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Measurement of Inclusive and Multijet Cross-Sections at DØ

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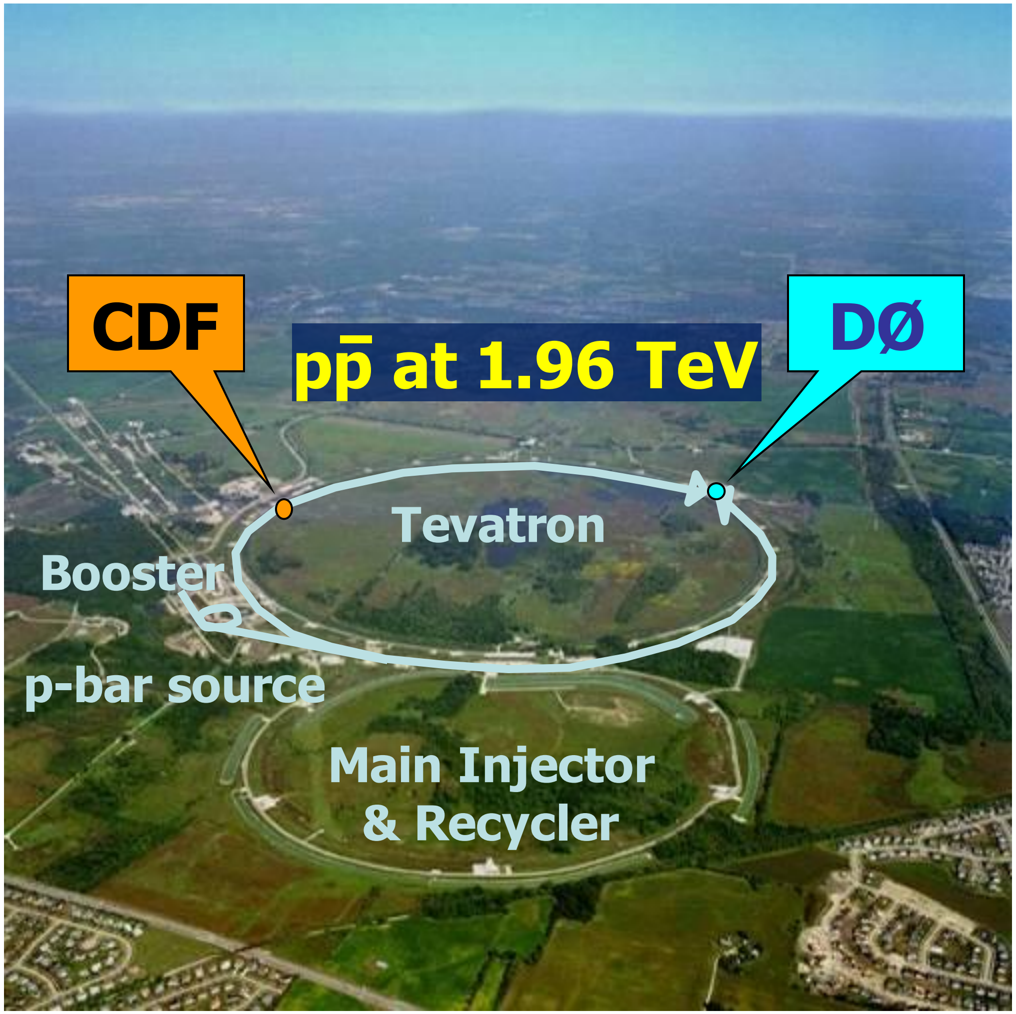
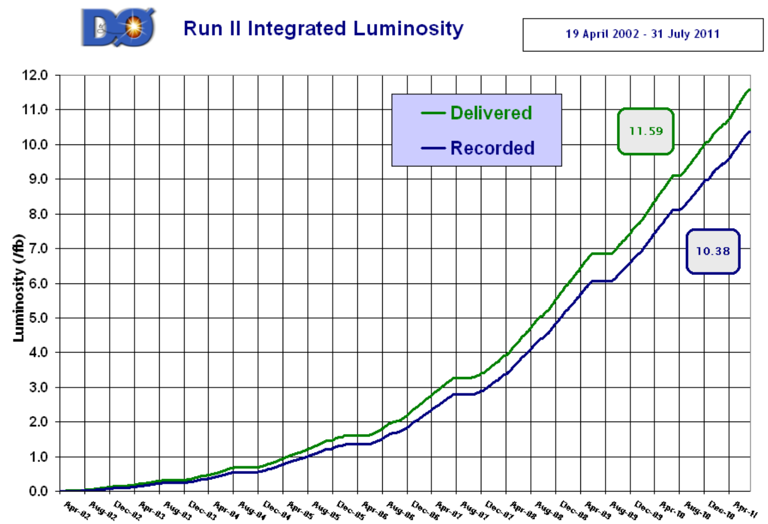
Fermilab Tevatron - Run II



- 36x36 bunches
- Collision at $\sqrt{s}$ = 1.96 TeV
- bunch crossing 396 ns
- Run II started in March 2001
- Peak Luminosity:2-3E32 cm^{-2} sec^{-1}
- Run II recorded: ~11 fb^{-1}

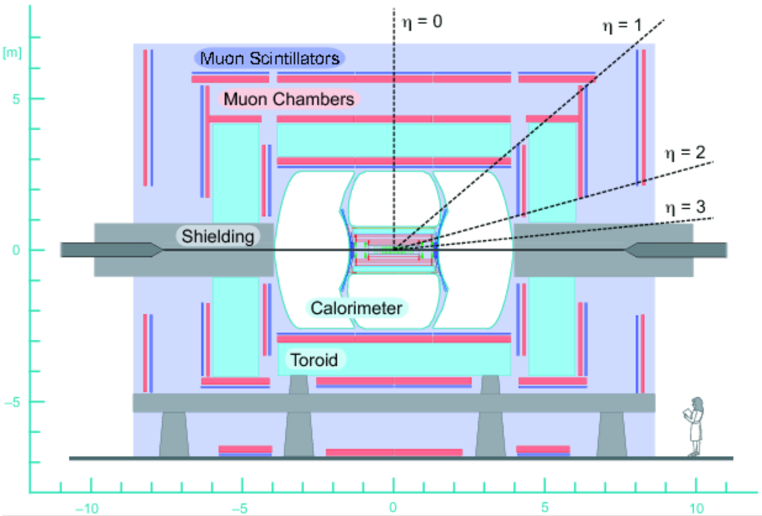


- Run II Goal: 12 fb^{-1} end of 2011

The DØ Detector

Resume:

- Good central tracking
  - Si μstrip tracker
  - Scintillating Fiber Tracker
  - 2T central solenoid
- Excellent Calorimetry
- Wide muon coverage
  - Central and forward toroids



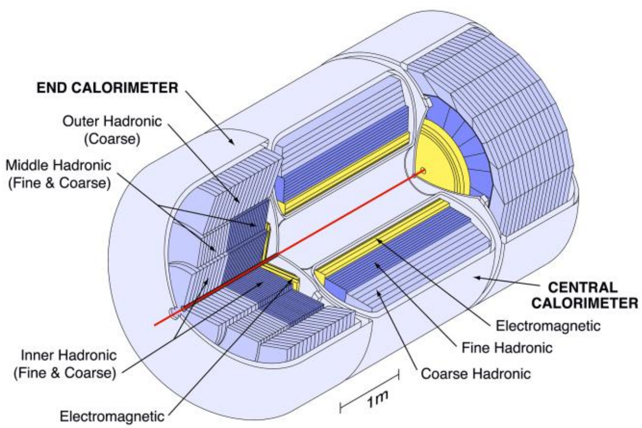
Coordinates Primer:

