Jets and PDFs with CMS data

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on behalf of CMS Collaboration

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CMS Compact Muon Solenoid

QCD@LHC 2016
Zurich

Outline

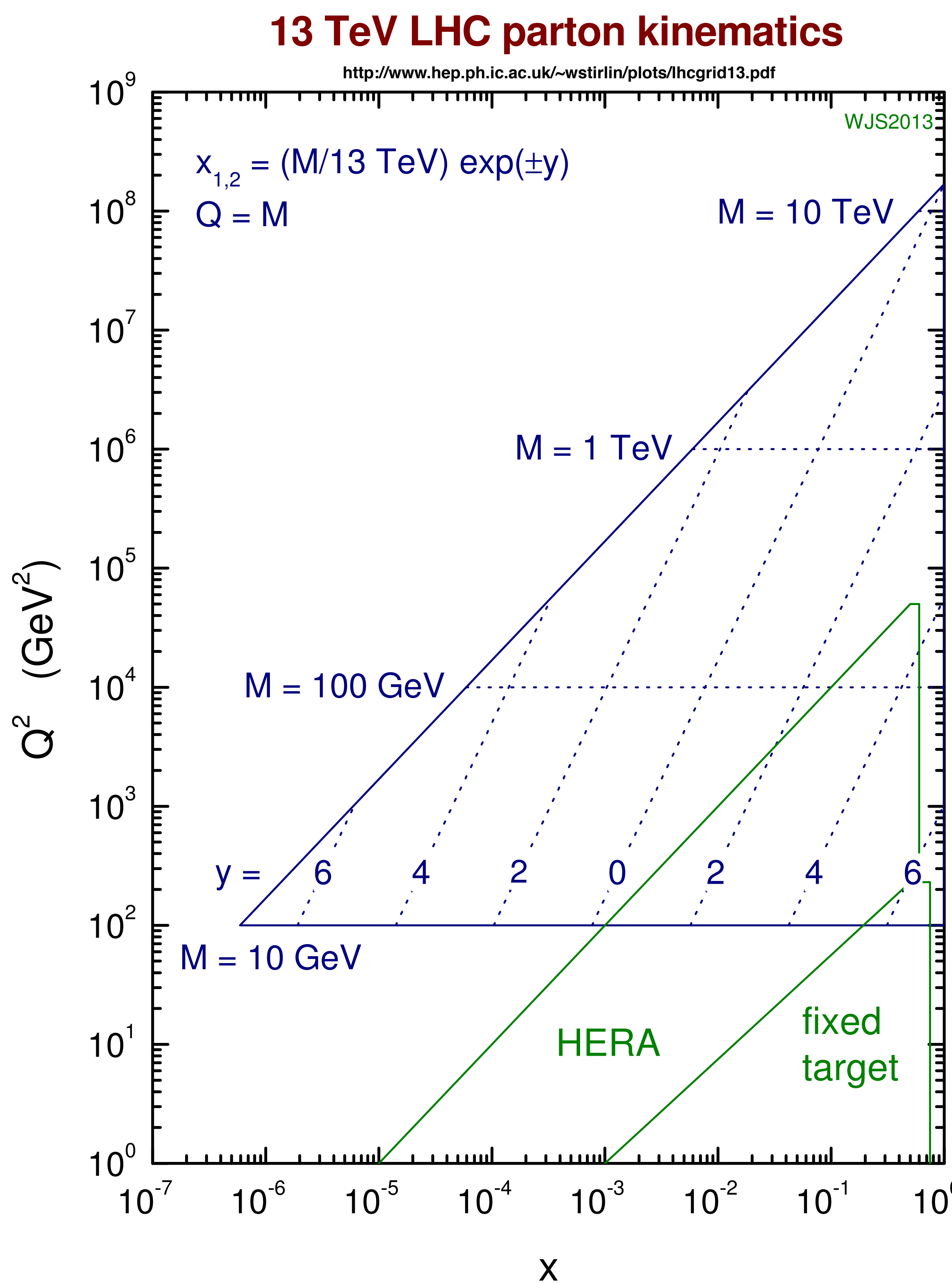
- Introduction
- CMS Experiment (Quick)
- Jet Reconstruction and Calibration

- **Jet Measurements with CMS Data**
  - Dijet Mass Cross Section
  - Inclusive Jet Cross Section
  - Dijet Azimuthal Decorrelations
  - 3-jet to 2-jet Cross Section Ratio

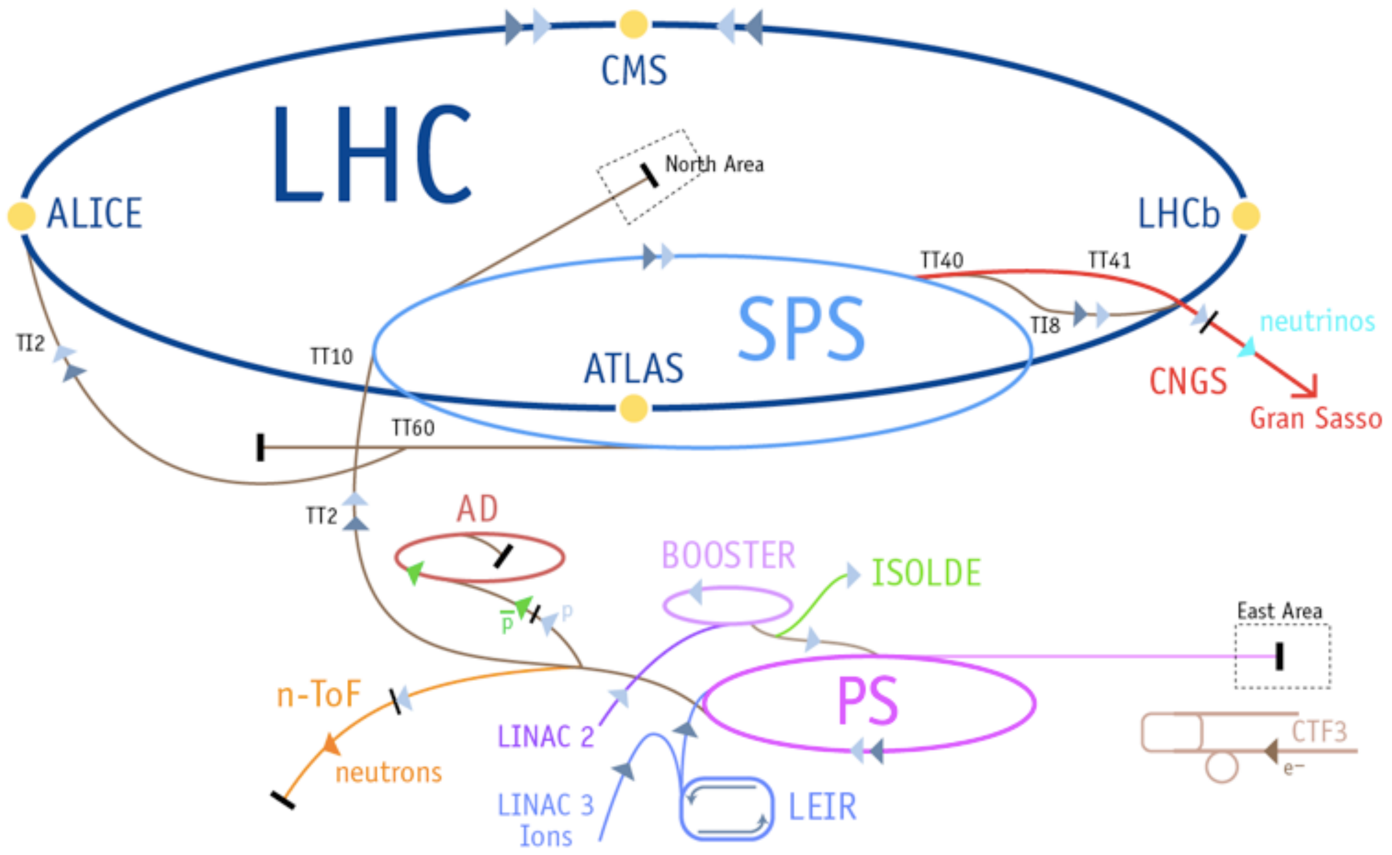
- **PDF Constraints and Strong Coupling ($\alpha S(Q)$) from Jet Measurements**
  - Constraints on PDF from the inclusive jet cross section in pp collisions @ $\sqrt{s}$ = 7 TeV
  - $\alpha S(Q)$ from 3-jet to 2-jet Cross Sections
  - $\alpha_S(Q)$ from Inclusive Jet Cross Section
  - $\alpha S(Q)$ from Three Jet Mass
- Conclusions

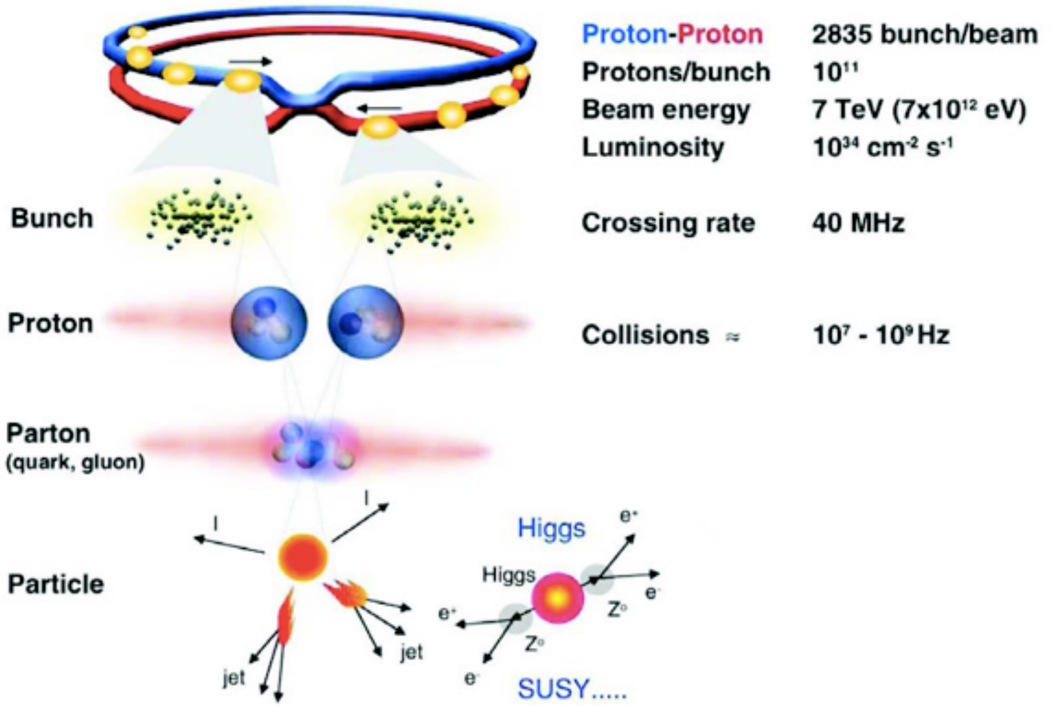
Introduction

- LHC is actually a jet factory.
- Jet measurements at LHC are highly important:
  - They provide a test of pQCD in a previously unexplored kinematic phase space.
  - A laboratory for SM predictions at high energy scales.
  - Precise determination of backgrounds to many new physics searches.
  - Determine the strong coupling and test its running at high Q scales.
  - PDFs can be constrained



Introduction

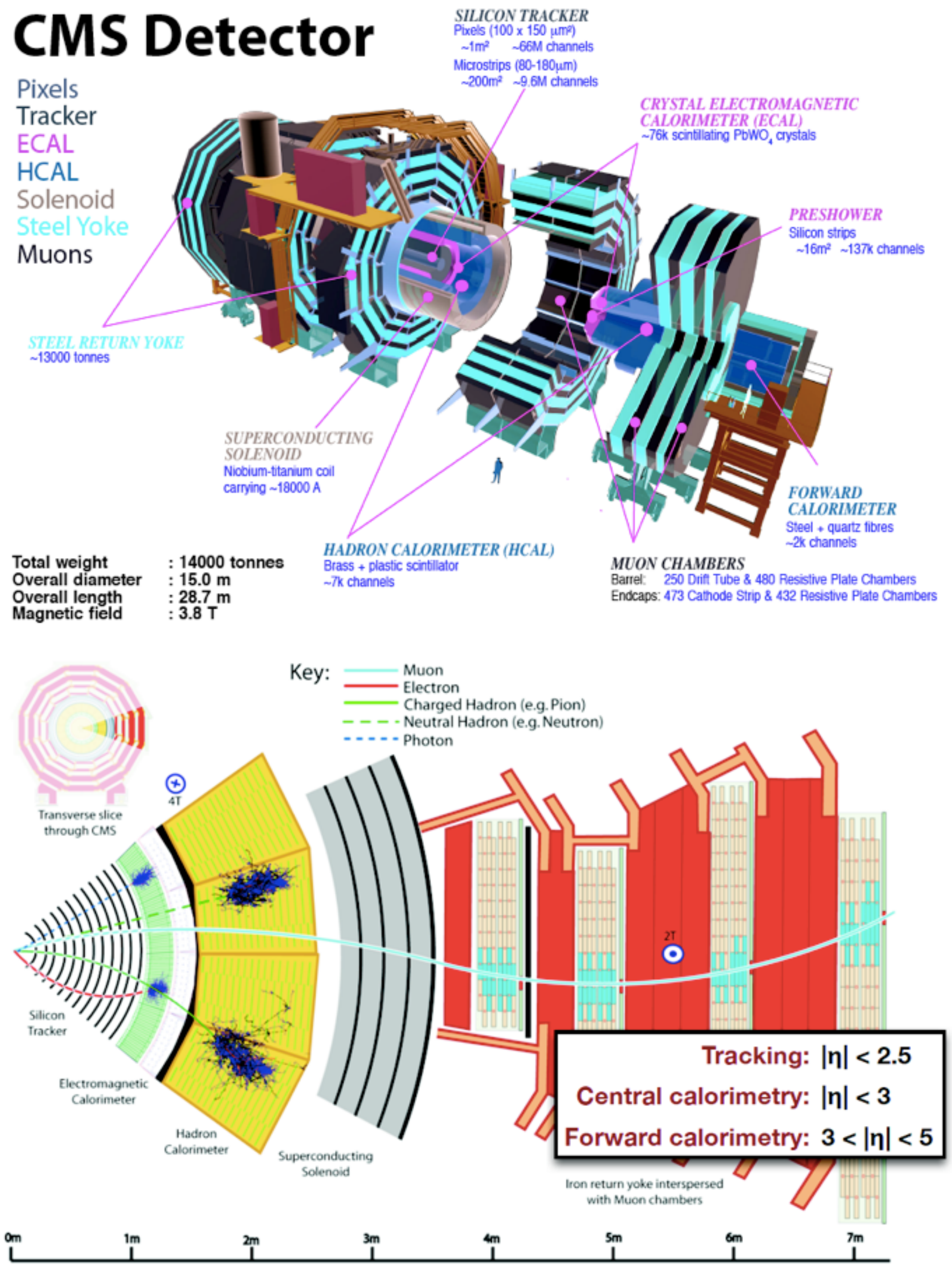




- The LHC is the world's largest and the most powerful collider (run at 7 TeV and 8 TeV so far)
- Located in the existing LEP tunnel between 50 and 175 m underground with 26.7 km circumference long.
- The LHC hosts four main detectors (ALICE, ATLAS, CMS, LHCb).
- The first *pp* collision in March 2010, the first *Pb-Pb* collision in November 2010, and the first p-Pb collisions in September 2012

CMS Detector

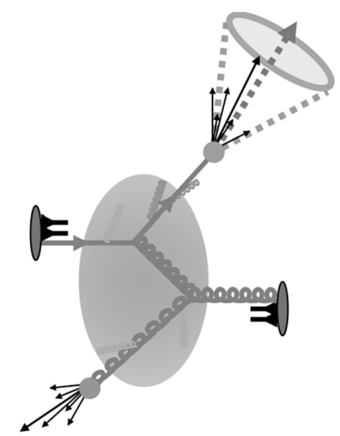
- The Compact Muon Solenoid (CMS) is a multi purpose detector at the LHC.
- The CMS detector design is similar to the structure of an onion.
- CMS consists of several layers of each one which is specialised to measure and identify different classes of particles.
- The detector requirements for CMS
  - Good muon identification and momentum resolution,
  - Good charged particle momentum resolution and reconstruction efficiency in the inner tracker,
  - Good electromagnetic energy resolution, good diphoton and dielectron mass resolution,
  - Good MET and dijet mass resolution.

