Multi-differential jet cross sections in CMS

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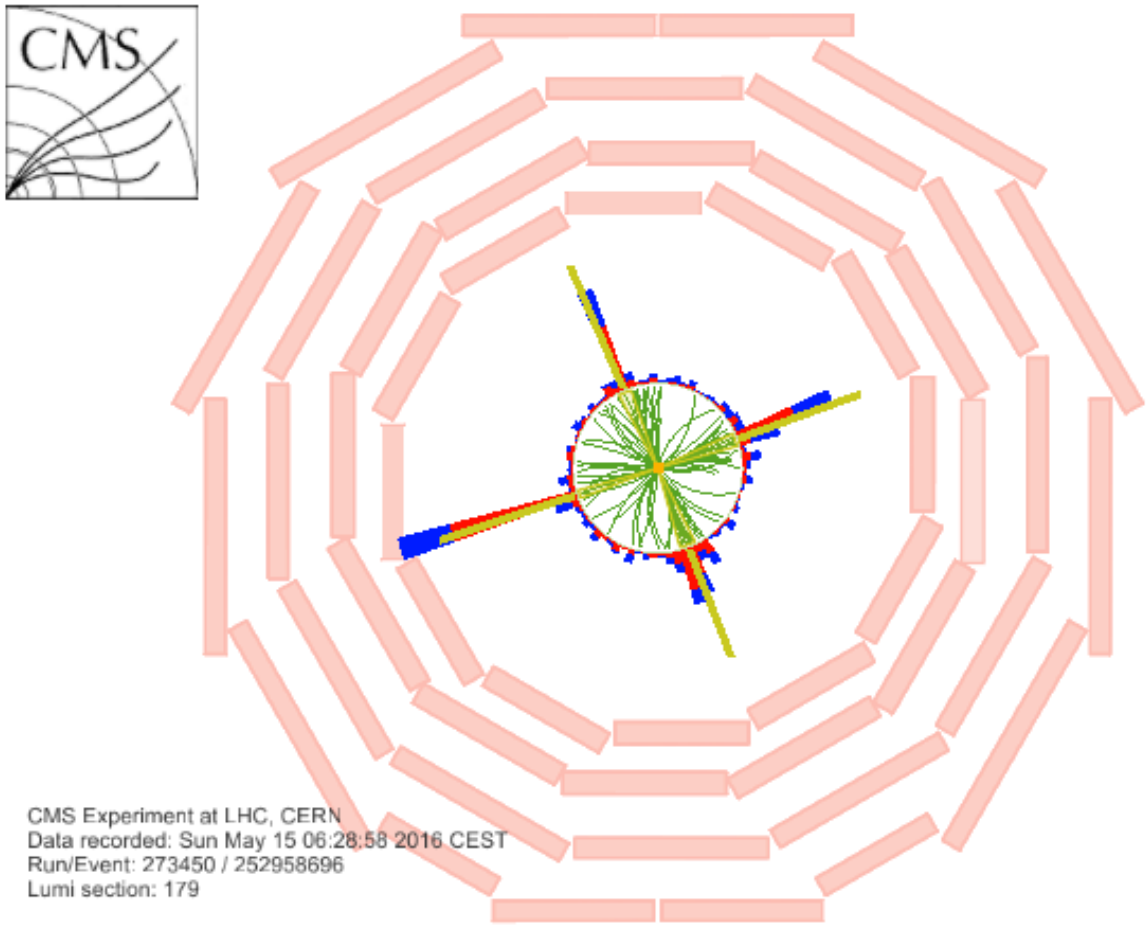
QCD

- Main background to almost any interesting and rare event at a hadron collider.
- Understood in terms of factorization theorems.
- Extraction of α_s and PDFs.
- Many subtleties remain unclear (MM schemes, PS and resummation, factorization breaking and soft gluons color correlations...)

Jets measurements

- Partons express themselves in terms of collimated streams of hadrons.



Double-differential inclusive jets cross sections in pp collisions at $\sqrt{s} = 8\text{TeV}$

Published in JHEP 1703 (2017) 156
CMS-SMP-14-001, CERN-EP-2016-196
e-Print: arXiv:1609.05331

Double-differential inclusive jet cross sections in pp collisions at $\sqrt{s} = 13\text{TeV}$

Published in Eur.Phys.J. C76 (2016) no.8, 451
CMS-SMP-15-007, CERN-EP-2016-104
e-Print: arXiv:1605.04436

Inclusive jets cross sections @8TeV and 13TeV

JHEP 1703 (2017) 156, Eur.Phys.J. C76 (2016) no.8, 451

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

- $p + p \rightarrow jet + X$ probes parton-parton interaction (Benchmark QCD test)

- Sensitive to α_s. Provides important PDFs constraints

- QCD describes data over 14 orders of magnitude!!

- Experimental uncertainties dominated by JES, unfolding and the integrated luminosity.

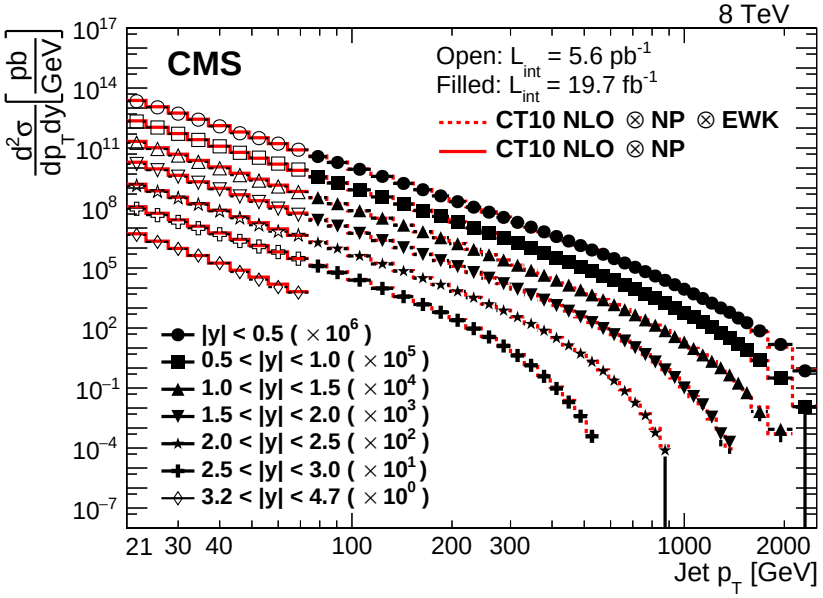
- Strongly p_T and y dependent PDF uncertainties (dominant)

