Recent QCD results from the Tevatron

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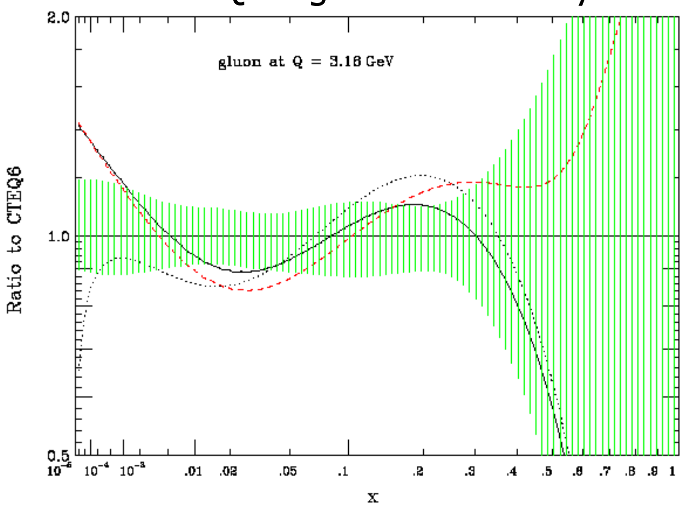
Ringberg Workshop "New Trends in HERA Physics 2011"
25 – 28 September 2011,
Ringberg Castle, Lake Tegernsee

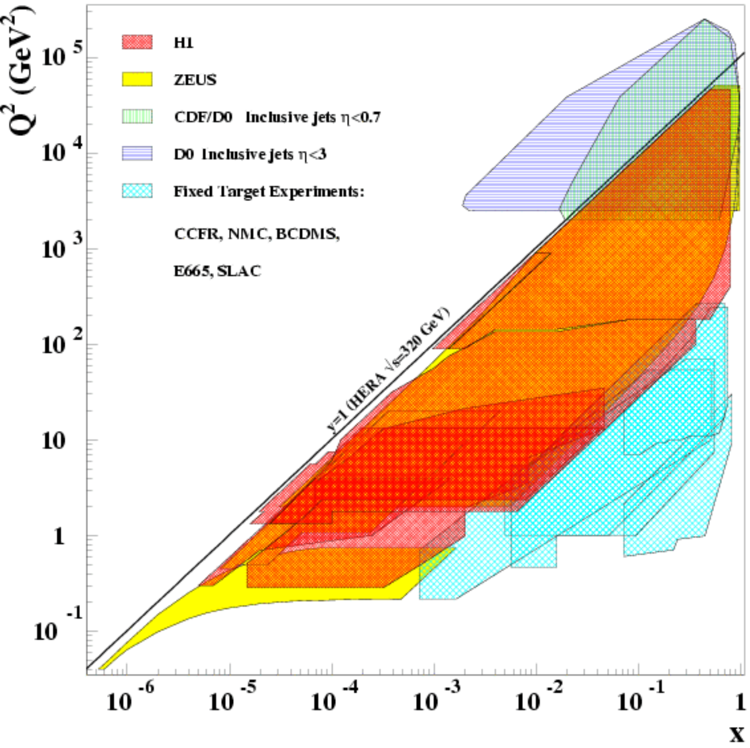
Hard QCD Processes

high p_T → hard **partonic** scattering

CTEQ6.1 gluon uncertainty



kinematic plane



Sensitive to:

- dynamics of interaction
  - validity of approximations (NLO, LLA, …)
  - QCD vs. new physical phenomena
- proton's parton content
  → unique sensitivity to high-x gluon
- strong coupling constant

Physics Objects

Jets

(all flavors)

Heavy Flavor

Physics Objects

Jets

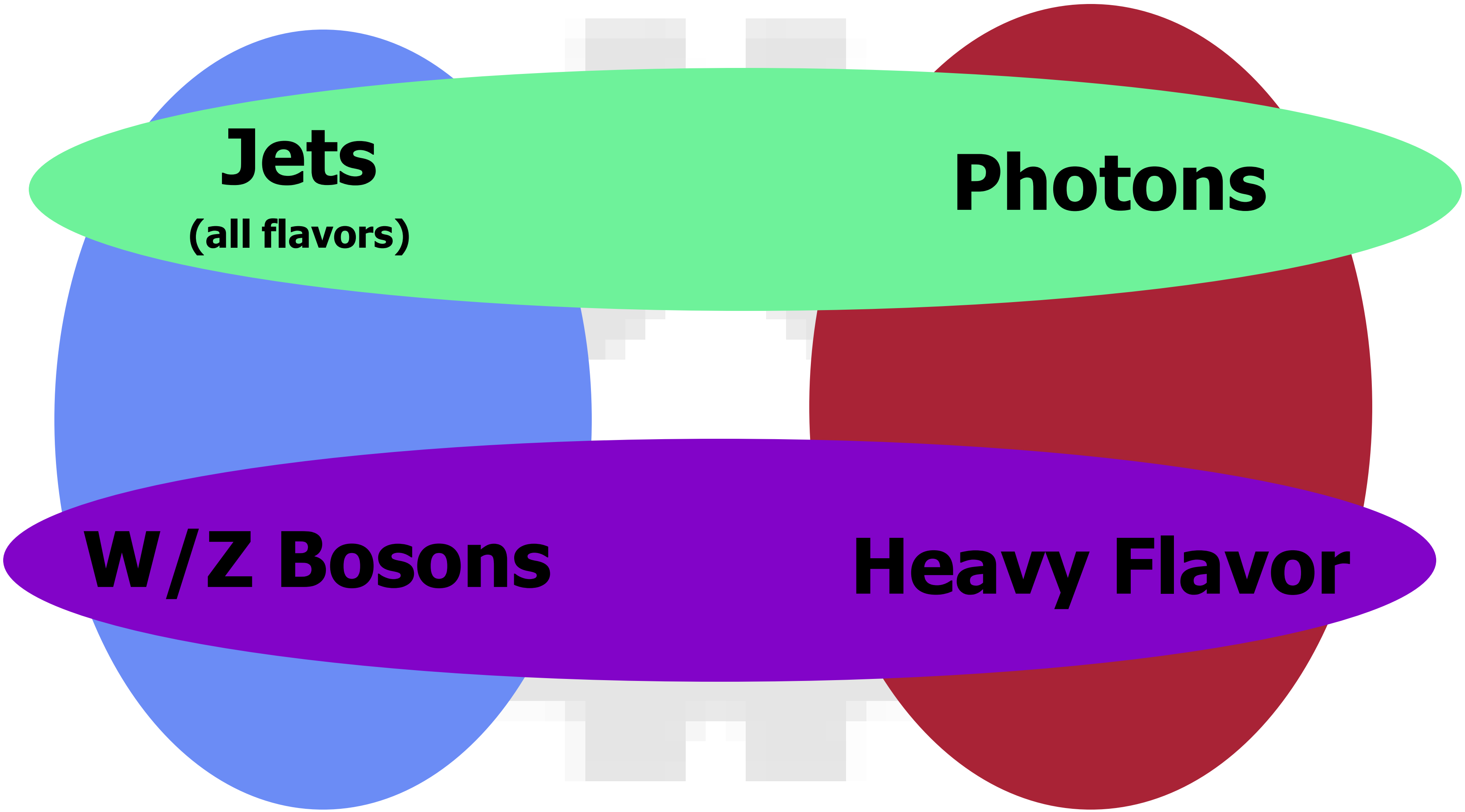
(all flavors)

Photons

W/Z Bosons

Heavy Flavor

Physics Objects

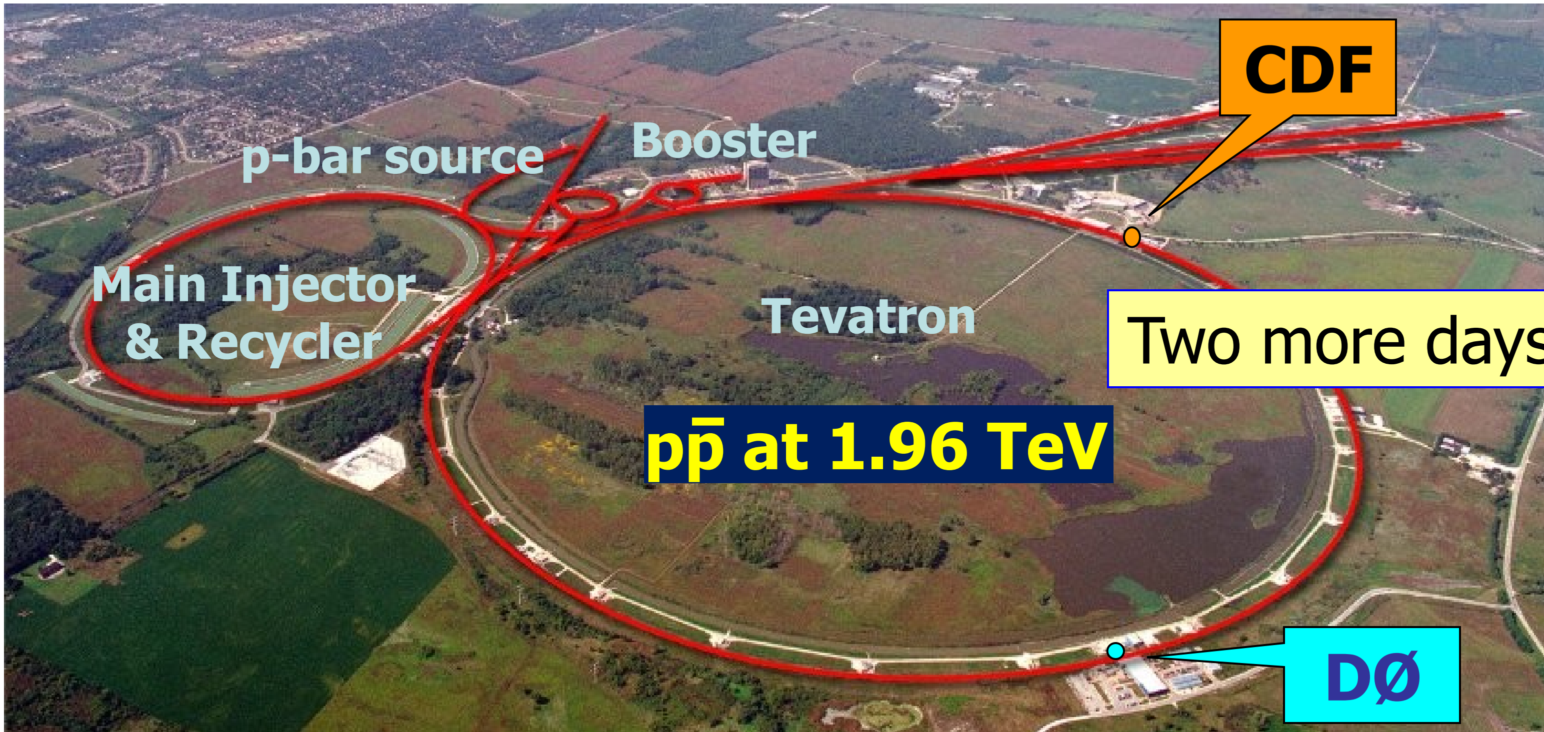


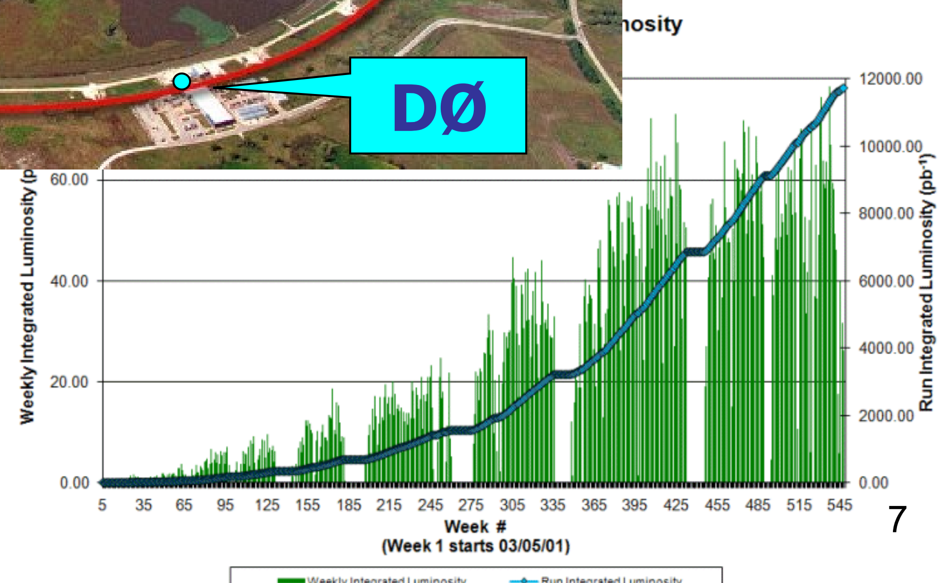
Multi-Parton Interactions / Underlying Event

Outline

- Photon Production (+ Jet)
- Vector Boson + Jet(s)
- Event Shapes
- Jet Production
- Determination of α_s

Fermilab Tevatron – Run II





- 36x36 bunches
- bunch crossing 396 ns
- Run II: March 2001 – Sept 2011
- Peak Luminosity: 4.2×10^{32} cm^{-2} sec^{-1}
- Run II total delivered: 12 fb^{-1}

Fermilab Tevatron – Records

Integrated Luminosity in One Store: 12150.17+ 12048.1 [1/nb], April 17, 2010, Store #7748. *For CDF and D0, respectively*

Integrated Luminosity in a Week: 73.070 [1/pb], April 13 - April 20 2009. *Average integrated Luminosity of CDF and D0.*

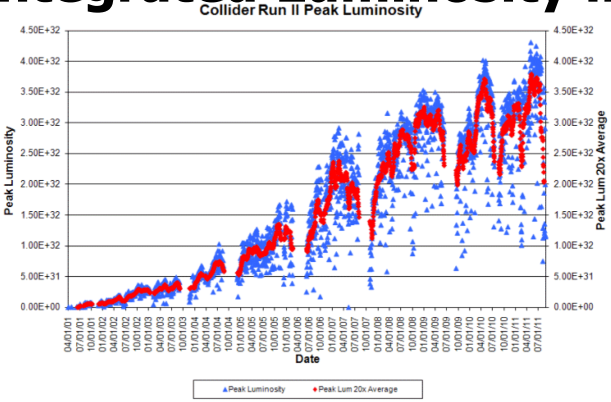
Integrated Luminosity in a Month to CDF: 273.423 [1/pb], March 2010. *D0 also set a record this month (avg 272.720 1/pb)*

Maximum number of PBars at Low Beta: 3326E9 , February 10, 2008, Store #5899. *From the Recycler*

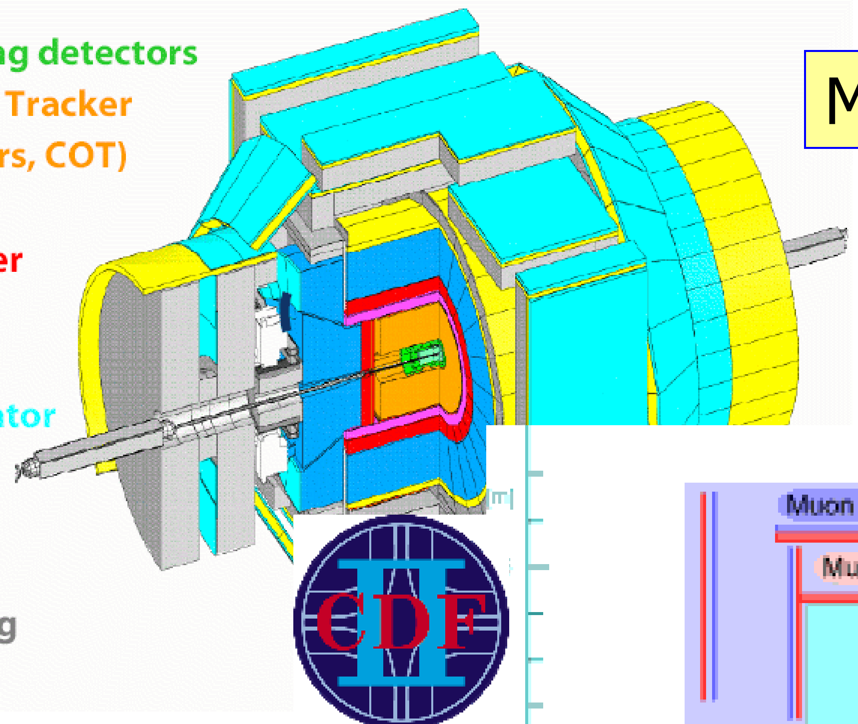
Maximum number of Protons at Low Beta: 18236. E9 , July 14, 2002, Store #1526.

Store Duration: 53.75 Hours, 29-31 July 2006, Store #4862

Integrated Luminosity in a Floating Week: 81.98 [1/pb], June 14, 2011.

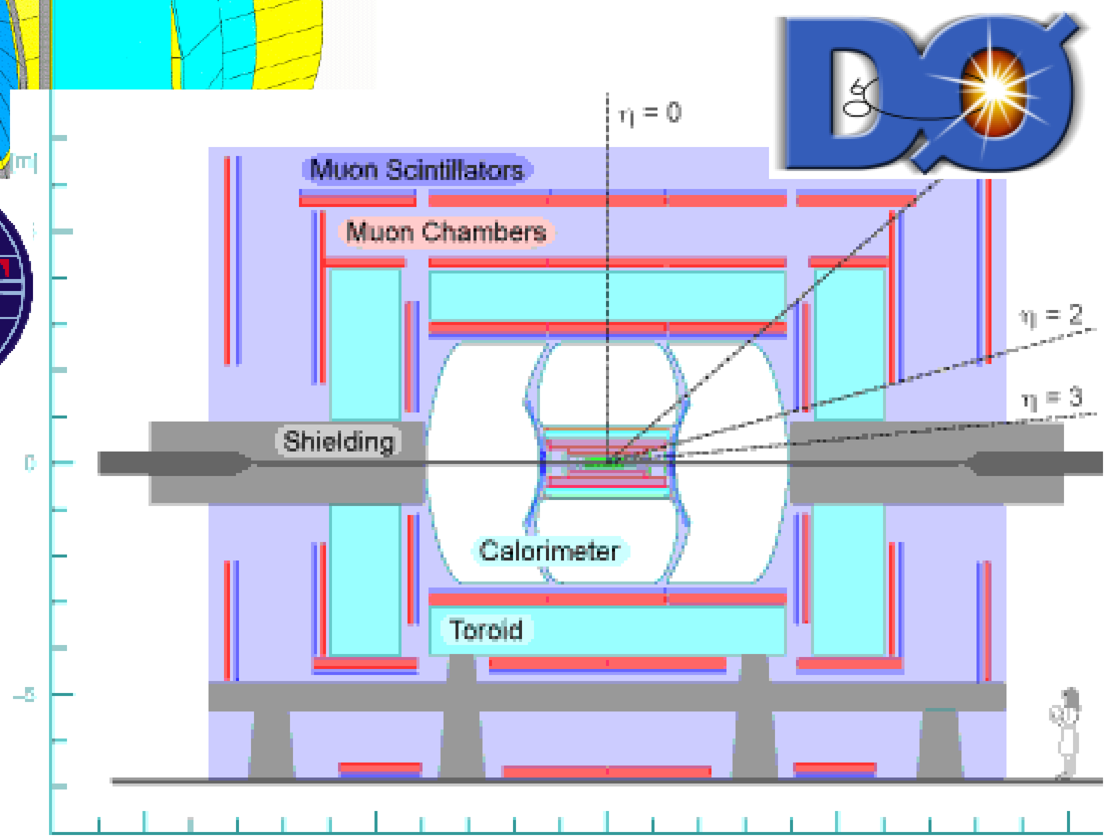


Run II Detectors



- 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
- (hermetic → missing ET)

Photons

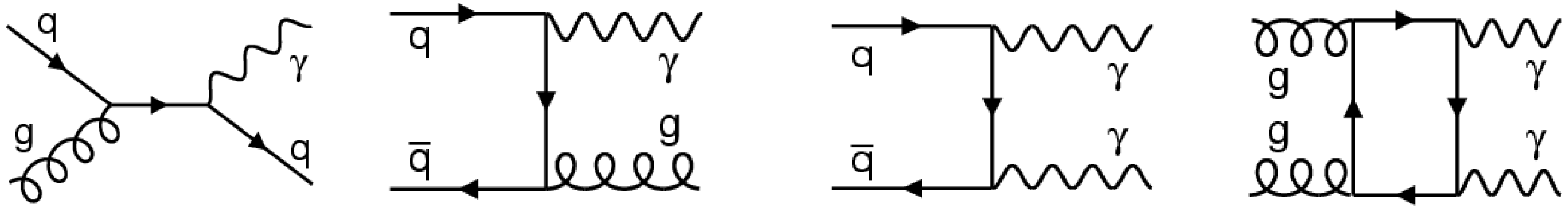
test theory

fixed order: NLO

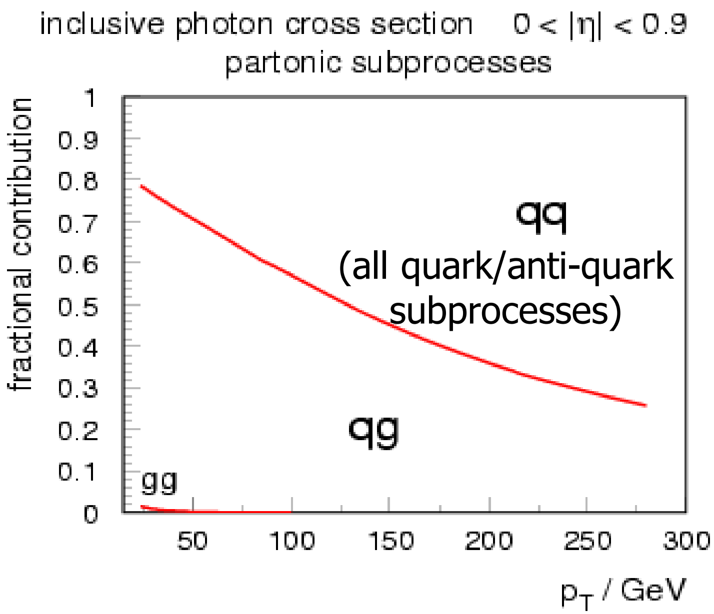
resummation

PDF constraints?