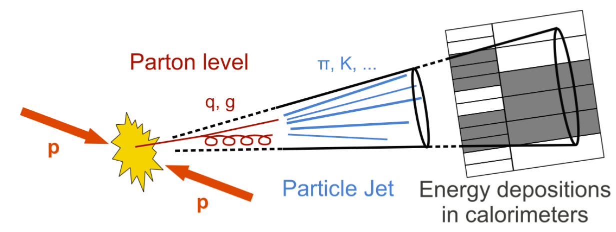


Jet Reconstruction and Calibration at CMS

Jet Reconstruction

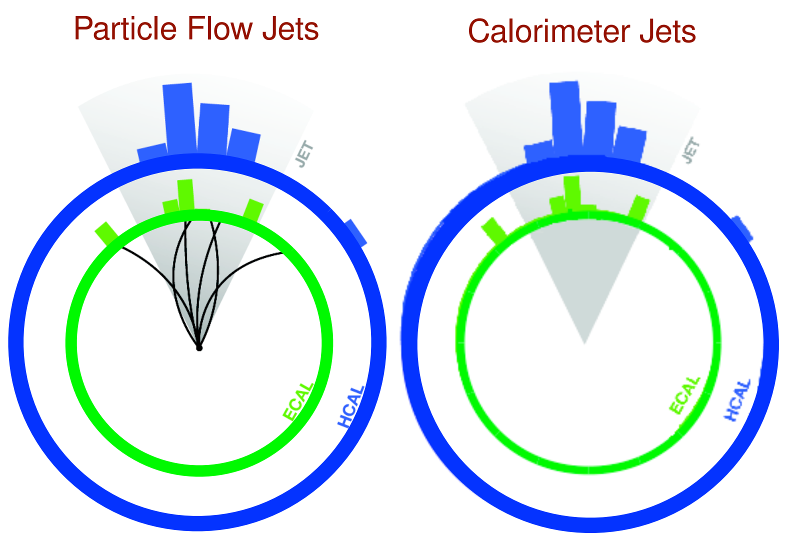
Jets are the experimental signatures of quarks and gluons. Invaluable objects to probe QCD.





- It is an object that is clustered out of collimated spray of particles by using a set of mathematical rules

$$d_{ij} = p_{T,i}^{2p} \qquad d_{ij} = min(p_{T,i}^{2p}, p_{T,j}^{2p})\frac{\Delta R_{ij}^2}{D^2}$$

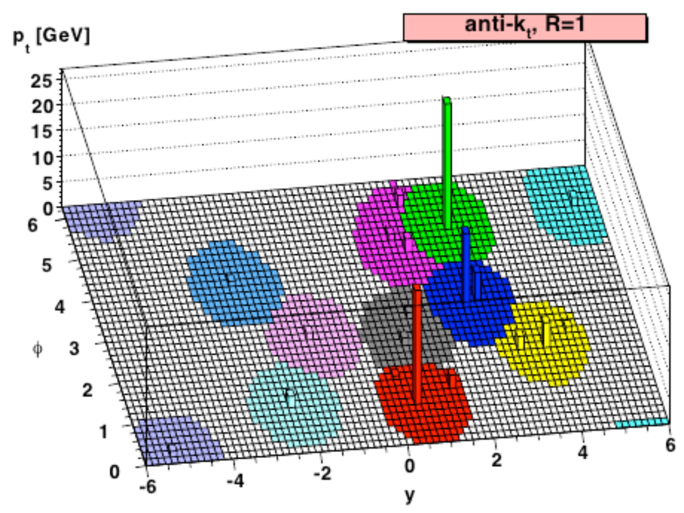


- CMS's default jet reconstruction algorithm is "anti-k_T jet" algorithm with p=-1 in the expression above
  - successive recombination (belongs to the k_T family)
  - infrared and collinear safe
  - geometrically cone-like (some round shape in the y-φ plane)
  - tends to cluster around the hard energy depositions

- The jet reconstruction in CMS follows the "E-Scheme"
  - addition of Lorentz vectors
  - massless particles → massive jets

calorimeter towers or particle-flow candidates → Jet clustering algorithm → CaloJets or PF Jets

CMS now uses PF jets only



Jet Energy Calibration

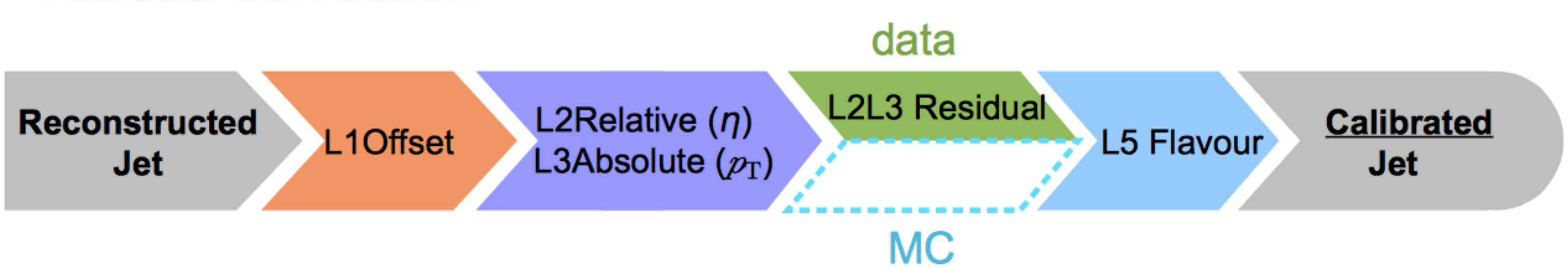
CMS- JME-13-004
arXiv:1607.03663v

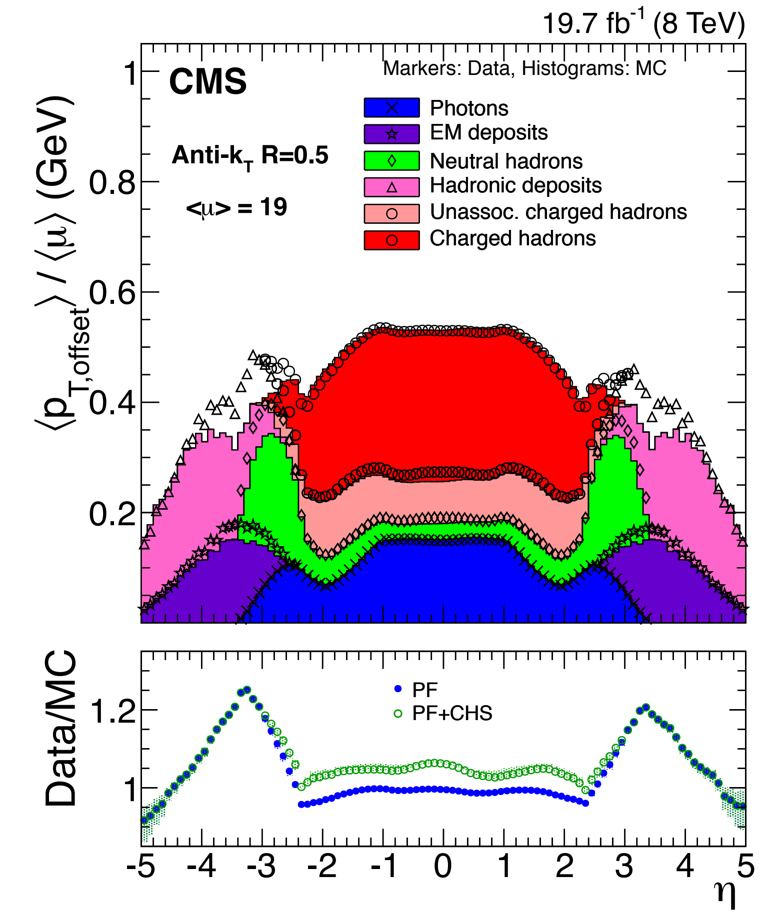
- We need to calibrate jets because the calorimeter response is non-linear in p_T and non- uniform across the detector.

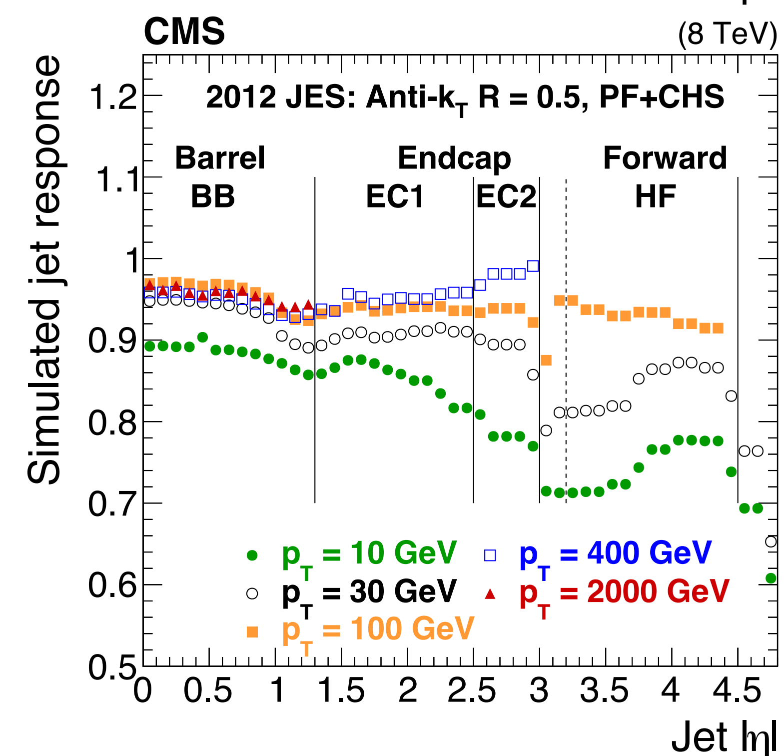
- The jet energy scale is the most important uncertainty related to jets.

Factorised approach is used like in Tevatron

- Offset: Required correction for pile-up and electronic noise.
- Relative (η): Required correction for jet response versus pseudorapidity relative to a control region. (Dijet Balance Method)
- Absolute(p_T): absolute JEC scale determined via $Z\to\mu^+\mu^-$+jet, $Z\to e^+e^-$+jet/γ+jet
- Corrections derived on MC and applied to data: if non-closure → residual correction





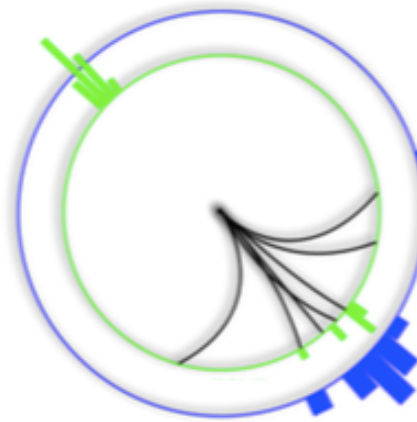


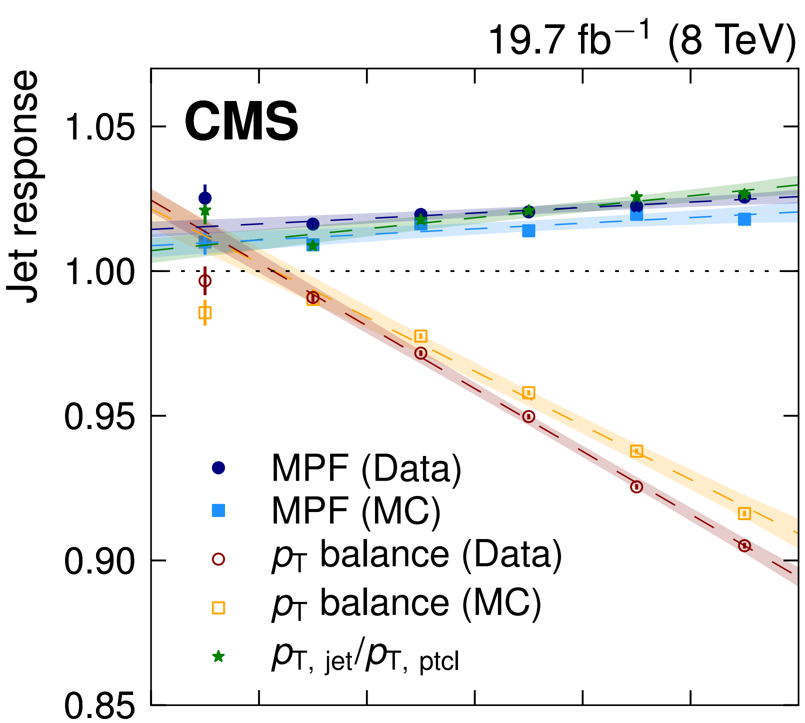
Jet Energy Calibration

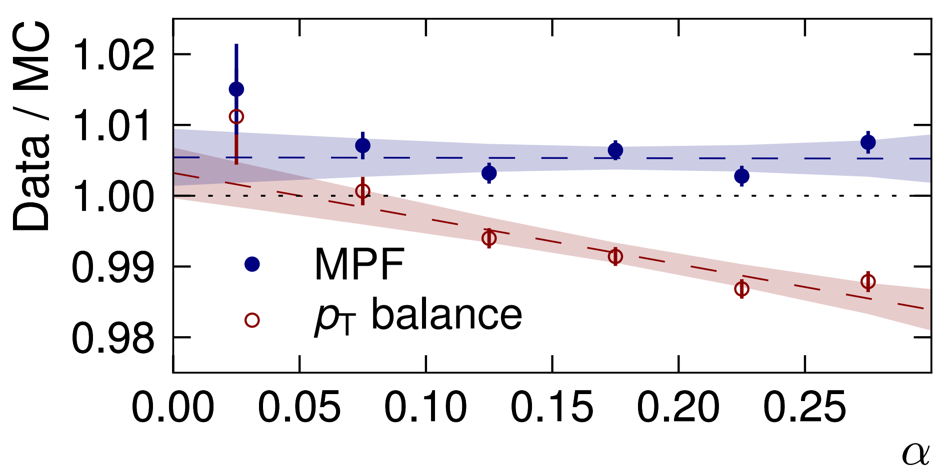
CMS- JME-13-004
arXiv:1607.03663v

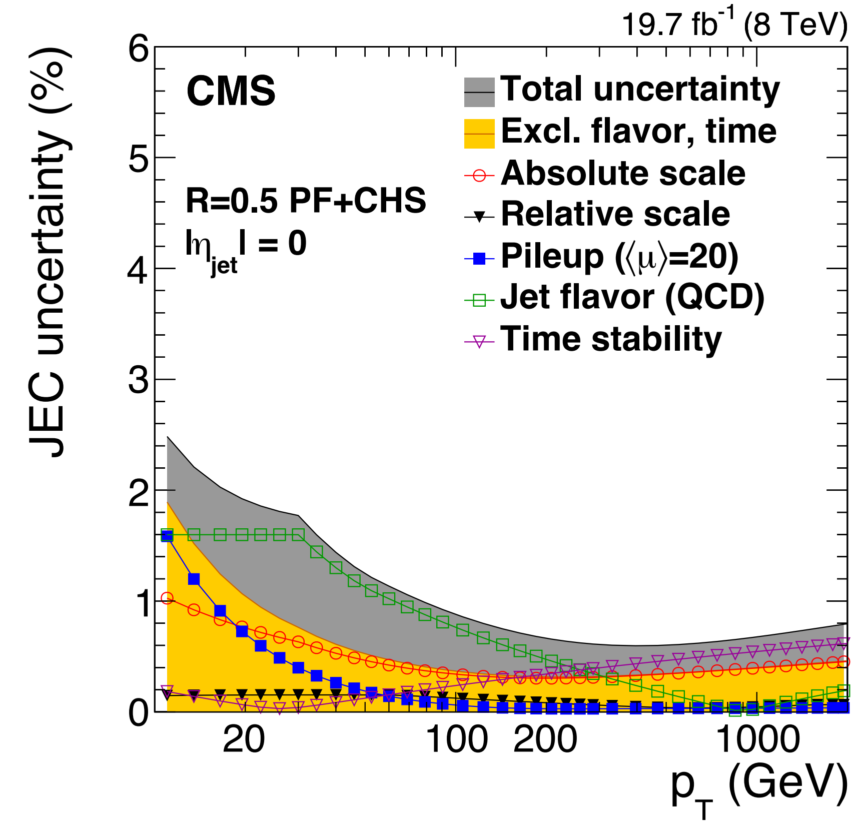
- Absolute correction factor in barrel derived from Z→ μμ+jet
- MPF and pT balance methods used for calibration

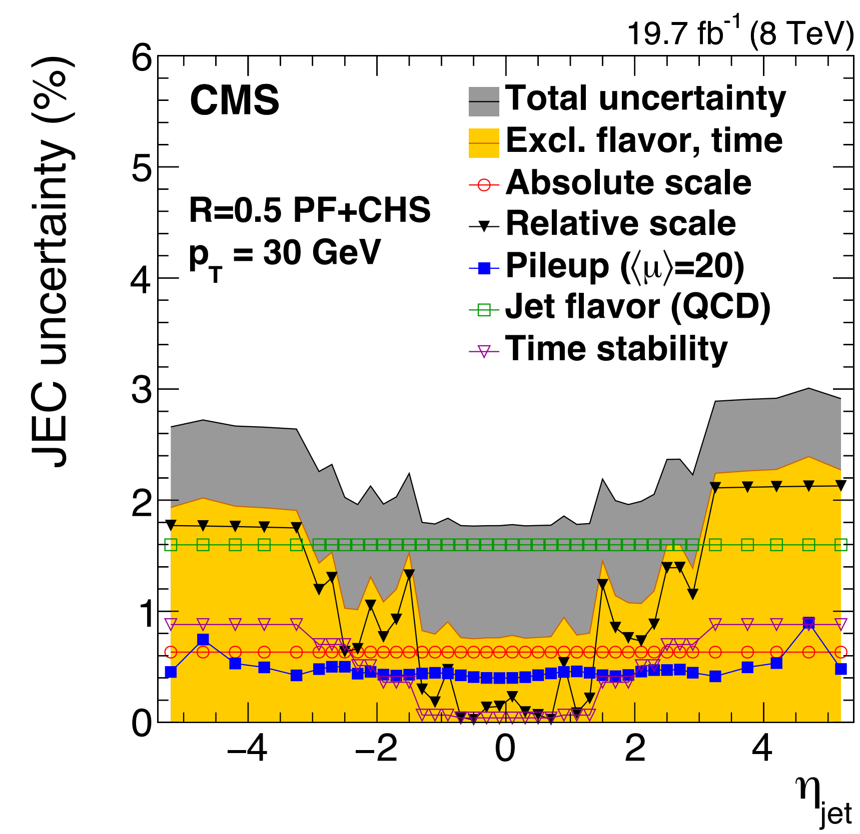
$$R_{\text{balance}} = \frac{p_T^{jet}}{p_T^{\gamma}} \quad R_{\text{MPF}} = 1 + \frac{\vec{E}_T^{miss} \cdot \vec{p}_T^{\,\gamma}}{(p_T^{\gamma})^2}$$