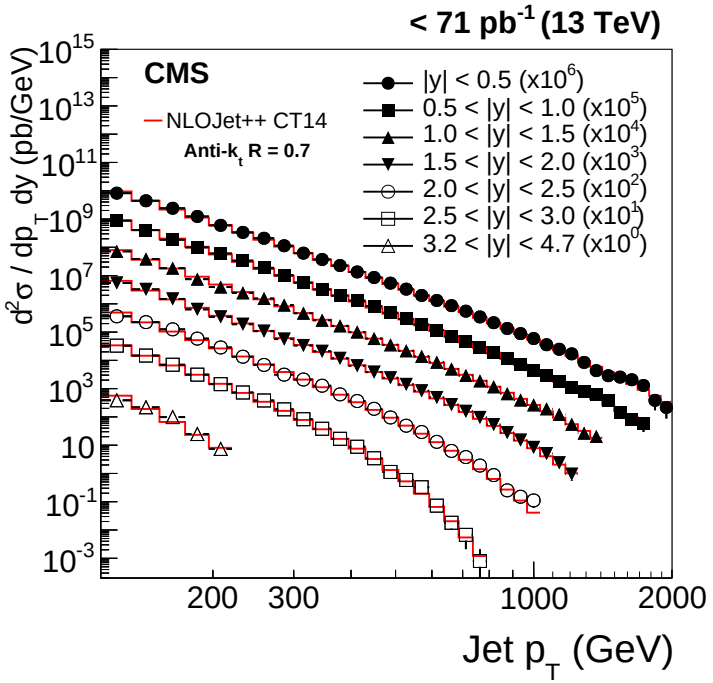
Inclusive jets cross sections @8TeV

- anti-k_t7, bins of rapidity $\in [0, 4.7]$

Inclusive jets cross sections @13TeV

- anti-k_t4 and anti-k_t7, bins of rapidity $\in [0, 4.7]$





Inclusive jets cross sections @8TeV and 13TeV

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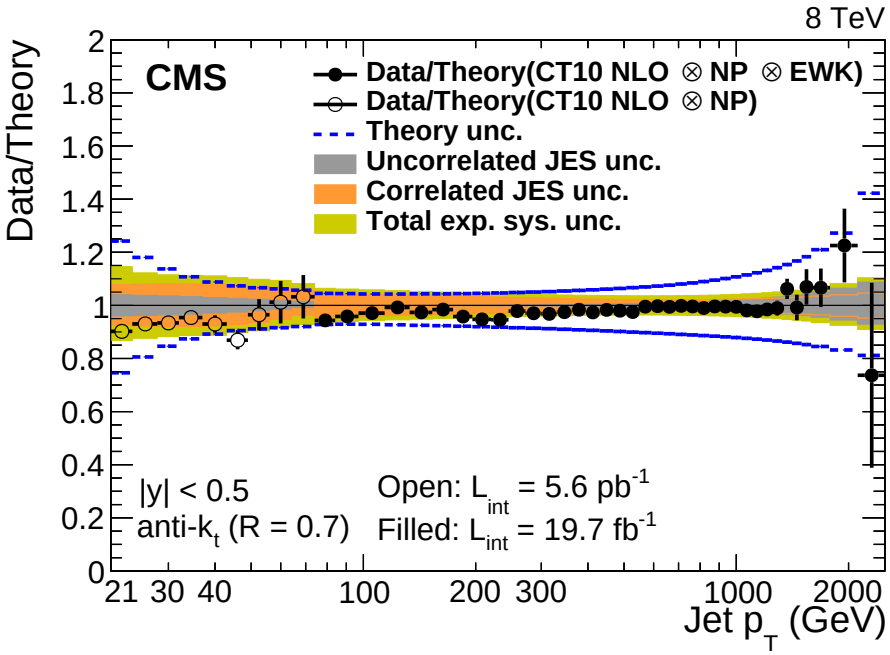
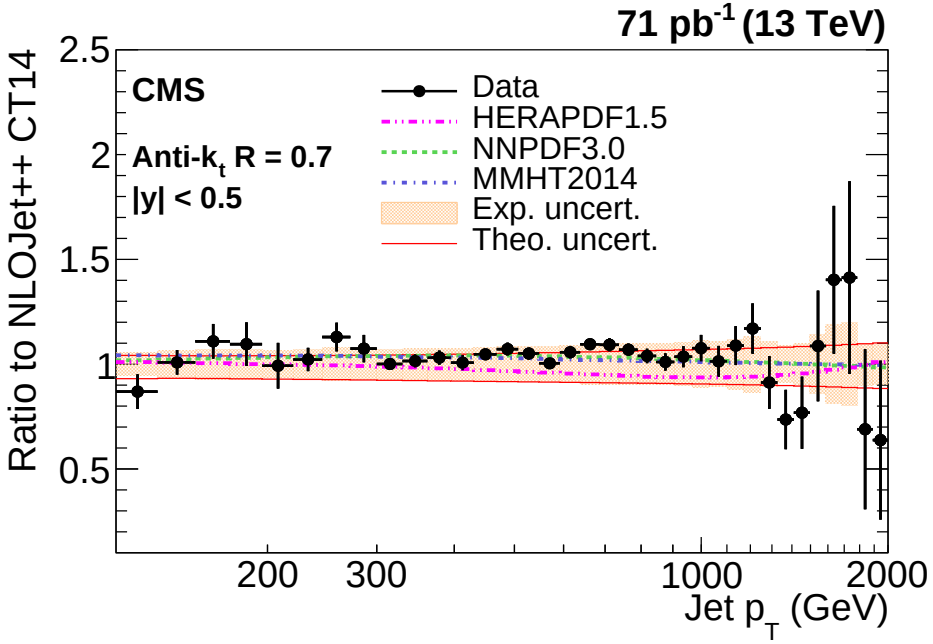




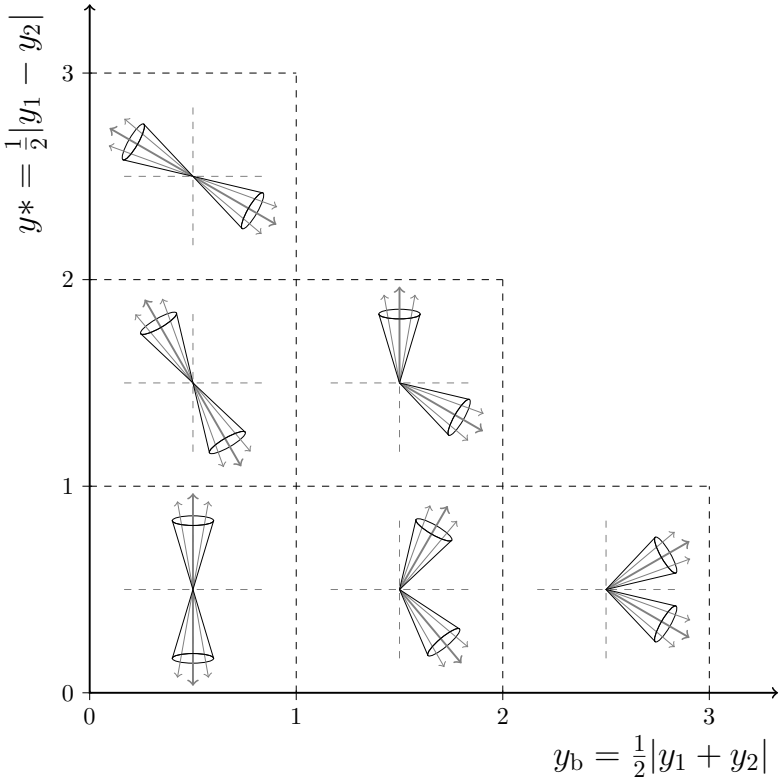
- Predictions are in good agreement with data
- More can be learnt from these measurements → see next slides

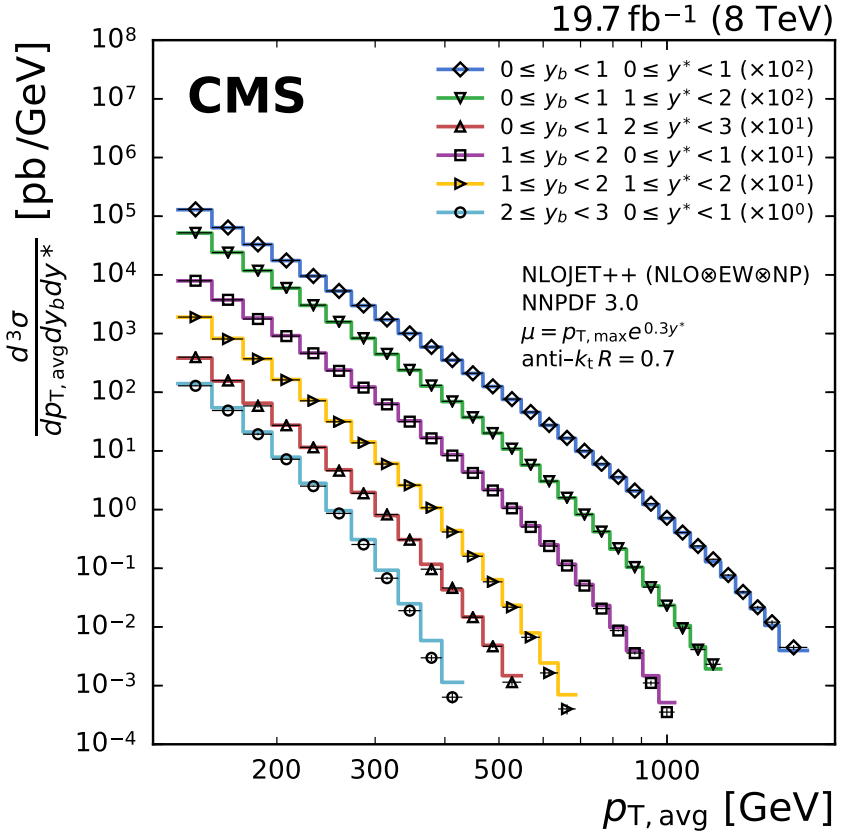
Measurement of the triple-differential dijet cross section in pp collisions at $\sqrt{s} = 8\text{TeV}$

arXiv: 1705.02628

Triple differential dijet cross section @8TeV

arXiv: 1705.02628





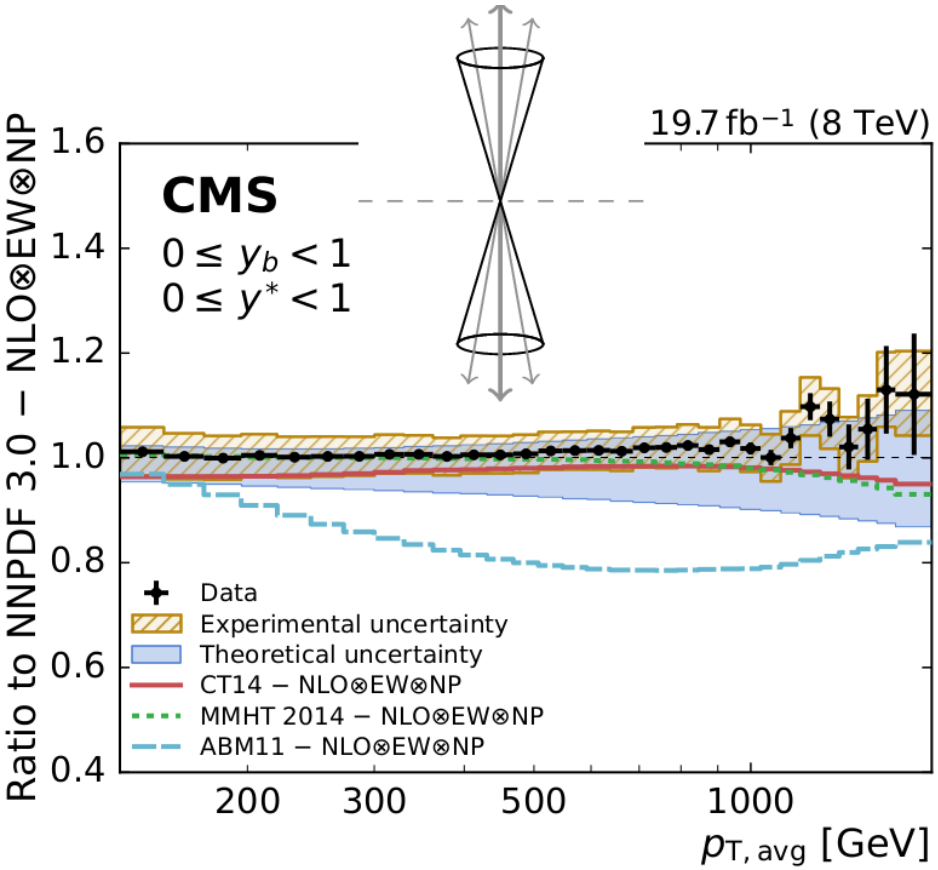
$$\frac{d^3\sigma}{dp_{T,avg}dy*dy_b} = \frac{1}{\epsilon \mathcal{L}_{\mathrm{int,eff}}} \frac{N}{\Delta p_{T,avg}\Delta y*\Delta y_b}$$

