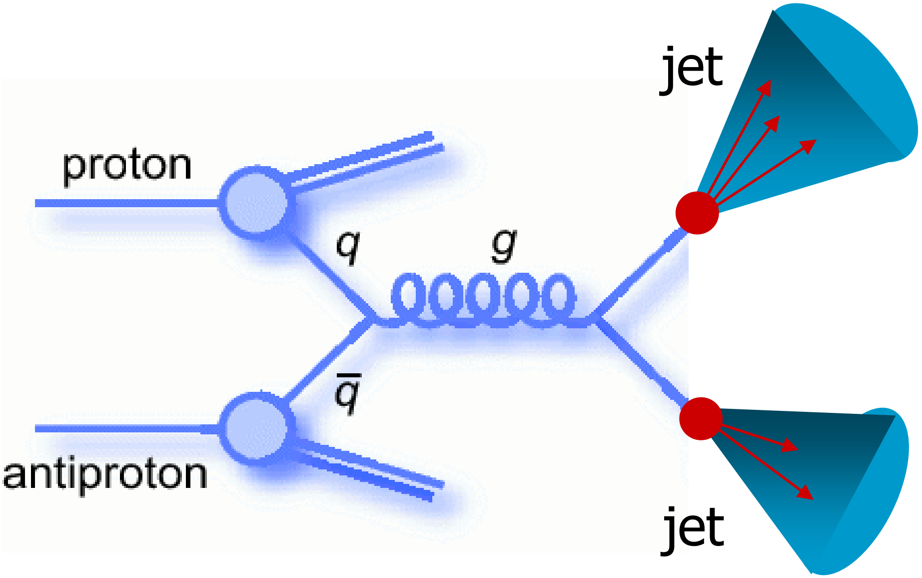
Jet Production at the Tevatron: Experimental Achievements and Theoretical Limitations

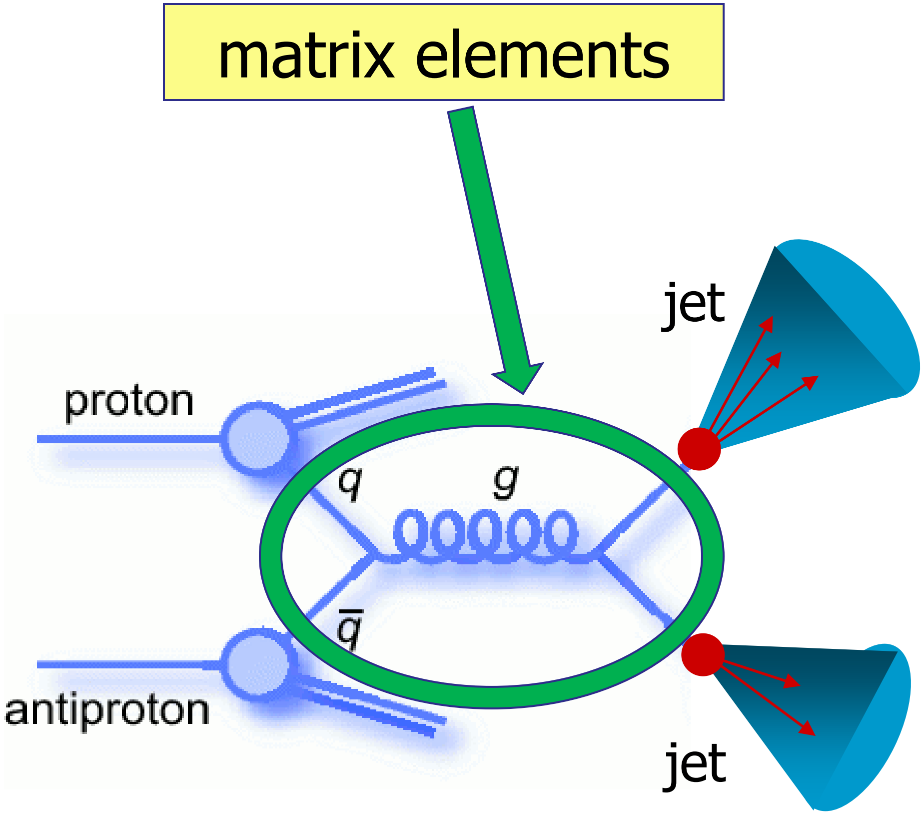
Markus Wobisch
Louisiana Tech University

QCD@LHC Workshop, MSU
August 20, 2012

The Process



The Ingredients (1)

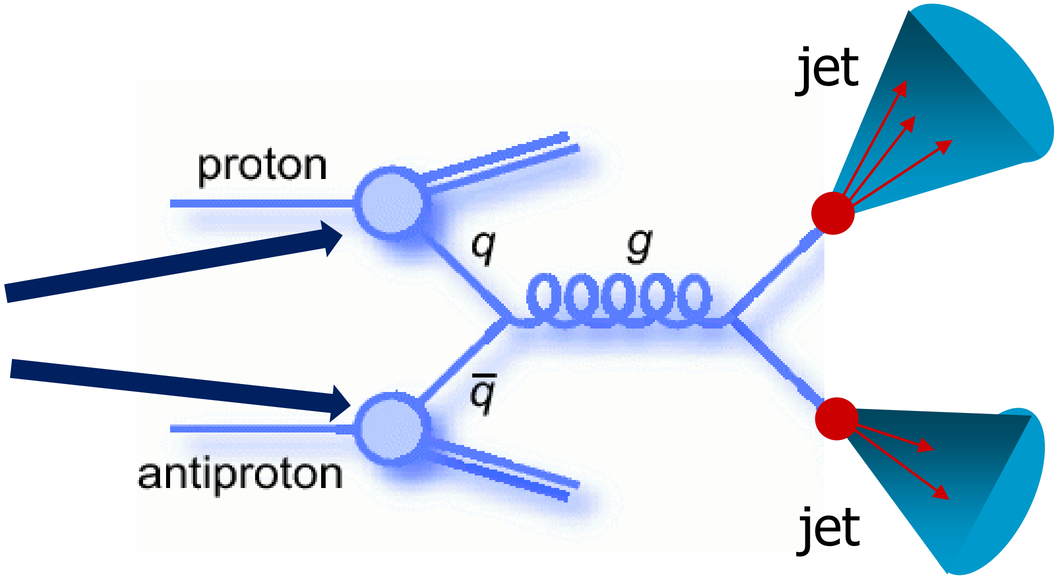


Dynamics:

- Any indications for New Physics?
- … or as predicted by pQCD?

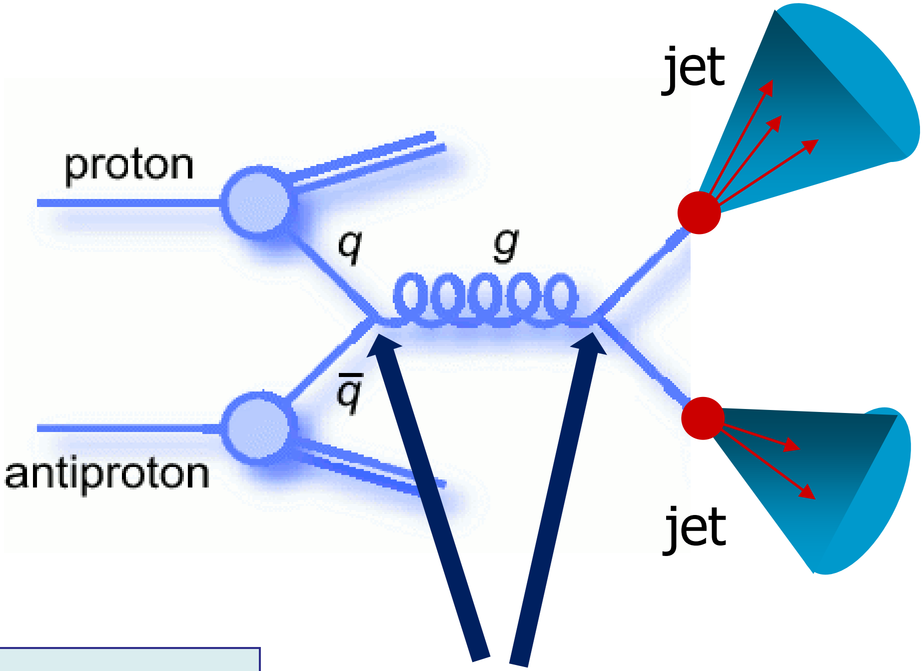
The Ingredients (2)

Parton distribution functions (PDFs) of the hadrons



- What are their values $f_i(x,Q)$?
- Do they follow DGLAP?
- Are they universal?

The Ingredients (3)



Strong coupling α_s

- What is $\alpha_s(M_Z)$?
- Is the running described by the RGE?
- Universality?

The Observable

(Multi-) jet final states defined by **jet algorithm**:

CDF, D0: **midpoint cone** algorithm $R_{cone}=0.7$ (0.5)

CDF: **inclusive k_T** algorithm R=0.7 also: R=0.5, 1.0

Measurement results are presented at **particle-level**
(see: Les Houches 2007)

→ Compared to **theory = pQCD * non-perturbative corrections**

Theory Predictions

pQCD – NLO: for incl. jets / dijet / 3-jet / R = 3-jet/2-jet
Code: NLOJET++ with fastNLO

pQCD – 2-loop threshold corrections: for incl. jets only
Code: fastNLO, based on code from Owens/Kidonakis

New Physics – LO:
Quark compositeness, ADD LED, TeV^{-1} ED: private code in D0
New Particles: PYTHIA & private code in CDF

Non-perturbative corrections:
PYTHIA (large number of tunes)
HERWIG

Choices

Renormalization/ Factorization Scales:

For “p_T related” obervables: related to measured observable (p_T, p_{Tmax}, $H_T/2$)

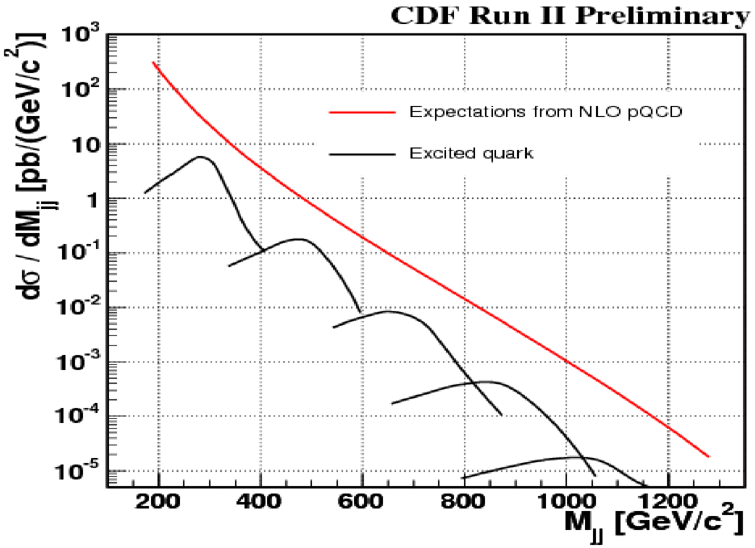
Dijet mass: $(p_{T1}+p_{T2})/2$

3-jet mass: $(p_{T1}+p_{T2}+p_{T3})/3$

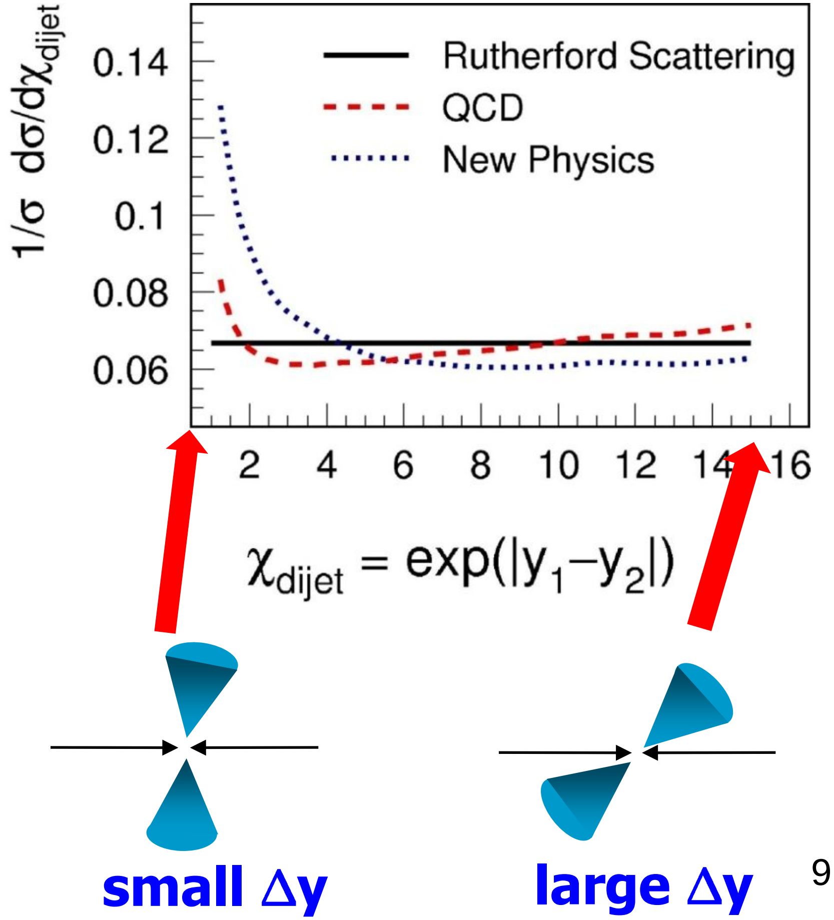
PDFs: MSTW, CTEQ, NNPDF, ABM, HERA

Do we see New Physics Signals?

New particle resonances in dijet mass spectrum



Tails of new high-energy phenomena in dijet angular distribution



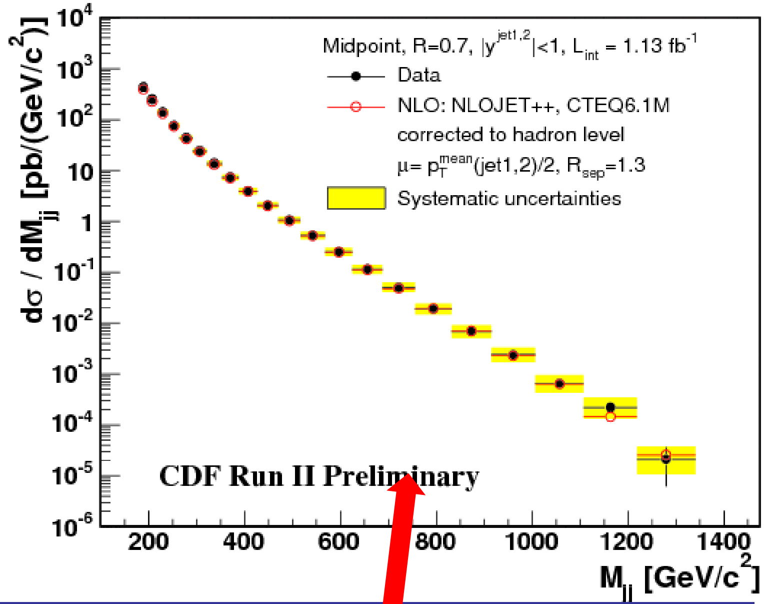
$$\chi_{dijet} = \exp(|y_1 - y_2|)$$

small Δy

large Δy

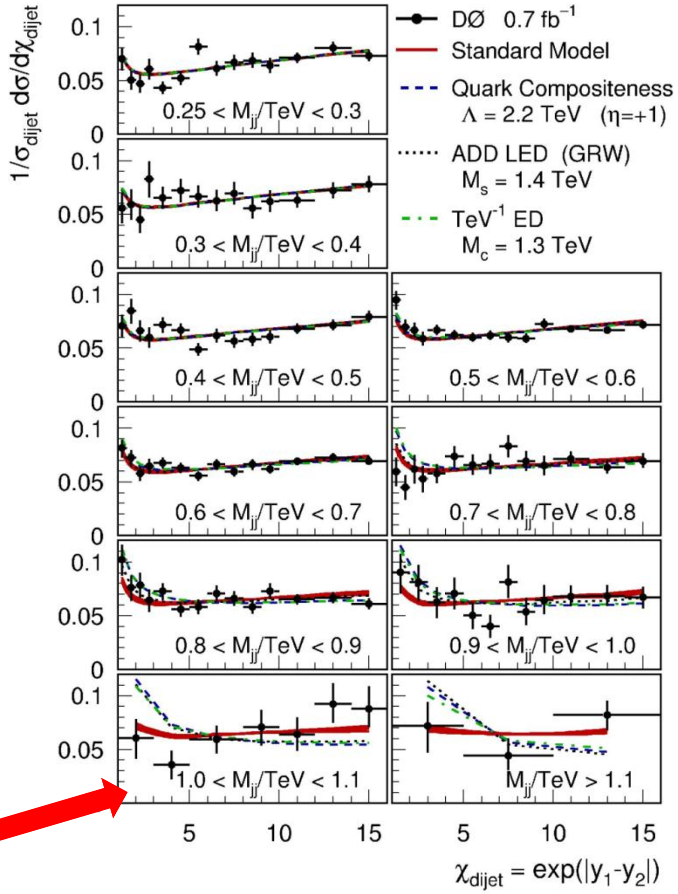
No, only QCD dynamics!

dijet mass spectrum



Limits on new resonances

dijet angular distributions



Limits on quark compositeness and extra spatial dimensions

$$\chi_{\text{dijet}} \equiv \exp(2y^*)$$

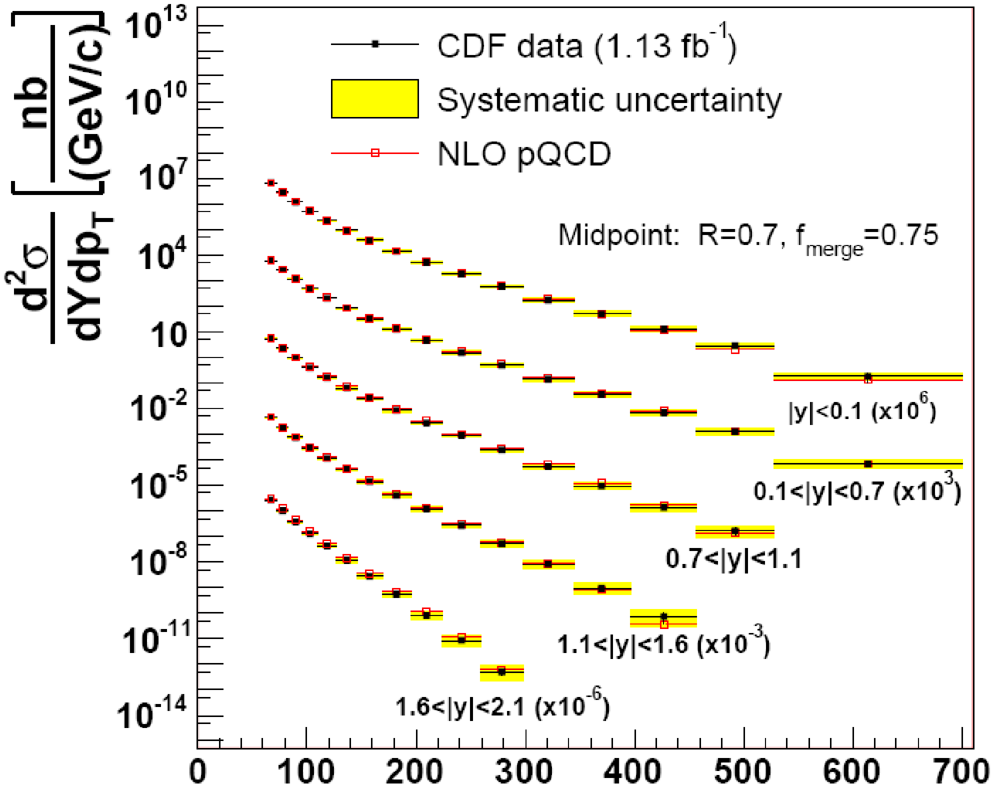
→ No indications for New Physics

→ Most stringent pre-LHC limits

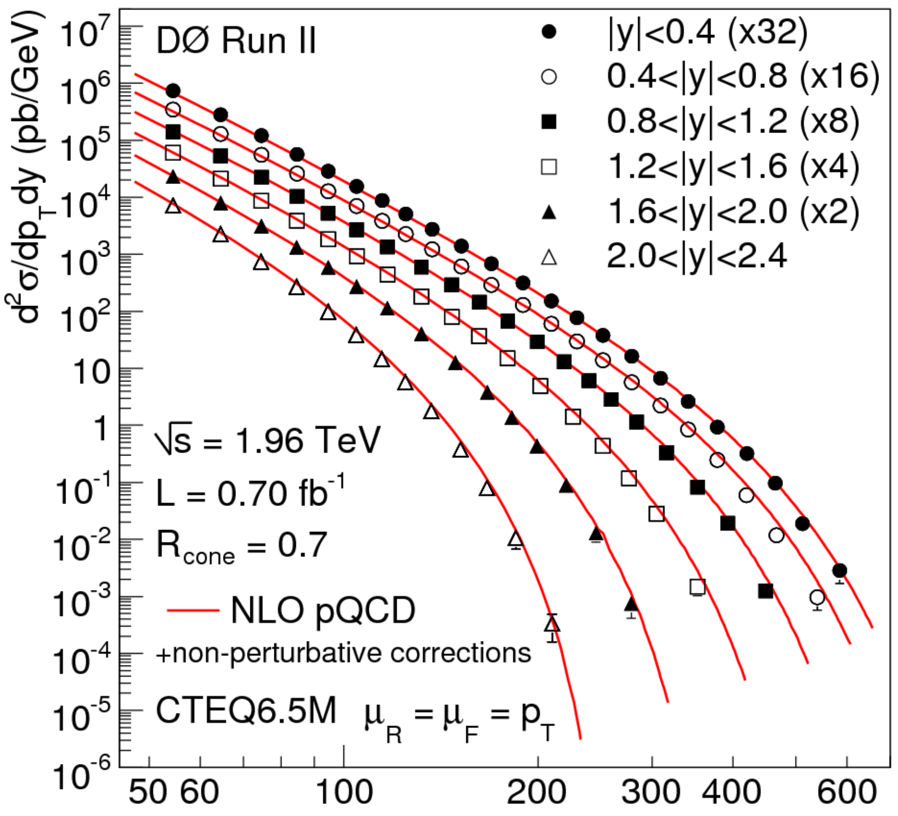
phenomenology

PDFs

Inclusive Jets



Phys. Rev. D 78, 052006 (2008)