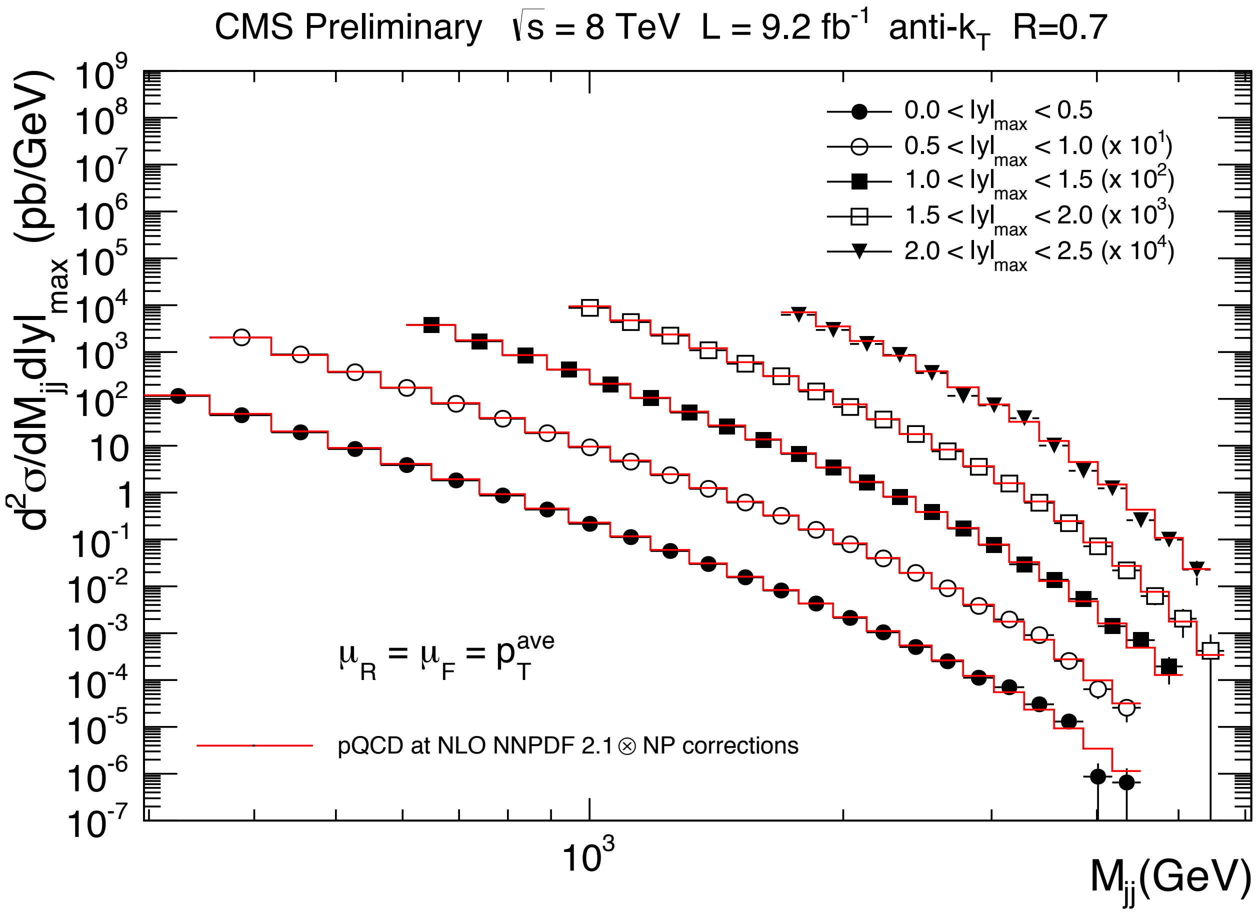


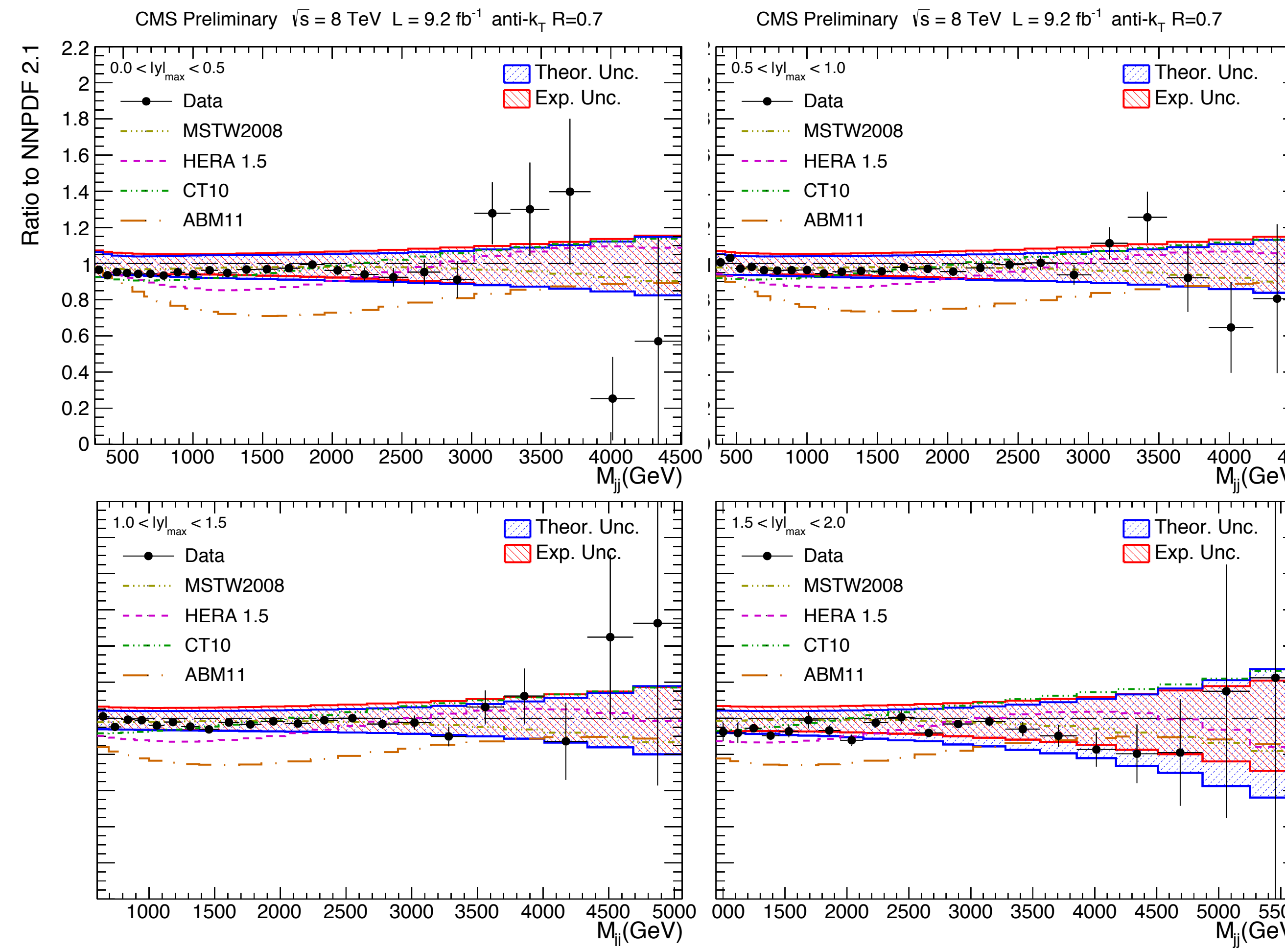


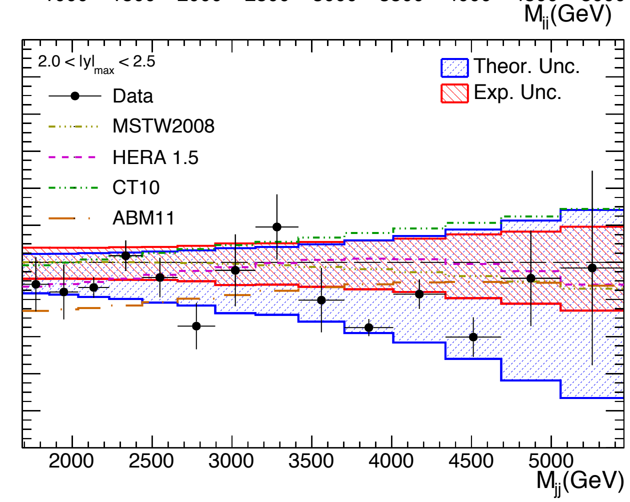
Jets Measurements with CMS Data

Dijet Mass Production Cross Section at 8 TeV

CMS-SMP-14-002







The invariant mass of the two jets can be given in terms of proton momentum fractions $x_{1,2}$

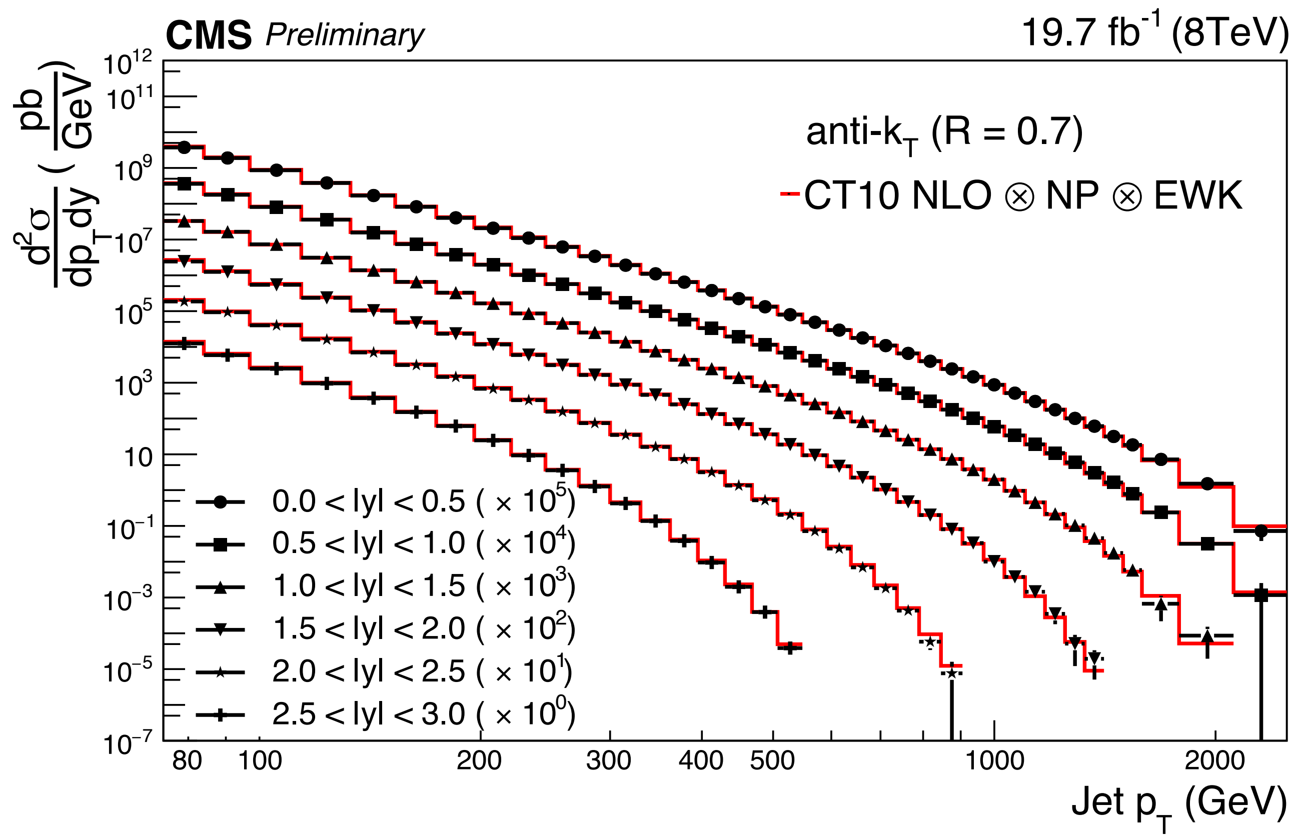
The dijet cross section as a function of Mjj^2 can be precisely calculated in perturbative QCD and it also allows sensitive searches for physics beyond the Standard Model, such as dijet narrow resonances or contact interaction searches.

Ratio of the dijet cross section to the theoretical prediction using the central value of the NNPDF2.1 PDF set for the five different bins. The solid histograms show the ratio of the cross sections calculated with the other PDF sets to that calculated with NNPDF2.1. The experimental and theoretical systematic uncertainties are represented by the red and blue bands, respectively.

