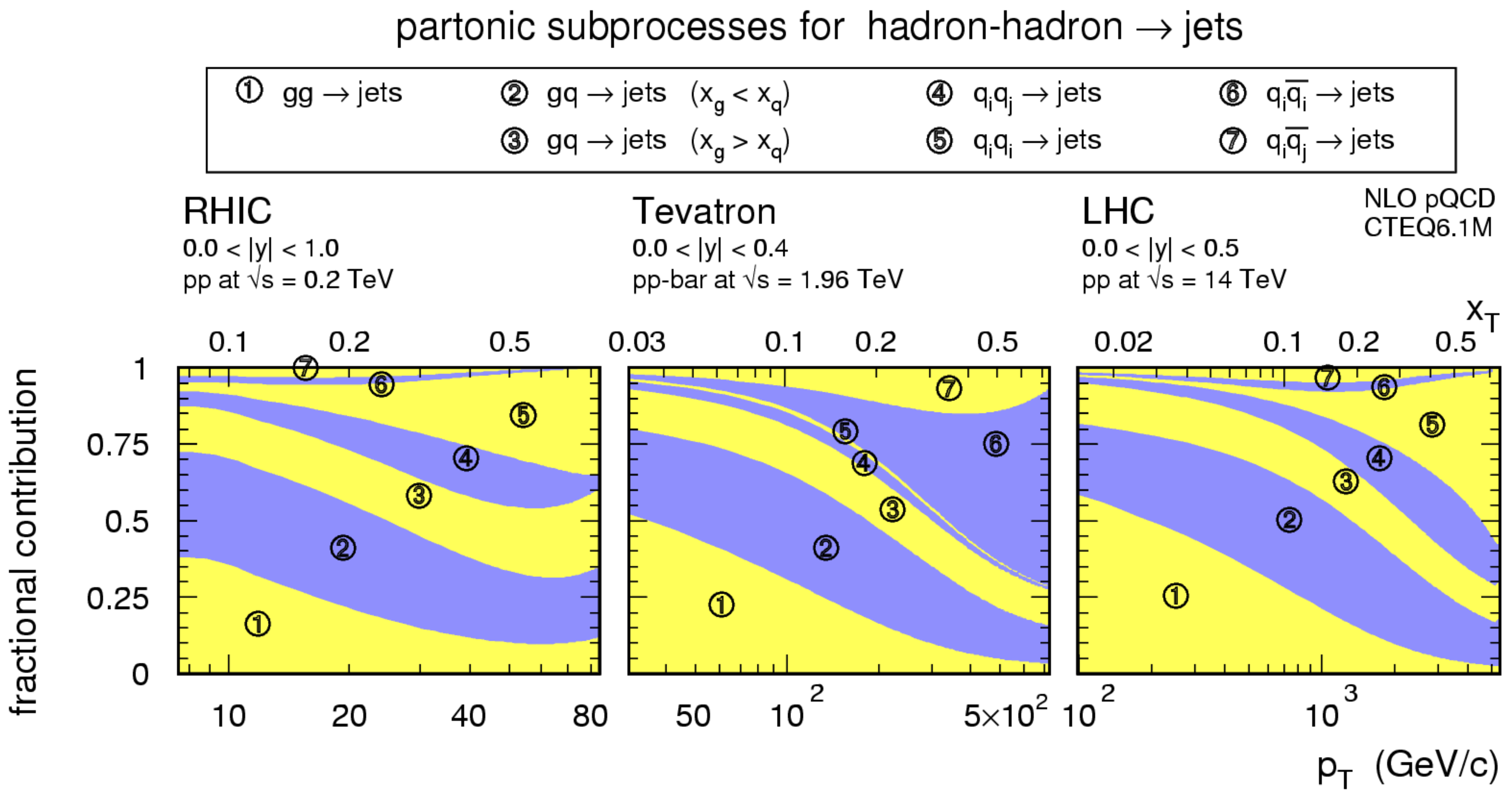
- need more than 1600fb-1 luminosity to compete with Tevatron@8fb-1
- more high-x gluon contributions
- but more steeply falling cross sect. at highest pT (=larger uncertainties)

