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Precision measurements of multijet production with the ATLAS experiment

Stanislav Poláček* **on behalf of the ATLAS Collaboration**

Institute of Particle and Nuclear Physics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

E-mail: stanislav.polacek@cern.ch

The production of jets at hadron colliders provides stringent tests of perturbative QCD. The latest measurements by the ATLAS experiment are presented in this note, using multijet events produced in the proton–proton collision data at $\sqrt{s}$ = 13 TeV delivered by the LHC. Jet cross-section ratios between inclusive bins of jet multiplicity are measured differentially in various observables sensitive to different features of the final state. Significant improvements of the overall ATLAS jet energy scale uncertainty, resulting from a reduction of several uncertainty components, are described. The state-of-the-art NLO and NNLO predictions are compared to the measurements and used to determine the strong coupling constant. A measurement of new event-shape jet observables defined in terms of reference geometries with cylindrical and circular symmetries using the energy-mover's distance as a metric between collider events is highlighted.

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*Speaker

1. Introduction

Jet measurements are important tests of quantum chromodynamics (QCD), probing various aspects of the theory, like the strong coupling constant α_S, the proton structure described by parton distribution functions, or the accuracy of the Monte Carlo (MC) modeling of the LHC collisions.

The ATLAS experiment [1] at the LHC at CERN uses multiple types of detector signals to reconstruct jets—the energy deposits in its calorimeters and tracks of charged particles obtained by the inner detector—resulting in better jet energy and angular resolution.

2. Latest multijet measurements at ATLAS

In the following sections, the latest ATLAS multijet measurements [2–4] using the full LHC Run 2 dataset of proton–proton collisions at 13 TeV center-of-mass energy with total integrated luminosity of 140.07 ± 1.17 fb^{-1} [5] are summarized.

2.1 Measurement of jet cross-section ratios

Jet cross-section ratios between inclusive bins of jet multiplicity [2] are measured as functions of various observables like the scalar sum

$$H_{T2} = p_{T,1} + p_{T,2}$$

of the transverse momenta $p_{T,1}$ and $p_{T,2}$ of the leading and subleading jets in an event (Figure 1(a)), the invariant mass of the two leading jets m_{jj}, or the absolute value of their rapidity separation Δy_{jj} (Figure 1(b)). The ratio of three- and two-jet production, R_{32}, and other ratios, R_{42}, R_{43}, and R_{54}, are presented. The ratios show good sensitivity to α_S while the sensitivity to systematic uncertainties and parton distribution functions is decreased.

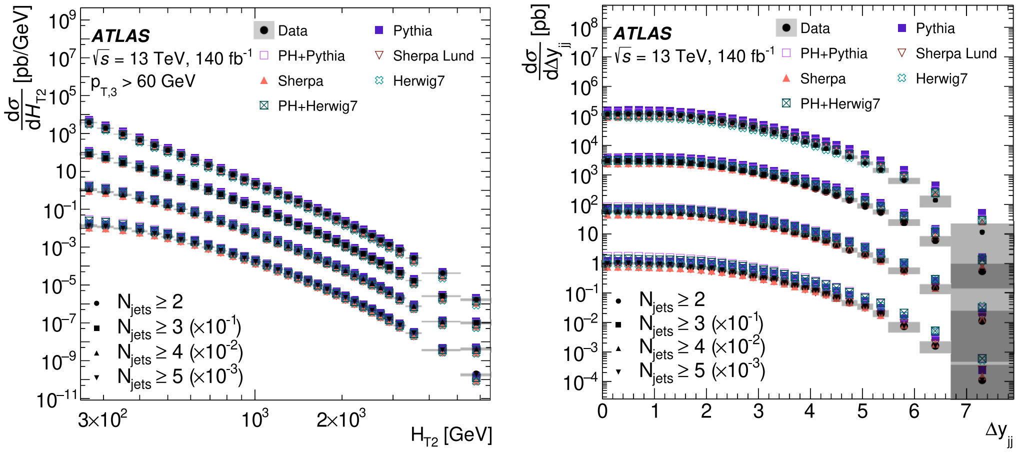
Jets selected in this measurement are required to have $p_T > 60$ GeV and $|y| < 4.5$, where y is the jet rapidity, and each event is required to have $H_{T2} > 250$ GeV. The data are unfolded to the particle level to account for acceptance and detector-related effects.

