ATLAS QCD jet measurements

Ota Zaplatílek [1]
behalf ATLAS Standard Model group

[1]FNSPE, CTU in Prague

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Introduction

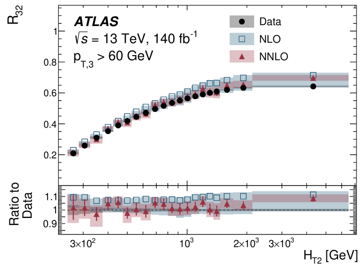
Recent ATLAS QCD jet measurements including:

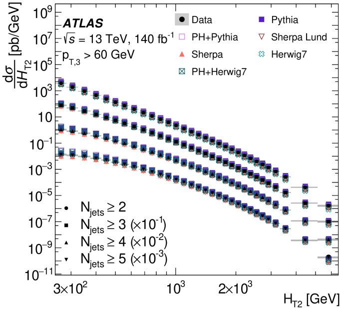
- Proton-proton, 13 TeV
- LHC Run 2 dataset, 140 fb^{-1} (resp. 139^{-1}), 2015-2018
- Anti-k_T $R = 0.4$ particle-flow jets
- Unfolded to particle level

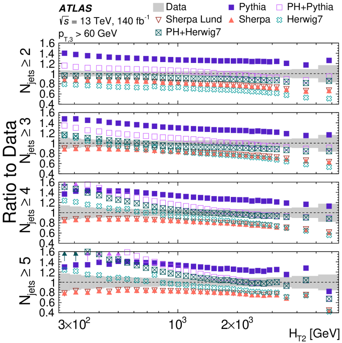
1) Measurements of jet cross-section ratios in 13 TeV proton-proton collisions with ATLAS (STDM-2020-04)
2) Measurements of Lund subjet multiplicities in 13 TeV proton-proton collisions with the ATLAS detector (STDM-2023-07)
3) Determination of the strong coupling constant from transverse energy–energy correlations in multijet events at $\sqrt{s} = 13$ TeV with the ATLAS detector (STDM-2018-51)
4) Measurements of multijet event isotropies using optimal transport with the ATLAS detector (STDM-2020-20)

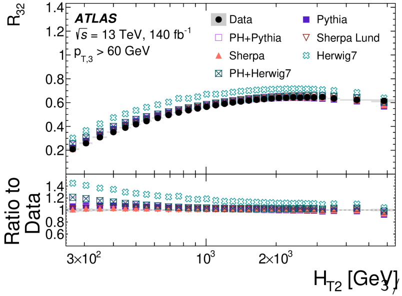
Jet cross-section ratio measurements

- Jet cross-section ratio: $R_{32}, R_{43}, R_{54}, R_{42}$ using inclusive bins of jet multiplicity N_{jets}
  - $R_{32} = \frac{\sigma(3\text{ jets})}{\sigma(2\text{ jets})}$ sensitive to $\alpha_s(Q^2)$
  - R_{43}, R_{42}, R_{54} as a reference for future theoretical developments
  - Double differential measurements: $(y_{\mathrm{jj}}, N_{\mathrm{jets}})$, $(y_{\mathrm{jj,\ max}}, N_{\mathrm{jets}})$, $(m_{\mathrm{jj}}, N_{\mathrm{jets}})$, $(m_{\mathrm{jj,\ max}}, N_{\mathrm{jets}})$
  - Triple differential measurements: $(H_{\mathrm{T},2}, N_{\mathrm{jets}}, p_{\mathrm{T},3})$ and $(p_{\mathrm{T}}^{\mathrm{N\ incl}}, N_{\mathrm{jets}}, p_{\mathrm{T},3})$





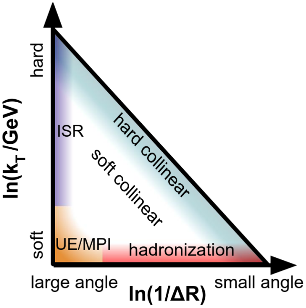


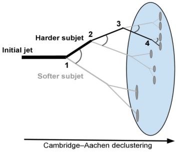


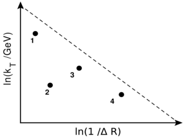
Lund subjet plane

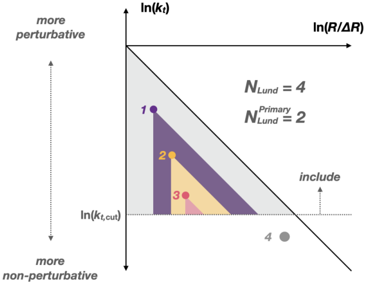
- Lund plane to probe different non-pQCD effects, testing current and future Parton Shower Models
- Lund plane multiplicity - counting number of subjets above a specified relative transverse momentum requirement in a jet's angle-ordered clustering history (jet re-clustering with Cambridge/Aachen alg.)