→ Tevatron results will dominate high-x gluon for some years …

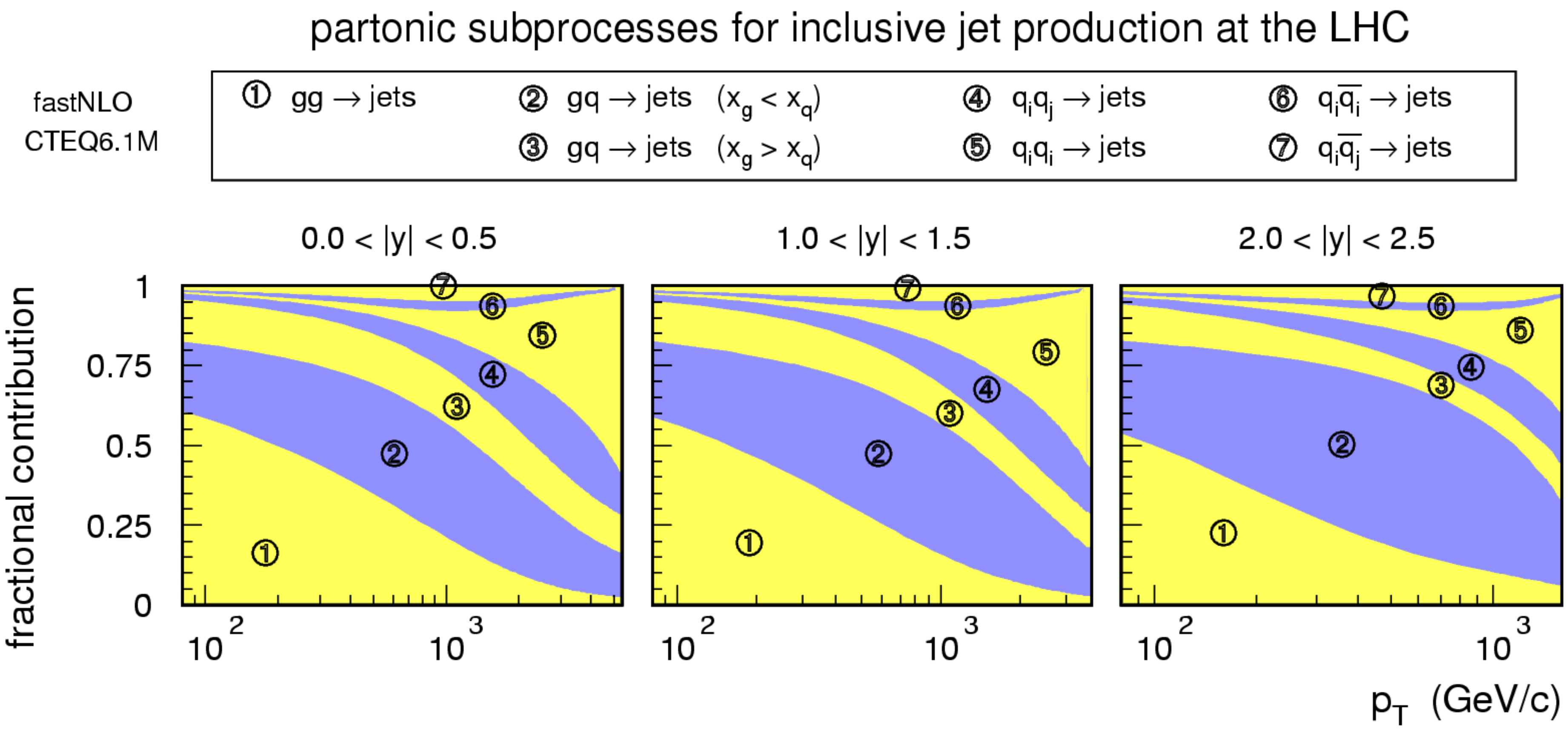

THANK YOU
THANK YOU

Backup

From the Tevatron to the LHC

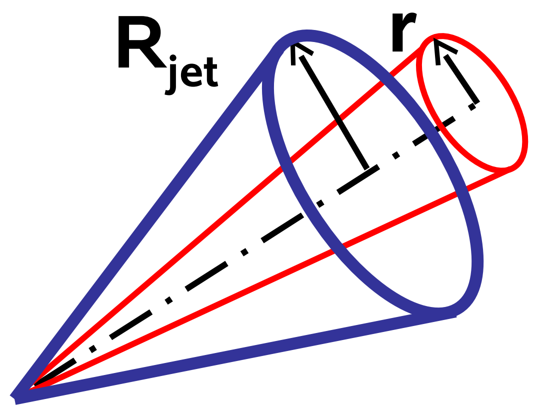


Partonic Subprocesses vs. |y|



Internal Jet Structure

CDF, PRD, hep-ex/0505013 (170pb-1)

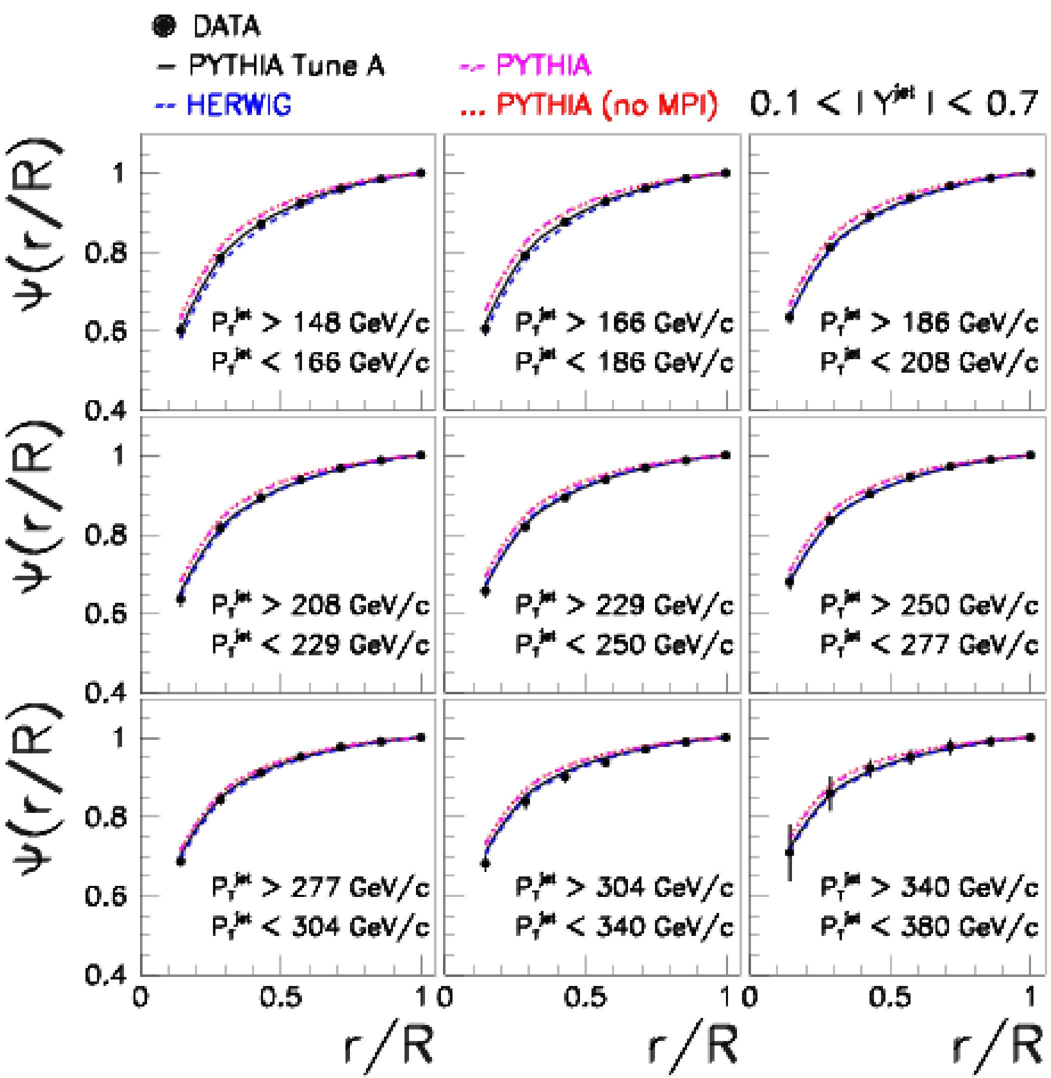


Integrated Jet Shape:

Fractional pT in Subcone vs.(r/R)

Sensitive to Soft and Hard Radiation – and UE

Well-Described by (tuned) MCs



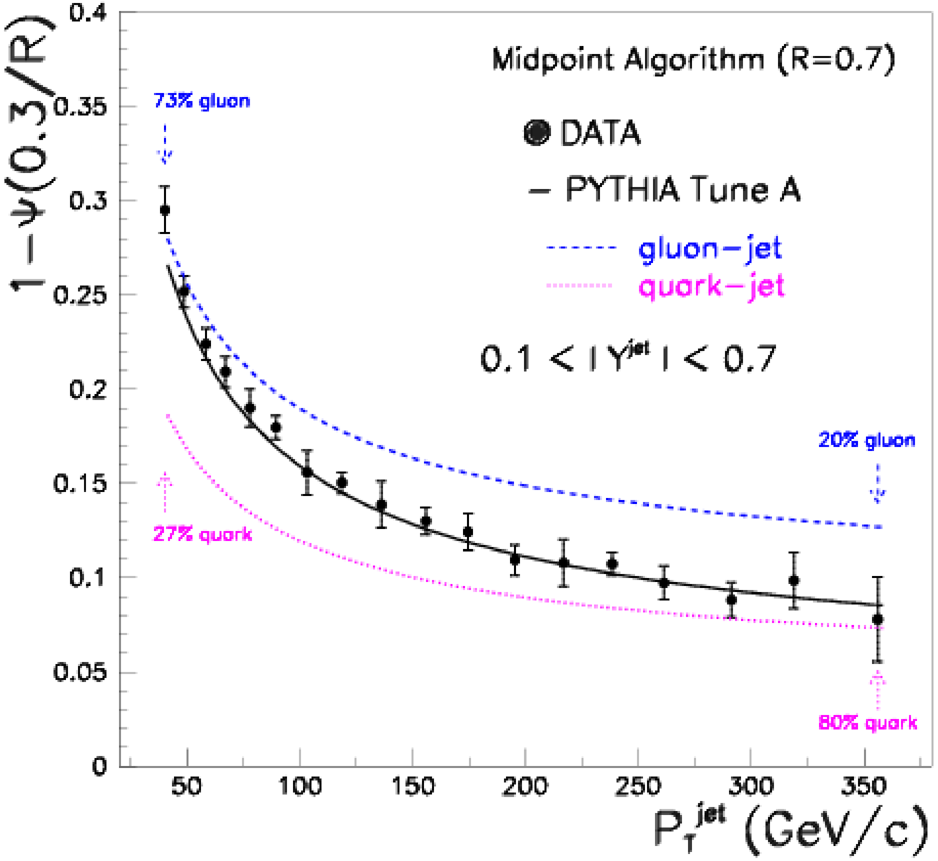
Internal Jet Structure

At fixed r=0.3 (38<pT<400GeV)

study pT dependence of predicted Psi(r/R) for quark- & gluon-jets

→ significant difference

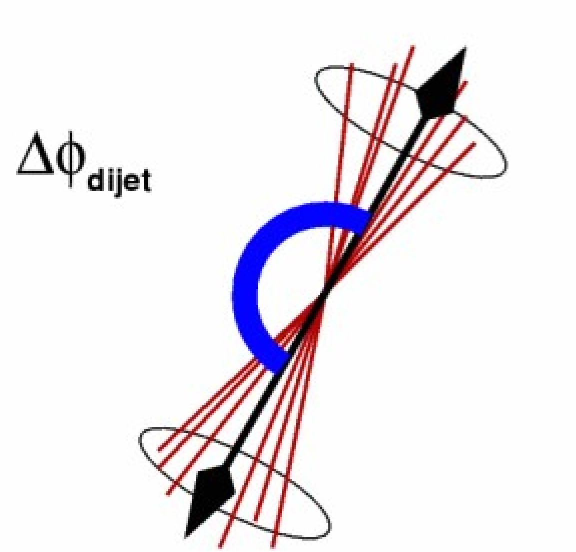
quark- & gluon-jet mixture in tuned PYTHIA gives good description of data



