Recent ATLAS jet measurements and PDF studies

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On behalf of the ATLAS experiment

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EMMI workshop,
Darmstadt, Germany,
July 6-10, 2026

Co-funded by the European Union

Ministry of Education, Youth and Sports of the Czech Republic

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

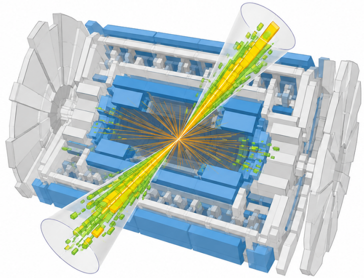
ATLAS EXPERIMENT

Motivation for jet physics at the LHC

Jets as probes of QCD

- QCD-dominated proton–proton collisions at the LHC
- Jets as direct probes of perturbative QCD over a wide kinematic range

- Precision QCD challenges:
  - Higher-order corrections
  - Scale and PDF dependence
  - Resummation and non-perturbative effects
- Precision QCD measurements constrain:
  - PDFs and α_s
  - SMEFT and new physics models



Precise jet measurements provide stringent tests of QCD, constrain α_s, and the gluon PDF at high Bjorken-x

Recent improvements of the ATLAS JES calibration

Jet Energy Scale (JES) calibration combines simulation-based techniques with in-situ measurements.

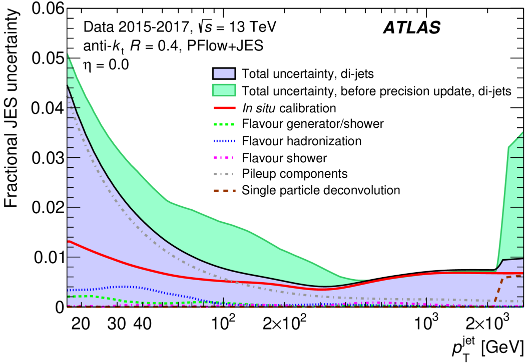
Recent improvements:

- Jet flavour response decomposition

  Jet flavour uncertainty decomposed into **matrix-element**, **parton-shower** and **hadronisation** components using dedicated MC comparisons, replacing the previous Pythia–Herwig++ comparison.

- Single Particle Deconvolution

  Full Run-2 $W \to \tau(\to \pi\nu)\nu$ events extend the in-situ charged-pion response measurement up to $\sim$ 300 GeV, improving the calibration of multi-TeV jets.



Jet measurements now achieve 1% JES precision for $p_{\mathrm{T}} > 100$ GeV.

Reduced JES uncertainties enable precision jet measurements and increase sensitivity to PDFs and α_s.

ATLAS jet cross-section ratios measurement

Publication links:

- (STDM-2020-04)
- (Phys. Rev. D 110, 072019 (2024))

Unfolded multi-differential differential measurements:

- $(H_{\mathrm{T},2},\ N_{\mathrm{jets}},\ p_{\mathrm{T},3})$, $(p_{\mathrm{T}}^{\mathrm{N\ incl}},\ N_{\mathrm{jets}},\ p_{\mathrm{T},3})$
- $(m_{\mathrm{jj}},\ N_{\mathrm{jets}})$, $(m_{\mathrm{jj,\ max}},\ N_{\mathrm{jets}})$
- $(\Delta y_{\mathrm{jj}},\ N_{\mathrm{jets}})$, $(\Delta y_{\mathrm{jj,\ max}},\ N_{\mathrm{jets}})$

Used for jet cross-section ratio definition:

$$R_{mn}(X) = \frac{\sigma(N_{\mathrm{jets}} \geq m;\ X)}{\sigma(N_{\mathrm{jets}} \geq n;\ X)}$$

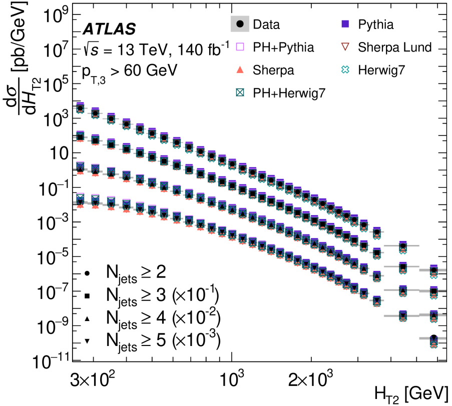
Dataset

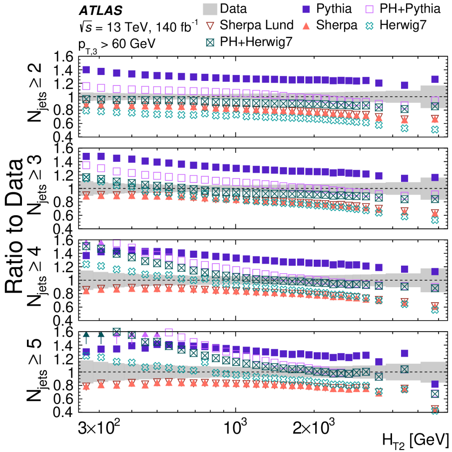
- LHC Full Run2 dataset 2015-2018
- pp collisions, 13 TeV, 140 fb^{-1}, 0.83% luminosity unc.

Reconstruction

- Anti-k_t $R = 0.4$ particle flow jets:
- $|y| < 4.5$, $p_{\mathrm{T}} > 60$ GeV
- $H_{\mathrm{T},2} = p_{\mathrm{T},1} + p_{\mathrm{T},2} \geq 250$ GeV

Multi-differential jet cross-section





- No single MC describes data well across all $H_{T,2} = p_{T,1} + p_{T,2}$ regions and jet multiplicity N_{jets}