The jet energy scale (JES) uncertainty [6] originating from the jet calibration procedure is the dominant source of the experimental systematic uncertainty. With respect to Ref. [6], the JES uncertainty was improved by reduction of the components related to the uncertainty of the response of quark- and gluon-initiated jets and to the extrapolation of the single-hadron response to jets. This leads to a reduction of the JES uncertainty by a factor of three at high jet p_T and up to a factor of two at lower p_T (Figure 2(a)).

State-of-the-art next-to-next-to-leading-order (NNLO) MC theoretical predictions are compared to the R_{32} ratio (Figure 2(b)). The NNLO calculations describe the data better than the next-to-leading-order (NLO) calculations and the scale uncertainty is reduced compared to the NLO case.

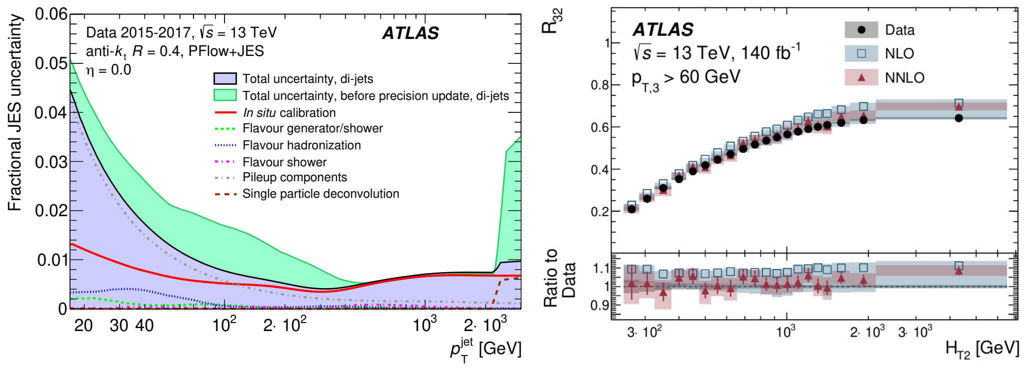
2.2 Determination of the strong coupling constant from transverse energy–energy correlations

This measurement uses two event-shape observables in multijet events for the extraction of the strong coupling constant α_S—the transverse energy–energy correlations (TEEC) and the associated azimuthal asymmetries (ATEEC) [3].



(a) (b)

Figure 1: The multijet cross-sections as functions of (a) H_{T2} and (b) Δy_{jj} in the inclusive bins of jet multiplicity N_{jets} compared to various MC predictions [2].



(a) (b)

Figure 2: (a) The JES uncertainty as a function of a jet transverse momentum $p_{\mathrm{T}}^{\mathrm{jet}}$, comparing the improved uncertainty (blue area) and the uncertainty before the precision update (green area) [2]. (b) The ratio R_{32} as a function of H_{T2} in the most inclusive bin of the third jet transverse momentum $p_{\mathrm{T},3}$ compared to the NLO and NNLO theoretical predictions [2].

The TEEC observable is defined as an energy-weighted distribution of differences in azimuthal angle ϕ between jet pairs

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} = \frac{1}{N}\sum_{A}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$

normalized to the total cross-section σ, where the index A runs over the sample of N multijet events, indices i, j, and k run over all jets in a given event, $E_{\mathrm{T}} = E/\cosh(y)$ is a jet transverse energy (E is

