Probing Perturbative QCD at the ATLAS Experiment

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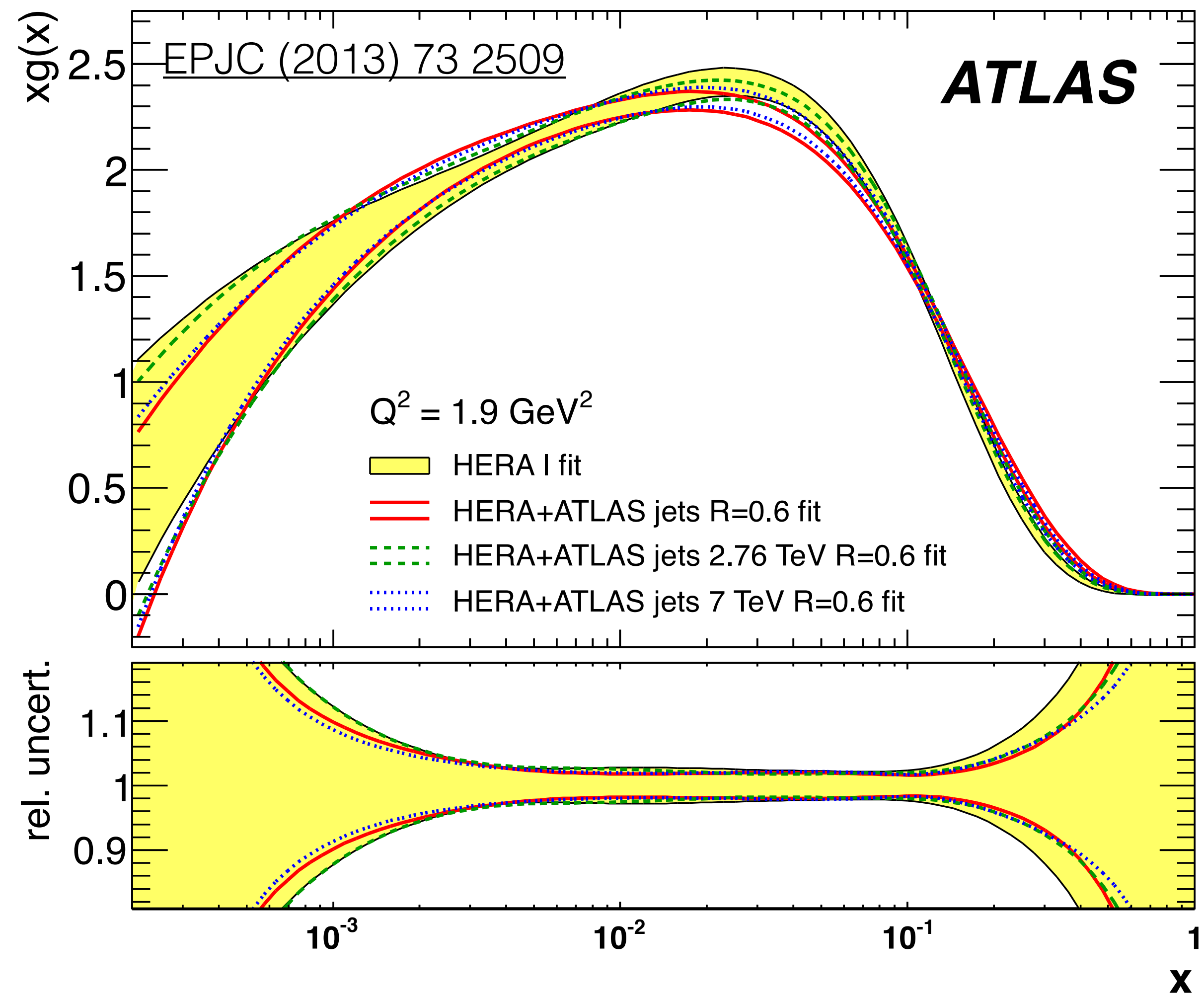
Introduction

- Jet cross-section measurements:
  - Probe proton structure and α_S
  - Test Monte Carlo predictions
  - Constrain PDF fits
- **Inclusive jet & dijet cross-section** measurements at 8 & 13 TeV
- Ratio of jet production in phase-space sensitive to α_S at higher order
  - **Dijet Azimuthal Decorrelations**
  - **Transverse energy-energy correlations** b/w jets

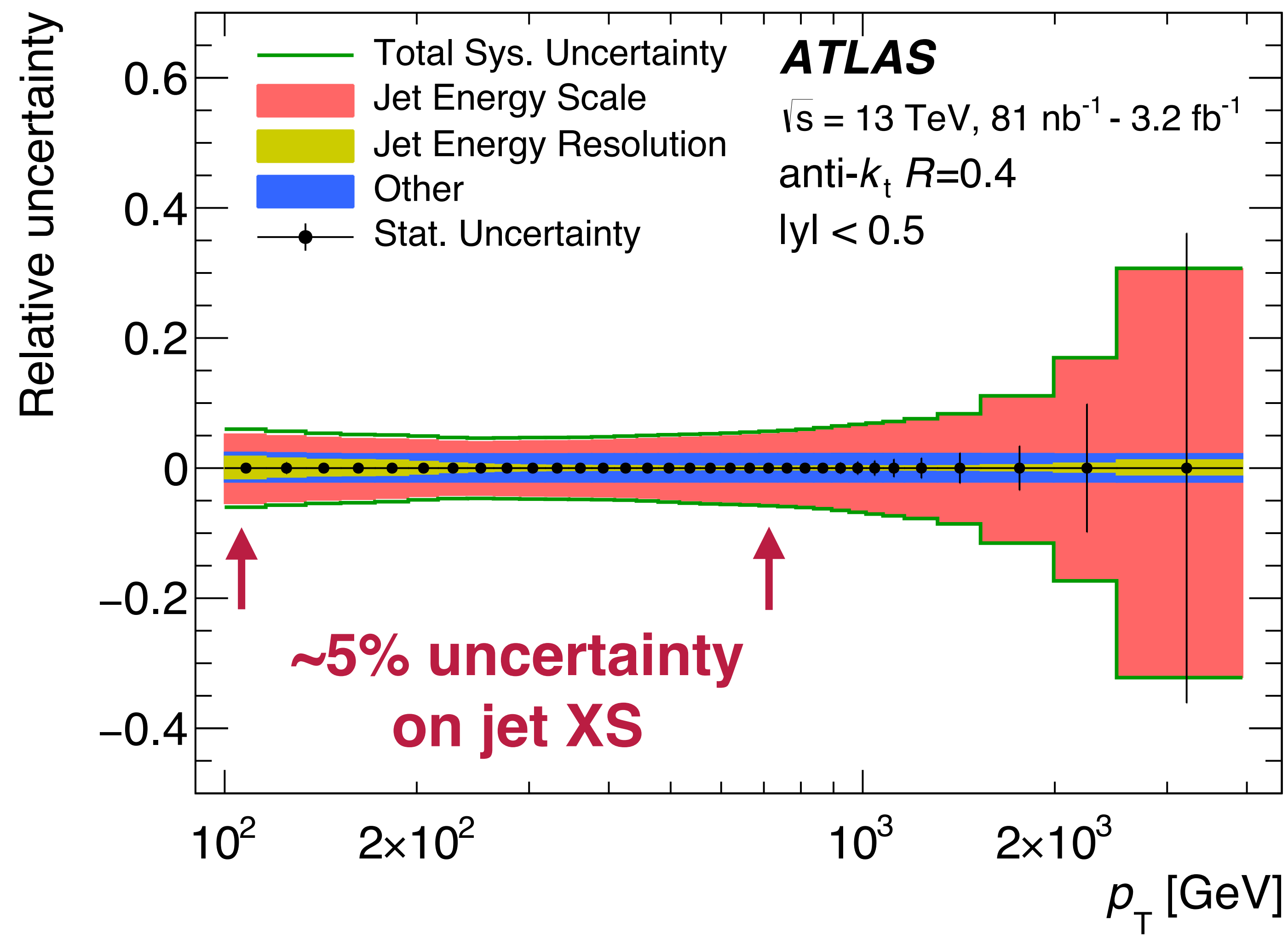
Gluon momentum distribution



HERA PDF fit before & after ATLAS constraints

Detector Jets

- Jets formed from calorimeter energy deposits using **anti-k_t** algorithm
- **Jet energy scale** and **resolution** calibrated with MC-based methods and *in situ* data-to-MC corrections
  - JES/JER are dominant experimental uncertainties
  - Reduced significantly from 7 TeV
- **Unfold data to hadron-level**, correcting for detector effects
  - Pythia-based transfer matrix

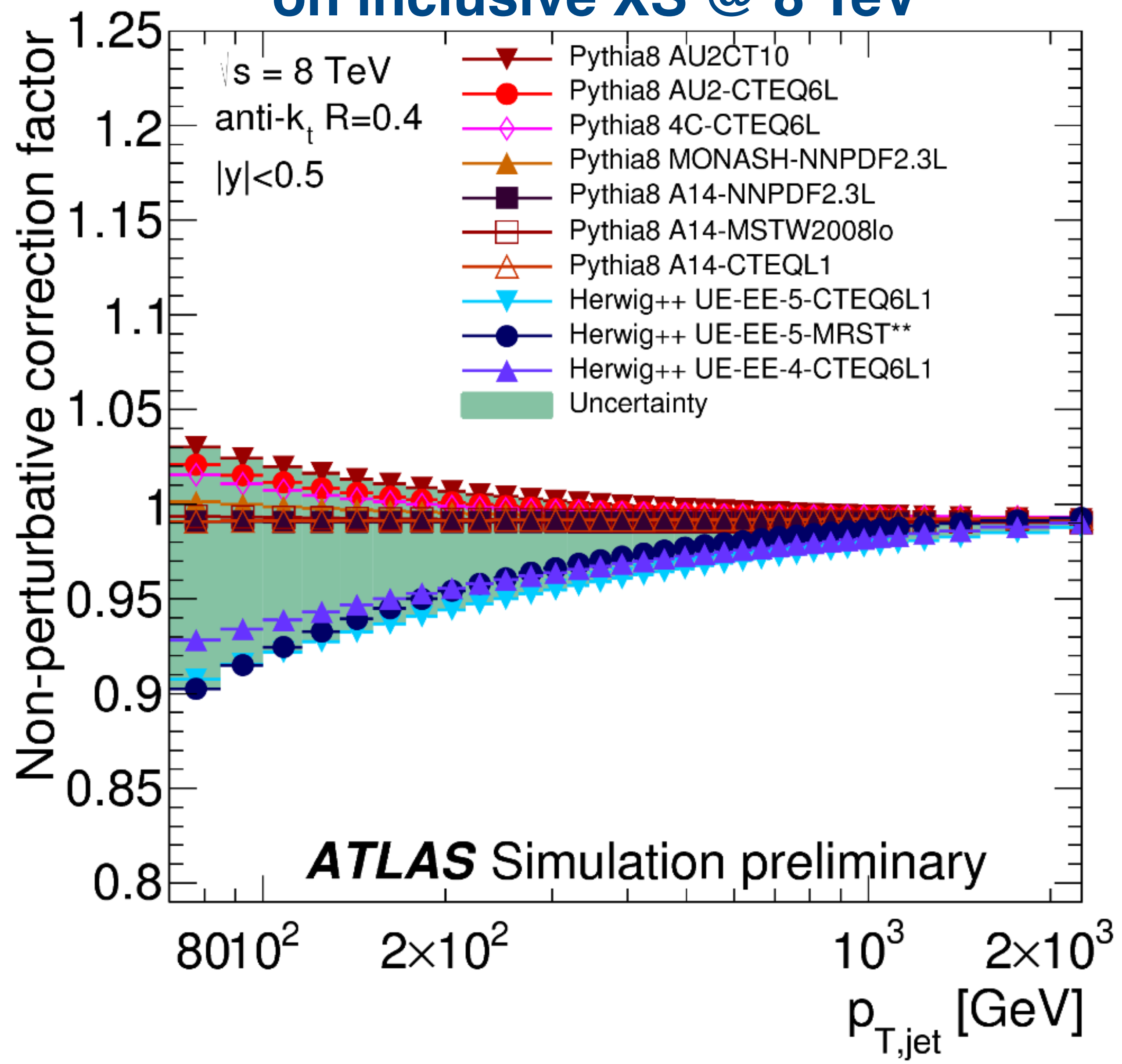


JES/JER uncertainty on 13 TeV XS

Theoretical Predictions

- Theoretical prediction of Matrix Element from **NLOJET++** interfaced with **various PDF sets**
- **Non-perturbative corrections** (hadronization, underlying event) from Pythia & Herwig tunes
  - **Large spread** between Pythia8 & Herwig++ taken as uncertainty

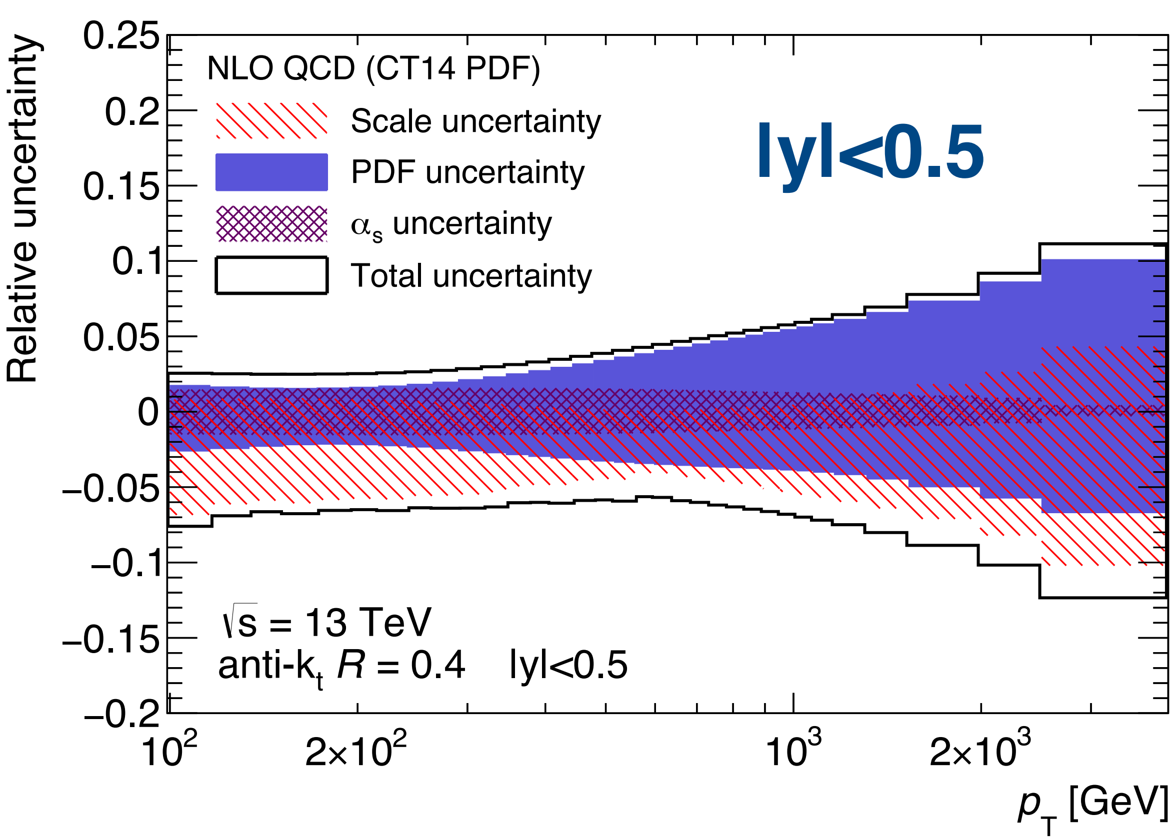
Non-perturbative correction on inclusive XS @ 8 TeV

