The ATLAS Measurements of Jet Production and the Strong Coupling Constant

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on behalf of the ATLAS collaboration

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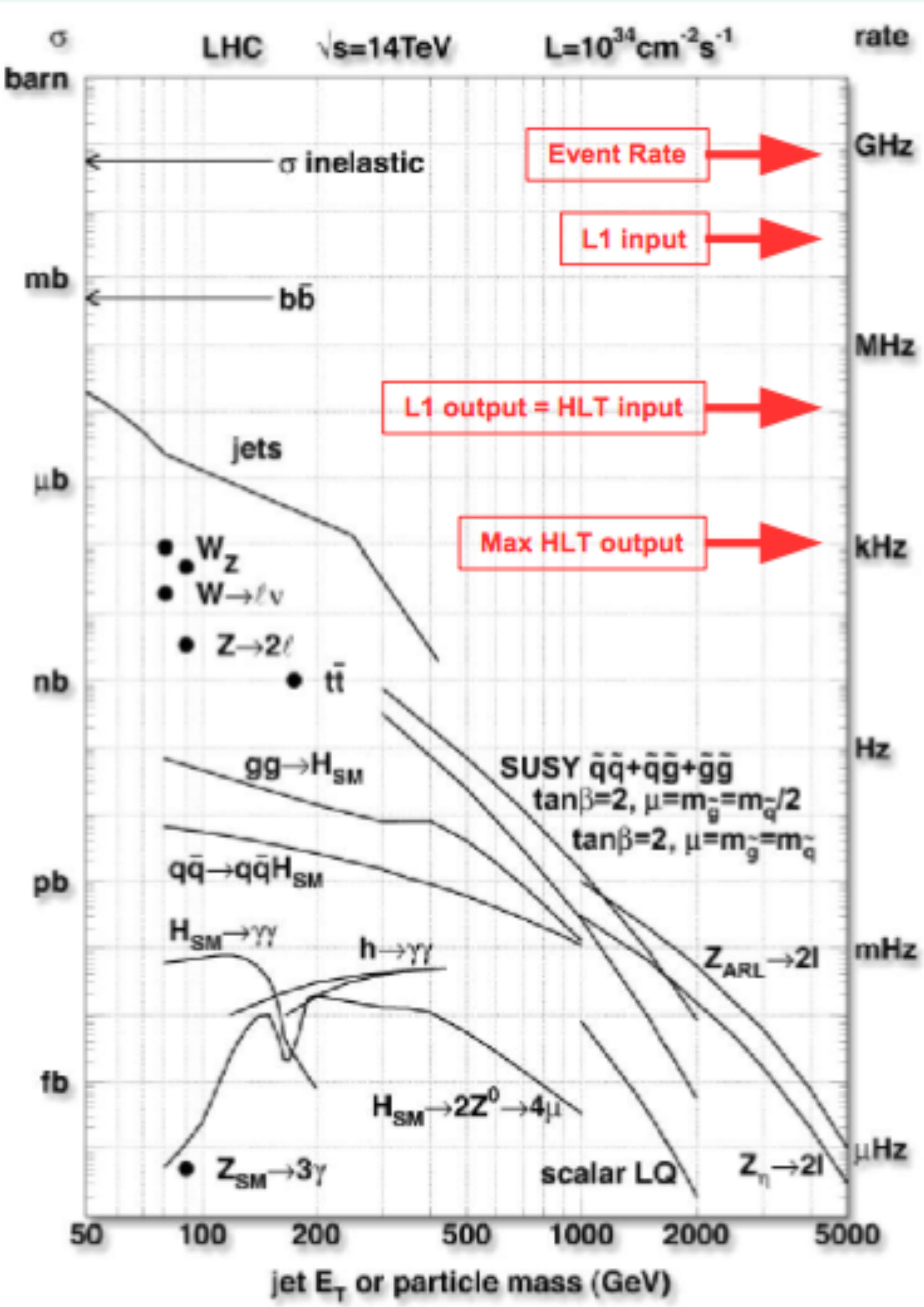
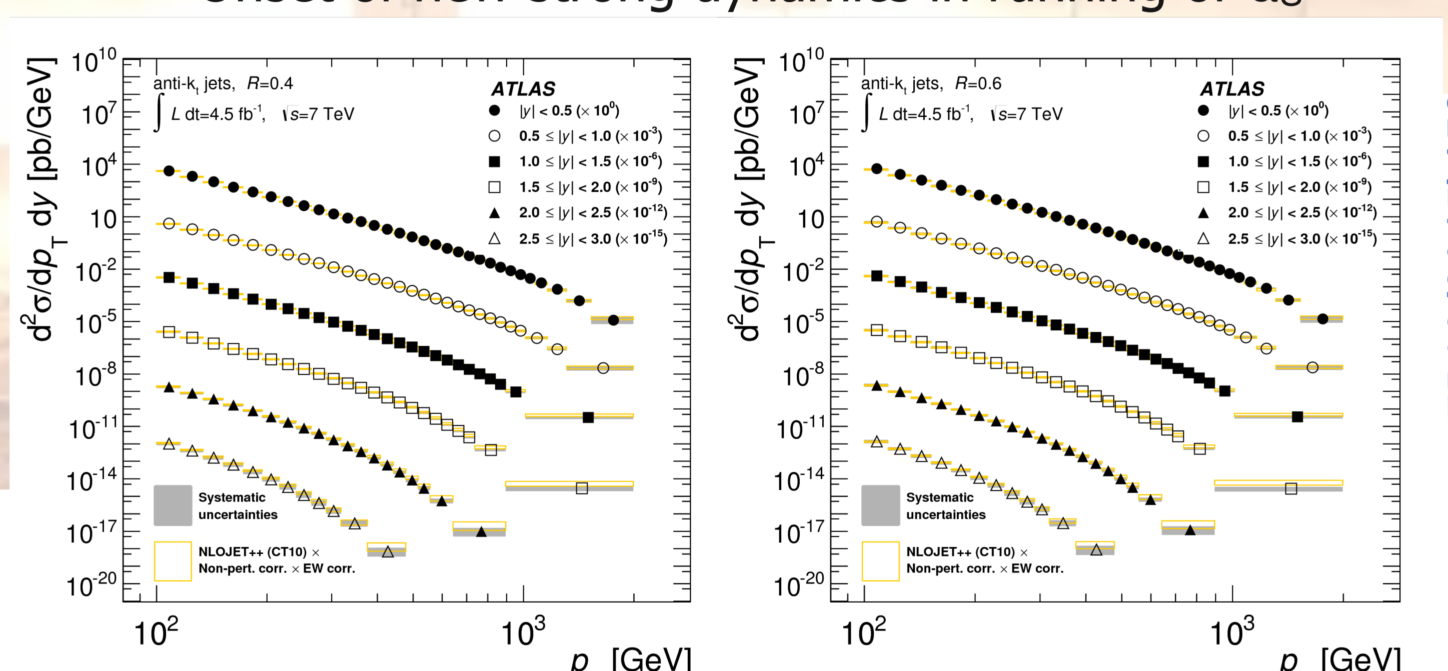
Testing the Standard Model with Jets



- With jets we can
  - Test the Standard Model in a wide range of parton energies
    - New energy reach with LHC measurements
  - Make comparisons to NLO pQCD calculation for up to 3- or 4-jet states
    - NNLO for inclusive jets, dijets
  - Test PDFs and tune Monte Carlo
  - Look for new strongly produced states
    - Onset of new strong dynamics in running of α_S

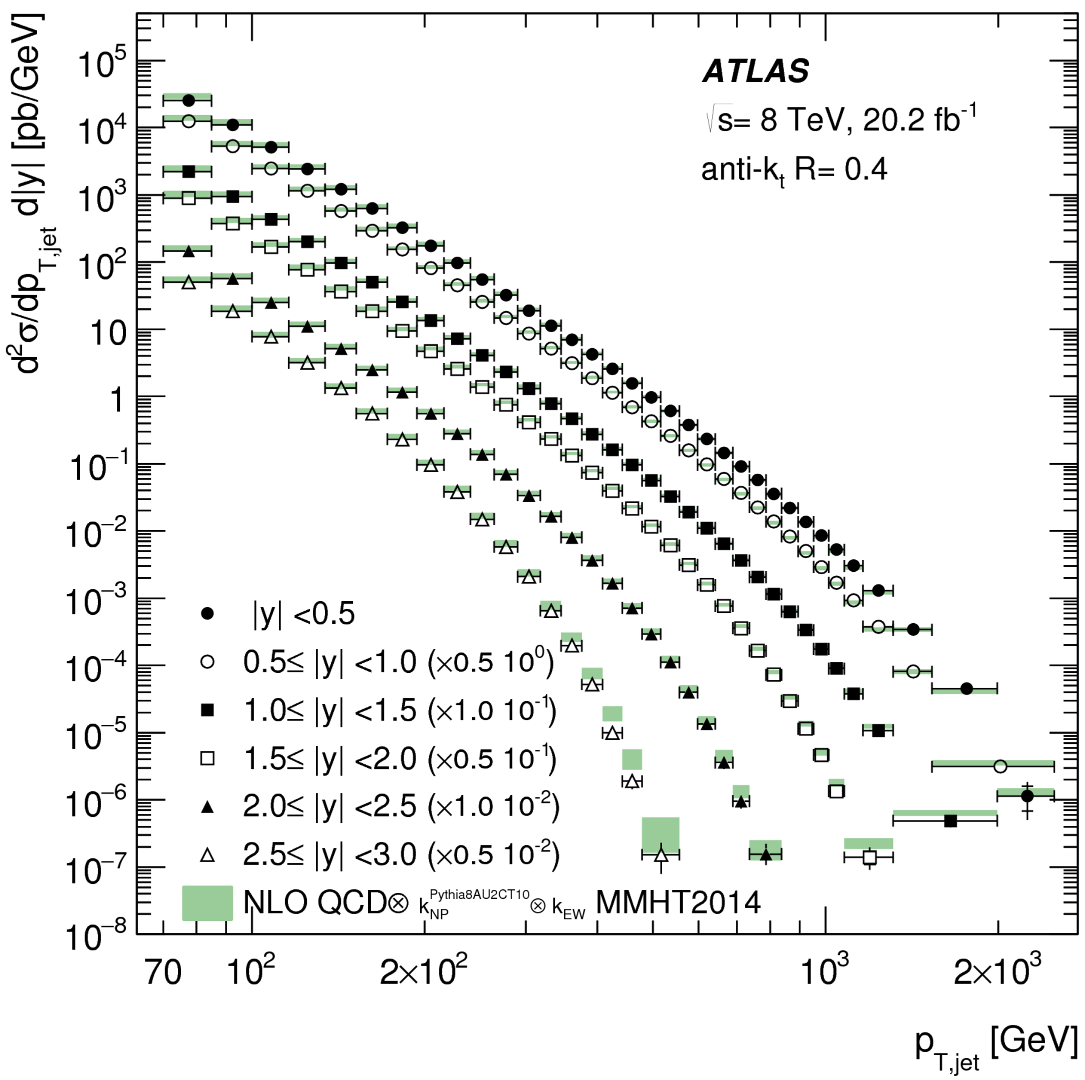


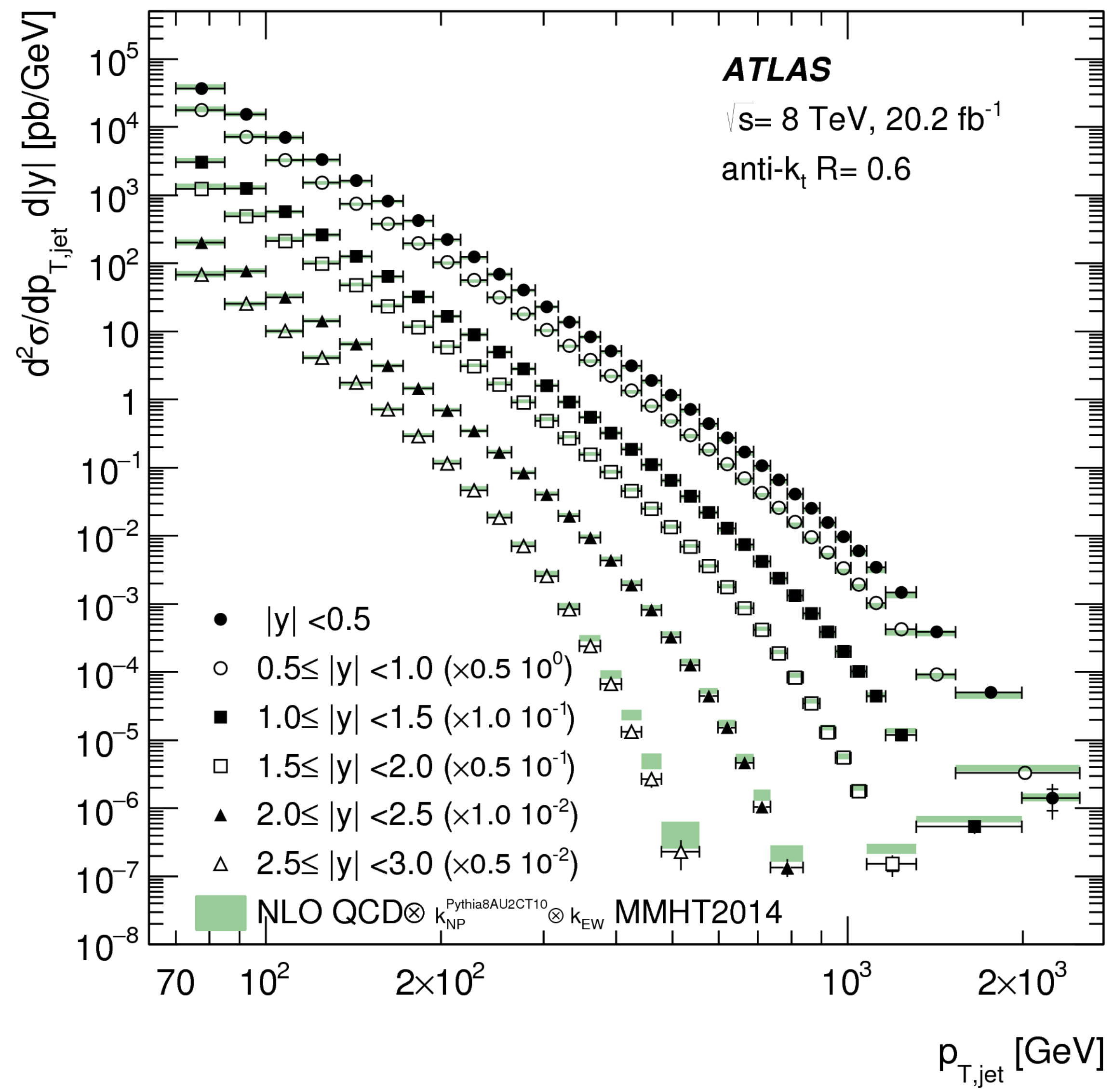
JHEP02(2015)153

Inclusive Jets at 8 TeV

- Based on 20.2 fb^{-1} taken in Run I
- Require jet pT > 70 GeV
- Require jet rapidity |y| < 3
- Measurement made with both R=0.4 and 0.6 jets
- Double differential measurement in jet p_T and y