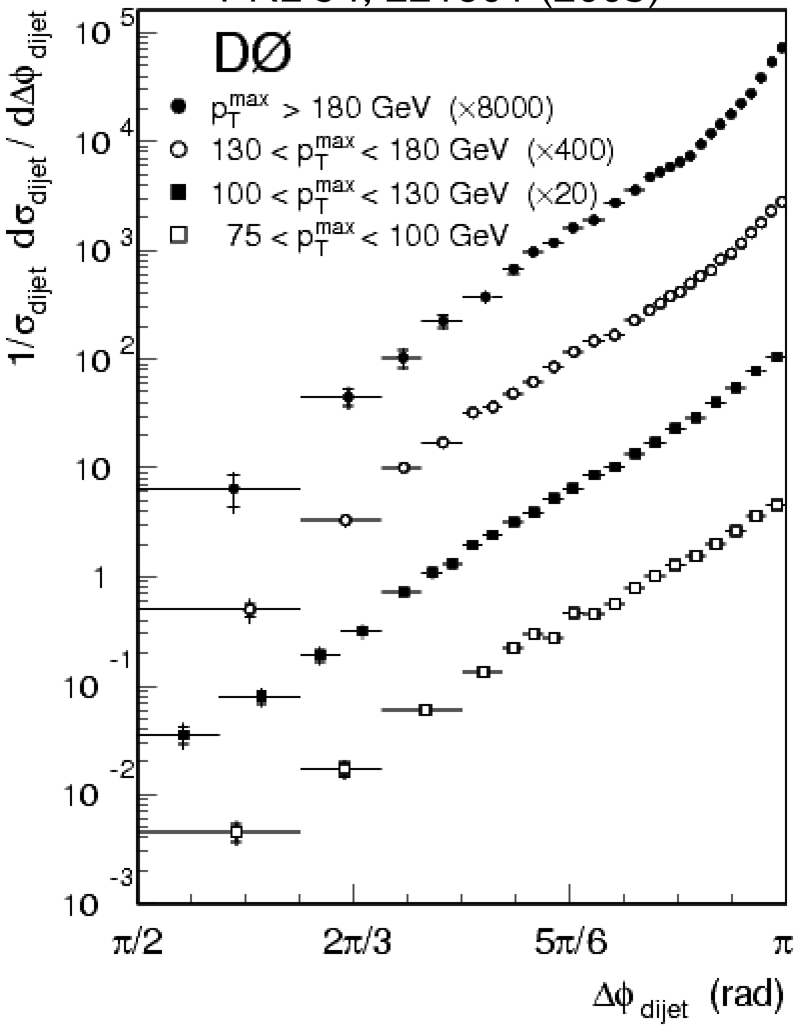
Dijet Azimuthal Decorrelation

Idea: Dijet Azimuthal Angle is Sensitive to Soft & Hard Emissions:

- Test Parton-Shower
- Test 3-Jet NLO



PRL 94, 221801 (2005)



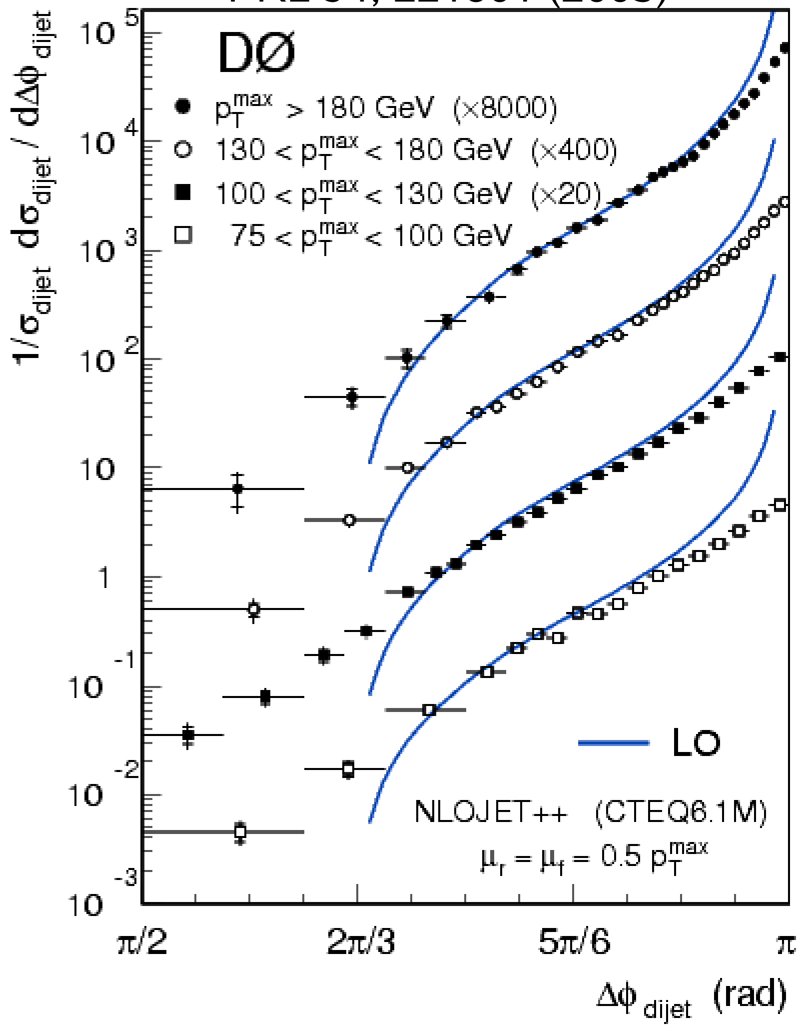
Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3

  & Divergence towards pi

PRL 94, 221801 (2005)