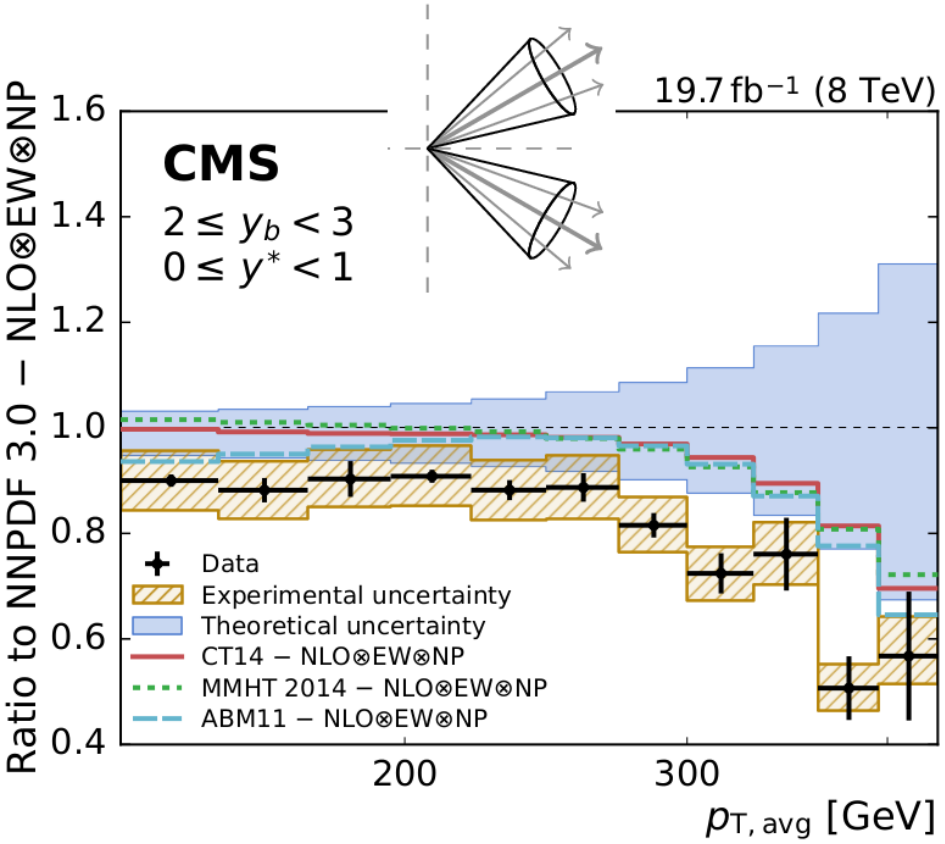
- $p_{T,avg}$ leading jets average p_T
- $y* = |y_1 - y_2)|/2$
- $y_b = |(y_1 + y_2)|/2$

- Test of pQCD
- Determination of coupling constant
- Constraints on PDFs

Triple differential dijet cross section @8TeV

arXiv: 1705.02628





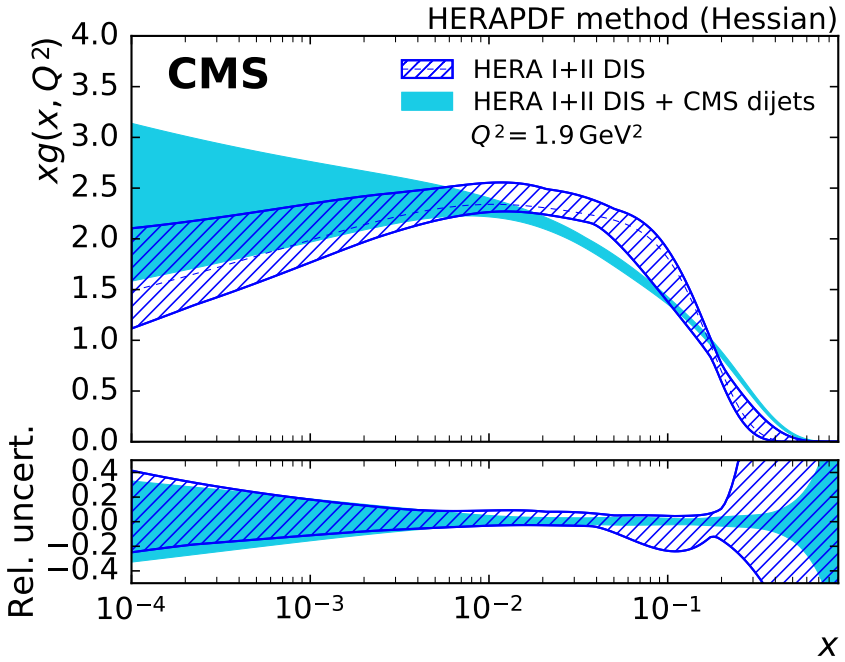
- For mid-x ($\sim$ partonic momentum fraction) regions data are well described
- Boosted topologies (large-x) lacks from PDF information
- Small experimental uncertainties in boosted topologies $\rightarrow$ potential constraints on PDF

PDF constraints

arXiv: 1705.02628

- Largest impact on the high-x region

- PDF uncertainty from experimental, model, and parameterisation uncertainty



α_s extraction

$$\text{At LO: } \frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2 \ (2\to 2)$$

α_s extraction at NLO:

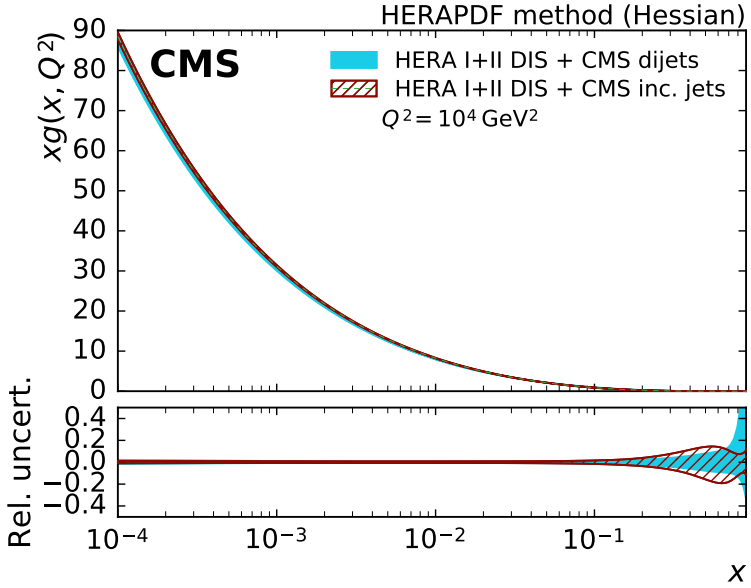
- α_s an additional free parameter in the PDF fit

$$\alpha_s(M_Z) = 0.1199 \pm 0.0015(exp)^{+0.0002}_{-0.0002}(mod)^{+0.0002}_{-0.0004}(par)$$

$$\Delta\alpha_s(M_Z) =^{+0.0026}_{-0.0016} (scale, refit)$$

- α_s measurement dominated by theory uncertainties

- World average value:
$\alpha_s(M_Z) = 0.1181 \pm 0.0011$



Strong coupling constant from the measurement of inclusive multijet event cross sections in pp collisions at $\sqrt{s} = 8\text{TeV}$

to be published (CMS PAS SMP-16-008)

Inclusive 2-jets, 3-jets and R_{32}

CMS PAS SMP-16-008

$$\frac{d\sigma}{d(H_{T,2}/2)} = \frac{1}{\epsilon \mathcal{L}_{\mathrm{int,eff}}} \frac{N_{\mathrm{event}}}{\Delta(H_{T,2}/2)}$$

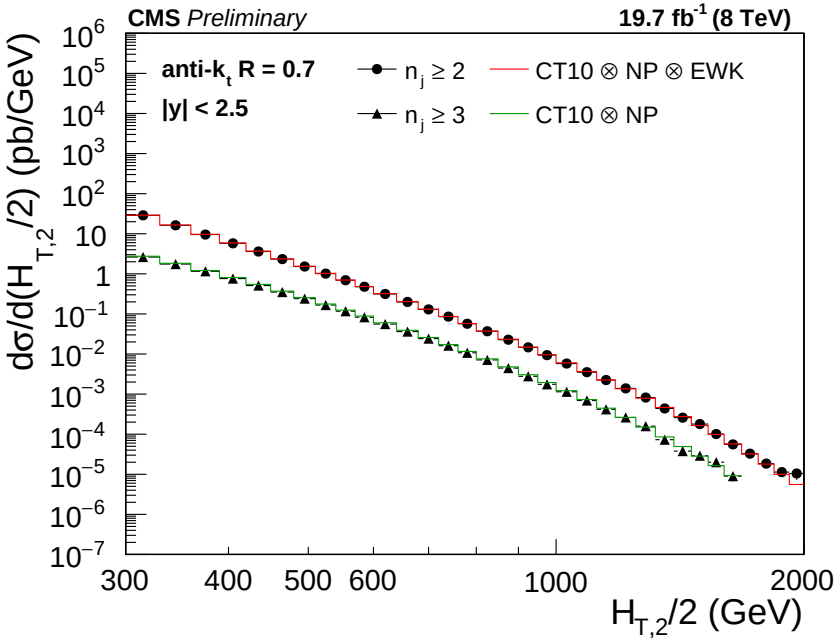
$H_{T,2}/2$: leading jets average p_T, and scale of the event

- Inclusive 3-jets, inclusive 2-jets were studied

$R_{32} = \frac{d\sigma_3}{d\sigma_2} \propto \alpha_s$

- JES is the dominant systematic uncertainty for σ_2 (3-10%) and σ_3 (3-8%)

- $R_{32} \rightarrow$ theoretical and experimental uncertainties partially cancel (exp. uncertainties $\sim 1\%$)