Phys. Rev. Lett. 101, 062001 (2008)

high precision results

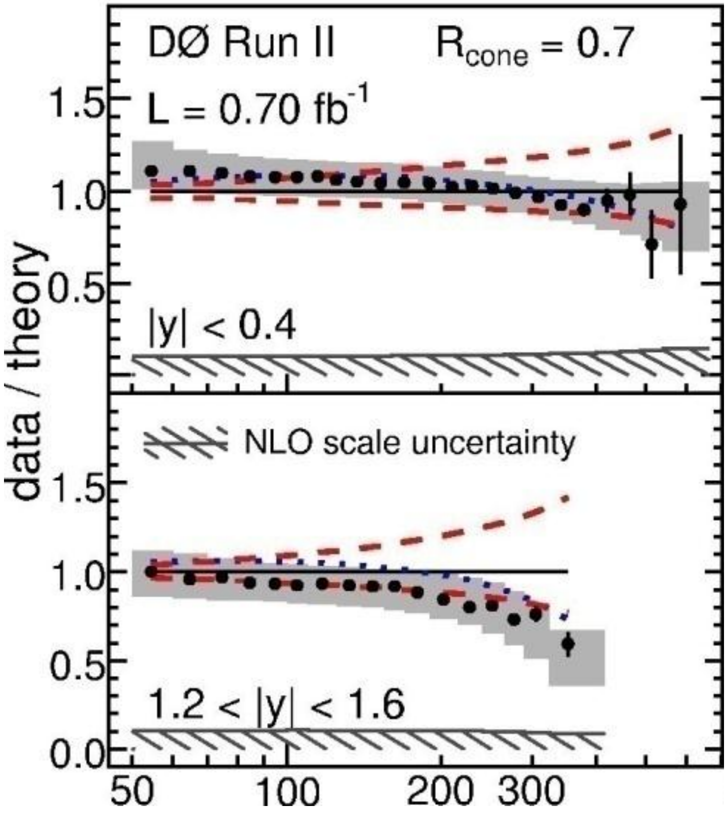
Inclusive Jets

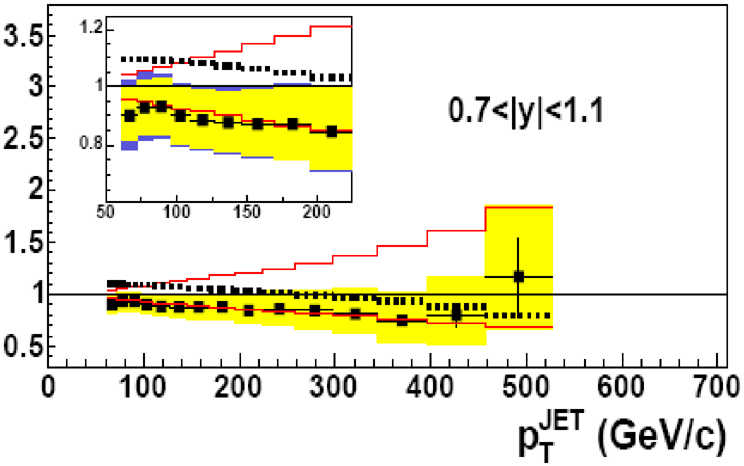
- consistency between CDF/D0
- well-described by NLO pQCD

data are now used in all global PDF fits

→2-loop threshold corrections are used for inclusion of data on NNLO PDF fits

→Do better: need NNLO calculation





■ CDF Data (1.13 fb^{-1}) / NLO

— PDF Uncertainty

┈ MRST 2004 / CTEQ6.1M

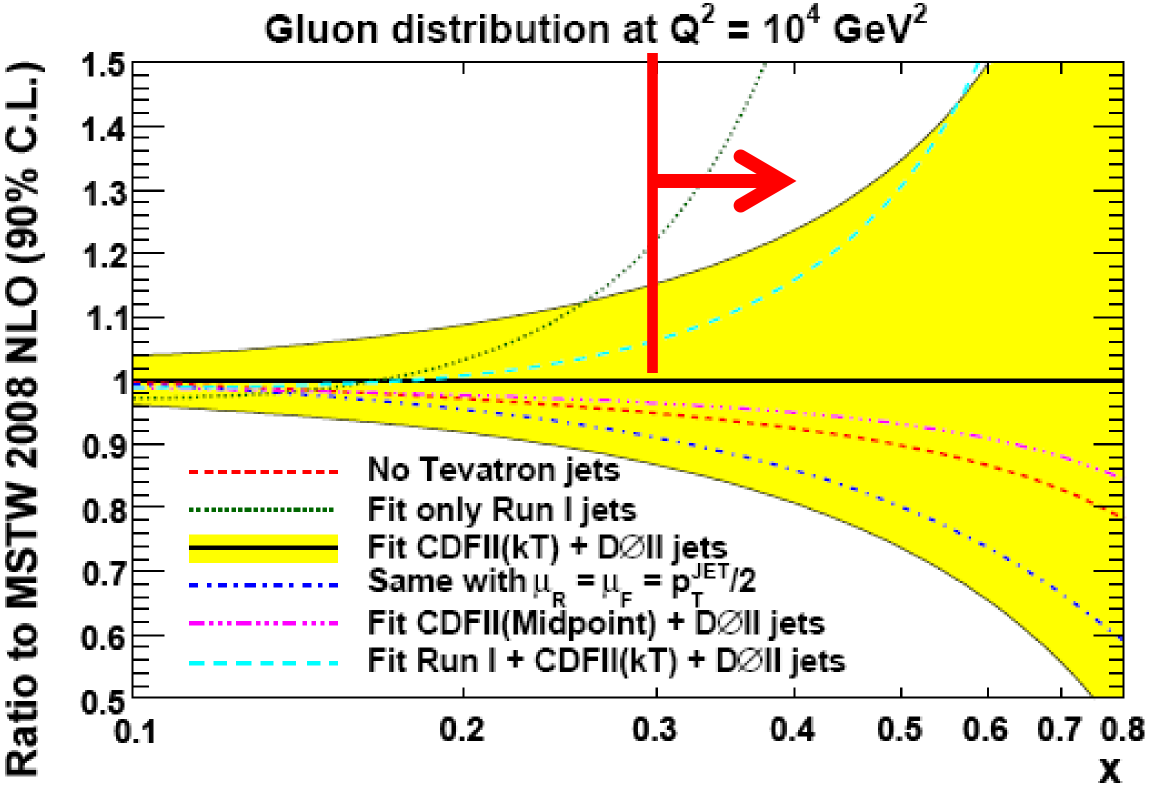
🟨 Systematic uncertainty

🟦 Including hadronization and UE

Midpoint: R=0.7, f_{merge}=0.75

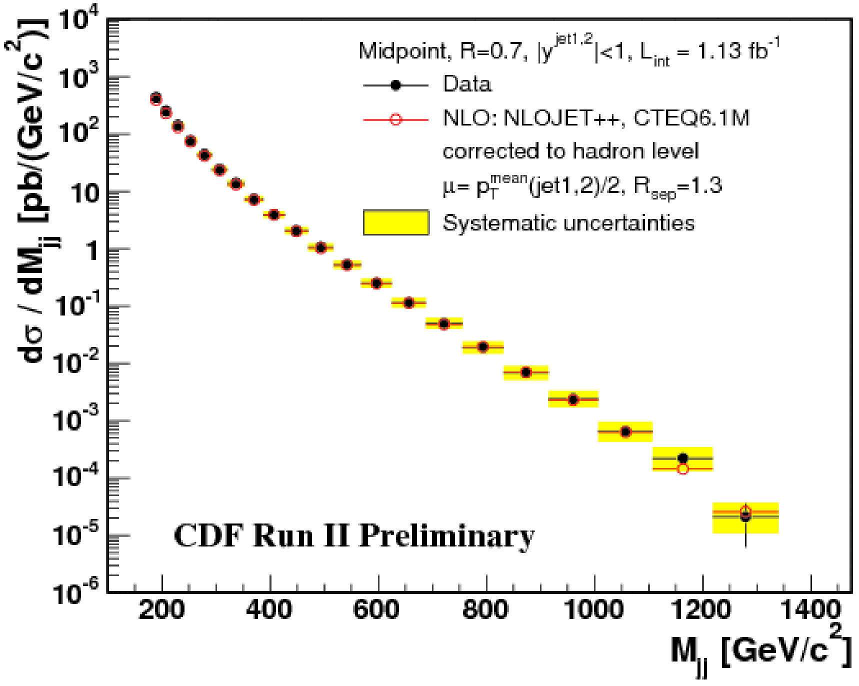
Run II jets in MSTW2008 PDF fit

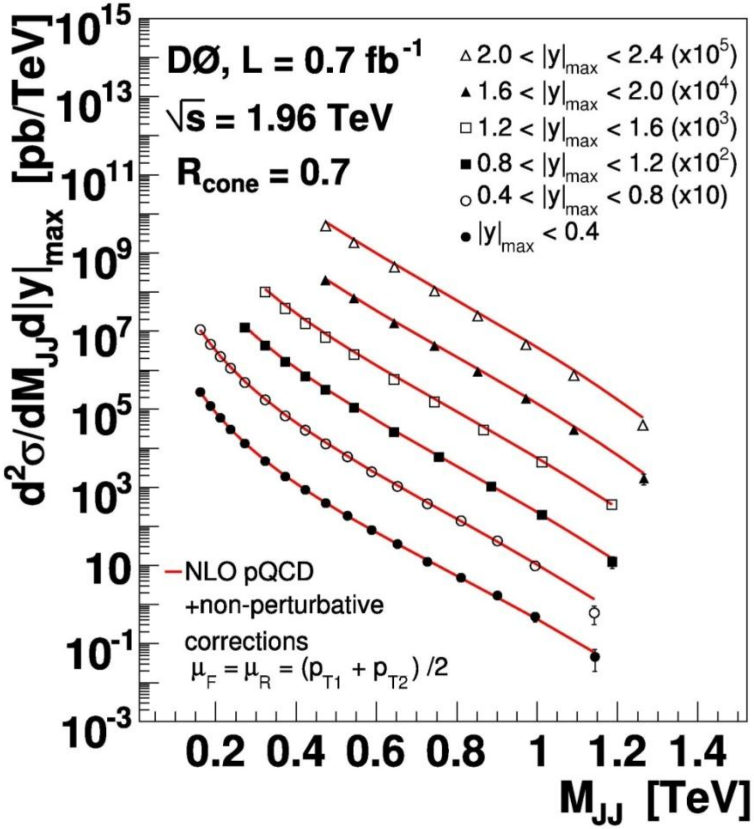
MSTW2008 paper (Fig 52. / see also Figs. 51, 53)



→ Tevatron jet data affect gluon for x > 0.2 – 0.3

Dijet mass distribution





→ Consistency between CDF and D0 results

→ Described by PDFs fitted to incl. jet data

→ smaller deviations at larger rapidities

Three-jet mass spectrum: O(α_s^3)

2-jet cross section:

O(α_s^2) x PDF^2

(correlation of α and gluon density)

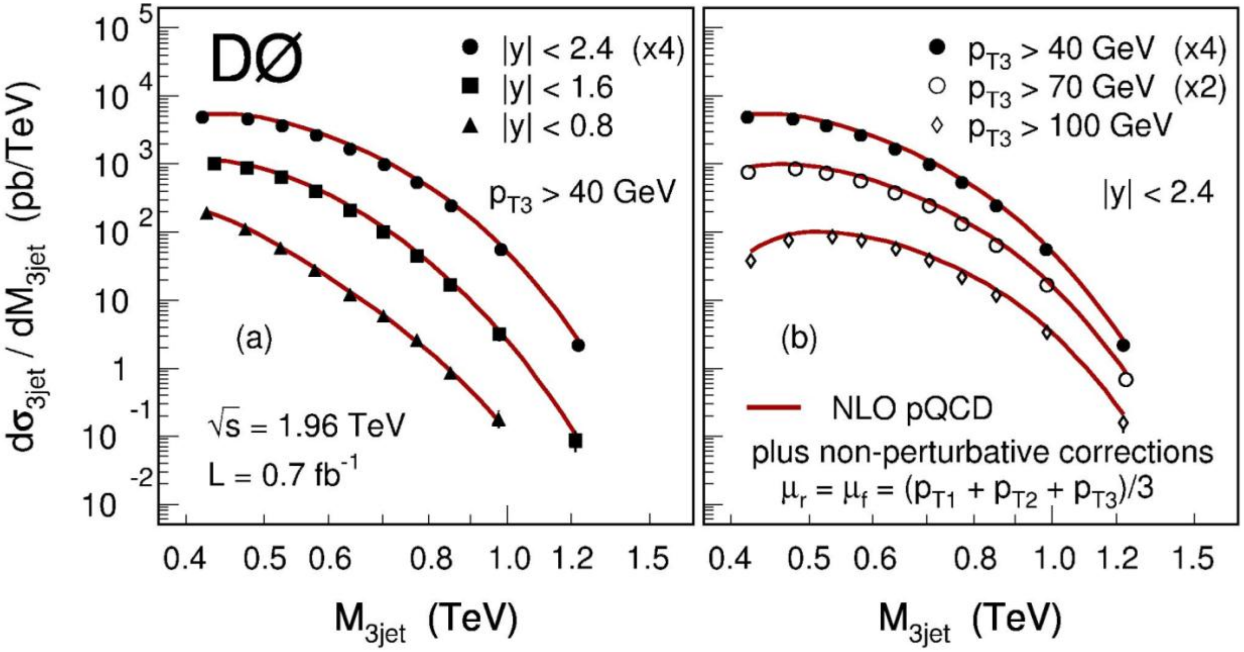
3-jet cross section:

O(α_s^3) x PDF^2

analyze 2-jet and 3-jet cross sections:

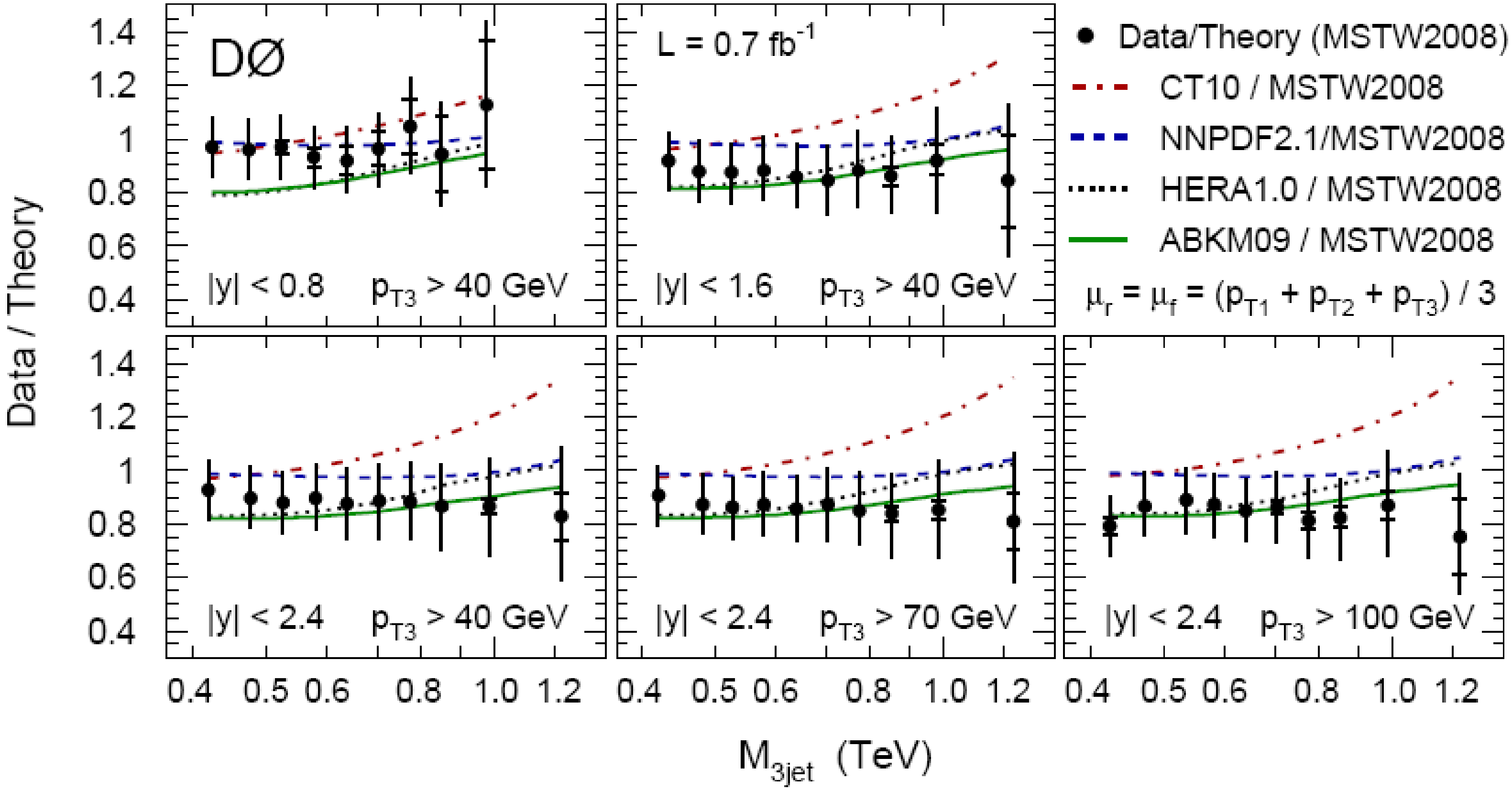
→ **decorrelate** α_s and gluon density in PDF fits

Phys. Lett. B **704**, 434 (2011)



$M_{3\text{-jet}}$ Constraining PDFs

Phys. Lett. B **704**, 434 (2011)



→ ratios data/theory show **different shapes / magnitudes** for recent PDFs

→ potential impact of 3-jet data in PDF fits! (need NNLO!)

phenomenology

$$\boxed{\alpha_s}$$

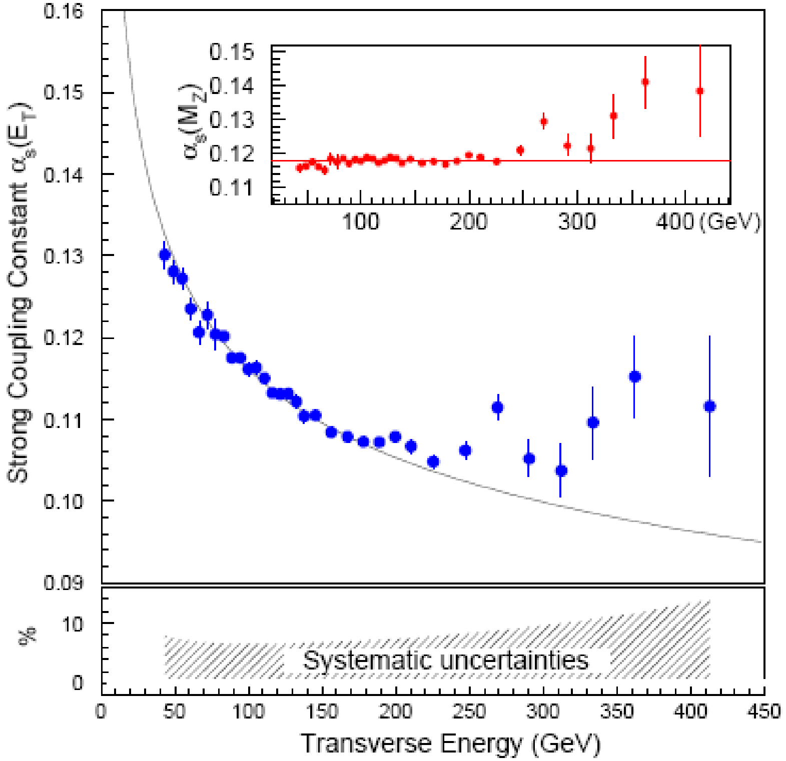
Determine $\alpha_s(M_Z)$

Is the running of $\alpha_s(Q)$ correctly predicted?

