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

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Outline

1. 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)

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

$$|y| < 0.5, \quad 0.5 \leq |y| < 1.0, \quad 1.0 \leq |y| < 1.5,$$
$$1.5 \leq |y| < 2.0, \quad 2.0 \leq |y| < 2.5, \quad 2.5 \leq |y| < 3.0.$$

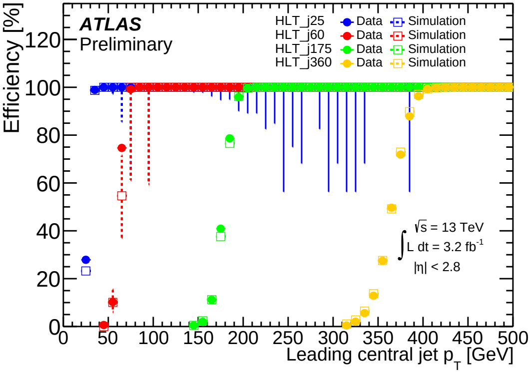
The **dijet** cross-section is measured as a function of the dijet invariant mass, in six y^* bins:

$$y^* < 0.5, \quad 0.5 \leq y^* < 1.0, \quad 1.0 \leq y^* < 1.5,$$
$$1.5 \leq y^* < 2.0, \quad 2.0 \leq y^* < 2.5, \quad 2.5 \leq y^* < 3.0.$$

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 generators[1] 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).

[1] The 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 $p_{\mathrm{T}}(m_{jj})$ 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} ($p_{\mathrm{T}}^{\mathrm{max}}$).

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

Uncertainties in the NLO calculation:

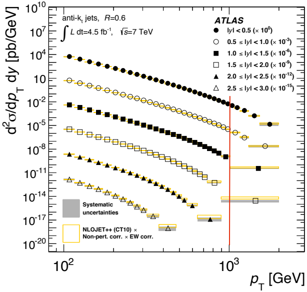
- $(\mu_{\mathrm{R}}, \mu_{\mathrm{F}})$ scale variations (dominant at low p_{T}).
- PDFs (dominant at high p_{T}).
- α_s variation (mostly constant in all p_{T} and $|y|$ ranges considered).

Additional theoretical uncertainty:

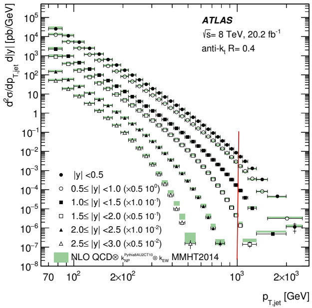
- An alternative scale choice based on each jet p_{T} ($p_{\mathrm{T}}^{\mathrm{jet}}$) was also considered.
- Difference w.r.t to $p_{\mathrm{T}}^{\mathrm{jet}}$ was treated as an uncertainty.

Results: Cross-section comparison

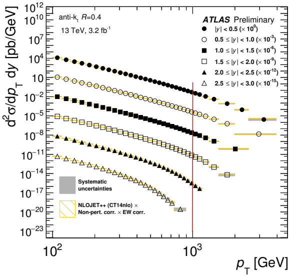
7 TeV (arXiv:1410.8857)