Jet ratio cross-section

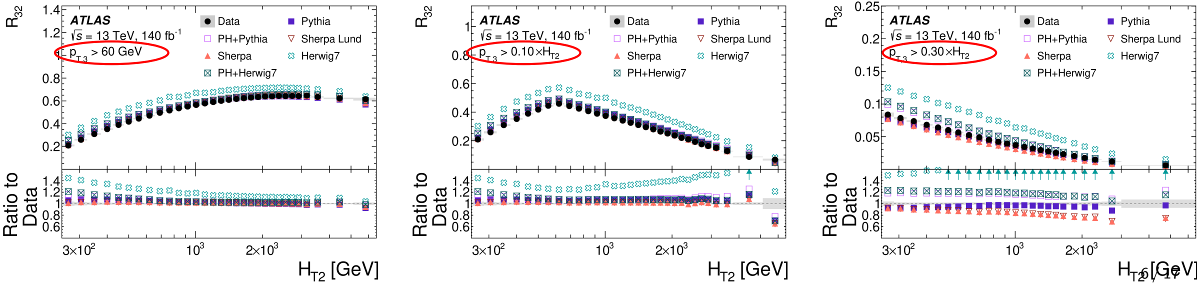
Jet cross-section ratio evaluated using the distributions for inclusive jet multiplicity N_{jets}

$$R_{32} = \frac{\sigma(3\text{ jets})}{\sigma(2\text{ jets})}, \quad R_{42} = \frac{\sigma(4\text{ jets})}{\sigma(2\text{ jets})}, \quad R_{43} = \frac{\sigma(4\text{ jets})}{\sigma(3\text{ jets})}, \quad R_{54} = \frac{\sigma(5\text{ jets})}{\sigma(4\text{ jets})}$$

R_{xy} ratio:

- Reduce correlated syst. unc.
- Reduce sensitivity to Jet Energy Scale (JES)
- Reduce sensitivity to Parton Distribution Functions (PDF)

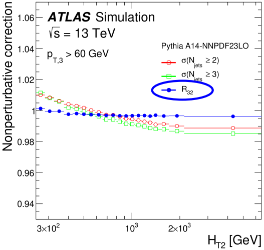
- R_{32} sensitive for α_s extraction
- R_{43}, R_{42}, R_{54} - for first time - as reference for future theoretical developments
- R_{32} and other jet cross-section ratios in several bins of pT,3 to probe resummation effects



Advanced pQCD predictions

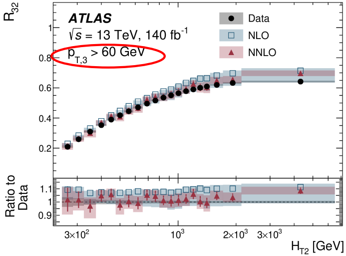
NLO and NNLO pQCD prediction

- Fixed-order NLO pQCD(NLOJET++)
- Fixed-order NNLO pQCD (Czakon, Mitov, Poncelet, Phys. Rev. Lett. 127 (2021) 152001)
  - $N_\mathrm{F} = 5$, $\mu_\mathrm{R} = \mu_\mathrm{F} = \hat{H}_\mathrm{T}$
  - MSHT20 PDF set, $\alpha_s = 0.118$

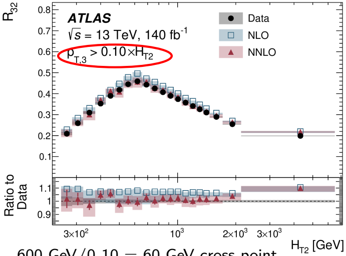


Non-perturbative corrections

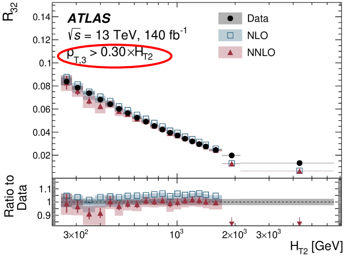
- Parton → Particle level prediction
- Bin-by-bin correction factor for hadronization and underlying event tune
- Pythia ATLAS A14NNPDF3.1 and Monash tunes



Increasing R_{32} since probability of emitting the 3rd jet increases with energy scale of the event



600 GeV/0.10 = 60 GeV cross point, back-to-back jet configuration at high scales, the 3rd jet very close to/captured by (sub)leading jet



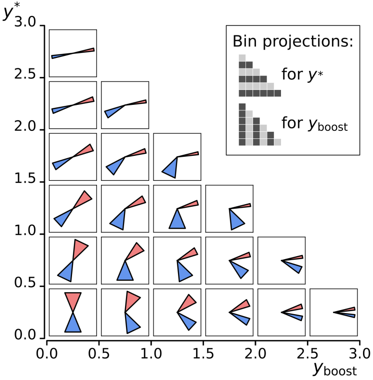
R_{32} decreasing due to steeply falling third-jet $p_{T,3}$ spectra

Inclusive dijet cross-section measurement

- Inclusive dijet measurement for $\sigma(p + p \to \mathrm{jet} + \mathrm{jet} + X)$, 140 fb^{-1} at $\sqrt{s} = 13$ TeV
- Unfolded double-differential cross-sections in $(m_{\mathrm{jj}},\ y^*)$ and $(m_{\mathrm{jj}},\ y_{\mathrm{boost}})$

$$\frac{d^2\sigma}{dm_{\mathrm{jj}}\, dy^*} \quad \text{and} \quad \frac{d^2\sigma}{dm_{\mathrm{jj}}\, dy_{\mathrm{boost}}}$$

$$m_{\mathrm{jj}}^2 = (P_1 + P_2)^2, \qquad y^* = \frac{1}{2}|y_1 - y_2|, \qquad y_{\mathrm{boost}} = \frac{1}{2}|y_1 + y_2|$$



m_{jj}:

- hard scale of the dijet system:

$$m_{\mathrm{jj}}^2 \sim 2\, p_{T,1}^2 \cosh^2(y^*)$$

y^*:

- central vs. forward topology
- related to the scattering angle:

$$\tanh(y^*) = \cos(\theta^*)$$

y_{boost}:

- low-boost vs. high-boost topology
- sensitive to asymmetric parton momentum fractions:

$$y_{\mathrm{boost}} = \frac{1}{2} \ln\left(\frac{x_1}{x_2}\right)$$

Experimental uncertainties

Experimental uncertainties

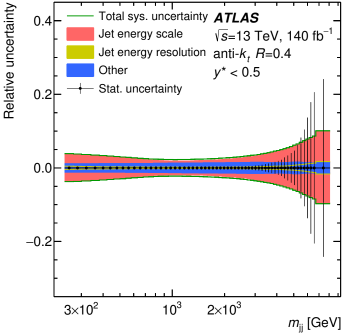
- Jet energy scale (JES)
- Jet energy resolution (JER)
- Unfolding bias, luminosity
- Deactivated Tile modules