arXiv:1706.03192

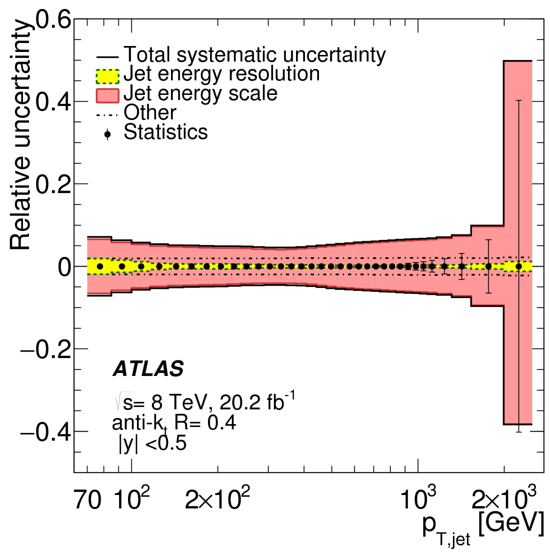


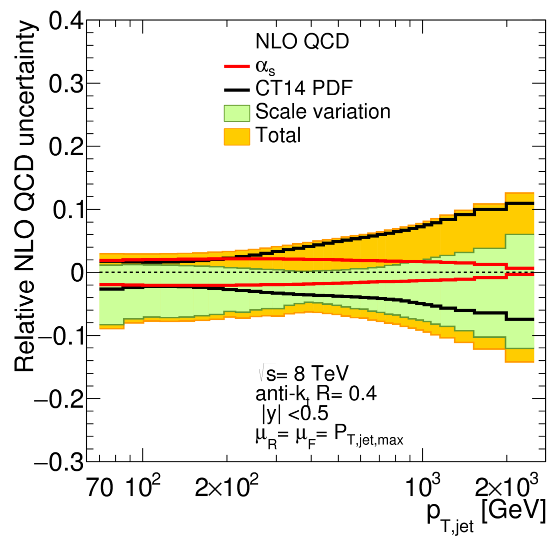


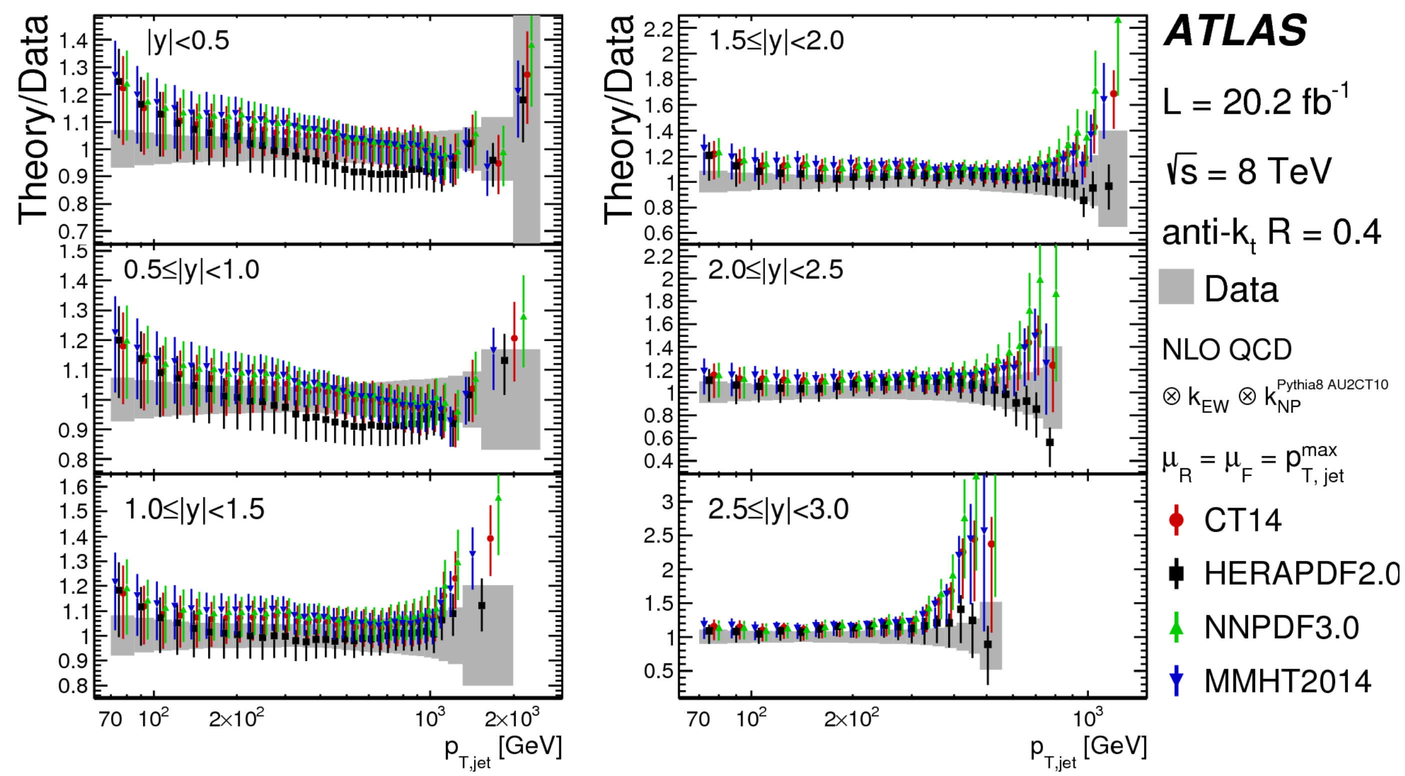
Measurement spans 11 orders of magnitude for central rapidity. Good agreement with NLO theory on log scale

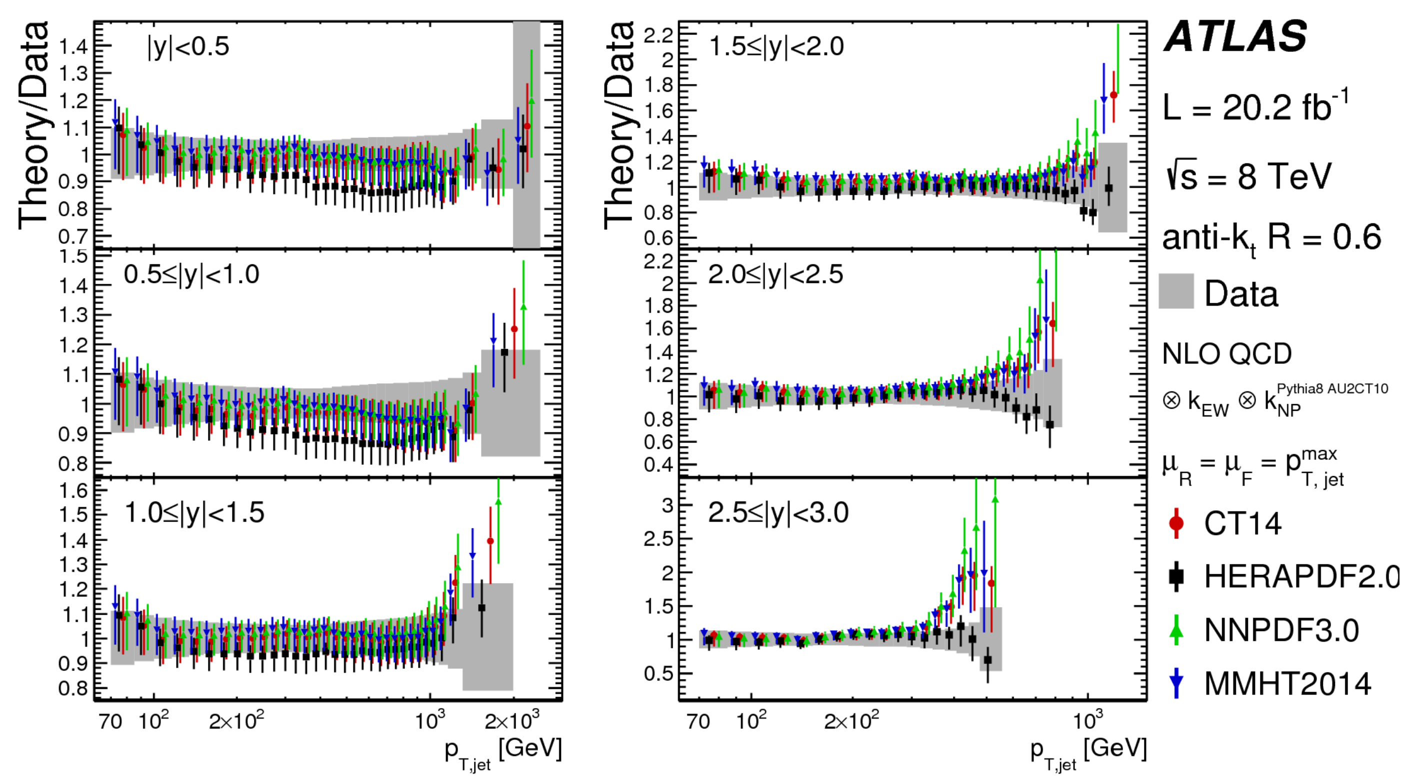
Inclusive Jets at 8 TeV

Detailed Theory/Data comparisons
- Theory predictions corrected for non-perturbative and electroweak effects
- Use a variety of PDFs
- Dominant experimental uncertainties are Jet Energy Scale and Jet Energy Resolution
  - Both well below 10% except at highest jet p_T
- PDFs, renormalization and factorization scales, α_S variations in theory systematic uncertainty









Good agreement with NLO at higher jet pT
NLO is high for jet pT below 100 GeV
NLO rises again above 1 TeV
Similar behavior for different PDFs

Inclusive Jets at 8 TeV - χ^2 Tests

Quantitative comparisons made to NLO pQCD (corrected for electroweak and non-perturbative effects)

- P_{obs} > 4% in all cases for R=0.4
  - Lowest values in 1.5<|y| < 2.0 and 2.5< |y|<3.0
- Better agreement in forward region for R=0.6 jets
  - Worse in central rapidity than for R = 0.4
- Disagreement between data & theory when combining y bins
  - All P_{obs} << 10^{-3}
  - Seen for both R=0.4 & 0.6 jets

Rapidity ranges	P_{obs} CT14	MMHT2014	NNPDF3.0	HERAPDF2.0
Anti-k_t jets R = 0.4				
$\|y\| < 0.5$	44%	28%	25%	16%
$0.5 \leq \|y\| < 1.0$	43%	29%	18%	18%
$1.0 \leq \|y\| < 1.5$	44%	47%	46%	69%
$1.5 \leq \|y\| < 2.0$	3.7%	4.6%	7.7%	7.0%
$2.0 \leq \|y\| < 2.5$	92%	89%	89%	35%
$2.5 \leq \|y\| < 3.0$	4.5%	6.2%	16%	9.6%
Anti-k_t jets R = 0.6				
$\|y\| < 0.5$	6.7%	4.9%	4.6%	1.1%
$0.5 \leq \|y\| < 1.0$	1.3%	0.7%	0.4%	0.2%
$1.0 \leq \|y\| < 1.5$	30%	33%	47%	67%
$1.5 \leq \|y\| < 2.0$	12%	16%	15%	3.1%
$2.0 \leq \|y\| < 2.5$	94%	94%	91%	38%
$2.5 \leq \|y\| < 3.0$	13%	15%	20%	8.6%

Inclusive Jets at 13 TeV

Measurement based on 3.2 fb^{-1} of data taken in 2015
- Only R=0.4 anti-kT jets
- Require jet p_T > 100 GeV
- Require jet rapidity $|y|$ < 3
- Double differential measurement in jet p_T and y
- Jet Energy Scale uncertainties and Jet Resolution generally below 5 % central, 10% forward except at highest p_Ts

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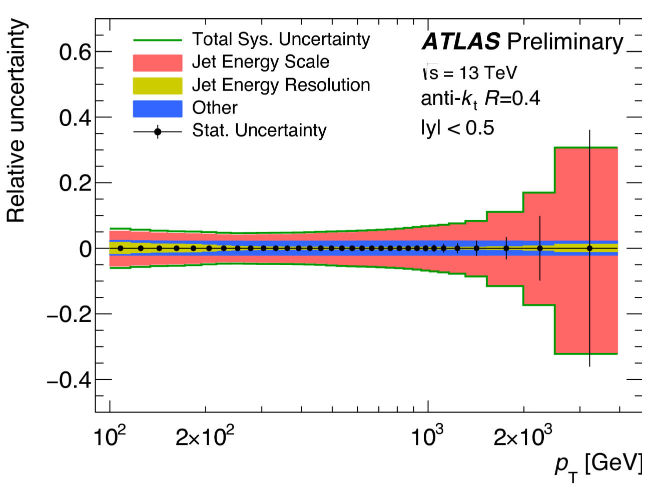
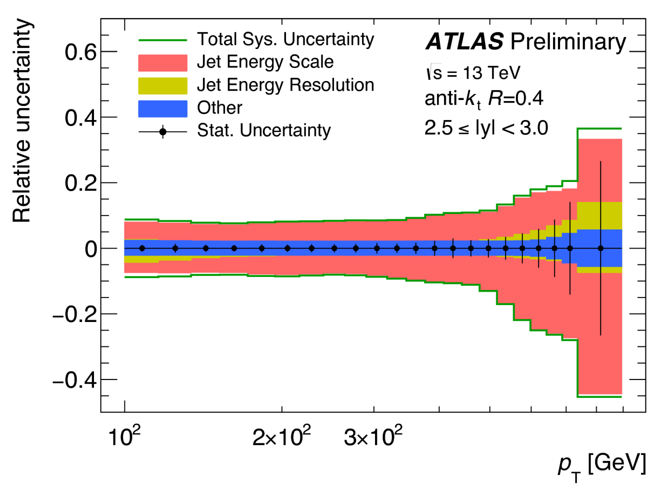
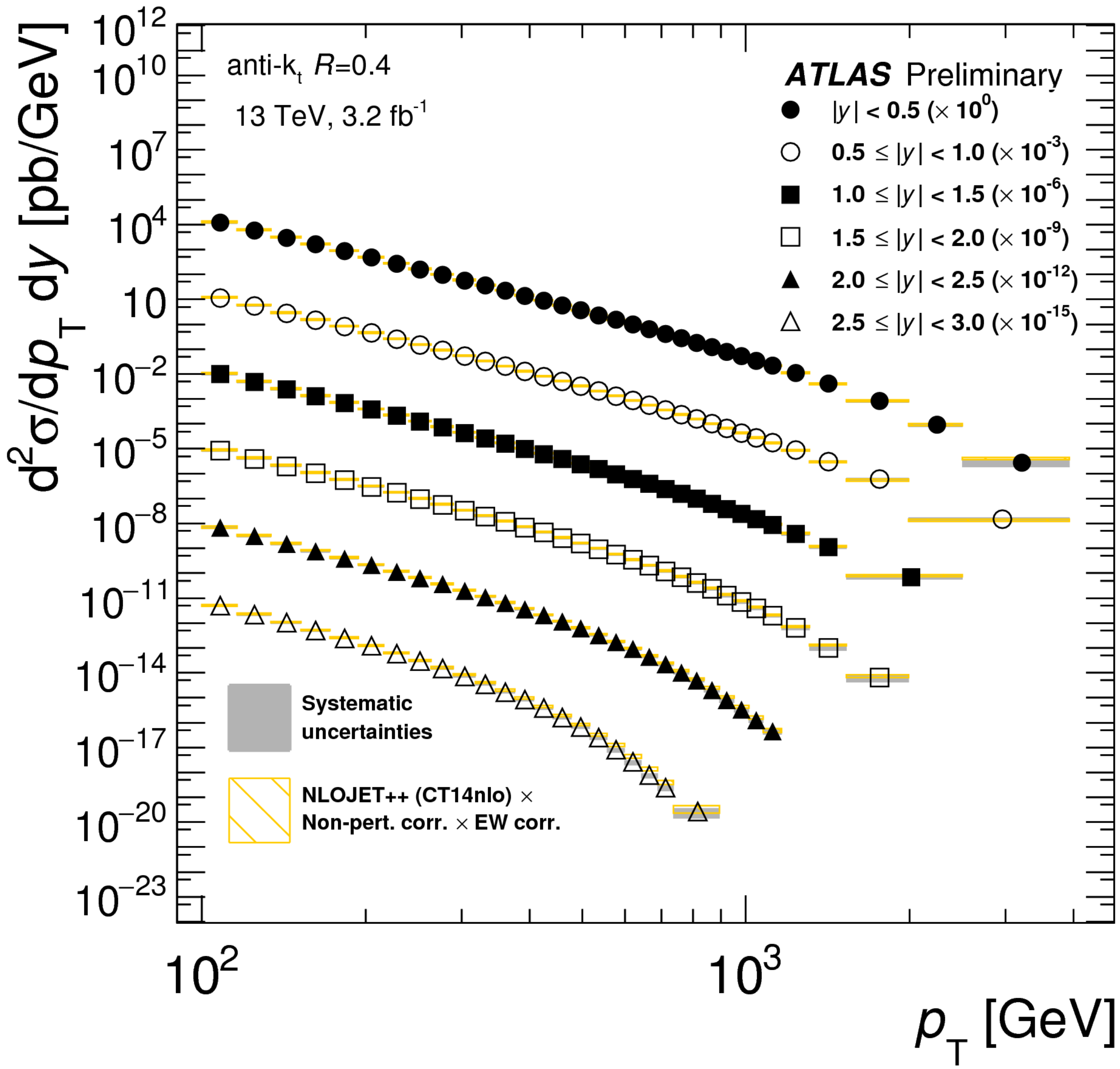
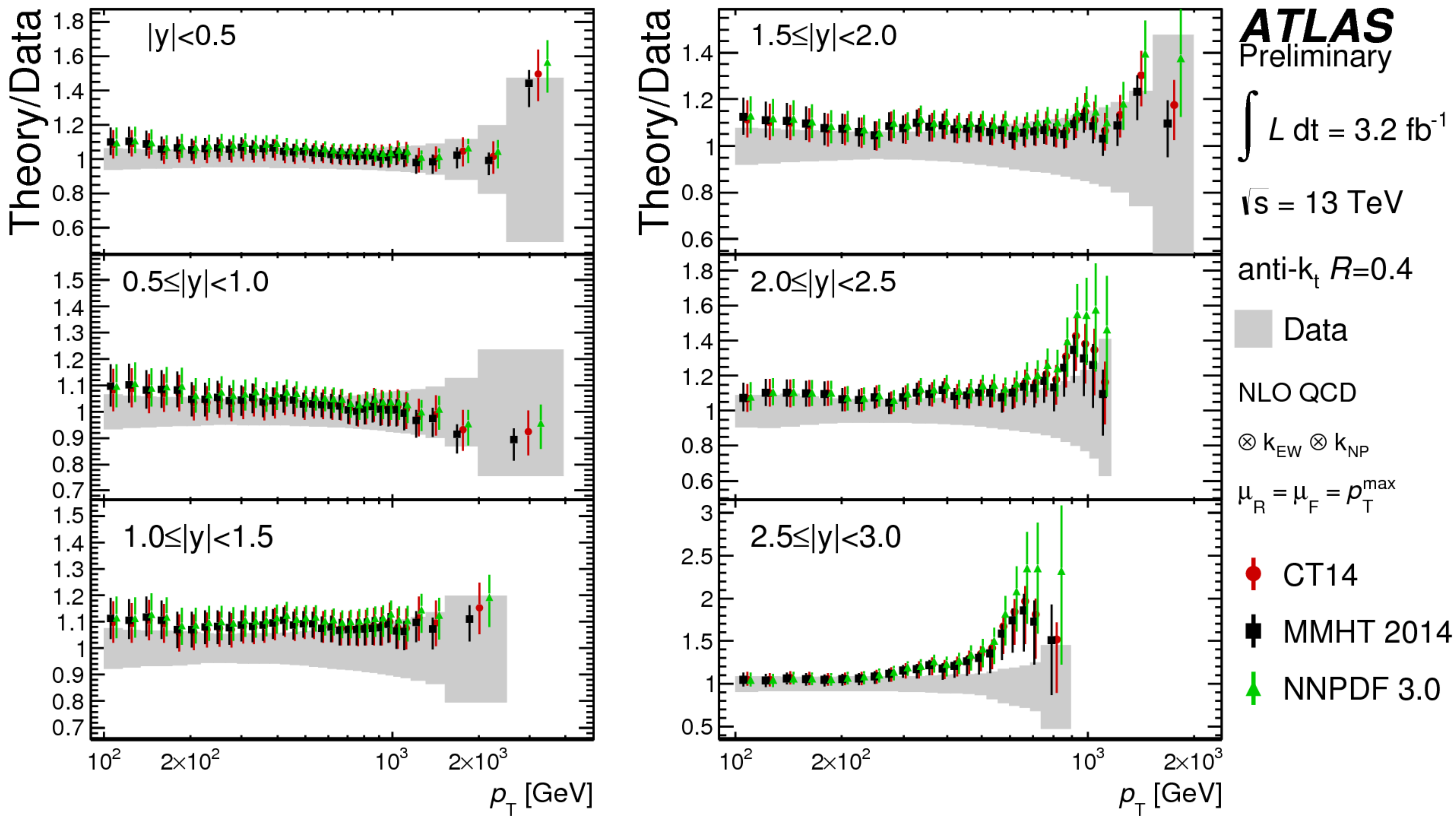






