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Jet measurements in proton-proton collisions from ATLAS

Ota Zaplatilek[a,*] **on behalf of the ATLAS Collaboration**

[a] *Department of Physics,*
Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague,
Brehova 78/7, 115 19 Prague 1, Czech Republic

E-mail: ota.zaplatilek@cern.ch

This article discusses two recent jet measurements from the ATLAS experiment at the LHC collider using proton–proton collisions. The first measurement deals with the transverse energy-energy correlation TEEC and its azimuthal asymmetry ATEEC. This measurement is used for the strong coupling parameter extraction to probe QCD prediction at the TeV scale. The extraction profits from new state-of-the-art NNLO pQCD calculations, significantly reducing theoretical uncertainty. The second measurement focuses on event isotropies in multijet events as new and generalized event-shape observables, allowing new possibilities for investigating QCD radiation and new opportunities for MC tuning.

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1. Introduction

This article reports on two jet measurements from the ATLAS experiment [1] at the LHC [2] collider based on the full Run 2 dataset of proton–proton collisions at the centre-of-mass energy of 13 TeV with an integrated luminosity of 139 fb^{-1} using calibrated particle-flow anti-k_T $R = 0.4$ jets. The first measurement concerns transverse energy-energy correlation, TEEC, and its associated angular asymmetry, ATEEC, which is additionally used to extract the strong coupling parameter α_s. The second measurement deals with new generalized event-shape variables in multijet events called event isotropies.

2. (A)TEEC measurements

The TEEC represents an infrared-safe and collinear-safe event-shape variable defined by Eq. (1) as the transverse energy-weighted distribution of the angular differences of each jet pair in the event

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}(\cos\phi)} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{(\sum_k E_{Tk}^{A})^2}\delta(\cos\phi - \cos\phi_{ij}), \tag{1}$$

where ϕ and E_T represent the jet's azimuthal angle and transverse energy, $E_T = E/\cosh y$, where E and y are jet energy and jet rapidity, respectively. The indices i and j run over all jets in the event simultaneously, while the index A runs over N hard-scattering multijet events in the dataset. The variable ϕ_{ij} describes the azimuthal angle between the two jets i and j. The associated azimuthal asymmetry of transverse energy-energy correlation, ATEEC, is defined as the difference between forward ($\cos\phi > 0$) and backward ($\cos\phi < 0$) parts of the TEEC

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma^{asym}}{\mathrm{d}(\cos\phi)} = \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}(\cos\phi)}\bigg|_{\phi} - \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}(\cos\phi)}\bigg|_{\pi-\phi}. \tag{2}$$

The analysis [3] required at least two jets with transverse momenta $p_\mathrm{T} > 60$ GeV in the central part of the detector (pseudorapidity $|\eta| < 2.4$) and the scalar sum of the two leading jets $H_{\mathrm{T},2} = p_{\mathrm{T},1} + p_{\mathrm{T},2} > 1000$ GeV. The (A)TEEC was calculated in one inclusive and eight exclusive bins of the $H_{T,2}$ variable.

Examples of the measured (A)TEEC distributions as a function of azimuthal angle $\cos\phi$ are shown in Figure 1. The unfolded ATLAS data at the particle level were compared to several MC predictions of Pythia8, Sherpa, and Herwig7. The low (high) $\cos\phi$ values of TEEC distribution is populated by back-to-back (collinear) jet events. The central region of TEEC distribution is dominated by gluon radiation in multijet events.

The dominant systematic uncertainties arose from Jet energy scale (JES), Jet energy resolution (JER) and Monte Carlo modelling. The measurements were also compared for the first time to new state-of-the-art next-to-next-leading order (NNLO) perturbative QCD (pQCD) calculations for the $2 \to 3$ process [4]. The NNLO pQCD prediction reduced the dominant theoretical scale uncertainty by a factor of three compared to previous calculations at the next-to-leading order (NLO).

The (A)TEEC measurements were also used to extract the strong coupling parameter $\alpha_\mathrm{s}(m_\mathrm{Z})$ at the scale of the Z boson mass using a χ^2 fit of NNLO pQCD theory to data. The results from the

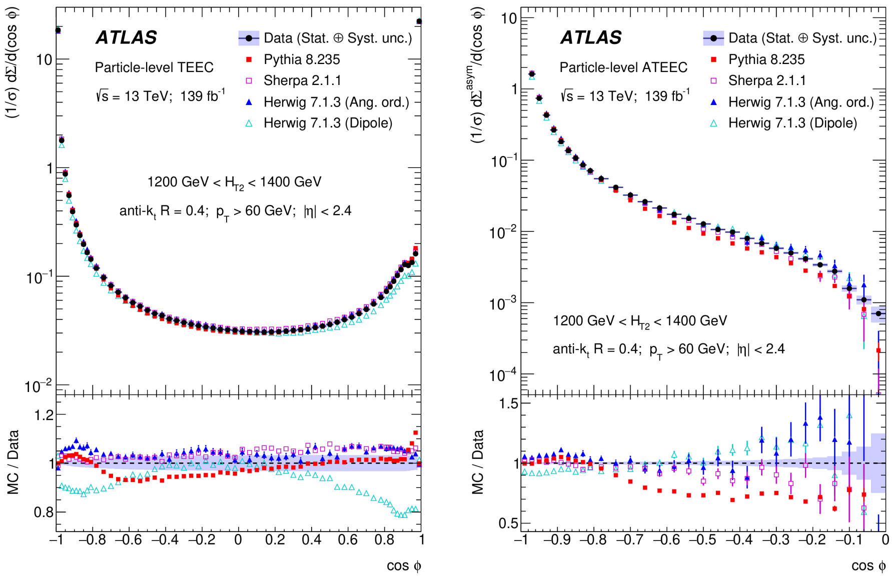

Figure 1: Particle level TEEC (left) and ATEEC (right) distributions as a function of the azimuthal angle $\cos\phi$ measured at the ATLAS experiment. The unfolded data are compared to MC predictions of PYTHIA8, SHERPA, and HERWIG7 in one chosen $H_{T,2}$ bin. Taken from Ref. [3].

