Jet Cross-Section Measurements in *pp* collisions

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LHCP 2024
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Why jet cross section measurements?

- Important inputs to parton distribution function (PDF) fits
  - *Particularly important for aspects like the high-x gluon PDF*
  - *Not calculable from first principles → need measurements!*
- Tests of perturbative QCD predictions
  - *Important to study behavior of new predictions*
- Sensitive to the strong coupling constant and its running
  - *Able to probe much higher energy scales for the running than other strategies*

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- Showing three measurements that highlight each of these applications
  - See also 2401.11355 for a nice jet cross section measurement that I can't cover today

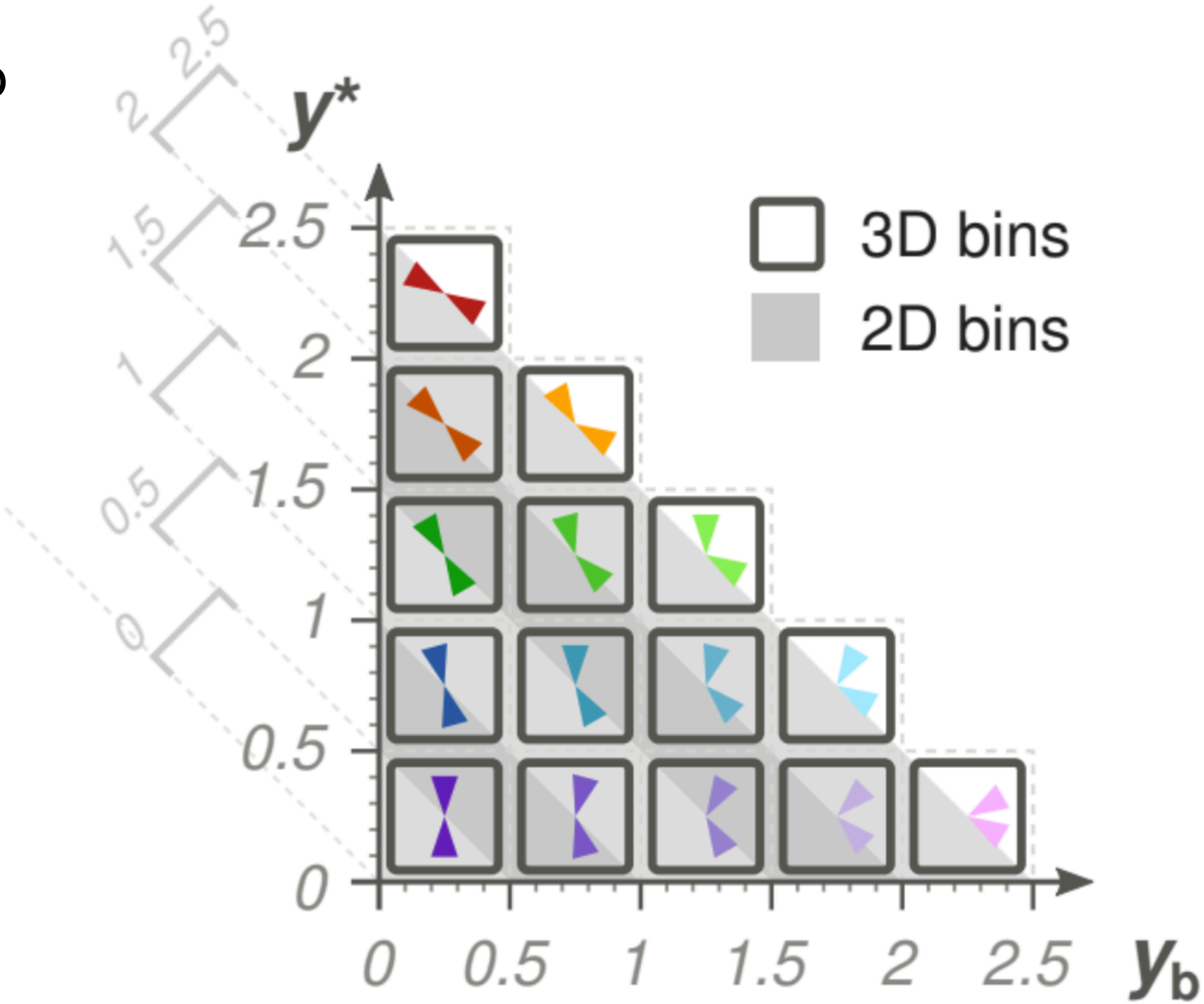
Double and triple differential dijet jet cross-sections

2312.16669

dijet cross section measurements

CMS

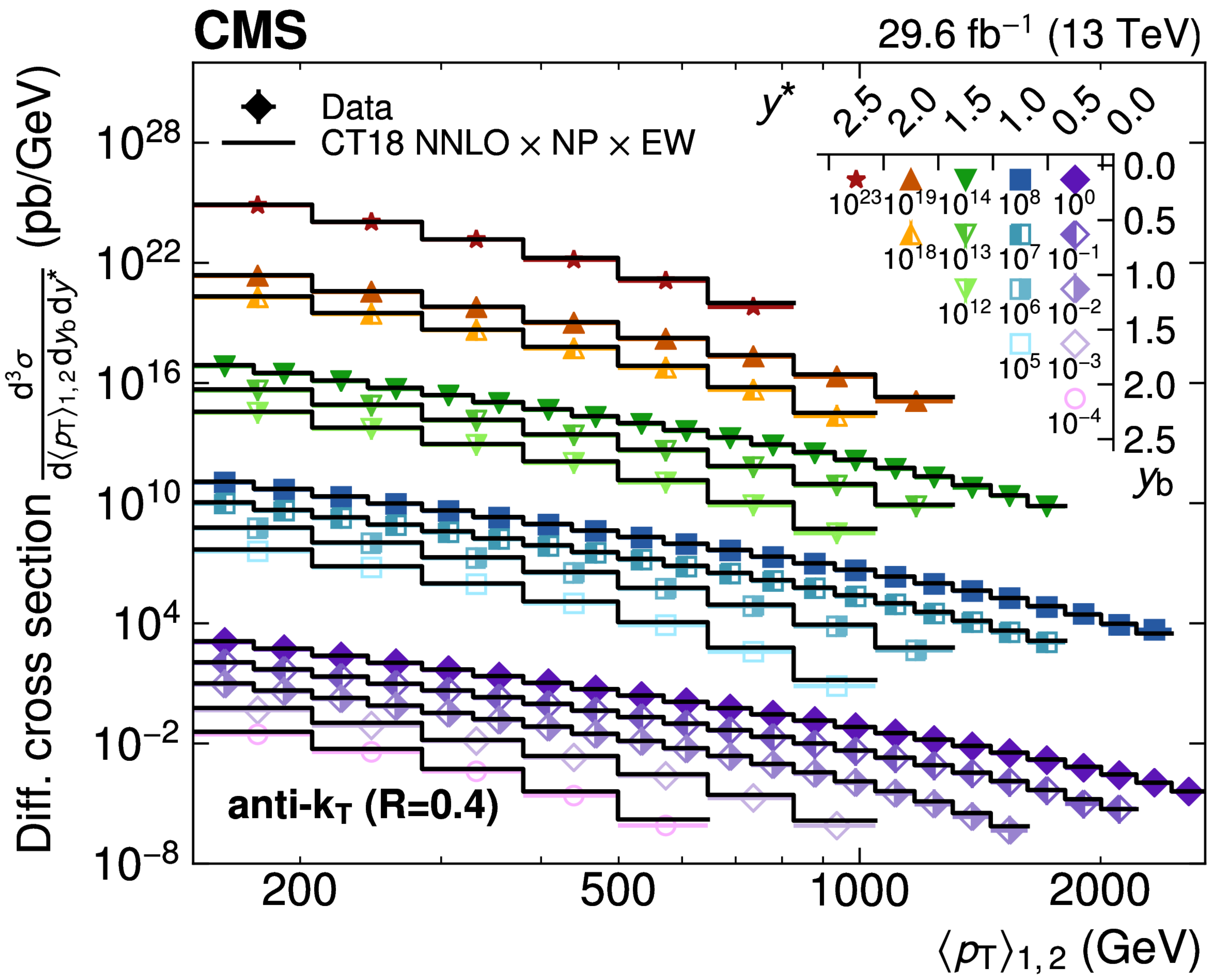
- Dijet cross-sections are sensitive to the gluon PDF and the strong coupling α_S
- CMS measures this double and triple differentially in the jet p_T, and various rapidity observables
  - *3D in y_b, y^*, and p_T*
  - *2D in y_{max}, p_T*
- Different regions of phase space dominated by different parts of the PDF



dijet cross section measurements

CMS

- Measuring 3D cross-section and 2D cross-section
  - *3D in y_b, y^*, and (p_T or m_{jj})*
  - *2D in y_{max}, (p_T or m_{jj})*
- Selecting different topologies to improve sensitivity to PDFs
- Comparing to **NNLO** predictions
  - Generally good agreement across a wide range of jet p_T



dijet cross section measurements

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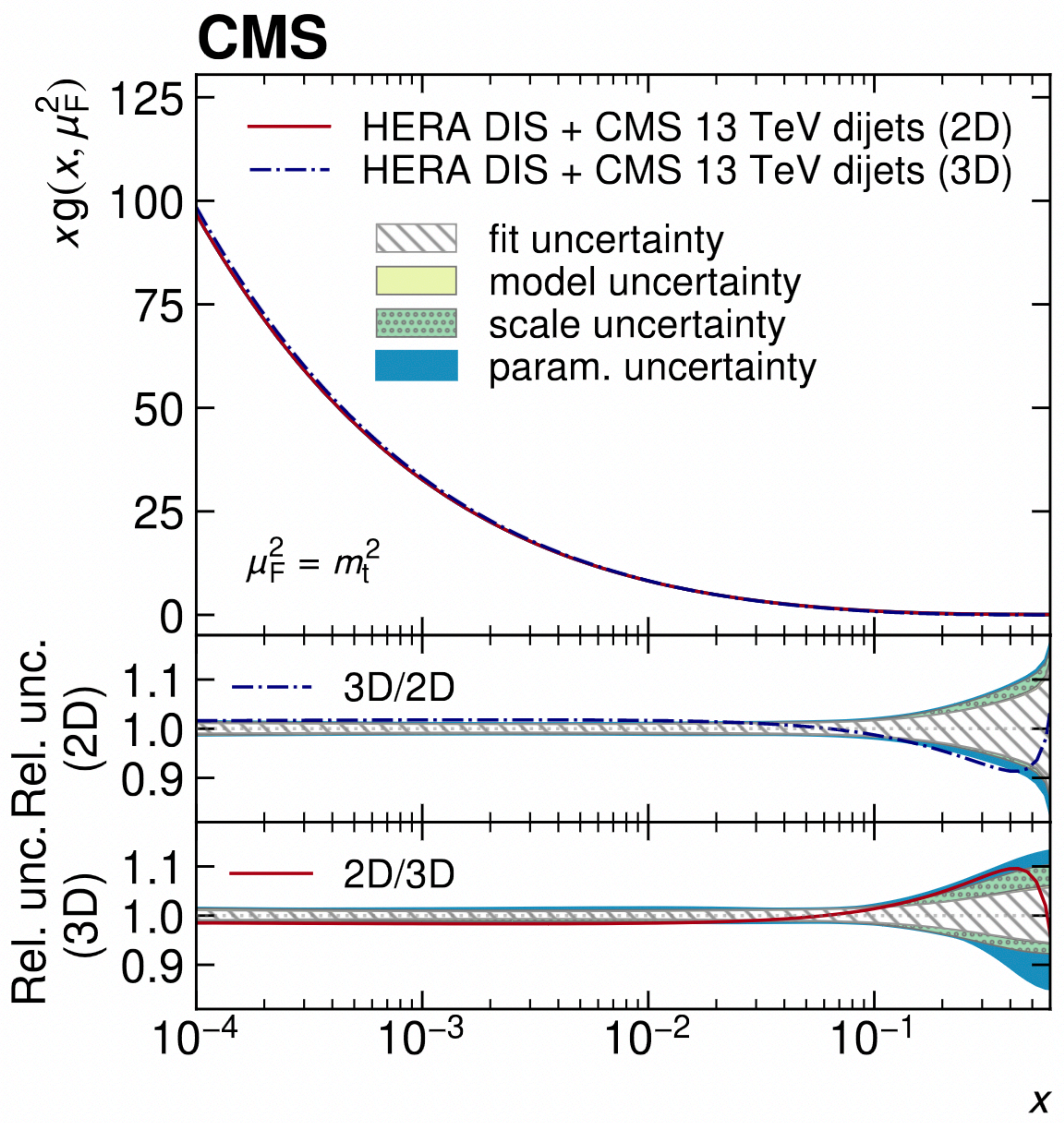
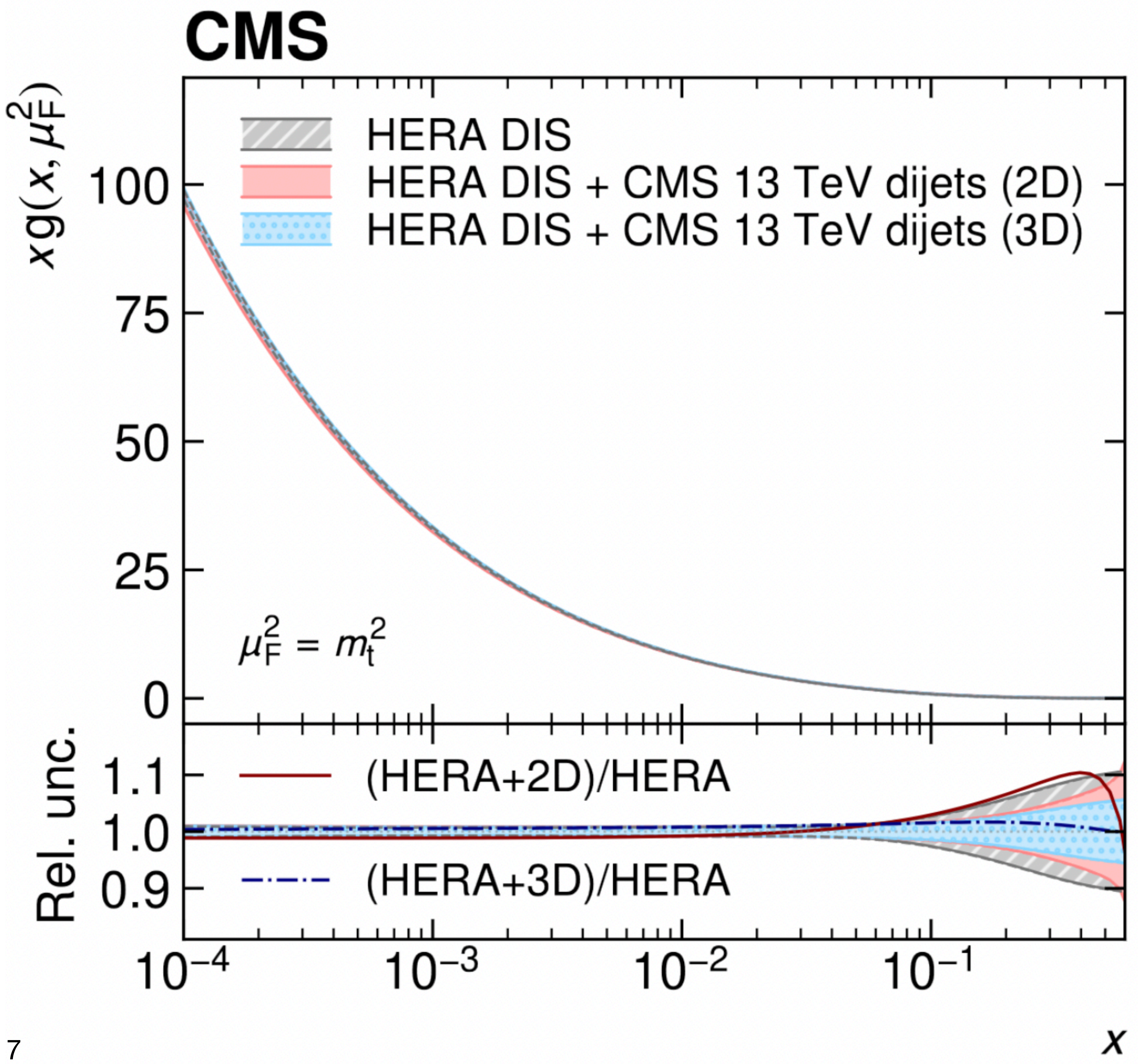
CMS