8 TeV (arXiv:1706.03192)



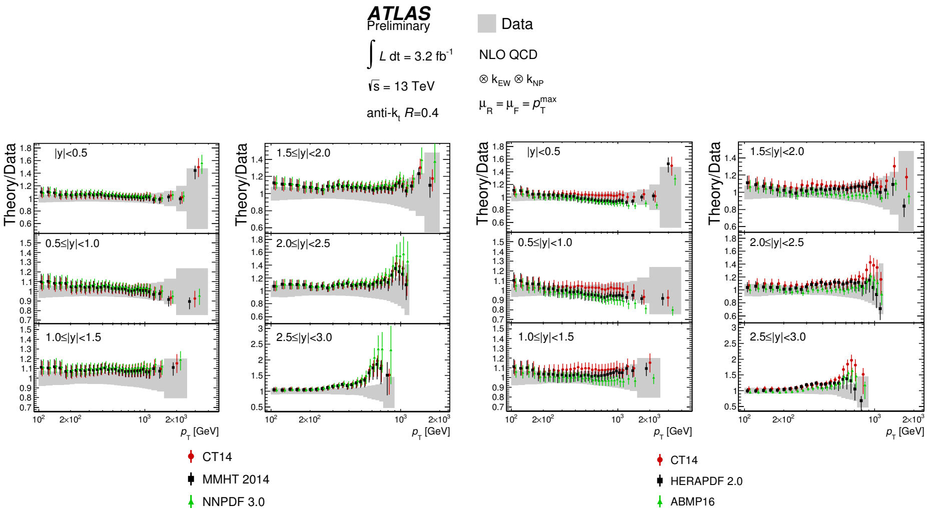
13 TeV (ATLAS-CONF-2017-048)



- 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)

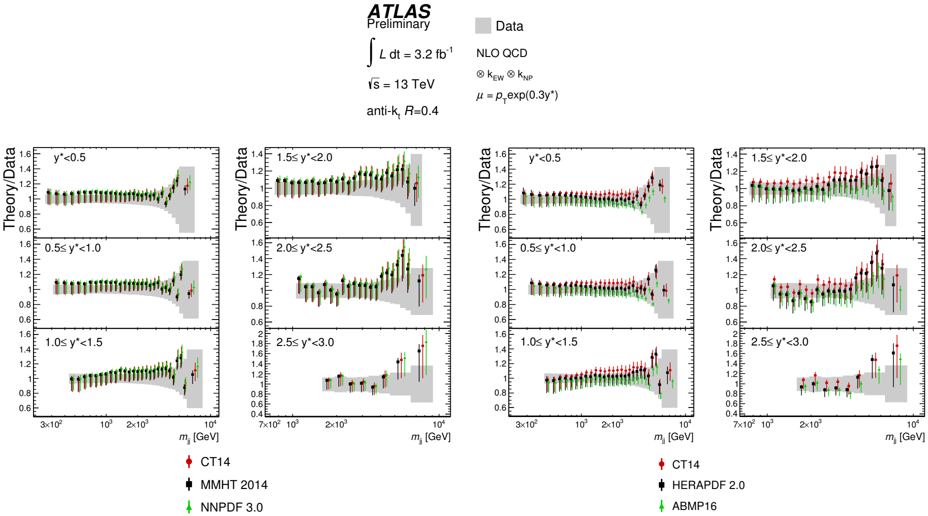
(ATLAS-CONF-2017-048)



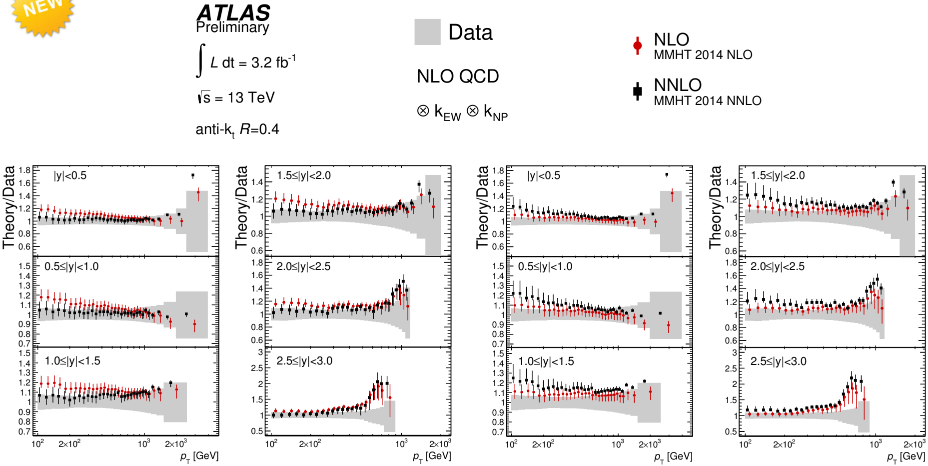
- NNPDF, CT14 and MMHT overestimate the cross-section for the last two $|y|$ bins.