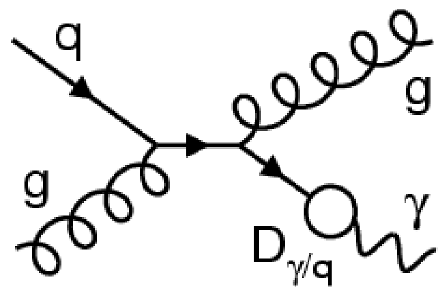
Direct Photon Production



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

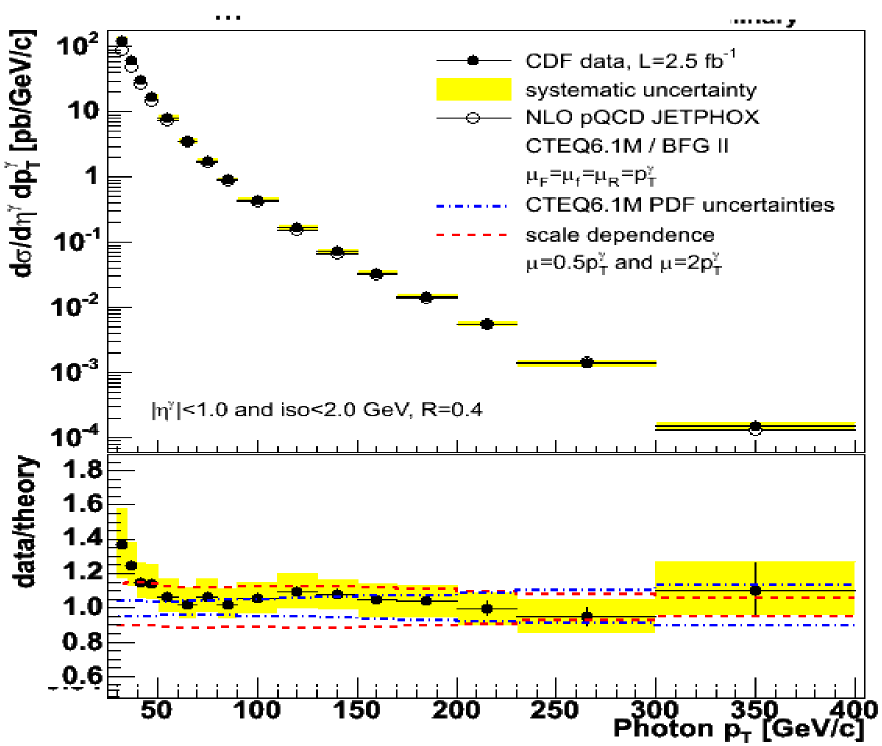


also fragmentation contributions:

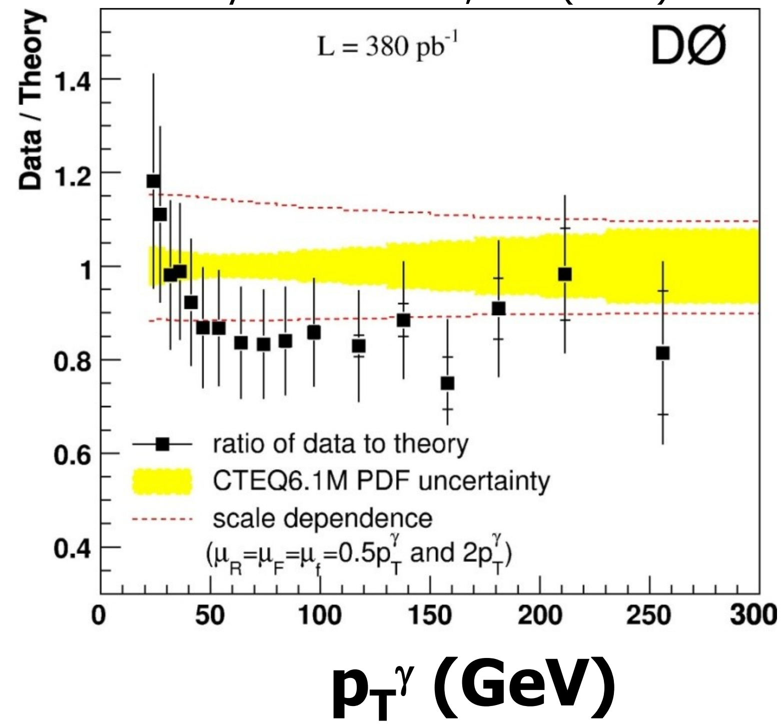


suppress by isolation criterion
→ observable: **isolated** photons

Incl. Isolated Photons



Phys. Lett. B 639, 151 (2006)



- CDF and D0 measurements: 20< p_T <400GeV → agreement
- theory vs. data: disagreement in low p_T shape
- experimental and theory uncertainties > PDF uncertainty
  → no PDF sensitivity yet
- first: need to understand discrepancies in shape

Isolated Photon + Jet

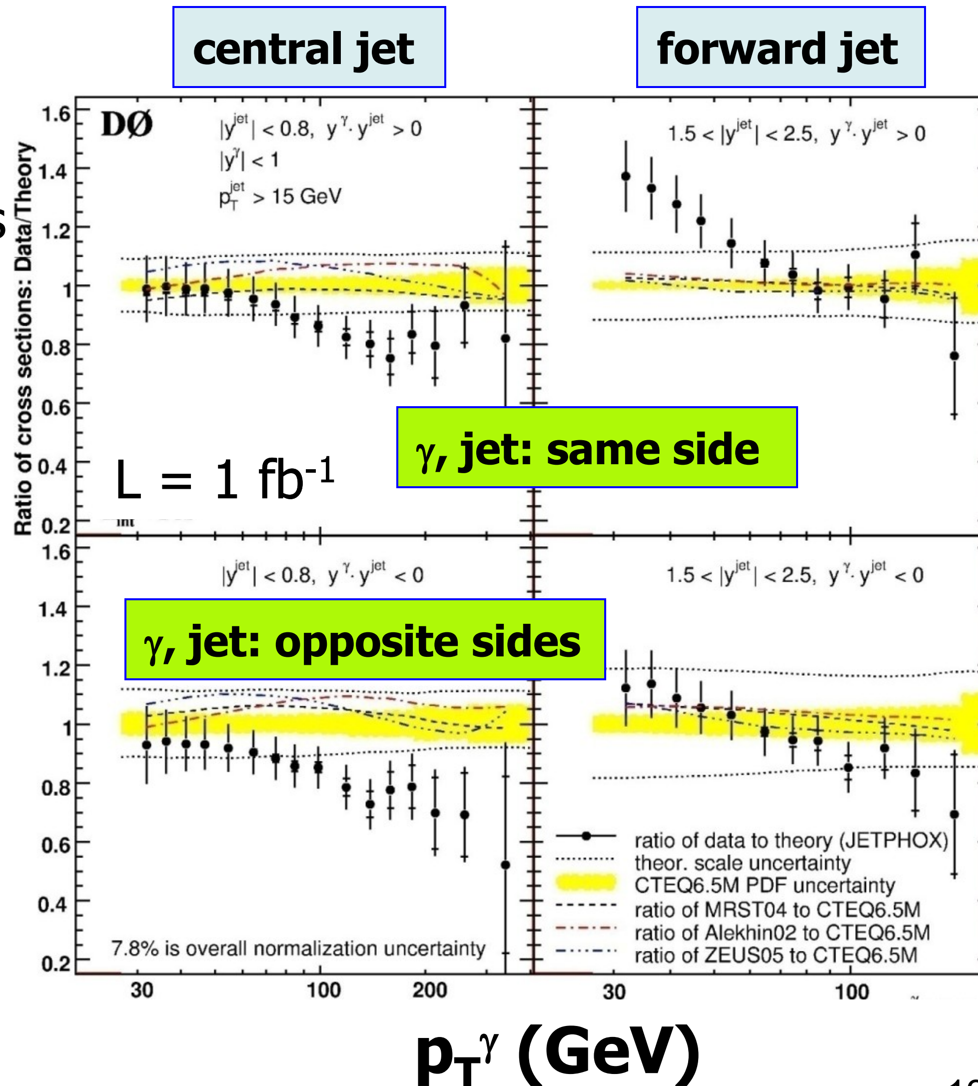
investigate source for disagreement
→measure more differential:

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

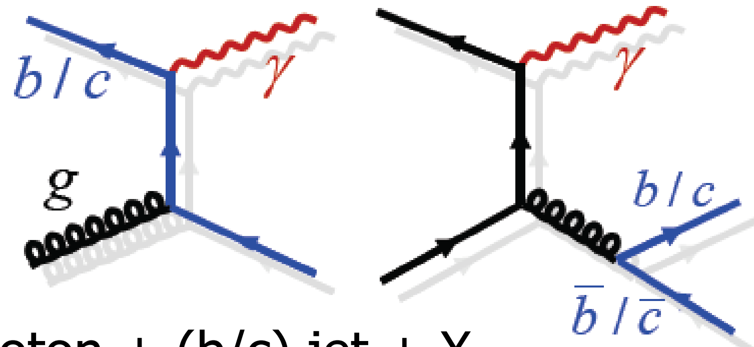
- measure in 4 regions of y^{γ} / $y^{\mathbf{jet}}$
  - photon: central
  - jet: central / forward
  - γ, jet: same side / opposite side

discrepancies in data/theory
→ figure out what is missing…
• higher orders, resummation, … ?

Phys. Lett. B 666, 2435 (2008)



Isolated Photon + HF Jet



Photon + (b/c) jet + X

Photon p_T : 30-150 GeV

0.01<x<0.3 → b, c, gluon PDF

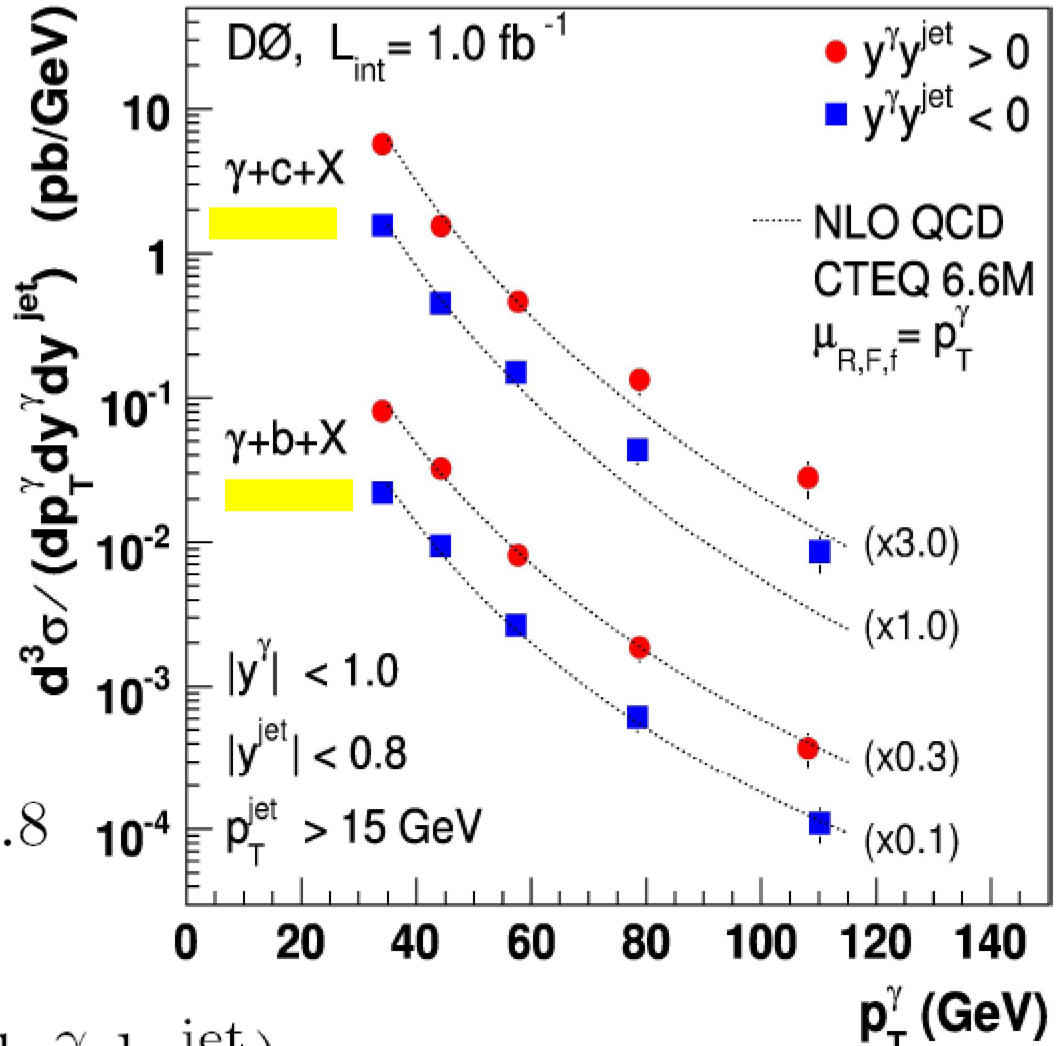
→ test gluon splitting contribution

tag **photon and jet**

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

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

Phys. Rev. Lett. 102, 192002 (2009)

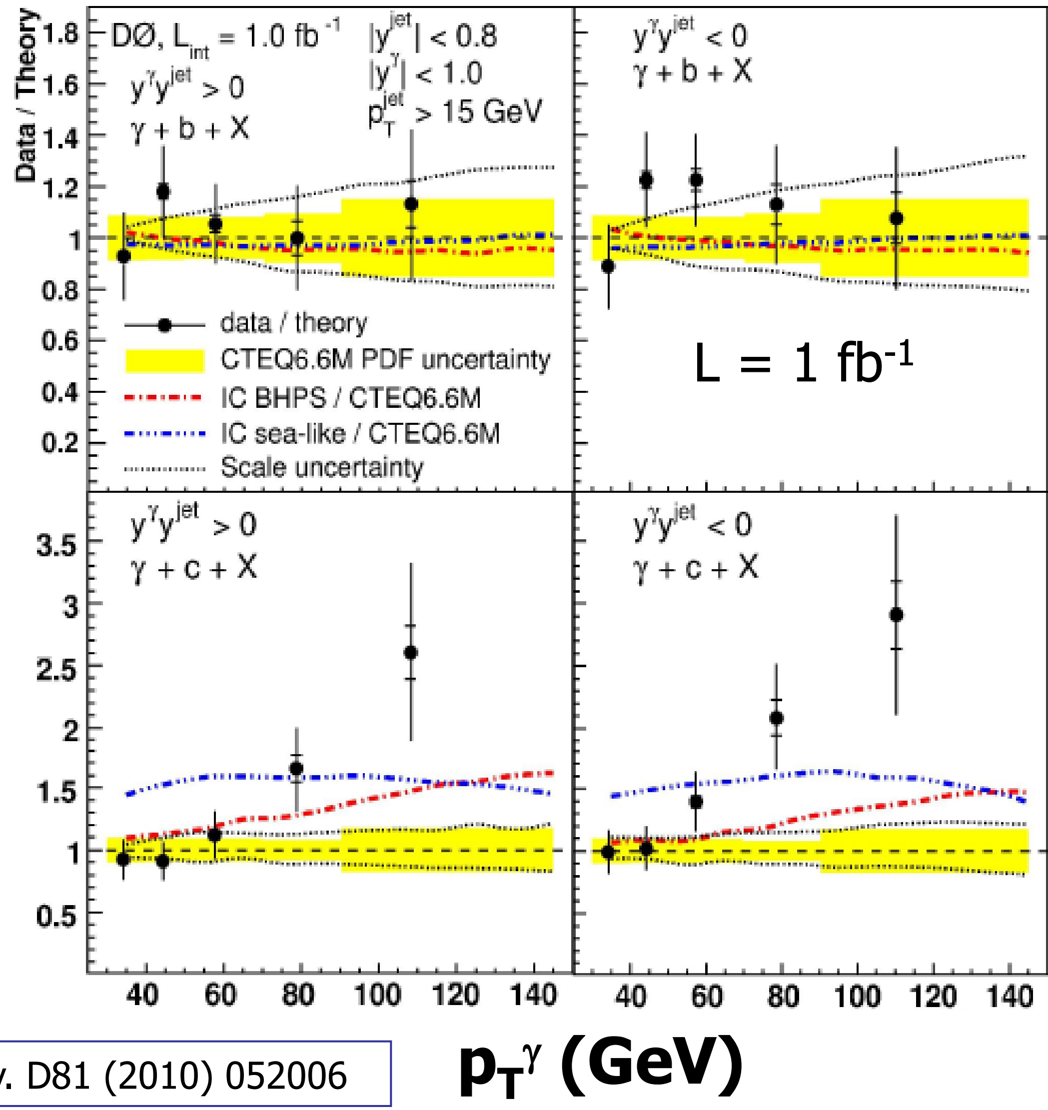


Isolated Photon + HF Jet

Phys. Rev. Lett. 102, 192002 (2009)

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

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

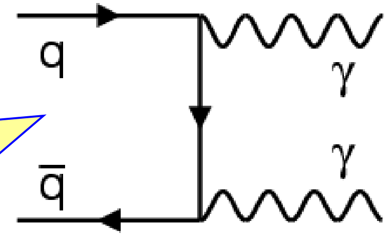


Consistent with CDF "photon + b-jet" in Phys. Rev. D81 (2010) 052006

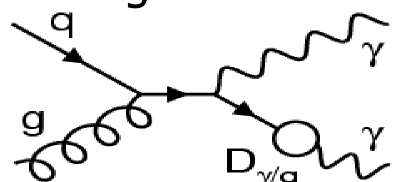
Di-photon production

- Di-Photon final state: one of main discovery channels for Higgs at the LHC
- Possible signatures of new physics, such as large Extra Dimensions

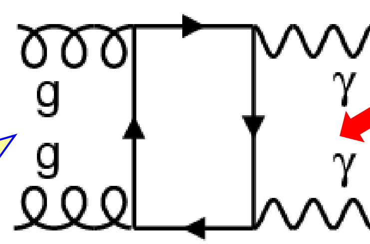
Leading order diagram:
dominant at
high di-photon mass
(Higgs background at LHC)



fragmentation:



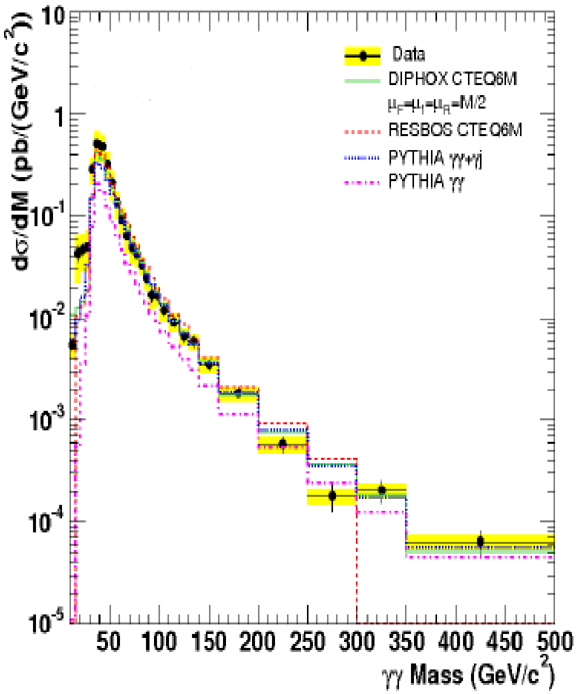
Next-to-next-to leading order contribution
→ suppressed by factor alphas²
But important at low mass
→ large gluon density

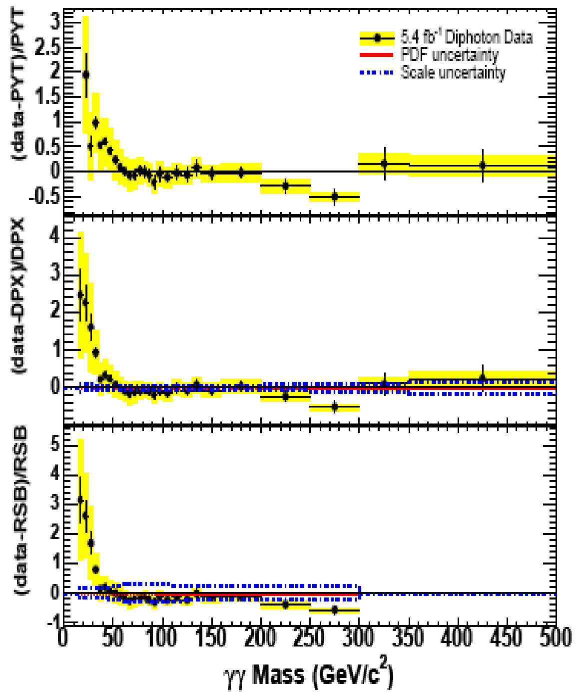


- **ResBos**:
  - NLO prompt di-photons
  - LO fragmentation contribution
  - Resummed initial state gluon radiation (important for qT)
- **DIPHOX**:
  - NLO prompt di-photons
  - NLO fragmentation (1 or 2 γ)
  - NNLO gg→γγ diagram
- **PYTHIA**
- **SHERPA**

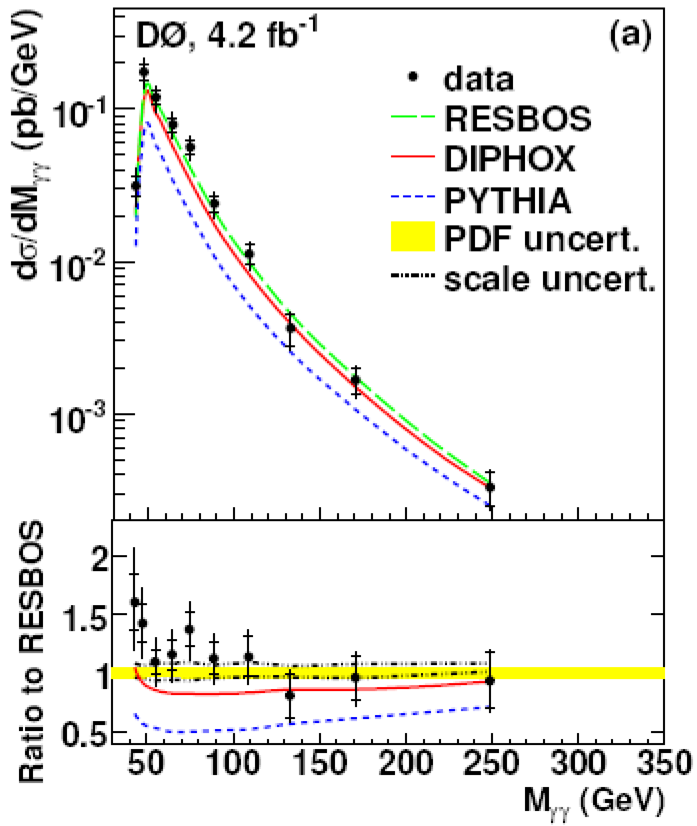
Di-photon Mass

arXiv:1106.5123 - submitted to Phys. Rev. Lett. and Phys Rev. D





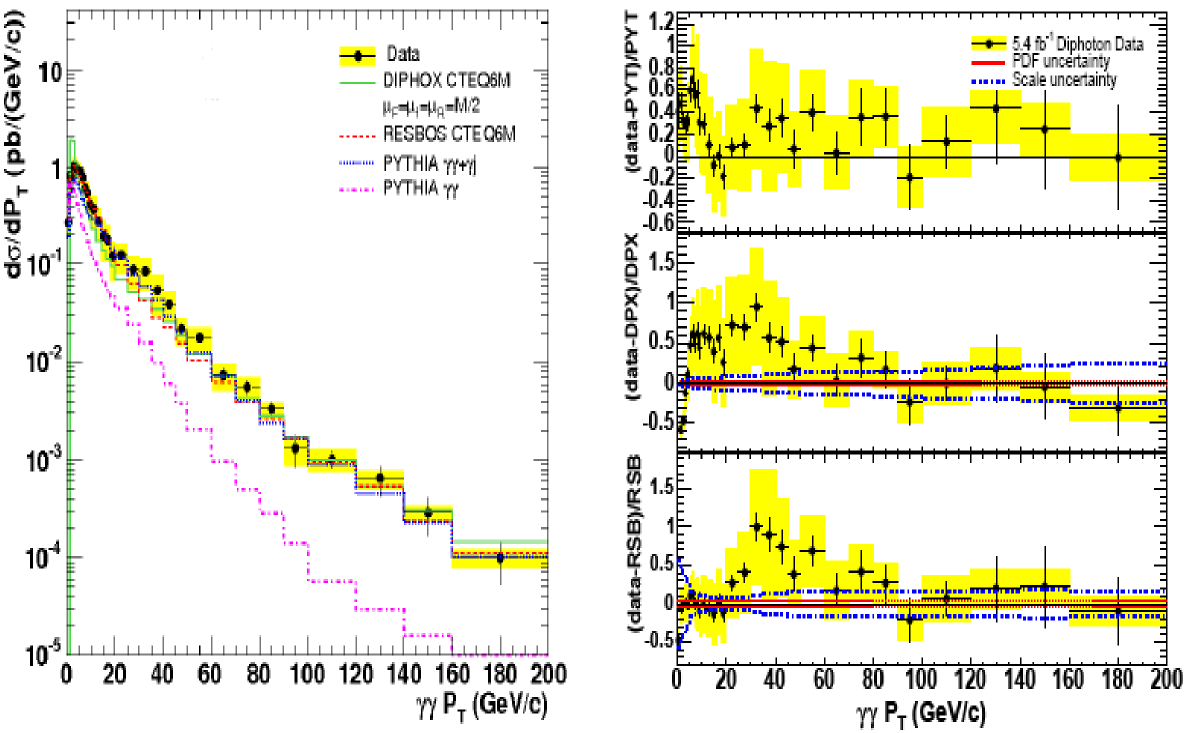
Phys. Lett. B 690, 108 (2010)



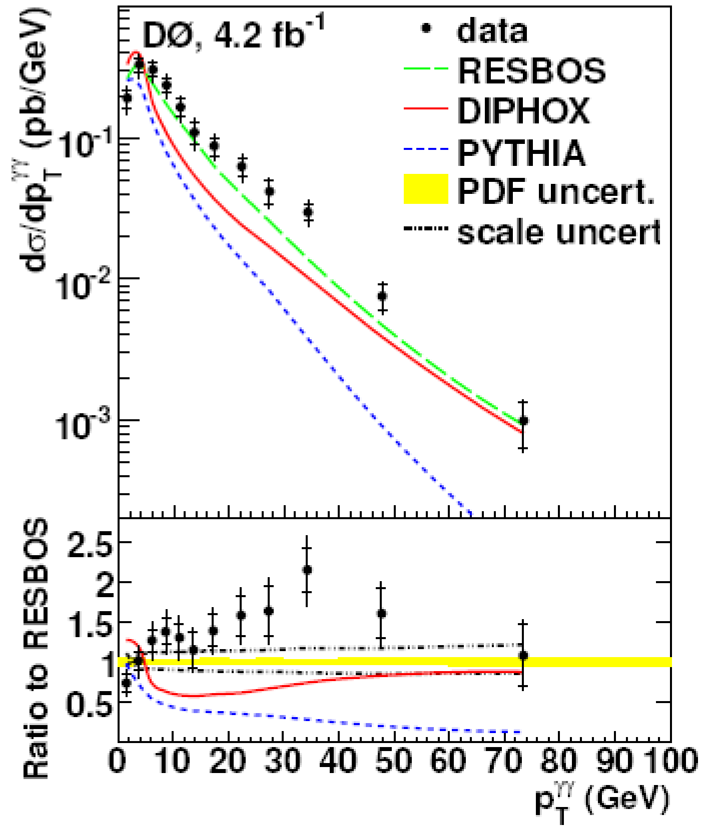
→ agreement between CDF and D0 data
→ theory describes data at high mass (> 50 GeV)
→ at low mass: theory too high