Unless otherwise noted –

ϕ = Azimuthal angle

η = pseudorapidity = $-\ln(\tan(\theta/2))$

y = rapidity = $\frac{1}{2}\ln[(1+\beta\cos\theta)/1-\beta\cos\theta)]$



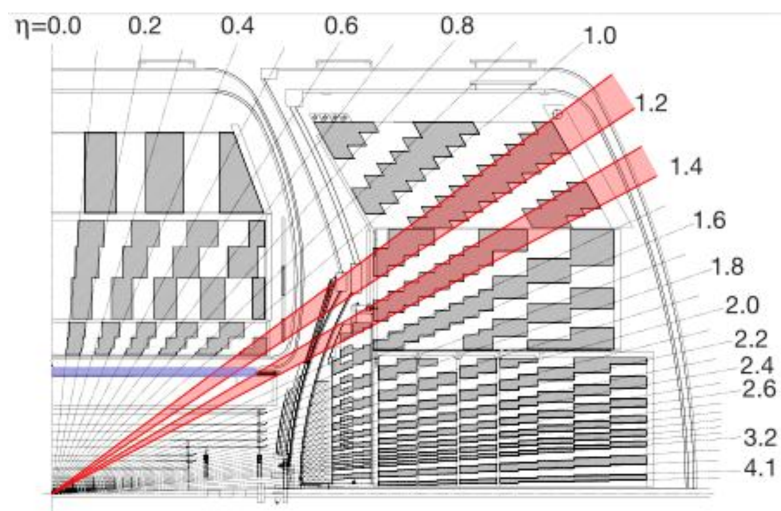
Calorimeter Details:

-lAr/U primarily

- Four EM layers (~20 X_0)

-3 to 4 Hadronic Layers (7 to 8 X_I)

- 0.1 x 0.1 segmentation in $\Delta\eta$ x $\Delta\phi$ (0.05 x 0.05 at EM shower max)



Energy Resolution:

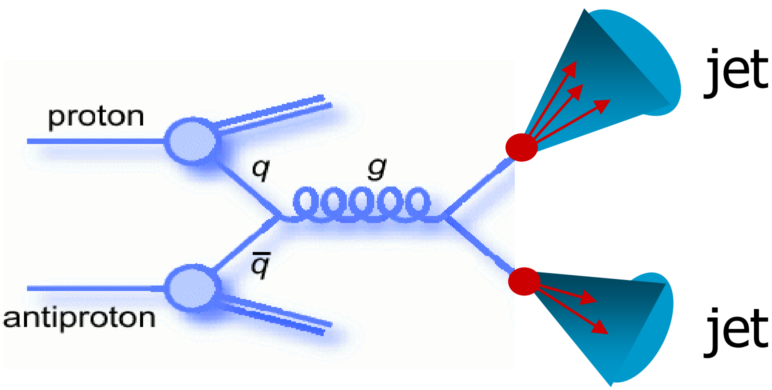
e: $\sigma_E / E = 15\% / \sqrt{E} + 0.3\%$

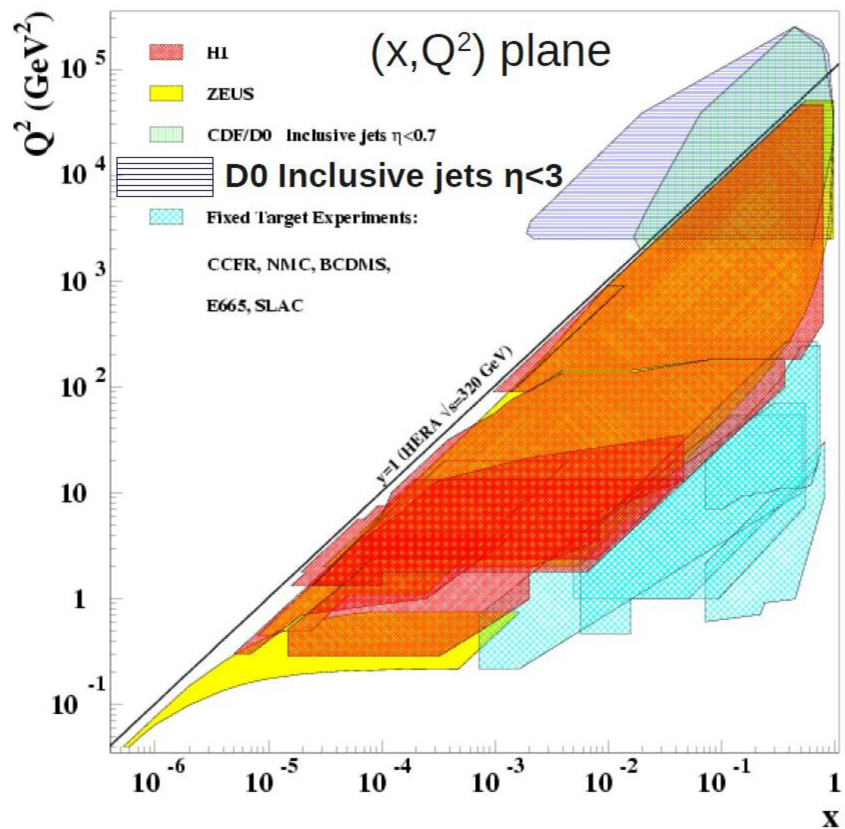
π: $\sigma_E / E = 45\% / \sqrt{E} + 4\%$

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,
- ...(?)...



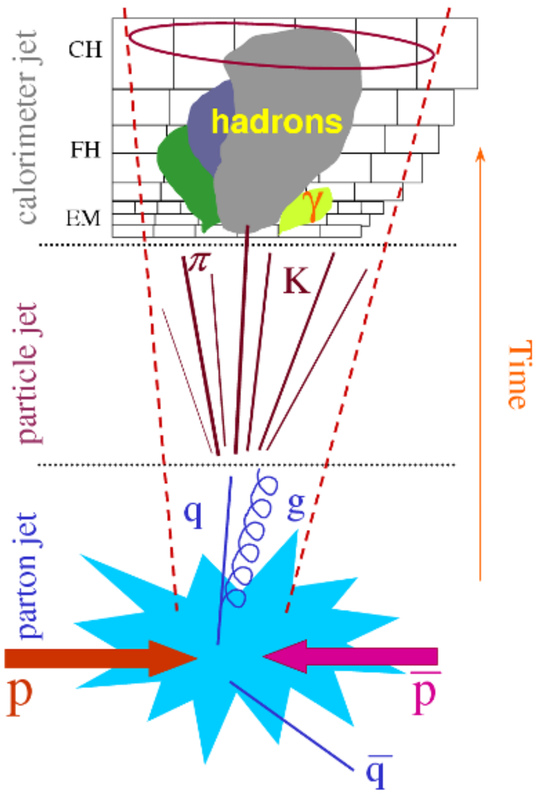


In the absence of new physics:

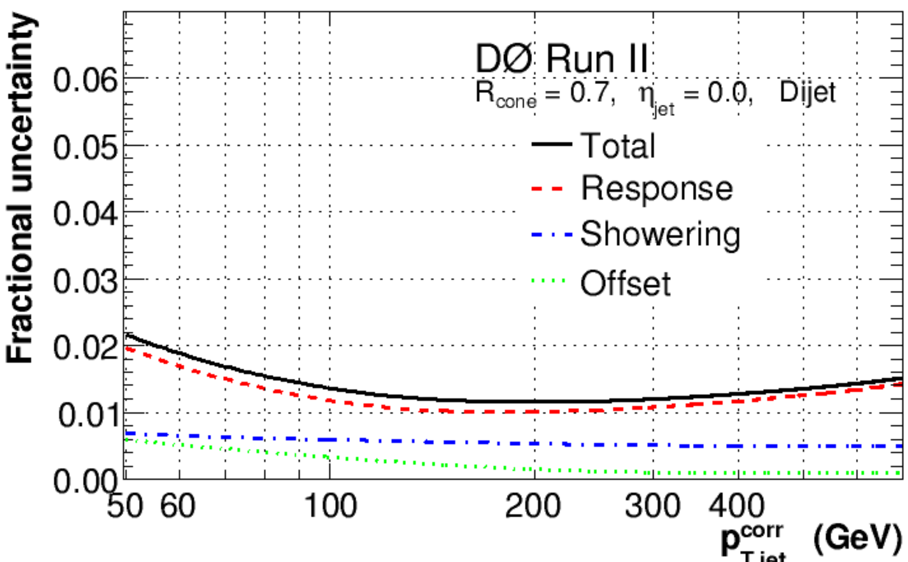
Theory @NLO is reliable (±10%)

