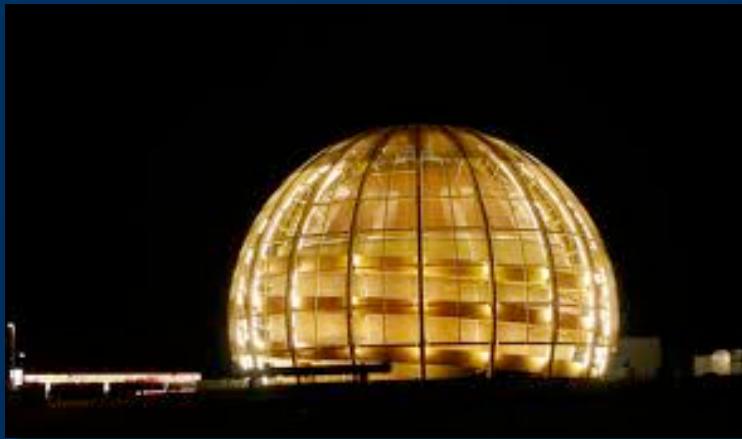


Jet Physics at the LHC and the Tevatron

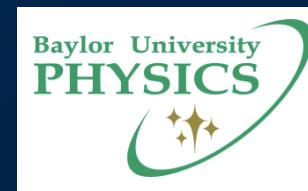
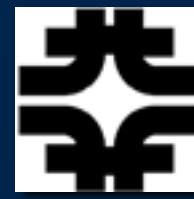


LHCP 2013
Barcelona, Spain

May 15, 2013

Jay R. Dittmann
Baylor University

For the LHC and Tevatron Collaborations



QCD and Jet Physics

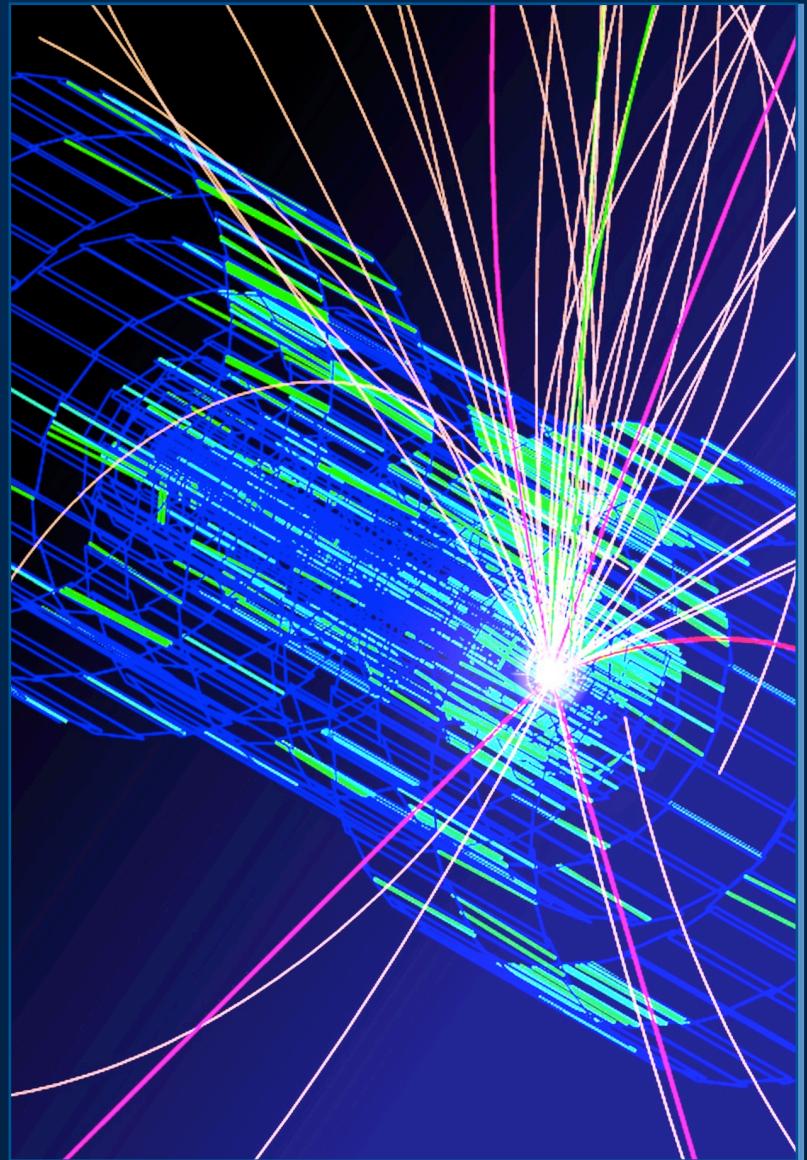
Practically all physics at hadron colliders involves QCD!

- ▶ QCD processes are a dominant background in a huge variety of measurements
- ▶ A better understanding of QCD translates to an improved sensitivity in searches for new phenomena

Why study jets?

Jet measurements ...

- ▶ Test the validity of perturbative QCD (pQCD) down to the smallest accessible distance scales
- ▶ Provide a superior understanding of Parton Distribution Functions (PDFs)
- ▶ Allow measurements of the strong coupling α_s
- ▶ Now have access to large energy scales and high statistics at the LHC!



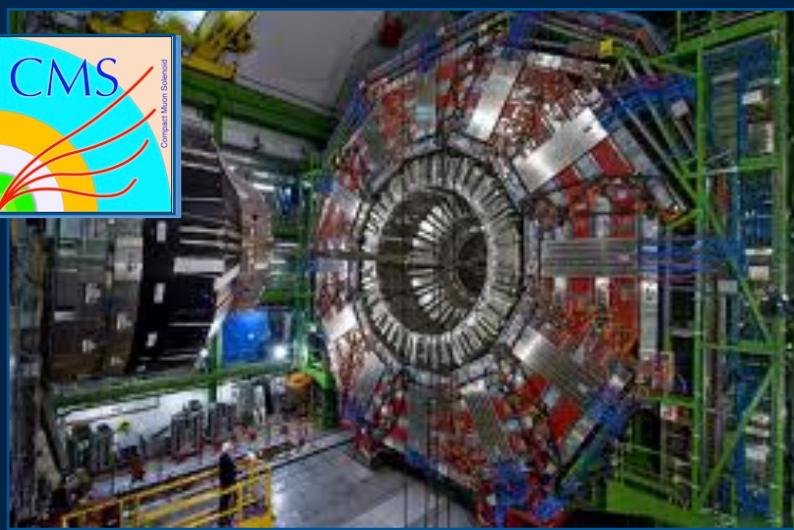
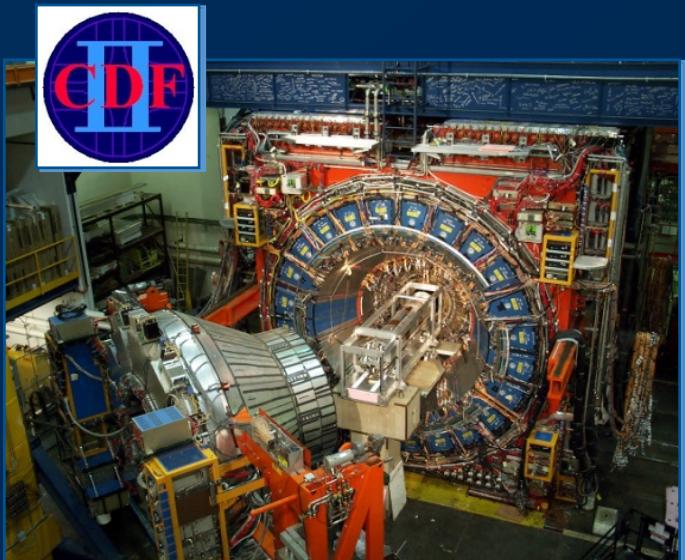
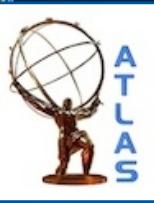
Outline

■ Jet Measurements

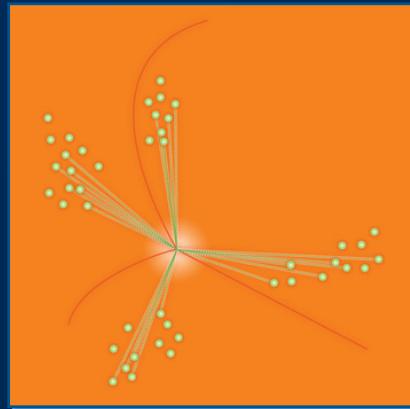
- ▶ Inclusive Jet Production
- ▶ Dijet Production
- ▶ Jet Ratios and the Extraction of α_s
- ▶ Jet Mass and Substructure

■ Summary

Please see parallel session talks for much more detail!



Jet Measurements

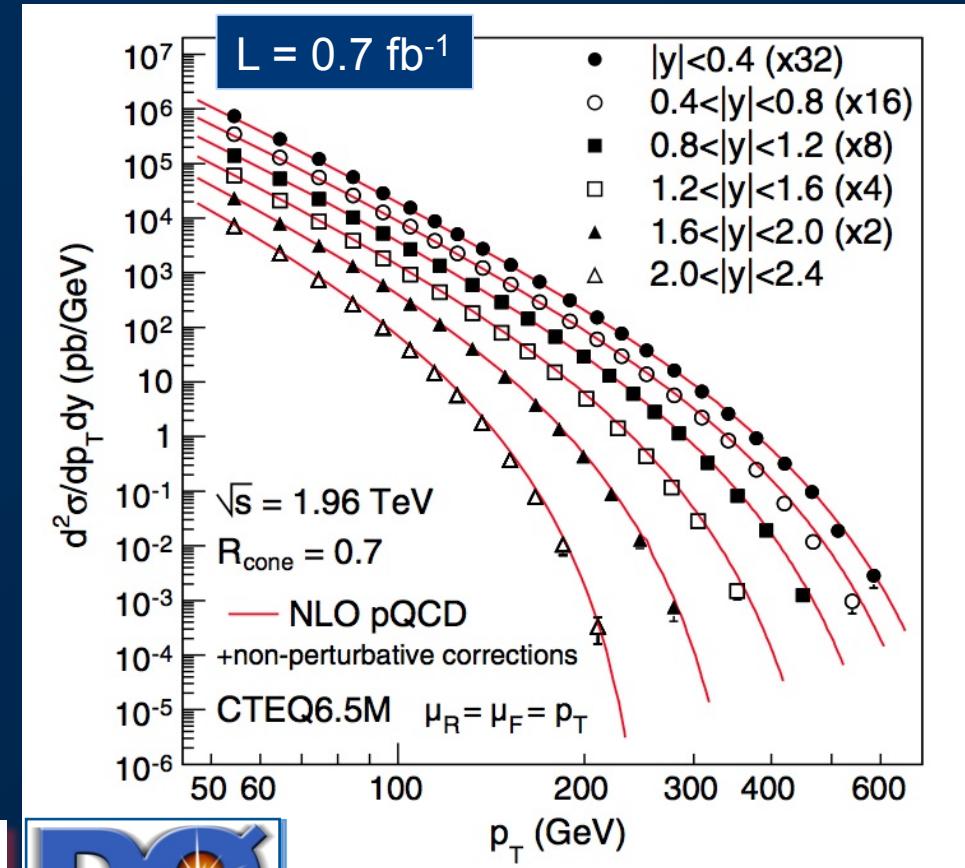
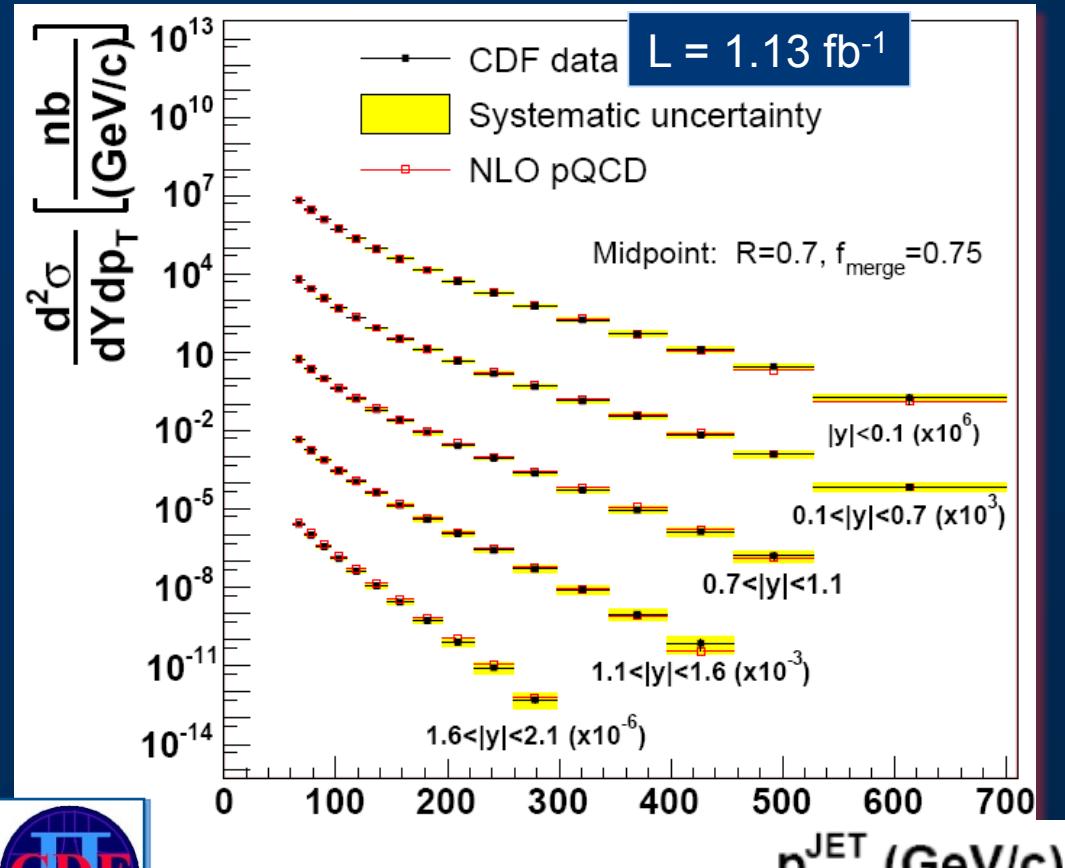


Inclusive Jet Production

Inclusive Jet Production



Inclusive Jet Cross Section at the Tevatron ($\sqrt{s} = 1.96$ TeV)



CDF: PRD 78, 052006 (2008)



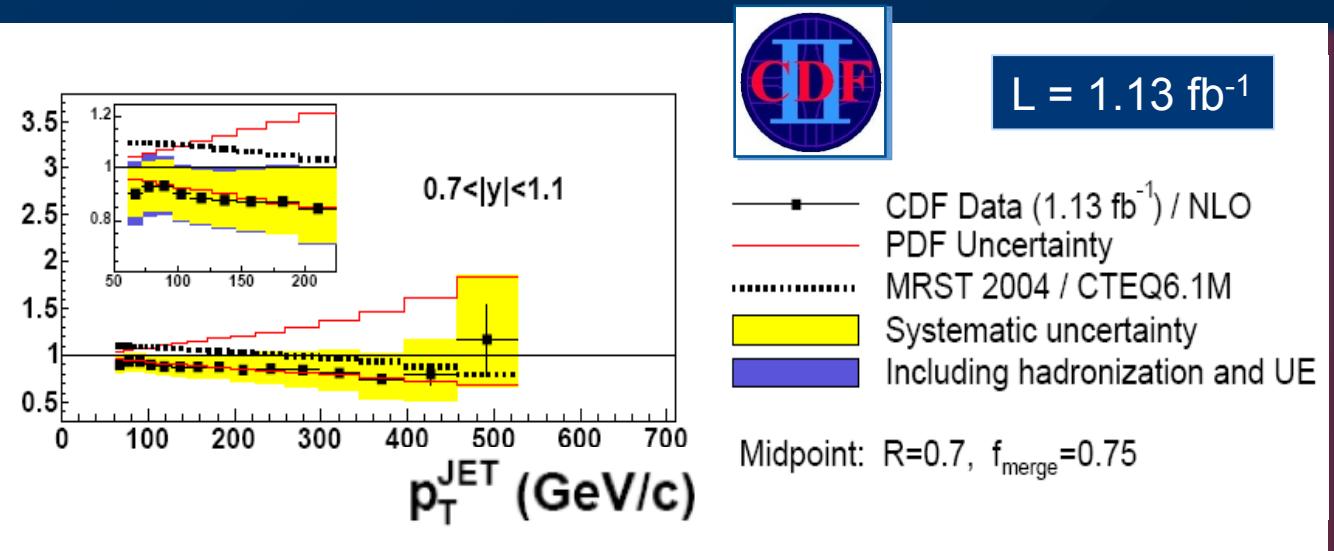
D0: PRD 85, 052006 (2012)

Test perturbative QCD over 8 orders of magnitude in $d\sigma^2/dp_T dy$

Inclusive Jet Production



Inclusive Jet Cross Section at the Tevatron ($\sqrt{s} = 1.96$ TeV)

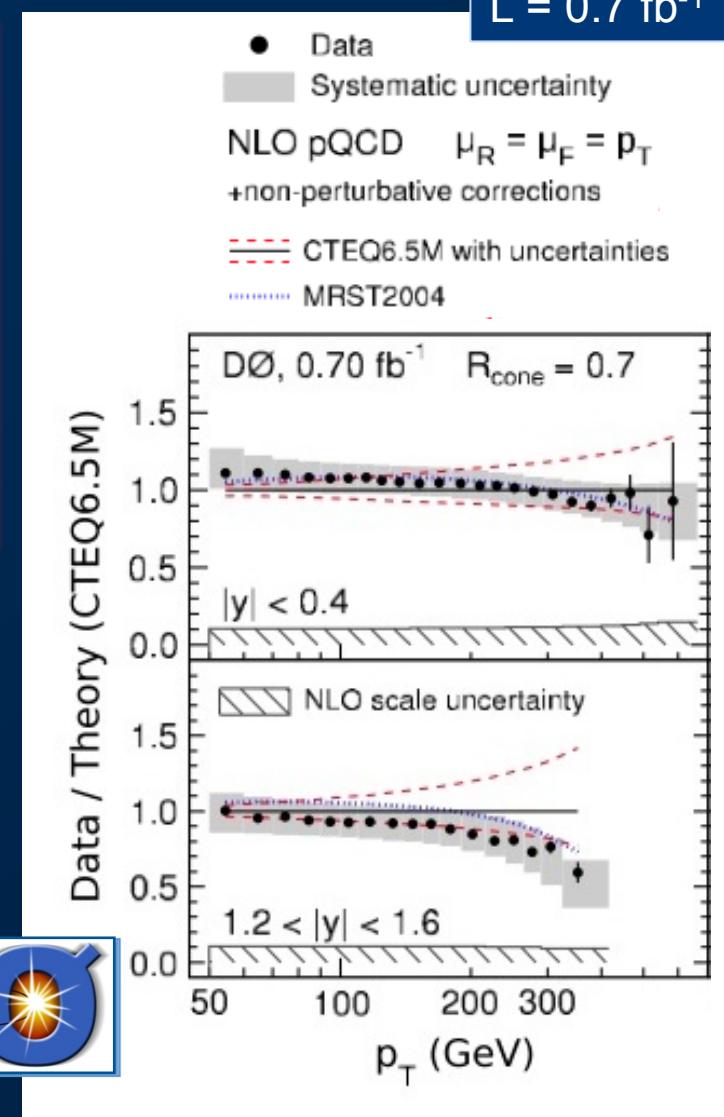


CDF: PRD 78, 052006 (2008)

- Both CDF and D0 agree with NLO QCD predictions!

(Both favor somewhat softer gluons at high x)

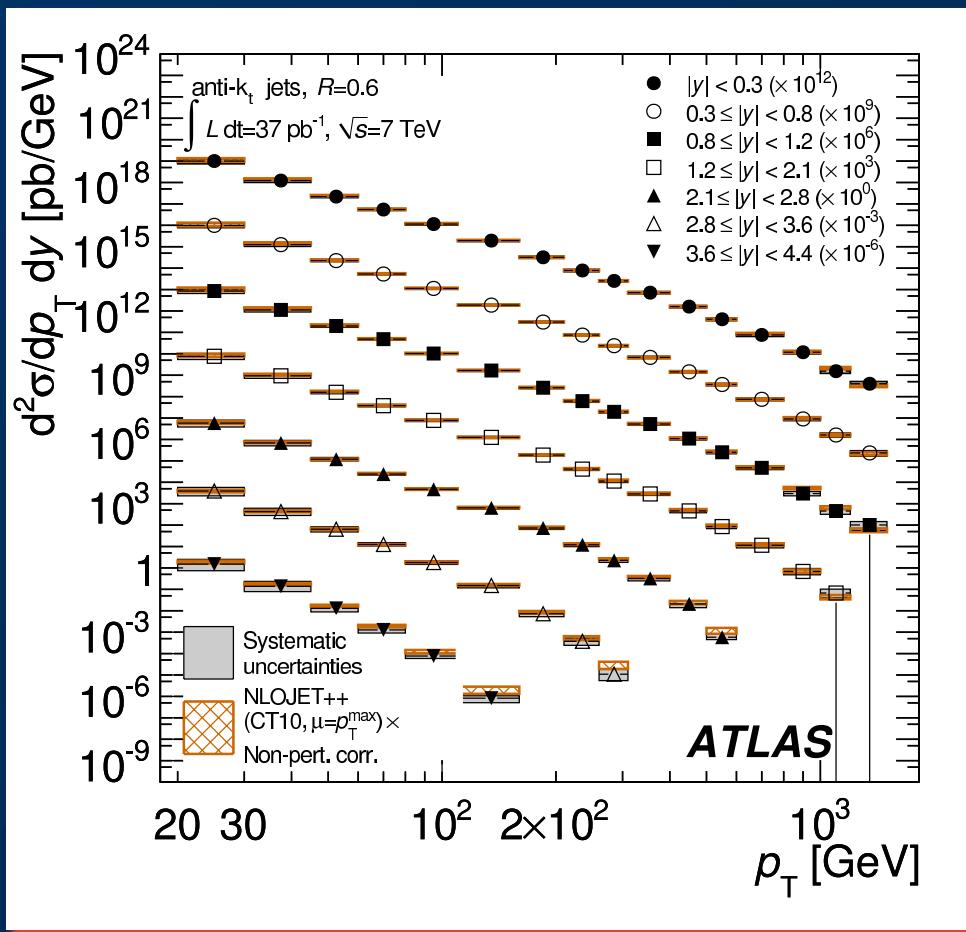
These measurements contributed to the development of many modern PDF sets used for LHC physics today!