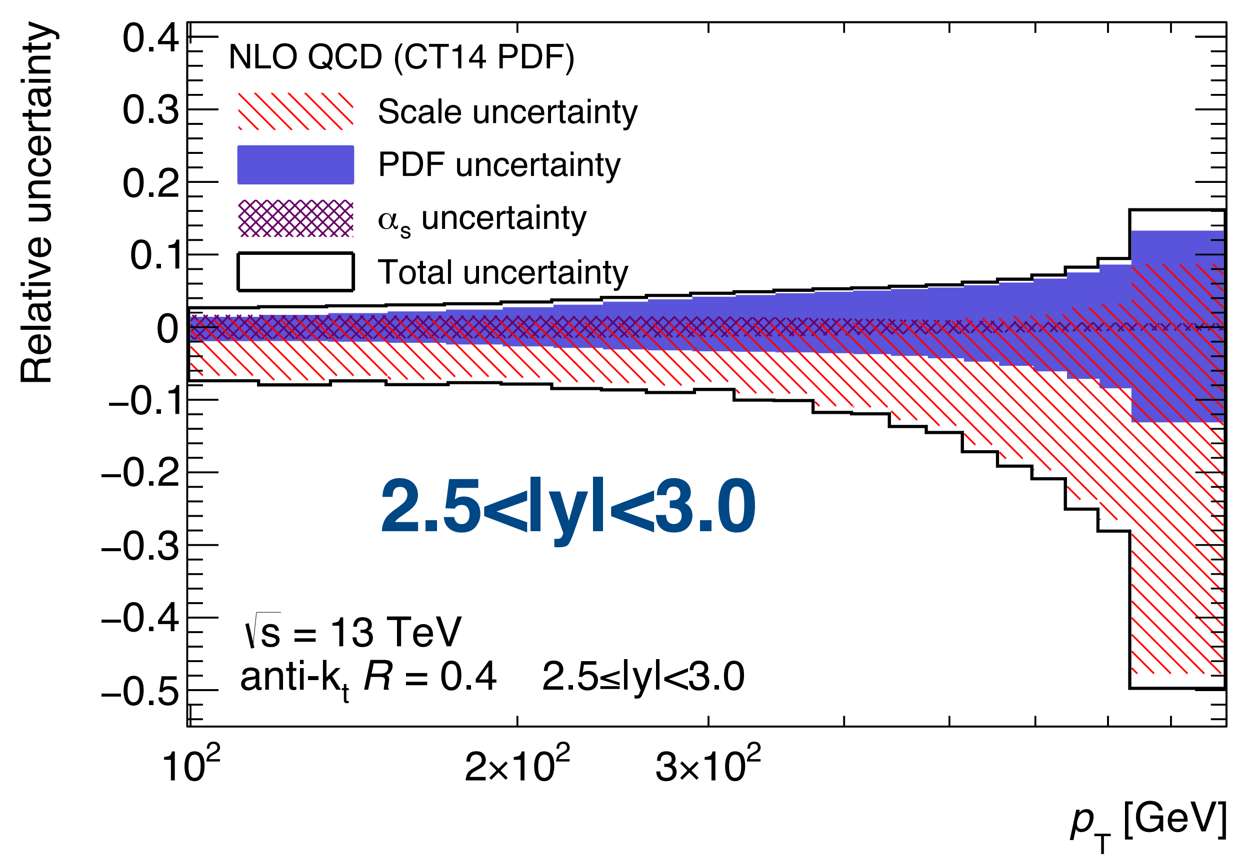


Theoretical Uncertainties

- **PDF** - Propagated using variations for each PDF set
- α_s - Tunable parameter in PDFs varied according to PDF4LHC recommendations
- **Factorization / renormalization scales** - $0.5 < \mu_{R,F} < 2.0$
  - **Dominant theory uncertainty** for all 4 analyses

13 TeV Inclusive XS uncertainties





Inclusive & Dijet Cross-Section

8 TeV Inclusive: JHEP 09 (2017) 020

13 TeV Inclusive & Dijet: JHEP 05 (2018) 195

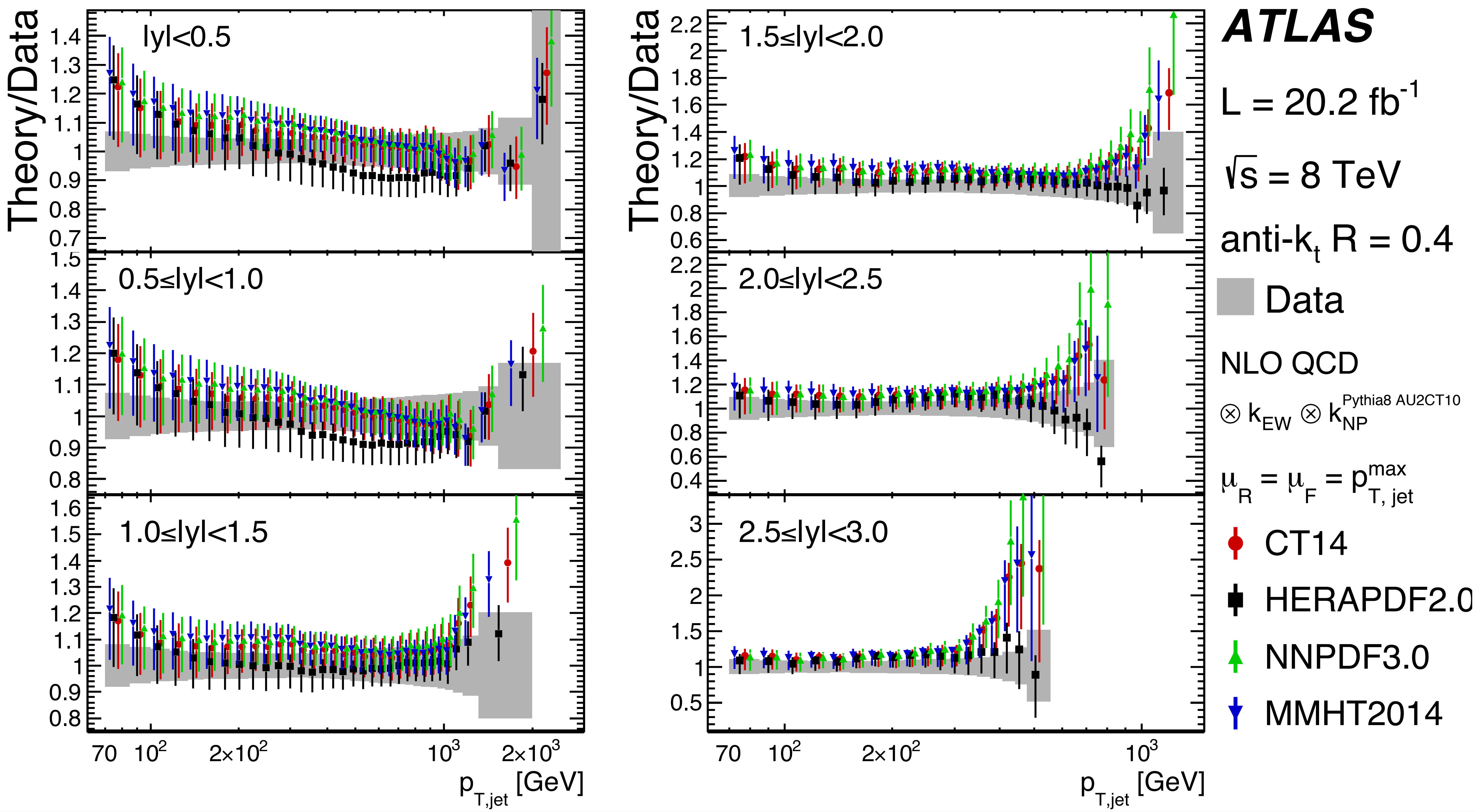
Previous 13 TeV Rivet Routine at ATLAS-CONF-2016-092

8 TeV Inclusive XS Results

- **CT14**, **HERAPDF2.0**, **NNPDF3.0**, **MMHT2014**
- Significant slopes at low-medium and medium-high p_T
- Good **fit agreement within |y|** bins, but poor inclusively ($P_{obs} \ll 10^{-3}$)

P_{obs} values from χ^2 goodness of fit

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%

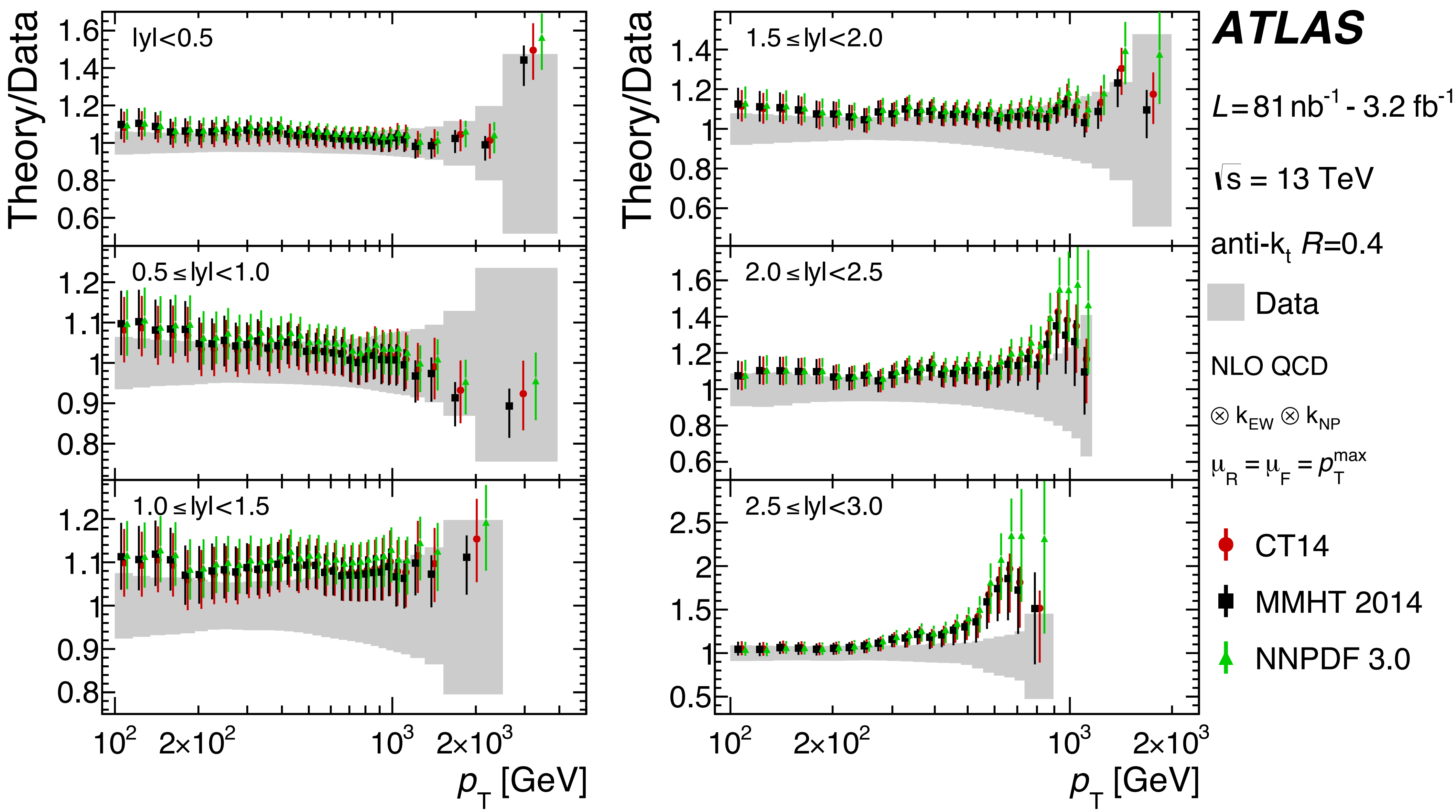


13 TeV Inclusive XS

- **CT14**, **MMHT2014**, **NNPDF3.0**
- **100 GeV to 3.5 TeV!**
- Conclusions unchanged from 8 TeV

P_{obs} values from χ^2 goodness of fit

Rapidity ranges		P_{obs}	
	CT14	MMHT 2014	NNPDF 3.0
p_T^{max}			
$\lvert y\rvert < 0.5$	67%	65%	62%
$0.5 \leq \lvert y\rvert < 1.0$	5.8%	6.3%	6.0%
$1.0 \leq \lvert y\rvert < 1.5$	65%	61%	67%
$1.5 \leq \lvert y\rvert < 2.0$	0.7%	0.8%	0.8%
$2.0 \leq \lvert y\rvert < 2.5$	2.3%	2.3%	2.8%
$2.5 \leq \lvert y\rvert < 3.0$	62%	71%	69%



Alternative correlation schemes

- **Data-theory tension** in inclusive measurements at 8 & 13 TeV
  - Not localized in |y|, no central-forward tension

13 TeV data-theory χ^2 agreement

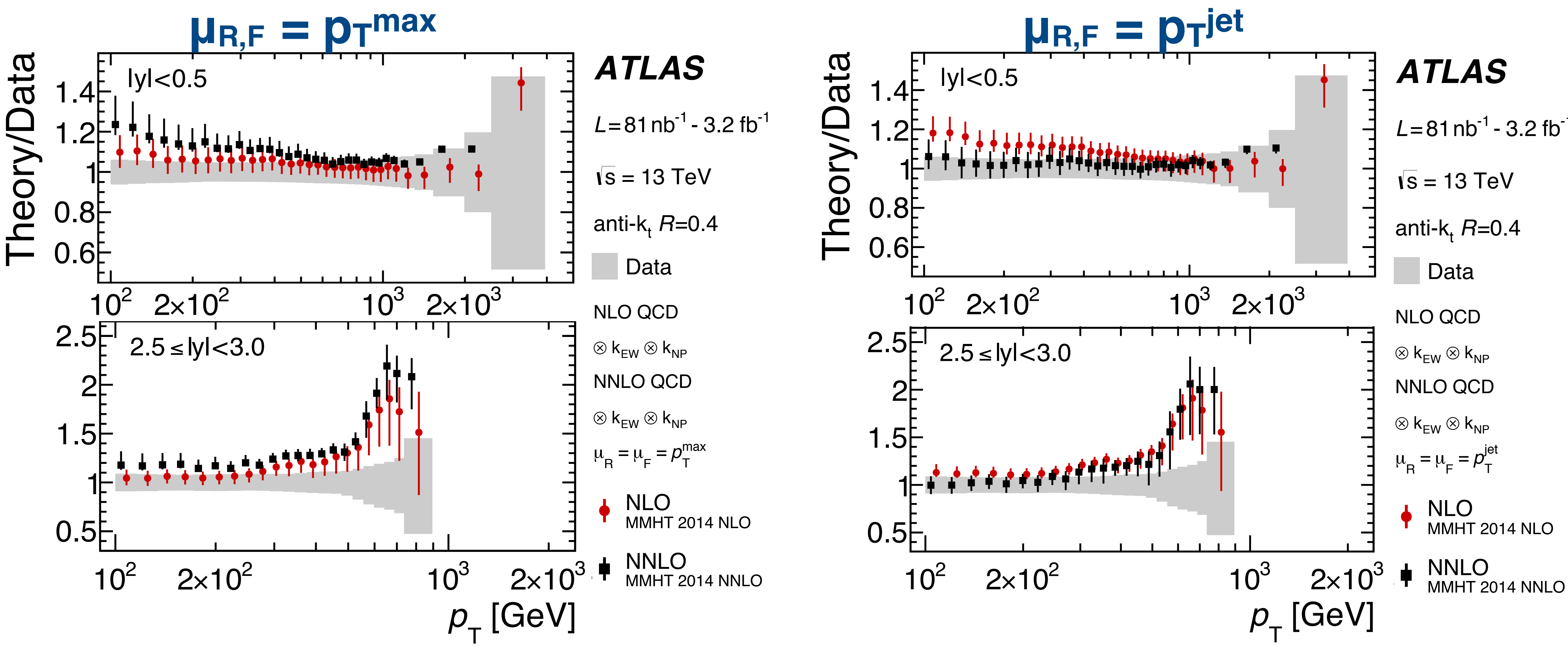
$\mu_{R,F}$

χ^2/dof all $|y|$ bins	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
p_T^{max}	419/177	431/177	404/177	432/177	475/177
p_T^{jet}	399/177	405/177	384/177	428/177	455/177

- Potential culprit: **2-point systematics** have unknown correlations
  - Comparison of 2 MC generators (non-perturbative corrections) or variations for uncertainties (theory scale uncertainty) - several for JES
- Explored 18 alternative correlation scenarios to **split 2-point systematics smoothly by p_T and |y|**
  - **Can improve χ^2 substantially** - 58 units for 13 TeV CT14 result
  - But all **justifiable** de-correlation scenarios still give small p-values
- Potential breakdown in 2-point systematic assumptions (phase-space dependence) or incomplete theoretical descriptions