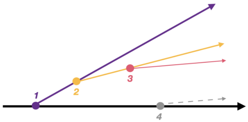
$$k_t = p_{\mathrm{T}}^{\mathrm{emistion}} \times \Delta R(p^{\mathrm{emition}}, p^{\mathrm{core}})$$





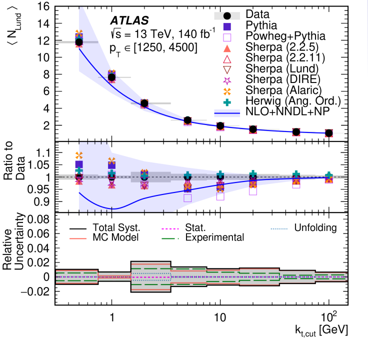




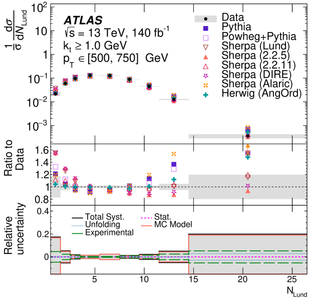


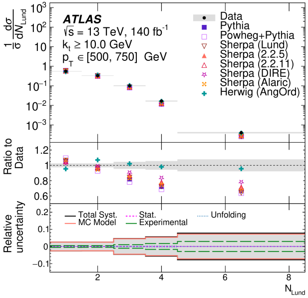
- N_{Lund} - Full Lund jet plane
- $N_{\mathrm{Lund}}^{\mathrm{Primary}}$ - Lund jet plane along only the primary C/A clustering sequence

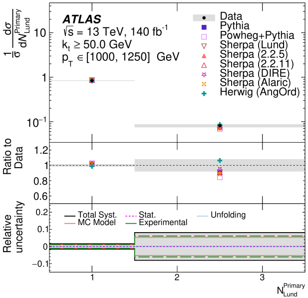
Lund plane subjet multiplicities



- $k_t > 10$ GeV cut (middle, right):
  - Best description with Herwig Angular order PS
  - Sherpa and Powheg+Pythia - increasing disagreement with increasing multiplicity
- $k_t < 10$ GeV cut (left):
  - More complicated trends
  - Herwig Angular best for low multiplicities
  - Sherpa DIRE best for high multiplicities







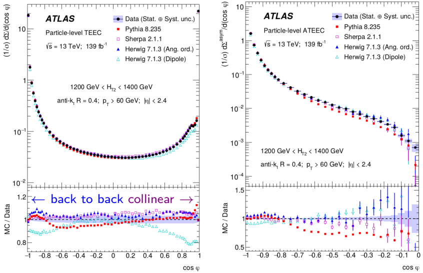
ATLAS TEEC and ATEEC measurements

- Transverse energy-energy correlation (TEEC) as transverse-energy-energy-weighted distribution of the azimuthal differences between jet pairs

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{Ti}E^A_{Tj}}{\left(\sum_k E^A_{Tk}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

- Transverse energy-energy correlation asymmetry (ATEEC) as azimuthal asymmetry of forward ($\cos\phi > 0$) and backward ($\cos\phi < 0$) TEEC parts

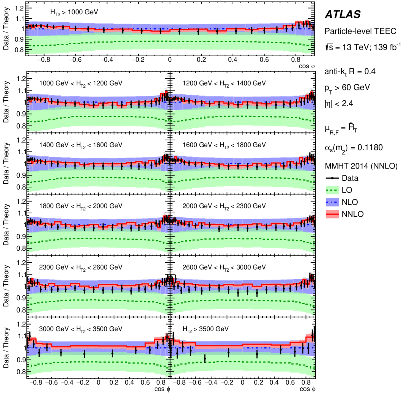
$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$



(A)TEEC Results

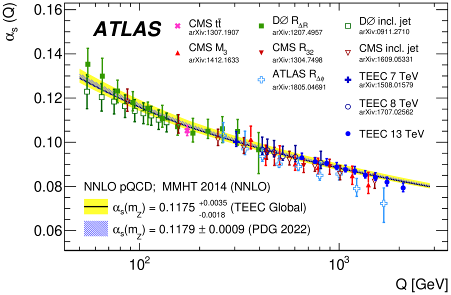
Data to Theory comparison:

- One inclusive $H_{T,2}$ bin and 10 exclusive $H_{T,2}$ bins
- NNLO calculation as state-of-art
  - Significant improvement with above $|cos(\phi)| > 0.8$
  - Significant reduction of theoretical uncertainties



$\alpha_s(Q)$ extraction:

- Running scale Q as half averaged $\hat{H}_T$ of all final-state partons in each $H_{T,2}$ bin