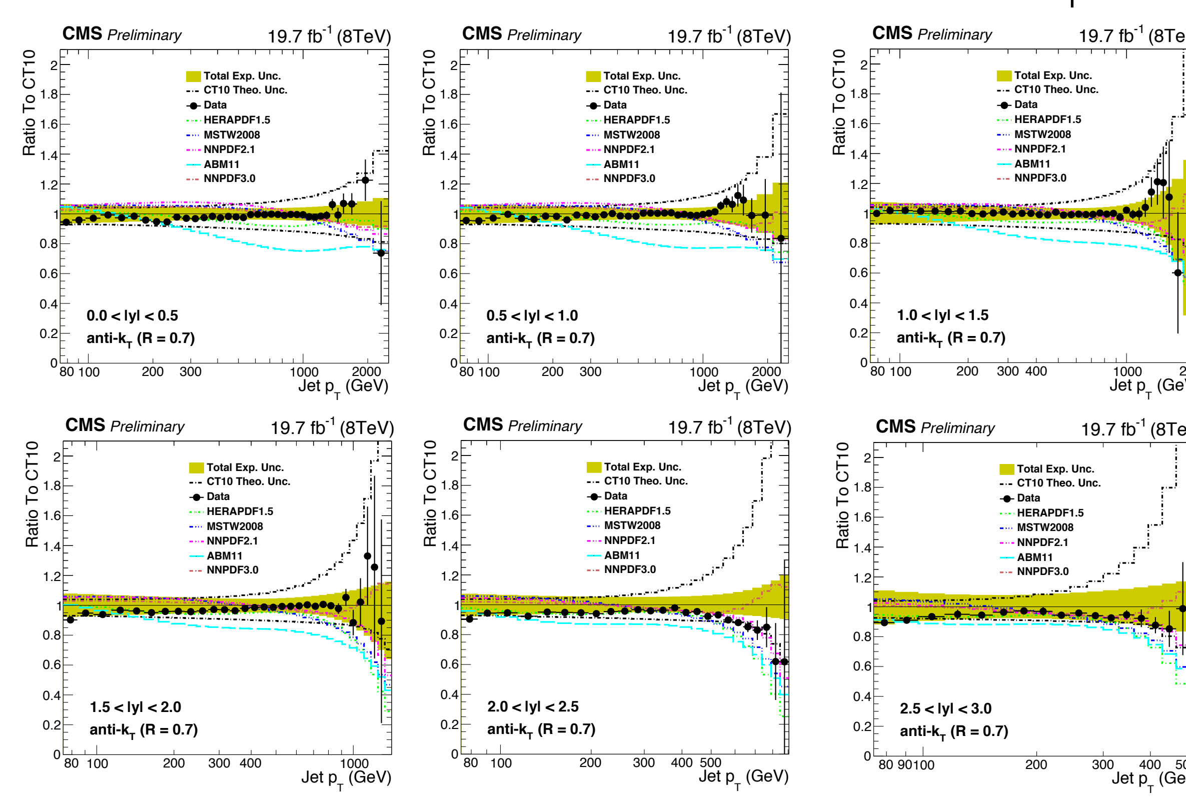
Inclusive Jet Cross Sections @ 8 TeV

CMS-SMP-14-001

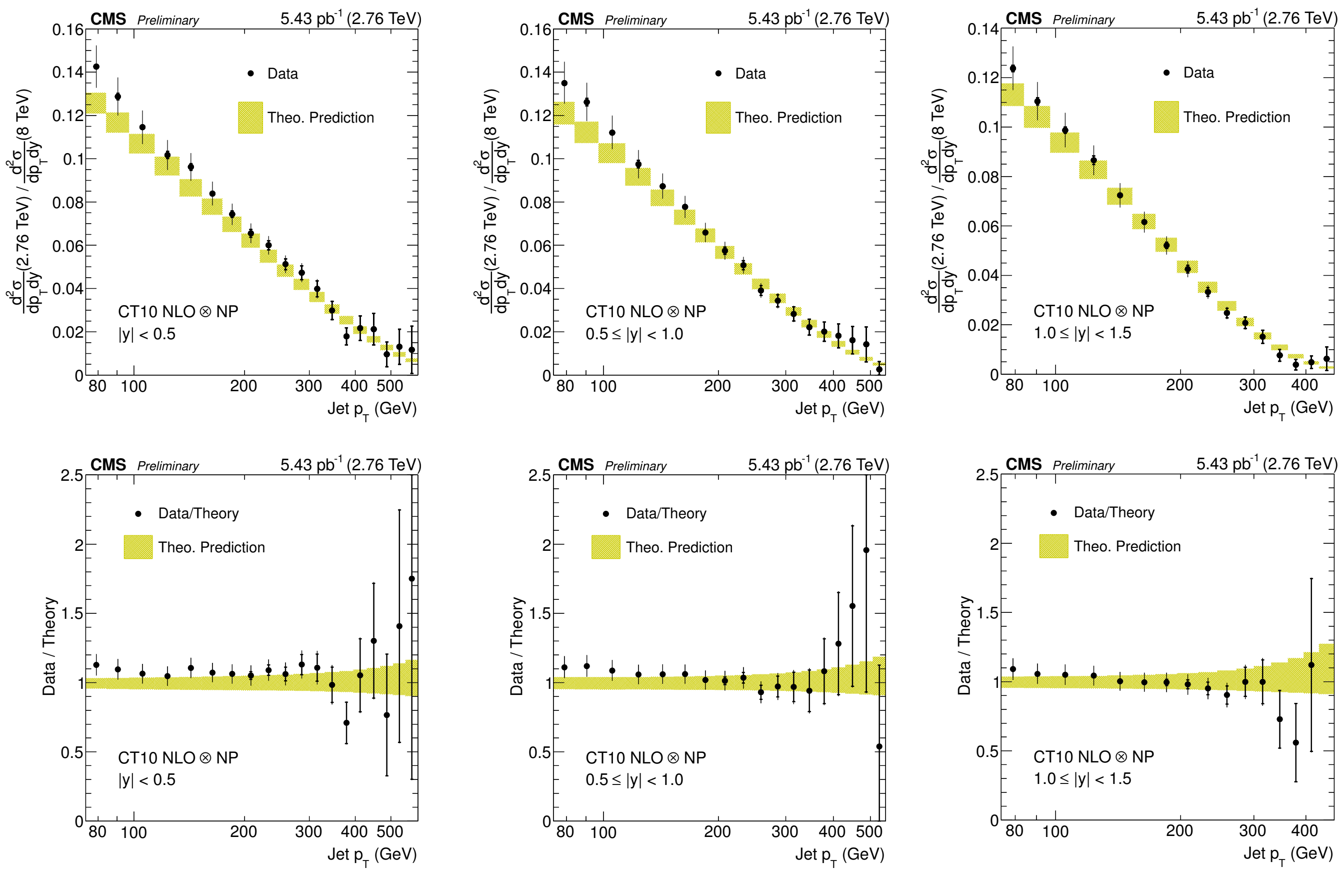
$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}_{\text{int,eff}}} \frac{N_{\text{jets}}}{\Delta p_T \left(2 \cdot \Delta|y|\right)}$$



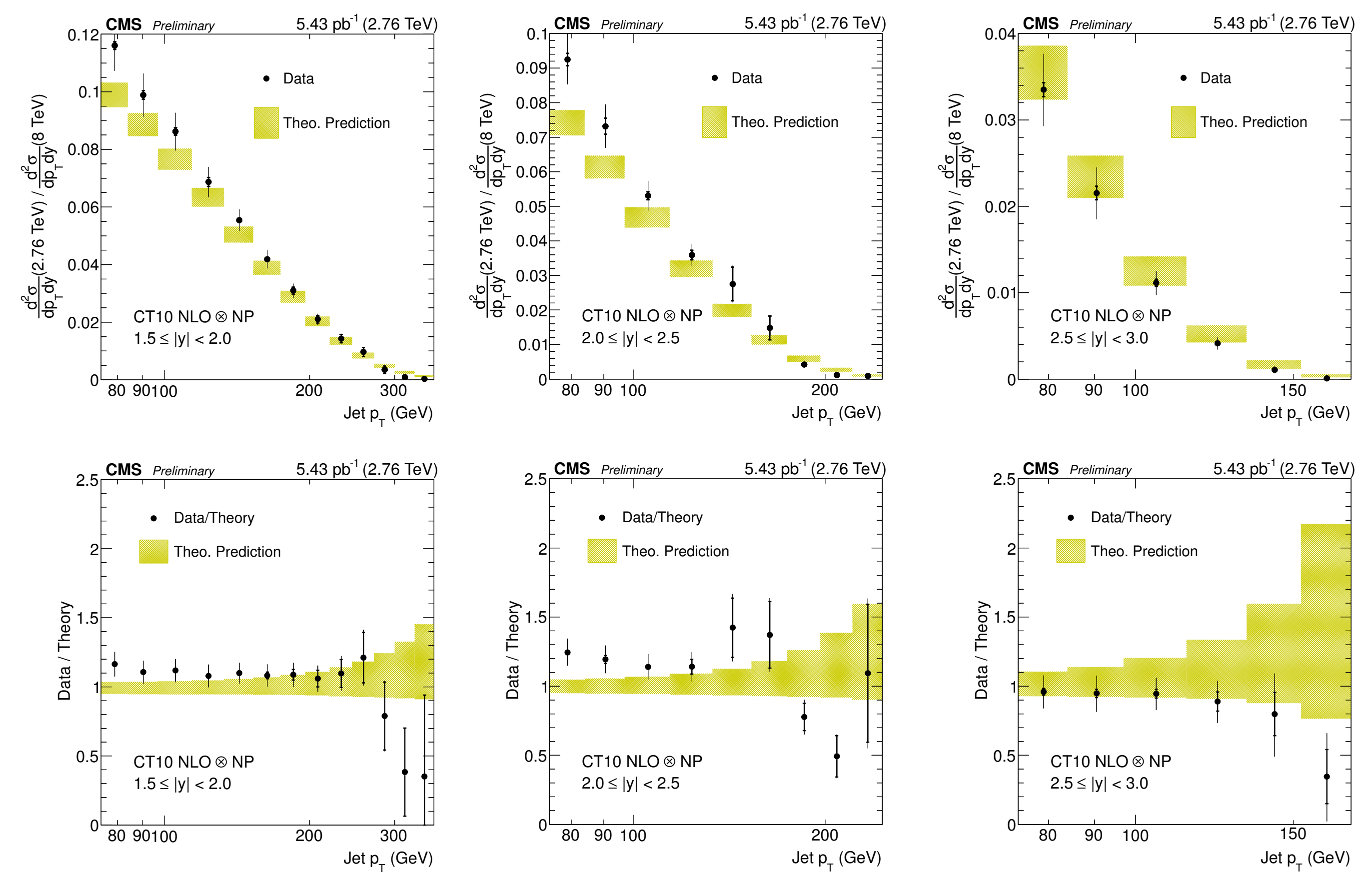
- Unfolded to particle level jet spectra using D'Agositini Multidimensional unfolding method.
- NLO calculations with non-perturbative corrections (NPC) are used for comparison with data. NPC are got as averaged value between NPC got with PYTHIA and HERWIG.
- A set of the different NLO PDFs is used to account for PDF uncertainty. (CT10, HERAPDF1.5, MSTW2008, ABM11, NNPDF2.1 and NNPDF3.0)
- Data are in agreement with NLO calculations within systematic uncertainties.



Ratio of Inclusive Jet Cross Sections @ 2.76 TeV to @ 8 TeV CMS-SMP-14-017



- 2.76 TeV c.o.m energy pp collisions provide essential reference for CMS heavy ion program.
- But also a good opportunity to fill the gap between Tevatron (@1.96 TeV) and LHC (7 & 8 TeV).



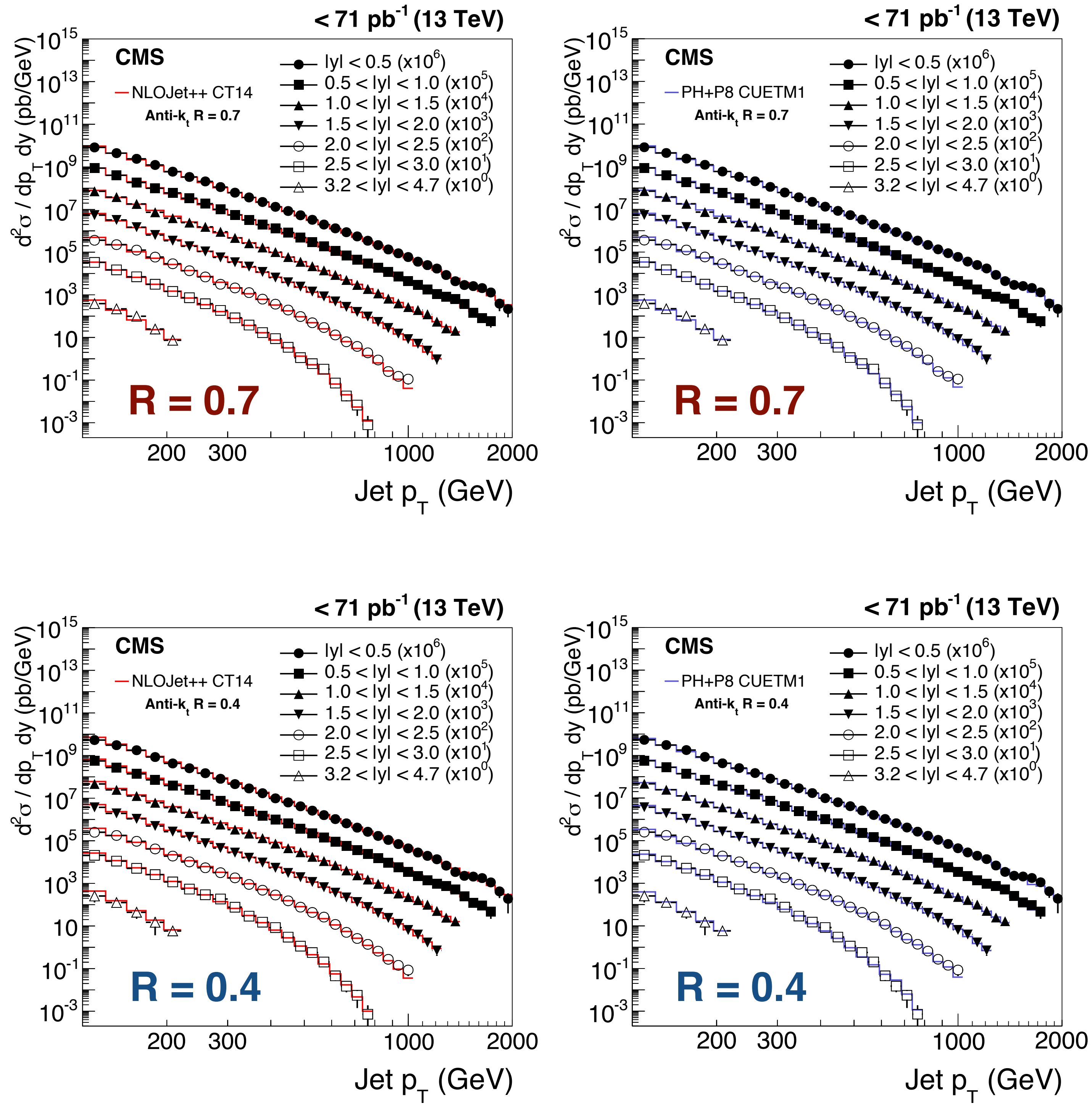
- The ratio of inclusive cross sections @ 2.76 TeV to 8 TeV is potentially PDF sensitive and could be used as an additional element while constraining PDFs.

Inclusive Jet Cross Sections @ 13 TeV

Eur. Phys. J. C 76 (2016) 451

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}} \frac{N_j}{\Delta p_T \Delta y}$$

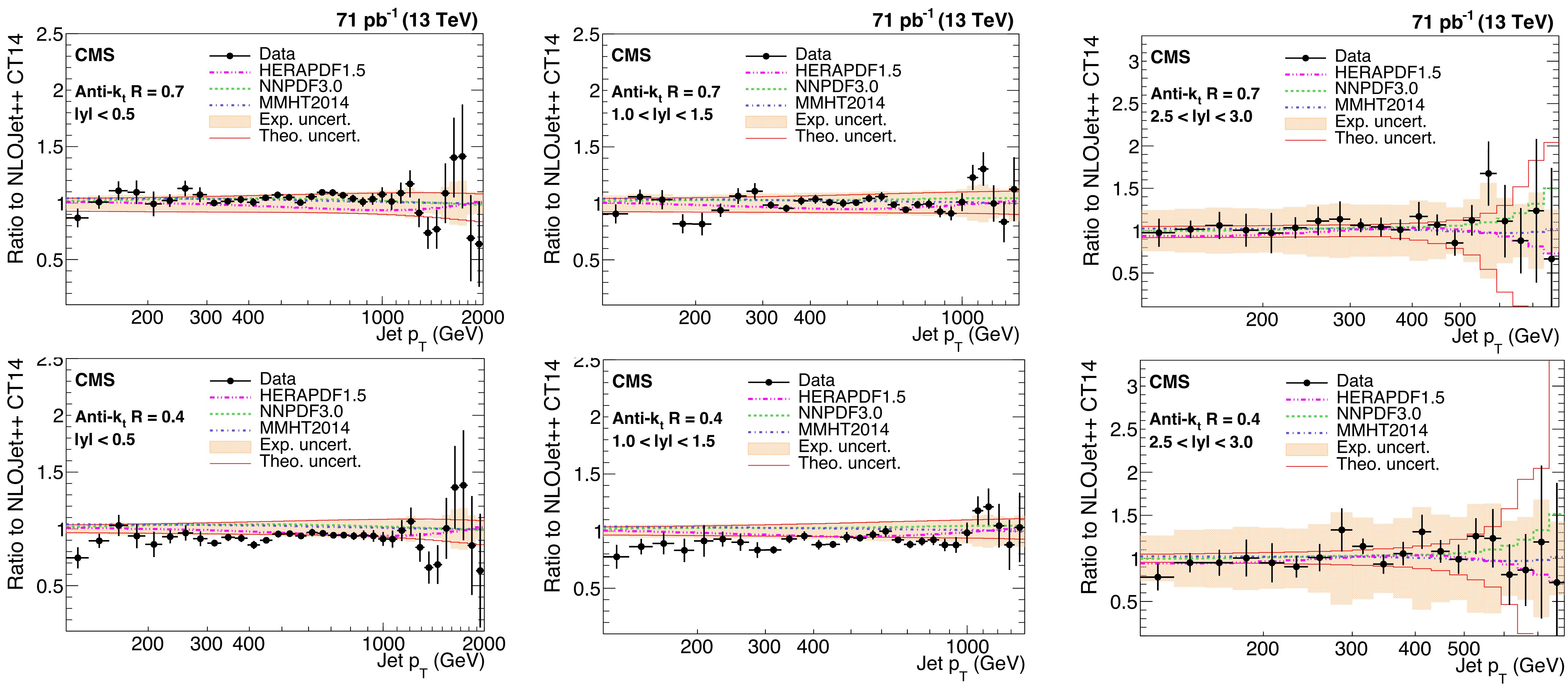
- Unfolded to particle level jet spectra using D'Agositini Multidimensional unfolding method.
- NLO calculations with non-perturbative corrections (NPC) are used for comparison with data. NPC are got as averaged value between NPC got with PYTHIA and HERWIG.
- A set of the different NLO PDFs is used to account for PDF uncertainty. (CT14, HERAPDF1.5, MMHT2014, and NNPDF3.0)
- Data are in agreement with NLO calculations within systematic uncertainties.