Good agreement with NLO predictions at log scale over many orders of magnitude

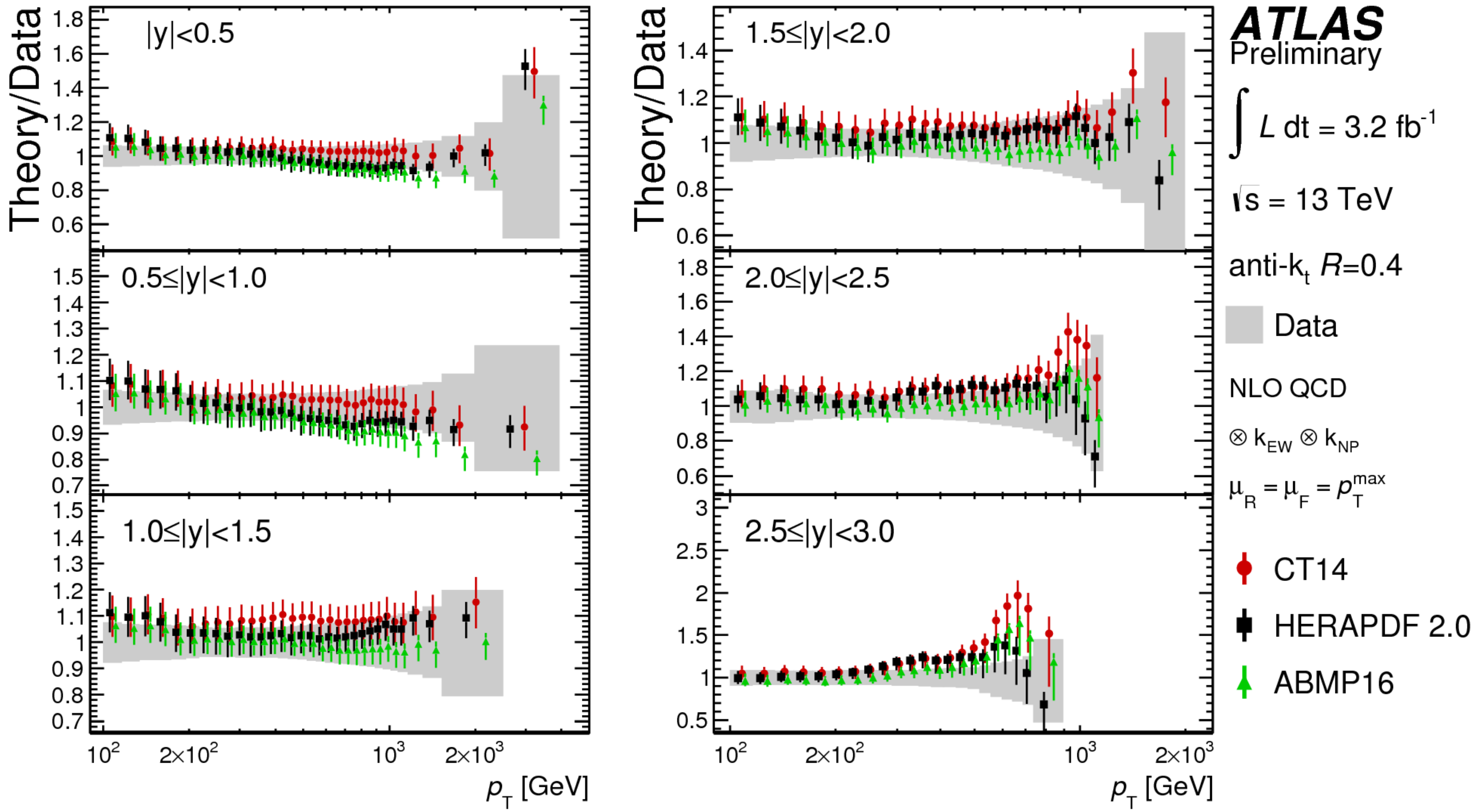
Inclusive Jets at 13 TeV



- Generally good agreement with NLO pQCD within uncertainties
- Shape consistent between various PDF sets
  - Exceptions are HERAPDF 2.0 and ABMP16 in the central region
- NLO tends to overshoot data for |y| > 2.0 with CT14, MMHT 2014 & NNPDF 3.0

- Quantitative χ^2 Tests made for each PDF set
  - Fair agreement in individual pT and y bins
  - Tension between data & theory when fitting to all pT& y bins (Also seen in the 8 TeV measurement)

Inclusive Jets at 13 TeV



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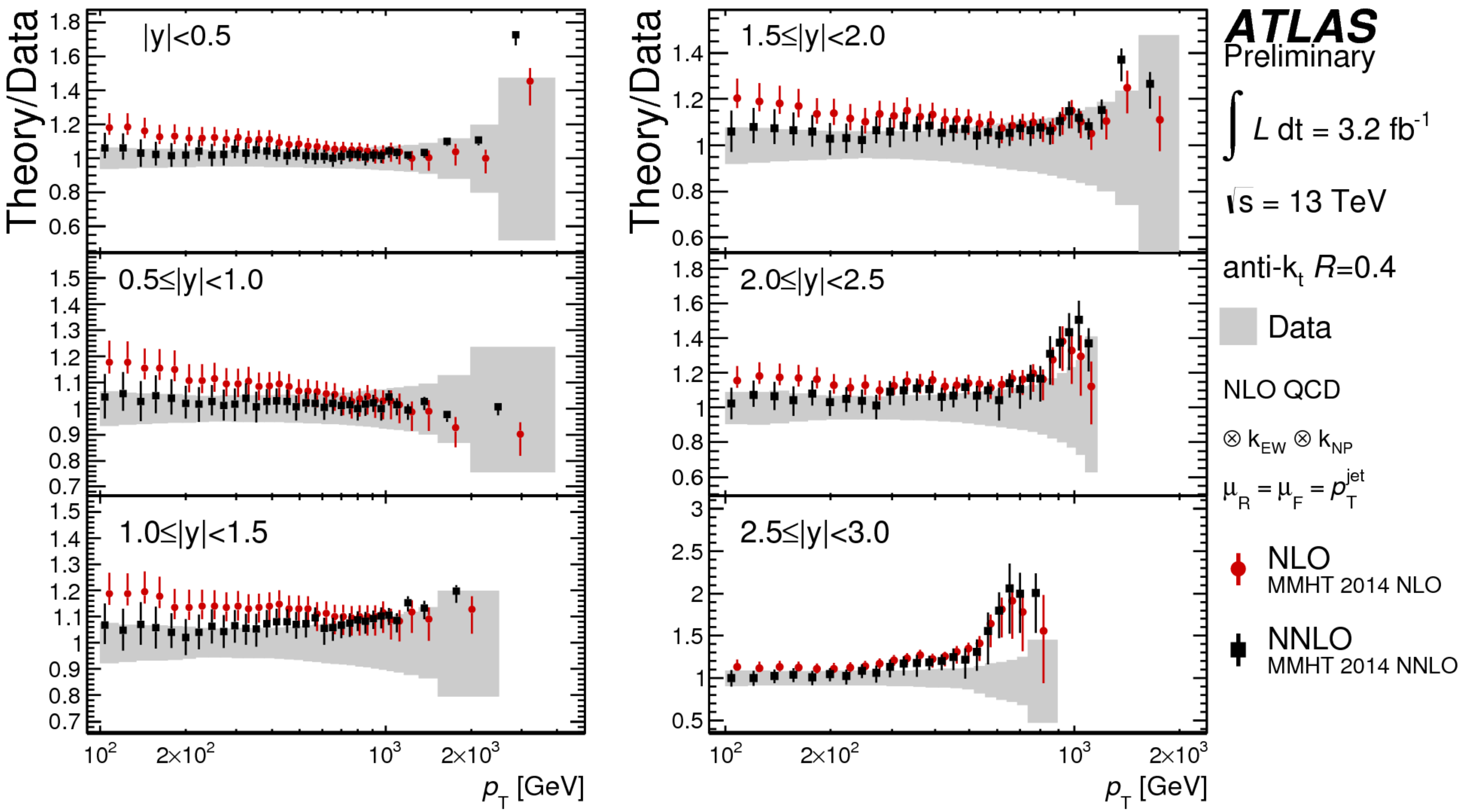
Inclusive Jets at 13 TeV

NEW

NNLO pQCD based on arXiv: 1611.01460v2, arXiv: 1704.00923
- Generated using the NNLOJET program & MMHT 2014 NNLO PDF

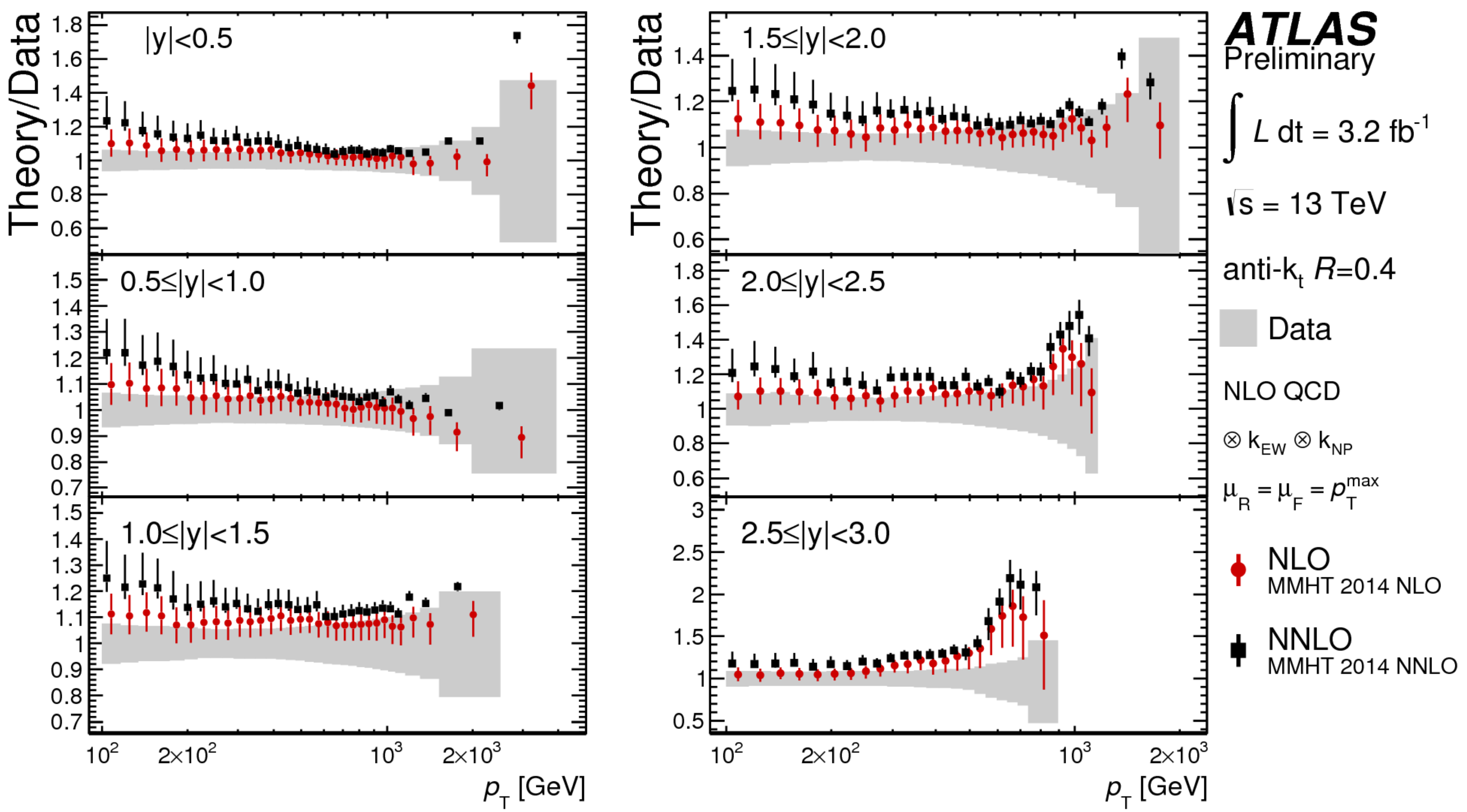


Ratio of NLO and NNLO theory predictions to data.
p_T^{jet} used for the QCD scale
- No significant deviations observed. NNLO slightly overestimates at |y|>2.5

Inclusive Jets at 13 TeV

NEW

NNLO pQCD based on arXiv: 1611.01460v2, arXiv: 1704.00923
- Generated using the NNLOJET program & MMHT 2014 NNLO PDF