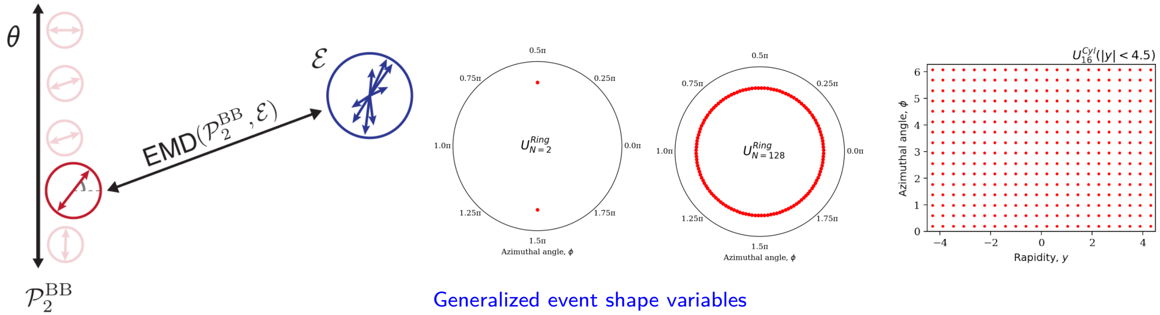


Good agreement with other measurements and RGE prediction

No deviation from RGE suggesting new coloured fermions

ATLAS Multijet event isotropy

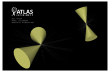
- Novel isotropy observables as generalization of Thrust JHEP 08 (2020) 084
- Solving *Optimal transport problem* using *Energy-Mover's Distance* (EMD)
  - Find minimal amount of work to rearrange one event $\mathcal{E}$ into referenced event $\mathcal{E}' \in \mathcal{U}$, (How far is a collider event $\mathcal{E}$ from a symmetric radiation patterns $\mathcal{U}$)
  - Isotropy $I(\mathcal{E}) = EMD(\mathcal{E}, \mathcal{U})$, $I \in \langle 0, 1 \rangle$, More isotropic event $I \to 0$, less isotropic event $I \to 1$
  - Three isotropy event shape observables: I^2_{Ring}, I^{128}_{Ring}, I^{16}_{Cyl}
  - I^2_{Ring} equivalent to transverse thrust but rescaled to range $\langle 0, 1 \rangle$



Generalized event shape variables

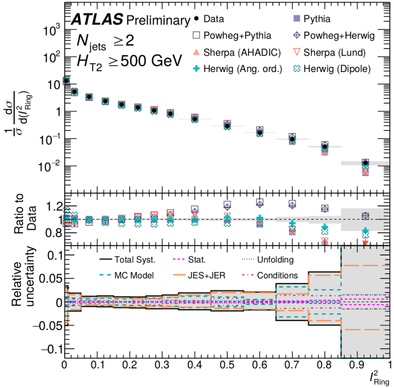
Infrared and collinear safe variables by construction

Event isotropy I^2_{Ring}



$I^2_{\text{Ring}} = 0.0001$ $\quad$ $I^2_{\text{Ring}} = 0.99$

- Unfolded data compared to several state-of-art MC model
- Good agreement in non-isotropy region (dijet like events) for LO and NLO
- More isotropic events more differences observed in different MC
- More isotropic events described better with MC NLO matrix elements (Powheg, Herwig) than LO (Pythia, Sherpa)
- Best description of I^2_{Ring} for NLO Herwig angle-ordered parton shower
- Dominant sys. unc.
  - Jet Energy Scale (JES) and Jet Energy Resolution (JER)
  - Choice of MC model for unfolding (MC Model)



← Balanced dijet event

Symmetric multijet event →

Conclusion

- Many interesting/useful ATLAS QCD jet measurements
  - R_{32} and (A)TEEC - α_s extraction
  - R_{xy} - reference for future MC development and MC tuning
  - Lund subjet multiplicities - reference for MC parton shower development
  - Event isotropies - new event shape variables, testing new features of QCD radiation, new insights to MC tuning

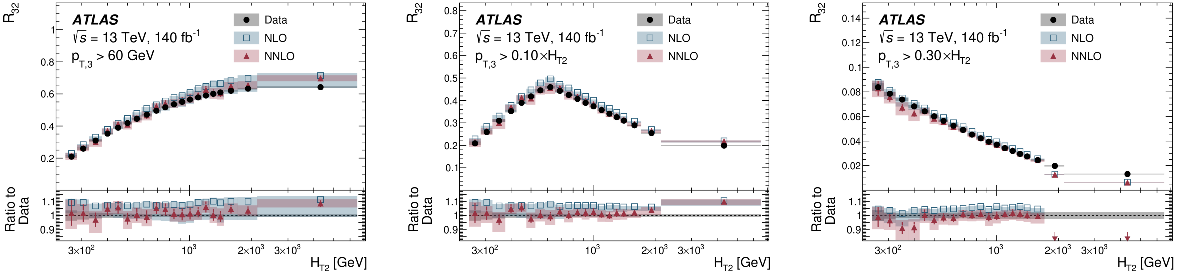
Thank you for your attention.

