

Measurement of jet production with the ATLAS detector and extraction of the strong coupling constant

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Outline

- ➊ Inclusive-jet cross-section at 8 TeV (20.2 fb^{-1})

[arXiv:1706.03192](#)

(13th June 2017)

- Inclusive-jet and dijet cross-sections at 13 TeV (3.2 fb^{-1})

ATLAS-CONF-2017-048

(6th July 2017)

- ➋ TEEC measurements and extraction of α_s

[arXiv:1707.02562](#)

(9th July 2017)

Overview (Jet cross-sections at 8 and 13 TeV)

- ▶ Measurement of the inclusive-jet cross section at 8(13) TeV with an integrated luminosity of $20.2(3.2)\text{ fb}^{-1}$.
- ▶ Measurement of the dijet cross section at 13 TeV with an integrated luminosity of 3.2 fb^{-1} .
- ▶ Measured cross-sections are compared to NLO QCD calculations corrected for non-perturbative and electroweak effects.
- ▶ Level of agreement with NLO predictions is quantified via a χ^2 test.
- ▶ Qualitative comparison with the recent NNLO QCD calculations for inclusive-jet cross-section at 13 TeV. (Our first NNLO comparison!)

Event Reconstruction and Selection

- ▶ Jets reconstructed using the anti- k_t algorithm, with a radius parameter value of R=0.4 (8 and 13 TeV) and R=0.6 (8 TeV).
- ▶ Jets calibrated using Monte Carlo simulation and data-driven methods.

Analysis	Selection	Phase-space
Inclusive-jet @8 TeV	$ y < 3.0$ $p_T > 70 \text{ GeV}$	$ y < 3.0$ $p_T : 70 - 2500 \text{ GeV}$
Inclusive-jet @13 TeV	$ y < 3.0$ $p_T > 100 \text{ GeV}$	$ y < 3.0$ $p_T : 100 - 3500 \text{ GeV}$
Dijet @13 TeV	$y^* < 3.0$ $p_{T2} > 75 \text{ GeV}$ $H_{T2} = (p_{T1} + p_{T2}) > 200 \text{ GeV}$	$y^* < 3.0$ $m_{jj} : 300 - 9000 \text{ GeV}$

$y^* = |y_1 - y_2| / 2$ where 1,2 subscripts label the highest and second highest p_T jet within $|y| < 3.0$

Cross-section definition

The **inclusive-jet** cross-section is measured as a function of the jet p_T , in six absolute jet rapidity $|y|$ bins:

$$\begin{aligned} |y| < 0.5, \quad 0.5 \leq |y| < 1.0, \quad 1.0 \leq |y| < 1.5, \\ 1.5 \leq |y| < 2.0, \quad 2.0 \leq |y| < 2.5, \quad 2.5 \leq |y| < 3.0. \end{aligned}$$

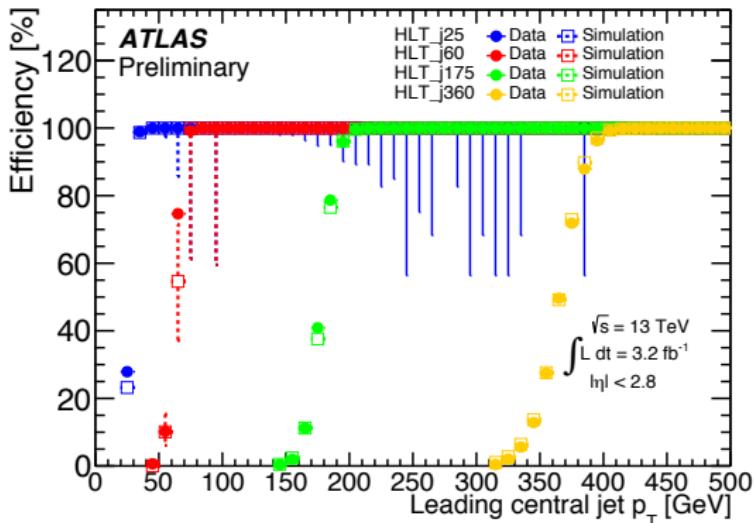
The **dijet** cross-section is measured as a function of the dijet invariant mass, in six y^* bins:

$$\begin{aligned} y^* < 0.5, \quad 0.5 \leq y^* < 1.0, \quad 1.0 \leq y^* < 1.5, \\ 1.5 \leq y^* < 2.0, \quad 2.0 \leq y^* < 2.5, \quad 2.5 \leq y^* < 3.0. \end{aligned}$$

Trigger

Trigger Data is selected using several jet transverse energy thresholds.

Trigger strategy Inclusive combination of single-jet triggers. arXiv:0901.4118



Jet Trigger Efficiency ATL-DAQ-PUB-2016-001

- The trigger efficiency is equal to or above 99.9% in the p_T range where it was considered.

Monte Carlo Generators

Pythia, Sherpa, Powheg and Herwig++ MC generators¹ used for:

- Deconvolution of detector effects (unfolding) (Pythia and Sherpa).
- Evaluation of non-perturbative (NP) corrections (Pythia).
- Estimation of NP correction uncertainties (Pythia and Herwig++).
- Propagation of experimental systematic uncertainties (Pythia and Powheg).

¹The MC versions and PDF sets used for each generator are detailed in backup slide 27

Bayesian Unfolding

- ▶ Iterative Dynamically Stabilised (IDS) method used to correct reconstructed spectra for detector inefficiencies and resolution effects.
- ▶ Based on a transfer matrix (TM) constructed using simulated events.
- ▶ **Inclusive-jet:** the TM is filled jet by jet by matching a reco jet with a particle-level jet within a radius of $R = 0.3$.
- ▶ **Dijet:** the TM is filled event by event when lying in the same y^* bin.
- ▶ Three steps of the unfolding procedure correcting for:
 - ① Matching impurity at reconstructed level (\mathcal{P}_j).
 - ② Migrations between neighbour $p_T(m_{jj})$ bins (\mathcal{A}_{ij}).
 - ③ Matching inefficiency at particle-level (\mathcal{E}_i).

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

Theoretical Predictions

- QCD calculations: Done with NLOJet++ plus non-perturbative and electroweak corrections

Nominal scale choice:

- leading jet p_T (p_T^{\max}).

PDFs: CT14, NNPDF 3.0, MMHT14, HERAPDF 2.0, ABMP16.