- Comparing PDF fits for HERA + 2D to HERA + 3D dijet measurements
  - Both provide good constraints on the high-x gluon PDF
    - Slightly better constraints from the 3D measurement





Measurement of jet cross sections and their ratios

Jet cross sections and their ratios

2405.20206

ATLAS

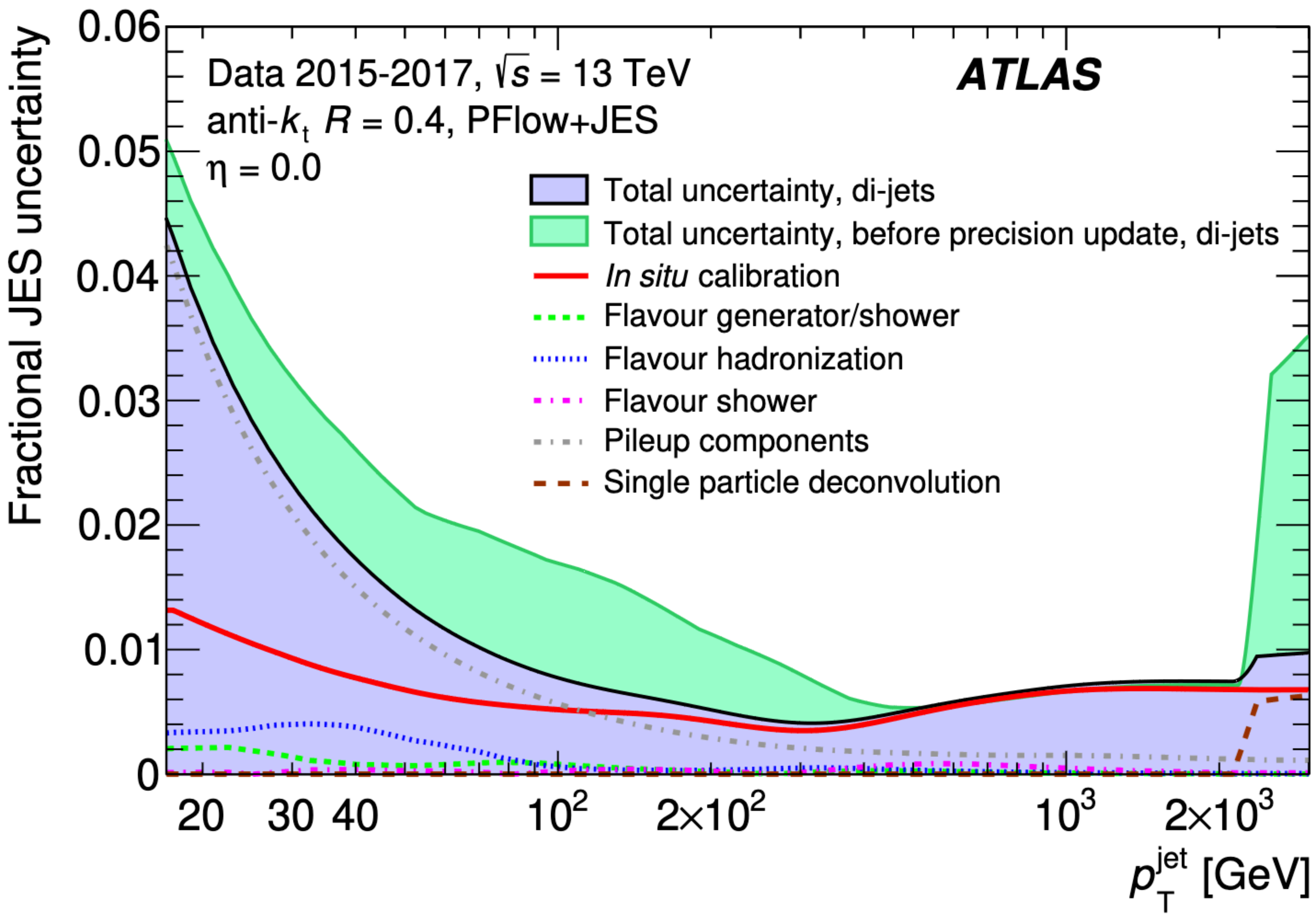
- Measuring several observables
  - H_{T2}: $p_{T,1} + p_{T,2}$
    - Good test of fixed order predictions
  - m_{j1j2}, Δy_{j1j2}, $m_{jj,\,max}$, $\Delta y_{jj,\,max}$
    - Sensitive to certain types of resummation effects, and difficult to model with parton showers
    - Relevant for modeling electroweak VBS and VBF processes
- Measuring the inclusive 2,3,4,5-jet cross sections, and their ratios
  - In particular R_{32} = 3-jet inclusive cross-section / 2-jet inclusive cross-section

Jet cross sections and their ratios

2405.20206

ATLAS

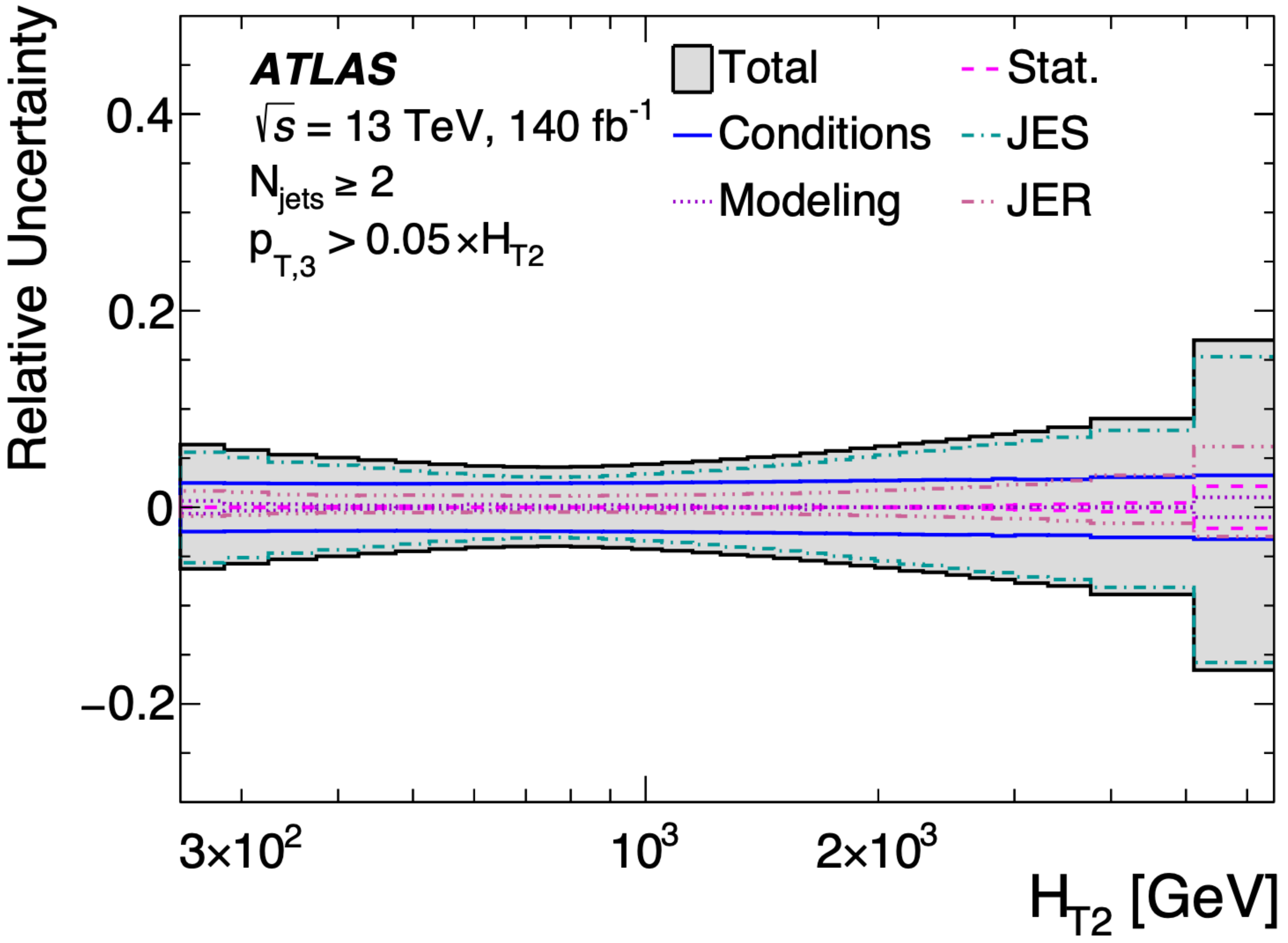
- Several improvements to the treatment of the jet energy scale uncertainties
  - Factorize differences between different Monte Carlo predictions into three components
  - Improved treatment of single particle uncertainties, including adding new *in situ* measurements of single particle response
- *Many more details in the paper!*

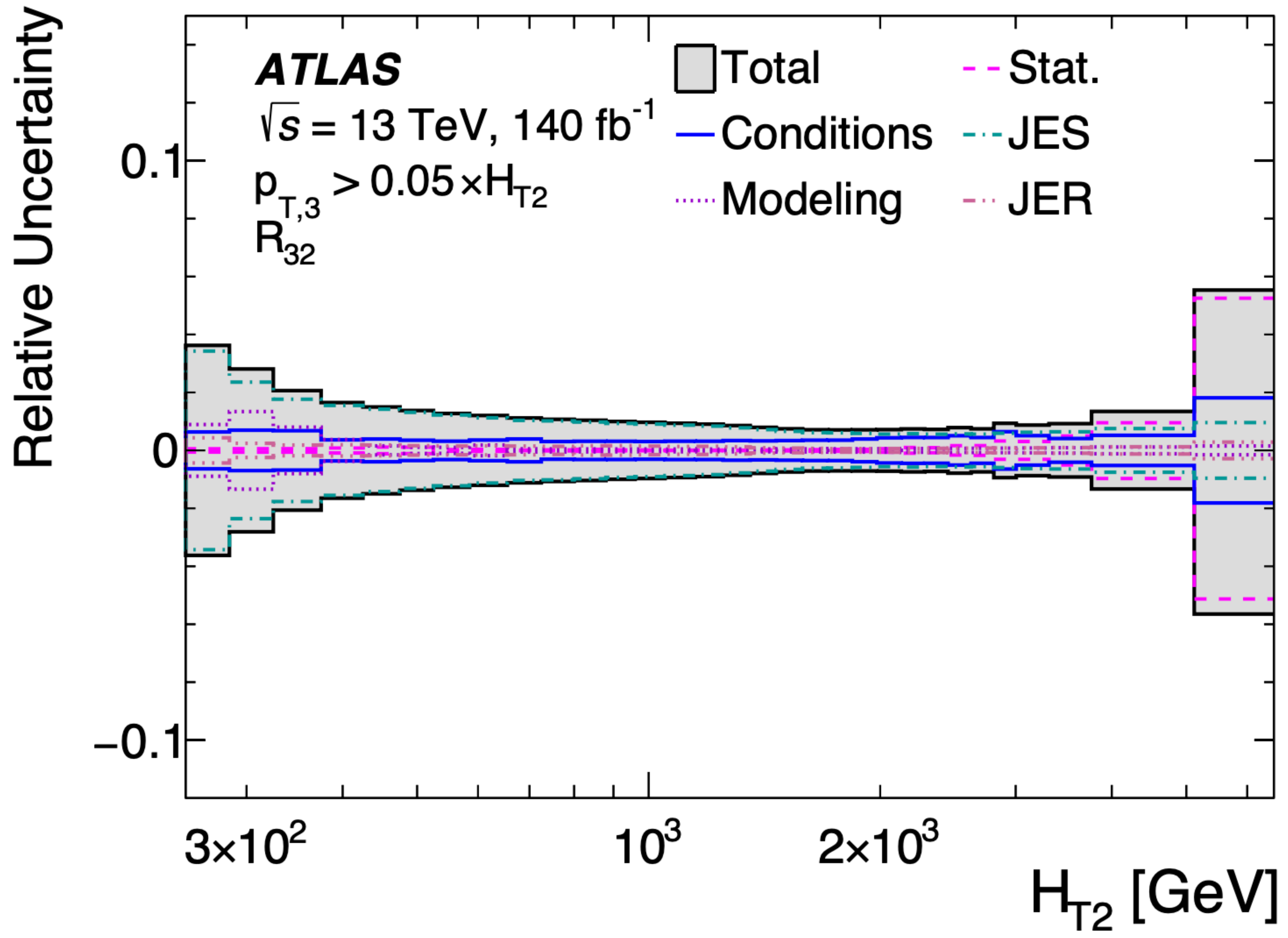


Jet cross sections and their ratios

ATLAS

- Taking the ratio results in much smaller uncertainties
- Very precise measurement, dominated by jet uncertainties
  - Modeling uncertainties reduced through MC-to-MC calibrations, which reduce double-counting with jet uncertainties
  - Jet energy scale uncertainty reductions directly translate to smaller uncertainties, especially for H_{T2}