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

(ATLAS-CONF-2017-048)



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



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

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

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	NNPDF3.0	HERAPDF2.0
	P_{obs}			
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	NNPDF 3.0	HERAPDF 2.0	ABMP16
	P_{obs}				
$p_{\text{T}}^{\text{max}}$					
$\|y\| < 0.5$	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	$p_T^{jet,max}$ $R = 0.4$	$R = 0.6$	p_T^{jet} $R = 0.4$	$R = 0.6$
$p_T > 70$ 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	P_{obs} CT14	MMHT 2014	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%

- 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:

$$\frac{1}{\sigma'}\frac{d\Sigma'}{d\phi} \equiv \frac{1}{N\Delta\cos\phi}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi-\cos\phi_{ij})$$

- 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:

$$\frac{1}{\sigma'}\frac{d\Sigma'^{\mathrm{asym}}}{d\phi} \equiv \frac{1}{\sigma'}\frac{d\Sigma'}{d\phi}\bigg|_{\phi} - \frac{1}{\sigma'}\frac{d\Sigma'}{d\phi}\bigg|_{\pi-\phi}$$

- 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 $p_\mathrm{T} > 100$ GeV, $|\eta| < 2.5$ and $H_{T2} > 800$ GeV.

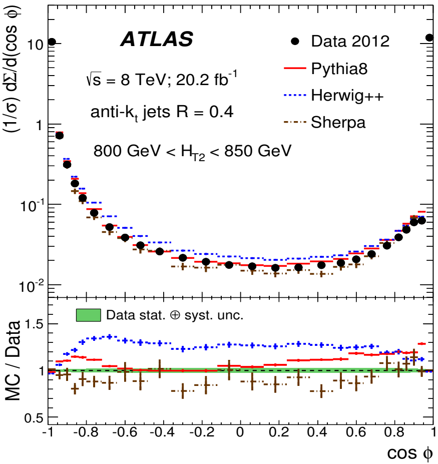
- To study the running of α_s, the data was binned in H_{T2}:

H_{T2} range [GeV]	Number of events	$\langle Q \rangle = \langle H_{\mathrm{T2}} \rangle / 2$ [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

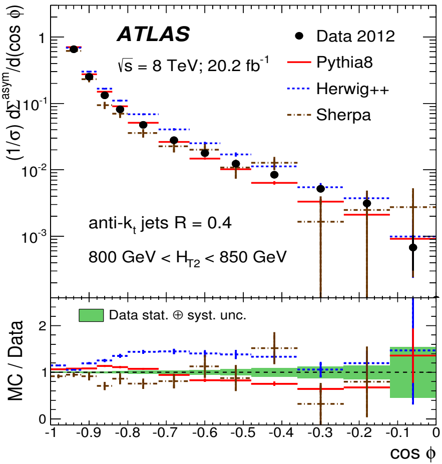
- Distributions were unfolded with an iterative Bayesian method.

Measured observables (arXiv:1707.02562)