Back-up

Jet cross-section ratio measurements - results

- Improved JES unc.
  - Jet flavor response
  - Single hadron response
- Cancellation of correlated sys. unc. in ratio
- $p_T > 60$ GeV, $H_{T,2} > 250$ GeV, $|y| < 4.5$

- Compared to several MC generators
- NLO pQCD (NLOJet++)
- NNLO pQCD (FivePointAmplitudes, OpenLoops2)
- High Energy Jets HEJ



Lund plane subjet multiplicities

Selection:

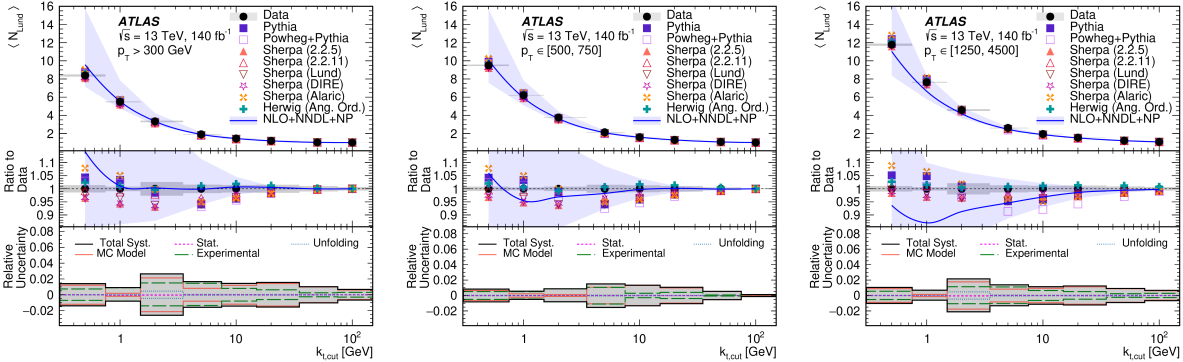
- Anti-k_{T} 0.4 particle-flow jets
- $p_{\mathrm{T},1} > 120$ GeV
- $p_{\mathrm{T},2} > 120$ GeV
- $|y_{\mathrm{jet}}| < 2.1$
- $p_{\mathrm{T},1}/p_{\mathrm{T},2} < 1.5$ (Dijet balance to reduce background, simplify interpretation)
- Only the two leading jets are included in the measurement

Specifics:

- p_{T} bins: 300–4500 GeV
- Relative rapidity bins: more-central and more-forward
  (quark-initiated jets as more centre, qluon-initiated jet as more forward)
- k_{t} bins: 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, 50.0, 100 GeV
- Bayesian unfolding, 4 iterations

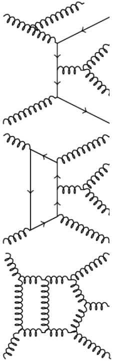
Lund plane subjet multiplicities

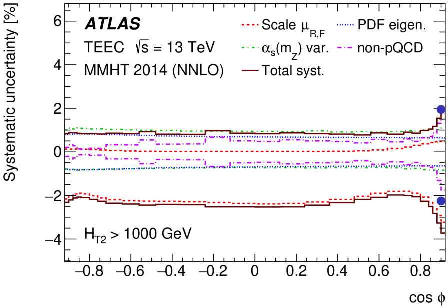
- Pythia: LO ME, default string hadronization, dipole p_T-ordered PS
- Powheg+Pythia: NLO ME, string hadronization, dipole p_T-order PS
- Sherpa (2.2.5): LO ME, default AHADIC cluster hadronization, default Catani-Seymour dipole PS
- Sherpa (2.2.5 Lund): LO ME, string hadronization, default Catani-Seymour dipole PS
- Sherpa (2.2.11): LO ME, tuned cluster hadronization, default p_T ordered PS
- Sherpa (2.2.11 DIRE): LO ME, tuned cluster hadronization, with alternative DIRE PS which incorporates some aspects of higher-order splitting functions in QCD
- Sherpa (3.0.0, ALARIC): LO ME, string hadronization, with ALARIC PS, extended to cover initial-state radiation
- Herwig (Ang. Ord): NLO ME, default cluster hadronization, default Angular order PS
- NLO matched to NNLL resummation (R. Medves, A. Soto-Ontoso and G. Soyez) , non-perturbative effects using (PS+HAD+MPI)/(PS)



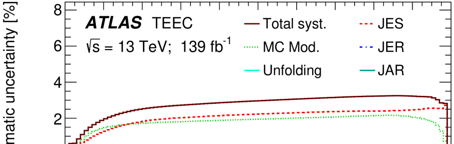
(A)TEEC analysis details

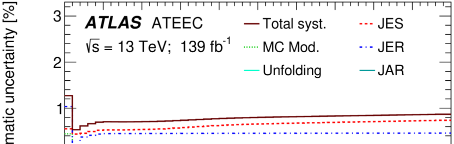
- Proton-proton collisions $\sqrt{s} = 13$ TeV, 139 fb^{-1}, FullRun2 Dataset, Unfolded data to particle level, (57.5 M events after selection)