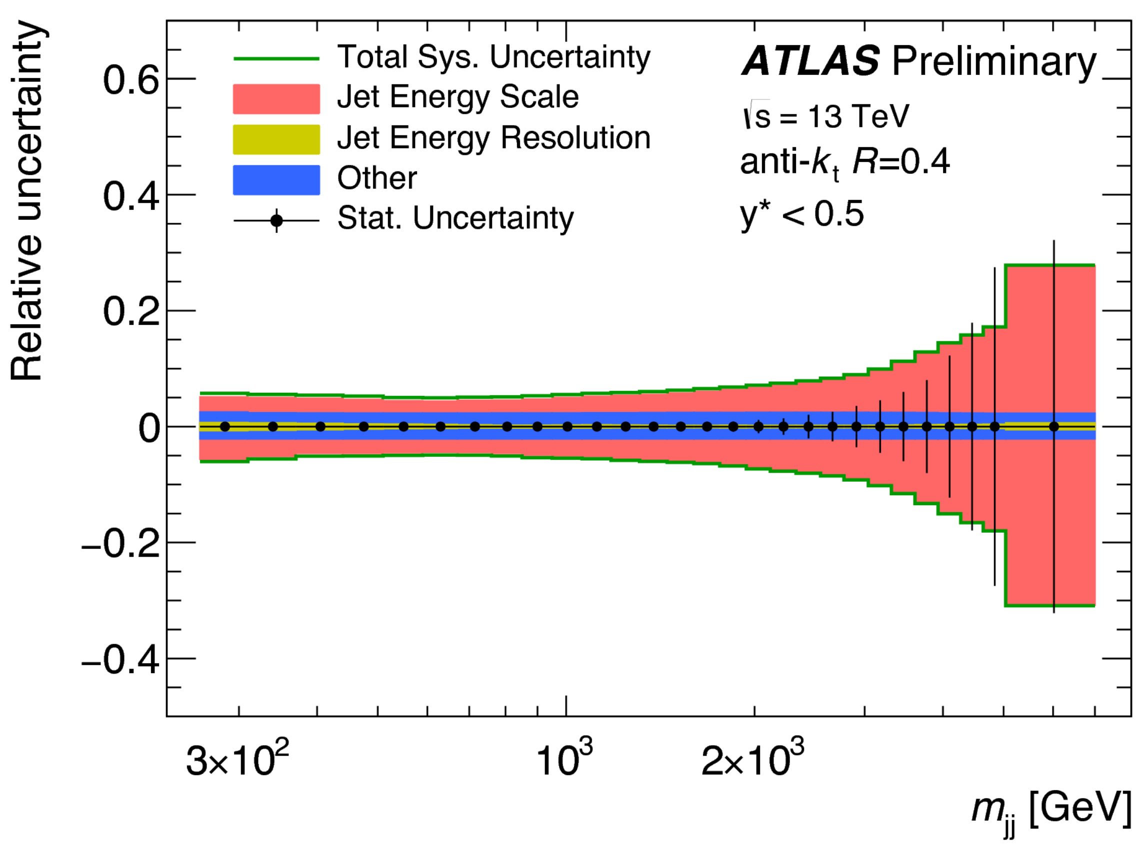
Ratio of NLO and NNLO theory predictions to data
p_T^{max} used for the QCD scale
- NNLO tends to overestimate in all bins

ATLAS EXPERIMENT

Dijets at 13 TeV

NEW

Measurement based on 3.2 fb^{-1} of data taken in 2015
- Only R=0.4 anti-kT jets
- Require jets with p_T > 75 GeV
- Require jet rapidity |y| < 3
- Require $H_{T2} = p_{T1}+p_{T2}$ > 200 GeV
    - Reduces instabilities in the NLO cross-section calculation
- Double differential measurement in M_{jj} and $y^* = |y_1-y_2|/2$
- Experimental systematic uncertainties near 5% for medium M_{jj}, rising to 30% at highest M_{jj}



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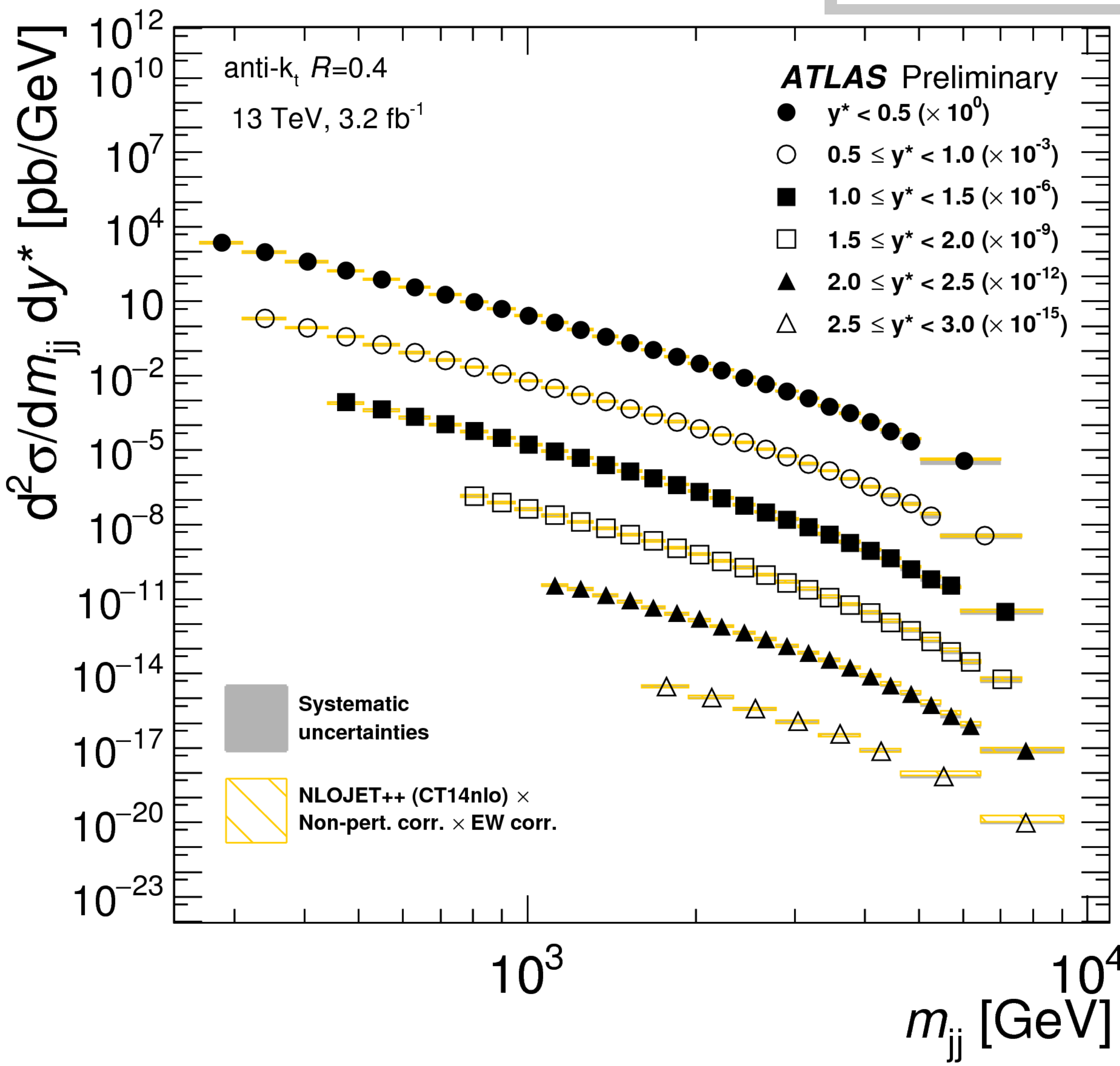
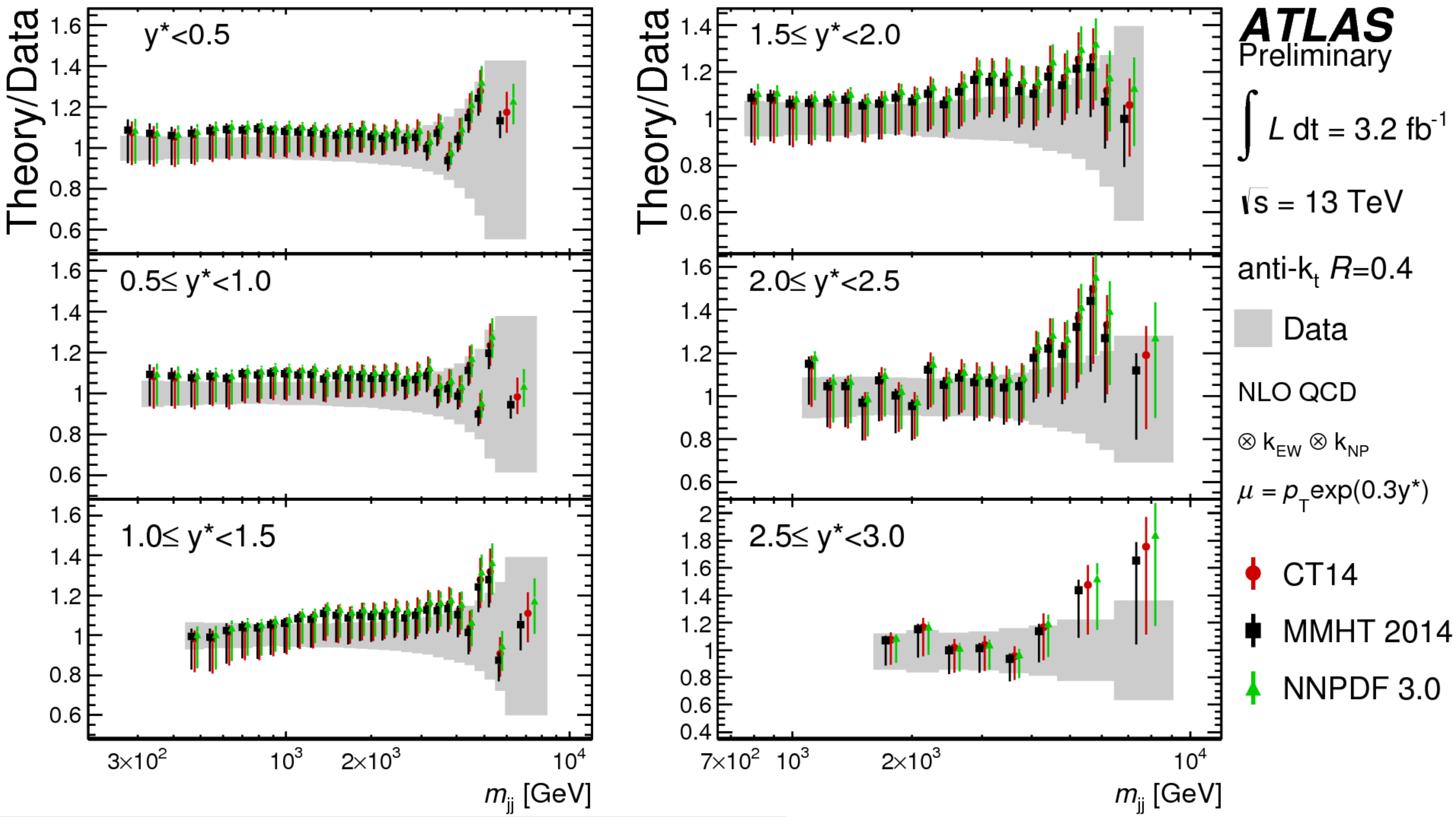


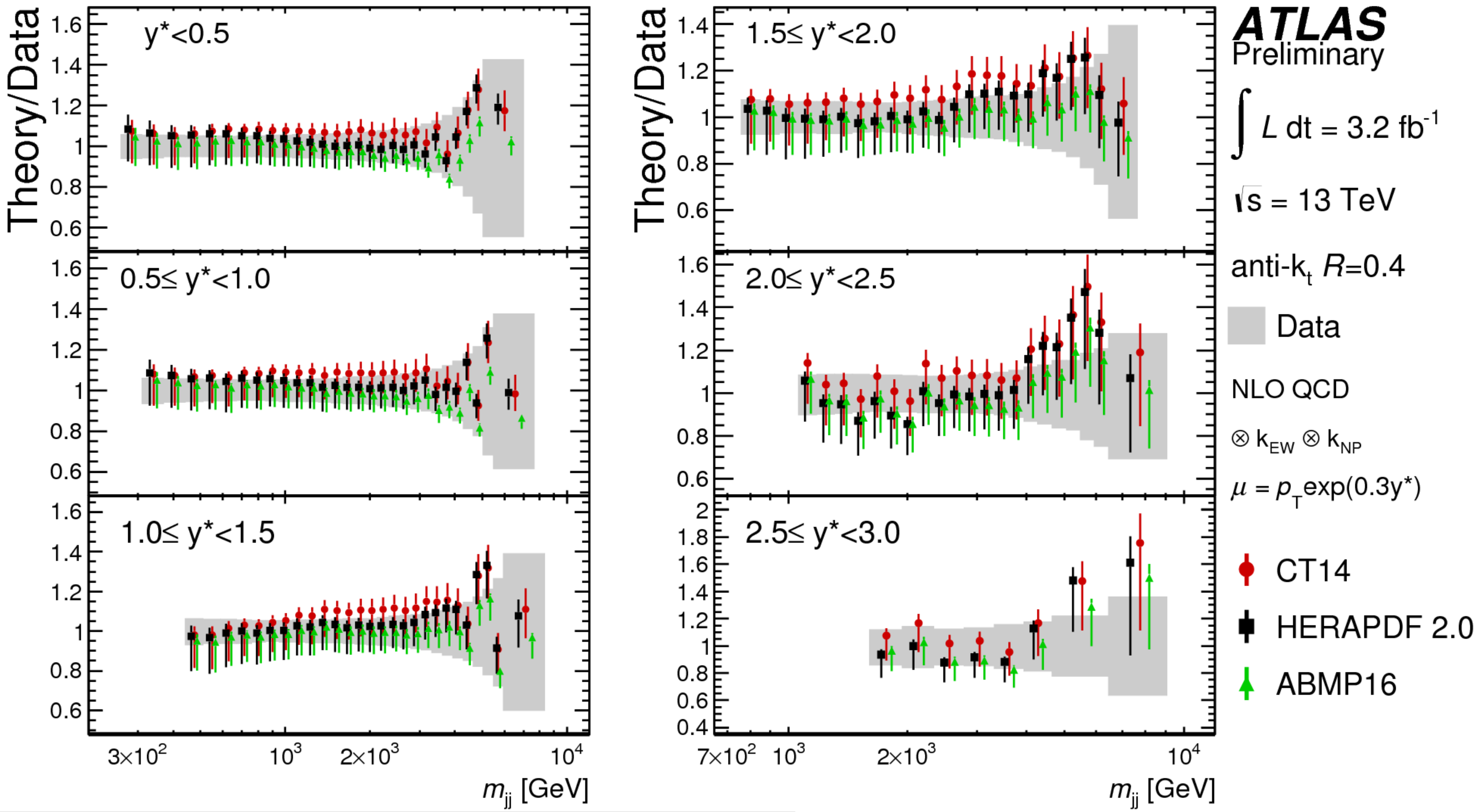
First measurement of dijet cross-section at 13 TeV

Dijets at 13 TeV



Good agreement seen between NLO pQCD and data within uncertainties
Detailed χ^2 Tests made for each PDF set
- Fair agreement in individual M_{jj} and y* bins
- Fair agreement as well when fitting to all y* regions

Dijets at 13 TeV



Good agreement seen between NLO pQCD and data within uncertainties

Detailed χ^2 Tests made for each PDF set

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- Fair agreement as well when fitting to all y* regions

Measurement of Transverse Energy-Energy Correlations

- Energy-Energy Correlations = Energy-weighted angular distributions
- Event shape independent of thrust axis or sphericity tensor
- Transverse version proposed for study at hadron colliders
- Calculated to order α_S^2 in QCD

$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d(\cos\phi)} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj}$$

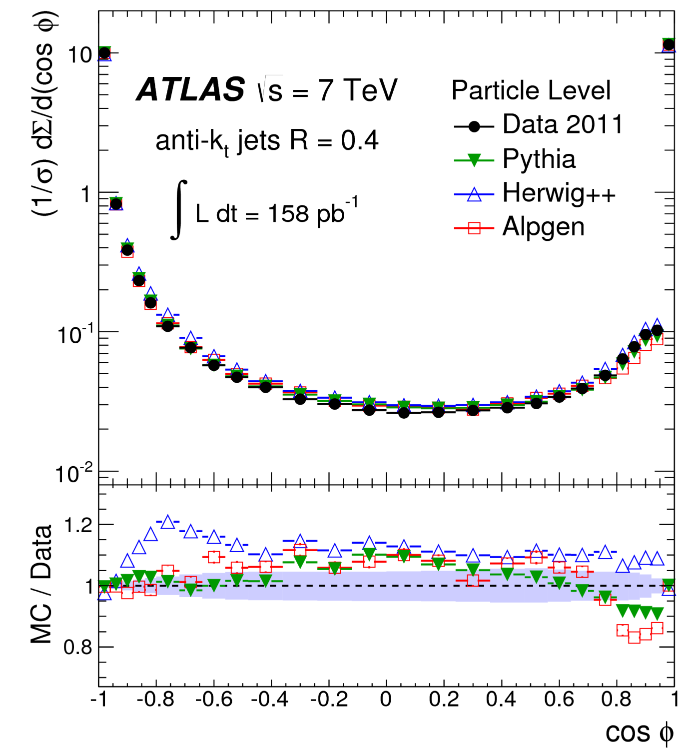
$$x_{Ti} = E_{Ti}/E_T \qquad E_T = \sum_i E_{Ti}$$