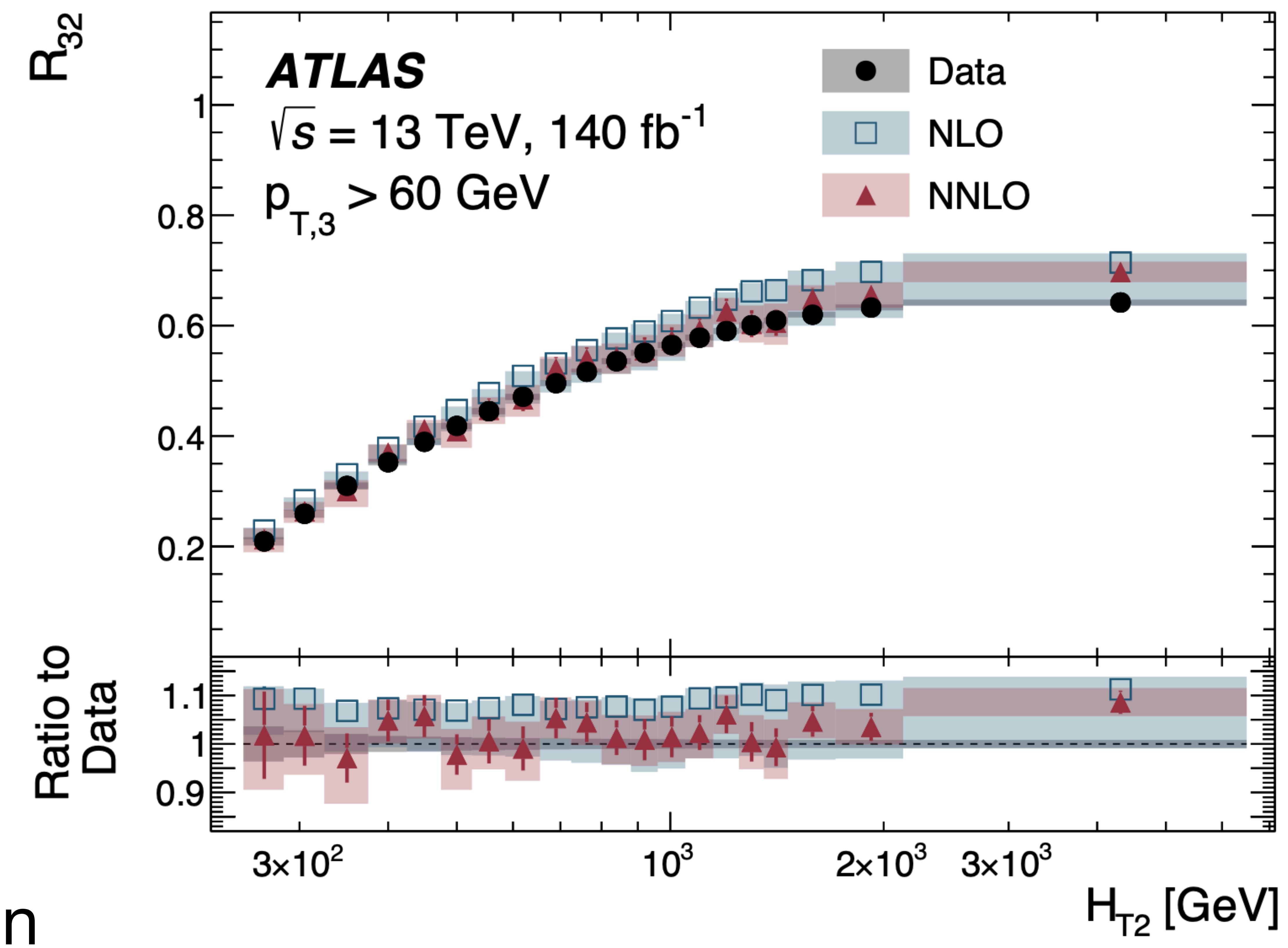




Jet cross sections and their ratios

ATLAS

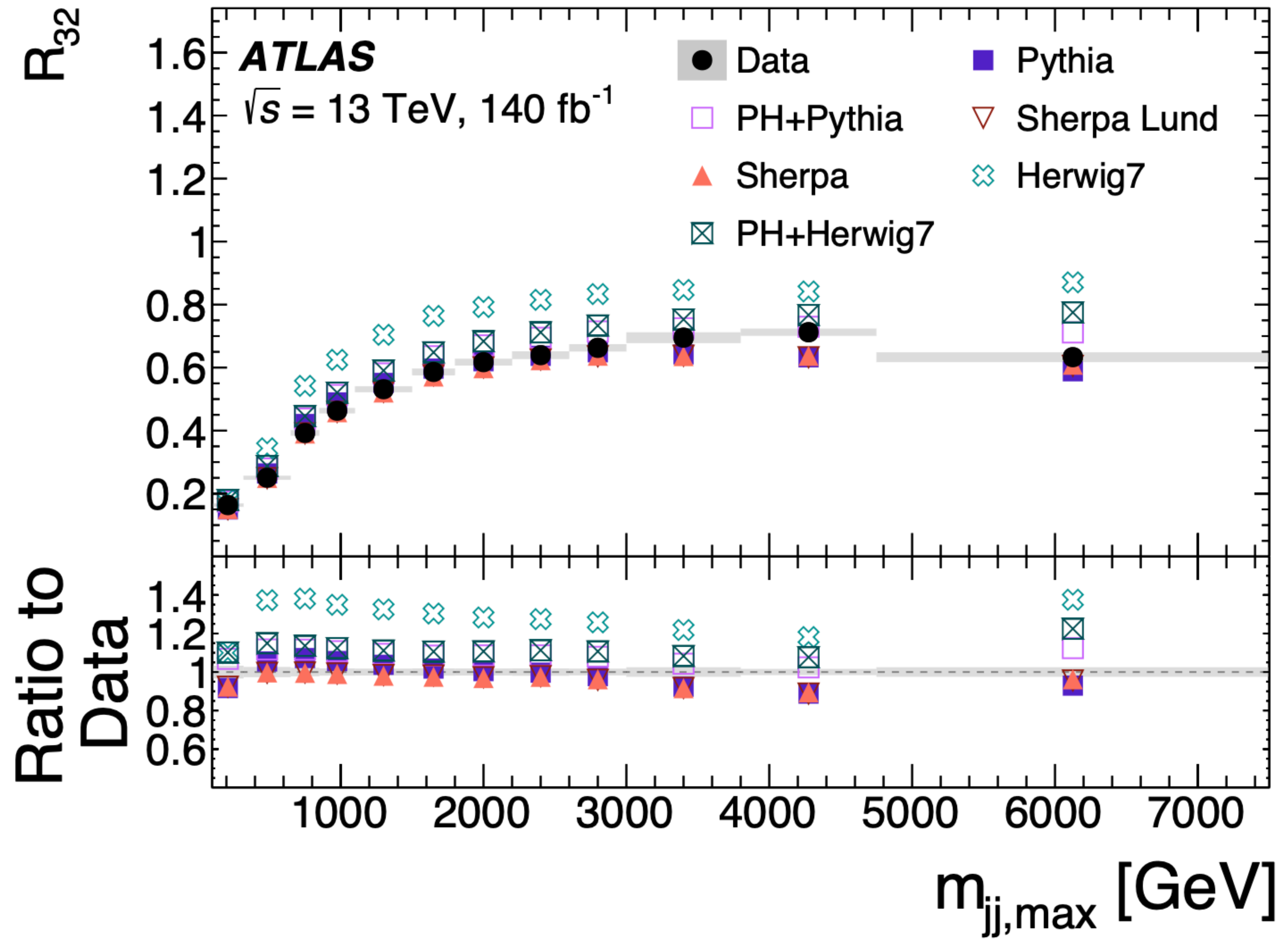
- Comparing R32 for HT2 to NLO and NNLO predictions
  - NLO and NNLO predictions both agree within uncertainties, but better agreement from NNLO
- Theory uncertainties include PDF, scale, and statistical uncertainties
  - Scale uncertainties dominate for NLO,
  - NNLO predictions have reduced scale uncertainties, but large statistical uncertainties
- 2→3 NNLO predictions are a significant step forward in the theoretical precision of jet production
  - Computationally difficult to run → would benefit from improvements to the prediction

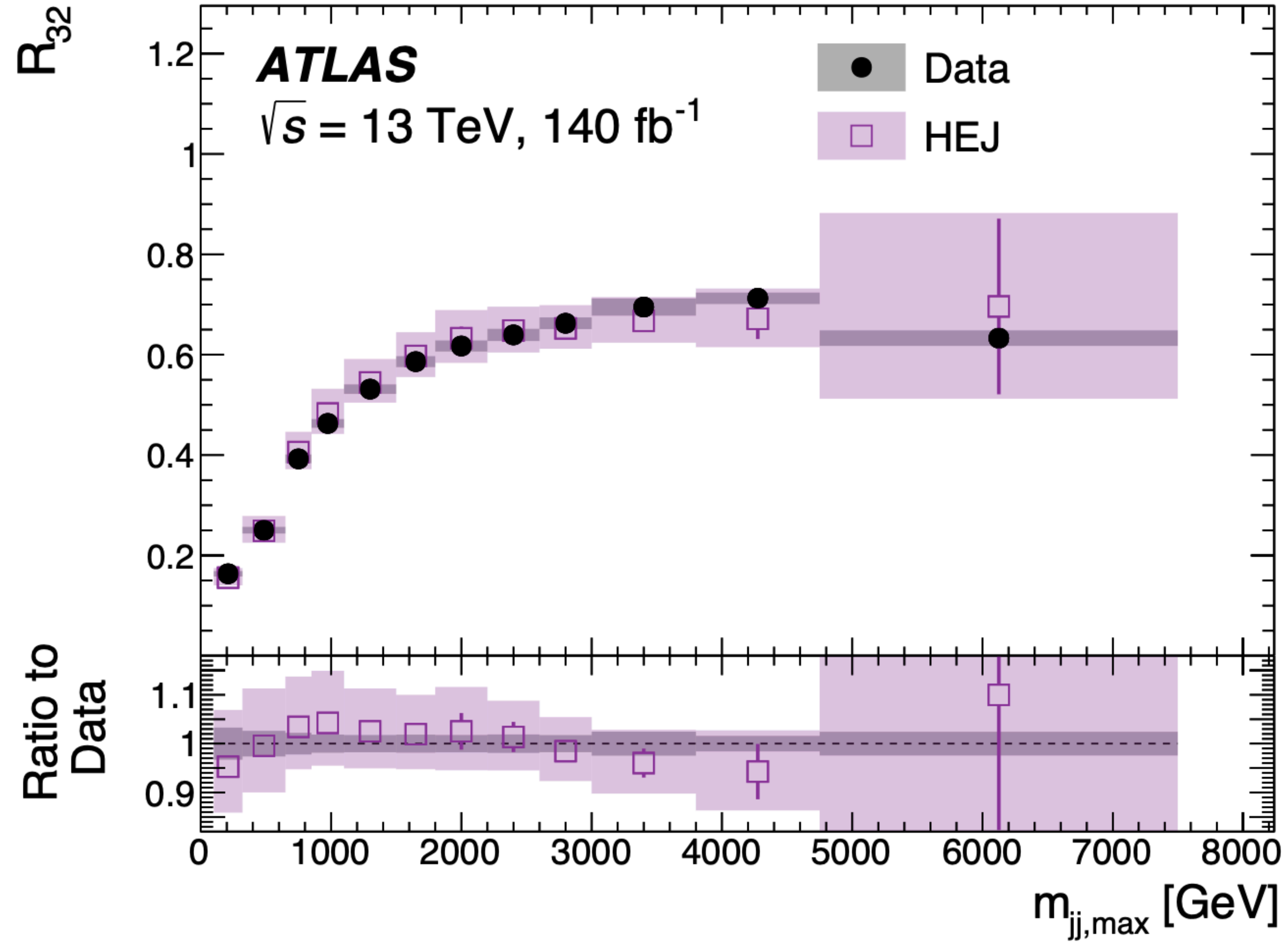


Jet cross sections and their ratios

ATLAS

- Dijet mass is difficult to model accurately
  - Most Monte Carlo predictions are not able to model this behavior well
- Comparing to a prediction from HEJ
  - Includes resummation effects not included by parton showers
  - Models the data well in certain regions, and better than most MC predictions





RΔΦ(pT)

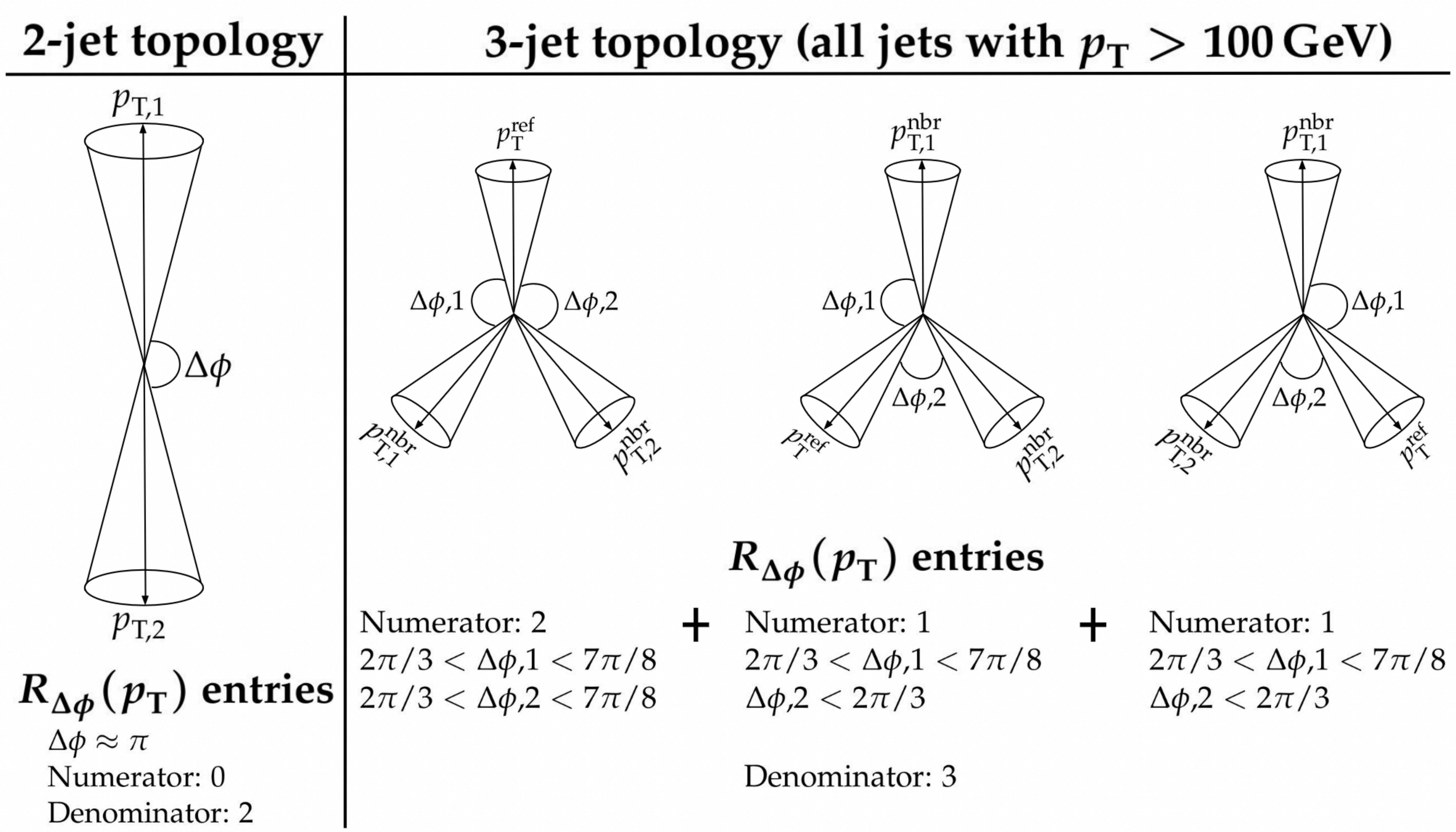
$R_{\Delta\phi}(p_T)$

CMS

2404.16082

$$R_{\Delta\phi}(p_T) = \frac{\sum_{i=1}^{N_{jet}(p_T)} N_{nbr}^{(i)}(\Delta\phi, p_{Tmin}^{nbr})}{N_{jet}(p_T)}$$

- Numerator includes pairs of jets with $2\pi/3 < \Delta\Phi < 7\pi/8$
    - Reducing contributions from 2-jet case by excluding back-to-back jets in numerator
- Sensitive to the strong coupling constant