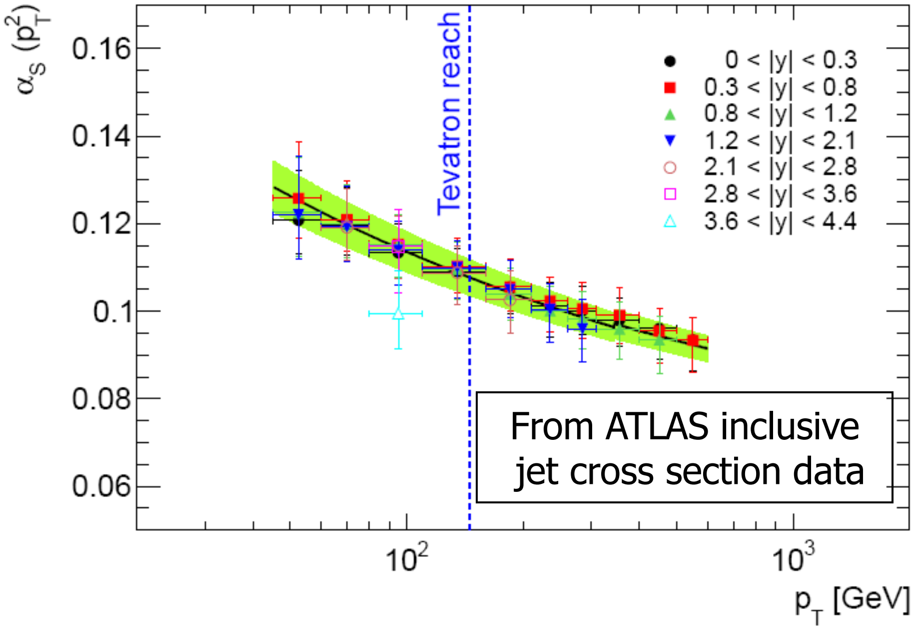
- Test RGE prediction

α_s results from inclusive jet cross section data

CDF Collaboration, T. Affolder et al.,
Phys. Rev. Lett. 88, 042001 (2002)

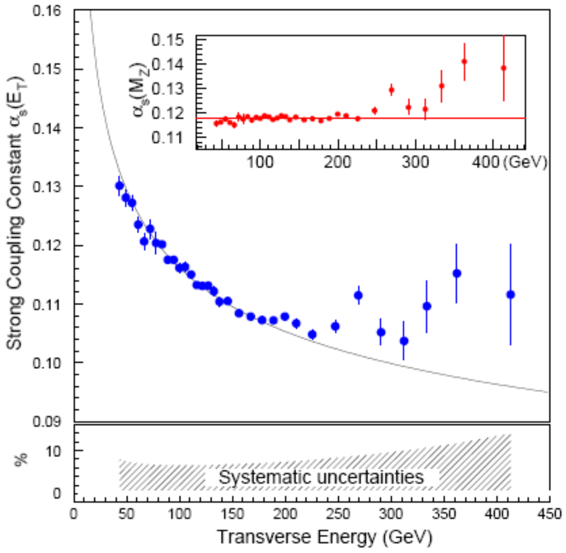


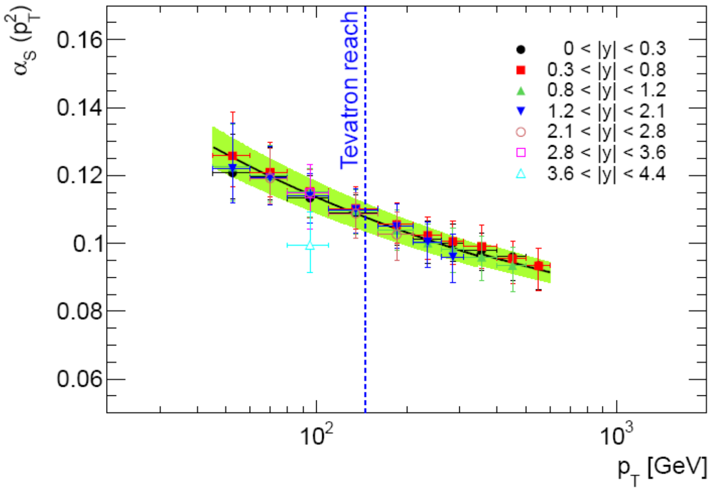
B. Malaescu, P. Starovoitov,
Eur.Phys.J. C72 (2012) 2041



From ATLAS inclusive
jet cross section data

α_s results from inclusive jet cross section data





Statements:

"Test running over 40 < E_T < 440 GeV"

"Test running up to p_T → 600 GeV"

→ Not really!
because analyses use PDFs for which DGLAP evolution is already done under assumption of running $\alpha_s(Q)$ according to the RGE

→ RGE was already assumed
→ Not an independent test

Strong Coupling Constant

From D0 inclusive jet cross section using MSTW2008NNLO PDFs as input

→ Cannot test RGE at p_T >200 GeV (RGE already assumed in PDFs)

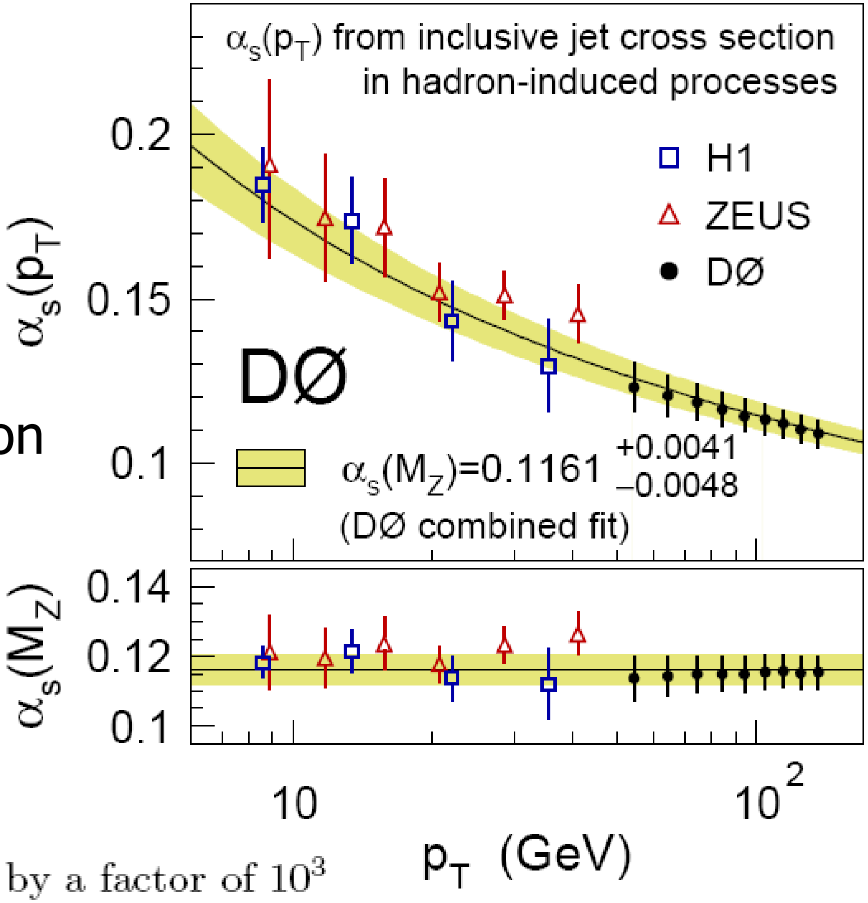
→ Exclude data points with $x_{max} \gtrsim 0.25$ (unknown correlation with PDF uncert.)

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

→ NLO + 2-loop threshold corrections

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

Phys. Rev. D **80**, 111107 (2009)



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 for $\alpha_s(M_Z)$

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)

→ Benefit from 2-loop threshold corrections calculation
→ Better: full NNLO

Going further …

… towards testing in the RGE
at higher momentum transfers

Don’t use cross section data
(don’t want to rely on PDF information)

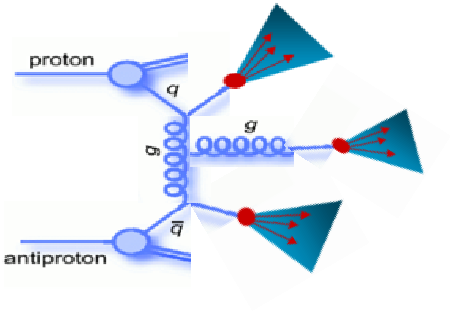
→ Use cross section ratios…

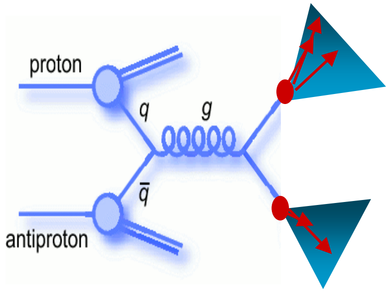
Cancelling PDFs in Ratios

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

→ Ratios of cross sections for 3-jet and 2-jet observables

R =





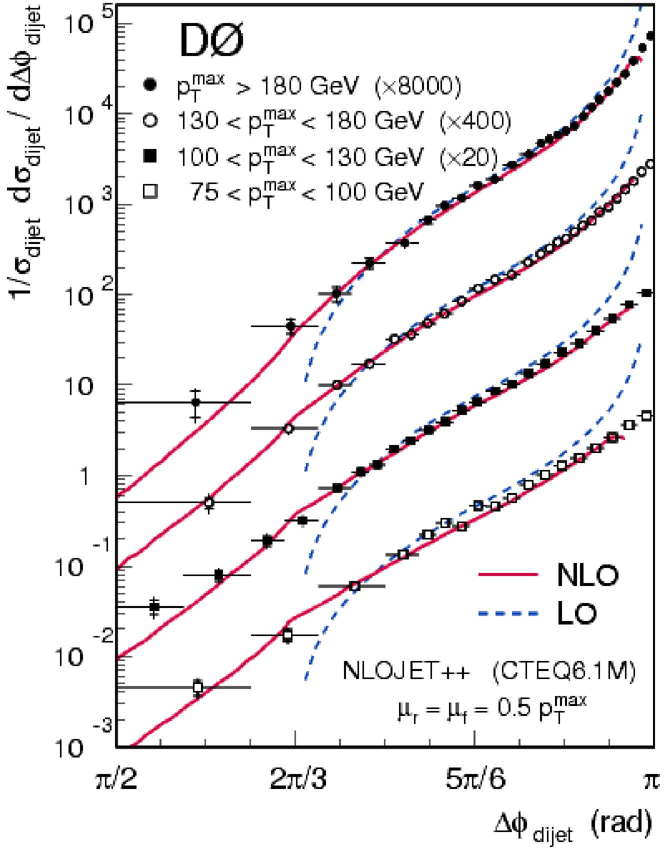
⟷ α_s

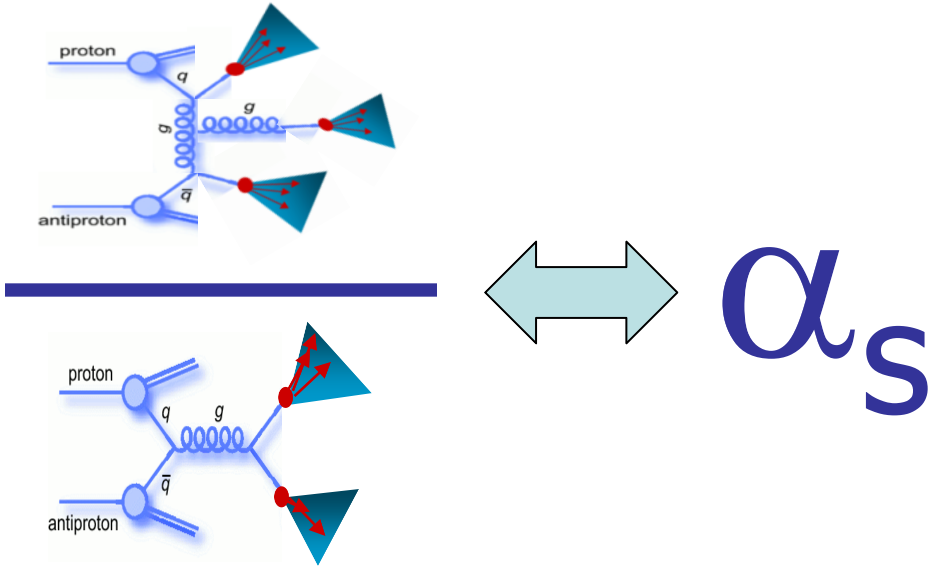
- Sensitive to α_s (3-jets: α_s^3 / 2-jets: α_s^2)
- Significantly reduced PDF sensitivity

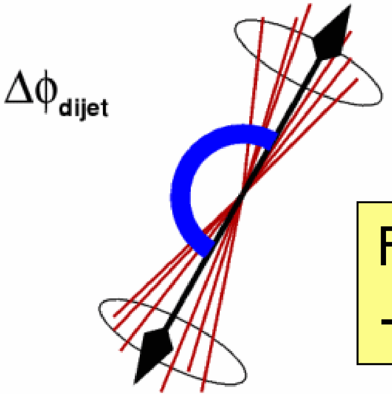
Dijet Azimuthal Decorrelations

$1/\sigma_{dijet} \;*\; d\sigma_{dijet} / d\Delta\phi_{dijet}$

PRL 94, 221801 (2005)







$\Delta\phi_{dijet}$ angle between the two leading p_T jets

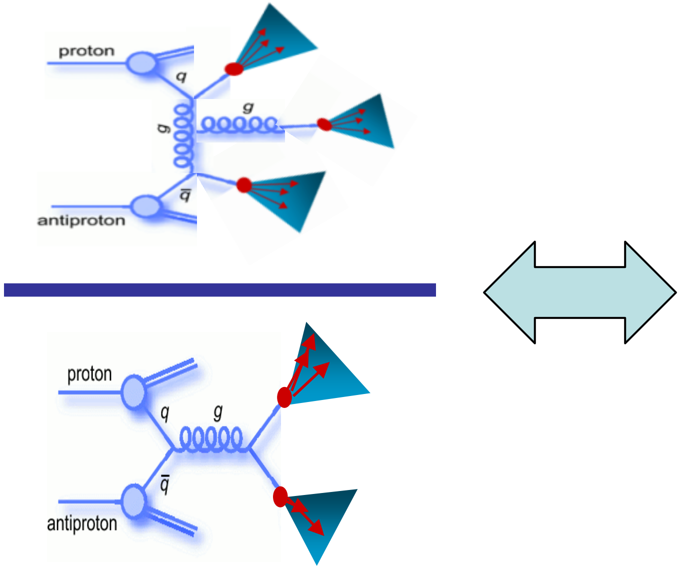
First test of 3-jet NLO
→ Good description

New result will be published in September

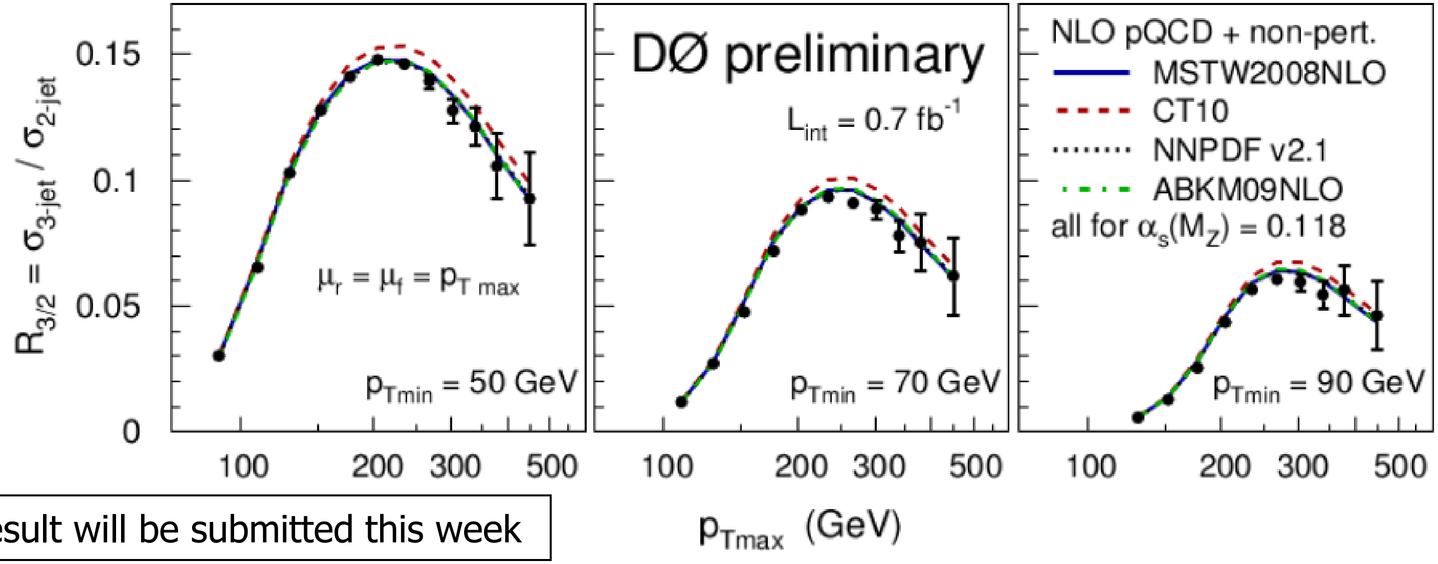
$R_{3/2} = \sigma_{3\text{-jet}} / \sigma_{2\text{-jet}}$

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

Measured vs. p_{Tmax}
for different p_{Tmin} requirements

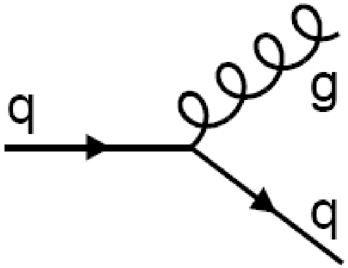


α_s



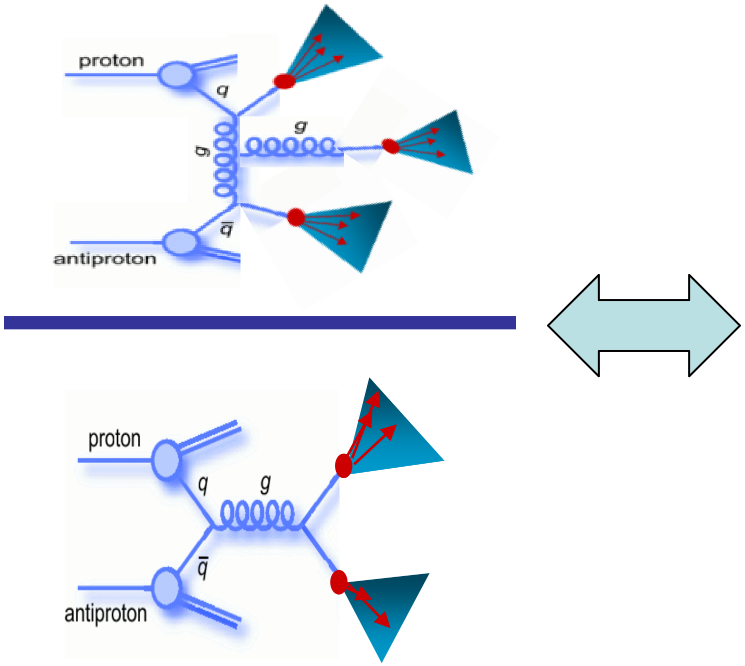
Final result will be submitted this week