NNLO Calculation at 13 TeV

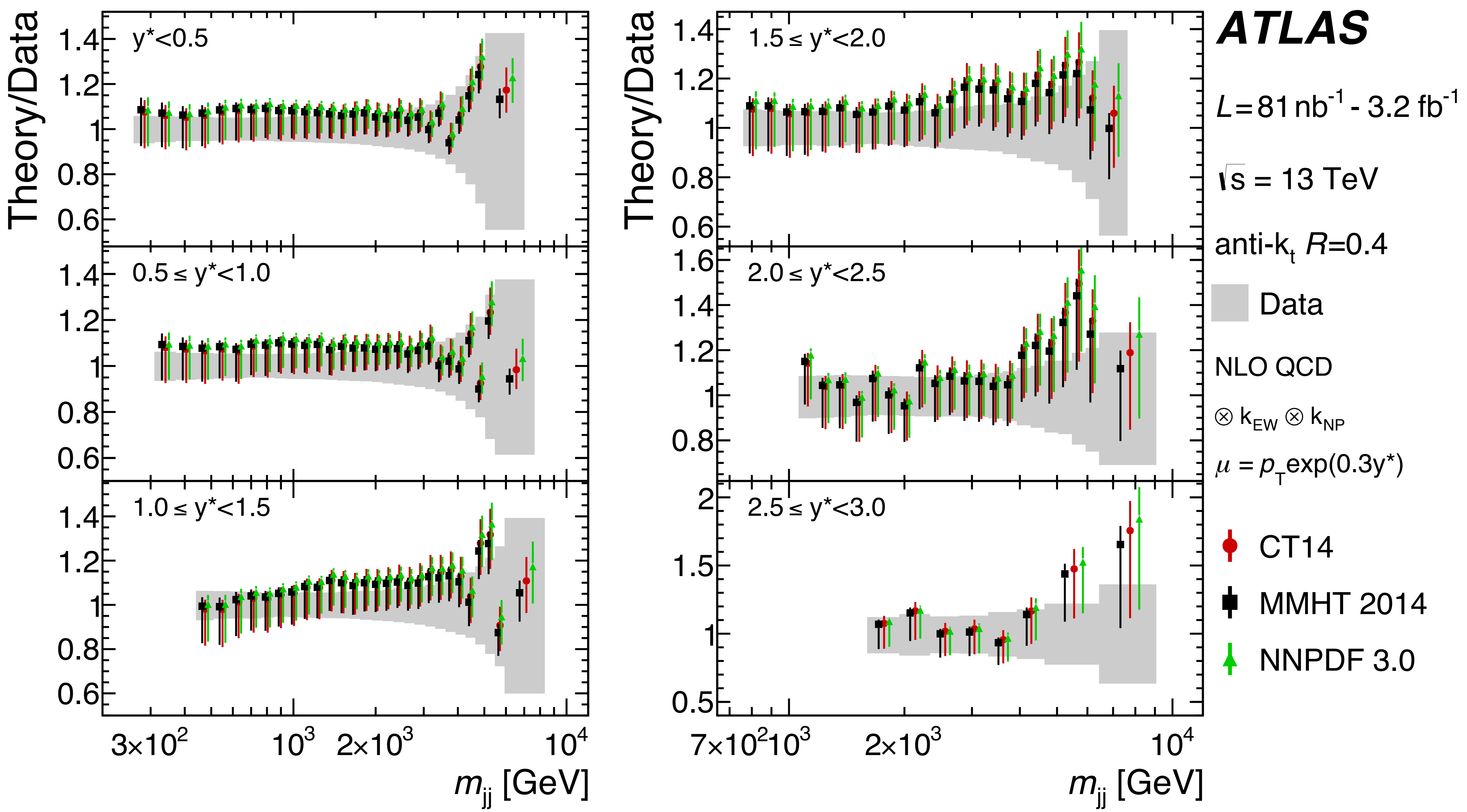
- NNLOJET with MMHT2014 NNLO PDF for **two $\mu_{R,F}$ scales** (p_T^{max} & p_T^{jet})
- **Significant scale-choice dependence seen for NNLO at low-p_T**
- Possible explanation is dependence on NNLO PDF *approximations*
    - May not reflect large NNLO corrections at low-p_T
    - Still under investigation



Dijet XS measurement

- **2-jet system** as a function of $\mathbf{m_{jj}}$ and **y*** (centrality)
  - **300 GeV to 9 TeV!**
- **Good data-theory agreement** for most PDFs

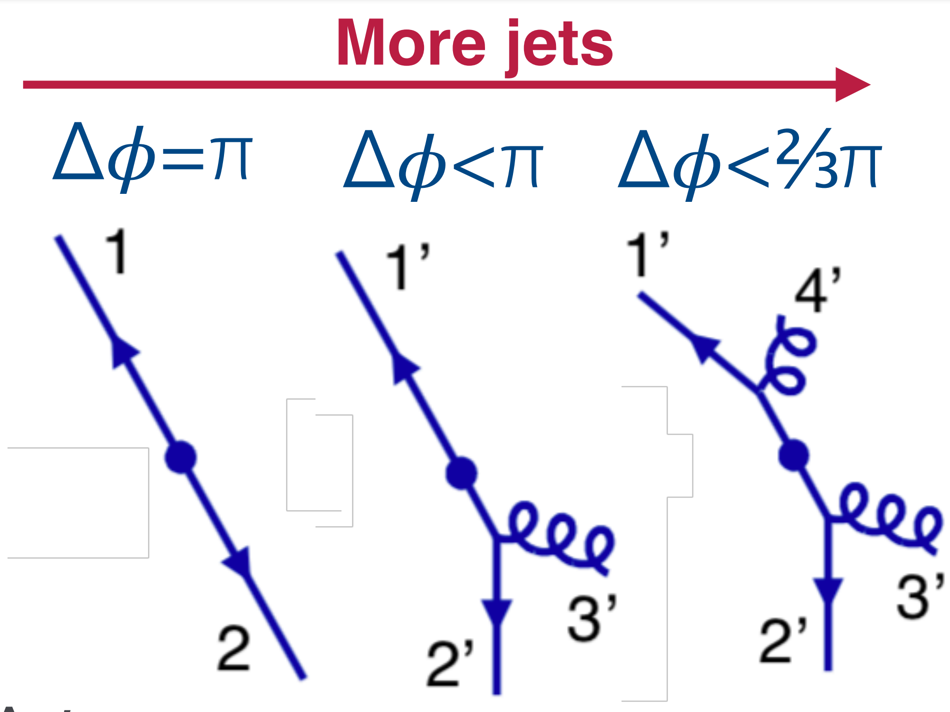
y^* ranges	CT14	MMHT 2014	P_{obs} NNPDF 3.0	HERAPDF 2.0	ABMP16
$y^* < 0.5$	79%	59%	50%	71%	71%
$0.5 \leq y^* < 1.0$	27%	23%	19%	32%	31%
$1.0 \leq y^* < 1.5$	66%	55%	48%	66%	69%
$1.5 \leq y^* < 2.0$	26%	26%	28%	9.9%	25%
$2.0 \leq y^* < 2.5$	43%	35%	31%	4.2%	21%
$2.5 \leq y^* < 3.0$	45%	46%	40%	25%	38%
all y^* bins	8.1%	5.5%	9.8%	0.1%	4.4%



Dijet Azimuthal Decorrelations

13 TeV measurement submitted to PRD

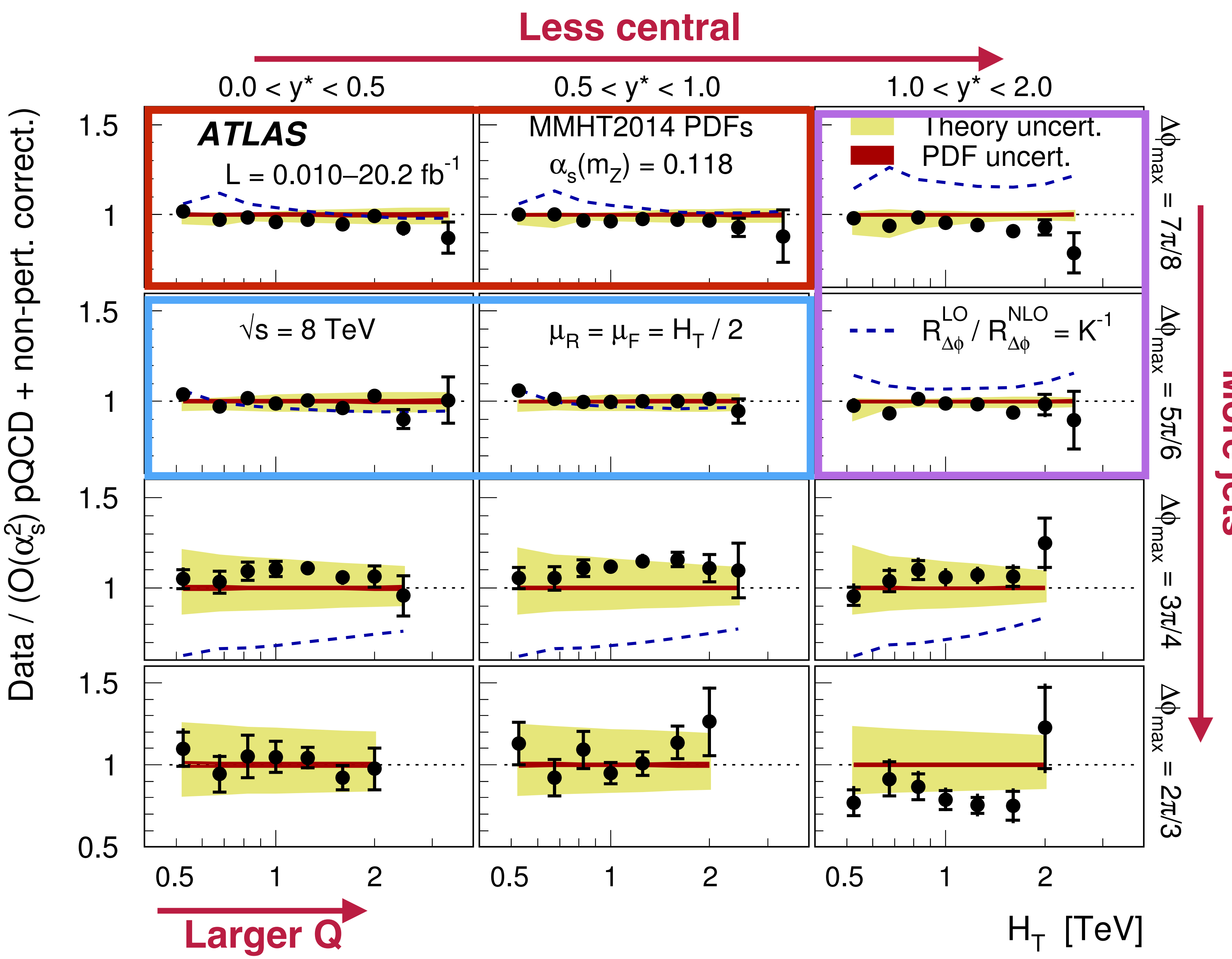
Dijet Azimuthal Decorrelations



- **$\Delta\phi$** b/w 2 leading jets (deviation from π)
  - More activity → smaller **$\Delta\phi$** (probing higher order α_s)
- **$R_{\Delta\phi}$** = fraction of inclusive jet events with $\Delta\phi < \Delta\phi_{max}$
- Binned into **$\Delta\phi_{max}$** = ⅞π, ⅚π, ¾π, ⅔π (hardness of additional radiation)
  - Theory prediction at **NLO up to 3 jets, LO for 4 jets**
- Binned by **H_T** = $\sum p_T$ (approximates Q) & **y*** (rapidity dependence of matrix elements) - **new parameterizations!**
- **MMHT2014 PDF** for central result - compared with CT14, NNPDFv2.3, ABMP16, & HERAPDF2.0

Data-to-theory Comparison

- Data-to-theory ratios show agreement within uncertainties
- **⅞π chosen for α_S calculation**
  - Reliable NLO prediction with small $\mu_{R,F}$ dependence
  - Most inclusive = best PDF cancellation & uncertainty
  - **⅚π also a good choice**
- **Reject 1 < y*< 2 region** given large NLO corrections