Uncertainties in the NLO calculation:

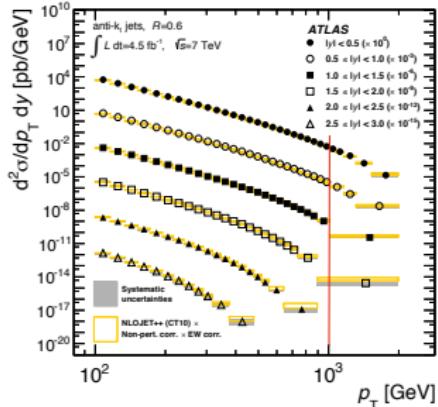
- (μ_R, μ_F) scale variations (dominant at low p_T).
- PDFs (dominant at high p_T).
- α_s variation (mostly constant in all p_T and $|y|$ ranges considered).

Additional theoretical uncertainty:

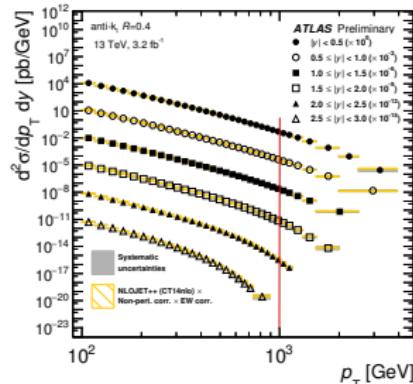
- An alternative scale choice based on each jet p_T (p_T^{jet}) was also considered.
- Difference w.r.t to p_T^{jet} was treated as an uncertainty.

Results: Cross-section comparison

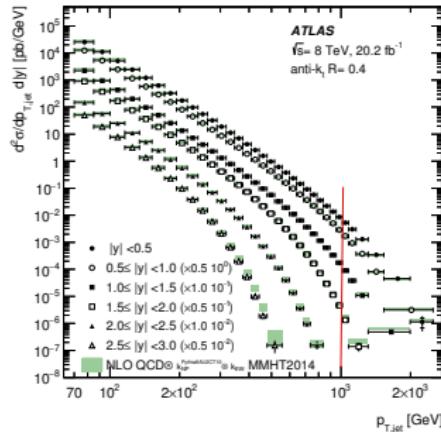
7 TeV (arXiv:1410.8857)



13 TeV (ATLAS-CONF-2017-048)



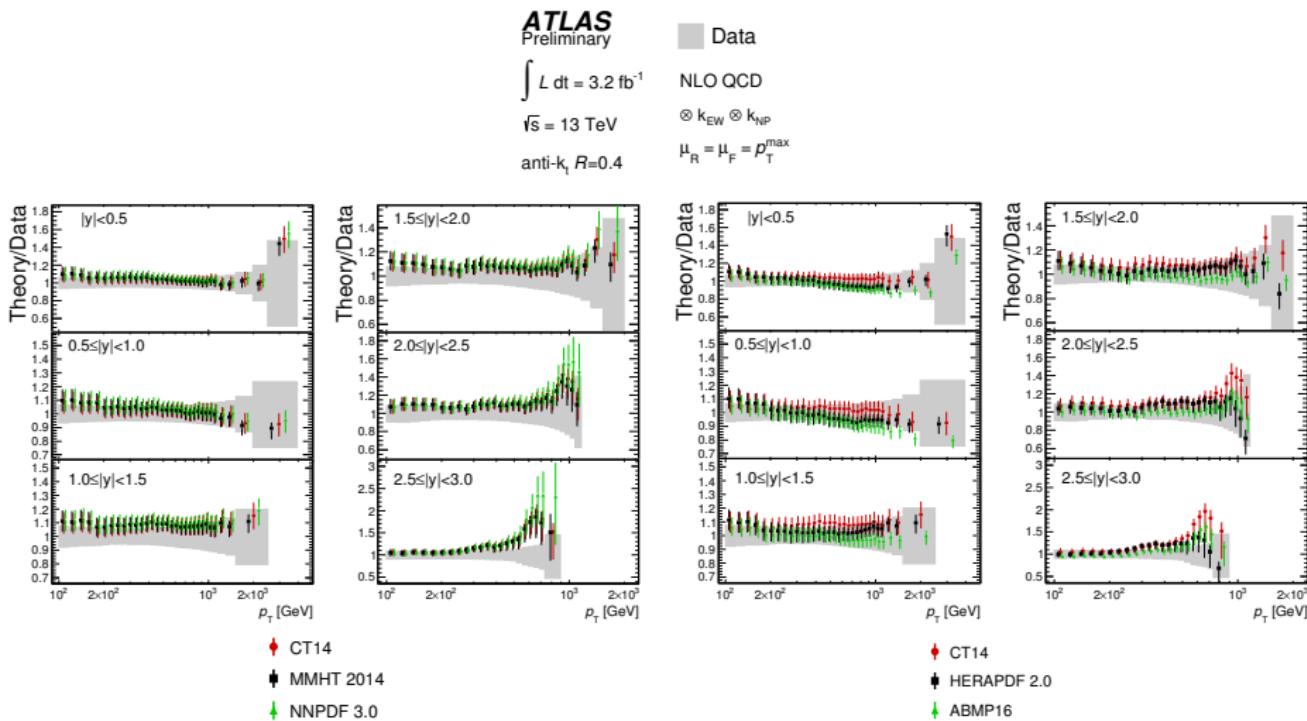
8 TeV (arXiv:1706.03192)



- ▶ 7 TeV result shown as a comparison with 8 and 13 TeV.
- ▶ Significant improvement in systematics and range w.r.t 7 TeV measurement.
- ▶ Greater p_T range reached by 13 TeV w.r.t 8 TeV.

Results: NLOJet++ vs Unfolded Data (Incl-jet 13 TeV)