Treatment

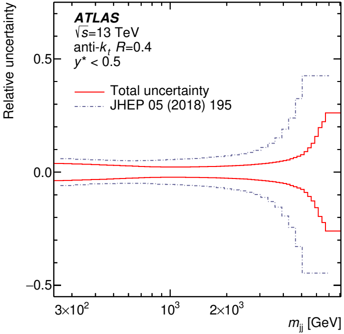
- 1172 JES components
- 34 JER components
- Full propagation through unfolding

Impact

- $\times$2–3 reduction
- precision-level NNLO comparison
- improved high-x PDF sensitivity

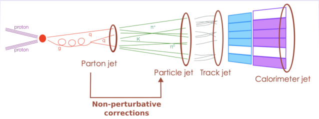


Total uncertainty in representative (m_{jj}, y^*) bin; JES dominates over most of the phase space.



Compared to the previous ATLAS dijet measurement, the total experimental uncertainty is reduced by a factor of 2–3.

Particle-level theory prediction



$$\sigma^{\text{particle}}_{\text{theory}} = \sigma^{\text{parton}}_{\text{pQCD}} \otimes \text{EW correction} \otimes \text{NP correction}$$

pQCD

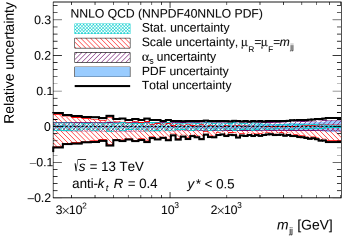
- NNLOJET
- NNLO QCD, full colour
- parton level
- $\mu_R = \mu_F = m_{\text{jj}}$
- Scale, PDF, α_s, stat. unc.
- PDF: CT, MSHT, NNPDF, ATLASPDF

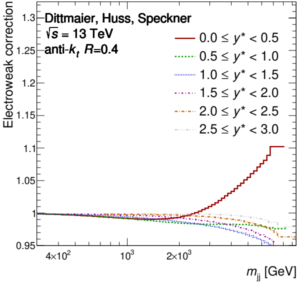
Electroweak correction

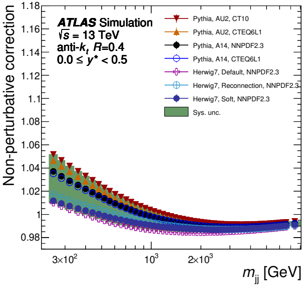
- $W^{\pm}$, Z, γ contributions
- tree and 1-loop level
- NLO precision for $2 \to 2$
- up to $\sim 10\%$ effect at high m_{jj}
- strong dependence on y^*

Non-perturbative correction

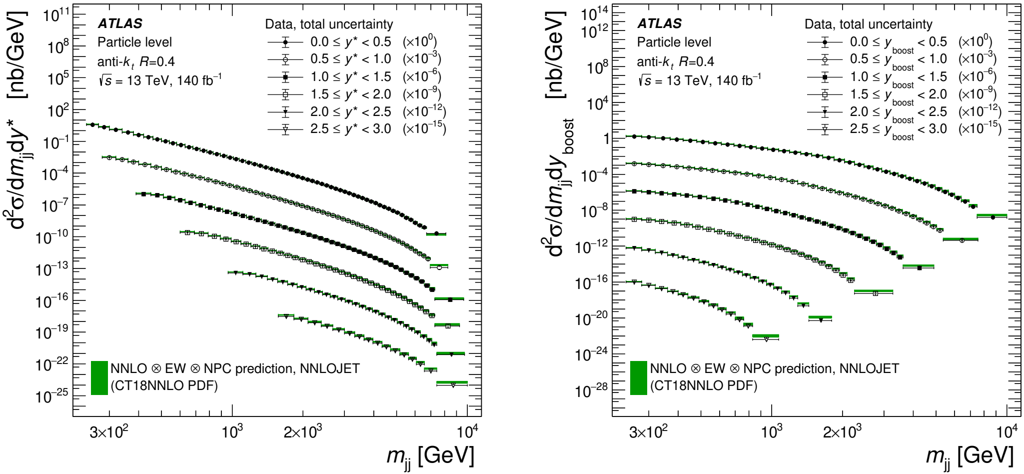
- Parton $\to$ particle level
- Multiple LO MC generators
- different HAD, PDF, UE
- On/off both HAD and MPI
- Pythia A14 as correction
- Envelope as uncertainty







Results: inclusive dijet cross-sections

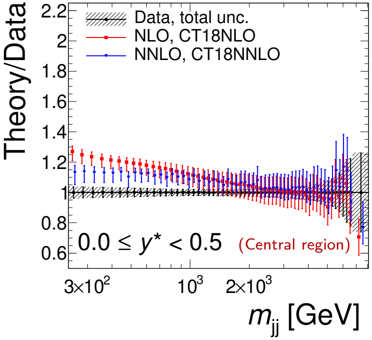


Comparison to NNLO QCD ⊗ EW ⊗ NP predictions at particle level

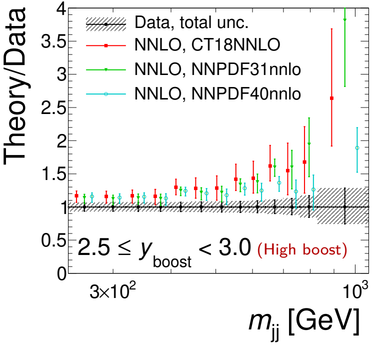
- First ATLAS measurement of $(m_{\mathrm{jj}}, y_{\mathrm{boost}})$
- Stringent test of QCD predictions over a wide kinematic range

Results: theory-to-data comparison

NLO vs. NNLO pQCD



PDF dependence at NNLO



- Theory generally above data
- NNLO improves description at high m_{jj}
- Low-m_{jj} region sensitive to scale choice

