Jet Measurements in CMS

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for the CMS Collaboration

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Outline

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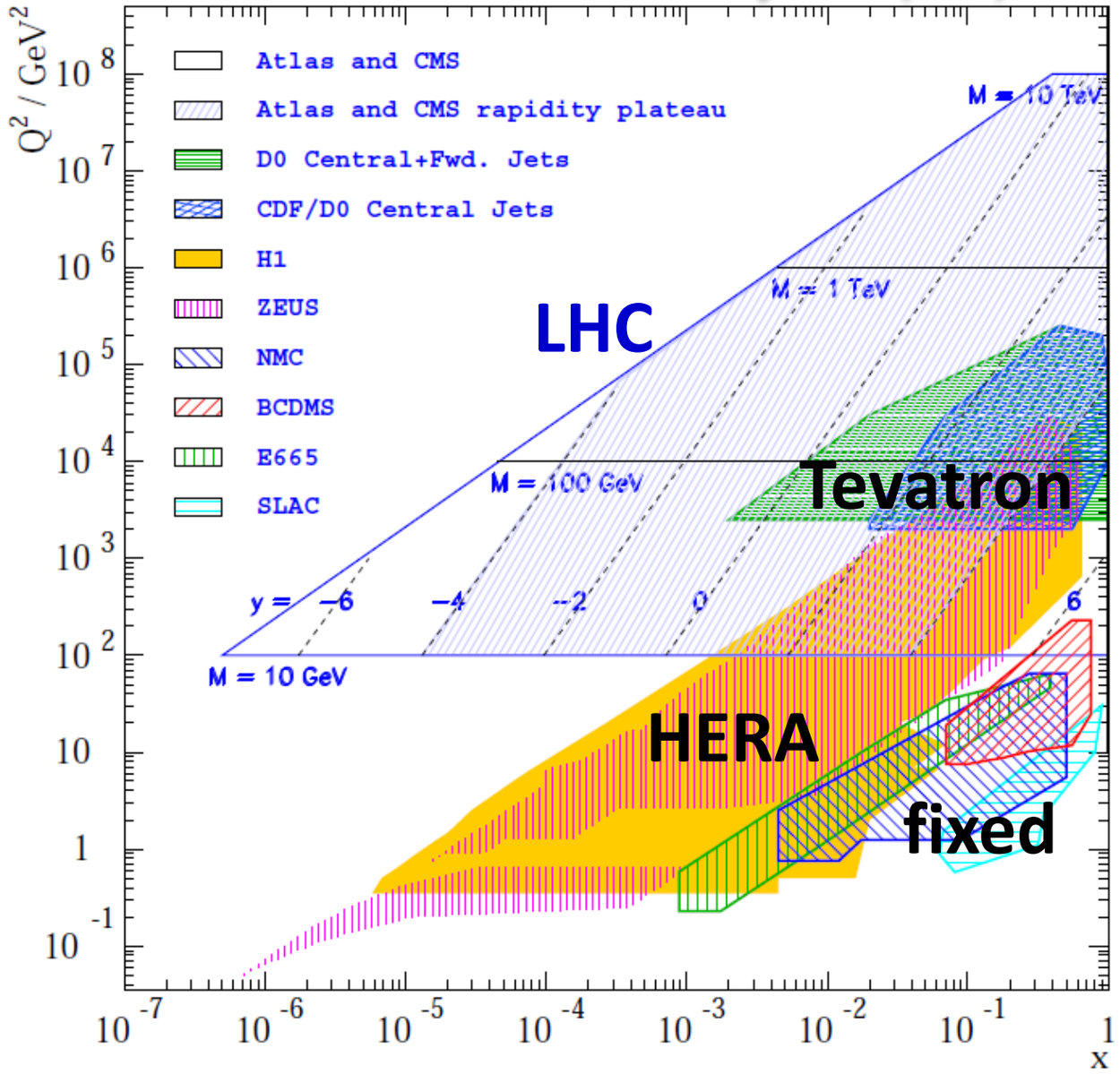
- Conclusions

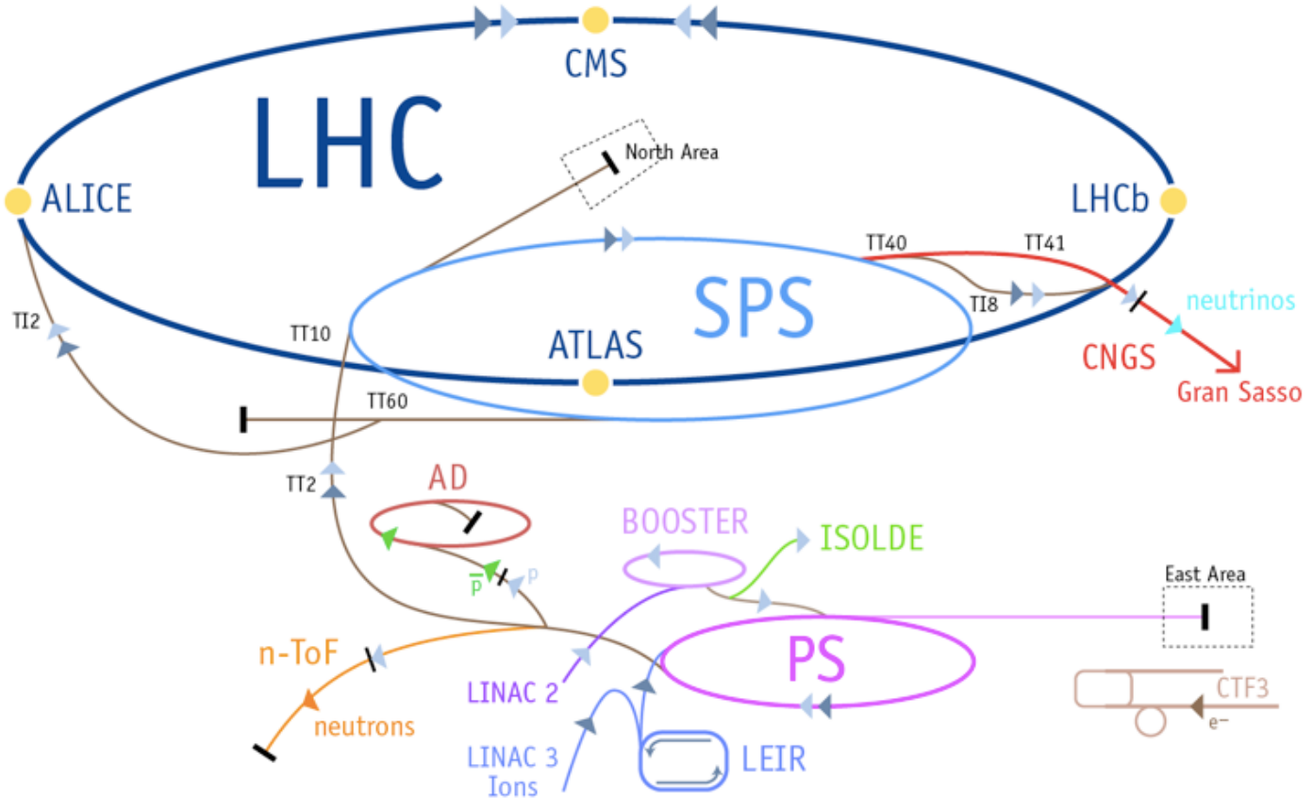
Introduction

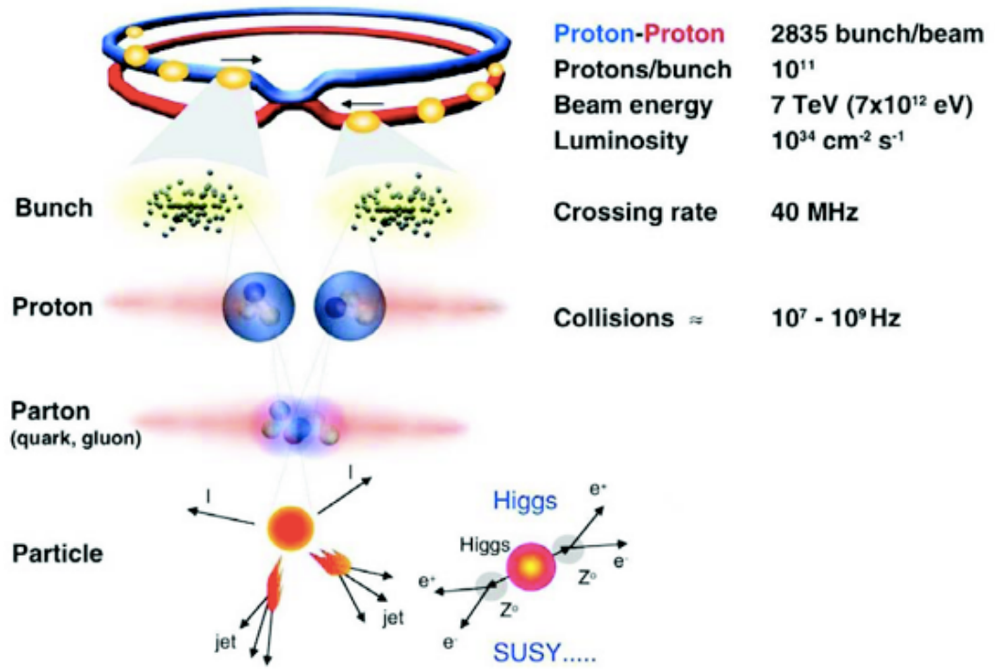
- LHC is actually a jet factory.
- Jet measurements at LHC are highly important:
  - They provide a test of pQCD in a previously unexplored kinematic phase space.
- A laboratory for SM predictions at high energy scales.
- Precise determination of backgrounds to many new physics searches.
- Determine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

S.Glazov, Braz.J.Ph. 37 (2007) 793



Introduction

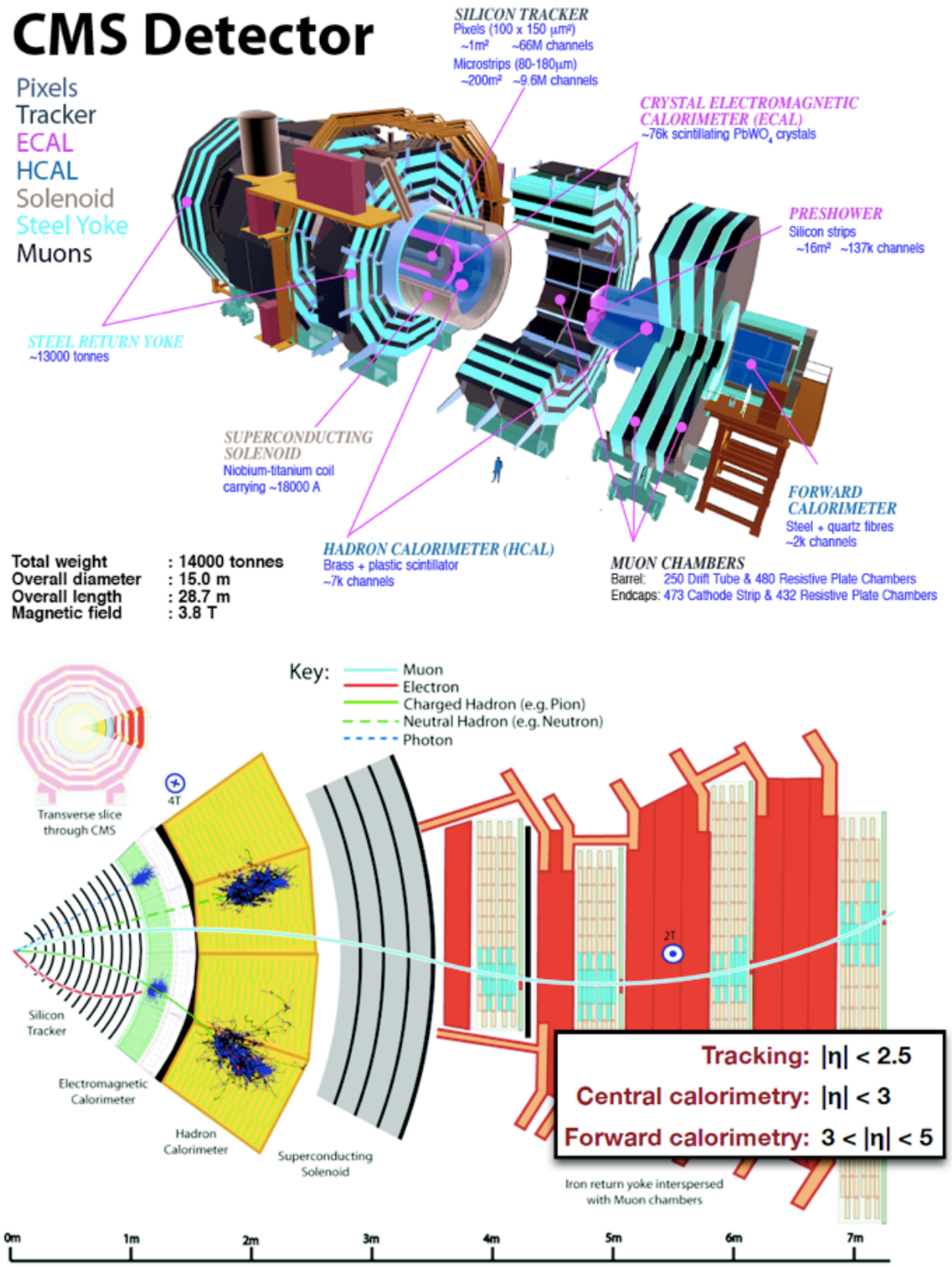




- The LHC is the world's largest and the most powerful collider (run at 7 TeV and 8 TeV so far)
- Located in the existing LEP tunnel between 50 and 175 m underground with 26.7 km circumference long.
- The LHC hosts four main detectors (ALICE, ATLAS, CMS, LHCb).
- The first *pp* collision in March 2010,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

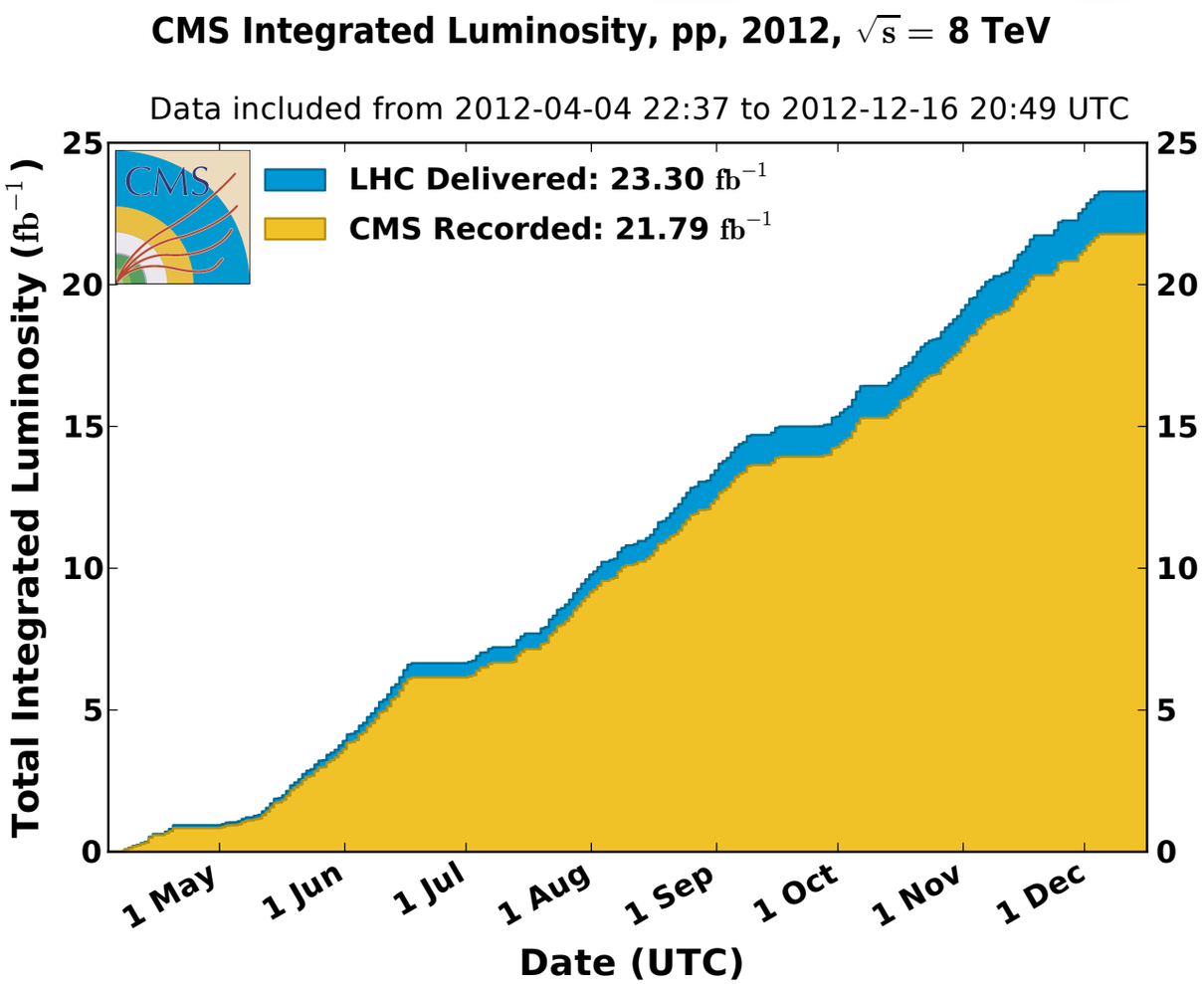
CMS Detector

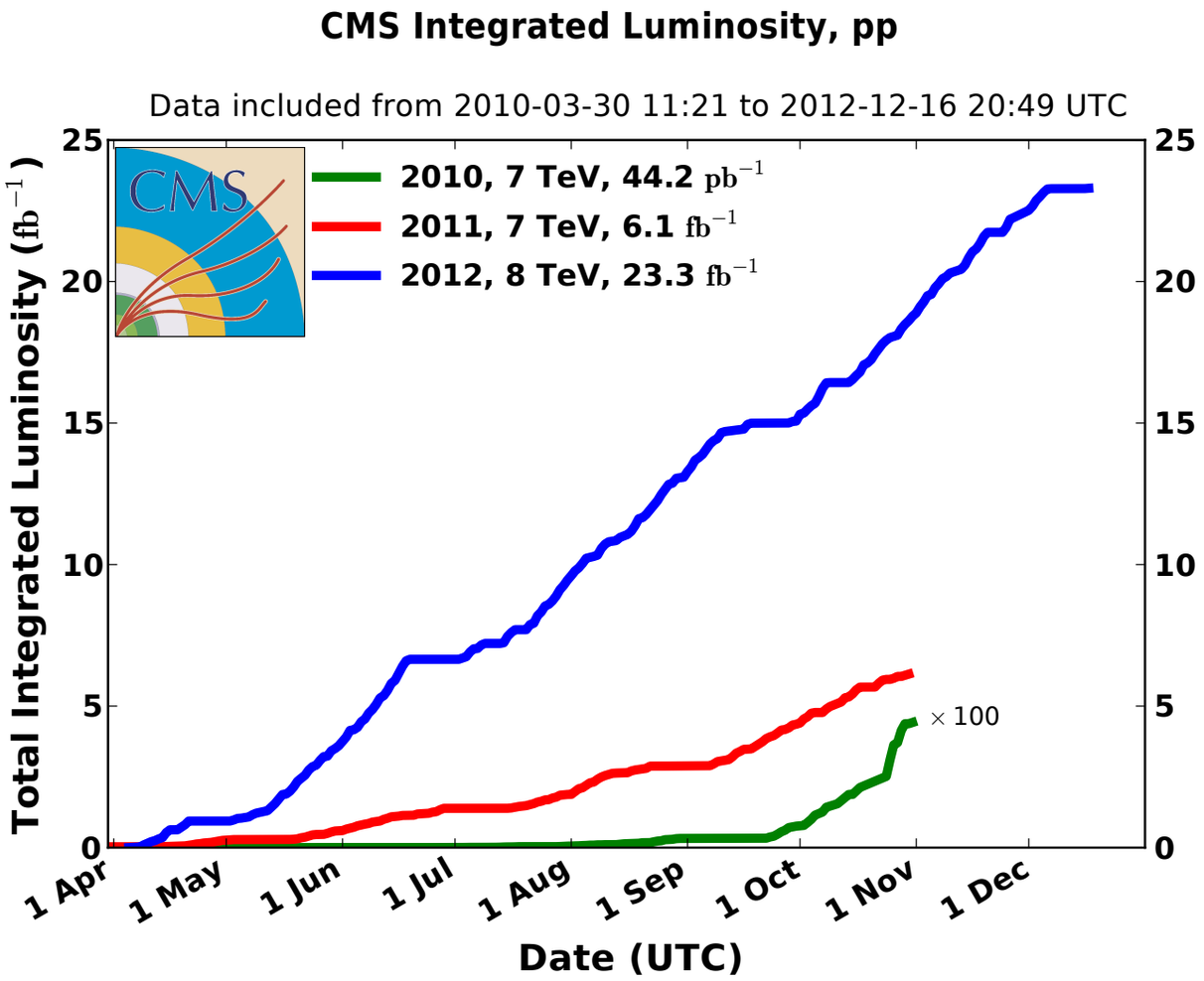
- The Compact Muon Solenoid (CMS) is a multi purpose detector at the LHC.
- The CMS detector design is similar to the structure of an onion.
- CMS consists of several layers of each one which is specialised to measure and identify different classes of particles.
- The detector requirements for CMS
  - 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.