Di-photon p_T

arXiv:1106.5123 - submitted to Phys. Rev. Lett. and Phys Rev. D



Phys. Lett. B 690, 108 (2010)

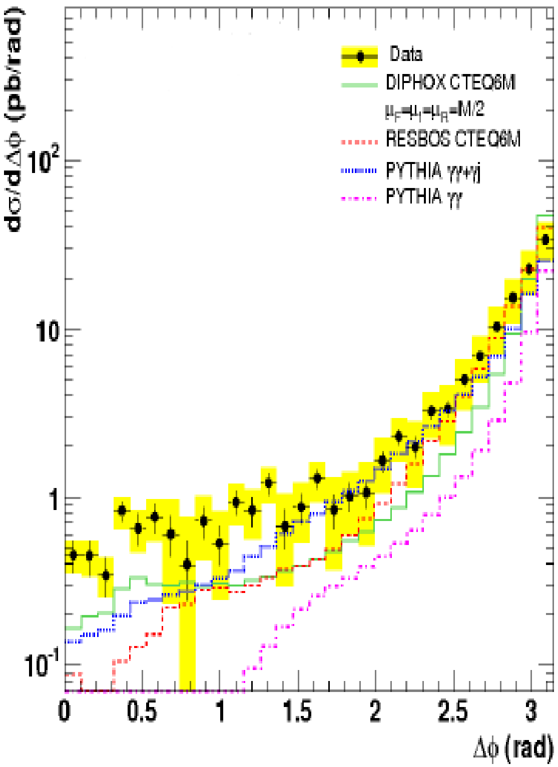


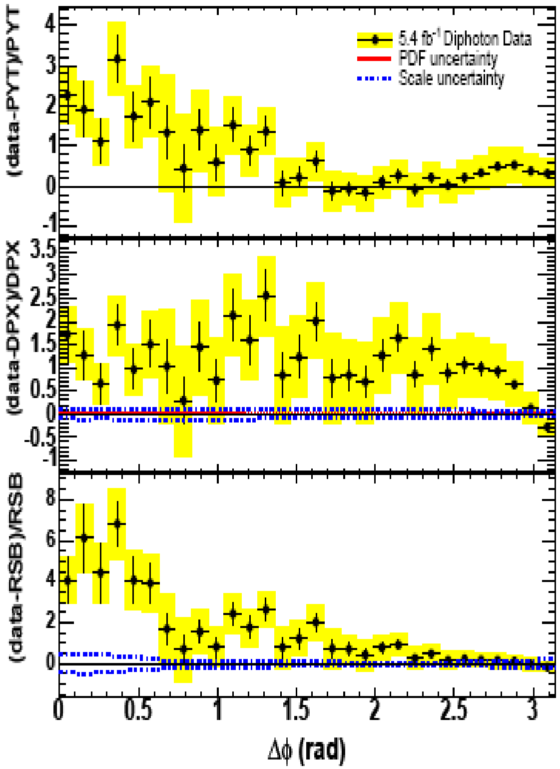
→ between 20-50 GeV: theory does not describe data

→ RESBOS (resummed gluon contributions) describes pT < 20 GeV

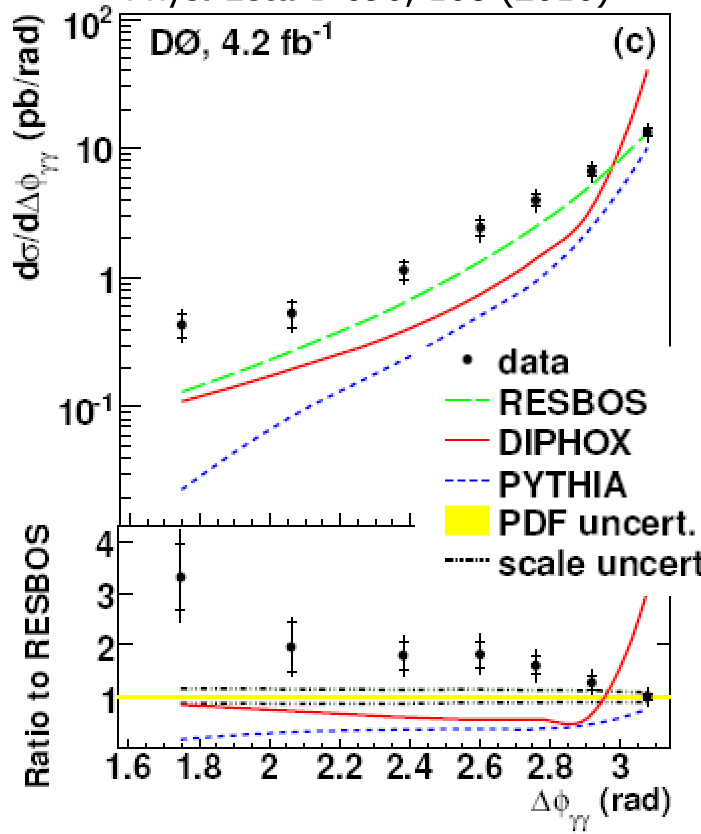
Di-photon $\Delta\phi$

arXiv:1106.5123 - submitted to Phys. Rev. Lett. and Phys Rev. D





Phys. Lett. B 690, 108 (2010)



→ no theory describes data over whole $\Delta\phi$ range

→ RESBOS (resummed gluon contributions) describes $\Delta\phi \rightarrow \pi$

Vector Boson + Jets

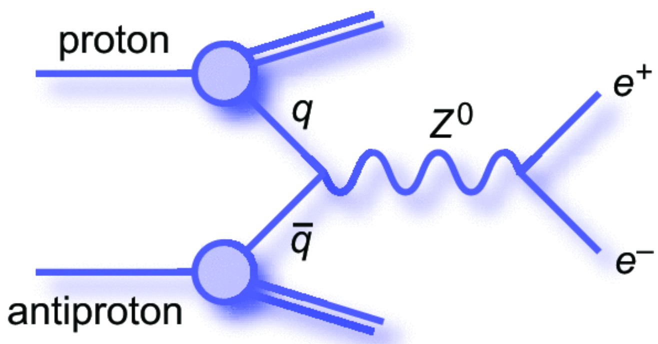
Fixed-order: NLO

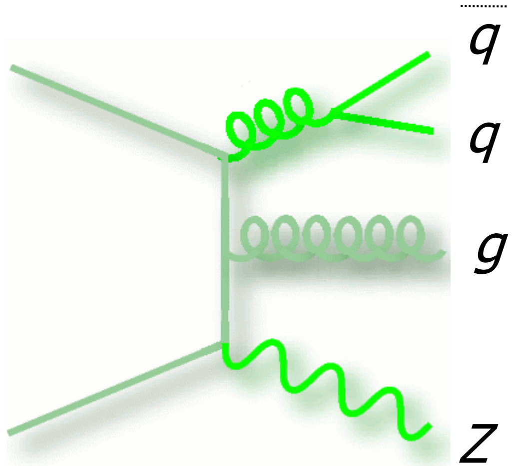
LO + Parton Shower

Matched Tree-Level + PS

Backgrounds to New Physics

Vector Boson + Jet





- relevant to other high-multiplicity processes
- background to Higgs
- test "matched" predictions → critical to Tevatron / LHC physics

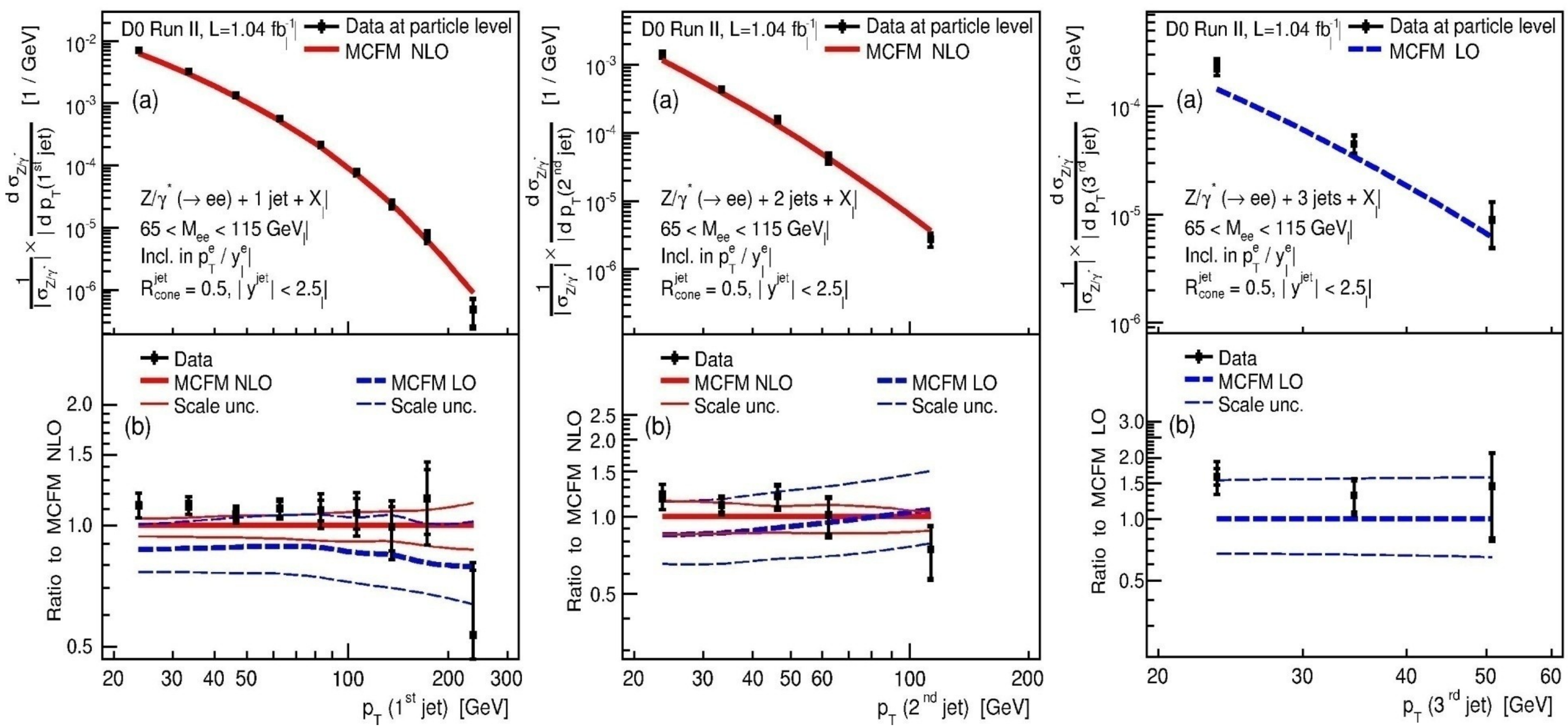
Provide detailed measurements of p_T and angular distributions of vector boson and jet
→ test perturbative QCD calculations
→ testing and tuning of phenomenological models

Z + jets → p_T –jet

Measurement of 1st, 2nd and 3rd jet p_T in Z events:
→normalize to inclusive Z production (cancel some uncertainties)
compare to pQCD @ LO / NLO

Phys. Lett. B 669, 278 (2008)

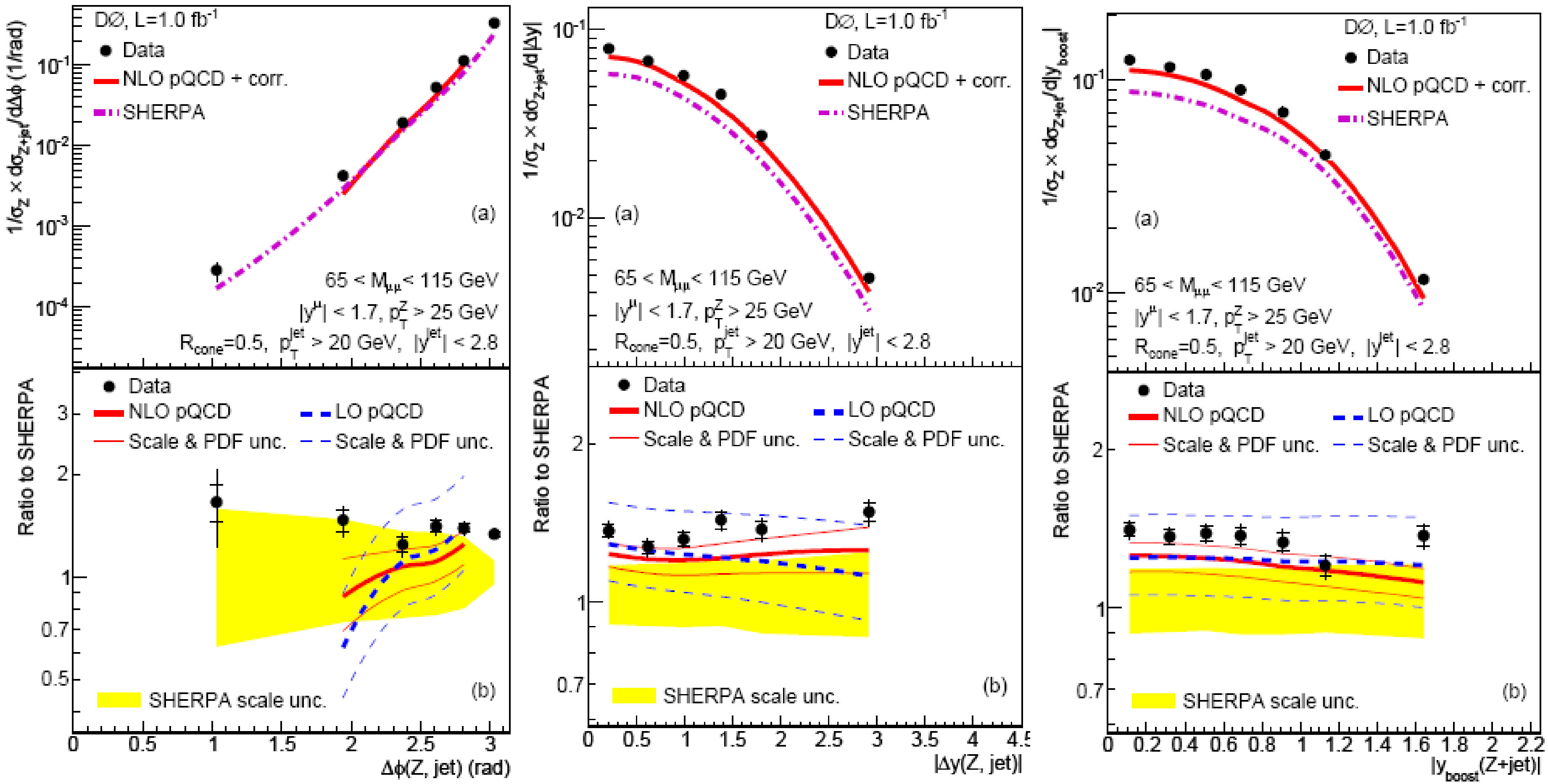
Leading jet in Z + jet + X **Second jet in Z + 2jet + X** **Third jet in Z + 3jet + X**



NLO describes data within scale range LO not too bad

Z + jets (angular distrib.)

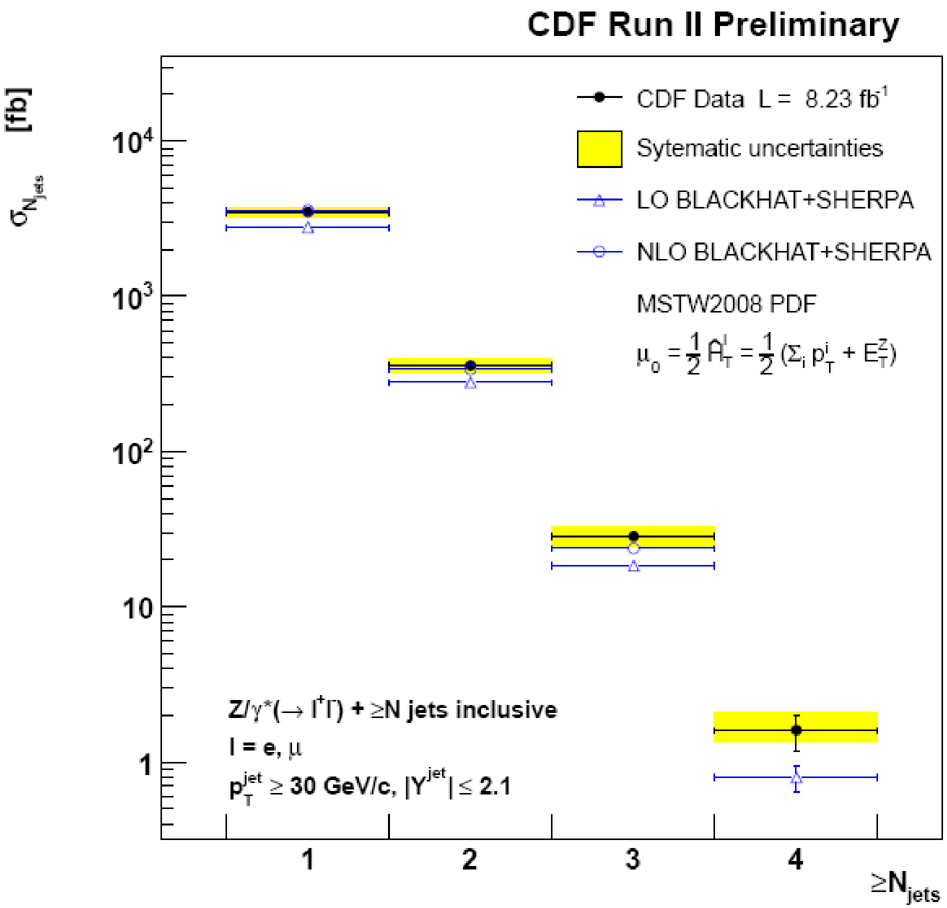
Angular variables: $\Delta\phi$(Z,jet) $|\Delta y|$(Z,jet) $|y_{boost}|$(Z,jet)



Overall: decent agreement

Z + jets

new preliminary CDF result (8.2fb^{-1}) Z($\rightarrow$ll) + *n* jets *n*=1-4, l=e,μ



Measure comprehensive set of differential distributions

→ detailed test of LO / NLO pQCD predictions (Blackhat+SHERPA)

→NLO for *n*=1-3
→LO for *n*=4

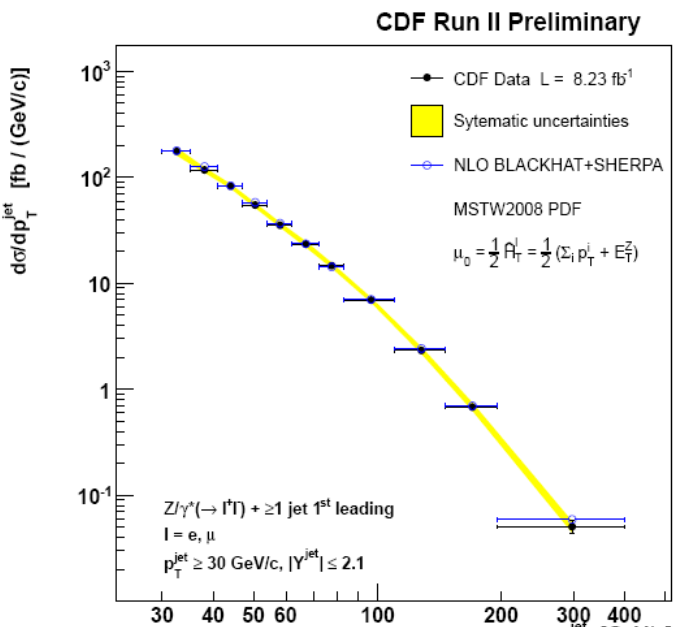
Here: cross section vs. jet multiplicity

→ described for n=1,2,3 (NLO)

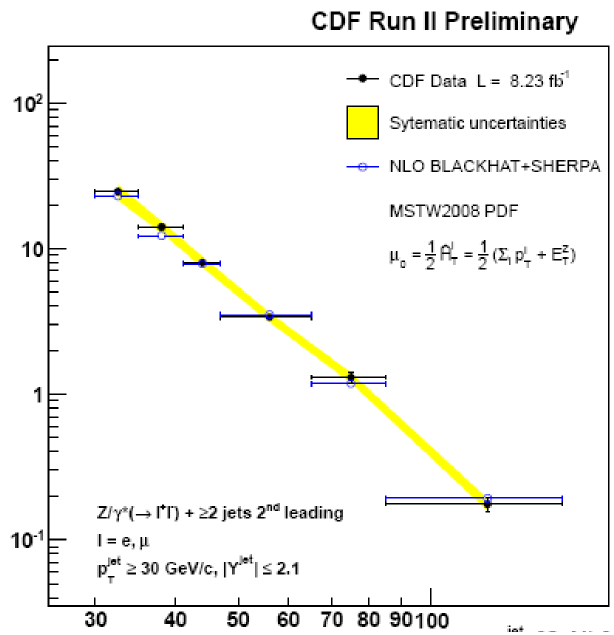
Z + jets

brandnew preliminary CDF result (8.2fb^{-1}) Z(→ll) + *n* jets n=1-4, l=e,μ

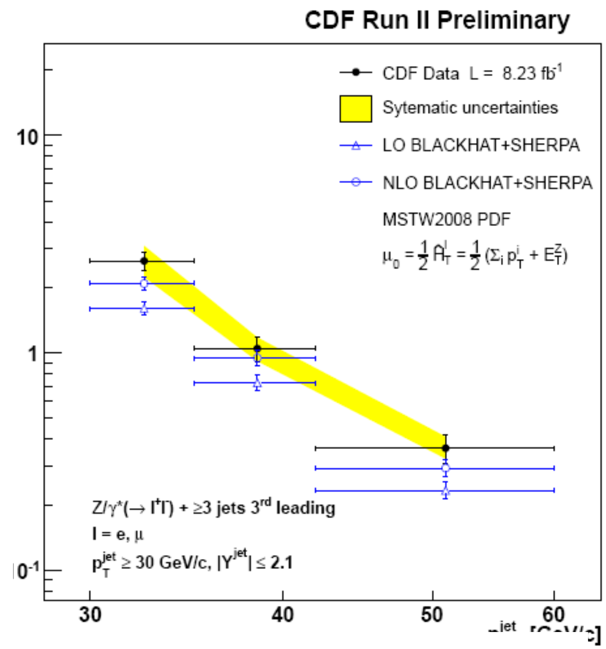
Here: p_{Tjet} distributions for jet #1, 2, 3



p_{Tjet1} (GeV/c)



p_{Tjet2} (GeV/c)



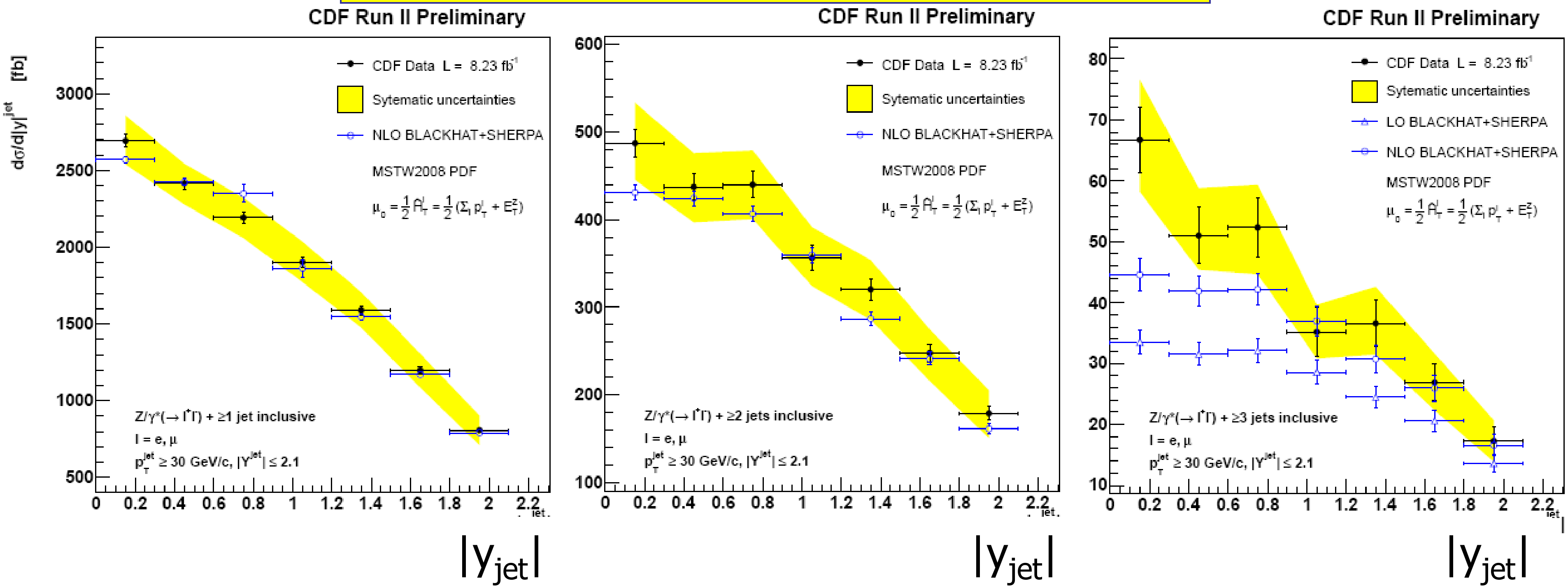
p_{Tjet3} (GeV/c)