→ **Precision phenomenology**
- broad kinematic reach ➔
- sensitivity to PDFs → high-x gluon
- sensitive to α_s

Comparing Data to Predictions



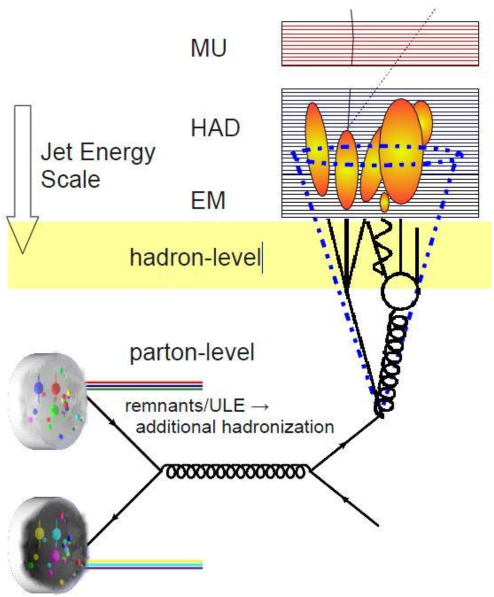
- Use Jet Definition to relate Observables defined on Partons, Particles, Detector
- Measure cross section for pp-bar → jets on "particle-level"
  - Correct for experimental effects (efficiencies, resolution, …) calculated using a fast detector parametrization
  - Include uncertainties and correlations from jet energy scale, non-pertubative effects & UE, id efficiencies, correction for muons & ν's, etc
  - Apply correction to the pQCD calculation
- Comparison to NLO pQCD implemented using NLOjet++, FastNLO program
  - Interpolation techniques for PDFs(x,μ), $\alpha_s(\mu)$



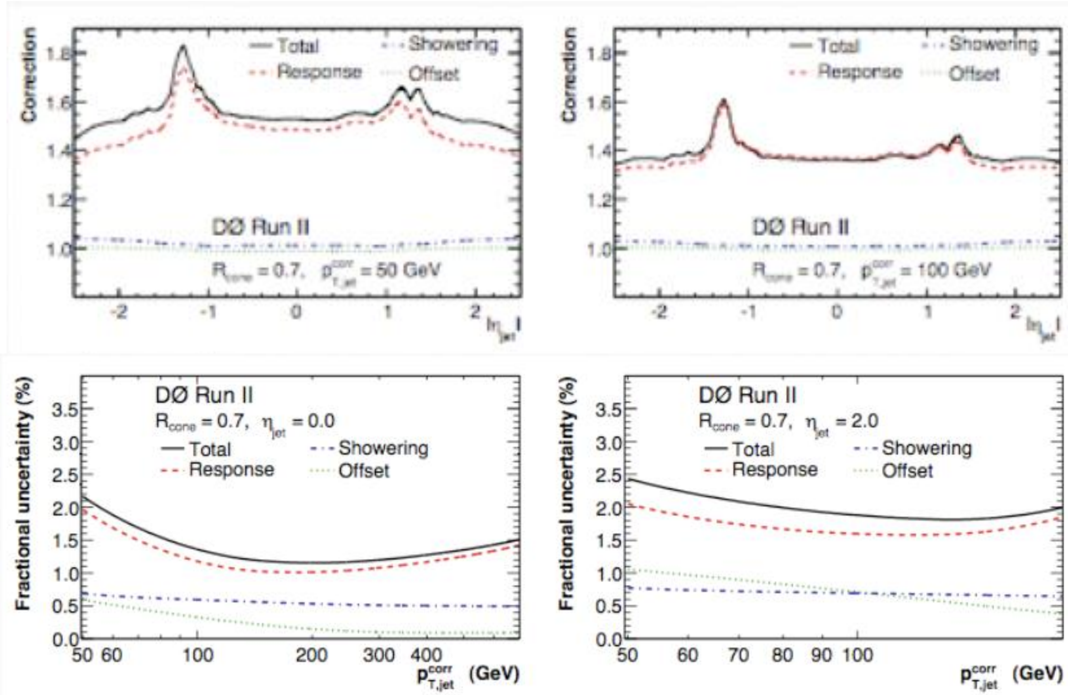
Energy scale uncertainty: 1-2% !

A Few Jet Details

- Jet Finding
  - DØ Run II Midpoint Algorithm
    - Can run on calorimeter towers/MC particles/pQCD partons
    - Fixed cone: R_{cone} = 0.5 or 0.7 (most jet studies)
    - pTmin = 8 GeV
  - Use all particles + midpoints btwn jets as seeds.
  - Merge jets if overlap in p_T by more than *f* = 50%.



- Jet Energy Scale (JES)
  - $E_{particle} = E_{cal} - O / (R \cdot S)$
    - E_{cal} = Calorimeter energy
    - O = Offset Energy
      - Electronics noise, U noise, pileup,…
    - S = Showering Correction
  - Response measured in γ + jet
    - EM scale set by Z mass fit.
    - Checked with dijet balance



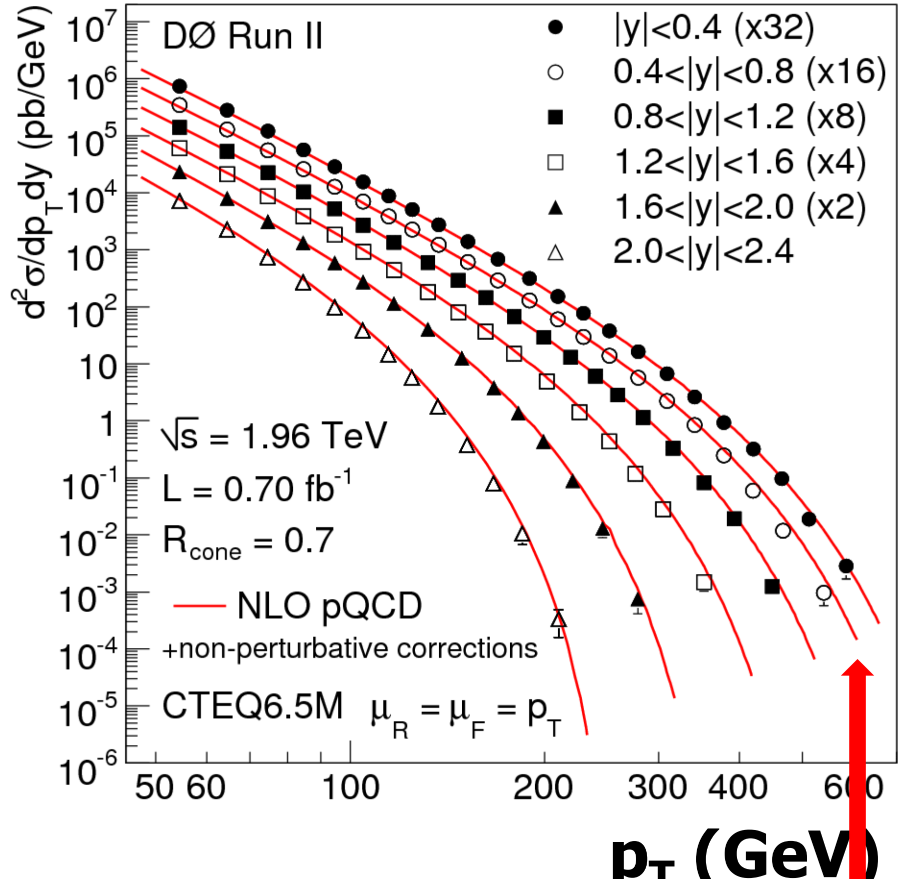
Inclusive Jets

The inclusive jet cross section – doubly differential vs. (p_T,y)