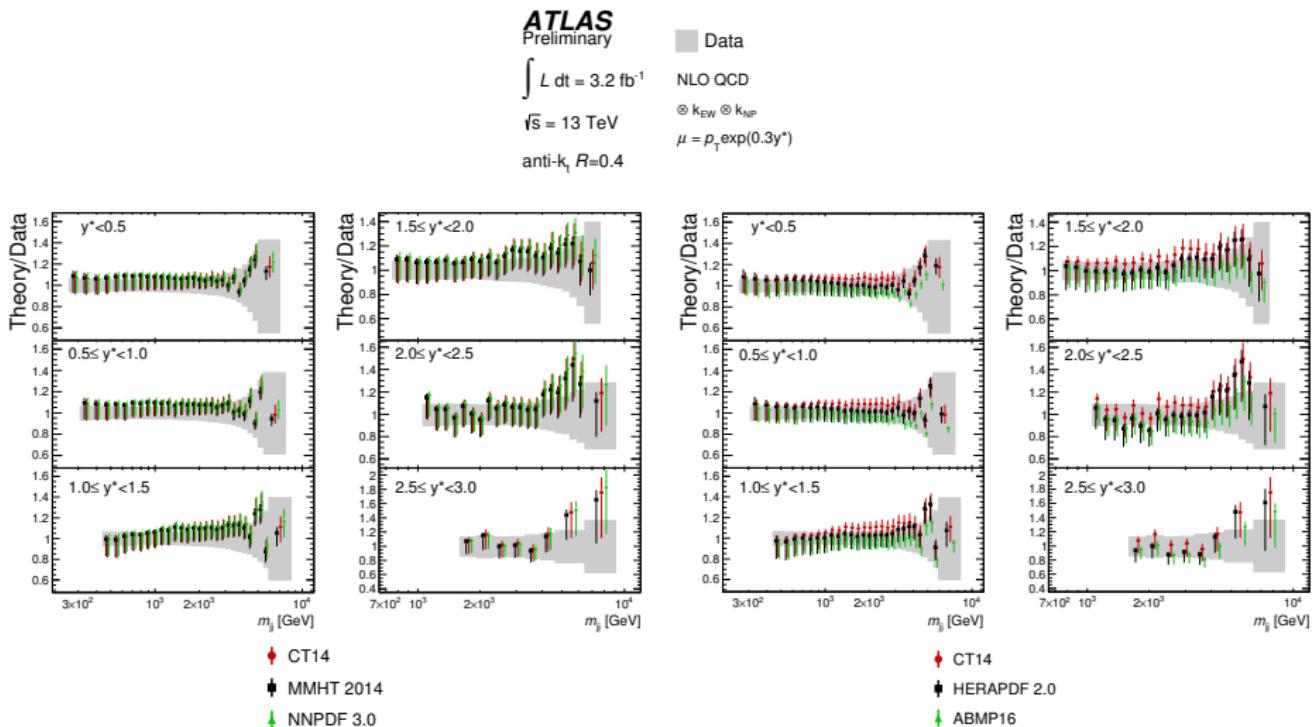
(ATLAS-CONF-2017-048)



- NNPDF, CT14 and MMHT overestimate the cross-section for the last two $|y|$ bins.

Results: NLOJet++ vs Unfolded Data (Dijet 13 TeV)

(ATLAS-CONF-2017-048)



Results: NNLOJet vs Unfolded Data (ATLAS-CONF-2017-048)

NEW

ATLAS
Preliminary

$$\int L dt = 3.2 \text{ fb}^{-1}$$

$\sqrt{s} = 13 \text{ TeV}$

anti- k_t $R=0.4$

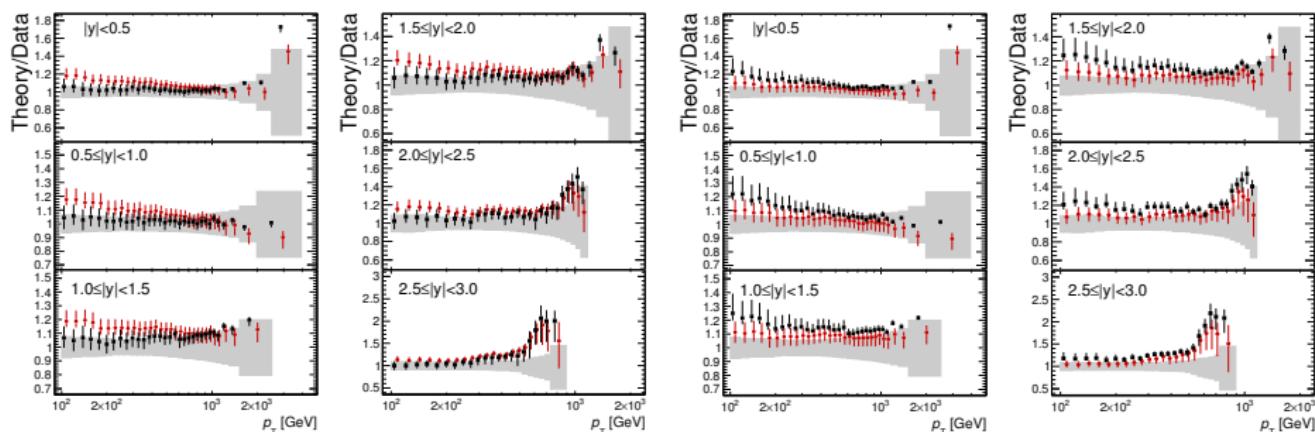
Data

NLO QCD

$\otimes k_{\text{EW}} \otimes k_{\text{NP}}$

NLO
MMHT 2014 NLO

NNLO
MMHT 2014 NNLO



$$\mu_R = \mu_F = p_T^{\text{jet}}$$

$$\mu_R = \mu_F = p_T^{\max}$$

This is what we want 😊

This is not what we want 😞

Results: p-values w.r.t NLO (Incl-jets 8 & 13 TeV)

8 TeV

Rapidity ranges	CT14	MMHT2014	P_{obs}	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

Rapidity ranges	CT14	MMHT 2014	P_{obs}	NNPDF 3.0	HERAPDF 2.0	ABMP16
p_T^{\max}						
$ y < 0.5$	67%	65%	62%	31%	50%	
$0.5 \leq y < 1.0$	5.8%	6.3%	6.0%	3.0%	2.0%	
$1.0 \leq y < 1.5$	65%	61%	67%	50%	55%	
$1.5 \leq y < 2.0$	0.7%	0.8%	0.8%	0.1%	0.4%	
$2.0 \leq y < 2.5$	2.3%	2.3%	2.8%	0.7%	1.5%	
$2.5 \leq y < 3.0$	62%	71%	69%	25%	55%	

- ▶ Consistent results between 8 and 13 TeV.

Results: global fits

8 TeV

χ^2/ndf	$p_T^{\text{jet},\text{max}}$		p_T^{jet}	
	$R = 0.4$	$R = 0.6$	$R = 0.4$	$R = 0.6$
$p_T > 70 \text{ GeV}$				
CT14	349/171	398/171	340/171	392/171
HERAPDF2.0	415/171	424/171	405/171	418/171
NNPDF3.0	351/171	393/171	350/171	393/171
MMHT2014	356/171	400/171	354/171	399/171

13 TeV

χ^2/ndf 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

- ▶ Strong tensions (p-values $\ll 10^{-3}$) at 8 and 13 TeV observed when considering all jet p_T and $|y|$ regions.
- ▶ Numerous studies on the correlation of the systematic sources were done but the tension remains.