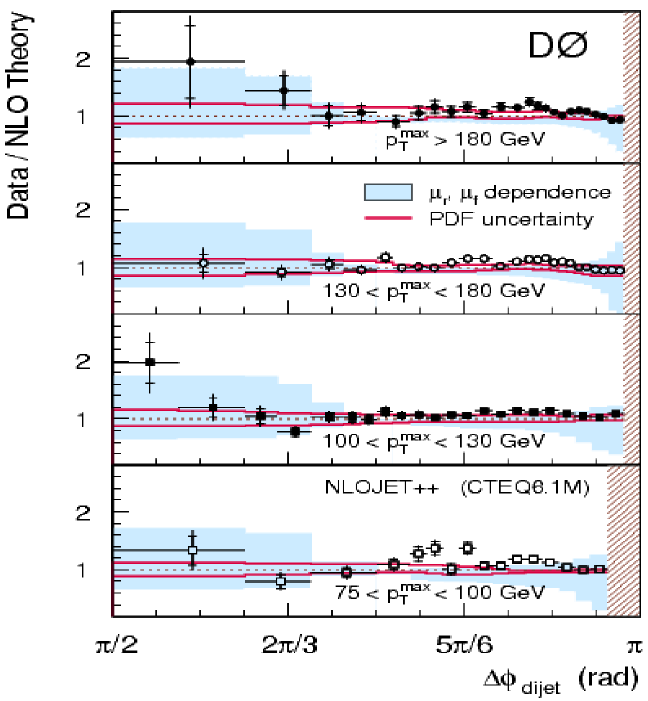


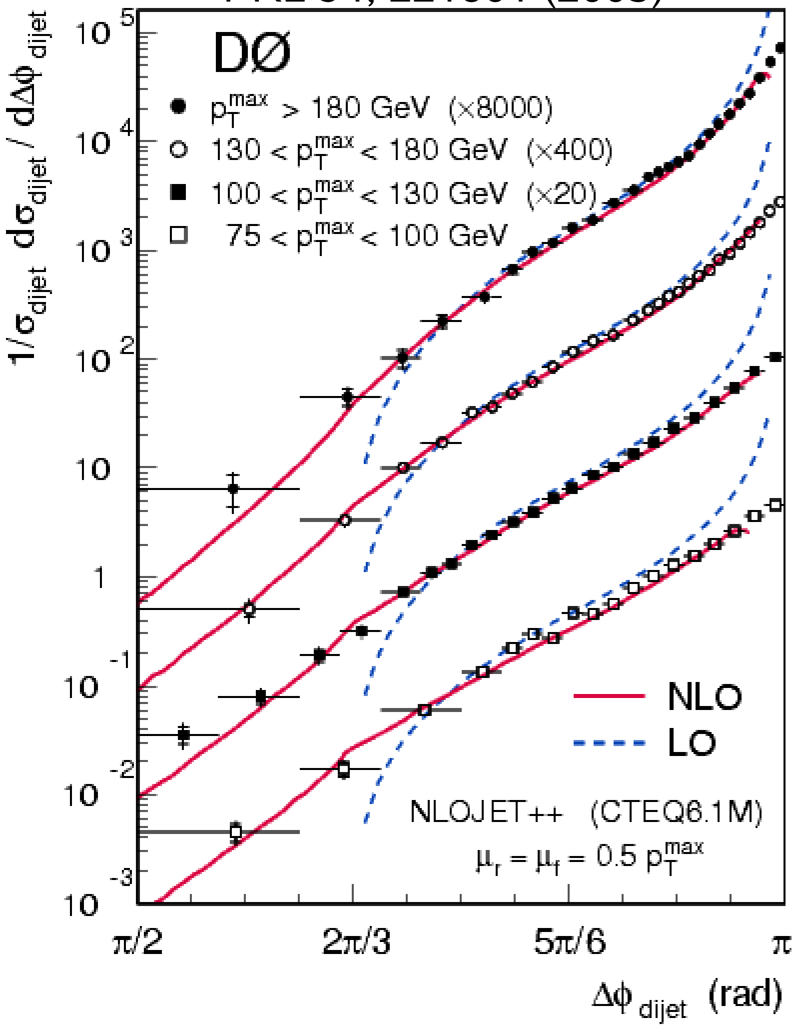
Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3
  & Divergence towards pi
- NLO is very good – down to pi/2
  & better towards pi
  … still: resummation needed

PRL 94, 221801 (2005)



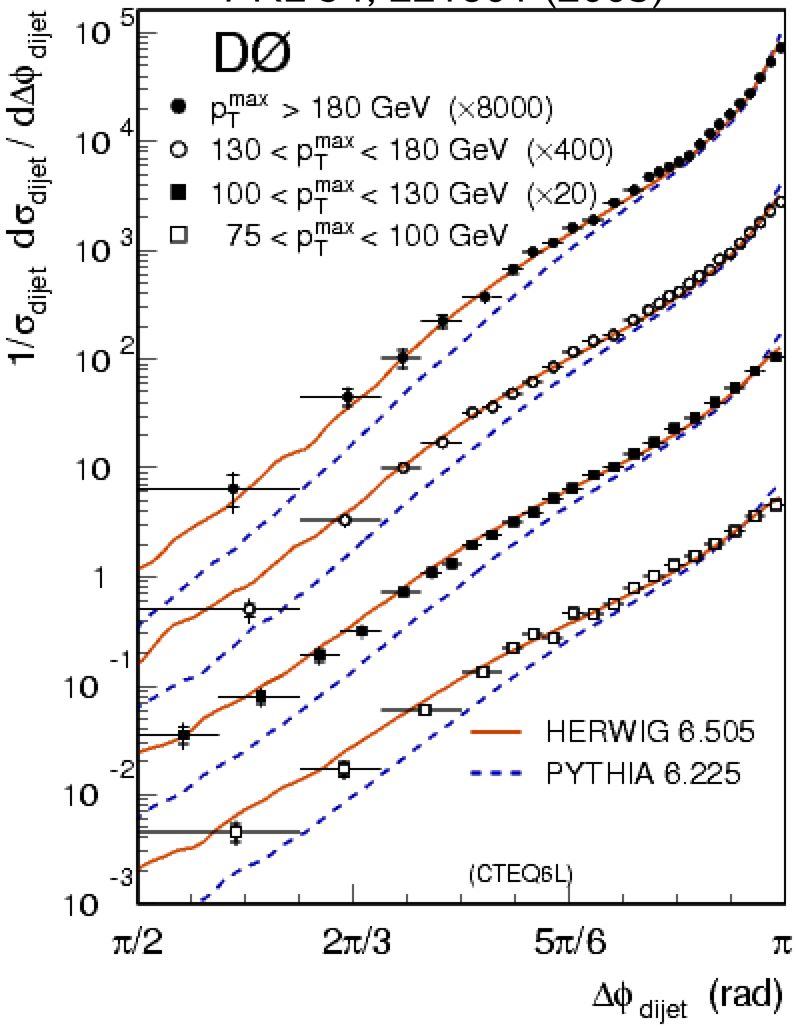


Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3
  & Divergence towards pi
- NLO is very good – down to pi/2
  & better towards pi
  … still: resummation needed
- HERWIG is perfect "out-the-box"
- PYTHIA is too low in tail …

PRL 94, 221801 (2005)



Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3

  & Divergence towards pi
- NLO is very good – down to pi/2

  & better towards pi

  … still: resummation needed
- HERWIG is perfect "out-the-box"
- PYTHIA is too low in tail …

  … but it can be tuned (tune DW)

  ("tune A" is too high!)