Phys. Rev Lett. 101, 062001 (2008)
Detailed Phys Rev. D in preparation

Analysis details:

- Use L = 0.7 fb-1 with well-measured JES
- Single jet trigger
- Require at least 1 jet with p_T > 50 GeV



Benefits 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

Strong Coupling Constant

Phys. Rev. D 80, 111107 (2009)

Use MSTW2008NNLO PDFs as input

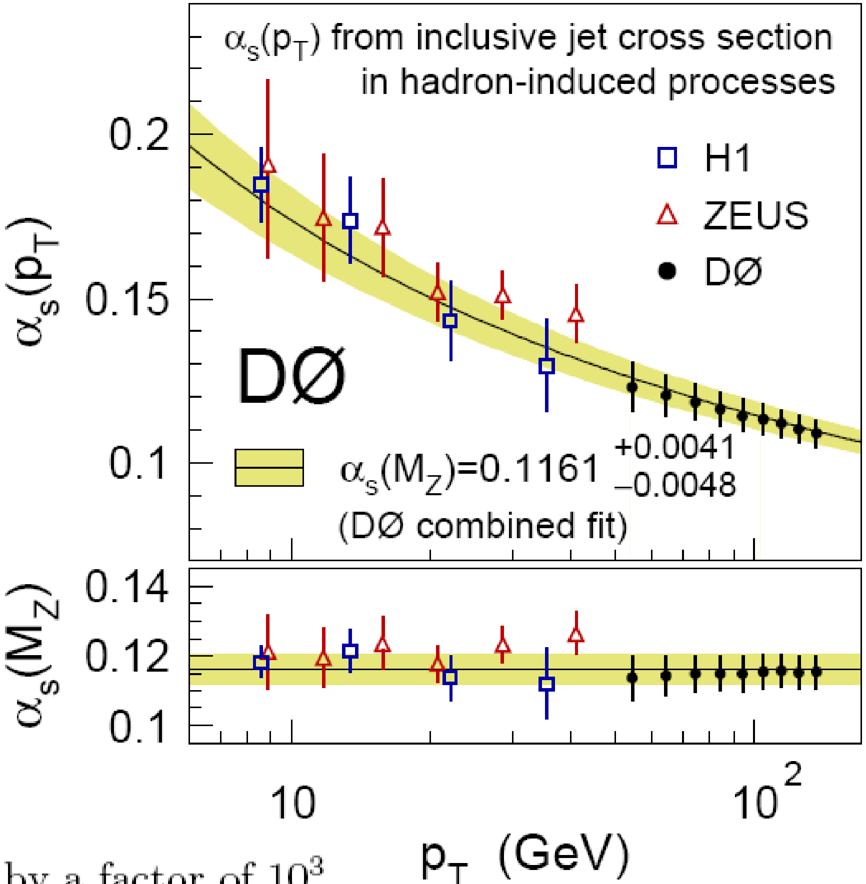
→ Cannot test RGE at $p_T > 200$ GeV
(RGE already assumed in PDFs)

→ 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

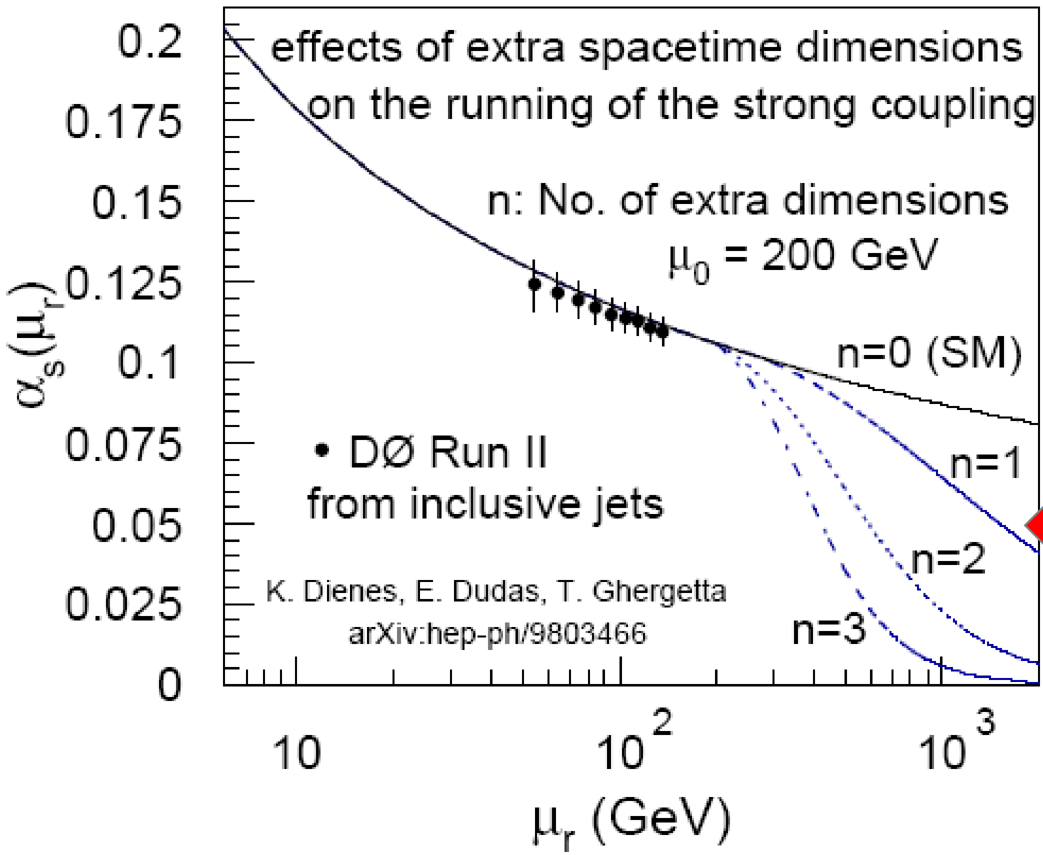
$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$



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 alpha-s (?)



→ so far tested
up to μ_r = 200 GeV

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)

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

Dijet Production

Described by eight variables – for example:

1. Dijet Mass Mjj
2. $y^* = \frac{|y_1 - y_2|}{2}$ or: $\chi_{\rm dijet} \equiv \exp(2y^*)$
3. $y^{\rm boost} = \frac{y_1 + y_2}{2}$
4. $\Delta\phi = |\phi_1 - \phi_2|$
5. p_{T2}/p_{T1}
6. M/E (jet1)
7. M/E (jet2)
8. Overall rotation in azimuthal angle

features of 2→2 process (1, 2)

PDFs (3)

"hard" higher-order effects (4, 5)

"soft" higher-order effects (6, 7)

irrelevant in unpolarized pp-bar (no reference axis) (8)