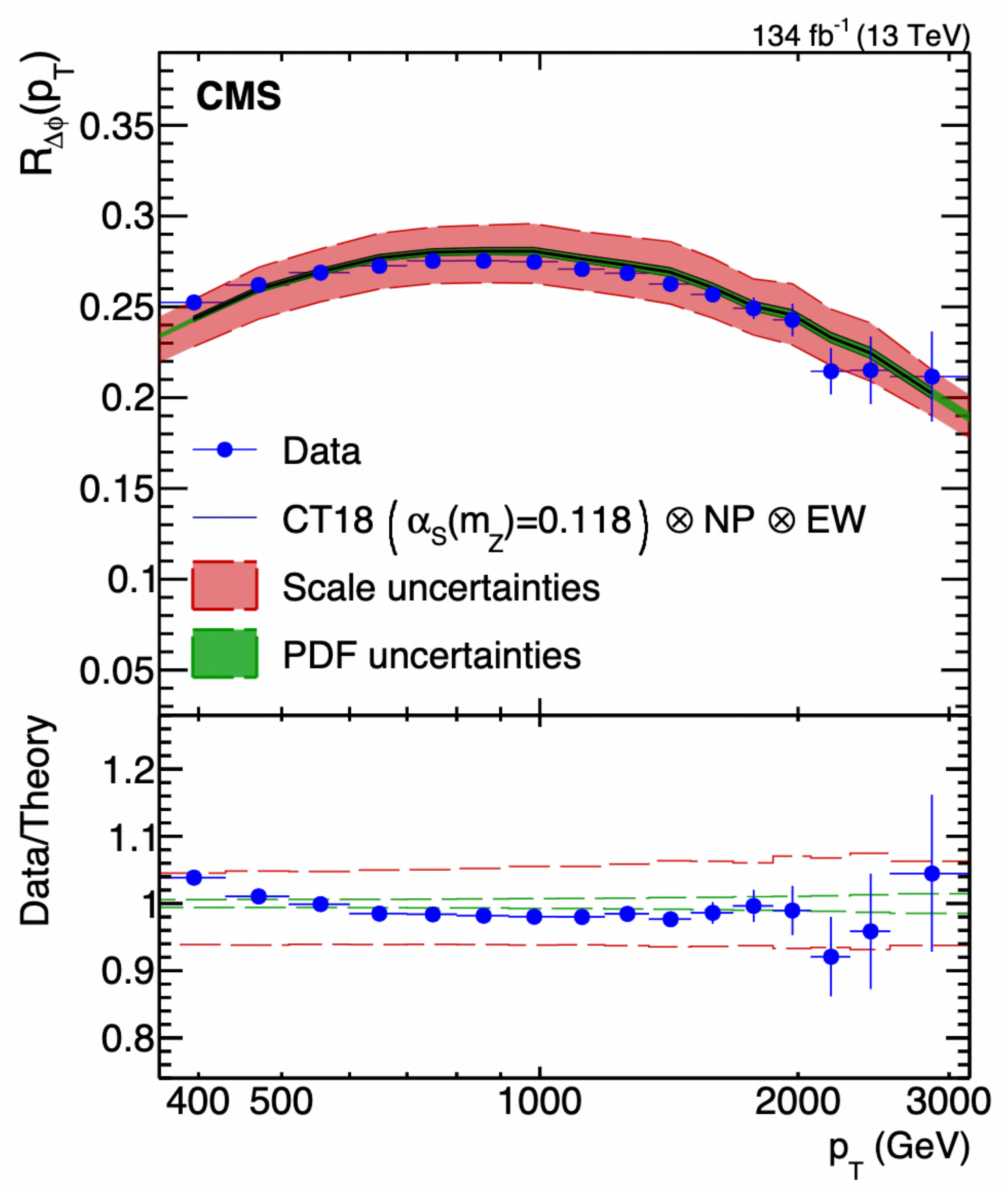


$R_{\Delta\Phi}(p_T)$

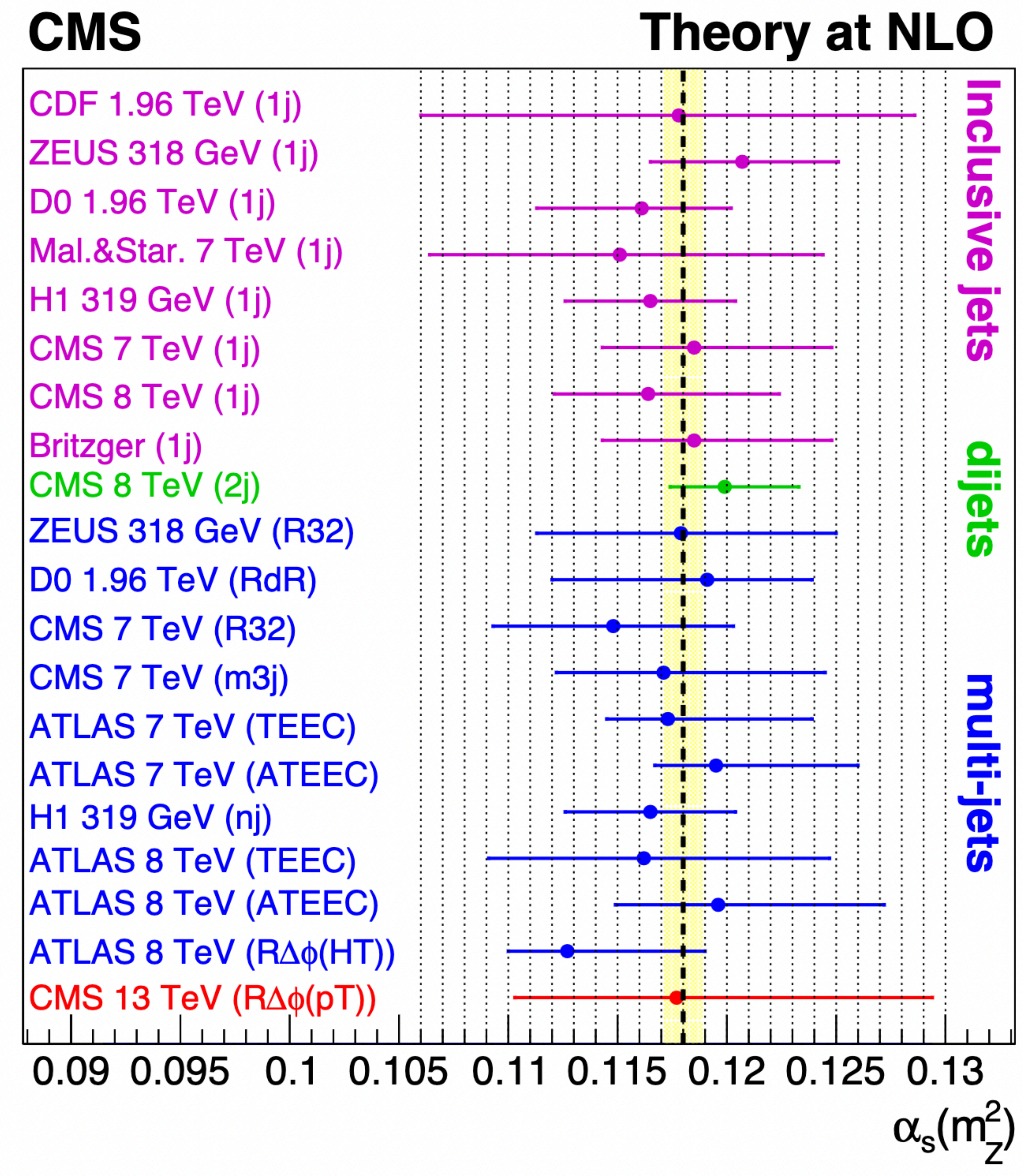
CMS

2404.16082

- Fitting $R_{\Delta\Phi}(p_T)$ as a function of p_T using NLO predictions
  - Good agreement with theory predictions



- Uncertainties dominated by theoretical scale uncertainties
  - *Need NNLO predictions for better precision*
- Agrees with the world average
  - *Note: only comparing to other hadron collider NLO extractions of α_S*

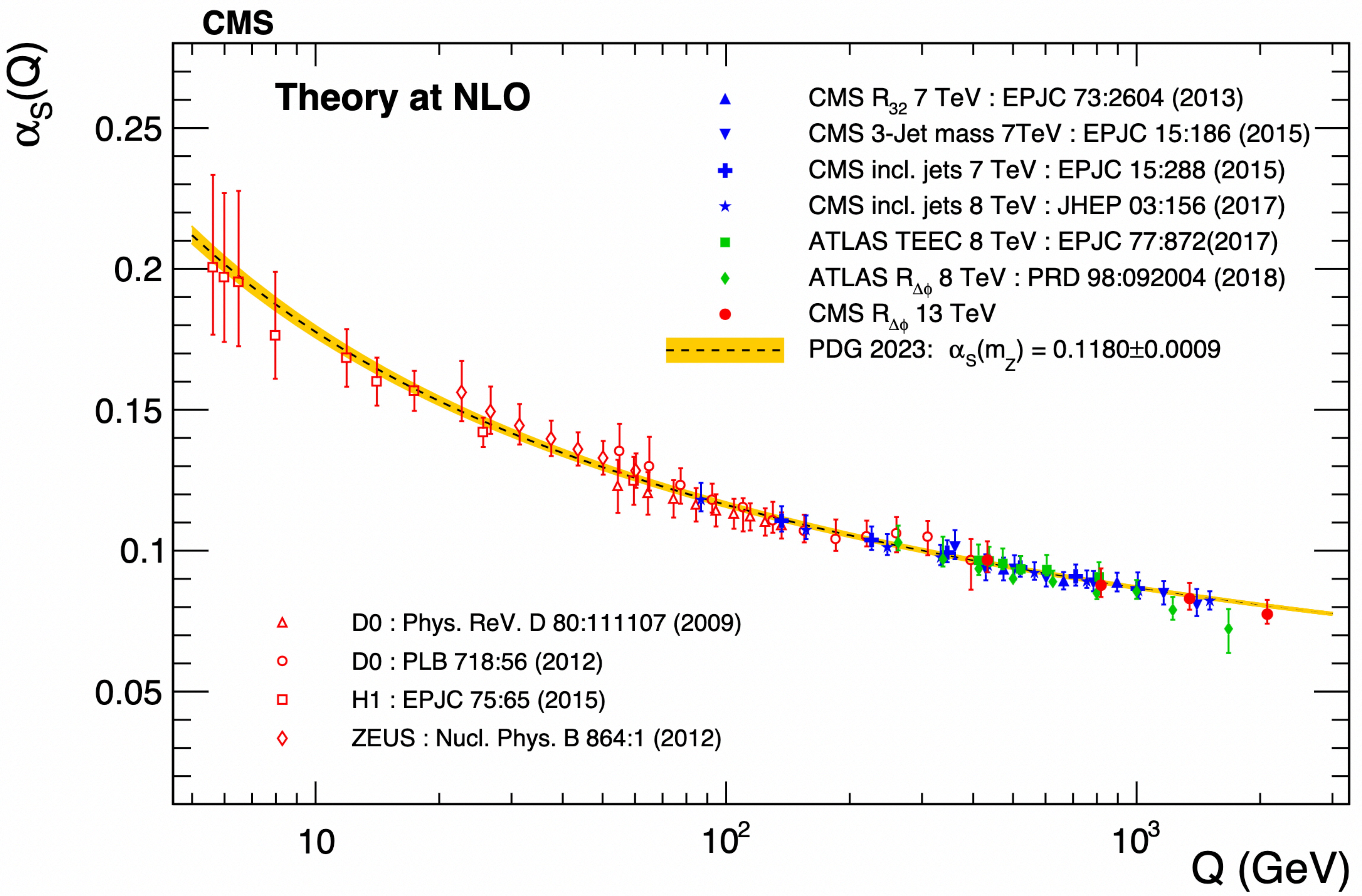


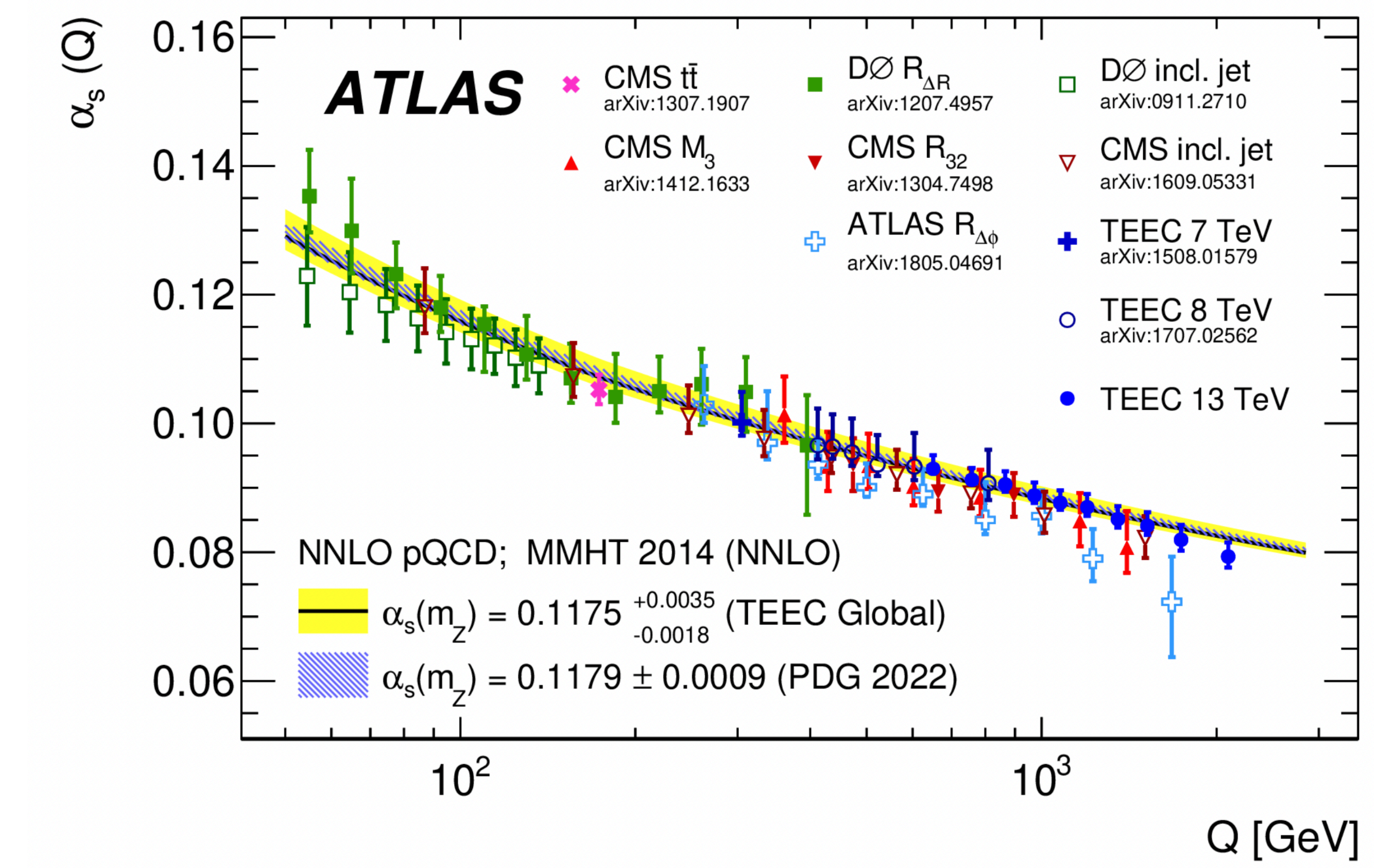
$R_{\Delta\phi}(p_T)$

2404.16082

CMS

- Test the running of α_S by fitting several different p_T ranges separately
  - Scale taken to be the jet p_T
- Tests running of α_S to high scales
- Good agreement with the world average for the running of α_S
  - Probe similar range as other 13 TeV α_S extraction by the ATLAS experiment at NNLO
    - *Only NLO extractions are shown in CMS comparison*





Summary

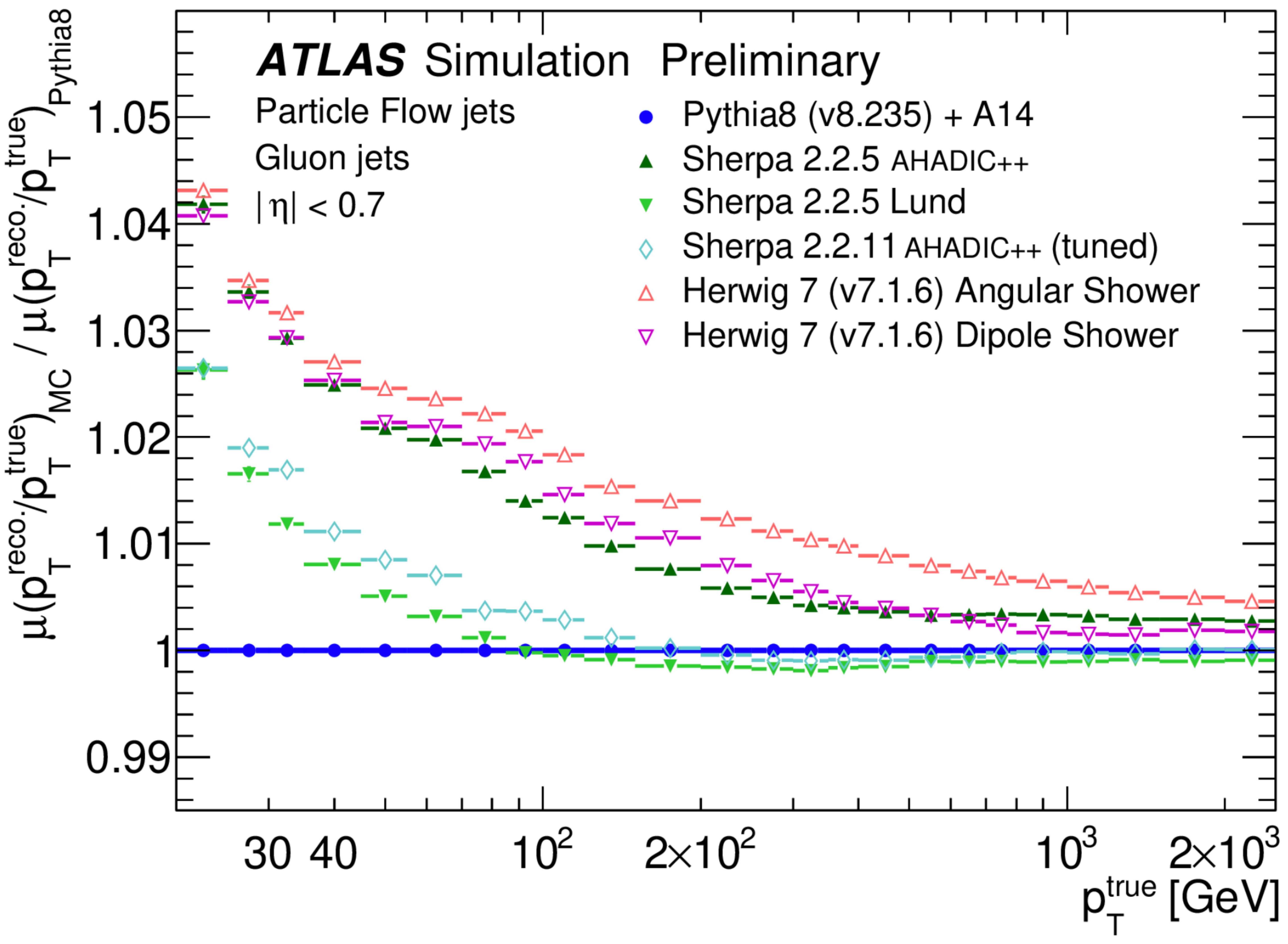
- Jet cross-section measurements provide important tests of QCD
  - *Constraints on PDFs, extractions of α_S and its running, and comparisons to fixed order predictions*
- NNLO predictions are becoming increasingly standard
  - *Enables stronger tests of QCD that are less dominated by theoretical scale uncertainties*
- Improvements to jet reconstruction and calibration directly translate to more precise measurements
  - *Requires understanding of detector effects and details of Monte Carlo simulations*

thanks!

jet fragmentation

ATLAS

- Modeling of gluon p_T response differs across generators
- Obvious trends from the hadronization model
  - *Calorimeter response depends on the type of hadron, not just the energy and rapidity*
  - Retuned Sherpa with LEP data on baryon and kaon fractions — significant effect on the p_T response!