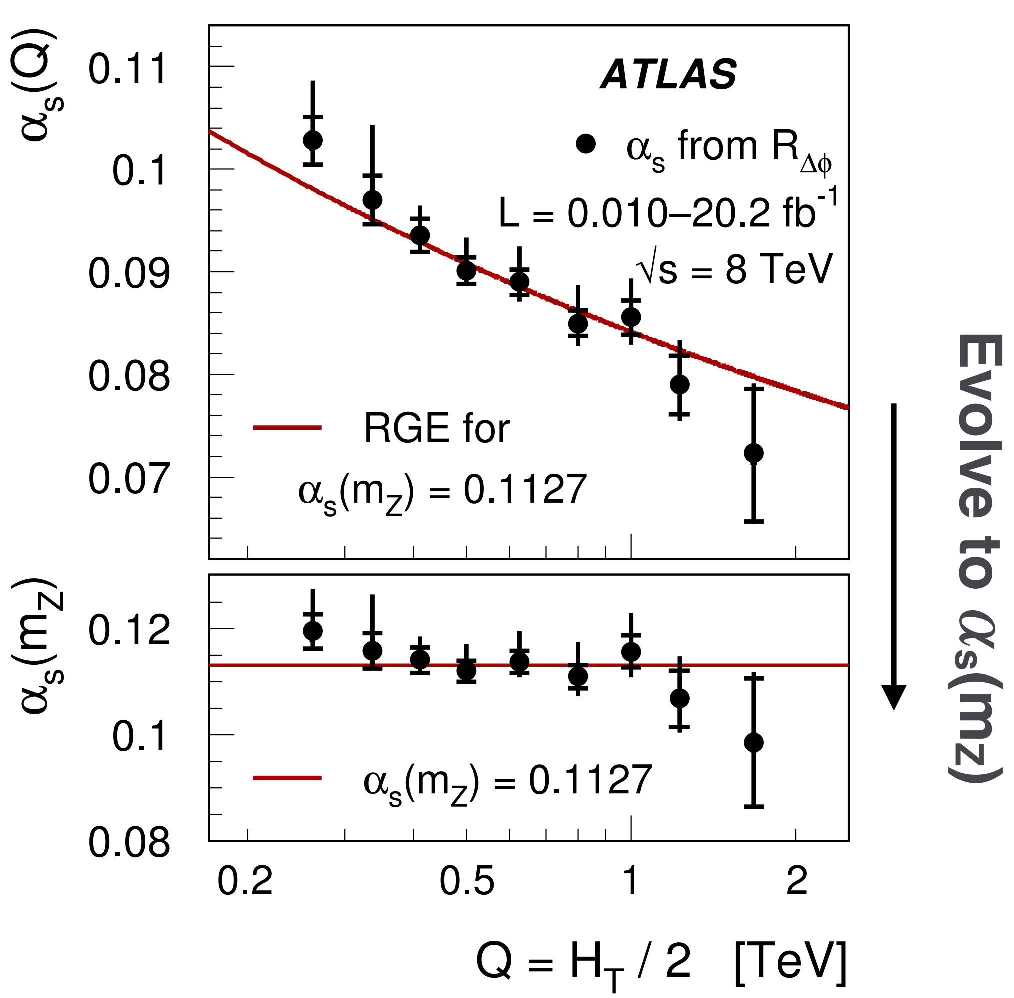


Measuring α_s

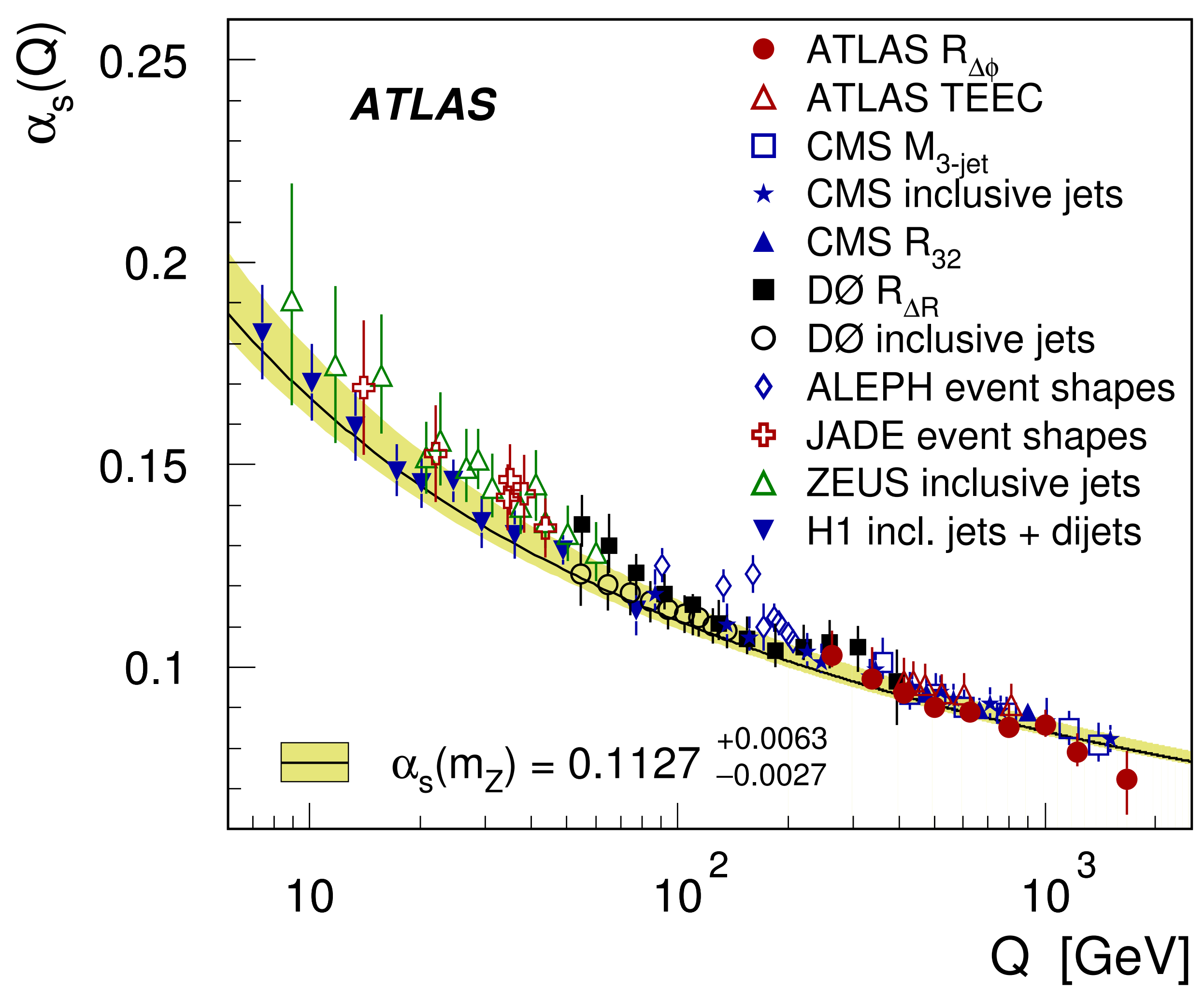
- Derive $\alpha_s(Q)$, evolve to $\alpha_s(m_Z)$ via RGE
- **RGE compatible**: Fit to $\alpha_s(m_Z)$ gives slope of $-0.0089 \pm 0.0035_{stat}$
- **H_T-inclusive fit** of $\alpha_s(m_Z) = 0.1127^{+0.0063}_{-0.0027}$ with χ^2/dof = 21.7 / 17
  - Probe Q b/w **262 and 1675 GeV!**

$\alpha_s(m_Z)$ region dependence	
World average	0.1181
⅞π region	0.1127
⅚π region	0.1179
Add forward y*	0.1135

α_s(Q) measurement



$R_{\Delta\phi}$ comparison w/ other experiments



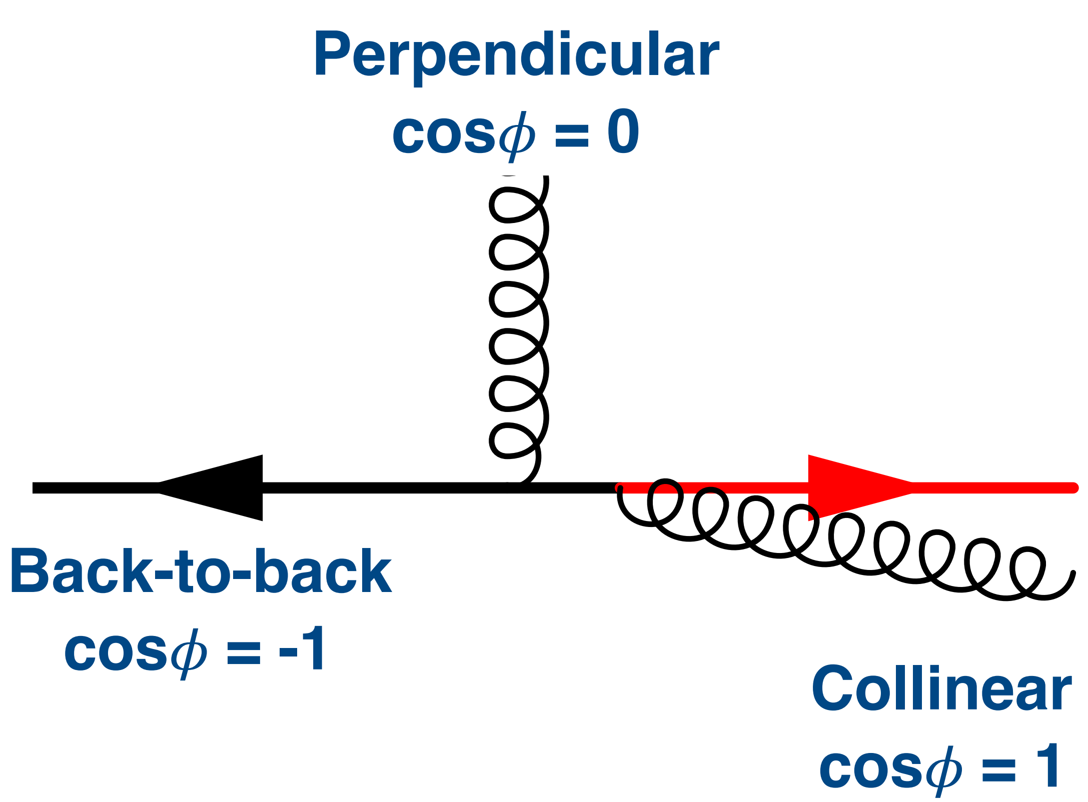
Transverse Energy-Energy Correlations

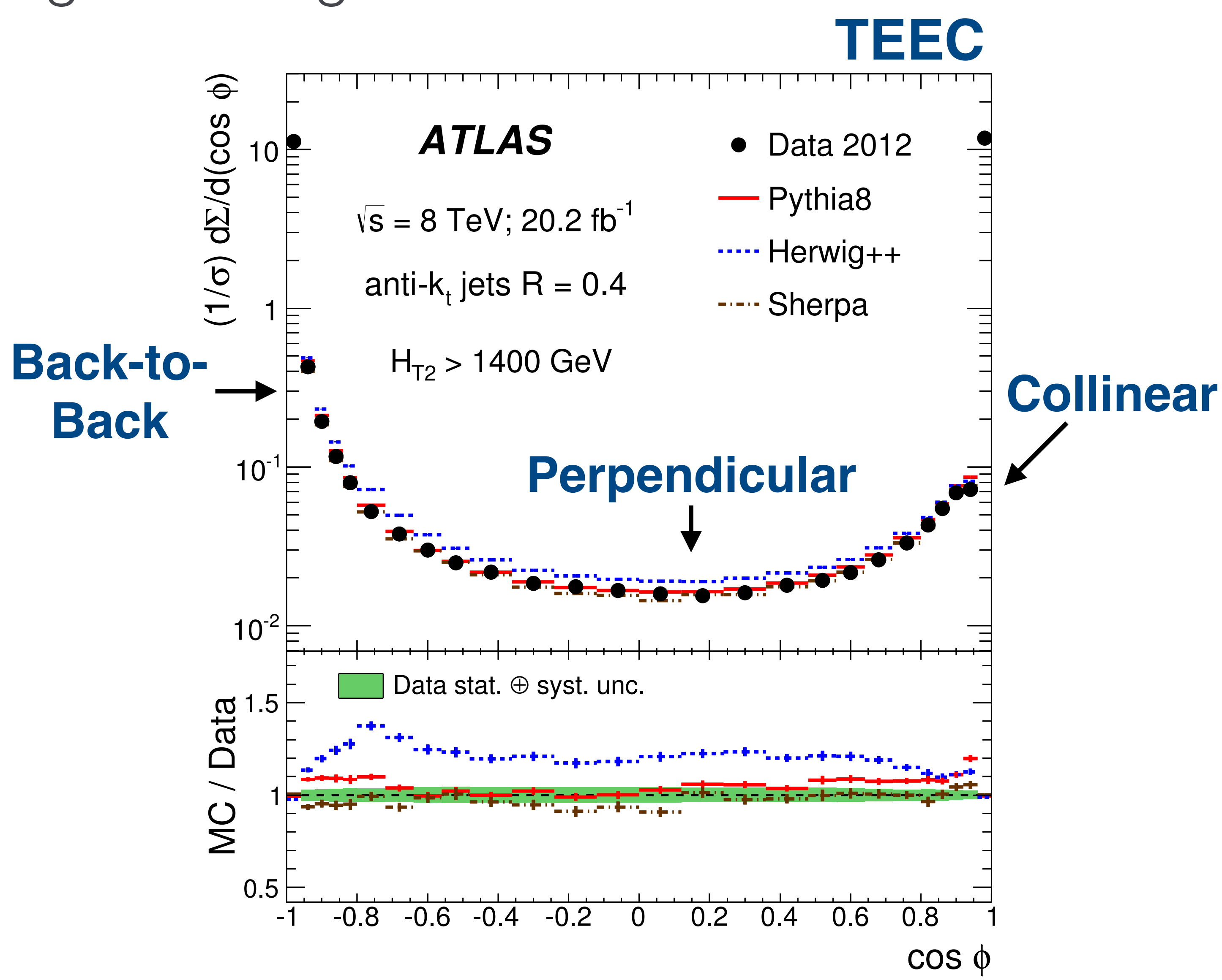
8 TeV measurement at Eur. Phys. J. 77 (2017) 872

HepData record 77269

Transverse Energy-Energy Correlations (TEEC)

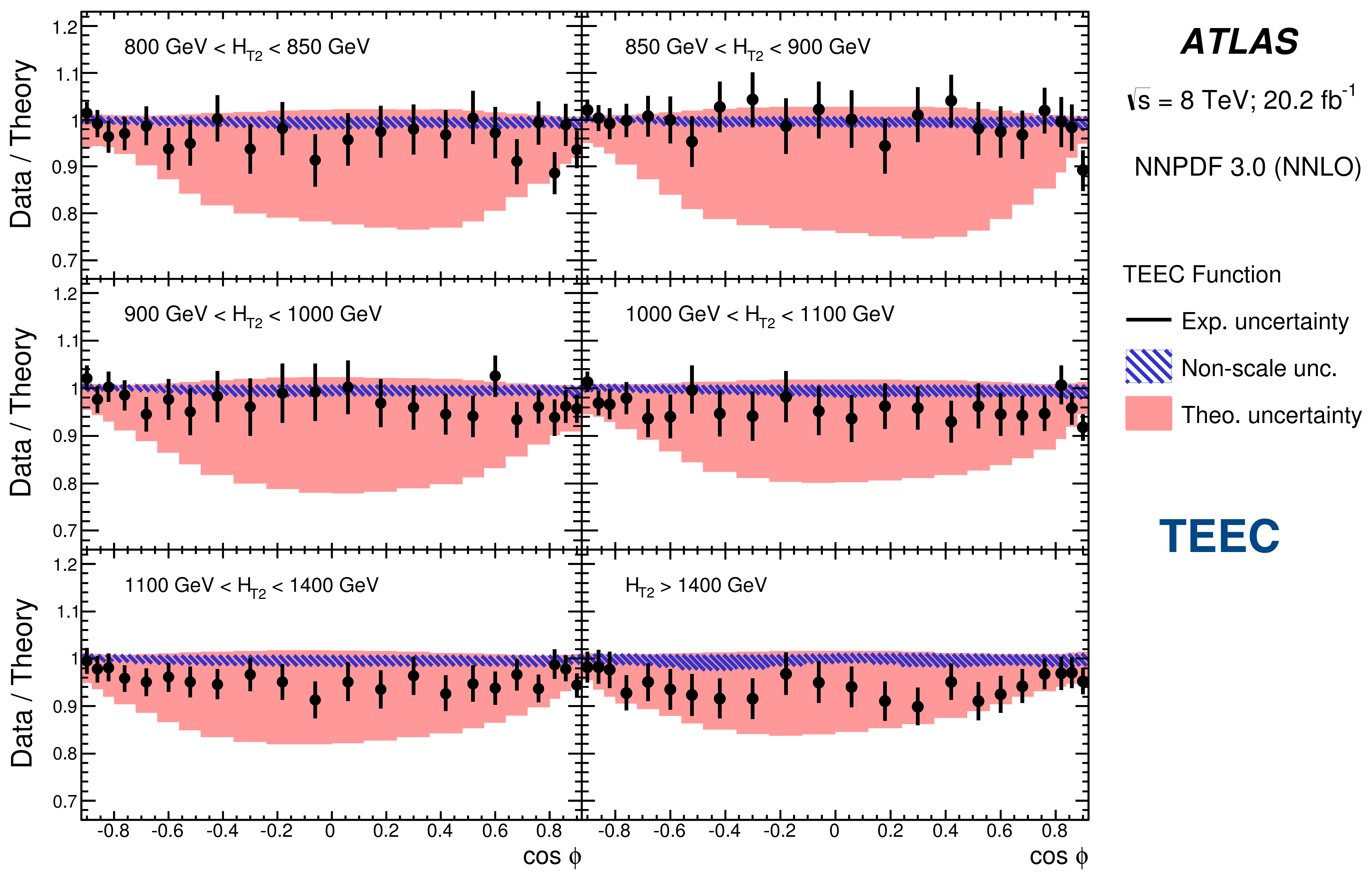
- **Energy-weighted angular distribution** (i.e. fractional E_T at angle ϕ of a jet)
  - Event shape variable that is infrared safe with small NLO corrections
- **Asymmetric TEEC** is forward-backward difference in cos ϕ (reduce scale uncert.)
- **Pythia & Sherpa agree** with unfolded data, angular-ordered showers in Herwig++ gives disagreement





Data-to-theory comparison

- Theory prediction from NLOJET++ using **NNPDF3.0**, MMHT2014, CT14, and HERAPDF2.0
  - **Good agreement with data**
- Dominant theory uncertainty $\mu_{R,F}$ reaches 20% in central region