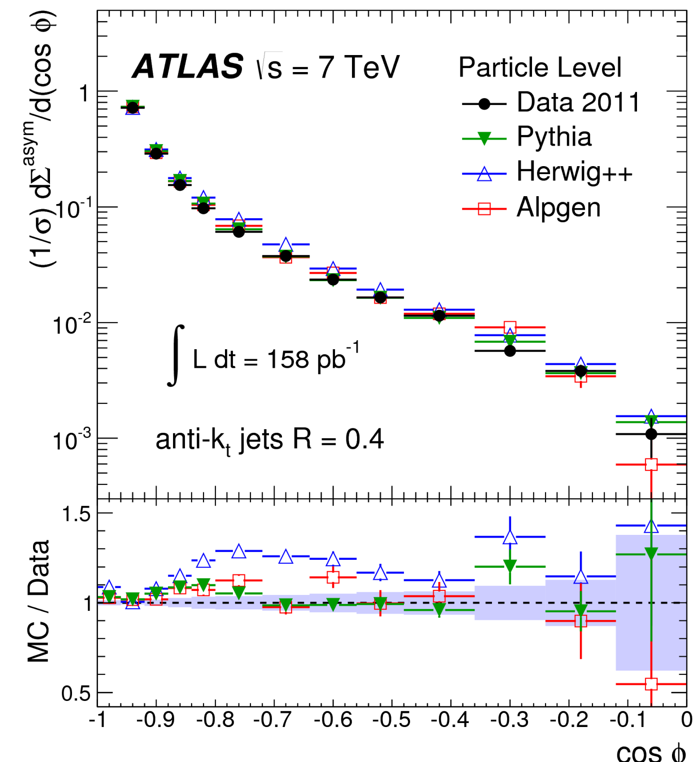
- The azimuthal asymmetry in the TEEC measurement (ATEEC) cancels effects that are uniform in cos(ϕ)

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d(\cos\phi)} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\bigg|_{\pi-\phi}$$

- First measured in ATLAS at 7 TeV and used to extract $\alpha_S(M_Z)$:

$$\alpha_s(m_Z) = 0.1173 \pm 0.0010\,(\text{exp.})\,^{+0.0065}_{-0.0026}\,(\text{theo.})$$





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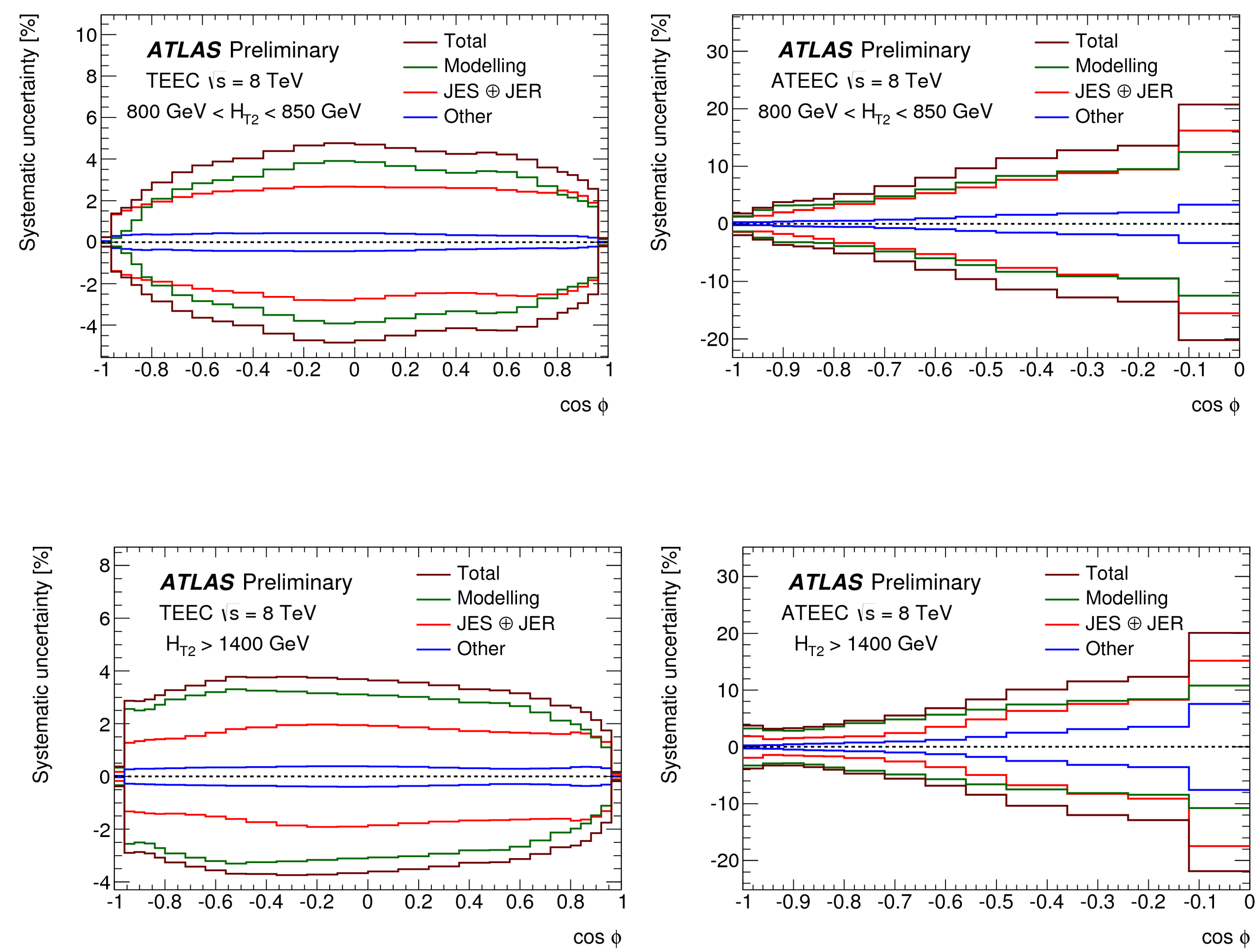
TEEC and ATEEC Measurement

Preliminary results for measurement based on 20.2 fb^{-1} of data taken at 8 TeV

- Require two jets with p_T > 100 GeV within |y| < 2.5
- Require $H_{T2} = p_{T1}+p_{T2}$ > 800 GeV
- For each accepted event define a weight

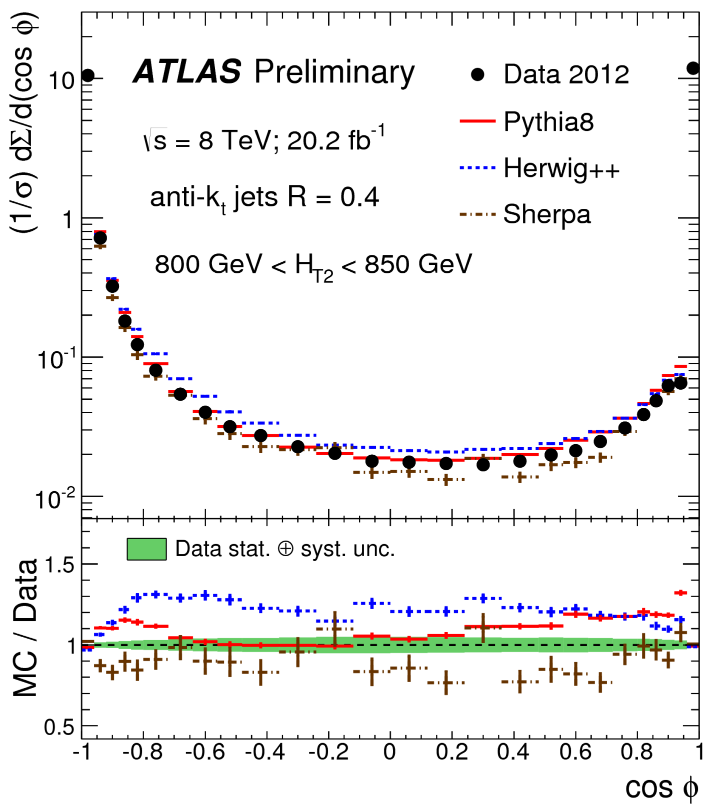
$$w_{ij} = x_{Ti}x_{Tj} = \frac{E_{Ti}E_{Tj}}{\left(\sum_k E_{Tk}\right)^2}$$

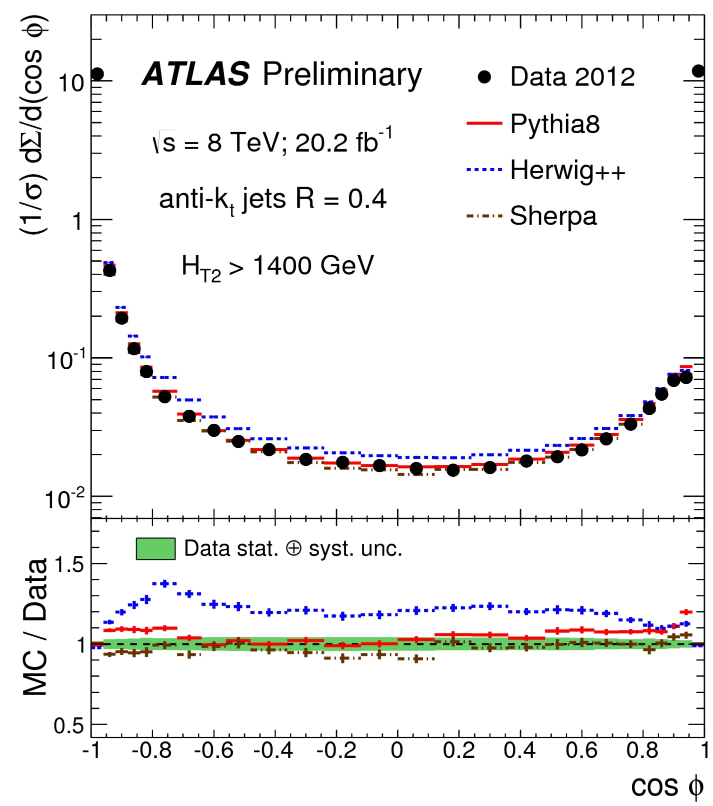
- Distributions are made double differentially in cos(ϕ) and H_{T2}.
- Resulting detector-level distributions are normalized to the total number of events.
- Data distributions are unfolded back to the particle level
- Compared to pQCD predictions using NLOJET++, corrected for non-perturbative effects.
    - Renormalization scale set to $(p_{T1}+p_{T2})/2$ (same as 7 TeV)
    - Factorization scale set to $(p_{T1}+p_{T2})/4$

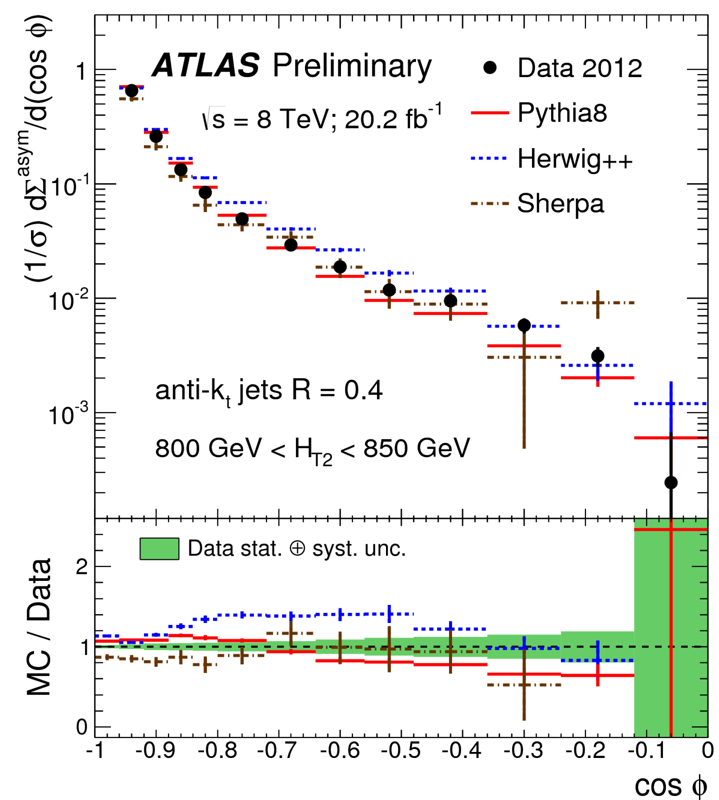


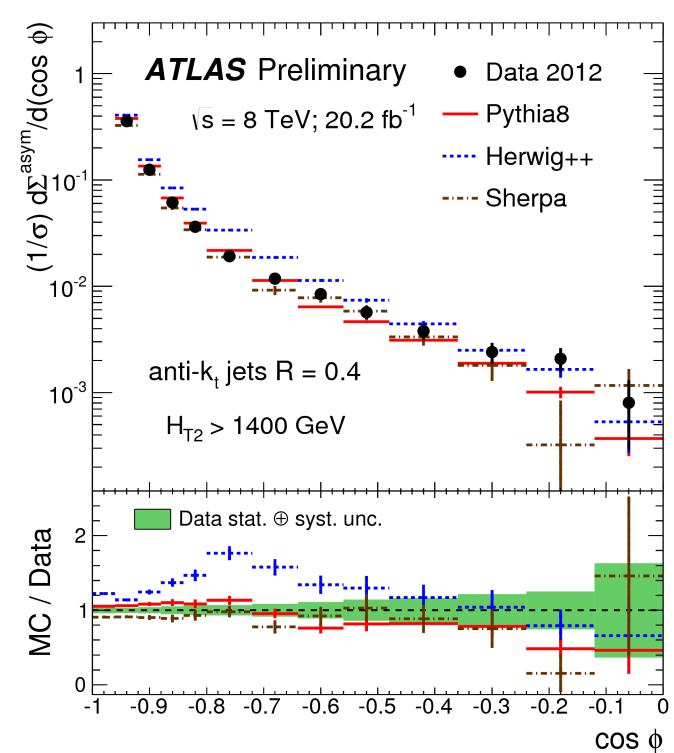
Systematic uncertainties in lowest (top) and highest (bottom) H_{T2} bins
==> Total systematic uncertainties below 5%

TEEC and ATEEC









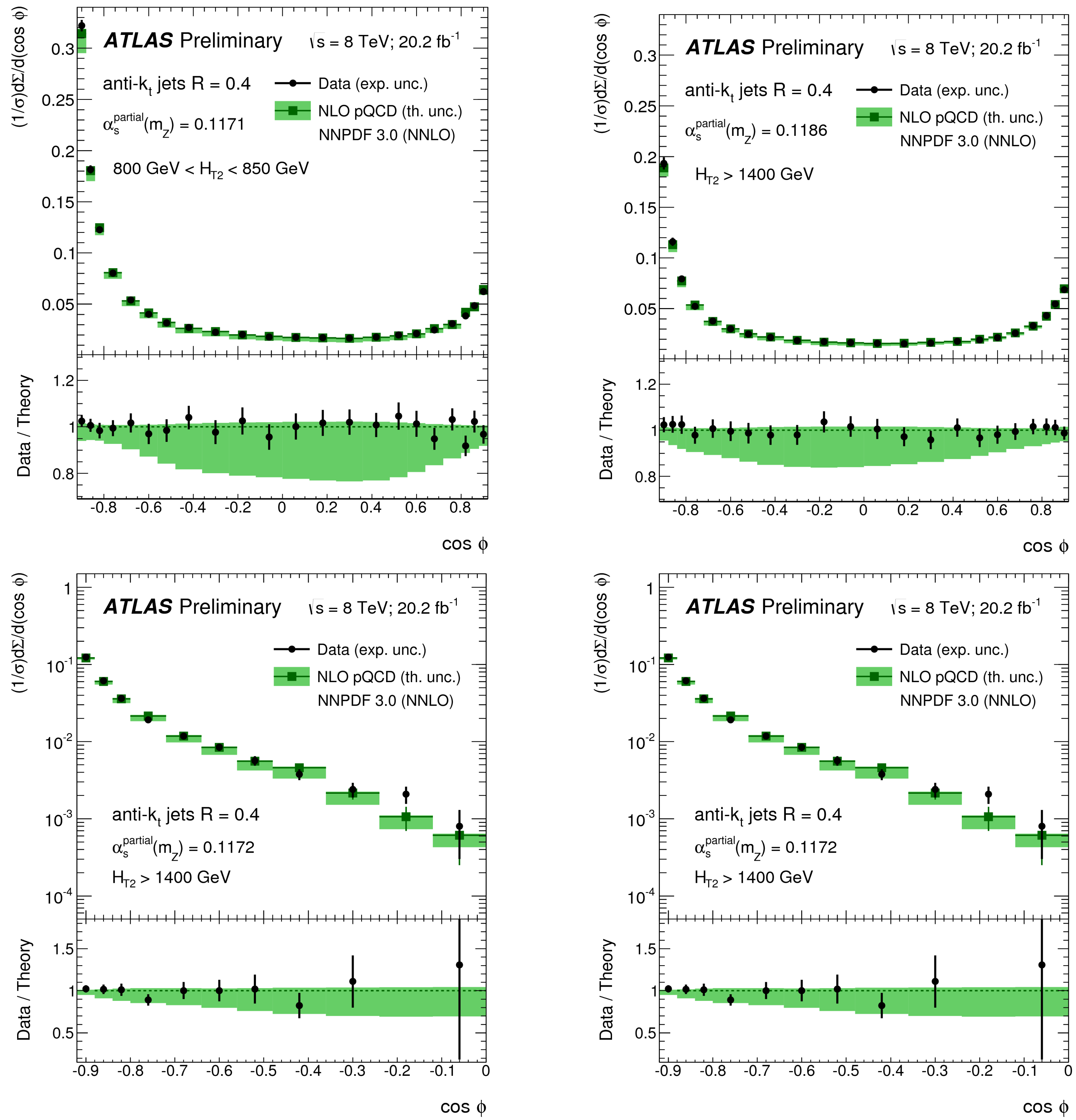
Particle-level result for TEEC and ATEEC measurements in the lowest and highest H_{T2} bin, compared with Pythia8, Sherpa, and Herwig++ MC generators

