QCD Studies in Jet Production and Jet Substructure at the Tevatron

Markus Wobisch

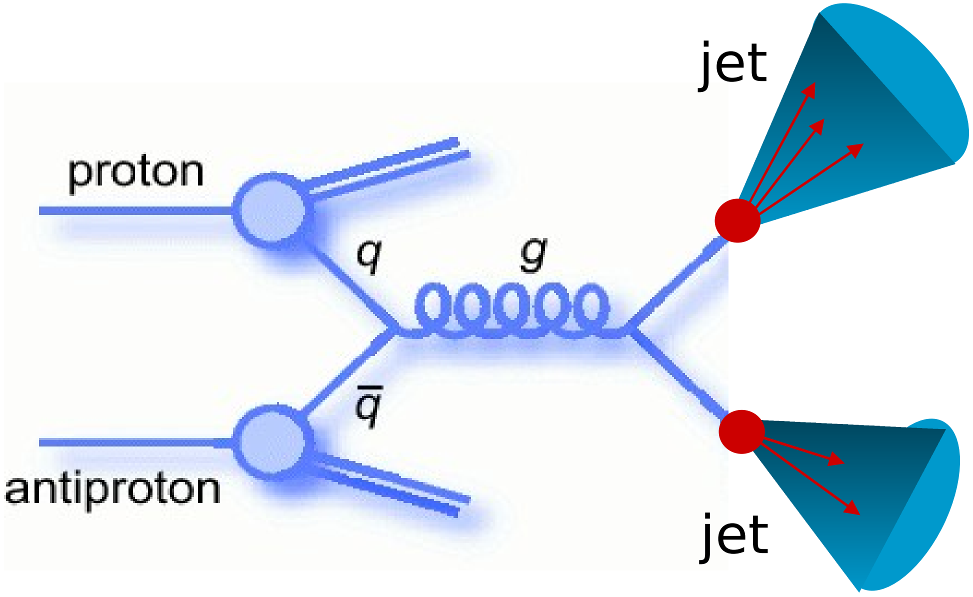
Louisiana Tech University

Rencontres de Moriond QCD
March 10, 2013

Overview

- Jet production in hadron collisions
- Jet studies in Run II of the Tevatron so far
- Measurements of jet substructure
- On determinations of α_s
- New multi-jet cross section ratios
- Measurements of $R_{3/2}$, $R_{\Delta\phi}$, $R_{\Delta R}$
- Determination of α_s from $R_{\Delta R}$

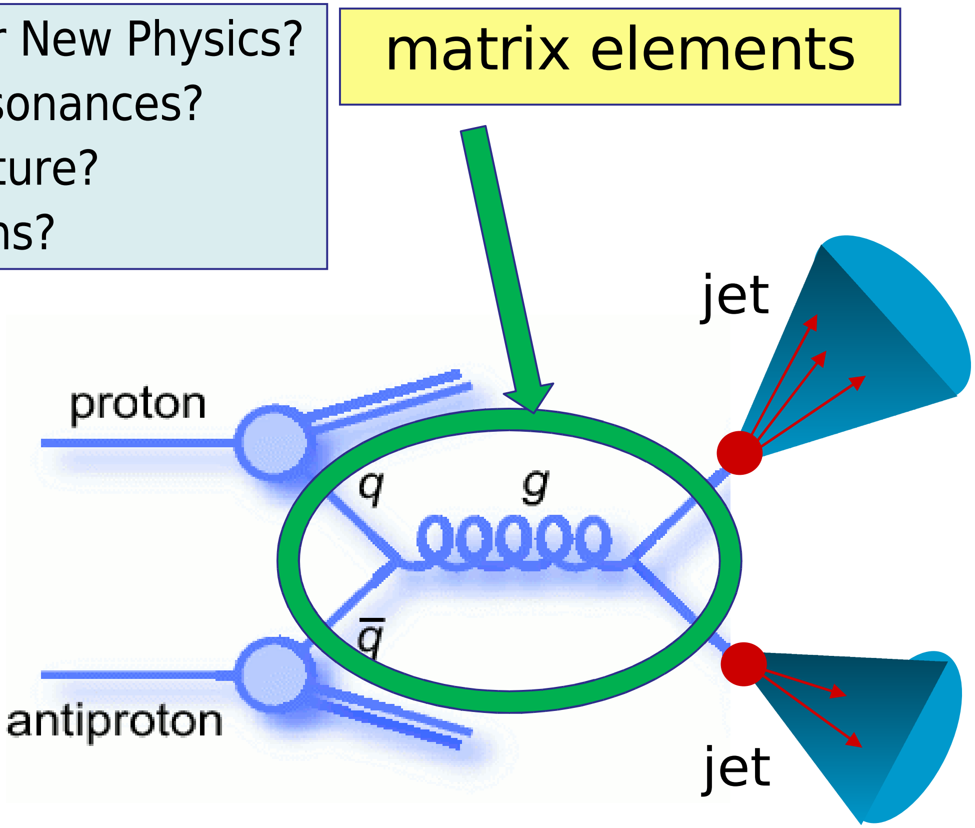
Jet production in hadron collisions



Jet production in hadron collisions

Dynamics: pQCD or New Physics?

- New Particle resonances?
- Quark Substructure?
- Extra Dimensions?



Jet production in hadron collisions

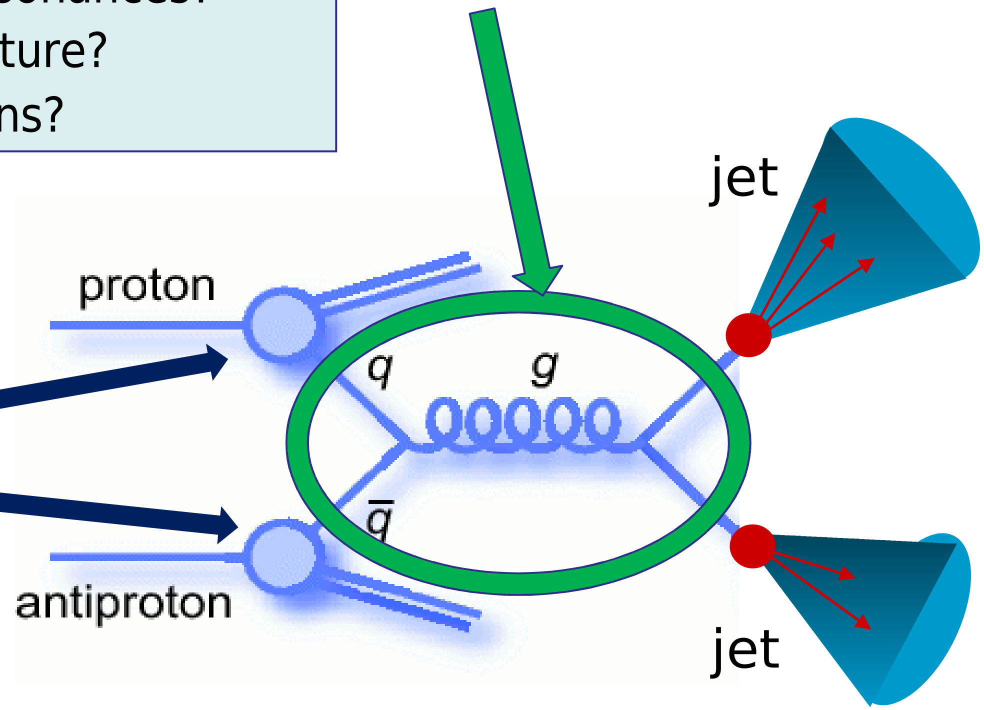
Dynamics: pQCD or New Physics?

- New Particle resonances?
- Quark Substructure?
- Extra Dimensions?

matrix elements

Parton distribution functions (PDFs)

- Values of $f_i(x,Q)$?
- $f_i(x,Q)$ vs. Q (DGLAP?)
- Universality?



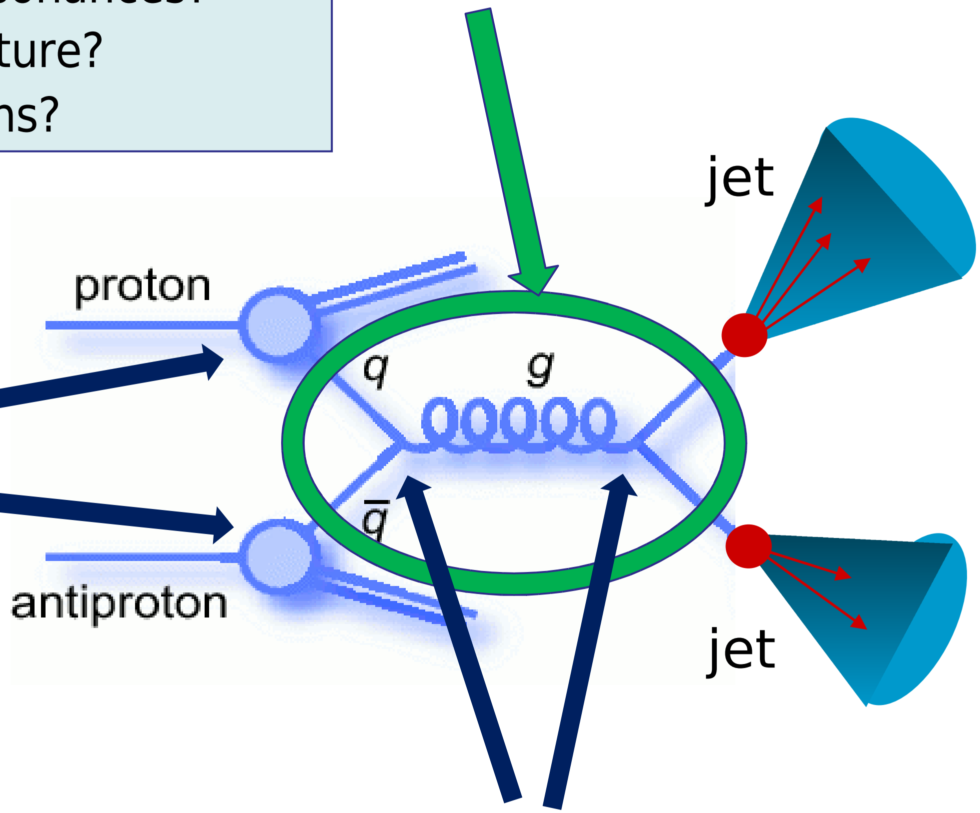
Jet production in hadron collisions

Dynamics: pQCD or New Physics?
- New Particle resonances?
- Quark Substructure?
- Extra Dimensions?

matrix elements

Parton distribution functions (PDFs)

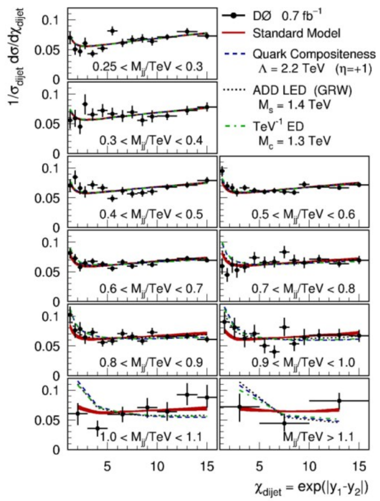
- Values of $f_i(x,Q)$?
- $f_i(x,Q)$ vs. Q (DGLAP?)
- Universality?

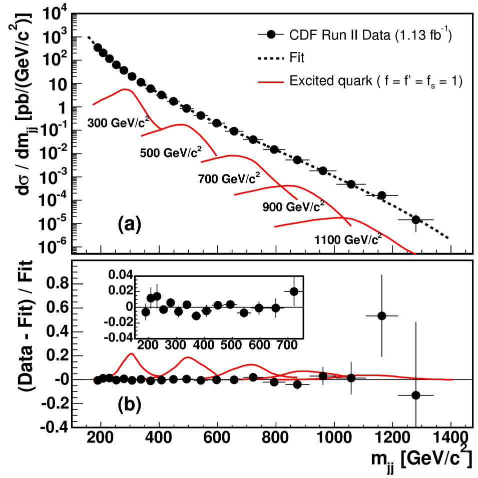


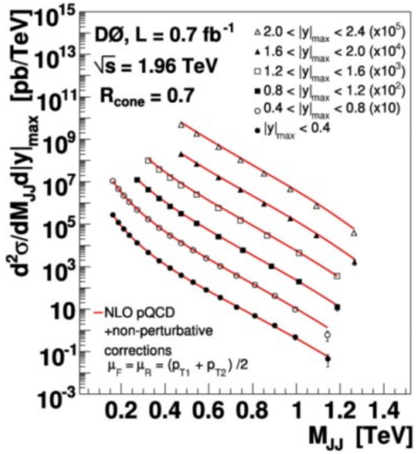
- Value of $\alpha_s(M_Z)$?
- $\alpha_s(Q)$ vs. Q (running: RGE?)
- Universality?