D0: PRD 85, 052006 (2012)

Inclusive Jet Production

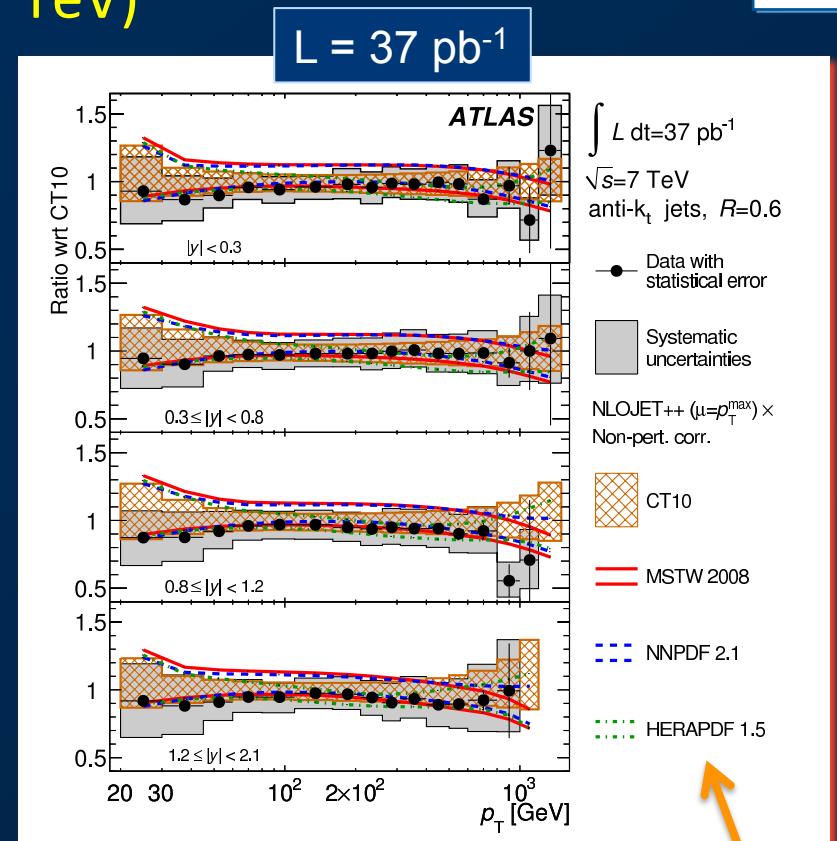
Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)



ATLAS: PRD 86 014022 (2012)

Theory: NLO QCD calculation (NLOJet++) + non-perturbative corrections

Jets: anti- k_T algorithm, two size parameters: $R = 0.4$ and 0.6



Several central rapidity ranges shown here; more available out to $|y| < 4.4$

4 PDF sets

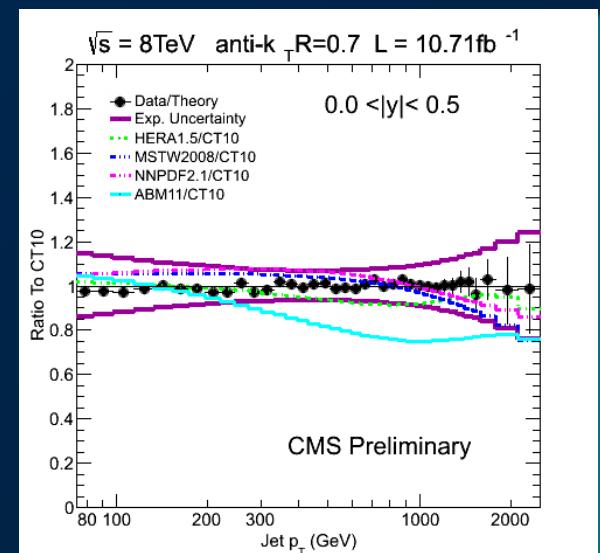
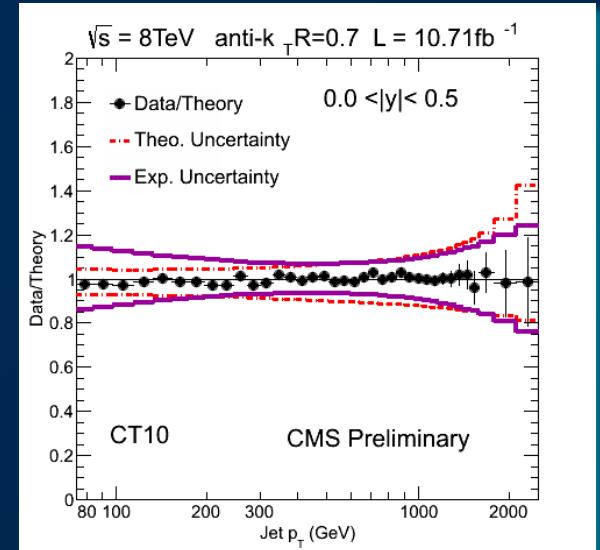
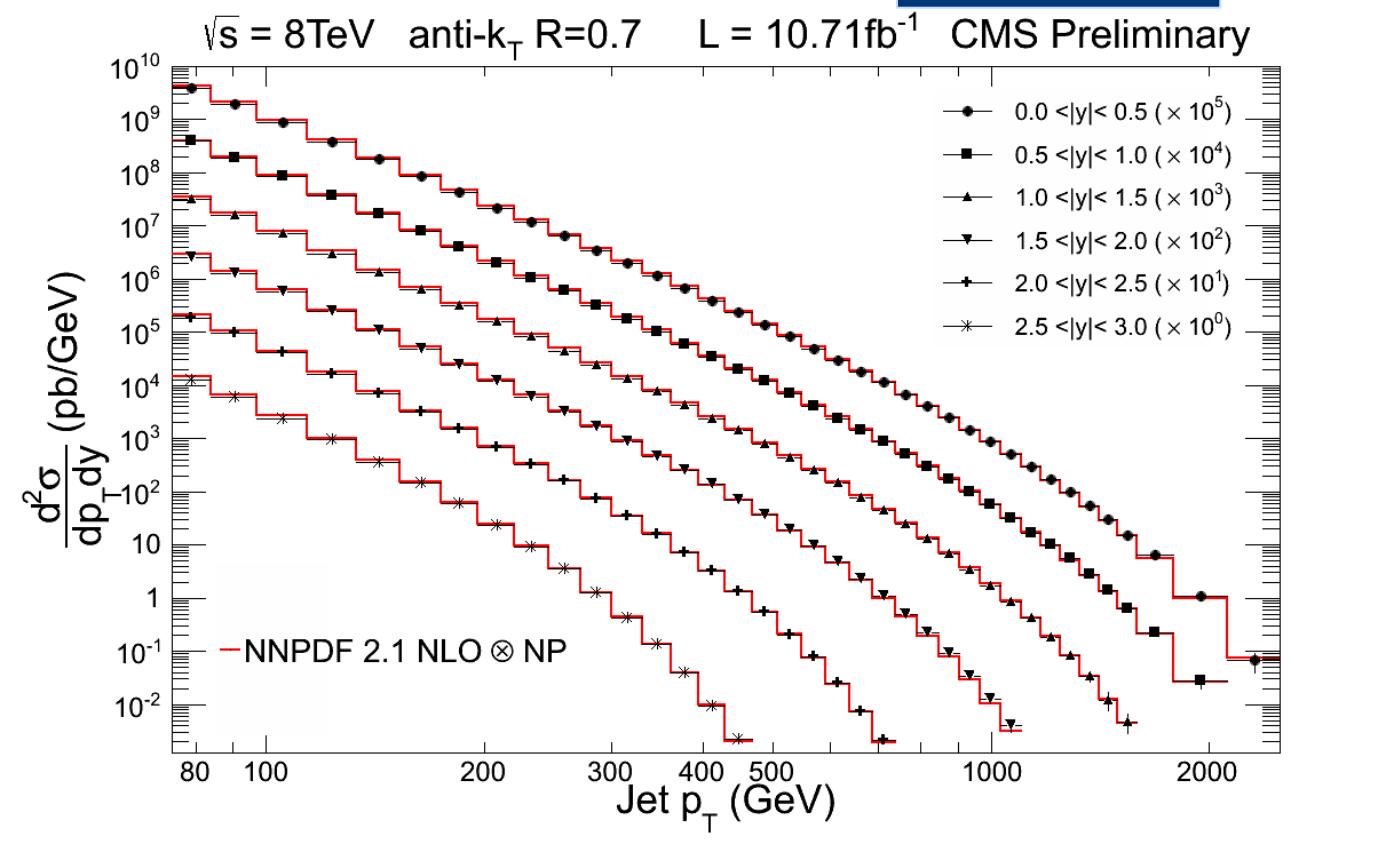
- ▶ Data and theory agree over many orders of magnitude, although theory predicts somewhat larger cross sections at large jet p_T

Inclusive Jet Production

Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 8 \text{ TeV}$)

CMS: SMP-12-012

$L = 10.71 \text{ fb}^{-1}$



Highest jet p_T about 2.5 TeV ! Jet rapidity $|y| < 3.0$

- ▶ Data and theory agree within 5–10% for various rapidity ranges and PDF sets
(except the ABM11 PDF set for small $|y|$ and $p_T > 300 \text{ GeV}$)

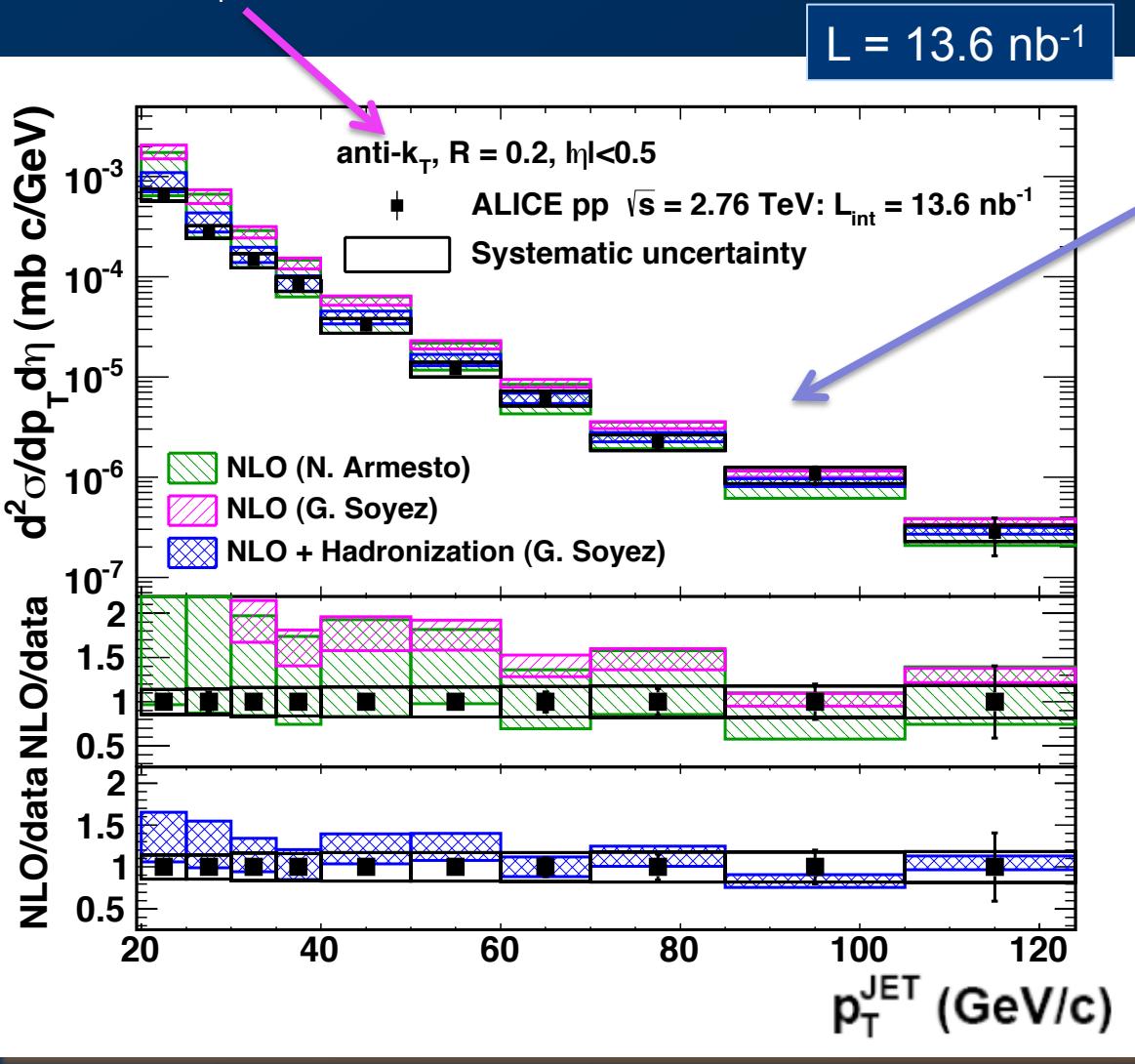
5 more rapidity ranges and
4 more PDF sets available!

Inclusive Jet Production

Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 2.76 \text{ TeV}$)

anti- k_T , $R = 0.2$ shown here

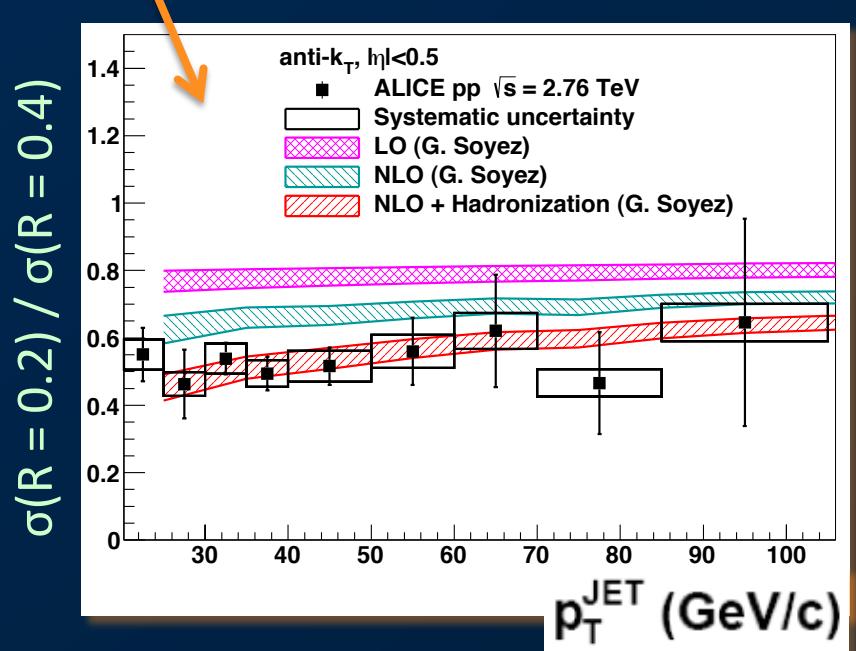
$L = 13.6 \text{ nb}^{-1}$



Test of pQCD for two jet size parameters, $R = 0.2$ and $R = 0.4$

NLO pQCD calculations w/ hadronization agree well with data.

Ratio of 0.2/0.4 provides a measure of radiation within the jet; also well-described by theory.

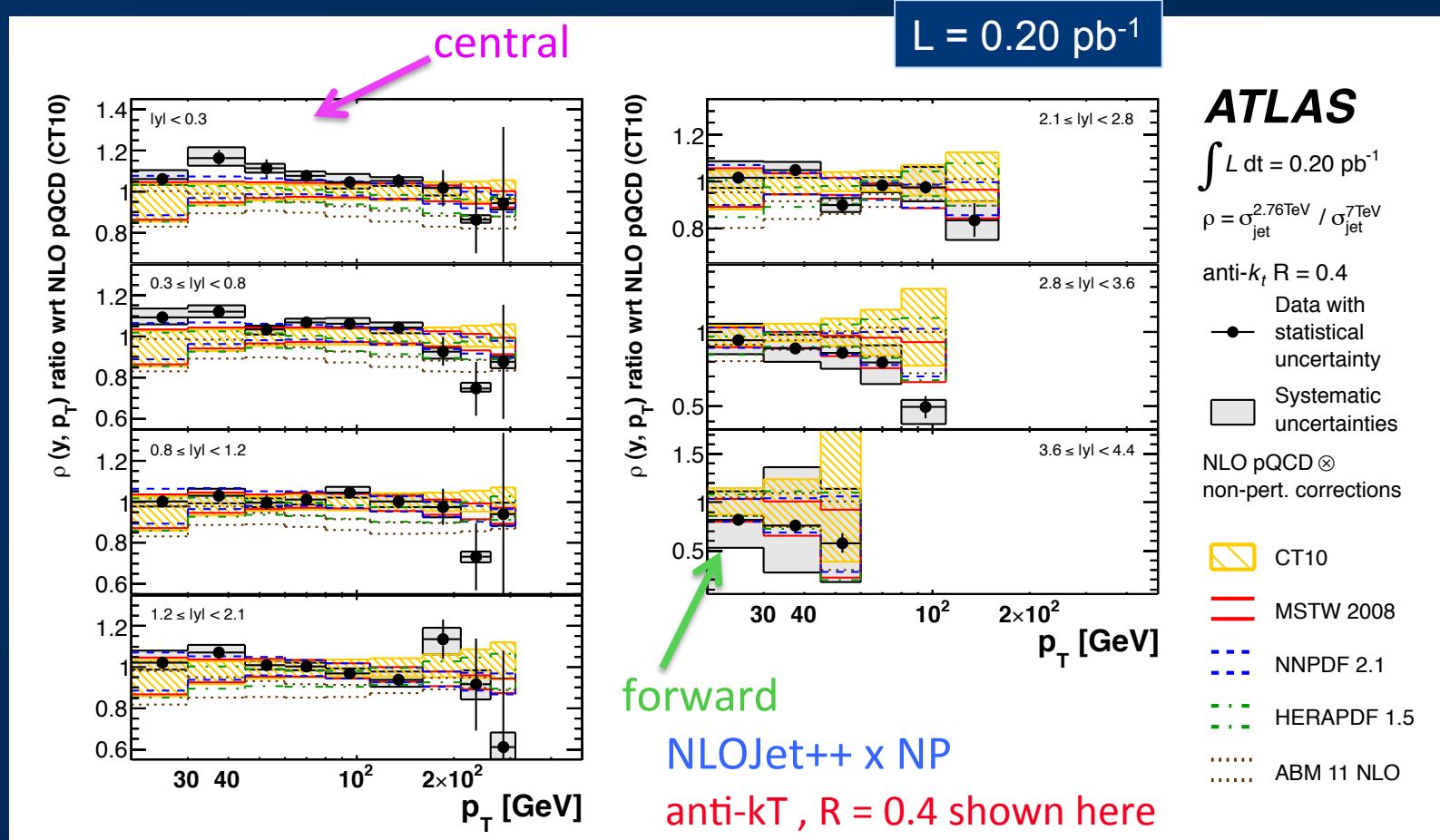


ALICE: arXiv:1301.3475

Inclusive Jet Production

Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 2.76 \text{ TeV}$)

Ratio $\rho = \sigma(2.76 \text{ TeV}) / \sigma(7 \text{ TeV})$ wrt NLO pQCD vs. p_T for various jet rapidity ranges



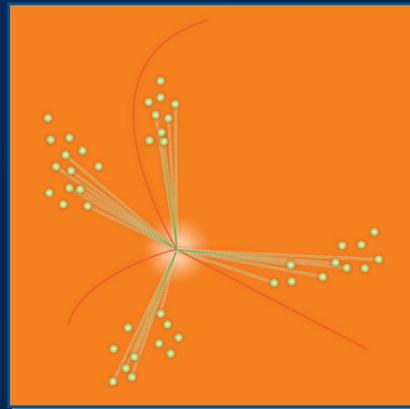
Ratio $\sigma(2.76 \text{ TeV}) / \sigma(7 \text{ TeV})$ vs. p_T has small experimental uncertainties!

Measured points are slightly higher than predictions in the central region, lower in the forward region

Many additional plots available!
 (e.g. POWHEG + PYTHIA + UE tune)

ATLAS: arXiv: 1304.4739, Submitted to Eur. Phys. J. C

Jet Measurements

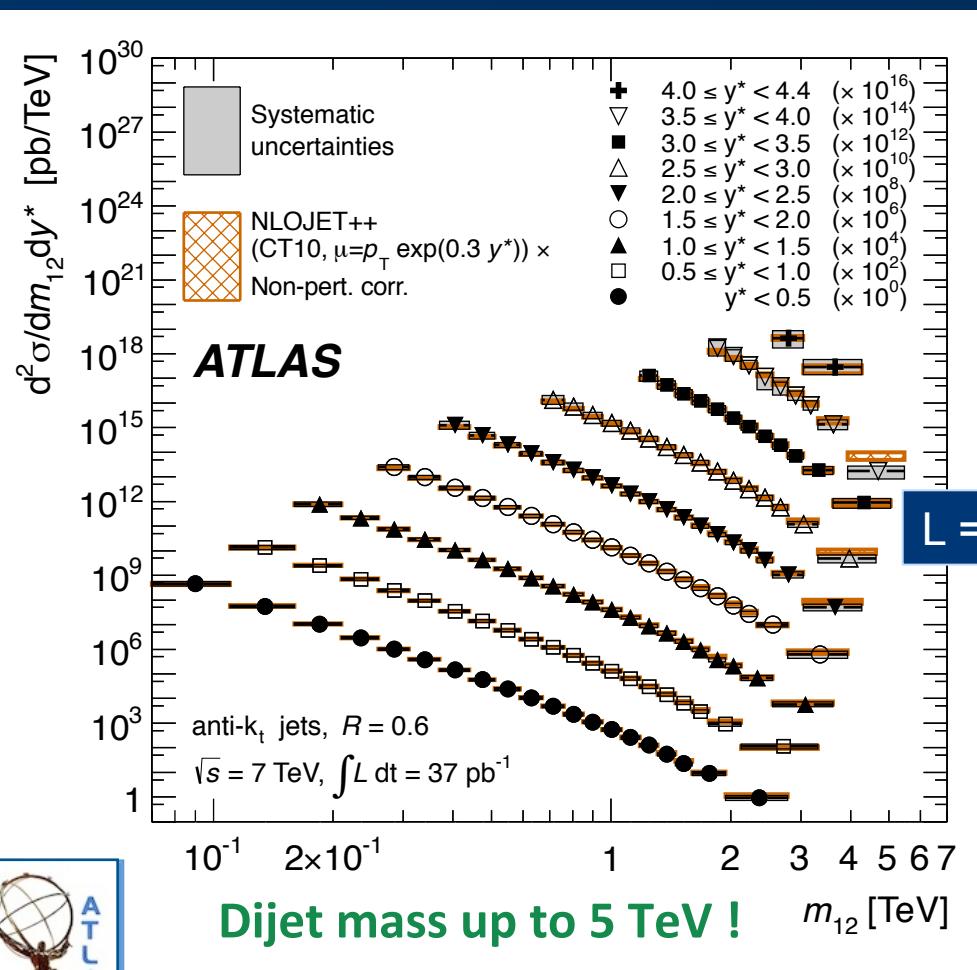


Dijet Production

Dijet Production



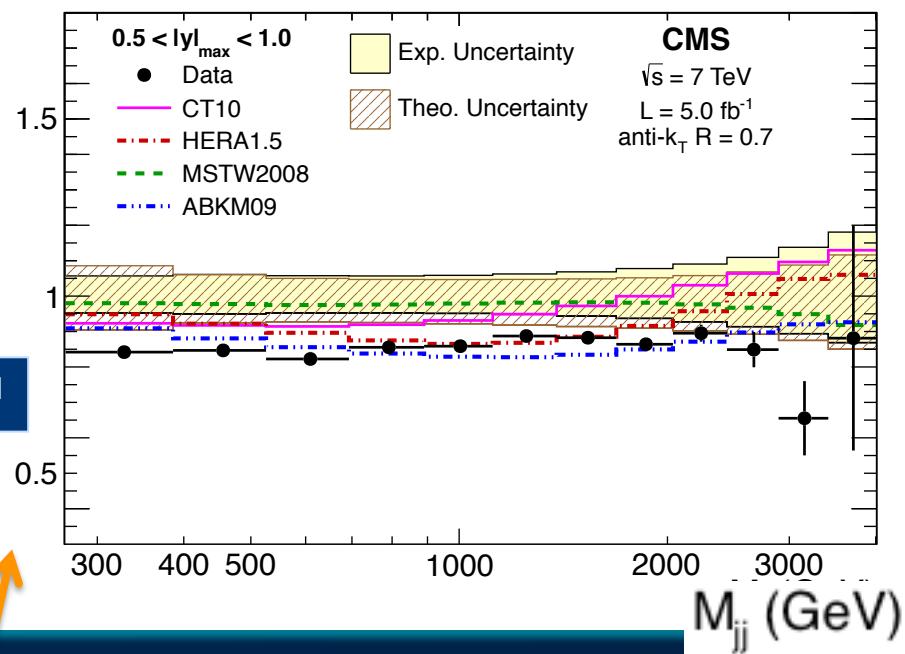
Double-Differential Dijet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)



ATLAS: PRD 86 014022 (2012)



CMS: arXiv:1212.6660, accepted by PRD



0.5 < $|y|$ < 1.0 shown here; four other rapidity ranges available out to $|y| = 2.5$.