CMS Detector

Collisions throughout the years





Very successful LHC operations in 2010-2012
8 TeV: Challenging environment
Very high pile-up, new techniques

13 TeV in 2015
LHC may exceed design luminosity and run at higher than design pile-up

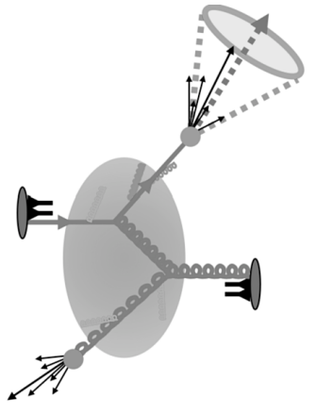
CMS Detector

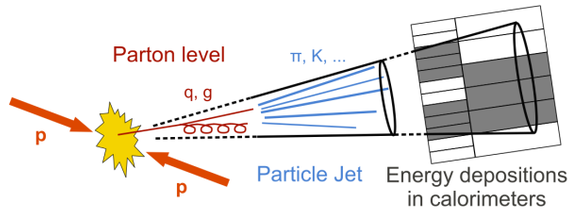
1/10 of the Collaborators

Jet Reconstruction and Calibration at CMS

Jet Reconstruction

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





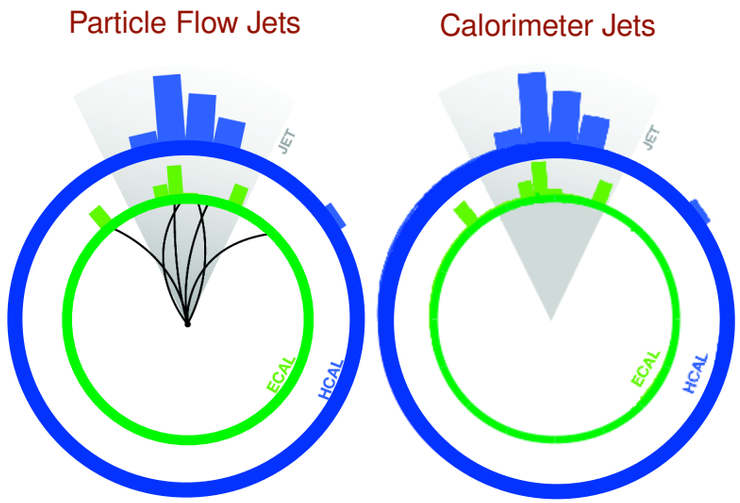
- It is an object that is clustered out of collimated spray of particles by using a set of mathematical rules

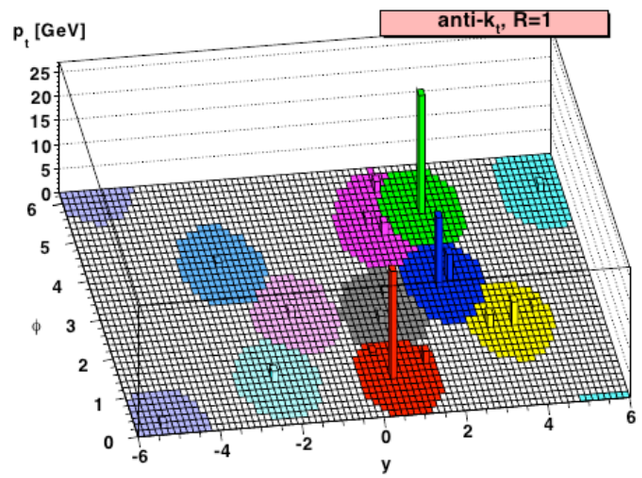
$$d_{ij} = p_{T,i}^{2p} \qquad d_{ij} = min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{D^2}$$

- 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





Jet Energy Calibration

CMS DP -2013/033

JINST 6 P11002

- 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.

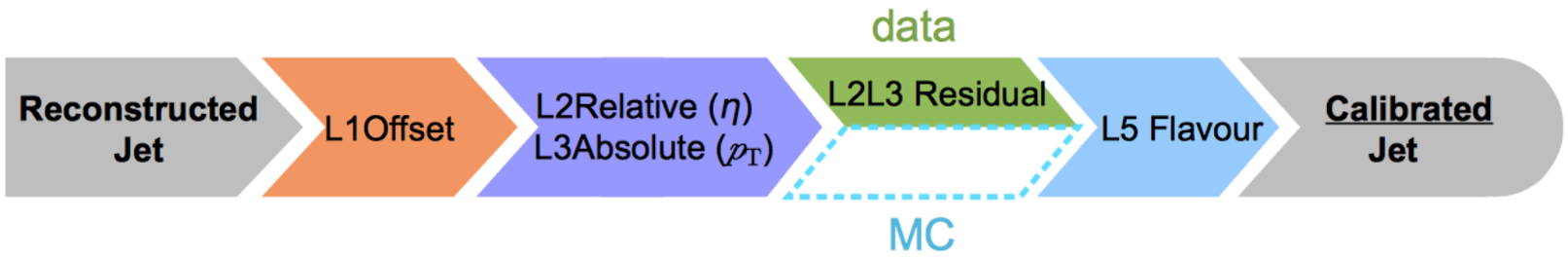
Factorised approach is used like in Tevatron

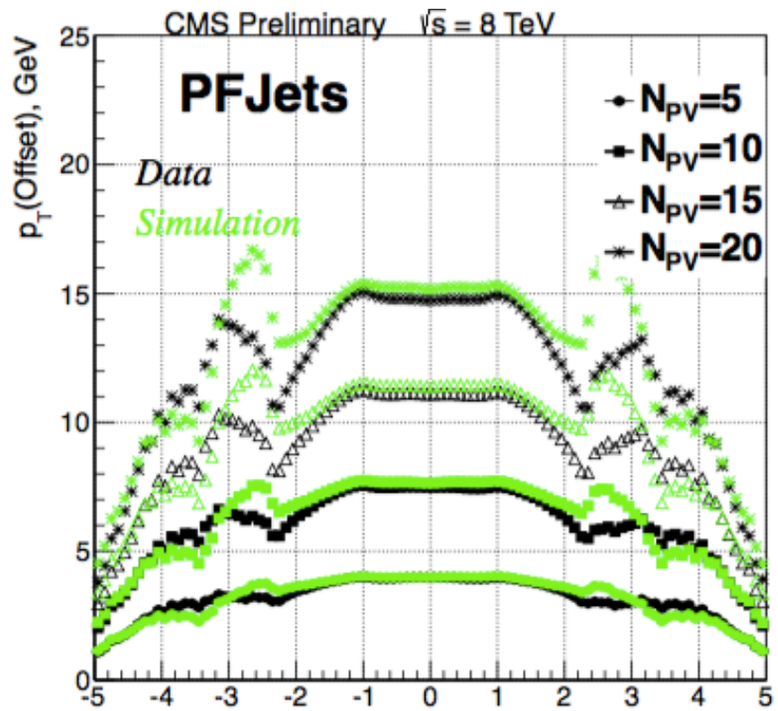
- Offset: Required correction for pile-up and electronic noise.

- Relative (η): Required correction for jet response versus pseudorapidity relative to a control region. (Dijet Balance Method)

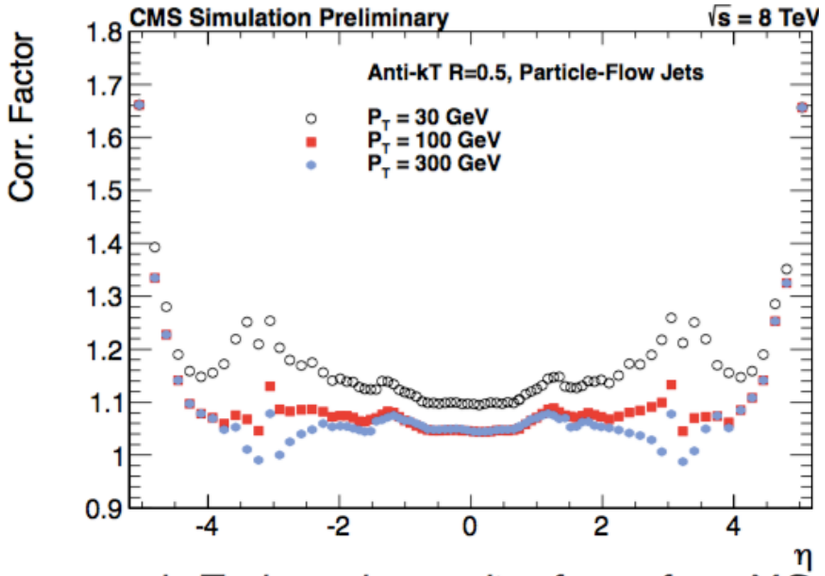
- Absolute(p_T): absolute JEC scale determined via $Z\rightarrow\mu^+\mu^-$+jet, $Z\rightarrow e^+e^-$+jet/γ+jet

- Corrections derived on MC and applied to data: if non-closure → residual correction





Additional energy due to pileup as a function of η (AK5 PFJets)



η and pT -dependent scaling factor from MC after applying pileup corrections

Jet Energy Calibration

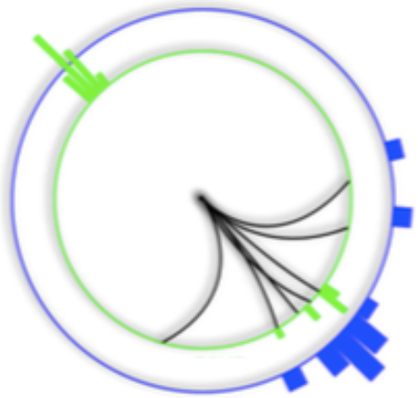
CMS DP -2013/033

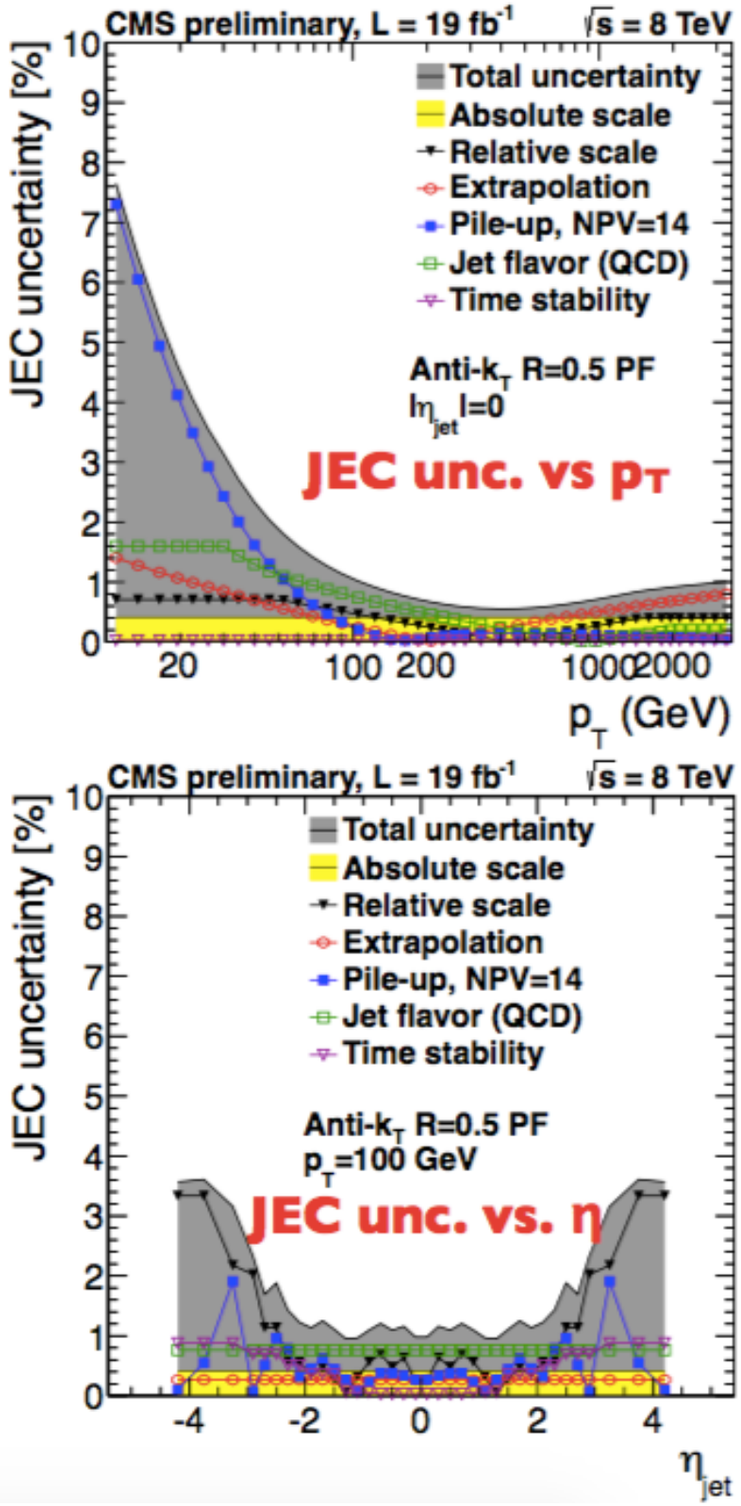
JINST 6 P11002

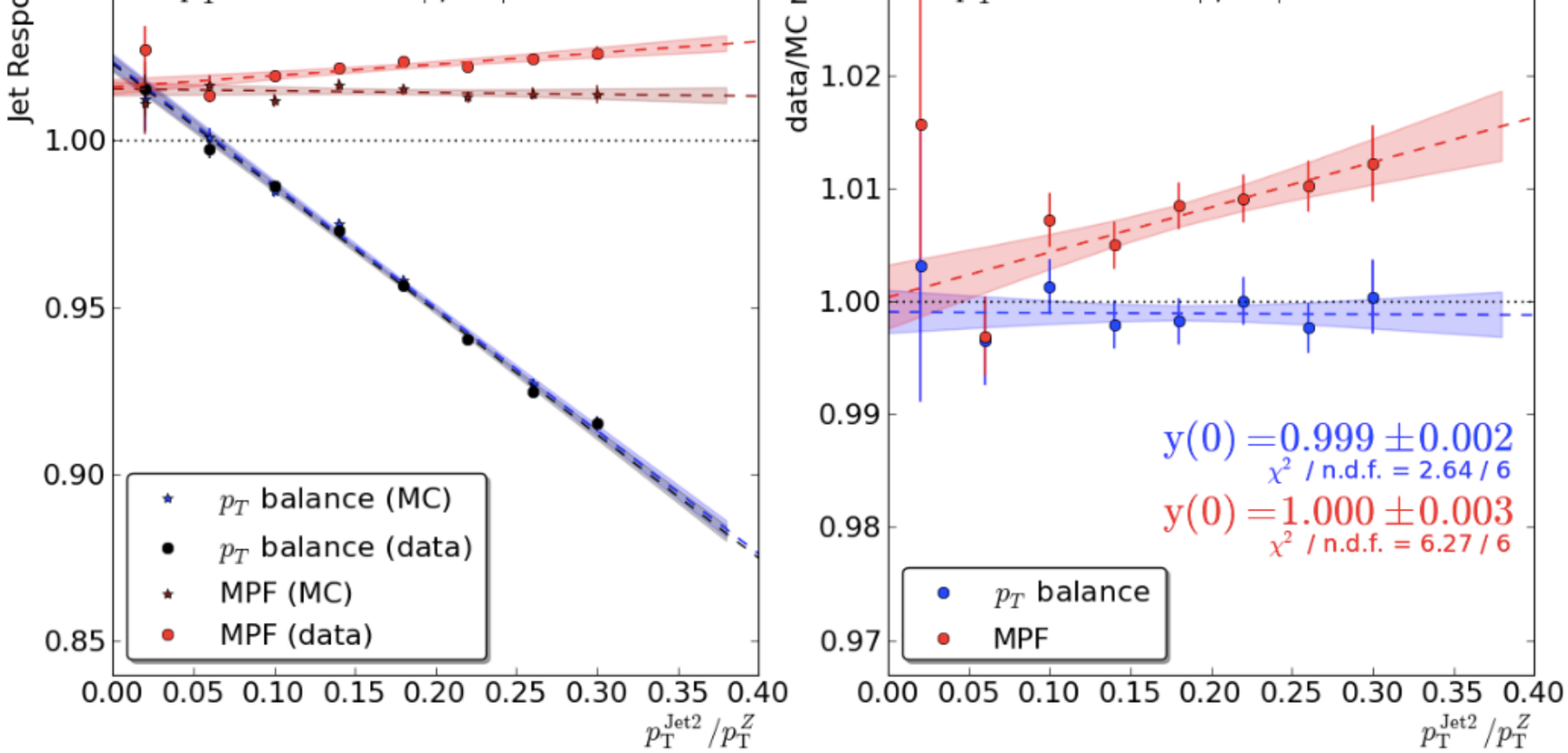
- Absolute correction factor in barrel derived from Z→ μμ+jet
- MPF and pT balance methods used for calibration

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

γ+Jet events:

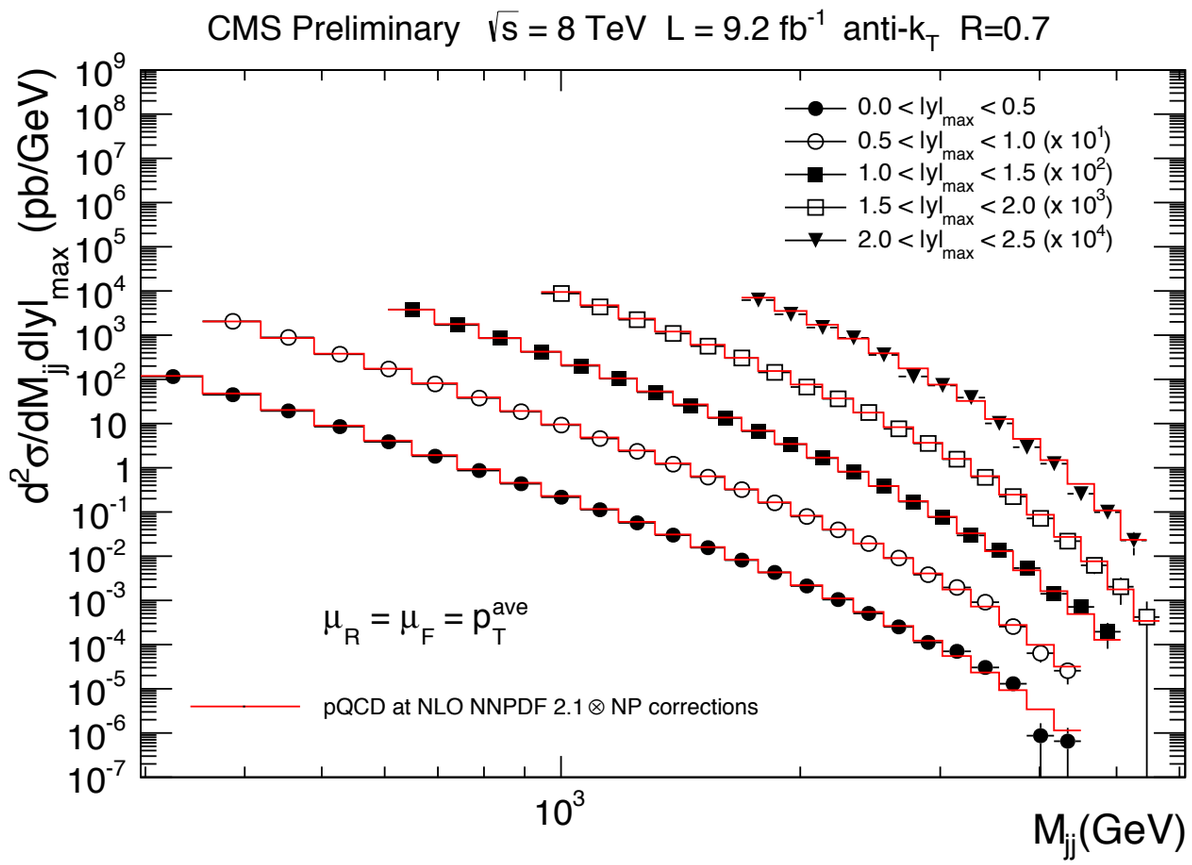


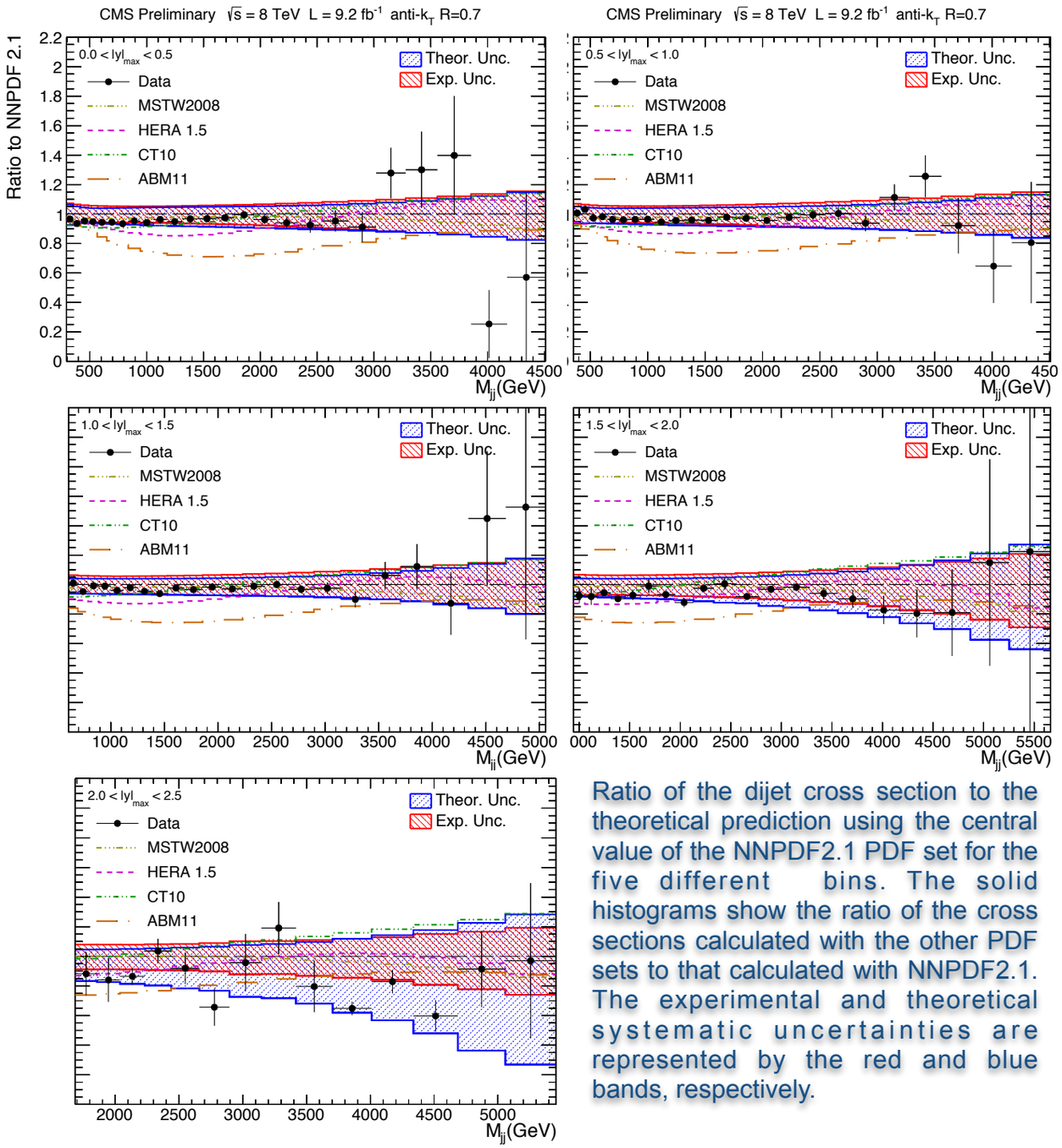




Jet Measurements in CMS

Dijet Mass Production Cross Section at 8 TeV CMS-PAS-SMP-14-002





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

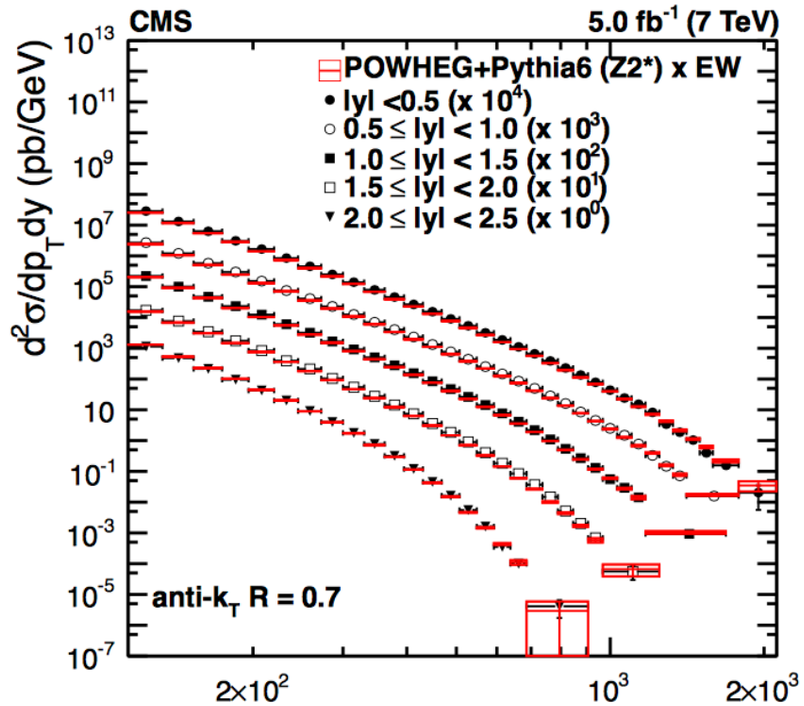
The dijet cross section as a function of M_{jj}^2 can be precisely calculated in perturbative QCD and it also allows sensitive searches for physics beyond the Standard Model, such as dijet narrow resonances or contact interaction searches.

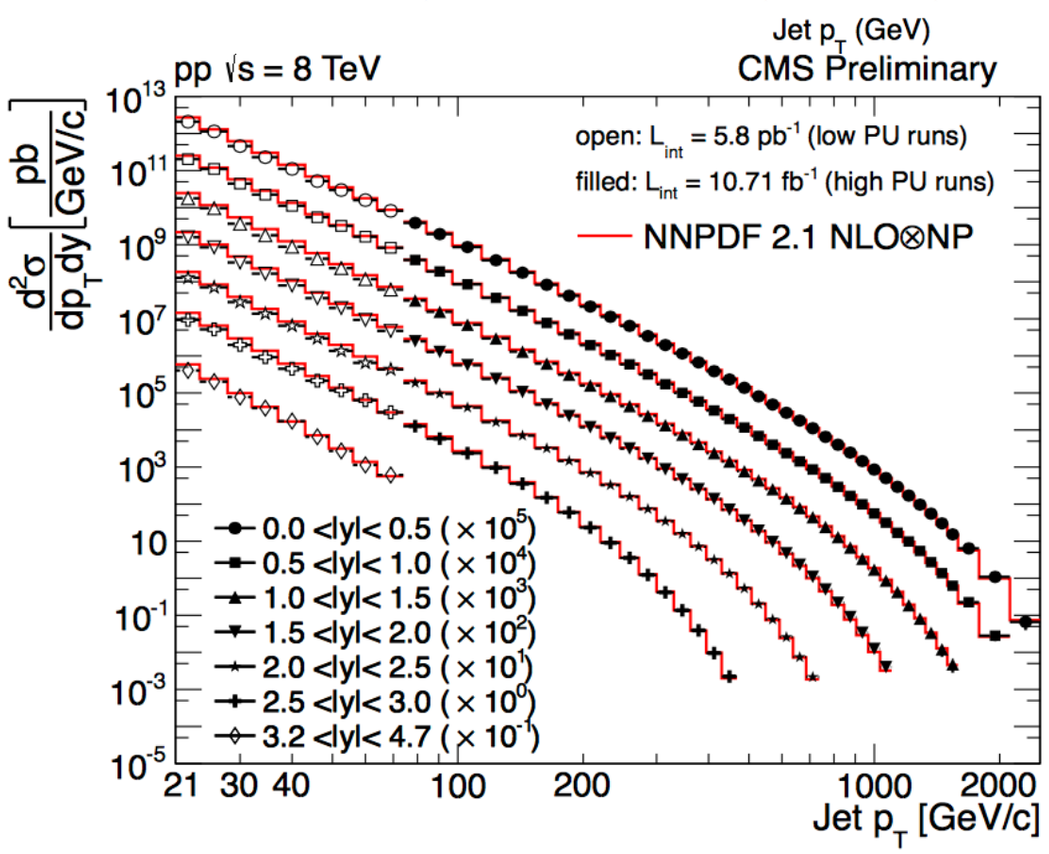
Ratio of the dijet cross section to the theoretical prediction using the central value of the NNPDF2.1 PDF set for the five different bins. The solid histograms show the ratio of the cross sections calculated with the other PDF sets to that calculated with NNPDF2.1. The experimental and theoretical systematic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

Inclusive Jet Cross Sections at 7 & 8 TeV

CMS-PAS-FSQ-12-031
arXiv:1410.6765

- Measured jet p_T spectra in 5 rapidity bins
- 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.
- Data are in agreement with NLO calculations within systematic uncertainties although NLO calculations are systematically overestimate cross-section in all rapidity bins.

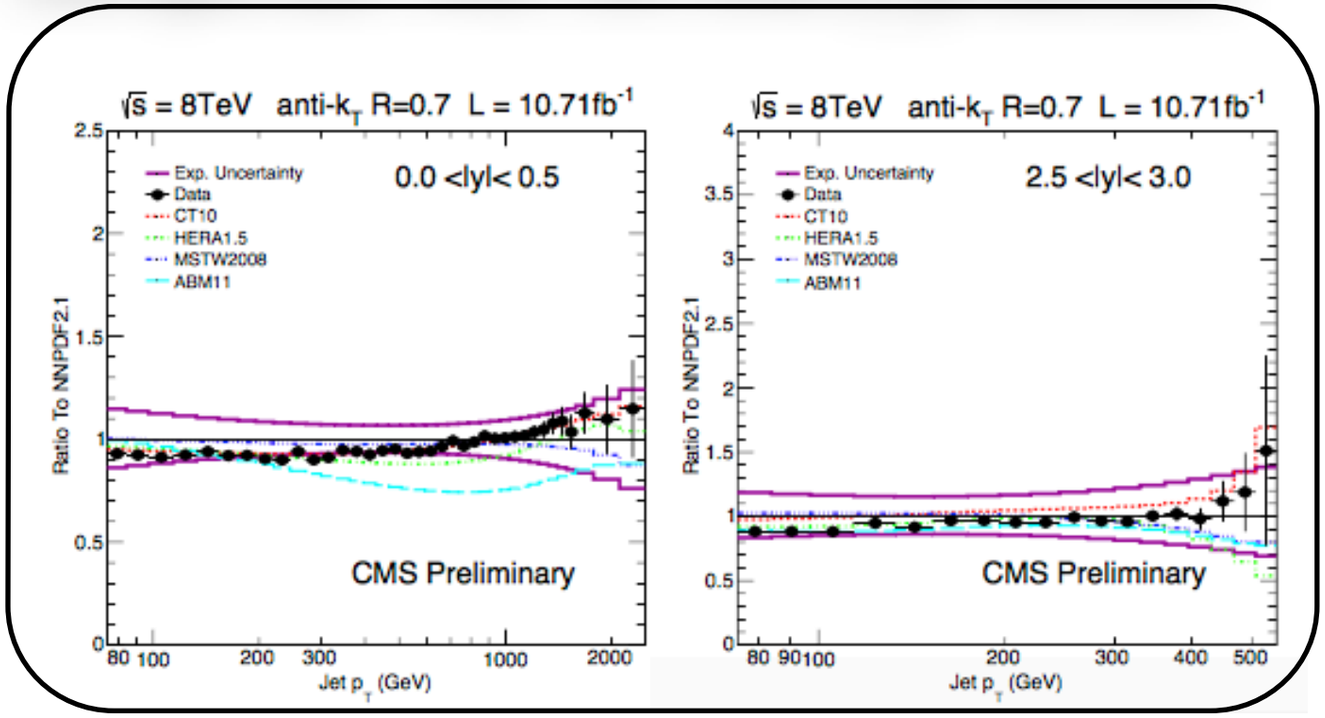


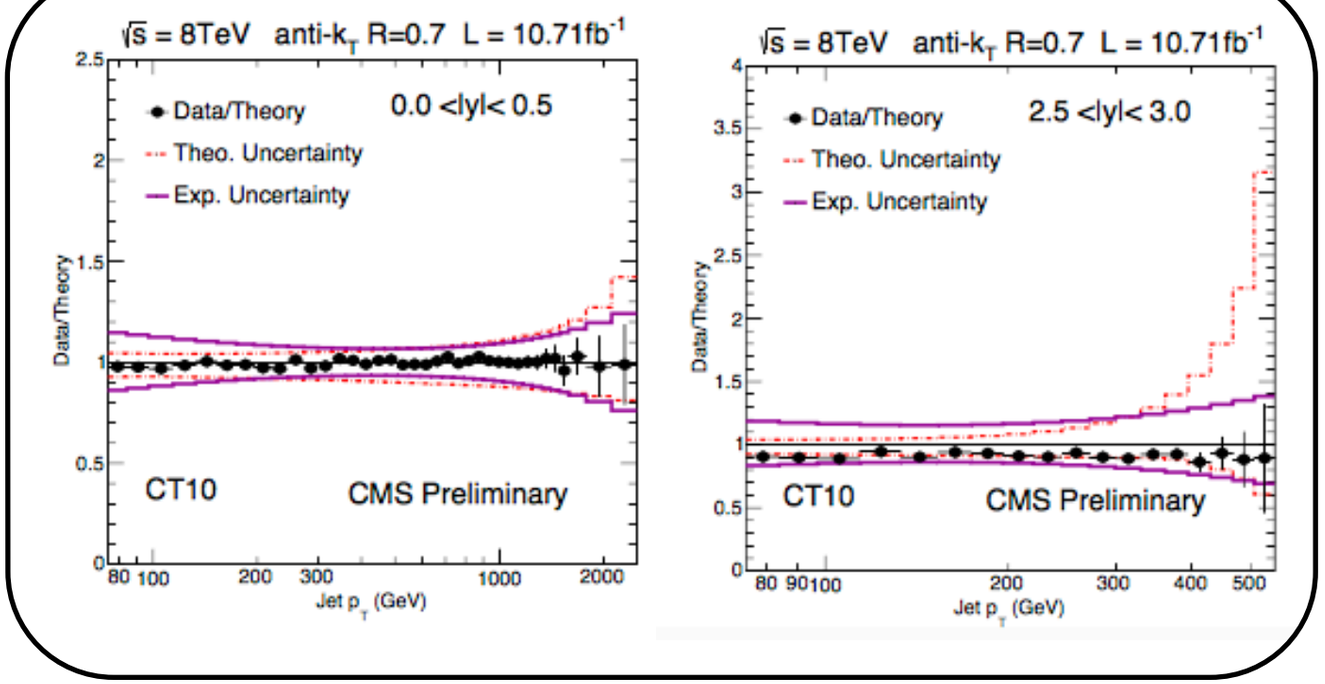


Inclusive Jet Cross Sections at 7 & 8 TeV

CMS-PAS-SMP-12-012

Comparison with the theory prediction





- Total experimental systematic uncertainty ~15-30% (15-40%) at central (forward) rapidities
- PDF uncertainty ~ 5-50% (higher for CT10 and HERA1.5)
- μ-scale uncertainty ~ 5-40%
- Experimental uncertainties smaller than theoretical at high pT
- Overall good agreement with pQCD@NLOxNP

Inclusive ak5 to ak7 Jet Cross Sections Ratio at 7 TeV

Phys. Rev. D 90 (2014) 072006

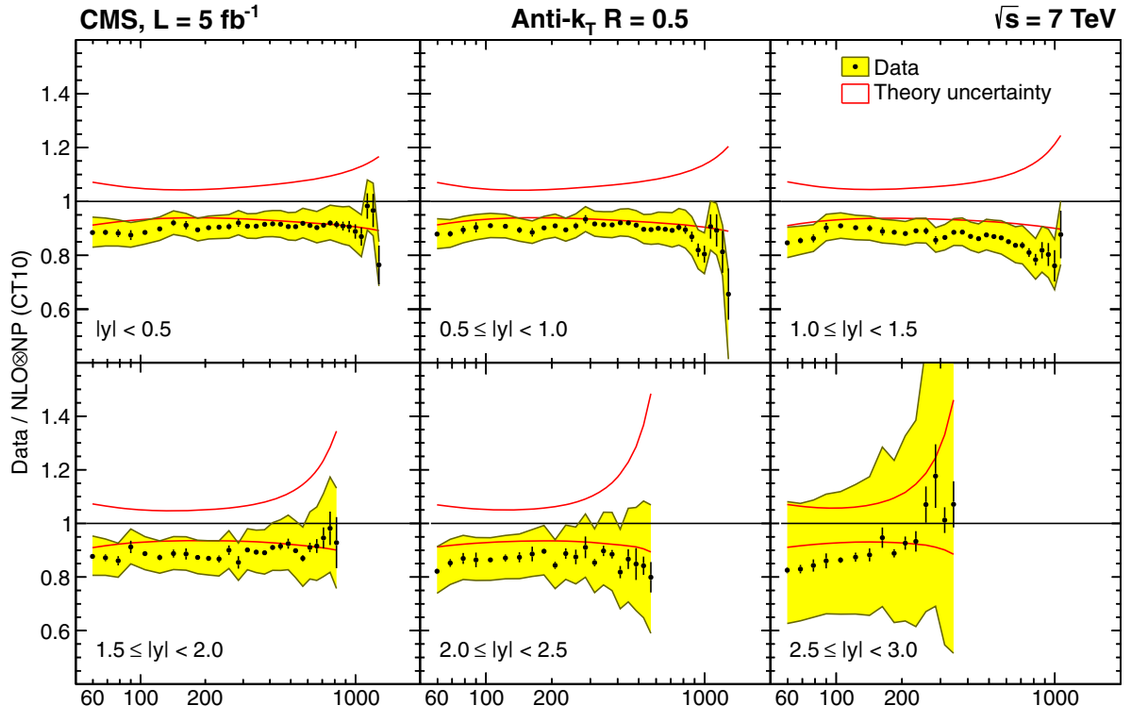
arXiv:1304.7498

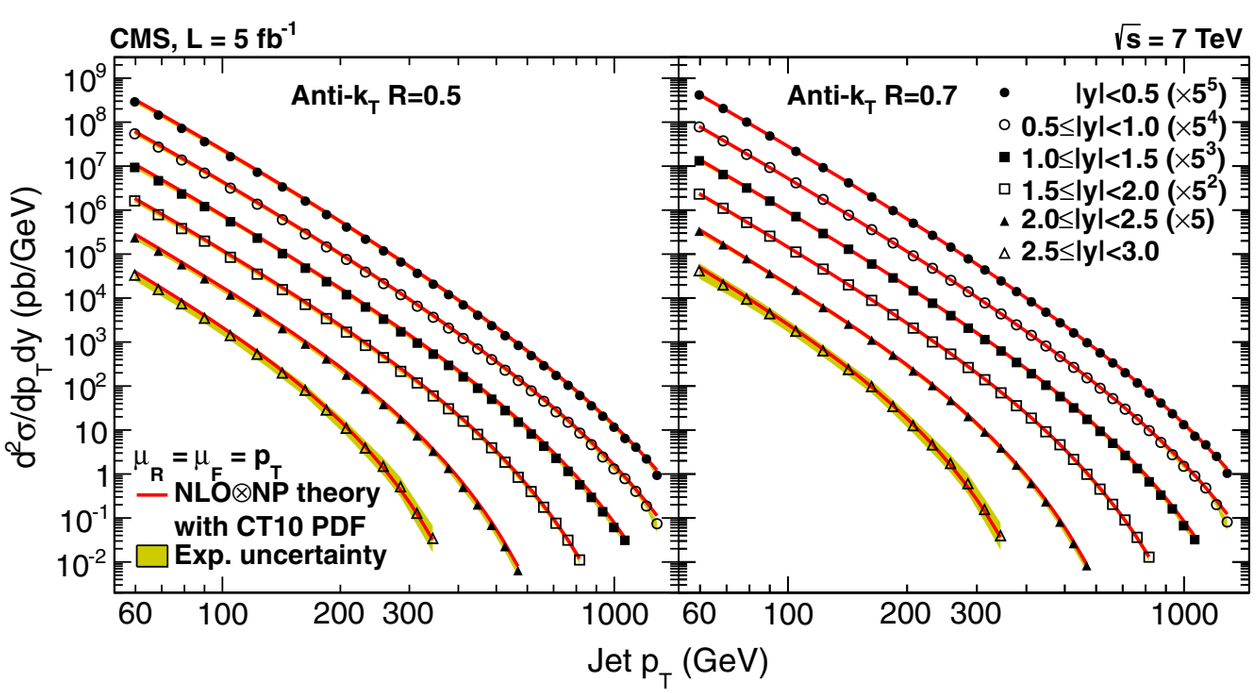
in a collinear approximation, impact of;