- Anti-k$_T$ $R = 0.4$ calibrated particle-flow jets
  - $p_T > 60$ GeV
  - $|\eta| < 2.4$
  - $H_{T,2} = p_{T,1} + p_{T,2} > 1$ TeV
- Extended energy range, improved experimental precision
  - Dominated by JES+JER and MC modeling
- NNLO pQCD calculations applied for the first time in $2 \to 3$ jets process
  - Significant reduction of theoretical unc.
  - Dominant scale unc. reduced by factor of 3 with new NNLO prediction





Strong coupling α_s extraction - χ^2 fit for $\alpha_s(m_Z)$

- χ^2 function for $\alpha_s = \alpha_s(m_Z)$ extraction
- Considering correlations of sys. unc., nuicent

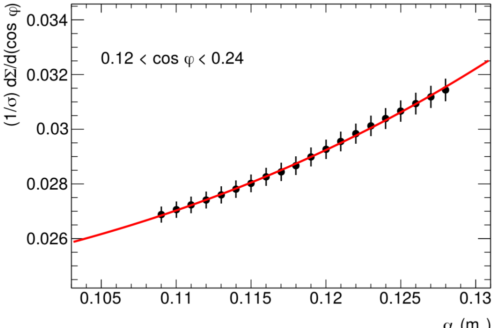
$$\chi^2(\alpha_s, \vec{\lambda}) = \sum_{\text{bins}} \frac{\left(x_i - F_i(\alpha_s, \vec{\lambda})\right)^2}{\Delta x_i^2 + \Delta\zeta_i^2} + \sum_k \lambda_k^2$$

$$F_i(\alpha_s, \vec{\lambda}) = \psi_i(\alpha_s)\left(1 + \sum_k \lambda_k \sigma_k^{(i)}\right)$$

$$\psi_i(\alpha_s) = \sum_{n=0}^{3} p_n(\cos\phi_i) \cdot [\alpha_s(m_Z)]^n$$

- $\psi_i(\alpha_s)$ ... analytical function, obtained by fitting predicted values of the TEEC (ATEEC) as a function of α_s in each ($H_{T,2}$, $\cos\phi$) bin to a third-order polynomial in α_s

- x_i ... ith data point
- F_i ... theoretical prediction
- Δx_i ... stat. unc. in data
- $\Delta\zeta_i$ ... stat. unc. in theoretical prediction
- $\sigma_k^{(i)}$ ... relative sys. unc. in bin i for kth source of correlation
- $\vec{\lambda}$ ... nuisance parameters a third-order polynomial in α_s



Strong coupling $\alpha_s(m_Z)$ - results

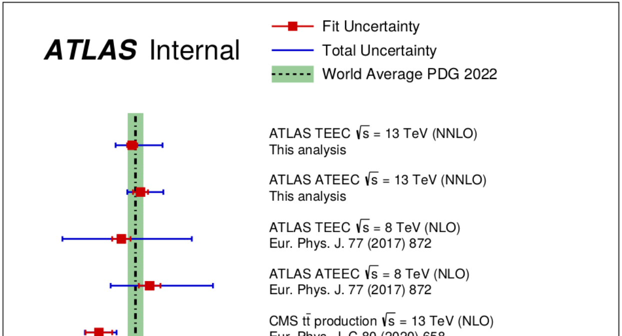
- $\alpha_s(m_Z)$ results:

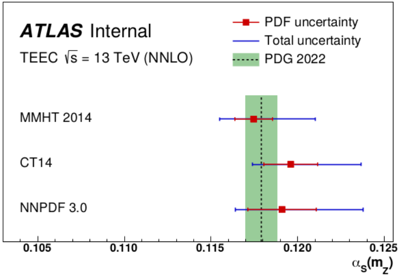
$$\alpha_s(m_Z)^{TEEC} = 0.1175 \pm 0.0006(\text{exp.})^{+0.0034}_{-0.017}(\text{theo.})$$

$$\alpha_s(m_Z)^{ATEEC} = 0.1185 \pm 0.0009(\text{exp.})^{+0.0025}_{-0.012}(\text{theo.})$$

- TEEC with better experimental precision, ATEEC with better theoretical precision
- Correlation coefficient

$$\rho = 0.86 \pm 0.02(\text{exp.})$$





Renormalization group equation

Evolution of $\alpha_s(\mu_R)$ using Renormalization group equation (RGE):

$$\mu_R^2 \frac{\alpha_s(\mu_R^2)}{d\mu_R^2} = \beta\left(\alpha_s(\mu_R^2)\right) = -\alpha_s^2(\mu_R^2) \sum_{i=0}^{\inf} \beta_i \left[\alpha(\mu_R^2)\right]^i$$