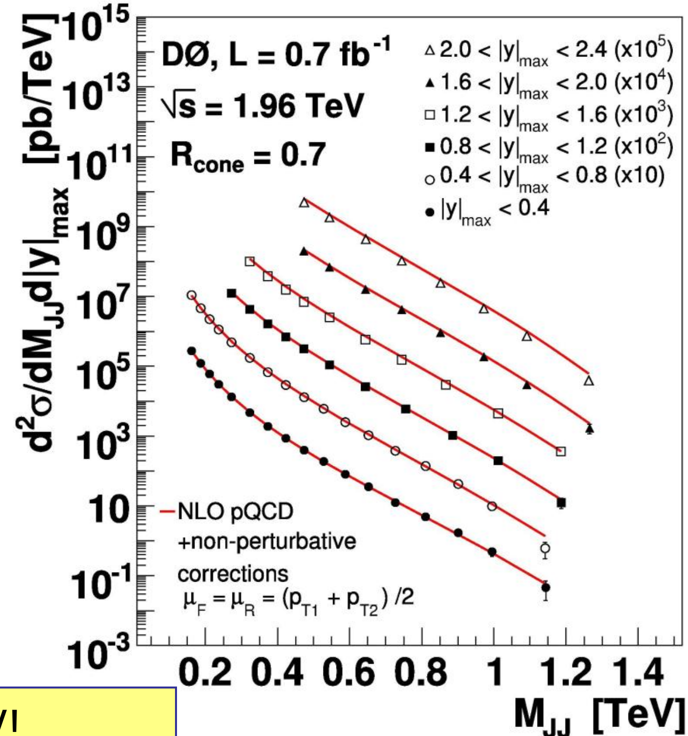
Dijet Mass Spectrum

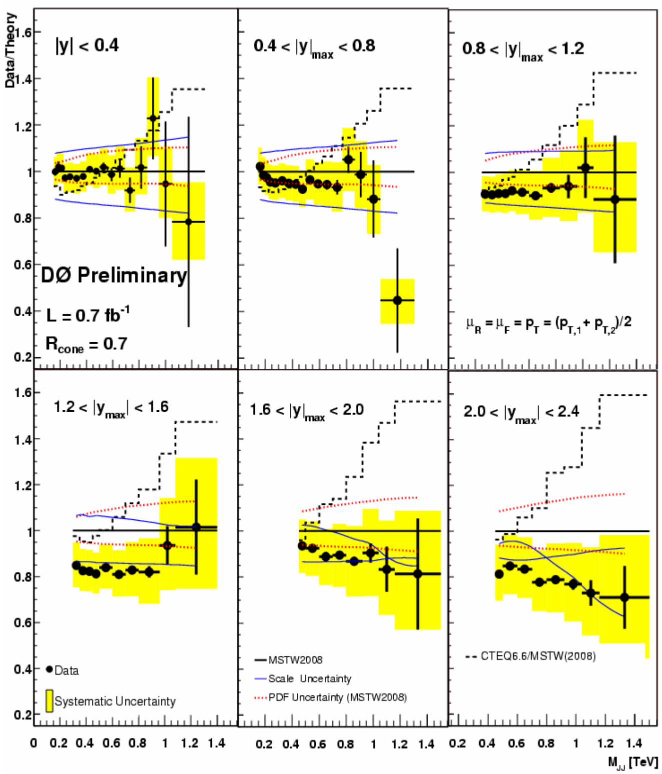
Phys. Lett. B 693, pp. 209-214 (2010)

Measure in six $|y|_{max}$ regions

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

Extend QCD tests to forward region





→ data with Mjj > 1.2 TeV!
→ described by NLO pQCD

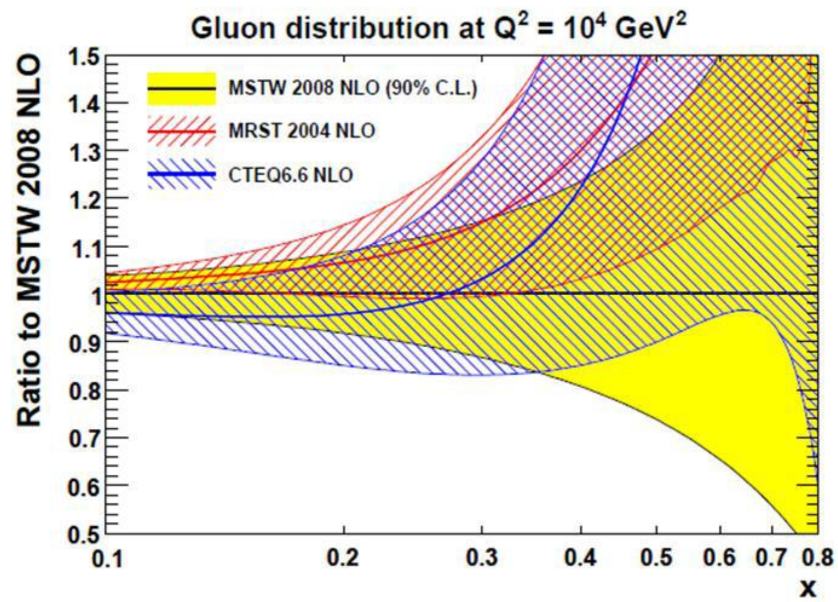
- no indications for resonances

→ PDF sensitivity at large |y|-max

- CTEQ6.6 prediction too high
- MSTW2008 consistent w/ data (but correlation of experimental and PDF uncertainties!)

Multi-Jet Production

- ***Inclusive jet production and dijets sensitive to PDFs and α_s^2***
- ***Three-jet production***
  - ***same PDF sensitivity***
  - ***But sensitive to α_s^3***
  - ***Sensitivity to contribution from higher order diagrams.***
- ***Testing higher-order processes provides direct insight into strong dynamics***



Three-jet Mass

First Measurement of three-jet cross section at the Tevatron

→ First corrected 3-jet mass distribution

→ First comparison to NLO pQCD calculations for 3-jet cross sections

Strategy:

Measure cross sect. vs. invariant three-jet mass

- in different rapidity intervals $|y| < 0.8, 1.6, 2.4$

For the largest rapidity interval

- for different p_T requirements of the 3rd jet $p_T^{Jet3} > 40, 70, 100$ GeV

Data Set:

- 0.7 fb-1 inclusive jet triggers
- Require at least 3 reconstructed jets passing data quality and jet id criteria
  - Jet 1 $p_T > 150$ GeV
  - Jet 2, 3 $p_T > 40$ GeV
  - All jets separated by $\Delta R > 1.4 = 2*R_{cone}$