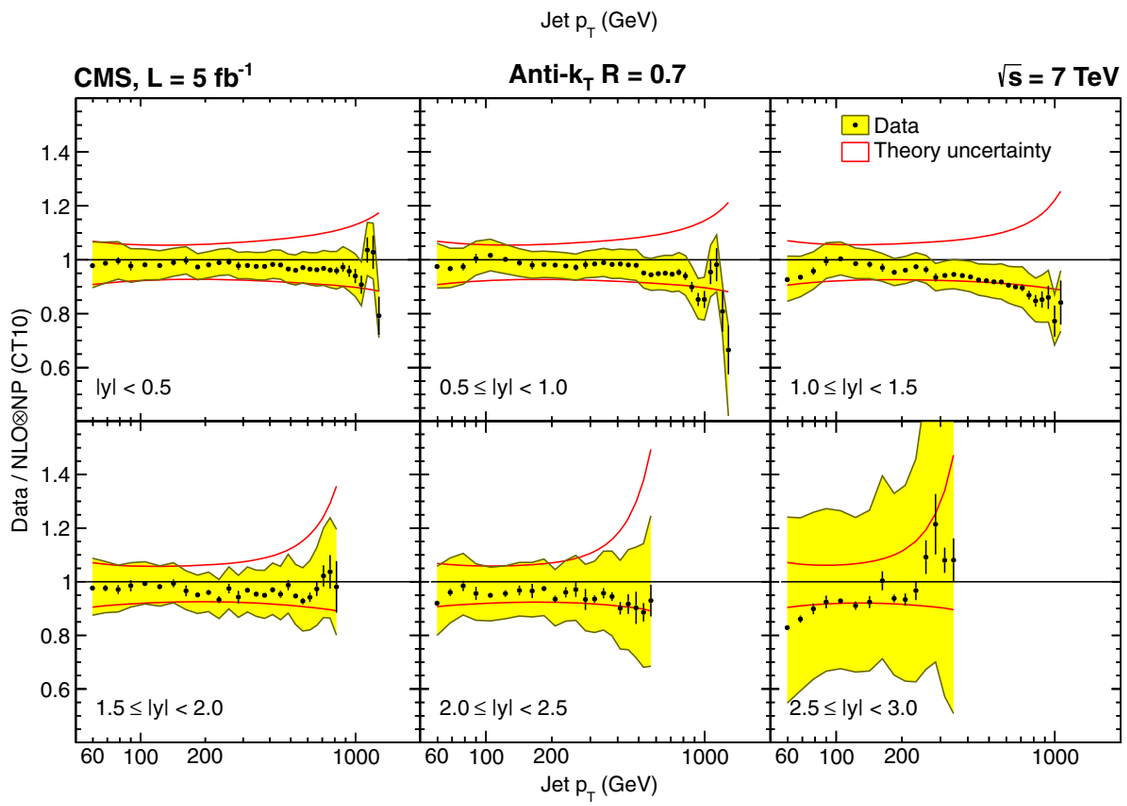
- perturbative radiation ~ $\ln(R)$
- nonperturbative effects of hadronization ~ $-1/R$
- underlying event on jet transverse momenta scales ~ R^2

for small R where R is defined as:

$$R(0.5,\ 0.7) = \left(\frac{d\sigma^{0.5}}{dp_T} \Big/ \frac{d\sigma^{0.7}}{dp_T} \right)$$







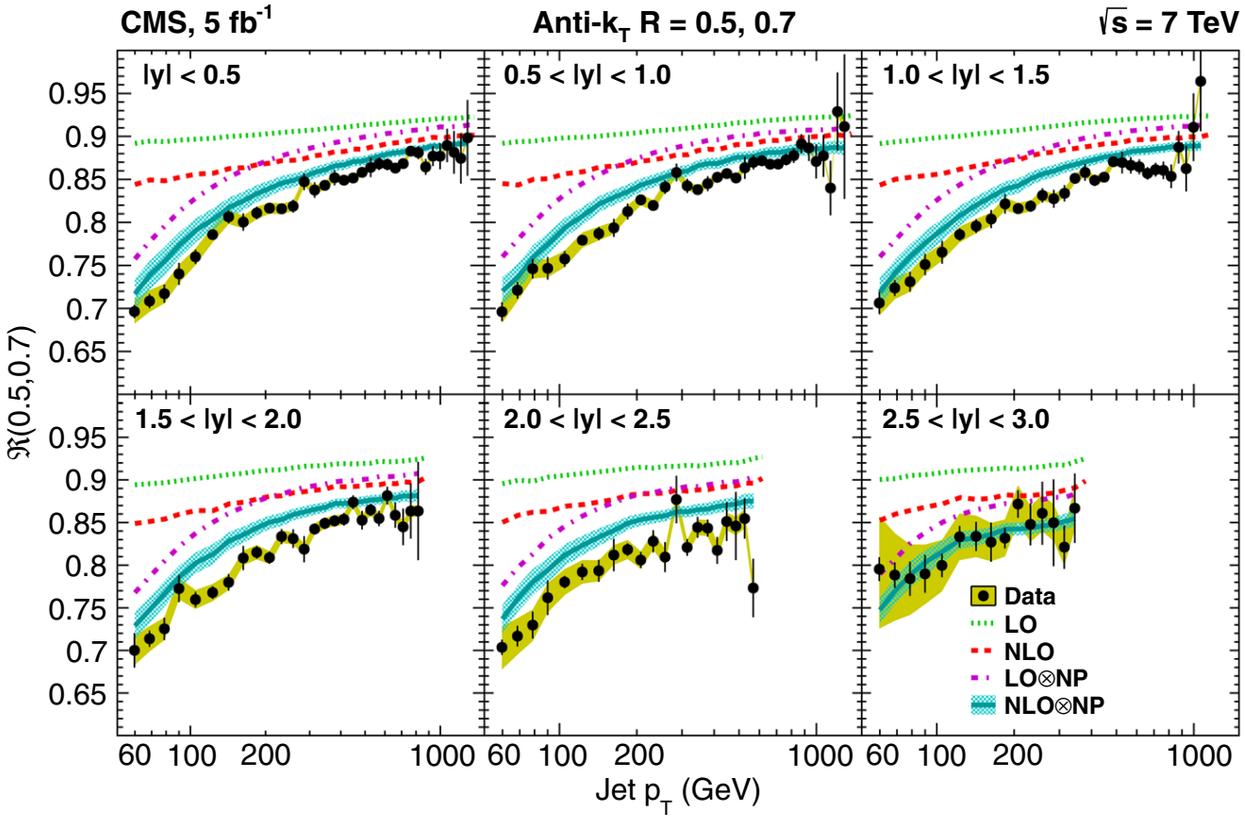
The perturbative QCD predictions are systematically above the data, improving at higher order.

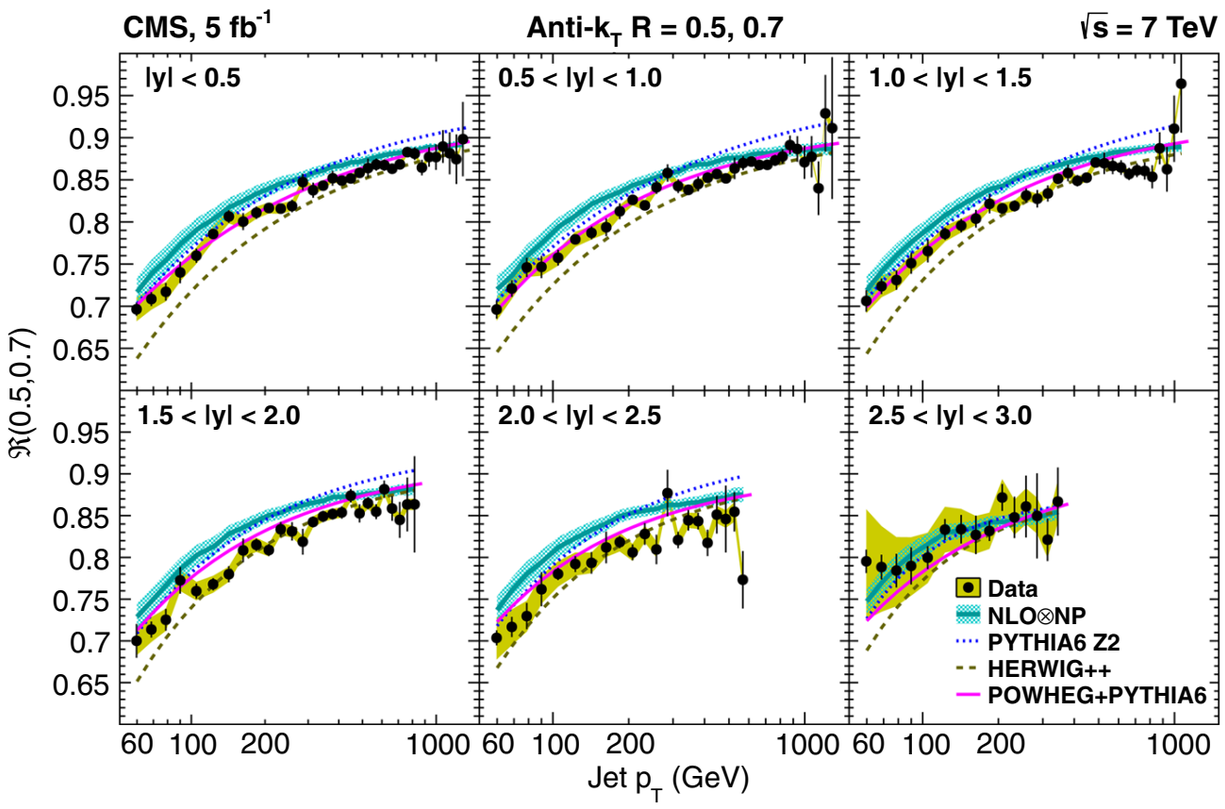
Inclusive ak5 to ak7 Jet Cross Sections Ratio at 7 TeV

Phys. Rev. D 90 (2014) 072006

arXiv:1304.7498

MC event generators PYTHIA6 and HERWIG++, which rely on parton showers to describe three-jet observables, are in better accord with the measured jet radius ratio R(0.5;0.7) than the fixed-order predictions.





Jet radius R dependent effects, measurable in data, require pQCD predictions with at least one order higher than NLO or a combination of NLO cross sections matched to parton shower models

Hadronic Event-Shape Variables in Multijet Final States @ 7 TeV

JHEP 10 (2014) 087
arXiv:1407.2856

Their measurements have improved our understanding of many perturbative and nonperturbative aspects of QCD including the determination of the strong coupling constant α_s details of parton radiation and hadronization, tests of the colour structure of the theory, as well as modelling and validation of Monte Carlo (MC) event generators

Transverse thrust: probes the hadronisation process and is sensitive to the modelling of two-jet and multijet topologies

$$\tau_{\perp} \equiv 1 - \max_{\hat{n}_{\mathrm{T}}} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_{\mathrm{T}}|}{\sum_i p_{\mathrm{T},i}}$$

Jet Broadening:

$$\eta_X \equiv \frac{\sum_{i \in \mathcal{C}_X} p_{\mathrm{T},i}\, \eta_i}{\sum_{i \in \mathcal{C}_X} p_{\mathrm{T},i}} \qquad \phi_X \equiv \frac{\sum_{i \in \mathcal{C}_X} p_{\mathrm{T},i}\, \phi_i}{\sum_{i \in \mathcal{C}_X} p_{\mathrm{T},i}}$$

$$B_X \equiv \frac{1}{2\,P_{\mathrm{T}}} \sum_{i \in \mathcal{C}_X} p_{\mathrm{T},i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

$$B_{\mathrm{tot}} \equiv B_{\mathrm{U}} + B_{\mathrm{L}}$$

Jet Masses:

$$\rho_X \equiv \frac{M_X^2}{P^2} \qquad \rho_{\mathrm{tot}} \equiv \rho_{\mathrm{U}} + \rho_{\mathrm{L}}$$

Third-jet resolution parameter:

$$Y_{23} \equiv \frac{\min(p_{\mathrm{T},3}^2\,,\, [\min(p_{\mathrm{T},i}\,,\, p_{\mathrm{T},j})^2 \times (\Delta R_{ij})^2 / R^2])}{P_{12}^2}$$

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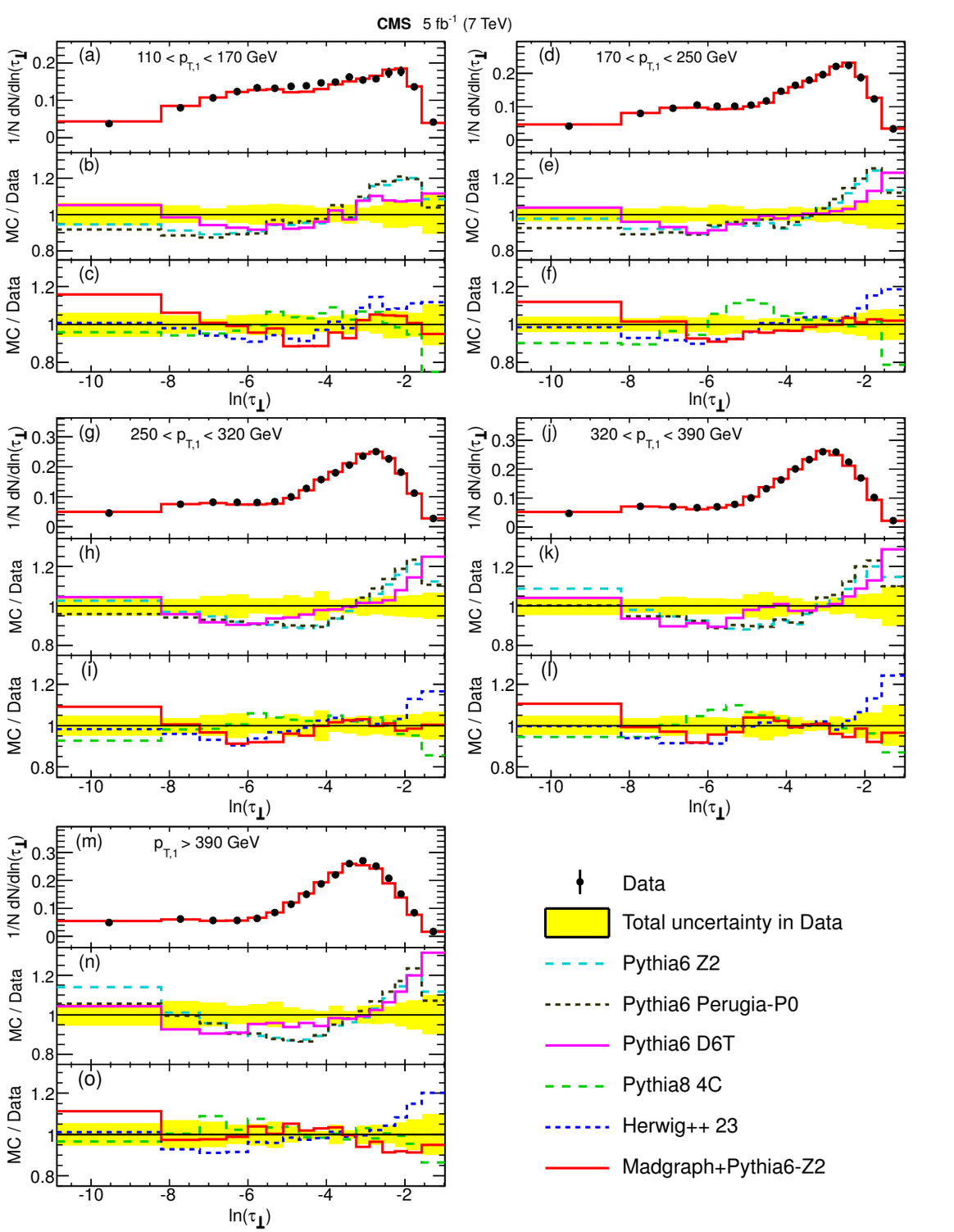