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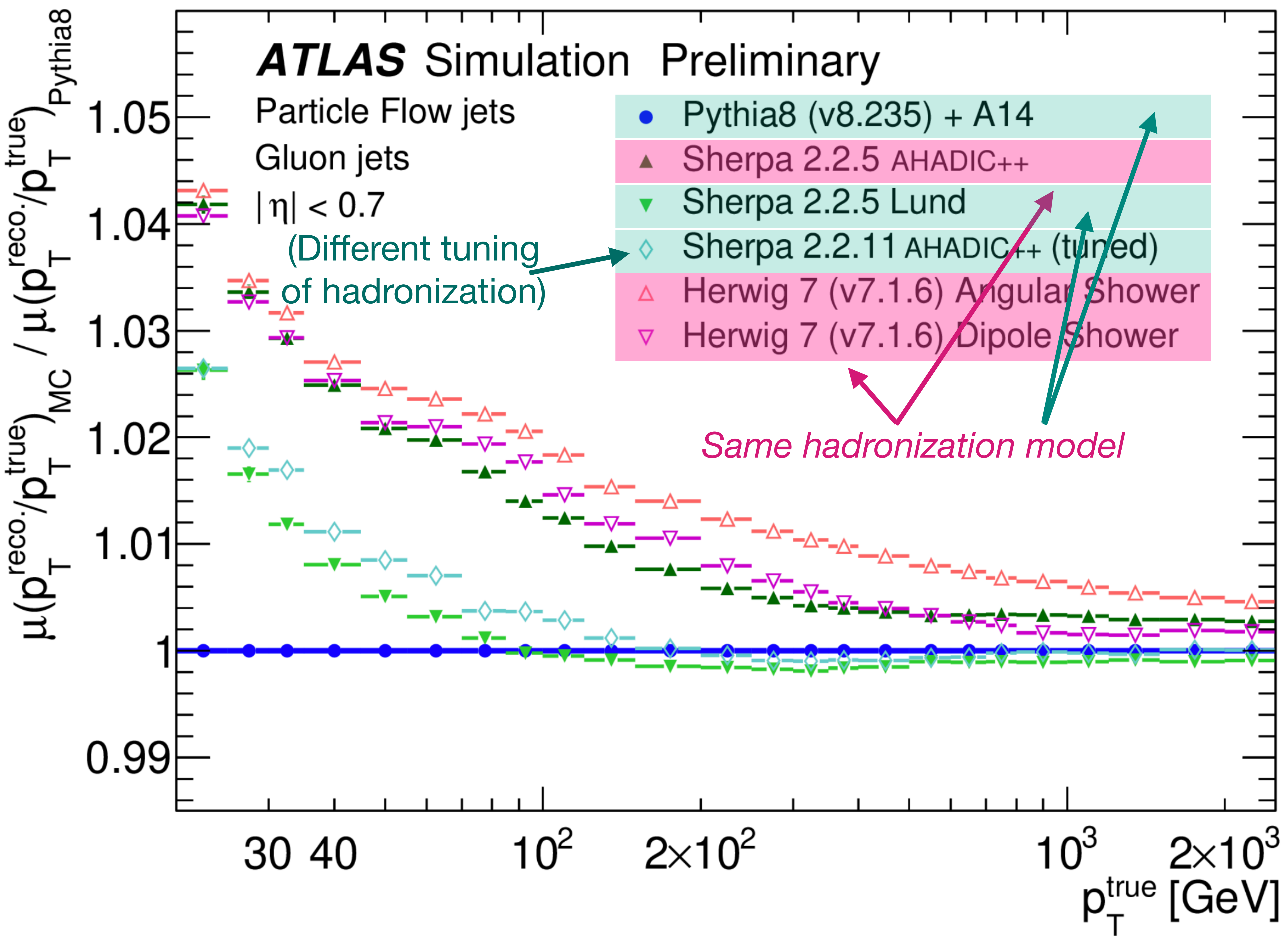

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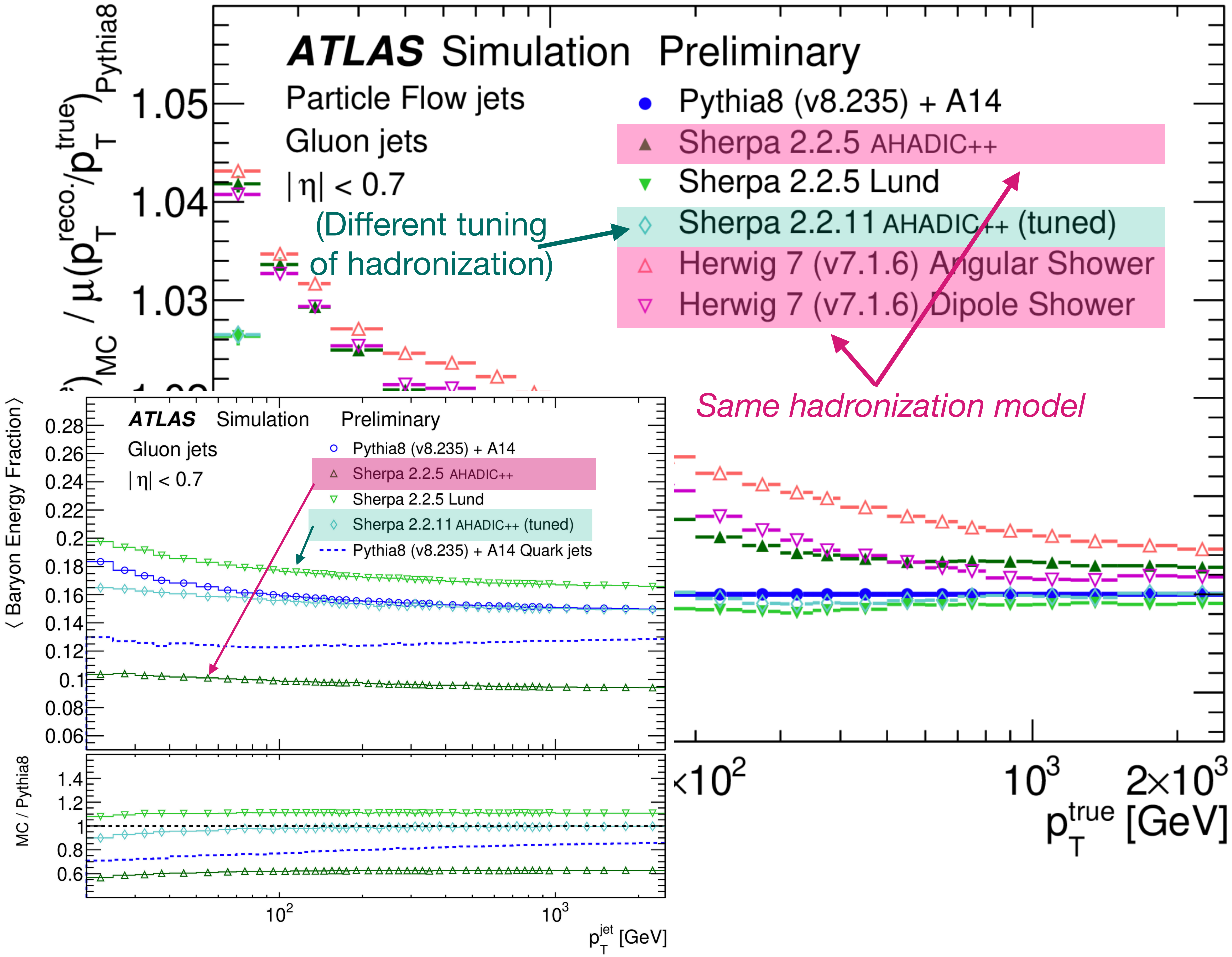
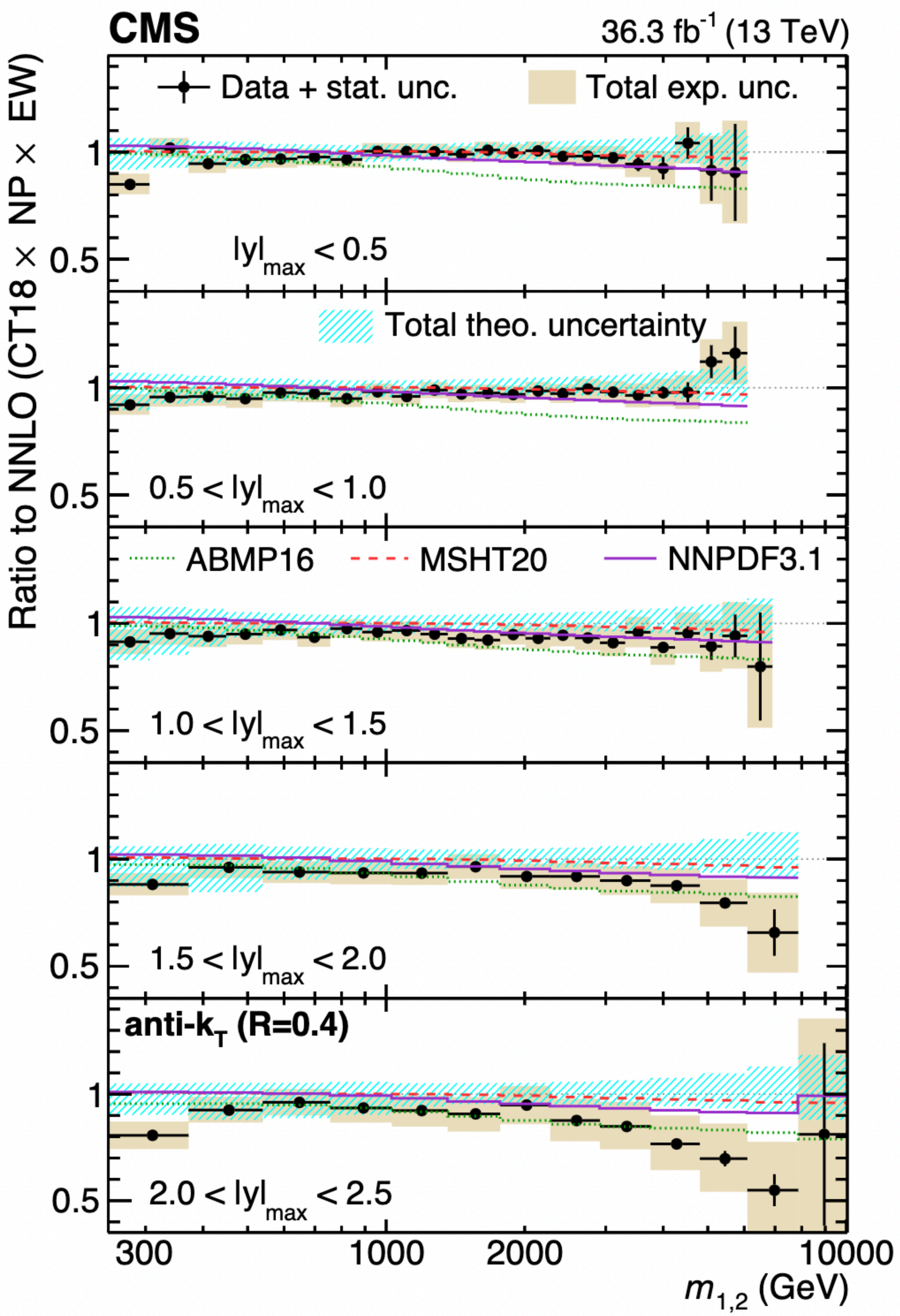


dijet cross section measurements

CMS

2312.16669

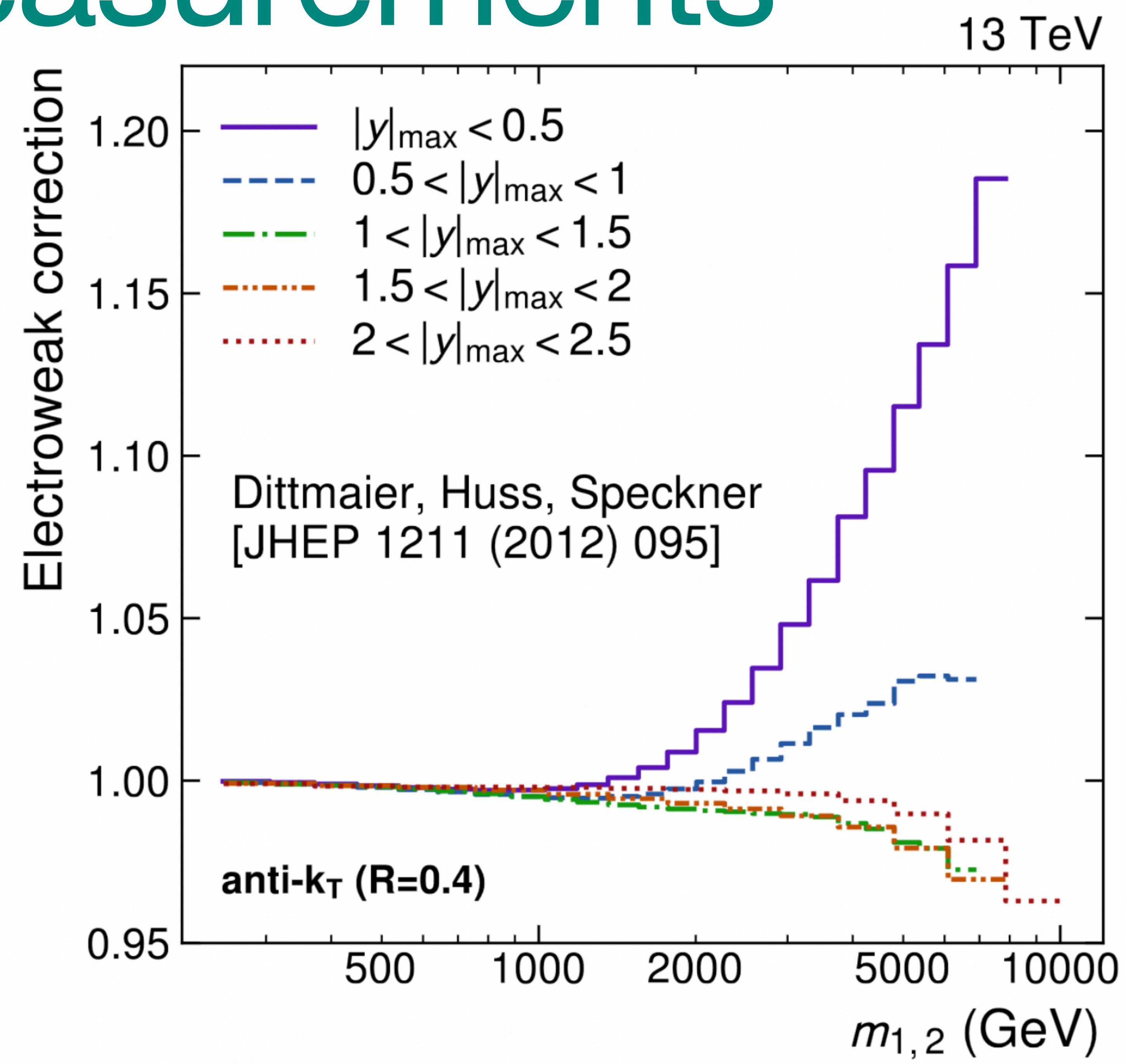
- Relatively good agreement with the theory predictions across most rapidities
  - Slightly worse agreement for very high dijet masses
- Small theory uncertainties thanks to NNLO predictions