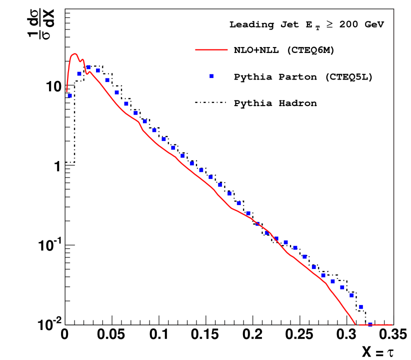
Strong coupling α_s

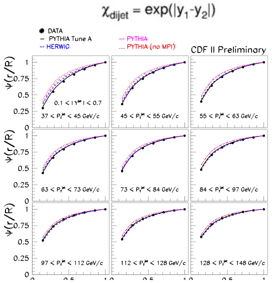
Run II jet studies – so far ...

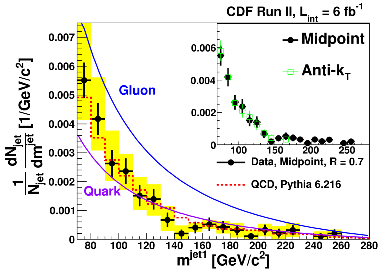


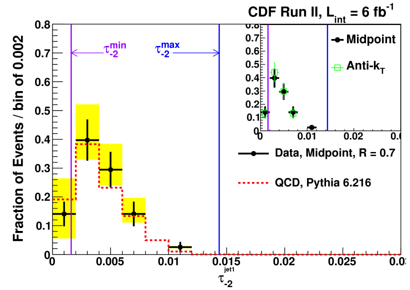


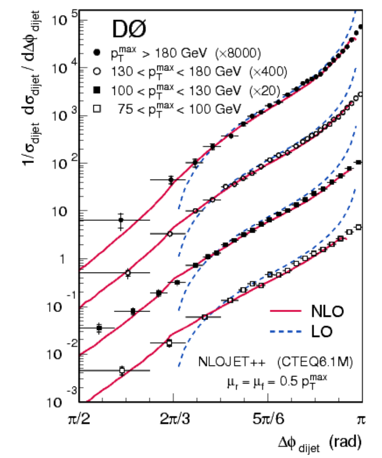


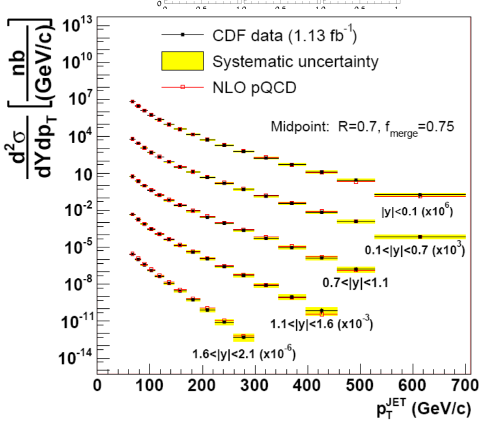


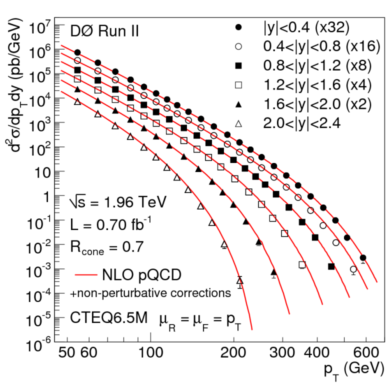


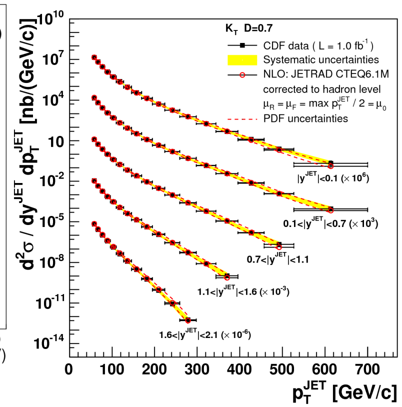


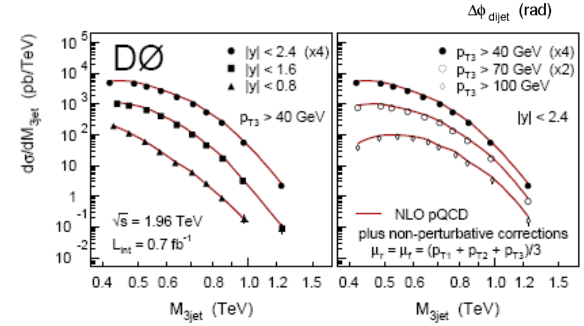




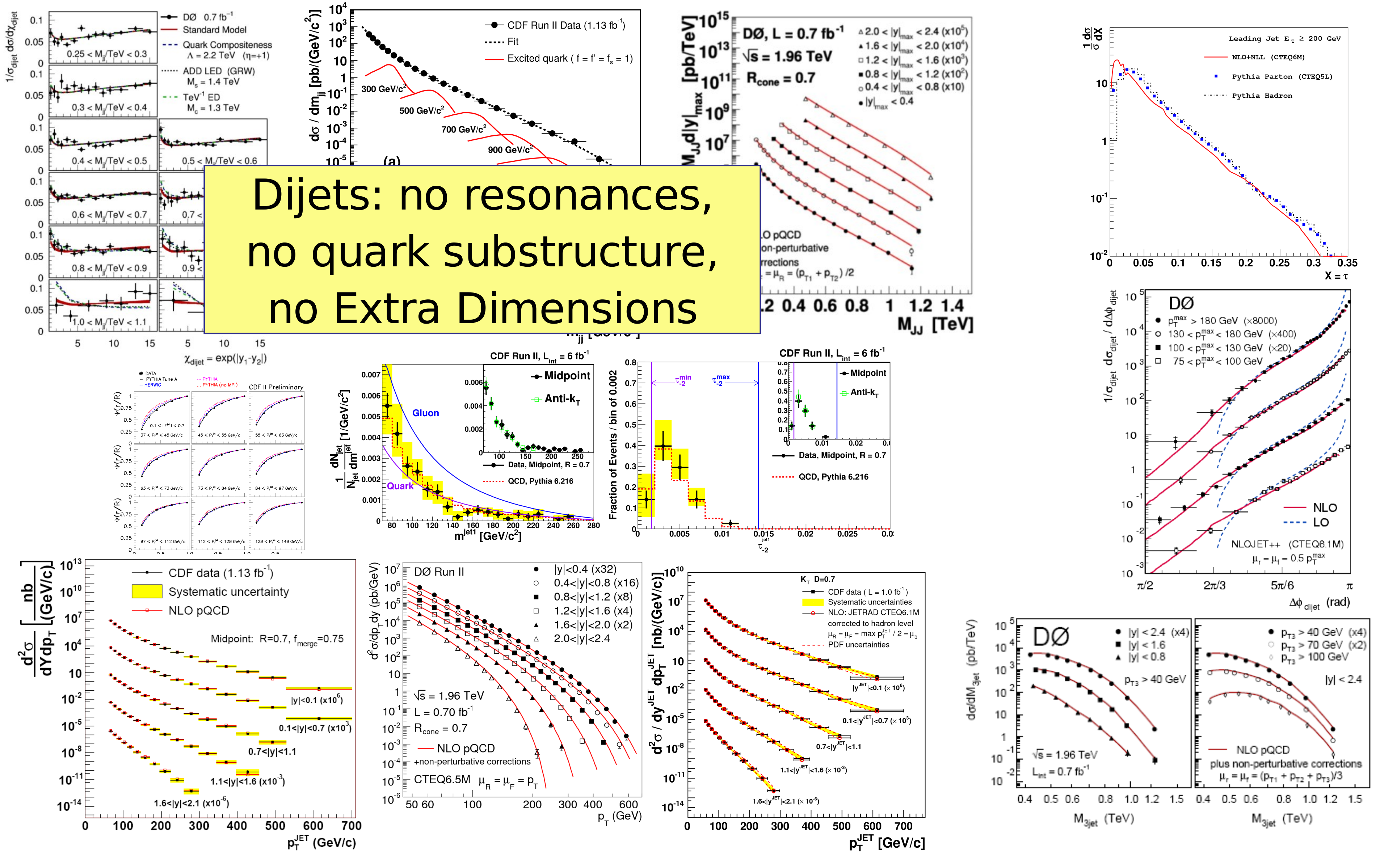






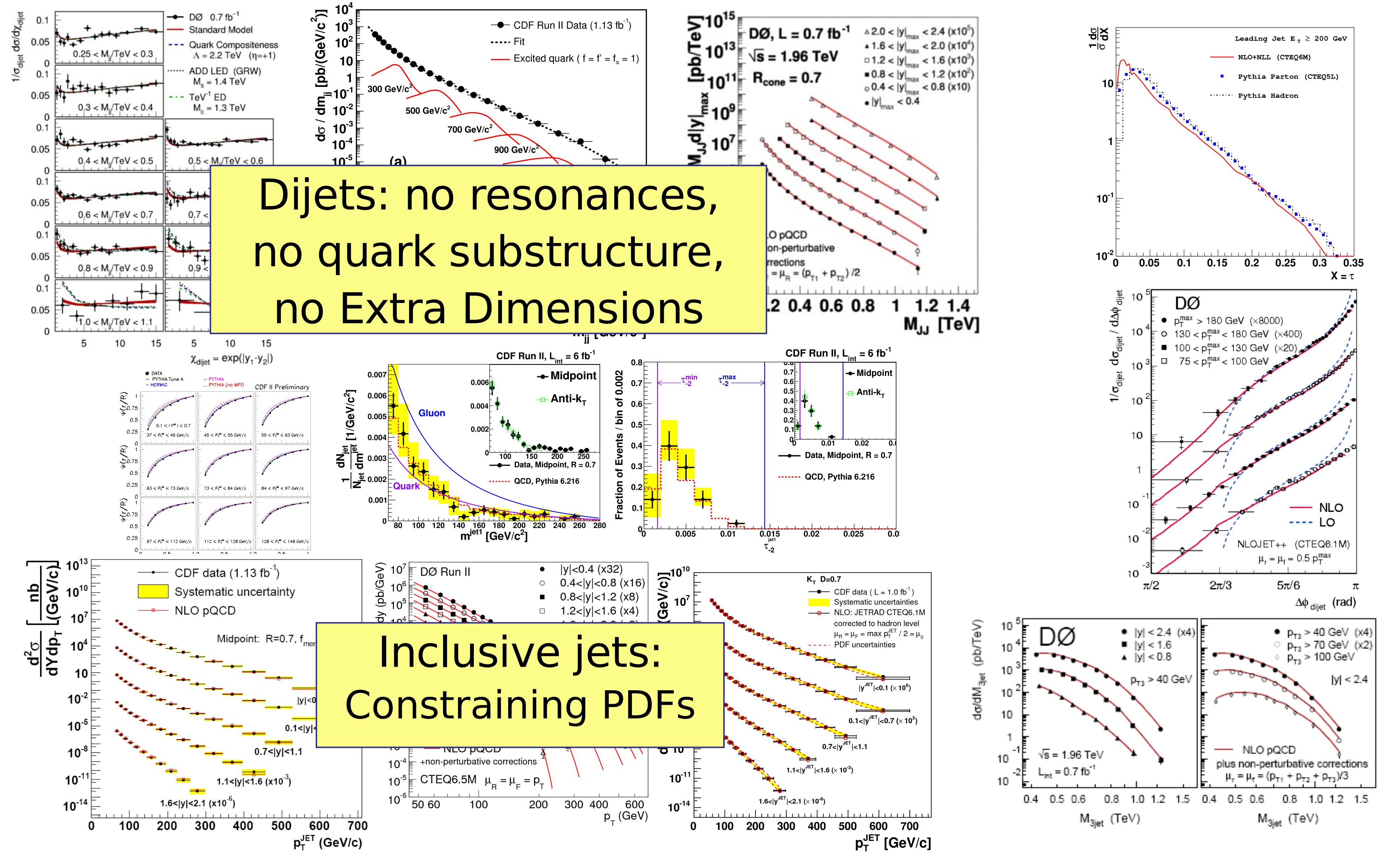


Run II jet studies – so far …



Dijets: no resonances, no quark substructure, no Extra Dimensions

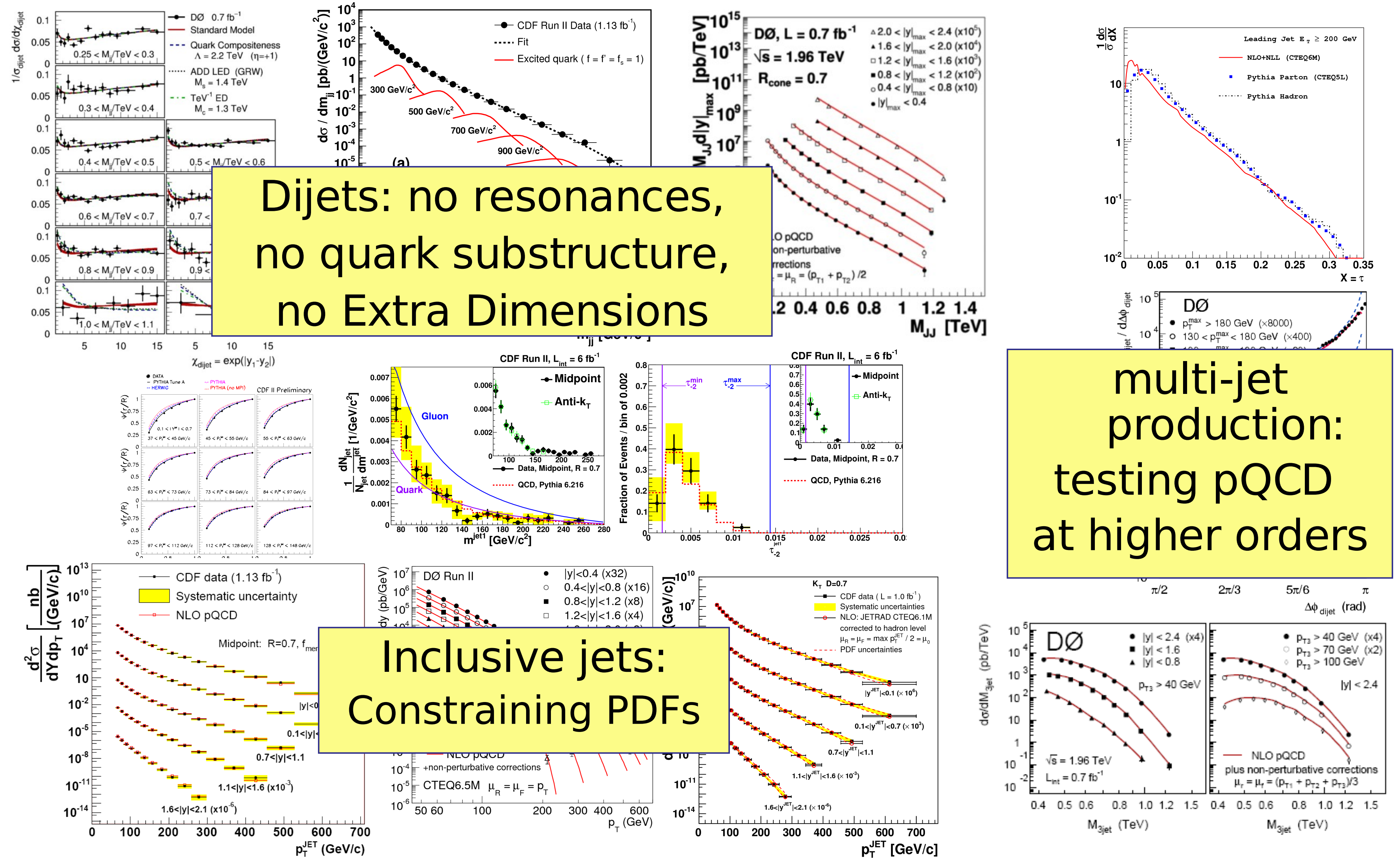
Run II jet studies – so far …



Dijets: no resonances, no quark substructure, no Extra Dimensions

Inclusive jets: Constraining PDFs

Run II jet studies – so far …

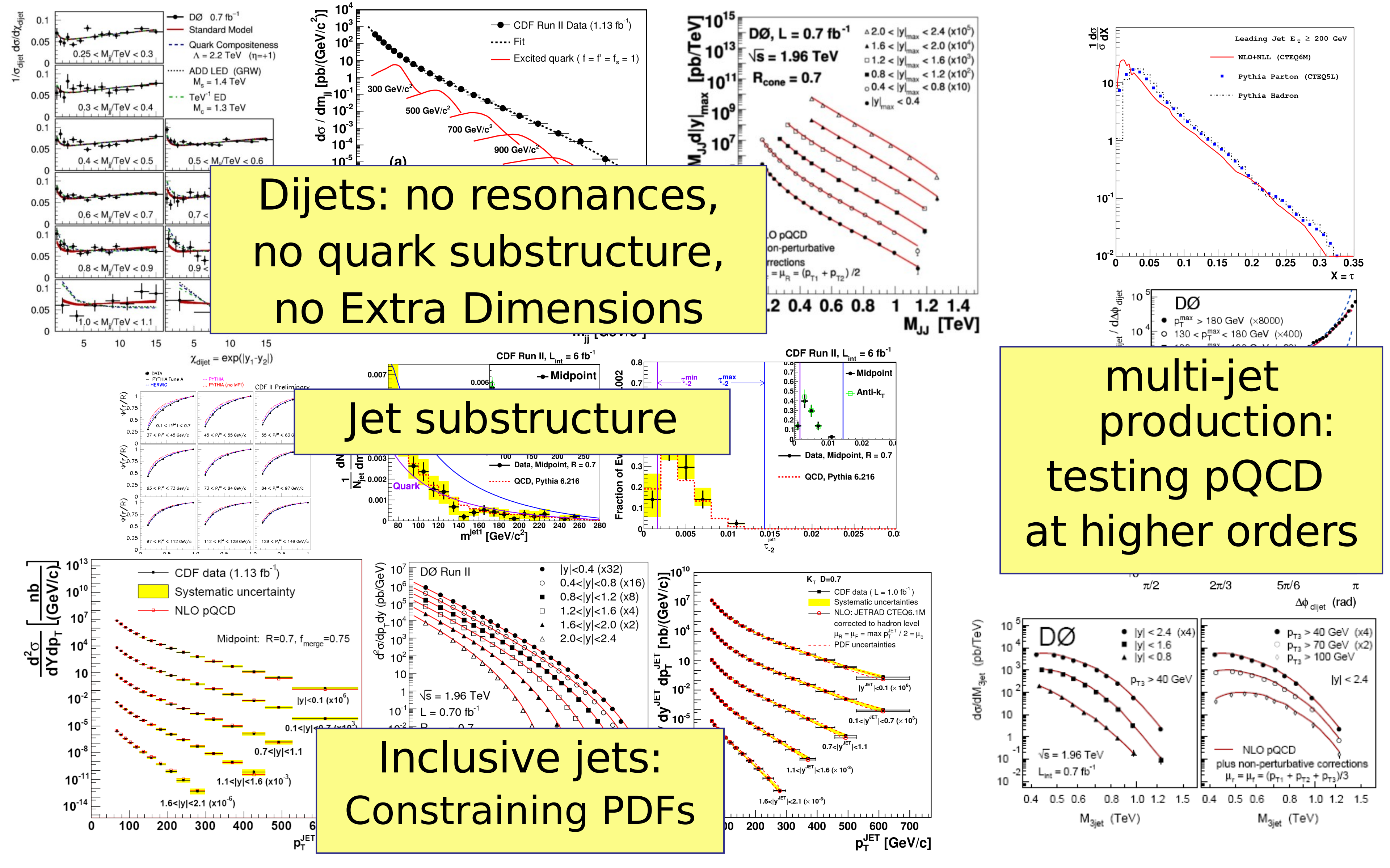


Dijets: no resonances, no quark substructure, no Extra Dimensions

multi-jet production: testing pQCD at higher orders

Inclusive jets: Constraining PDFs

Run II jet studies – so far …