- ▶ Data and theory agree to $\sim 10\%$ for various rapidity ranges and PDF sets

Experimental and theoretical uncertainties comparable in size

Dijet Production

Flavour Composition of Dijet Events ($\sqrt{s} = 7 \text{ TeV}$)

Jet flavor is determined by template fits to the kinematic properties of secondary vertices inside jets

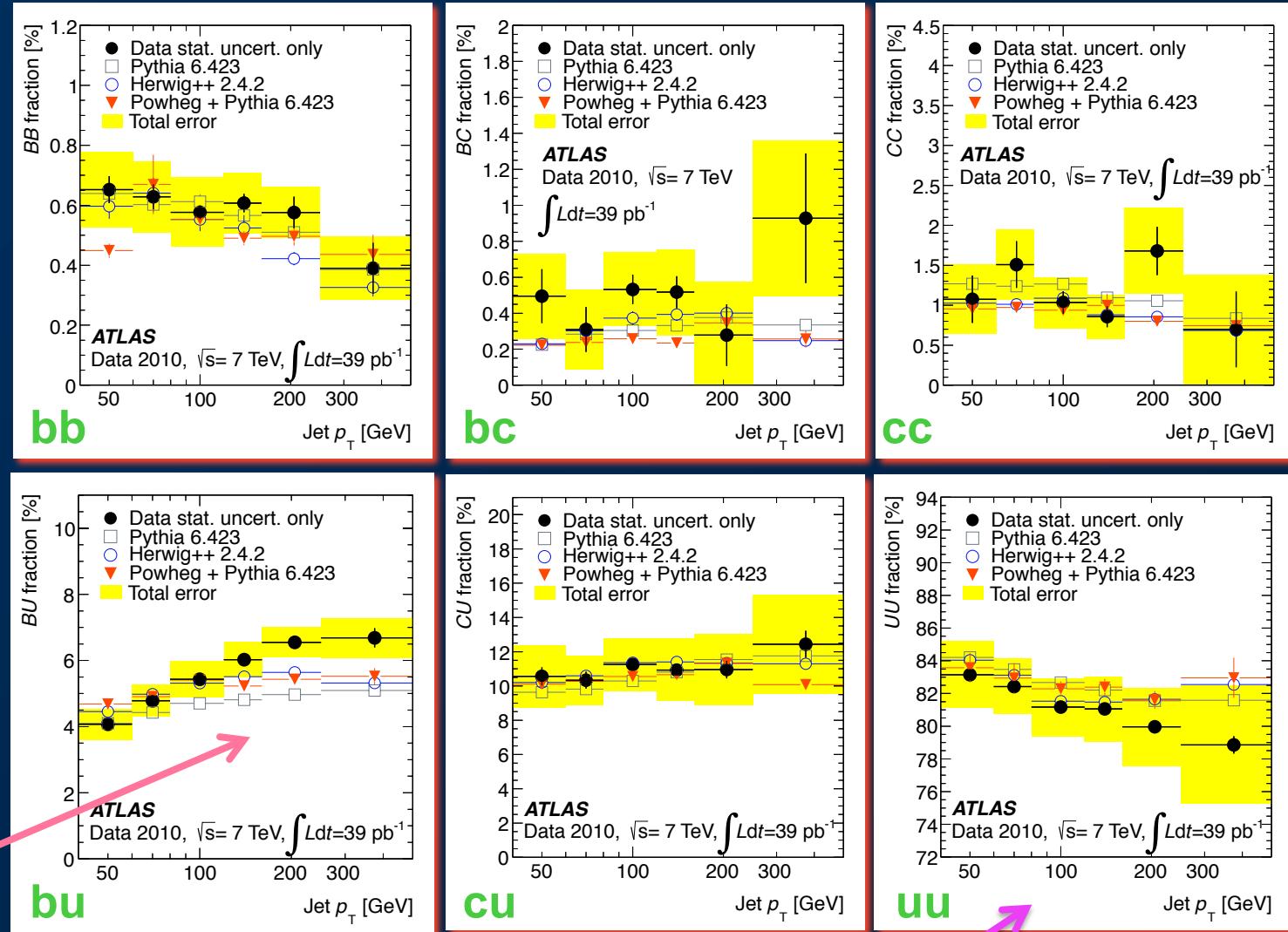
Templates differentiate between b, c, and light quarks (denoted "u")

- ▶ Data and theory agree for most flavour pairs

Some disagreement in the bottom-light quark fraction at high jet p_T

ATLAS: Eur. Phys. J. C (2013) 73:2301

$L = 39 \text{ pb}^{-1}$



mostly light dijets (80%)



Dijet Production

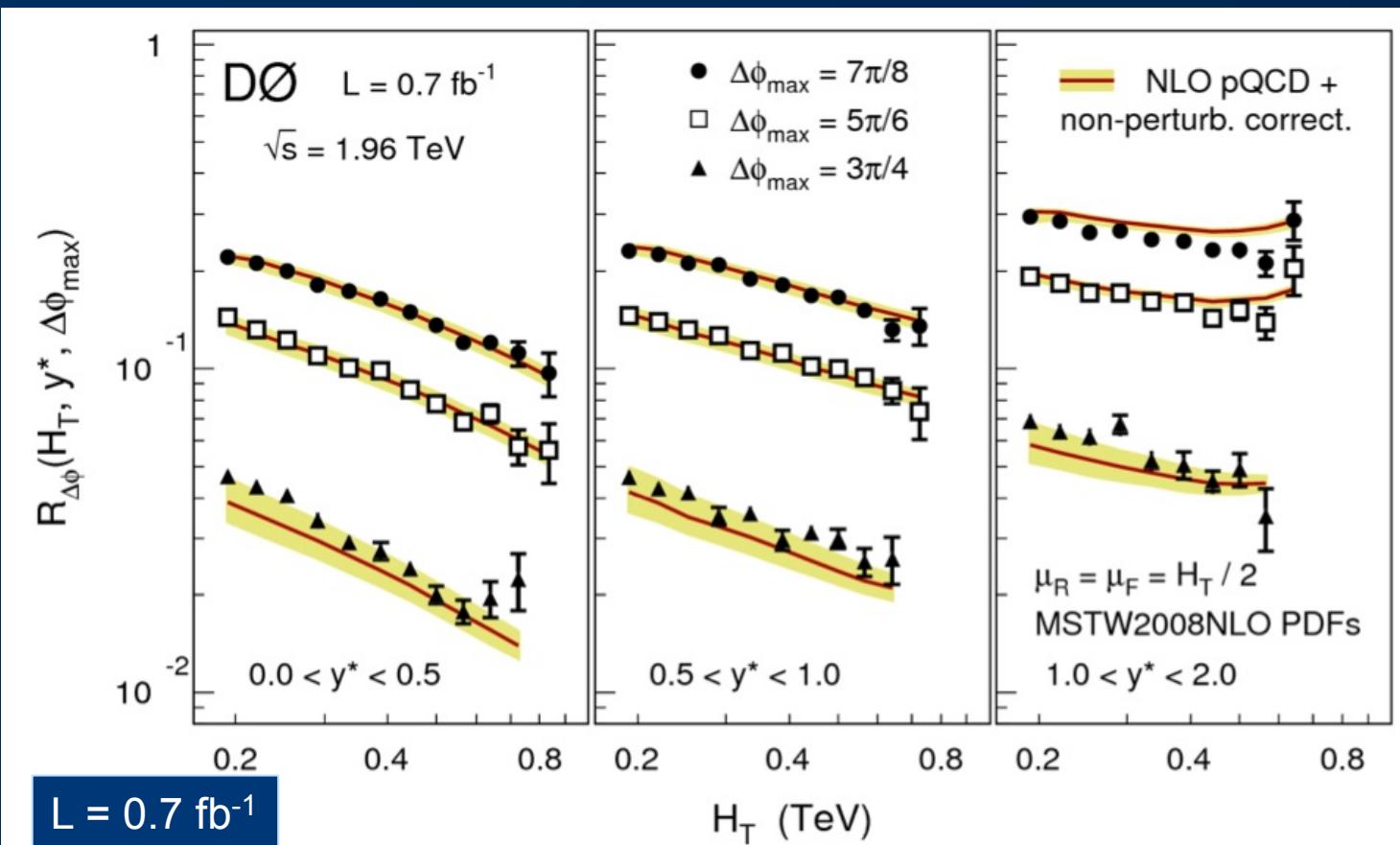
Dijet Azimuthal Decorrelations ($\sqrt{s} = 1.96$ TeV)

Measure $R_{\Delta\phi}(H_T, y^*, \Delta\phi_{\max})$, the fraction of all dijet events with $\Delta\Phi < \Delta\Phi_{\max}$

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

See M. Wobisch et al, JHEP 1301 (2013)

D0: Phys. Lett. B 721, (2013) 212



H_T is the total transverse momentum in the event.

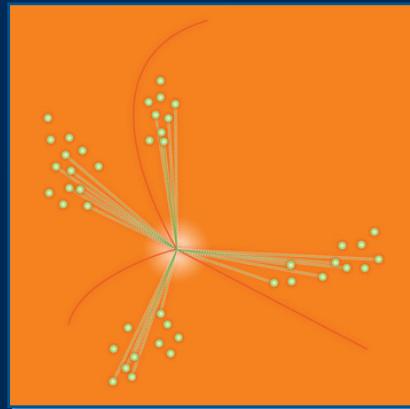
$H_T/2$ is a scale for α_s

$$y^* = \frac{1}{2} |y_1 - y_2|$$

First measurement of combined H_T and rapidity dependence!

- ▶ Weaker H_T dependence at larger rapidity y^*

Jet Measurements



Jet Ratios
Extraction of α_s



Inclusive Jet Ratios

Inclusive 3-Jet / Inclusive 2-Jet Ratio ($R_{3/2}$) ($\sqrt{s} = 1.96$ TeV)

D0: Phys. Lett. B 720, 6 (2013)

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

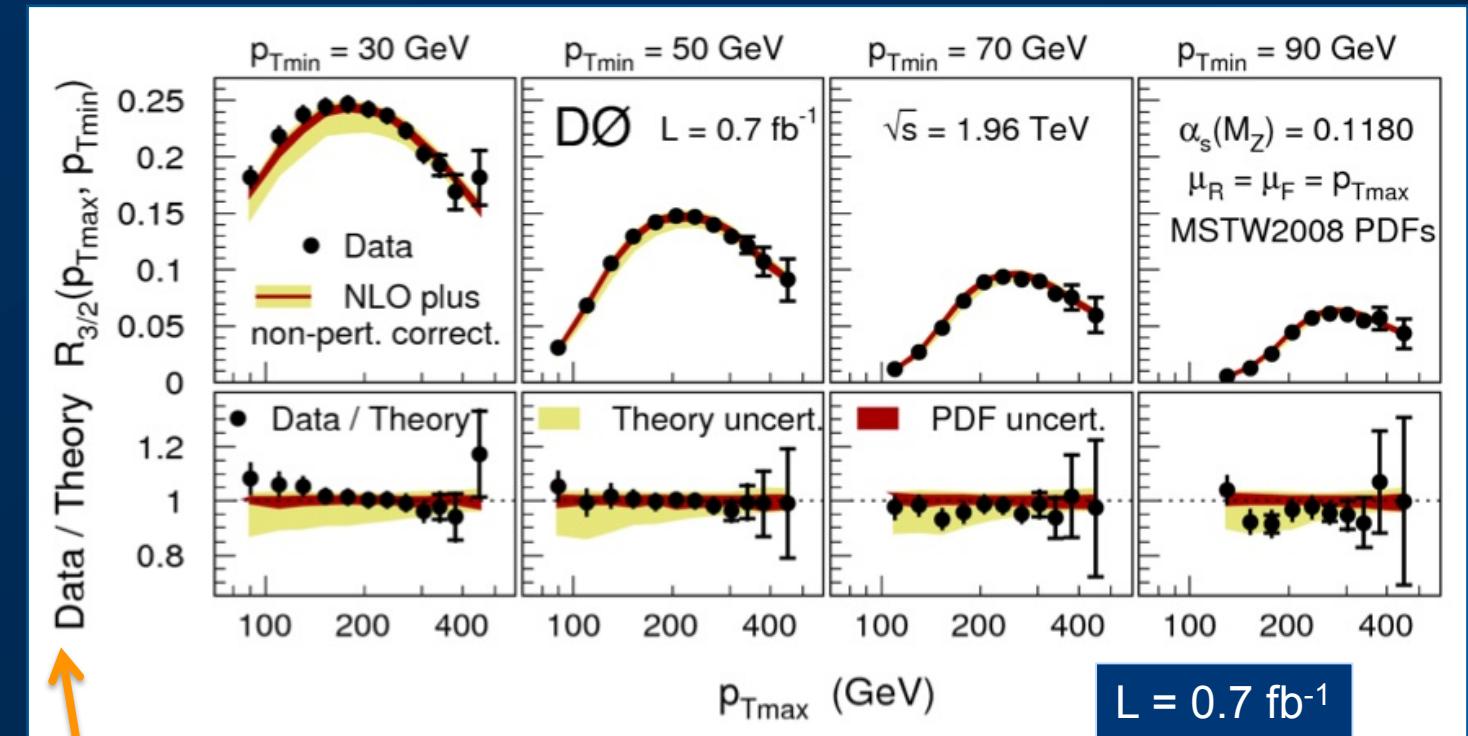
Explicitly require:
 ≥ 3 jets (numerator)
 ≥ 2 jets (denominator)

based on the $p_{T\min}$
 requirement

Measure $R_{3/2}(p_{T\max})$ in
 different bins of $p_{T\min}$

Probes α_s at the
 scale $p_{T\max}$

$p_{T\min}$ is the hardness
 criterion for the 3rd jet

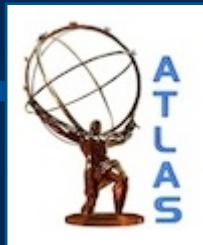


Data/Theory
 ratio for $R_{3/2}$

► Data are well-described by theory for
 $p_{T\min} = 50, 70, 90$ GeV

Also see D0's angular correlations of jets $R_{\Delta R}$ – see backup slides!

Inclusive Jet Ratios



Inclusive 3-Jet / Inclusive 2-Jet Ratio ($R_{3/2}$, $N_{3/2}$) ($\sqrt{s} = 7 \text{ TeV}$)

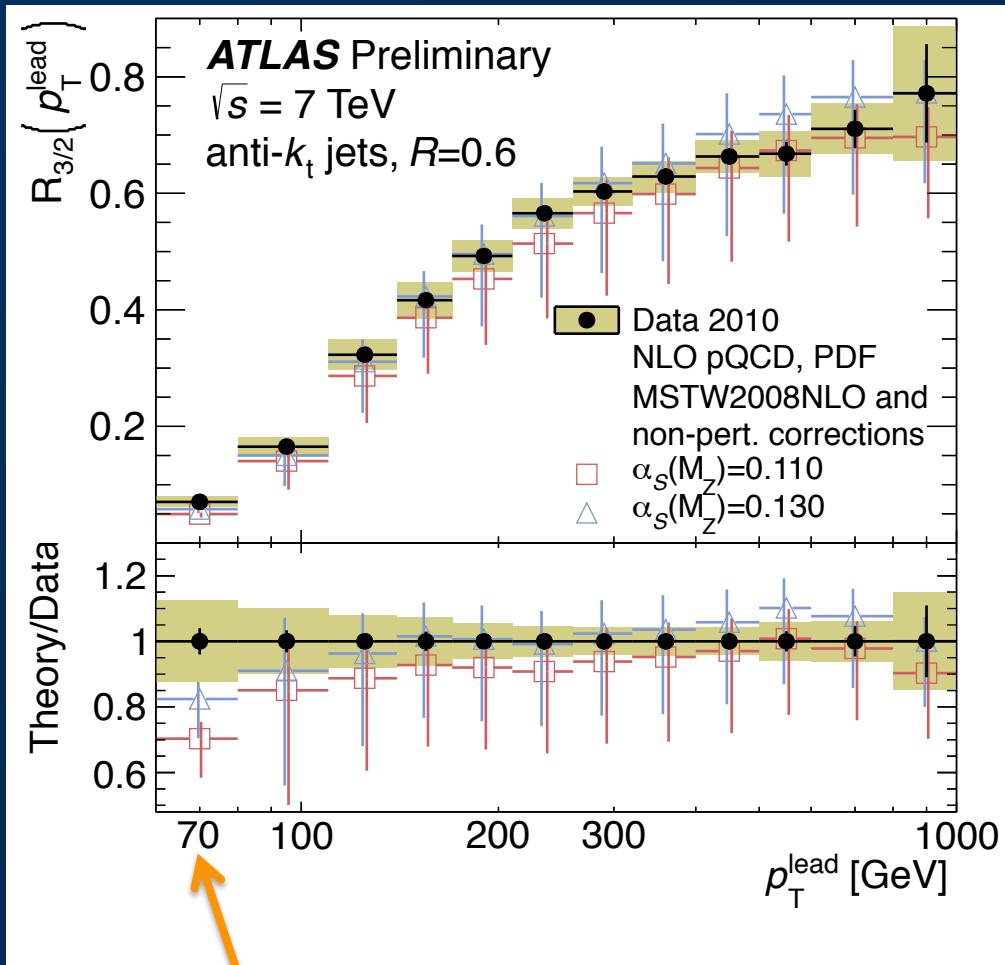
$$R_{3/2} = \frac{\sigma_{3\text{-jet}}}{\sigma_{2\text{-jet}}} \quad (\text{lead jet})$$

$$N_{3/2} = \frac{\sigma_{3\text{-jet}}}{\sigma_{2\text{-jet}}} \quad (\text{all jets})$$

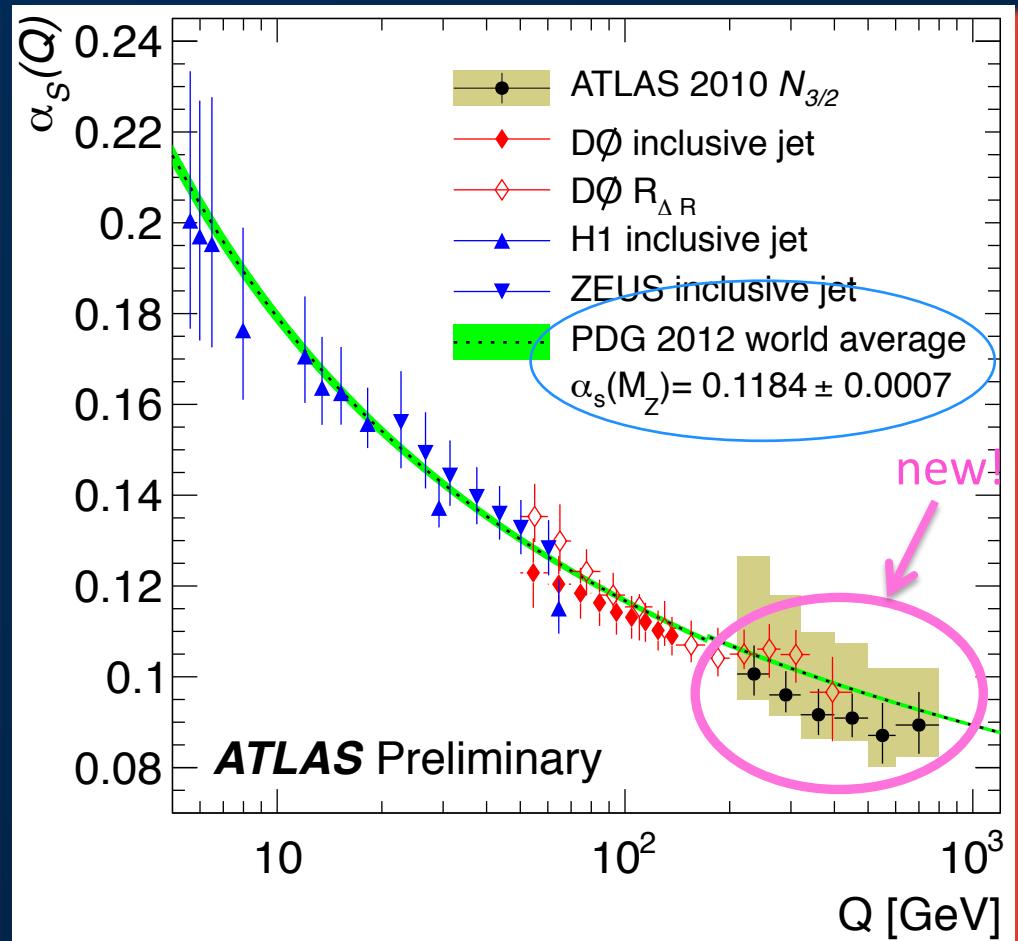


α_s ▶ Extract α_s :

$$\alpha_s(M_Z) = 0.111 \pm 0.006 \text{ (exp.)} {}^{+0.016}_{-0.003} \text{ (theory)}$$



► Good agreement overall, except here for $p_T^{\text{lead}} < 140 \text{ GeV}$



ATLAS: ATLAS-CONF-2013-041

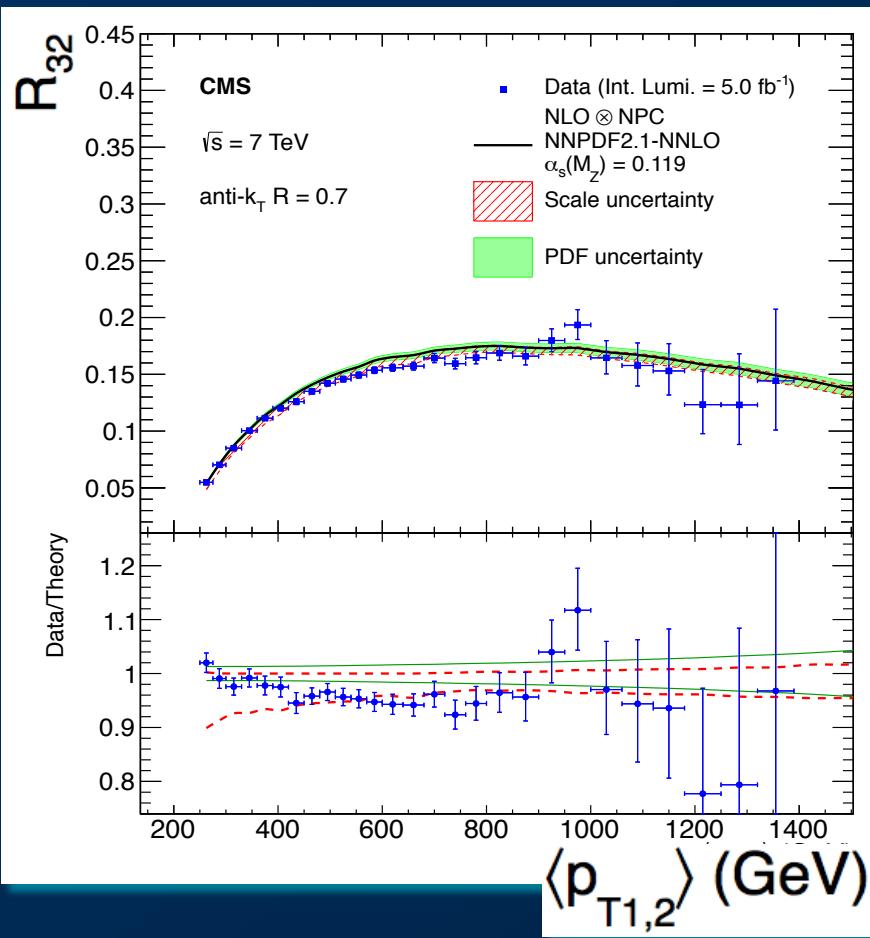
Inclusive Jet Ratios



Inclusive 3-Jet / Inclusive 2-Jet Ratio ($R_{3/2}$) ($\sqrt{s} = 7 \text{ TeV}$)

Measure $R_{3/2}$ vs. $\langle p_{T1,2} \rangle$, the average p_T of the two leading jets in the event

$$250 < \langle p_{T1,2} \rangle < 1390 \text{ GeV}$$

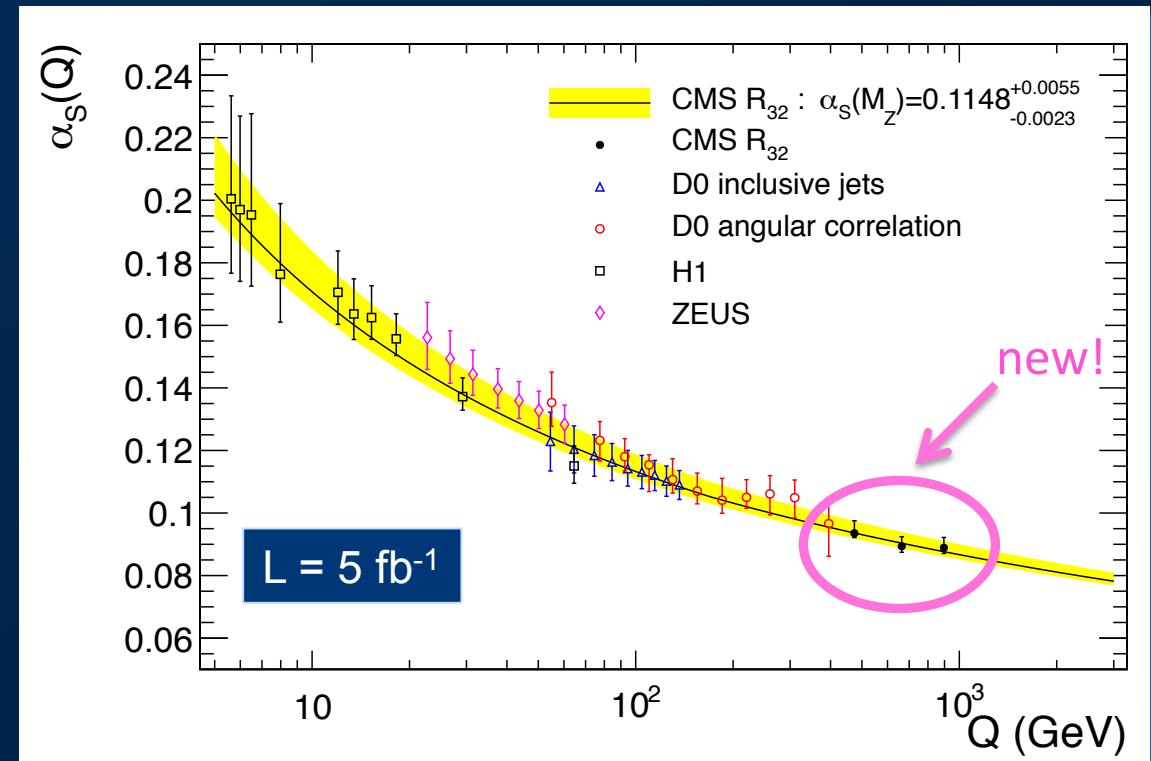


Compare data to NLO QCD → Good agreement!

