Hadronic Event Shapes and Transverse Energy-Energy Correlations using the ATLAS detector

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Test QCD from event-shape functions

The study of collider observables, including **event-shapes functions**, is well established to test QCD as they characterize the topology of the collisions.

The most recent ATLAS measurements of event shapes are:

- Measurement of hadronic event shapes in multijet final states at $\sqrt{s} = 13$ TeV with the ATLAS detector. [JHEP01 (2021) 188]
- Determination of the strong coupling constant and test of asymptotic freedom from Transverse Energy-Energy Correlations in multijet events at $\sqrt{s} = 13$ TeV with the ATLAS detector. [ATLAS-CONF-2020-025]

Other relevant ATLAS measurements are:

- Measurement of TEECs in multijet events at 7 TeV using the ATLAS detector and determination of the strong coupling. [Phys. Let. B 750 (2015) 427-447]
- Determination of the strong coupling from TEECs in multijet events at 8 TeV using the ATLAS detector. [Eur. Phys. J. 77 (2017) 872]

Transverse thurst

Transverse thrust: the idea is to select the axis $\vec{n}_T$ that maximizes the projection of the jet momenta in the transverse plane,

$$T_\perp = \max_{\vec{n}_T} \frac{\sum_i^{\text{jets}} |\vec{p}_{\mathrm{T}i} \cdot \vec{n}_T|}{\sum_i^{\text{jets}} |\vec{p}_{\mathrm{T}i}|} \; ; \qquad T_{minor} = \frac{\sum_i^{\text{jets}} |\vec{p}_{\mathrm{T}i} \times \vec{n}_T|}{\sum_i^{\text{jets}} |\vec{p}_{\mathrm{T}i}|} \; .$$

It is also useful to define $\tau_\perp = 1 - T_\perp$.

- IR safety, they are not afected by long-distance effects in e^+e^- collisions.
- $\tau_\perp = T_m \simeq 0$ for back-to-back, pencil-like configurations (left).
- $\tau_\perp \simeq 1/3$ for planar conf. (right), $T_m \simeq 2/3$ for spherical configurations.

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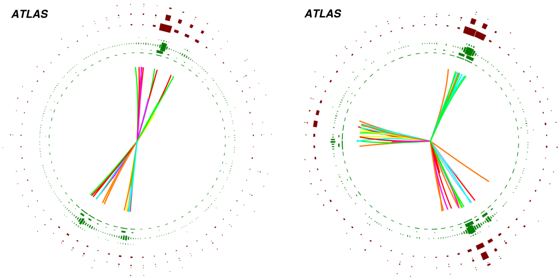


Linearised sphericity tensor

Linearised sphericity tensor: there is a family of event-shape variables derived from its eigenvalues. The formal definition of the tensor is given by

$$\mathcal{M}_{xyz} = \frac{1}{\sum_i^{\text{jets}} |\vec{p}_i|} \sum_i^{\text{jets}} \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix} .$$

This tensor is a good quantity to extract information of the event's isotropy. Its eigenvalues satisfy $\lambda_1 + \lambda_2 + \lambda_3 = 1$ and are ordered as $\lambda_1 \geq \lambda_2 \geq \lambda_3$.

Transverse linearised sphericity tensor: constructed using only the momentum components in the transverse plane, $\mathcal{M}_{xy}$. Its eigenvalues are μ_1 and μ_2.

The main event-shape variables derived from these tensors are:

$$S = \frac{3}{2}(\lambda_2 + \lambda_3) \; ; \quad S_\perp = \frac{2\mu_2}{\mu_1 + \mu_2} \; ; \quad A = \frac{3}{2}\lambda_3 \; .$$

- **Sphericity:** Larger values of $S_\perp \in [0, 1]$ for more isotropic events in the T.P.
- **Aplanarity:** Larger values of $A \in [0, 1/2]$ for less planar events.

Event selection. Data and MC samples

The data sample corresponds to the full dataset recorded during the LHC p-p Run 2 at $\sqrt{s} = 13$ TeV. The available integrated luminosity is 139 fb^{-1}.

For this analysis, multi-jet events with the following cuts are selected:

- Jet reconstruction: anti-k_{T} algorithm with $R = 0.4$ and PFlow.
- Jet selection: $p_{\mathrm{T}} > 100$ GeV and $|\eta| < 2.4$ for each jet.
- Event selection: $H_{\mathrm{T2}} = p_{\mathrm{T1}} + p_{\mathrm{T2}} > 1$ TeV using trigger HLT_j460.

The measurements are performed for different regimes given by H_{T2} and n_{jet}.

