Precision measurements of multijet production with the ATLAS experiment

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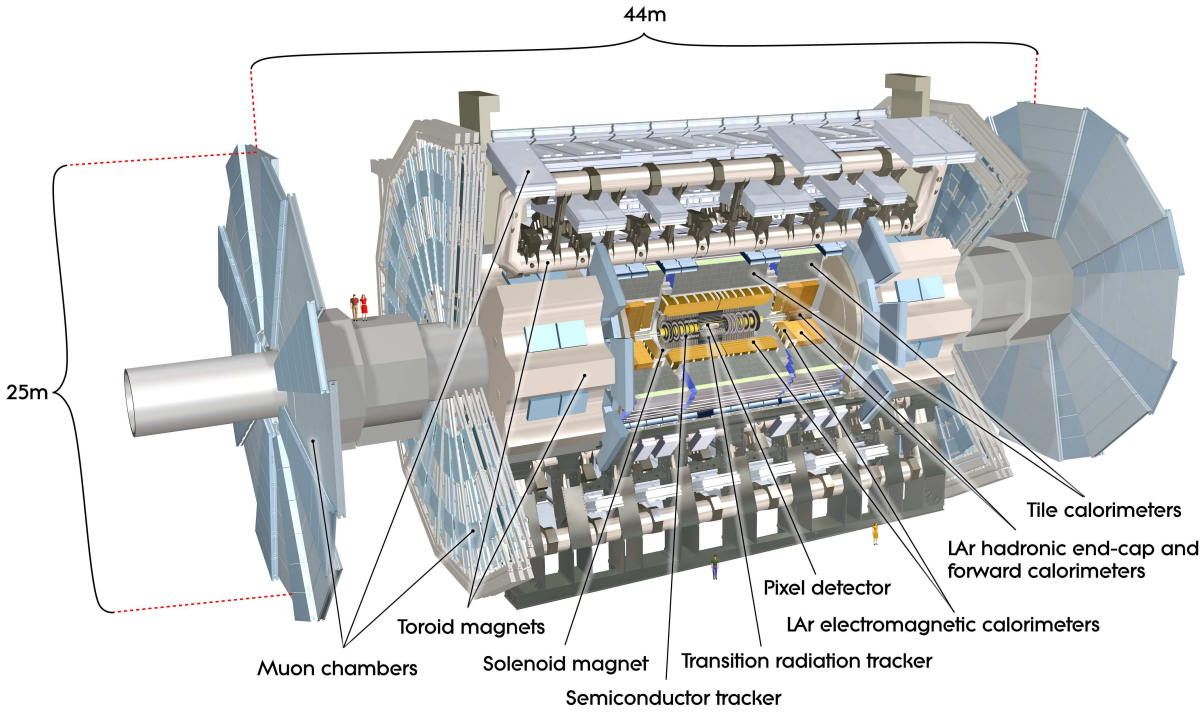
Introduction

- Jet measurements – stringent tests of QCD
  - Strong coupling α_S
  - Proton structure – PDFs
  - Tests of MC modeling
- ATLAS
  - Multi-purpose detector at LHC
  - Measuring jets using calorimeter energy deposits and Inner Detector particle tracks