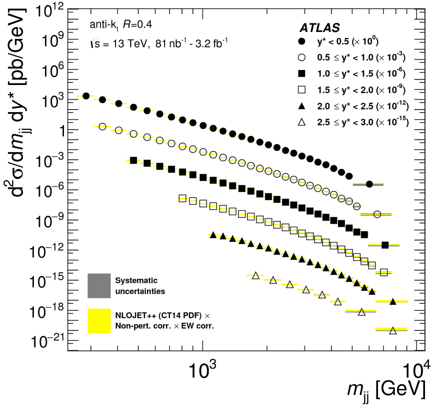
- Sensitivity to PDFs and α_s
- Clear PDF dependence
- Best qualitative agreement from NNPDF4.0

	χ^2/ndf (m_{jj}, y^*)	χ^2/ndf $(m_{\mathrm{jj}}, y_{\mathrm{boost}})$
CT18NNLO	341/237	179/160
NNPDF40NNLO	359/237	181/160
ATLASPdf21 T3	**291/237**	**162/160**

Comparison to previous measurements

- First ATLAS measurement of $(m_{\mathrm{jj}}, y_{\mathrm{boost}})$
- 40× larger dataset with improved detector reconstruction
- ×2–3 reduction of experimental uncertainties
- First comparison to full-colour NNLO pQCD
- Increased sensitivity to PDFs and α_s

	This ATLAS [?]	Previous ATLAS [?]
Observable	(m_{jj}, y^*) $(m_{\mathrm{jj}}, y_{\mathrm{boost}})$	(m_{jj}, y^*)
Dataset	13 TeV 140 fb^{-1}	13 TeV 3.2 fb^{-1}
Jets	particle-flow $R = 0.4$	topological $R = 0.4,\ 0.6$
pQCD theory	NNLO full colour $\mu_R = \mu_F = m_{\mathrm{jj}}$	NLO leading colour $\mu_R = \mu_F = p_{\mathrm{T},1} e^{0.3y^*}$
Particle level	muons and neutrinos excluded	muons and neutrinos included
Precision	×2–3 better	baseline
# bins	237+160	146



Previous ATLAS dijet measurement (STDM-2016-03)

ATLAS PDF programme: ATLASpdf2X

ATLASpdf21: Determination of proton PDFs using precision ATLAS measurements

- HERA DIS data provide the baseline PDF determination
- Complementary PDF constraints from ATLAS precision measurements
  - W/Z, V+jets, isolated photons, inclusive jets, $t\bar{t}$
  - NNLO pQCD theory
  - 21-parameter PDF parametrisation at $Q_0^2 = 1.9\ \mathrm{GeV}^2$
    - u_v, d_v, $\bar{u}$, $\bar{d}$, $(s+\bar{s})$, g
    - PDF complexity determined using χ^2 saturation test,
  - HERA-style χ^2 fit
    - correlated systematics via nuisance parameters

The next-generation **ATLASpdf26** fit is currently under preparation.

HERA DIS

$\Downarrow$

W/Z production
V+jets
isolated photons
inclusive jets
$t\bar{t}$ production

$\Downarrow$

ATLASpdf21

ATLAS Collaboration, EPJC 82 (2022) 438

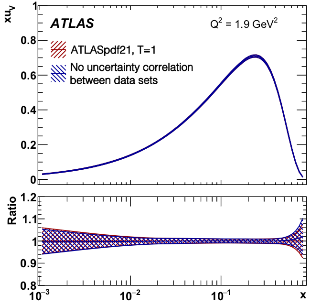
ATLASpdf21: light-quark constraints and correlations

Valence quarks

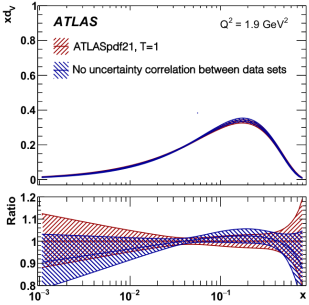
- HERA $\rightarrow$ strong constraint on u_v
- ATLAS $\rightarrow$ improved constraint on d_v
- Correlated uncertainties important for d_v

Light-quark sea

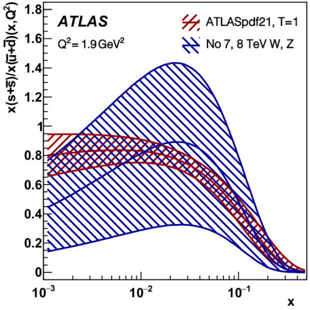
- W/Z and V+jets
- Strange-quark content: $R_s = x(s+\bar{s})/(\bar{u}+\bar{d})$
- Light-sea asymmetry: $x(\bar{d}-\bar{u})$



u_v



d_v



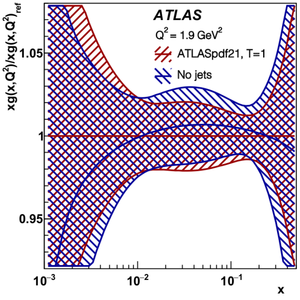
Light sea

ATLAS measurements provide complementary constraints on d_v and the light-quark sea.

ATLASpdf21: gluon PDF constraints

Inclusive jets

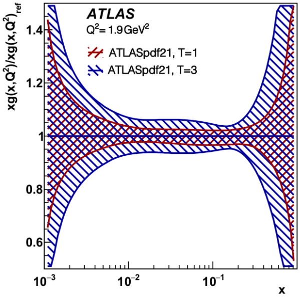
- Improve g PDF at medium/high-x
- Reduce PDF uncertainty



Impact of inclusive jets

PDF uncertainties

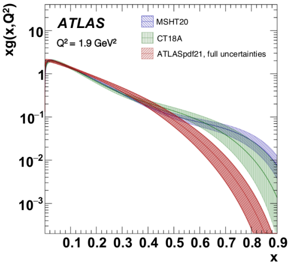
- $\Delta\chi^2 = \chi^2 - \chi^2_{\text{min}}$
- T1: $\Delta\chi^2 = 1$
- T3: $\Delta\chi^2 = 9$



T1 (red) vs. T3 (blue)

Global PDFs

- Agreement at medium-x
- Sizeable differences at high-x
- Run-2 jets/dijets will probe the high-x region



Comparison with CT18A and MSHT20

The next-generation **ATLASpdf26** fit will include the full Run-2 inclusive dijet measurement.