Dijets: no resonances, no quark substructure, no Extra Dimensions

Jet substructure

multi-jet production: testing pQCD at higher orders

Inclusive jets: Constraining PDFs

Substructure of high p_T jets (1)

Jets have internal structure / masses

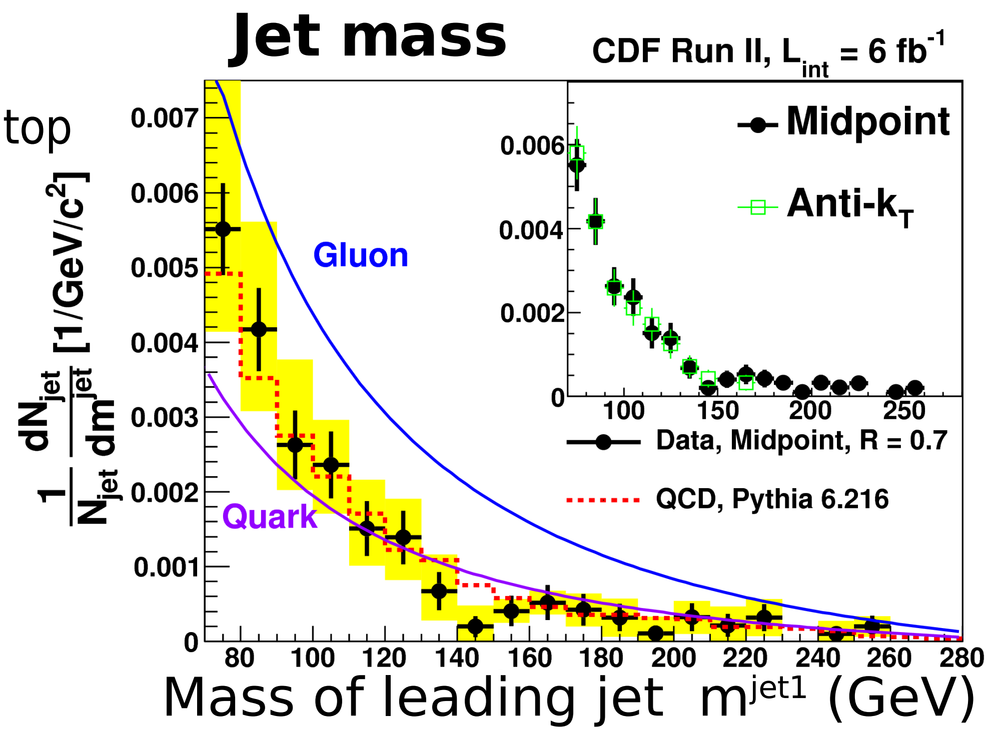
High jet masses (m_{jet} > 100 GeV):

--> background for NP, Higgs, boosted top

--> predicted by pQCD:

Selection: leading p_T jets with
p_T > 400 GeV, $0.1 < |\eta| < 0.7$
midpoint cone and anti-k_T R=0.7

Phys. Rev. D **85,** 091101 (2012)



Alameida et al. arXiv:0810.0934

approx. NLO for jet mass:

$$J(m^{jet}, p_T, R) \simeq \alpha_s(p_T) \frac{4C_{q,g}}{\pi m^{jet}} \log\left(\frac{R\, p_T}{m^{jet}}\right)$$

quark jets: $C_q = 4/3$ gluon jets: $C_g = 4$

high mass region (70-280 GeV)
~ described by pQCD
(expect approx. 80% quark jets at high p_T)

Substructure of high p_T jets (2)

Angularity: $$\tau_{-2} \equiv \frac{1}{m^{jet}} \sum_{i=1}^{n_{part}} E_i \frac{[1-\cos\theta_i]^3}{\sin^2\theta_i}$$

Phys. Rev. D **85,** 091101 (2012)