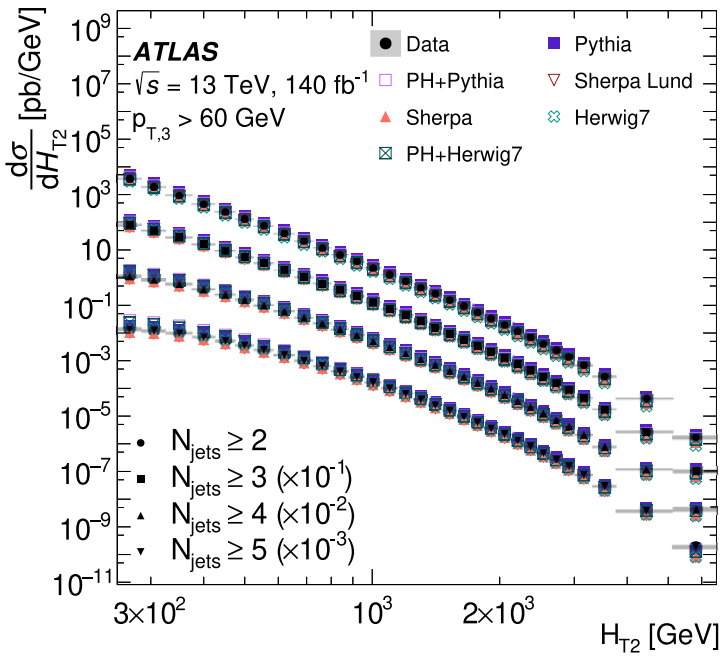
Latest multijet measurements

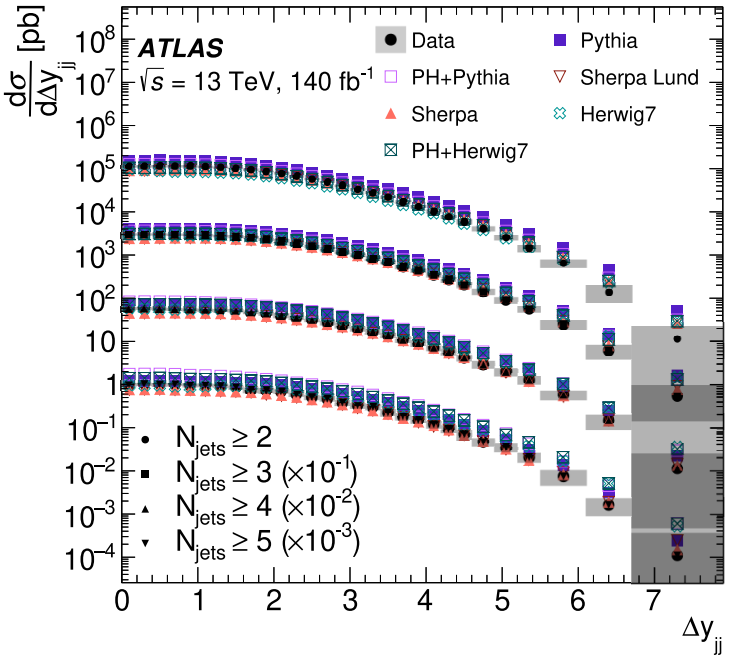
- Latest multijet measurements at ATLAS
  - [1] ATLAS Collaboration, Measurements of jet cross-section ratios in 13 TeV proton–proton collisions with ATLAS, 2024, CERN-EP-2024-119
  - [2] ATLAS Collaboration, Determination of the strong coupling constant from transverse energy–energy correlations in multijet events at $\sqrt{s} = 13$ TeV with the ATLAS detector, 2023, CERN-EP-2022-282
  - [3] ATLAS Collaboration, Measurements of multijet event isotropies using optimal transport with the ATLAS detector, 2023, CERN-EP-2023-079

- Using LHC Run 2 dataset of 13 TeV proton–proton collisions
  - Integrated luminosity
    - Latest value 140.07 ± 1.17 fb^{-1} [4]
    - Relative uncertainty 0.83%

Jet cross-section ratios [1] – observables

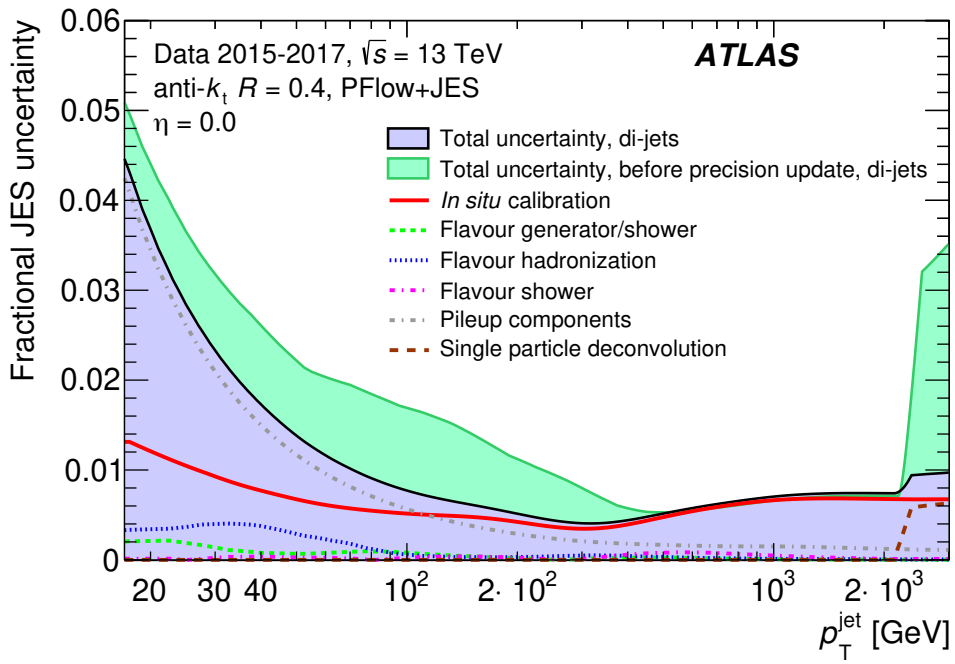
- Ratios between bins of inclusive jet multiplicity
  - Good sensitivity to α_S, decrease sensitivity to systematics and PDFs
  - R_{32}, R_{42}, R_{43}, R_{54}
- In variables sensitive to
  - Energy scale – e.g: $H_{T2} = p_{T,1} + p_{T,2}$
  - Topology – e.g: m_{jj}, Δy_{jj}
- $p_T > 60$ GeV, $|y| < 4.5$, $H_{T2} > 250$ GeV