TEEC and ATEEC - α_S Measurement

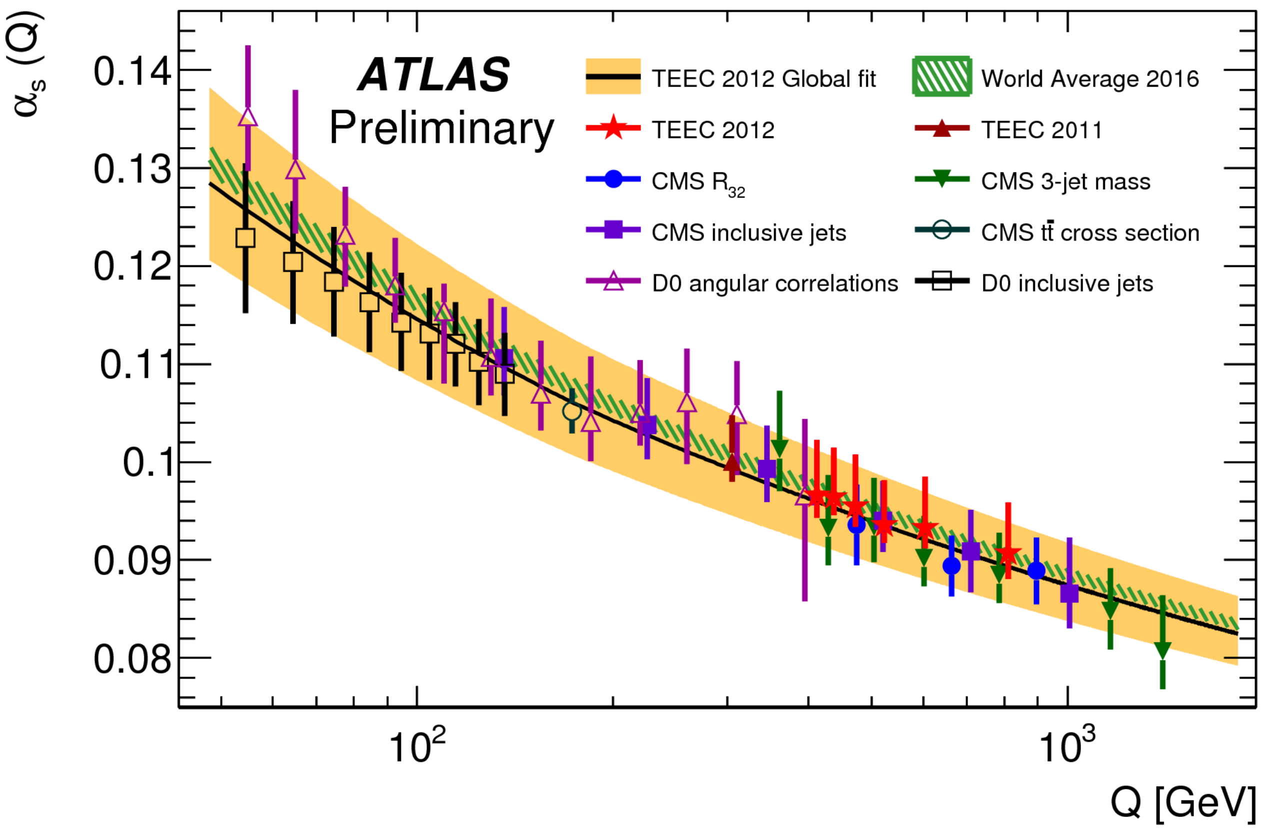
TEEC is essentially an energy-weighted ratio of three-jet to two-jet cross sections

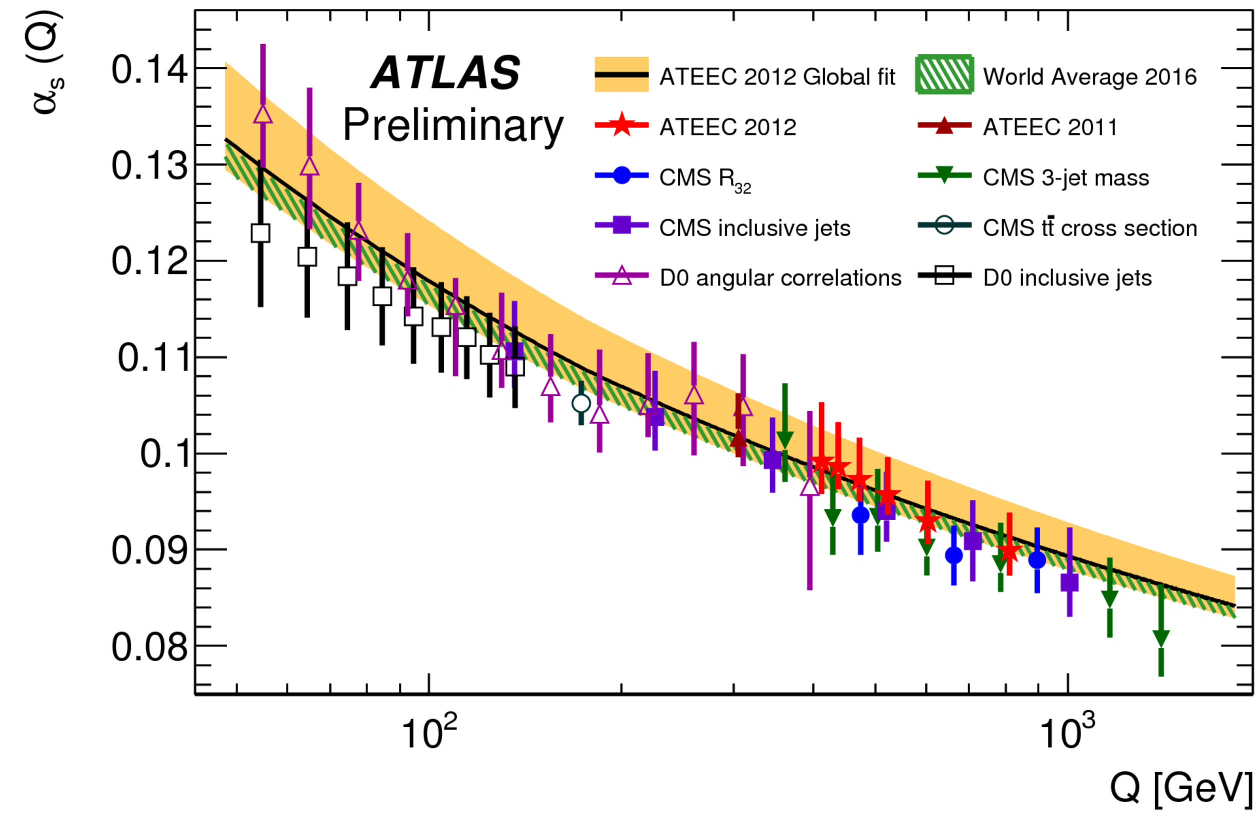
$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{\Sigma_{a_i,b_i} f_{a_1}(x_1) f_{a_2}(x_2) \otimes \hat{\Sigma}^{a_1a_2\to b_1b_2b_3}}{\Sigma_{a_i,b_i} f_{a_1}(x_1) f_{a_2}(x_2)\otimes \hat{\sigma}^{a_1a_2\to b_1b_2}}$$

- The observables TEEC and ATEEC can be fit to the NLOJET++ predictions, varying α_S
- The fitted value of α_S can then be related to $\alpha_S(M_Z)$ using the two-loop RGE
- The fitted TEEC and ATEEC bins in H_{T2} can then be combined into a global fit value for each observable



TEEC and ATEEC - α_S Measurement





Global Fitted Value From TEEC:

$$\alpha_s(m_Z) = 0.1162 \pm 0.0011 \text{ (exp.) } {}^{+0.0076}_{-0.0061} \text{ (scale)} \pm 0.0018 \text{ (PDF)} \pm 0.0003 \text{ (NP)}$$

From ATEEC:

$$\alpha_s(m_Z) = 0.1196 \pm 0.0013 \text{ (exp.) } {}^{+0.0061}_{-0.0013} \text{ (scale)} \pm 0.0017 \text{ (PDF)} \pm 0.0004 \text{ (NP)}$$

Good agreement with world average value of 0.1185±0.0006 (PDG)

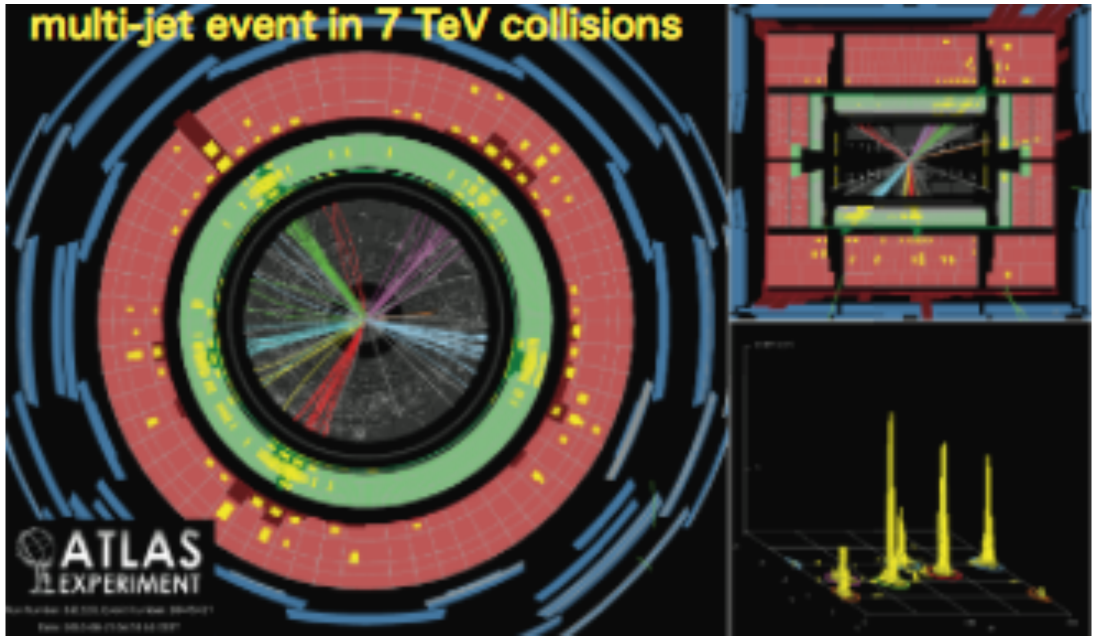
Summary

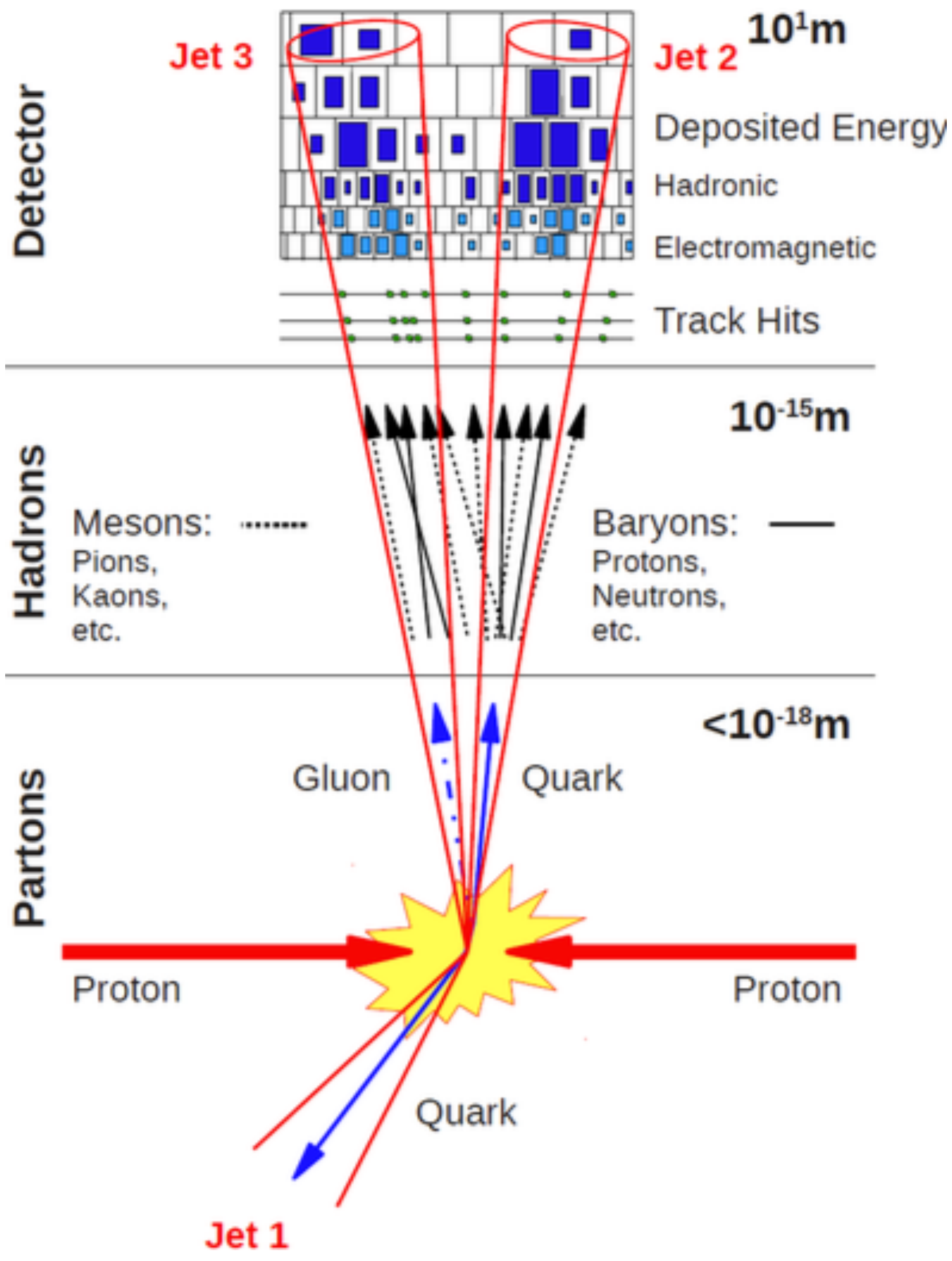
- ATLAS has measured the inclusive jet cross section at 7, 8, and 13 TeV
  - Good agreement of pQCD at NLO
  - NNLO comparisons
  - Test of PDFs particularly in the forward rapidities
- ATLAS has made the first measurement of dijet cross-sections at 13 TeV
- ATLAS has measured transverse energy-energy correlations in dijet events
  - Used to measure the strong coupling constant
  - TEEC/ATEEC: $\alpha_s(m_Z) = 0.1162 \pm 0.0011\text{ (exp.)}\ ^{+0.0076}_{-0.0061}\text{ (scale)} \pm 0.0018\text{ (PDF)} \pm 0.0003\text{ (NP)},$ $\alpha_s(m_Z) = 0.1196 \pm 0.0013\text{ (exp.)}\ ^{+0.0061}_{-0.0013}\text{ (scale)} \pm 0.0017\text{ (PDF)} \pm 0.0004\text{ (NP)}.$
  - Comparable to 7 TeV result: $\alpha_s(m_Z) = 0.1173 \pm 0.0010\text{ (exp.)}\ ^{+0.0065}_{-0.0026}\text{ (theo.)}$

Backup

What is a Jet?