→ good agreement for jets #1, #2

Z + jets

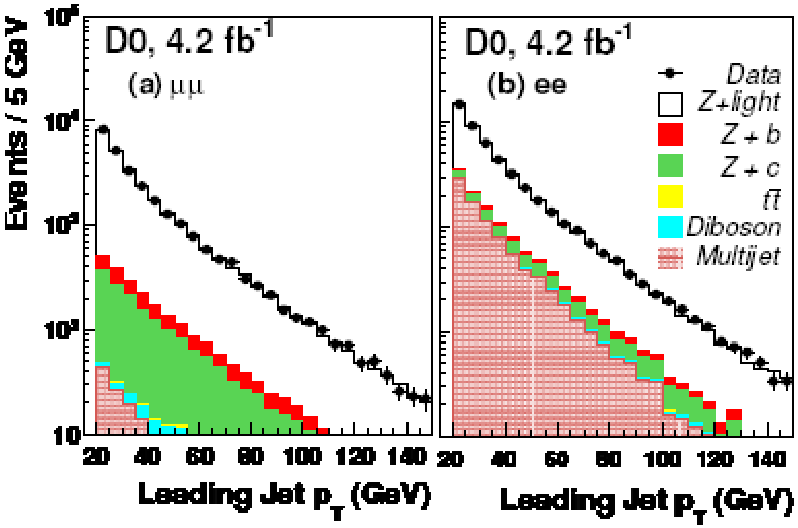
brandnew preliminary CDF result (8.2fb^{-1}) Z(→ll) + *n* jets n=1-4, l=e,μ

Here: rapidity distributions for jet #1, 2, 3

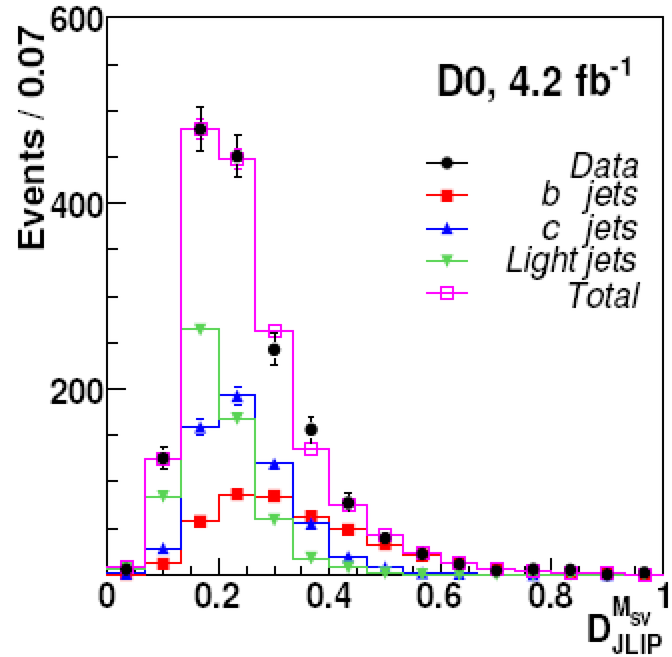


→ good agreement for jet #1, reasonable for #2, poor for #3 (large k-factor)

Z+ b jet



Discriminant distribution



$$\frac{\sigma(Z + b\,\text{jet})}{\sigma(Z + \text{jet})} = 0.0193 \pm 0.0022(\text{stat}) \pm 0.0015(\text{syst})$$

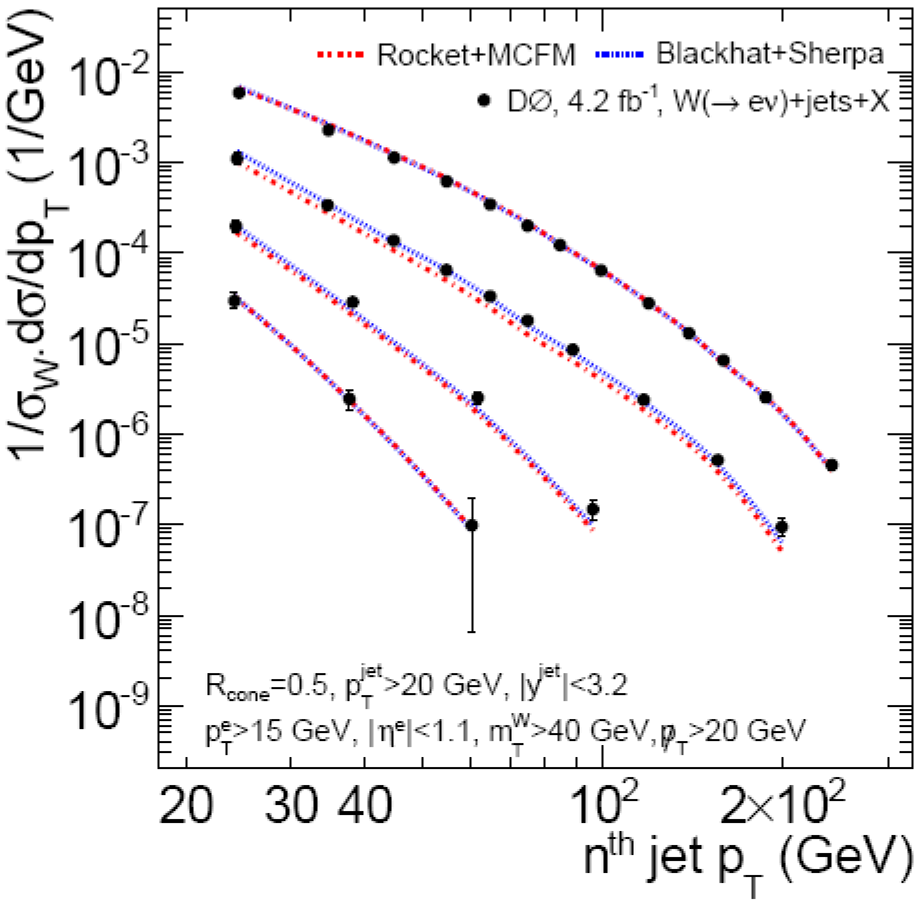
NLO MCFM

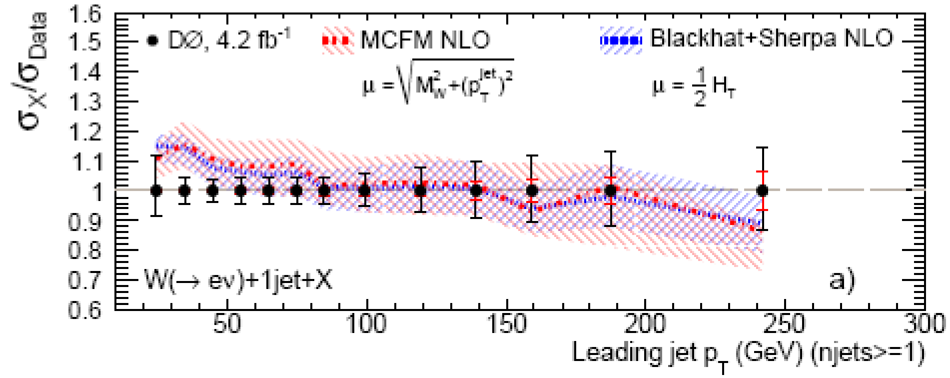
$$0.0192 \pm 0.0022$$

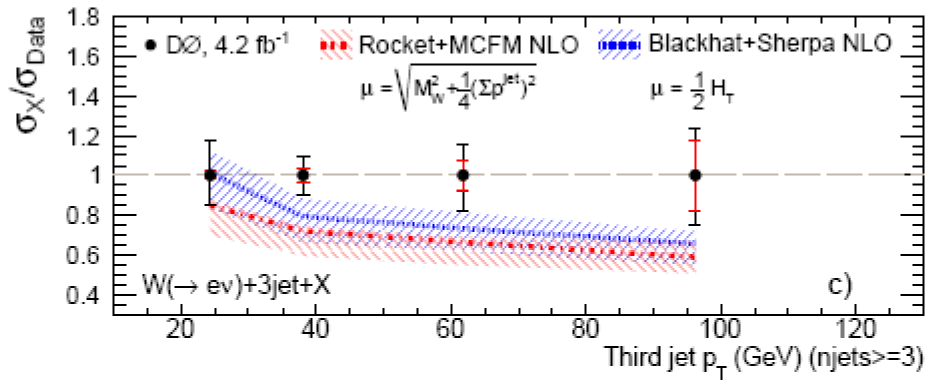
prediction decreases by 3.6% when the effects from detector response, resolution as well as hadronization and underlying event are taken into account.

W+jets

p_{Tjet} distributions for jet #1, 2, 3, 4 → test NLO (n=1,2,3) LO (n=4)







NLO describes 1st jet well – 3rd jet less well

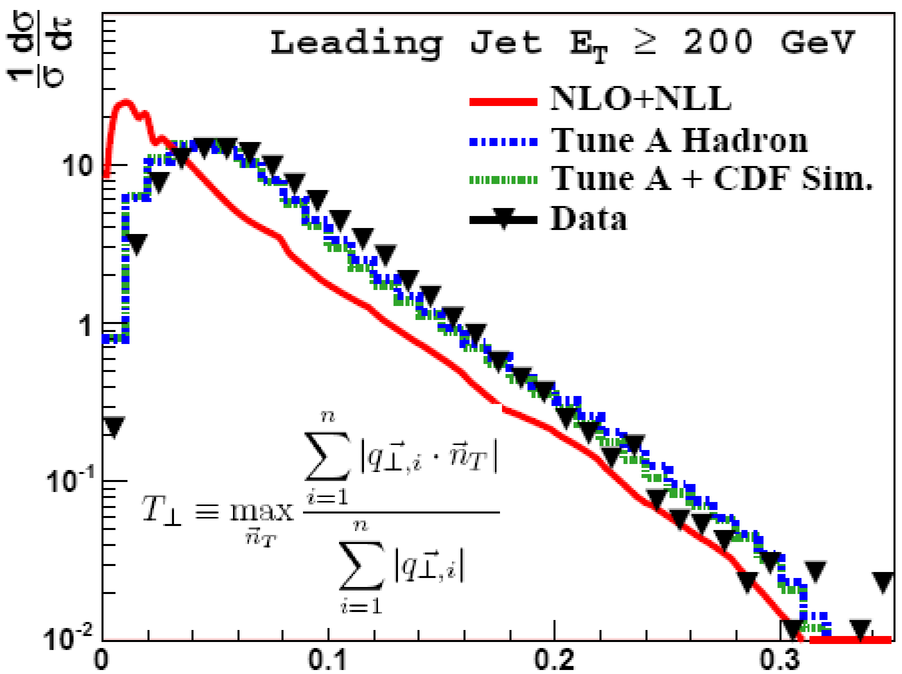
Event Shapes

Successfully used in e+e- collisions

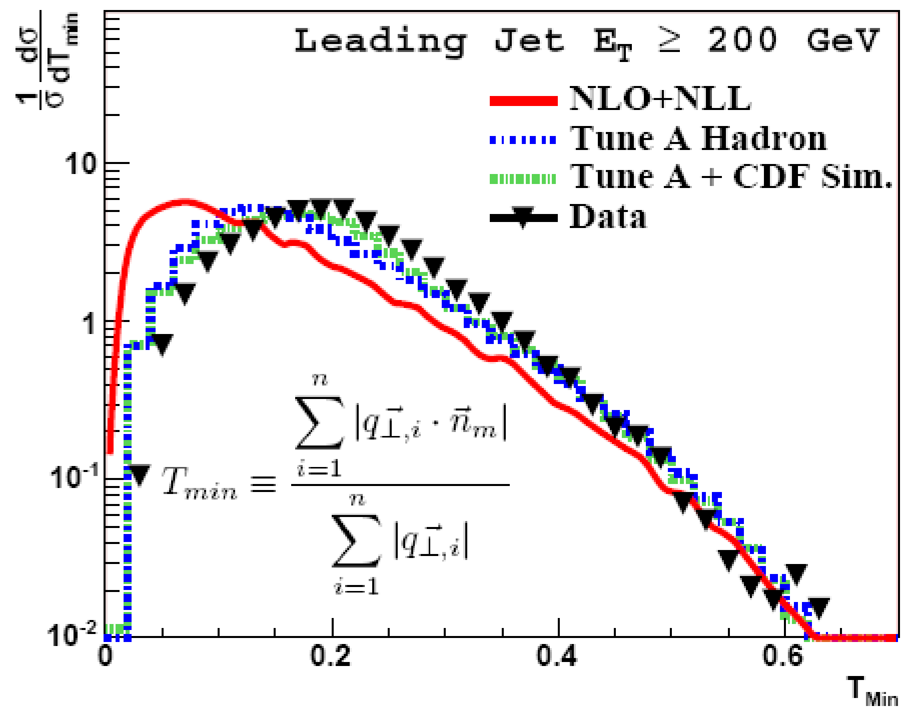
→ first tests at hadron colliders

Event Shapes

Theory: A. Banfi, G. Salam and G. Zanderighi J. High Energy Phys. 1006, 038 (2010).



$$\tau \equiv 1 - T_\perp$$



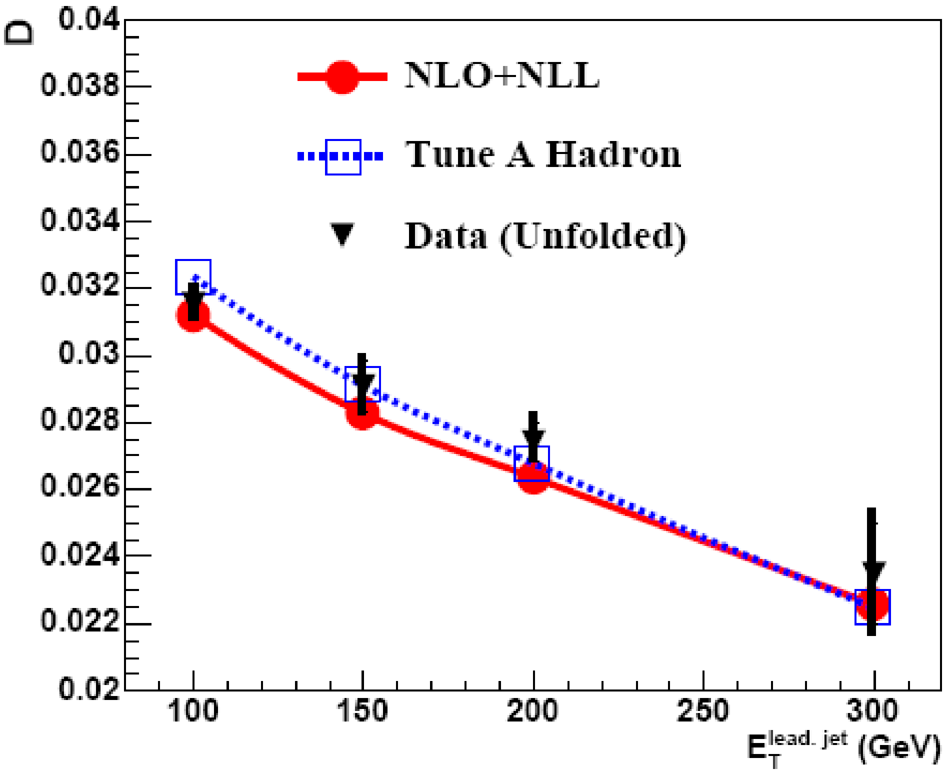
New CDF measurement of transverse thrust and thrust minor
(show uncorrected data)
→ Large underlying event corrections

Event Shapes

Define new variable
"thrust differential"
as a weighted sum of T_{min} and τ

$$D(\langle\tau\rangle, \langle T_{min}\rangle) = \gamma_{MC}(\alpha \langle T_{min}\rangle - \beta \langle\tau\rangle)$$

→ Insensitive to underlying event



Present (corrected) average values of <D> as a function of $E_T^{leading\ jet}$
→Compared to PYTHIA (tune A)
→and to analytical NLO+NLL calculation (parton-level) in CEASAR

A. Banfi, G. P. Salam and G. Zanderighi, J. High Energy Phys. 0408, 062 (2004).

→ See also recent CMS result: events shapes based on jets

Jets

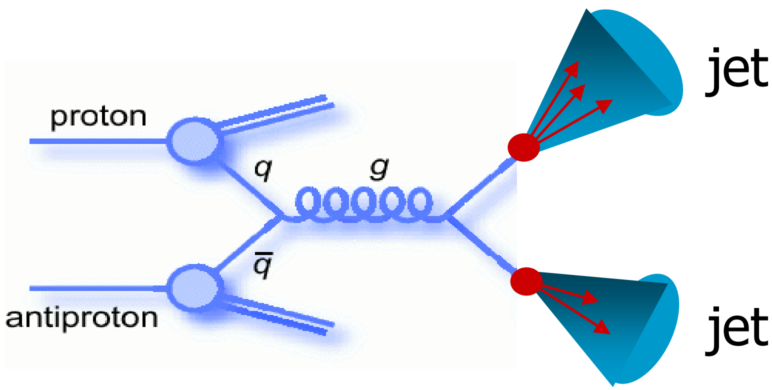
SM production well-understood

→ use data for SM and NP phenomenology

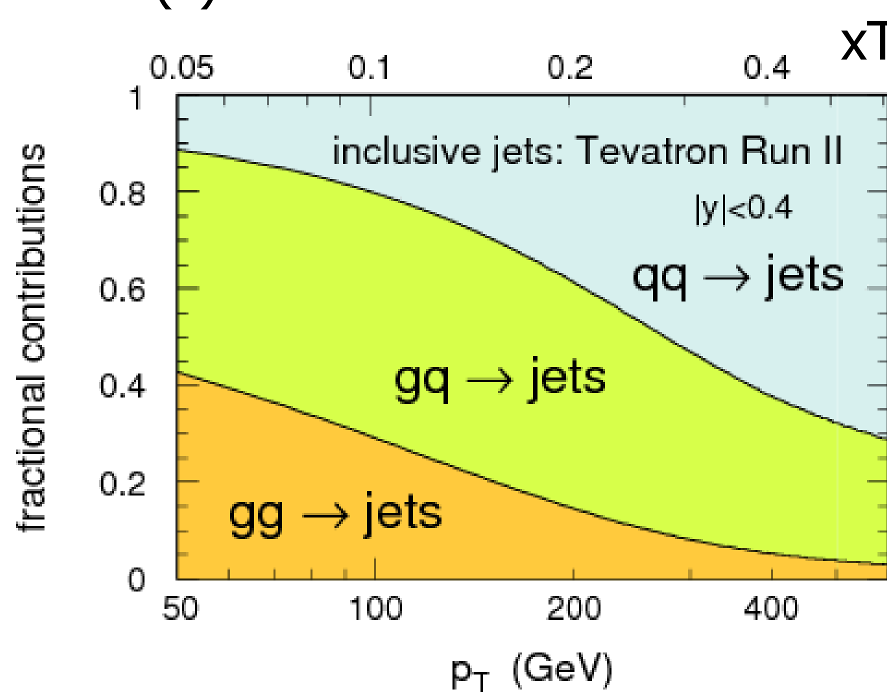
→ quantitative results

Jet Production

largest high pT cross section
at a hadron collider
→ **highest energy reach**



Unique sensitivity to **new physics**:
- new particles decaying to jets,
- quark compositeness,
- extra dimensions,
- …(?)…

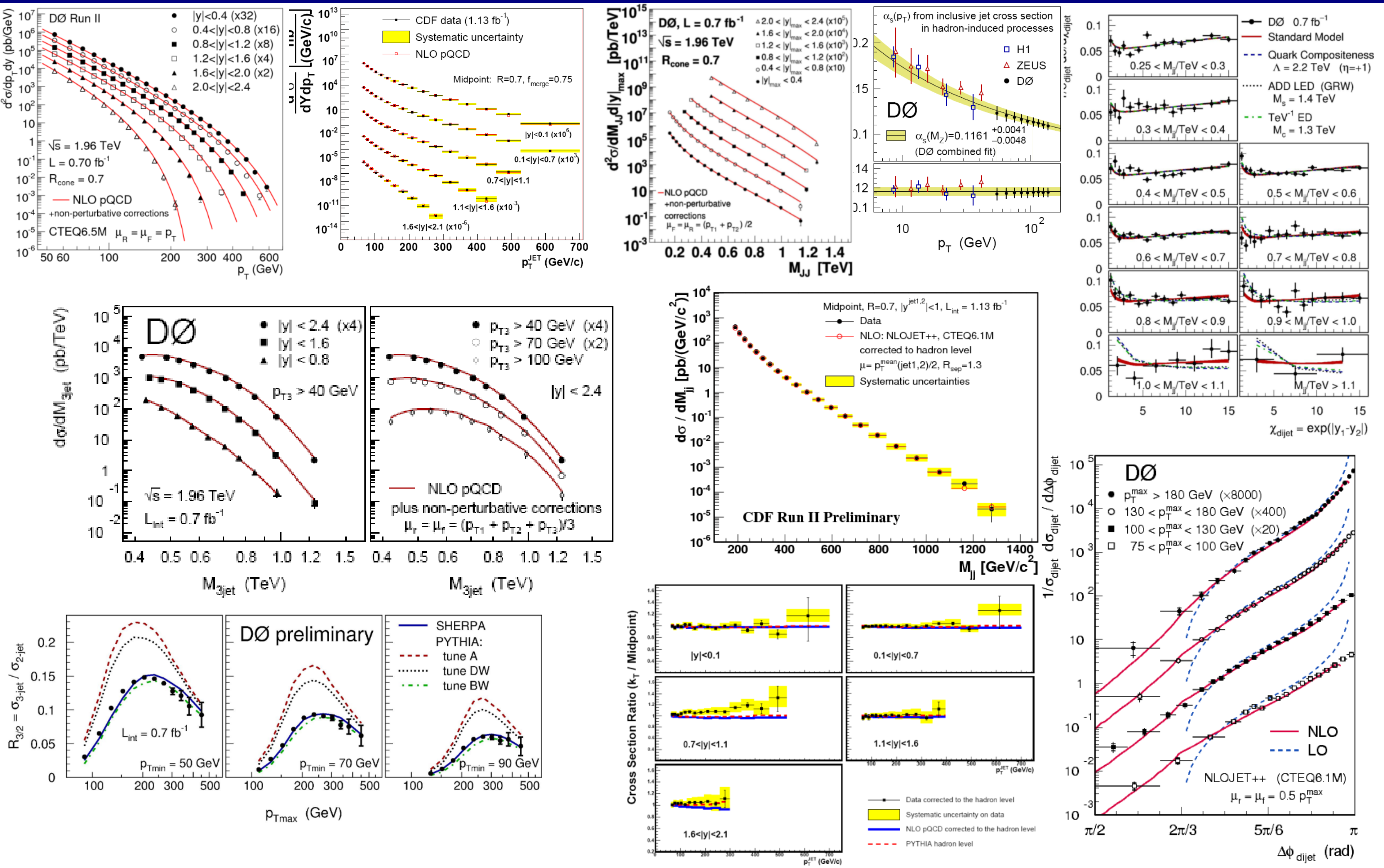


In the absence of new physics:

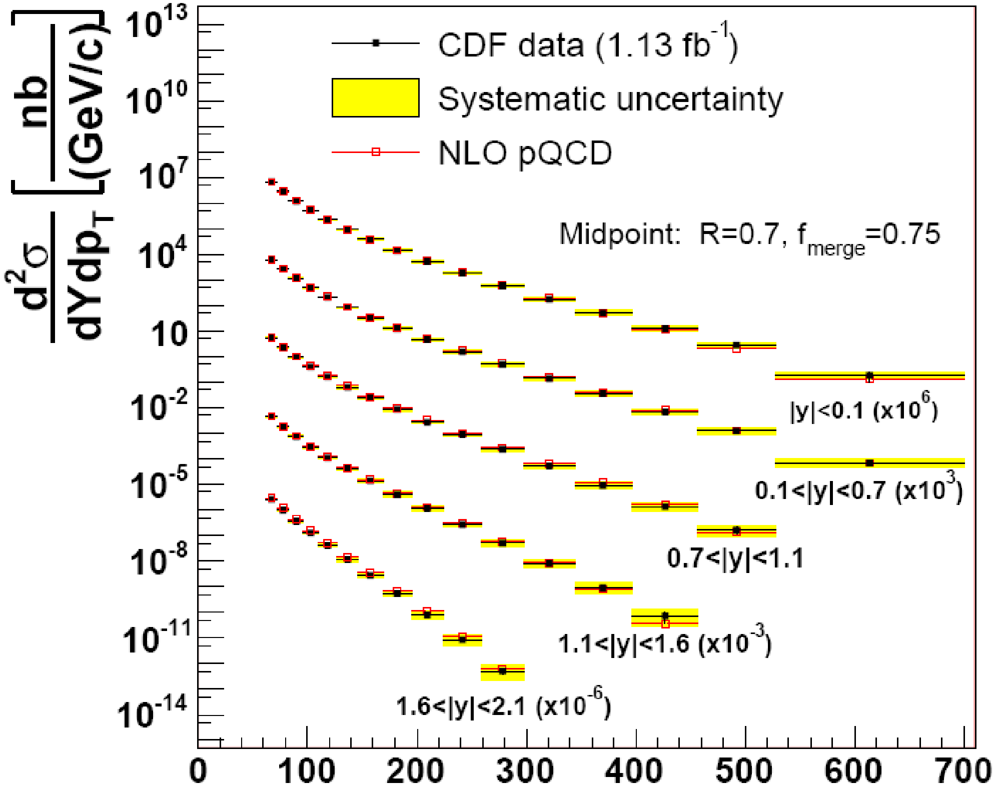
theory @NLO is reliable (10%)

→ **Precision phenomenology**
- sensitivity to PDFs → high-x gluon
- sensitive to

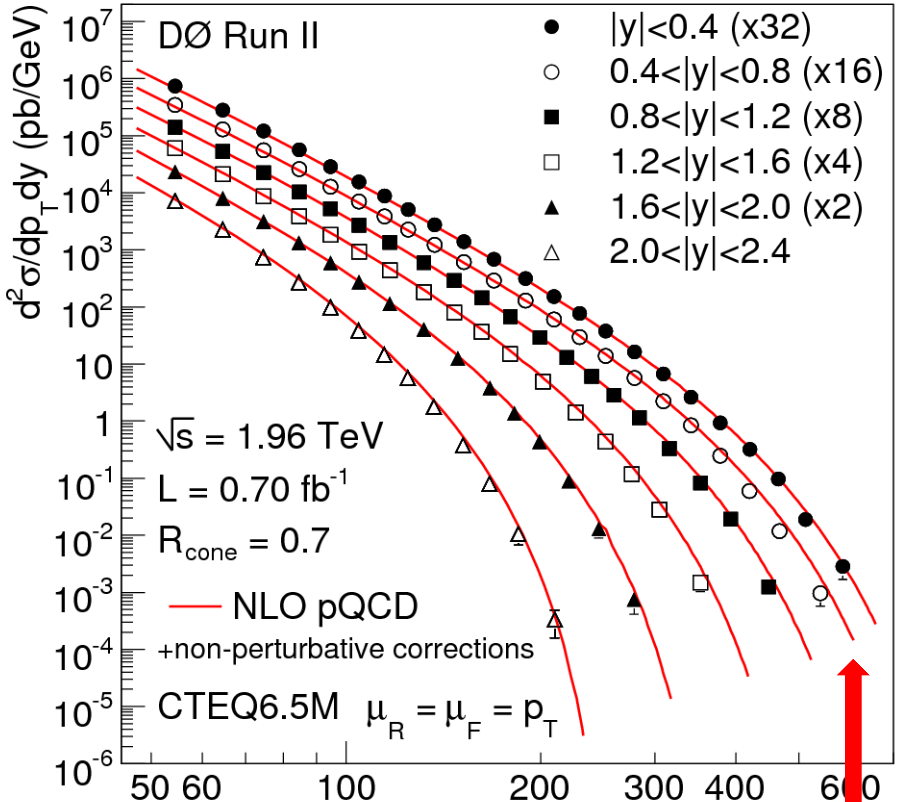
TeV Run II Jet Results



Inclusive Jets



Phys. Rev. D 78, 052006 (2008) **p_T (GeV)**



Phys. Rev. Lett. 101, 062001 (2008) **p_T (GeV)**

benefit from:

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

steeply falling p_T spectrum:

1% error in jet energy calibration

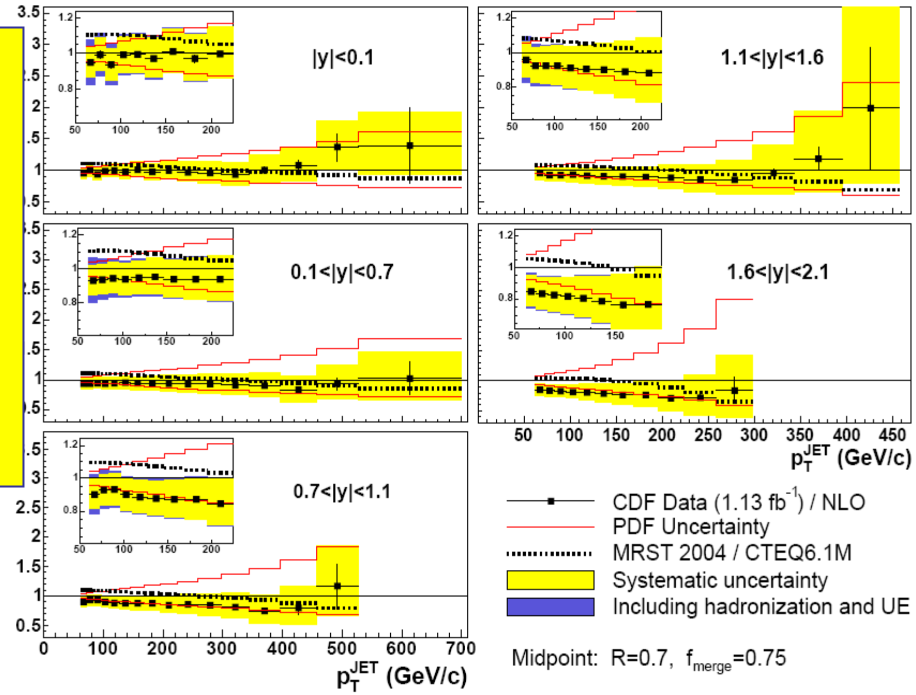
→ 5—10% (10—25%)

central (forward) x-section

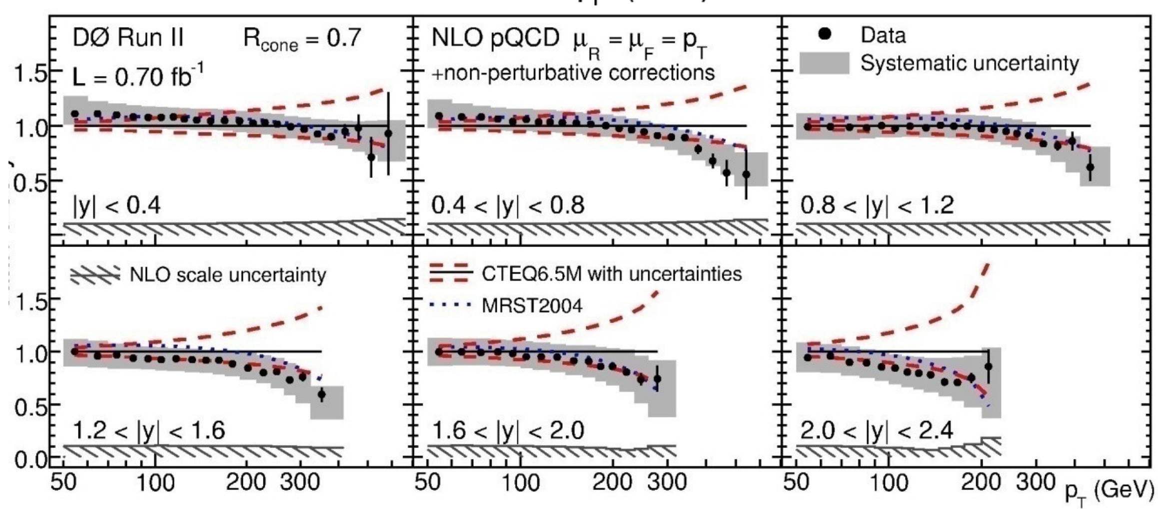
Inclusive Jets

- high precision results
- consistency between CDF/D0
- well-described by NLO pQCD
- experimental uncertainties:
  smaller than PDF uncertainties!!

→ sensitive to distinguish between PDFs



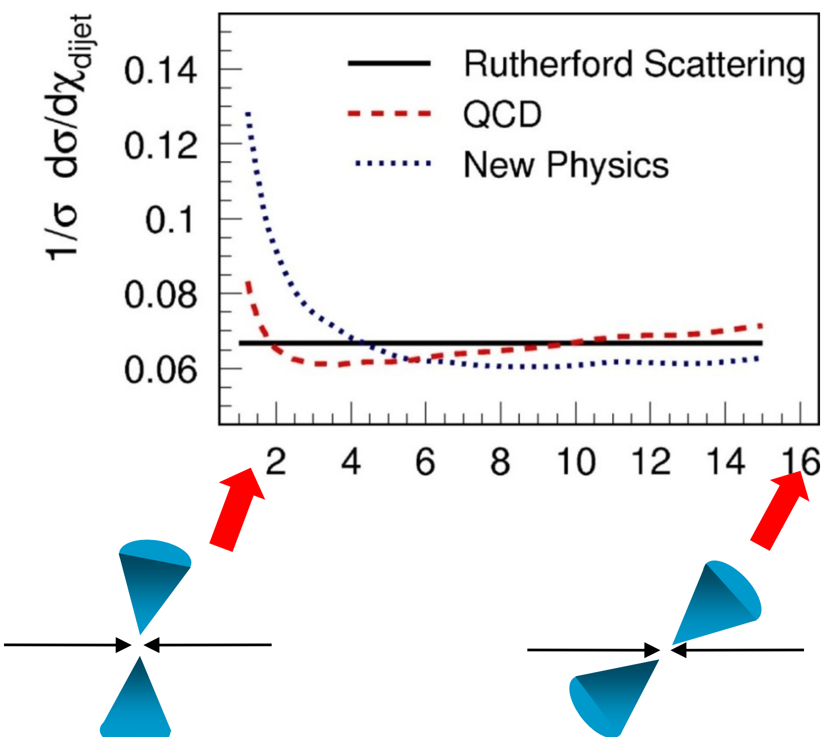
data are used in PDF fits:
- MSTW2008
- NNPDF2.0/2.1
- CT10



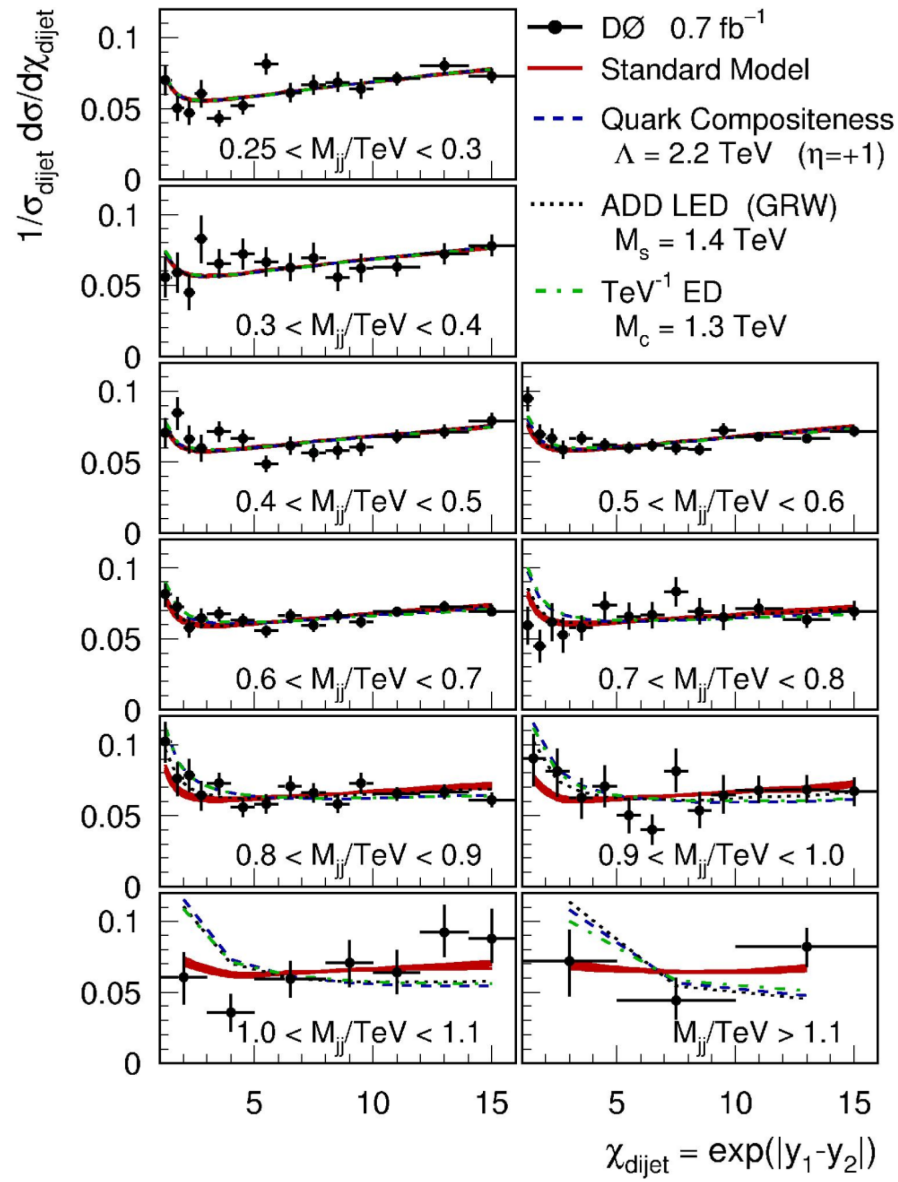
Dijet Angular Distribution

→ Redo the Rutherford Experiment

$$\chi_{\mathrm{dijet}} = \exp(|y_1 - y_2|) = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



small Δy **large Δy**



Dijet Angular Distribution

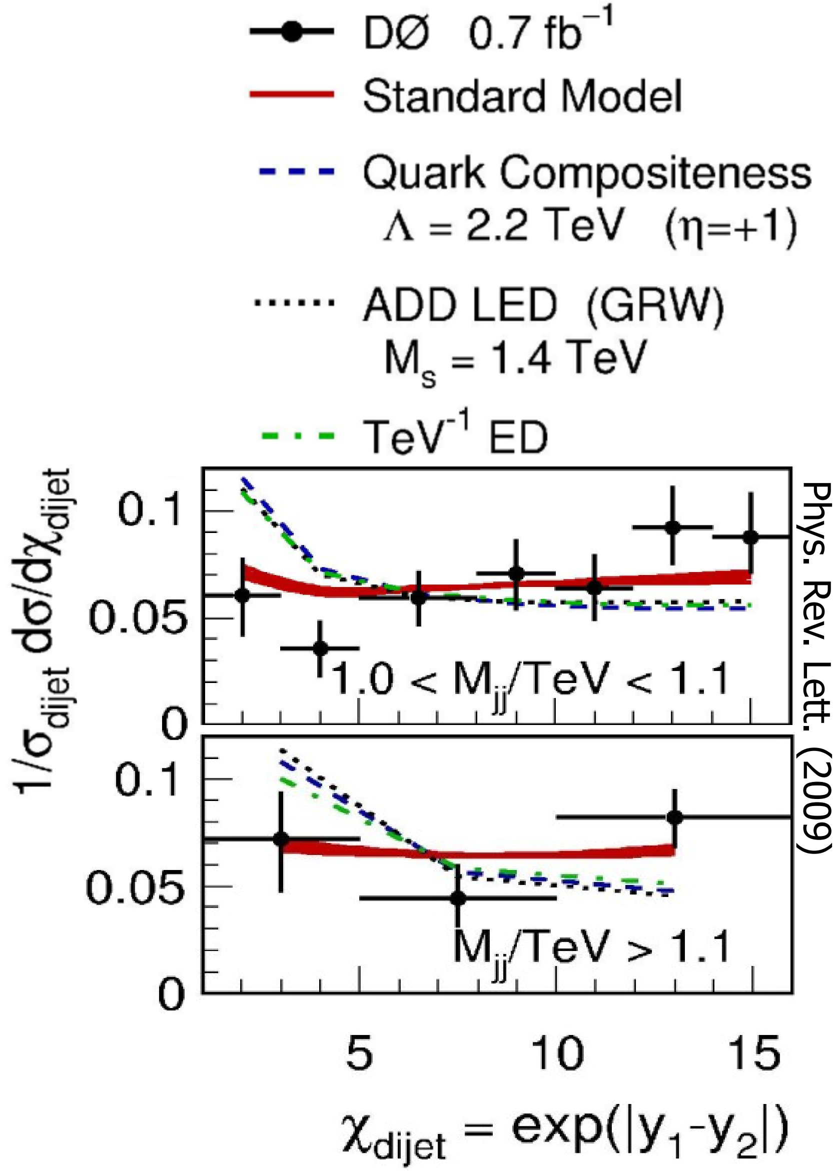
Measurement for dijet masses from 0.25 TeV to >1.1 TeV

→ First time:
Rutherford experiment above 1 TeV
→ Data described by Standard Model

Constrain models of Spatial Extra Dimensions and quark compositeness:

- Quark Compositeness Λ > 2.9TeV
- ADD LED (GRW) Ms > 1.6 TeV
- TeV^{-1} ED Mc > 1.6 TeV

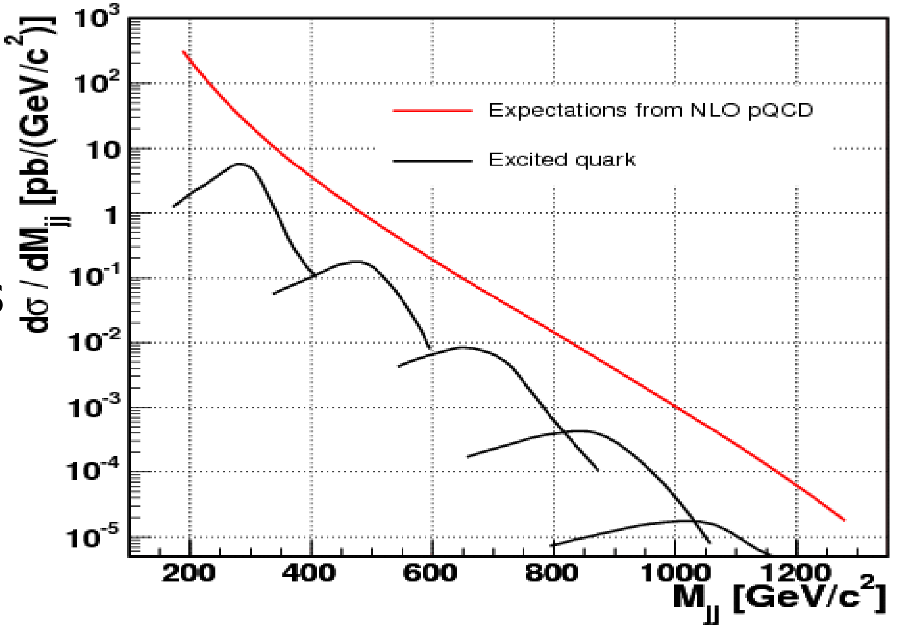
→ Most stringent pre-LHC limits



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, techni-rho, axigluons, colorons



Dijet Mass Distribution

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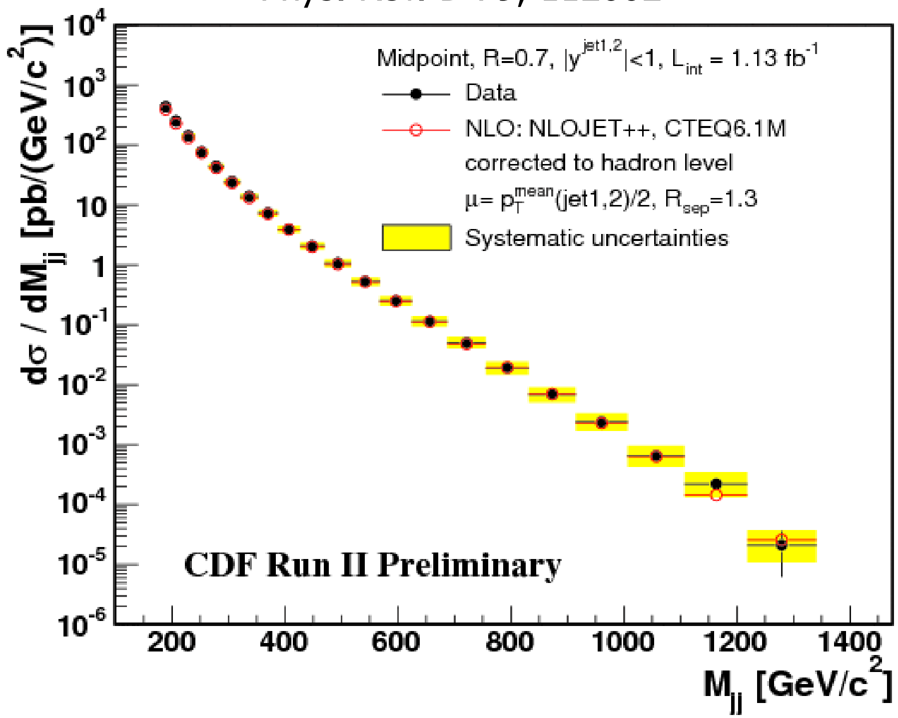
Phys. Rev. D 79, 112002