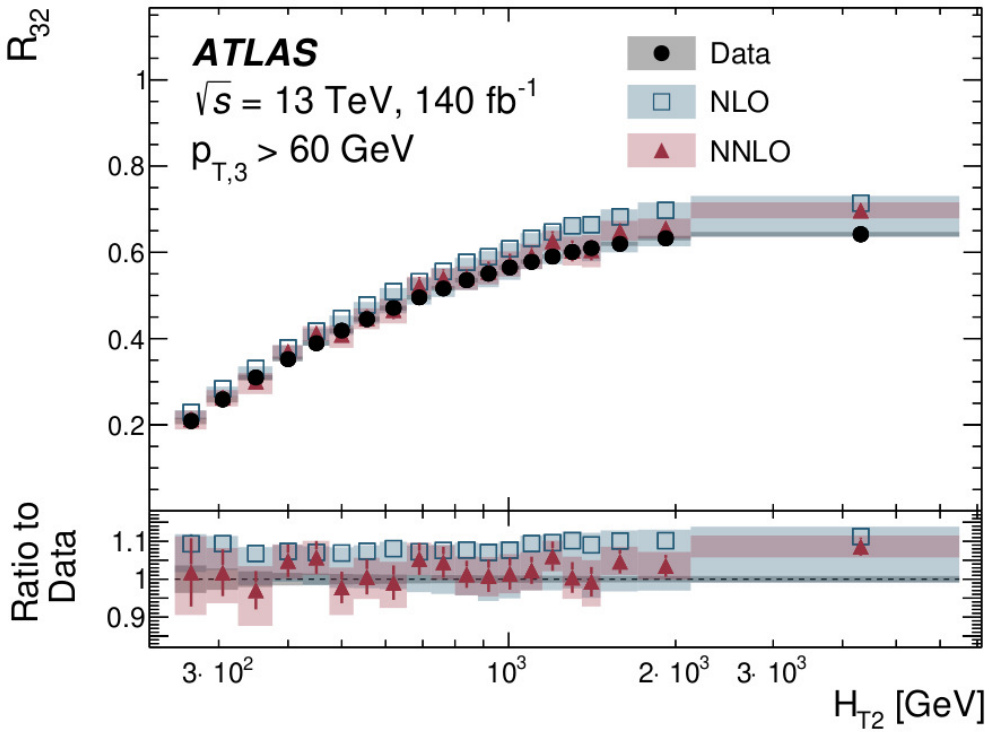
Jet cross-section ratios [1] – JES uncertainty improvement

- Jet energy scale (JES) calibration
  - Dominant source of systematic uncertainty
  - Latest jet calibration results [5, 6]
- Several recent improvements
  - Jet-flavor response dependence
  - Single hadron response extrapolation to jets
- Reduction by factor of 3 at high p_T and up to 2 at lower p_T