TEEC

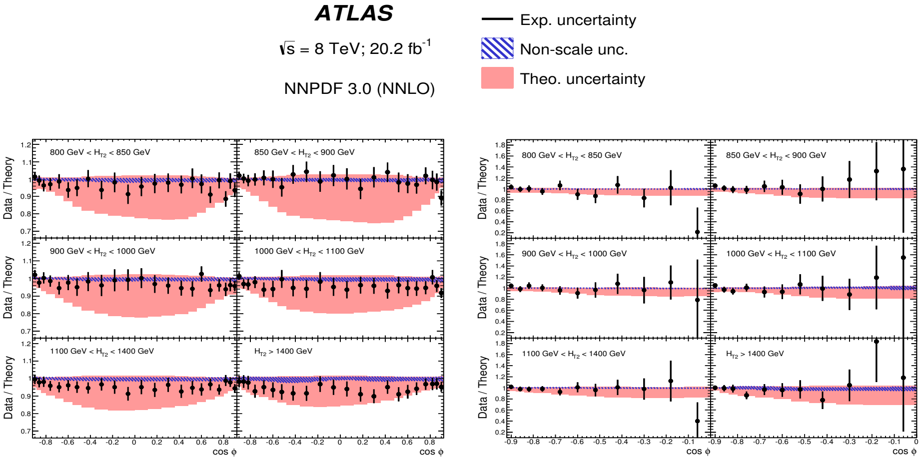


ATEEC



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

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



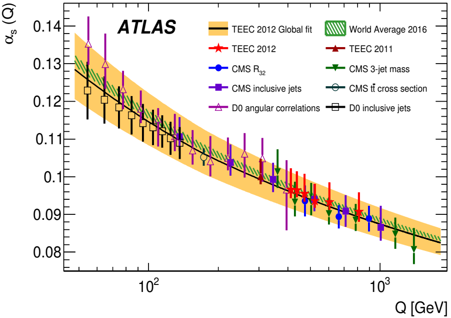
TEEC ATEEC

- pQCD correctly describes the data within uncertainties.

Results (arXiv:1707.02562)

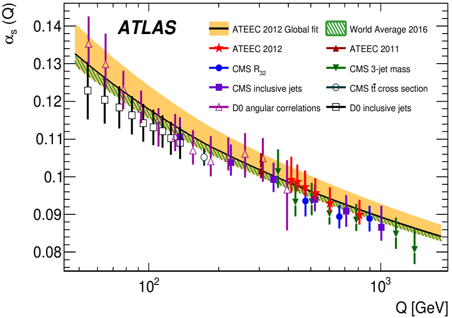
- The global fit is done by considering all H_{T2} bins into a single one.
- Partial and global fits are in agreement with previous measurements.
- The uncertainty due to normalization scales is the dominant one.

TEEC



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

ATEEC



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

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 $\text{p}_\text{T}^\text{jet}$ scale.
- NNLO overestimates the cross-sections when using $\text{p}_\text{T}^\text{max}$ 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:

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

- Good agreement with previous experiments and current world average.

back-up slides

Inclusive-jet and dijet cross-sections analyses

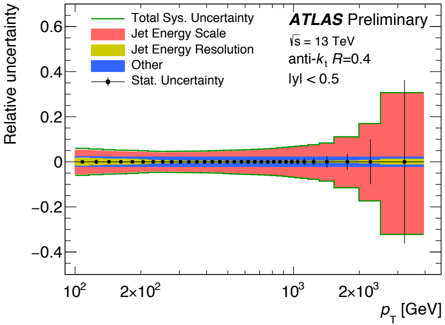
Monte Carlo Generators @8TeV & @13TeV

- 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.

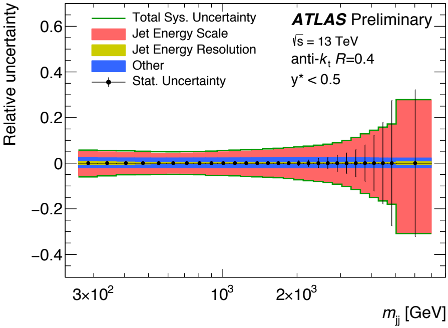
Experimental uncertainties @13 TeV (ATLAS-CONF-2017-048)