Extract

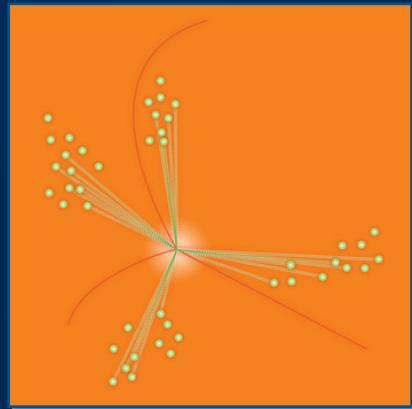
$$\alpha_s(M_Z) = 0.1148 \pm 0.0014 \text{ (exp.)} \pm 0.0018 \text{ (PDF)} {}^{+0.0050}_{-0.0000} \text{ (scale)}$$

First determination of α_s from measurements at Q scales up to 1 TeV



CMS: arXiv:1304.7498, submitted to Eur. Phys. J. C

Jet Measurements



Jet Mass and Substructure

Jet Mass and Substructure

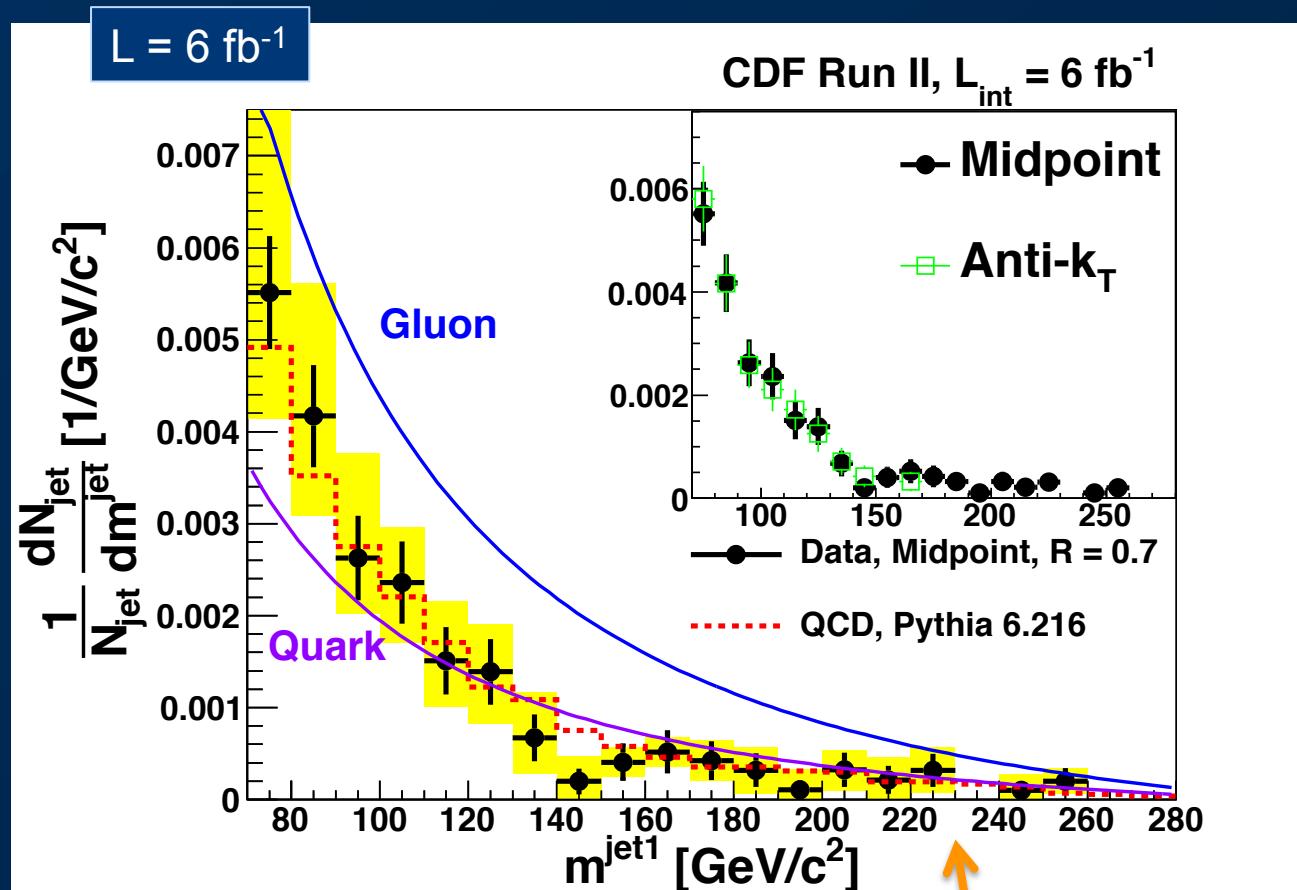
Jet Mass and Substructure ($\sqrt{s} = 1.96$ TeV)

Studying high- p_T massive jets provides an important test of perturbative QCD

Jet selection:

- midpoint and anti- k_T ($R = 0.7$)
- leading jet $p_T > 400$ GeV
- $0.1 < |\eta| < 0.7$

Compare to simple NLO approximation:
 Almeida et al, PRD 79, 074012 (2009).



CDF: PRD 85, 091101 (2012)

- High mass region (70–280 GeV) well described by perturbative QCD

80% of jets are quark jets at high p_T

Jet Mass and Substructure

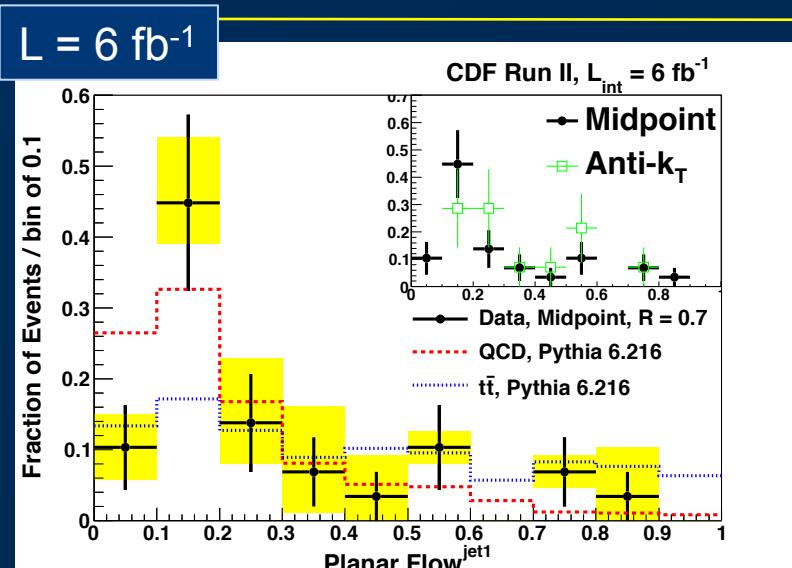
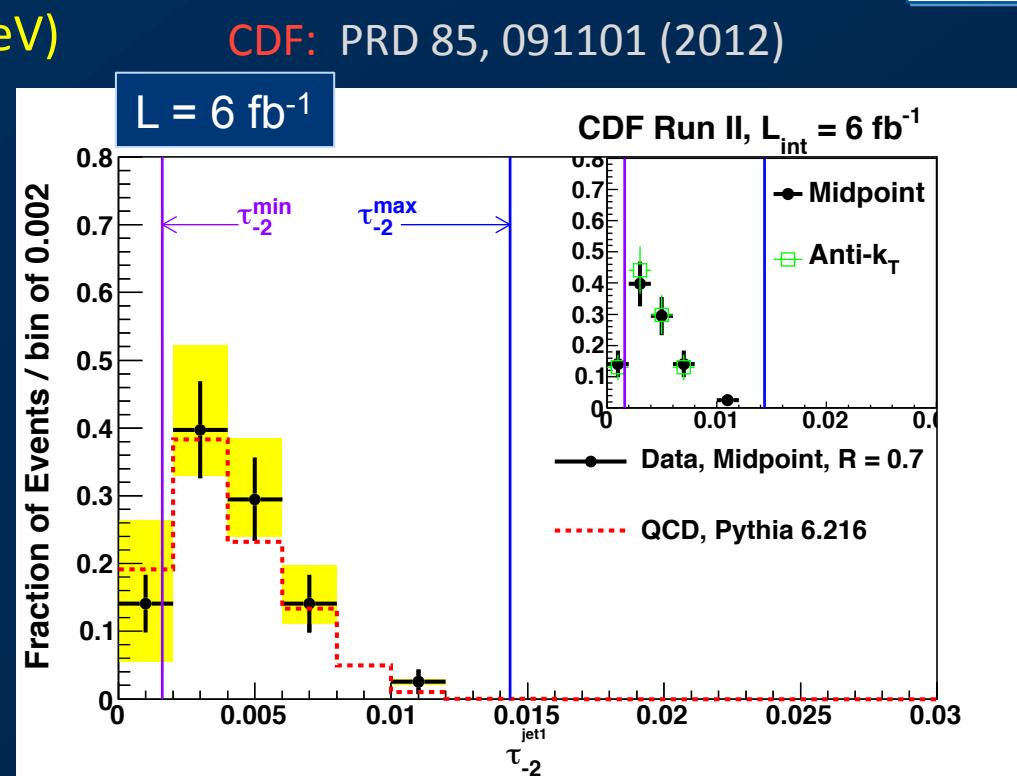
Jet Mass and Substructure ($\sqrt{s} = 1.96$ TeV)

Angularity:

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

Sensitive to radiation near the edge of the jet cone and has a characteristic shape for QCD jets.

- ▶ Both the shape and kinematic endpoints of the distribution described well by PYTHIA (require jet mass to be 90–120 GeV)

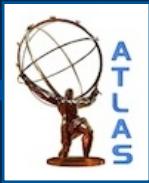


Planar flow:

Jets with three or more energetic constituents, such as those arising from a boosted top quark, are more planar with $Pf \sim 1$. Massive QCD jets tend to have $Pf \sim 0$.

- ▶ With higher statistics, one can discriminate high pT QCD and top quark jets (require jet mass to be 130–210 GeV)

Jet Mass and Substructure



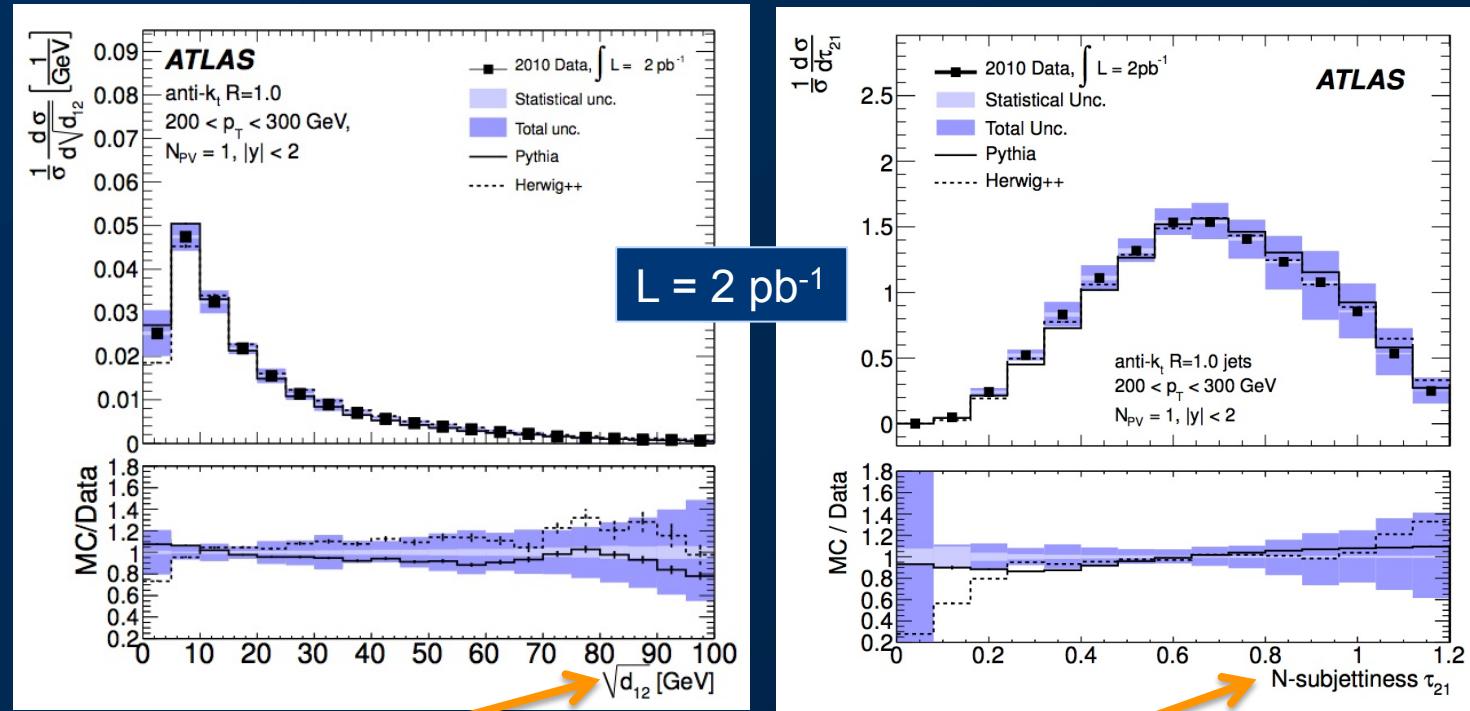
Jet Mass and Substructure of Inclusive Jets ($\sqrt{s} = 7 \text{ TeV}$)

In addition to quantities like jet direction and p_T , the masses and internal structure of jets contain additional useful information to identify the hadronic decays of boosted heavy particles!

Study anti- k_T ($R = 1.0$) and Cambridge-Aachen ($R = 1.2$) jets

Measure jet invariant mass, k_T splitting scales, and N -subjettiness

- ▶ Broad agreement between data and leading-order parton shower MC predictions (PYTHIA & HERWIG++)



k_T splitting scale $\sqrt{d_{12}}$

Defined by the k_T -distance of the final clustering step using the k_T algorithm

Tends to be larger for heavy particle decays

N -subjettiness $\sqrt{\tau_{21}}$

Smooth observable related to subjet multiplicity

=1: narrow jet with no substructure
=0: better described by two subjets

ATLAS: JHEP 05 (2012) 128

Jet Mass and Substructure

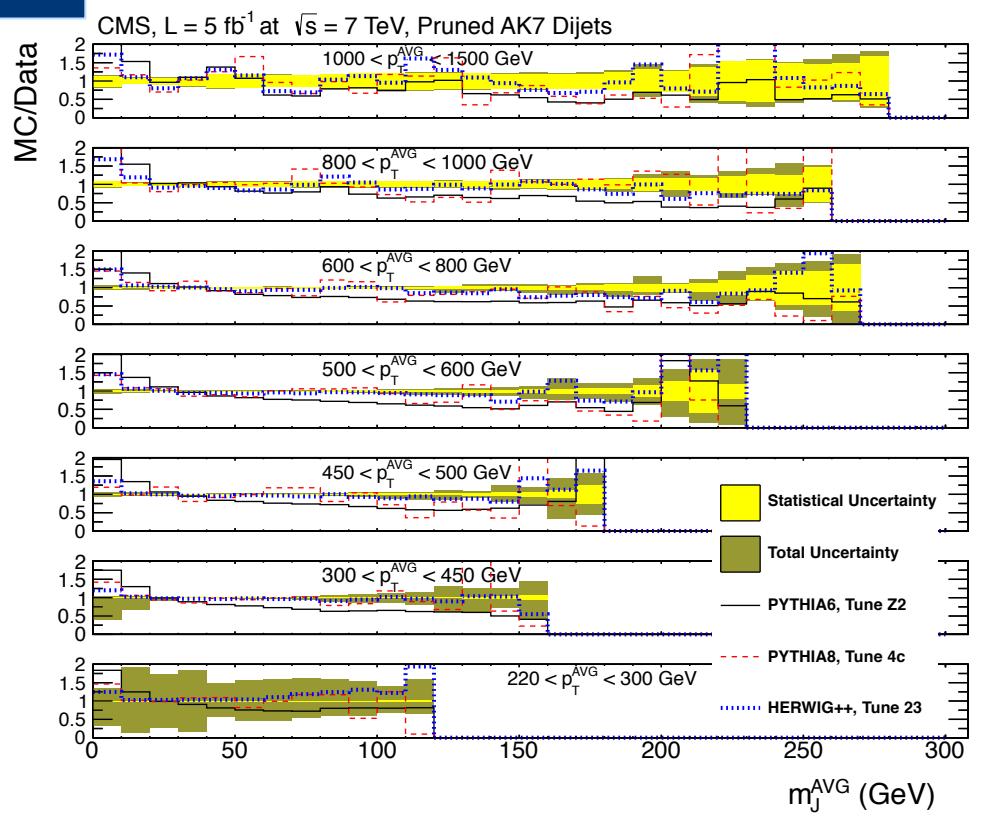
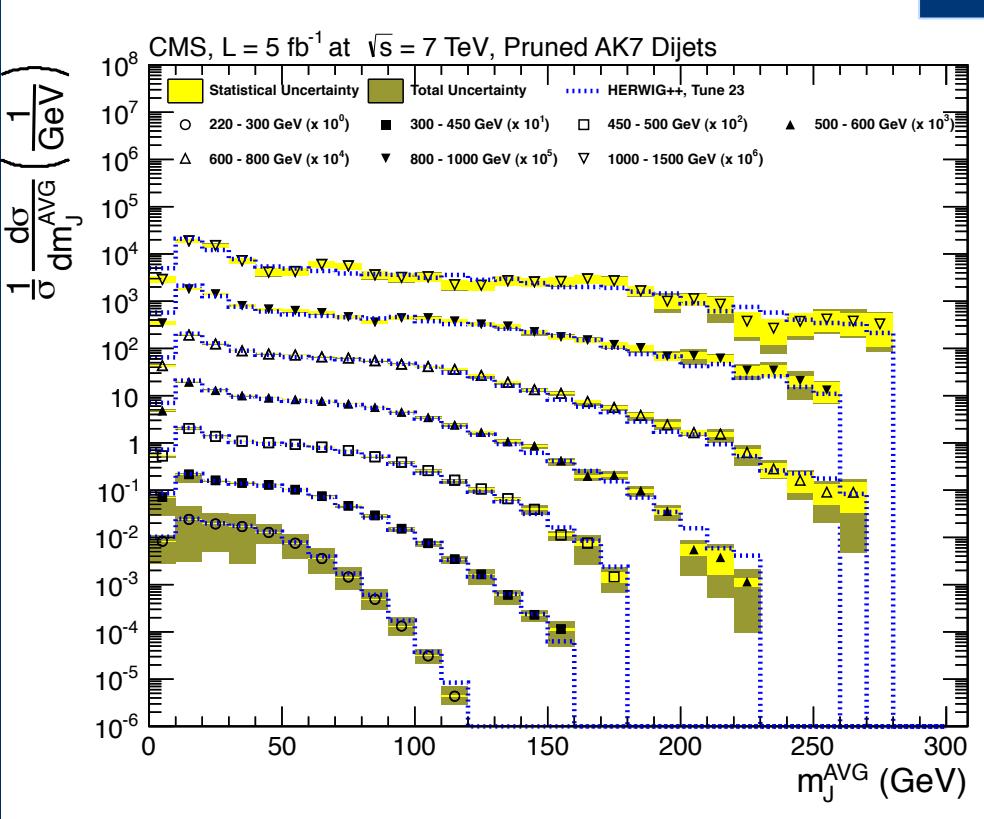


Jet Mass in Dijet Events ($\sqrt{s} = 7 \text{ TeV}$)

Different jet “grooming” techniques are studied, which distinguish merged jets of large p_T from softer QCD gluon radiation.

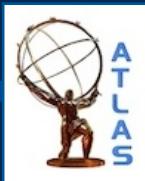
$L = 5 \text{ fb}^{-1}$

CMS: arXiv:1303.4811, accepted by JHEP



- Agreement with HERWIG++ modeling of parton showers appears to be best for $p_T^{\text{AVG}} > 300 \text{ GeV}$ and $m_J^{\text{AVG}} > 20 \text{ GeV}$.

- More aggressive grooming procedures lead to somewhat better agreement between data and MC simulation.