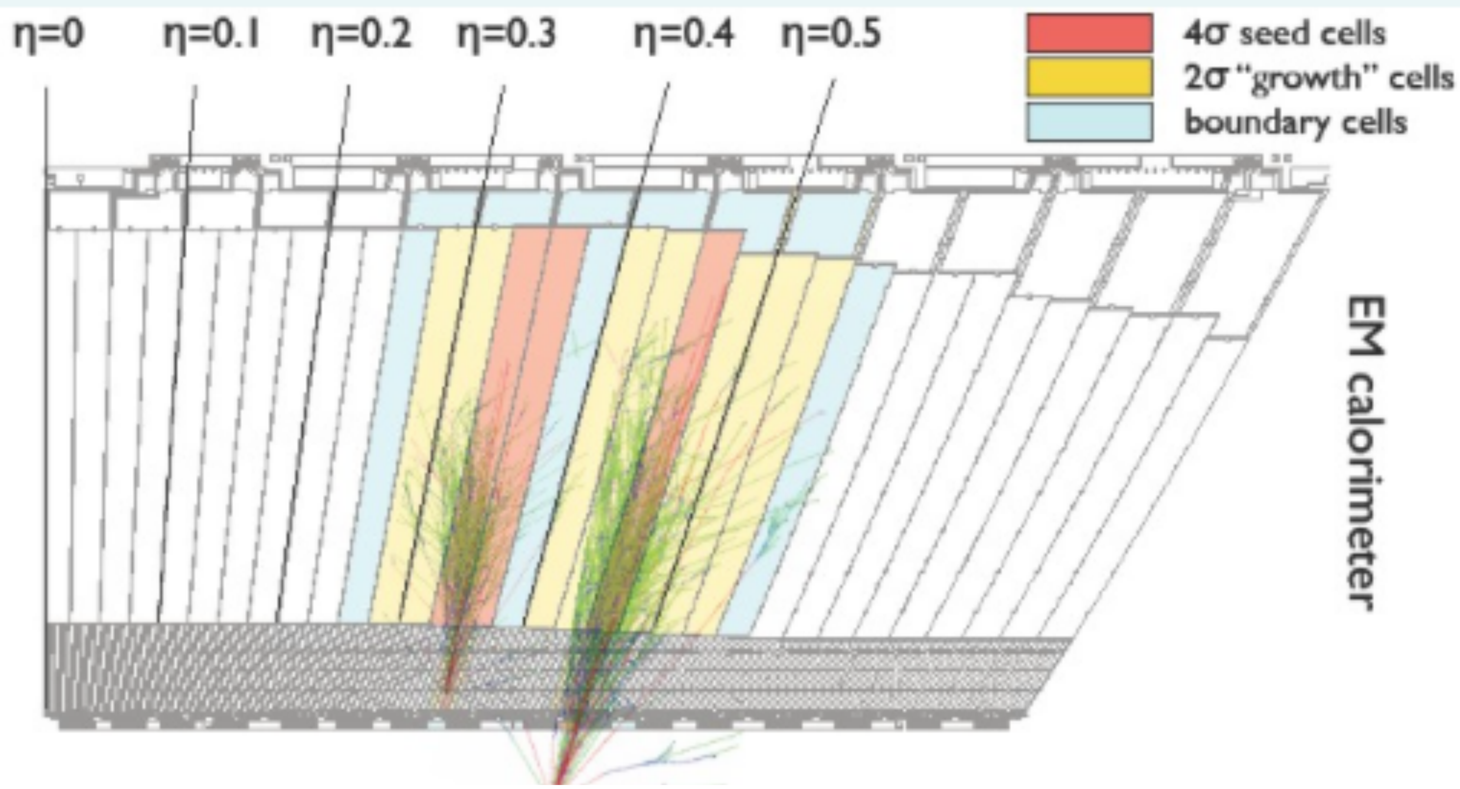
- A jet is a collimated spray of particles initiated by the production of a parton (quark or gluon)
  - Jets are the most common objects produced in p-p colliders.
- ATLAS uses Anti-kT recombination algorithm to find jets
  - ATLAS uses topological calorimeter clusters as input
  - ATLAS used both R= 0.4 and 0.6 in Run 1 for jet studies; generally one radius used in Run 2
- ATLAS corrects jets to the "particle level"
  - Measurements are unfolded to particle level with a variety of methods (Bayesian, IDS, SVD, bin-by-bin)

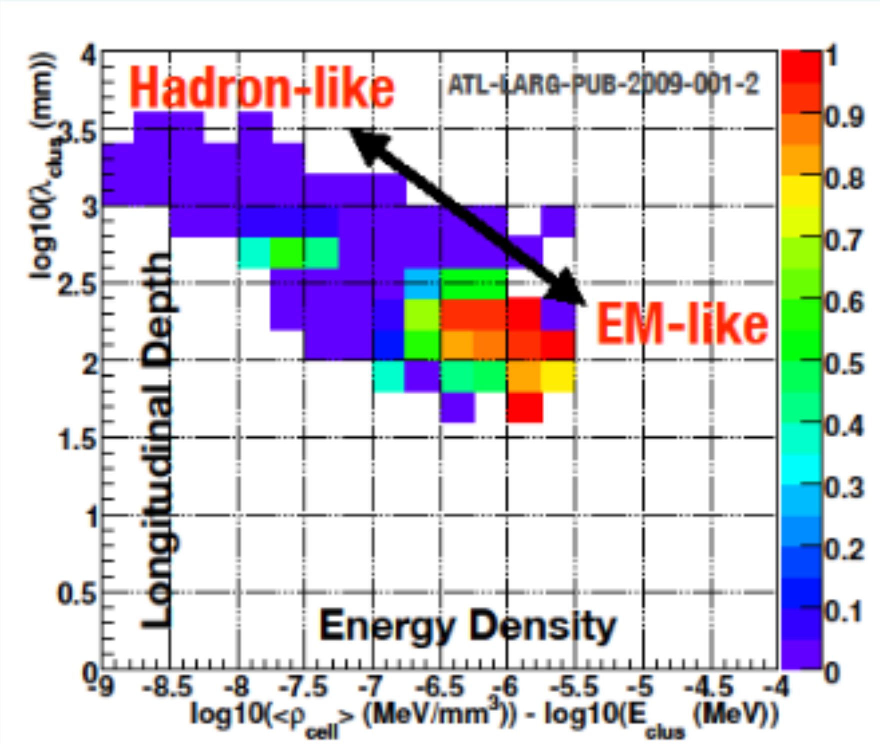


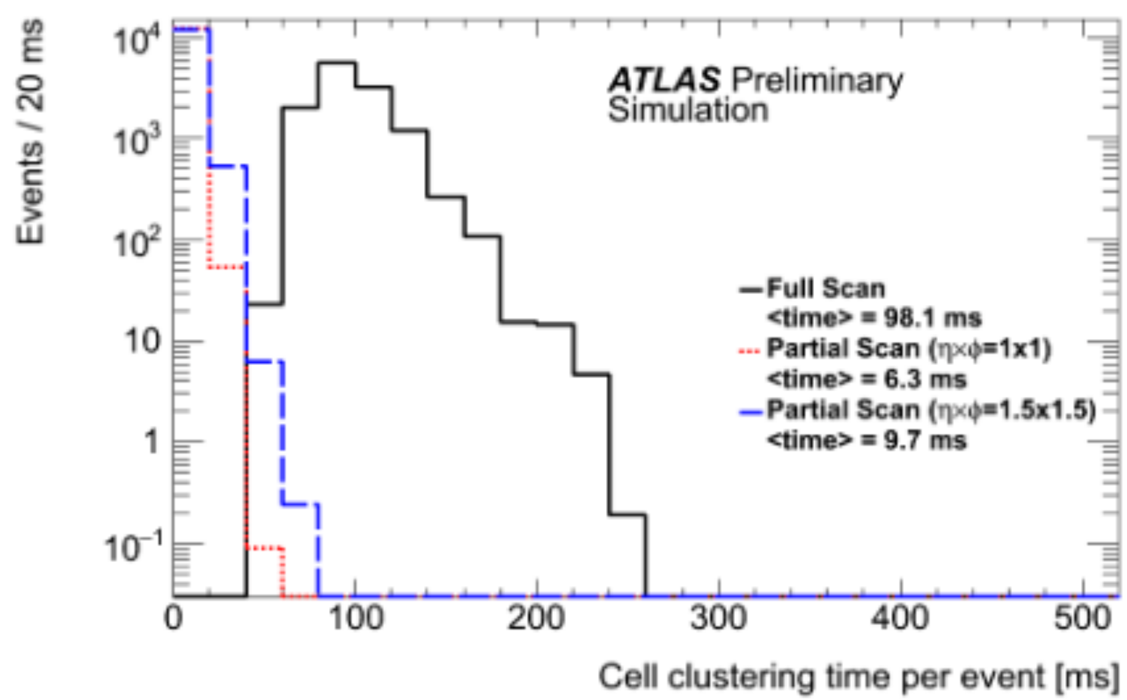


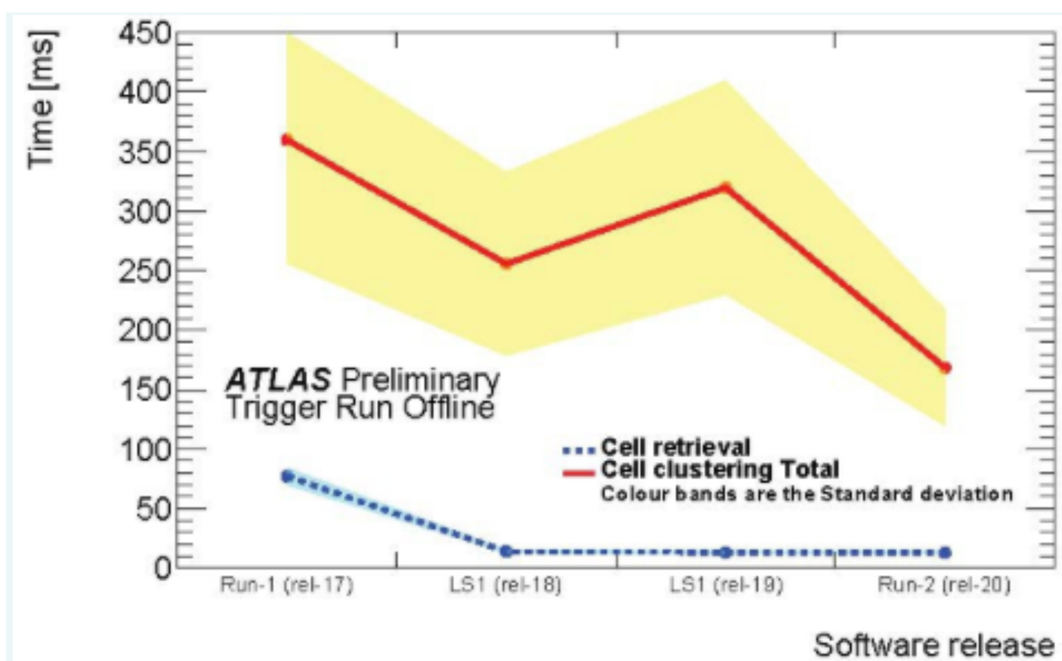
$$d_{ij}^2 = min(1/p_{T,i}^2, 1/p_{T,j}^2) \cdot ((y_i - y_j)^2 + (\phi_i - \phi_j^2))/R^2$$