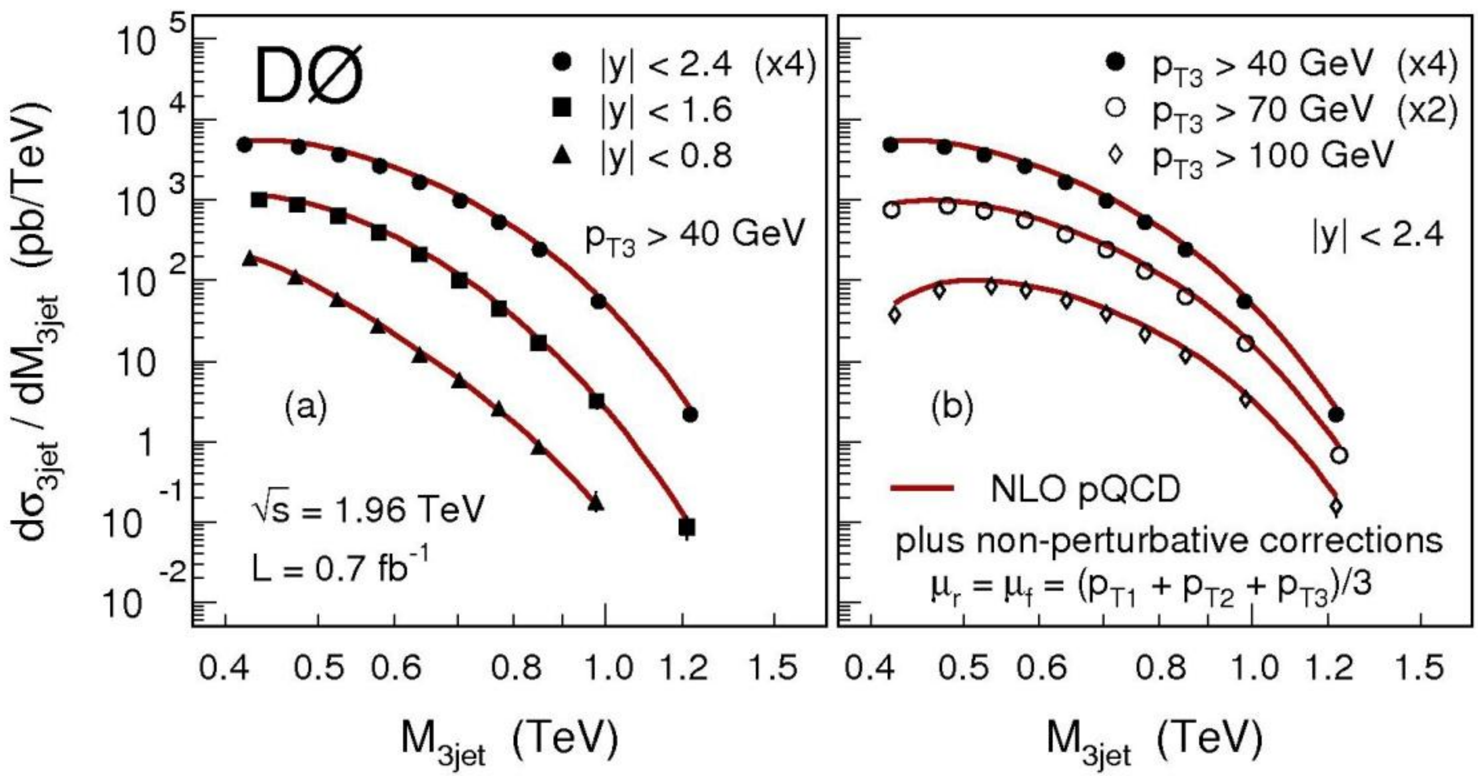
Three-jet Mass

$$\frac{d\sigma}{dM_{3jet}} = \frac{1}{L \cdot \Delta M_{3jet}} \cdot \left(\sum_{i=1}^{N_{evt}} \frac{1}{\epsilon_v^i} \right) \cdot C_{unsmear}$$

"Measurement of Three-Jet Differential Cross Sections $d\sigma_{3jet}/dM_{3jet}$ in pp Collisions at $\sqrt{s}$ = 1.96 TeV"
Submitted To Phys. Lett. B

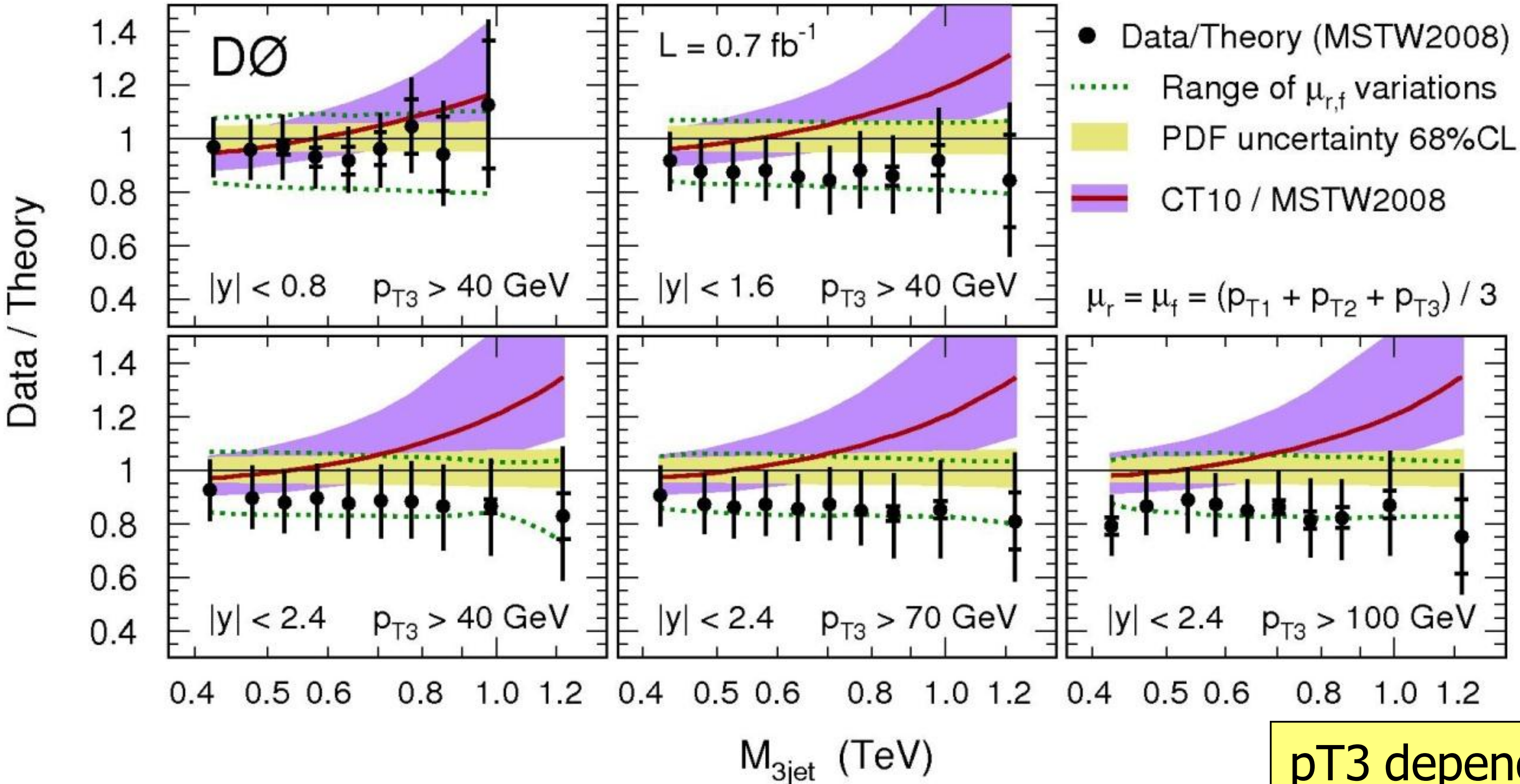
Rapidity dependence

p_T^{Jet3} dependence



Three-jet mass distrib.