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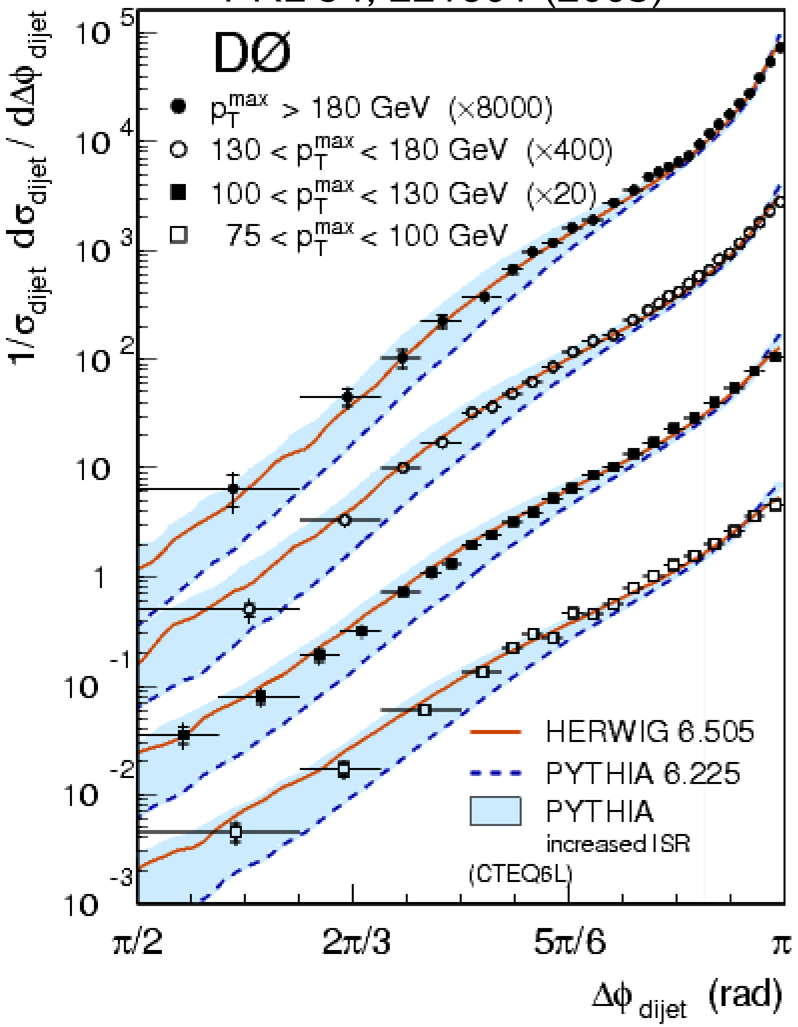

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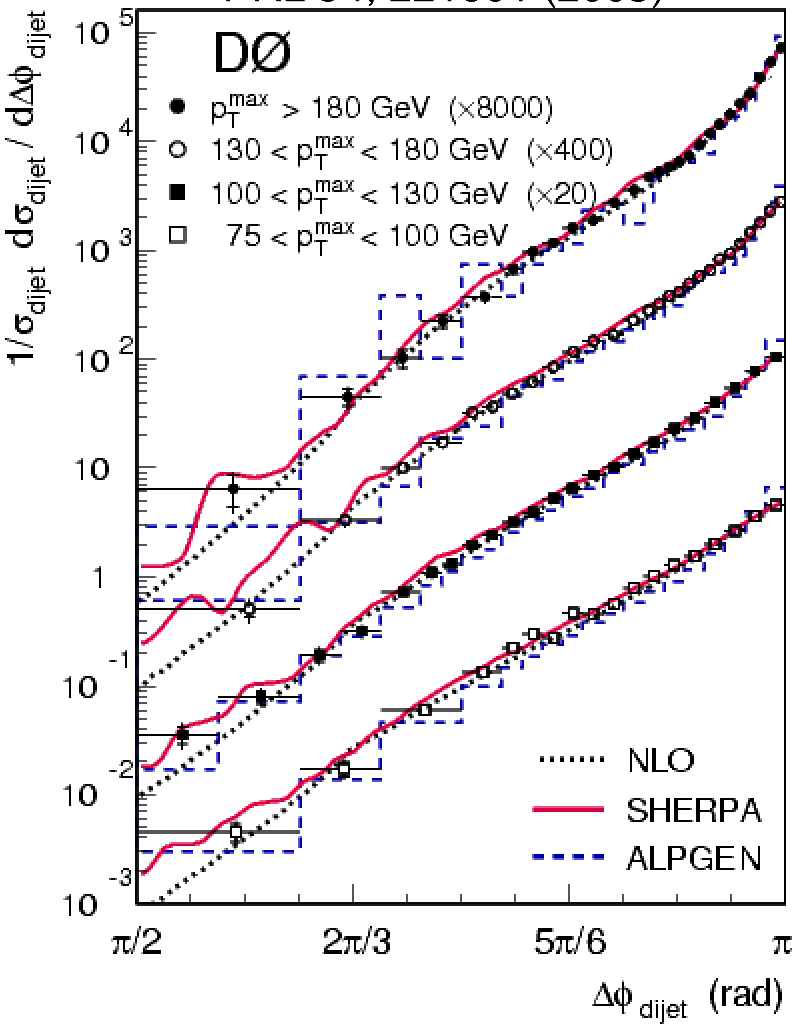
Matched predictions:

- SHERPA is great
- ALPGEN looks good – but low
  efficiency → large stat. fluctuations

PRL 94, 221801 (2005)