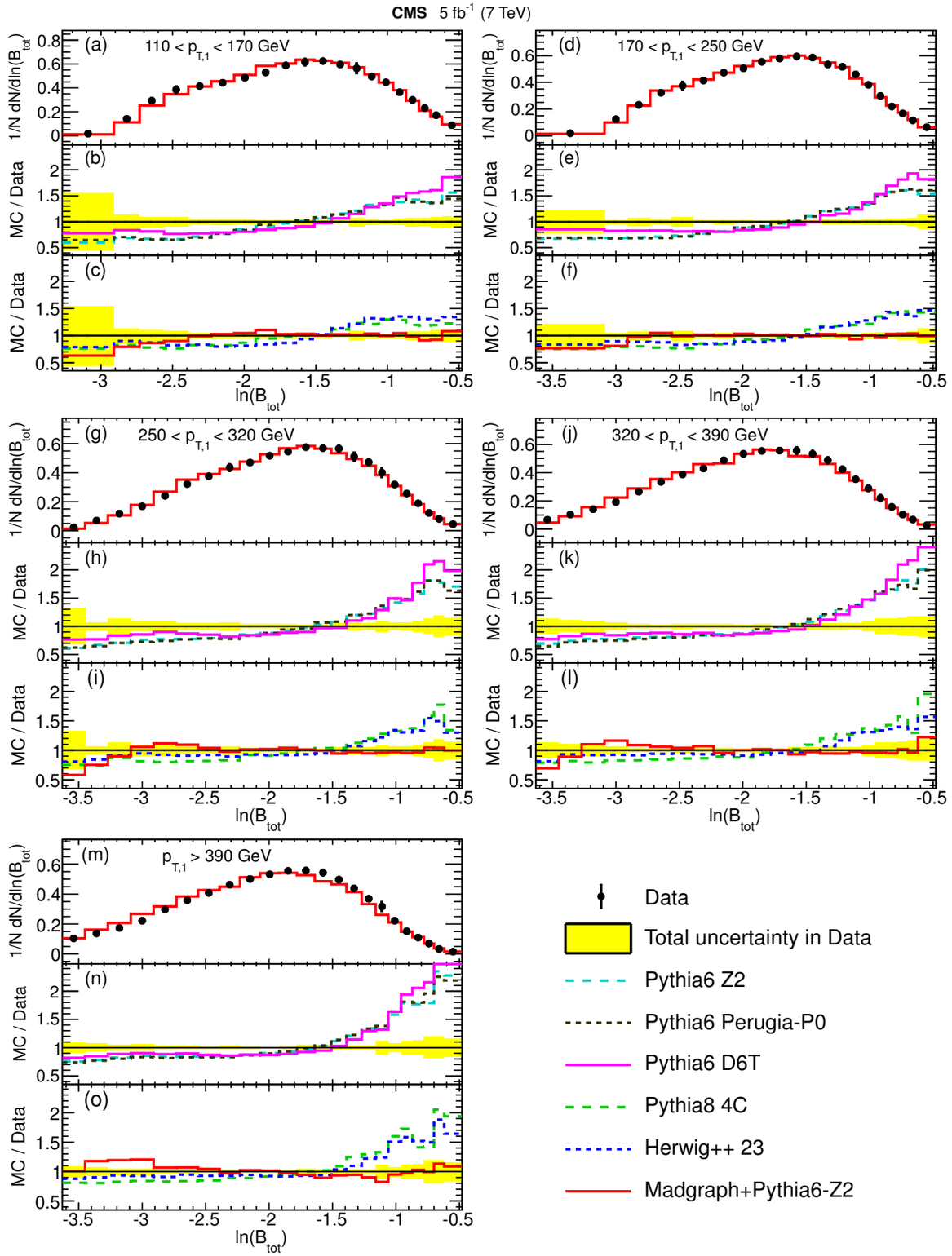

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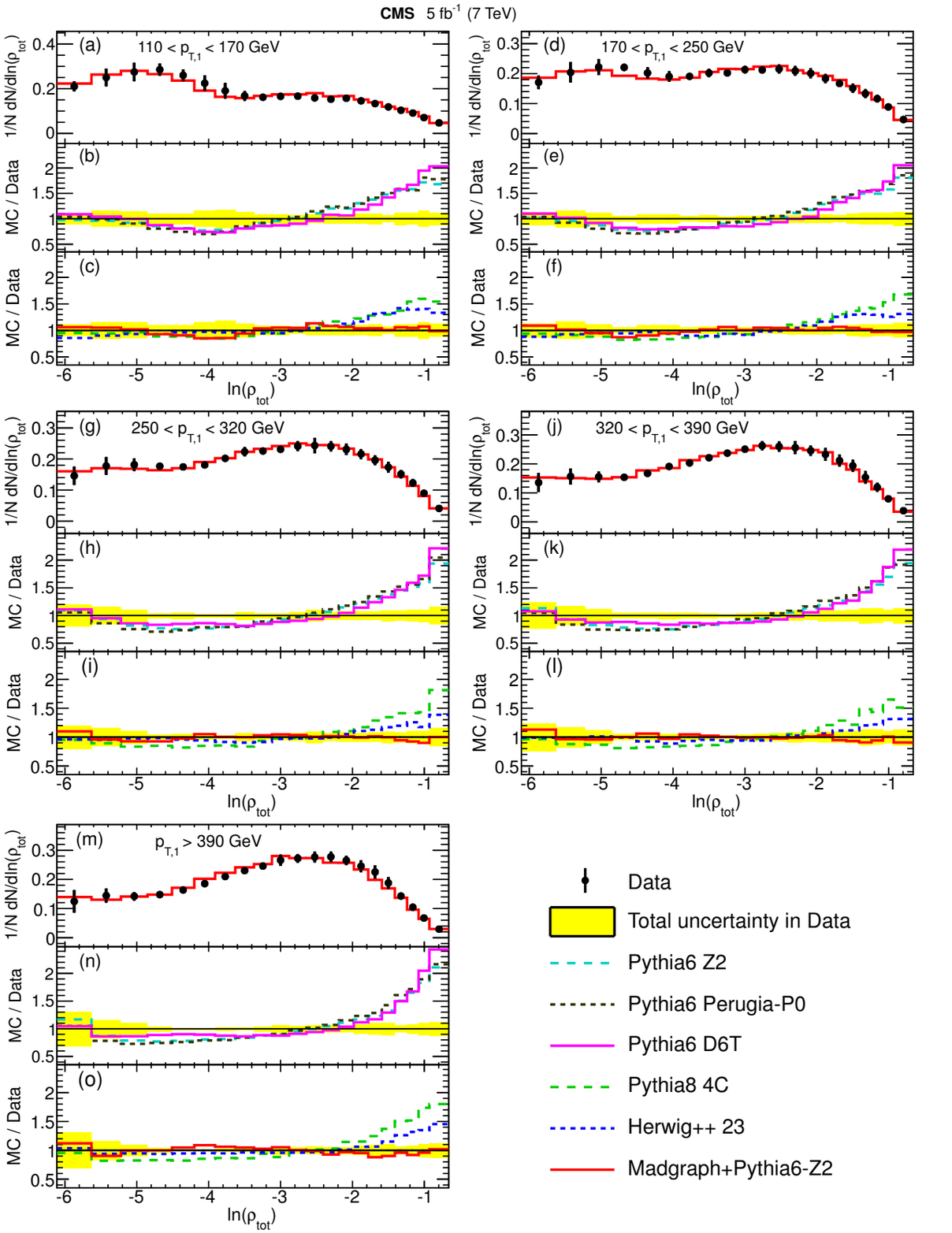
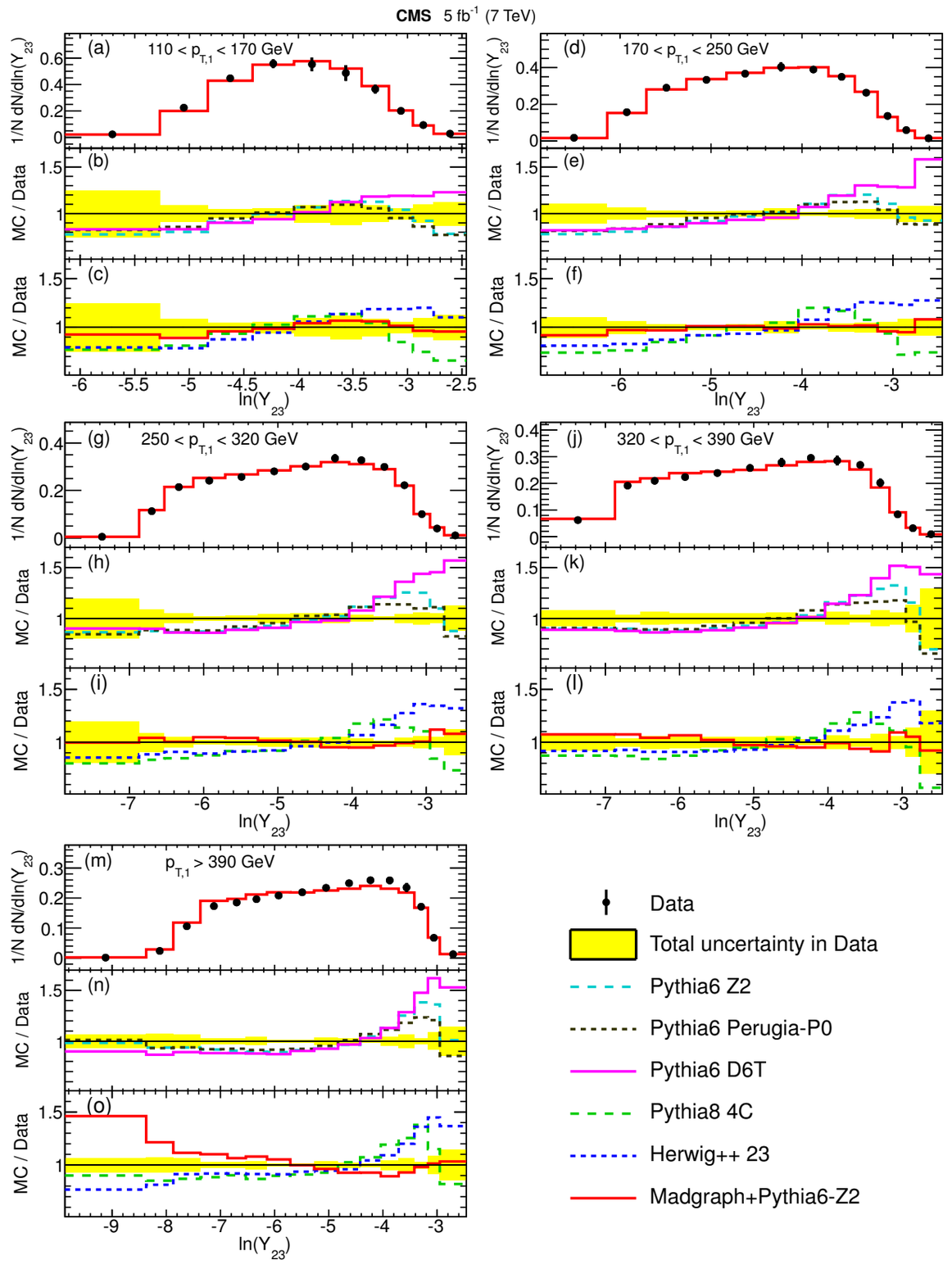


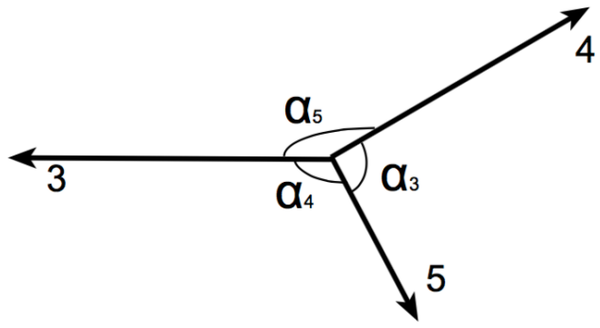


Topological Observables in Inclusive 3&4 Jet Events @ 7 TeV

CERN-PH-EP-2014-302
arXiv.1502.04785

Topological variables, which are sensitive to QCD color factors, the spin structure of gluons, and hadronization models

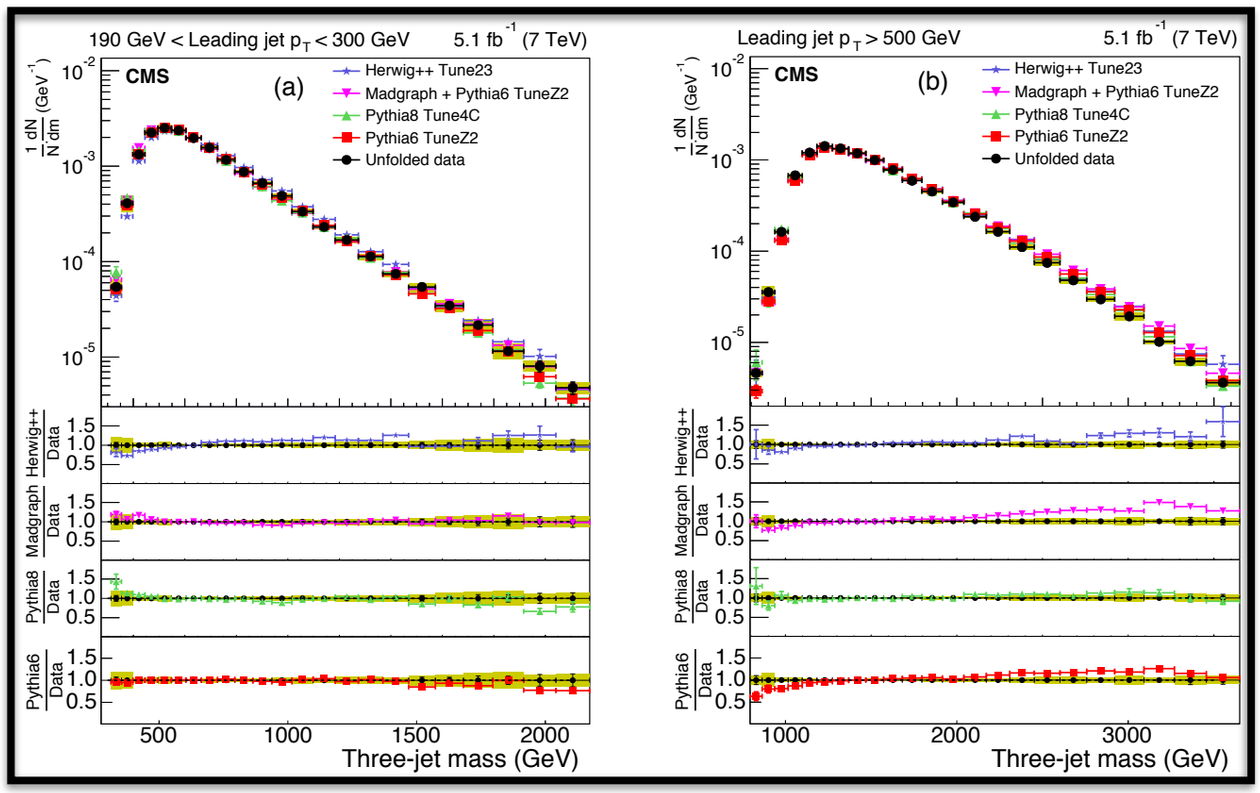
Three-jet Variables

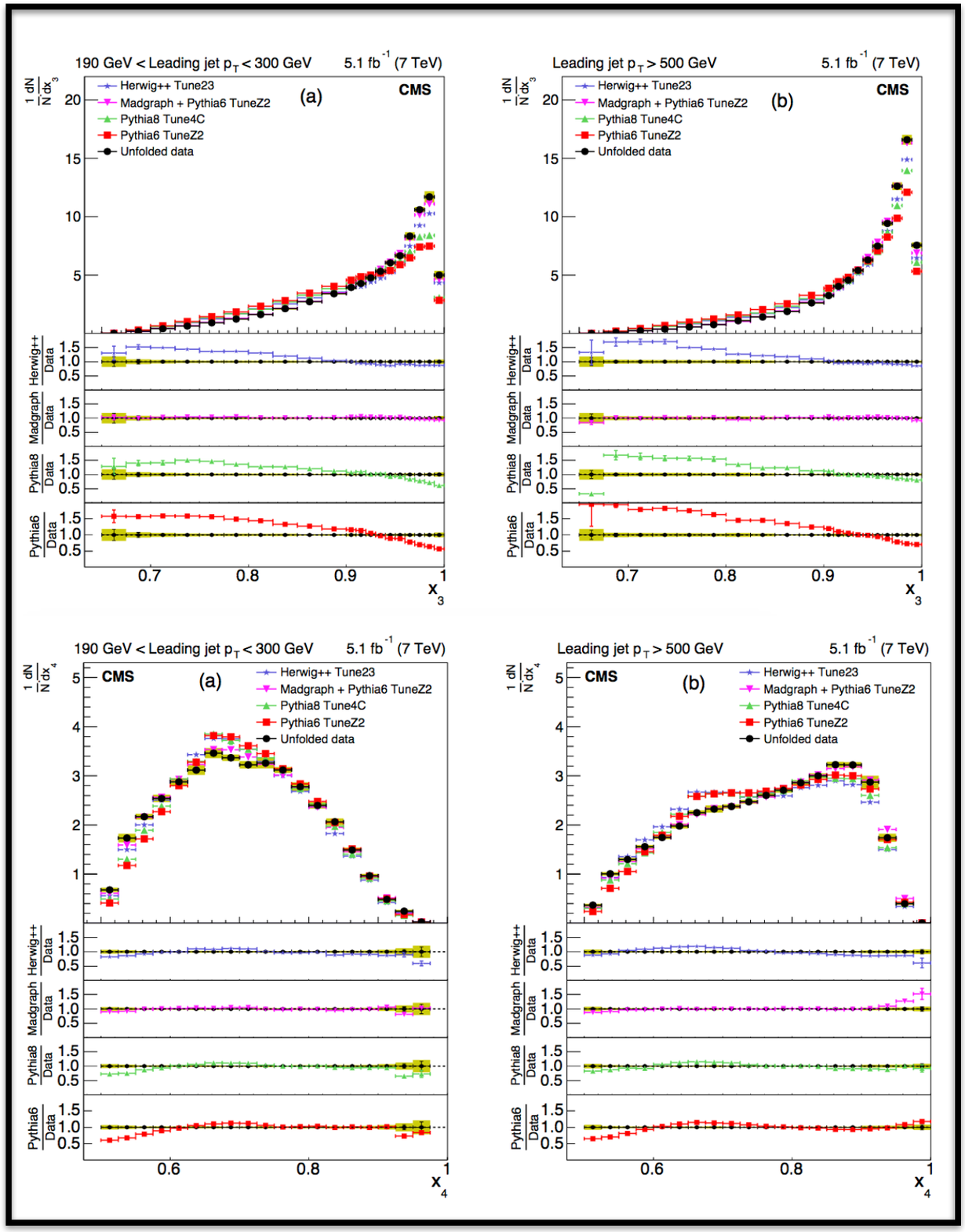


$$x_i = 2E/\sqrt{\hat{s}_{345}}$$

$$E_{CM} = \sqrt{\hat{s}_{345}}$$

(three-jet mass)





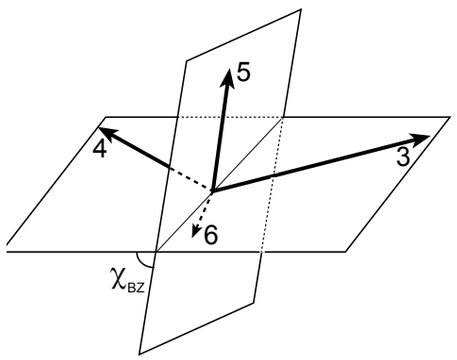
Topological Observables in Inclusive 3&4 Jet Events @ 7 TeV

arXiv.1502.04785

Four-jet Variables

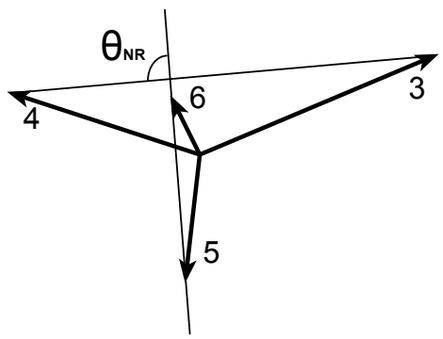
$$E_{CM} = \sqrt{\hat{s}_{3456}}$$ (four-jet mass)