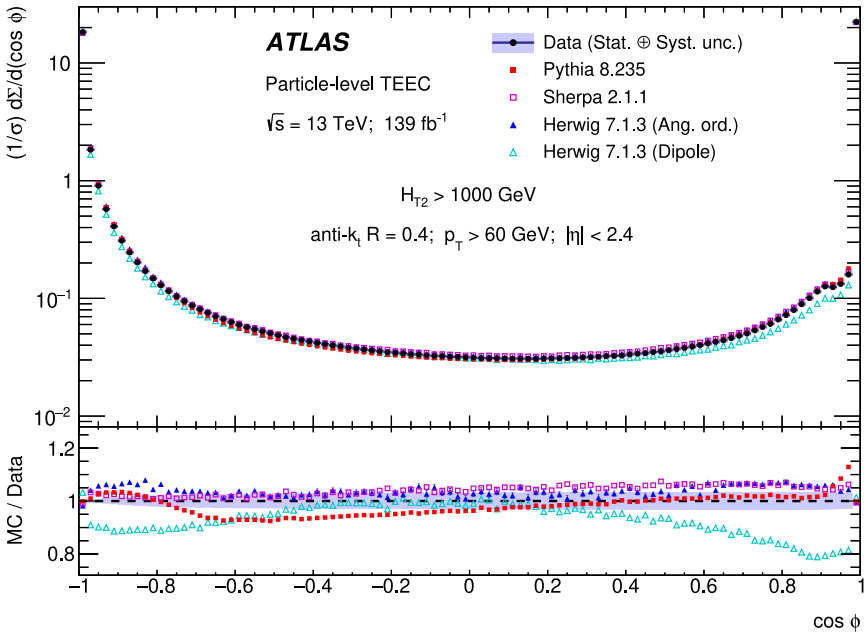
Jet cross-section ratios [1] – theoretical predictions

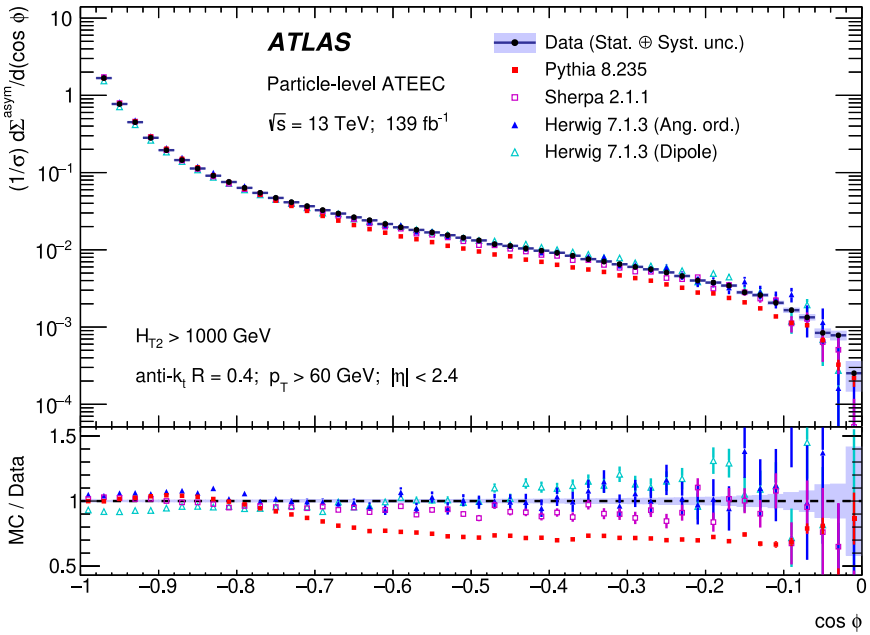
- Measurement compared to theory predictions
  - Data corrected to the particle level using unfolding procedure
- State-of-the-art NNLO prediction of 2- and 3-jet production
  - Better data description than NLO
  - Reduced scale systematic uncertainty
- Possible α_S extraction using χ^2 fit