- μ_R .... renormalization scale
- $\beta\left(\alpha_s(\mu_R^2)\right)$ .... beta function
- $\beta_0 = 11 - \frac{2}{3} n_f$ .... tree level
- $\beta_1 = 102 - \frac{38}{3} n_f$ .... one-loop level
- $\beta_2 = \frac{2857}{2} - \frac{5033}{18} n_f - \frac{325}{54} n_f^2$ ... two-loop level

- n_f ... the number of active flavours at the scale Q,
  - i.e. the number of quarks with mass $m < Q$.

Approximate analytic solution for α_s at NNLO in pQCD:

$$\frac{\alpha_s(\mu_R^2)}{4\pi} = \frac{1}{\beta_0 x}\left[1 - \frac{\beta_1}{\beta_0^2}\frac{\log x}{x} + \frac{\beta_1^2}{\beta_0^4 x^2}\left(\log^2 x - \log x - 1 + \frac{\beta_2\beta_0}{\beta_1}\right)\right]$$

- $x = \log\left(\frac{\mu_R^2}{\Lambda^2}\right)$
- Λ as QCD scale where: $\alpha_s(\mu_R^2 = \Lambda^2) \sim 1$, $\Lambda \approx 200$ MeV

QCD as asymptotically free theory.

Event isotropy analysis details

- Proton-proton collisions, $\sqrt{s} = 13$ TeV, 139 fb^{-1}, FullRun2 Dataset, Unfolded data to particle level, CONF-STDM-2022-056
- Anti-k$_{\mathrm{T}}$ $R = 0.4$ calibrated particle-flow jets
  - $N_{jet} \geq 2$
  - $p_{\mathrm{T}} > 60$ GeV
  - $|y| < 4.5$
  - $H_{T,2} = p_{T,1} + p_{T,2} \geq 400$ GeV
- Four inclusive jet multiplicity bins, $N_{jet} \geq 2, 3, 4, 5$
- Three inclusive $H_{T,2}$ bins, $H_{T,2} \geq 500, 1000, 1500$ GeV
- Event Isotropy is unfolded simultaneously in N_{jet} and $H_{T,2}$ bins

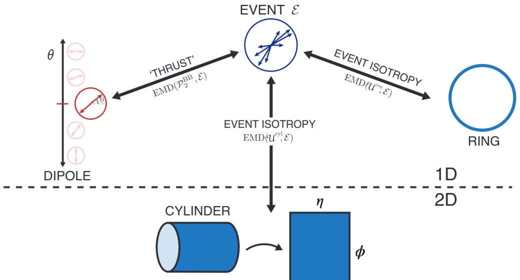
Event isotropy measurement - Energy-Mover's Distance (EMD)

$$EMD_\beta(\mathcal{E}, \mathcal{E}') = \min_{f_{ij} \geq 0} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} \theta_{ij}^{\beta},$$

$$\sum_{i=1}^{M} f_{ij} = E'_j, \qquad \sum_{j=1}^{M'} f_{ij} = E_i,$$

$$\sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} = \sum_{i=1}^{M} f_{ij} = \sum_{j=1}^{M'} f_{ij} = E_{tot}$$

Geometry	Energy Weight	Ground Measure	$\mathcal{U}$
Cylinder	$w_i^{\mathrm{cyl}} = p_{Ti}/p_{T\,\mathrm{tot}}$	$\theta_{ij}^{\mathrm{cyl}} = \frac{12}{\pi^2+16y_{\max}^2}\left(y_{ij}^2 + \phi_{ij}^2\right)$	$\mathcal{U}_N^{\mathrm{cyl}}(\lvert y\rvert < y_{\max})$
Ring	$w_i^{\mathrm{ring}} = p_{Ti}/p_{T\,\mathrm{tot}}$	$\theta_{ij}^{\mathrm{ring}} = \frac{\pi}{\pi-2}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_N^{\mathrm{ring}}$
Ring (Dipole)	$w_i^{\mathrm{ring}} = p_{Ti}/p_{T\,\mathrm{tot}}$	$\theta_{ij}^{\mathrm{ring}} = \frac{1}{1-\frac{1}{\sqrt{3}}}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_2^{\mathrm{ring}}$



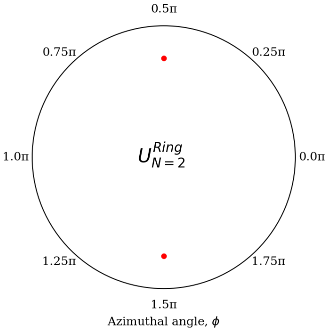
Event isotropy measurement - Energy-Mover's Distance (EMD)