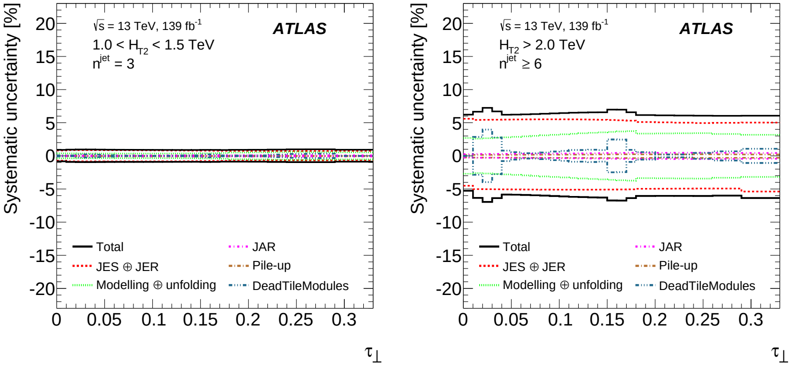
The table below contains the properties of the MC samples used in the analysis:

Generator	ME order	FS partons	PDF set	Parton shower
PYTHIA	LO	2	NNPDF 2.3 LO	p_{T}-ordered
SHERPA	LO	2,3	CT14 NNLO	dipole
MADGRAPH	LO	2,3,4	NNPDF 3.0 NLO	p_{T}-ordered
HERWIG	NLO	2,3	MMHT2014 NLO	angle-ordered $\oplus$ dipole

Unfolding and experimental uncertainties

Data at detector level are unfolded to the particle level using the Iterative Bayesian unfolding. The method makes use of a transfer matrix that parameterises the probability of an event generated in one bin to be reconstructed in another bin.

The systematic sources are indicated on the legend from figures below:



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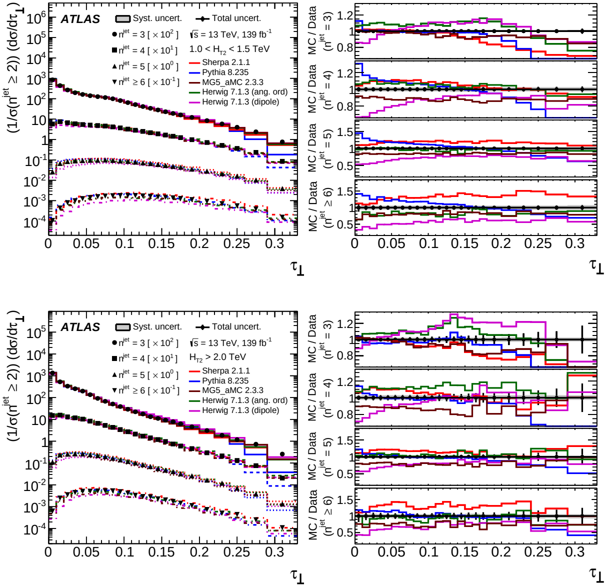
The exp. uncertainties increase for larger values of H_{T2} and jet multiplicity n_{jet}.

Transverse thrust unfolded results



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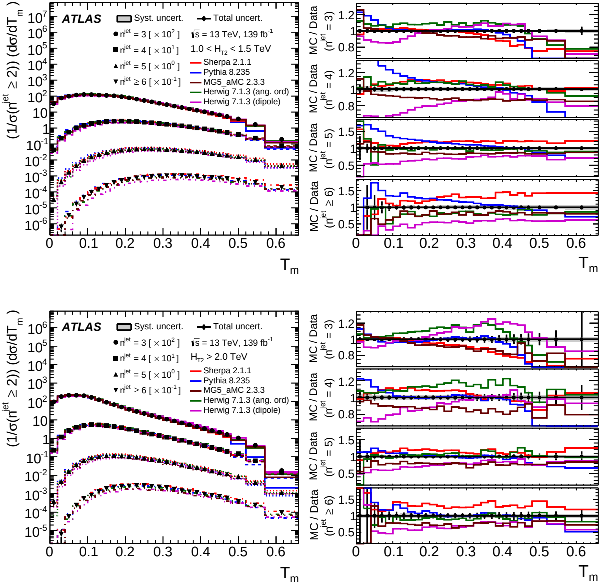
Transverse thrust minor unfolded results



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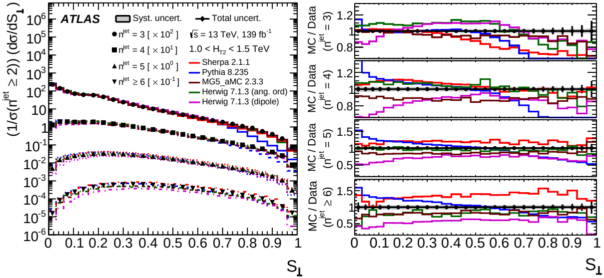
Transverse sphericity unfolded results



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- All MC predictions qualitatively describe the main features of the data.
- At low jet multiplicities, shape discrepancies are observed.
- At high jet multiplicities, shapes are better described but discrepancies in the normalisation are observed.
- These discrepancies show that these data provide a powerful testing ground for the understanding of the strong interaction at high energies.