Bengtsson–Zerwas angle

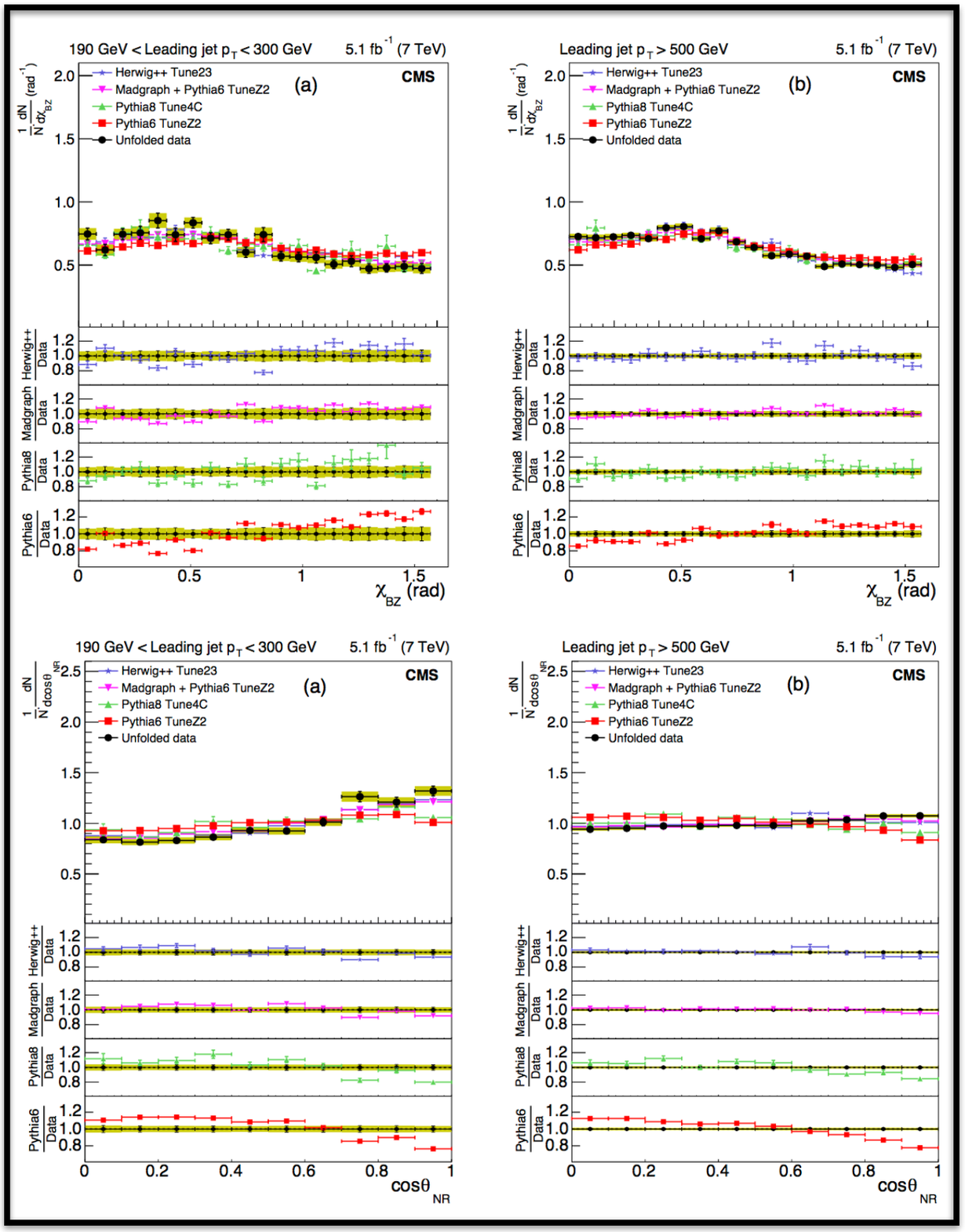


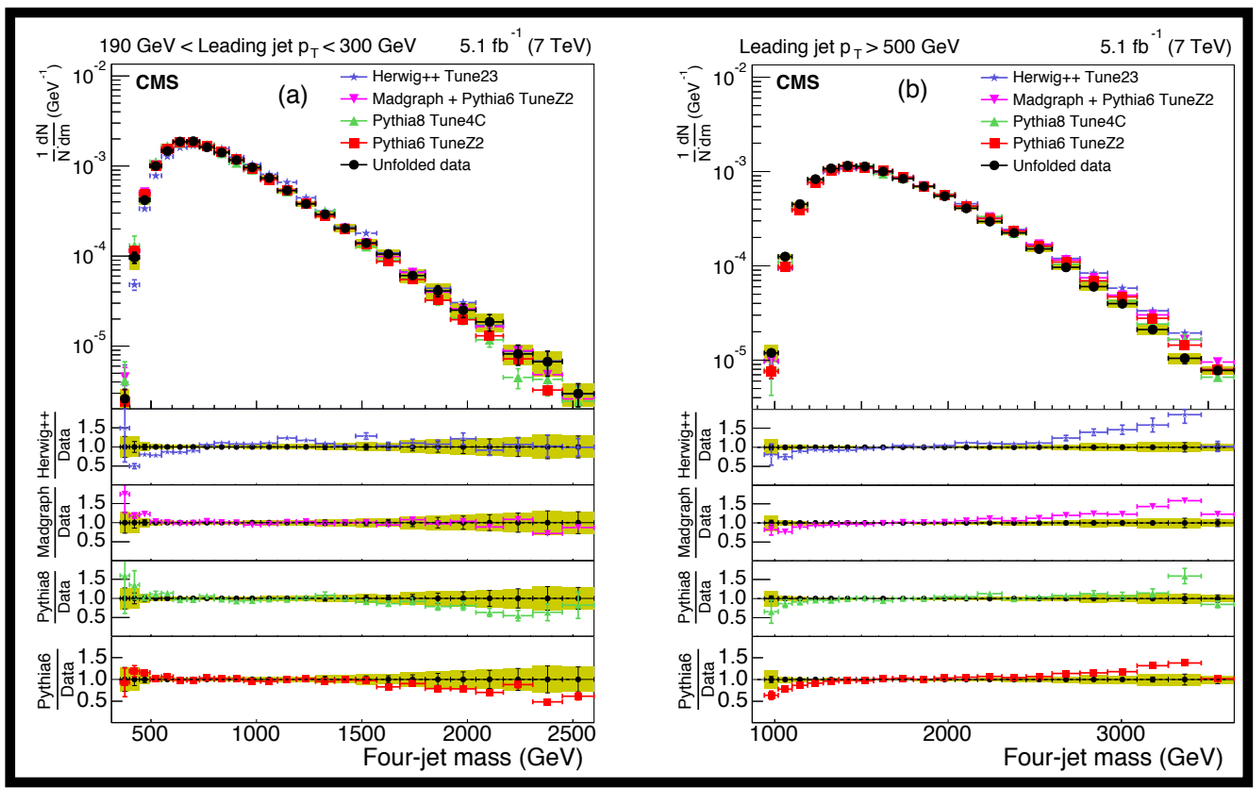
$$\cos\chi_{\rm BZ} = \frac{(\vec{p}_3\times\vec{p}_4)\cdot(\vec{p}_5\times\vec{p}_6)}{|\vec{p}_3\times\vec{p}_4||\vec{p}_5\times\vec{p}_6|}$$

Nachtmann–Reiter angle



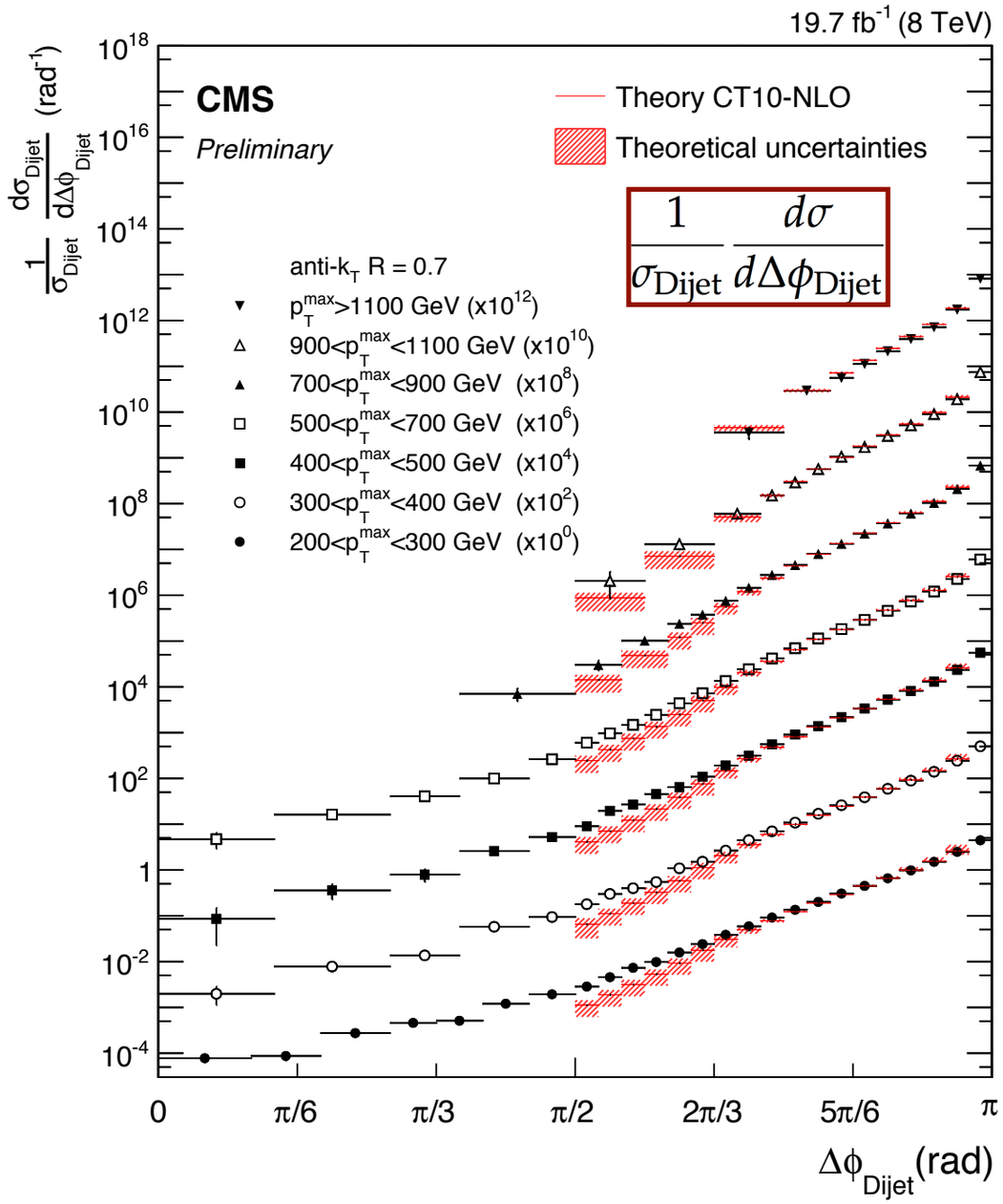
$$\cos\theta_{\rm NR} = \frac{(\vec{p}_3-\vec{p}_4)\cdot(\vec{p}_5-\vec{p}_6)}{|\vec{p}_3-\vec{p}_4||\vec{p}_5-\vec{p}_6|}$$

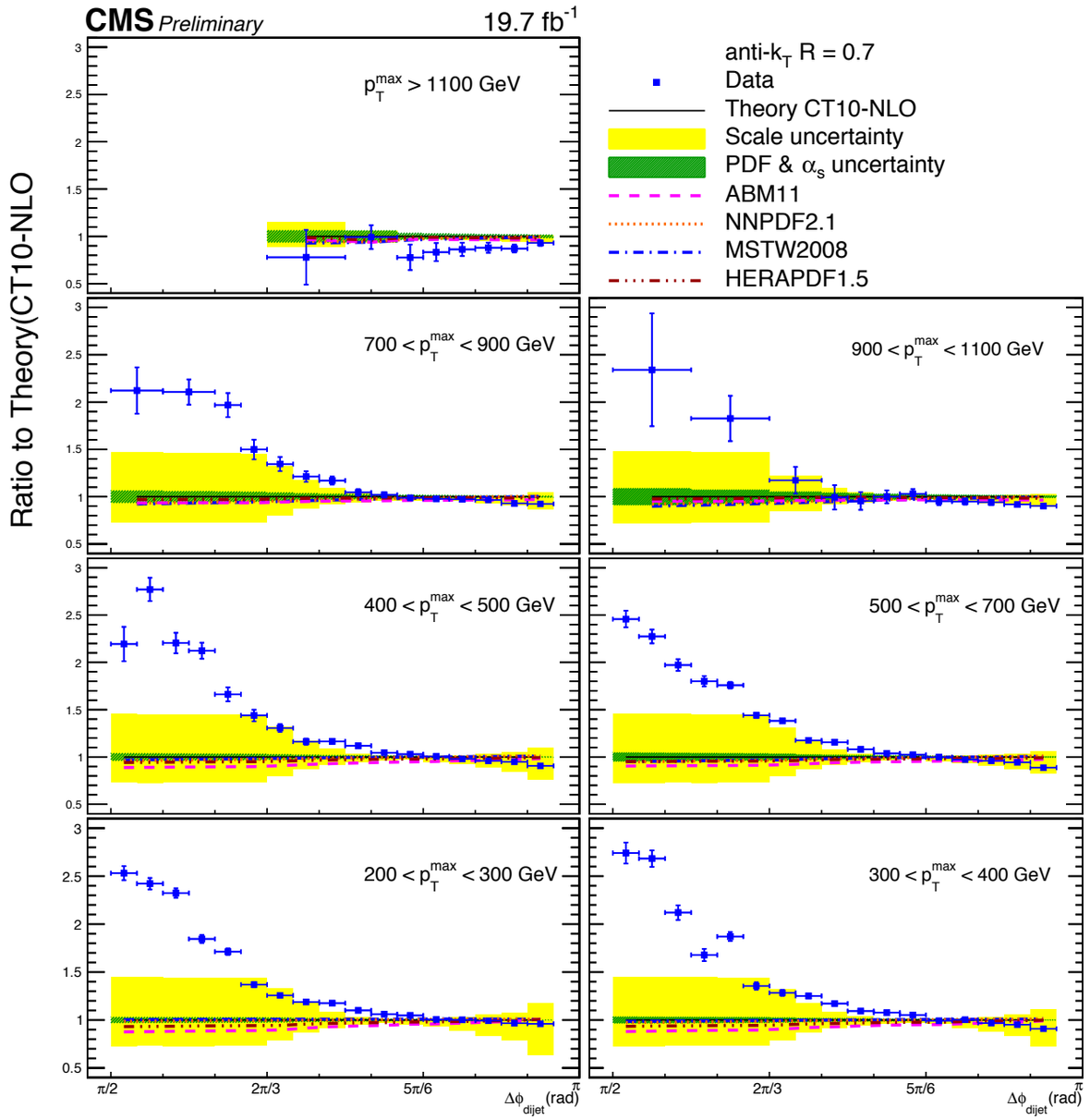




Dijet azimuthal decorrelations in pp collisions at @ 8 TeV

CMS-PAS-SMP-14-015

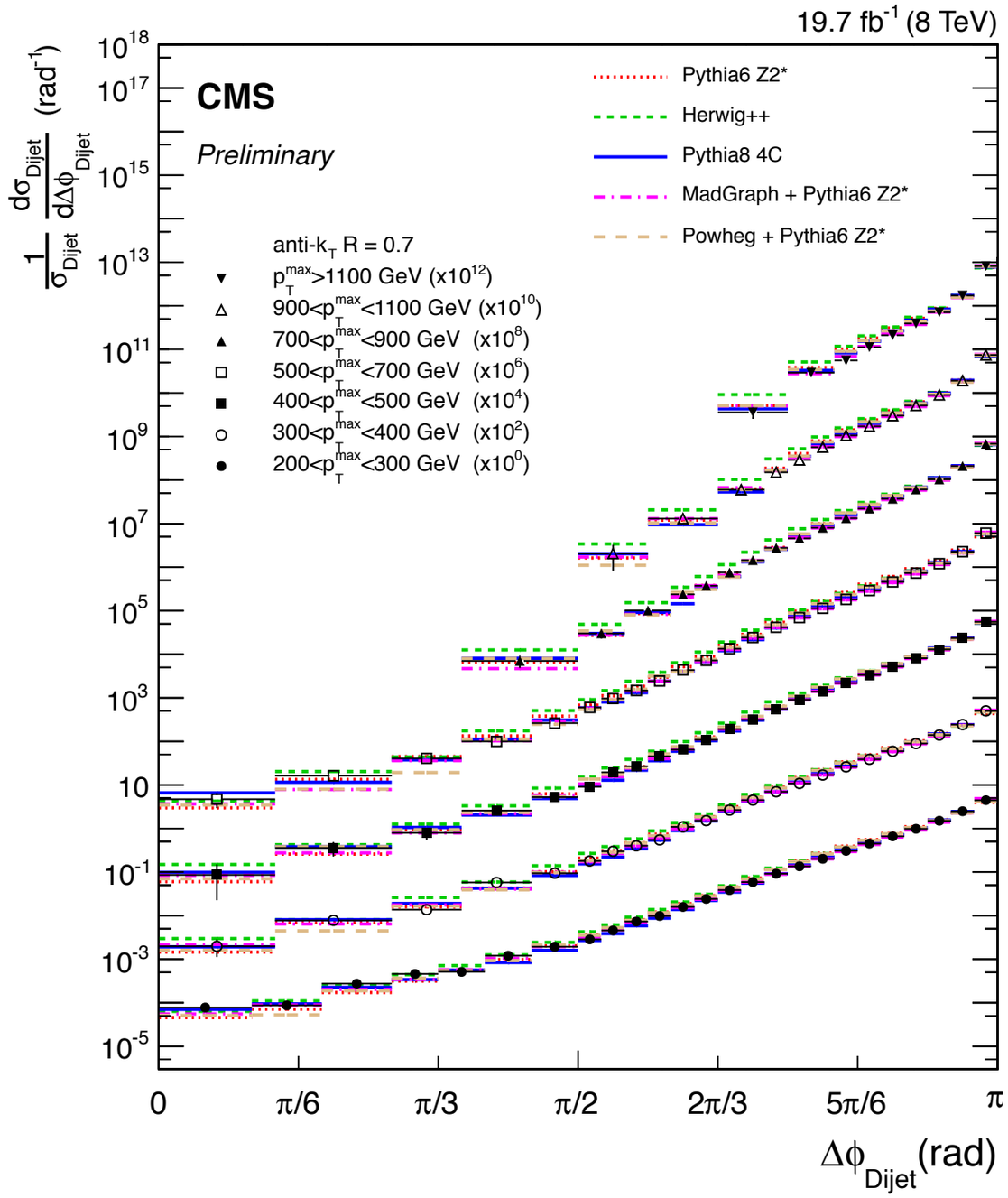




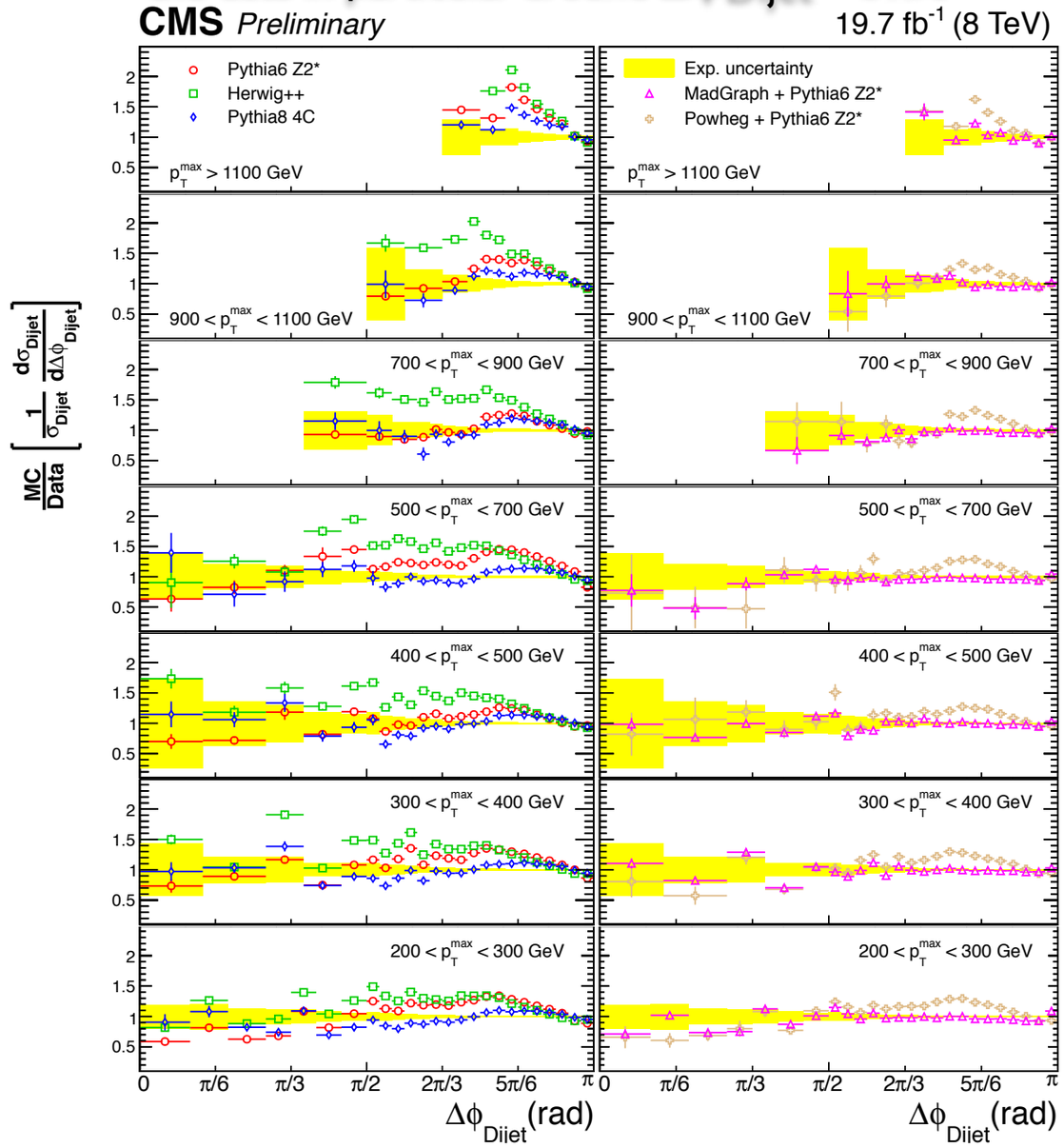
The fixed-order calculations are performed using the NLOJET++ program version 4.1.3, within the framework of the FASTNLO package version 2.3.1. The differential cross section is calculated for 3-jet production at NLO predictions for the range of $2\pi/3 < \Delta\varphi_{Dijet} < \pi$

Dijet azimuthal decorrelations in pp collisions at @ 8 TeV

CMS-PAS-SMP-14-015



PYTHIA6 and HERWIG++ systematically overshoot the data in particular around $\Delta\varphi_{Dijet} = 5\pi/6$



Madgraph agrees with data throughout the whole ΔφDijet region. In contrast PYTHIA6, HERWIG++, PYTHIA8 and POWHEG overestimate data for $\pi/2<\Delta\varphi_{Dijet}<\pi$.