Jet Shapes

Jet Shapes in Top Pair Events ($\sqrt{s} = 7 \text{ TeV}$)

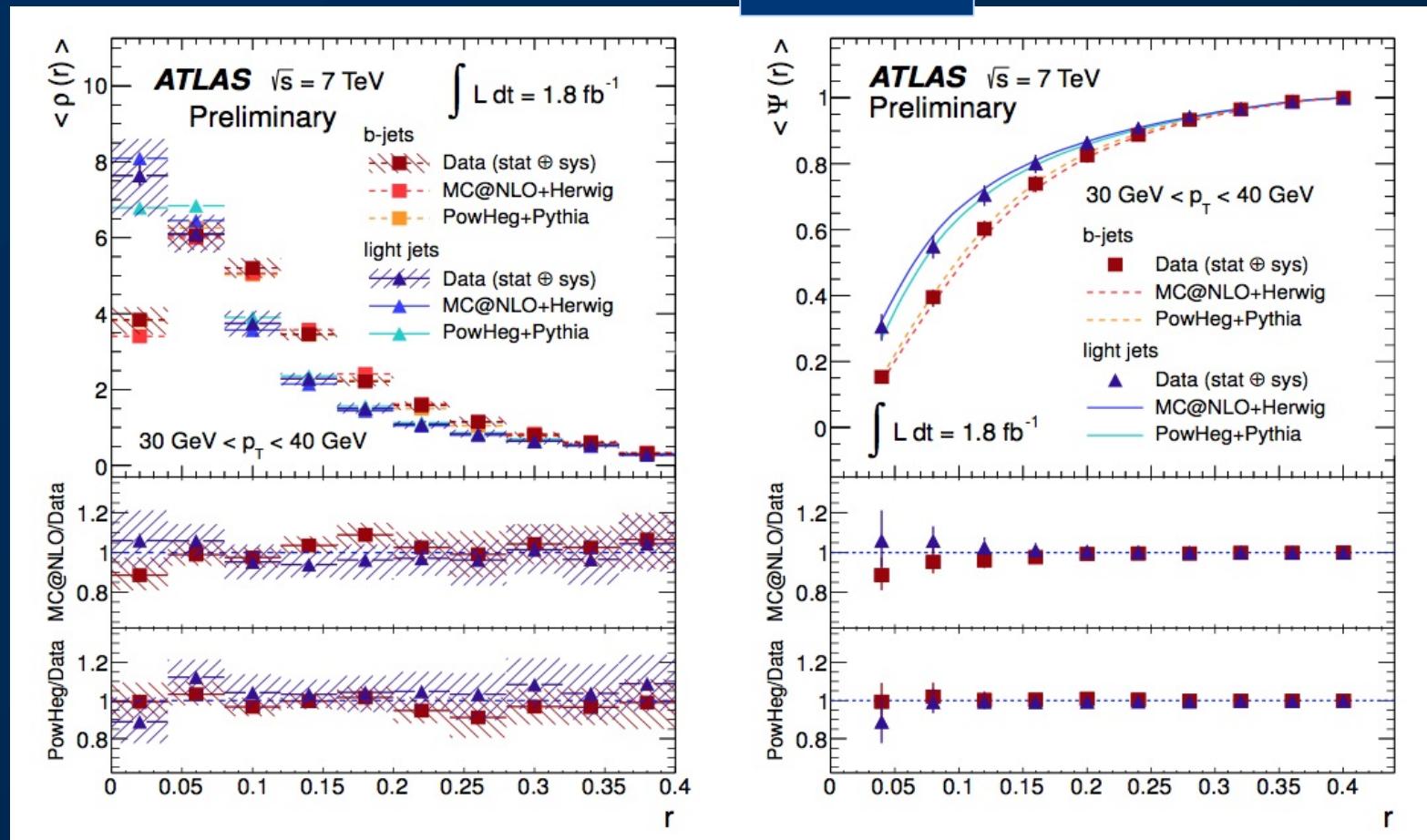
The differential and integrated shapes of jets initiated by b quarks from top quark decays are compared to the jets from light-quark decays.

- Light-quark jets are found to have a narrower distribution of the momentum flow inside the jet cone than b -quark jets.

- Observations are in agreement with NLO calculations + parton shower

See paper for many specific comparisons and results!

$L = 1.8 \text{ fb}^{-1}$



ATLAS: STDM-2011-48, to be submitted to Eur. Phys. J. C

Summary

Summary

New Jet Physics measurements continue to be described extremely well by QCD!

Inclusive jet and dijet measurements...

- extend to higher and higher jet p_T
- test perturbative QCD over many orders of magnitude at various \sqrt{s}
- continue to differentiate between and constrain different PDF sets

Jet ratios...

- study hard gluon radiation and higher-order effects
- can be used to extract a value of α_s and test the running of α_s

Jet mass and substructure...

- provide a powerful test of the parton shower approximation in QCD
- can distinguish jets from the decays of heavy particles

- ▶ Tevatron measurements have greatly advanced our understanding of QCD over the years
- ▶ The LHC has brought us to an era of Precision QCD at the energy frontier!

Acknowledgements

Thank you to many collaborators at Fermilab and CERN who performed and reviewed these analyses, and many theorists who have worked hard to prepare careful theoretical predictions.

I would like to thank the following people for very helpful conversations and material for this presentation:

- ▶ Dmitry Bandurin
- ▶ Kenichi Hatakeyama
- ▶ Sung-Won Lee
- ▶ Piergiulio Lenzi
- ▶ Christina Mesropian
- ▶ Klaus Rabbertz
- ▶ João Gentil Mendes Saraiva
- ▶ Markus Wobisch

Many thanks to the organizers
for a wonderful conference!



Jet graphic courtesy Symmetry Magazine (Sandbox Studio)

Additional information...

- ▶ Many more Tevatron QCD and Jet results are available here:

CDF:

<http://www-cdf.fnal.gov/physics/new/qcd/QCD.html>

D0:

http://www-d0.fnal.gov/Run2Physics/qcd/D0_public_QCD.html

- ▶ Many more LHC QCD and Jet results are available here:

ATLAS:

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults>

CMS:

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP>

ALICE:

<https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults>

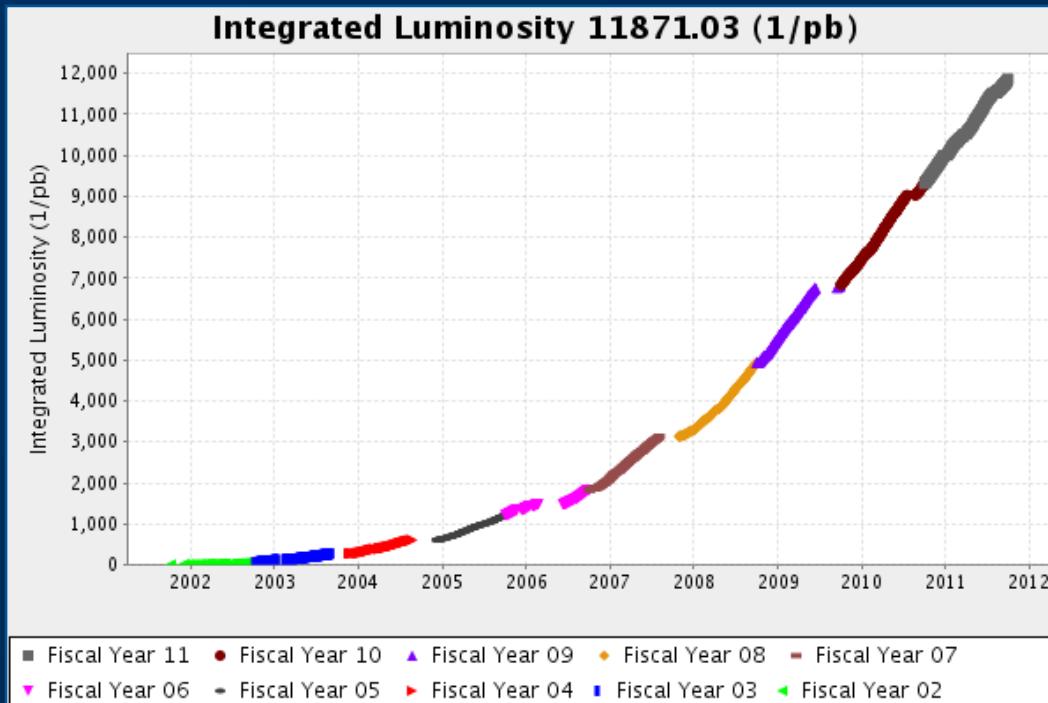
Backup Slides

The Fermilab Tevatron

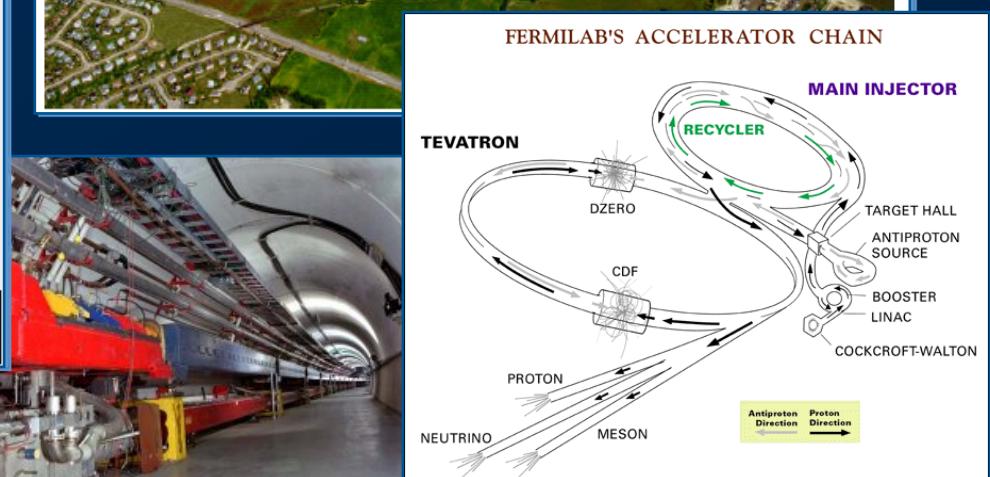
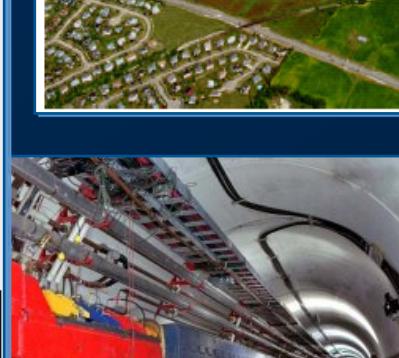
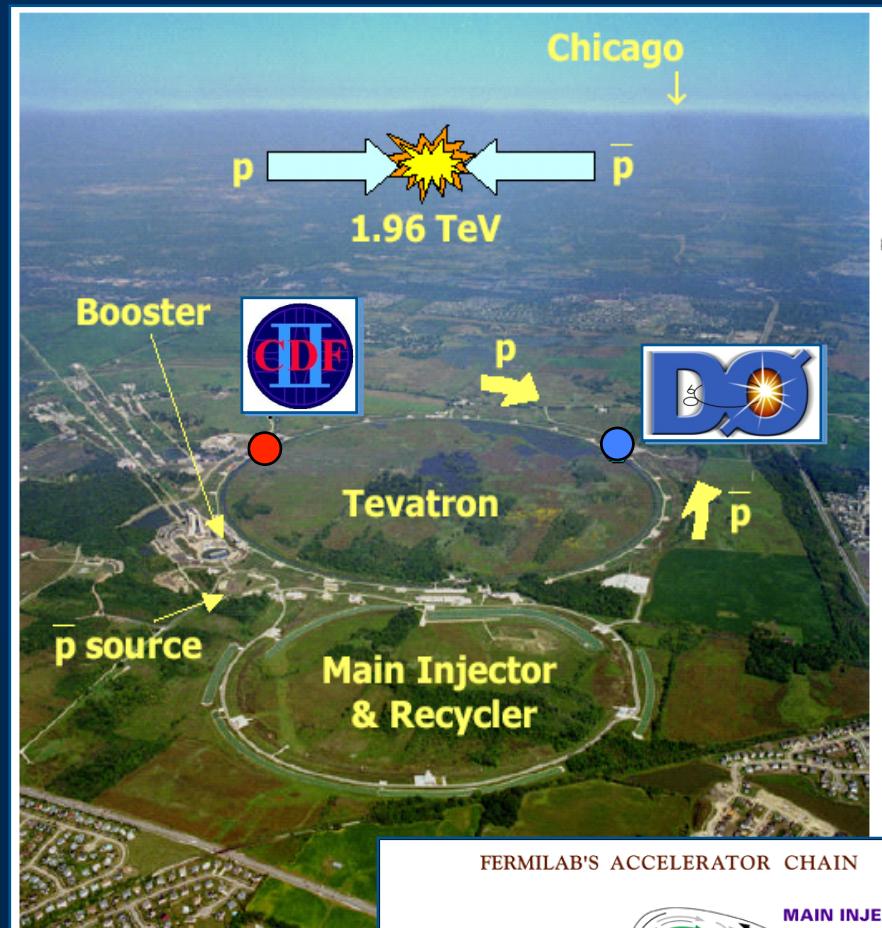
Run II at the Tevatron

- ▶ Proton-antiproton collisions at 1.96 TeV
- ▶ In operation from 2001 – 2011
- ▶ Peak luminosity $4.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- ▶ Delivered integrated luminosity nearly 12 fb^{-1}

The Tevatron operated *beautifully* in recent years.



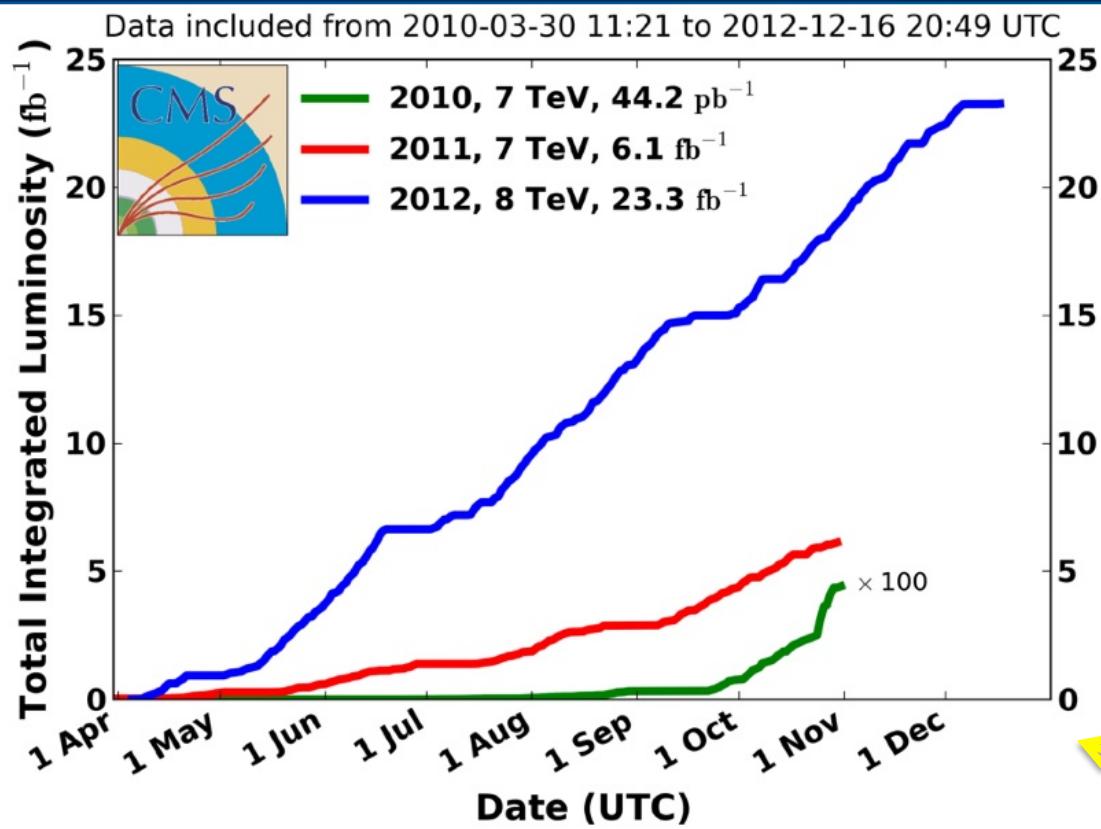
Up to about 10 fb^{-1} of data available for each experiment (**CDF** and **D0**).



The Large Hadron Collider (LHC) at CERN

- ▶ Proton-proton collisions (also lead ion collisions)
- ▶ In operation from 2008 – present
- ▶ Peak luminosity $7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- ▶ Total delivered pp integrated luminosity:
 - about 23 fb^{-1} (at 8 TeV)
 - about 6 fb^{-1} (at 7 TeV)

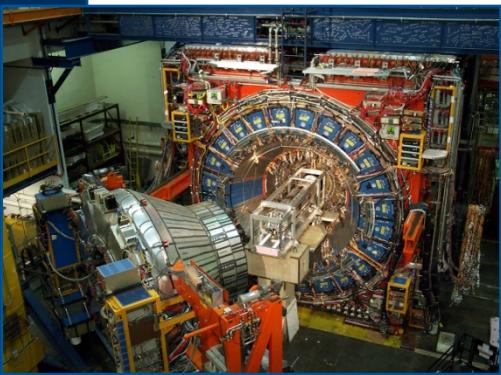
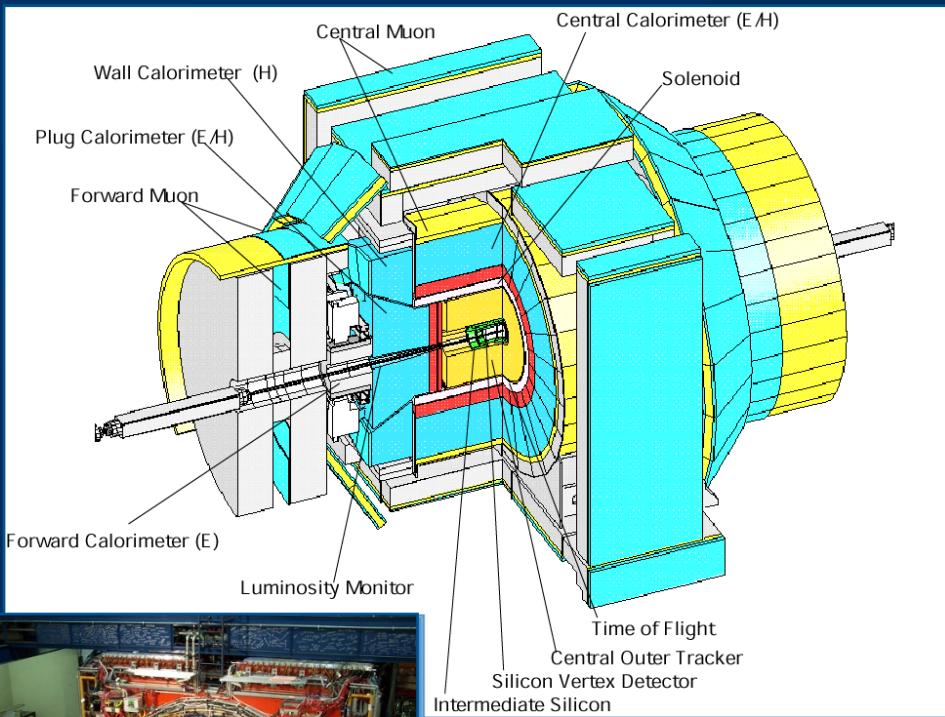
Total integrated luminosity delivered by LHC



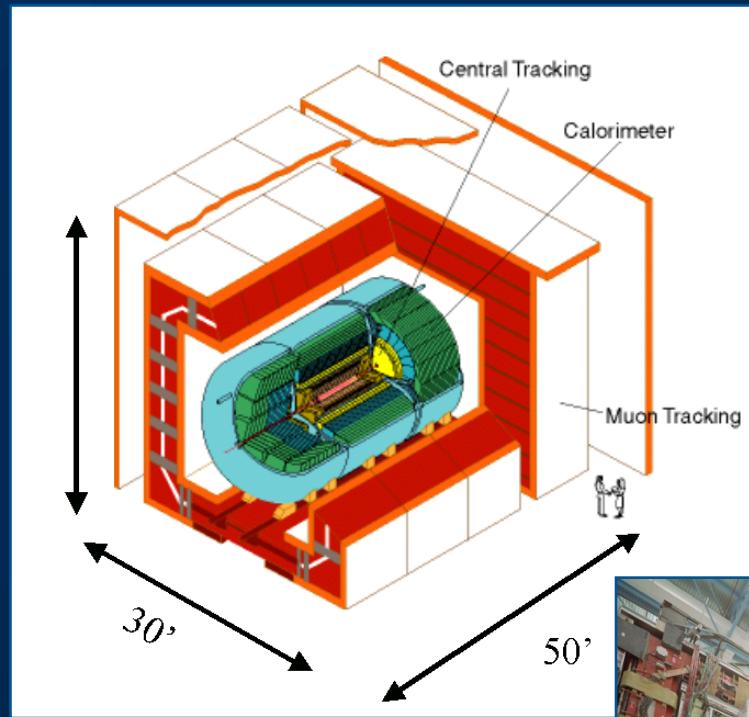
The LHC's excellent performance !