New Observable: $R_{\Delta R}$ → angular correlations of jets



$R_{\Delta R}$

average number of neighboring jets
for jets from an inclusive jets sample



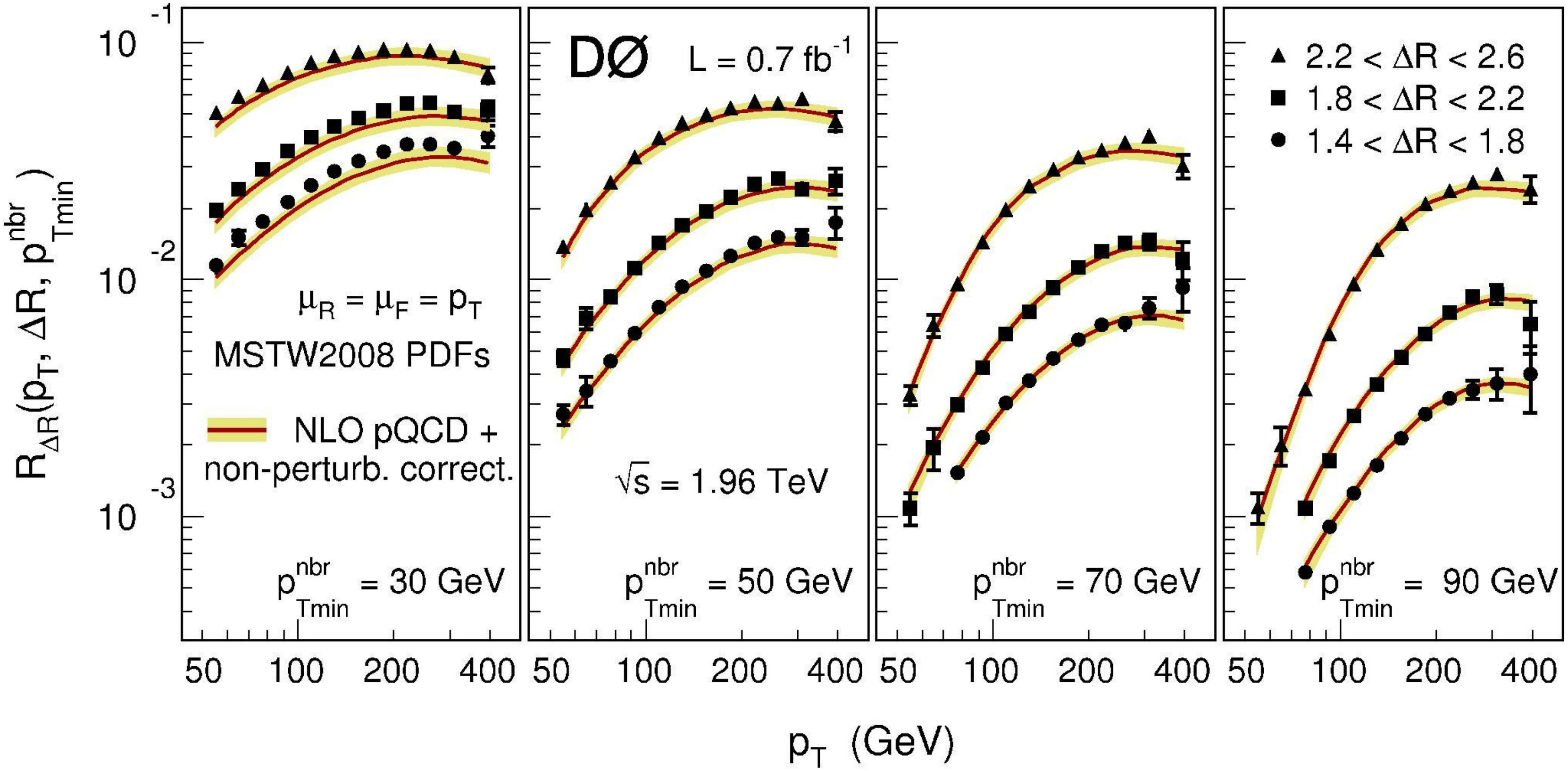
α_s

Depends on 3 variables → **triple differential** measurement

- inclusive jet p_T
- distance ΔR to neighbor jet in $(\Delta\phi,\Delta y)$
- neighbor jet $p_{T\text{-nbr-min}}$ requirement

$R_{\Delta R}$ results

Average number of neighboring jets within ΔR to an inclusive jet



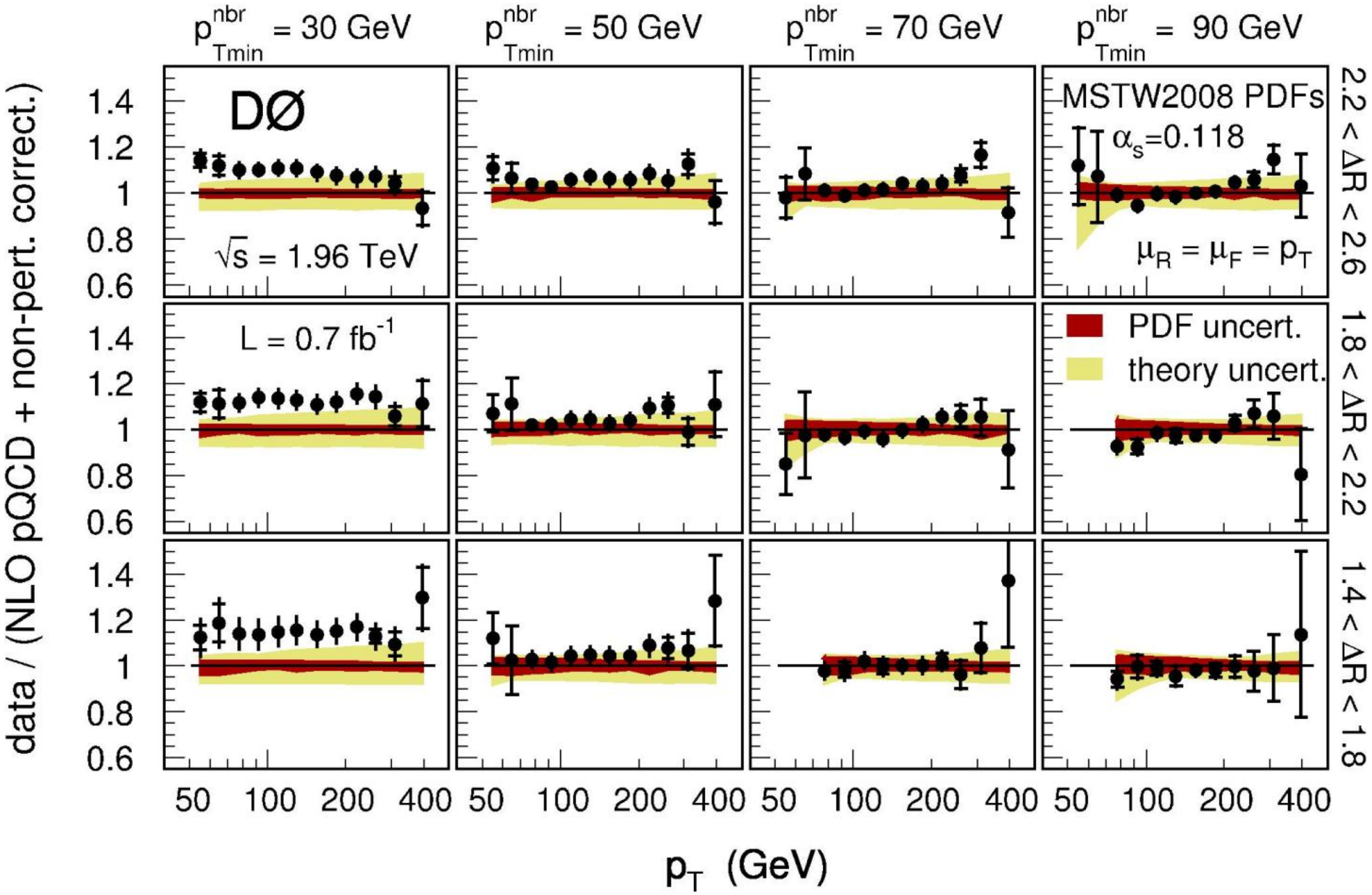
arXiv:1207.4957

→ Very precise results (uncertainties: 2-5%)

→ Dependence of $R_{\Delta R}$ on (p_T , ΔR, $p_{T\text{-nbr-min}}$) described by pQCD

$R_{\Delta R}$ data/theory

arXiv:1207.4957



- Good agreement for $p_{T\text{-nbr-min}}$ = 50 GeV and higher
- Not so good for requirement $p_{T\text{-nbr-min}}$ = 30 GeV (low p_T physics?)

Running of $\alpha_s(p_T)$

→ Extract α_s from $R_{\Delta R}$ data

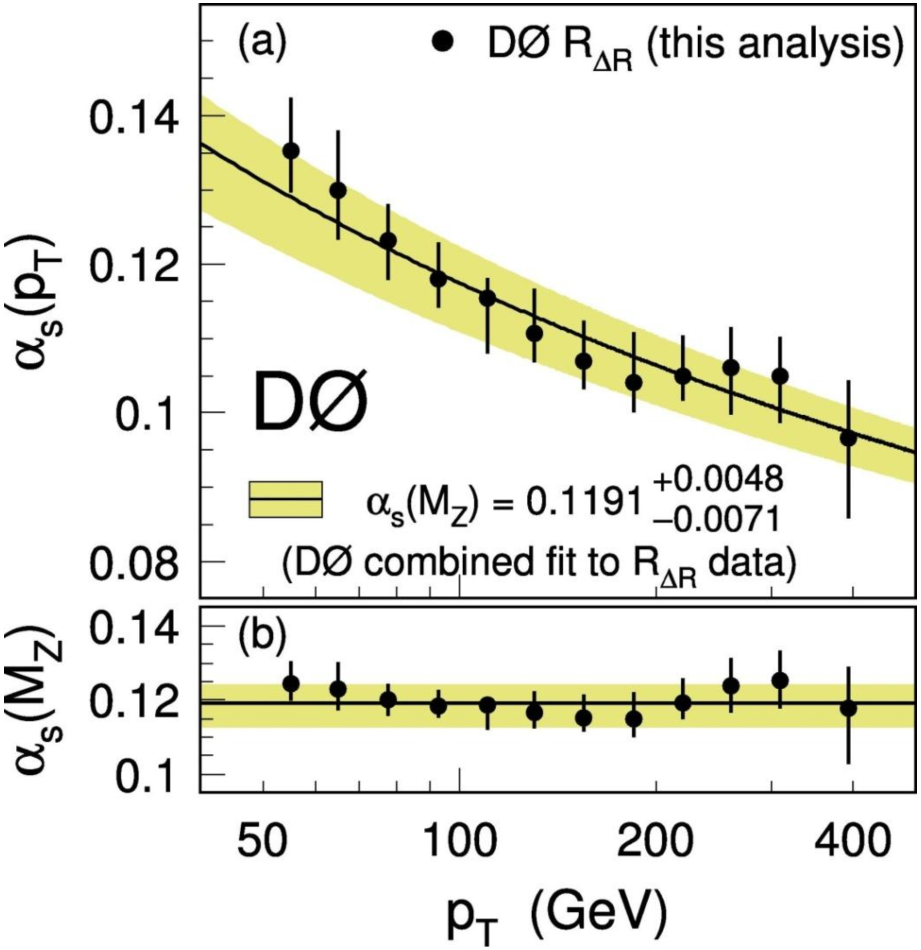
Use $p_{Tnbr\text{-}min}$ >= 50, 70, 90 GeV

At each p_T, combine all data points with different $p_{T\text{-}nbr\text{-}min}$ and ΔR requirments

Determine results for $\alpha_s(p_T)$ at 12 p_T values

- → $\alpha_s(p_T)$ results up to 400 GeV
- → $\alpha_s(p_T)$ decreases with p_T as predicted by the RGE

arXiv:1207.4957



Running of $\alpha_s(p_T)$

→ Extract α_s from $R_{\Delta R}$ data

Use $p_{T\text{nbr-min}}$ >= 50, 70, 90 GeV

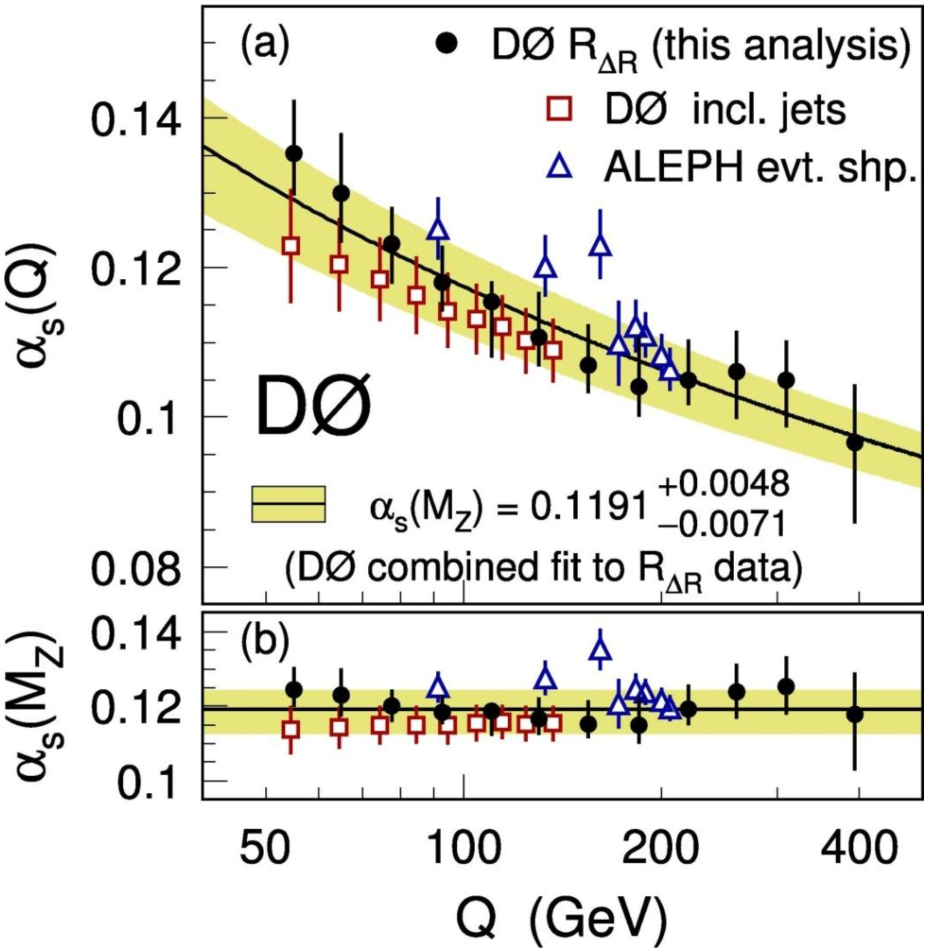
At each p_T, combine all data points with different $p_{T\text{-nbr-min}}$ and ΔR requirments

Determine results for $\alpha_s(p_T)$ at 12 p_T values

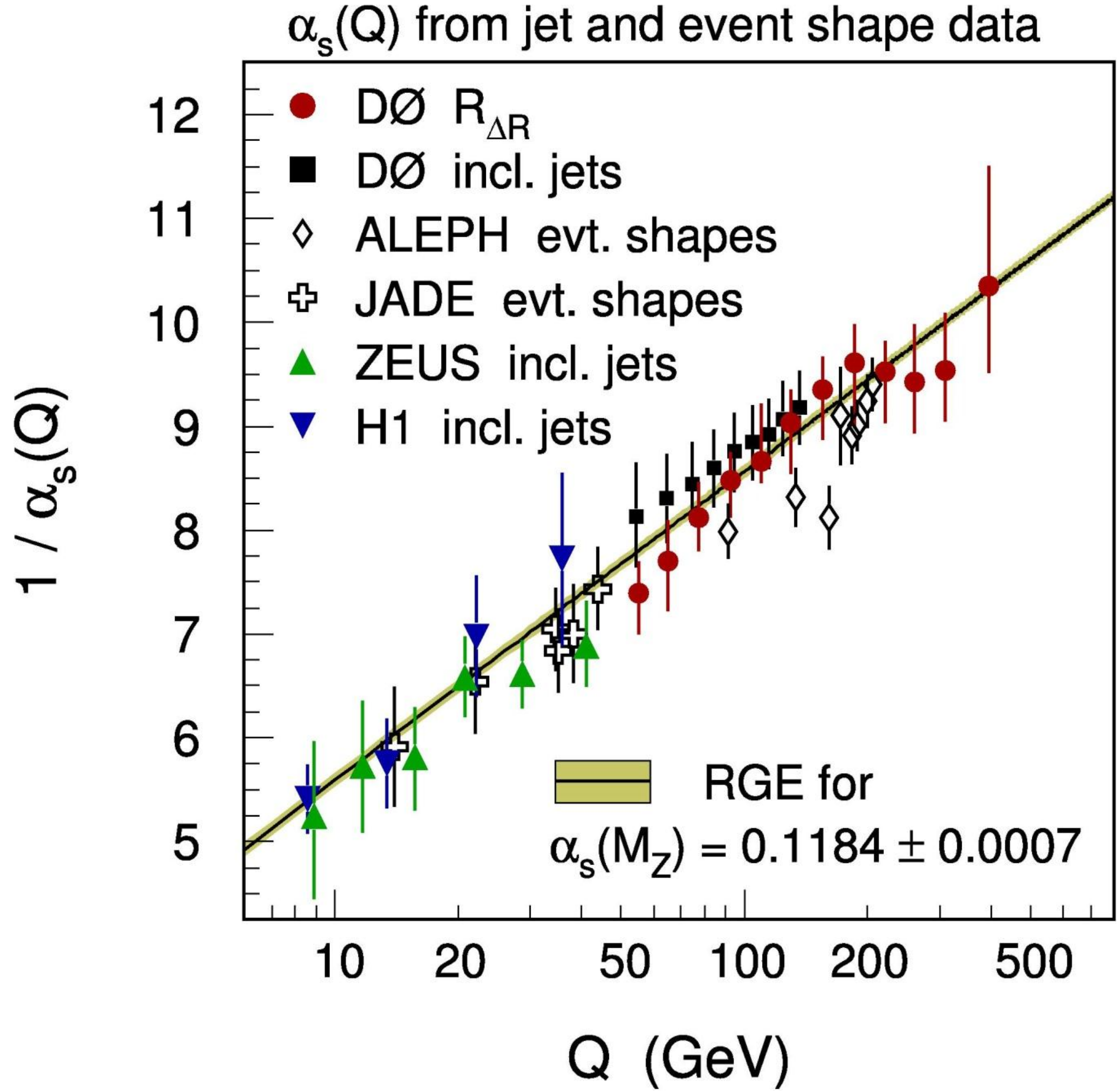
→ $\alpha_s(p_T)$ results up to 400 GeV

→ $\alpha_s(p_T)$ decreases with p_T as predicted by the RGE

arXiv:1207.4957



Running of $\alpha_s(Q)$ → 400 GeV

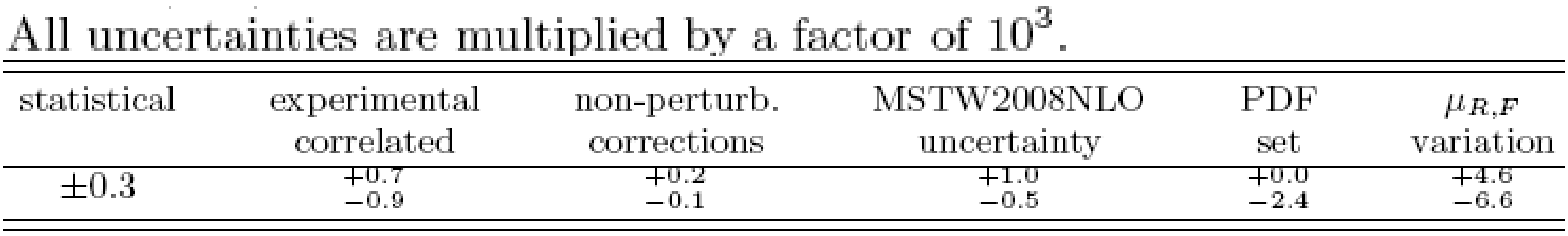


Results agree with
other results from
jet and event shape data

Combined $\alpha_s(M_Z)$ from $R_{\Delta R}$

Combining all data points with $p_{T\text{nbr}} > 50, 70, 90$ GeV (all ΔR, all p_T):

$$\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}$$



All uncertainties are multiplied by a factor of 10^3.