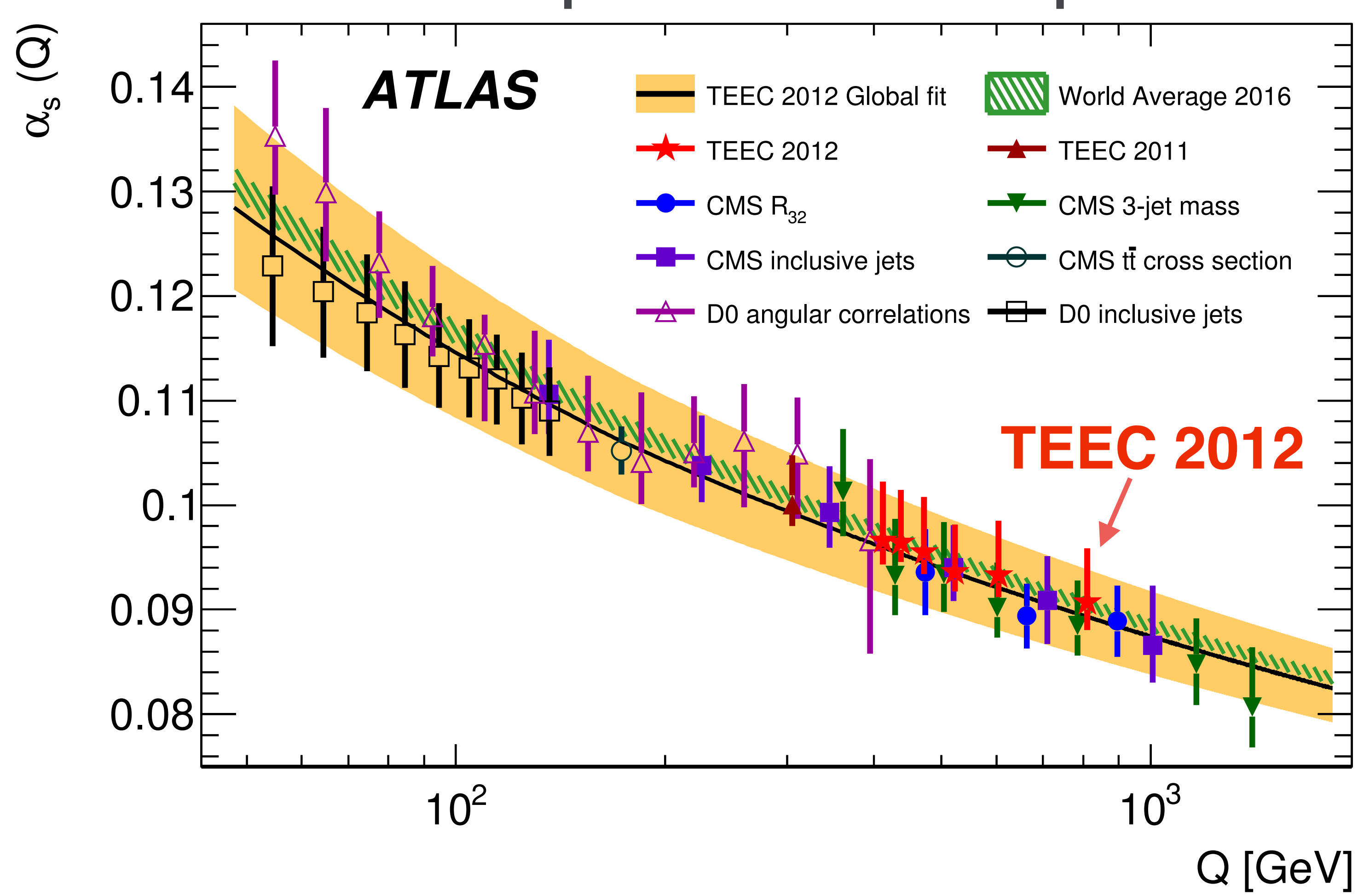
TEEC

Comparing with World Average

PDF	TEEC $\alpha_S(m_Z) \pm$ scale	TEEC χ^2/dof	Asymmetric TEEC $\alpha_S(m_Z) \pm$ scale	Asymmetric TEEC χ^2/dof
MMHT2014	$0.1151^{+0.0064}_{-0.0047}$	173/131	$0.1185^{+0.0047}_{-0.0010}$	57.0/65
CT14	$0.1165^{+0.0067}_{-0.0061}$	161/131	$0.1203^{+0.0053}_{-0.0014}$	55.4/65
NNPDF3.0	$0.1162^{+0.0076}_{-0.0061}$	174/131	$0.1196^{+0.0061}_{-0.0013}$	60.3/65
HERAPDF2.0	$0.1177^{+0.0064}_{-0.0040}$	169/131	$0.1206^{+0.0050}_{-0.0014}$	54.2/65
World average	**0.1181**			

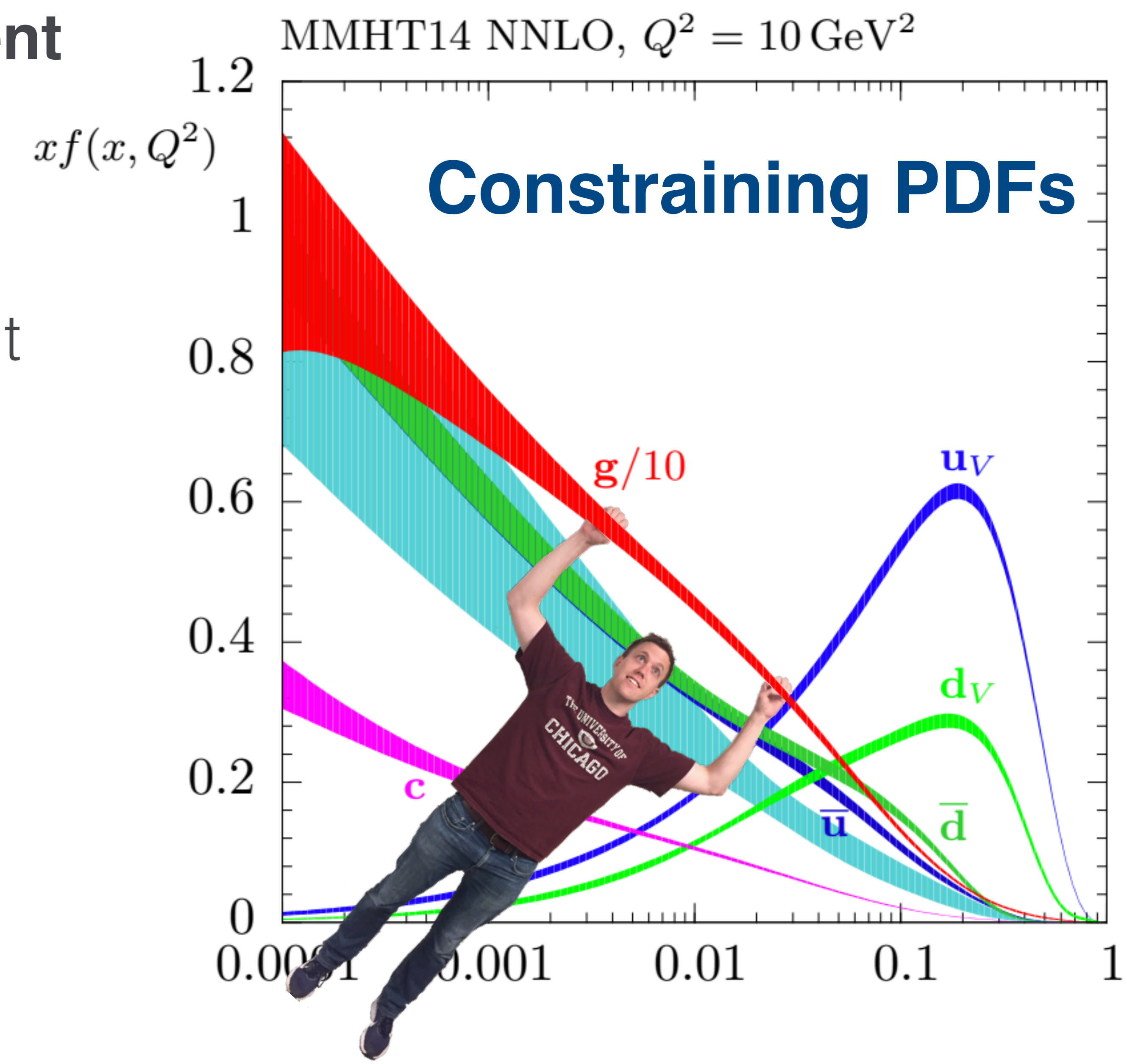
- Vary $\alpha_S(m_Z)$ in each PDF set and find best fit to data
- Good agreement with world average & RGE
- Only modeling uncertainty is pulled → **further tuning of multijet MC generators** possible

TEEC comparison w/ other experiments



Conclusion

- Generally **good theory-data agreement**
  - Some tension in inclusive jet cross-section measurements
- **New NNLO results** are reasonable but have large scale-choice dependence
- New jet cross-section measurements **can constrain PDFs** & help **improve MC generators**
  - Some HEPData & Rivet routines are already available - others are coming soon



More interesting talks!

Jet substructure to probe perturbative QCD - talk by Deepak Kar

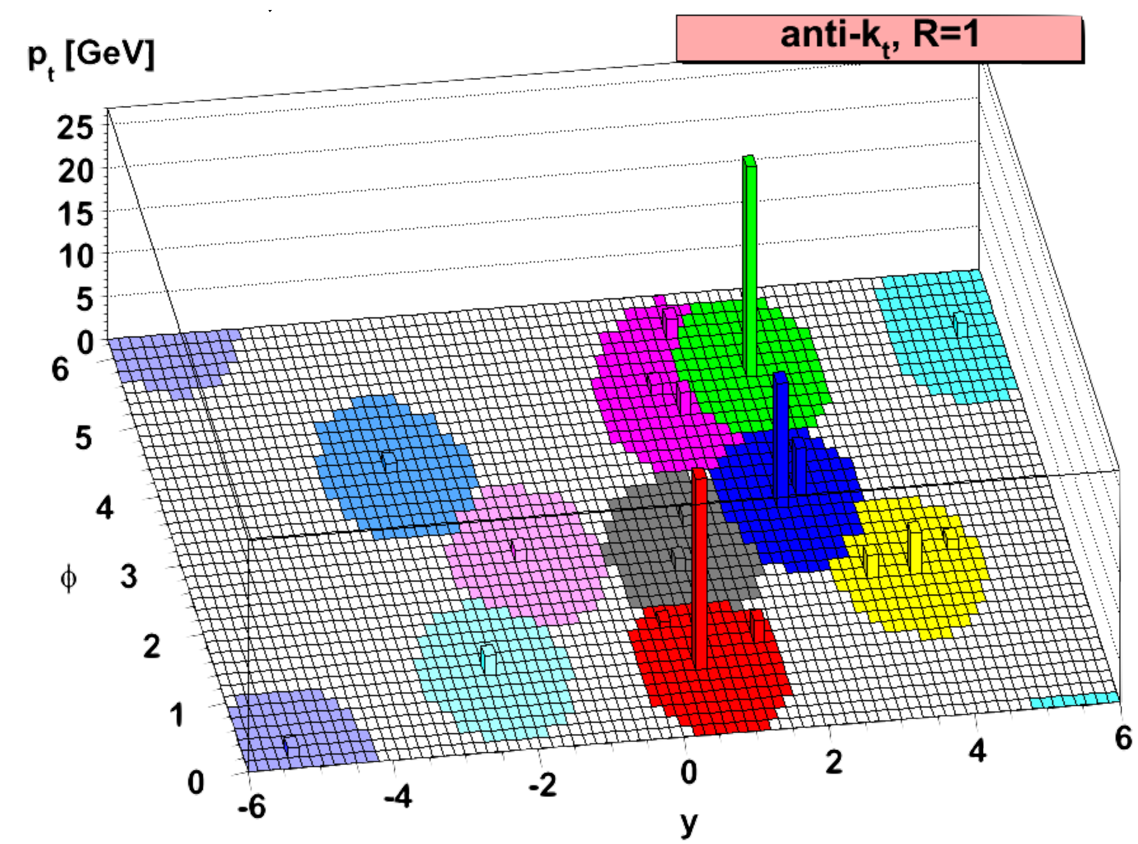
Constraining proton PDFs w/ ATLAS data - talk by Claire Gwenlan

Backup

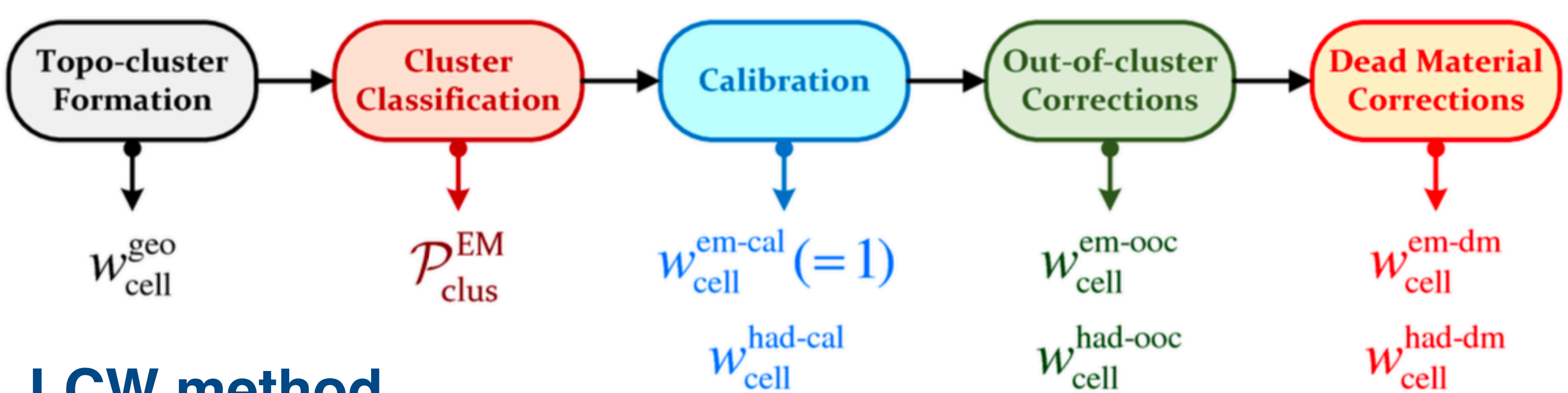
Backup: Details on Jet Reconstruction & Unfolding

Jet Reconstruction Details

- Jets formed from **calorimeter** energy deposits with **anti-k_t** jet-finding algorithm
  - Jets driven by hardest particles, are fairly insensitive to pileup
  - **Jet radius** affects the sensitivity to non-perturbative effects
- Inputs to jets are clusters (collections of neighboring calorimeter cells)
  - **Inherent noise suppression** from 4-2-0 clustering algorithm
  - Topo-cluster-level **LCW** calibration corrects for hadronic **non-compensation** & other effects

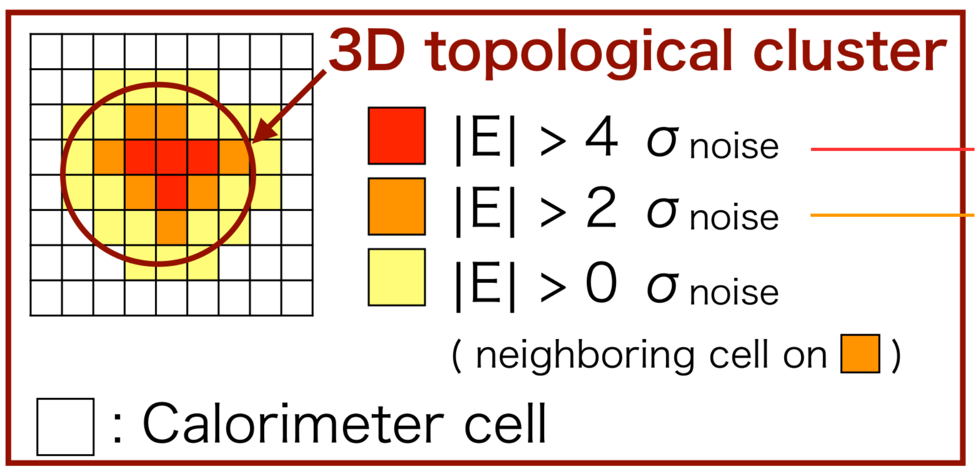


Jet Reconstruction (arXiv:0802.1189)



LCW method

Topocluster construction



Jet Calibration Details

Early Run2 Calibration Paper: Phys. Rev. D 96 (2017) 072002

EM & PFlow jets → **Jet area-based pile-up correction** → **Residual pile-up correction** →

Jet finding applied to (corrected) topological clusters at EM (PFlow) scale.

Applied as a function of event pile-up p_T density and jet area.

Removes residual pile-up dependence, as a function of μ and N_{PV}.