- 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

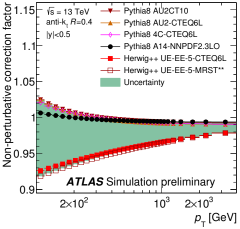
Splitting option	Sub-component(s) definition(s), completed by complementary
1	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5))\cdot$ uncertainty
2	$L(\ln(p_T[\text{TeV}]), \ln(0.1), \ln(2.5)) \cdot 0.5\cdot$ uncertainty
3	$L(p_T[\text{TeV}], 0.1, 2.5)\cdot$ uncertainty
4	$L(p_T[\text{TeV}], 0.1, 2.5) \cdot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

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

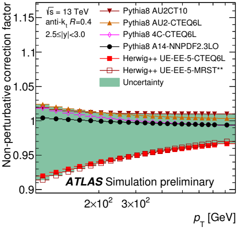
NP corrections at 13 TeV (ATLAS-CONF-2017-048)

Considers effects from underlying-event and hadronisation.

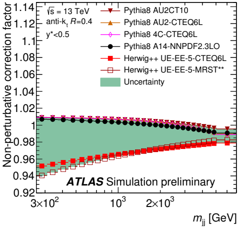
- $C_{NP} = \frac{MC(UE\ ON, HAD\ ON)}{MC(UE\ OFF, HAD\ OFF)}$



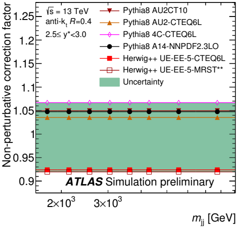
(a) $|y| < 0.5$



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



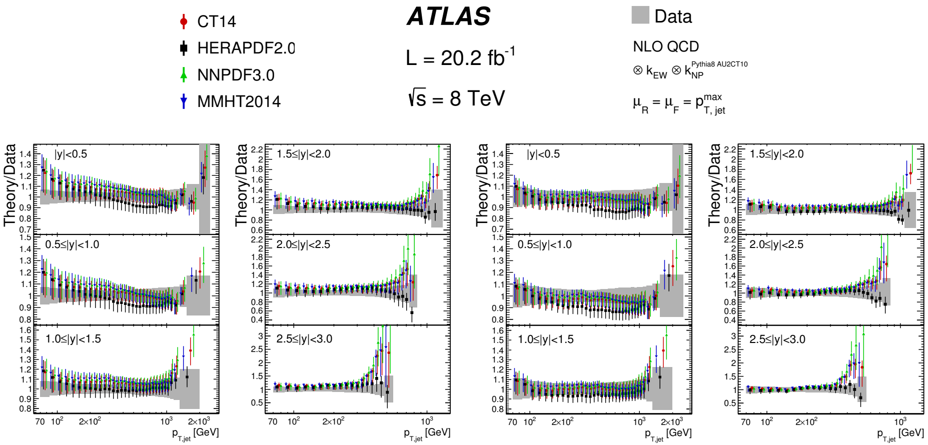
(c) $y^* < 0.5$



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

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

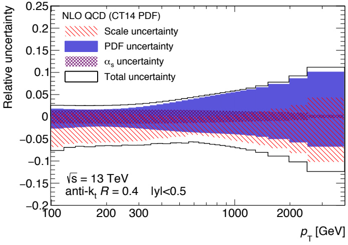
(arXiv:1706.03192)



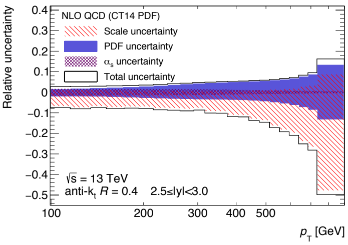
anti-k_t $R = 0.4$

anti-k_t $R = 0.6$

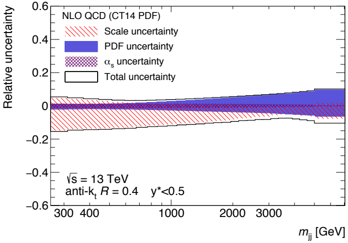
NLO QCD uncertainties at 13 TeV (ATLAS-CONF-2017-048)