statistical	experimental correlated	non-perturb. corrections	MSTW2008NLO uncertainty	PDF set	$\mu_{R,F}$ variation
± 0.3	$^{+0.7}_{-0.9}$	$^{+0.2}_{-0.1}$	$^{+1.0}_{-0.5}$	$^{+0.0}_{-2.4}$	$^{+4.6}_{-6.6}$

- Very high experimental precision
- Strongly dominated by scale uncertainty @NLO

→ **Need 3-jet and 2-jet NNLO**

Summary

Precise jet measurement from the Tevatron
→ Everything well-described by theory
→ Existing "problems" likely related to PDFs

→ So far: use 2-loop threshold corrections
to include inclusive jet data in NNLO PDF fits

New result → angular correlations: $R_{\Delta R}$ (p_T, ΔR, $p_{T\text{-nbr-min}}$)
Precise measurement w/ systematic uncertainties <5%
Well described by pQCD for $p_{Tnbr} > 50$ GeV

α_s continues to decrease above 208 GeV → up to 400 GeV
→ Currently limited to NLO
→ Dominant uncertainty: renormalization scale dependence

Conclusion

- Today, PDF fits @ NNLO are the state-of-the-art
- Hadronic jets provide essential high-x input

→ urgent: need dijet NNLO
to use inclusive jet and dijet data in PDF fits
(better description of radius dependence
and smaller scale dependence)

3-jet / 2-jet ratios can be used for high-precision
α_s determinations / largely independent of PDFs

→ Dominant uncertainty: renormalization scale dependence
→ Need 3-jet NNLO for more precision
→ NNLO is required for inclusion in world average

Need 2-jet & 3-jet NNLO for jet phenomenology

Backup

Properties of the NNLO

Virtual Corrections → Reduced Scale Dependence

Real Corrections → 2nd "bonus" parton

- LO: #partons = #jets
- NLO: #partons = #jets + 1 (one "bonus" parton)
- NNLO: #partons = #jets + 2 (two "bonus" partons)

→ better modeling of the final-state topology @ NNLO

- 3 partons in one jet (→ jet radius dependence)
- 2 jets with two partons each (→ jet radius dependence)
- 2 ISR partons (→ pT kick of final state)

Technical note:

NNLO is required to make it into the world average of α_s

Things we know / don't know about the NNLO (1)

NNLO for any quantity:

Structure of perturbative expansion is known
(N. Glover hep-ph/0204316)

$$L = \ln(\mu_r/p_T)$$

$$\frac{d\sigma}{dp_T} = \alpha_s^2(\mu_r)\,A_2 + \alpha_s^3(\mu_r)\,(A_3 + 2b_2LA_2) + \alpha_s^4(\mu_r)\,(A_4 + 3b_2LA_3 + (3b_2^2L^2 + 2b_3L)A_2)$$

The NNLO coefficient A_4 is unknown

… but one can make assumptions – Glover tries: $A_4 = \pm A_3^2/A_2$

For these assumptions on A_4 → reduce scale uncertainty on $\alpha_s(p_T)$
from $R_{\Delta R}$ data from +4.6 / -6.6
to + / -

Things we know / don't know about the NNLO (2)

NNLO for inclusive jets & dijets requires NLO plus

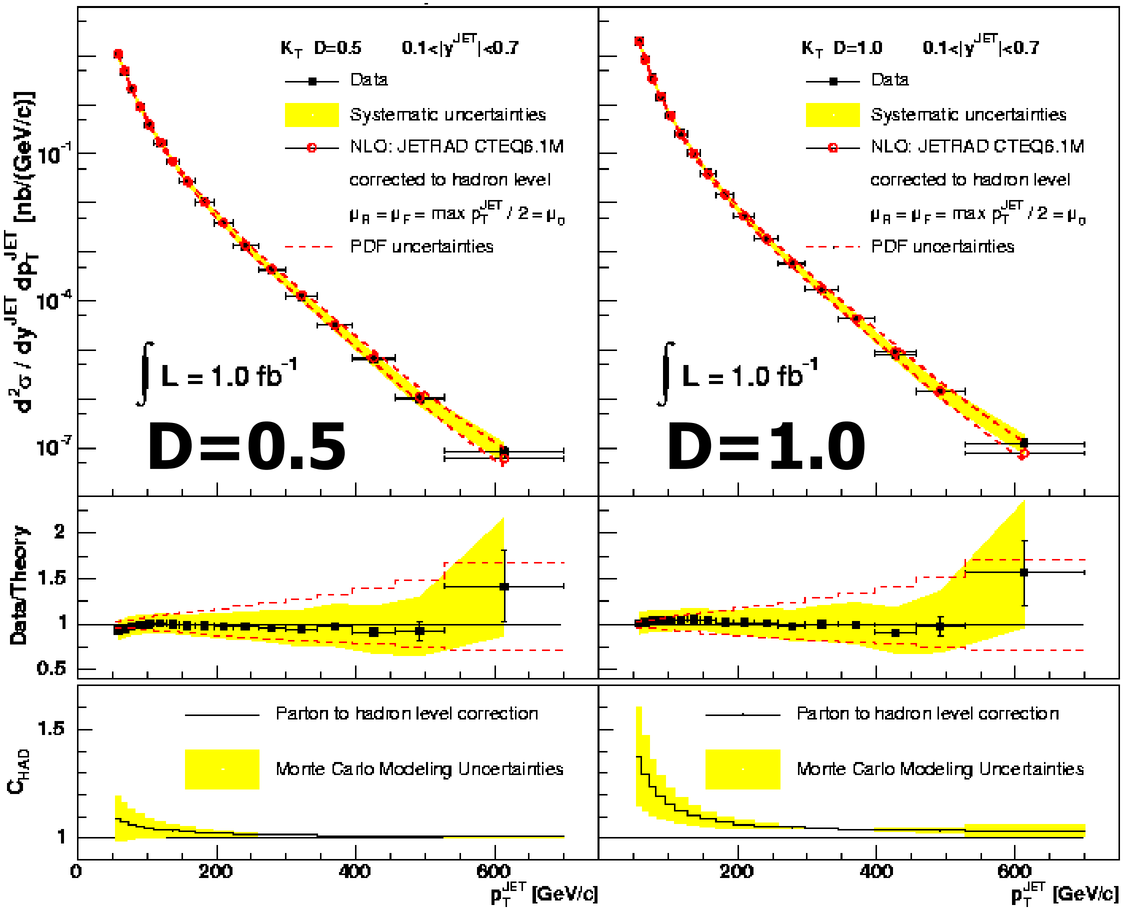
- 2-loop corrections to (2→2) ← not available
- 1-loop corrections to (2→3) ← part of 3-jet NLO
- Real corrections (2→4) ← part of 3-jet NLO

→ Use 3-jet NLO to compute radius dependence of inclusive jet cross NNLO cross section

Radius Dependence of Jet Cross Sections

Jet cross section depends on radius in jet definition

Phys. Rev. D 75, 092006 (2007)



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

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

→ agreement for all R values

→ LO test of radius depend.

→ For quantitative test:
study **ratios** and compute prediction 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
- 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:

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

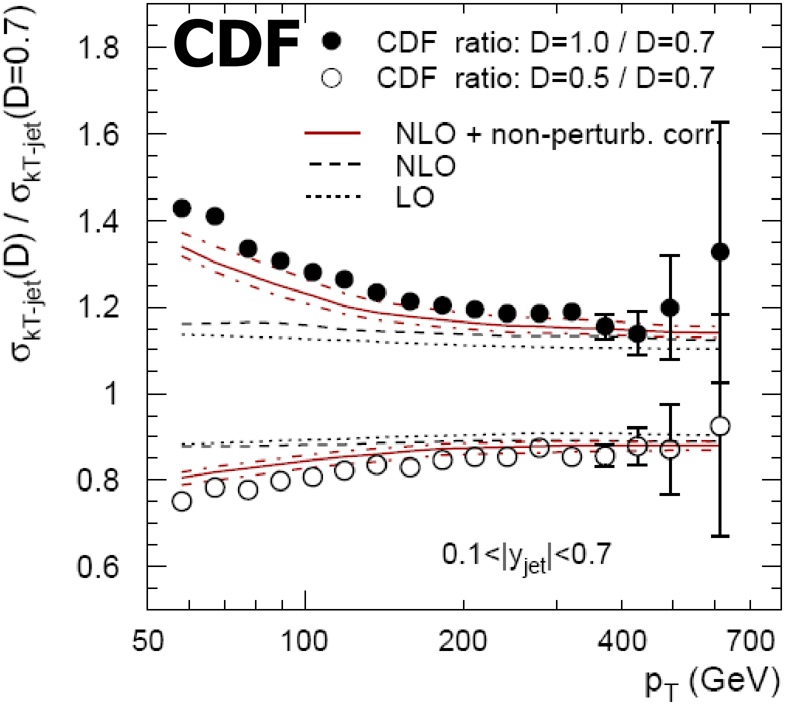
→ use for NLO study of radius dependence of jet cross sections

Radius Dependence of Jet Cross Sections @NLO

T. Kluge, M.W. – work in progress

Study cross section **ratios**:

(R=1.0/R=0.7) and (R=0.5/R=0.7) and compare with true NLO calculation



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

only at highest p_T :

→ agreement at the edge of scale dependence

disagreement at lower p_T :

→ larger radius dependence in data

→ NLO corrections are <20%

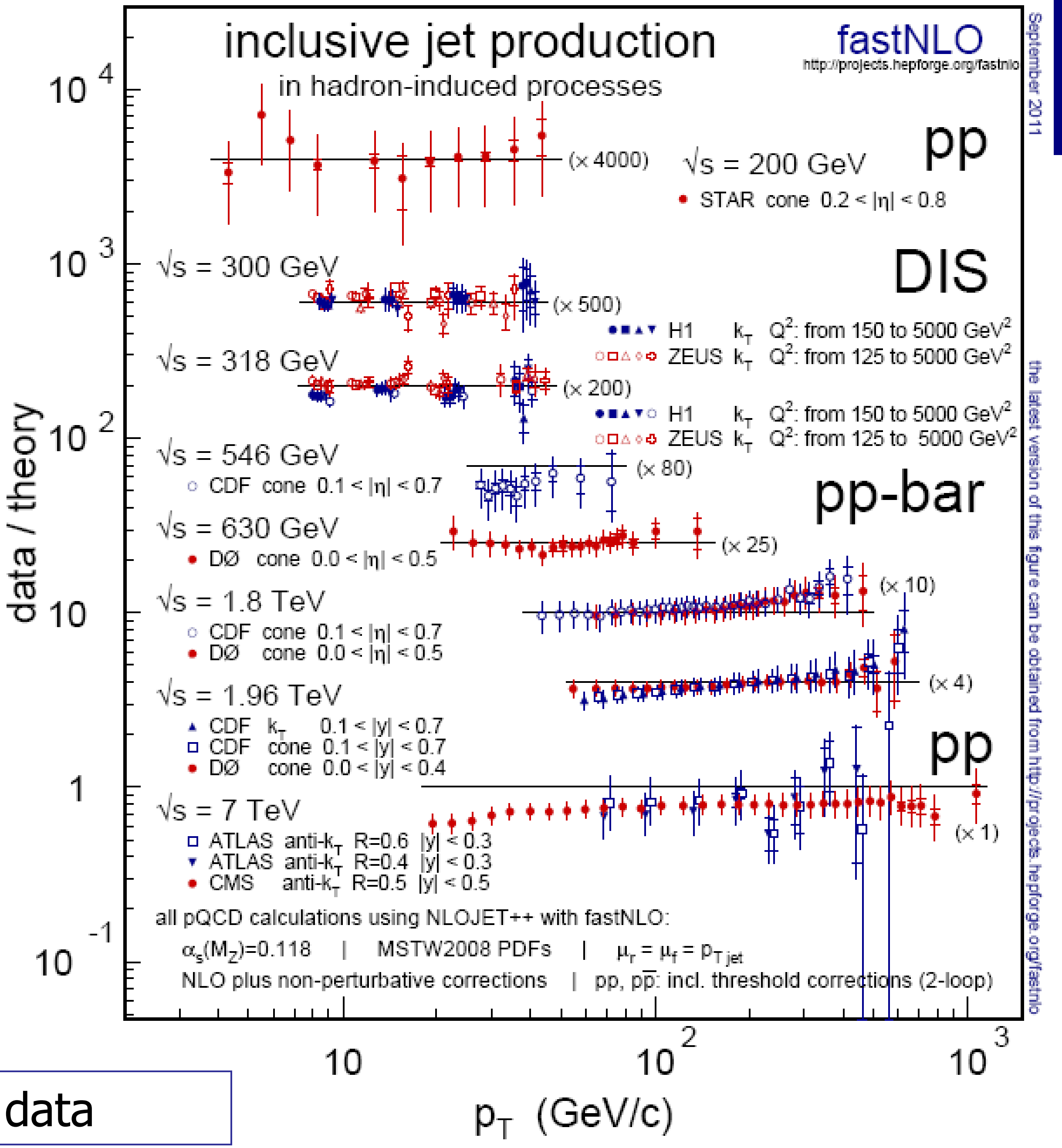
→ most of p_T range: dominated by non-pert. corrections

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

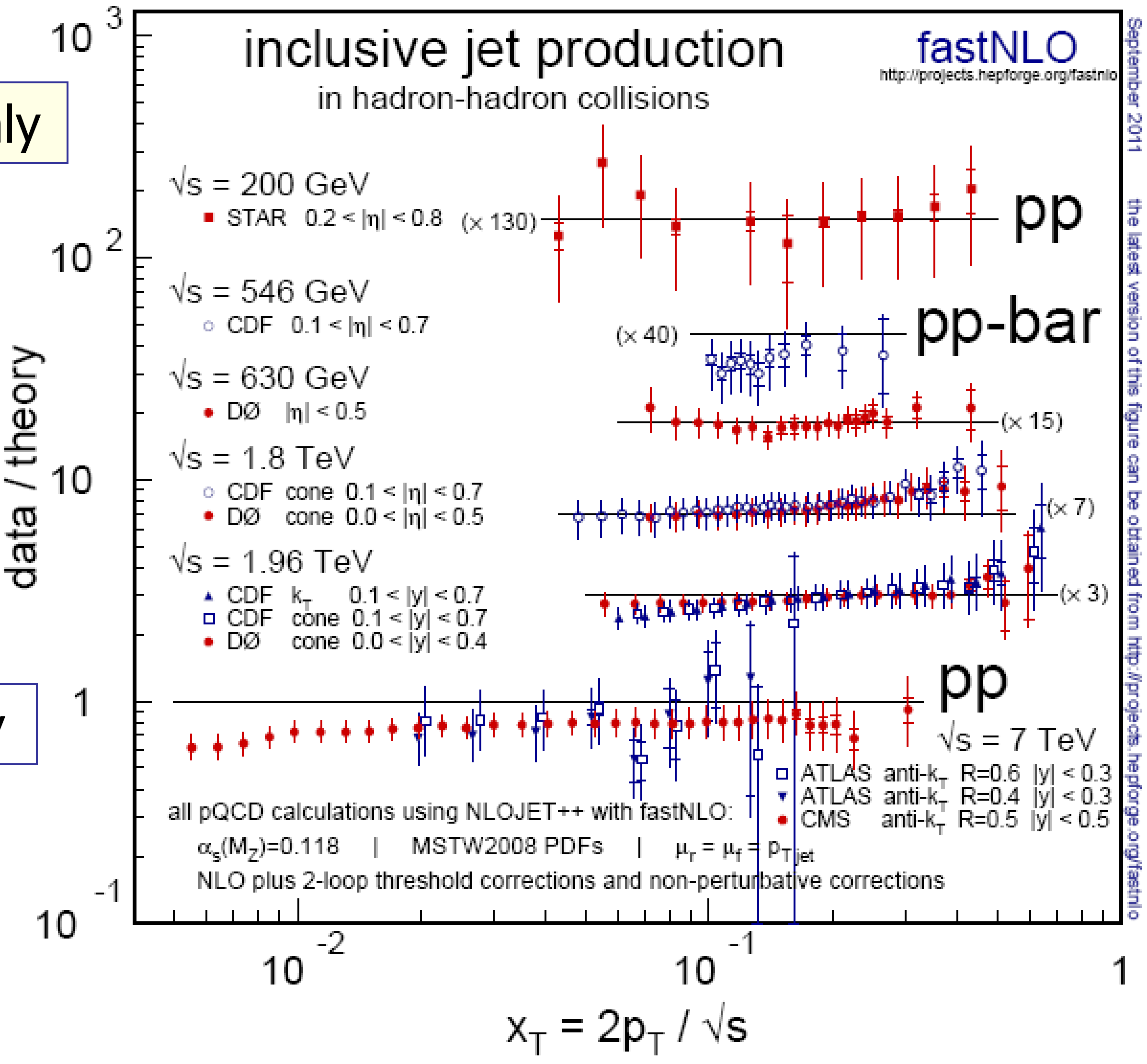
plot vs. $x_T = 2p_T/\mathrm{sqrt}(s)$

Interpretation:

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

demonstrate PDF sensitivity

highest x_T-reach by Tevatron data

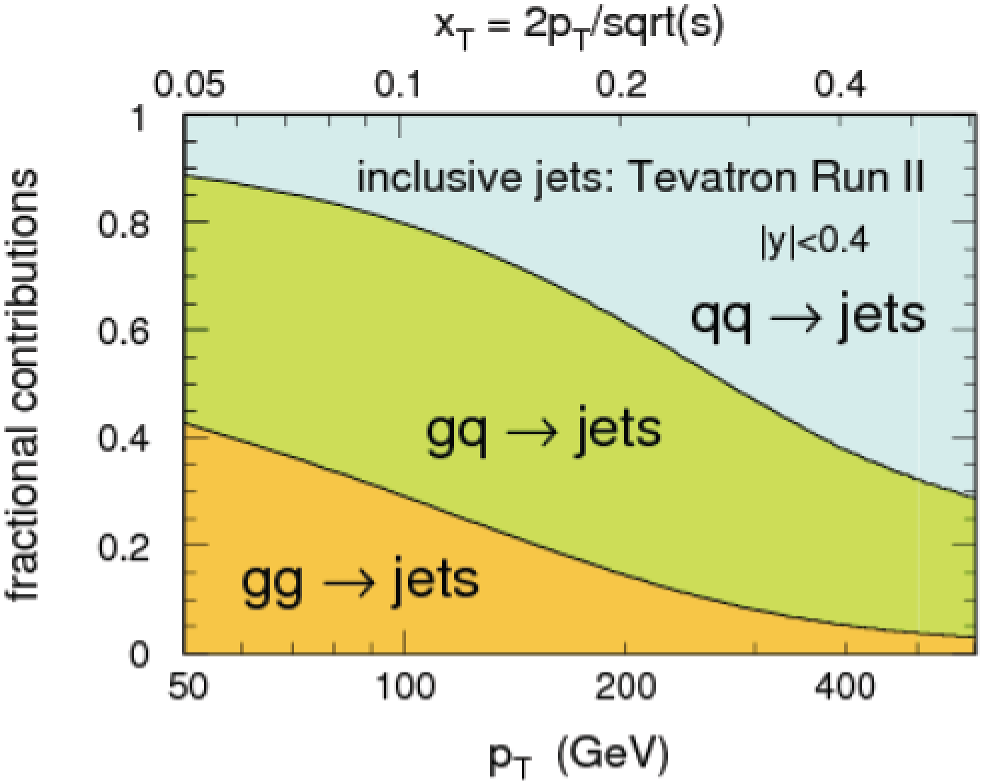


PDF sensitivity

Theory: pQCD @NLO is reliable (±10%)