Inclusive Jet Cross Sections @ 13 TeV

Eur. Phys. J. C 76 (2016) 451

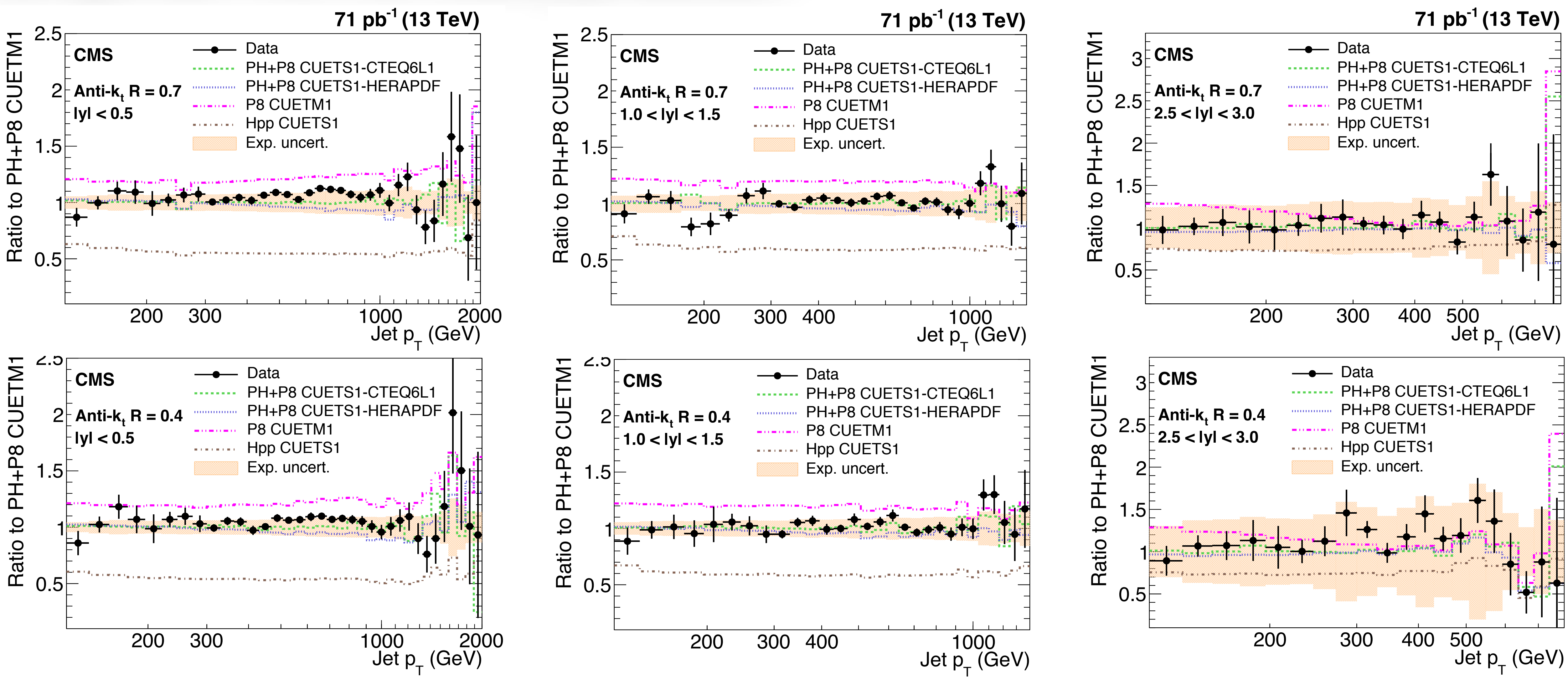
Comparison with the theory prediction



Inclusive Jet Cross Sections @ 13 TeV

Eur. Phys. J. C 76 (2016) 451

Comparison with the theory prediction



- Jet cross sections for R = 0.7 are accurately described !
- However, for R = 0.4, theory overestimates the cross section by 5–10% almost everywhere!
- POWHEG + PYTHIA8 for two different tunes, perform equally well for R = 0.4 and R= 0.4
- This result is consistent with the previous measurement* performed at $\sqrt{s}$ = 7 TeV

* Phys. Rev. D 90 (2014) 072006

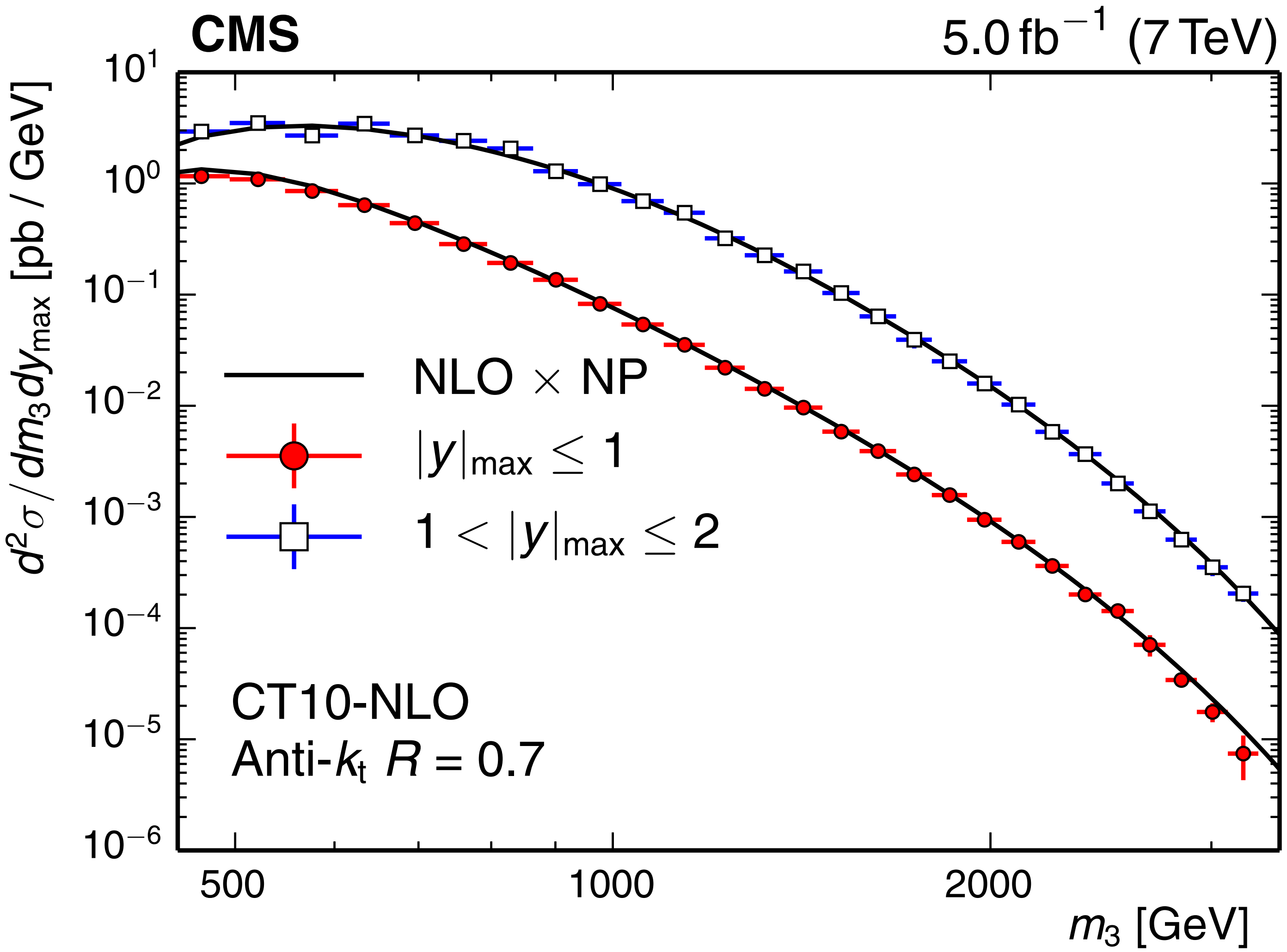
Inclusive 3-Jet Production

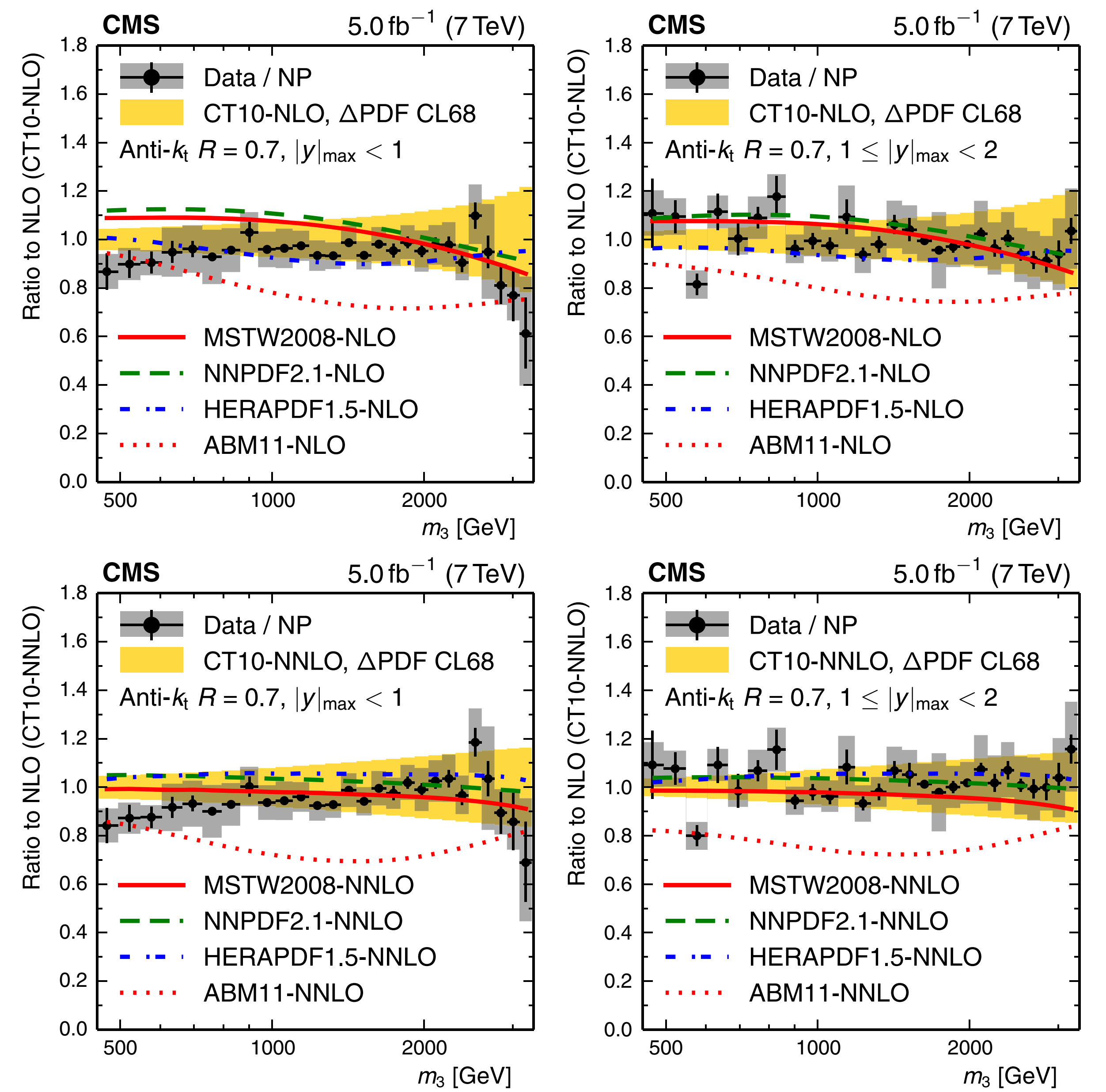
Eur. Phys. J. C (2015) 75:186

$$\frac{d^2\sigma}{dm_3\, dy_{max}} = \frac{1}{\epsilon\mathcal{L}} \frac{N}{\Delta m_3 (2\Delta|y|_{max})}$$

$$m_3^2 = (p_1 + p_2 + p_3)^2$$

$$y_{max} = \mathrm{sgn}(|\max(y_1, y_2, y_3)| - |\min(y_1, y_2, y_3)|).\max(|y_1|, |y_2|, |y_3|)$$





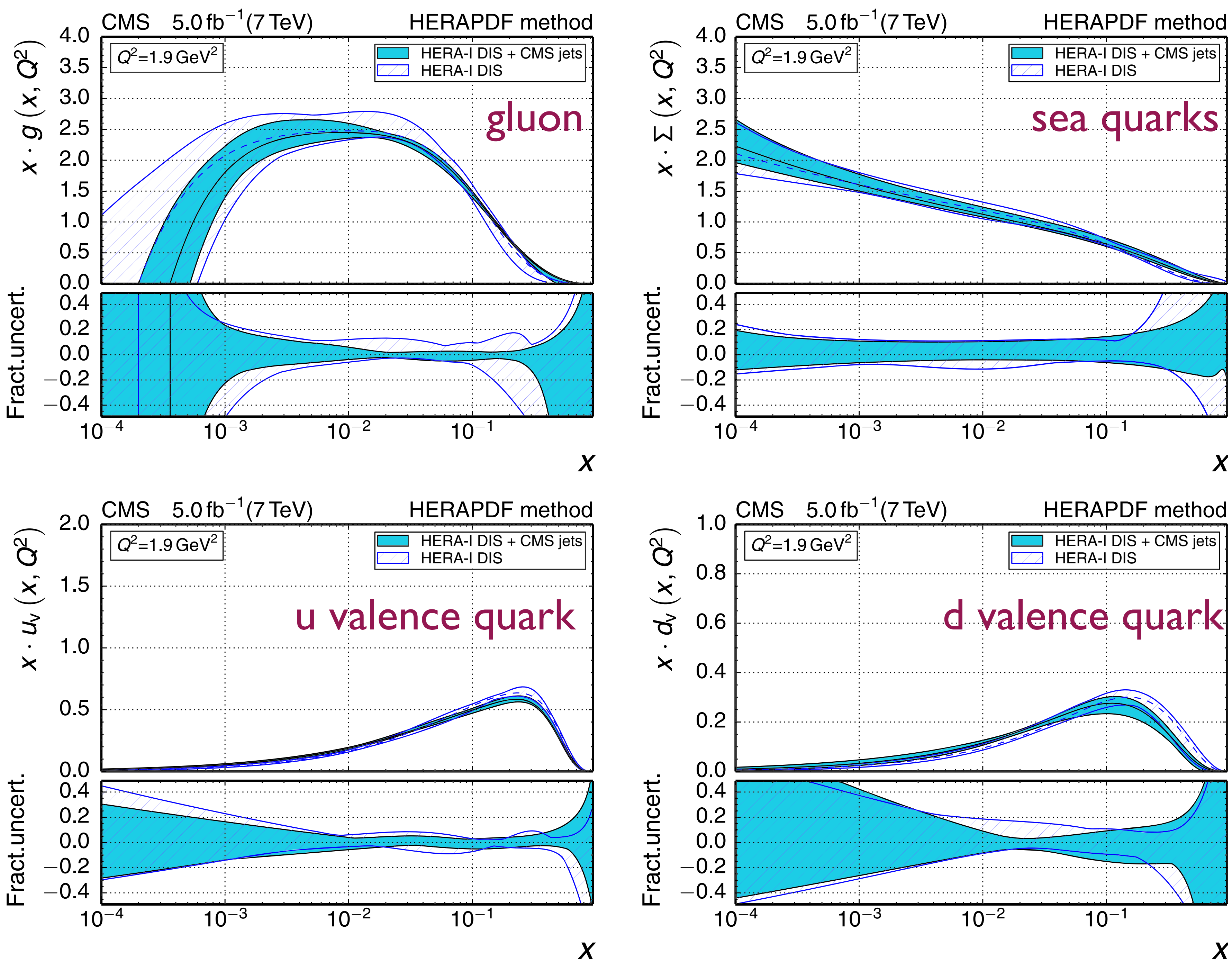
Within experimental and theoretical uncertainties, which are of comparable size, the data are in agreement with predictions of perturbative QCD at next-to-leading order.