ATLAS TopoClusters

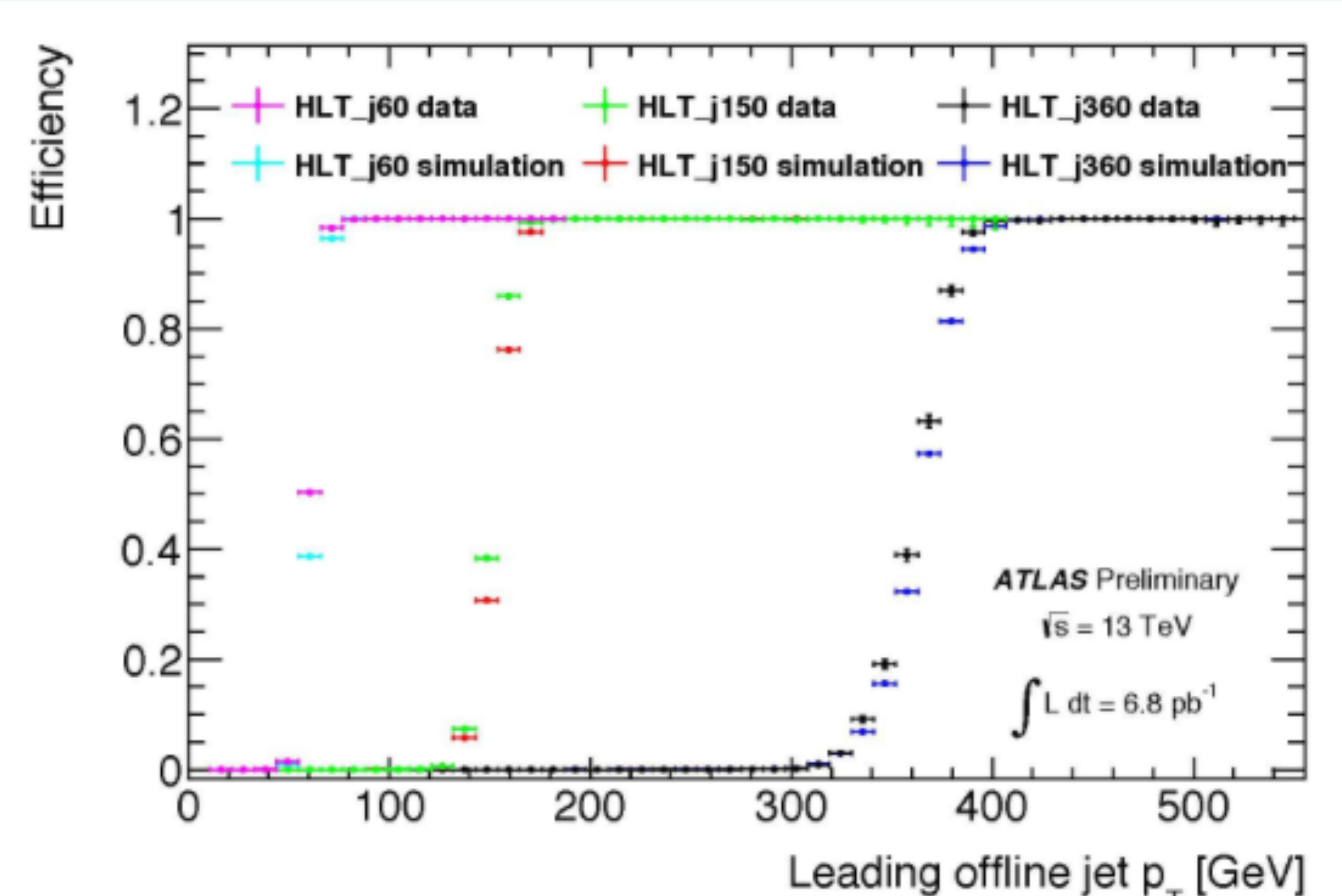






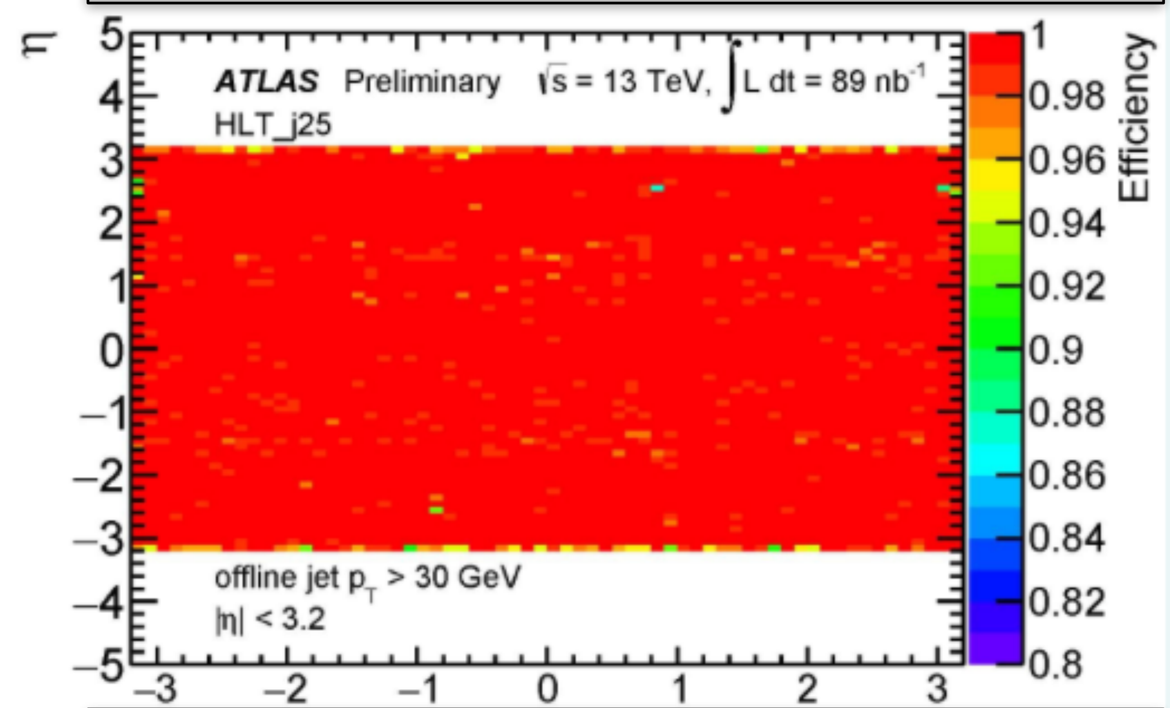


Run 2 Jet Trigger Perfomance

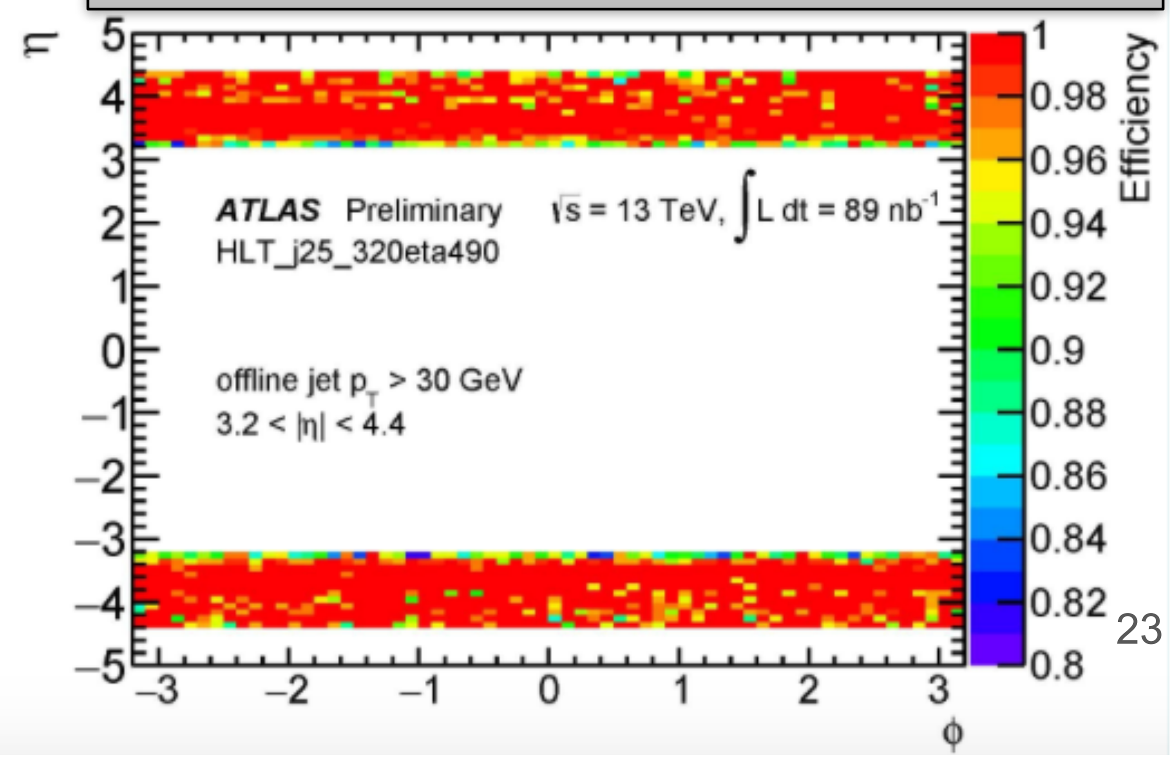


Jet trigger efficiency in bins of p_T of the leading jet for different HLT chains. Data and Monte Carlo predictions are shown.

Jet trigger efficiency in bins of η and ϕ of the leading jet for HLT_j25 chain in central region (|η| < 3.2)



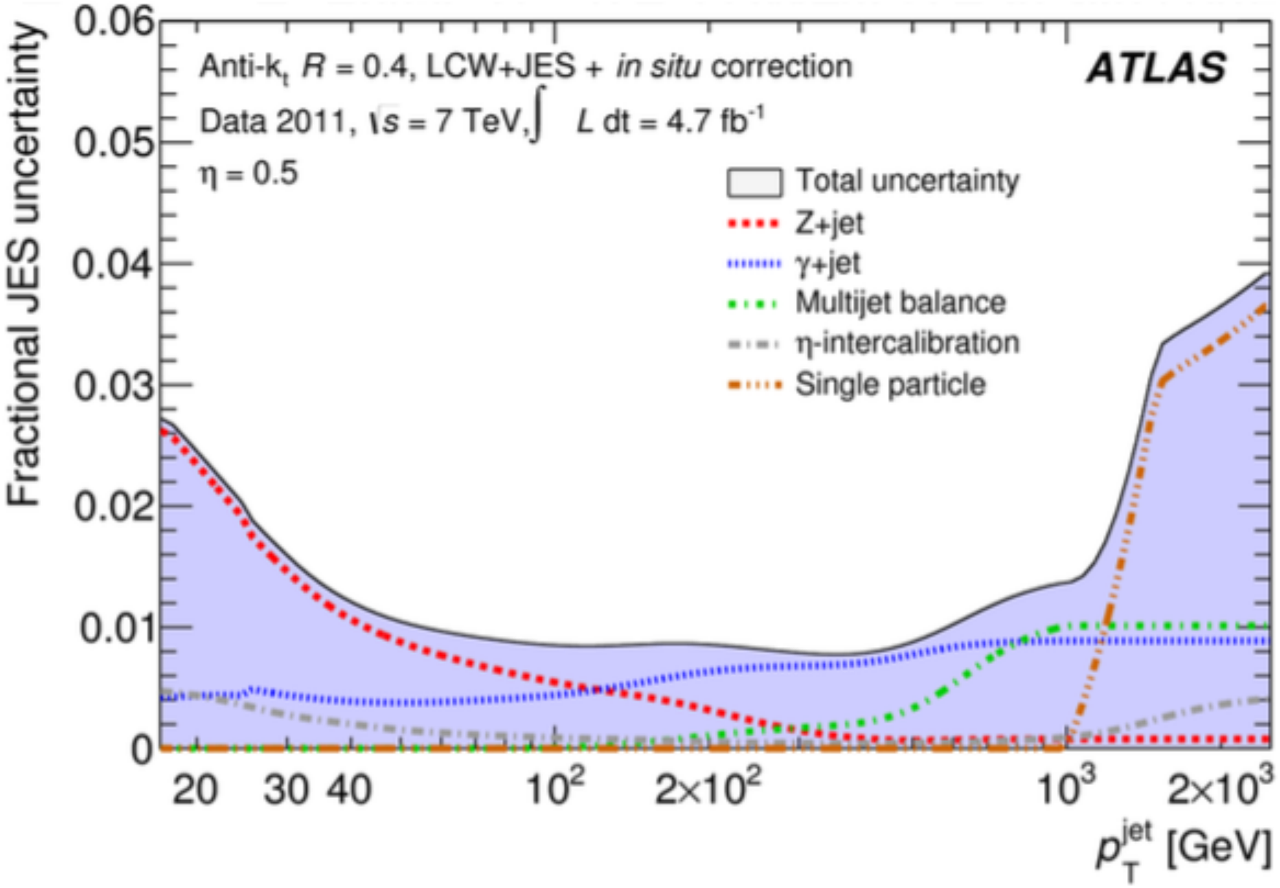
Jet trigger efficiency in bins of η and ϕ of the leading jet for HLT_j25 chain in central region (|η| > 3.2)



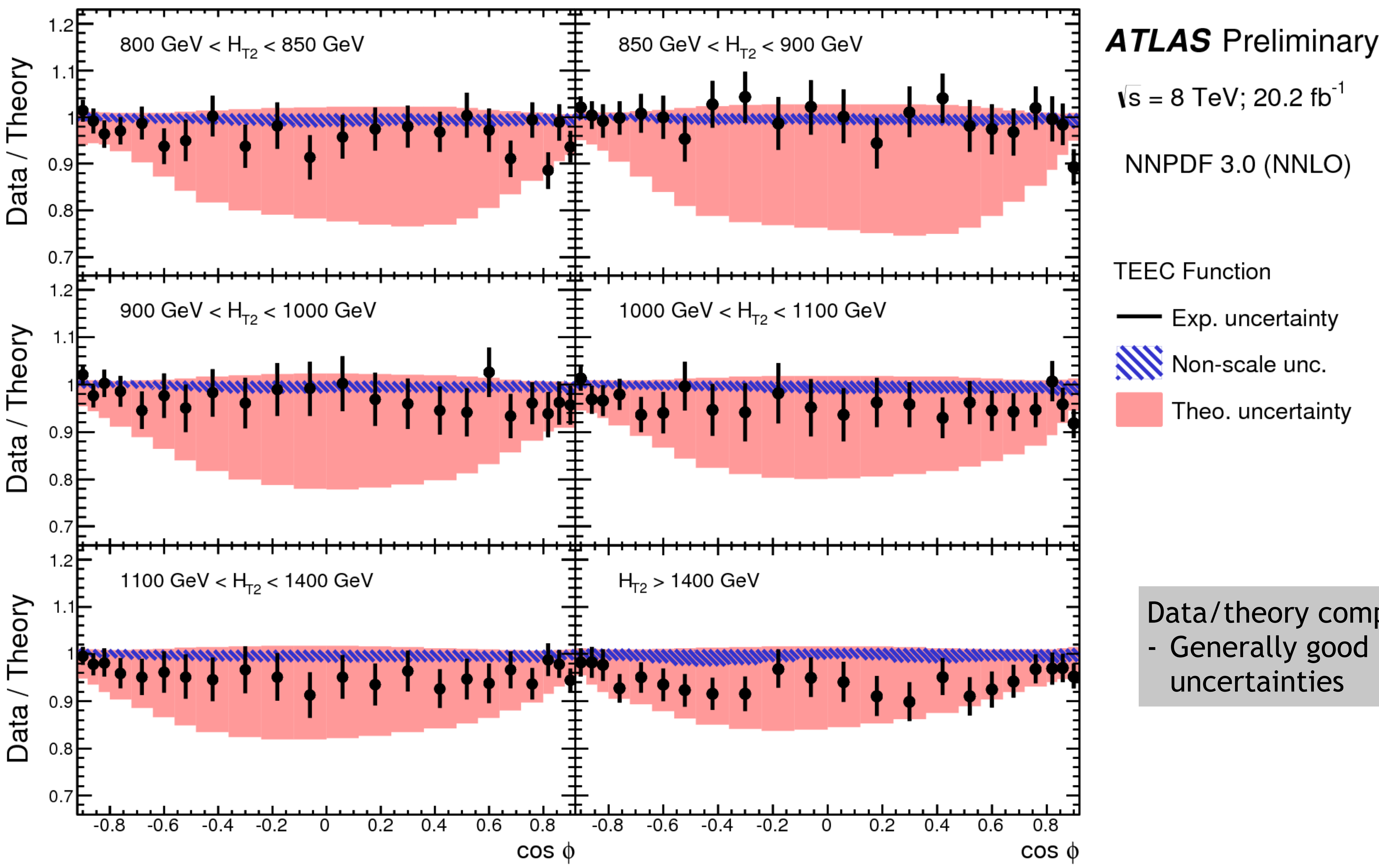
Reminder: η ≡ Pseudorapidity

Precison Jet Physics

- Jet Energy Scale uncertainties
  - Both experiments use a variety of techniques to minimize uncertainties due correcting the jet energy
    - In-situ studies Z+jet, gamma+jet, dijet and multi-jets
      - Decrease the JES uncertainty through pT balance and eta-intercalibration.
    - Techniques to cope with high pile-up environment
      - Jet-area/median subtraction, Charged-hadron subtraction and pile-up jet taggers.
  - For many region of pT and rapidity, Jet Energy uncertainties are lower than theoretical uncertainties
    - Precision Jet Physics!!

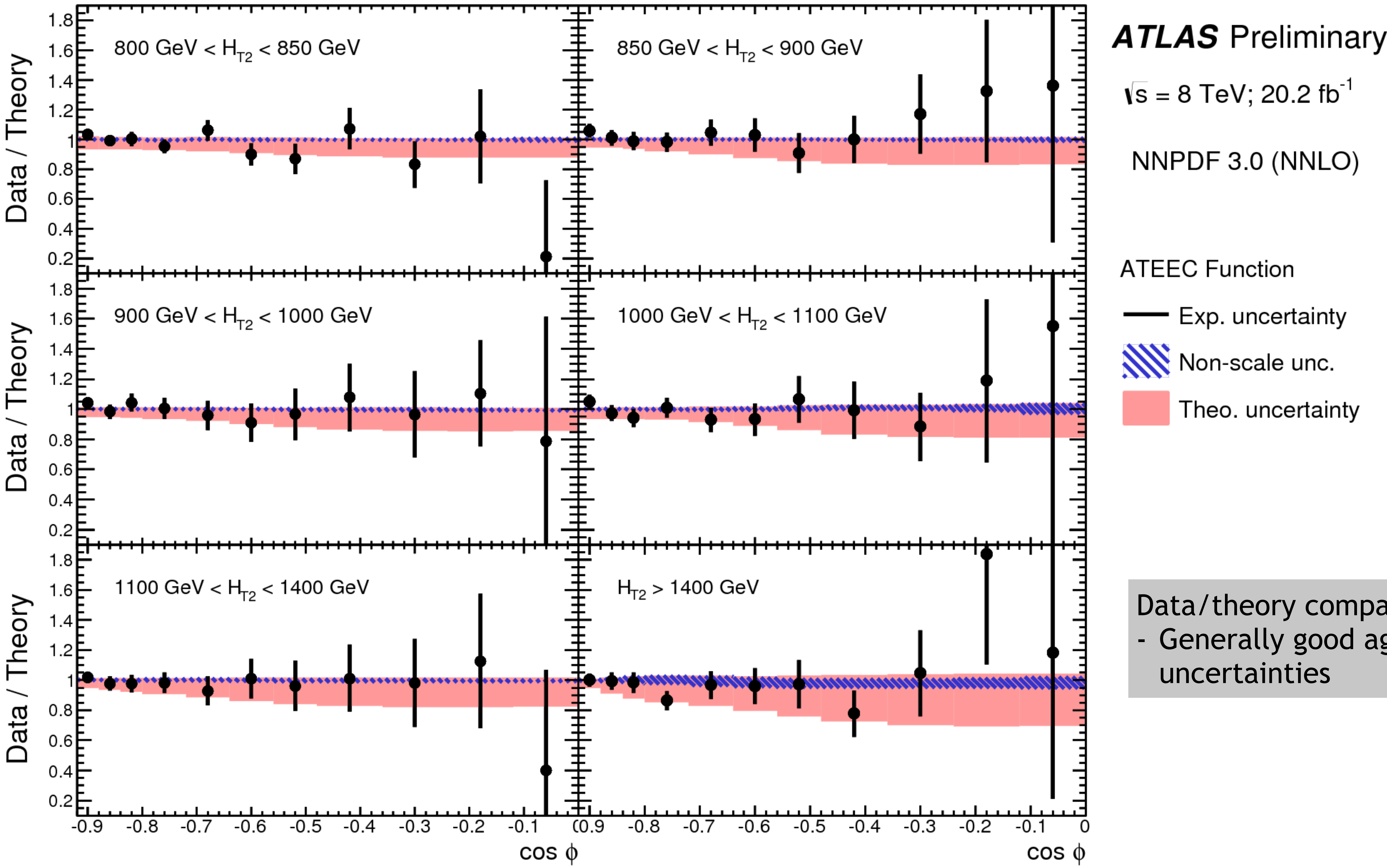


TEEC and ATEEC



Data/theory comparison
- Generally good agreement within uncertainties

TEEC and ATEEC



Data/theory comparison

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