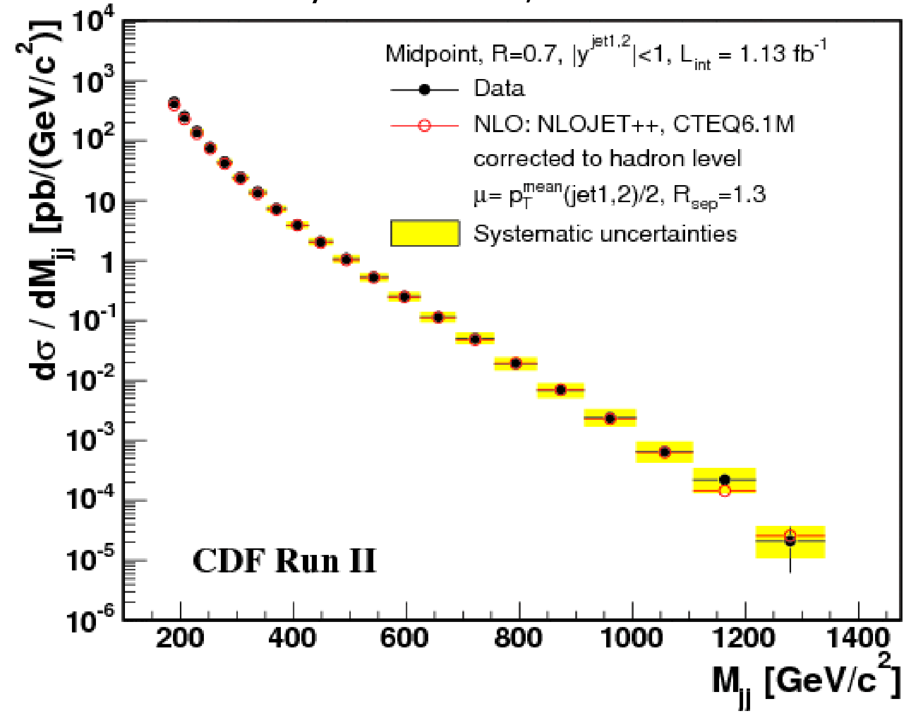


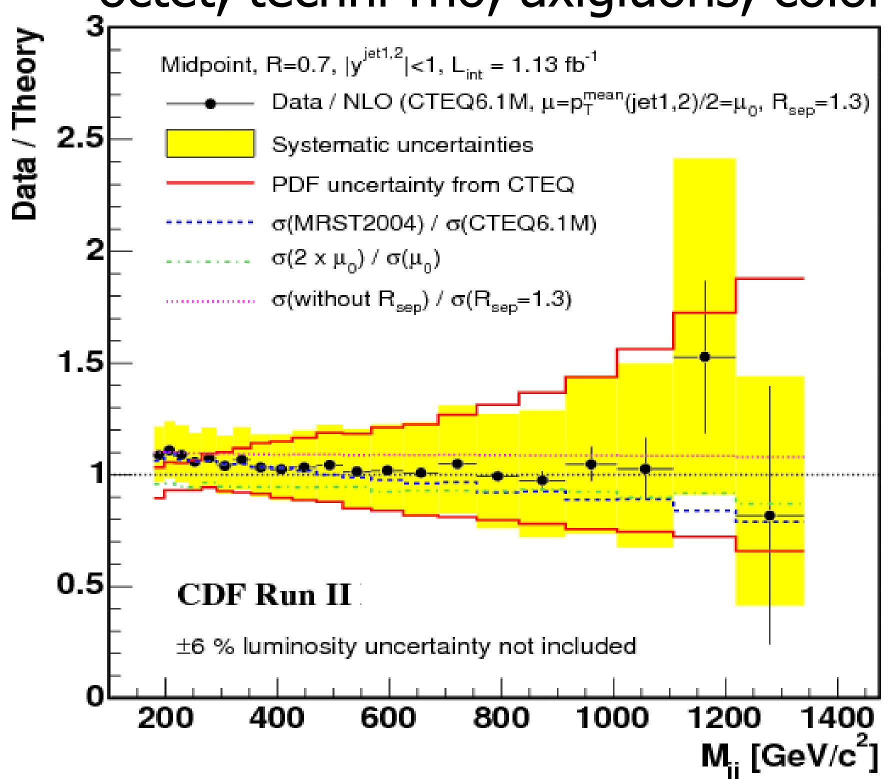
Dijet Mass Distribution

central dijet production $|y|<1$

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

Phys. Rev. D 79, 112002



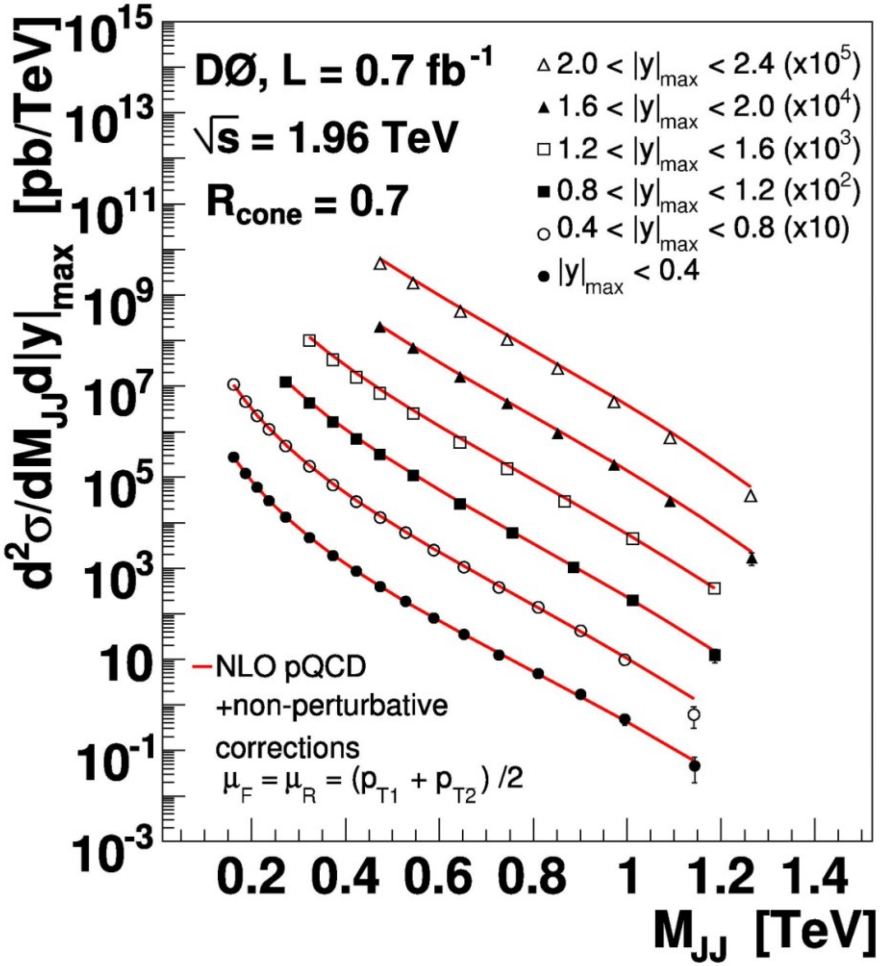


→ data with $M_{2\text{-jet}} > 1.2$ TeV !
→ all described by NLO pQCD

no indications for resonances
→ set limits on new particles

Dijet Mass Spectrum

Phys. Lett. B **693**, 531 (2010)



→ First measurement of rapidity dependence of dijet mass spectrum in six $|y|_{max}$ regions

$0 < |y|_{max} < 2.4$

→ extend QCD test to forward region

→ up to $M_{2\text{-jet}} > 1.2$ TeV

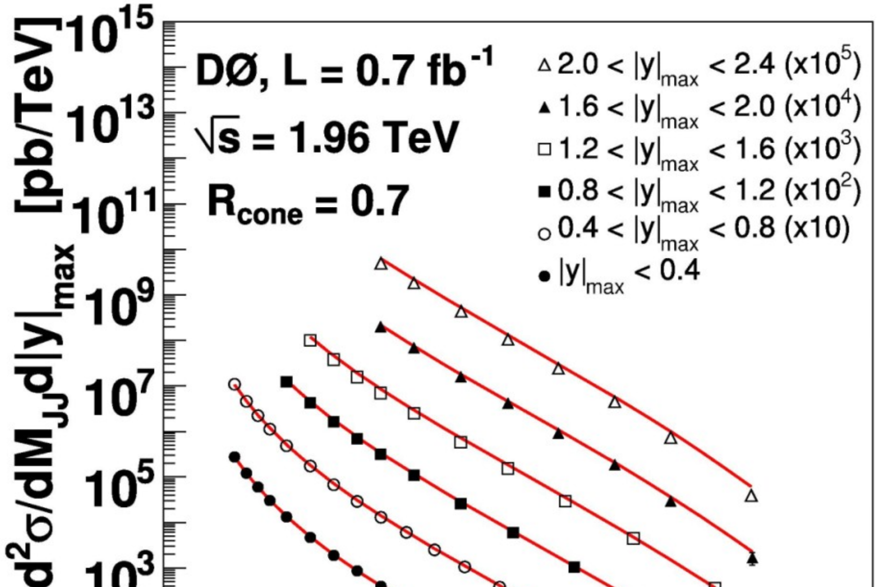
→ good agreement with Standard Model predictions

no hints for:

- dijet mass bumps (resonances, decaying into dijets)
- excess at high masses (indications of new physics at higher energies)

Dijet Mass Spectrum

Phys. Lett. B **693**, 531 (2010)



→ First measurement of rapidity dependence of dijet mass spectrum in six $|y|_{max}$ regions

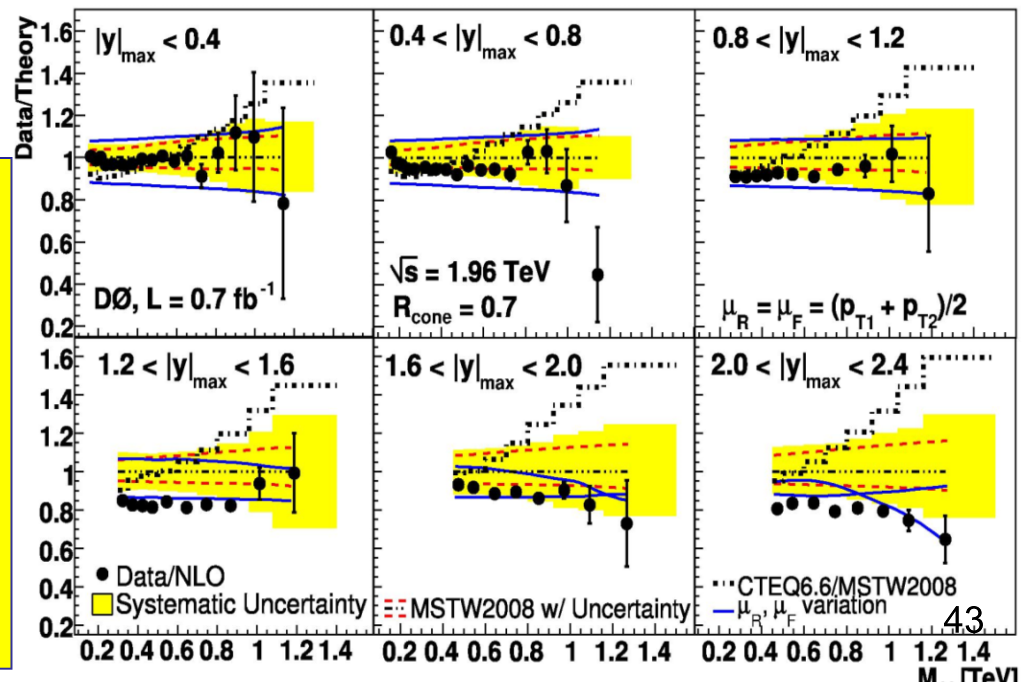
$0 < |y|_{max} < 2.4$

→ extend QCD test to forward region

→ up to $M_{2\text{-jet}}$ > 1.2 TeV

→ PDF sensitivity at large $|y|_{max}$

- MSTW2008 consistent w/ data (but correlation of experimental and PDF uncertainties!)
- CTEQ6.6 prediction too high (how significant? → CTEQ paper)
- theory uncertainty at large $|y|_{max}$



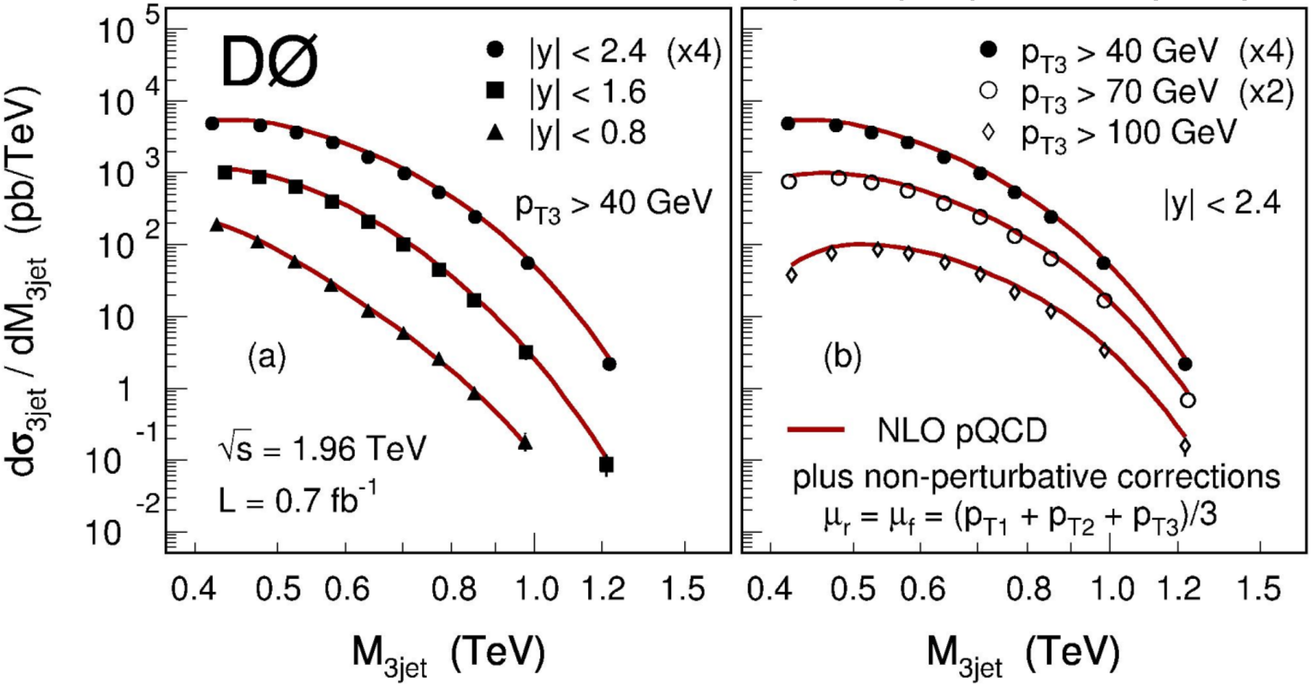
3-jet Mass Spectrum

accepted by Phys. Lett. B (2011)

2-jet cross section:
$O(\alpha_s^2)$ x PDF^2
(correlation of α and gluon density)

3-jet cross section:
$O(\alpha_s^3)$ x PDF^2

analyze 2-jet and 3-jet cross sections:
→ **decorrelate** α_s and gluon density in PDF fits

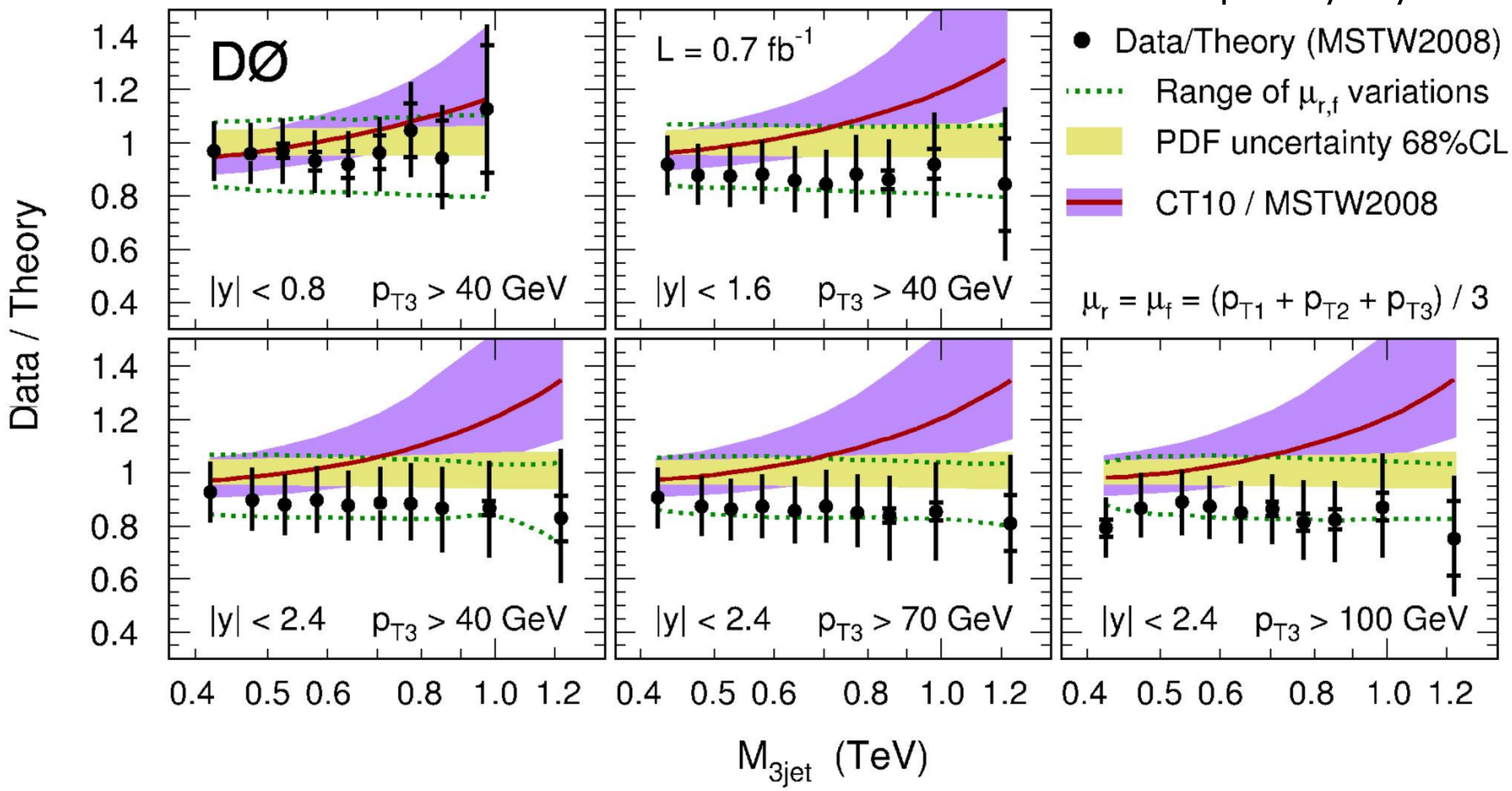


First Run II measurement of 3-jet cross section vs.
- rapidity $|y_{1,2,3}|$ (left)
- p_{T3} requirement (right)

→ up to $M_{3\text{-jet}}$ > 1.2 TeV
→ extend QCD tests to $O(\alpha_s^3)$ processes

$M_{3\text{-jet}}$ data/theory

Accepted by Phys. Lett. B (2011)

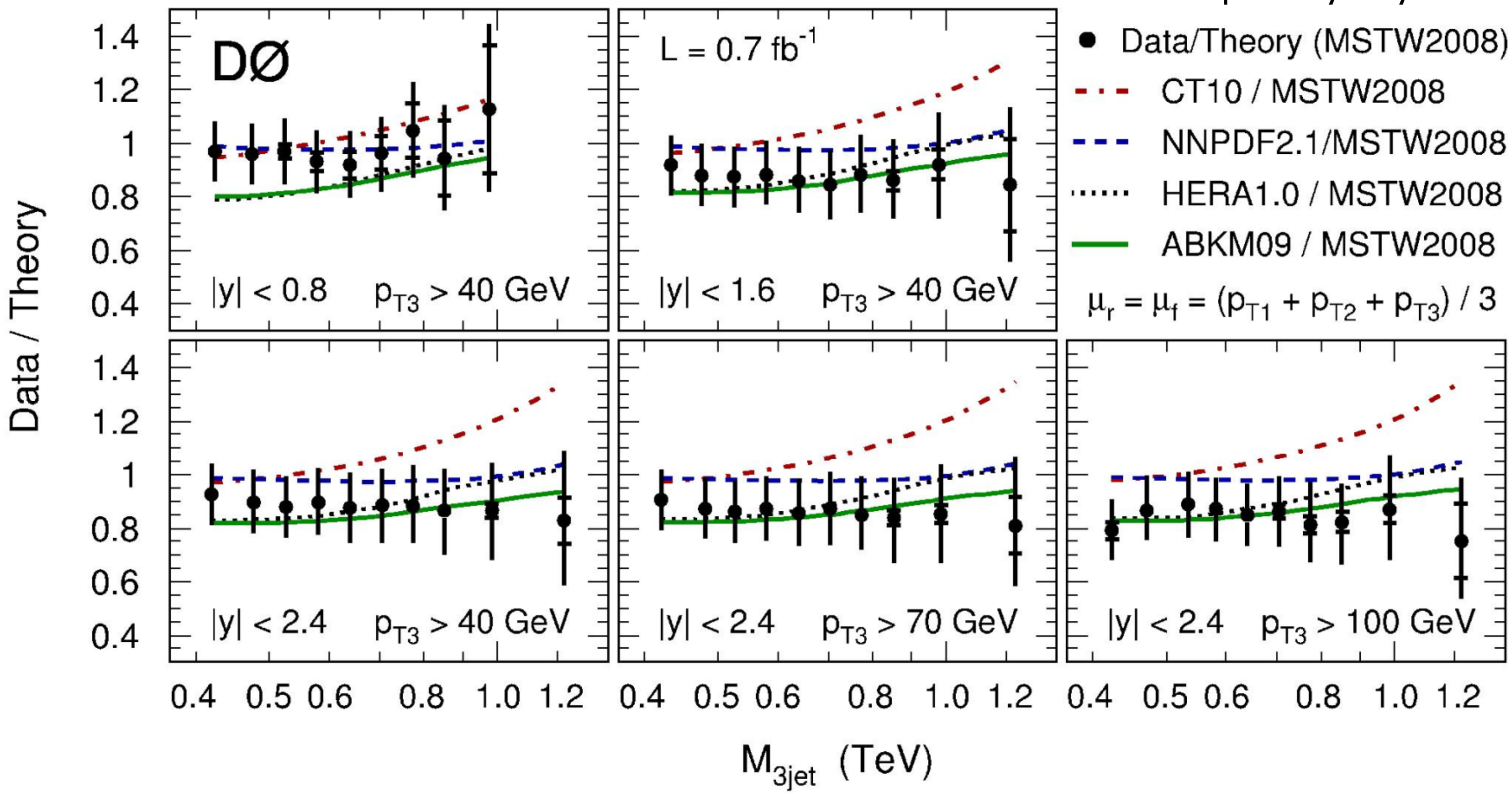


similar to dijet mass result:

- **MSTW2008**: slightly higher than data at all $M_{3\text{-jet}}$ (but consistent)
- **CT10** agrees at low $M_{3\text{-jet}}$ - different shape: too high at high $M_{3\text{-jet}}$
- CT10, MSTW2008 68% CL uncertainty bands: no overlap at high $M_{3\text{-jet}}$

$M_{3\text{-jet}}$ data/thy (other PDFs)

Accepted by Phys. Lett. B (2011)



compare all recent PDFs (MSTW2008, CT10, ABKM09, HERA1.0)

- NNPDF2.1 very similar to MSTW2008
- ABKM09 very similar to HERAPDF1.0 (5-20% lower than MSTW)
- CT10 has strong increase for $M_{3\text{-jet}}$ > 0.6 TeV (x > 0.3)

$M_{3\text{-jet}}$ detailed analysis

Agreement between theory and data depends on

- PDF
- Choice of $\alpha_s(M_Z)$ – especially since $\sigma_{3\text{-jet}}$ is of $O(\alpha_s^3)$
- Choice of scales μ_R, μ_F

Comments

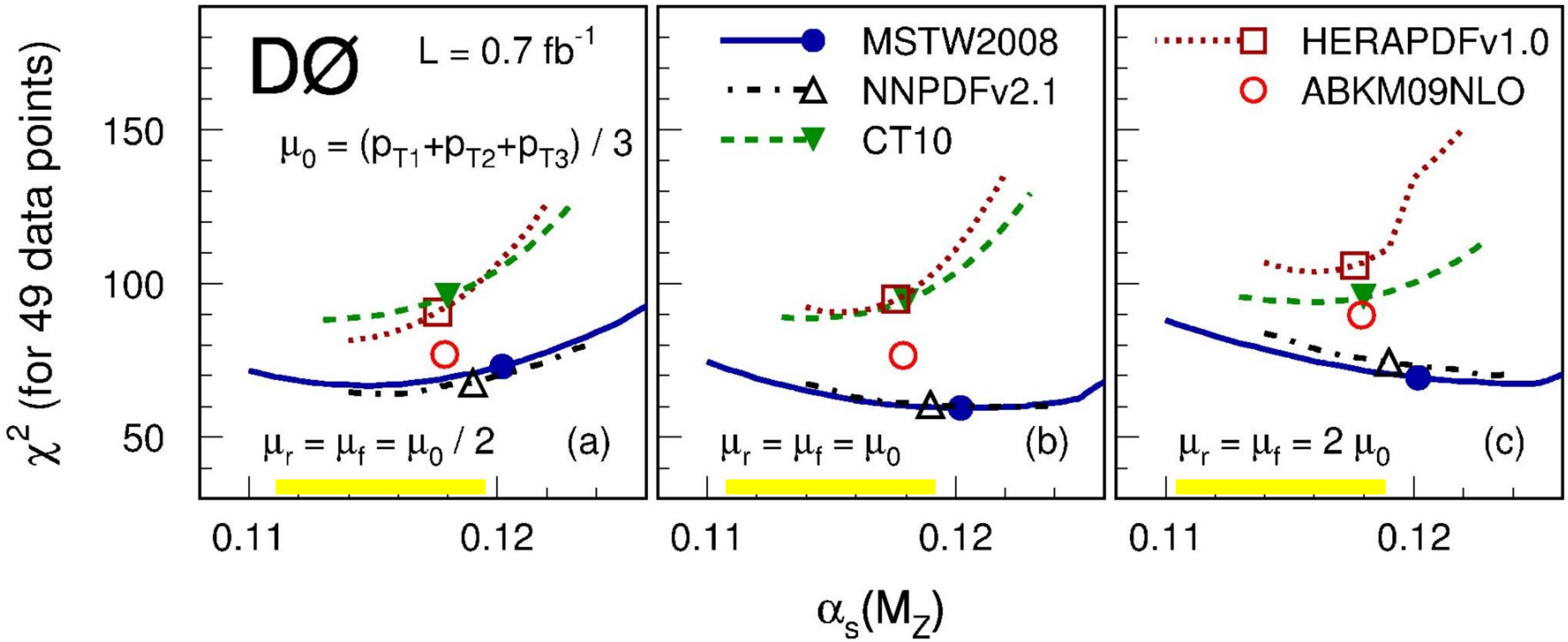
- Different PDF fits have different preferred $\alpha_s(M_Z)$ values
- Different PDF fits use a different scale for inclusive Tevatron jets:
  - CT10: $\mu_R, \mu_F = p_T/2$
  - other groups : $\mu_R, \mu_F = p_T$ (better behaved at large |y| which gives strong constraints for high-x PDFs)