The CDF and D0 Experiments

The CDF Experiment



The D0 Experiment

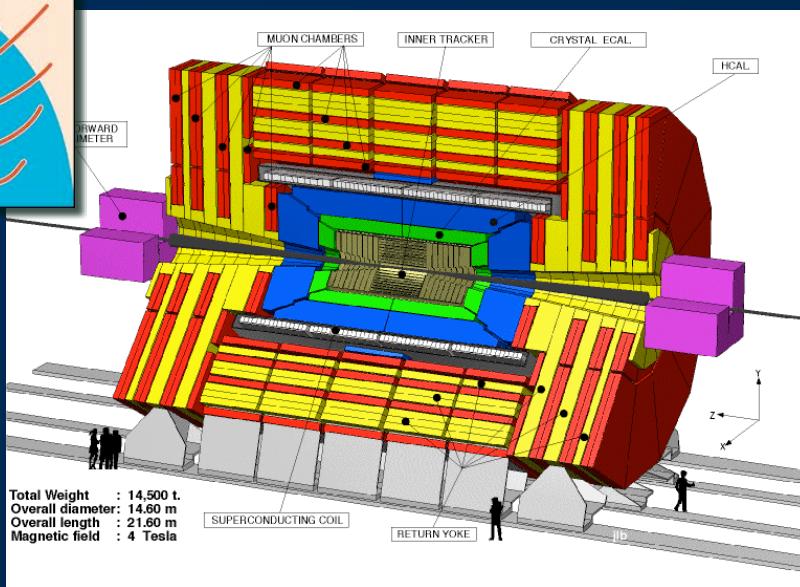
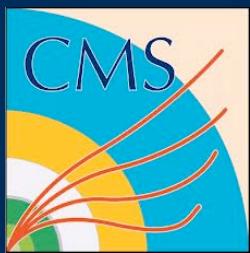
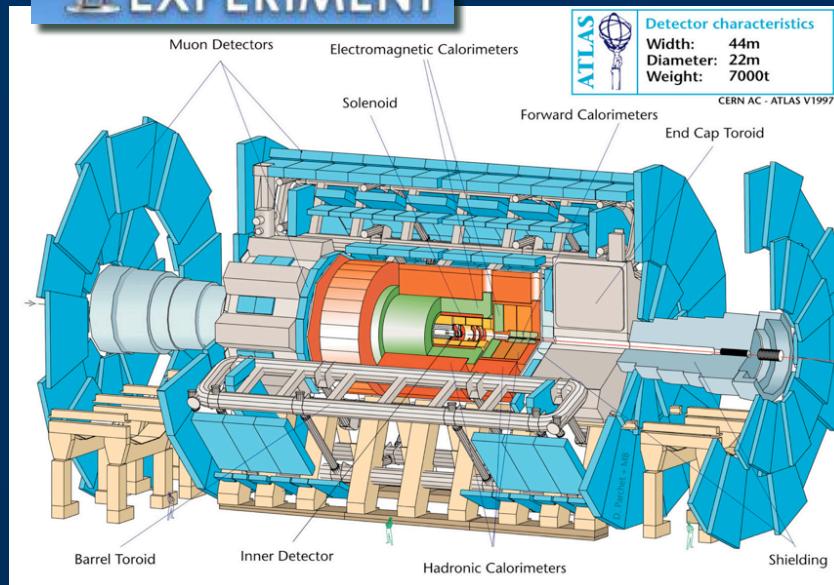


Two Multi-Purpose Detectors:

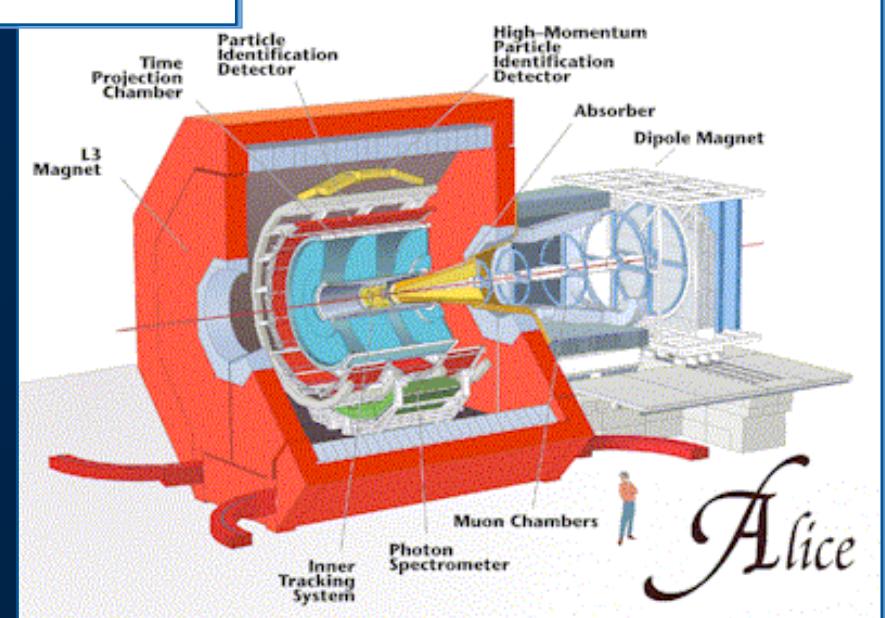
- ▶ e , μ , and τ identification
- ▶ jet and missing energy measurement
- ▶ heavy-flavor tagging through displaced vertices and soft leptons

The data-taking efficiency for both experiments was high (> 90%)

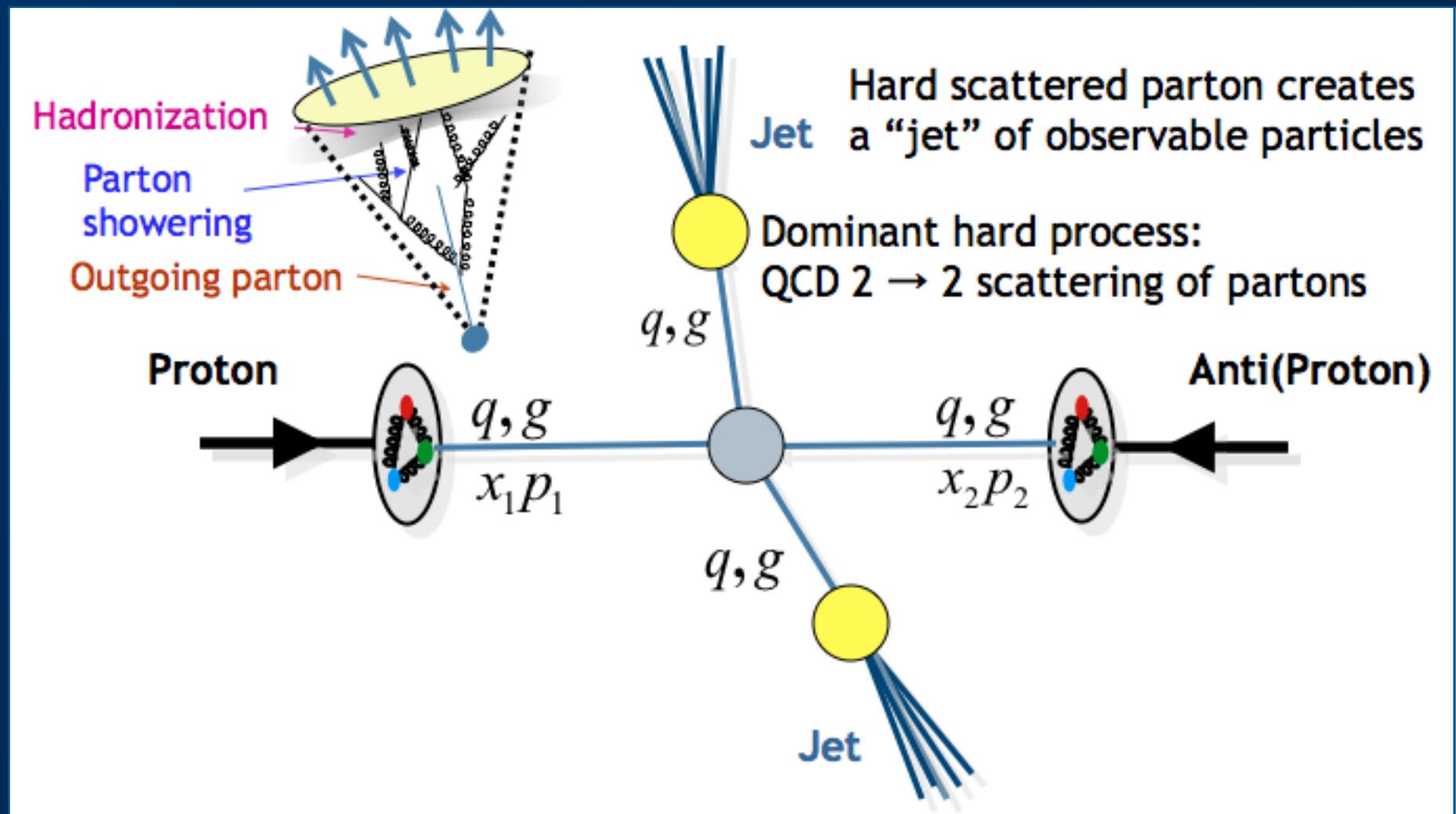
The ATLAS, CMS, and ALICE Experiments



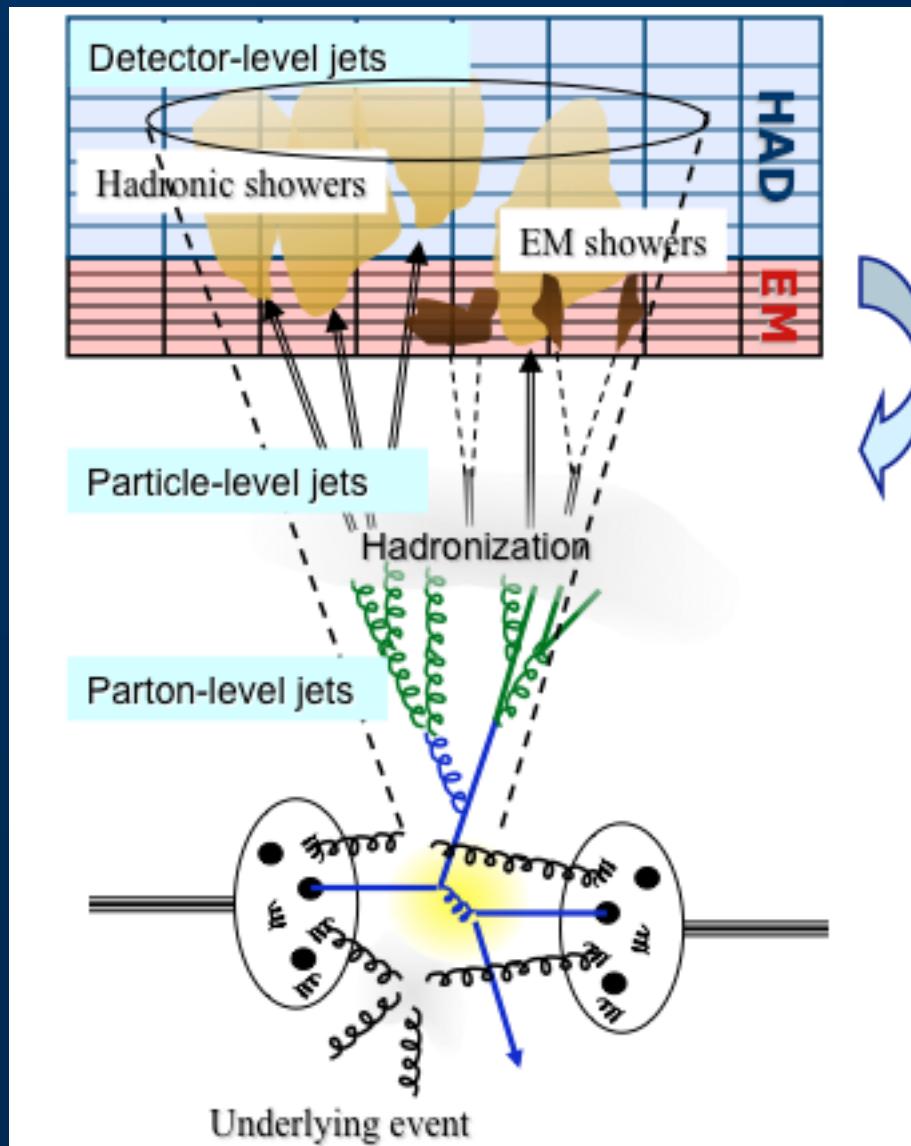
Three of the experiments
running at CERN !



Jets at Hadron Colliders



Measuring Jets



Experimentally, jets are measured in the detectors.

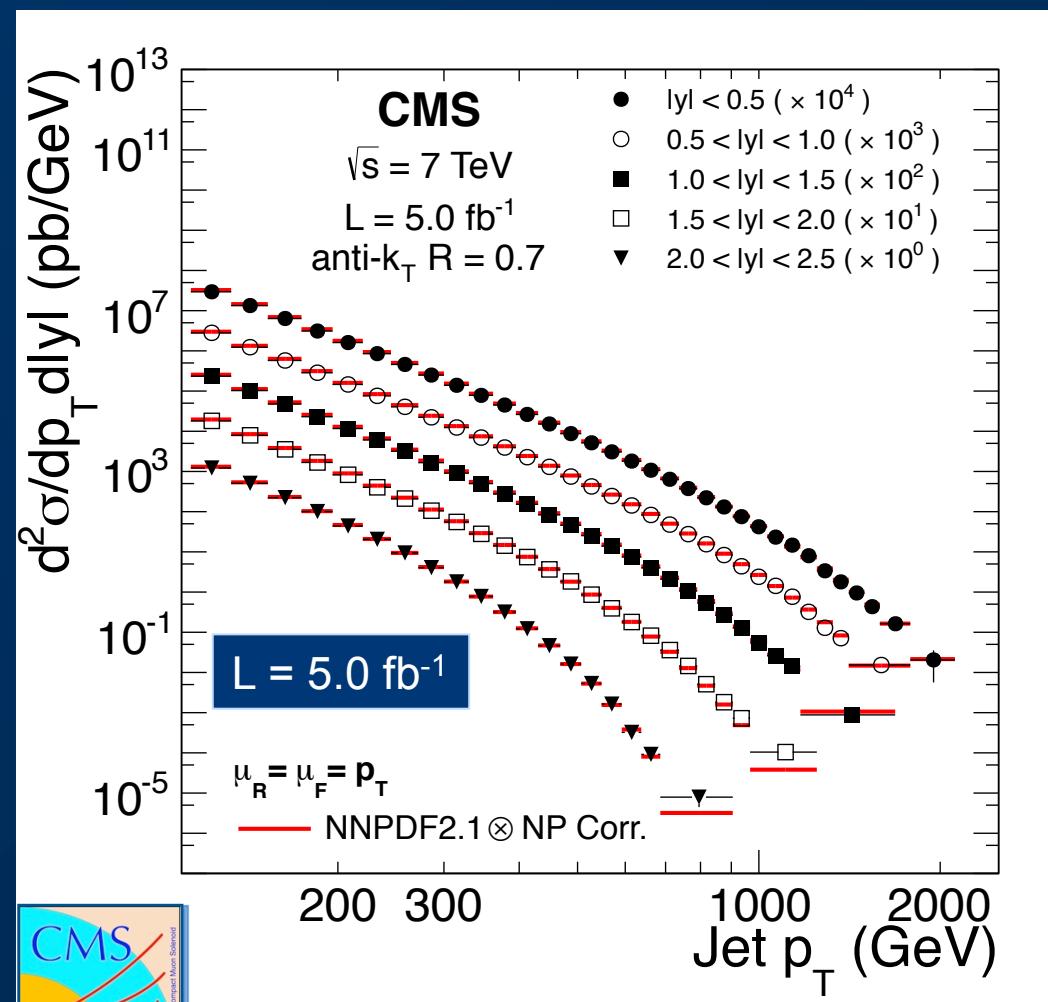
Need to “unfold” the measured jets to the “true” particle level for comparisons with theoretical predictions

Big experimental challenge!

Inclusive Jet Production



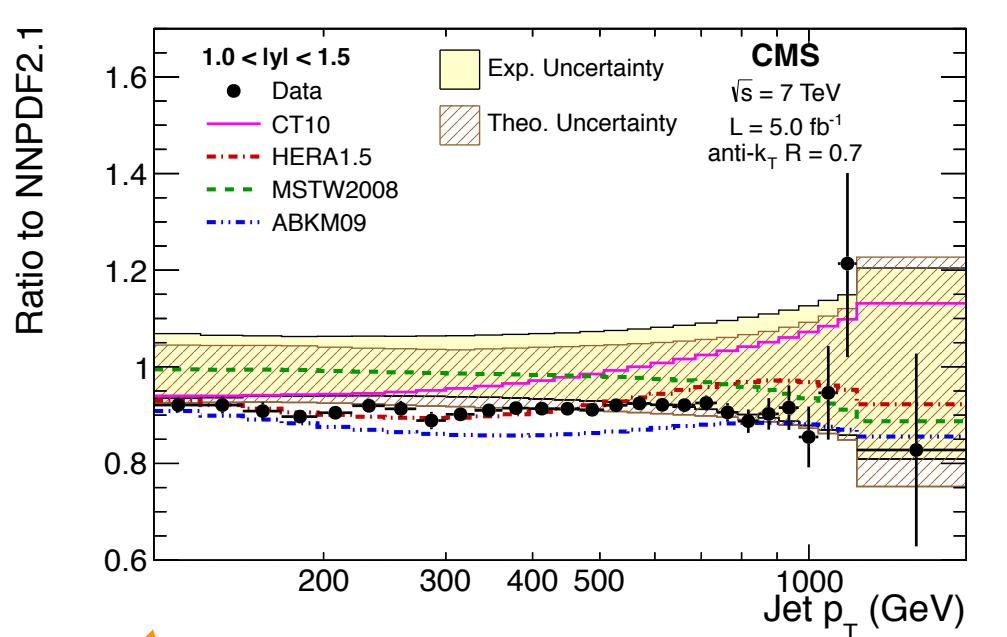
Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)



CMS: arXiv:1212.6660, accepted by PRD

Highest jet p_T about 2 TeV !

Theory: NLO QCD calculation + non-perturbative correction

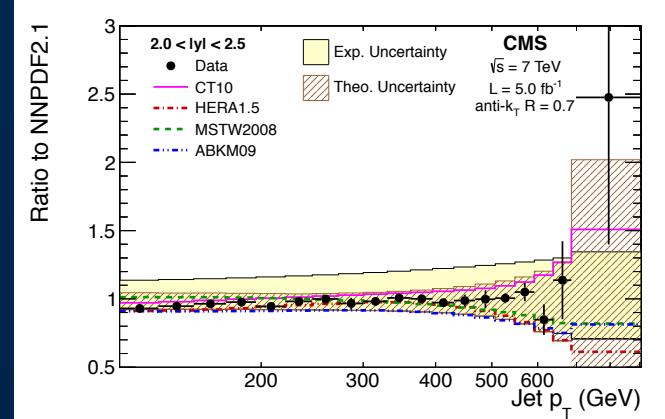
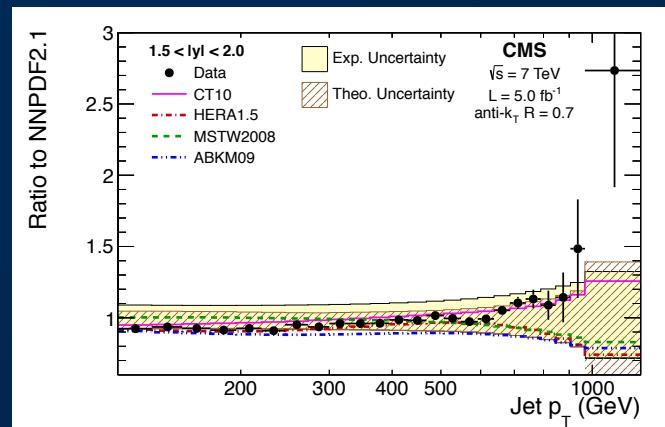
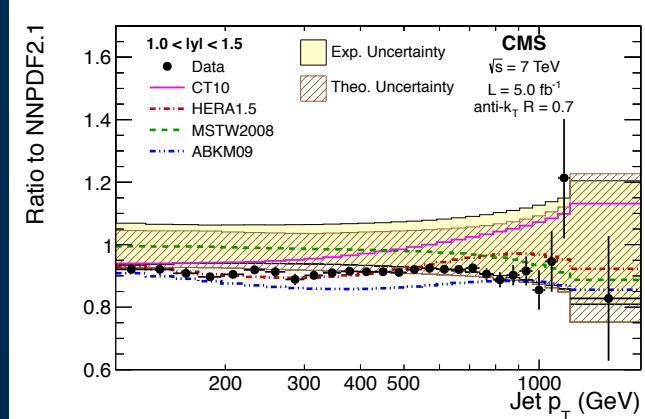
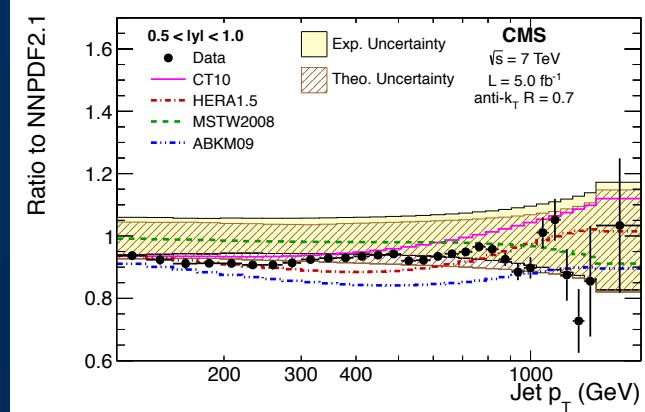
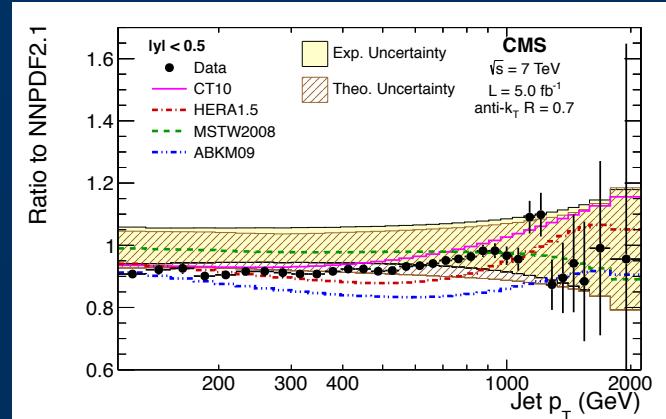


1.0 < $|y| < 1.5$ shown here; several other rapidity ranges available

Inclusive Jet Production



Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)



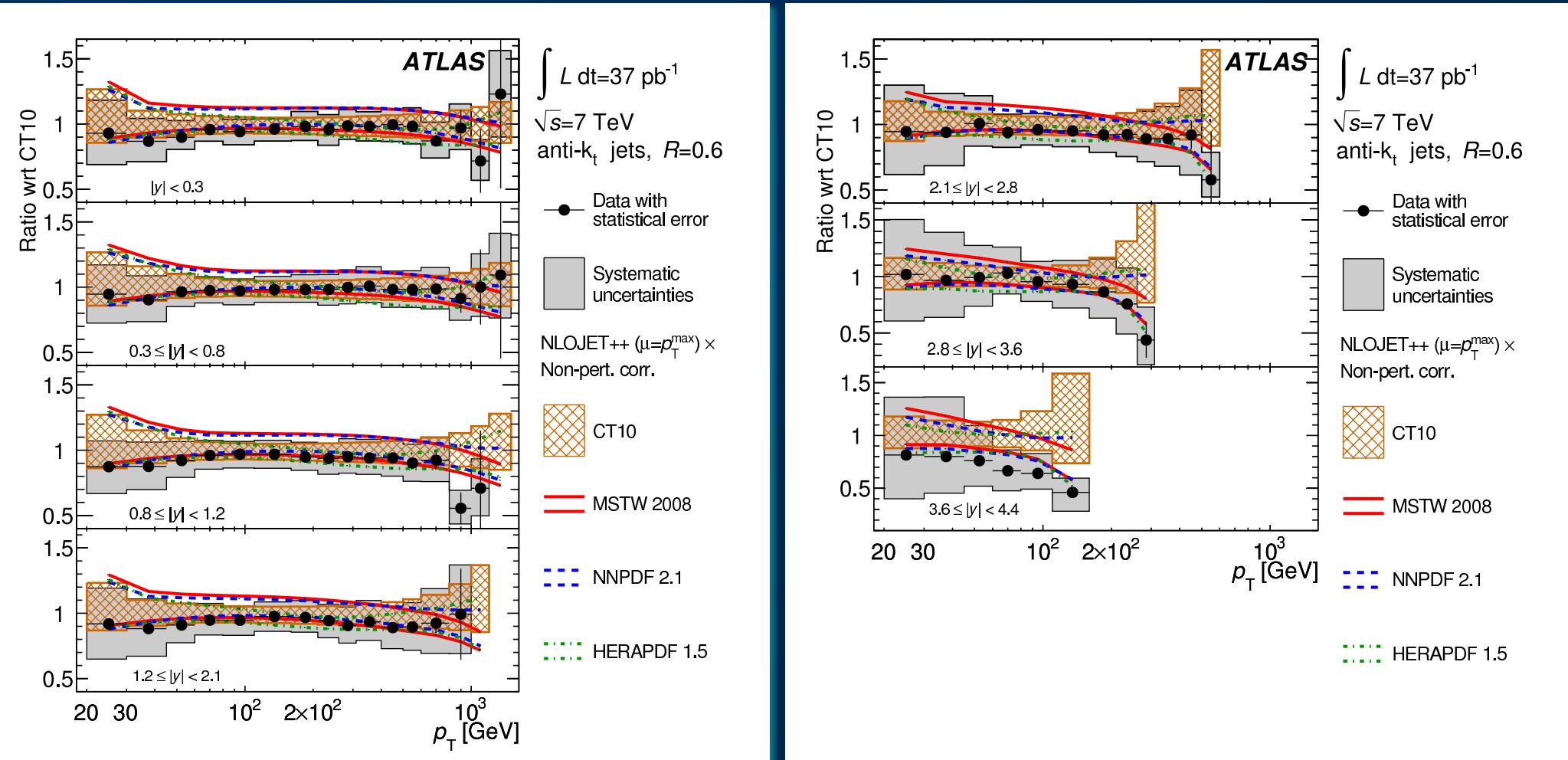
CMS: arXiv:1212.6660, accepted by PRD



Inclusive Jet Production

Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)

ATLAS: PRD 86 014022 (2012)