Summary

Recent ATLAS jet measurements

- Full Run-2 ATLAS data enable precision QCD studies with jets
- Jet cross-section ratios provide complementary probes of higher-order QCD and α_s

Inclusive dijet cross-section measurement

- First ATLAS measurement of the double-differential $(m_{\mathrm{jj}}, y_{\mathrm{boost}})$ cross-section
- First comparison to full-colour NNLO pQCD predictions
- Strong sensitivity to PDFs, particularly the high-x gluon distribution

Towards future ATLAS PDF fits

- ATLASpdf21 demonstrates the constraining power of ATLAS precision measurements
- New Run-2 inclusive jet and dijet measurements provide an excellent basis for next-generation ATLAS PDF determinations

Thank you for your attention!

Back-up

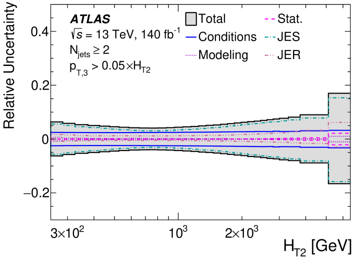
JES and JER

- JES and JER as series of simulation-based techniques and in-situ measurements
- Jet-flavor response:
  - Jet-flavor response as relative jet energy response for simulated quark-and gluon-initiated jets varied between different MC generators
  - Jet flavor response reduced from leading source uncertainty to completely subdominant effect.
- Extrapolation of single hadron response measurements to jets
  - Updated response to electromagnetic shower (JINST 14 (2019) P12006)
  - Updated response to high-p_T pions up to 250 GeV, extracted from in situ measurement using $W \to \tau(\pi\nu)\nu$ events replacing previous test-beam measurement
  - Extrapolation with updated alternative Geant4 physics lists and detector geometry

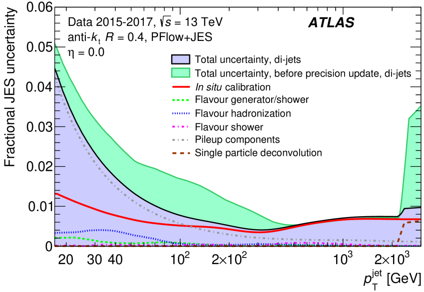
Break through with improved experimental systematic uncertainties

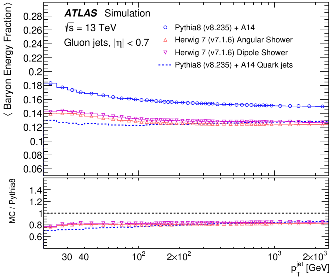
Dramatic improvement of Jet Energy Scale (JES) uncertainty due to:

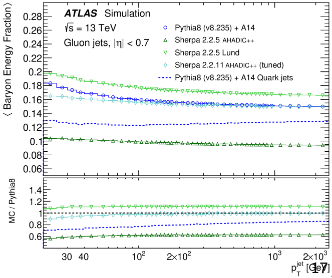
- Improved Single Particle Deconvolution with for high p_T jets, reduced by factor 3
- Improved Jet Flavor Response Decomposition for low and middle p_T jet, reduced by factor 2
  - Flavor generator/shower: Pythia8 vs. Sherpa 2.2.5, both with Lund
  - Flavor hadronization: Sherpa 2.2.11 (AHADIC cluster-based had.) vs. Sherpa 2.2.2.5 (Lund had.)
  - Flavor shower: Herwig 7.1. with angle-ordered and dipole PS