For a fair comparison: study theory(PDF)/data agreement

- versus $\alpha_s(M_Z)$
- for different scales $\mu_R, \mu_F = \mu_0, \mu_0/2, 2\mu_0$
  with $\mu_0 = (p_{T1} + p_{T2} + p_{T3}) / 3$

$M_{3\text{-jet}}$ detailed analysis

Accepted by Phys. Lett. B (2011)

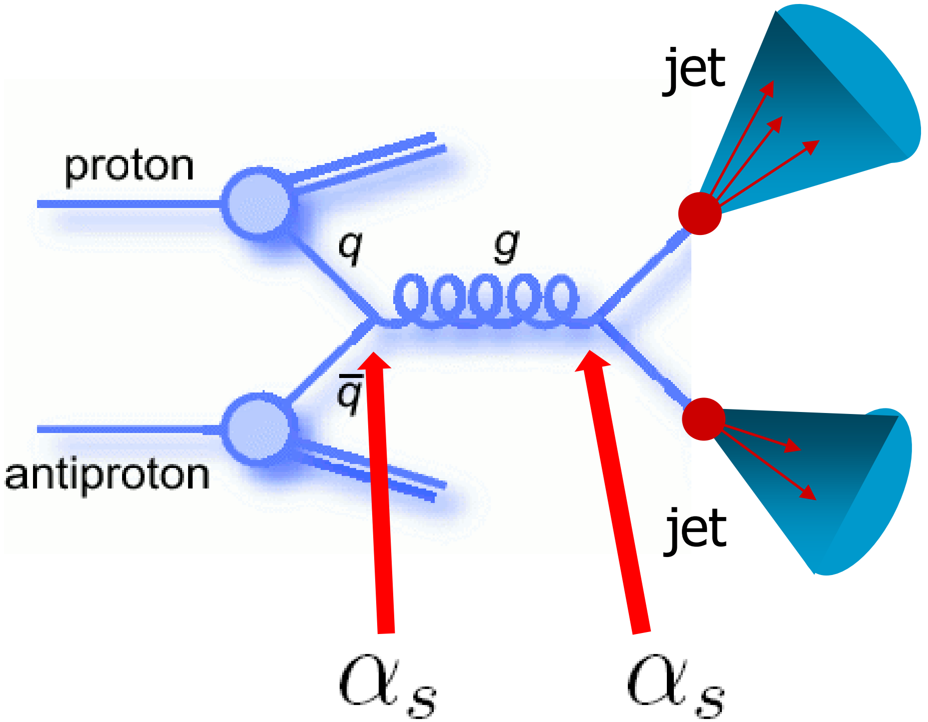


Find that previous conclusions are independent of μ_R, μ_F and $\alpha_s(M_Z)$ choices

Best agreement for MSTW2008/NNPDF for μ_R, μ_F = μ_0 and $\alpha_s(M_Z)$ = world average

Strong Coupling Constant

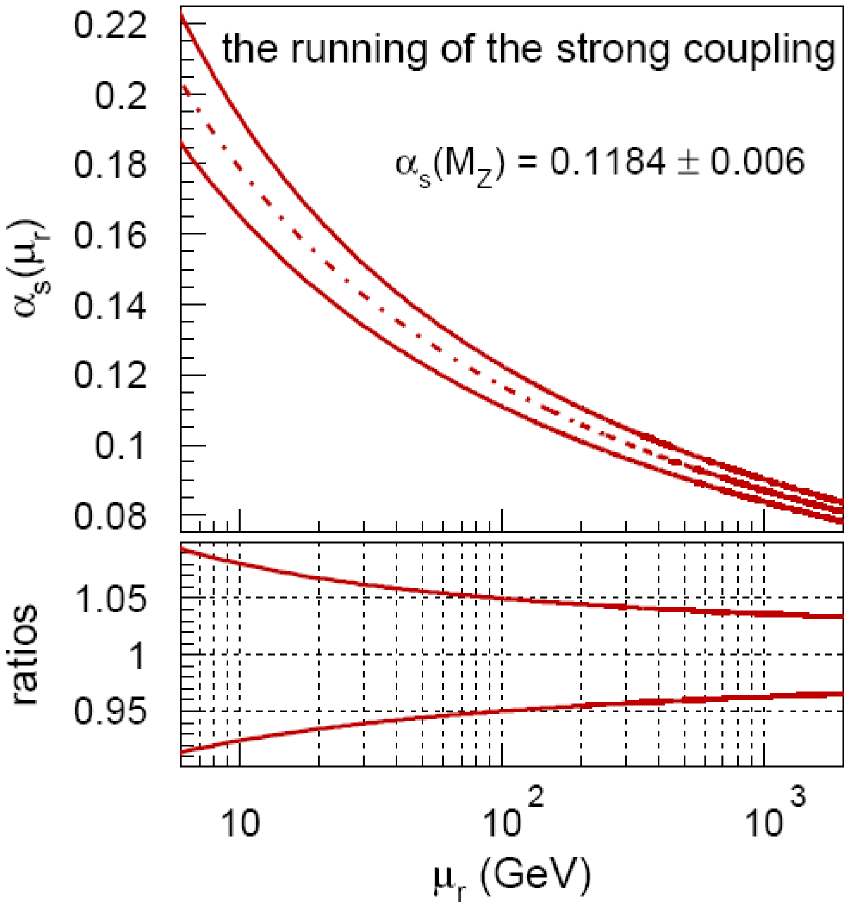
inclusive jet cross section is sensitive to α_s



$$\sigma_{\mathrm{pert}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

previous CDF result from Run I: PRL88, 042001 (2002)

α_s and the RGE



- $\alpha_s(\mu_R)$: depends on renormalization scale → predicted by "RGE"

- Values $\alpha_s(\mu_R)$ are not predicted

- $\alpha_s(\mu)$ ← RGE → $\alpha_s(M_Z)$

- Agreement: compare $\alpha_s(M_Z)$

QCD test (2 aspects):

- Determine $\alpha_s(M_Z)$ → check process independence
- Test RGE → running $\alpha_s(\mu_R)$

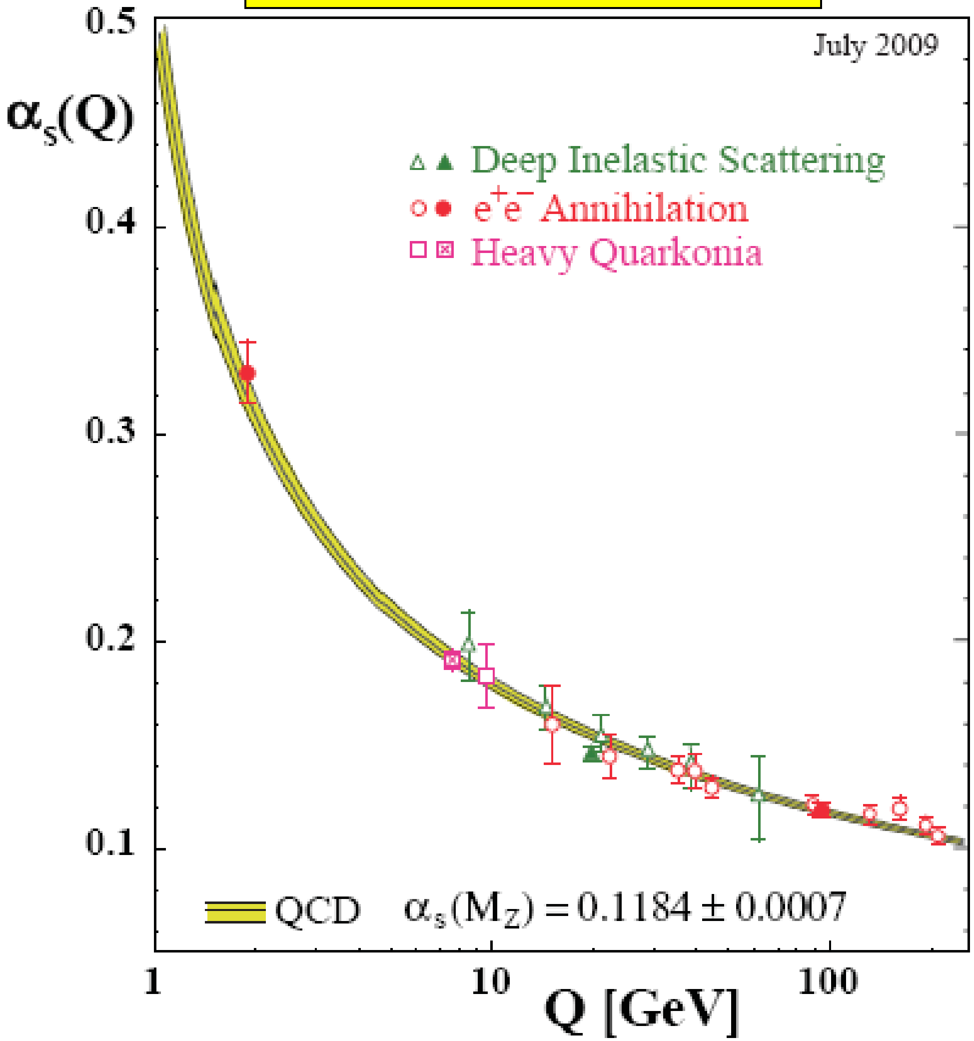
RGE: $$Q^2 \frac{\partial \alpha_s(Q^2)}{\partial Q^2} = \beta\left(\alpha_s(Q^2)\right)$$

$\alpha_s(M_Z)$ extraction at large p_T requires high (experimental & theory) precision

$$\beta(\alpha_s(Q^2)) = -\beta_0\alpha_s^2(Q^2) - \beta_1\alpha_s^3(Q^2) - \beta_2\alpha_s^4(Q^2) - \beta_3\alpha_s^5(Q^2) + \mathcal{O}(\alpha_s^6)$$

Knowledge of α_s

S. Bethke, arXiv:0908.1135



Renormalization Group Equation has been tested for momenta up to 209 GeV

(LEP e^+e^- data)

→ But not yet for larger scales

Basic principle

Perturbative cross section formula:

$$\sigma_{\text{pert}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n \right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

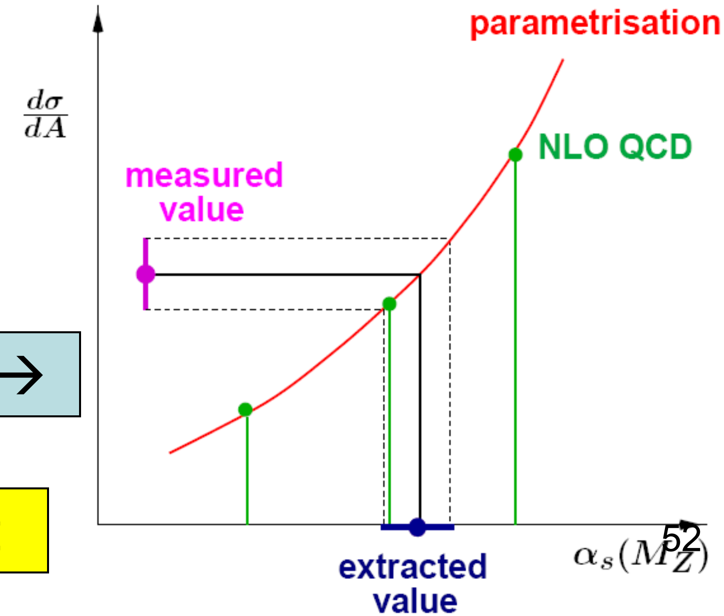
- pQCD matrix elements: explicit α_s dependence
- f_1, f_2 (PDFs): implicit α_s dependence

Determine α_s from data:

- Vary α_s until sigma-theory agrees with sigma-experiment

→ chi2 minimization

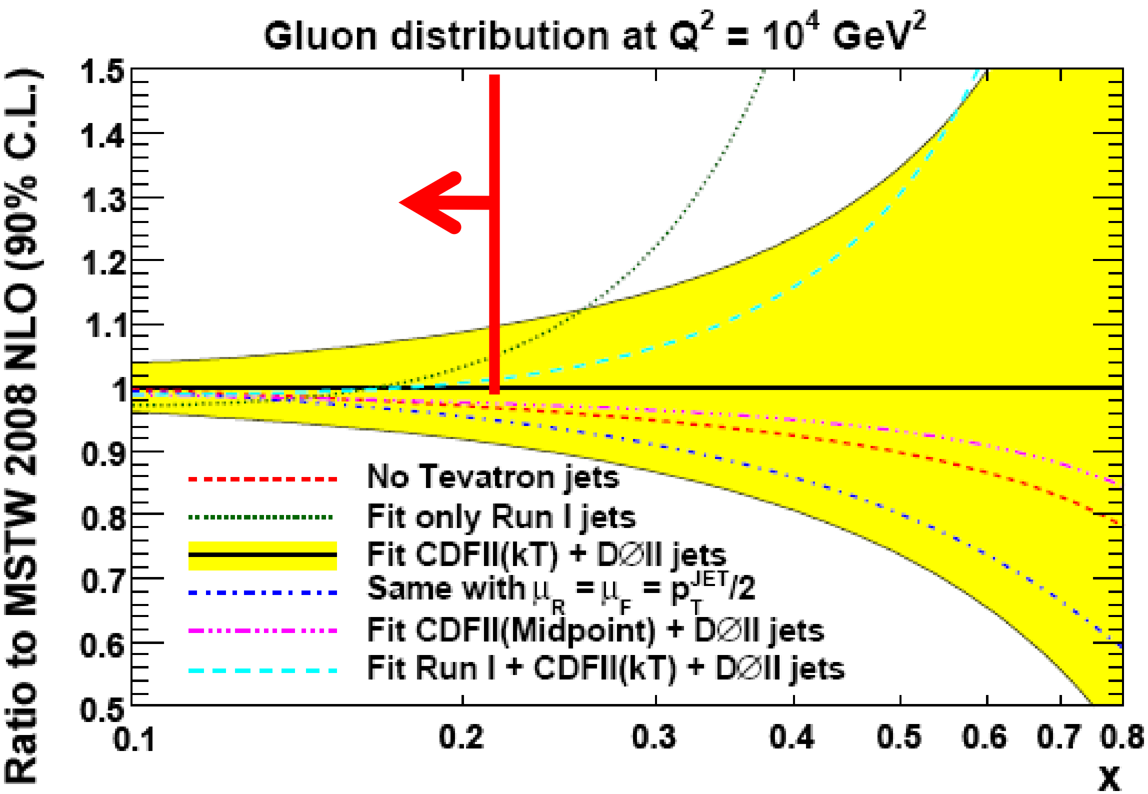
For a single bin →



→ Procedure requires PDFs as external input

PDFs and input data

MSTW2008 paper (Fig 52. / see also Figs. 51, 53)



Currently:
Main constraints on high-x gluon density come from Tevatron jet data

Goal:
Minimize correlations between data and PDF uncertainties

→ Restrict α_s analysis to kinematic regions where impact of Tevatron data for PDFs is small.

→ Tevatron jet data don't affect gluon for x < 0.2 – 0.3

Incl. Jets: x-sensitivity

Jet cross section has access to x-values of: (in LO kinematics)

$$x_a = x_T \frac{e^{y_1} + e^{y_2}}{2}, \quad x_b = x_T \frac{e^{-y_1} + e^{-y_2}}{2} \quad \text{with} \quad x_T = \frac{2\,p_T}{\sqrt{s}}$$

What is the x-value for a given incl. jet data point @(p_T, |y|) ?

→ Not completely constrained – unknown kinematics since we integrate over other jet(s)

→ Construct "test-variable" (treat as if other jet was at y=0):

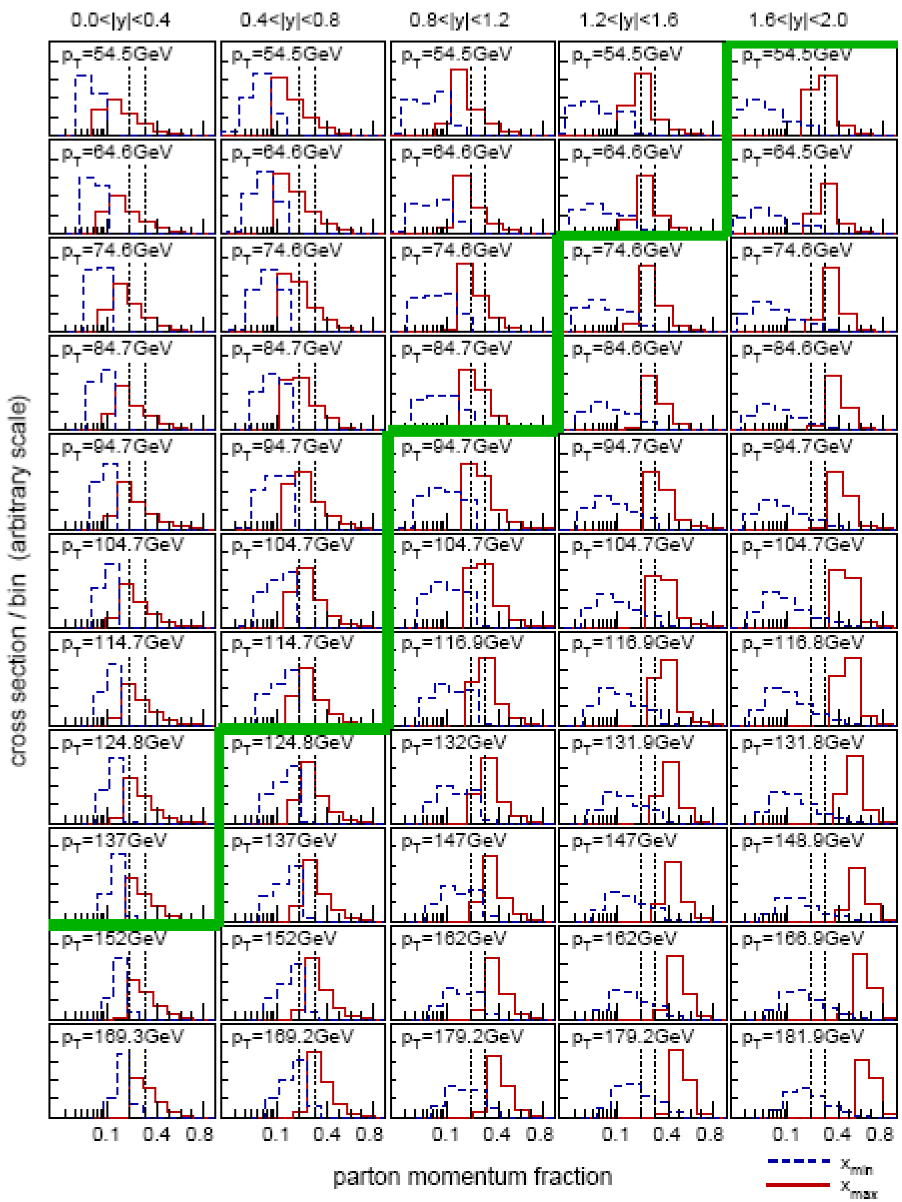
$$x = x_T \cdot (e^{|y|} + 1)/2$$

→ Apply cut on this test-variable to restrict accessible x-range

→ Find: requirement x-test < 0.15 removes most of the contributions with x > 0.2 – 0.3

→ 22 (of 110) data points remaining at 50 < p_T < 145 GeV

x_{min} / x_{max} distributions



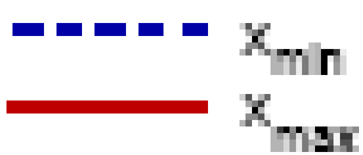
Every analysis bin → one plot

Each plot: x-min/x-max distributions

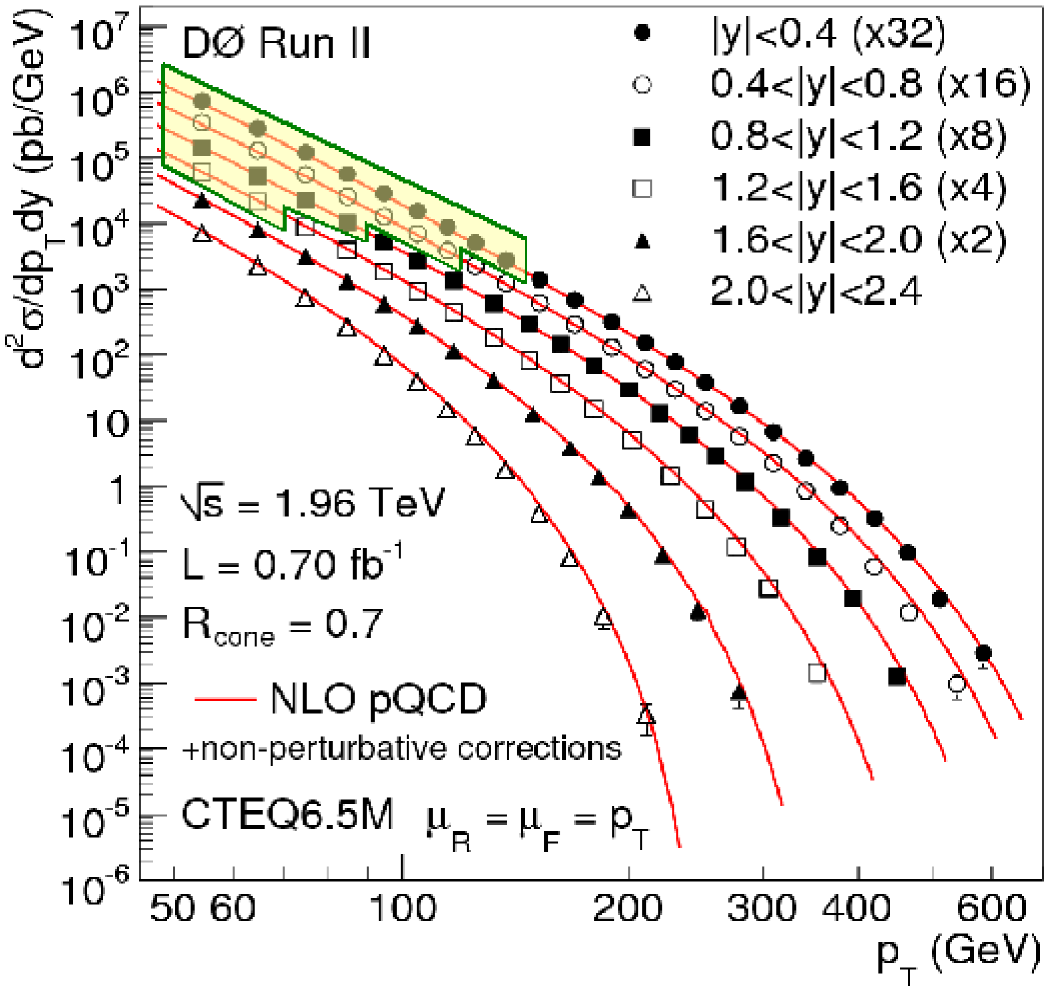
Cut on test-variable x-test < 0.15
→ 22 (of 110) data points remain

These have small contributions from
x > 0.2 – 0.3

← Only data points above green line are used



Data Sample



22(out of 110) inclusive jet cross section data points at $50 < p_T < 145$ GeV

→ Input in α_s analysis

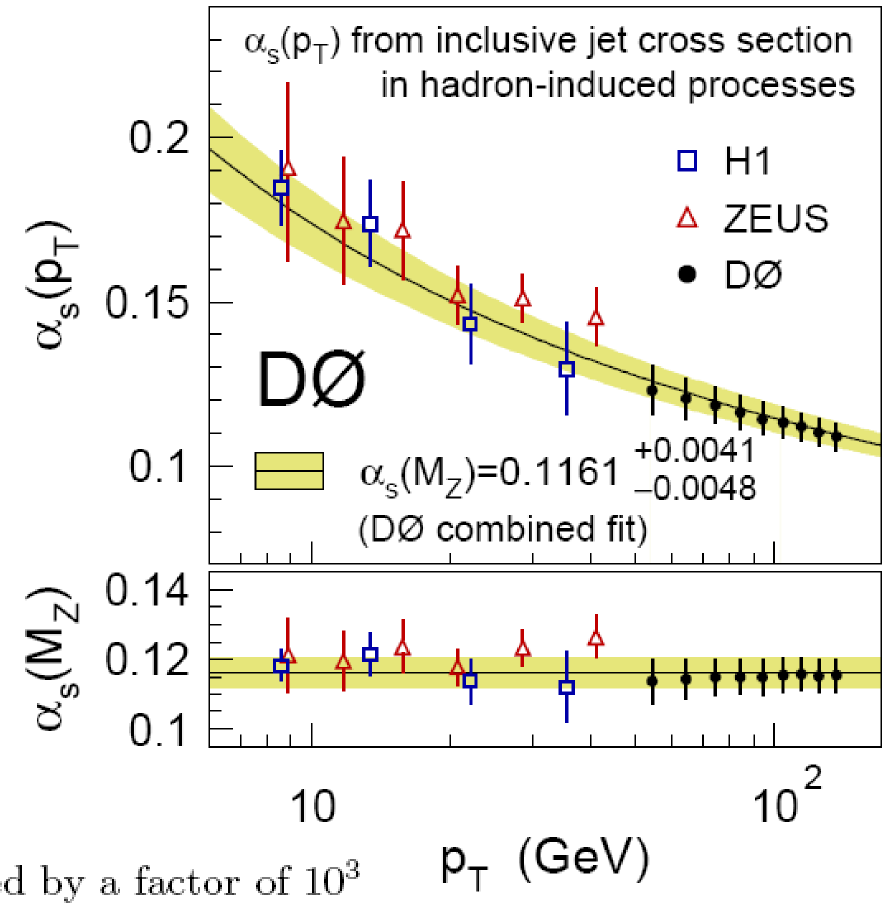
Strong Coupling Const.