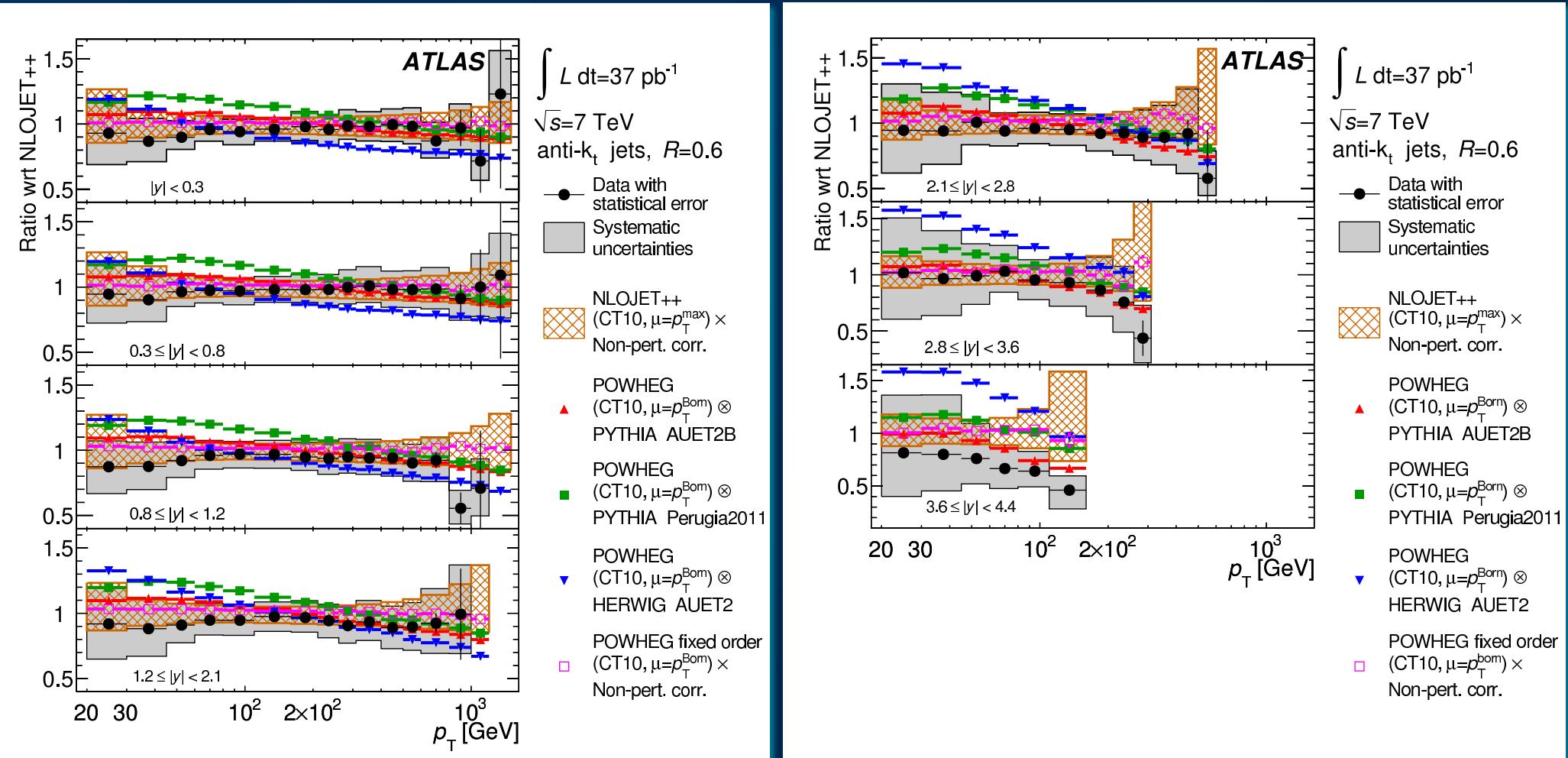




Inclusive Jet Production

Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)

ATLAS: PRD 86 014022 (2012)

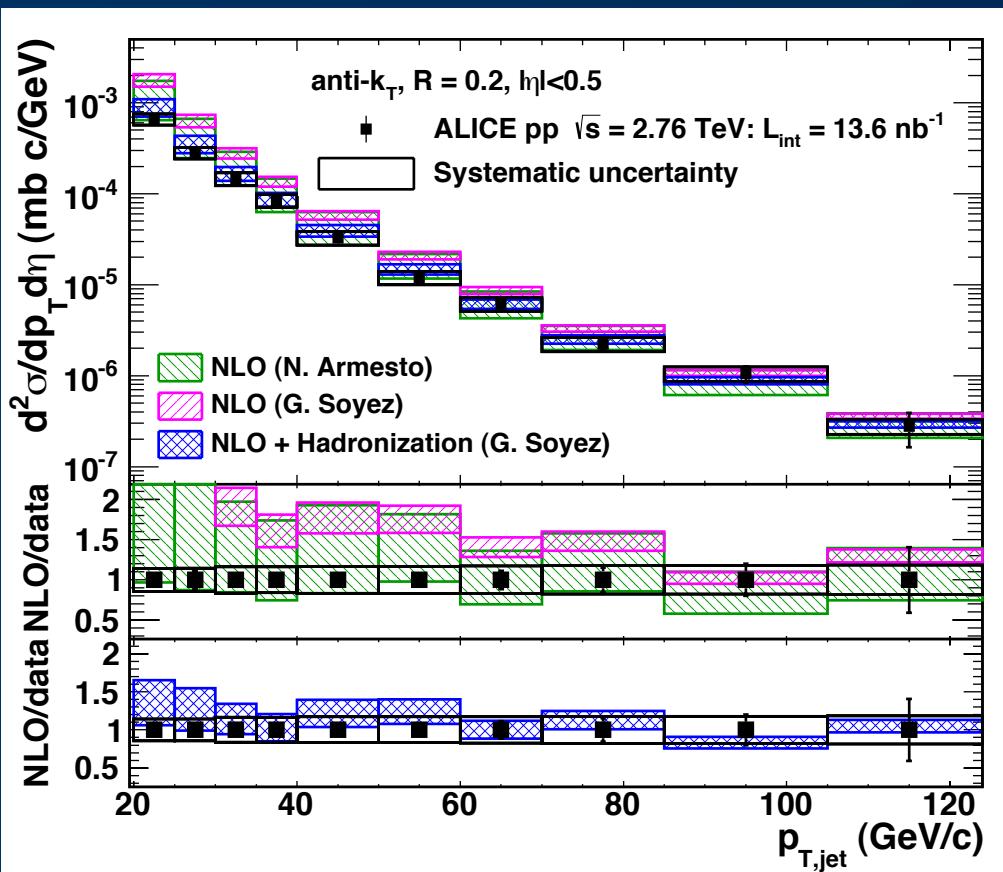


Inclusive Jet Production

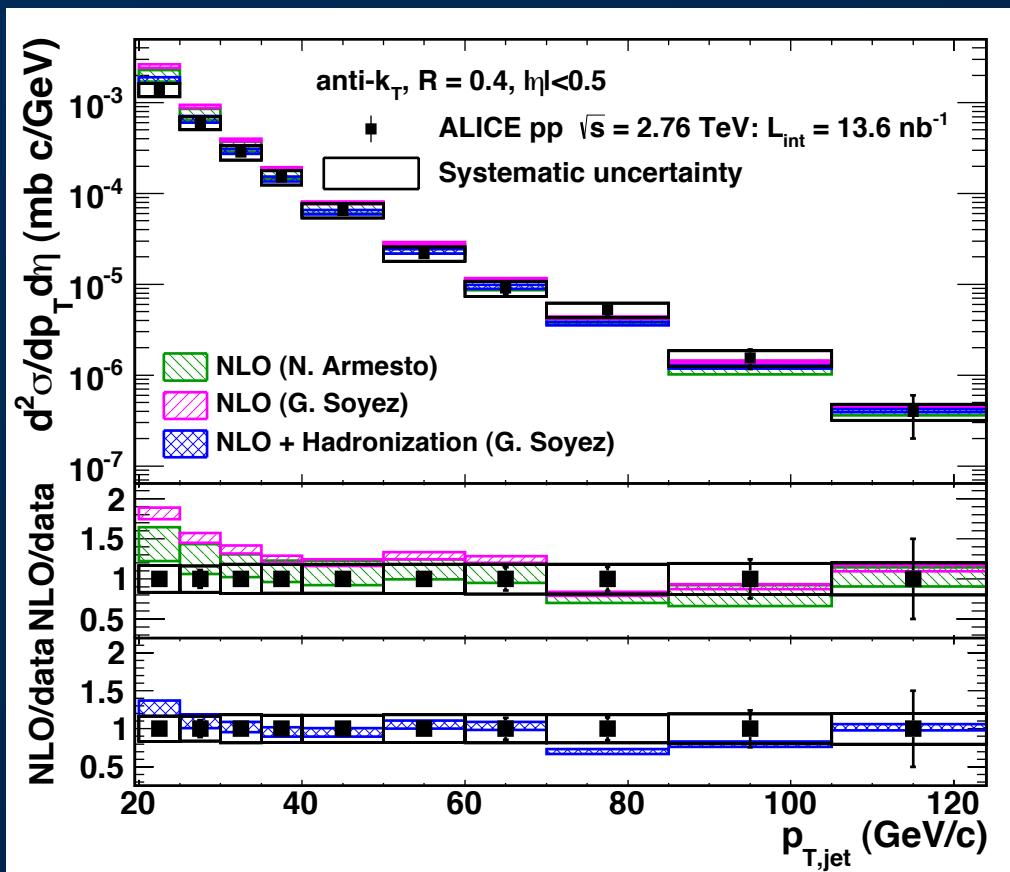


Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 2.76 \text{ TeV}$)

anti- k_T , R = 0.2



anti- k_T , R = 0.4

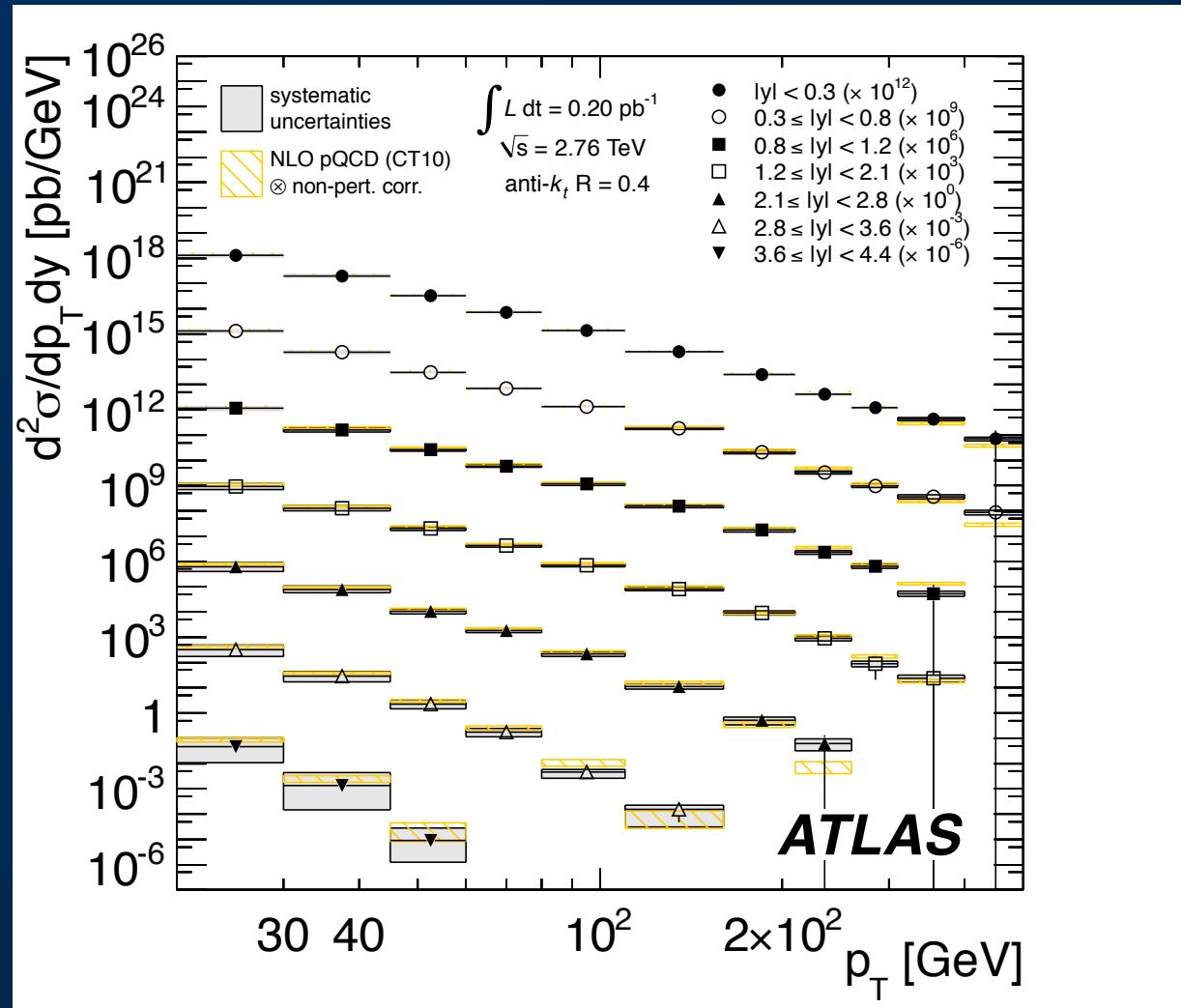


Inclusive Jet Production

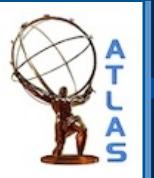


Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 2.76 \text{ TeV}$)

ATLAS: arXiv: 1304.4739, Submitted to Eur. Phys. J. C

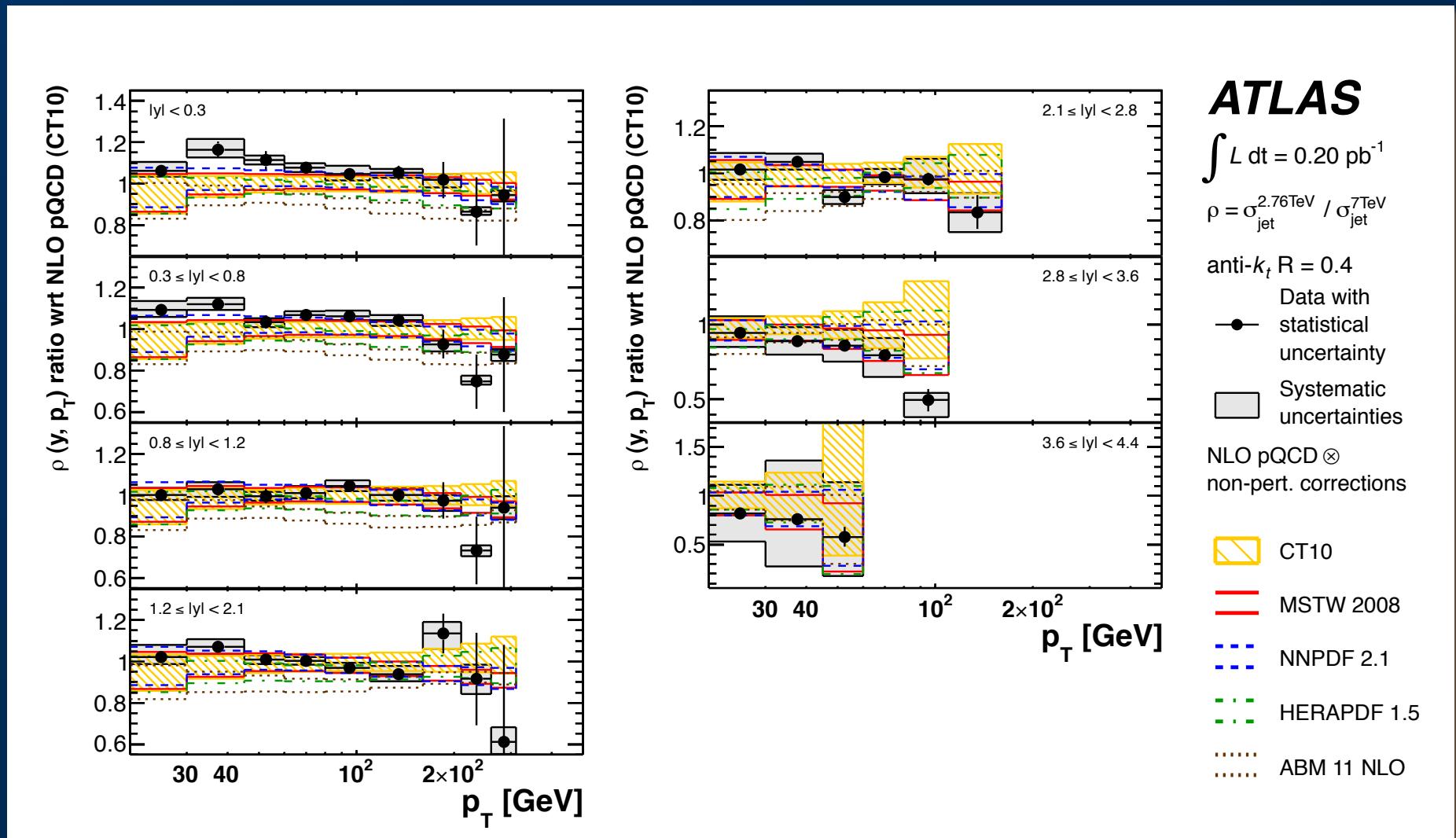


Inclusive Jet Production



Inclusive Jet Cross Section at the LHC ($\sqrt{s} = 2.76 \text{ TeV}$)

ATLAS: arXiv: 1304.4739, Submitted to Eur. Phys. J. C

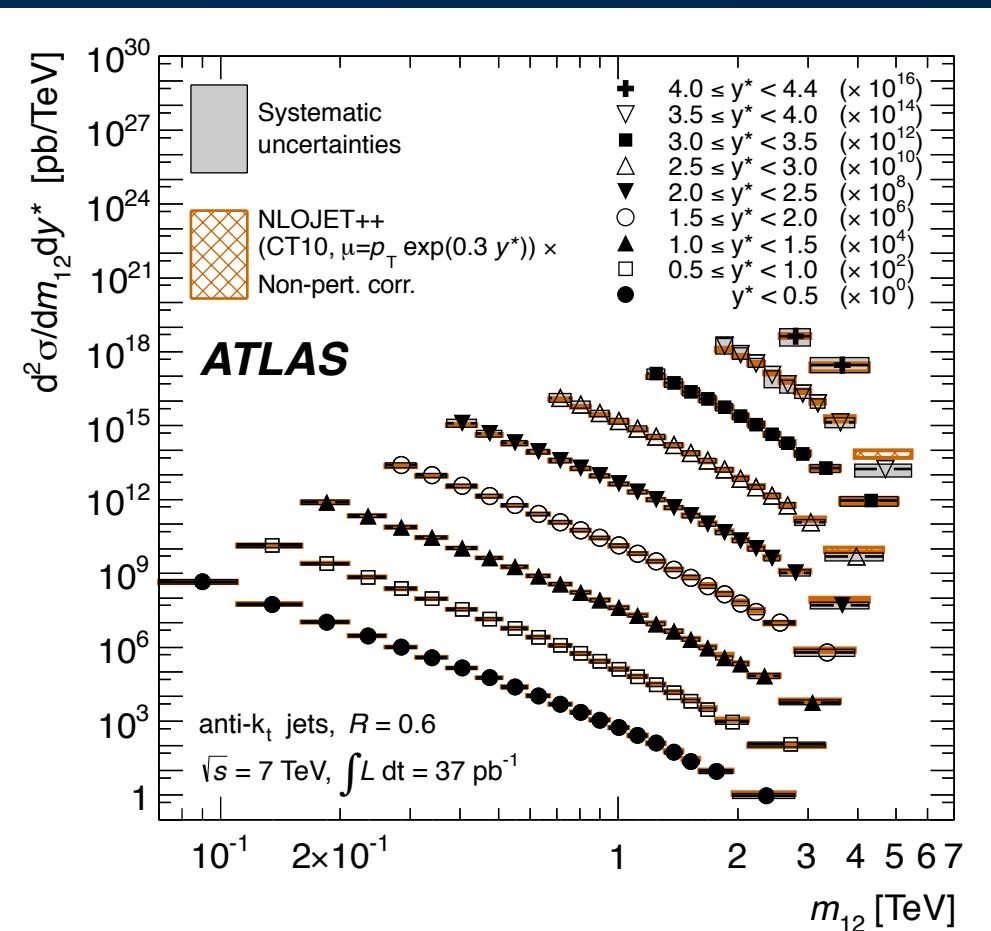
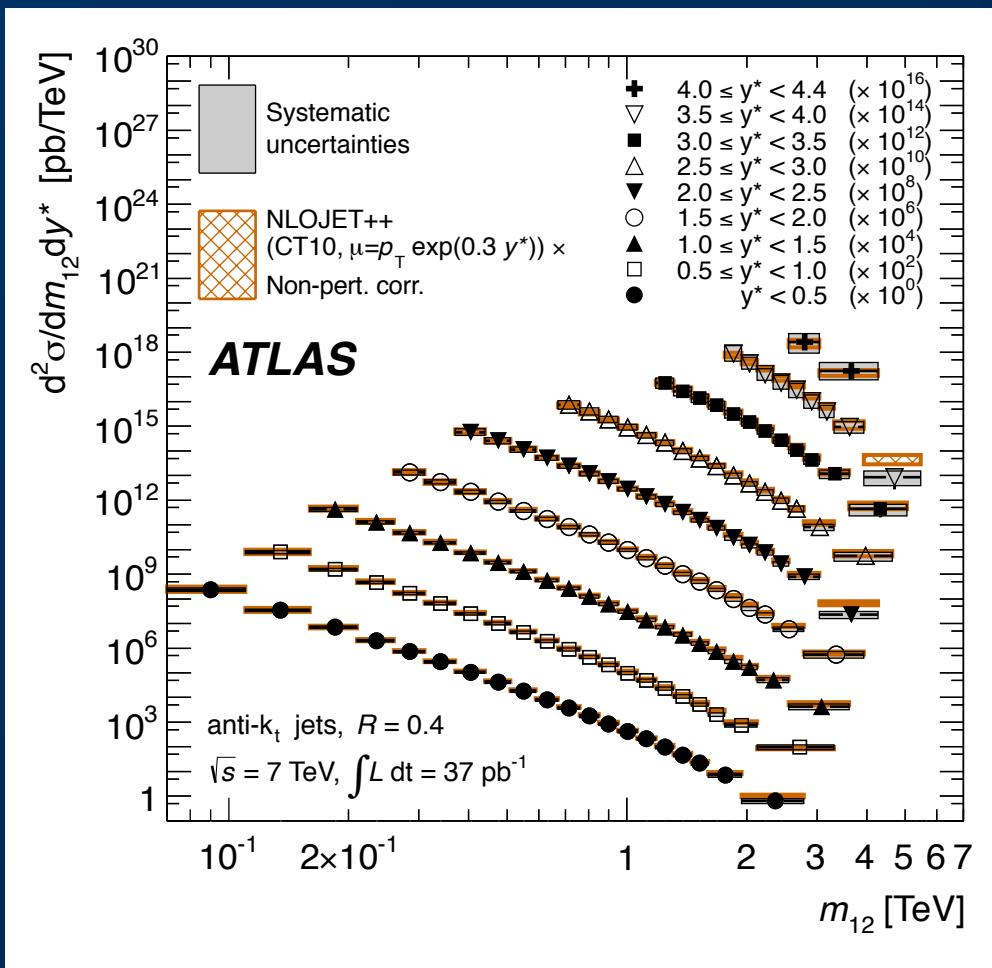




Inclusive Jet Production

Double-Differential Dijet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)

ATLAS: PRD 86 014022 (2012)