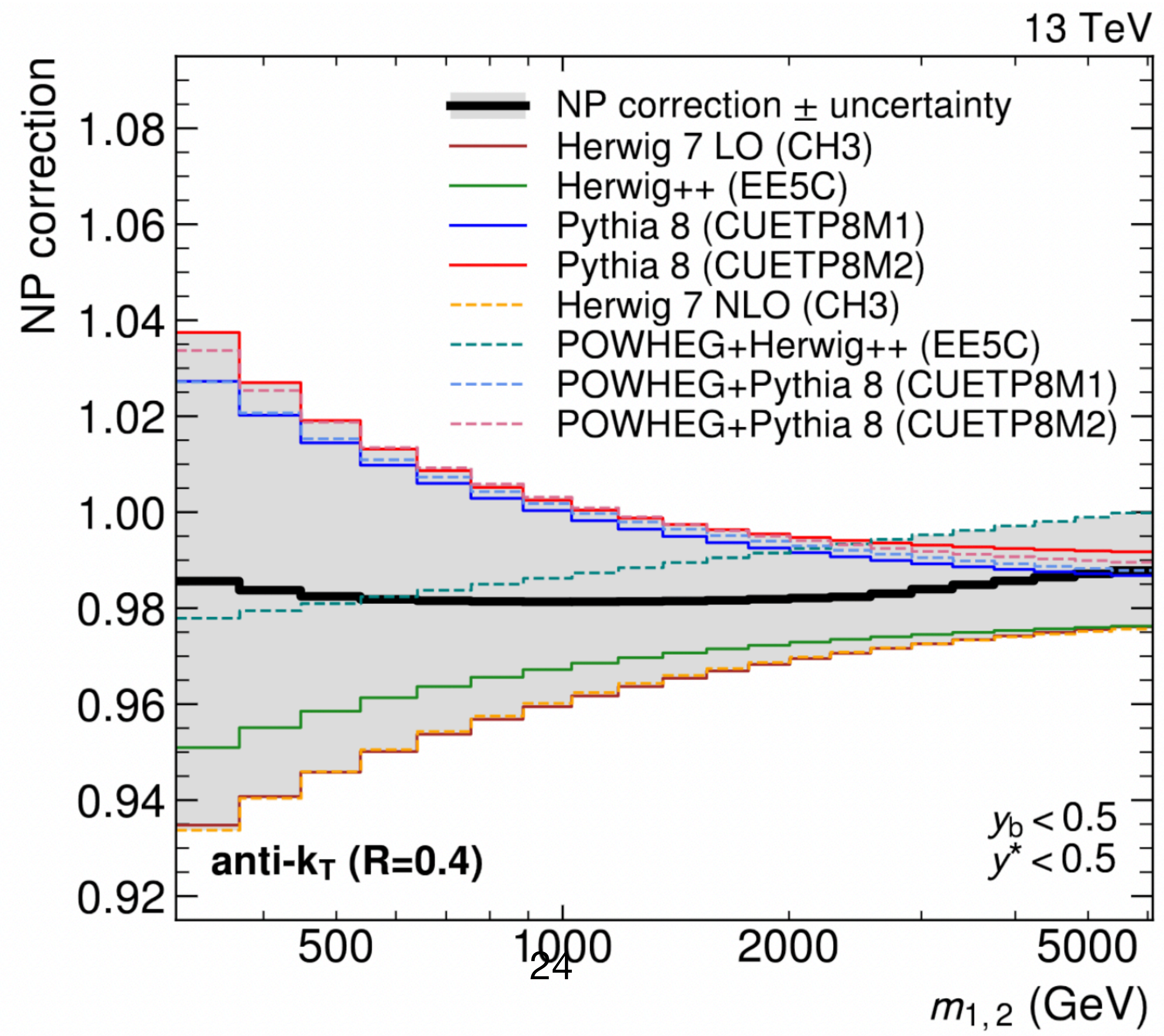


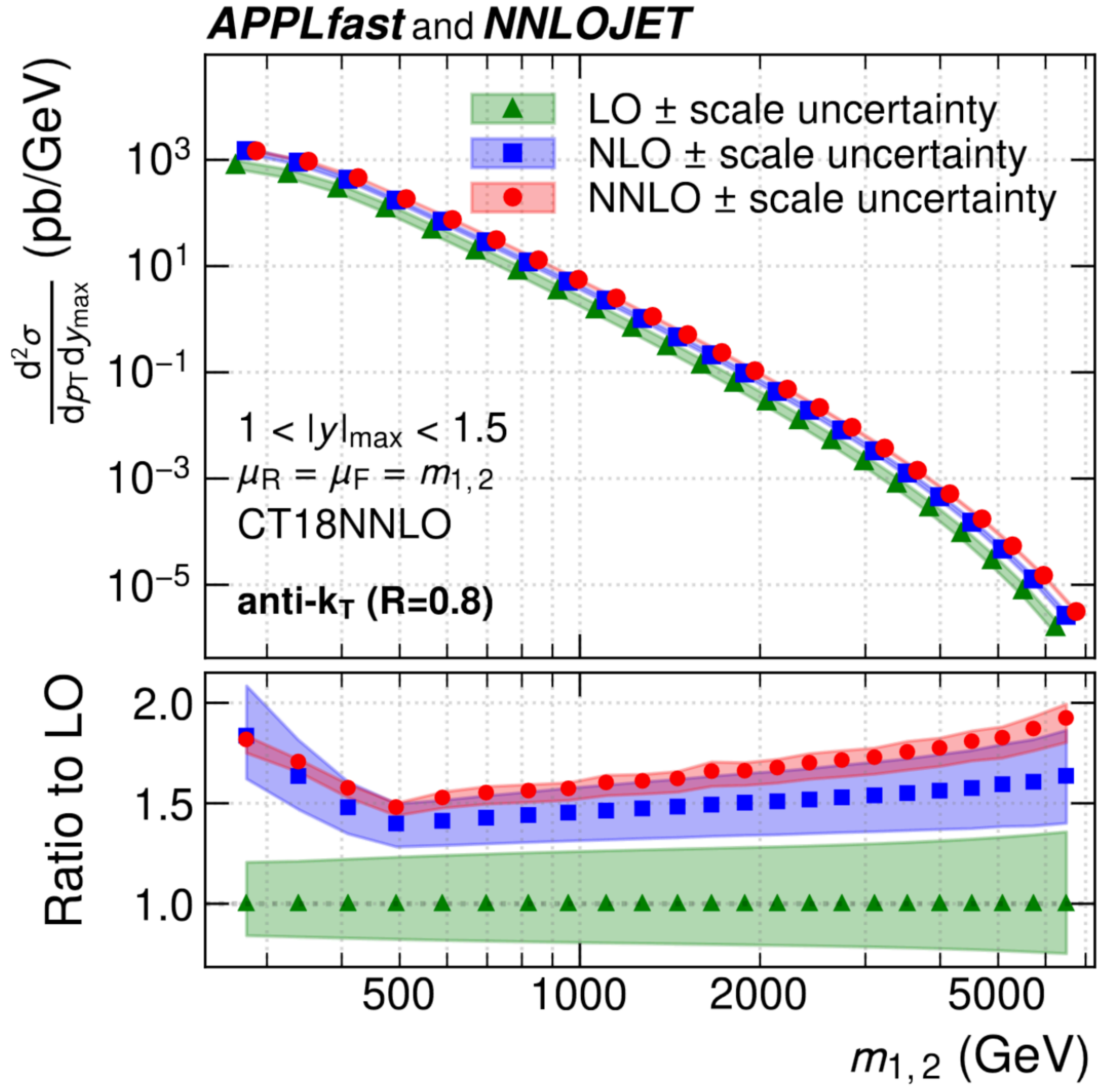
dijet cross section measurements

CMS

- Electroweak corrections important for high dijet mass
- Nonperturbative corrections relatively small, with uncertainties larger at smaller dijet masses
- Perturbative convergence reasonable, though worse at high dijet mass



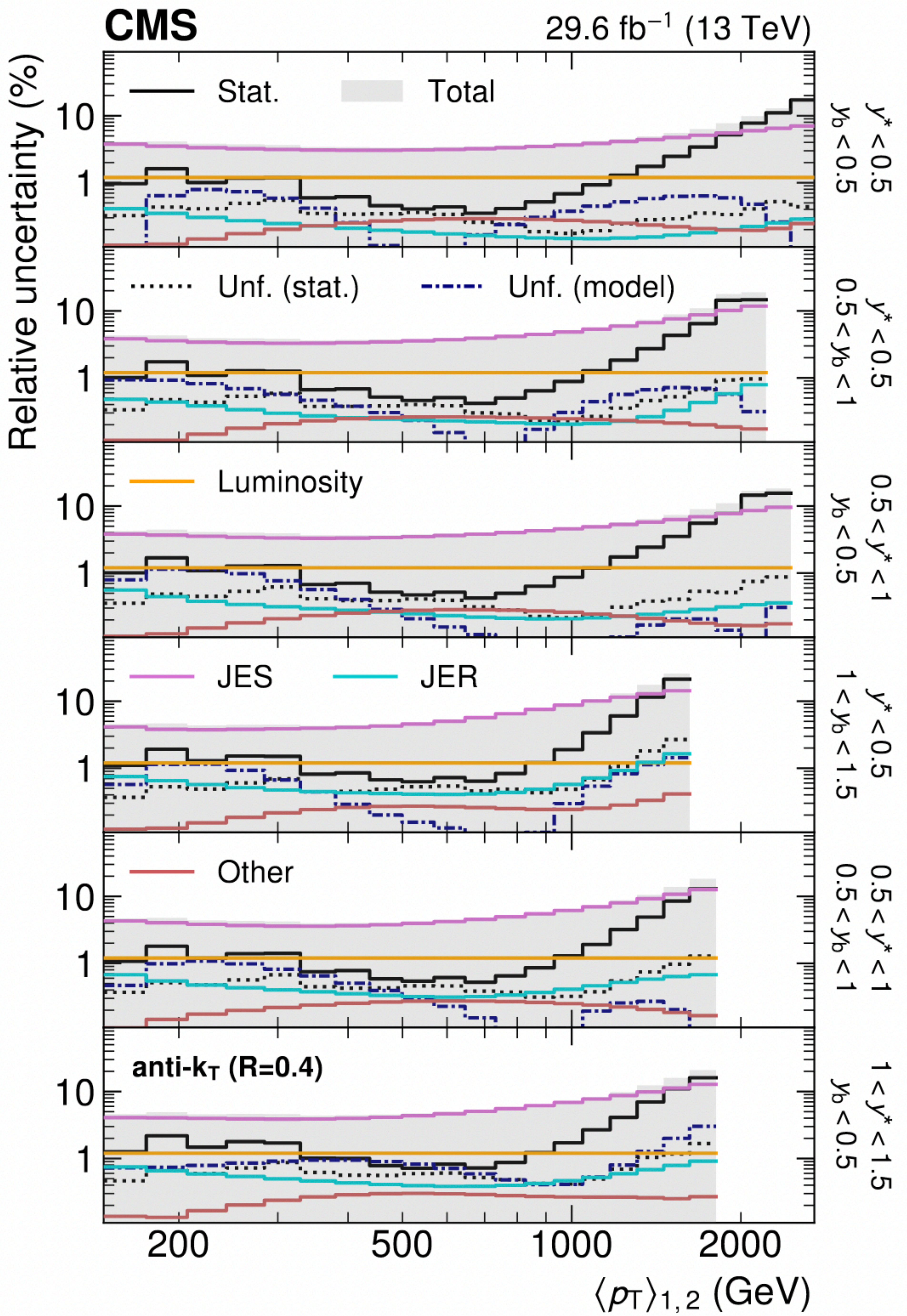




dijet cross section measurements

CMS

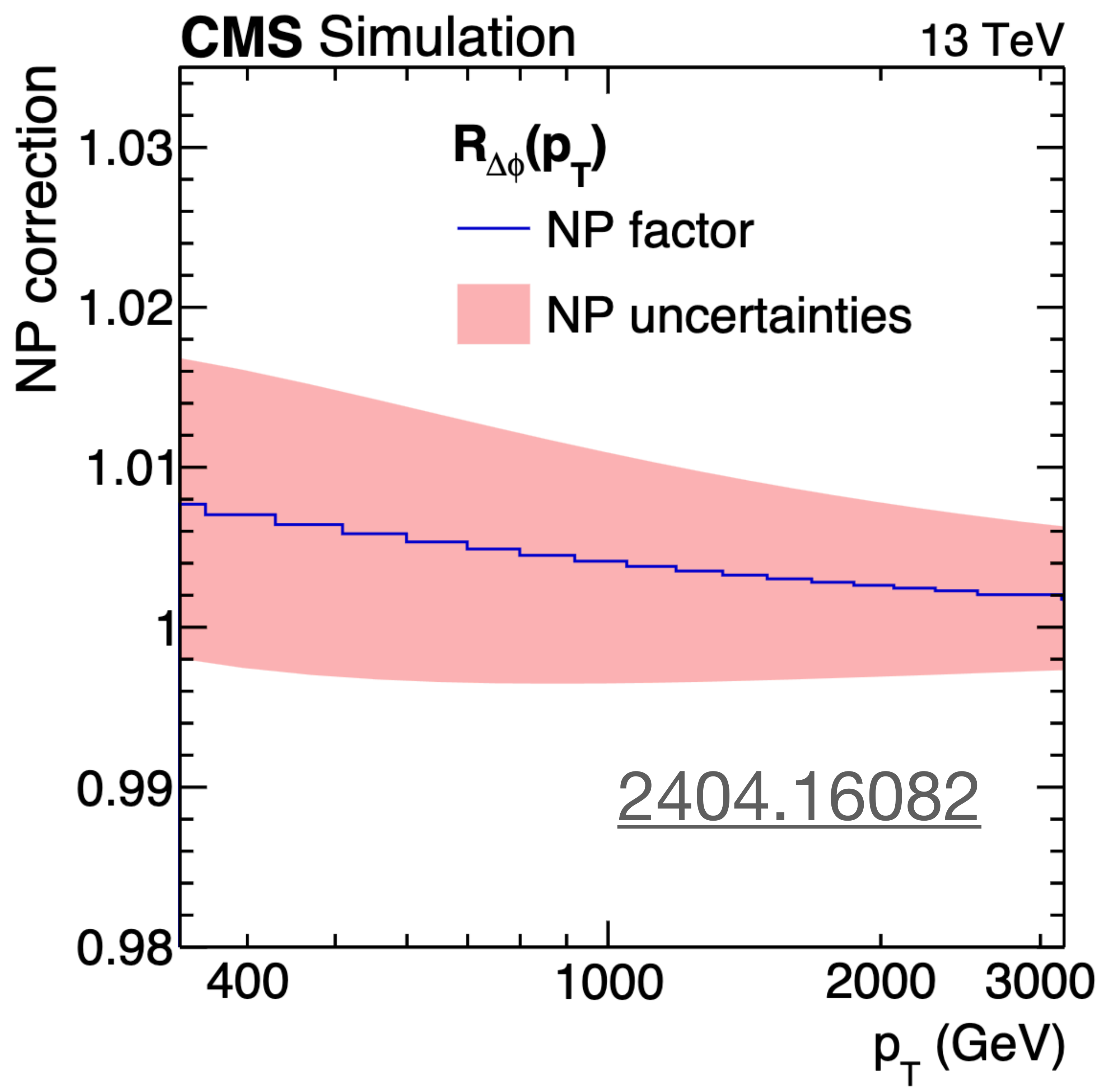
- Uncertainties generally dominated by uncertainties on the jet energy scale
- At high p_T, the statistical uncertainties begin to dominate
  - Using more data will improve the reach of this region, which is very relevant for constraining the high-x gluon PDF