Systematic Uncertainties: Correlation Studies at 8 TeV

- ▶ To test in a realistic way the sensitivity to the correlations, alternative scenarios were provided for the two-point systematics.
- ▶ Different options for splitting the systematics in sub-components as a function of p_T and $|y|$ where studied.
- ▶ For the theoretical uncertainties 3 other splitting options were tried as discussed [here](#).
- ▶ The χ^2 is reduced by up to 87 units by splitting both the theoretical and experimental uncertainties.
- ▶ Despite this, the corresponding p_{obs} values are still $\ll 10^{-3}$

Results: p-values (Dijets 13 TeV)

y^* ranges	CT14	MMHT 2014	NNPDF 3.0	P_{obs}	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%	

- ▶ As opposed to the inclusive case, good agreement when considering all y^* bins together.

TEEC measurements and extraction of α_s

Motivation

- ▶ Transverse energy-energy correlations (**TEEC**) and its associated asymmetry (**ATEEC**) leads to precision tests of pQCD.
- ▶ NLO calculations corrected by NP and EW effects compared with data.

TEEC:

$$\frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} \equiv \frac{1}{N \Delta \cos \phi} \sum_{A=1}^N \sum_{ij} \frac{E_{Ti}^A E_{Tj}^A}{\left(\sum_k E_{Tk}^A \right)^2} \delta(\cos \phi - \cos \phi_{ij})$$

- N: Number of events, labelled by index A.
- Indices i and j run over all jets in a given event.
- ϕ_{ij} azimuthal angle between jet i and jet j.

ATEEC:

$$\frac{1}{\sigma'} \frac{d\Sigma'^{\text{asym}}}{d\phi} \equiv \left. \frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} \right|_\phi - \left. \frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} \right|_{\pi-\phi}$$

- ▶ Determination of $\alpha_s(m_Z)$ is performed in different energy regimes, testing the running of α_s predicted by the QCD β -function.
- ▶ New coloured fermions would imply modifications to the β -function.

MC Generators and Selection

MC **Pythia**, **Herwig++**, and **Sherpa** were used for the description of jet production.

Trigger Data collected using a single-jet trigger with $E_T > 360$ GeV.

Selection Jets with $p_T > 100$ GeV, $|\eta| < 2.5$ and $H_{T2} > 800$ GeV.

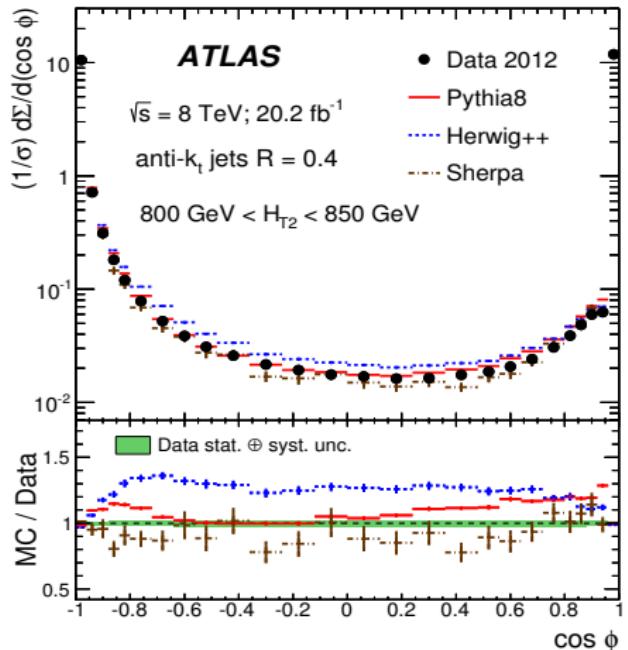
- ▶ To study the running of α_s , the data was binned in H_{T2} :

H_{T2} range [GeV]	Number of events	$\langle Q \rangle = \langle H_{T2} \rangle / 2$ [GeV]
[800, 850]	1 809 497	412
[850, 900]	1 240 059	437
[900, 1000]	1 465 814	472
[1000, 1100]	745 898	522
[1100, 1400]	740 563	604
[1400, 5000]	192 204	810

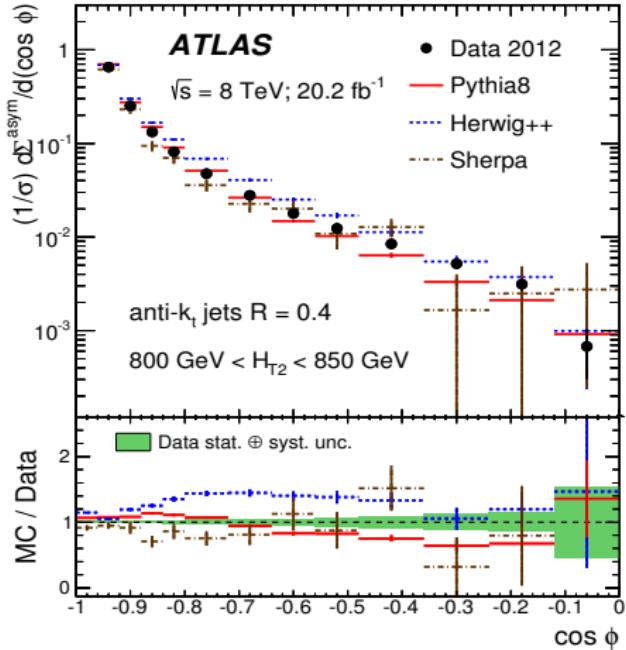
- ▶ Distributions were unfolded with an iterative Bayesian method.

Measured observables (arXiv:1707.02562)