global χ^2 fit using all $H_{T,2}$ bins simultaneously are found below

$$\begin{aligned} \alpha_s(m_Z)^{\text{TEEC}} &= 0.1175 \pm 0.0006(\text{exp.})^{+0.0034}_{-0.0017}(\text{theo.}) \\ \alpha_s(m_Z)^{\text{ATEEC}} &= 0.1185 \pm 0.0009(\text{exp.})^{+0.0025}_{-0.0012}(\text{theo.}). \end{aligned} \tag{3}$$

The $\alpha_s(m_Z)$ values were also extracted for each particular exclusive $H_{T,2}$ bin and evolved using NNLO Renormalization Group Equation (RGE). The renormalization scale Q was chosen as average $\hat{H}_T$ of all final state partons in the particular $H_{T,2}$ bin to include the effect of the third parton correctly. The results for running $\alpha_s(Q)$ are in a good agreement with the other ATLAS and non-ATLAS measurements, PDG results, and the RGE prediction up to the highest energy scales.

3. Measurement of event isotropies

The second measurement deals with multijet event isotropies [5], a new generalized and complementary event-shape variables, proposed in Ref. [6]. The event isotropies remain infrared-safe and collinear-safe; they increase the dynamic range of the measurement, and they become more sensitive to isotropic radiation. The event isotropies quantify how much the event looks like a referenced symmetric event under the given radiation pattern defined using the Wasserstein metrics system within the Optimal transport problem using Energy-Mover's Distance (EMD) [7]. This new metrics system can be understood as the minimal amount of work to rearrange an event to the referenced one defined within a given symmetric radiation pattern.

Three different event isotropies of I^2_{Ring}, I^{128}_{Ring}, and I^{16}_{Cyl} were investigated under three different isotropy radiation patterns: dipole isotropy in azimuthal angle ϕ, isotropy in the full azimuthal angle ϕ, and cylindrical isotropy in the azimuthal angle and rapidity $(\phi \times y)$.

The analysis was performed using jet selection: $p_T > 60$ GeV, $|y| < 4.5$, and $H_{T,2} = p_{T,1} + p_{T,2} > 400$ GeV in four inclusive jet multiplicity bins ($N_{jets} > 2, 3, 4, 5$) and three inclusive $H_{T,2}$ bins ($H_{T,2} > 500, 1000, 1500$ GeV). Demonstrative results of the unfolded data to several state-of-art MC predictions (Pythia, Sherpa, Powheg, and Herwig7 considering different hadronization and parton shower models) can be found in Figure 2.

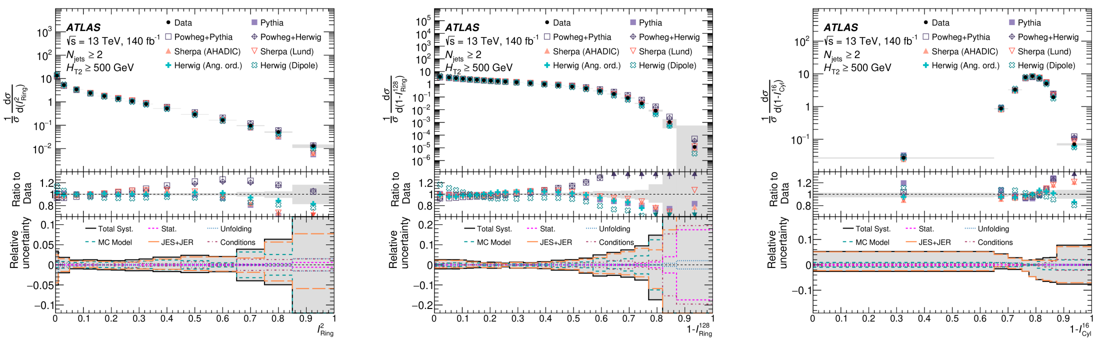

Figure 2: Unfolded event isotropy I^2_{Ring} (left), $1 - I^{128}_{\mathrm{Ring}}$ (middle), and $1 - I^{16}_{\mathrm{Cyl}}$ (right) distributions compared to several MC predictions in most inclusive N_{jets} and $H_{T,2}$ bins. Each figure shows a normalized distribution of differential cross-section in the top panel, MC to data ratio in the middle panel, and relative systematic uncertainties in the bottom panel. Taken from Ref. [5].

In general, MC-to-data differences increase for more complex and symmetric events. Better agreement is found for NLO than LO MC generators. Additionally, no differences are observed for the MC generators with different hadronization models (cluster-based and string-based models in Sherpa and similarly in Powheg). Nevertheless, the differences are found when different shower models are applied (Herwig7 with Angular and Dipole ordering).

The multijet event isotropies allow the investigation of more features of QCD radiation than traditional canonical event-shape variables. Since no MC generator describes data precisely, the event isotropies also provide new insight into MC tuning.

4. Conclusion

This proceeding discussed the results from two data analyses of multijet events conducted within the ATLAS experiment at the LHC collider. The first analysis involved the measurement of (A)TEEC correlations, which included a comparison to new state-of-the-art NNLO pQCD calculations for the first time. The running strong coupling parameter was also extracted, indicating good agreement with other measurements and the RGE. The second analysis for event isotropies comprehensively compared MC theory and data to enable new avenues for MC tuning and exploring QCD radiation.

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