3-jet to 2-jet cross-sections

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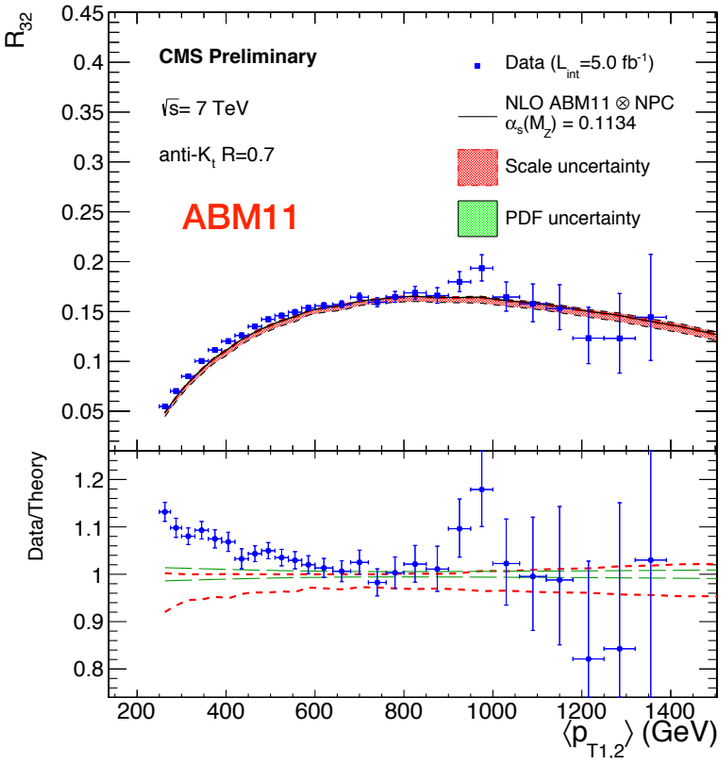
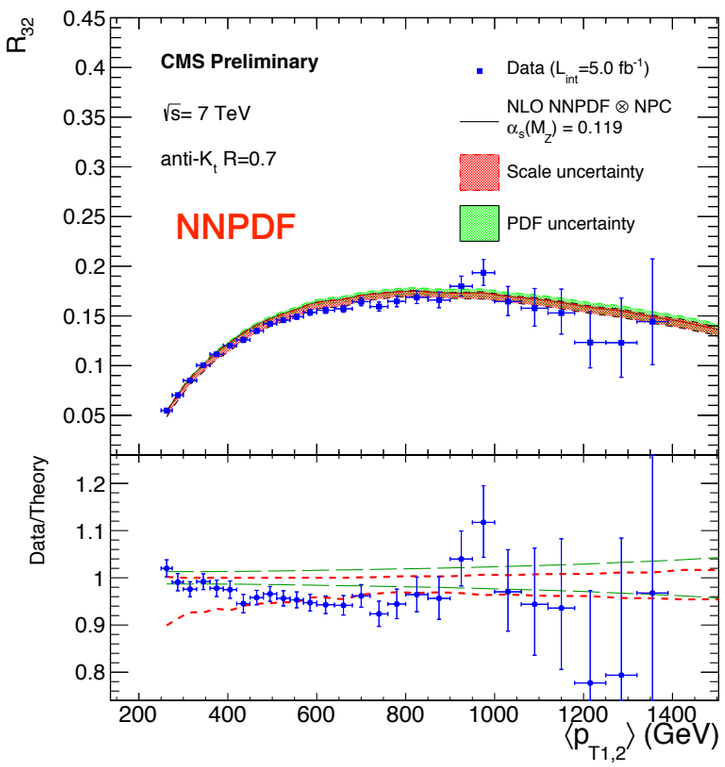
- The plateau of the ratio is sensitive to QCD coupling constant $\alpha(s)$
- Less sensitive to the dominant Jet Energy Scale (JES) uncertainty than inclusive measurements.

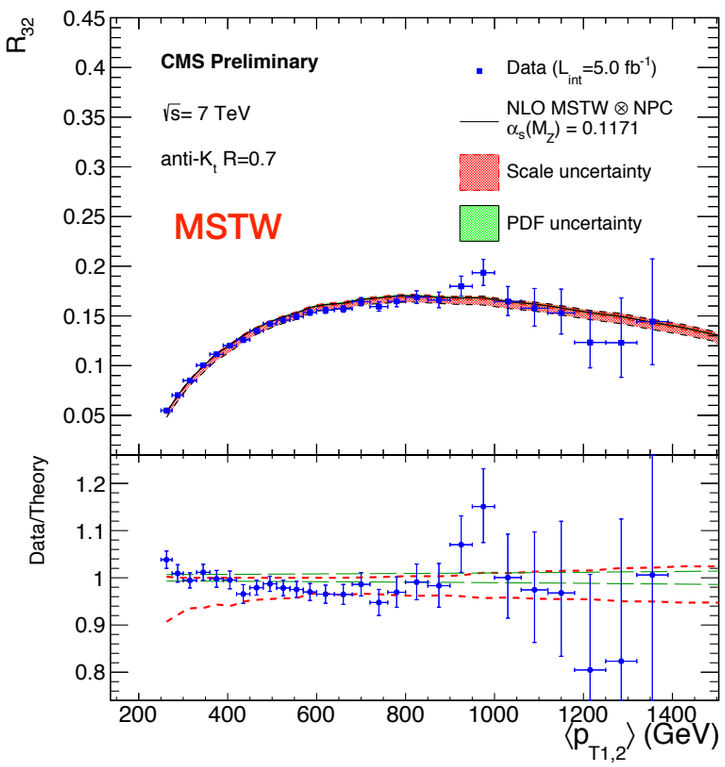
3-jet to 2-jet Ratio is defined as:

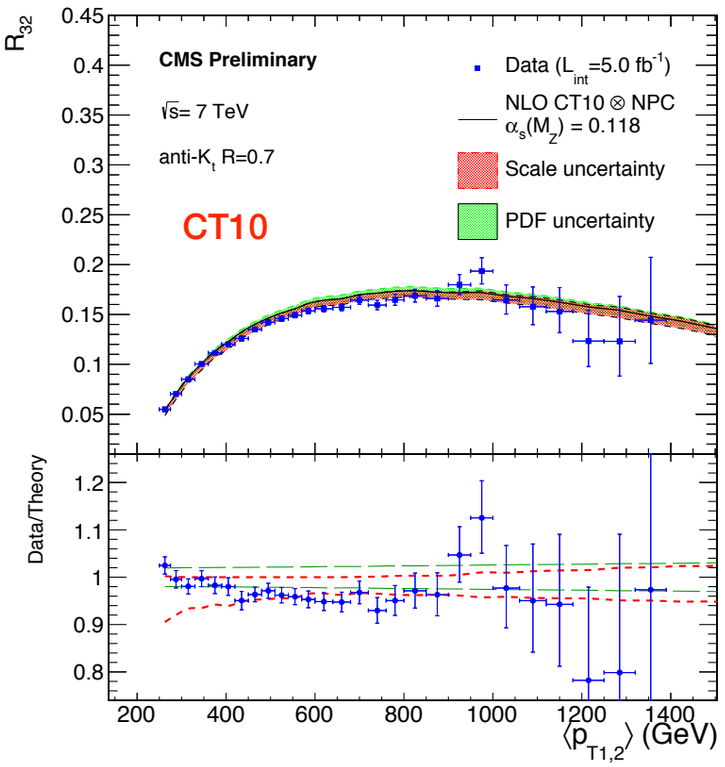
$$R_{32} = \frac{d\sigma_3/dH_T}{d\sigma_2/dH_T}$$

H_T is defined as the scalar transverse momentum sum of all jets



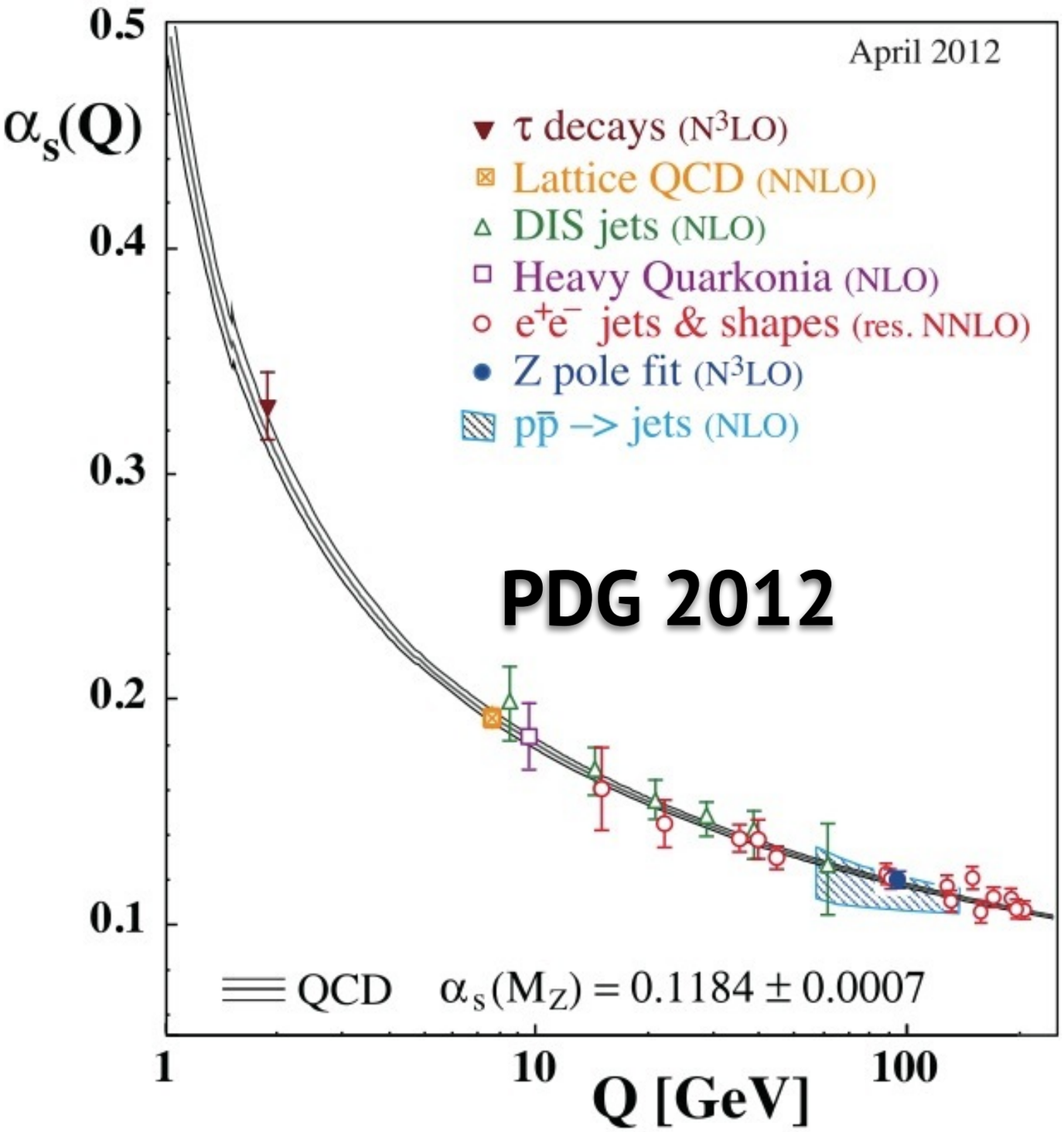




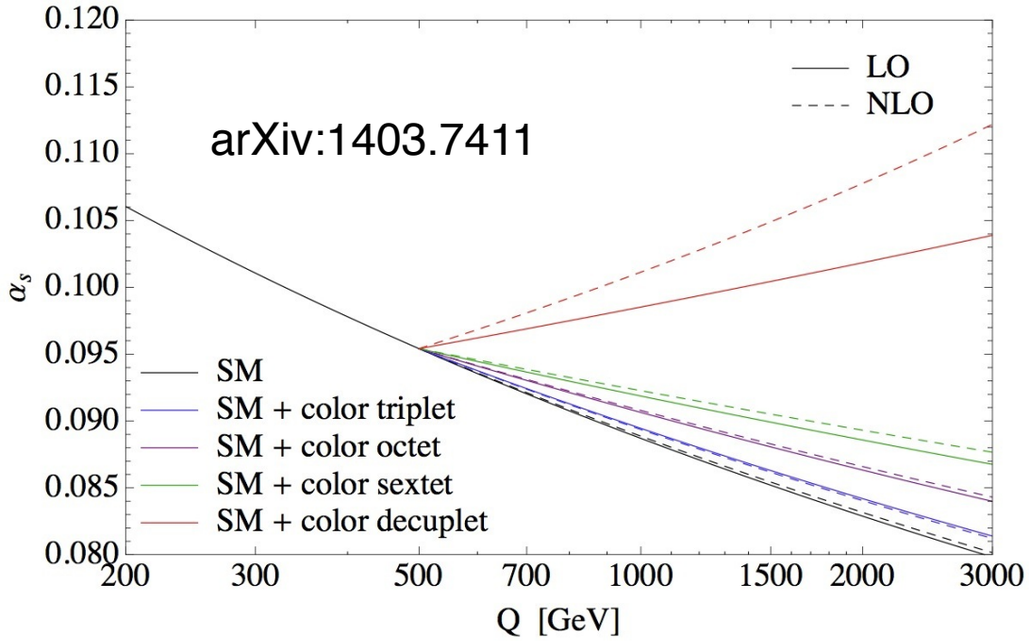


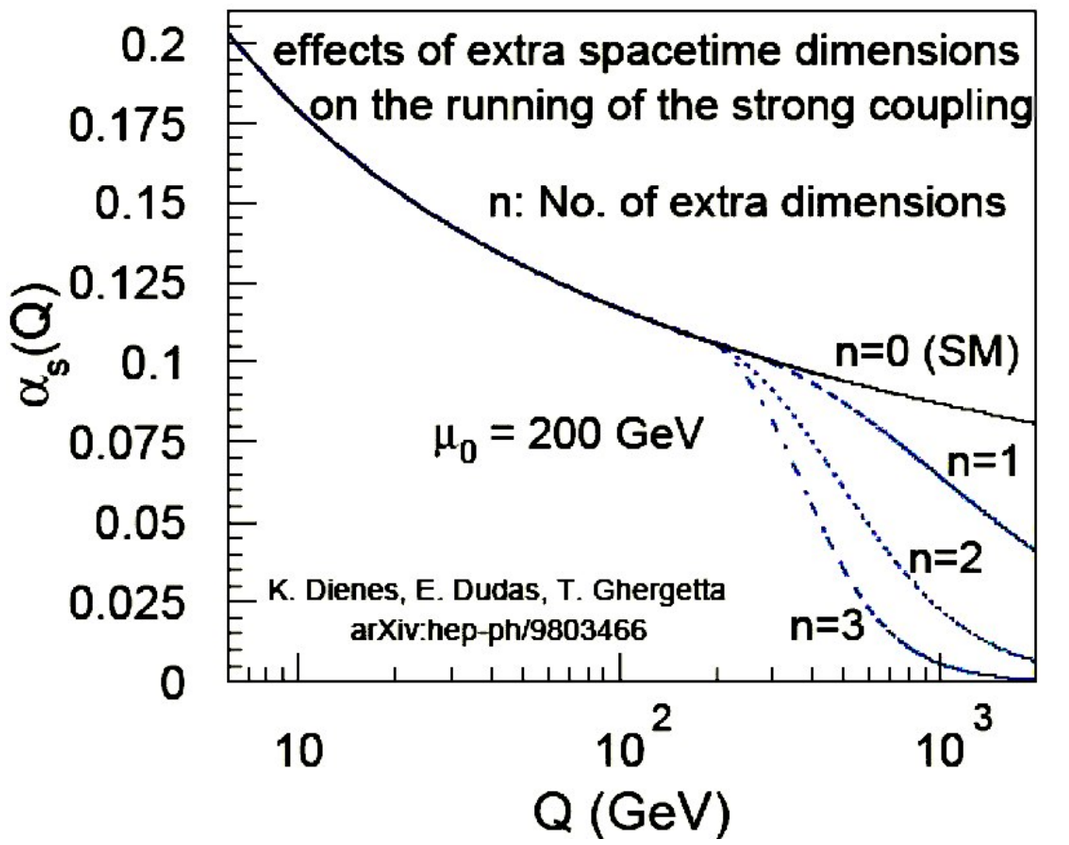
Strong Coupling $\alpha_s(Q)$ from Jet Measurements