Sensitive to radiation near the edge of the cone

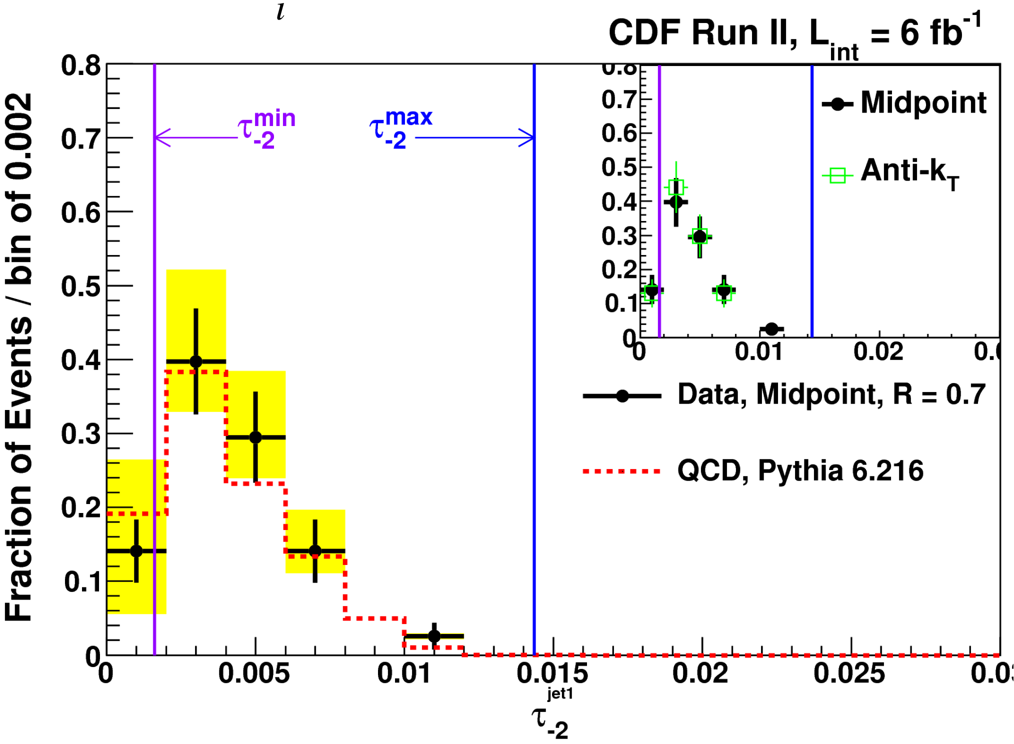
--> characteristic shape for QCD jets

$$z \equiv m^{jet}/p_T$$

$$\tau_{-2}^{min} \sim (2/z)^{-3}$$

$$\tau_{-2}^{max} \sim zR^2/2^3$$

Measure angularity for $90 < m^{jet1} < 120$ GeV



Distribution (shape and kinematic endpoints) described by PYTHIA

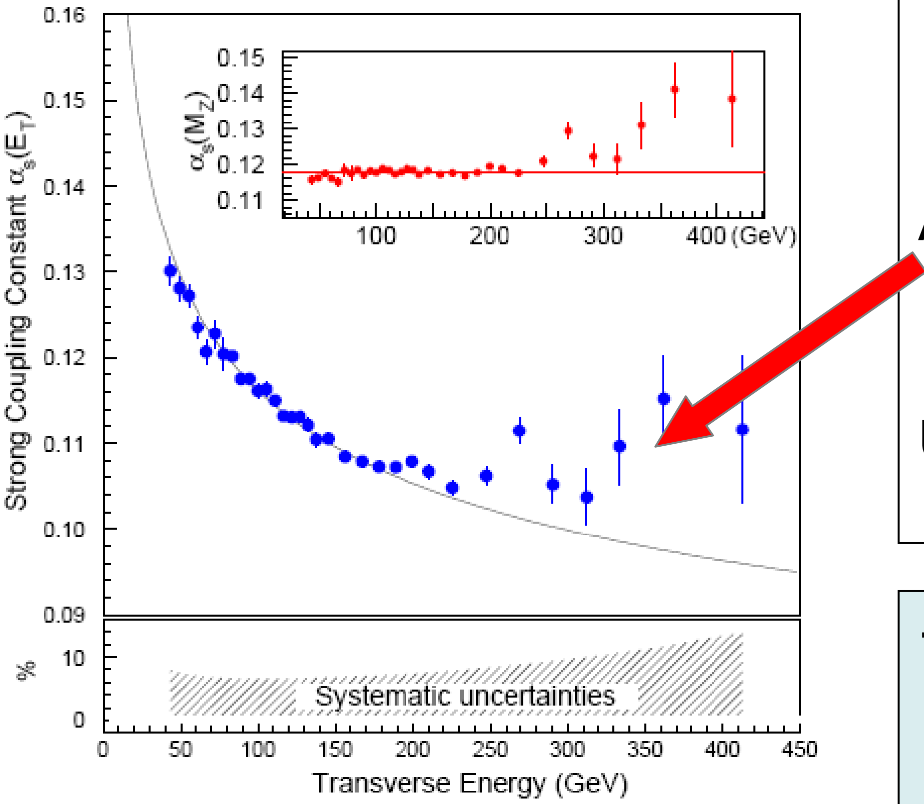
Also measured: **planar flow** (not shown here)

Determinations of α_s

$$\alpha_s$$

Run I α_s results from inclusive jet cross section

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



Running of α_s as predicted for p_T < 200 GeV

Above 200 GeV: running changes

Usually attributed to errors in high x- PDFs

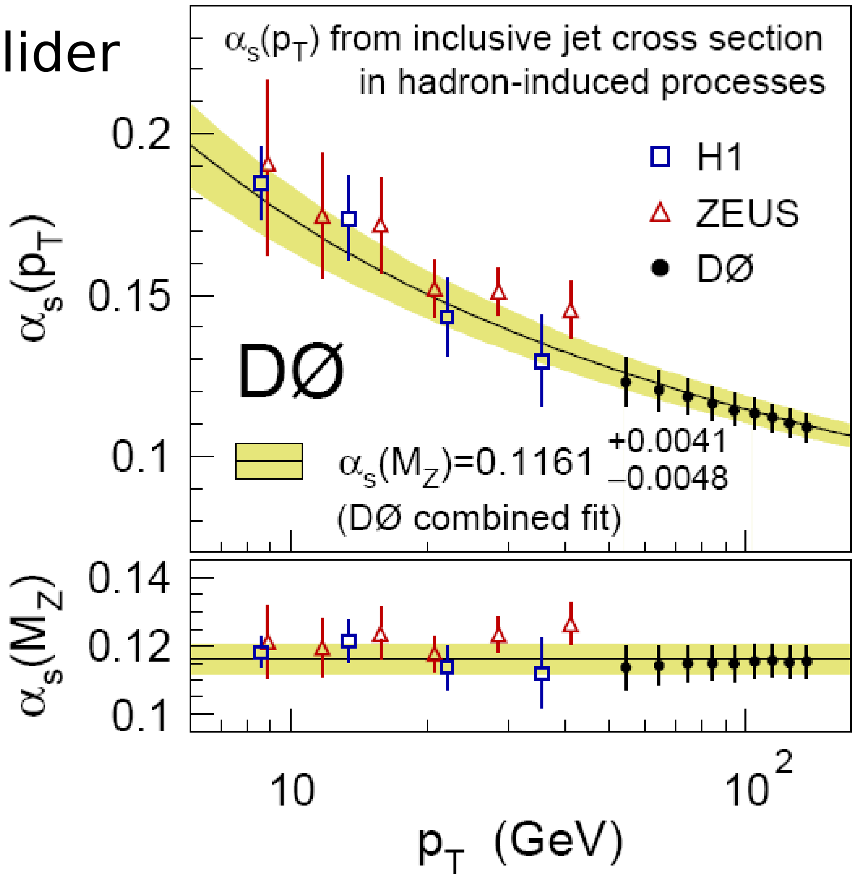
→ conceptual limitations when extracting α_s from cross section data due to PDFs

$\alpha_s(M_Z)$ from inclusive jets

From D0 inclusive jet cross section:
most precise $\alpha_s(M_Z)$ from a hadron collider

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

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



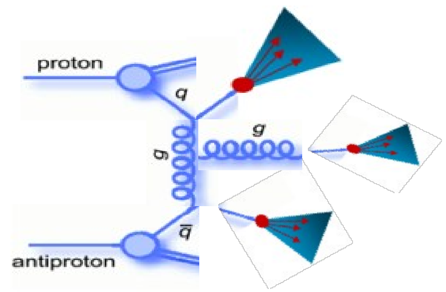
to avoid conceptual issues
related to the PDFs:
restricted to p_T < 145 GeV (x < 0.2)

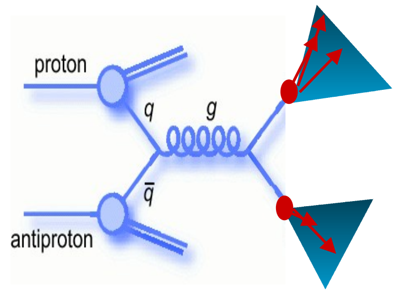
Better: determine α_s at high p_T from other quantities
to avoid/minimize the PDF issues

Cancelling PDFs in Ratios

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

R =



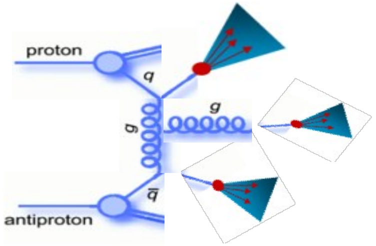


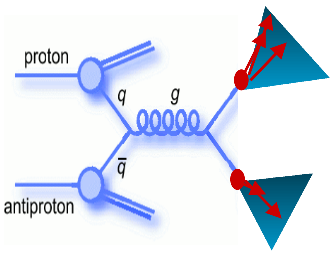
$\Leftrightarrow \alpha_s$

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

The R-Trilogy

Three quantities - all: 3-jet/2-jet ratios





α_s

$R_{3/2}$: inclusive 3-jet and 2-jet cross section ratio

$R_{\Delta\phi}$: dijet azimuthal decorrelations

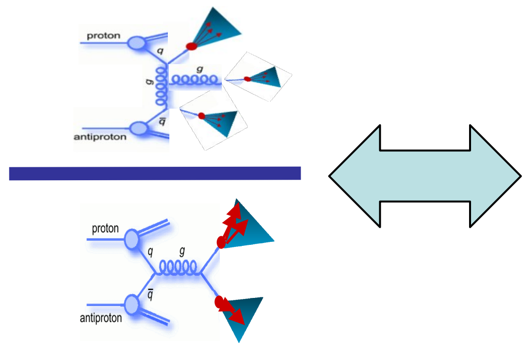
$R_{\Delta R}$: angular correlations of jets

New quantities!

All: conditional probabilities to find a third jet in a di-jet event
But: probe different aspects / different theoretical uncertainties

Multi-jet cross section ratio $R_{3/2}$

Explicitly require
  >= 3 jets (numerator)
  >= 2 jets (denominator)
according to p_{Tmin} requirement



α_s

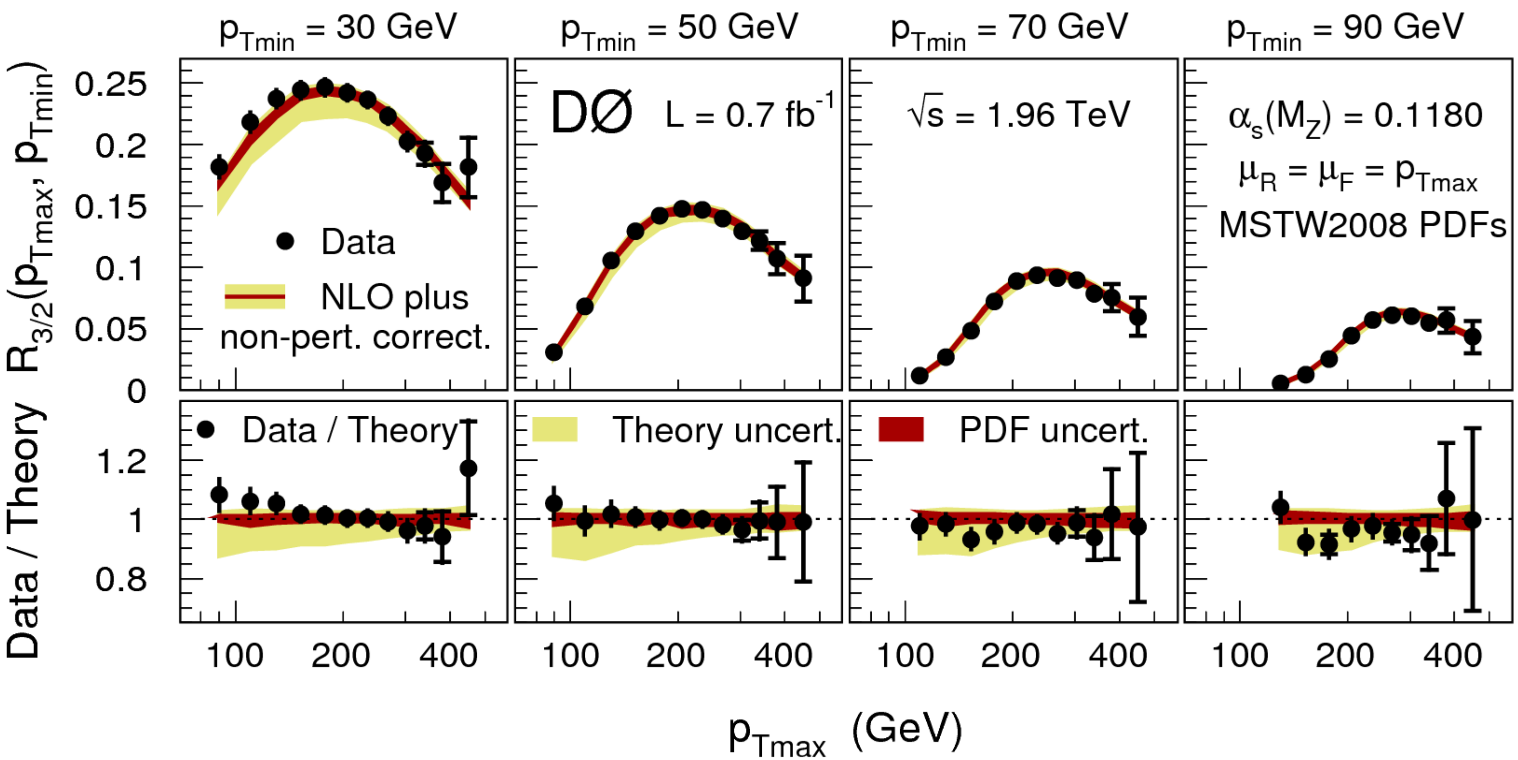
$$R_{3/2} = \frac{\sigma_{3-jet}}{\sigma_{2-jet}}$$

Measure $R_{3/2}(p_{Tmax}, p_{Tmin})$

- probes α_s at the scale p_{Tmax}
- p_{Tmin} is "hardness" criterion for 3rd jet

Multi-jet cross section ratio $R_{3/2}$

Phys. Lett. B. 720, 6 (2013)



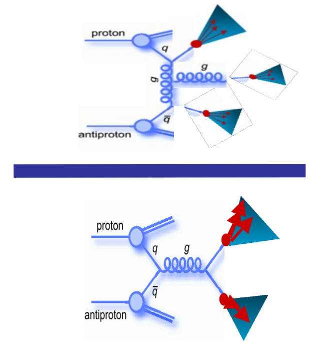
Well described by theory for p_{Tmin} = 50, 70, 90 GeV

large (non-symmetric) scale dependence at low p_{Tmax}

A new quantity: $R_{\Delta\phi}$

$R_{\Delta\phi}$: fraction of all dijet events with $\Delta\phi < \Delta\phi_{max}$