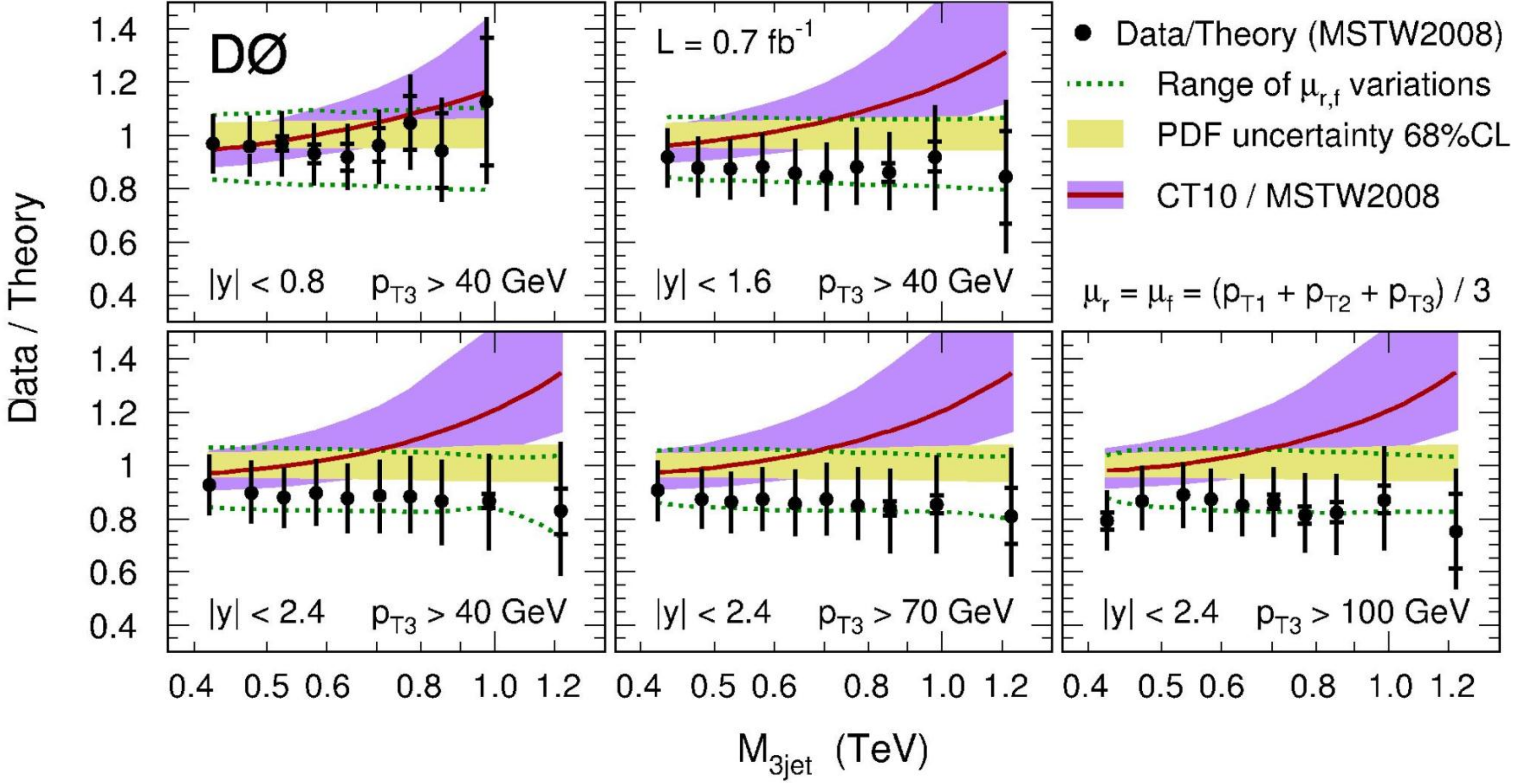
→ sensitivity to PDFs

→ unique: high-x gluon



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

Phys. Lett. B **704**, 434 (2011)

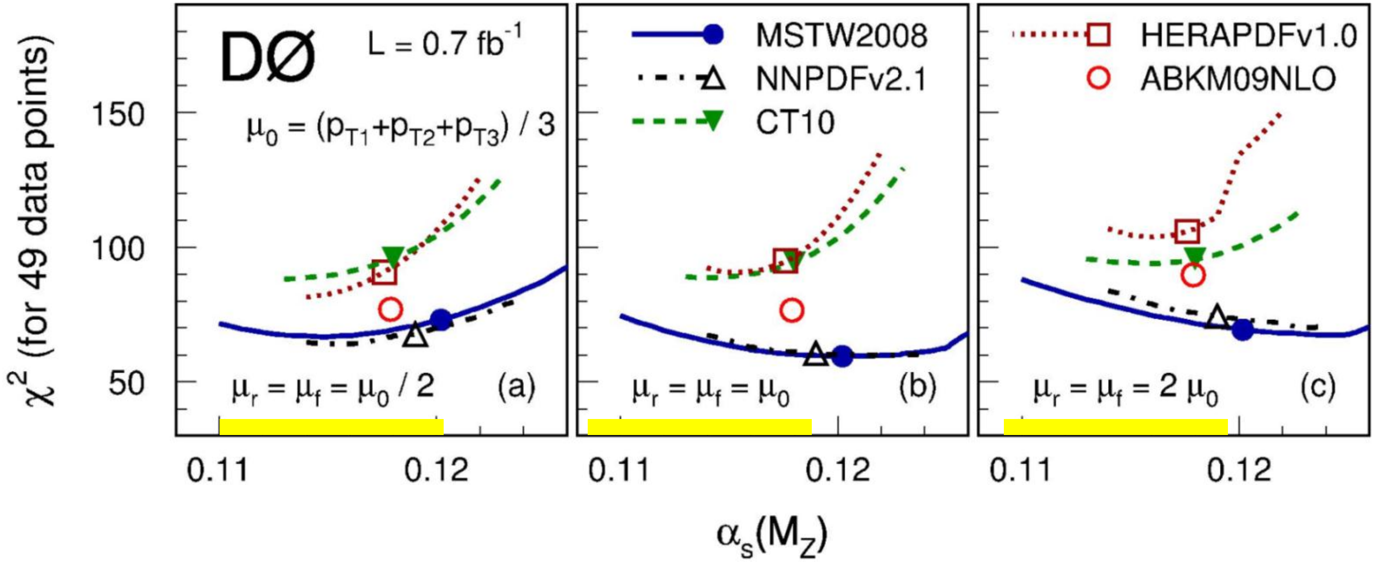


similar to dijet mass result:

- **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 $M_{3\text{-jet}}$

detailed χ^2 analysis → test PDFs

Phys. Lett. B **704**, 434 (2011)



Agreement between theory and data depends on

- value of $\alpha_s(M_Z)$
- choice of PDFs
- choice of renormalization/factorization scales

→ **Quantify agreement**: Study **chi²** for all variations

→ best agreement for MSTW2008, NNPDFv2.1

→ not so good for CTEQ10, HERAv1.0

α_s and the Renormalization Group Equation

$\alpha_s(\mu_R)$: depends on μ_R
the renormalization scale

Observables must be independent of μ_R → RGE

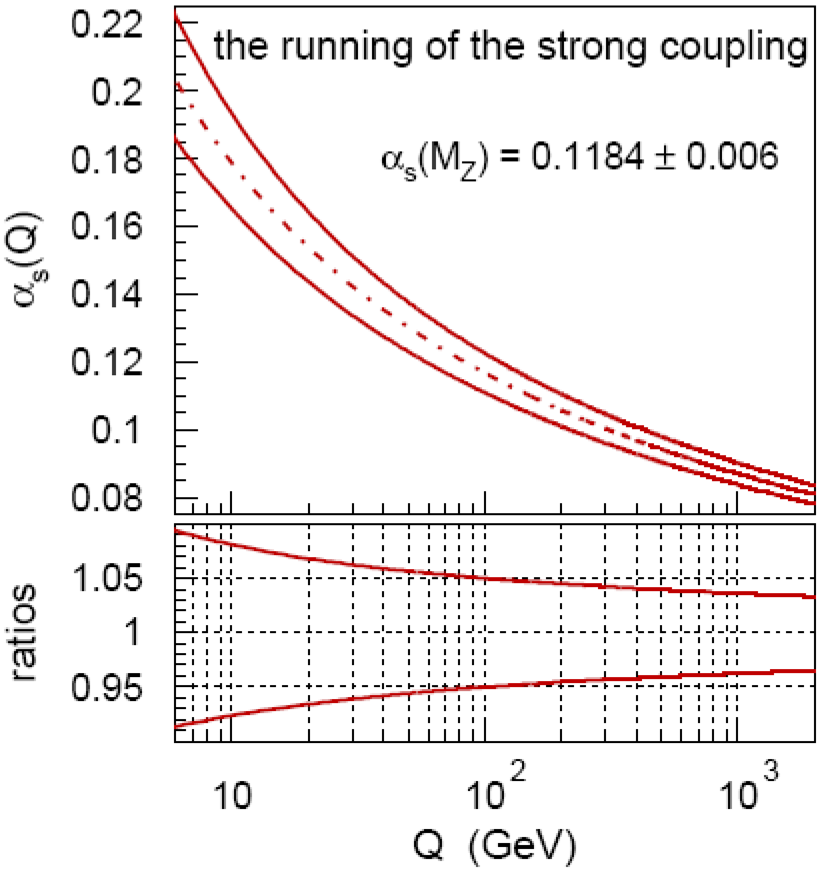
Renormalization **G**roup **E**quation

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

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

RGE relates $\alpha_s(Q_0)$ at one scale Q_0 to $\alpha_s(Q)$ at any other scale Q

RGE predicts all $\alpha_s(Q)$ curves which are possible



α_s and the Renormalization Group Equation

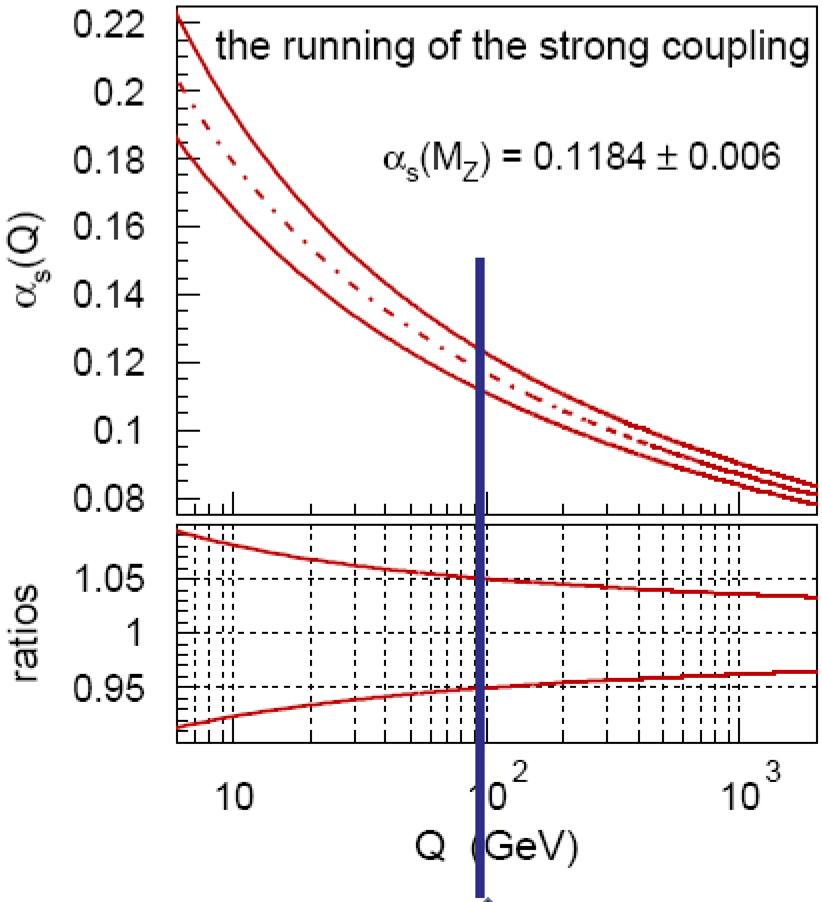
$\alpha_s(\mu_R)$: depends on μ_R
the renormalization scale

Observables must be independent of μ_R → RGE

Renormalization **G**roup **E**quation

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

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

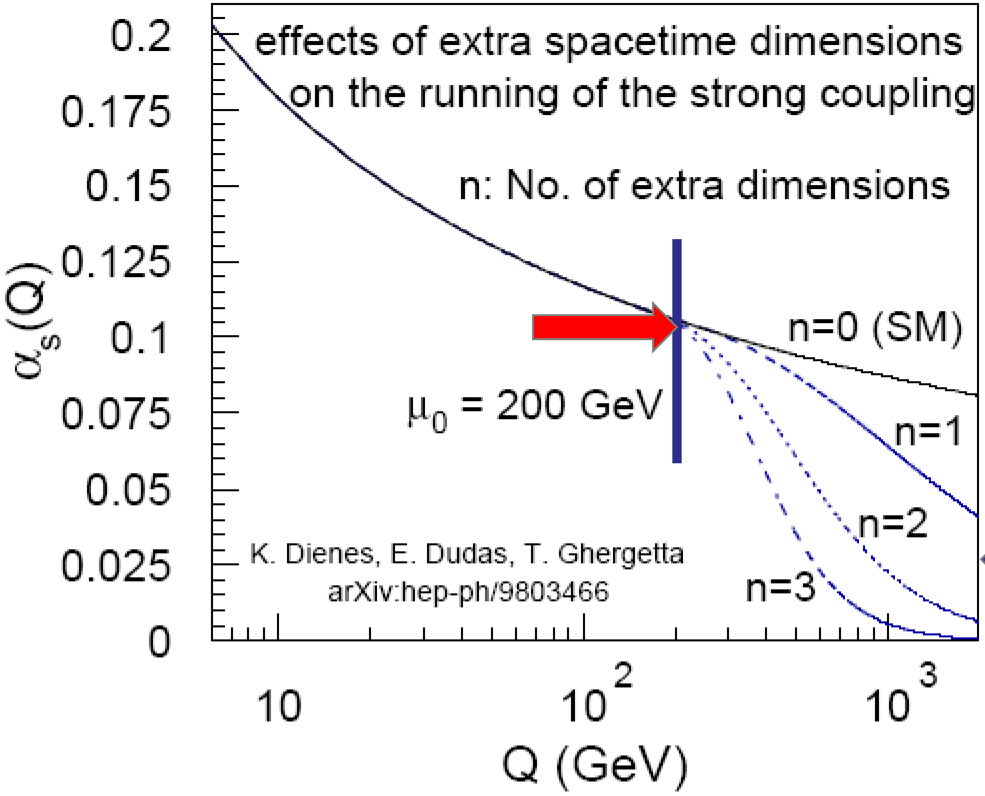


RGE relates $\alpha_s(Q_0)$ at one scale Q_0 to $\alpha_s(Q)$ at any other scale Q

RGE predicts all $\alpha_s(Q)$ curves which are possible

Agreement: label curves by $\alpha_s(\mu_R = M_Z)$

$\alpha_s(Q)$ beyond 208 GeV ?



K. Dienes, E. Dudas, T. Ghergetta
arXiv:hep-ph/9803466

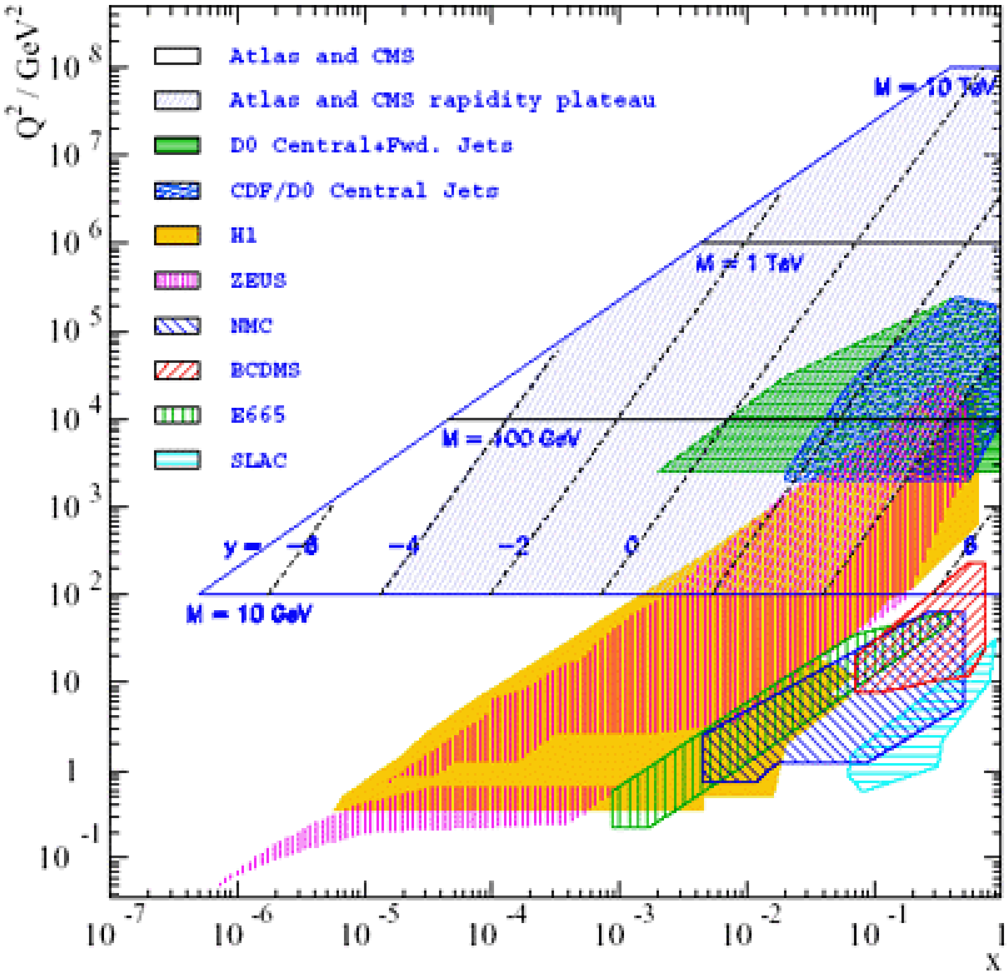
→ so far tested
up to Q = 208 GeV

Running of $\alpha_s(Q)$ could be
modified for scales
$Q > \mu_0$
e.g. by extra dimensions

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

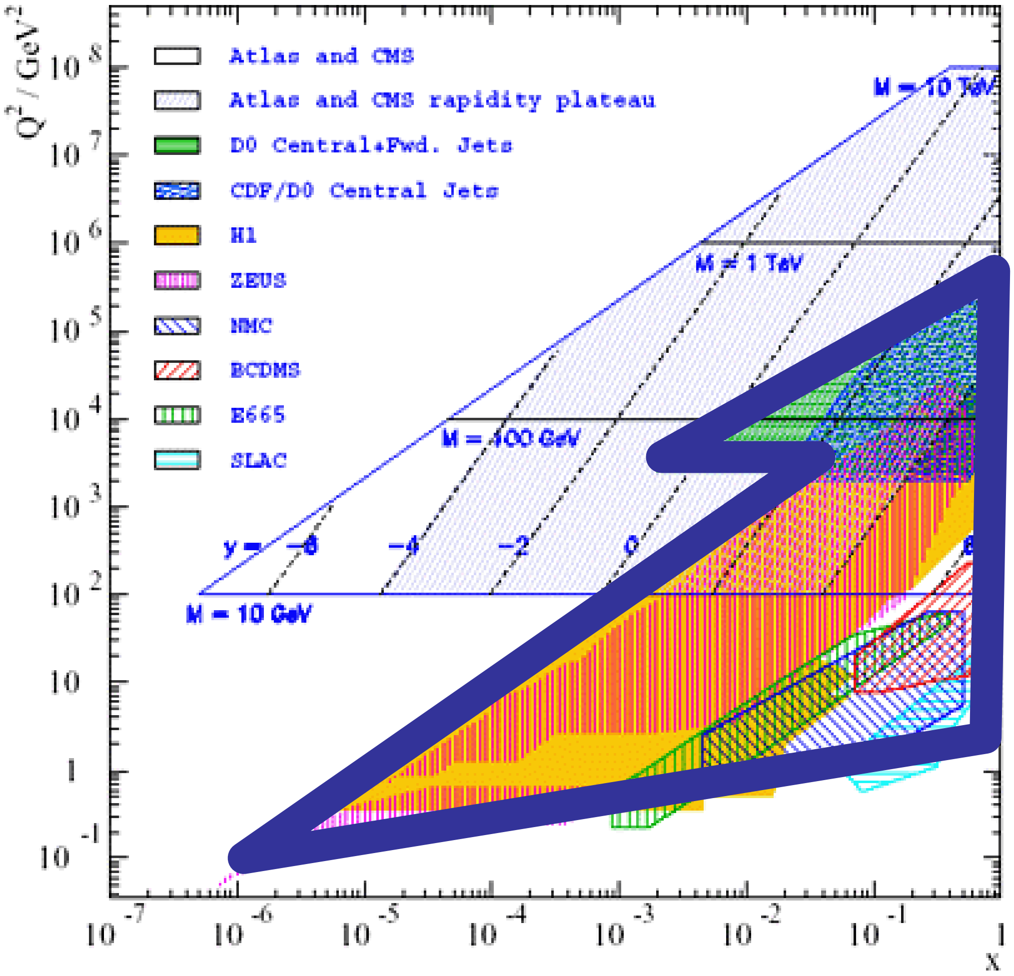
This analysis: study $\alpha_s(Q)$ for Q → 400 GeV