Rapidity dependence

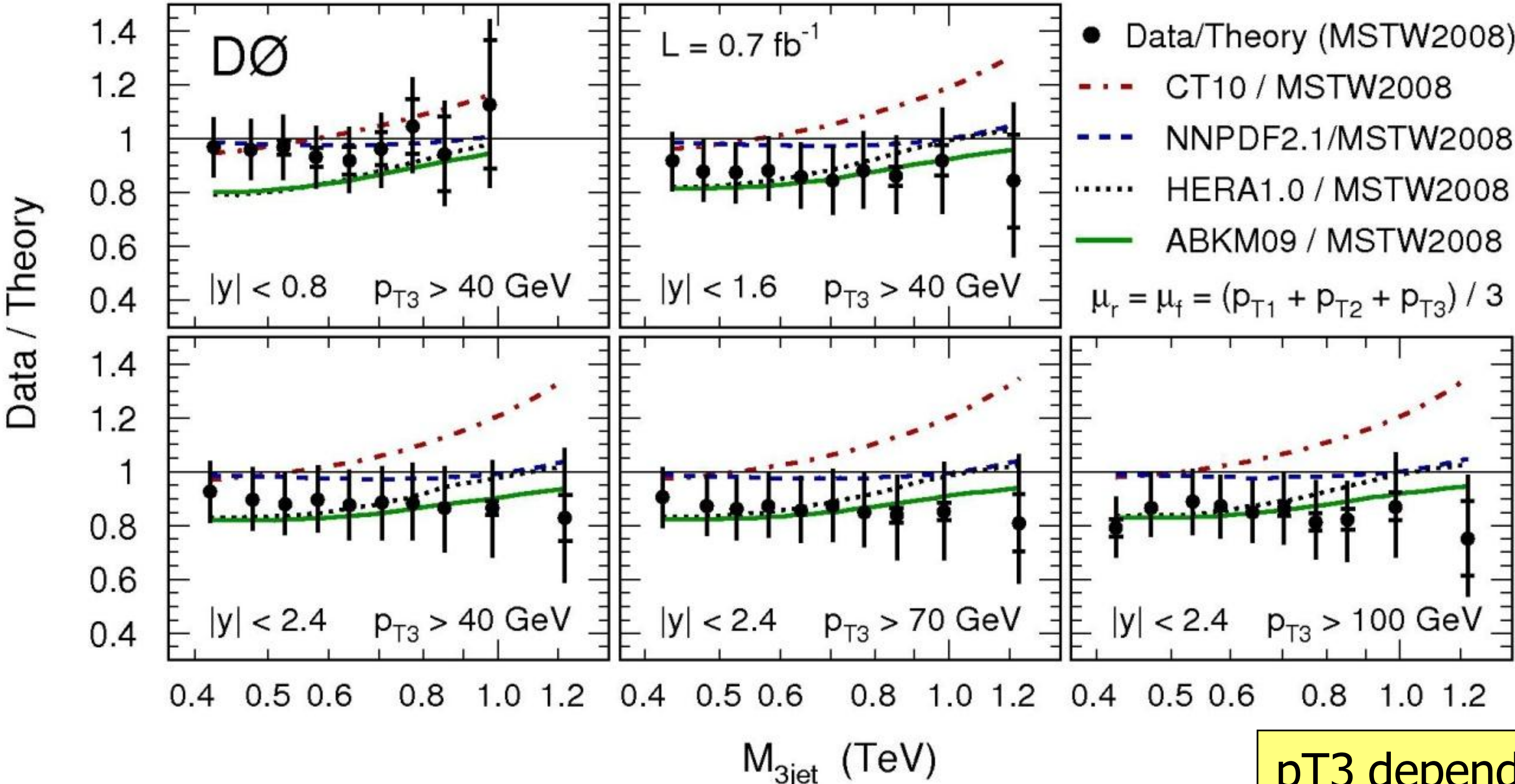


pT3 dependence

Good agreement with MSTW2008, CT10 at low mass

Three-jet mass distrib.

Rapidity dependence

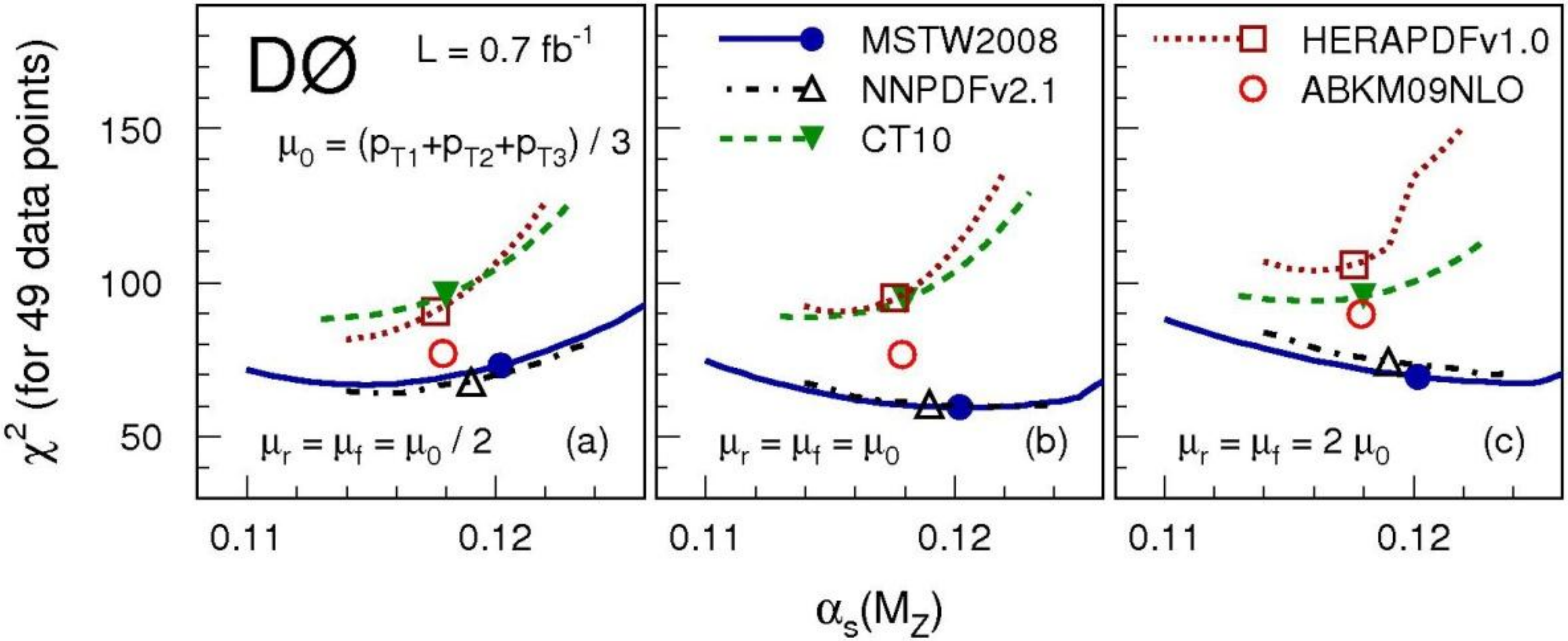


pT3 dependence

NNNPDFv2.1 similar to MSTW2008. HERAPDF similar to CT10

Three-jet mass PDF sensitivity

$\sigma \propto \alpha_S^3 \cdot \mathrm{PDF}^2$



Calculate χ^2 for all data points including all correlated uncertainties except PDF uncert. (test of central PDF)

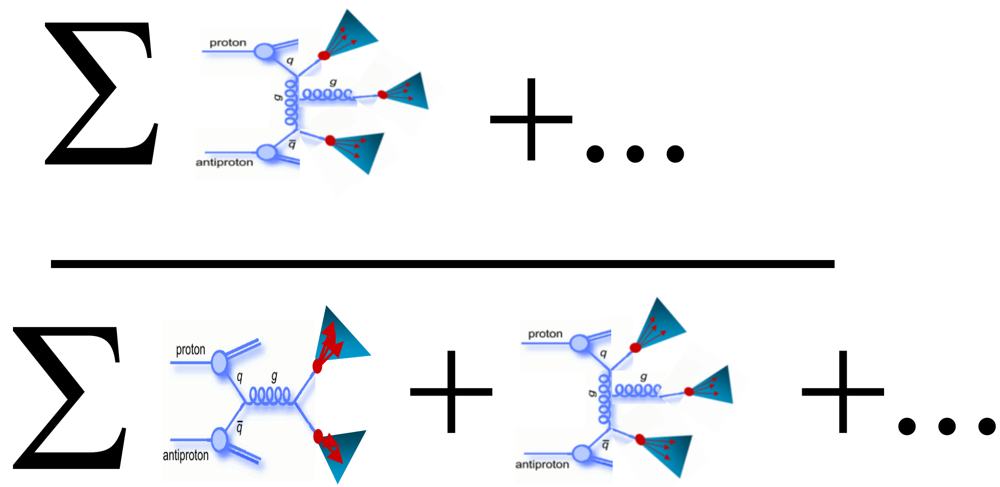
For α_S close to the world average, observed lowest χ^2 for the default scales. Lowest χ^2 for MSTW2008 and NNPDFv2.1