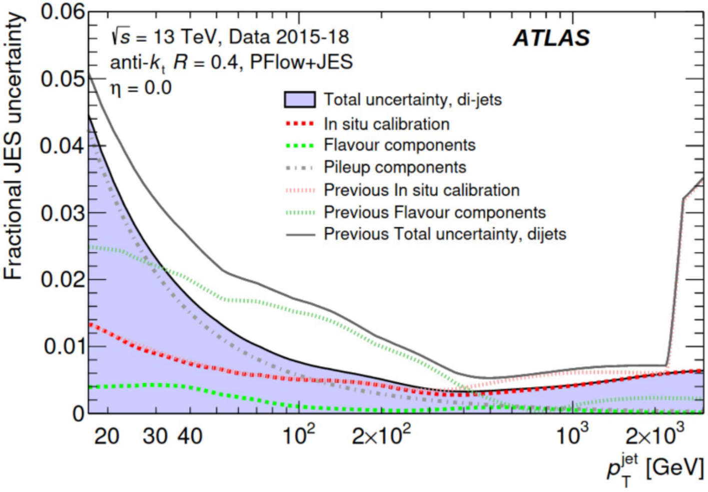
Measurement dominated by JES





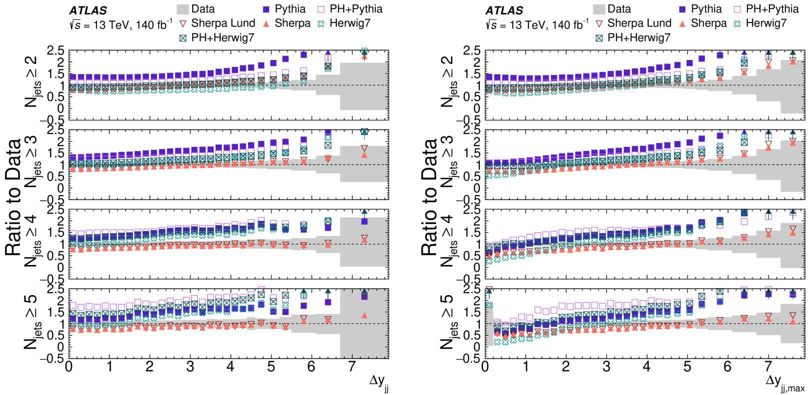


JES and effect of updated jet flavor response



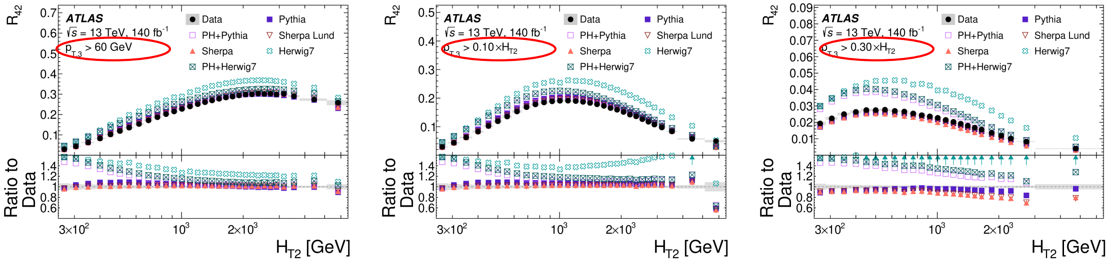
Link to talk of Antti Pirttikoski

Multi-differential jet cross-section

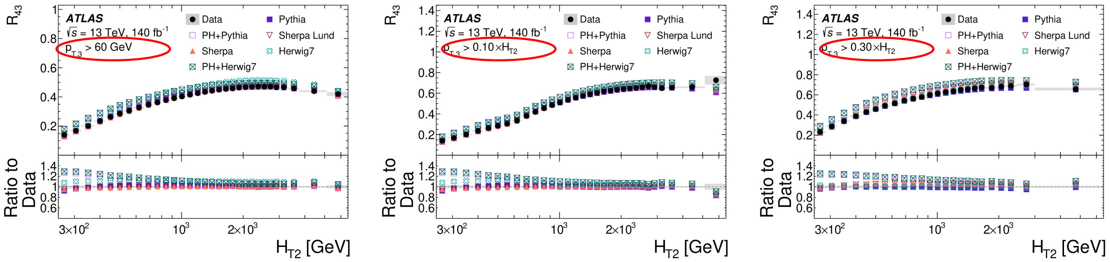


- Increasing discrepancies for vector boson-scattering (VBS) and fusion (VBF) phase-space with large y_{jj}, $y_{jj,\ max}$,
  - y_{jj} as invariant dijet mass of the two leading jets
  - $y_{jj,\ max}$ as maximal invariant mass in the event of any two combined jets

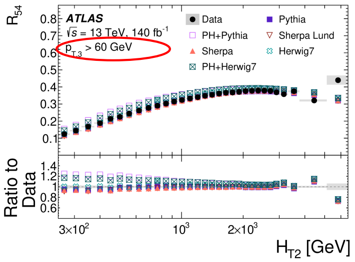
Jet cross-section ratio R_{42}



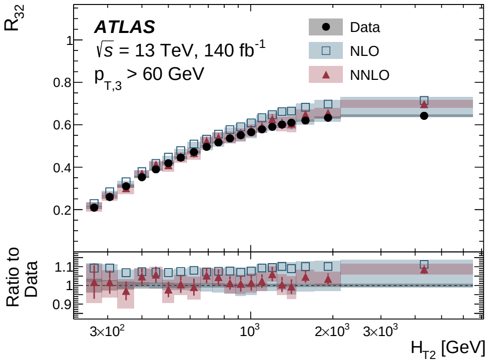
Jet cross-section ratio R_{43}



Jet cross-section ratio R_{54}

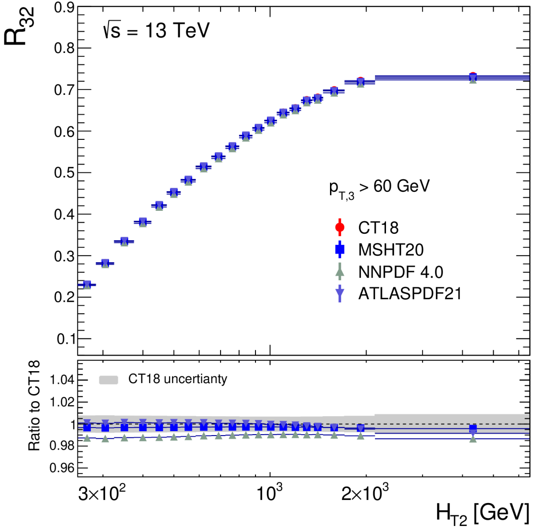


χ^2 table for R_{32}

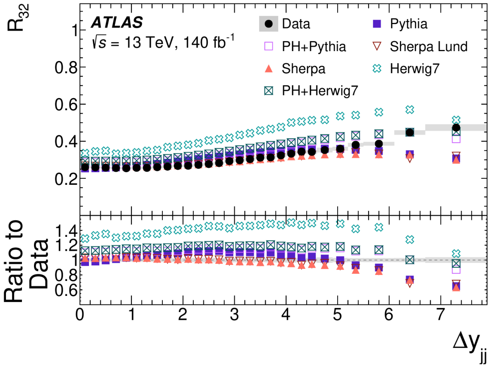


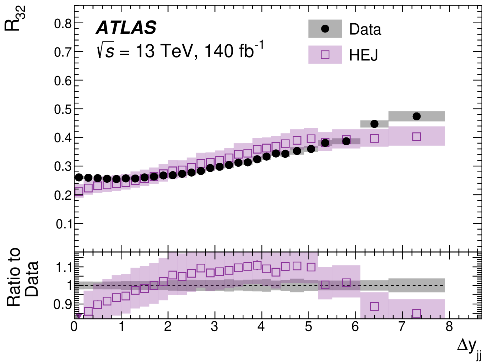
	$\chi^2/d.o.f.$	
	NLO	NNLO
$p_{T,3} > 60$ GeV	0.48	0.36
$p_{T,3} > 0.05 \times H_{T2}$	0.55	0.32
$p_{T,3} > 0.10 \times H_{T2}$	1.05	0.24
$p_{T,3} > 0.20 \times H_{T2}$	1.11	0.30
$p_{T,3} > 0.30 \times H_{T2}$	9.24	5.49