PDF Constraints &
Strong Coupling Constant
$\alpha_S(Q)$
from Jet Measurements

Constraints on PDF from the inclusive jet cross section in pp collisions @ $\sqrt{s}$ = 7 TeV

Eur. Phys. J. C (2015) 75:288

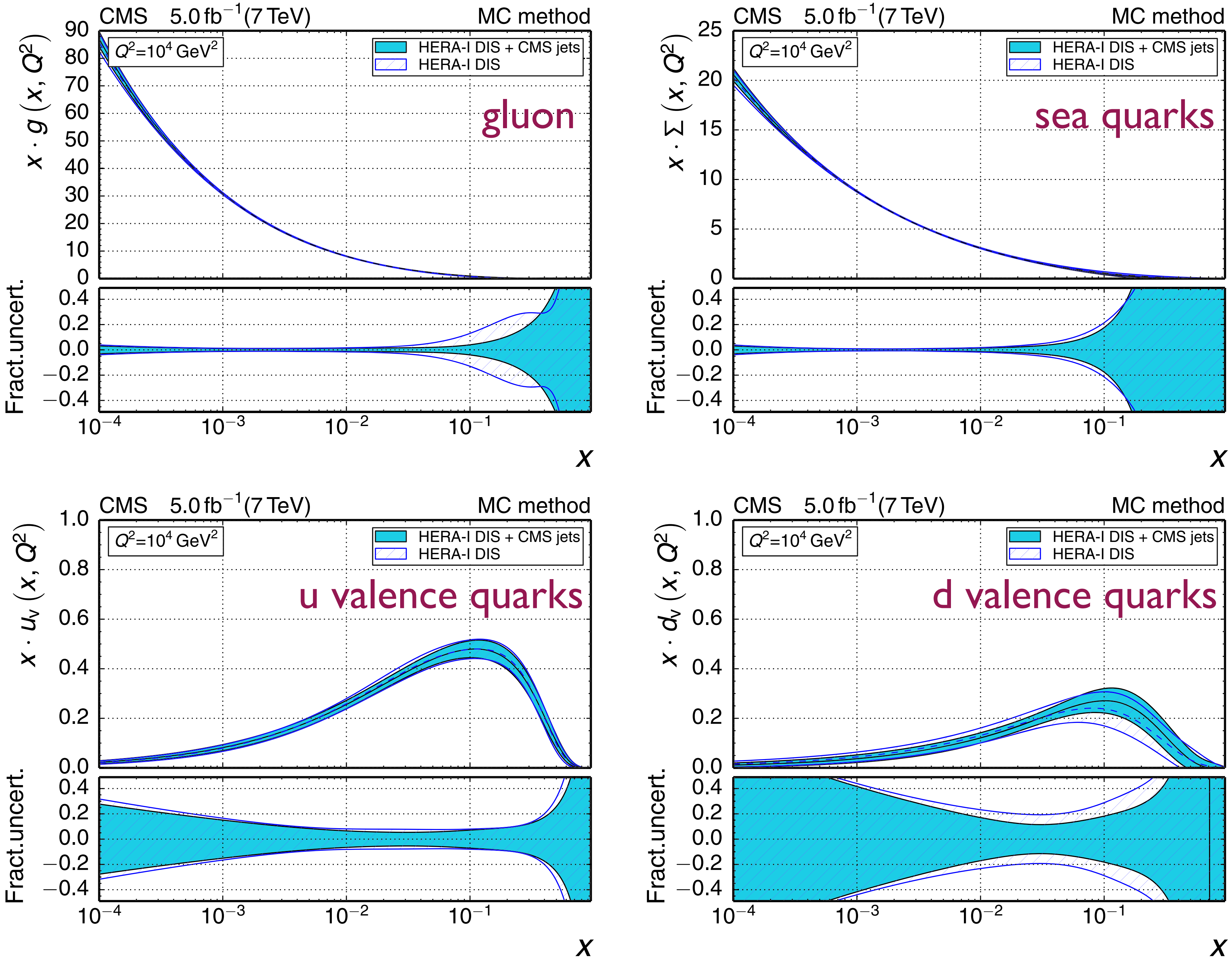
u/d valence quarks, sea quarks and gluon PDFs from HERA-I DIS and HERA-I DIS⊕CMS with HERAPDF method



Constraints on PDF from the inclusive jet cross section in pp collisions @ $\sqrt{s}$ = 7 TeV

Eur. Phys. J. C (2015) 75:288

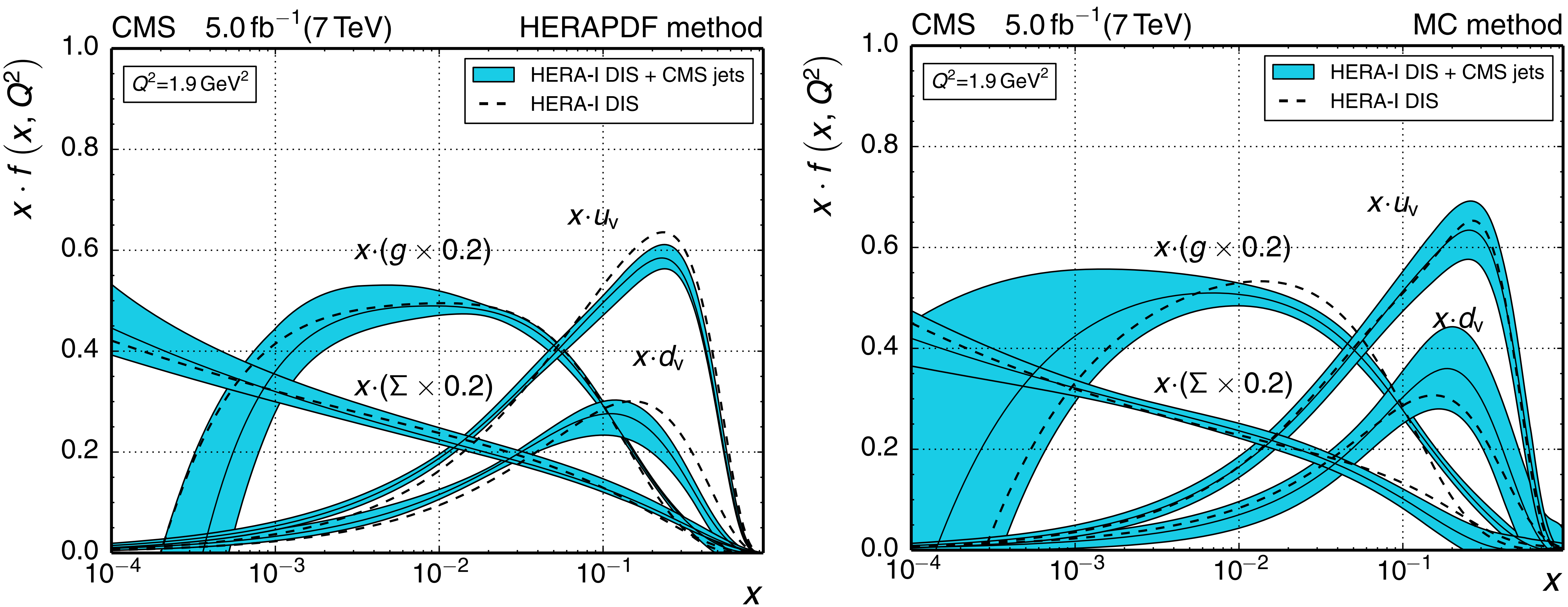
u/d valence quarks, sea quarks and gluon PDFs from HERA-I DIS and HERA-I DIS⊕CMS with MC method



Constraints on PDF from the inclusive jet cross section in pp collisions @ $\sqrt{s}$ = 7 TeV

Eur. Phys. J. C (2015) 75:288

Overview of the gluon, sea, u valence, and d valence PDFs before (dashed line) and after (full line) including the CMS inclusive jet data into the fit.

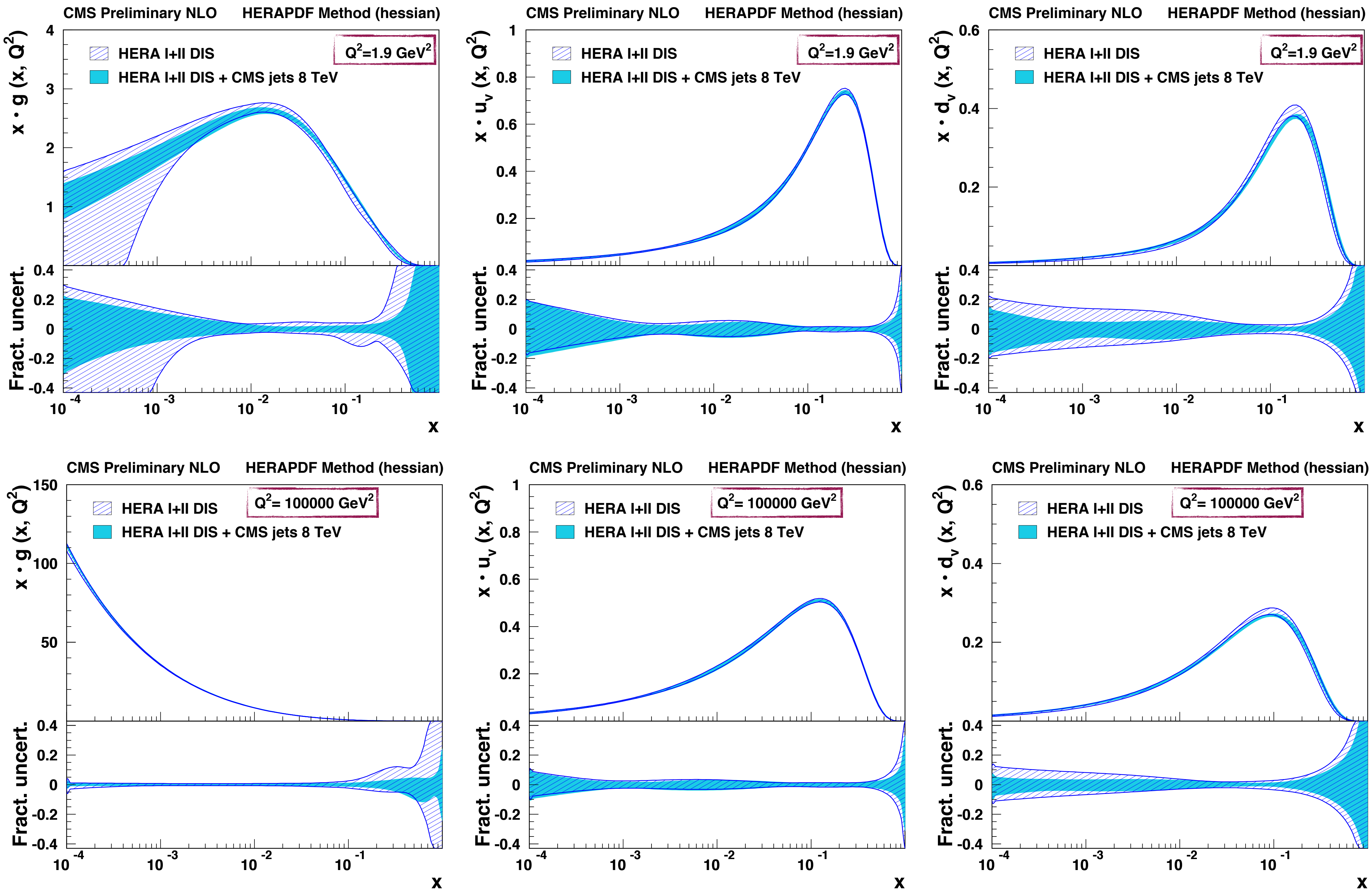


The plots show the PDF fit outcome from the HERAPDF method (top) and from the MC method with data-derived regularisation (bottom). The PDFs are shown at the starting scale Q^2= 1.9GeV^2

Constraints on PDF from the inclusive jet cross section in pp collisions @ $\sqrt{s}$ = 8 TeV

CMS-SMP-14-001

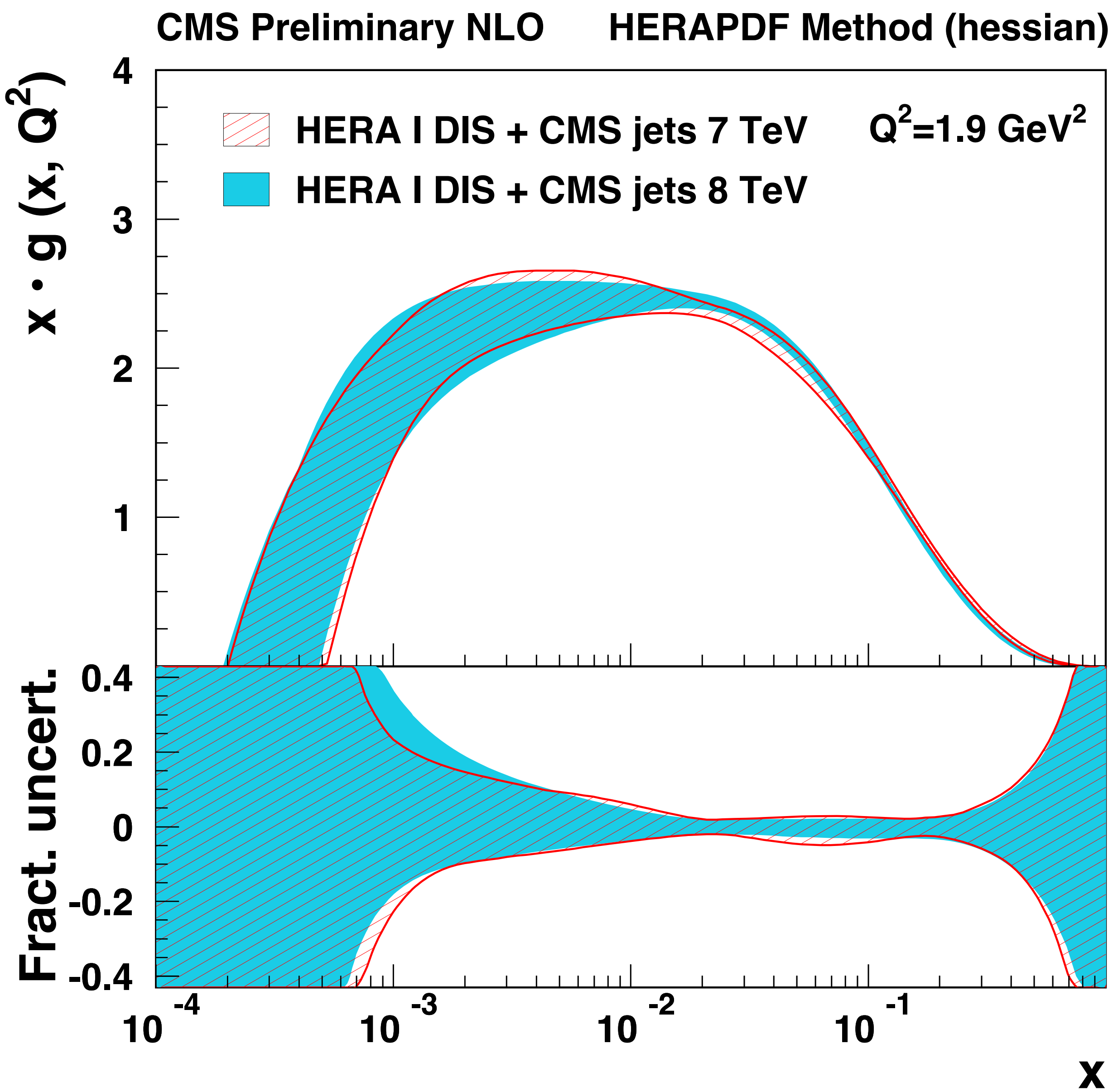
u/d valence quarks and gluon PDFs from HERA-I DIS and HERA-I DIS⊕CMS with HERAPDF method for Q^2 =1.9 GeV^2 and Q^2 =100000 GeV^2

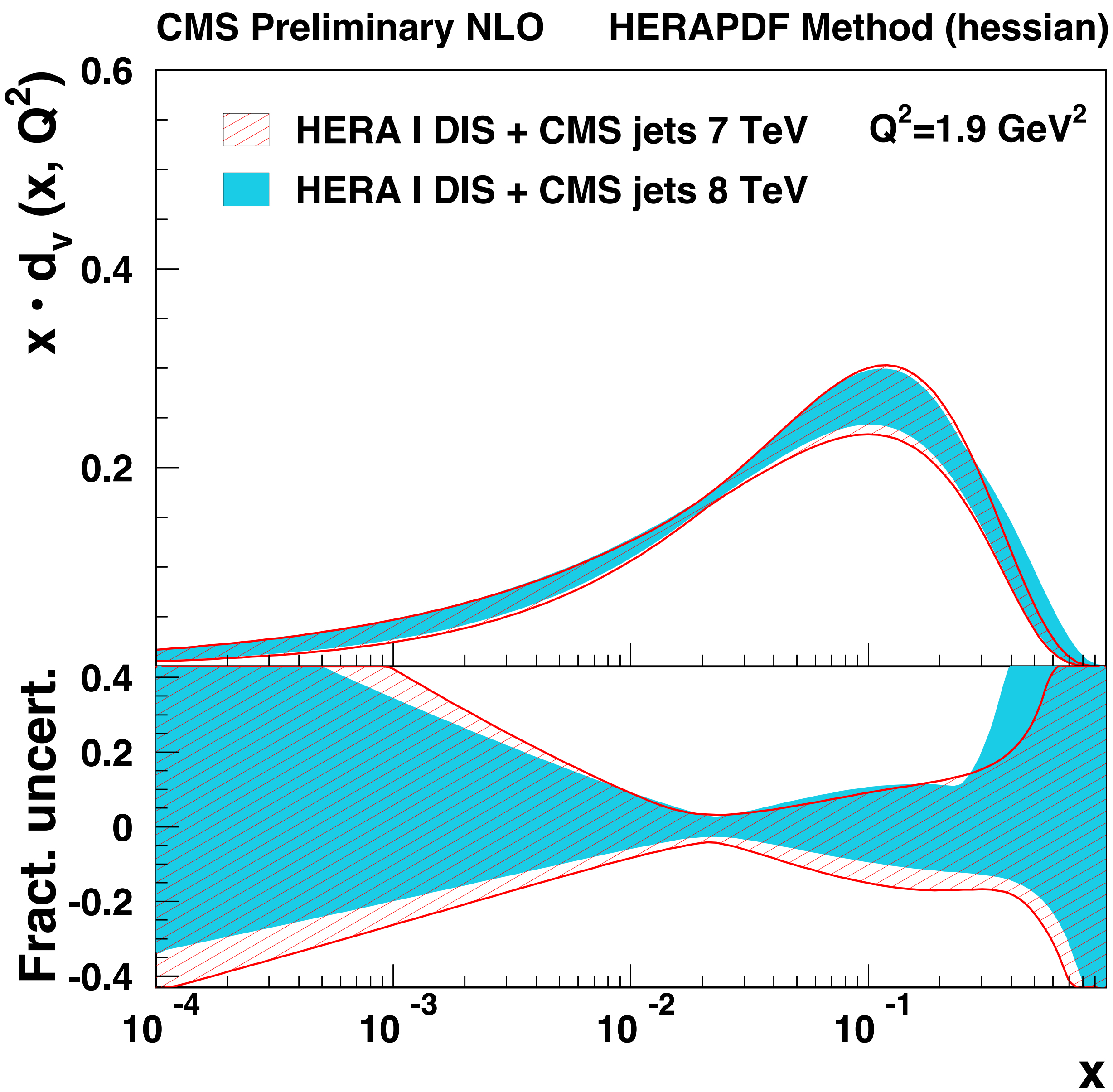


Constraints on PDF from the inclusive jet cross section in pp collisions @ $\sqrt{s}$ = 8 TeV