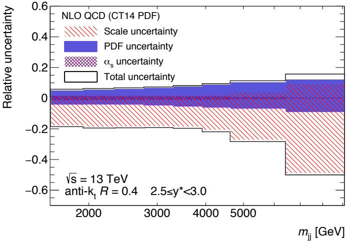
(a) $|y| < 0.5$



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



(c) $y^* < 0.5$

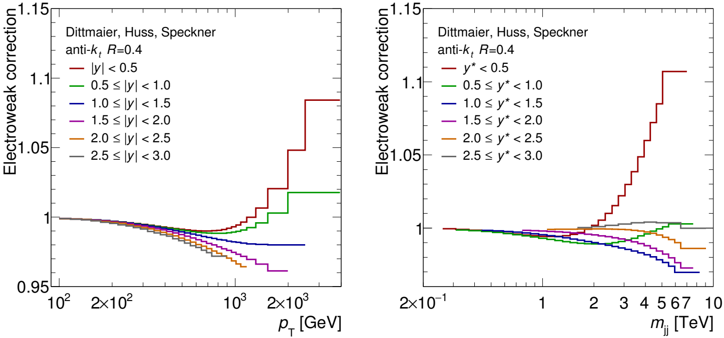


(d) $2.5 \leq y^* < 3.0$

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

$$\frac{\sigma\left(2\to 2,\mathrm{LO}^{(\mathrm{QCD})}+\mathrm{NLO}^{(\mathrm{EW})}\right)}{\sigma\left(2\to 2,\mathrm{LO}^{(\mathrm{QCD})}\right)}$$

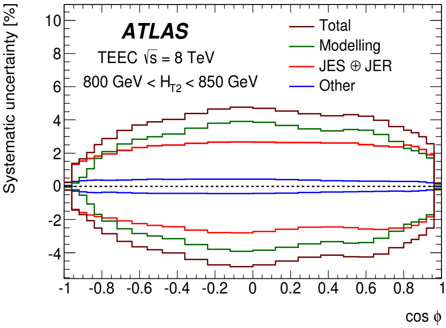


Measurement of α_s analysis

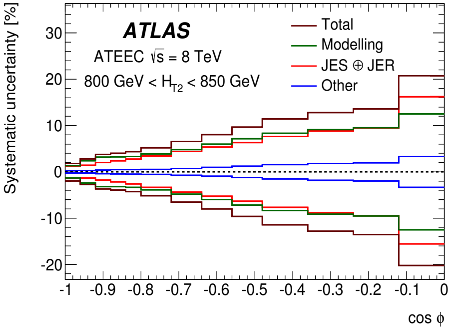
Experimental uncertainties (arXiv:1707.02562)

- 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 dominanting uncertainty.
- It was obtained from the difference in the unfolded distributions between Pythia and Herwig++.

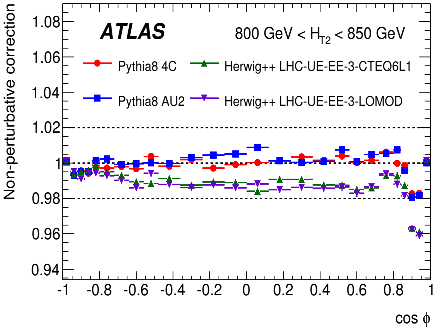
TEEC

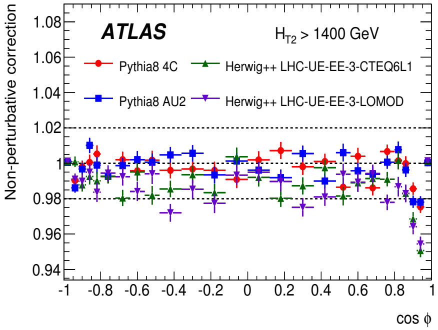


ATEEC



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).
  - σ_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 $\alpha_s(m_Z)$.