PDF knowledge



PDFs are determined in global analyses:
CTEQ, MSTW, NNPDF

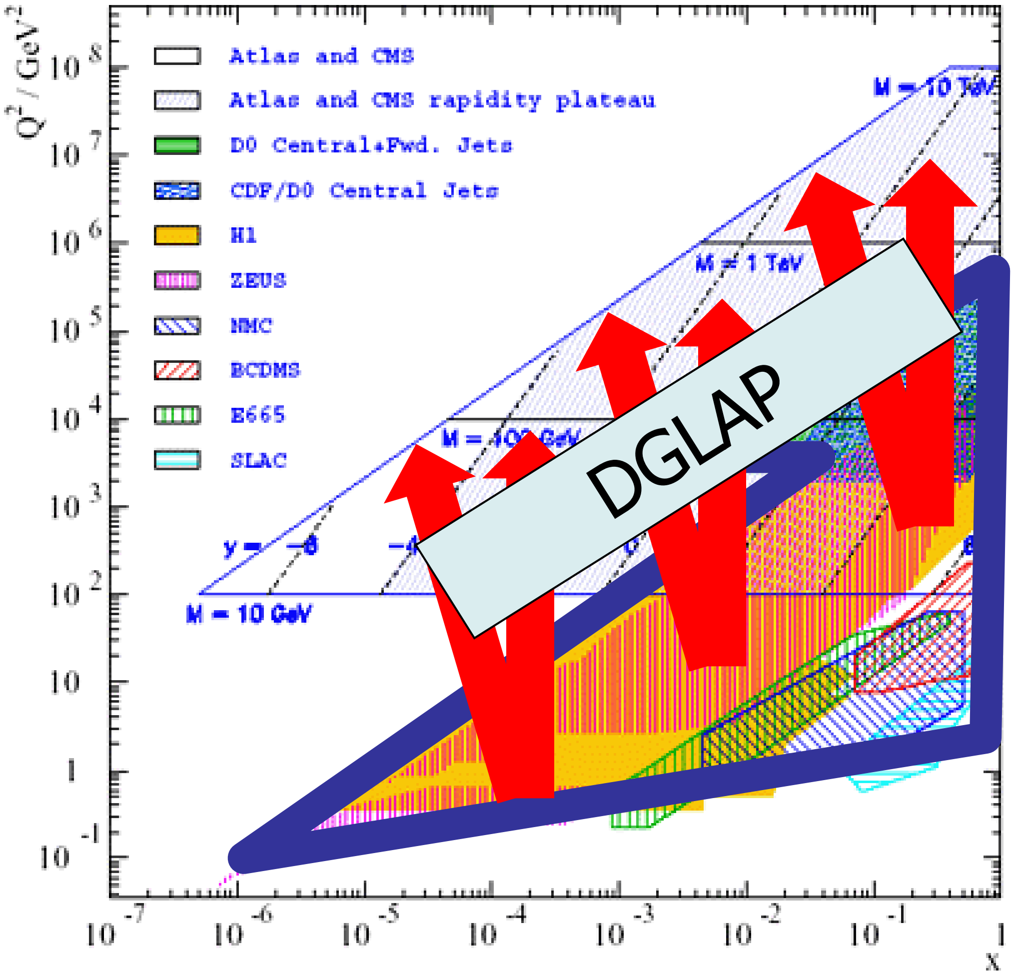
PDF knowledge



PDFs are determined in global analyses:
CTEQ, MSTW, NNPDF

Most experimental constraints on PDFs are from data at **lower scales**

PDF knowledge



PDFs are determined in global analyses:
CTEQ, MSTW, NNPDF

Most experimental constraints on PDFs are from data at **lower scales**

PDF knowledge at high scales from "DGLAP" evolution
→ **uses RGE for $\alpha_s(Q)$**

$$\frac{\partial g(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[\int_x^1 \left(P_{gq}\left(\frac{x}{x_1}\right)q_s(x_1,Q^2) + P_{gg}\left(\frac{x}{x_1}\right)g(x,Q^2)\right)\right].$$

DGLAP: Dokshitzer–Gribov–Lipatov–Altarelli–Parisi

Inclusive 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)

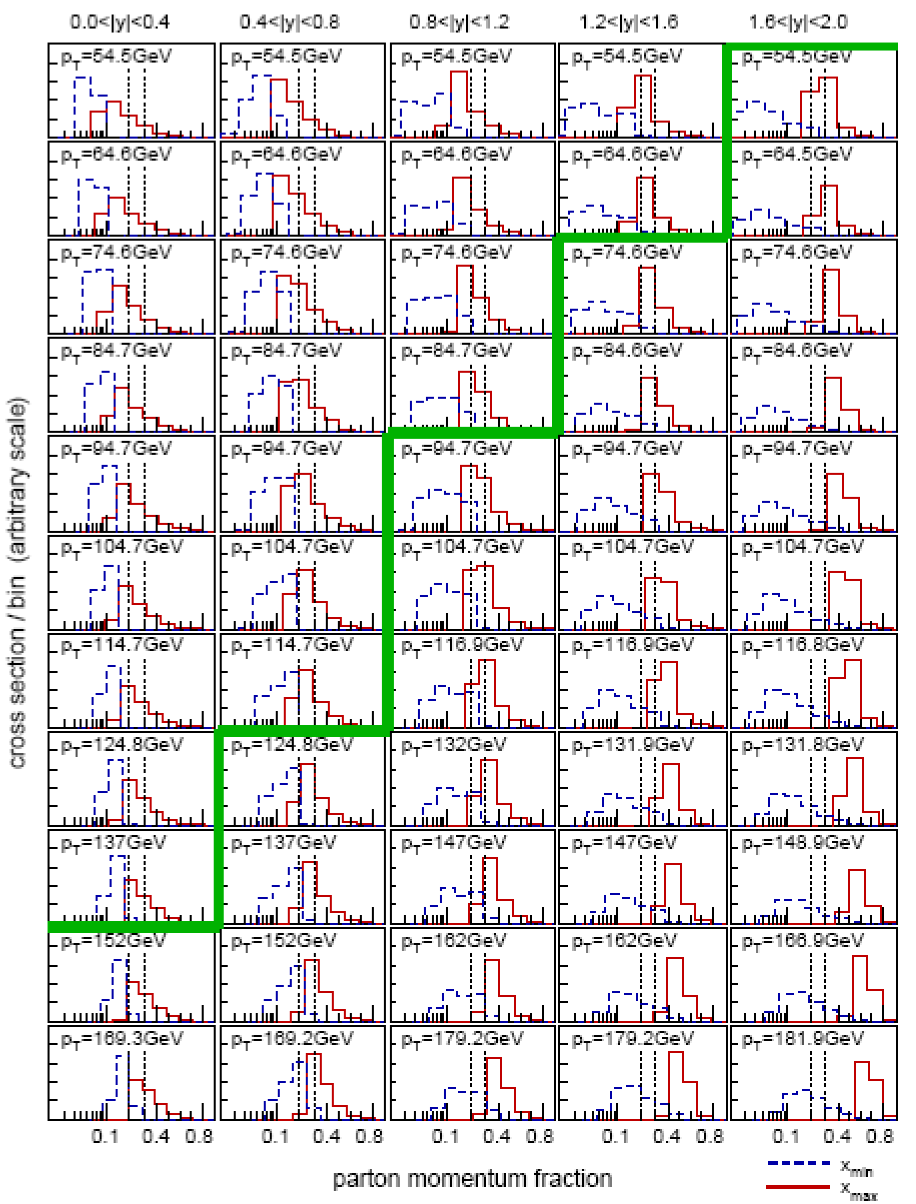
→ Construct a "test-variable" (treat as if other jet was at y=0):

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

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

→ Find: requirement $x_{test} < 0.15$
removes most of the contributions with $x > 0.2 – 0.3$

x_{min} / x_{max} distributions



Every analysis bin → one plot

Each plot: x_{min}/x_{max} distributions

Cut on test-variable $x_{test} < 0.15$

→ keep 22 (of 110) data points

These have small contributions from

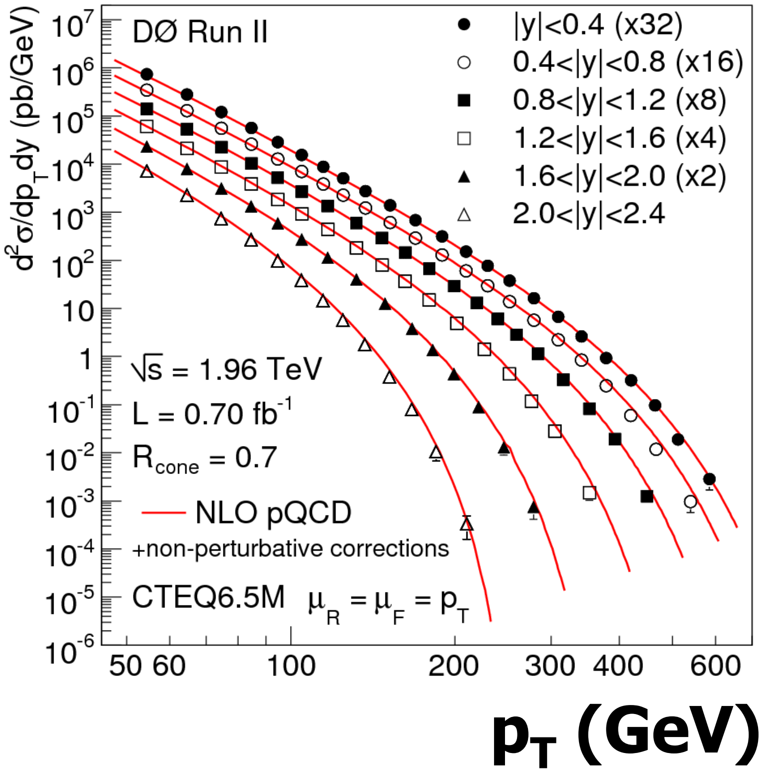
$x > 0.2 – 0.3$

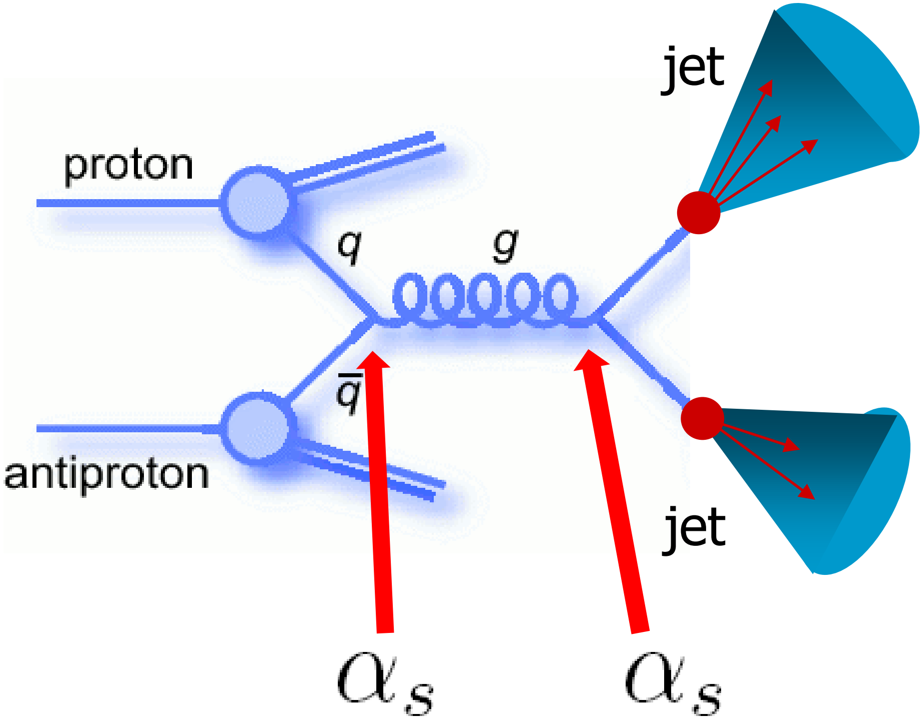
← Only data points above green line are used

╌╌ x_{min}

━━ x_{max}

D0 $\alpha_s(p_T)$ from Run II inclusive jet cross section data

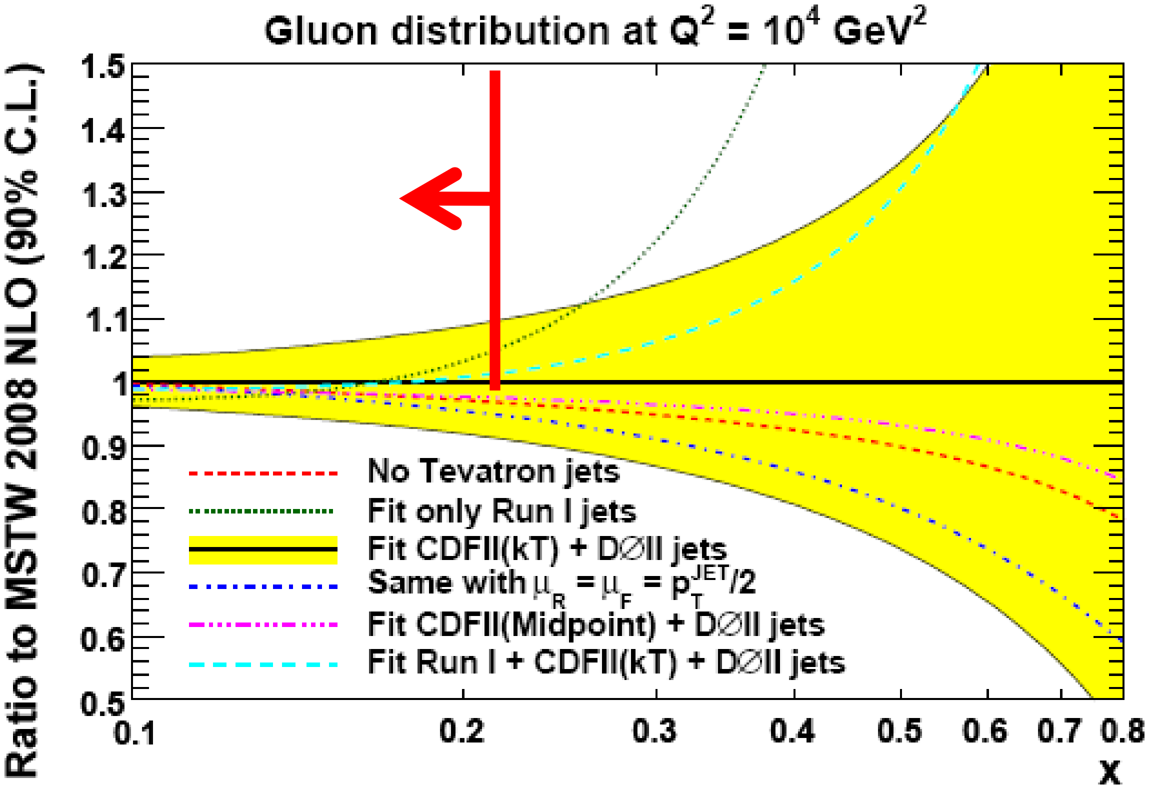




→ Avoid potential inconsistencies

PDFs and input data

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



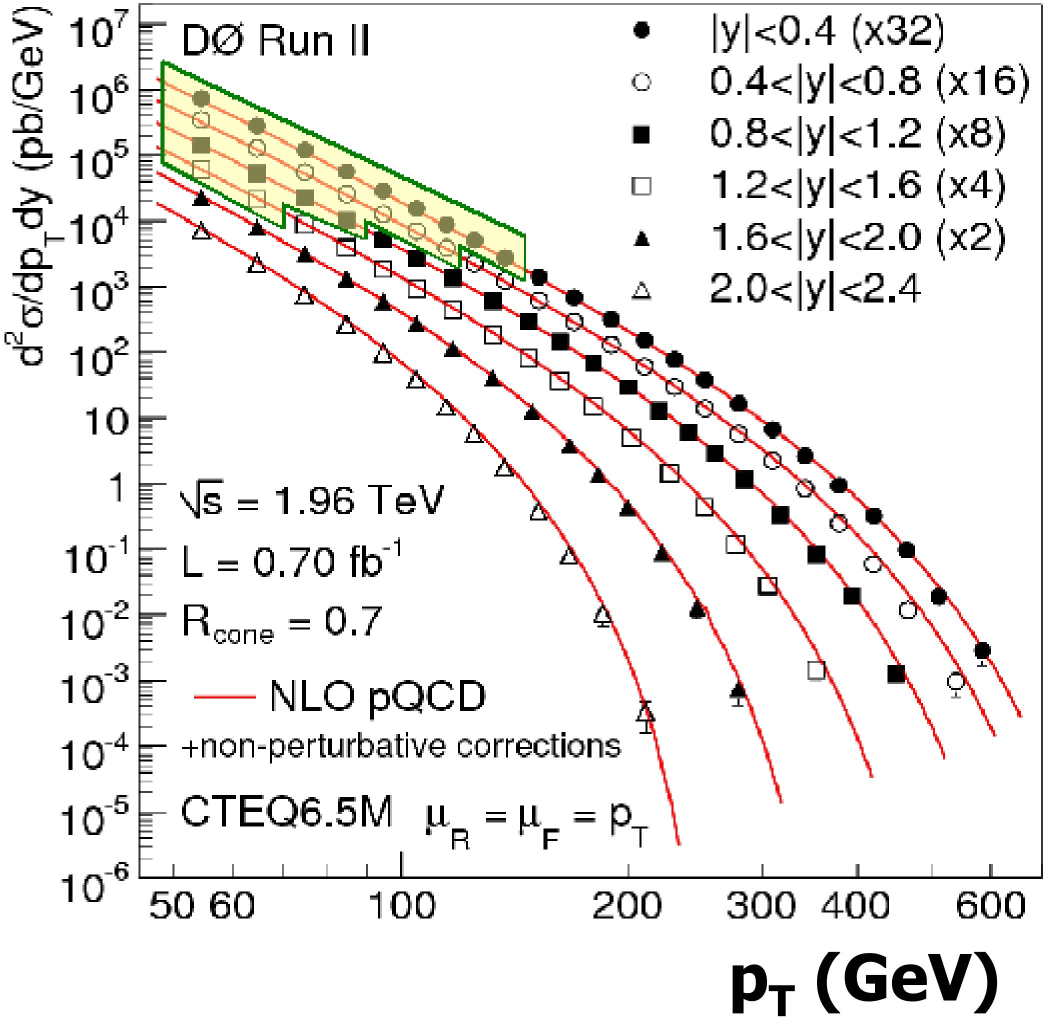
Currently:
Main constraints on high-x gluon density come from Tevatron jet data

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

Data Sample for α_s analysis



22 (out of 110) inclusive jet cross section data points have small contributions from x > 0.2 – 0.3

→ Data points
at 50 < p_T < 145 GeV

→ Input in α_s analysis

Restriction to
50 < p_T < 145 GeV
avoids p_T regions in which RGE has not yet been tested!
(no circular argument here)