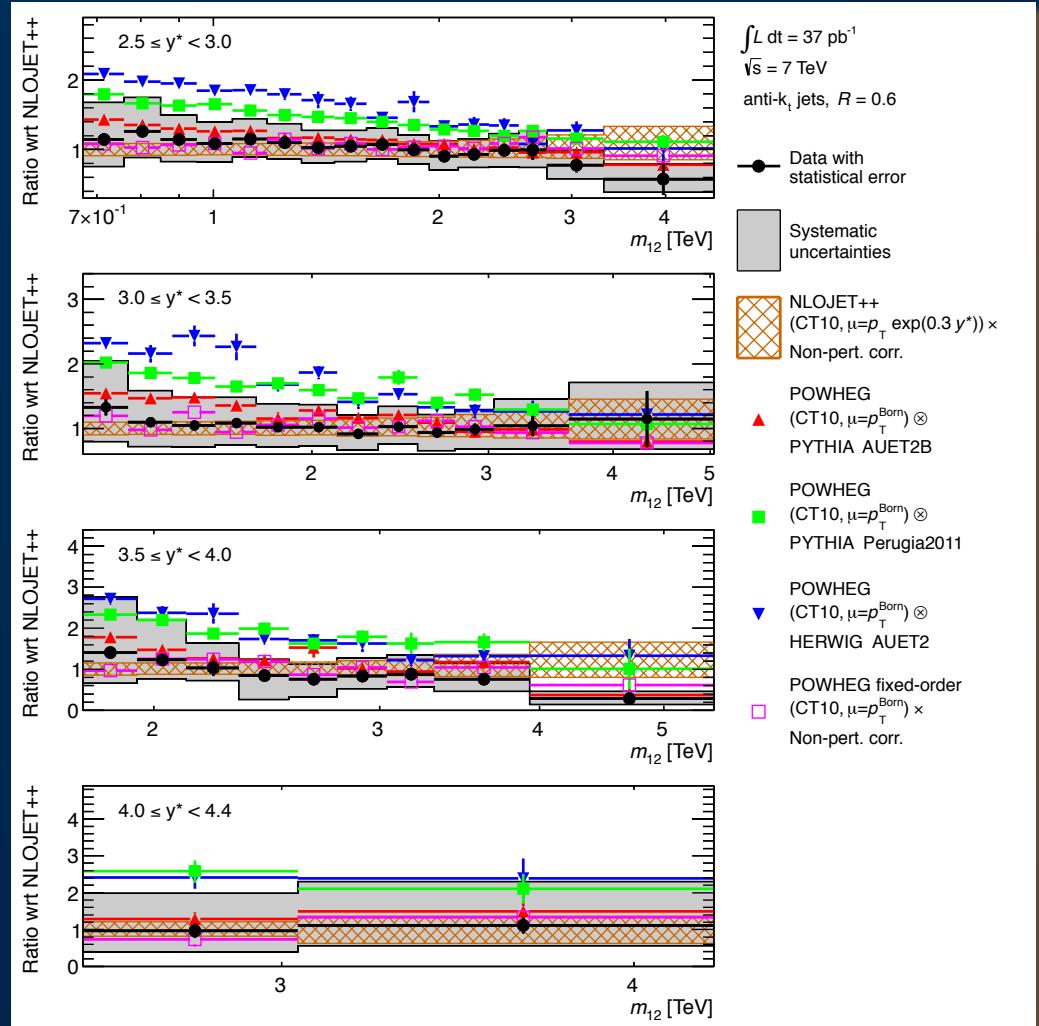
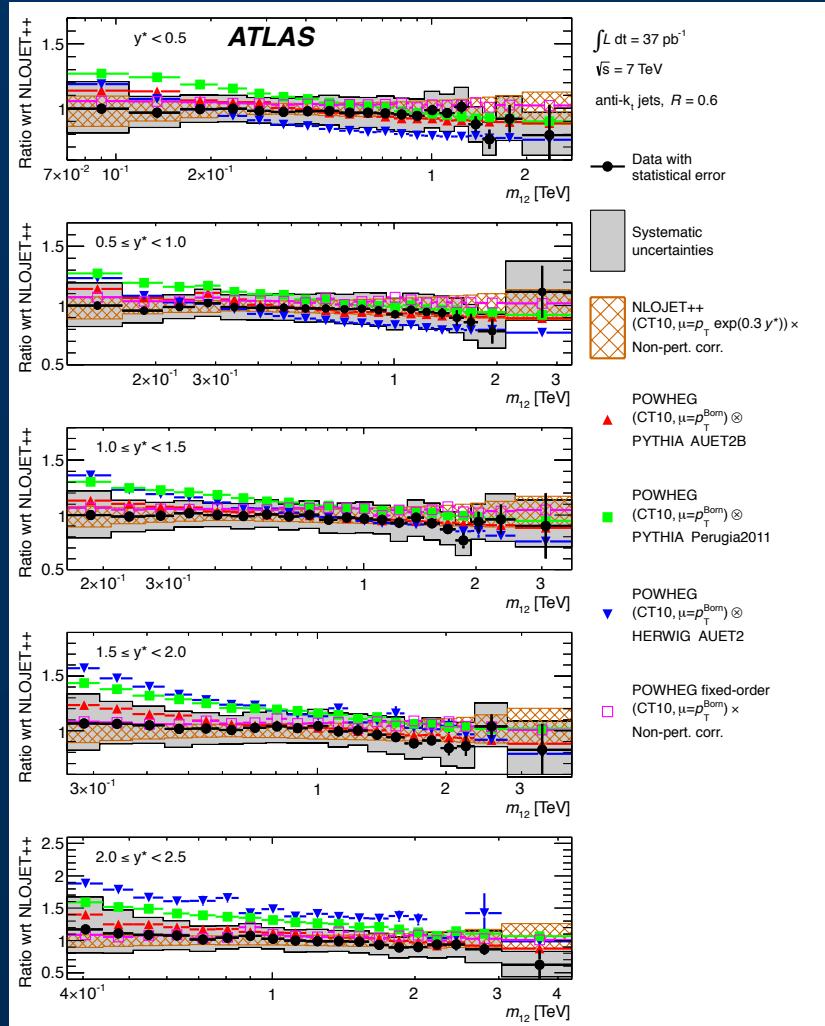




Inclusive Jet Production

Double-Differential Dijet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)

ATLAS: PRD 86 014022 (2012)

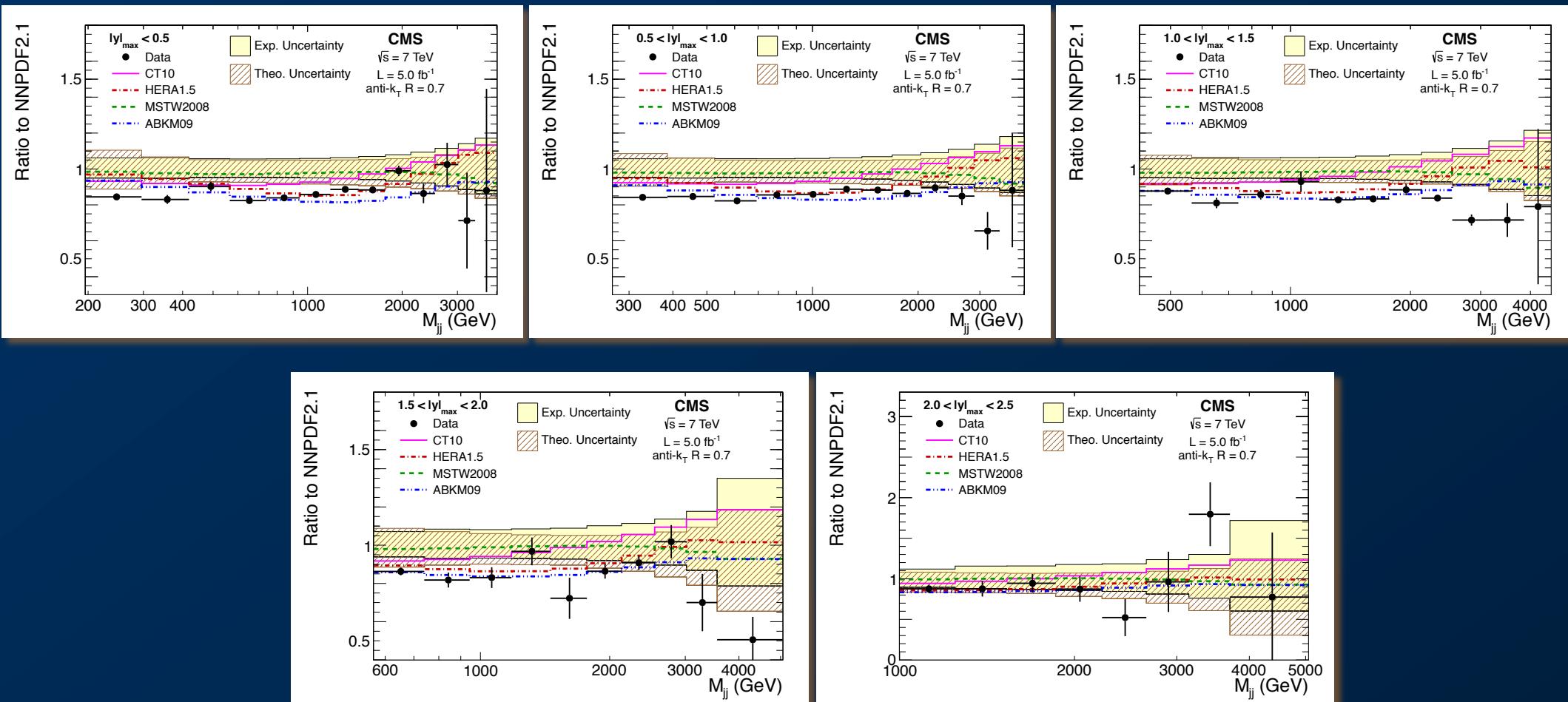


Inclusive Jet Production



Double-Differential Dijet Cross Section at the LHC ($\sqrt{s} = 7 \text{ TeV}$)

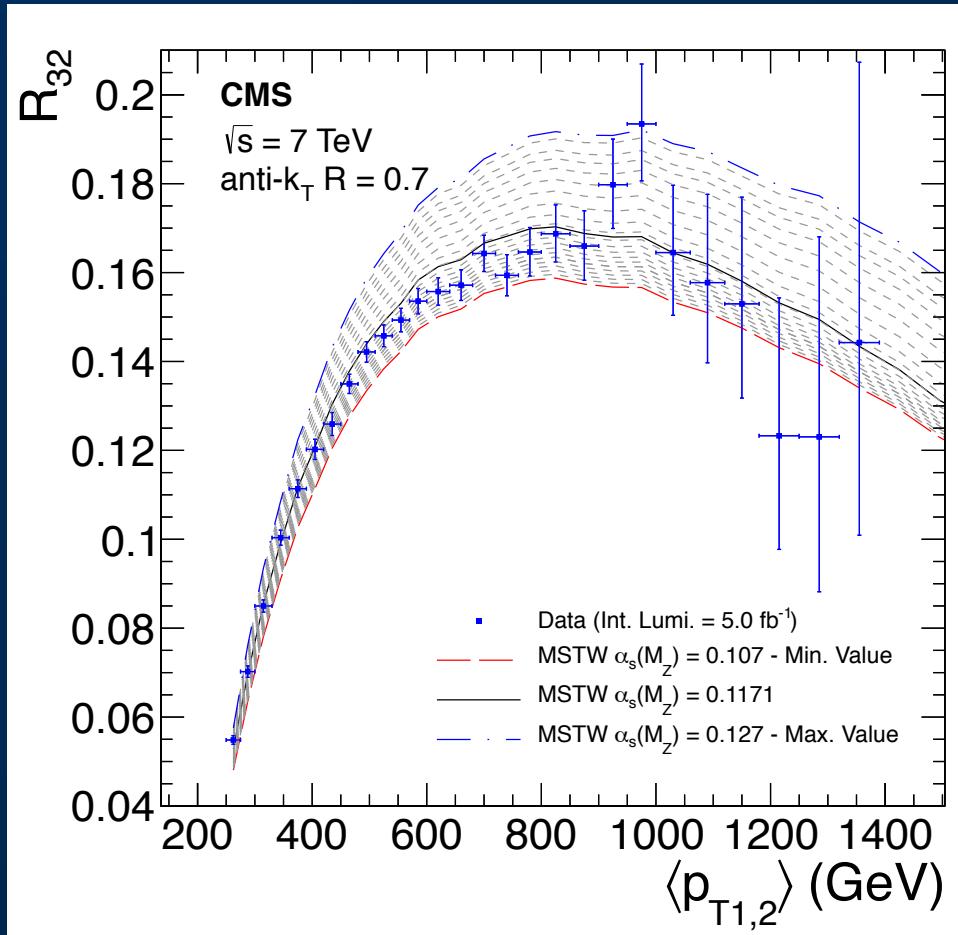
CMS: arXiv:1212.6660, accepted by PRD



Inclusive Jet Ratios



Inclusive 3-Jet / Inclusive 2-Jet Ratio ($R_{3/2}$) ($\sqrt{s} = 7 \text{ TeV}$)

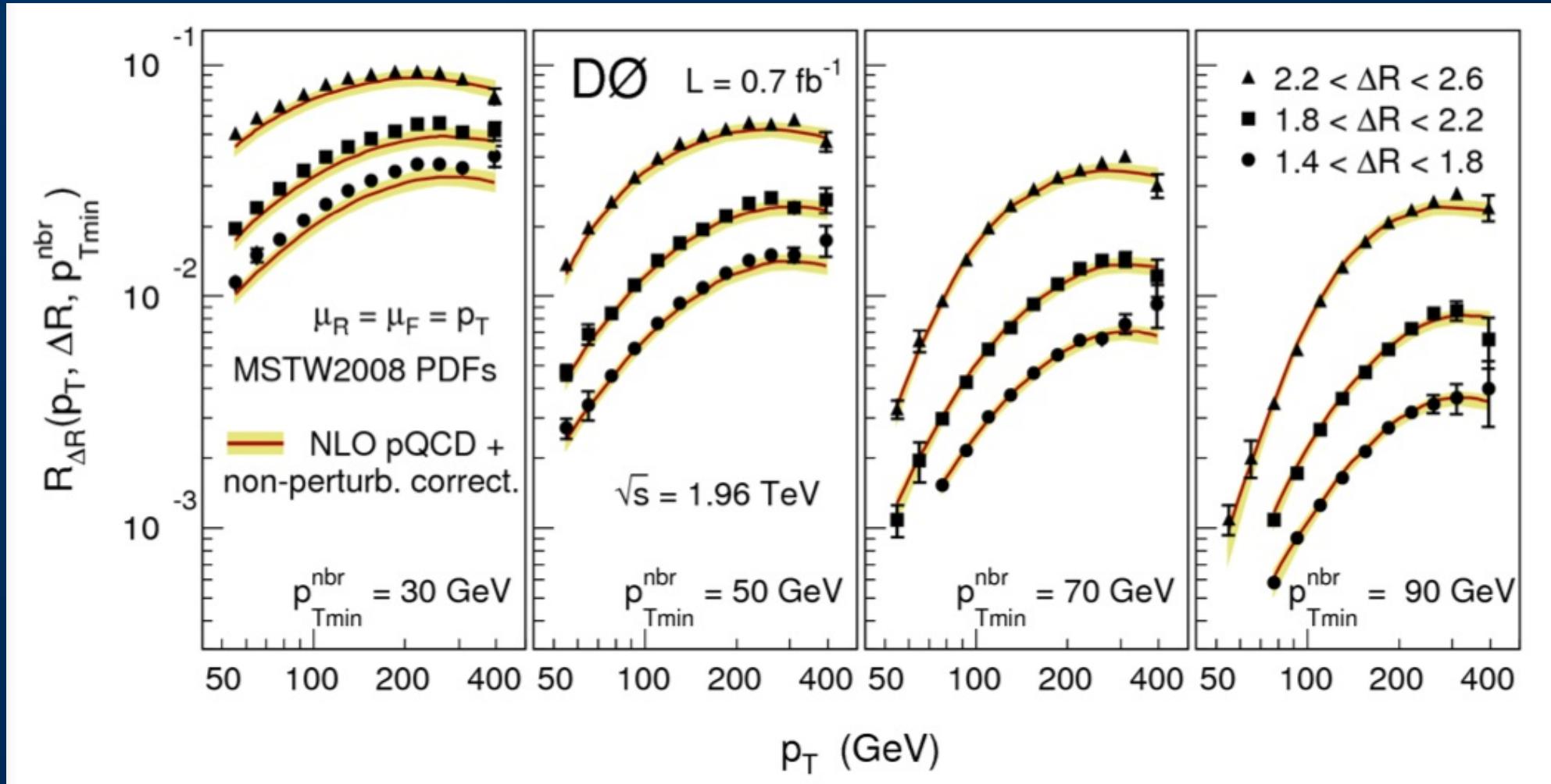


CMS: arXiv:1304.7498, submitted to Eur. Phys. J. C

Angular Correlations



Angular Correlations of Jets ($\sqrt{s} = 1.96$ TeV)

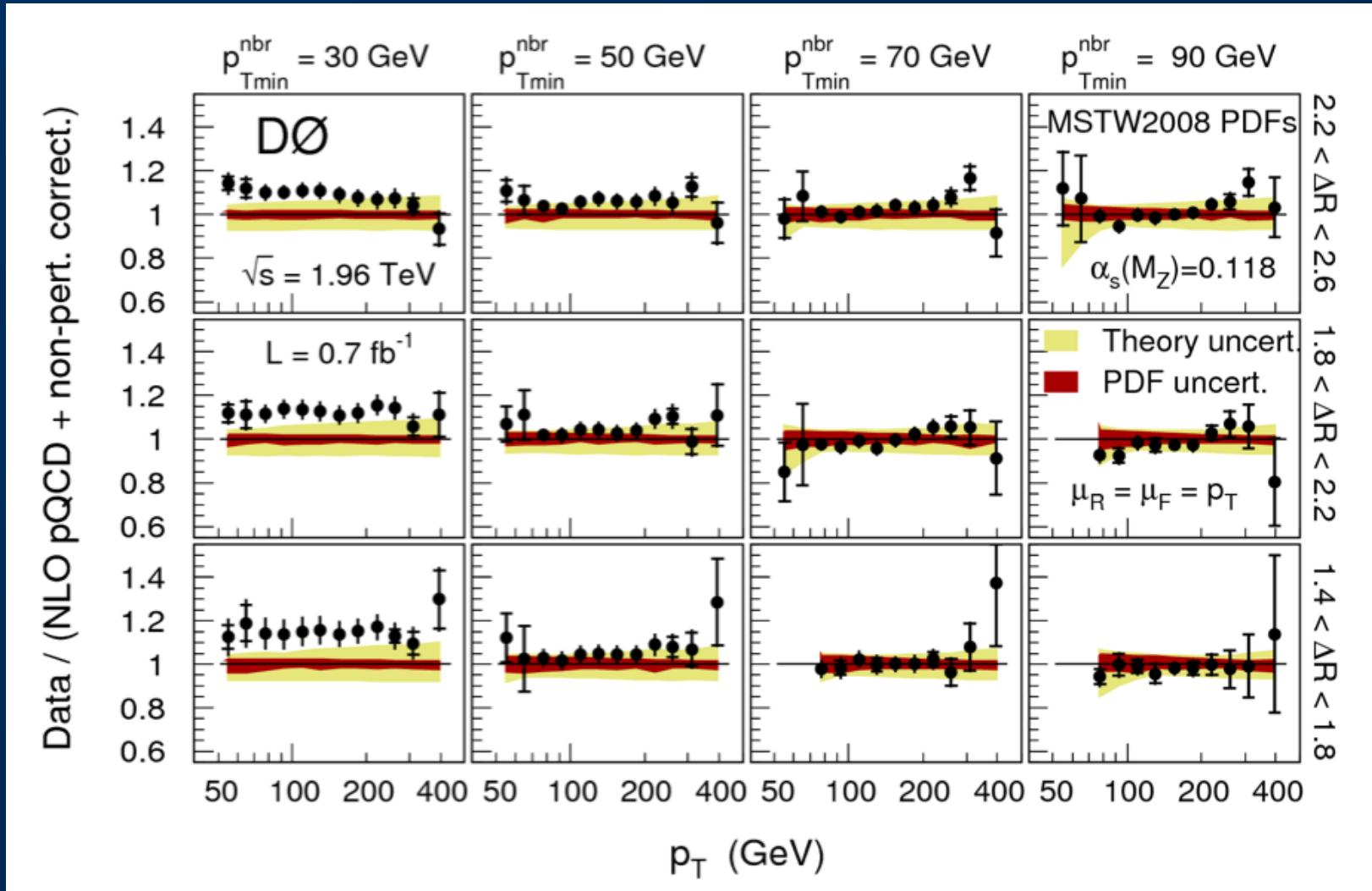


DØ: Phys. Lett. B 718, (2012) 56

Angular Correlations



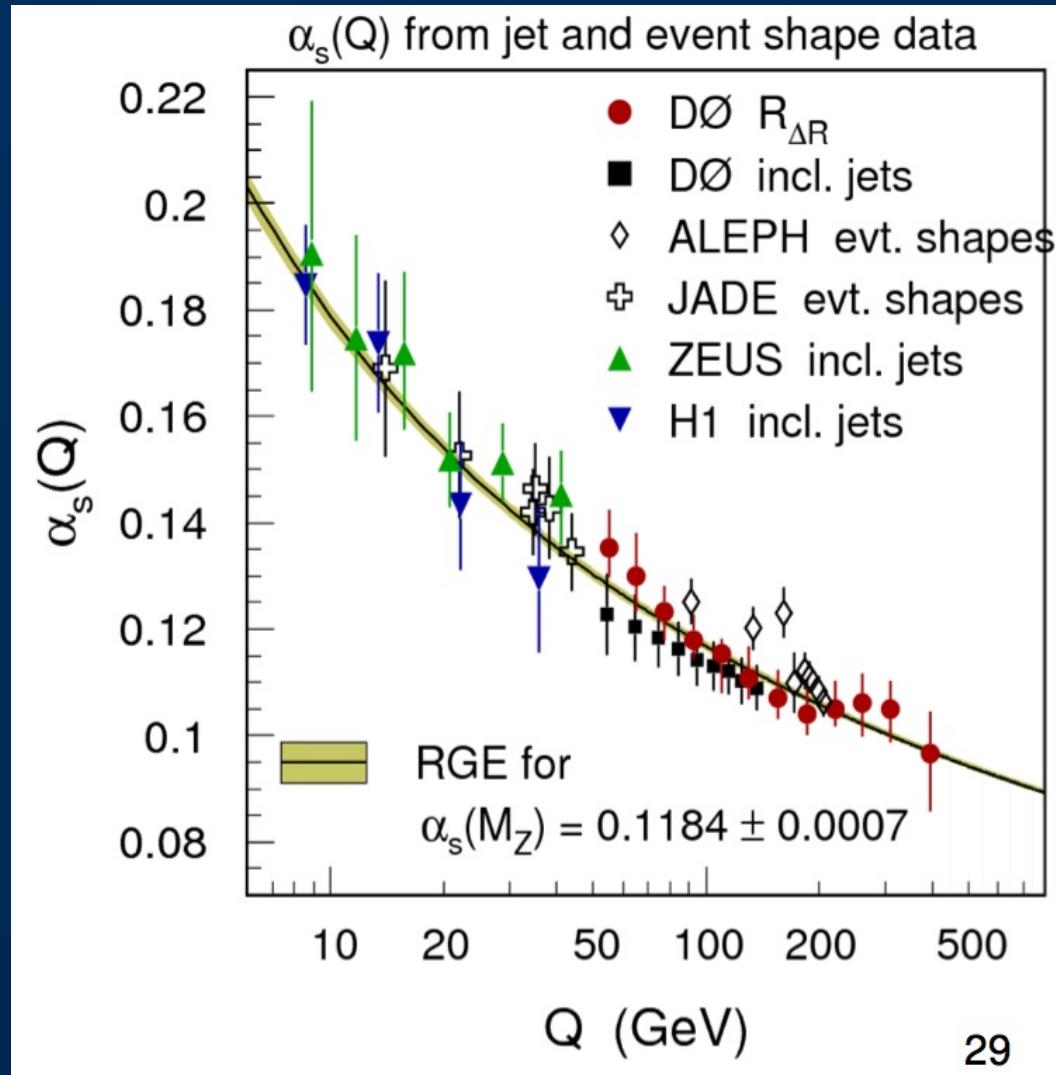
Angular Correlations of Jets ($\sqrt{s} = 1.96$ TeV)





Angular Correlations

Angular Correlations of Jets ($\sqrt{s} = 1.96$ TeV)



DØ: Phys. Lett. B 718, (2012) 56