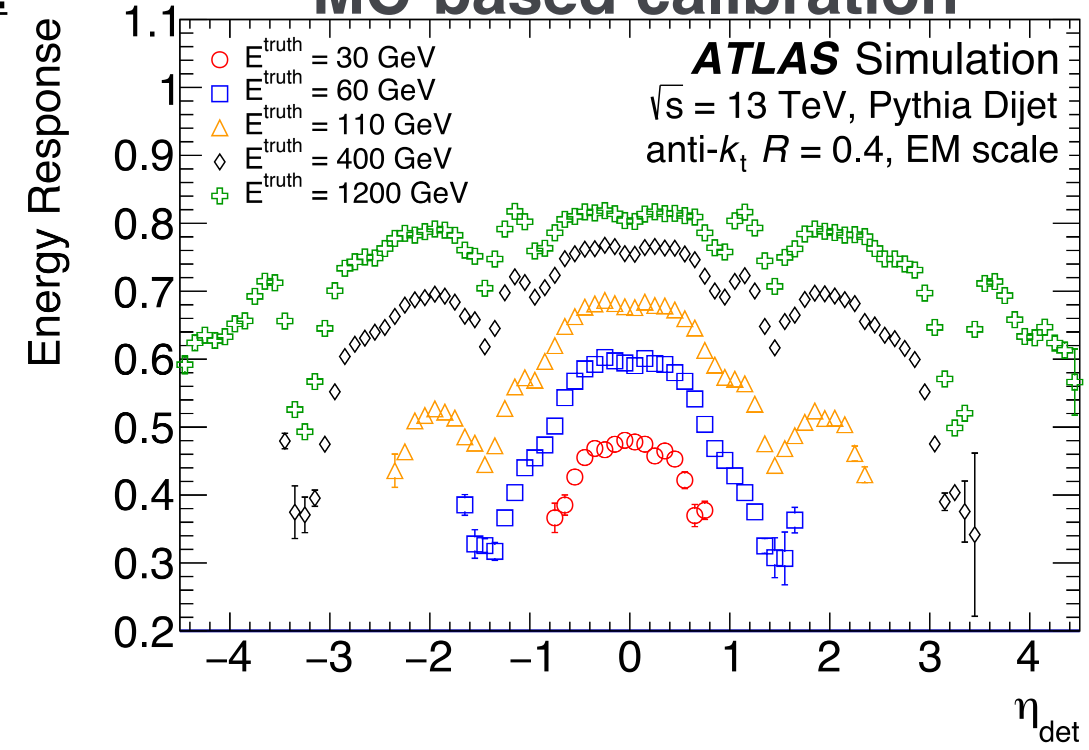
→ **Absolute MC-based calibration** → **Global sequential calibration** → **Residual *in situ* calibration**

Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.

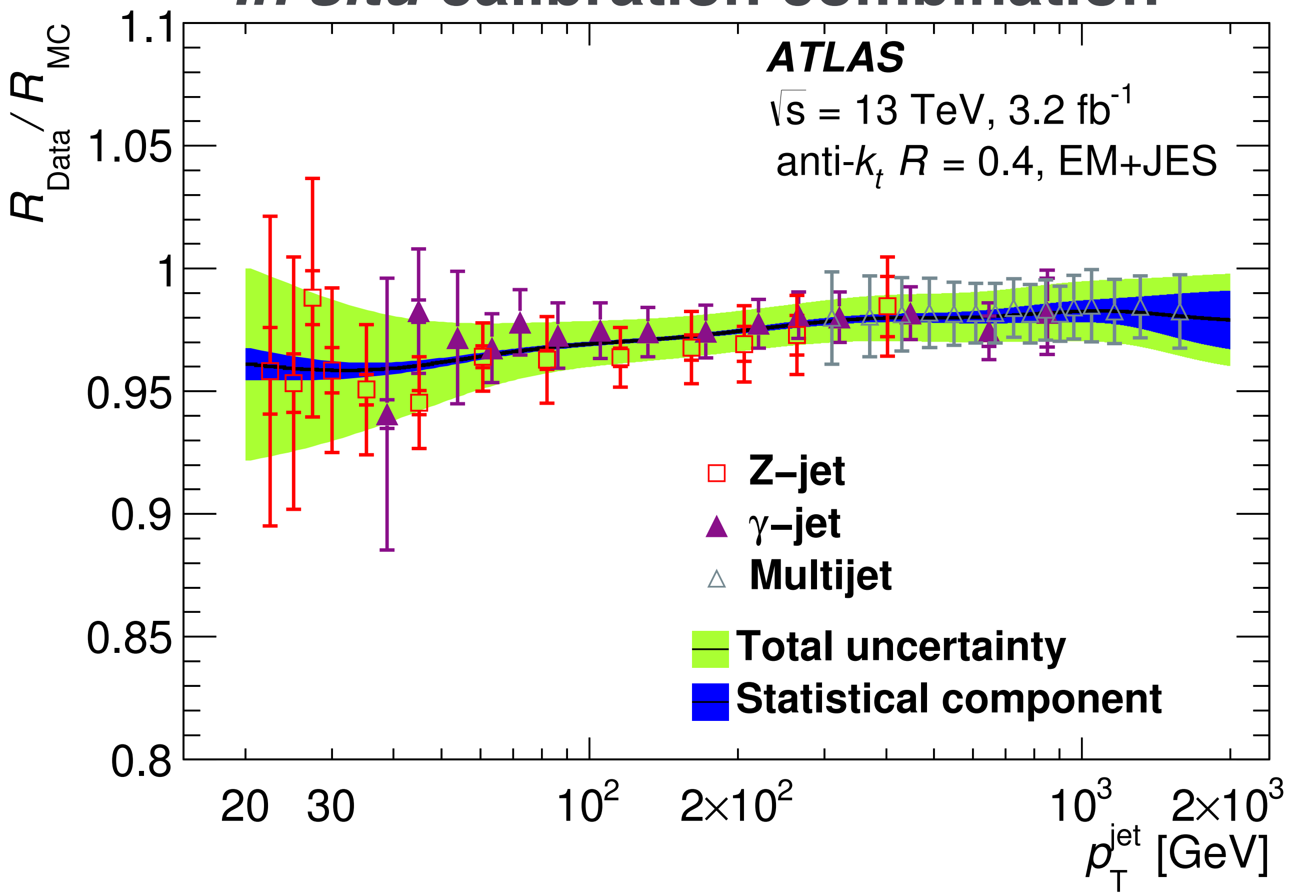
Reduces flavor dependence and energy leakage effects using calorimeter, track, and muon-segment variables.

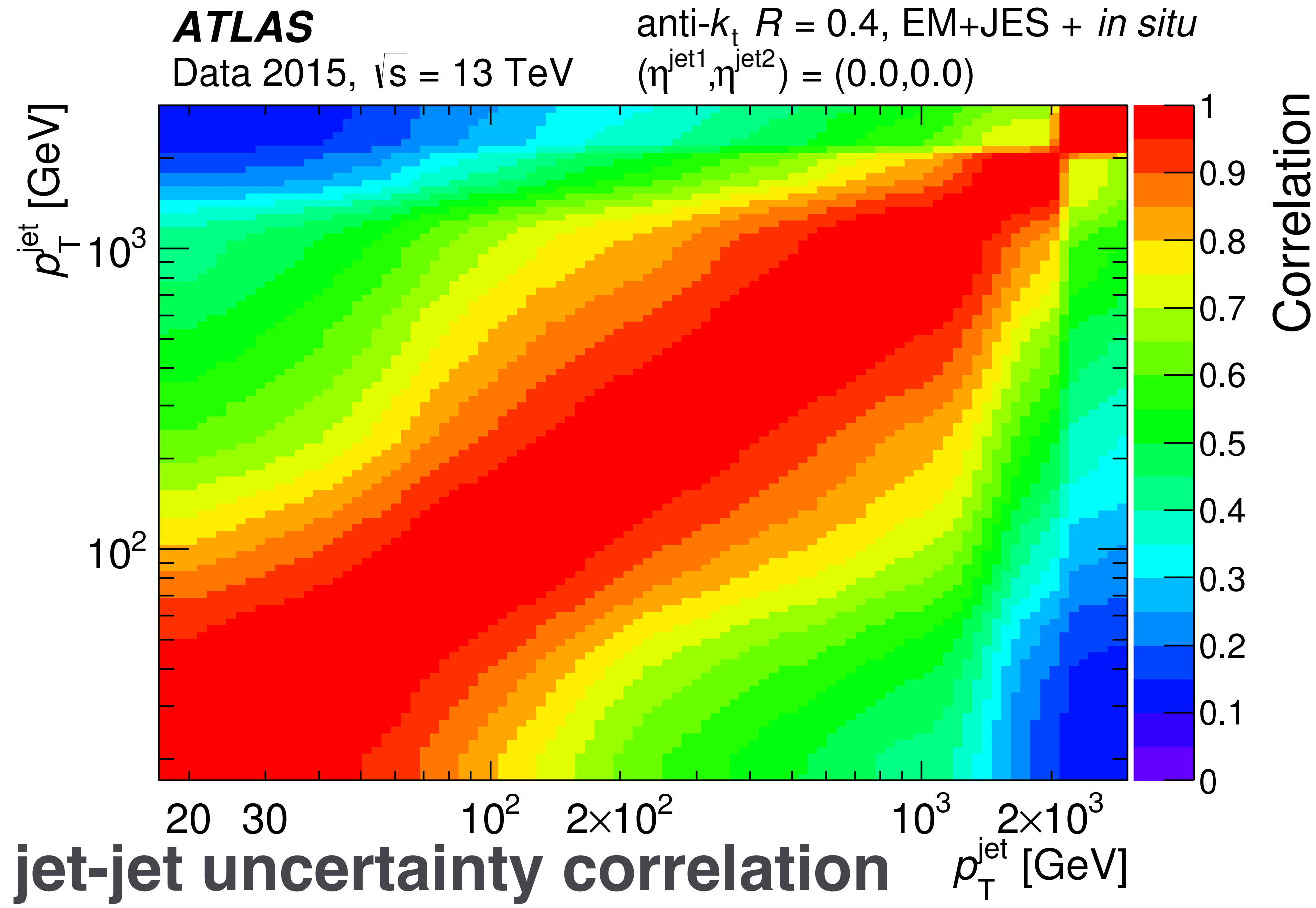
*A residual calibration is derived using in situ measurements and is applied **only to data**.*

MC-based calibration



In situ calibration combination





jet-jet uncertainty correlation

Unfolded measurement

- Data unfolded with MC-based transfer matrix (Pythia8)

particle level↔reconstructed

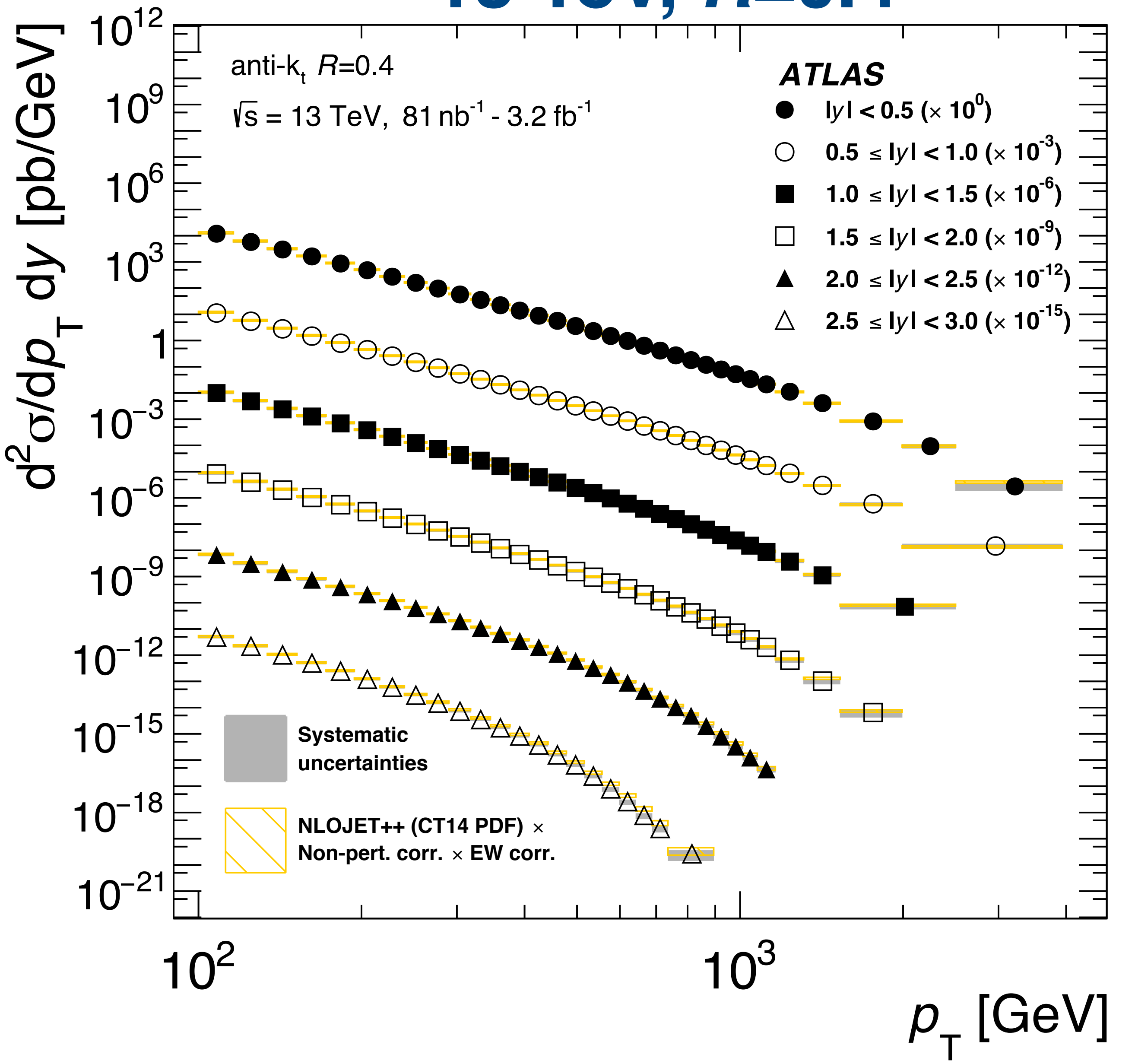
$$N_i^{\text{part}} = \sum_j N_j^{\text{reco}} \cdot \boxed{\mathcal{P}_j} \cdot \mathcal{A}_{ij} \, / \boxed{\mathcal{E}_i}$$

sum over bins

- Accounts for bin migrations: reco-matching purity & truth-matching efficiency
- **Systematic** uncertainties propagated through unfolding matrix
- **Statistical** uncertainties propagated with **pseudo-experiments**
  - Covariance matrix respects bin-to-bin correlations

Double-differential distribution (p_T & |y|)

13 TeV, *R*=0.4

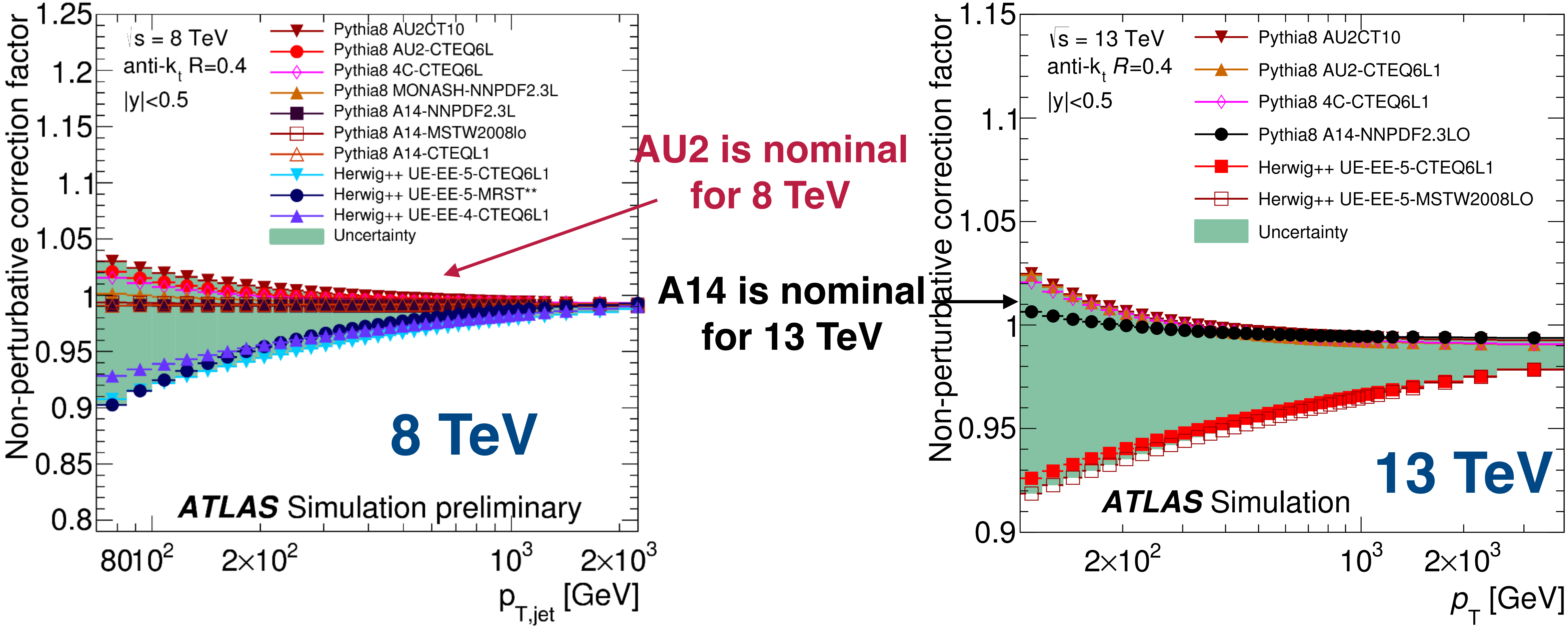


Smooth distributions, Good agreement by eye!