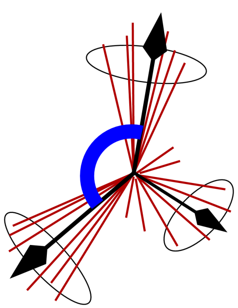
$$R_{\Delta\phi} = \frac{\sigma_{dijet}(\Delta\phi < \Delta\phi_{max})}{\sigma_{dijet}(inclusive)}$$



$\Longleftrightarrow$ α_s

Introduced in: JHEP 1301 (2013) 172 / arXiv:1211.6773

M. W., K. Chakravarthula, R. Dhullipudi, L. Sawyer, M. Tamsett



Numerator is a 3-jet quantity (due to $\Delta\phi_{max}$ requirement)

but no need to tag the third jet :: more inclusive than $R_{3/2}$

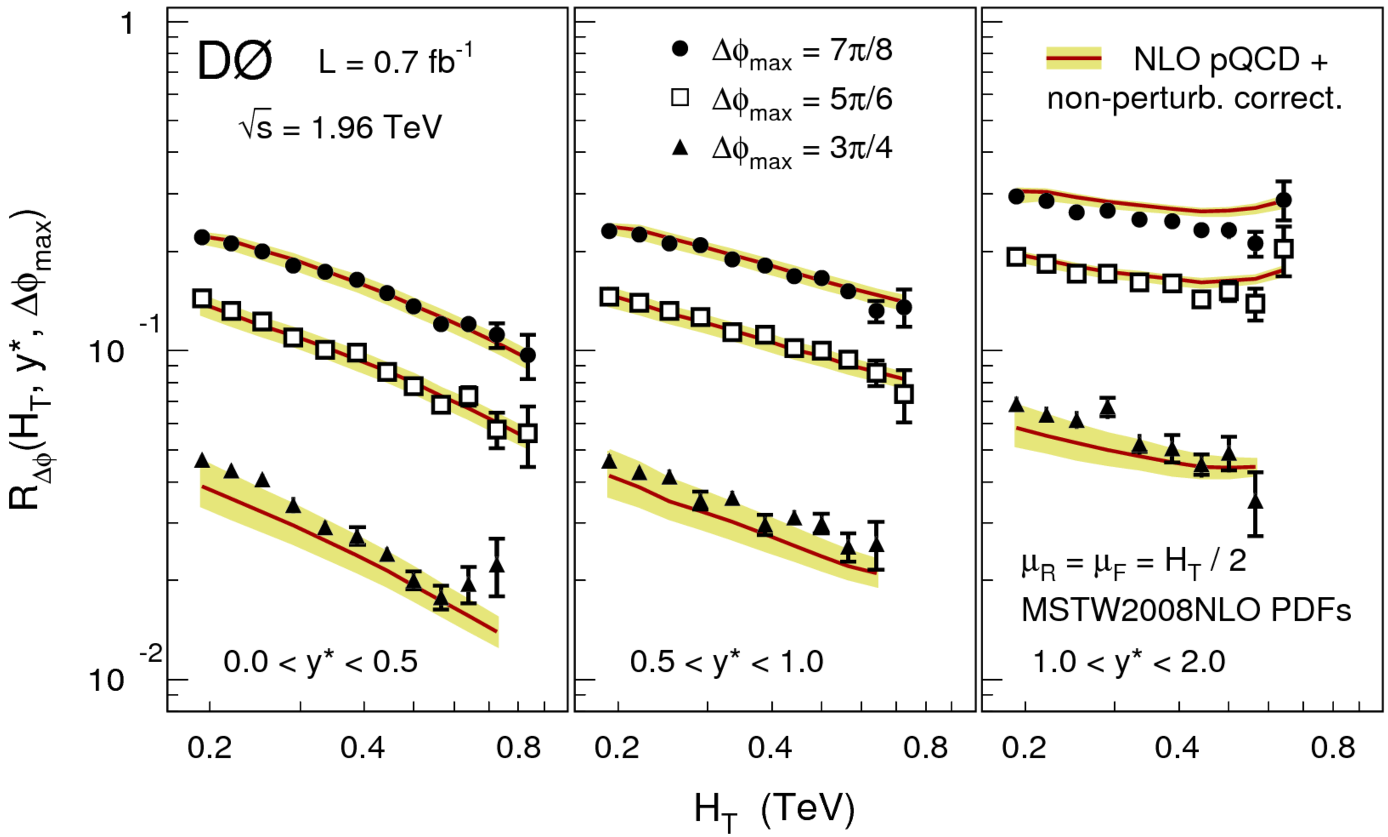
Measure $R_{\Delta\phi}(H_T, y^*, \Delta\phi_{max})$ with $y^* = \frac{1}{2}|y_1 - y_2|$

$H_T/2$ is scale for α_s :: y^*, $\Delta\phi_{max}$: kinematic regions

Dijet Azimuthal Decorrelations $R_{\Delta\phi}$

Submitted to Phys. Lett. B.

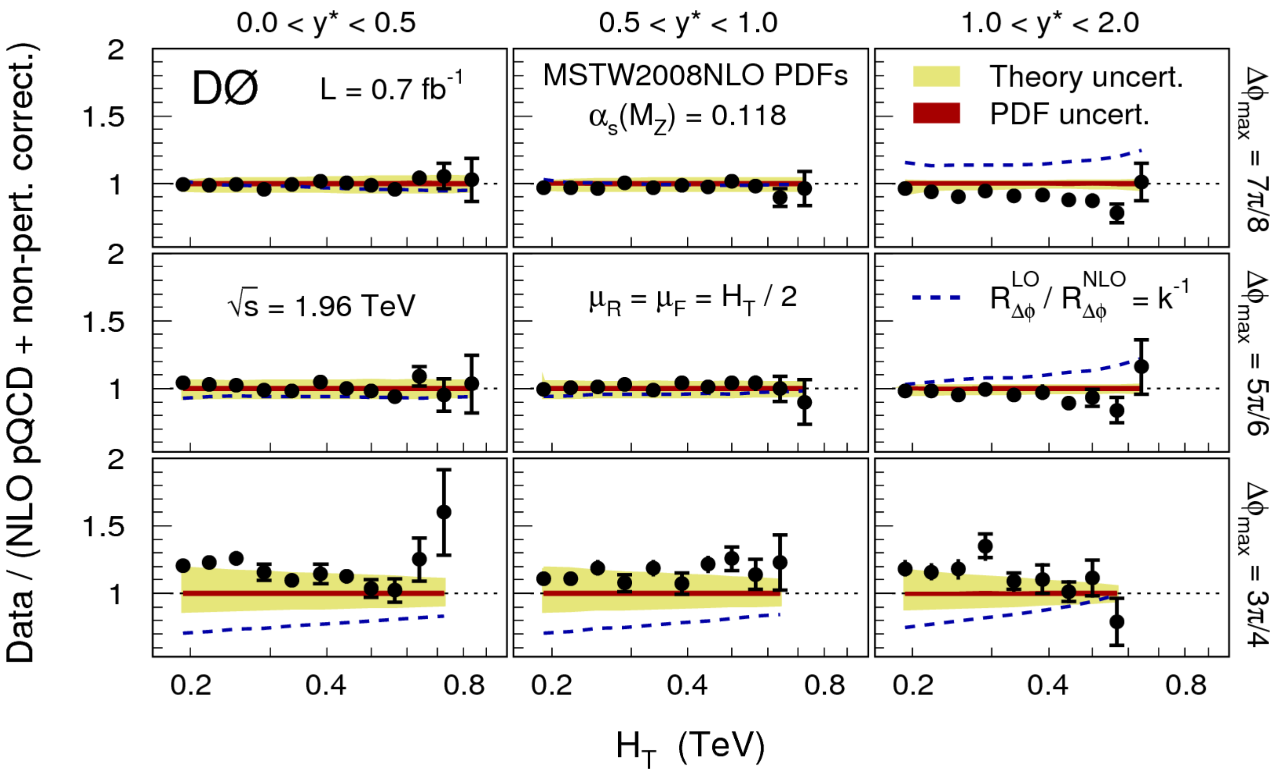
First measurement of the combined H_T and rapidity dependence



Weaker H_T dependence at larger rapidity y*

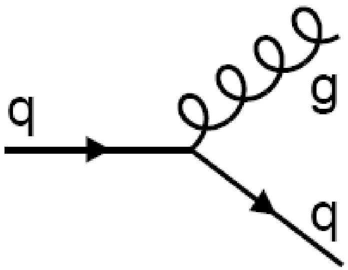
Dijet Azimuthal Decorrelations $R_{\Delta\phi}$

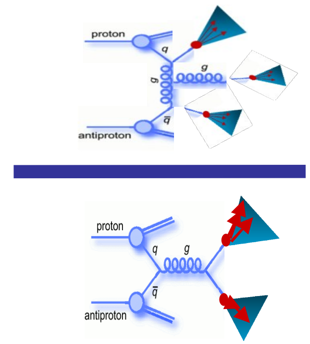
Submitted to Phys. Lett. B.



- Well described by theory for $\Delta\phi_{max}$ = $7\pi/8$, $5\pi/6$
- large scale dependence for $3\pi/4$ (larger 4-jet contributions)
- shape not well described for y* > 1

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





⟺ α_s

$R_{\Delta R}$

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

Requirement of a nearby neighboring jet
→ 3-jet quantity

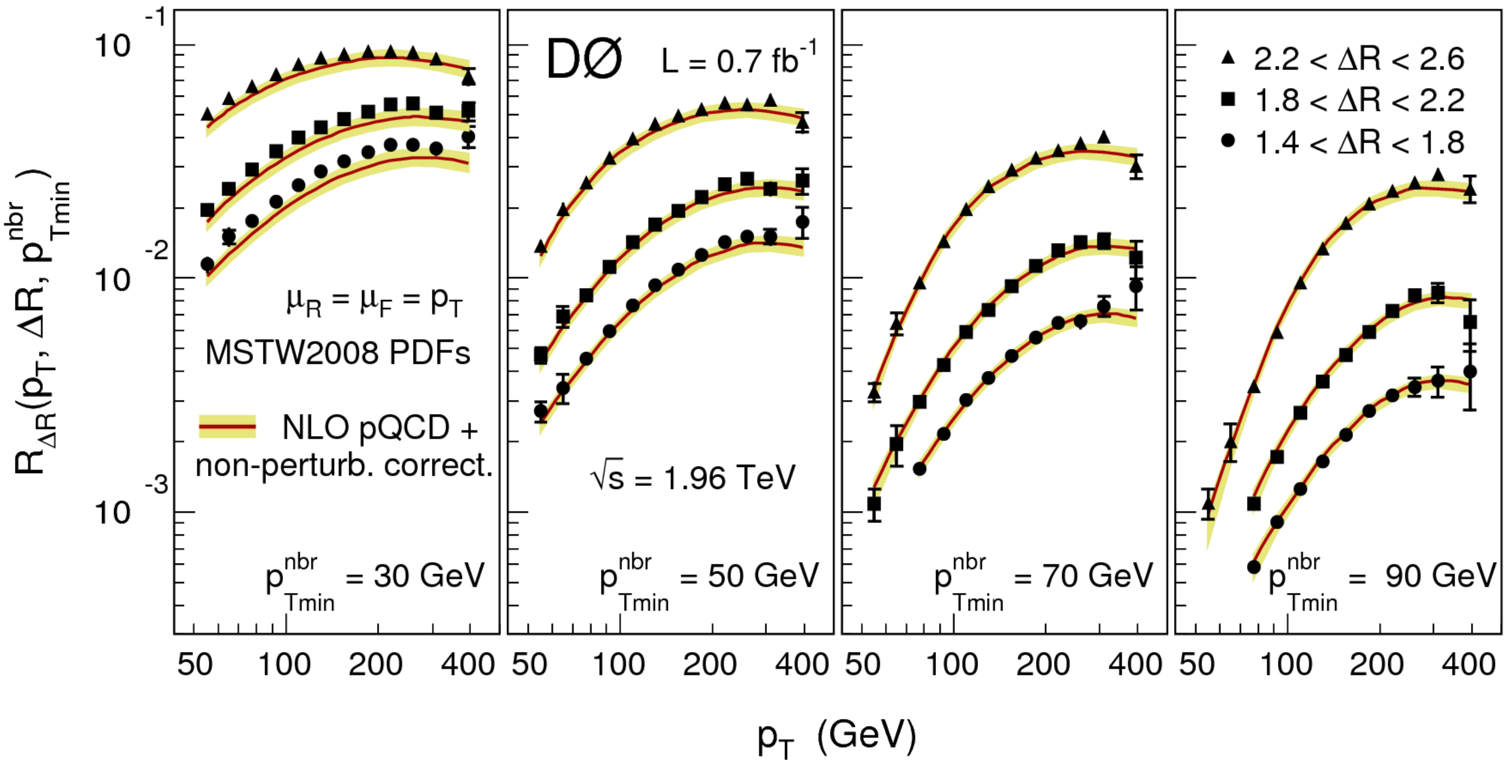
Depends on 3 variables → measure in three dimensions

- inclusive jet p_T → scale for α_s
- distance ΔR to neighboring jet in the (y,ϕ) plane
- neighbor jet $p_{T\text{-nbr-min}}$ requirement

Angular correlations of jets $R_{\Delta R}$

Phys. Lett. B. 718, 56 (2012)