Radius Dependence of Jet Cross Sections

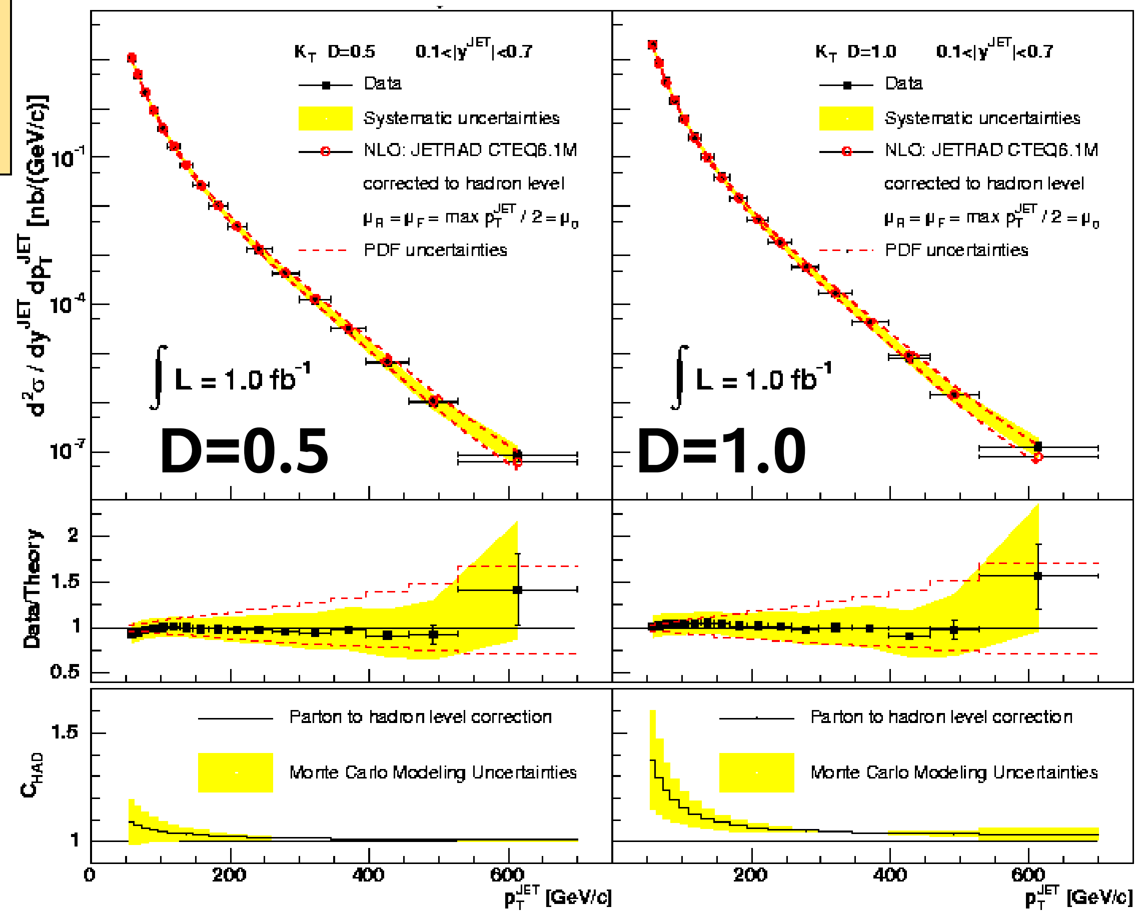
jet cross section depends on radius in jet definition
→ important testing ground

CDF: radius dependence for incl. jets (kT jet algorithm) for D (=radius) parameter D = 0.5, 0.7, 1.0

→ results for each D value are compared to NLO pQCD calculation + non-pert corr.

→ agreement for all D values

Phys. Rev. D 75, 092006 (2007)



(similar analysis in DIS by ZEUS)

→ … but effectively only a LO test of radius dependence

→ better: study **ratios** and compute at true NLO (using 3-jet NLO)

Radius Dependence of Jet Cross Sections @NLO

Ratio of cross sections: $$R(D) = \frac{\sigma(D)}{\sigma(D_0)} = 1 + c_1\alpha_s + c_2\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

- Jet cross section at **LO** → **no** radius dependence (R=1)
- Jet cross section at **NLO** → **LO** contribution to radius dependence

$$\frac{[\sigma(D)]_{\mathrm{NLO}}}{[\sigma(D_0)]_{\mathrm{NLO}}} = \left[\frac{\sigma(D)}{\sigma(D_0)}\right]_{\mathrm{LO}} = R_{\mathrm{LO}}(D)$$

- Jet cross section at **NNLO** → **NLO** contribution to radius dependence

NNLO calculation not available → missing: 2-loop virtual corrections

→ but: 2-loop virtual correction don't depend on radius (2→2 kinematics)

→ contributions from 2-loop corrections cancel in difference

Use **three-jet NLO calculation** to compute **difference**

→ obtain **NLO** result for ratio:

$$\frac{[\sigma(D) - \sigma(D_0)]_{\mathrm{NLO}}}{[\sigma(D_0)]_{\mathrm{NLO}}} + 1 = \left[\frac{\sigma(D)}{\sigma(D_0)}\right]_{\mathrm{NLO}} = R_{\mathrm{NLO}}(D)$$