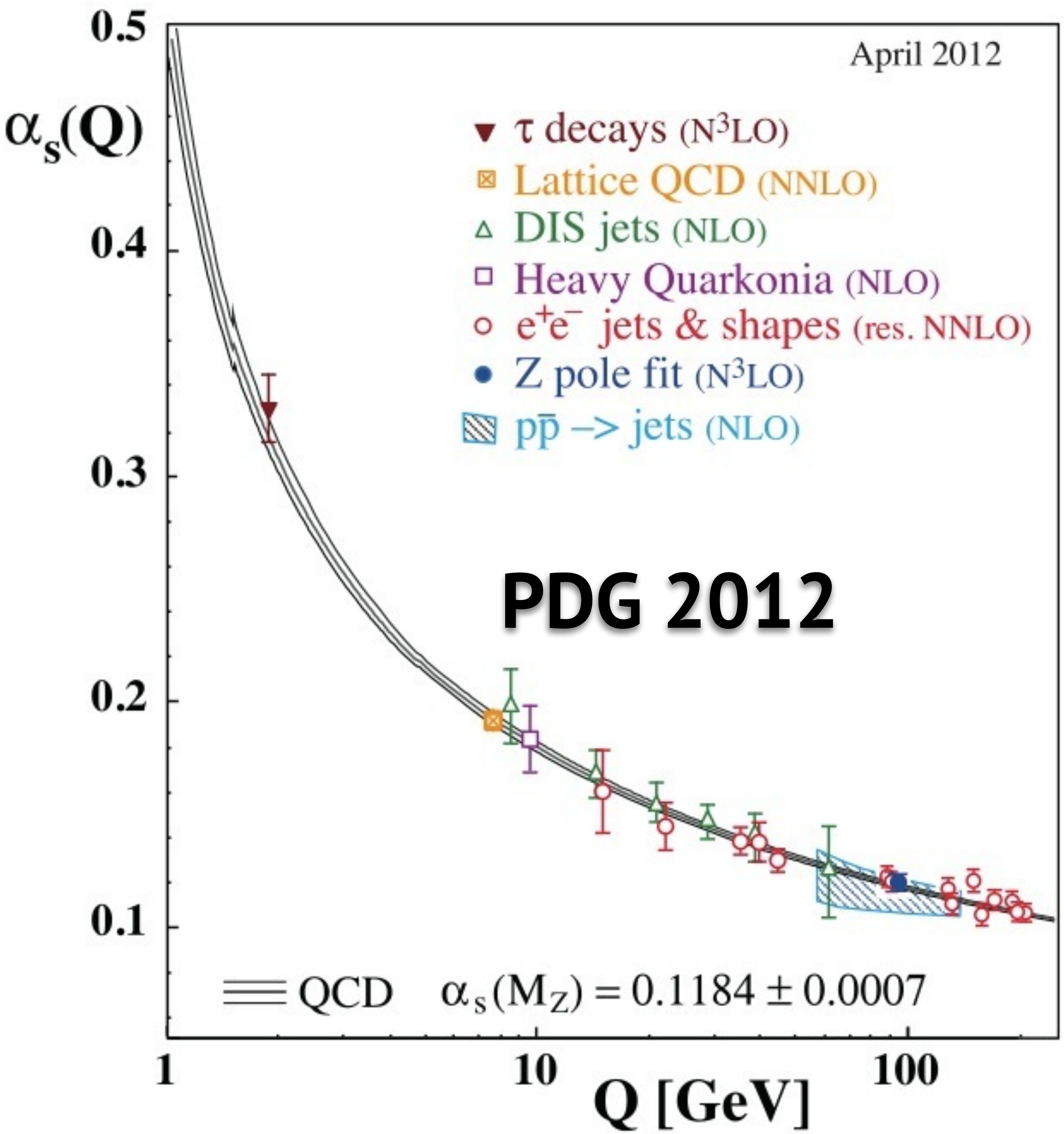
CMS-SMP-14-001

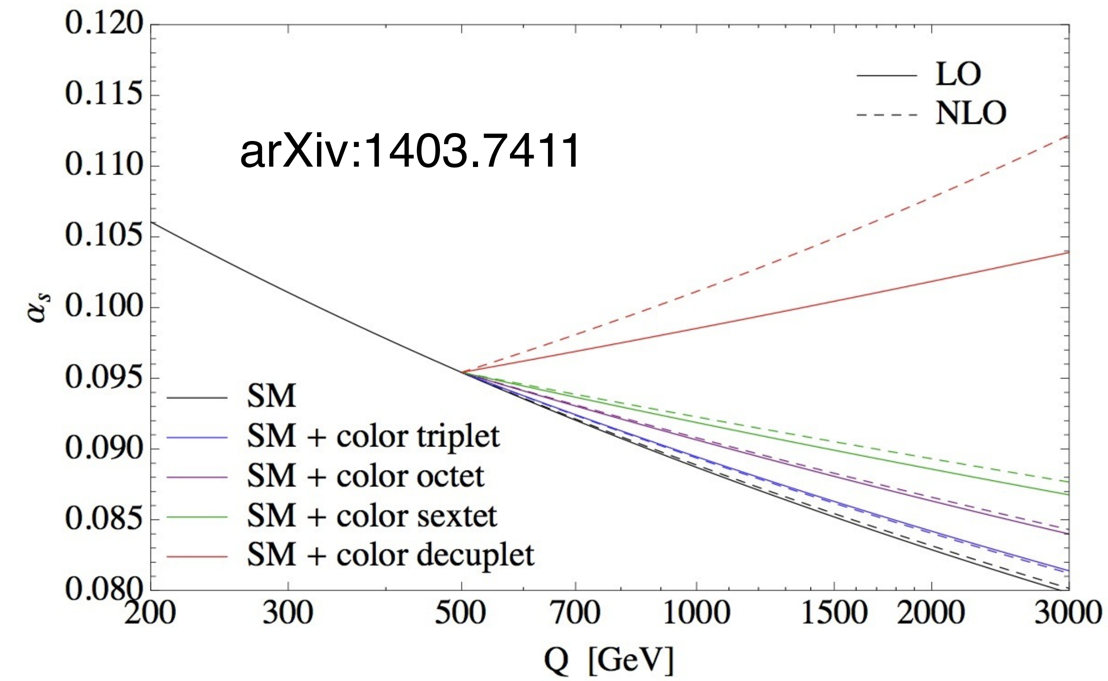
Comparison of 7 TeV and 8 TeV results

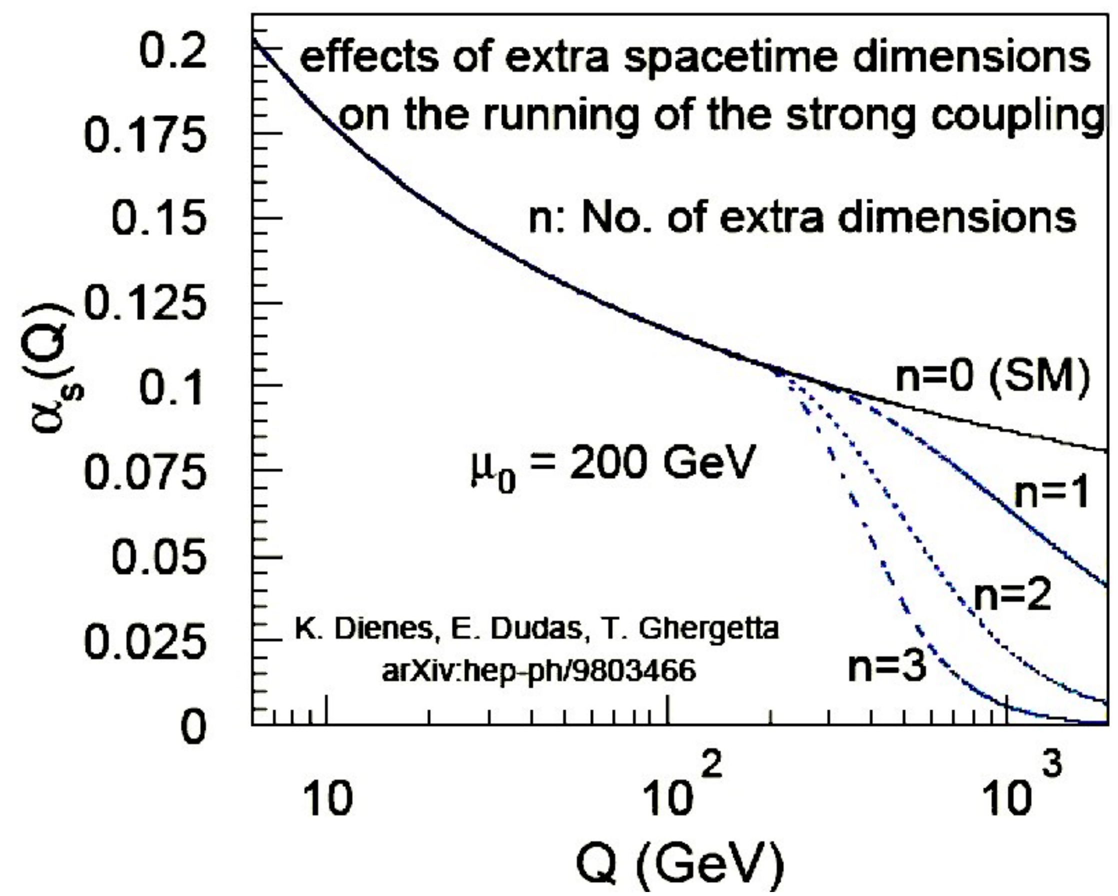




Sensitivity to Strong Coupling







$\alpha_S(Q)$ from 3-jet to 2-jet Cross Sections

Eur.Phys.J. C73 (2013) 2604

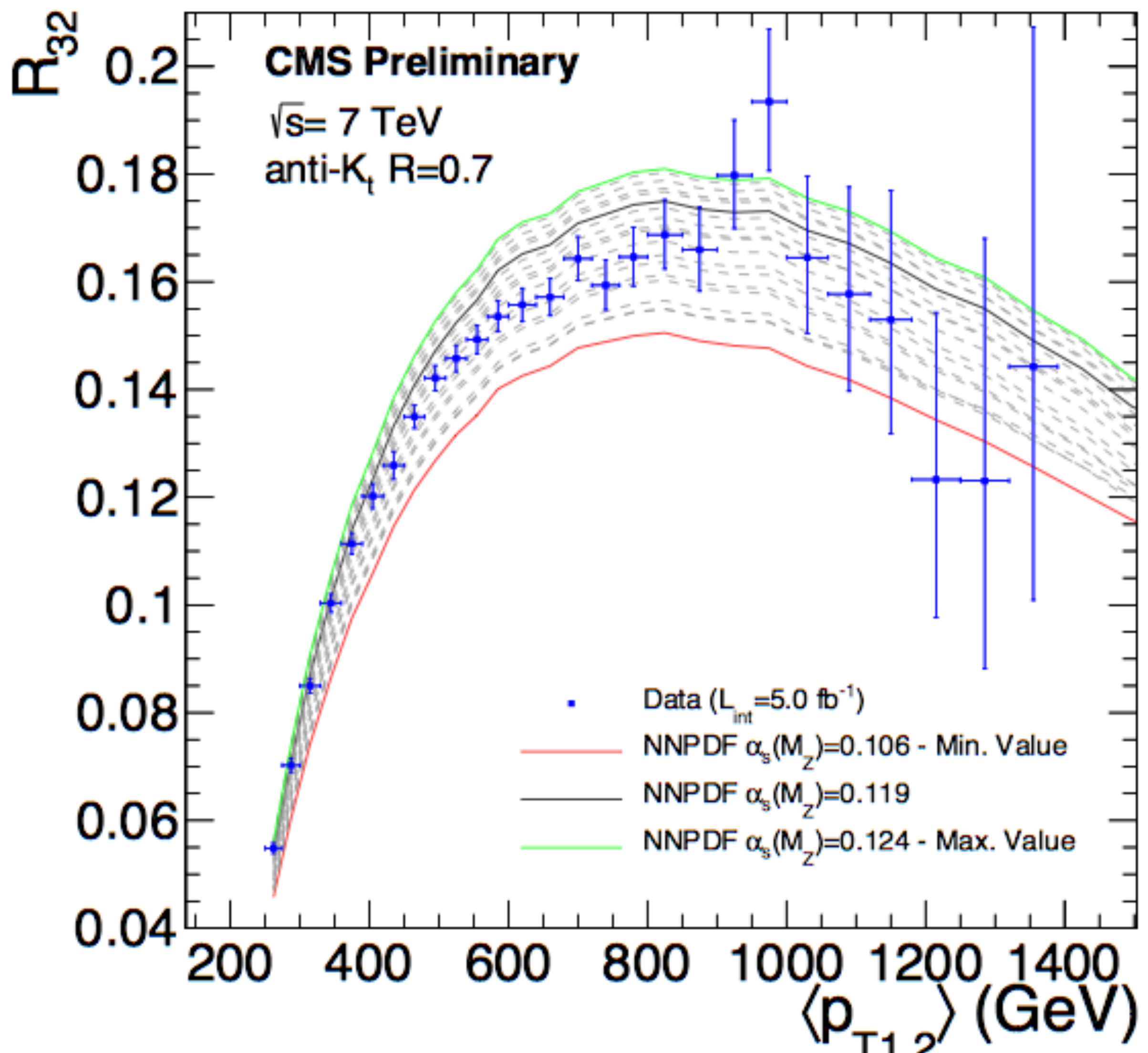
Determination of the strong coupling at transverse momenta in the TeV range

The $\alpha_S(M_Z)$ has been varied in the range:

0.106-0.124	for	NNPDF2.1
0.104-0.120		ABM11
0.107-0.127		MSTW2008
0.110-0.130		CT10

in steps of 0.001

The value of $\alpha_S(M_Z)$ is by minimising the χ^2 between the experimental measurement and the theoretical predictions



using the NNPDF2.1 PDF sets is

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\ (\text{exp.}) \pm 0.0018\ (\text{PDF}) \pm 0.0050 (\text{theory})$$

world average: 0.1184 ± 0.0007

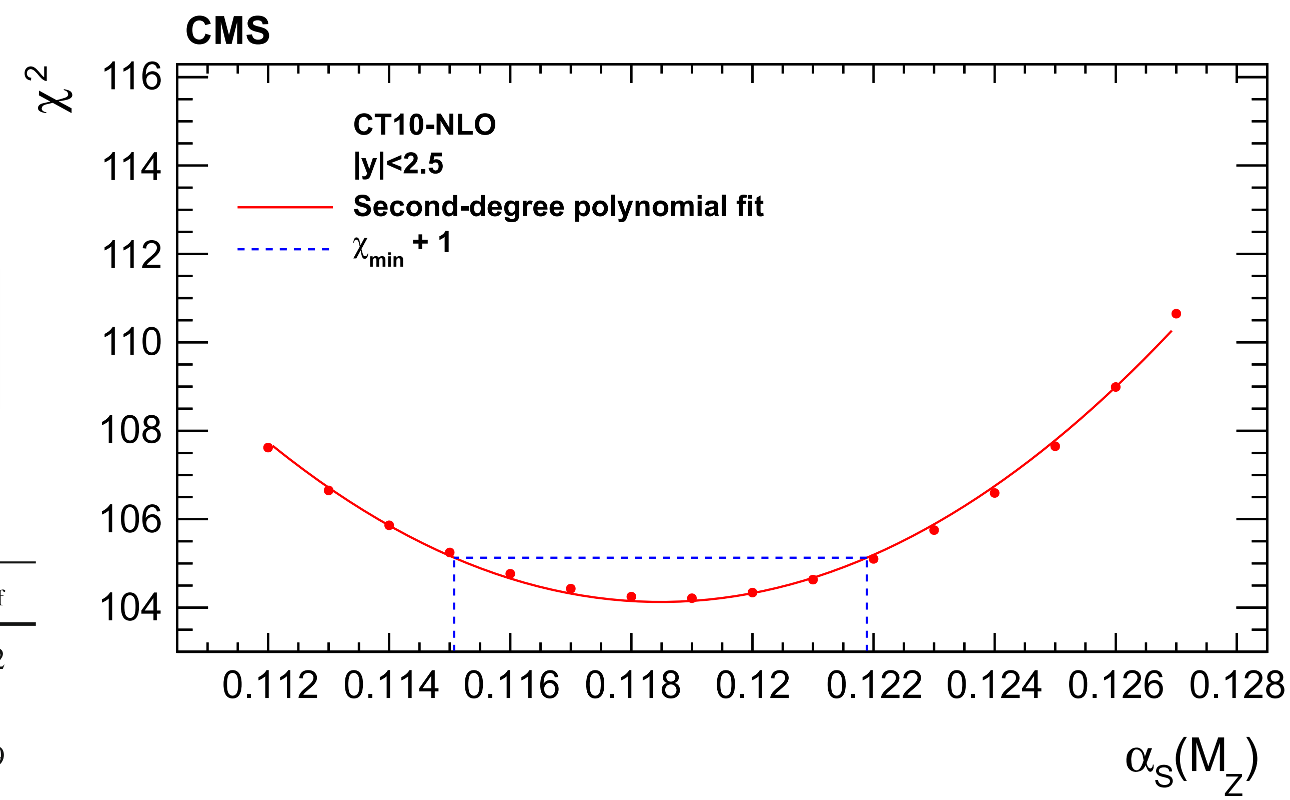
The NLO predictions using the NNPDF2.1 NNLO PDF set for a series of $\alpha_S(M_Z)$ values of together with the measured R32. $\alpha_S(M_Z)$ has been varied in the range 0.106-0.124, 0.104-120, 0.107-0.127 and 0.110-0.130 in steps of 0.001 for NNPDF2.1, ABM11, MSTW2008 and CT10 respectively.