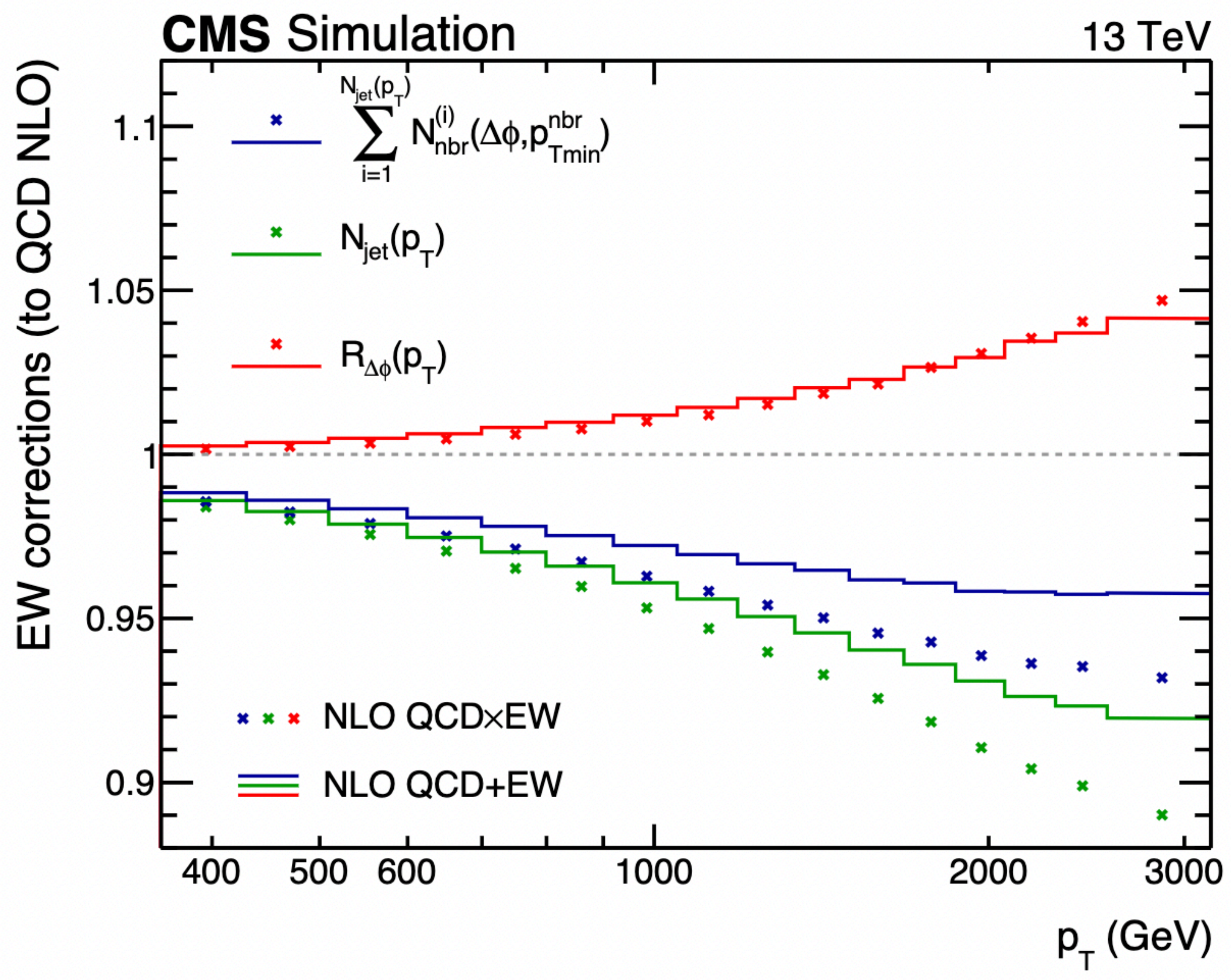


$R_{\Delta\phi}(p_T)$

CMS

- Small nonperturbative corrections and uncertainty
- Electroweak corrections are typically less than 5%
  - Largest at high p_T



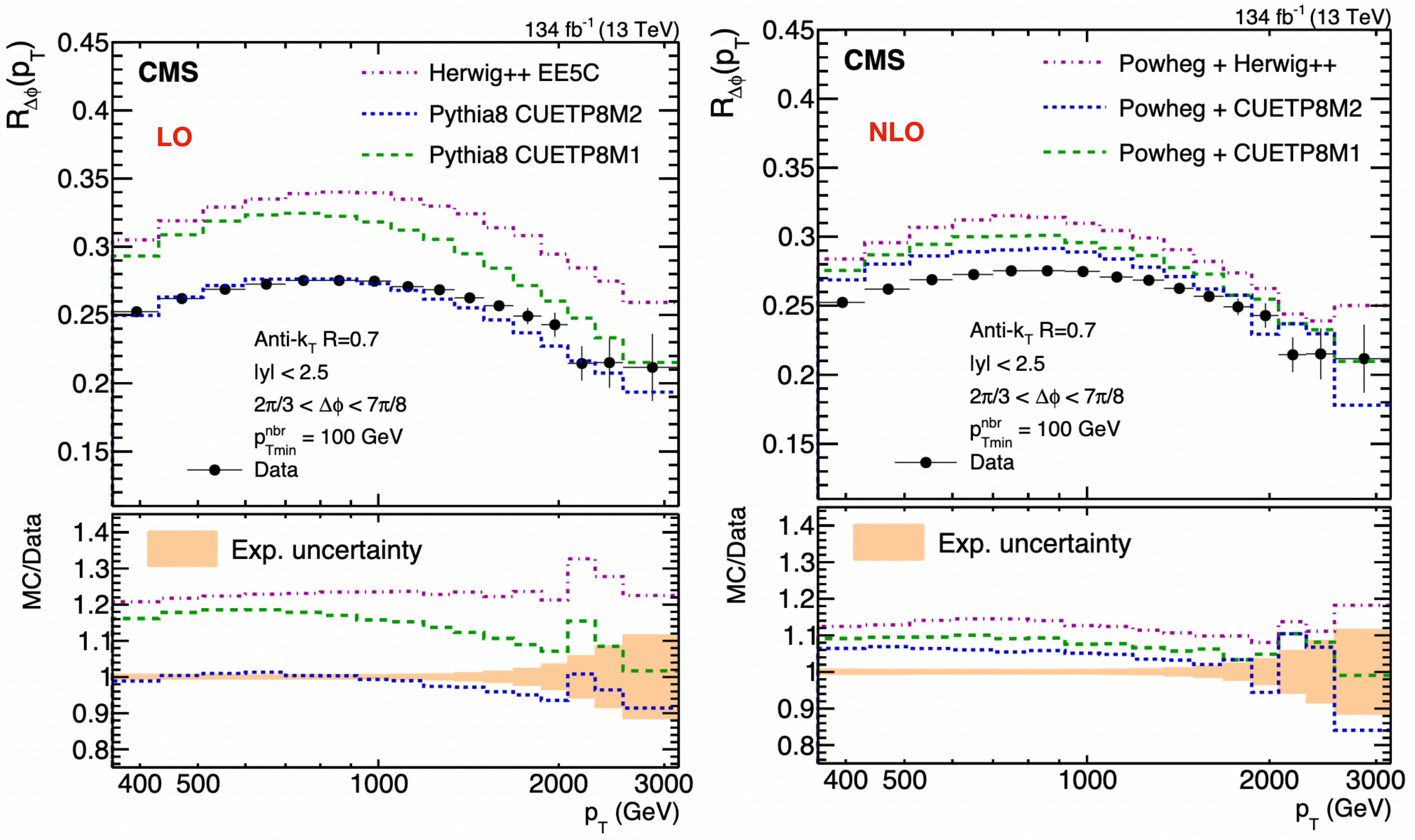


$R_{\Delta\phi}(p_T)$

CMS

https://arxiv.org/pdf/2404.16082

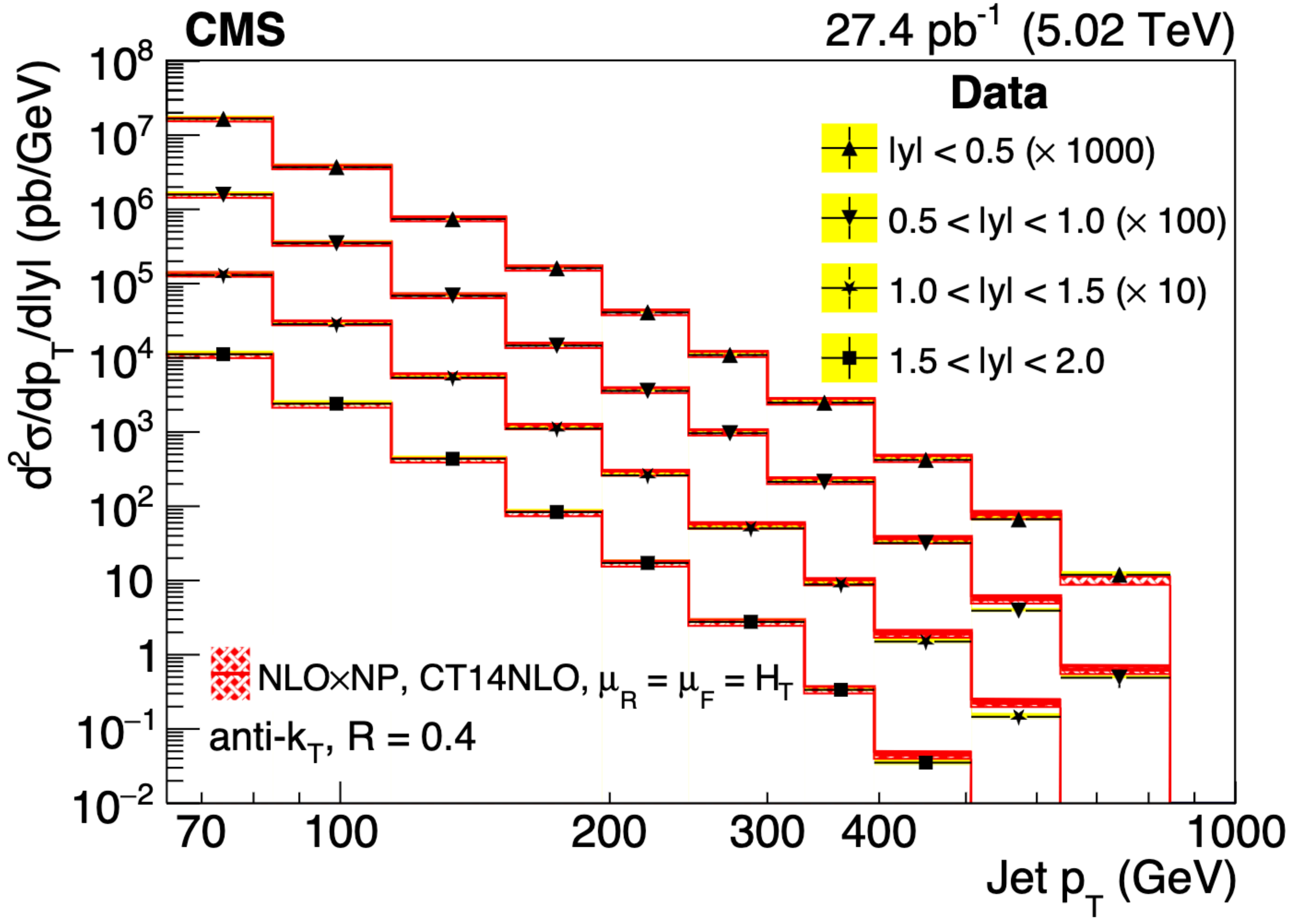
- Using Powheg + Herwig and Powheg + Pythia at LO and NLO
  - NLO has 2->2 at NLO and 2->3 at LO
- Comparing to two different Pythia8 tunes
  - Tunes based on LO predictions

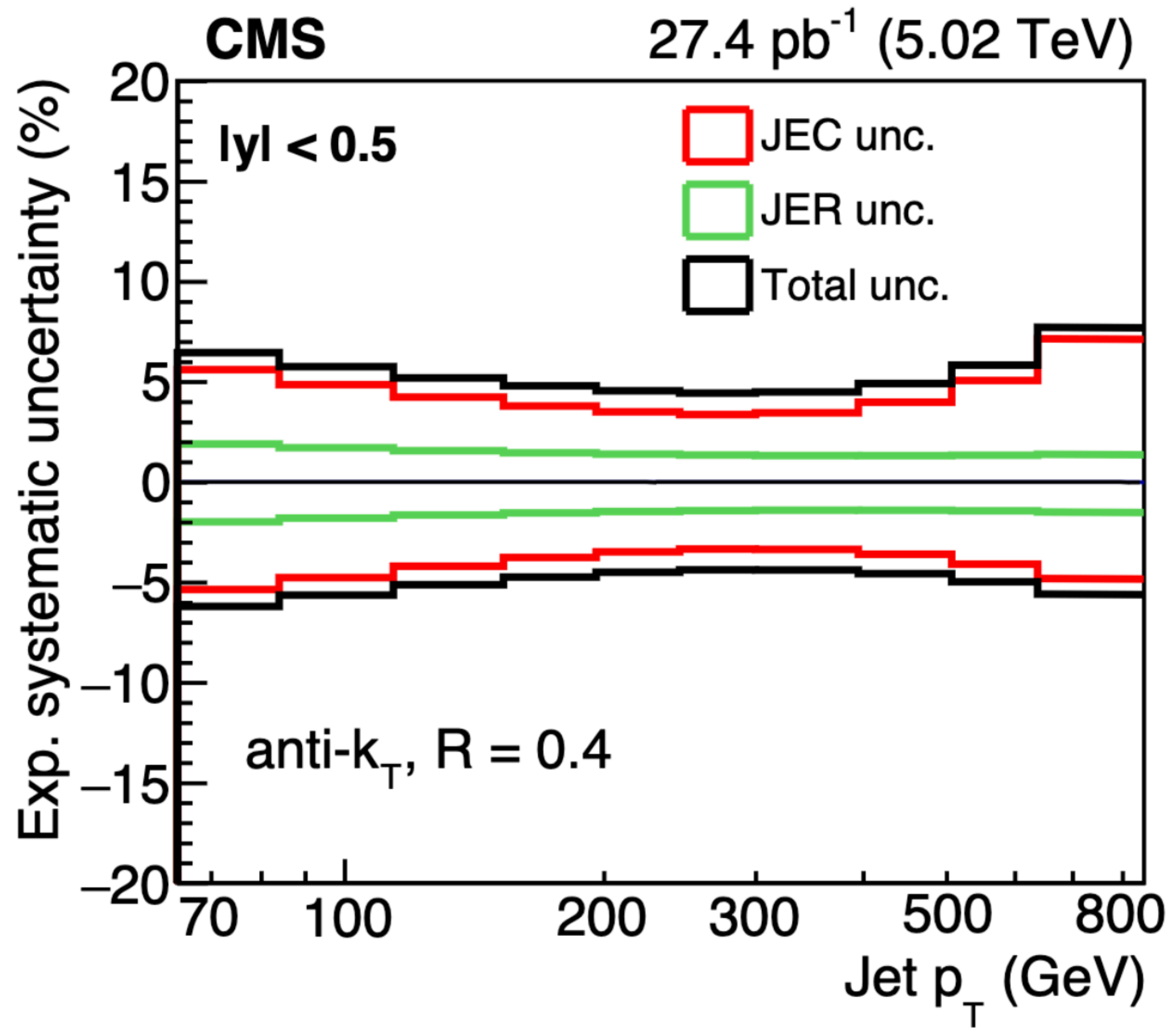


Inclusive jet cross section at 5 TeV

CMS

- Measuring differential in the jet p_T and the rapidity
  - *Spans 7 orders of magnitude!*
- Relevant for PDFs and α_S, and provides reference for heavy collisions