Exctraction of α_S from TEEC [2] – observables

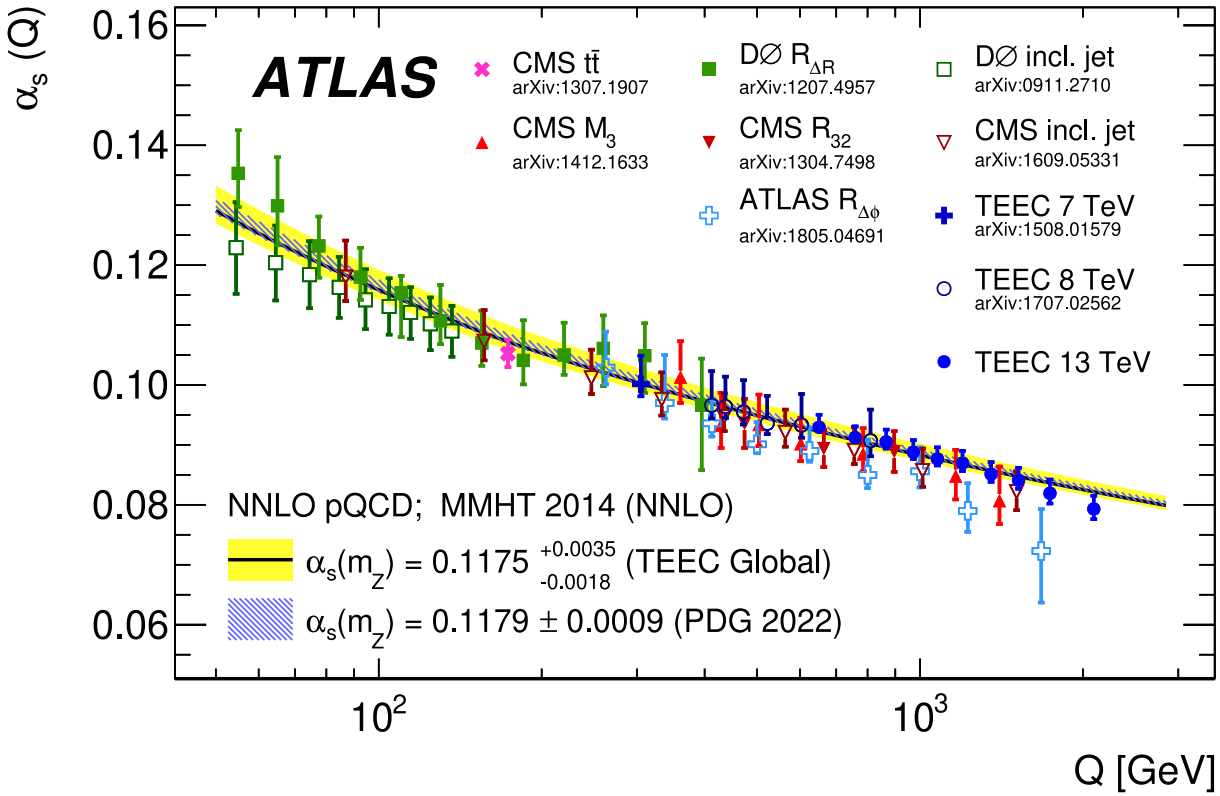
- Transverse energy–energy correlations (TEEC) defined as:
  - $\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} = \frac{1}{N}\sum_{A}^{N_{\text{events}}}\sum_{ij}^{N_{\text{jets}}}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$
  - Energy-weighted distribution of the ϕ differences between jet pairs
- Its asymmetry (ATEEC)
  - Defined as forward-backward difference of the TEEC
- $p_{\mathrm{T}} > 60$ GeV, $|y| < 2.4$, $H_{\mathrm{T2}} > 1$ TeV
- TEEC and ATEEC measured as functions of $\cos\phi$ in H_{T2} bins