$R_{3/2}$: Introduction

Goal: test pQCD (and α_s) independent of PDFs

Conditional probability:

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



- 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 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}

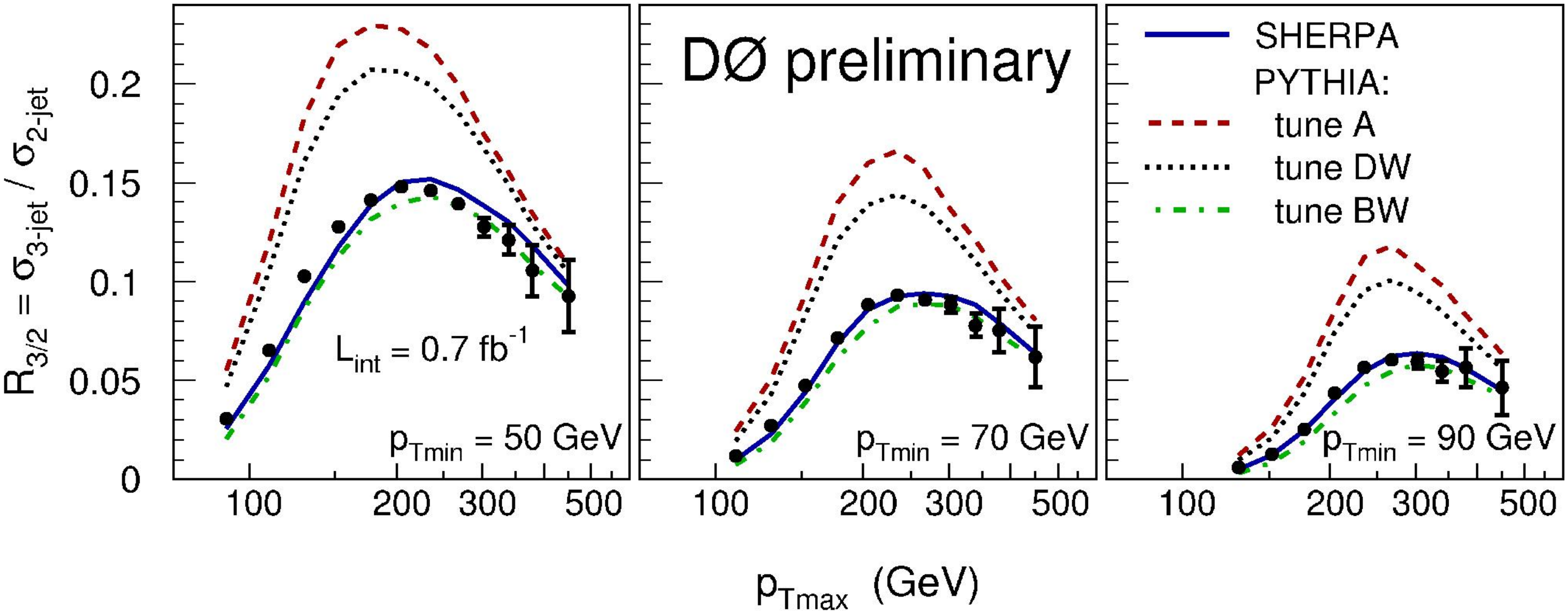
→ probe running of α_s in Tevatron energy regime → up to 500 GeV

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

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

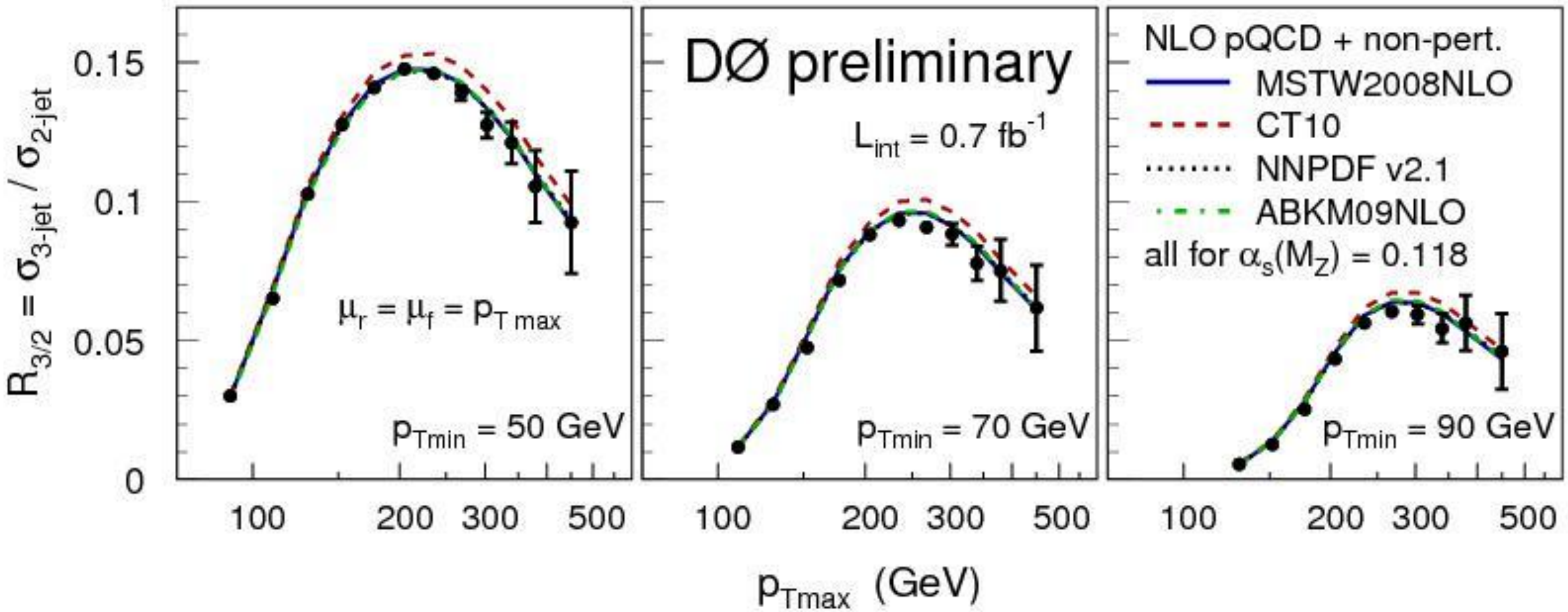


SHERPA: good description (default version w/ MSTW2008LO PDFs)

PYTHIA: huge dependence on tune

- Reasonable description by tune BW
- Popular tunes A, DW → totally off

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



Comparison to NLO pQCD

- Generated using FastNLO extrapolation of NLOJET++
- Good agreement. CT10 slightly high at high pT.
- Variation due to PDFs on the order of data uncertainties

Maybe: extract strong coupling → up to p_T>400 GeV (yet untested)

Conclusions

- DØ continues to produce a wide-range of important QCD results, ranging from low p_T scattering, through an assortment of single and double differential jet measurements
- Presented
  - Extraction of aS from inclusive jet spectrum
  - Measurement of double differential dijet mass cross-sections
  - Measurement of double differential trijet cross-sections
  - Rations of inclusive trijet to dijet cross-sections
- With data currently under analysis, expect more precision QCD measurements
  - Inclusive jets at high p_T
  - Triple differential jet cross sections
  - High precision central and forward direct photon measurements
- Tevatron will continue though Sept 2011
  - Are there additional measurements that can be made with 12 fb^{-1}?

For the latest public DØ QCD results, see http://www-d0.fnal.gov/Run2Physics/qcd/