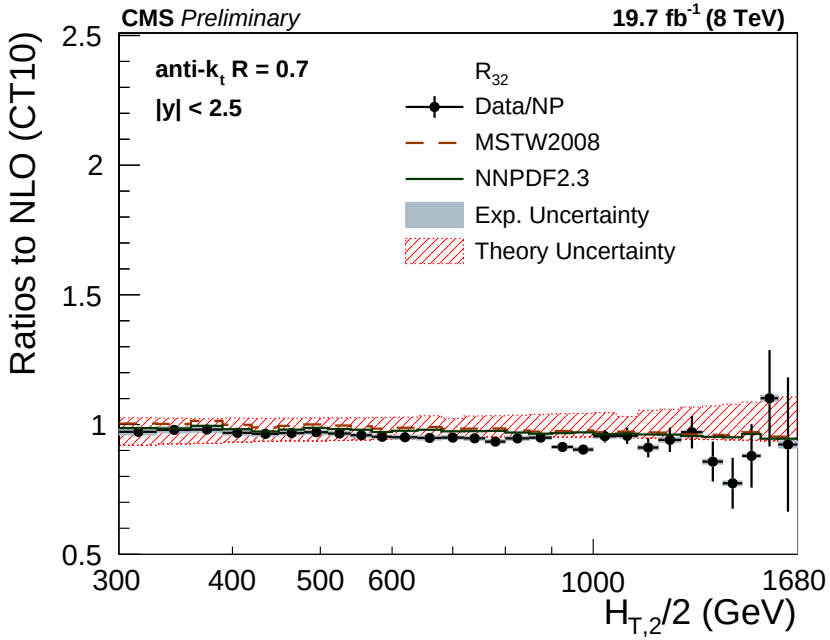
Inclusive 2-jets, 3-jets and R_{32}

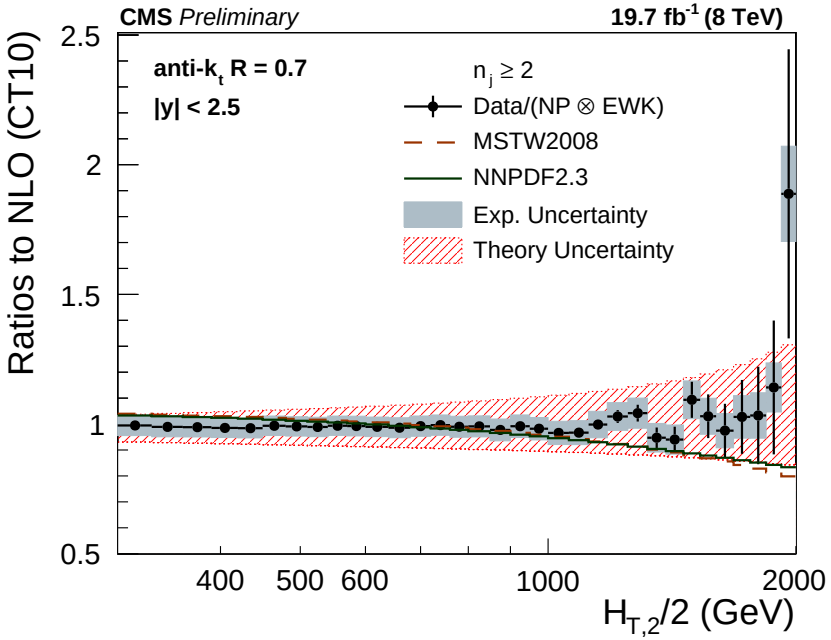
CMS PAS SMP-16-008

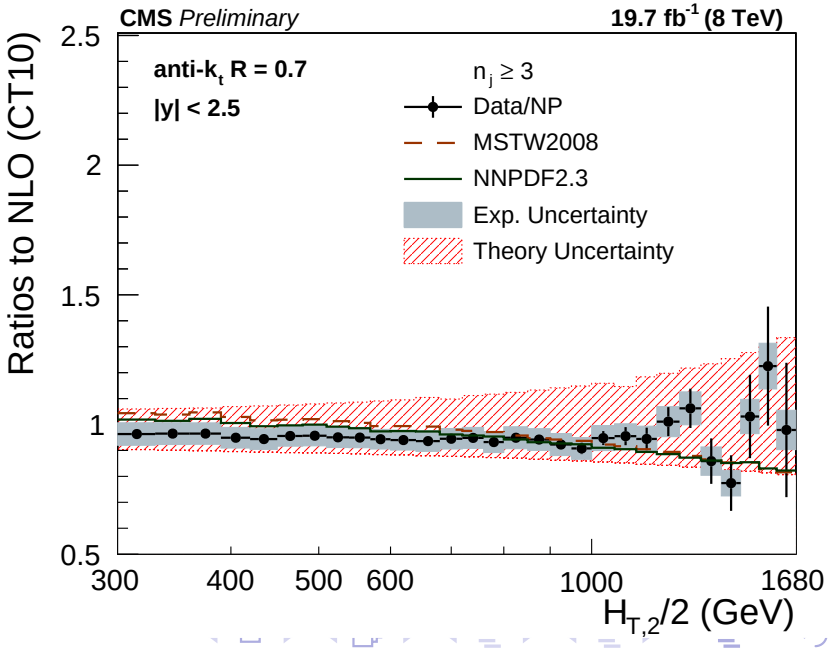
- Data are well described by the predictions

- Uncertainties: large $H_{T,2}/2 \rightarrow$ PDF dominates in the upward direction, scale uncertainties in the downward direction

- $R_{32} \rightarrow$ uncertainties significantly reduced.





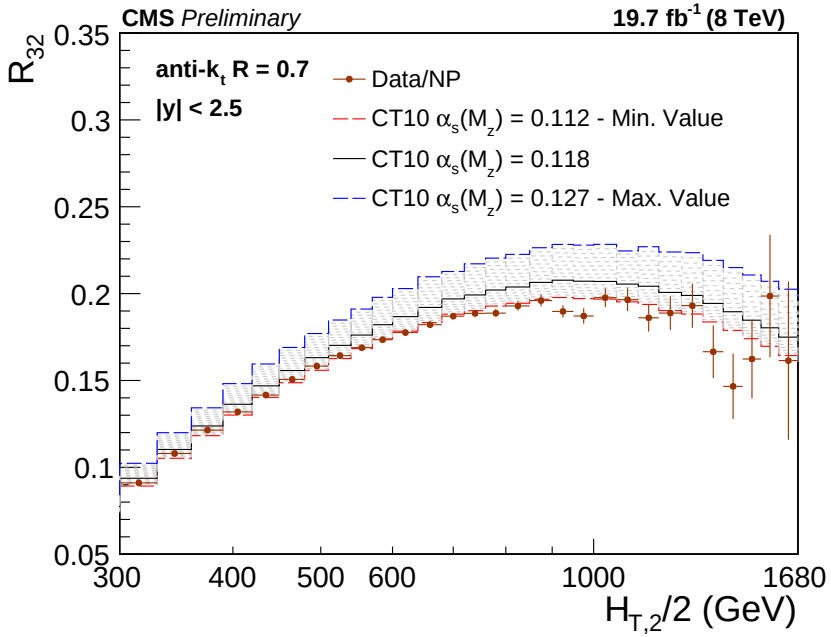


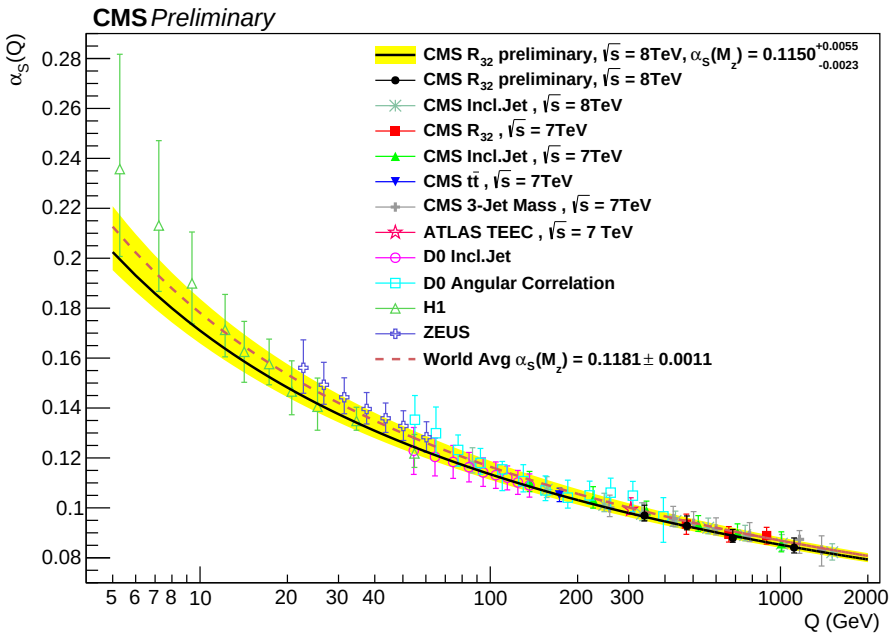
CMS PAS SMP-16-008

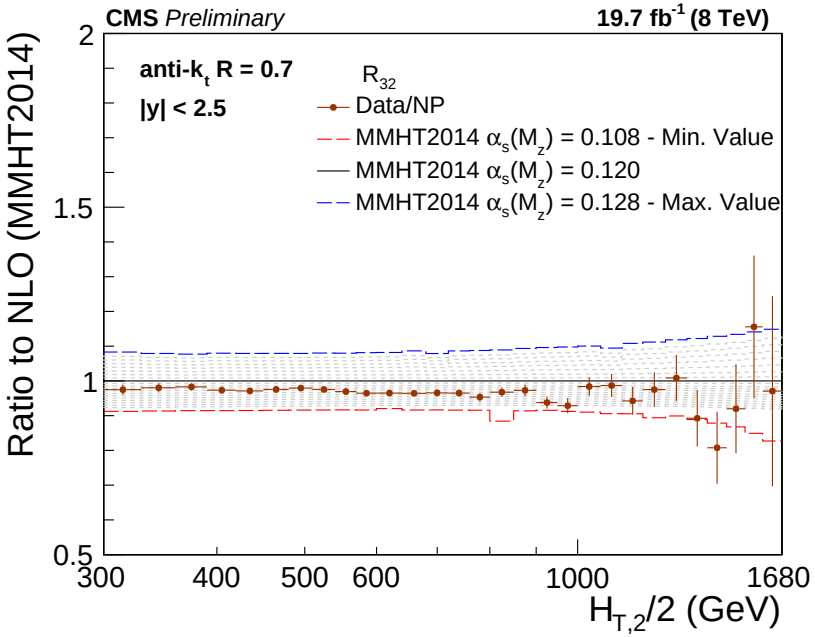
- Minimizing the χ^2 between the experimental measurement and the theoretical predictions