Transverse Energy-Energy Correlations

TEEC function: transverse energy-weighted azimuthal angular distribution of produced jet pairs in the final state,

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} = \frac{1}{\sigma}\sum_{i,j}^{\mathrm{jets}}\int \mathrm{d}\sigma_{pp\to\mathrm{jets}}\,\frac{E_{\mathrm{T}i}E_{\mathrm{T}j}}{E_{\mathrm{T}}^{2}}\,\delta(\cos\Delta\varphi_{ij}-\cos\phi)\ .$$

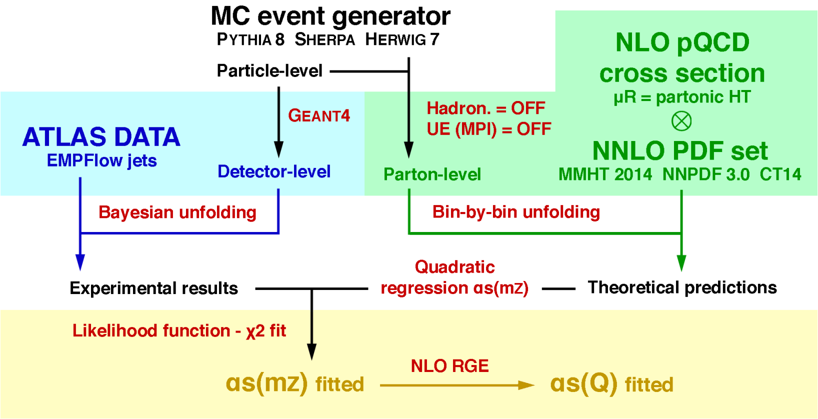
E_{T} is the sum of the jet transverse energy and the normalization to σ ensures that the integral of the function over $\cos\phi$ is unity.

ATEEC function: its forward-backward azimuthal angular asymmetry,

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

- Large sensitivity to QCD radiation and the strong coupling $\alpha_{\mathrm{s}}(Q^2)$.
- IR safety, they are not affected by IR divergences in e^+e^- collisions.
- Smaller sensitivity to IR divergences than other variables in *pp* collisions.
- Mild sensitivity to PDFs and factorization and renormalization scale variations.

Analysis workflow



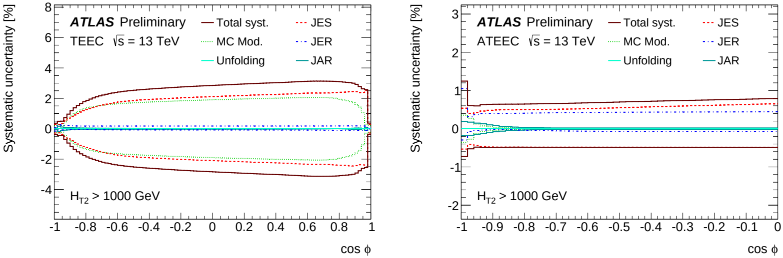
- TEEC function computed at fixed-order with a collinear cut $|\cos\phi| < 0.92$.
- Non-pQCD corrections computed with PYTHIA 8 tunes A14, AU2 and 4C.

Event selection and experimental uncertainties

The data sample corresponds to the full dataset recorded during the LHC *p*-*p* Run 2 at $\sqrt{s} = 13$ TeV. The available integrated luminosity is 139 fb^{-1}.

- PFlow anti-k_T R=0.4 reconstructed jets with $p_T > 60$ GeV and $|\eta| < 2.4$.
- Multi-jet events $H_{T2} = p_{T1} + p_{T2} > 1$ TeV using the HLT_j460 single-jet trigger.

The dominant uncertainties arise from knowledge of the jet energy scale and resolution and the modelling of the strong interaction in the unfolding.