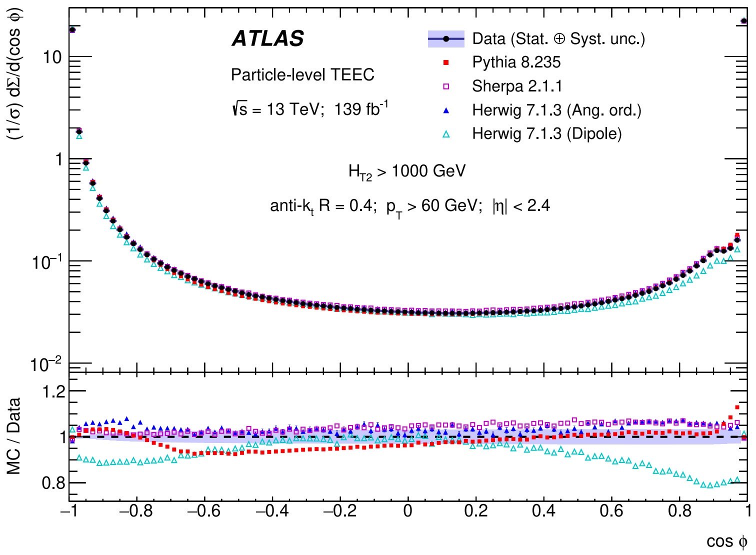


Figure 3: The distribution of the TEEC as a function of $\cos\phi$ in the inclusive $H_{\mathrm{T2}} > 1000$ GeV bin compared to various MC predictions [3].

its energy and y its rapidity), φ_{ij} is the azimuthal angle difference between jets i and j, and δ is the Dirac delta function.

The ATEEC observable is defined as the forward–backward difference of the TEEC distribution

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma^{\mathrm{asym}}}{\mathrm{d}\cos\phi} = \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\pi-\phi}.$$

Jets are required to have $p_{\mathrm{T}} > 60$ GeV and $|y| < 2.4$. The sum of transverse momenta of the two leading jets in each event is required to be $H_{\mathrm{T2}} > 1$ TeV. The data are unfolded to the particle level.

The TEEC (Figure 3) and ATEEC distributions are presented as functions of $\cos\phi$ in bins of H_{T2} and compared to the NNLO theoretical predictions, allowing the extraction of α_{S} by using a χ^2 fit. The extracted values at the scale of the Z boson mass m_Z for the TEEC (Figure 4) and ATEEC distributions using a global fit to all H_{T2} bins simultaneously are

$$\alpha_{\mathrm{S}}(m_Z) = 0.1175 \pm 0.0006(\mathrm{exp.})^{+0.0034}_{-0.0017}(\mathrm{theo.}),$$
$$\alpha_{\mathrm{S}}(m_Z) = 0.1185 \pm 0.0009(\mathrm{exp.})^{+0.0025}_{-0.0012}(\mathrm{theo.}),$$

respectively. The introduction of the NNLO corrections to the theoretical calculations leads to a reduction of the theoretical uncertainties by a factor of three.

2.3 Measurement of multijet event isotropies using optimal transport

A measurement of a new event-shape observable quantifying the isotropy of collider events is presented [4].

The event isotropy $I \in [0, 1]$ of an event $\mathcal{E}$ is defined as

$$I(\mathcal{E}) = \mathrm{EMD}(\mathcal{E}, \mathcal{U}),$$

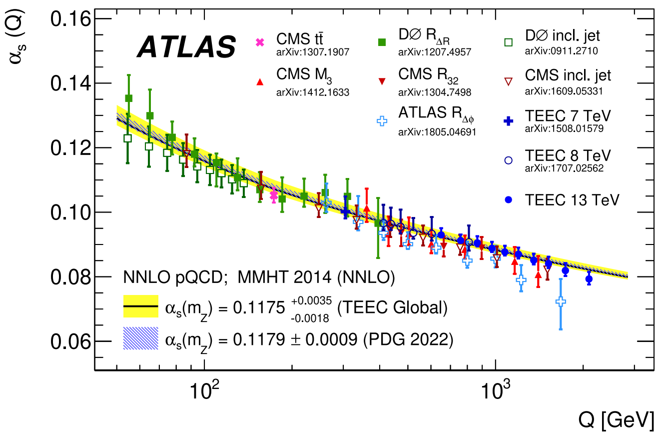


Figure 4: Values of α_S at a scale Q determined from TEEC functions and from previous analyses compared to the world average (hatched band) and global TEEC fit (solid band) [3].

measuring a distance of an event from a (quasi-)uniform radiation pattern $\mathcal{U}$, using the energy-mover's distance (EMD), defined as a minimal amount of 'work' needed to transport event $\mathcal{E}$ into event $\mathcal{U}$ of equal energy by moving energy of particles of one event to particles of the other event.