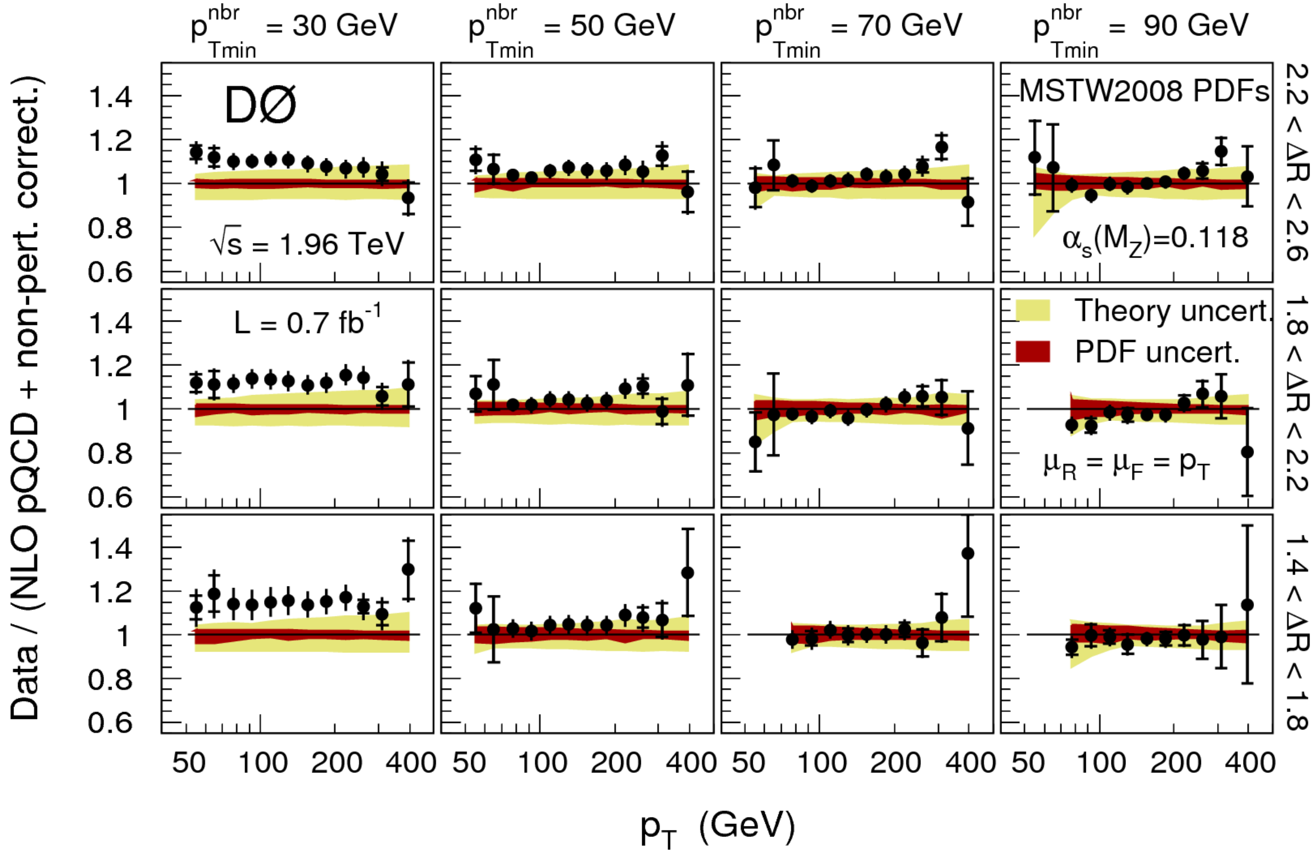
First measurement of the new quantity $R_{\Delta R}(p_T, \Delta R, p_{T\text{-nbr-min}})$



$R_{\Delta R}(p_T, \Delta R, p_{T\text{-nbr-min}})$ increases with p_T and with ΔR

Angular correlations of jets $R_{\Delta R}$

Phys. Lett. B. 718, 56 (2012)



Theory describes data for $p_{T\text{-nbr-min}}$ = 50, 70, 90 GeV

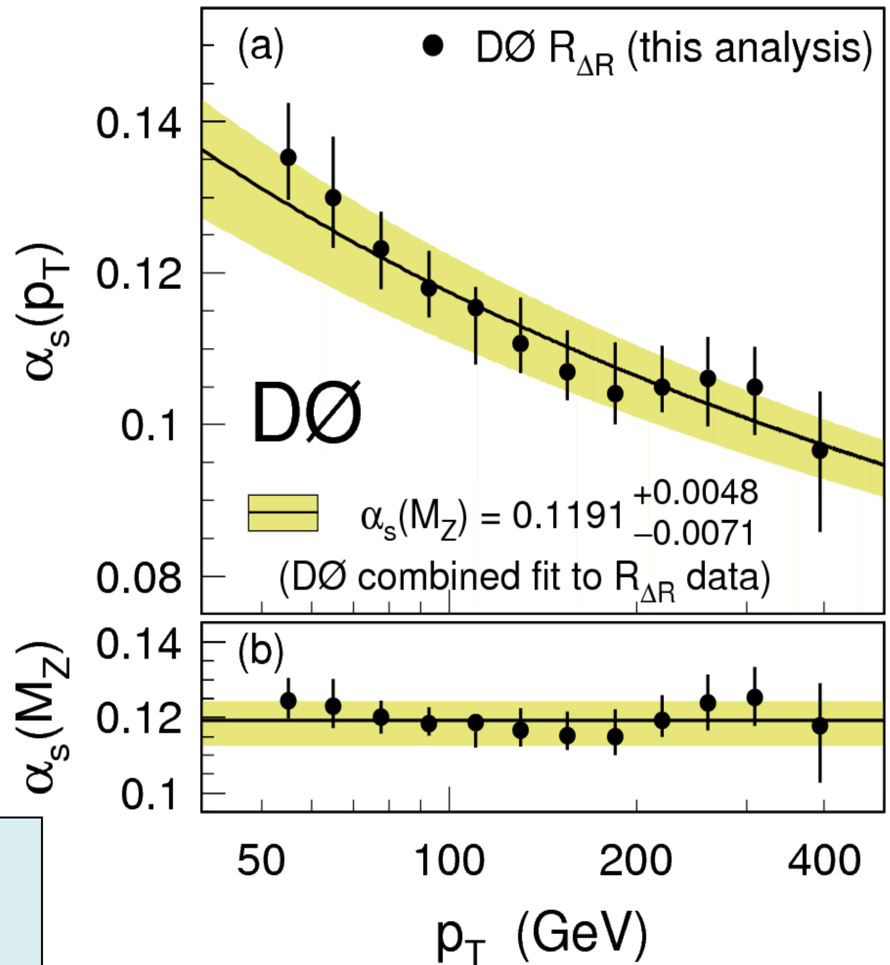
Running of $\alpha_s(p_T)$ from $R_{\Delta R}$ data

Phys. Lett. B. 718, 56 (2012)

Use data for
$p_{Tnbr\text{-}min}$ >= 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

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

Phys. Lett. B. 718, 56 (2012)

Combining all data points with $p_{T\text{-nbr-min}}$ > 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

→ for higher precision: need 2-jet and 3-jet at NNLO

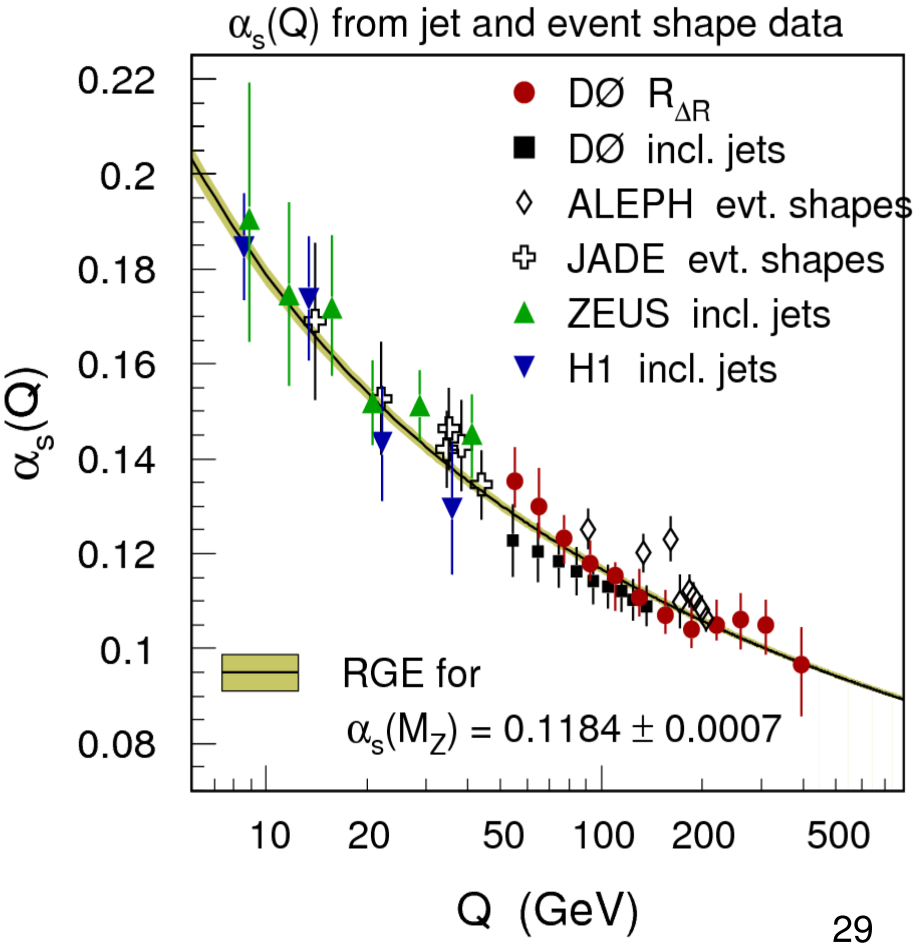
Summary

Tevatron: still innovative

New quantities for pQCD tests

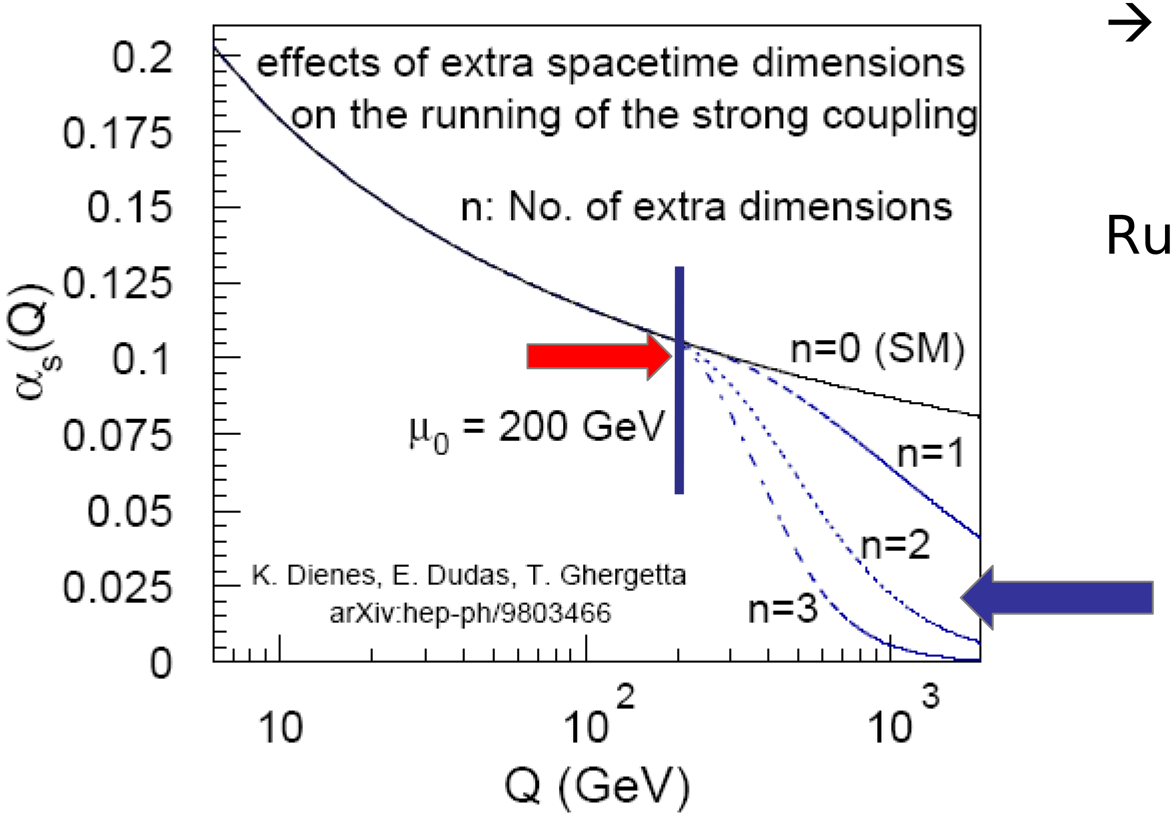
- jet substructure:
  mass, angularity, planar flow
- multijet cross section ratios:
  $R_{3/2}$, $R_{\Delta\phi}$, $R_{\Delta R}$
- very detailed tests of pQCD
  in 2->3 processes
- precise α_s results
  (minimum PDF sensitivity)
- limited by NLO theory precision

Phys. Lett. B. 718, 56 (2012)



Backup

α_s(Q) for Q > 208 GeV ?