- Using MSTW2008 PDF:
$\alpha_s(M_Z) = 0.1150 \pm 0.0010(exp) \pm 0.0013(PDF) + \pm 0.0015(NP)^{+0.0050}_{-0.0000}(scale)$

- Result for $\alpha_s(M_Z)$ is in agreement with the world average value of
$\alpha_s(M_Z) = 0.1181 \pm 0.0011$

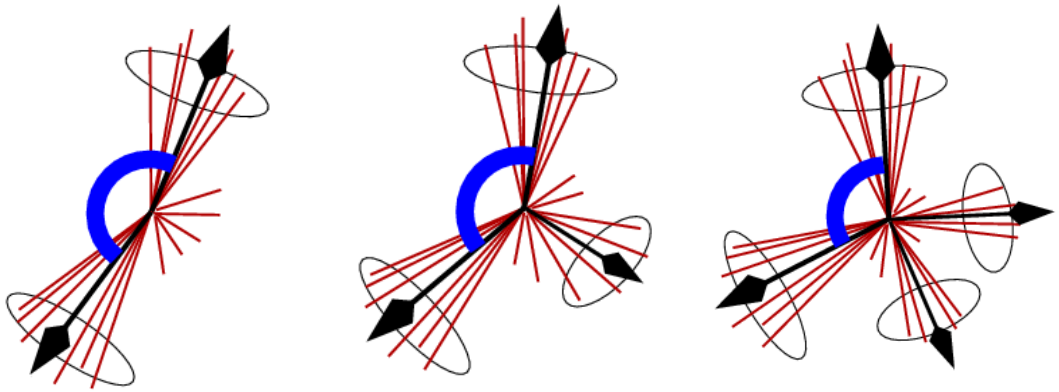






Measurements of inclusive 2-jet, 3-jet and 4-jet azimuthal correlations in pp collisions at 13TeV

to be published (CMS PAS SMP-16-014)



Dijet cross section @13TeV

CMS PAS SMP-16-014

$$\frac{1}{d\sigma_{1,2}}\frac{d\sigma_{1,2}}{d\Delta\phi_{1,2}}$$

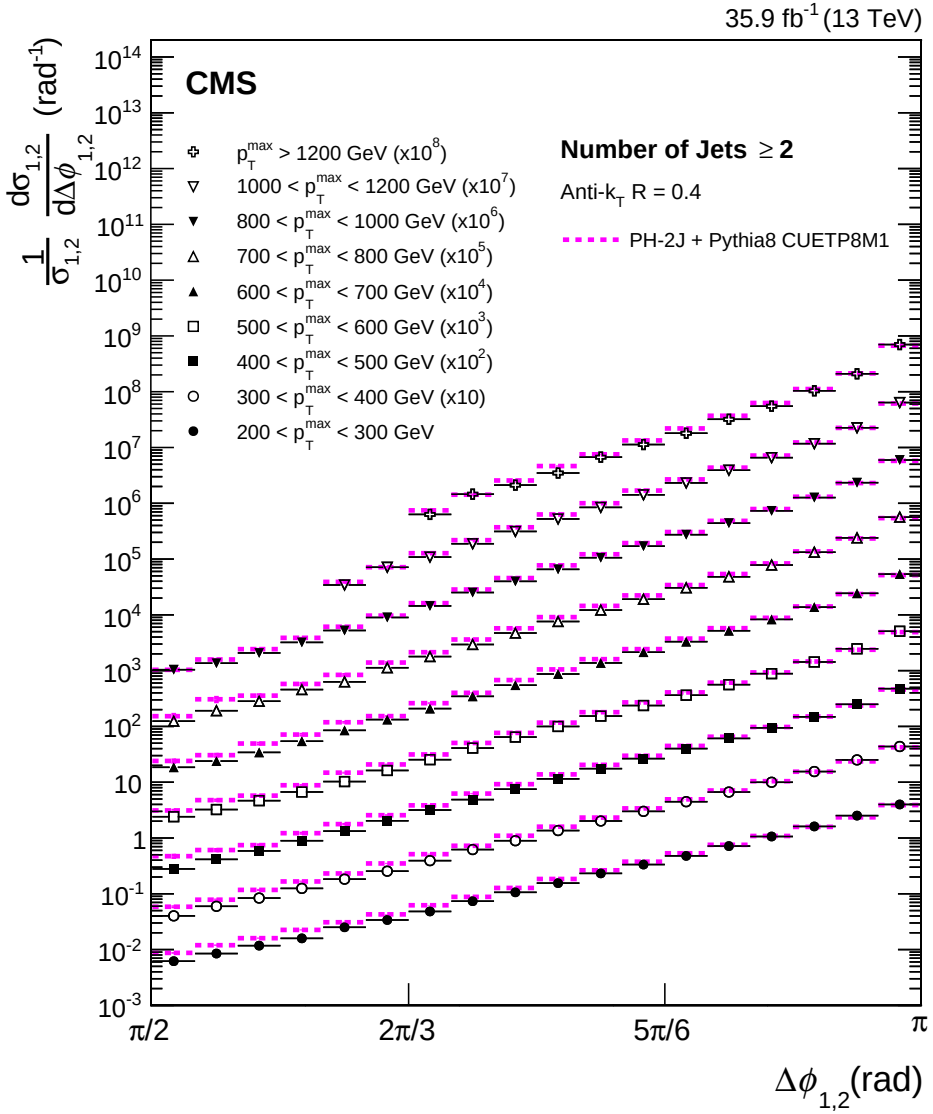
- Interesting tool to test theoretical predictions of multijet production processes

- Region away from π is sensitive to hard radiation from ME

- Region close to π is sensitive to resummed contributions from PS

- Overall description of the data is achieved and understood

- JES is the dominant systematic uncertainty (from 3% at $\pi/2$ to 0.1% at π)



Dijet azimuthal angular correlations

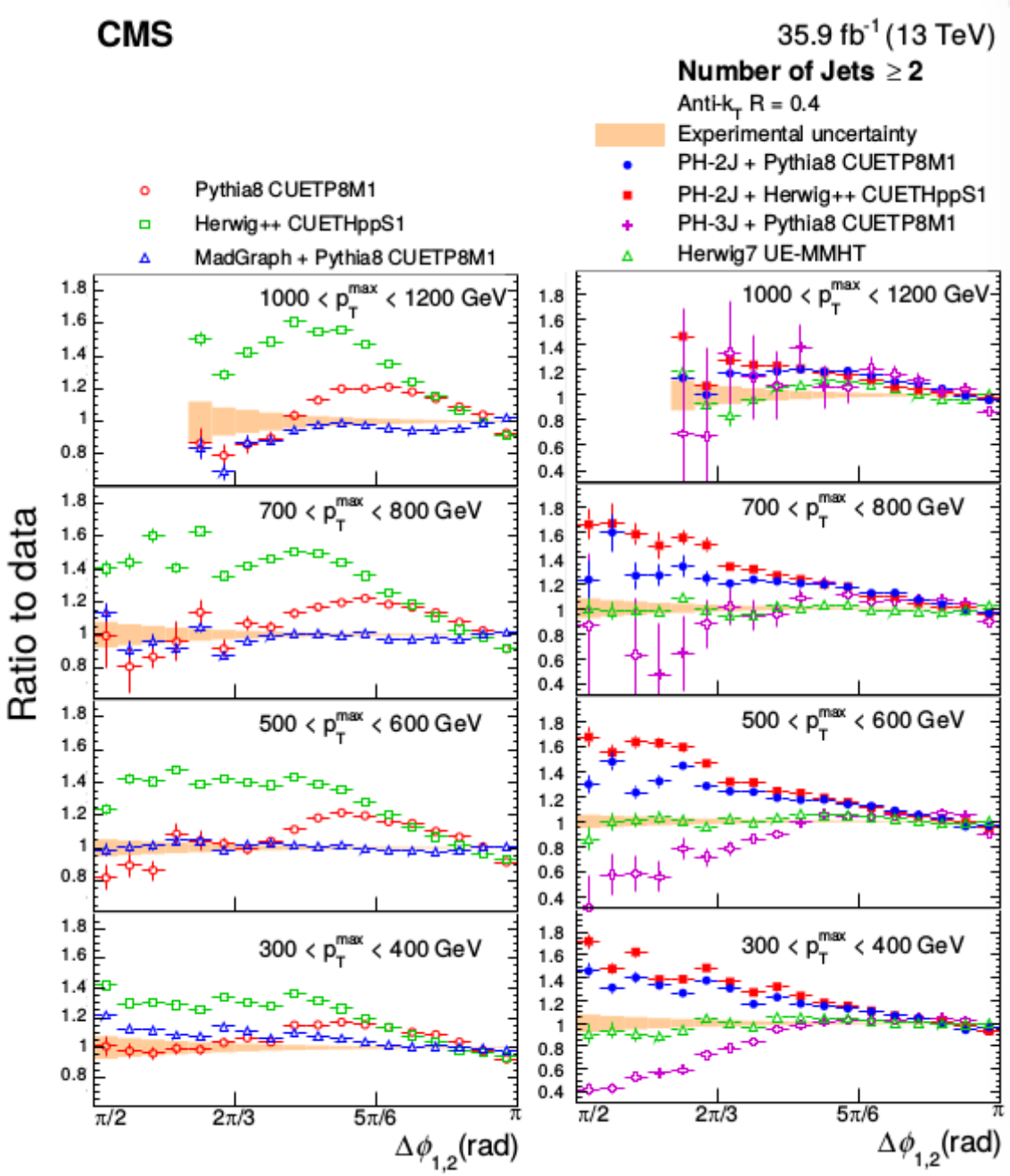
CMS PAS SMP-16-014

- PS radiation is not able to describe large $\Delta\phi$ decorrelations whereas ME partons (MadGraph)