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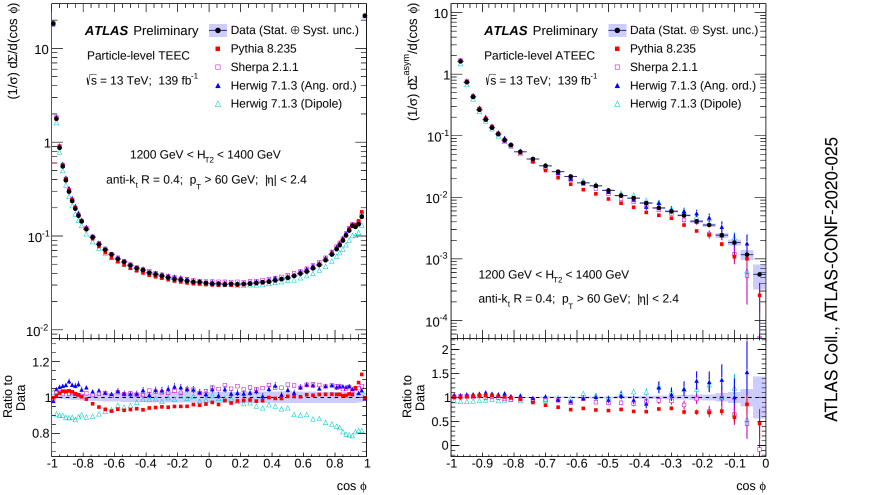
TEEC and ATEEC unfolded results



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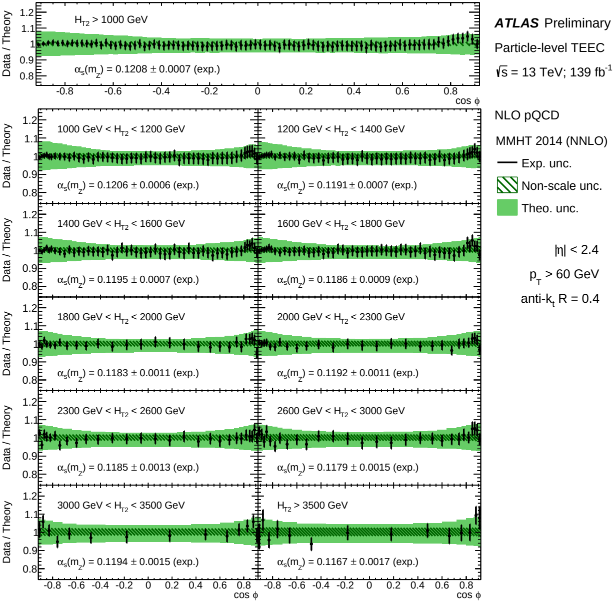
- SHERPA and HERWIG7 (Ang. ord.) give similar overall good description of data.
- The $\alpha_s(Q^2)$ values are extracted from fits of the pQCD calculations to the data.

Determination of the strong coupling from TEECs



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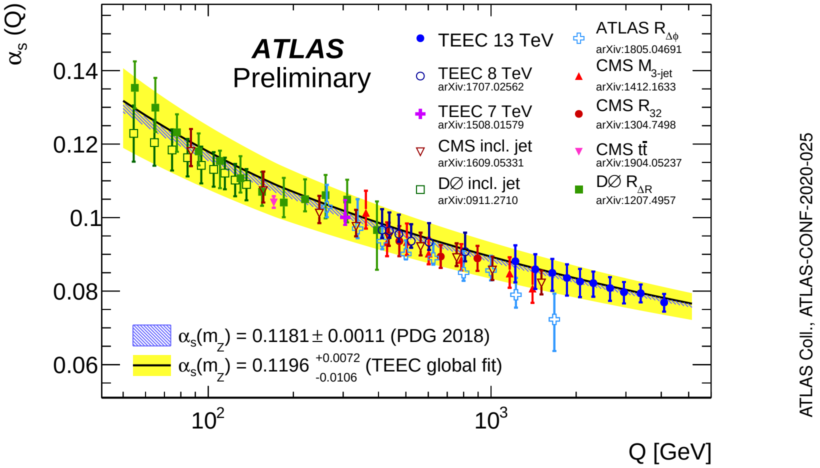
Test of asymptotic freedom from TEECs



- The $\alpha_s(m_Z)$ values are evolved to μ_R using the NLO solution of the RGE.
- These data can be used also as a test for new physics at large scales. [arXiv:1807.00894]

Conclusions

TEEC analysis tests asymptotic freedom beyond TeV scale at NLO accuracy.

$$\alpha_s(m_Z) = 0.1196 \pm 0.0004\ (\text{exp.})^{+0.0072}_{-0.0105}\ (\text{theo.}) \quad [\text{TEEC global fit}]$$
$$\alpha_s(m_Z) = 0.1195 \pm 0.0006\ (\text{exp.})^{+0.0084}_{-0.0107}\ (\text{theo.}) \quad [\text{ATEEC global fit}]$$

- Data results can be used to validate multi-jet production from MC event generators and to test new physics at large scale regimes.
- The agreement between data and theoretical predictions at NLO in pQCD is excellent at large momentum transfers.
- The strong coupling α_s is determined in ten intervals, testing asymptotic freedom beyond the TeV scale.
- The extracted values are in good agreement with the current world average and with previous determinations.
- NNLO corrections will reduce the scale uncertainties which are dominant.