Cross-section: Theoretical Prediction

Switch from AU2 to A14 in 13 TeV reduced non-perturbative correction

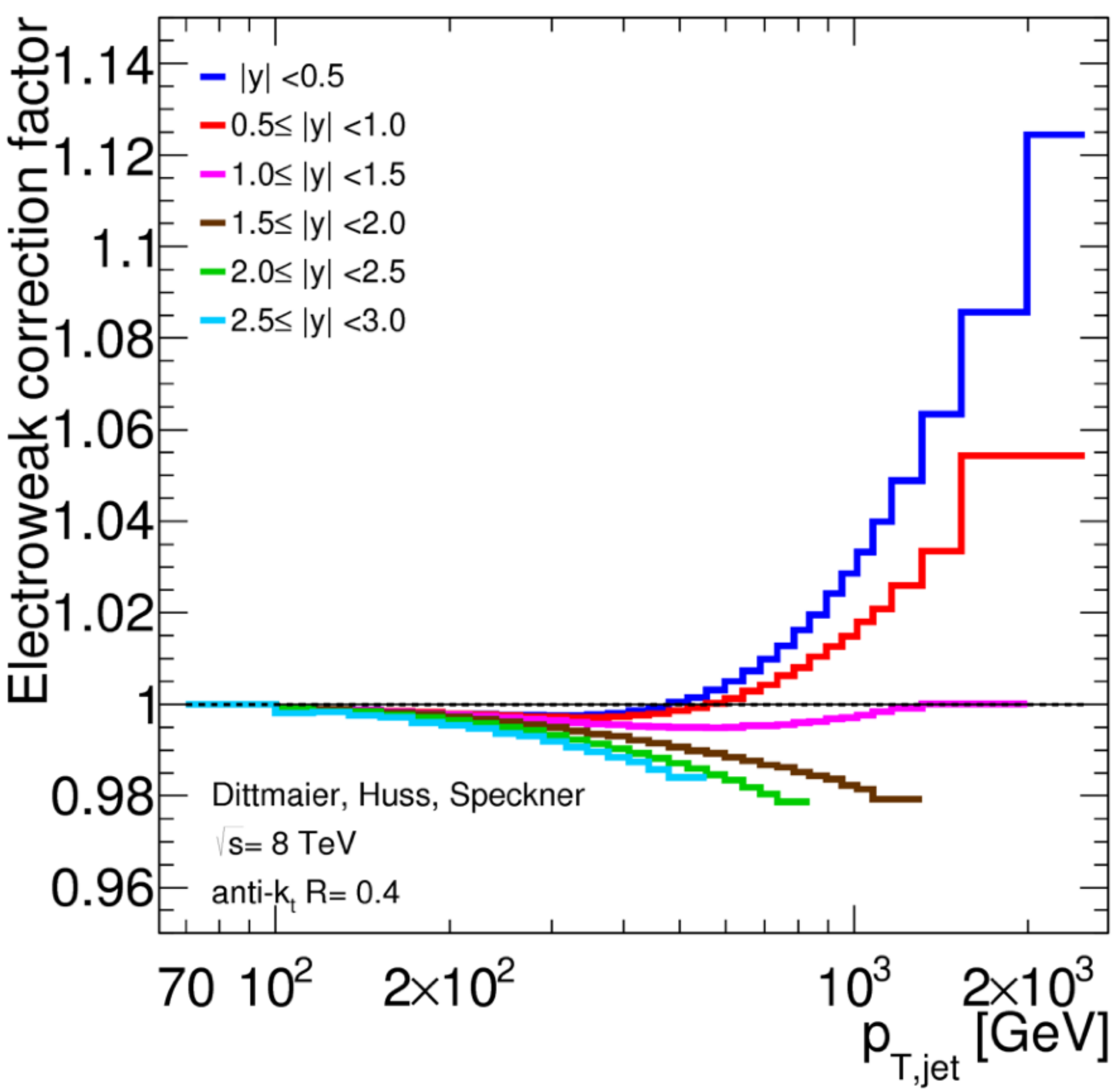
Non-perturbative correction on inclusive XS for *R*=0.4



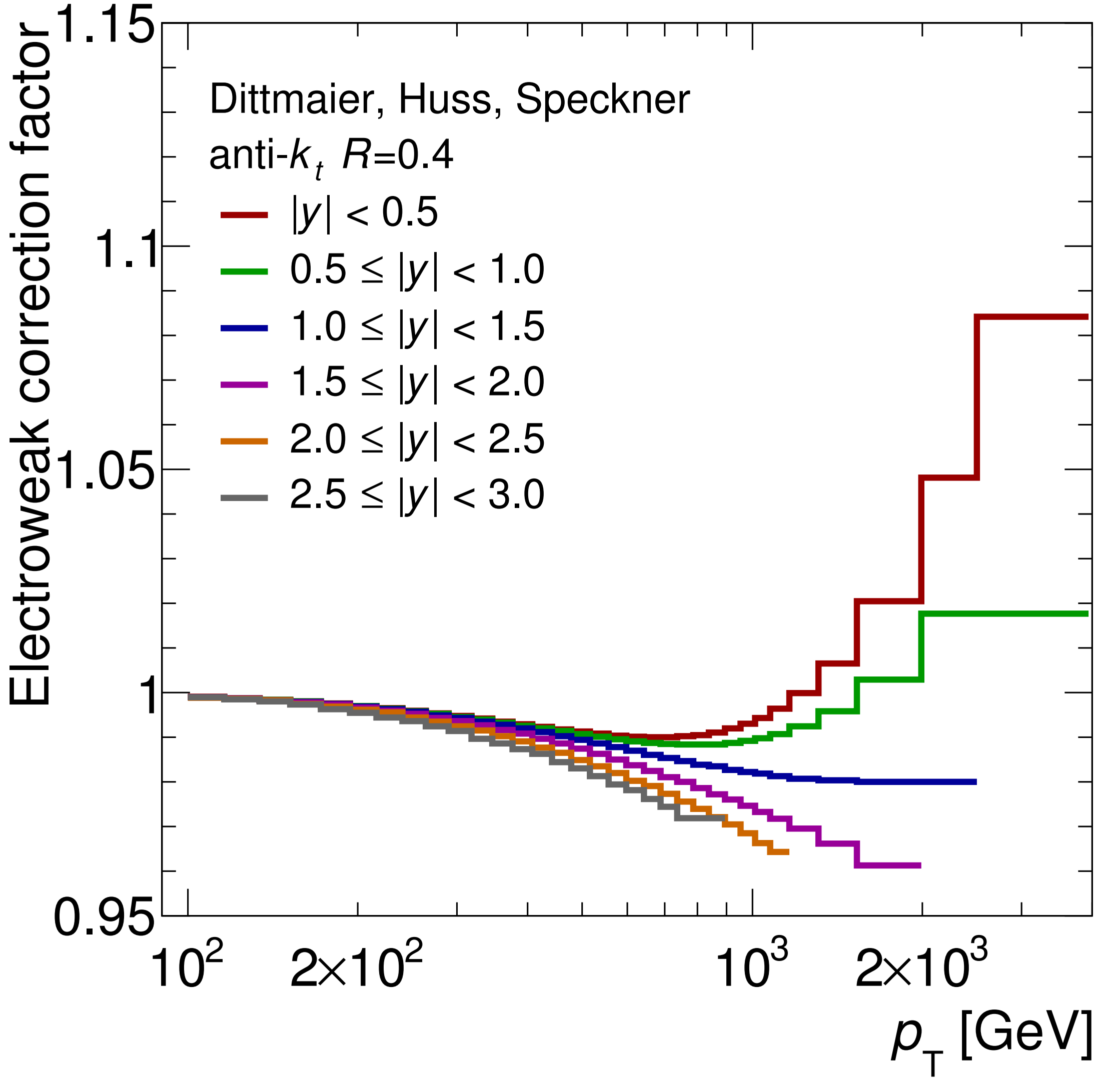
Electroweak Corrections

- Dedicated **EW correction** vary with **|y|**
  - Significant corrections at high-p_T

8 TeV



13 TeV

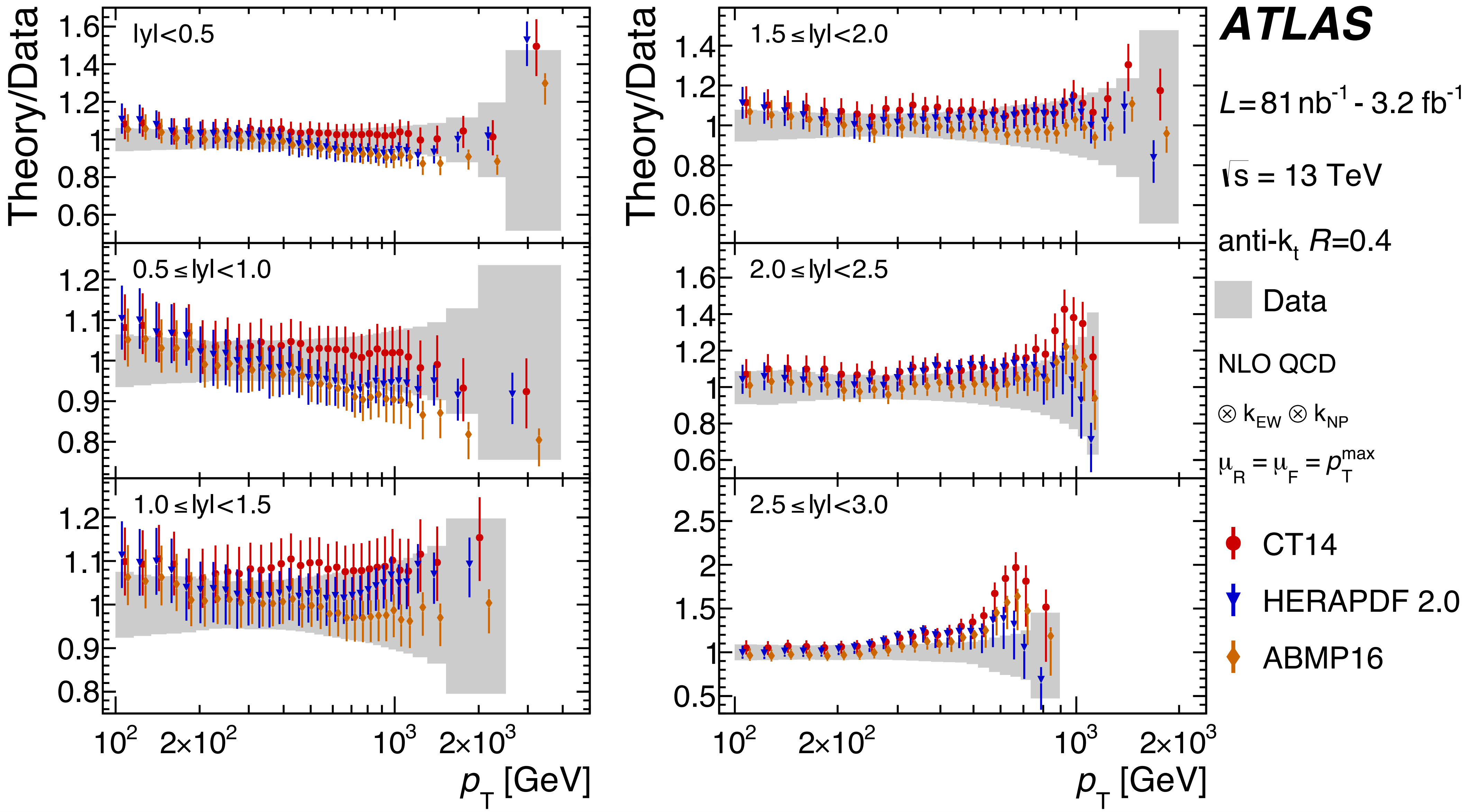


13 TeV Inclusive XS: PDF Set 2

- **CT14**, **HERAPDF2.0**, **ABMP16**
- Shape differences give slightly worse agreement

P_{obs} values from χ^2 goodness of fit

Rapidity ranges p_T^{max}	CT14	HERAPDF 2.0	ABMP16
$\lvert y\rvert < 0.5$	67%	31%	50%
$0.5 \leq \lvert y\rvert < 1.0$	5.8%	3.0%	2.0%
$1.0 \leq \lvert y\rvert < 1.5$	65%	50%	55%
$1.5 \leq \lvert y\rvert < 2.0$	0.7%	0.1%	0.4%
$2.0 \leq \lvert y\rvert < 2.5$	2.3%	0.7%	1.5%
$2.5 \leq \lvert y\rvert < 3.0$	62%	25%	55%