Extraction of α_S from TEEC [2] – strong coupling

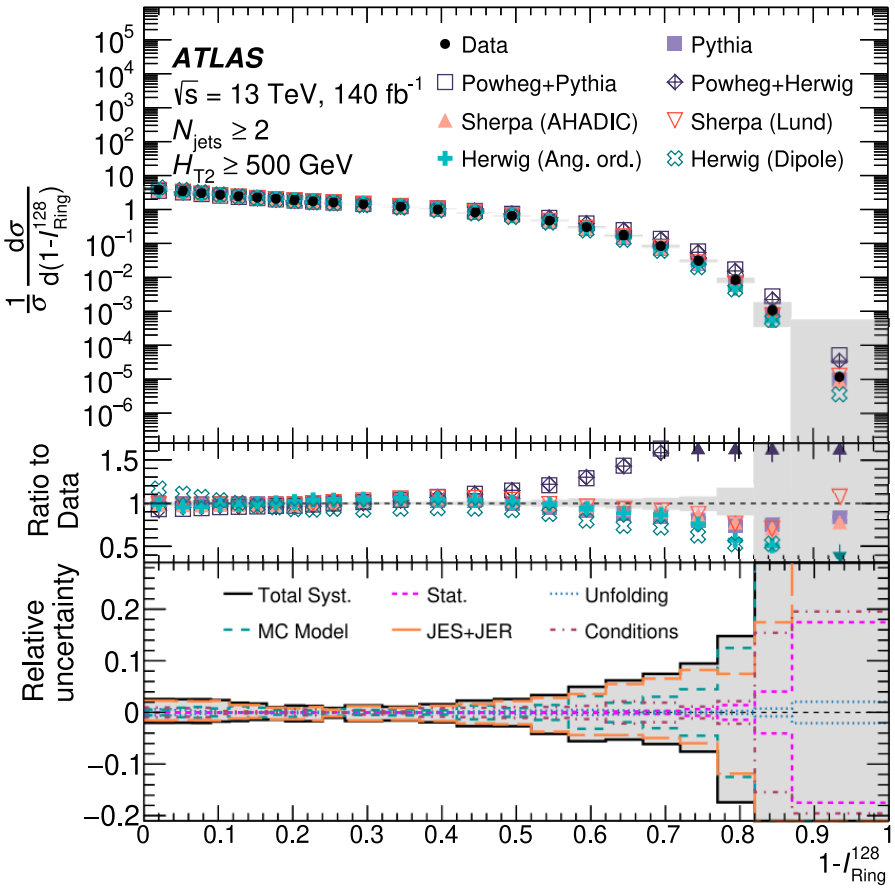
- Measurement compared to the NNLO theoretical predictions
  - Allows for α_S extraction using χ^2 fit
  - Reduces theory uncertainties by factor of 3 w.r.t. NLO
- TEEC and ATEEC α_S extraction results:
  - $\alpha_S(m_Z) = 0.1175 \pm 0.0006(\text{exp.})^{+0.0034}_{-0.0017}(\text{theo.})$
  - $\alpha_S(m_Z) = 0.1185 \pm 0.0009(\text{exp.})^{+0.0025}_{-0.0012}(\text{theo.})$



Multijet event isotropies [3]

- New event shape variable – event isotropy $I(\mathcal{E}) = \mathrm{EMD}(\mathcal{E}, \mathcal{U})$
  - Quantifying event $\mathcal{E}$ 'distance' from a symmetrical radiation pattern $\mathcal{U}$
  - Measure: Energy-Mover's Distance (EMD) – used for the first time
    - = minimal amount of 'work' needed to transport event $\mathcal{E}$ to $\mathcal{E}'$ of equal energy by moving energy of particles of $\mathcal{E}$ to particles of $\mathcal{E}'$

- $p_{\mathrm{T}} > 60$ GeV, $|y| < 4.4$, $H_{\mathrm{T2}} > 400$ GeV
- Events compared with 3 reference geometries
  - Cylindrical, ring-like, dipole-like
  - In bins of H_{T2} and jet multiplicity
- Useful for improving MC simulations at LHC



Conclusion

- Three multijet ATLAS measurements in 13 TeV proton–proton collisions using full LHC Run 2 dataset

- Jet cross-section ratios in jet multiplicity
  - Several improvements to the JES uncertainties $\rightarrow$ significant reduction of the total uncertainty
  - Measurement compared to new NNLO predictions, can be used to α_S extraction
- Exctraction of α_S from TEEC
  - Theory uncertainty reduced by factor of 3 using NNLO predictions
  - Good agreement with previous measurements
- Multijet event isotropies
  - First application of new event shape variable
  - Comparison to 3 reference geometries
  - Useful for improving MC simulations

[1] ATLAS Collaboration. Measurements of jet cross-section ratios in 13 TeV proton-proton collisions with ATLAS. 2024. https://cds.cern.ch/record/2899111.

[2] ATLAS Collaboration. Determination of the strong coupling constant from transverse energy-energy correlations in multijet events at $\sqrt{s} = 13$ TeV with the ATLAS detector. *JHEP*, 2307:085, 2023. http://cds.cern.ch/record/2846586.

[3] ATLAS Collaboration. Measurements of multijet event isotropies using optimal transport with the ATLAS detector. *JHEP*, 2310:060, 2023. https://cds.cern.ch/record/2860057.

[4] ATLAS Collaboration. Luminosity determination in *pp* collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC. Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC. *Eur. Phys. J. C*, 83(10):982, 2023. https://cds.cern.ch/record/2844887.

[5] ATLAS Collaboration. New techniques for jet calibration with the ATLAS detector. *Eur. Phys. J. C*, 83:761, 2023. https://cds.cern.ch/record/2854733.

[6] ATLAS Collaboration. Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Eur. Phys. J. C*, 81(8):689, 2021. https://cds.cern.ch/record/2722869.