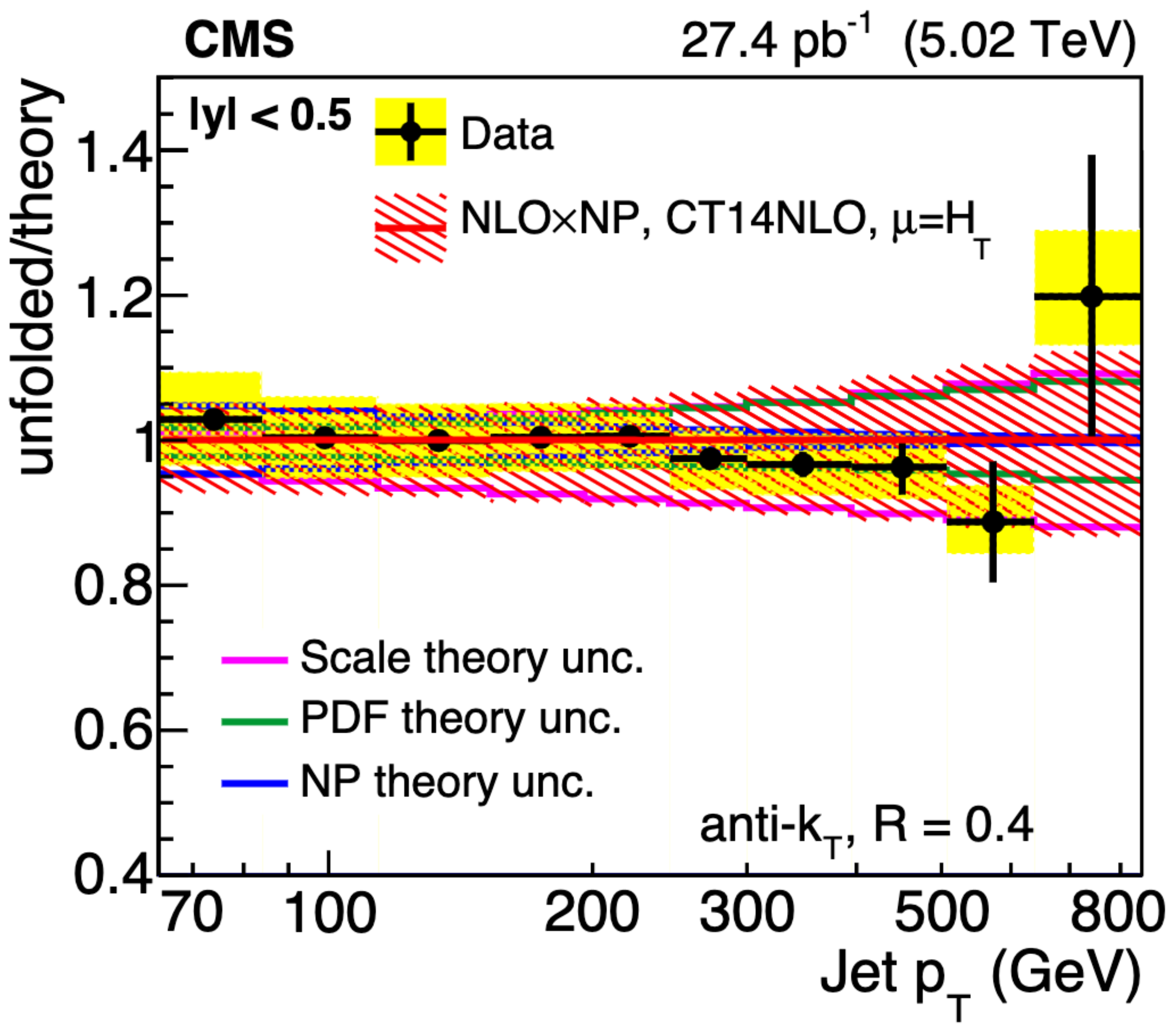


- Dominated by the jet energy scale uncertainties
  - Energy resolution effects are subdominant

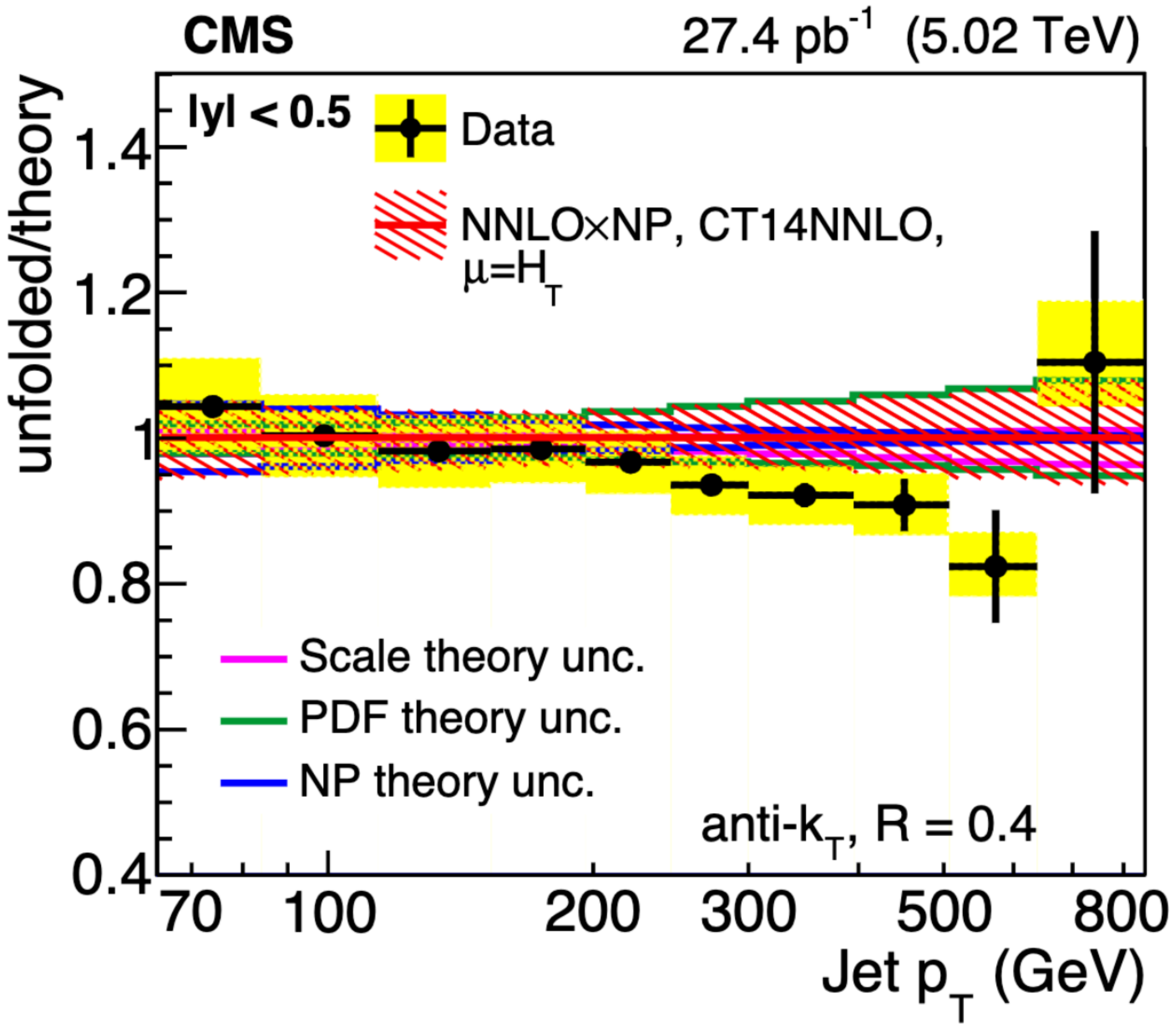
Inclusive jet cross section at 5 TeV

CMS

- For NLO predictions, scale uncertainties dominate
- NNLO predictions significantly reduce scale uncertainties
  - PDF uncertainties dominate for high p_T
  - Nonperturbative uncertainties dominate at low p_T
- Jet scale taken to be $p_{T,jet}$ or H_T
  - Generally worse agreement for $p_{T,jet}$
  - Consistent with other studies on the preferred scale choice



https://arxiv.org/pdf/2401.11355



Inclusive jet cross section at 5 TeV

CMS

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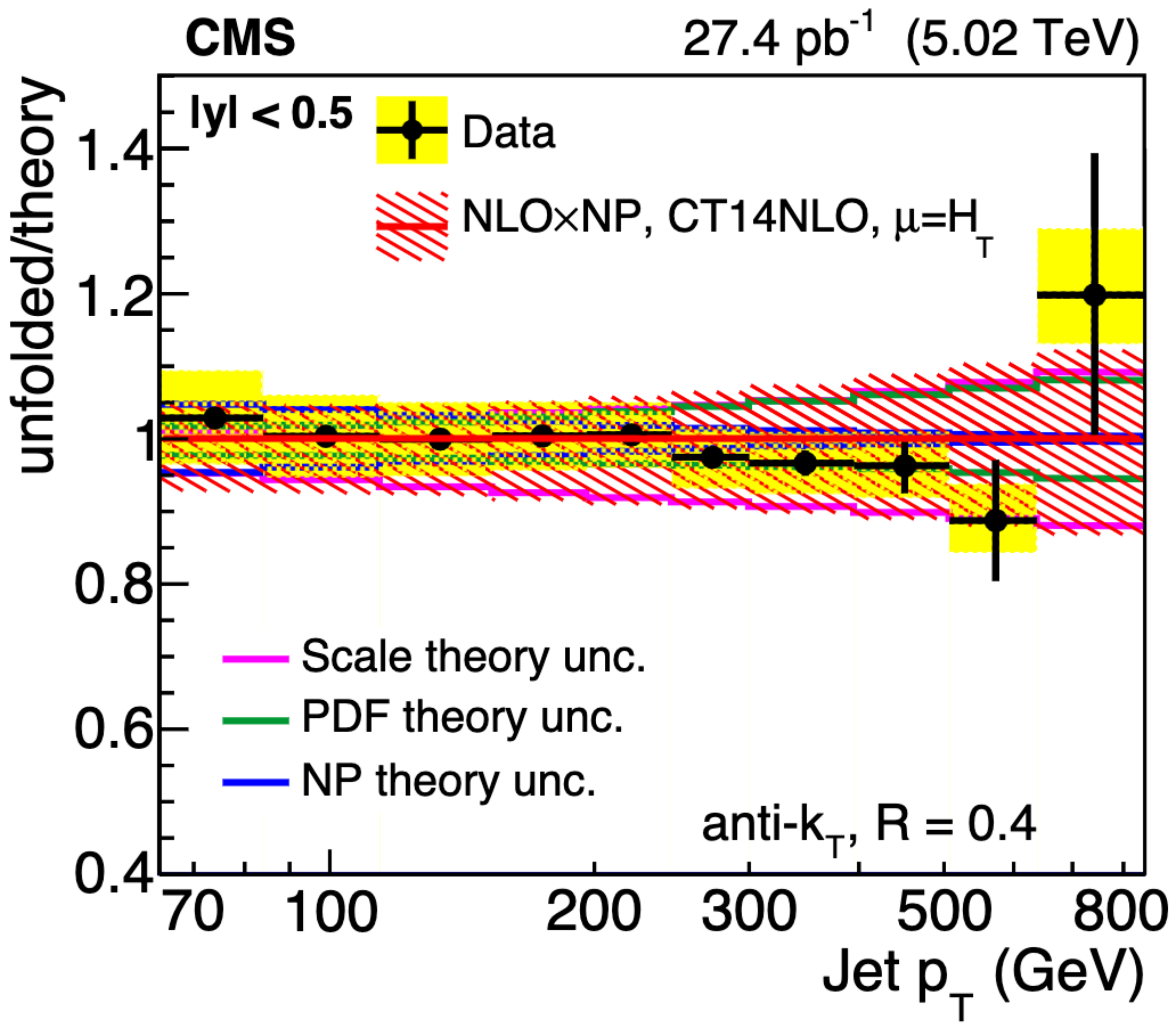

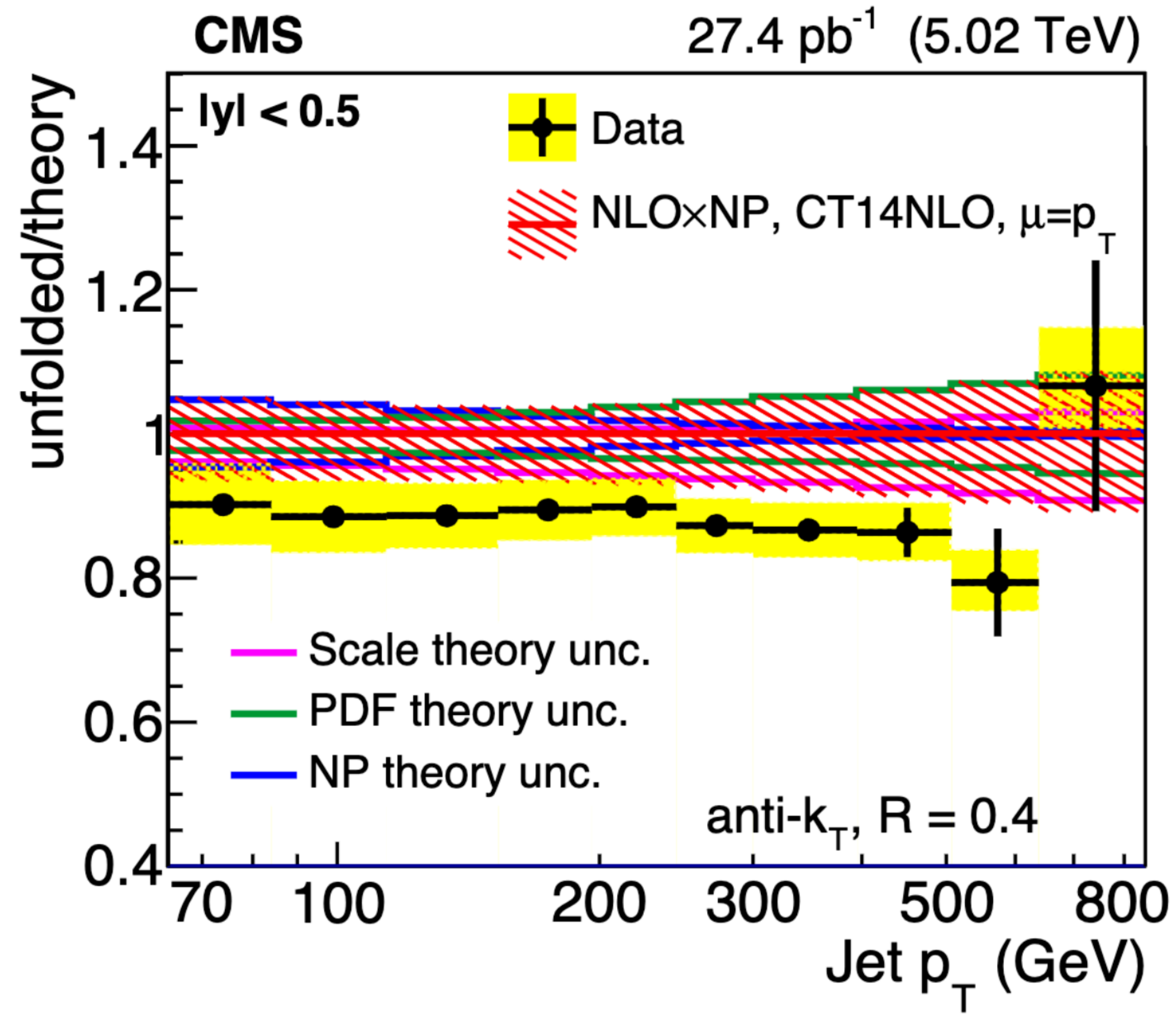

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Inclusive jet cross section at 5 TeV

CMS

- Dominated by jet energy scale uncertainties, with jet energy resolution uncertainties subdominant

- Nonperturbative corrections increase at low p_T, but very small at high jet p_T