Sensitivity to Strong Coupling



PDG 2012



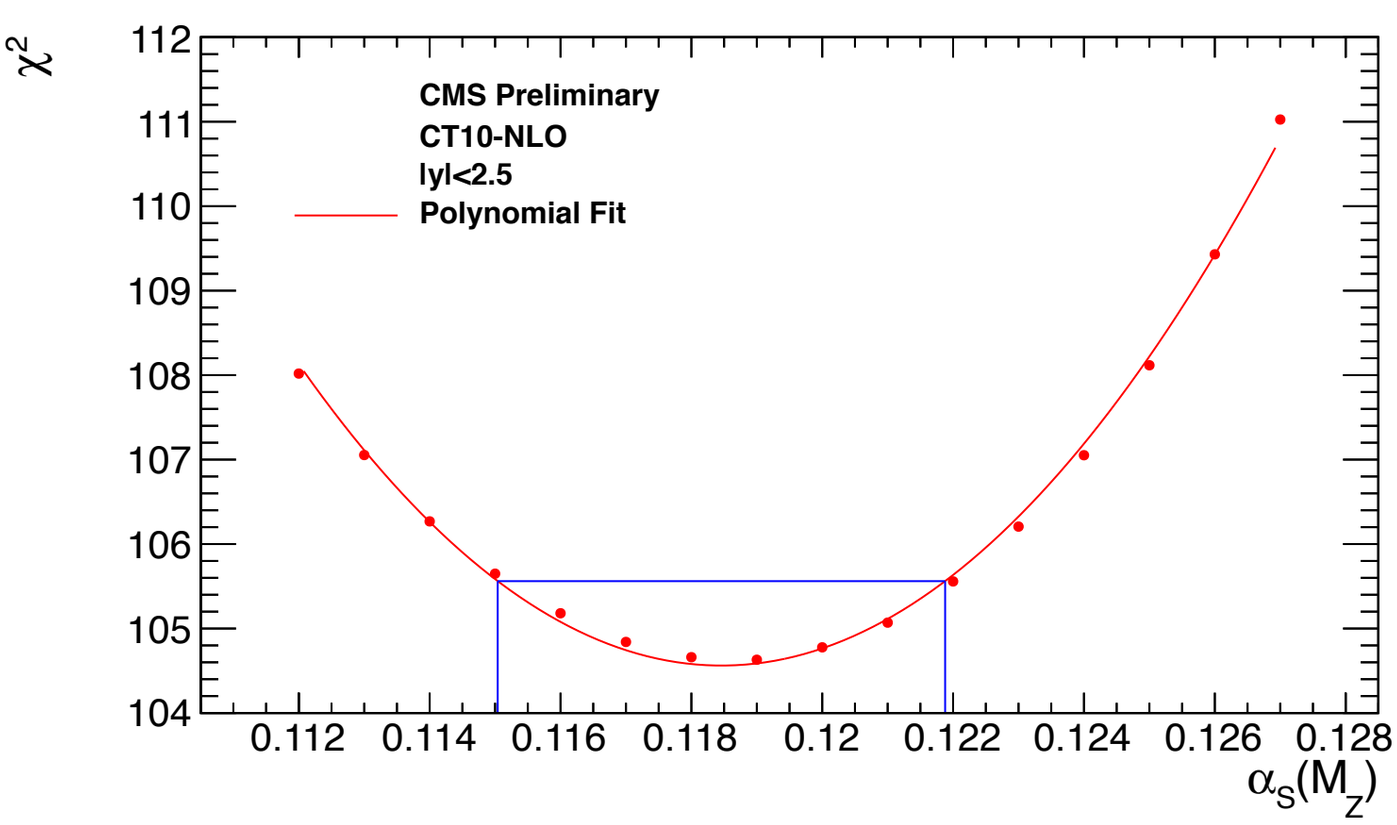


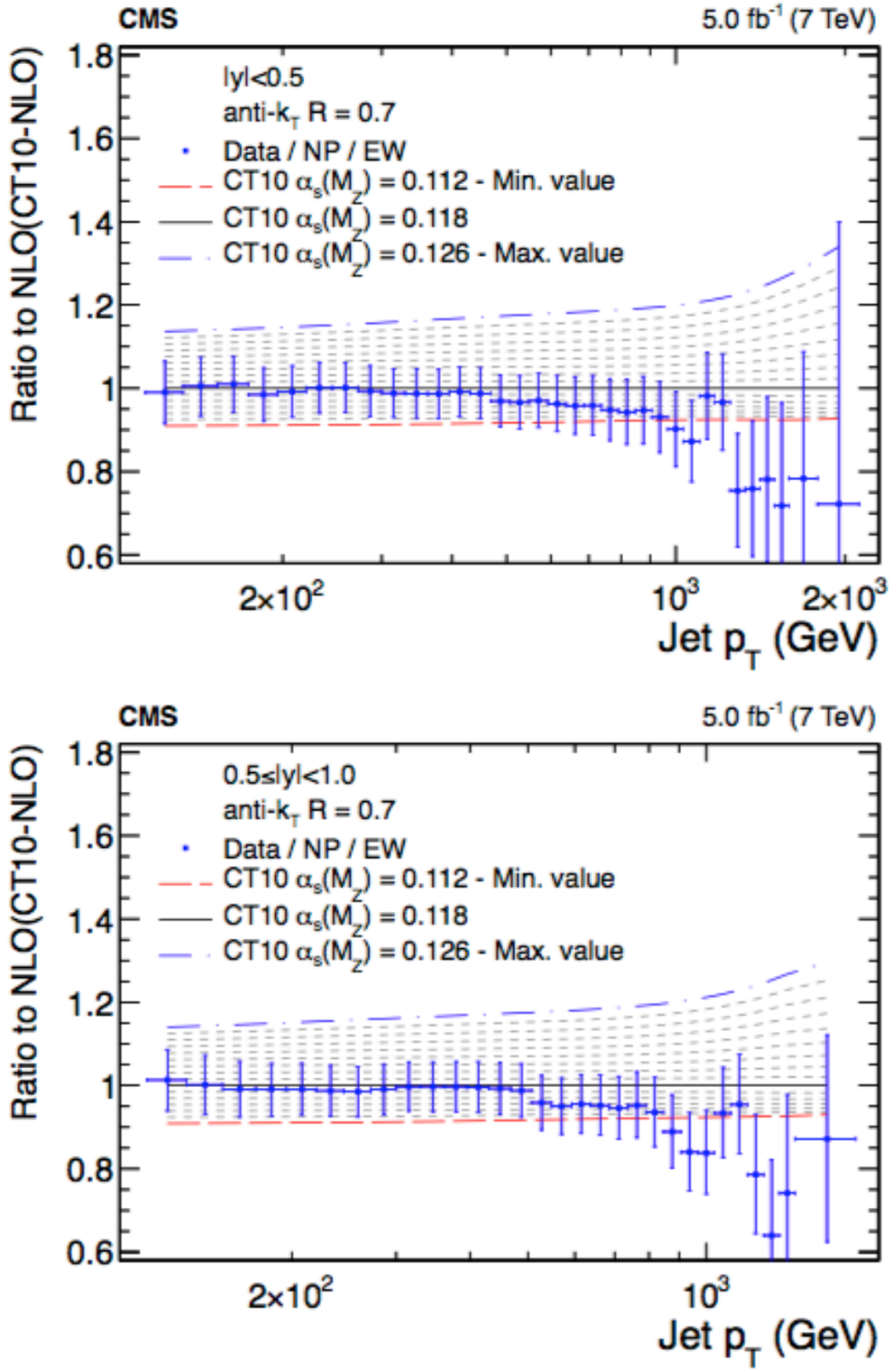
$\alpha_S(Q)$ from Inclusive Jet Cross Section

arXiv:1410.6765

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

$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp})\,^{+0.0060}_{-0.0037}\,(\text{theo})$$





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

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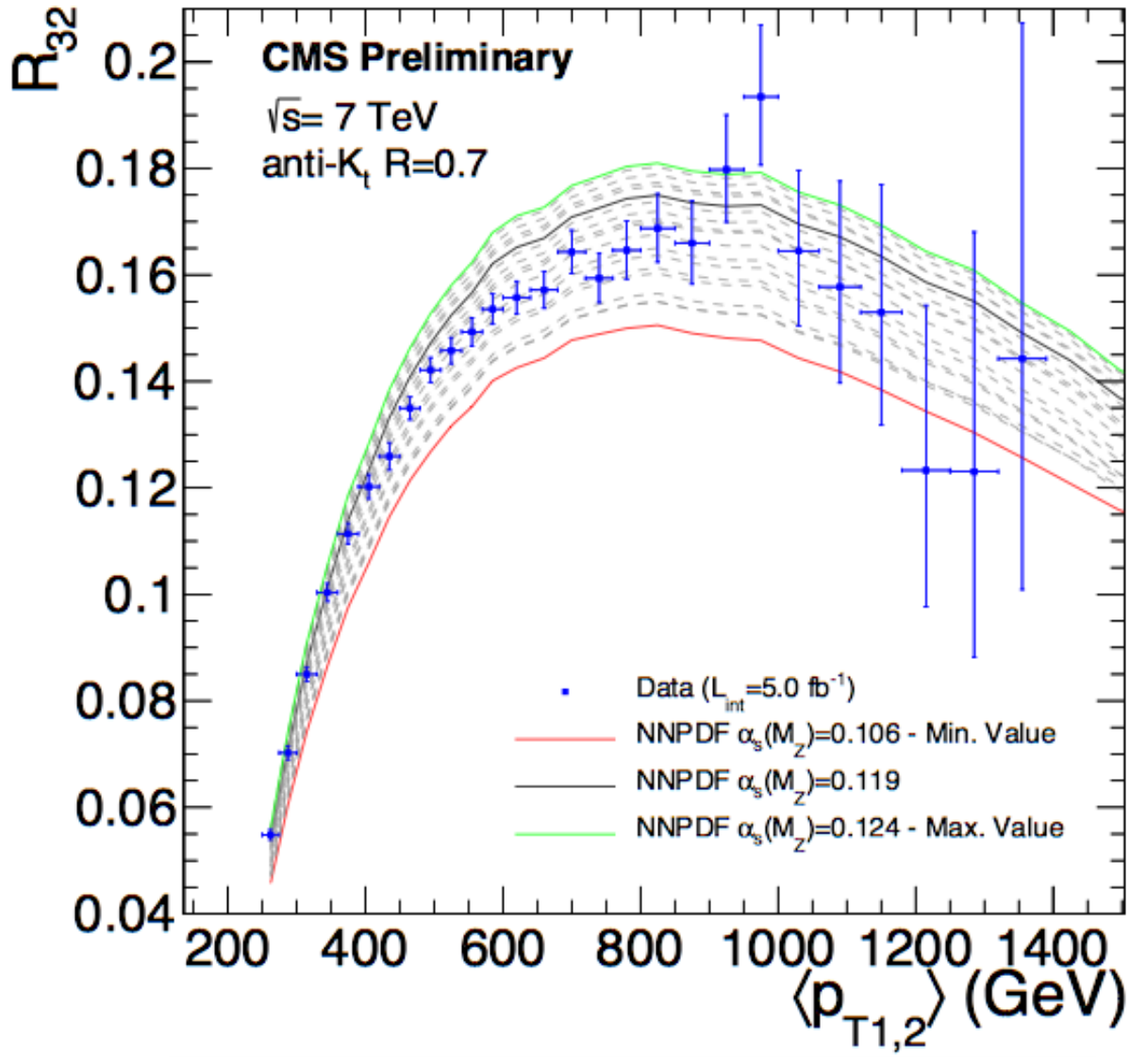
Determination of the strong coupling at transverse momenta in the TeV range

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 Three Jet Mass

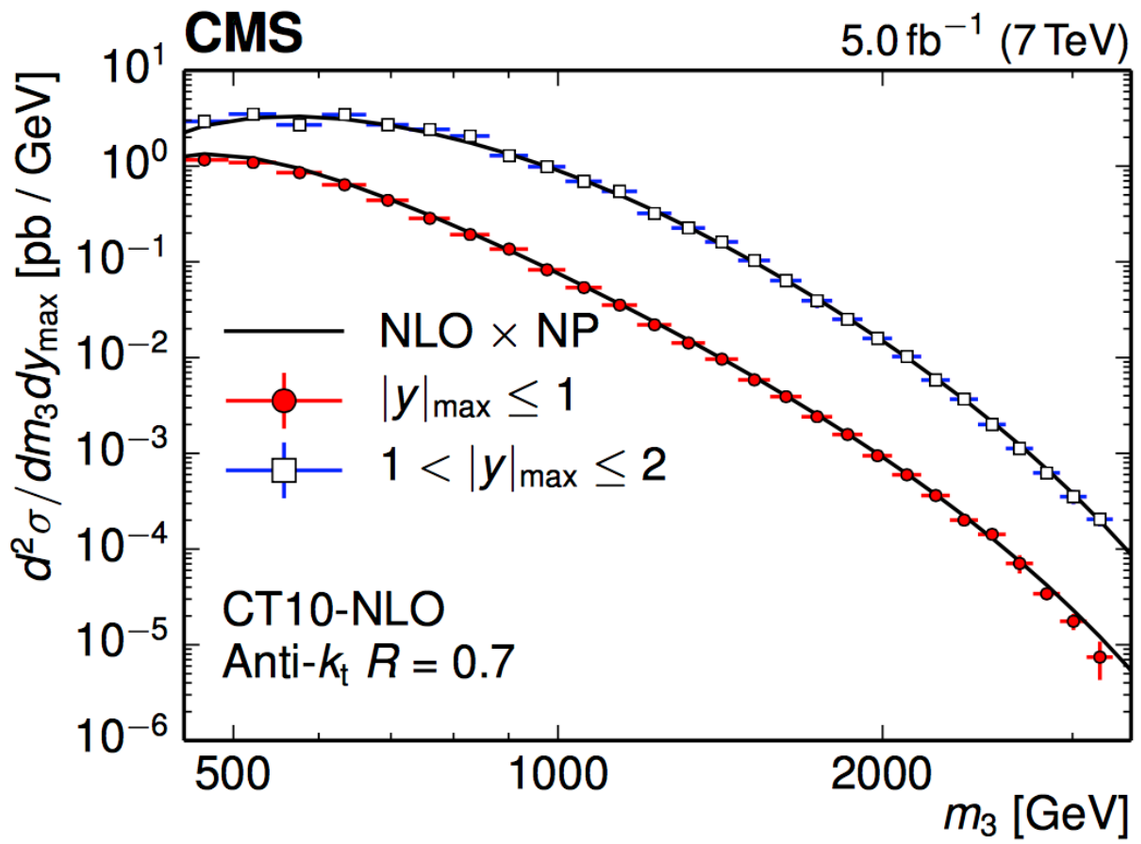
arXiv:1412.1633

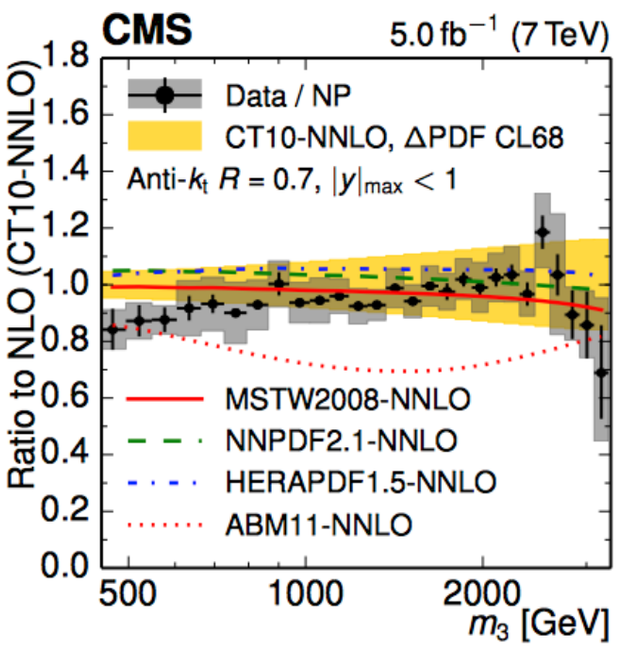
- Measurement of double differential cross section:

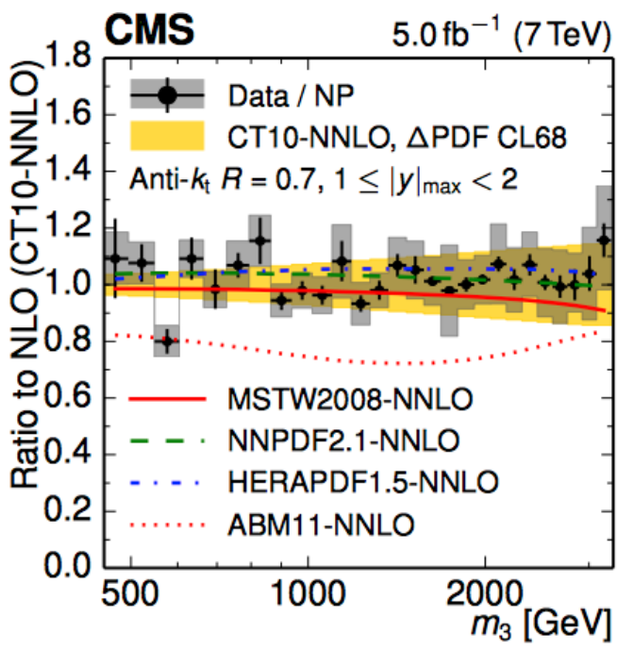
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_3\,\mathrm{d}y_{\max}} = \frac{1}{\epsilon\mathcal{L}}\frac{N}{\Delta m_3(2\Delta|y|_{\max})}$$

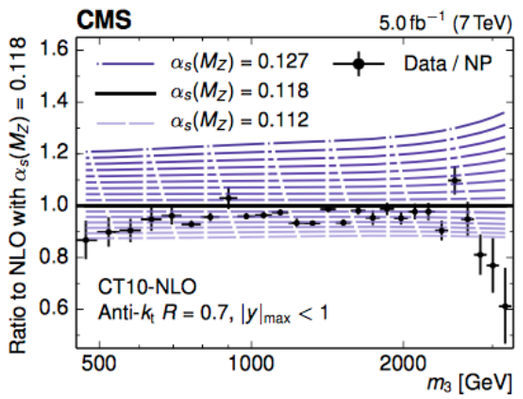
$$m_3^2 = (p_1 + p_2 + p_3)^2 \quad |y|_{\max} = \max(|y_1|, |y_2|, |y_3|)$$

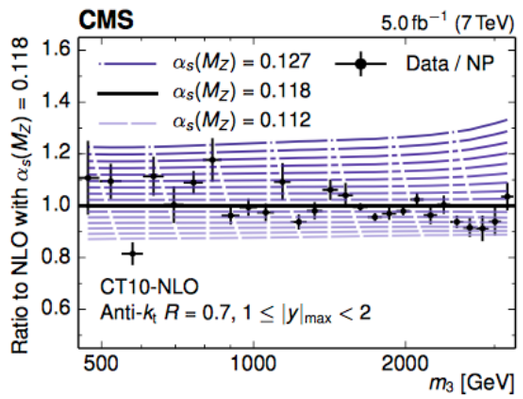
- Sensitive to PDFs and αs
- Require jet pT > 100 GeV
- Two rapidity bins: $|y|_{max} < 1$ and $1 < |y|_{max} < 2$
- Scale choice: $\mu_r = \mu_f$ = m3/2
- Good agreement with pQCD











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

$\alpha_s(Q)$ Overview

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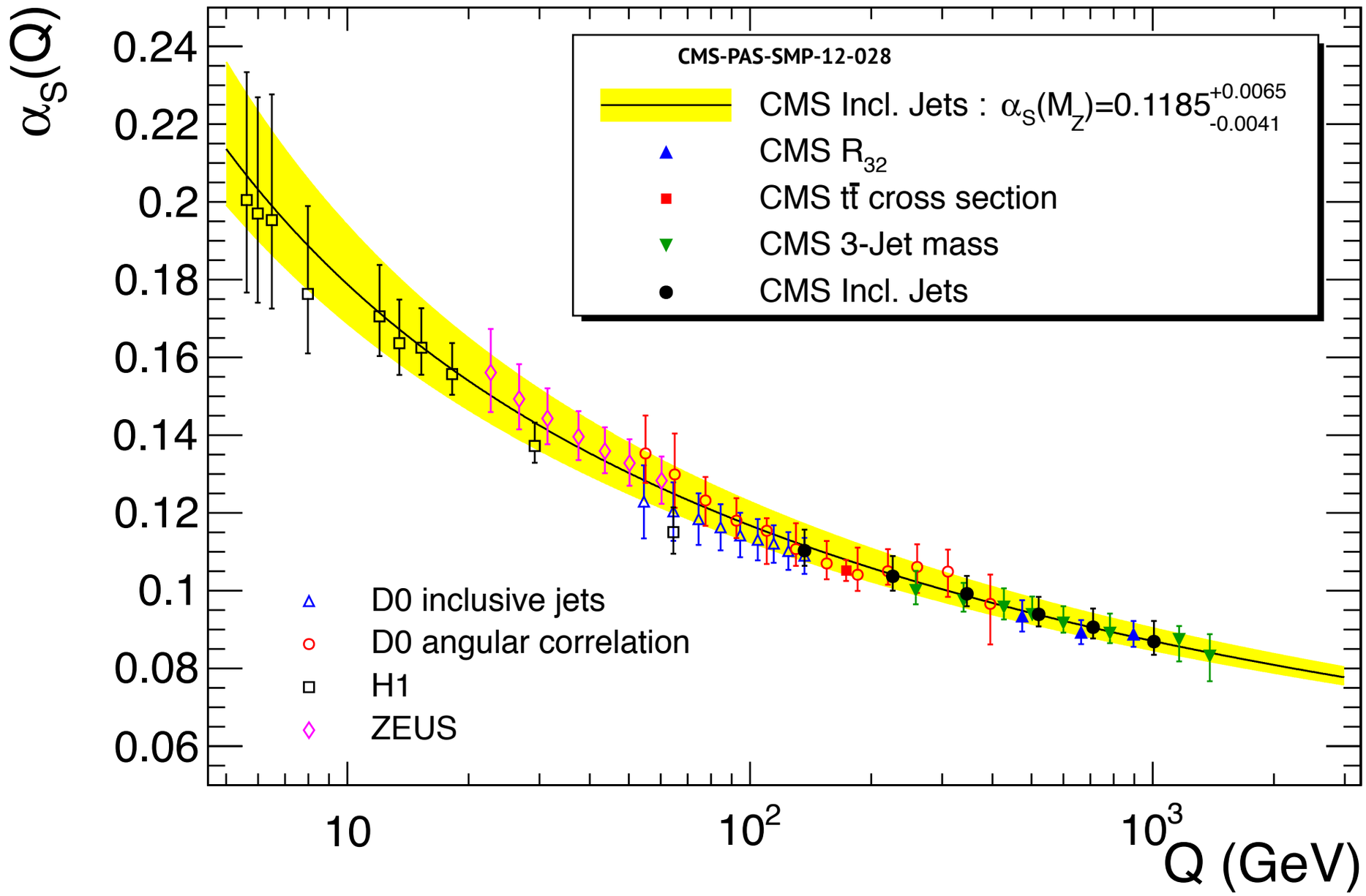

The strong coupling α_s (yellow band) as a function of the momentum transfer, Q, where the value at $Q = M_Z$ has been evolved using the three-loop RGE.

Conclusions

- CMS has completed a very large number of analyses with *pp* collisions at 7 & 8 TeV
- 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
- 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 !