$\alpha_S(Q)$ from Inclusive Jet Cross Section

Eur. Phys. J. C (2015) 75:288

Using predictions from theory at next-to-leading order, complemented with electroweak corrections, the strong coupling constant is determined from the inclusive jet cross section to be:

$$\alpha_S(M_Z) = 0.1185 \pm 0.0019(\text{exp.}) \pm 0.0028(\text{PDF}) \pm 0.0004(\text{NP})^{+0.0053}_{-0.0024}(\text{scale})$$



$\|y\|$ range	No. of data points	$\alpha_S(M_Z)$	χ^2/n_{dof}
$\|y\| < 0.5$	33	0.1189 ± 0.0024 (exp) ± 0.0030 (PDF) ± 0.0008 (NP)$^{+0.0045}_{-0.0027}$ (scale)	16.2/32
$0.5 \leq \|y\| < 1.0$	30	0.1182 ± 0.0024 (exp) ± 0.0029 (PDF) ± 0.0008 (NP)$^{+0.0050}_{-0.0025}$ (scale)	25.4/29
$1.0 \leq \|y\| < 1.5$	27	0.1165 ± 0.0027 (exp) ± 0.0024 (PDF) ± 0.0008 (NP)$^{+0.0043}_{-0.0020}$ (scale)	9.5/26
$1.5 \leq \|y\| < 2.0$	24	0.1146 ± 0.0035 (exp) ± 0.0031 (PDF) ± 0.0013 (NP)$^{+0.0037}_{-0.0020}$ (scale)	20.2/23
$2.0 \leq \|y\| < 2.5$	19	0.1161 ± 0.0045 (exp) ± 0.0054 (PDF) ± 0.0015 (NP)$^{+0.0034}_{-0.0032}$ (scale)	12.6/18
$\|y\| < 2.5$	133	0.1185 ± 0.0019 (exp) ± 0.0028 (PDF) ± 0.0004 (NP)$^{+0.0053}_{-0.0024}$ (scale)	104.1/132

$\alpha_S(Q)$ from Three Jet Mass

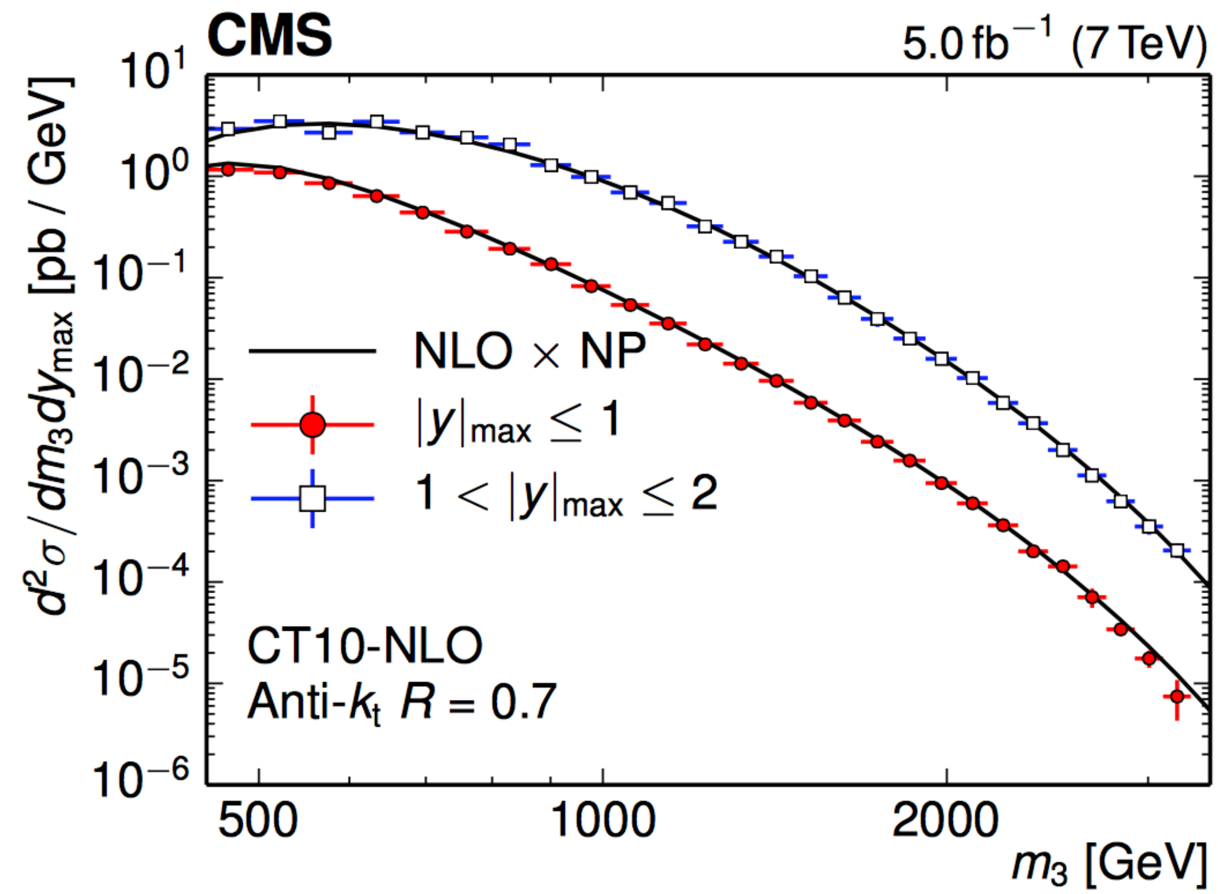
Eur. Phys. J. C (2015) 75:186

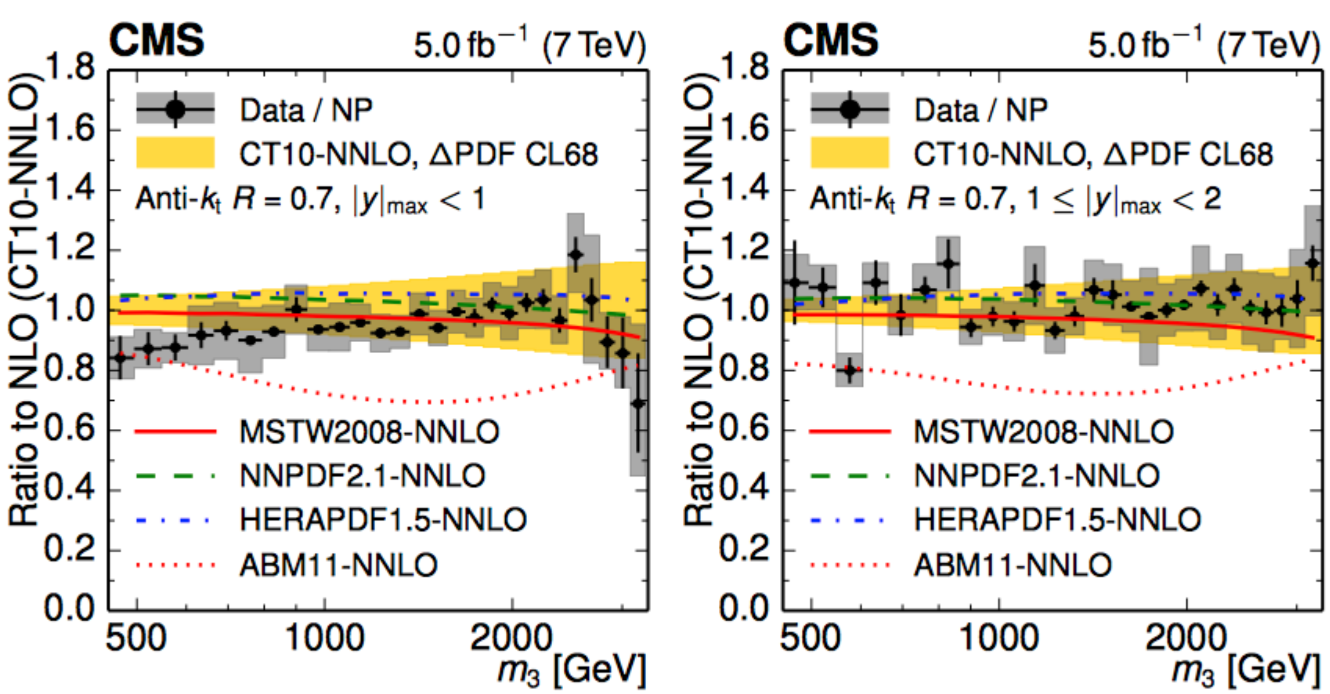
- Measurement of double differential cross section:

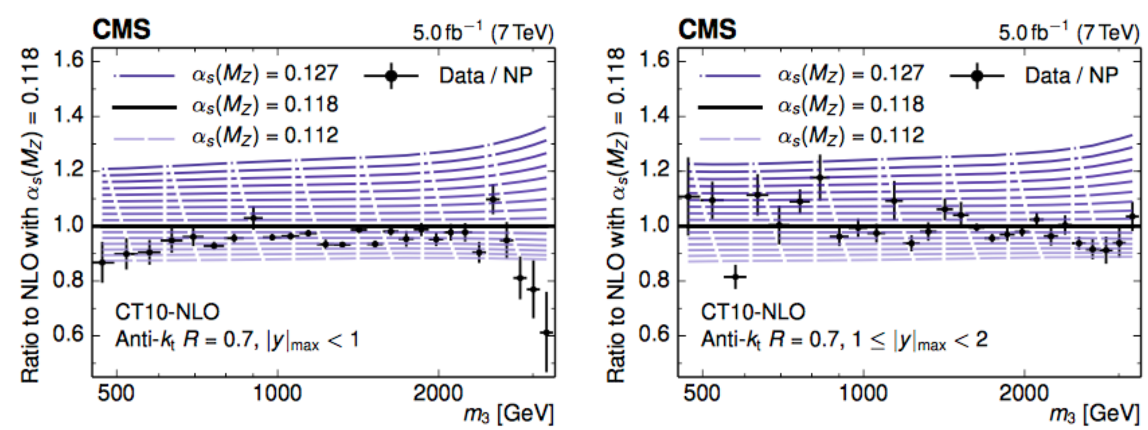
$$\frac{d^2\sigma}{dm_3\, dy_{\max}} = \frac{1}{\epsilon\mathcal{L}} \frac{N}{\Delta m_3 (2\Delta|y|_{\max})}$$

$$m_3^2 = (p_1 + p_2 + p_3)^2 \quad |y|_{\max} = \max(|y_1|, |y_2|, |y_3|)$$

- Sensitive to PDFs and αs
- Require jet pT > 100 GeV
- Two rapidity bins: $|y|_{max} < 1$ and $1 < |y|_{max} < 2$
- Scale choice: $\mu_r = \mu_f$ = m3/2
- Good agreement with pQCD



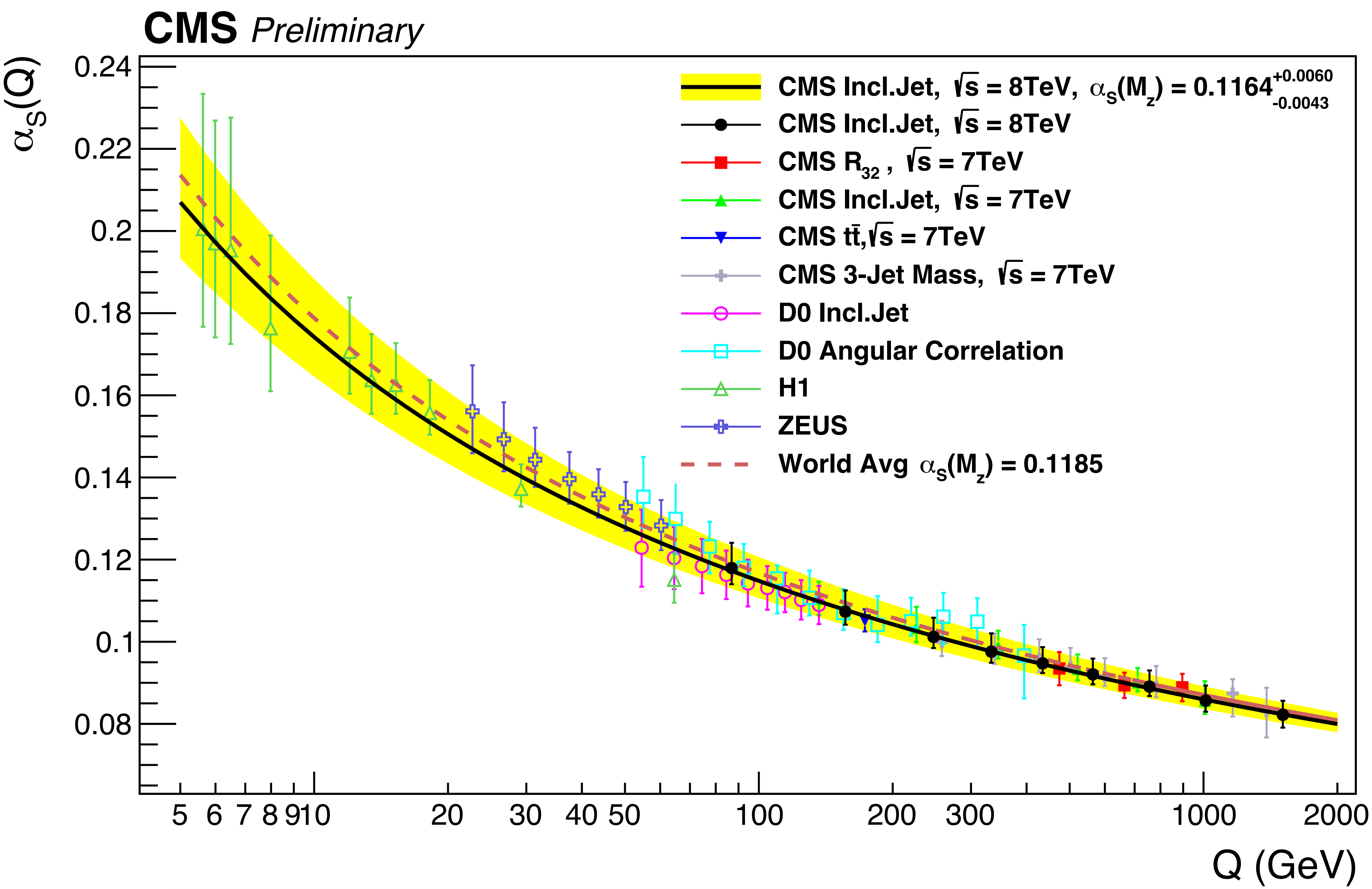




$$\alpha_S(M_Z) = 0.1171 \pm 0.0013\,(\text{exp})\,^{+0.0073}_{-0.0047}\,(\text{theo})$$

$\alpha_S(Q)$ Overview

CMS-SMP-14-001



The strong coupling α_s (yellow band) as a function of the momentum transfer, Q, where the value at $Q = M_Z$ has been evolved using the three-loop RGE.

Jets and PDFs Related CMS Results available on HEPData

- Measurement of the double-differential inclusive jet cross section in proton-proton collisions at sqrt(s) = 13 TeV
- Measurement of the inclusive jet cross section in pp collisions at sqrt(s) = 2.76 TeV
- Measurement of the ratio of inclusive jet cross sections using the anti-kt algorithm with radius parameters R = 0.5 and 0.7 in pp collisions at sqrt(s) = 7 TeV
- Measurement of the inclusive 3-jet production differential cross section in proton-proton collisions at 7 TeV and determination of the strong coupling constant in the TeV range
- Measurements of differential jet cross sections in proton-proton collisions at sqrt(s)=7 TeV with the CMS detector

http://hepdata.cedar.ac.uk/search/exp$002bcms

Conclusions

- CMS has completed a very large number of analyses with *pp* collisions at 7 & 8 & 13 TeV center of mass energies.
- Excellent understanding of the detector has been achieved, even at high pile-up conditions!
- The level of the precision of *'Jet Measurements'* are quite high!
- Jet measurements provides sufficient results to constrain PDFs and determine strong coupling constant $\alpha_S(Q)$.
- Many results have been published and lots of new are going to be published from Run II.

http://cms-results.web.cern.ch/cms-results/public-results/publications/


Thanks !