TEEC

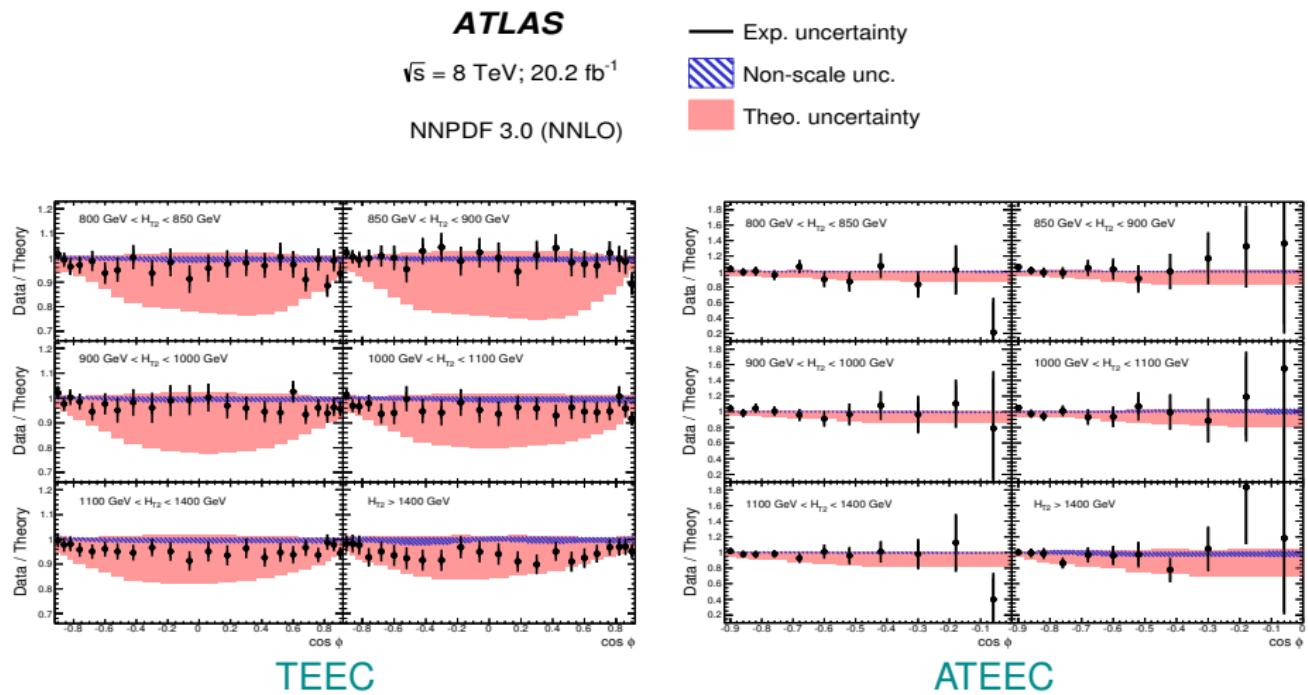


ATEEC



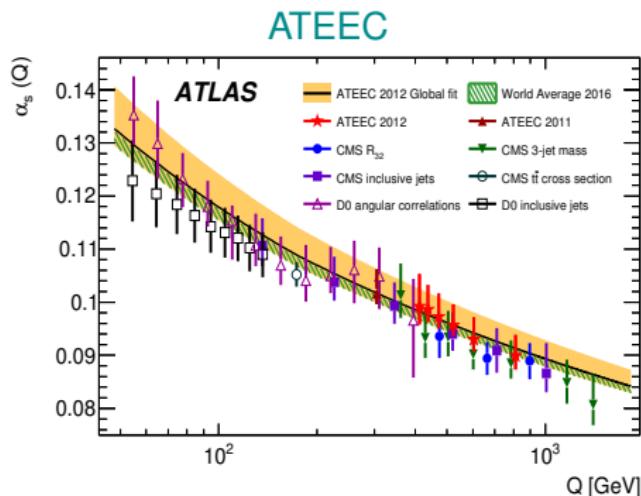
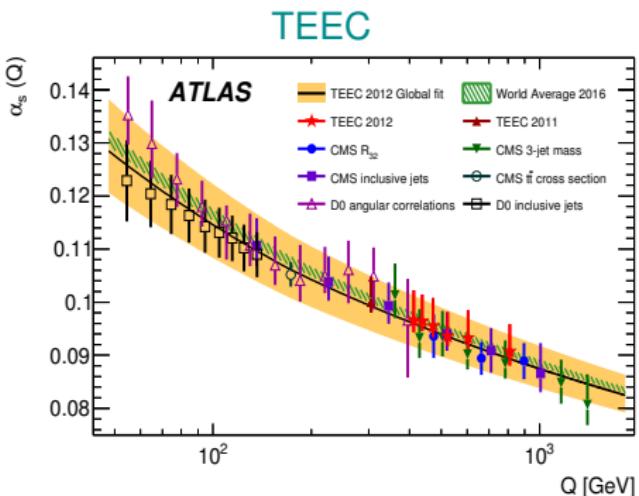
- ▶ Peak at $\cos \phi = -1$: back-to-back configuration in dijet events.
- ▶ Peak at $\cos \phi = +1$: self-correlations of one jet with itself ($i = j$).

Results: NLOJet++ vs Unfolded Data (arXiv:1707.02562)



- ▶ pQCD correctly describes the data within uncertainties.

- ▶ The **global fit** is done by considering all H_{T2} bins into a single one.
- ▶ **Partial** and **global** fits are in agreement with previous measurements.
- ▶ The uncertainty due to **normalization scales** is the dominant one.



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

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

Conclusions: Inclusive-jet and dijet analyses

- ▶ The measurements of the inclusive jet and dijet cross-sections at 8 and 13 TeV was presented.
- ▶ The Data were collected with the ATLAS detector during 2012(2015) corresponding to an integrated luminosity of 20.2(3.2) fb^{-1} .
- ▶ Quantitative(Qualitative) comparisons between data and NLO(NNLO) pQCD calculations, corrected by NP and EW effects, were performed.
- ▶ Fair agreement when considering jet cross-sections in individual $|y|, y^*$ bins independently.
- ▶ Tensions between data and theory observed when considering data from all jet p_T and $|y|$ regions.
- ▶ No significant deviations between data and NNLO when using p_T^{jet} scale.
- ▶ NNLO overestimates the cross-sections when using p_T^{max} scale.

Conclusions: Measurement of α_s

- ▶ The measurement of α_s based on energy-energy correlation observables (TEEC & ATEEC) was presented.
- ▶ The Data was collected with the ATLAS detector during 2012 corresponding to an integrated luminosity of 20.2 fb^{-1} .
- ▶ NLO calculations, corrected by NP and EW effects, are compared to the measurement.
- ▶ The result shows excellent agreement between data and theory.
- ▶ Determination of α_s was done by a χ^2 fit to the theoretical predictions for different $\langle Q \rangle$ values.
- ▶ Global fits were performed in TEEC and ATEEC observables, leading to:

$$\alpha_s(m_Z) = 0.1162 \pm 0.0011 \text{ (exp.)} \quad {}^{+0.0076}_{-0.0061} \text{ (scale)} \pm 0.0018 \text{ (PDF)} \pm 0.0003 \text{ (NP)},$$
$$\alpha_s(m_Z) = 0.1196 \pm 0.0013 \text{ (exp.)} \quad {}^{+0.0061}_{-0.0013} \text{ (scale)} \pm 0.0017 \text{ (PDF)} \pm 0.0004 \text{ (NP)},$$

- ▶ Good agreement with previous experiments and current world average.

back-up slides

Inclusive-jet and dijet cross-sections analyses

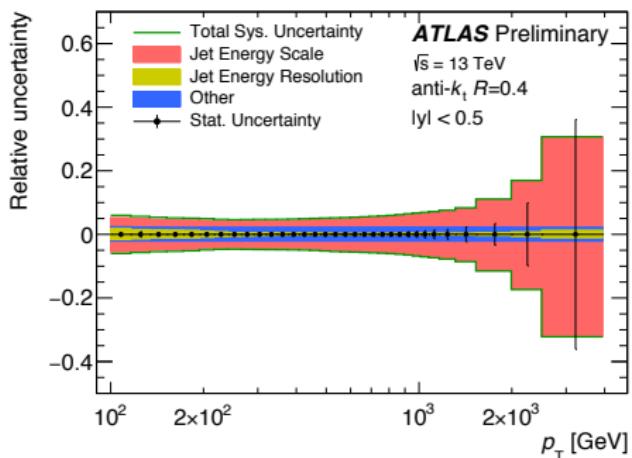
Monte Carlo Generators @8TeV & @13TeV

- ▶ Simulated events using the Pythia v8.160(v8.186) MC generator with CT10(NNPDF 2.3) LO PDF and AU2(A14) tune.
- ▶ Evaluation of non-perturbative uncertainties: Pythia v8.186 and Herwig++ v2.7.1.