→ so far tested at LEP up to Q = 208 GeV

Running of α_s(Q) could be modified for scales Q > μ_0 e.g. by extra dimensions

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

$\alpha_s(M_Z)$ from inclusive jets

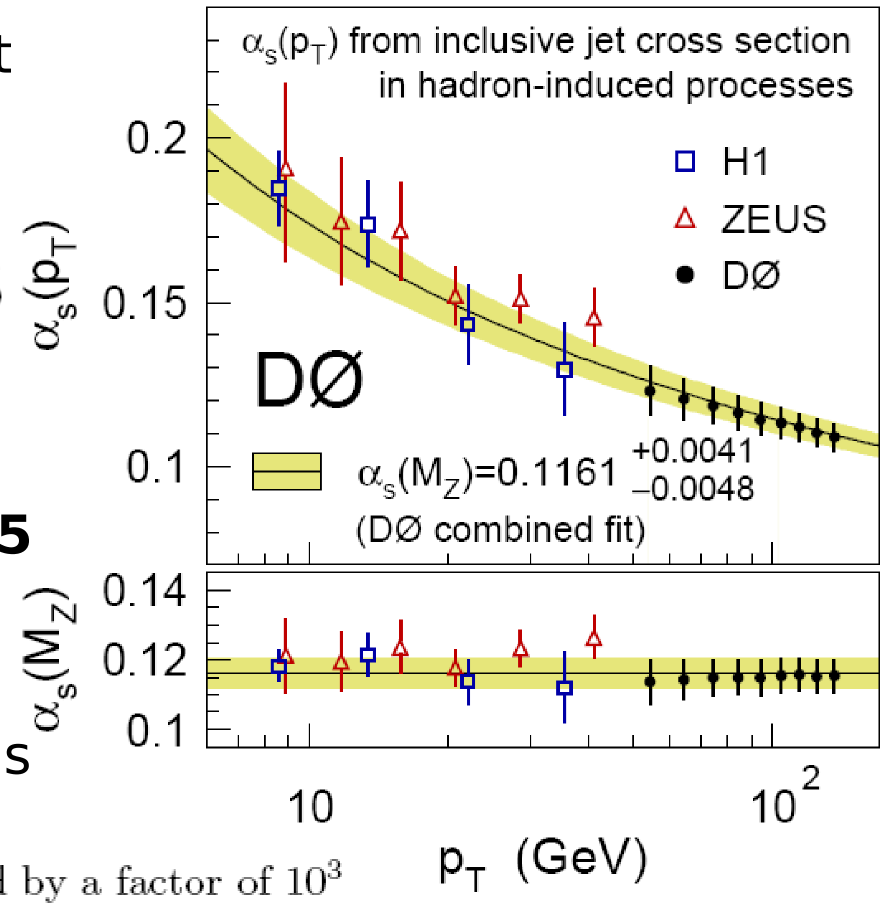
From D0 inclusive jet cross section using MSTW2008NNLO PDFs as input

→ 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**

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



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

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 $\alpha_s(M_Z)$

From inclusive jet cross section

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

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

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

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.

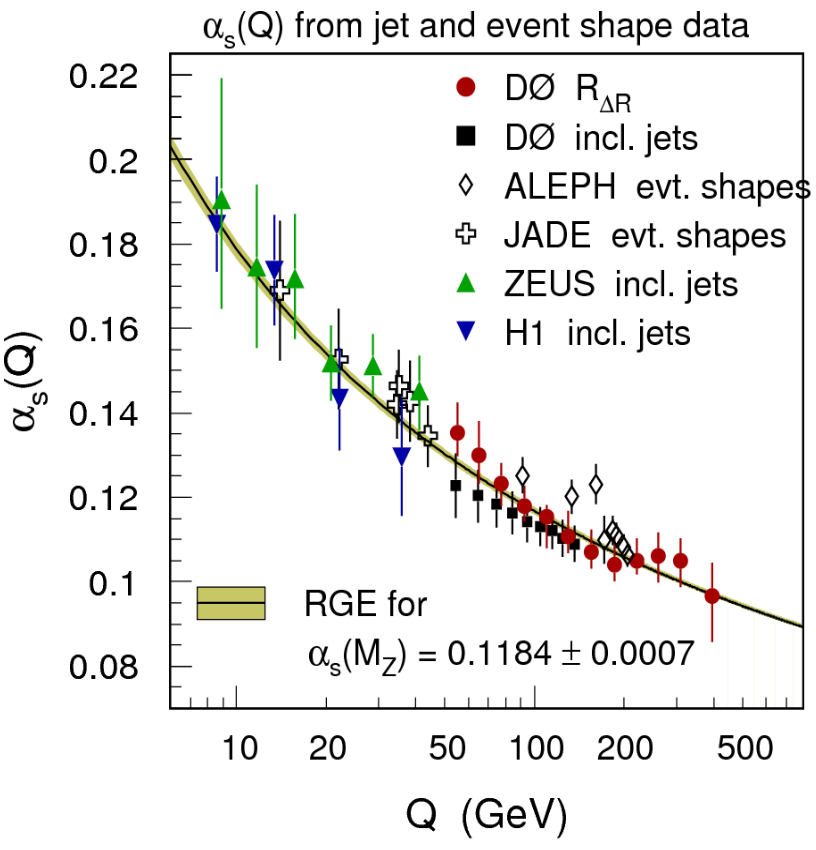
$p_{T\min}^{\rm nbr}$ (GeV)	ΔR	$\alpha_s(M_Z)$	total uncertainty	$\chi^2/N_{\rm dof}$
30 GeV	1.4–1.8	0.1290	$^{+7.3}_{-7.8}$	6.9 / 11
30 GeV	1.8–2.2	0.1276	$^{+7.8}_{-4.9}$	12.6 / 11
30 GeV	2.2–2.6	0.1249	$^{+13.3}_{-9.0}$	15.3 / 11
50 GeV	1.4–1.8	0.1197	$^{+8.9}_{-6.1}$	7.3 / 11
50 GeV	1.8–2.2	0.1168	$^{+8.3}_{-3.9}$	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

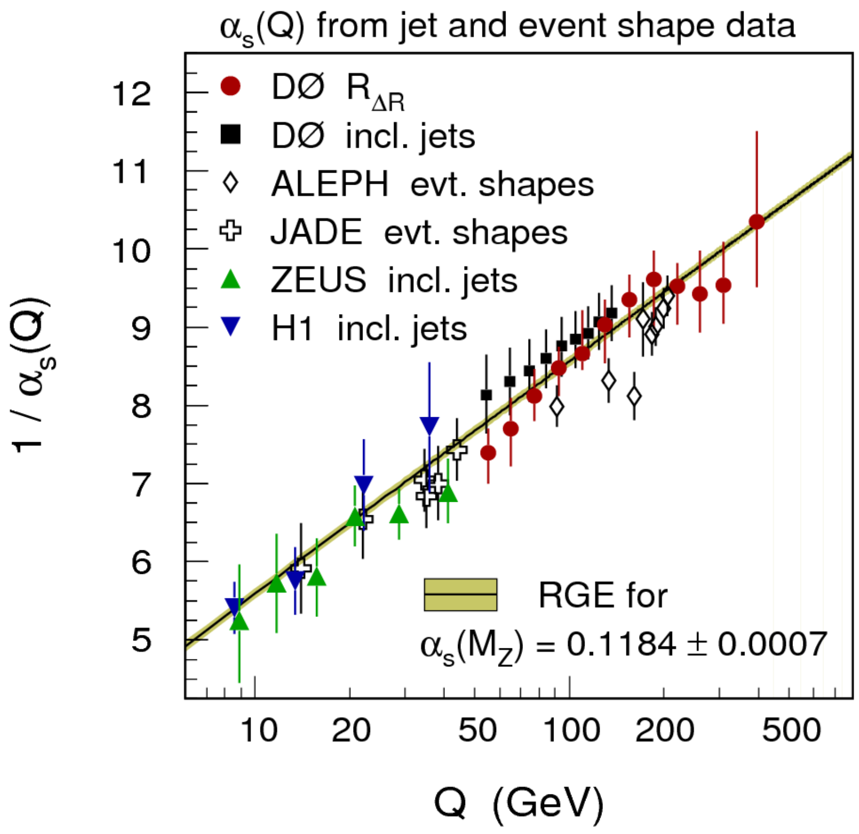
Always good χ^2
→ Confirm RGE

no ΔR
dependence!

Consistency for
p_{Tnbr} >=50 GeV

$\alpha_s(Q)$ – asymptotic freedom





New quantity: $R_{\Delta R}$

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 ($\Delta\phi$,Δy)
   - with $p_{Tnbr} > p_T{}^{min}{}_{nbr}$

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

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

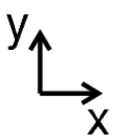
→ $R_{\Delta R}$ looks at any jet and any neighboring jet
… more inclusive than $R_{3/2}$ (require to tag three leading jets)
… more inclusive than $R_{\Delta\phi}$ (require to tag two leading jets)

$R_{\Delta R}$ examples

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

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

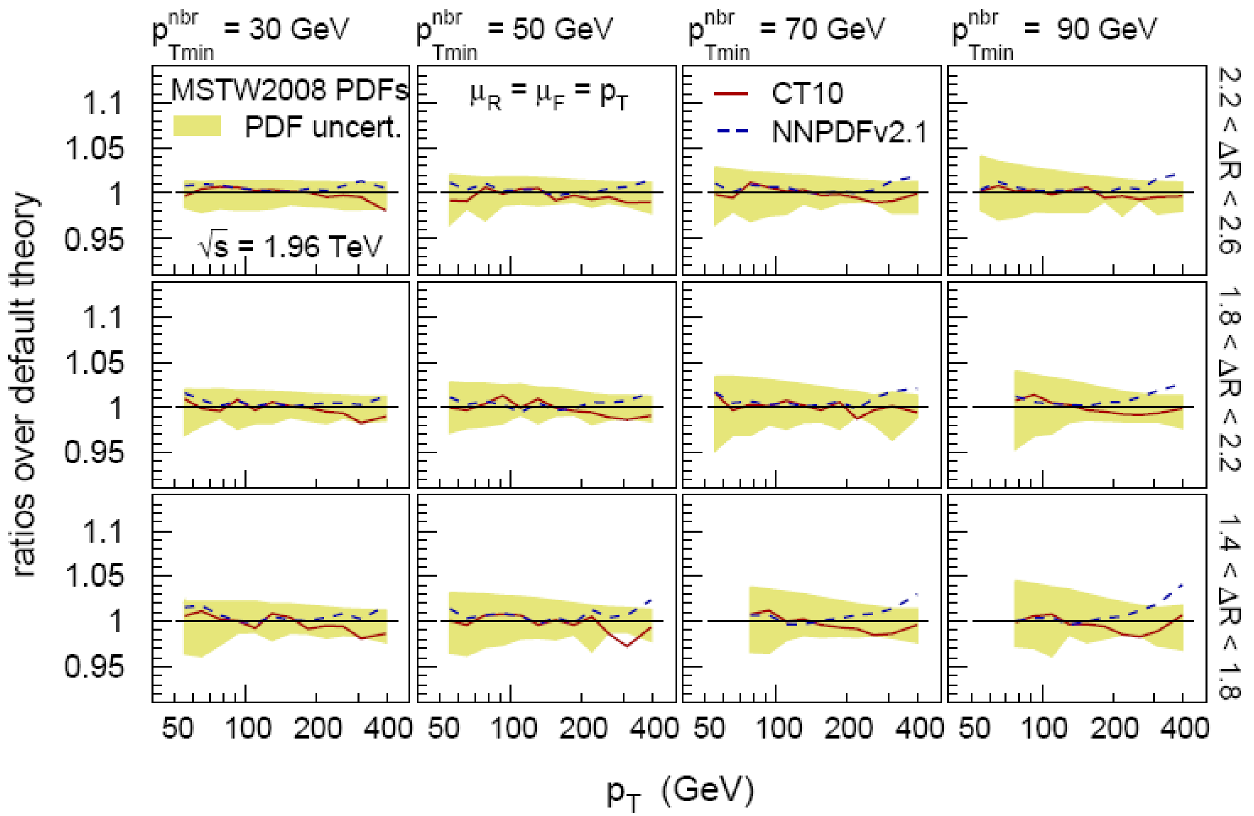
in this example all jets have same (p_T, y)



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	$R_{\Delta R} = 0$	$R_{\Delta R} = 2/3$	$R_{\Delta R} = 1$