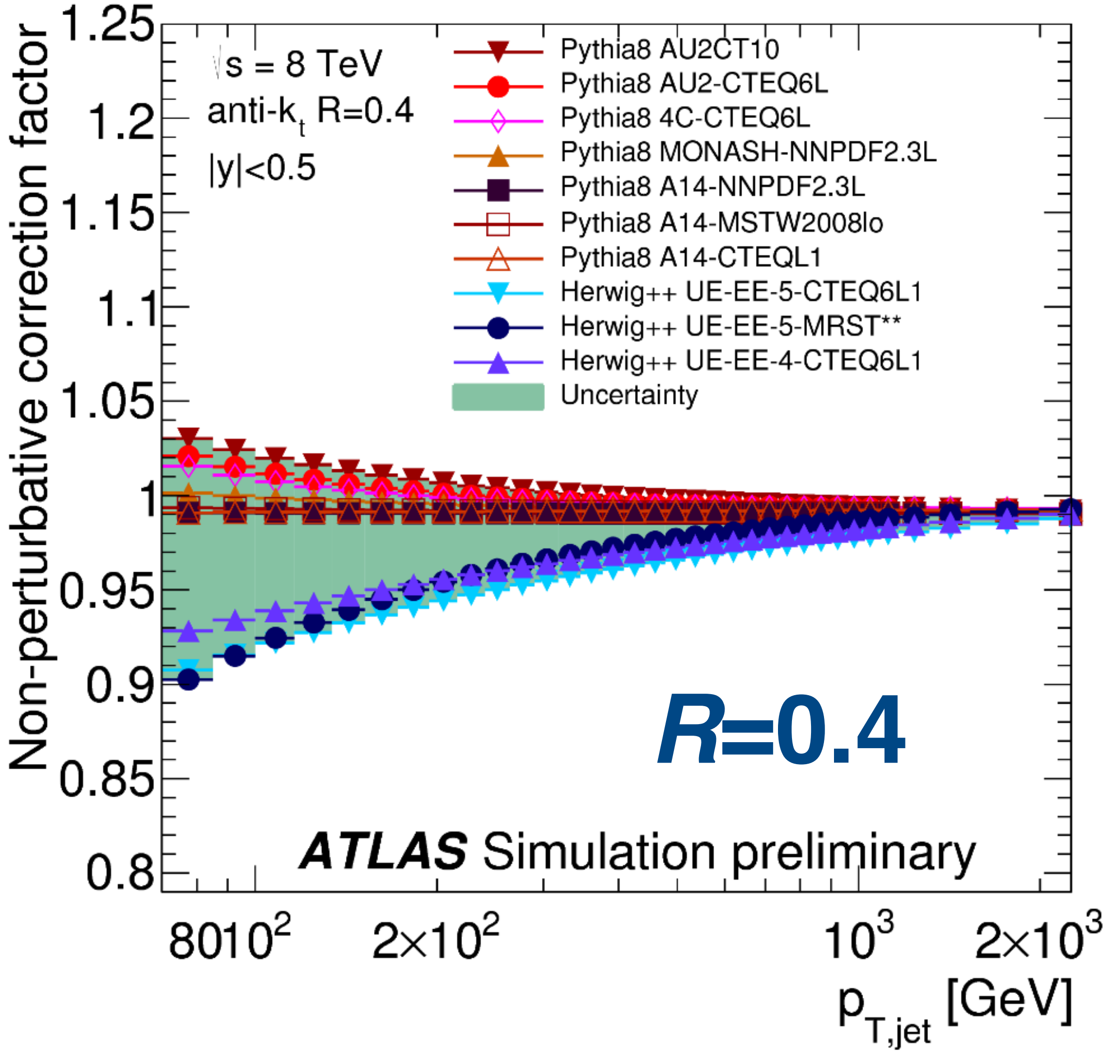


Backup: R=0.6 jets

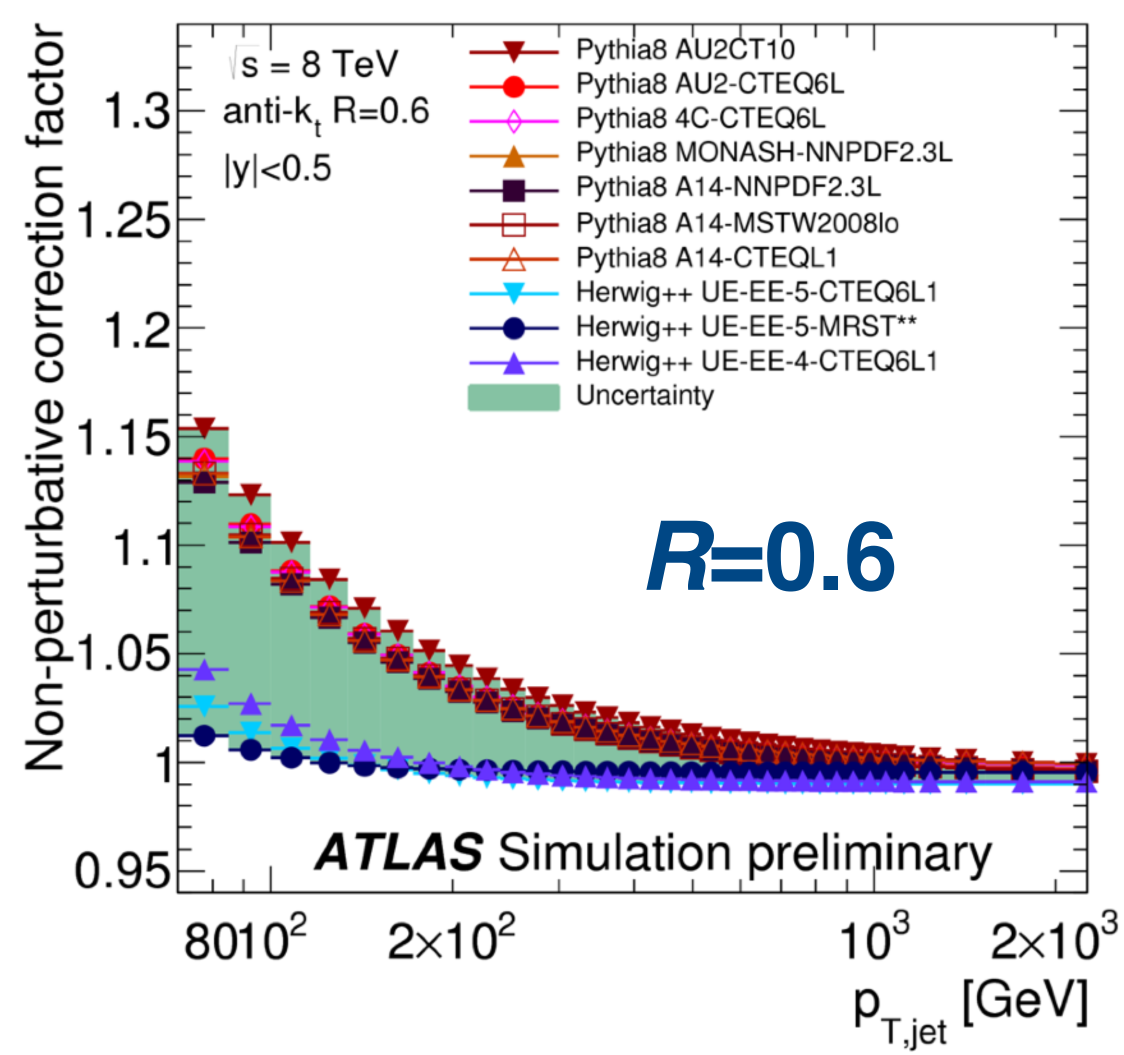
R=0.6: Theoretical Predictions

- Theoretical prediction of Matrix Element from **NLOJET++** interfaced with **various PDF sets**
- **Non-perturbative corrections** (hadronization, underlying event) taken from Pythia & Herwig tunes
  - Large spread between Pythia8 & Herwig++
  - Strong dependence on **jet radius**

Non-perturbative correction on inclusive XS @ 8 TeV

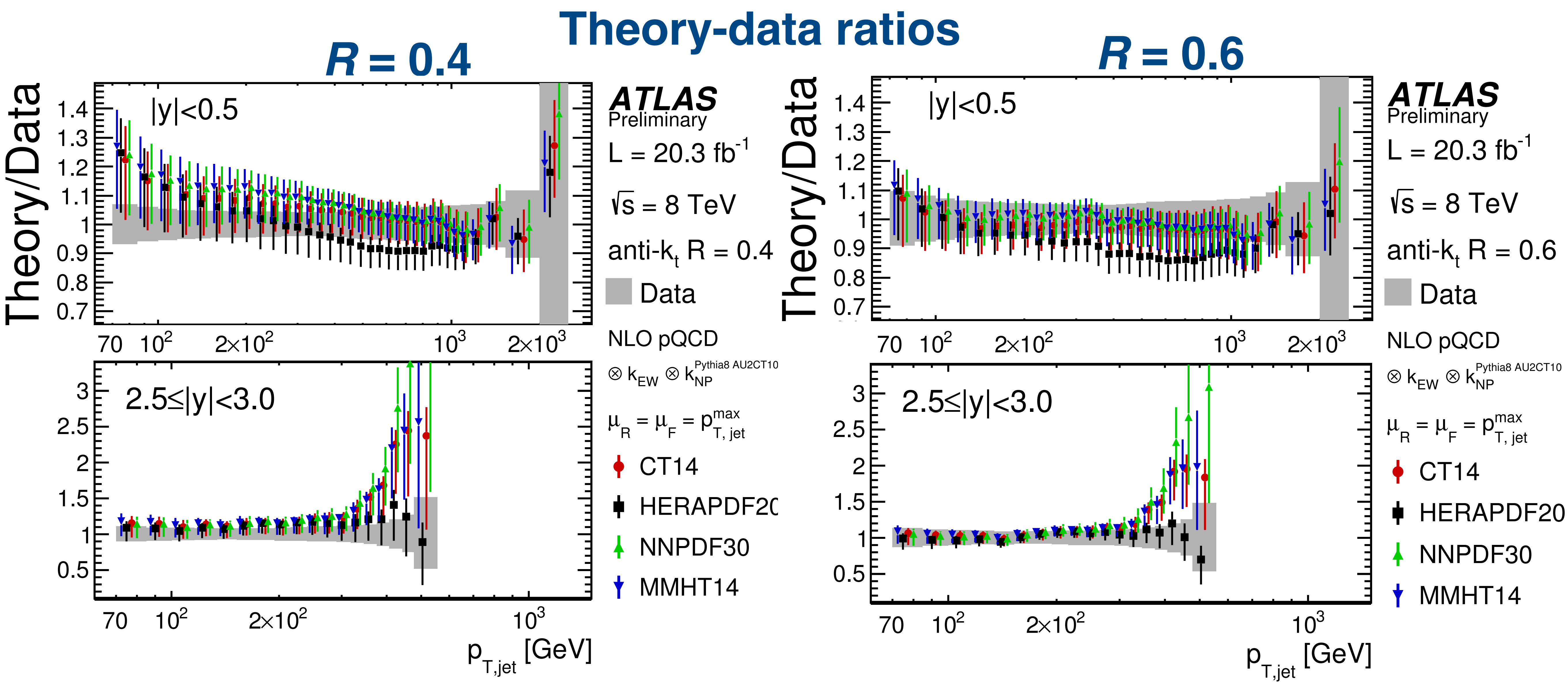


Spread taken as uncertainty



Varying Jet Width at 8 TeV

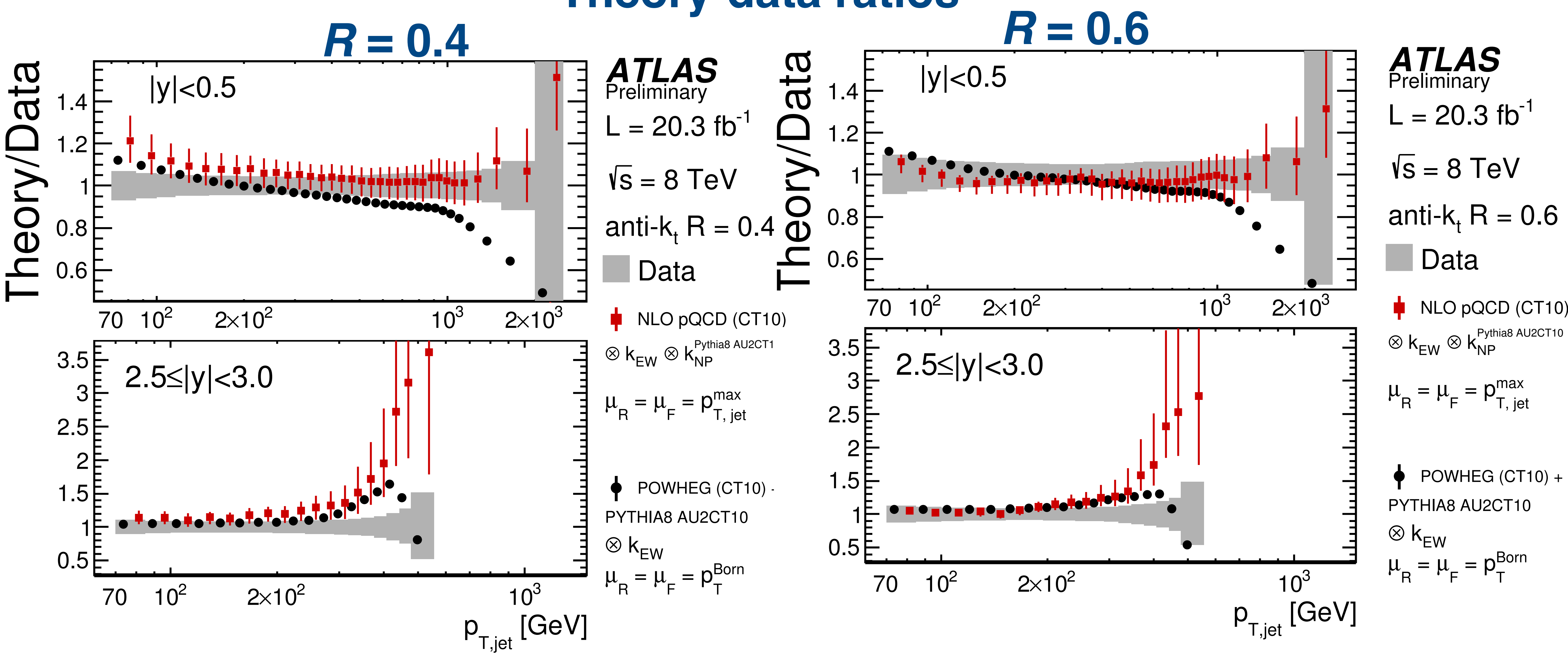
- **Good data-theory agreement for *R*=0.6** jets above |y| > 1, but some tension for central jets
- Comparison with R=0.4 shows sensitivity to details of parton showering & non-perturbative corrections



Parton Shower Matching at 8 TeV

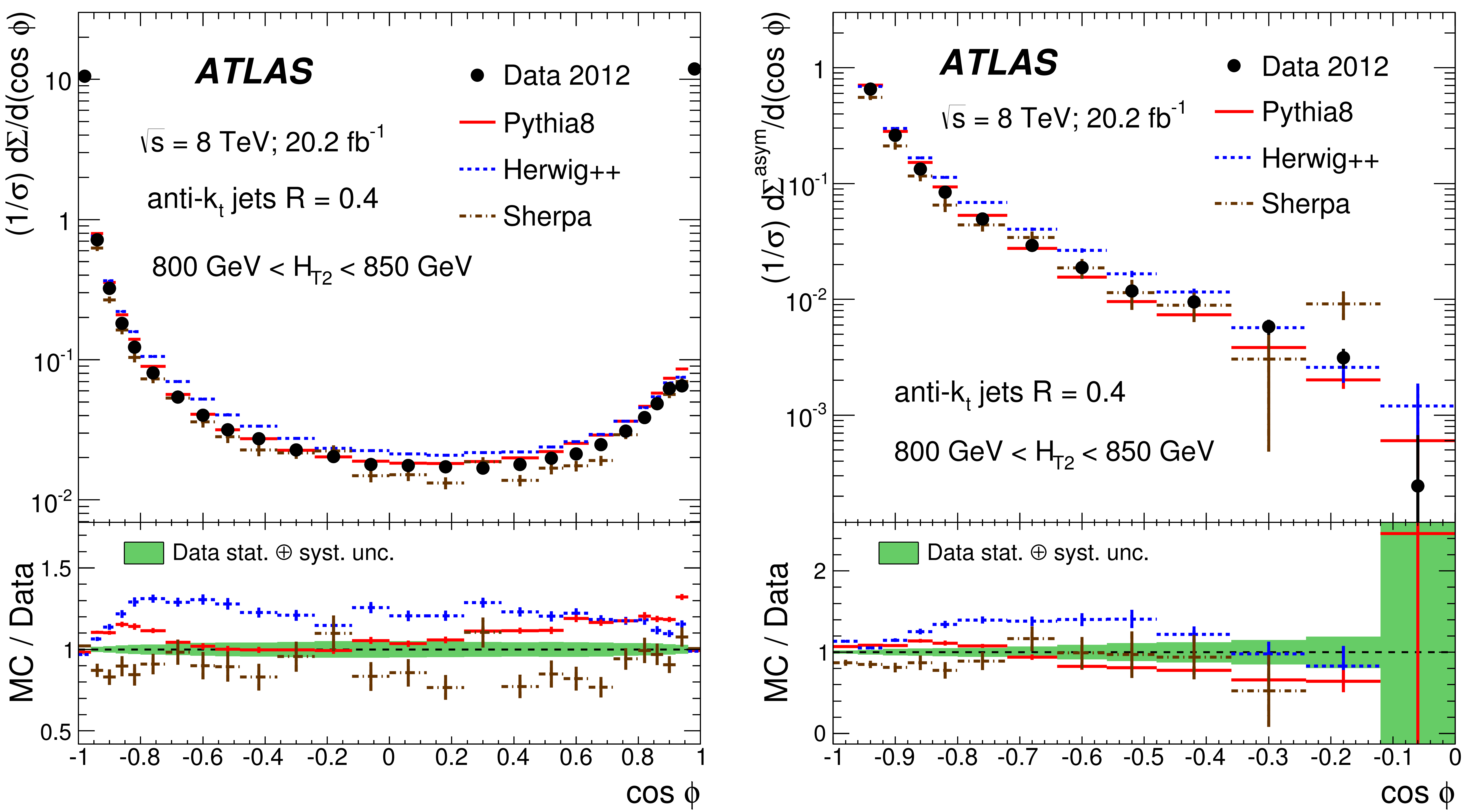
- **NLO prediction** (CT10) vs fully simulated **Powheg+Pythia8** (with parton shower matching)
- ***R*=0.4 vs *R*=0.6**: NLO prediction deviates up to 15% for low-p_T central jets, while **Powheg+Pythia8 agrees within 5%**
    - **Importance of parton showering in XS measurements**

Theory-data ratios



Asymmetric TEEC

TEEC vs Asymmetric TEEC



TEEC vs Asymmetric TEEC