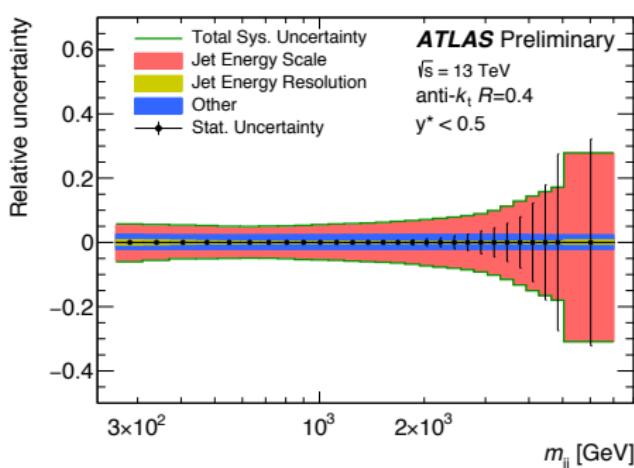
Experimental uncertainties @13 TeV (ATLAS-CONF-2017-048)

- ▶ The Jet Energy Scale, Jet Energy Resolution and Luminosity uncertainties were estimated and taken into account using MC and data-driven techniques.
- ▶ The JES is the dominating uncertainty.

inclusive-jet



dijet



Systematic uncertainties Correlation Studies at 8 TeV

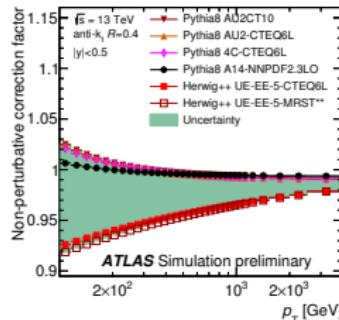
Splitting option	Sub-component(s) definition(s), completed by complementary
1	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot \text{uncertainty}$
2	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot 0.5 \cdot \text{uncertainty}$
3	$L(p_T[\text{TeV}], 0.1, 2.5) \cdot \text{uncertainty}$
4	$L(p_T[\text{TeV}], 0.1, 2.5) \cdot 0.5 \cdot \text{uncertainty}$
5	$L((\ln(p_T[\text{TeV}]))^2, (\ln(0.1))^2, (\ln(2.5))^2) \cdot \text{uncertainty}$
6	$L((\ln(p_T[\text{TeV}]))^2, (\ln(0.1))^2, (\ln(2.5))^2) \cdot 0.5 \cdot \text{uncertainty}$
7	$L(y , 0, 3) \cdot \text{uncertainty}$
8	$L(y , 0, 3) \cdot 0.5 \cdot \text{uncertainty}$
9	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot L(y , 0, 3) \cdot \text{uncertainty}$
10	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot \sqrt{1 - L(y , 0, 3)^2} \cdot \text{uncertainty}$
11	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot L(y , 0, 3) \cdot 0.5 \cdot \text{uncertainty}$
12	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot \sqrt{1 - L(y , 0, 3)^2} \cdot 0.5 \cdot \text{uncertainty}$
13	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot \sqrt{1 - L(y , 0, 1.5)^2} \cdot \text{uncertainty}$ $L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot L(y , 1.5, 3) \cdot \text{uncertainty}$

$$L(x, min, max) = \begin{cases} 0 & \text{if } x < min \\ \frac{x-min}{max-min} & \text{if } min < x < max \\ 1 & \text{if } x > max \end{cases}$$

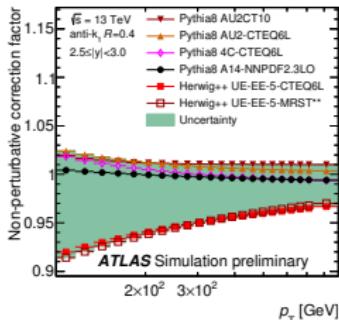
NP corrections at 13 TeV (ATLAS-CONF-2017-048)

Considers effects from underlying-event and hadronisation.

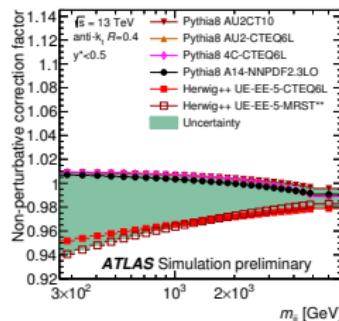
$$\blacktriangleright C_{NP} = \frac{MC(UE\ ON, HAD\ ON)}{MC(UE\ OFF, HAD\ OFF)}$$