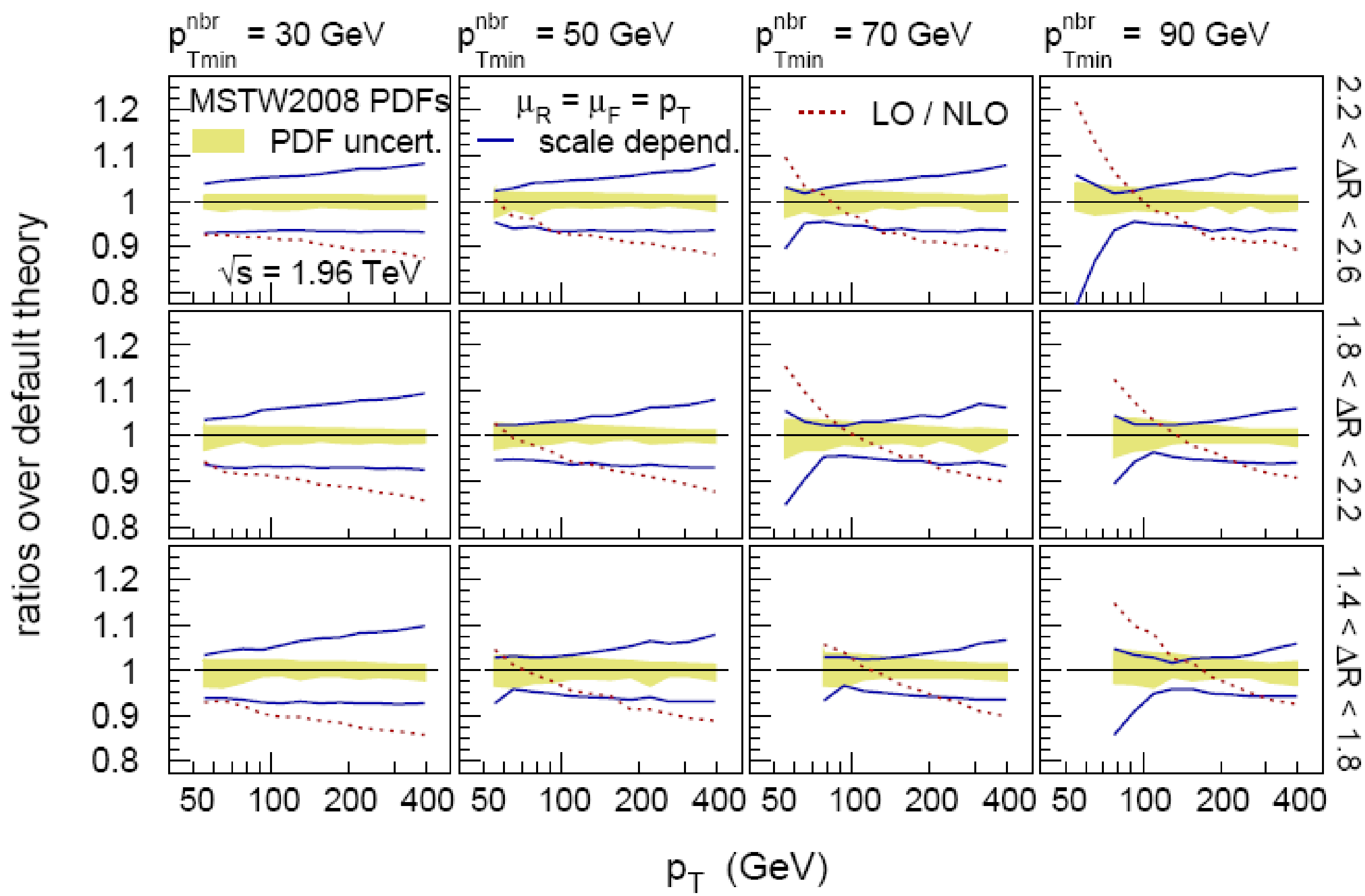
$R_{\Delta R}$ PDF sensitivity



- 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

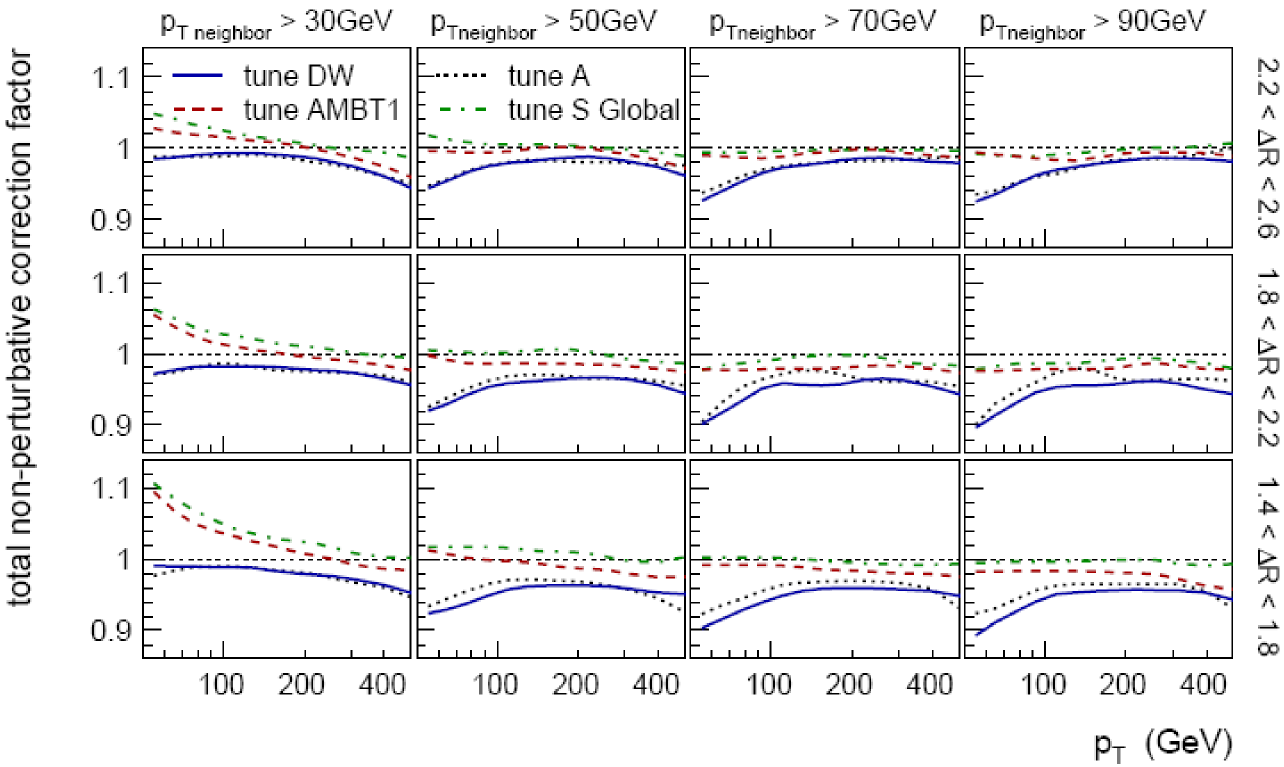


- inverse of k-Factor: LO/NLO (dotted line) → close to unity
- Scale dependence (solid lines) → small (5-10%)

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

Product of correction factors for:

- Hadronization
- Underlying event

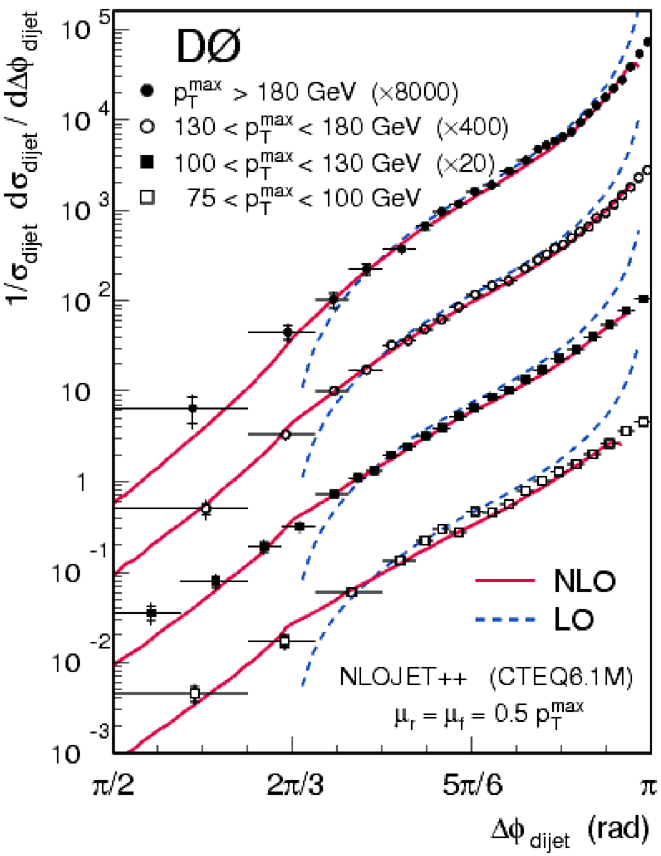


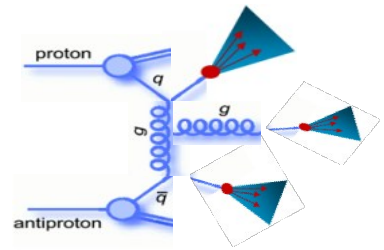
- Small (<10%, typically 3-5%)
- “old” and “new” PYTHIA tunes agree well at high p_T

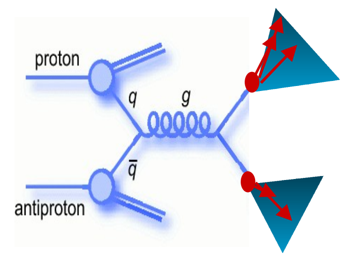
Dijet Azimuthal Decorrelations

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

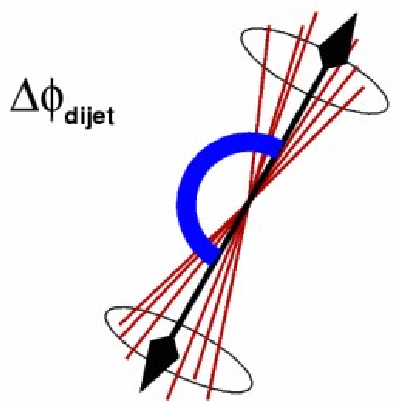
PRL 94, 221801 (2005)







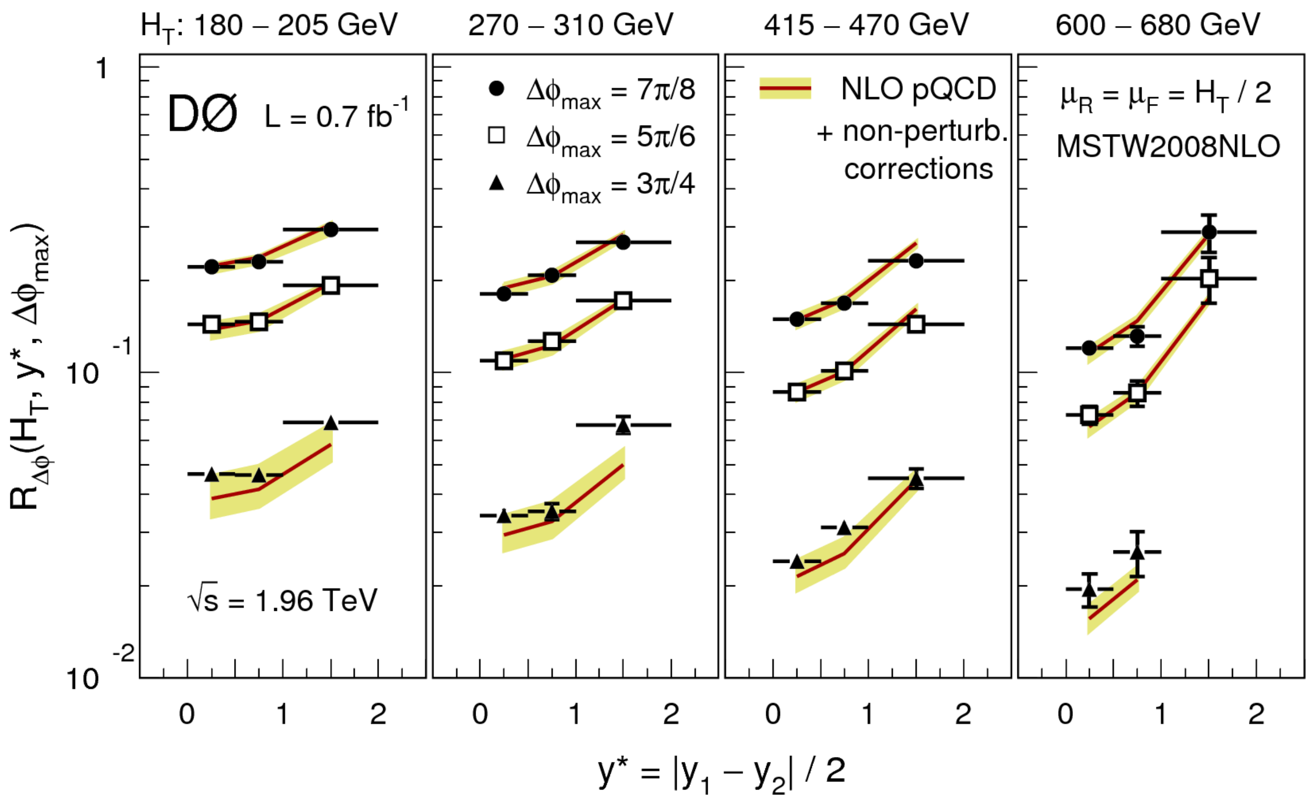
↔ α_s



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

First test of 3-jet NLO
→ Good description

Dijet Azimuthal Decorrelations



See increase with y*