Reduced sensitivity to pdf

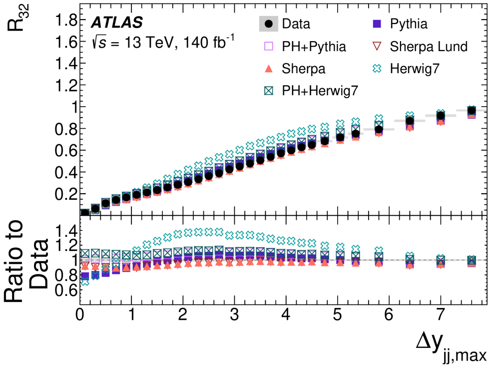


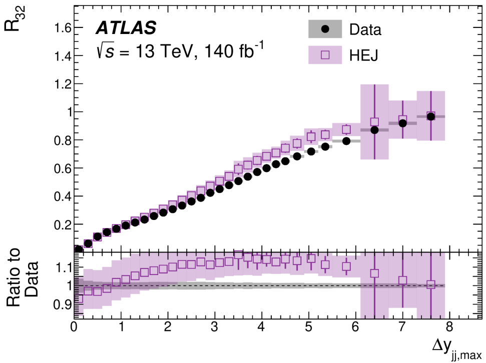
HEJ with resummation of logarithmic correction



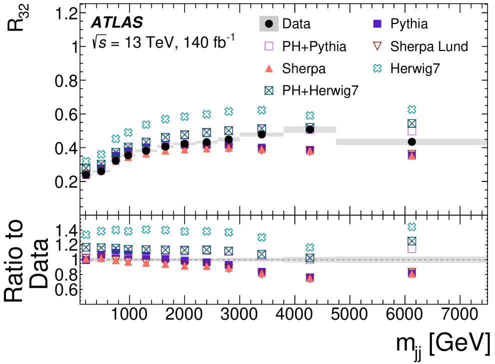


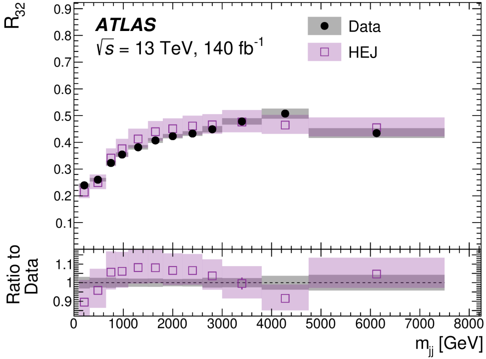
HEJ with resummation of logarithmic correction



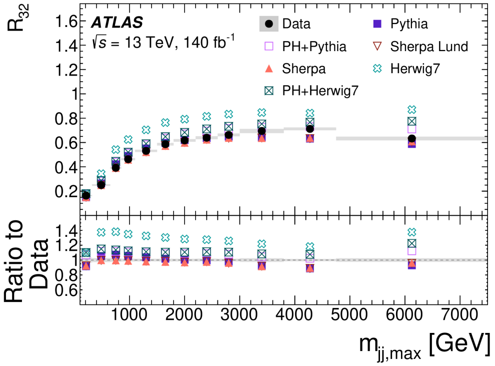


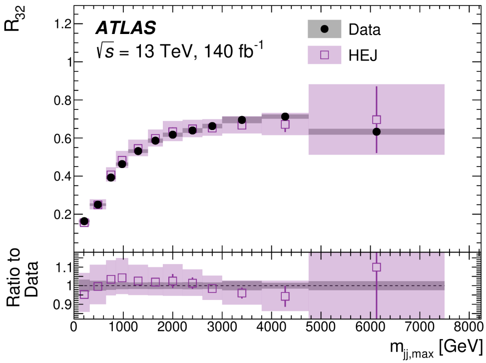
HEJ with resummation of logarithmic correction



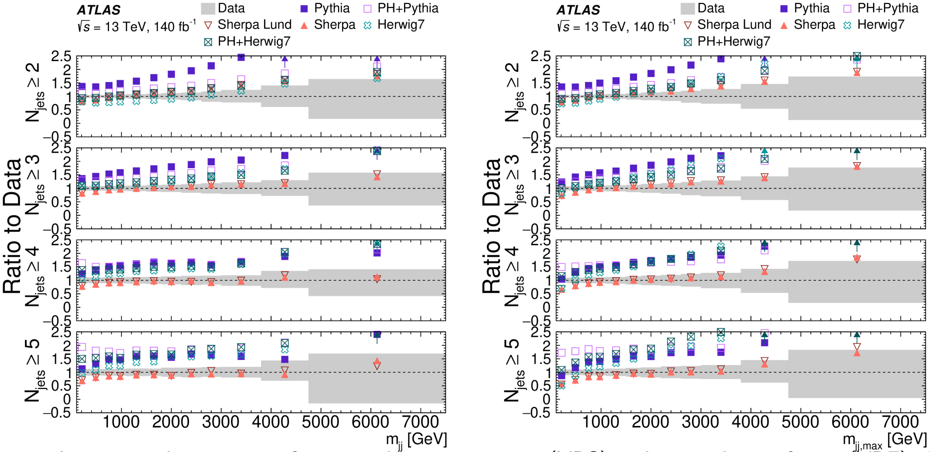


HEJ with resummation of logarithmic correction





Multi-differential jet cross-section



- Increasing discrepancies for vector boson-scattering (VBS) and vector-boson fusion (VBF) phase-space with large $m_{jj,max}$ and $\Delta y_{jj,max}$
  - m_{jj} as dijet invariant mass of the two leading jets (dominated by high p_T jets)
  - $m_{jj,\,max}$ as dijet invariant mass of any pair of jets in the event that maximize m_{jj} (dominated forward jets with with large angles between the two)

Conclusion and highlights

Multi-differential cross-section measurements for multijet QCD

- Significant benefits from improved experimental JES uncertainties
- MC and pQCD predictions tested against data using energy-scale related ($H_{T,2}$) and angular related (Δy) variables
- Novel way to indirectly test vector-boson scattering/fusion interaction with forward jets and probe logarithmic contribution and resummation effects

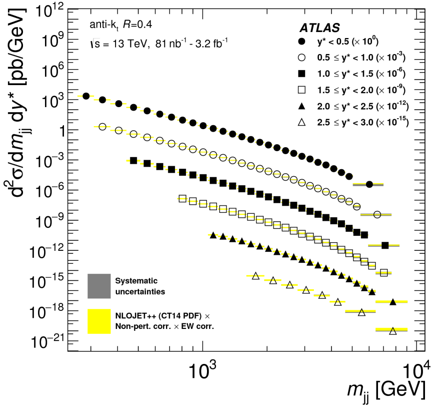
- R_{32} for the first time at 13 TeV, pp collisions + α_s extraction ongoing
- R_{42}, R_{43}, R_{54} for the first time, now experimentally accessible with LHC Full Run 2 dataset, as reference for future MC and theory developments, HEP data and Rivet routine available

Thank you for your attention.