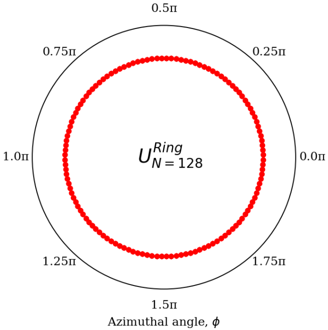
$$EMD_\beta(\mathcal{E}, \mathcal{E}') = \min_{f_{ij} \geq 0} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} \theta_{ij}^{\beta},$$

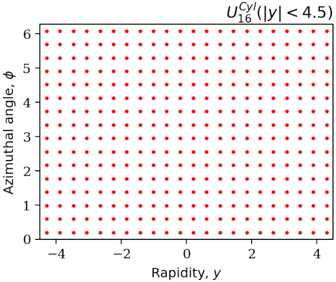
$$\sum_{i=1}^{M} f_{ij} = E'_j, \quad \sum_{j=1}^{M'} f_{ij} = E_i, \quad \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} = \sum_{i=1}^{M} f_{ij} = \sum_{j=1}^{M'} f_{ij} = E_{tot}$$

Geometry	Energy Weight	Ground Measure	$\mathcal{U}$
Cylinder	$w_i^{\text{cyl}} = p_{Ti}/p_{T\text{tot}}$	$\theta_{ij}^{\text{cyl}} = \frac{12}{\pi^2+16y_{\text{max}}^2}\left(y_{ij}^2 + \phi_{ij}^2\right)$	$\mathcal{U}_N^{\text{cyl}}(\lvert y\rvert < y_{\text{max}})$
Ring	$w_i^{\text{ring}} = p_{Ti}/p_{T\text{tot}}$	$\theta_{ij}^{\text{ring}} = \frac{\pi}{\pi-2}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_N^{\text{ring}}$
Ring (Dipole)	$w_i^{\text{ring}} = p_{Ti}/p_{T\text{tot}}$	$\theta_{ij}^{\text{ring}} = \frac{1}{1-\frac{1}{\sqrt{3}}}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_2^{\text{ring}}$

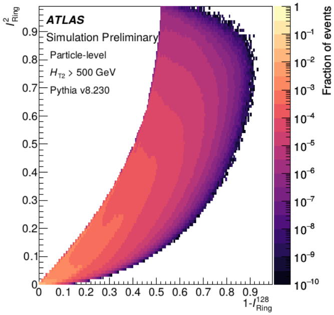
Event isotropy measurement - Referenced geometries

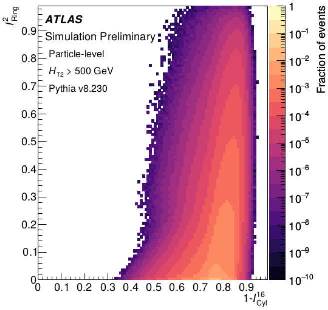


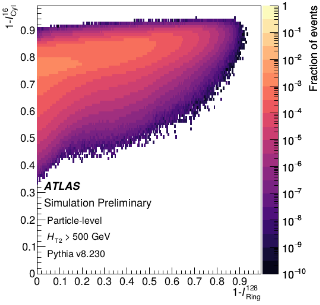




Event isotropy measurement - Correlation for different event isotropy variables

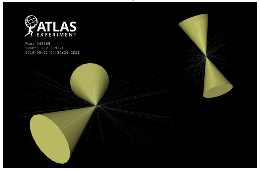


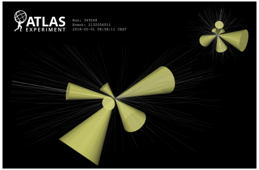




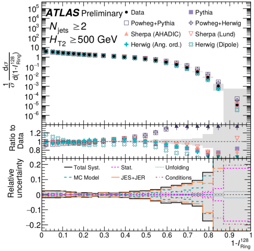
Event isotropy $1 - I^{128}_{\text{Ring}}$

- Cross-section falls down by 6 order of magnitudes $\rightarrow$ increased dynamic range
- Different isotropic patterns than for I^{2}_{Ring}
- Very different trends for Powheg+Pythia and Powheg+Herwig than for other MC
- Large differences for Herwig angle-order and dipole shower models
- No differences for Sherpa AHADIC (cluster-based) and Lund (string-based) hadronization models
- Large stat. unc. for high isotropy multijet events
- Dominant sys. unc.
  - JES+JER
  - MC Model