- Even though Powheg-2J and Powheg-3J are provided with multi-leg ME, they are not able to describe large decorrelations better than P8

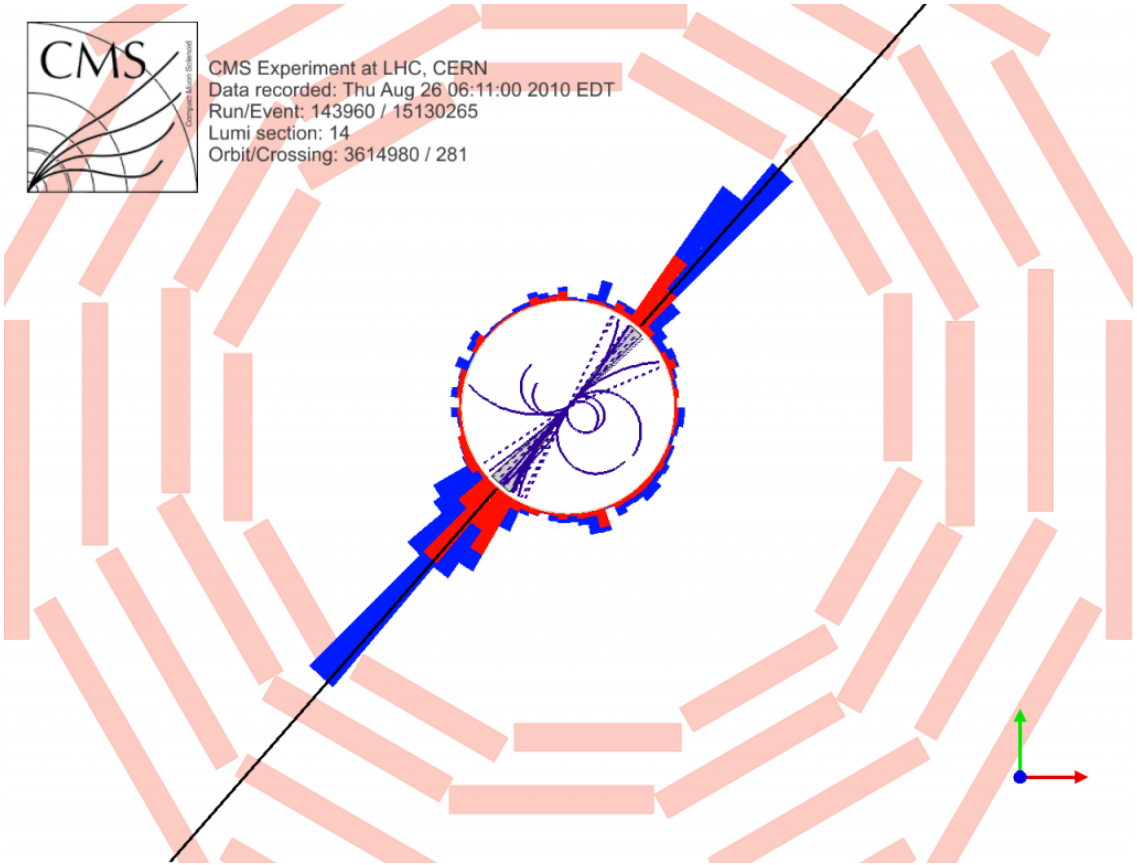
- Herwig7 (MC@NLO for matching to PS), gives a good description of the data

- For this observable MC@NLO method of combining parton shower with the NLO parton level calculations has advantages compared to the POWHEG method



Azimuthal angular correlations in high transverse momentum dijet events

to be published (CMS PAS SMP-17-009)



Dijet azimuthal correlations

CMS PAS SMP-17-009

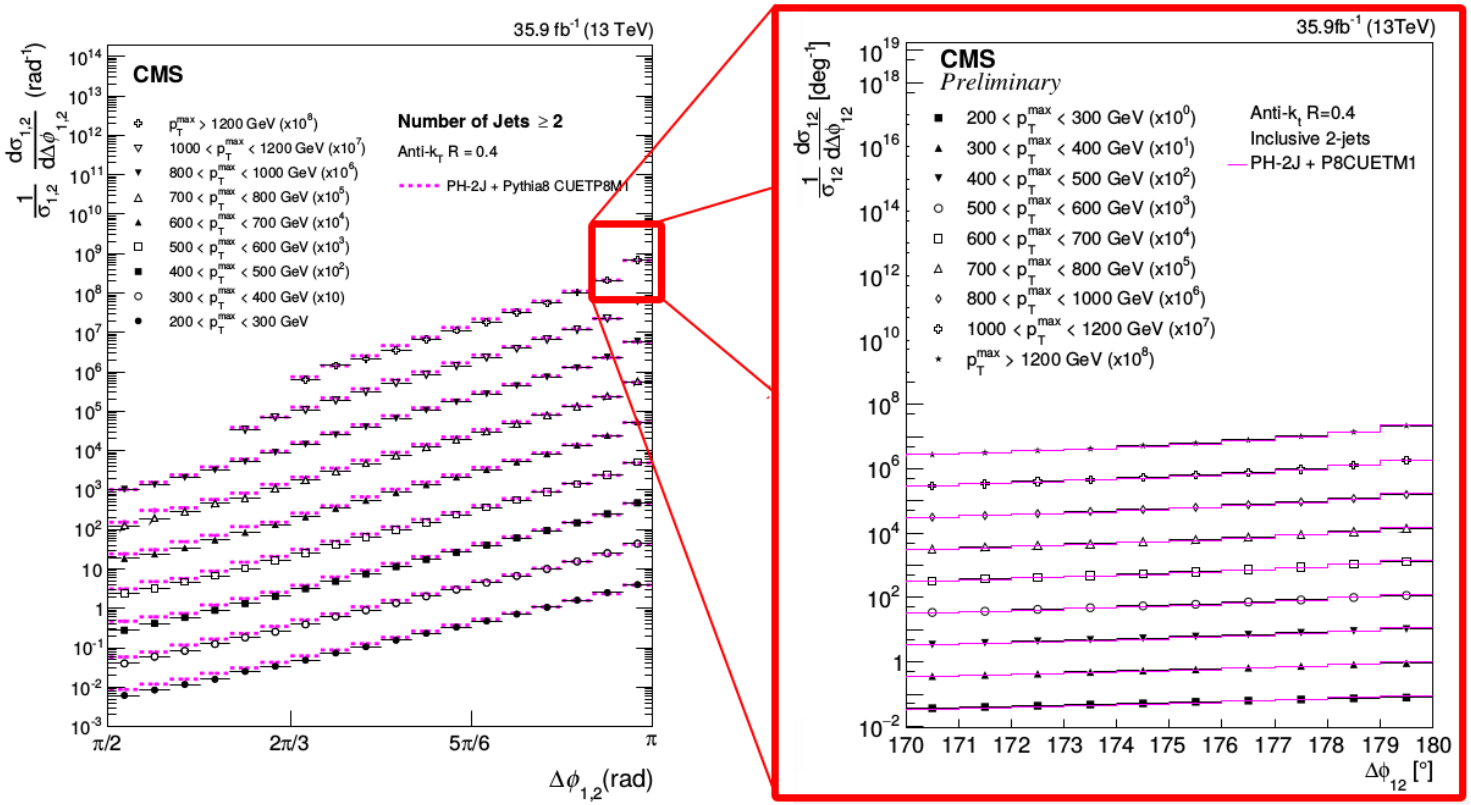
- Measurement never done before, focused on the resummation region

- Finer binning (1°) for a detailed investigation of the region $\Delta\phi \sim 180°$