Comparison to previous measurements

- First ATLAS measurement of $(m_{\rm jj}, y_{\rm boost})$
- $40\times$ larger dataset with improved detector reconstruction
- $\times 2$–3 reduction of experimental uncertainties
- First comparison to full-colour NNLO pQCD
- Increased sensitivity to PDFs and α_s

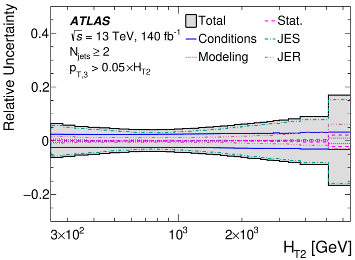
	This ATLAS [?]	Previous ATLAS [?]
Observable	$(m_{\rm jj}, y^*)$ $(m_{\rm jj}, y_{\rm boost})$	$(m_{\rm jj}, y^*)$
Dataset	13 TeV $140\ \mathrm{fb}^{-1}$	13 TeV $3.2\ \mathrm{fb}^{-1}$
Jets	particle-flow $R = 0.4$	topological $R = 0.4,\ 0.6$
pQCD theory	NNLO full colour $\mu_R = \mu_F = m_{\rm jj}$	NLO leading colour $\mu_R = \mu_F = p_{\rm T,1} e^{0.3y^*}$
Particle level	muons and neutrinos excluded	muons and neutrinos included
Precision	$\times 2$–3 better	baseline
# bins	237+160	146



Previous ATLAS dijet measurement (STDM-2016-03)

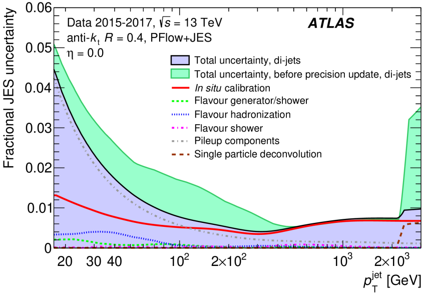
Breakthrough in JES experimental systematic uncertainties

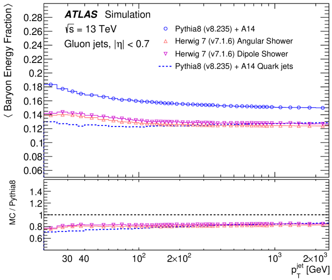
Jet Energy Scale (JES) and Jet Energy Resolution (JER) based on series of simulation-based techniques and in-situ measurements

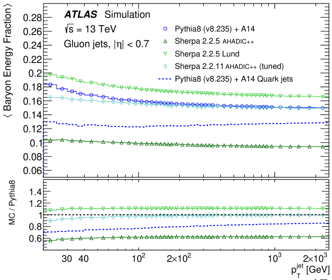


Dramatic improvements of JES uncertainty in 2024:

- Improved Jet Flavor Response Decomposition for low and middle p_T jet, reduced by factor 2
- Improved Single Particle Deconvolution with $W \to \tau(\to \pi\nu)\nu$ for high p_T jets, reduced by factor 3
- Both cross-sections and jet cross-section ratios still dominated by JES



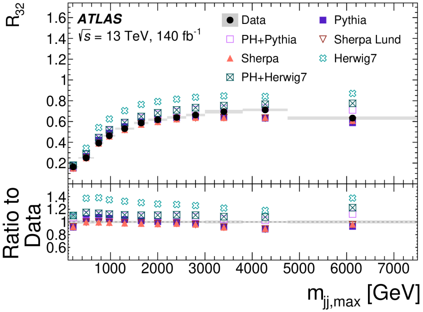


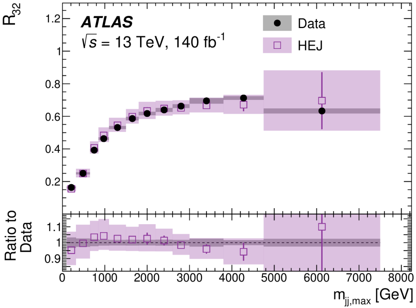


Advanced pQCD predictions - HEJ

High Energy Jet framework (HEJ)

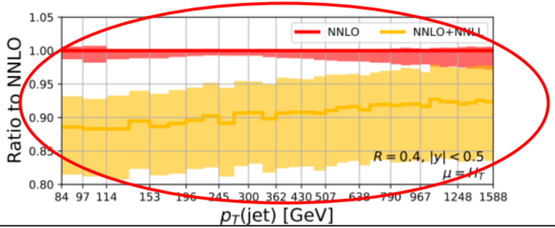
- Resummation of logarithmic corrections and matching in high energy limit, relevant for large rapidity differences and large invariant mass
  - $\mu_R = \mu_F = \hat{H}_T/2$
  - NNPDF3.1NLO PDF set, $\alpha_s = 0.118$





- HEJ improves R_{32} modeling for m_{jj}, $m_{jj,\,max}$ and $\Delta y_{jj,\,max}$

5. μ_R, μ_F, and resummation effects



On the left, NNLL resummation effects can modify the cross-section by approximately -10%, derived for incl. jets with $\mu_R = \mu_R = H_T$,

T. Generet et al., arXiv:2604.25490.

No results for dijets so far.