- → Use best theory prediction:
  NLO + 2-loop threshold corrections
  (Kidonakis/Owens)
  with MSTW2008NNLO PDFs

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

- → Most precise result
  from a hadron collider

- → Consistent with HERA results
  and world average



All uncertainties are multiplied by a factor of 10^3

	Total uncertainty	Experimental uncorrelated	Experimental correlated	Nonperturb. correction	PDF uncertainty	$\mu_{r,f}$ variation
0.1161	$^{+4.1}_{-4.8}$	±0.1	$^{+3.4}_{-3.3}$	$^{+1.0}_{-1.6}$	$^{+1.1}_{-1.2}$	$^{+2.5}_{-2.9}$

Theoretical Precision

Main result: use best theory predictions
NLO + 2-loop threshold corrections (Kidonakis/Owens)
with MSTW2008NNLO PDFs

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

Use only NLO
with MSTW2008NLO PDFs

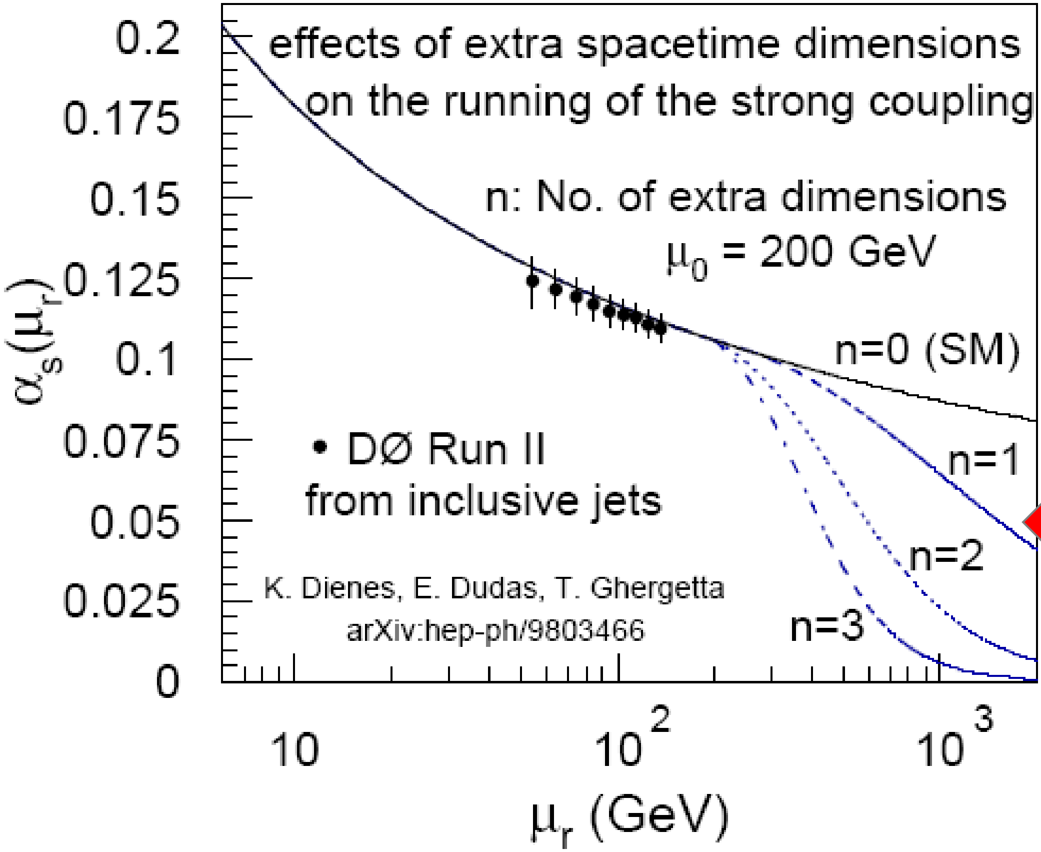
$$0.1202^{+0.0072}_{-0.0059}$$

- Larger value of "NLO-only" result:
  → due to missing $O(\alpha_s^4)$ contributions
- Larger uncertainty of "NLO-only" result:
  → due to increased scale dependence (main effect)
  → and increased PDF uncertainty (minor effect)

All uncertainties are multiplied by a factor of 10^3

	Total uncertainty	Experimental uncorrelated	Experimental correlated	Nonperturb. correction	PDF uncertainty	$\mu_{r,f}$ variation
0.1161	$^{+4.1}_{-4.8}$	±0.1	$^{+3.4}_{-3.3}$	$^{+1.0}_{-1.6}$	$^{+1.1}_{-1.2}$	$^{+2.5}_{-2.9}$

Running of α_s (?)



→ so far tested
up to μ_r = 209 GeV (LEP)

Could be modified
for scales $\mu_r > \mu_0$
e.g. by extra dimensions

here: μ_0 = 200 GeV
and n=1,2,3 extra dim.
(n=0 → Standard Model)

But: α_s extraction from inclusive jets uses PDFs which were derived assuming the RGE

→ We cannot use the inclusive jets to test the RGE in yet untested region

Going further …

… towards testing in the RGE
in novel energy regimes

→ Cannot rely on PDF information
(PDF parametrizations already assume
RGE in DGLAP evolution)

Cancelling PDFs: Ratios

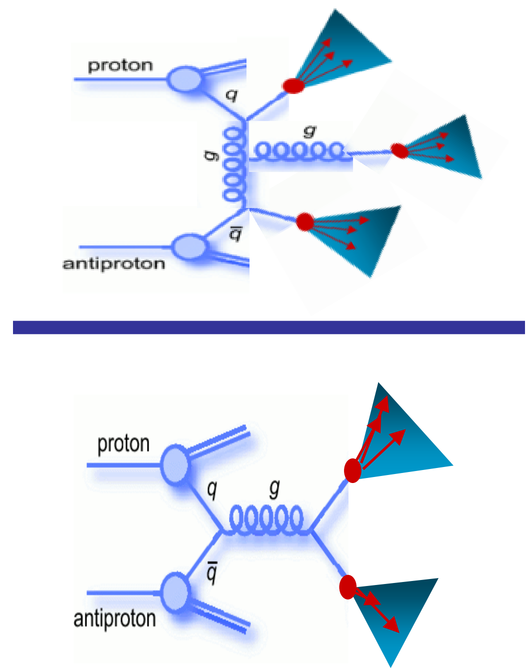
Goal: test pQCD (and α_s) **independent** of PDFs

Conditional probability:

$R_{3/2}$

$= P(3^{rd}\text{ jet} \mid 2\text{ jets})$

$= \sigma_{3\text{-}jet} / \sigma_{2\text{-}jet}$



$\Leftrightarrow \alpha_s$

- Probability to find a third jet in an inclusive dijet event
- Sensitive to α_s (3-jets: α_s^3 / 2-jets: α_s^2)
- (almost) independent of PDFs

$R_{3/2} = \sigma_{3\text{-}jet} / \sigma_{2\text{-}jet}$

Measure as a function of two momentum scales:

- p_{Tmax} : common scale for both $\sigma_{2\text{-}jet}$ and $\sigma_{3\text{-}jet}$
- p_{Tmin} : scale at which 3rd jet is resolved ($\sigma_{3\text{-}jet}$ only)

Sensitive to α_s at the scale p_{Tmax} → probe running of $\alpha_s(p_{Tmax})$

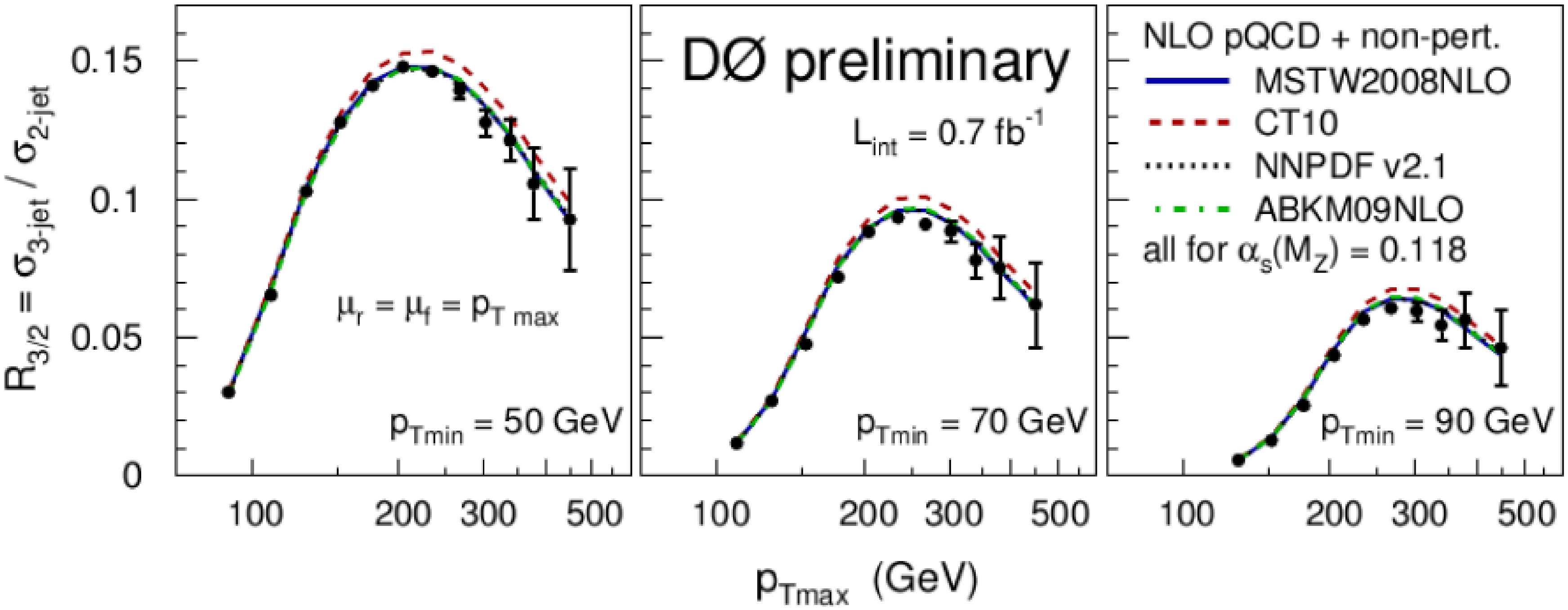
Details:

- inclusive *n*-jet samples (*n*=3,2) with *n* (or more) jets above p_{Tmin}
- $|y| < 2.4$ for all *n* leading p_T jets
- $\Delta R_{jet,jet} > 1.4$ (insensitive to overlapping jet cones)
- study p_{Tmax} dependence for different p_{Tmin} of 50, 70, 90 GeV

→ Measurement of $R_{3/2}(p_{Tmax}\,;\,p_{Tmin})$

$R_{3/2}$ vs. NLO pQCD

Using $R_{3/2}$ to test NLO matrix elements



For a given $\alpha_s(M_Z) = 0.118$:

→ NLO results for MSTW2008NLO, NNPDF v2.1, ABKM09NLO agree

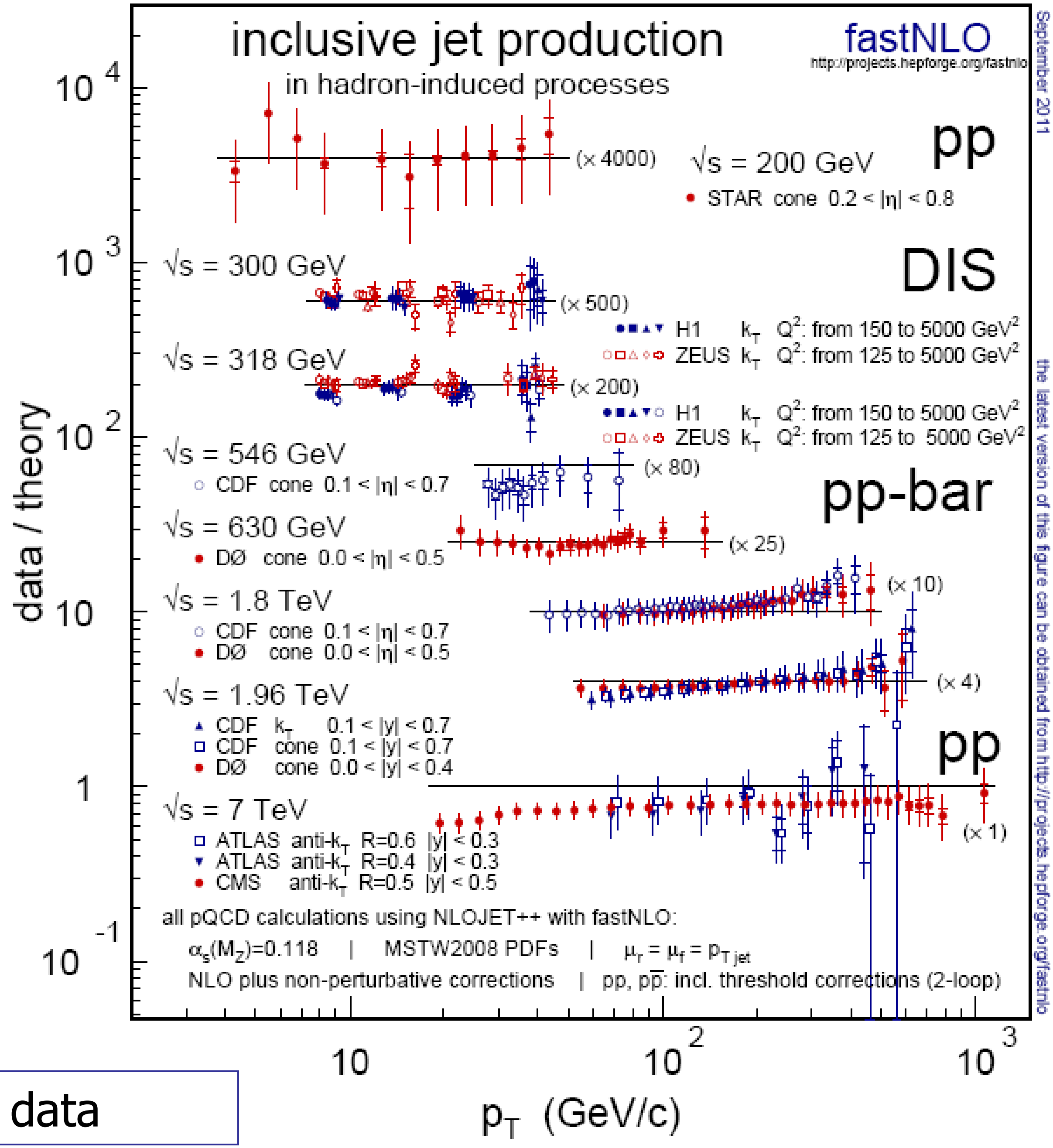
→ CT10 slightly higher at high p_T

Overview

fastNLO Collab., arXiv: 1109.1310

Theory-data comparison for jet cross section data in processes with initial-state hadrons

- RHIC
- HERA 1, 2 (high Q2 only)
- Tevatron Run I, II (central rapidities only)
- First LHC results (central rapidities only)



Highest pT reach by LHC data

Overview: x_T dependence

fastNLO Collab., arXiv: 1109.1310

hadron-hadron collisions only

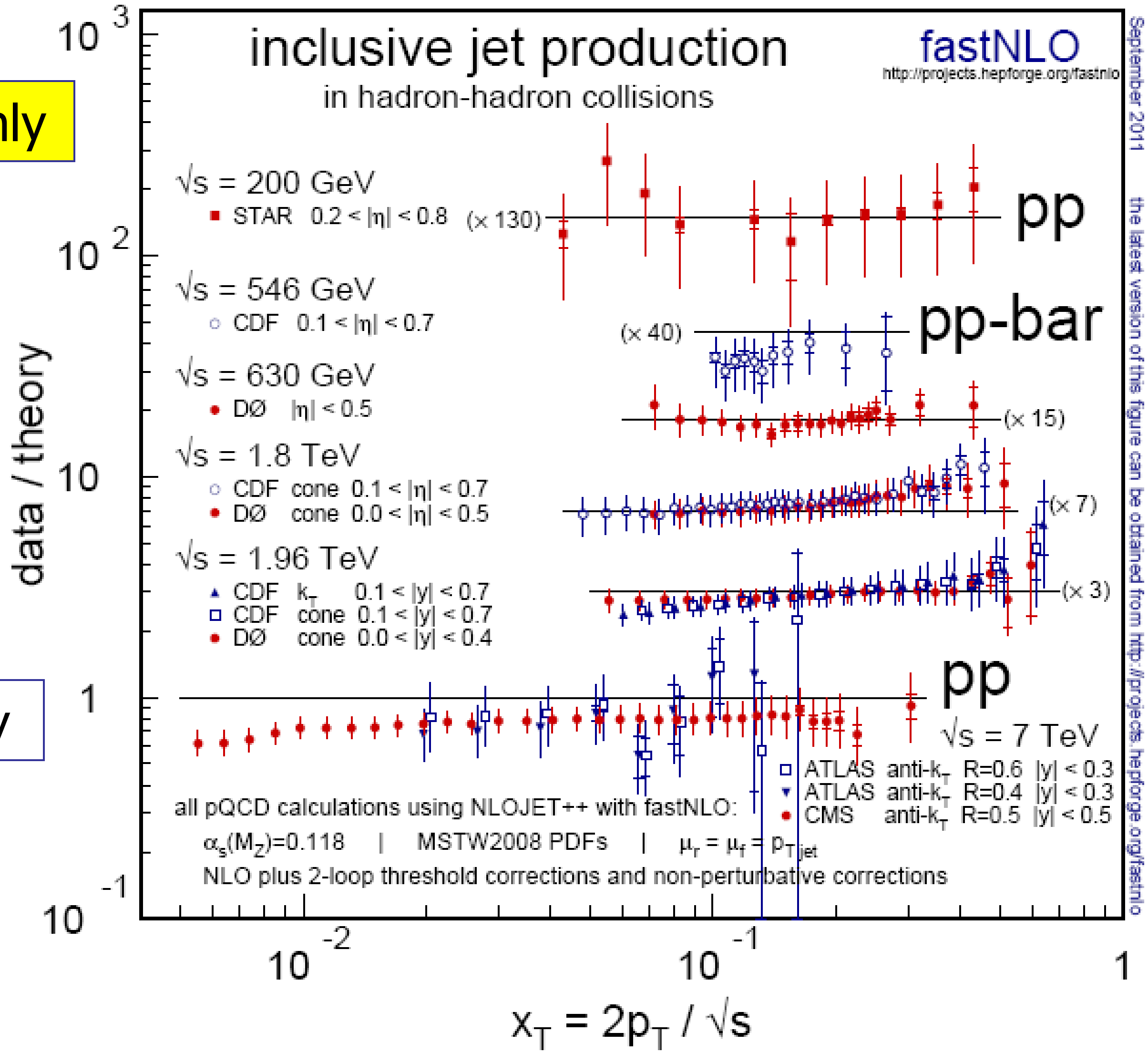
plot vs. $x_T = 2p_T/\text{sqrt}(s)$

Interpretation:

for $y_1=y_2=0 \rightarrow x_T = x$

demonstrate PDF sensitivity

highest x-reach by Tevatron data



Summary

→ **precision measurements** of fundamental observables @2TeV
→ **consistent results** from CDF and D0

- **photon production (inclusive, plus jet, plus HF jet, diphoton)**
  → need to find missing pieces in theory
- **Z/W + jet production (p_T spectra, angular distributions)**
  → many distributions for pQCD tests and for model tuning
  → NLO describes some of the basic variables (not all)
- **event shape variables**
  → interesting new (in pp) testing ground from soft to hard QCD
- **jet production (inclusive p_T, dijet angle and mass, 3-jet mass, ratio R_{32})**
  → precision measurements – pQCD very successful
  → constraints on $\alpha_s(M_Z)$ and high-x gluon

Backup

Question

In the RGE one performs matching at the flavor thresholds

→ one threshold at m_{top} (= 170 - 180 GeV) where n_f makes a step from 5 to 6

→ For inclusive jets / dijets at the Tevatron/LHC:
Do we really want to do that?

- What n_f should one use for computing single jet inclusive / or inclusive dijet cross sections for $\mu = p_T > m_{top}$

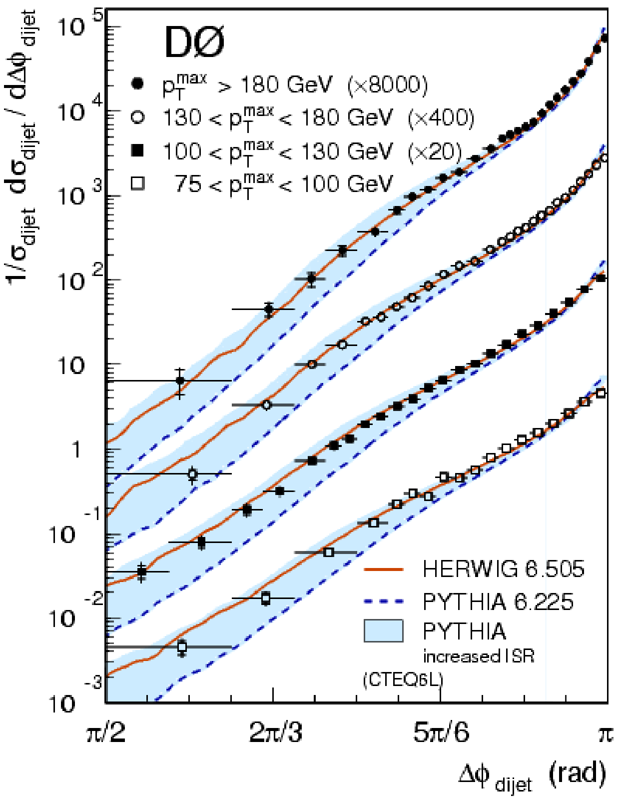
So far, fastNLO (used in all global PDF fits to compute Tevatron jets) uses $n_f = 5$ everywhere

Reasoning: We do not measure jets from top decays at $p_T > m_{top}$

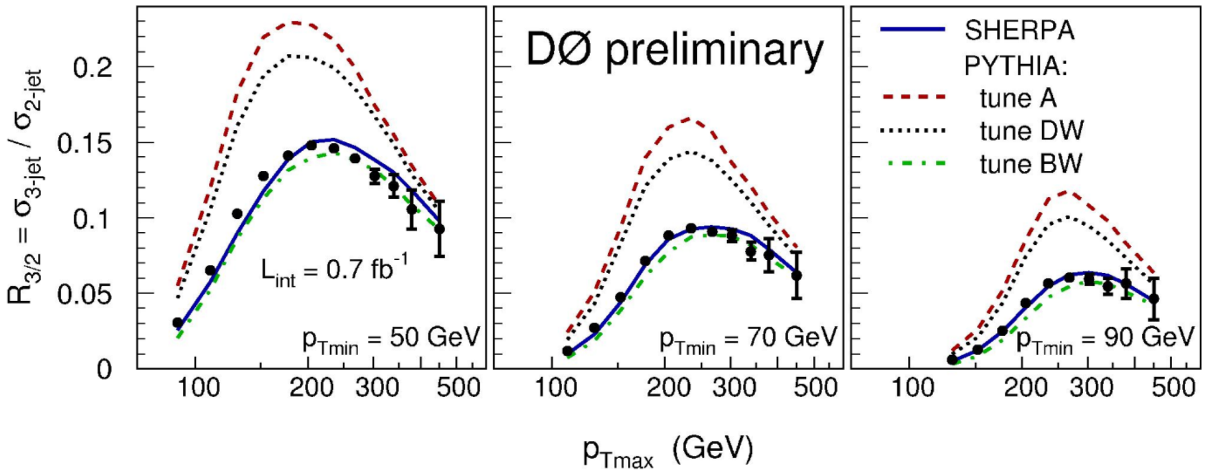
→ Make people aware – in that case RGE should also use $n_f = 5$

MC tuning

"soft" ISR does not describe Inclusive dijet $\Delta\phi$ distribution
→ needs more ISR → tune DW



Different when explicitly requiring a third jet → R32



tune DW much too hard for R32
→ Prefers "BW" (original) soft ISR