- Testing the predictions coming from different Parton Shower models

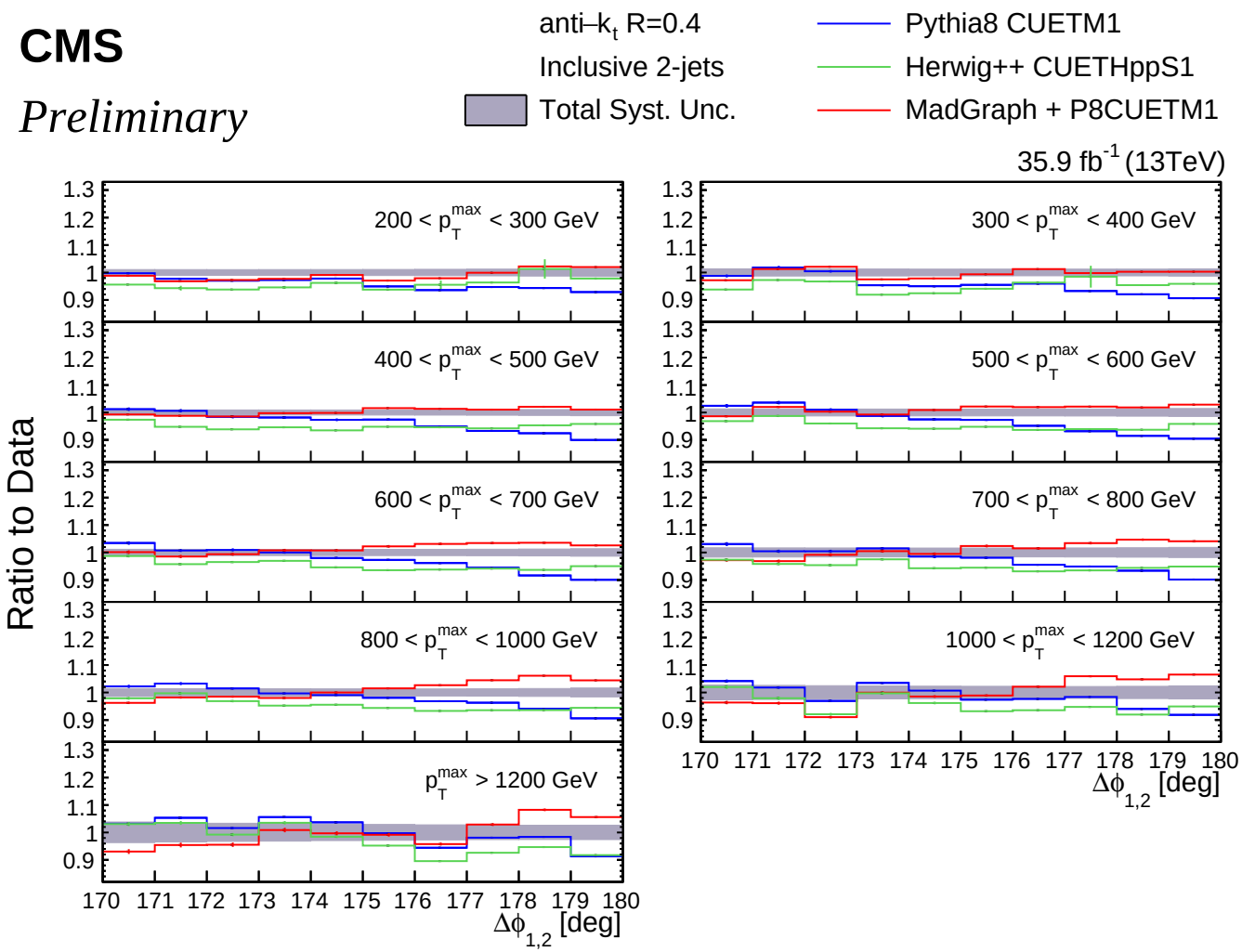
- Studying the influence of matching and merging formalisms

- Soft radiation interference and factorization breaking



Dijet azimuthal correlations in inclusive 2-jets events

CMS PAS SMP-17-009

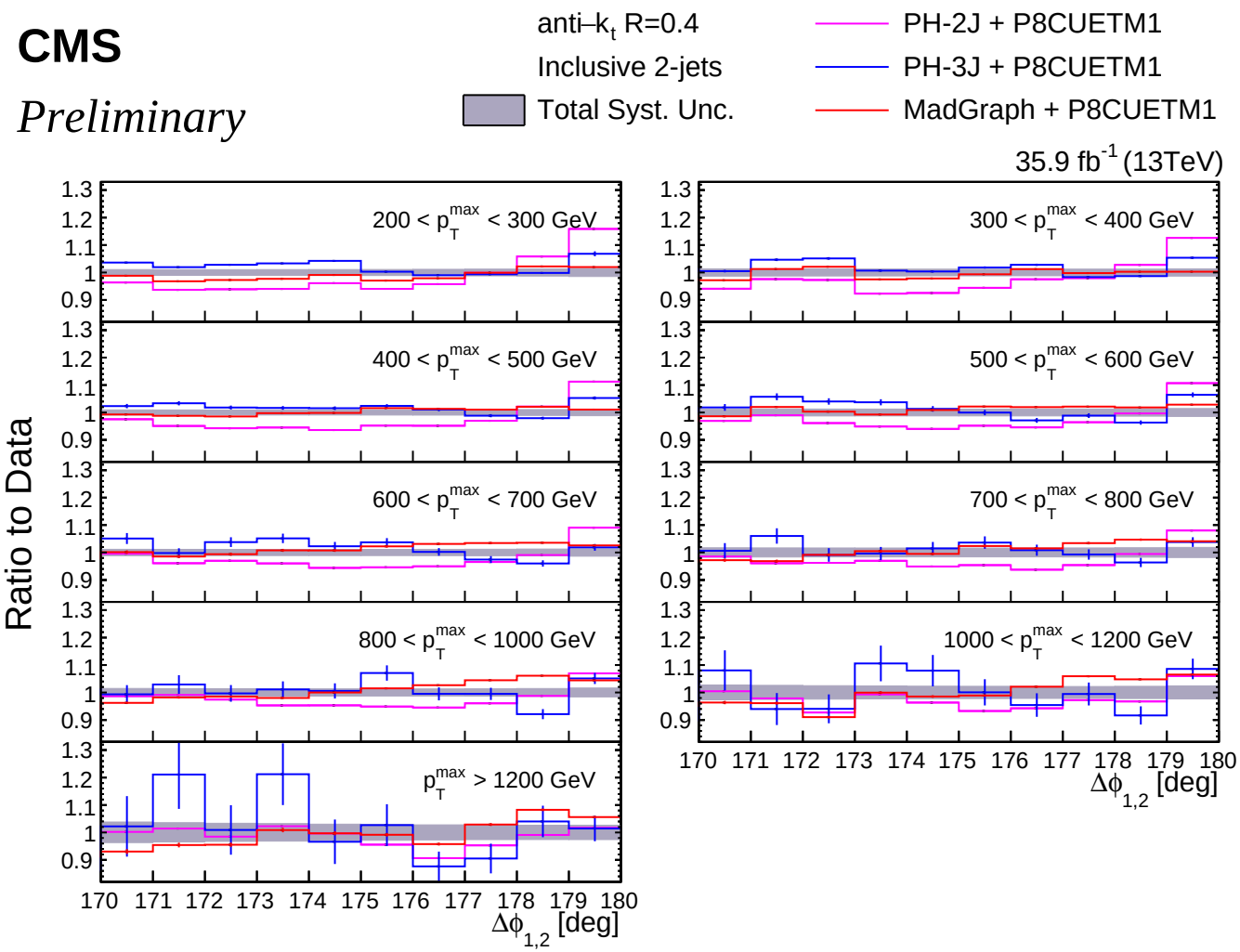


- For small values of $\Delta\phi_{1,2}$ the three generators give a good description of the data.
- For large $\Delta\phi_{1,2}$ and high p_T^{max} Madgraph predictions overshoot the data whereas P8 and Herwig++ undershoot it
- Differences of up to 10%

- Correlations towards high p_T^{max} which are not captured either by the PS nor the multi-leg ME from MadGraph

Dijet azimuthal correlations in inclusive 2-jets events

CMS PAS SMP-17-009



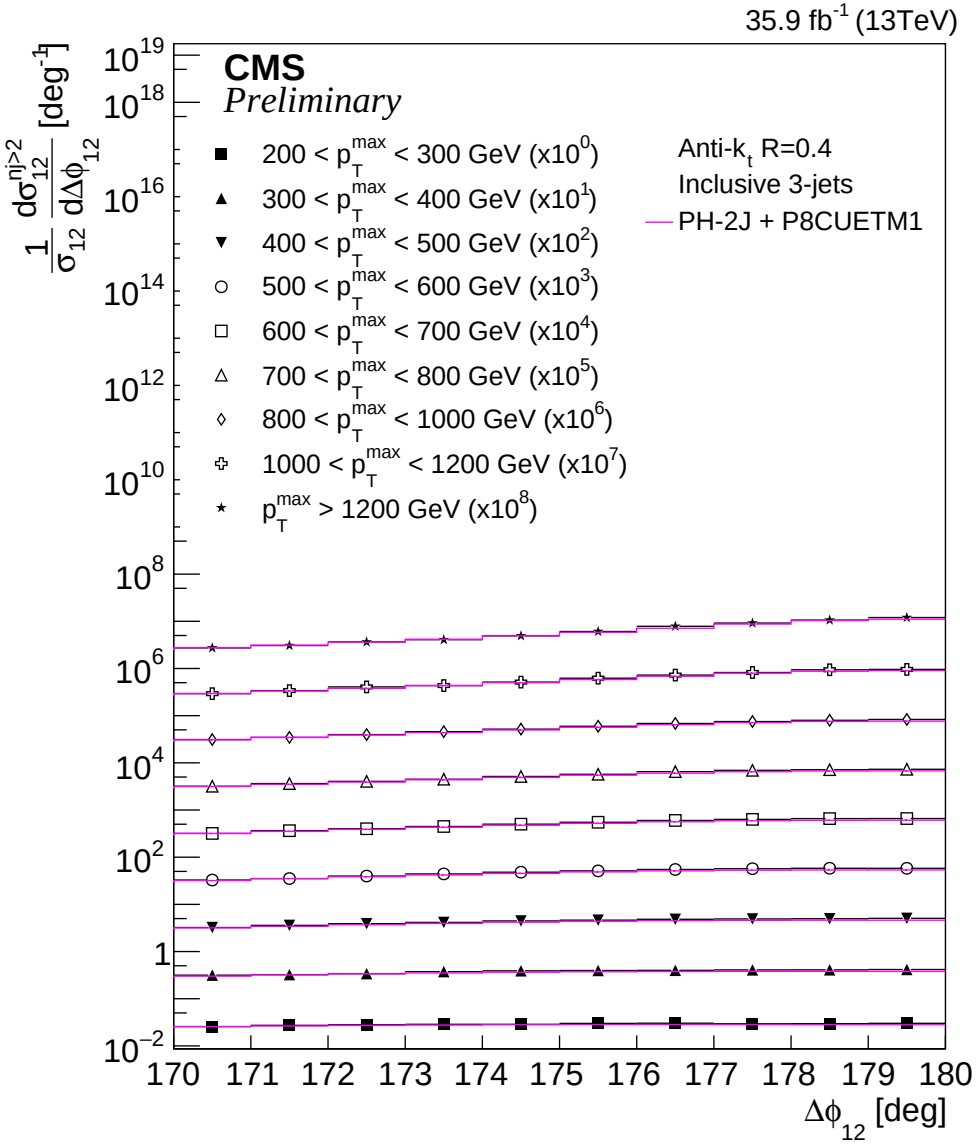
- Powheg 3J give a good description
- Powheg-2J undershoots the data for mid values of $\Delta\phi_{1,2}$ and overshoots it in up to 15% for large $\Delta\phi_{1,2}$
- Biggest discrepancies are found in the last bin
- MadGraph and Powheg 3J, both go to up to 2→4 partons
- Powheg 2J is effectively 2→3 LO