Three choices of reference events $\mathcal{U}$ are used in this analysis—a ring-like geometry constructed using 128 points $\mathcal{I}^{N=128}_{\text{Ring}}$ (Figure 5), a special case of two points $\mathcal{I}^{N=2}_{\text{Ring}}$ corresponding to a well-balanced back-to-back dijet event, and a cylindrical geometry $\mathcal{I}^{N=16}_{\text{Cyl}}$ with 16 azimuthal segments resulting in a reference grid in the rapidity–azimuth plane.

Jets selected in this analysis are required to have $p_T > 60$ GeV and $|y| < 4.5$. The sum of the transverse momenta of the two leading jets in each event is required to be $H_{T2} > 400$ GeV. The data are unfolded to the particle level.

The event isotropy is measured in inclusive bins of jet multiplicity N_{jet} and H_{T2} and compared to theoretical predictions of various MC generators. As the event isotropy is sensitive to isotropic radiation patterns, it serves as a valuable test of MC modeling of LHC collisions and can be used to improve the MC simulations.

3. Conclusion

The latest ATLAS multijet measurements using the full LHC Run 2 dataset of proton–proton collisions at 13 TeV are presented.

The measurements of the jet cross-section ratios between inclusive bins of jet multiplicity and transverse energy–energy correlations highlight the importance of the NNLO theoretical predictions, showing better agreement with the data than the NLO calculations and allowing a more precise extraction of the strong coupling constant α_S than the NLO calculations.

The measurement of the jet cross-section ratios also includes the latest improvements of the jet calibration, resulting in a sub-percent JES uncertainty for jets with transverse momenta above 100 GeV.

The novel event isotropy observable is used as a sensitive probe of the MC modeling of LHC collisions.

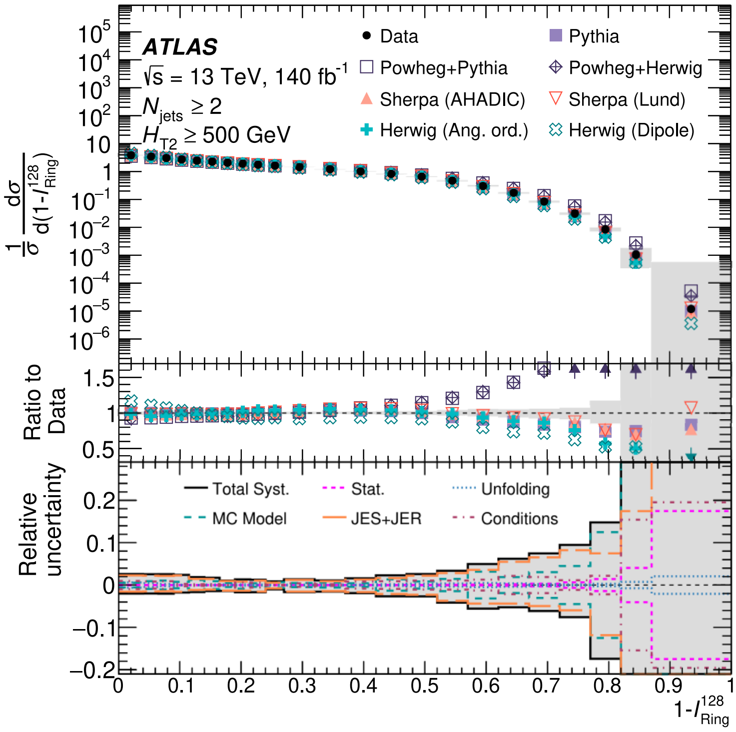


Figure 5: The distribution of $1 - \mathcal{I}^{N=128}_{\text{Ring}}$ in the most inclusive bin of N_{jets} and H_{T2} compared to various MC predictions [4].

References

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