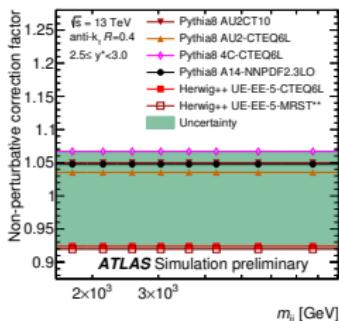
(a) $|y| < 0.5$



(b) $2.5 \leq |y| < 3.0$



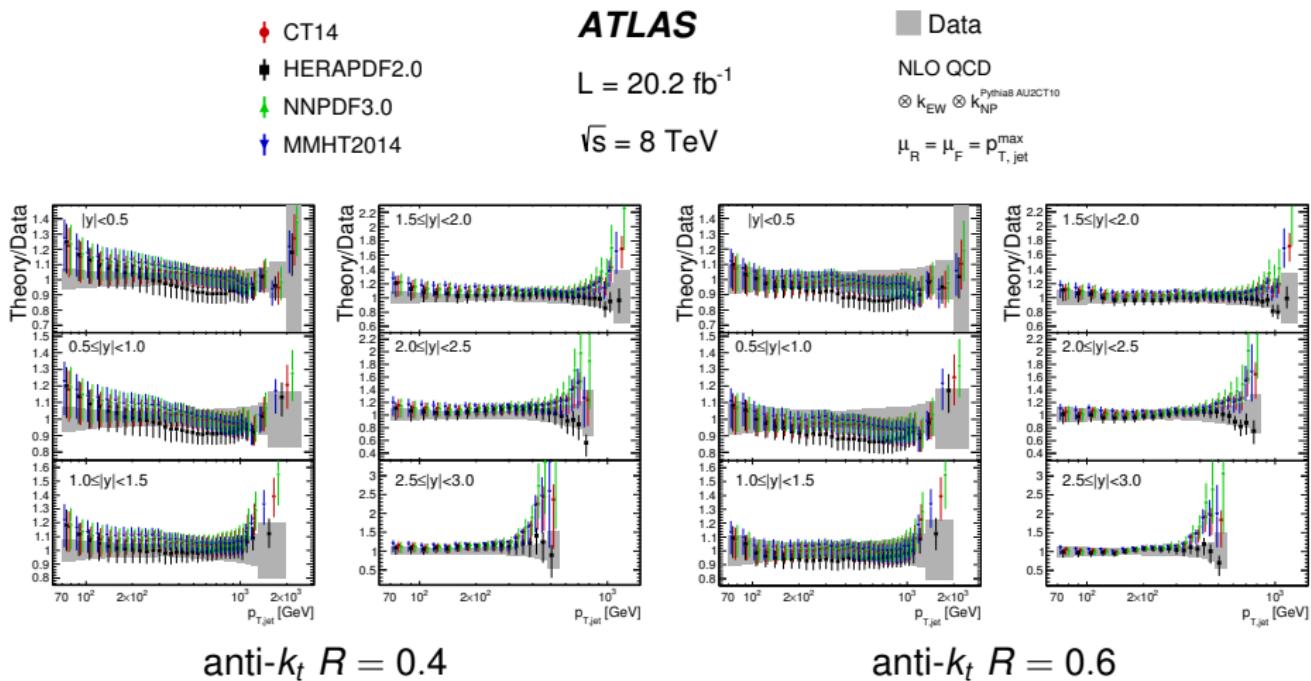
(c) $y^* < 0.5$



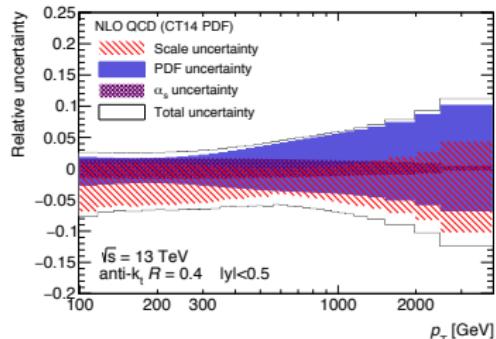
(d) $2.5 \leq y^* < 3.0$

Results: NLOJet++ vs Unfolded Data (8 TeV)

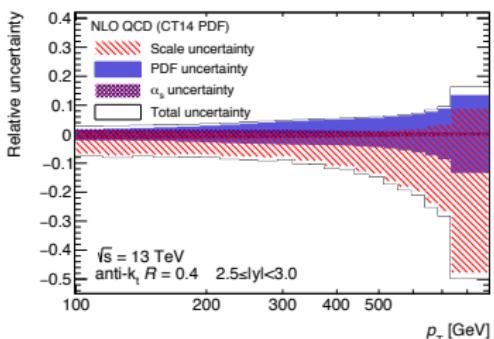
(arXiv:1706.03192)



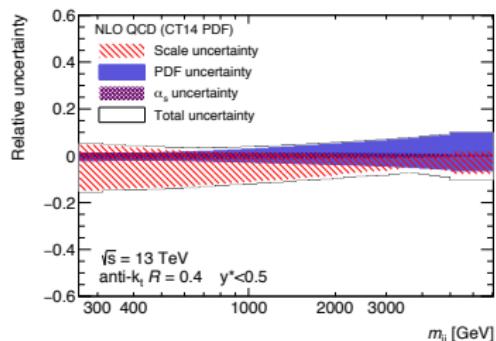
NLO QCD uncertainties at 13 TeV (ATLAS-CONF-2017-048)



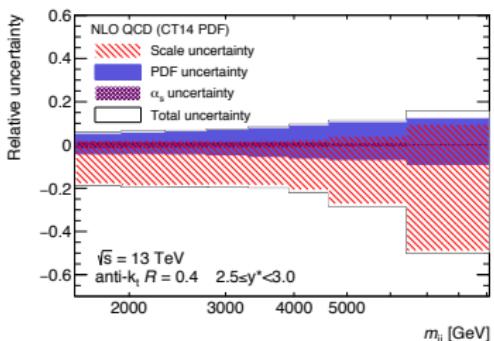
(a) $|\text{y}| < 0.5$



(b) $2.5 \leq |\text{y}| < 3.0$



(c) $y^* < 0.5$

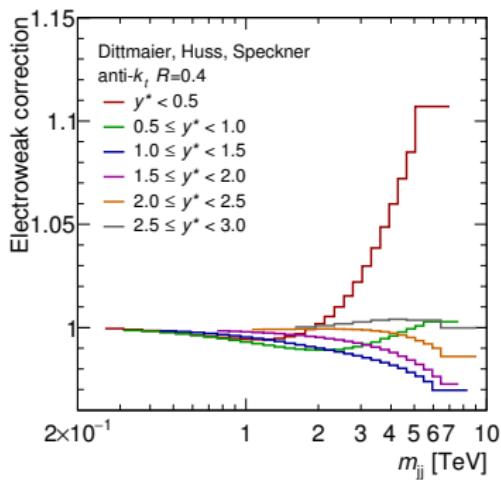
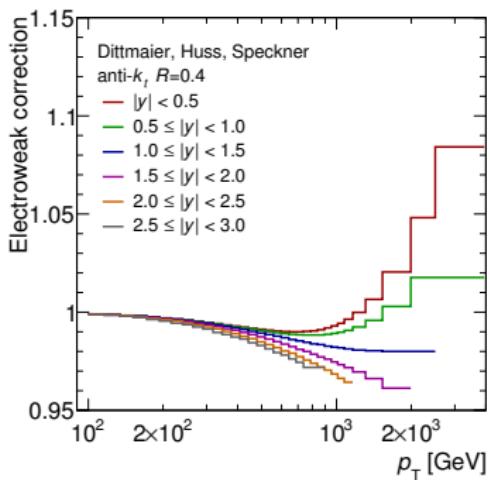