Dijet azimuthal correlations in inclusive 3-jets events

CMS PAS SMP-17-009

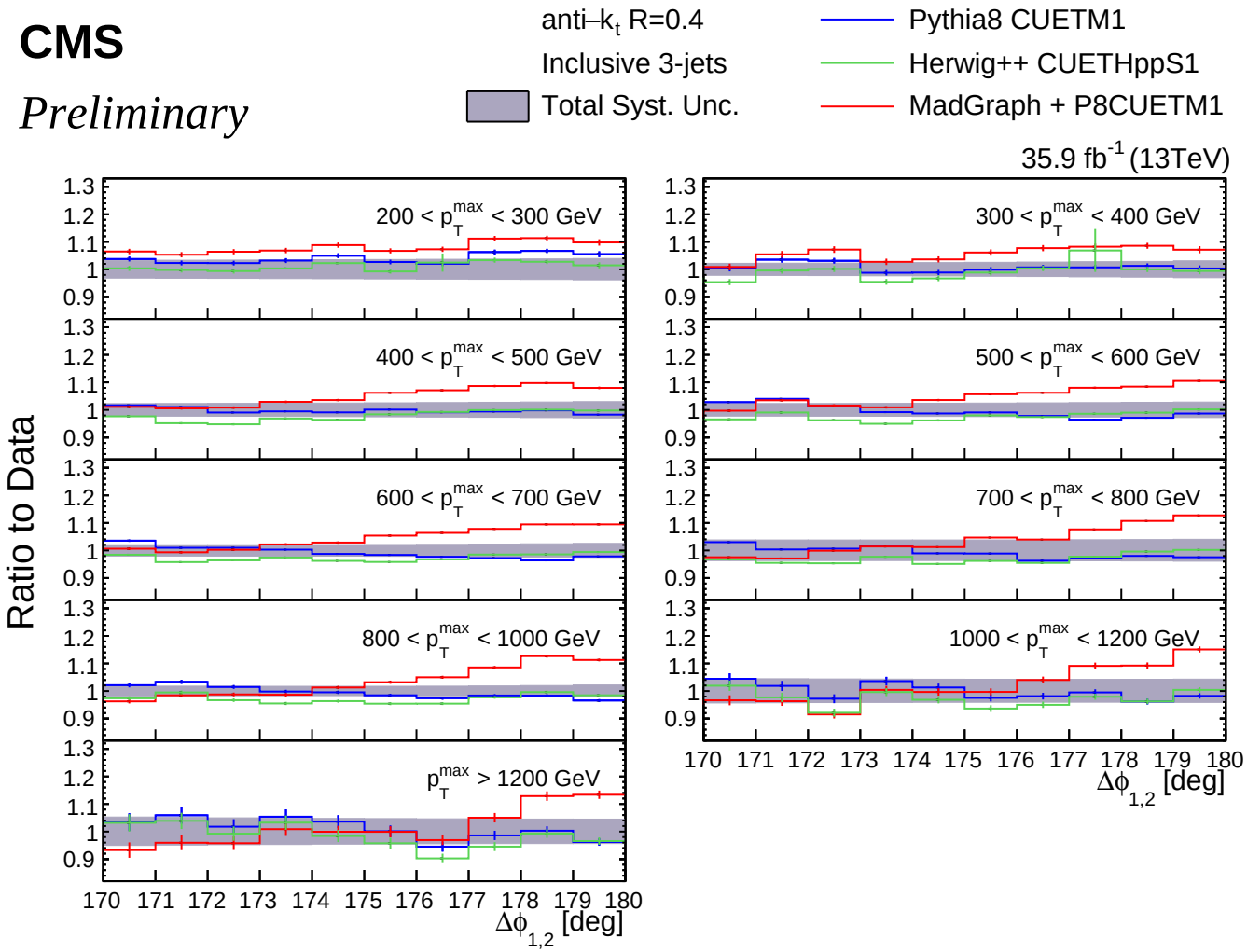
- Requiring at least a third jet with p_T larger than 30GeV

- Imposes a second scale, 1-2 orders of magnitude smaller than the hard scale



Dijet azimuthal correlations in inclusive 3-jets events

CMS PAS SMP-17-009

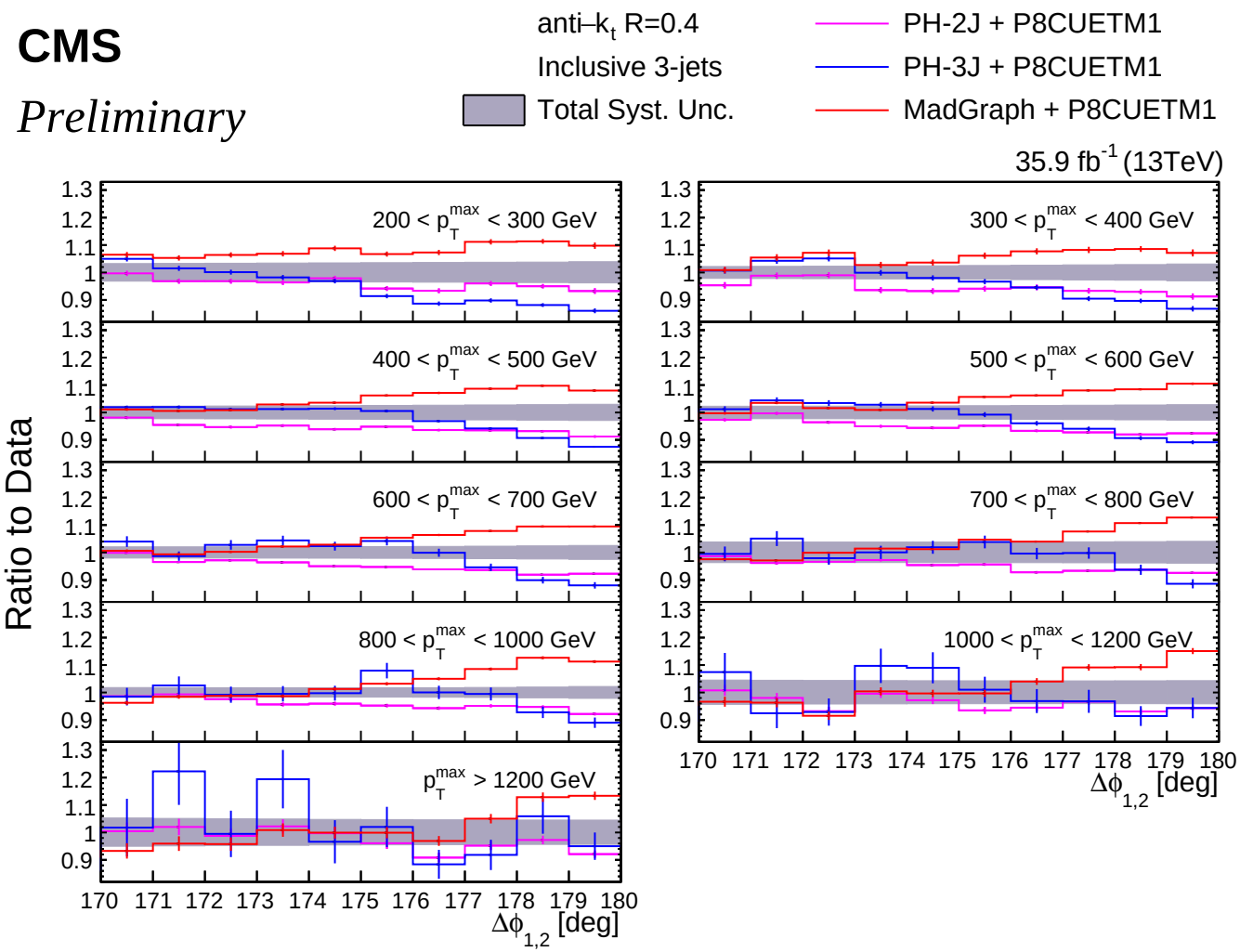


- MadGraph overshoots the data in up to 15% towards large $\Delta\phi_{1,2}$ despite the fact that it performs well in the inclusive 2-jets case

- P8 and Herwig++ are in agreement with the data in all the p_T^{max} regions (opposed to the 2-jet inclusive case)

Dijet azimuthal correlations in inclusive 3-jets events

CMS PAS SMP-17-009



- Powheg 2J and Powheg 3J similarly undershoot the data in up to 10% towards 180°

- Decorrelations in the 3-jets inclusive case are well described by partons coming from PS exclusively, whereas the results from merging different multiplicities in Madgraph and Powheg are not able to

Summary

Inclusive jet cross sections @$\sqrt{s} = 8$ and $\sqrt{s} = 13$TeV

- Sensitive to α_s
- Provides important PDFs constraints
- QCD describes data within 14 orders of magnitude!!

Measurement of the triple-differential dijet cross section

- Test of pQCD
- Determination of coupling constant and constraints on PDF

Strong coupling constant from inclusive multijet events

- Test of QCD
- R_{32} is used to extract α_s

Dijet azimuthal angular correlations @$\sqrt{s} = 13$TeV

- Overall description of the data is achieved and understood
- For this observable MC@NLO method of combining parton shower with the NLO parton level calculations has advantages compared to the POWHEG method

Azimuthal angular correlations in high transverse momentum dijet events

- New analysis focused on the resummation region
- Predictions can describe either the 2-jets inclusive, or the the 3-jets inclusive distributions, but not both
- Differences of up to 15%

Thank you for your attention.