PDF sensitivity

Inclusive jet cross section:

$$\alpha_s(p_T) \propto \sqrt{\frac{\sigma_{\mathrm{data}}}{\mathrm{PDF}^2}}$$

3-jet / 2-jet cross section ratio:

$$\alpha_s(p_T) \propto R_{\mathrm{data}} \cdot \left(\frac{\mathrm{PDF'}}{\mathrm{PDF}}\right)^2$$

New Observable: $R_{\Delta R}$

1. Start with central inclusive jet sample ($|y|<1$)

2. Loop over all inclusive jets
   For each inclusive jet: count No. of neighboring jets
   - in distance ΔR in $(\Delta\phi,\Delta y)$
   - with $p_{T\text{nbr}} > p_T^{\text{min}}{}_{\text{nbr}}$

3. Ratio: sum of all neighboring jets / total number of inclusive jets
   → average number of neighboring jets $R_{\Delta R}(p_T, \Delta R, p_T^{\text{min}}{}_{\text{nbr}})$

Note: for $\Delta R < \pi$ → only contributions from (at least) 3-jet events

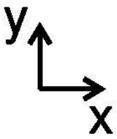
→ $R_{\Delta R}$ looks at any jet and any neighboring jet
… more inclusive than $R_{3/2}$ (require to tag three leading jets)
… more inclusive than $R_{\Delta\phi}$ (require to tag two leading jets)

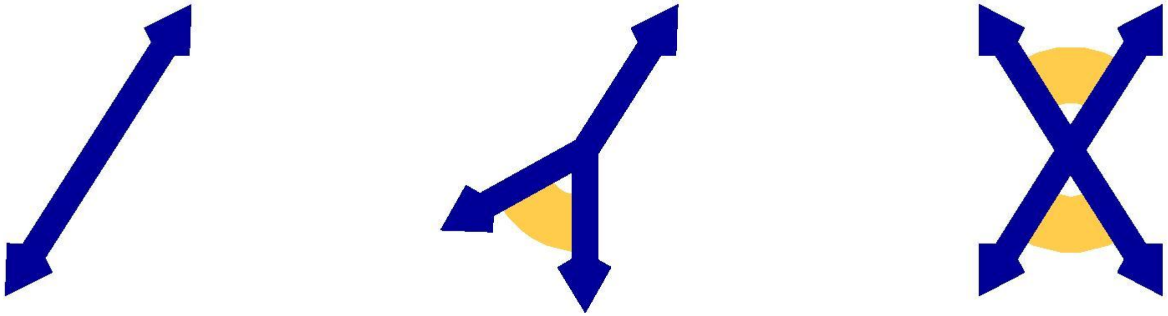
examples

$R_{\Delta R}$ = average number of neighboring jets per jet

here: for $\Delta R < \pi/2$

in this example all jets have same (p_T, y)





	2 jets	3 jets	4 jets
	no neighbors within ΔR:	two jets have one neighbor each:	each of the four jets has one neighbor:
	0 neighbors	2 neighbors	4 neighbors
if all events were like this	$R_{\Delta R} = 0$	$R_{\Delta R} = 2/3$	$R_{\Delta R} = 1$

$R_{\Delta R}$: analysis phase space

Measure triple differentially: $R_{\Delta R}$ (p_T, ΔR, $p_{T\text{-nbr}}$)

Phase space for $R_{\Delta R}$ (p_T, ΔR, $p_{T\text{-nbr}}$) measurement:

- Central inclusive jets: $|y| < 1$
- Inclusive jets in p_T range: $50 < p_T < 450$ GeV
- 4 different p_T requirements for neighbor jet: $p_{T\text{-nbr}} > 30, 50, 70, 90$ GeV
- Jet-jet distances in 3 ranges of ΔR: 1.4 – 1.8 – 2.2 – 2.6 ($\ll \pi$)

Criteria:

- inclusive jet p_T requirements (→ high trigger efficiencies)
- y, ΔR requirements such that $(y_{max} + \Delta R_{max}) < 3.6$ (→ in acceptance)
- ΔR such that always $\Delta R > 2 * R_{cone}$ (→ no overlapping jet cones)
- $p_{T\text{-nbr}}$ requirements from soft to hard

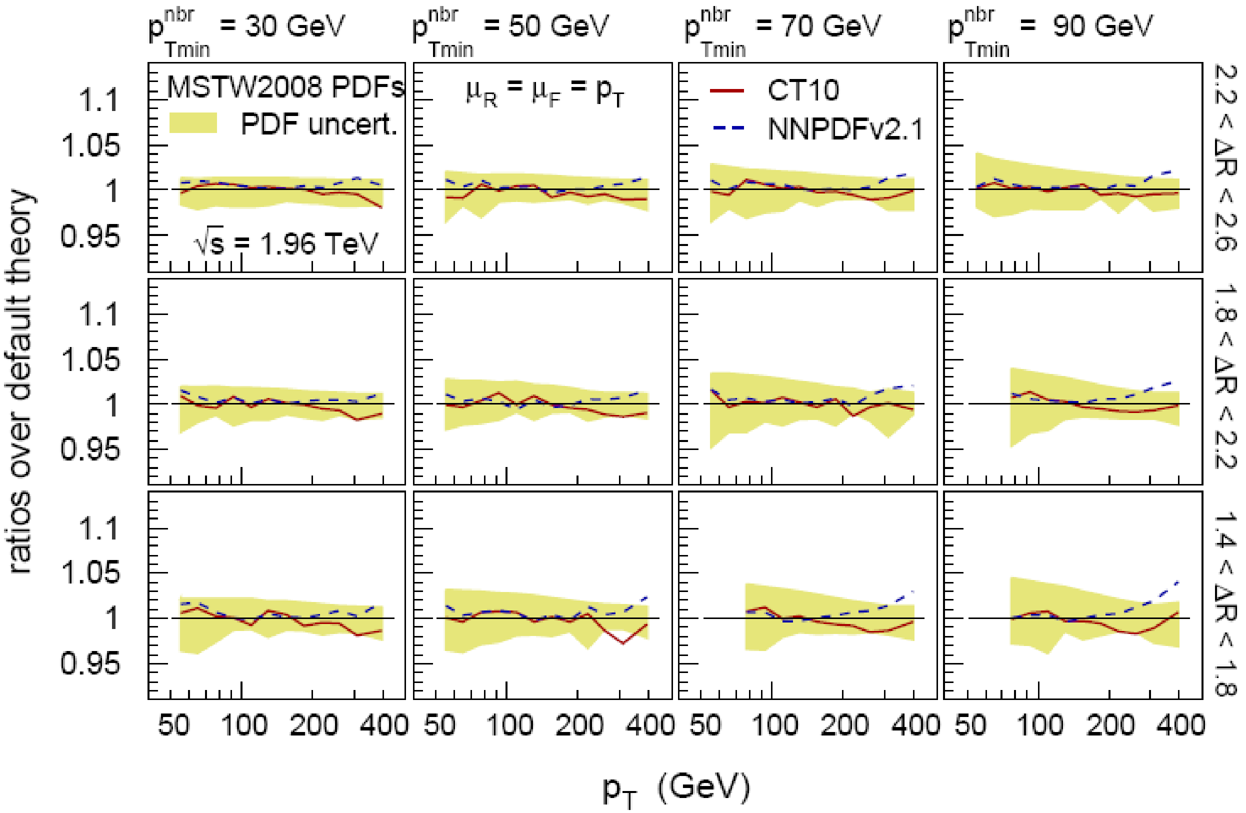
$R_{\Delta R}$ in theory

Theory properties

Next slides show that $R_{\Delta R}$ is theoretically well-behaved:

- Small PDF uncertainties / small PDF set dependence
- Small k-factor (k = NLO/LO)
- Small renormalization/factorization scale dependencies
- Small non-perturbative corrections

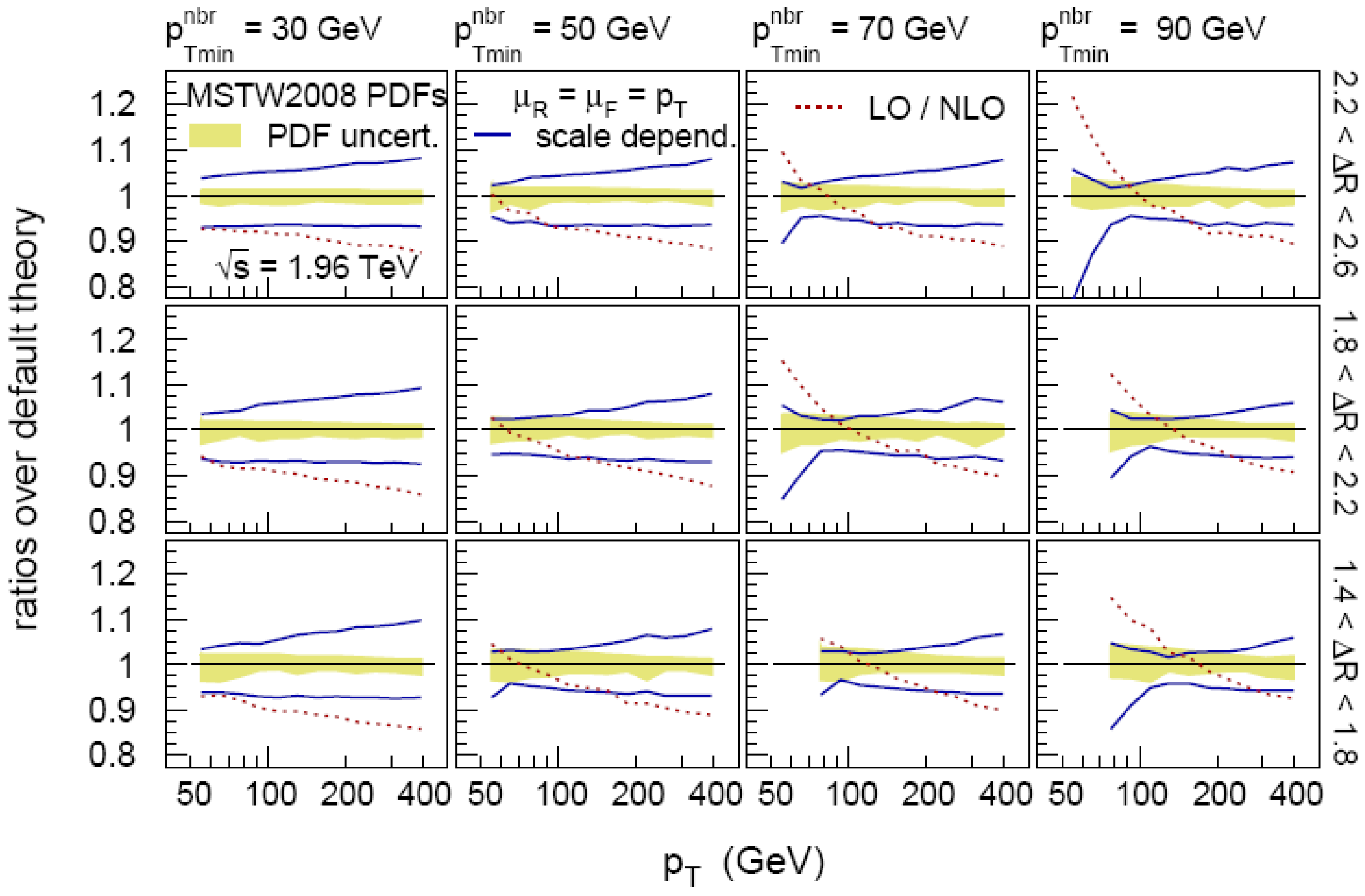
$R_{\Delta R}$ PDF sensitivity



- MSTW 68% C.L. PDF uncertainty: 2-3%
- MSTW2008, CT10, NNPDFv2.1 agree better than 3%

→ PDF sensitivity is weak

$R_{\Delta R}$ scale dep. / k-factor

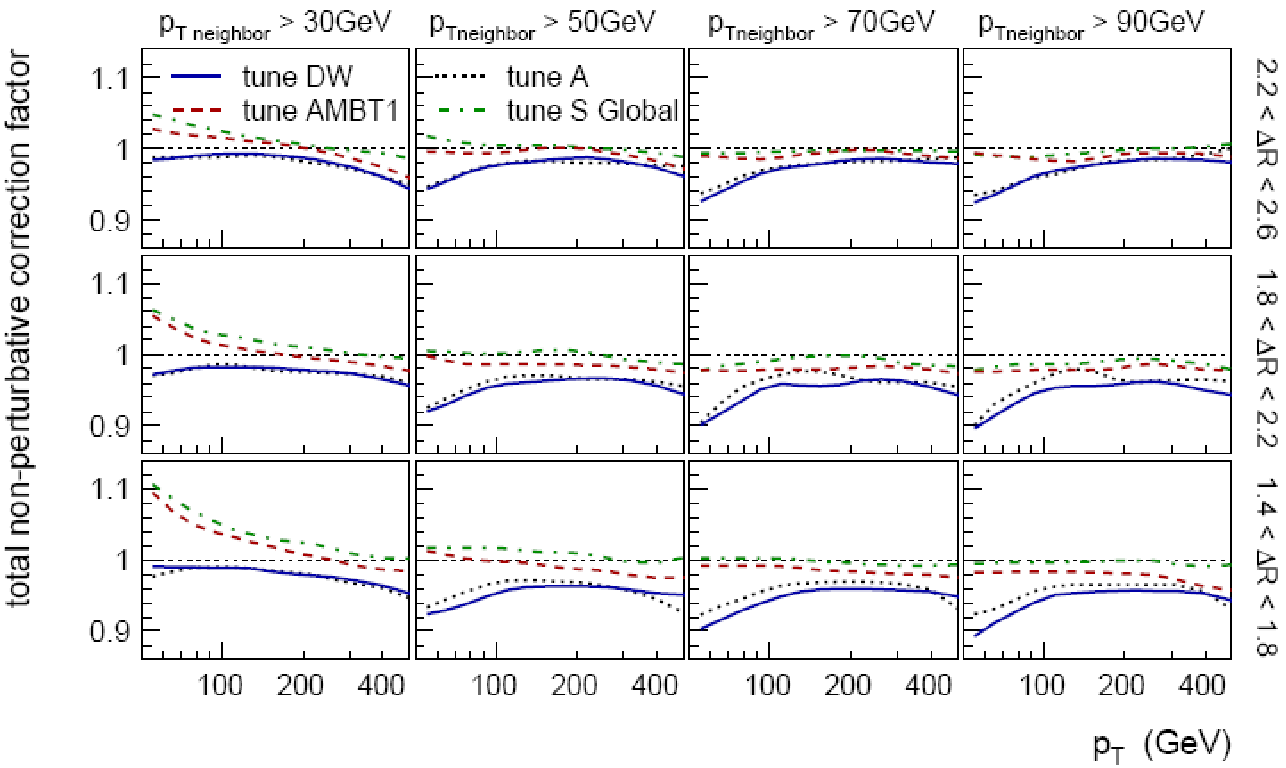


- inverse of k-Factor: LO/NLO (dotted line) → close to unity
- Scale dependence (solid lines) → small (5-10%)

$R_{\Delta R}$ non-pert corrections

Product of correction factors for:

- Hadronization
- Underlying event



- Small (<10%, typically 3-5%)
- "old" and "new" PYTHIA tunes agree well at high p_T

α_s from $R_{\Delta R}$ - theory

Perturbative:

- NLOJET++/fastNLO for 2-jet and 3-jet NLO calculation
- PDFs: MSTW2008NLO
- PDF uncertainty: MSTW 68% C.L. PDFs / CT10, NNPDFv2.1
- Central scale $\mu_R = \mu_F = \mu_0 = p_T$
- Scale uncertainty by independent variation
  μ_R, μ_F in $(0.5, 2)\ \mu_0$ with $0.5 < (\mu_R/\mu_F) < 2$

Non-Perturbative Corrections:

PYTHIA with different tunes
- tune "DW" (old parton shower, old underlying event)
- tune "AMBT1" (new parton shower, new underlying event)

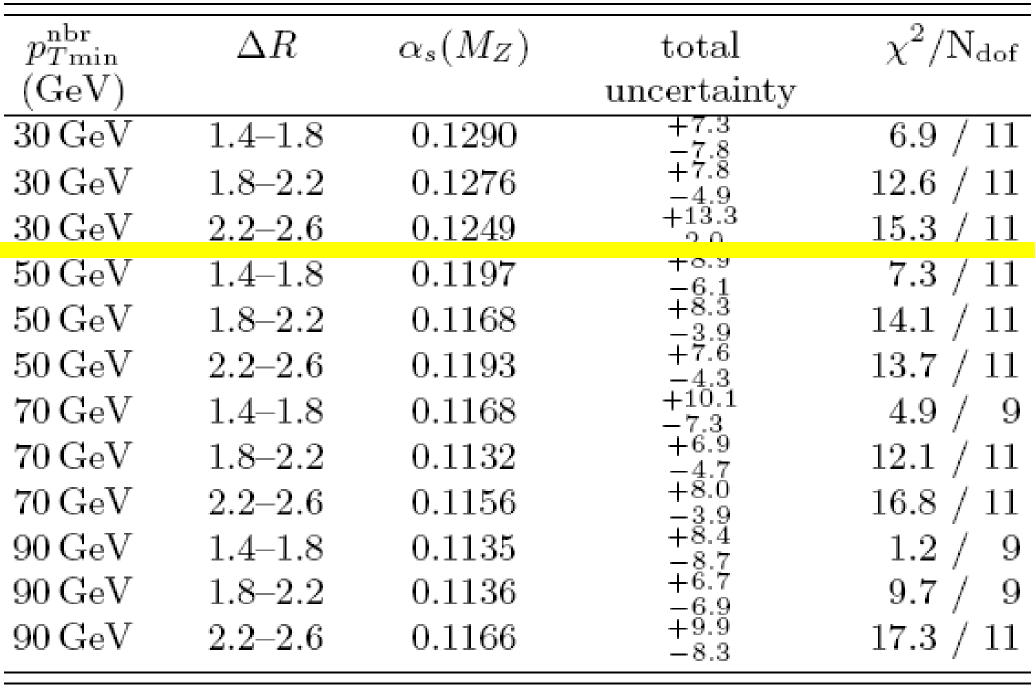
→ cross checked with tunes "A", "S Global"

α_s from $R_{\Delta R}$

138 data points: up to 12 p_T bins in 12 (p_{Tnbr} , ΔR) regions (4 ΔR * 3 p_{Tnbr})

Initial check: Is there any (p_{Tnbr} , ΔR) dependence
→ In each (p_{Tnbr} , ΔR) region: determine combined $\alpha_s(M_Z)$ and χ^2

TABLE I: The $\alpha_s(M_Z)$ results and the χ^2 values from the fits to the $R_{\Delta R}$ data in each of the 12 kinematic regions, defined by the $p_{T\min}^{\rm nbr}$ and ΔR requirements. The uncertainties are multiplied by a factor of 10^3.



$p_{T\min}^{\rm nbr}$ (GeV)	ΔR	$\alpha_s(M_Z)$	total uncertainty	$\chi^2/N_{\rm dof}$
30 GeV	1.4–1.8	0.1290	$^{+7.3}_{-7.8}$	6.9 / 11
30 GeV	1.8–2.2	0.1276	$^{+7.8}_{-4.9}$	12.6 / 11
30 GeV	2.2–2.6	0.1249	$^{+13.3}_{-3.0}$	15.3 / 11
50 GeV	1.4–1.8	0.1197	$^{+8.9}_{-6.1}$	7.3 / 11
50 GeV	1.8–2.2	0.1168	$^{+8.3}_{-3.9}$	14.1 / 11
50 GeV	2.2–2.6	0.1193	$^{+7.6}_{-4.3}$	13.7 / 11
70 GeV	1.4–1.8	0.1168	$^{+10.1}_{-7.3}$	4.9 / 9
70 GeV	1.8–2.2	0.1132	$^{+6.9}_{-4.7}$	12.1 / 11
70 GeV	2.2–2.6	0.1156	$^{+8.0}_{-3.9}$	16.8 / 11
90 GeV	1.4–1.8	0.1135	$^{+8.4}_{-8.7}$	1.2 / 9
90 GeV	1.8–2.2	0.1136	$^{+6.7}_{-6.9}$	9.7 / 9
90 GeV	2.2–2.6	0.1166	$^{+9.9}_{-8.3}$	17.3 / 11

Always good χ^2
→ Confirm RGE

no ΔR dependence!

Consistency for
p_{Tnbr} >=50 GeV