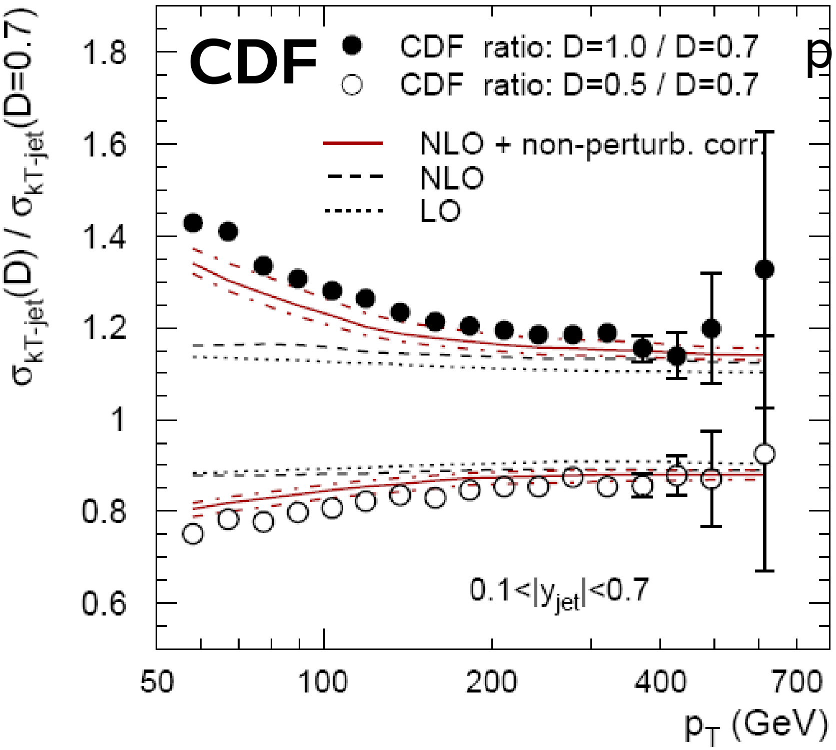
→ use for first NLO study of radius dependence of jet cross sections

Radius Dependence of Jet Cross Sections @NLO

Study cross section **ratios**:

T. Kluge, M.W. – work in progress

(D=1.0/D=0.7) and (D=0.5/D=0.7) and compare with true NLO calculation plus non-perturbative corrections



scales: mu=pT (0.5pT, 2pT)

only at highest pT:

→ agreement at the edge of scale dependence

disagreement at lower pT:

→ larger radius dependence in data

→ NLO corrections are <20% for Tevatron

→ most of pT range: dominated by non-pert. corrections

Radius Dependence of Jet Cross Sections @NLO

Study cross section **ratios**:

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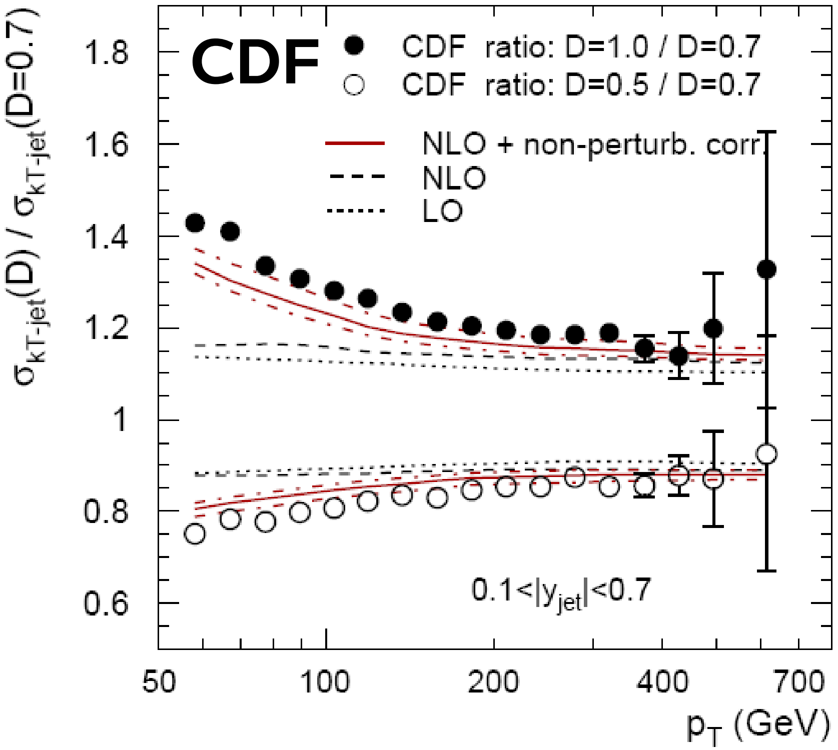

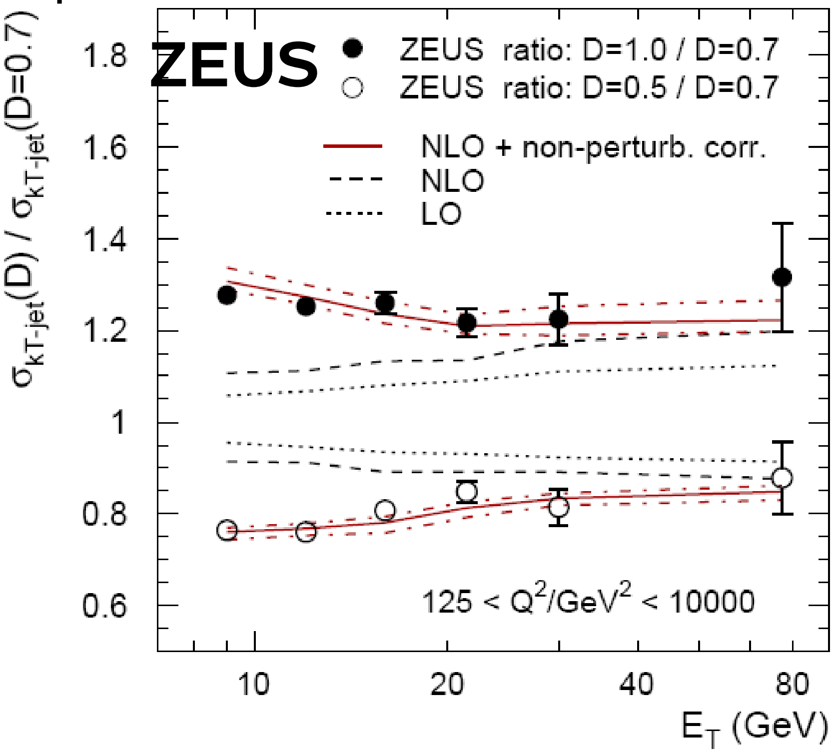

→ NLO corrections are <20% for Tevatron ~60-100% for HERA

→ most of pT range: dominated by non-pert. corrections

→ HERA data described / Tevatron data not → underlying event???