(d) $2.5 \leq y^* < 3.0$

EW corrections at 13 TeV (ATLAS-CONF-2017-048)

- ▶ NLO pQCD predictions are corrected for the effects of γ and W^\pm/Z interactions at the tree and 1-loop level
- ▶ The correction is defined as the ratio

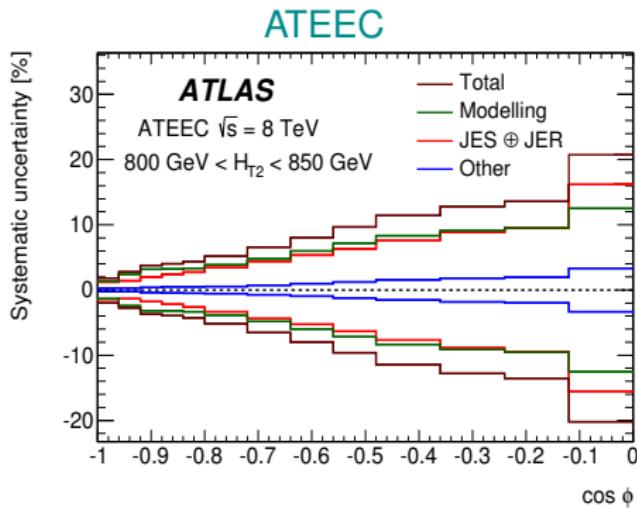
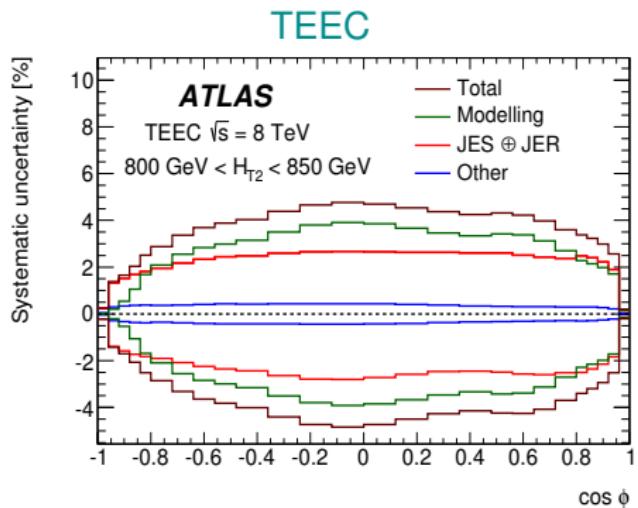
$$\frac{\sigma(2 \rightarrow 2, \text{LO}^{(\text{QCD})} + \text{NLO}^{(\text{EW})})}{\sigma(2 \rightarrow 2, \text{LO}^{(\text{QCD})})}$$



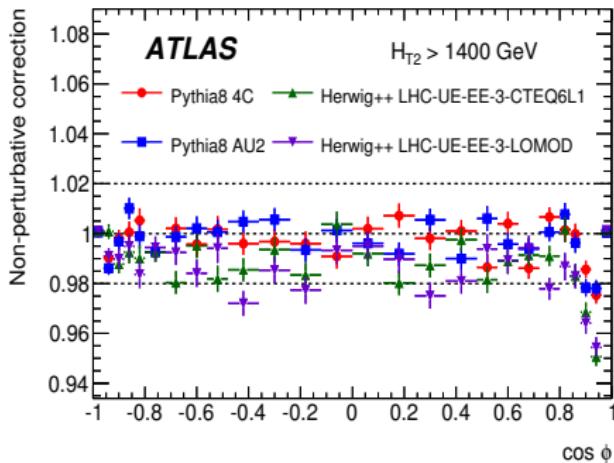
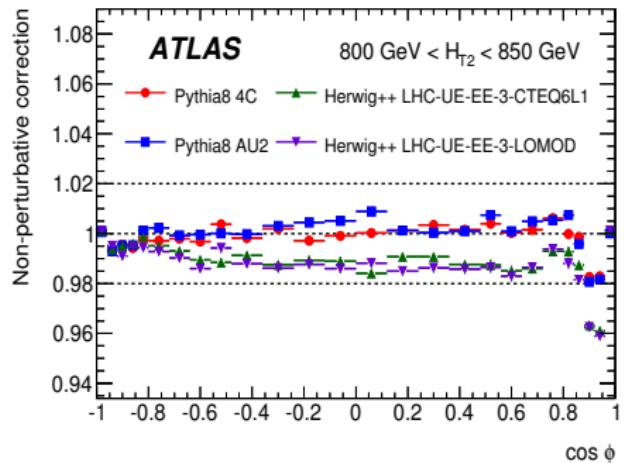
Measurement of α_s analysis

Experimental uncertainties (arXiv:1707.02562)

- ▶ The Jet Energy Scale, Jet Energy Resolution and Luminosity uncertainties were estimated and taken into account using MC and data-driven techniques.
- ▶ The **MC modelling** is the dominating uncertainty.
- ▶ It was obtained from the difference in the unfolded distributions between Pythia and Herwig++.



NP corrections (TEEC) (arXiv:1707.02562)



- ▶ Pythia8 with the AU2 tune is used for the nominal corrections.

Determination of α_s

- The evaluation of α_s is obtained by minimizing a χ^2 function:

$$\chi^2(\alpha_s, \vec{\lambda}) = \sum_{\text{bins}} \frac{(x_i - F_i(\alpha_s, \vec{\lambda}))^2}{\Delta x_i^2 + \Delta \xi_i^2} + \sum_k \lambda_k^2$$

$$F_i(\alpha_s, \vec{\lambda}) = \psi_i(\alpha_s) \left(1 + \sum_k \lambda_k \sigma_k^{(i)} \right)$$

- x_i : data points in each distribution (TEEC or ATEEC).
- Δx_i ($\Delta \xi_i$): Statistical uncertainty in data (theory).
- $\sigma_k^{(i)}$: k -th source of systematic uncertainty in the bin i .
- $\psi_i(\alpha_s)$ are analytical expressions parametrizing the dependence with α_s obtained by fitting the predictions for each bin as a function of $\alpha_s(m_Z)$:

$$\psi_i(\alpha_s) = a_i \alpha_s^2 + b_i \alpha_s + c_i$$

- The obtained values of $\alpha_s(m_Z)$ are then evolved to $\alpha_s(Q)$ using:

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \log x} \left[1 - \frac{\beta_1}{\beta_0^2} \frac{\log(\log x)}{\log x} \right]; \quad x = \frac{Q^2}{\Lambda^2},$$

where Λ is the QCD scale, obtained in each case from the fitted value of $\alpha_s(m_Z)$.