$1 - I^{128}_{\text{Ring}} = 0.83$

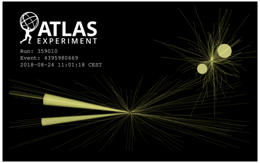


$\leftarrow$ Balanced dijet event

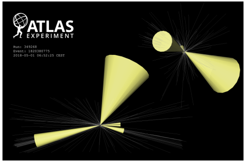
Symmetric multijet event $\rightarrow$

Event isotropy $1 - I^{16}_{\text{Cyl}}$

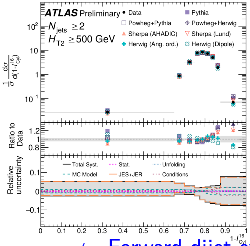
- Unique shape for $1 - I^{16}_{\text{Cyl}}$ observable
- Peak position correlated with average number of jets
- No MC describes $1 - I^{16}_{\text{Cyl}}$ variable accurately
- Pythia, Powheg+Pythia, Powheg+Herwig are consistent and overestimate data at high $1 - I^{16}_{\text{Cyl}}$ values
- No differences for Sherpa AHADIC (cluster-based) and Lund (string-based) hadronization models
- Dominant sys. unc.
  - JES+JER
  - MC Model



$1 - I^{16}_{\text{Cyl}} = 0.48$



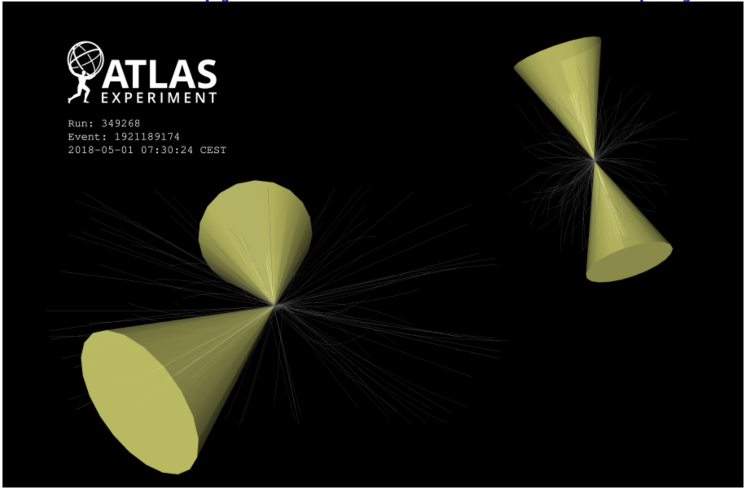
$1 - I^{16}_{\text{Cyl}} = 0.91$



← Forward dijet event on one side of the detector

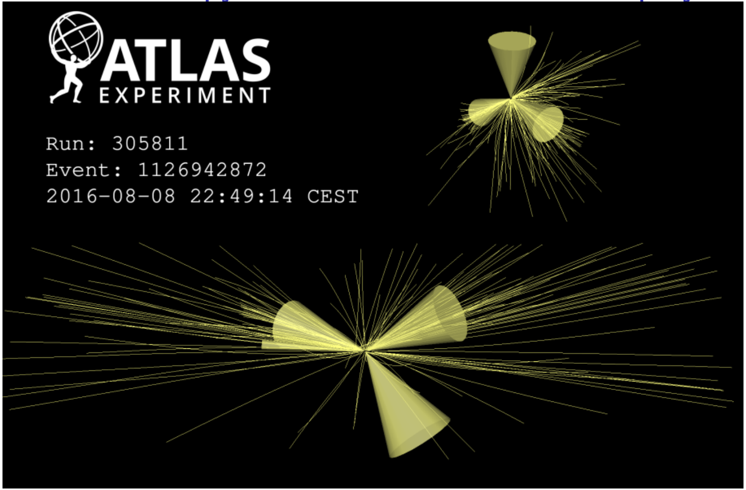
Multijet event covering central and forward region in $(y \times \phi)$ plane →

Event isotropy measurement - Event display 4



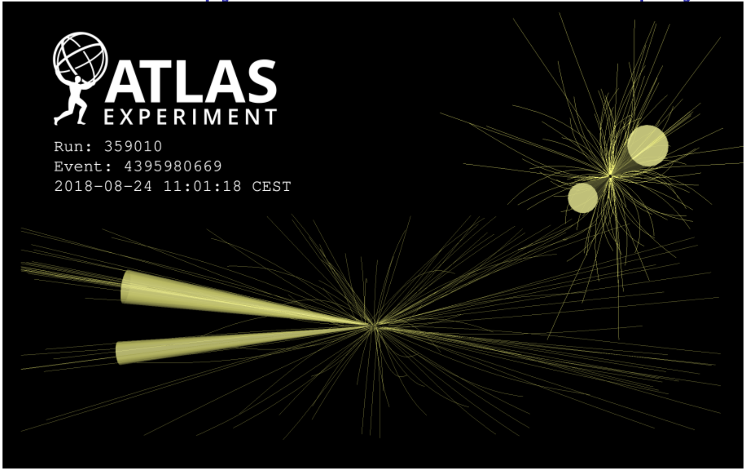
$$N_{jet} = 2,\ I^2_{\text{Ring}} = 0.0001$$

Event isotropy measurement - Event display 1



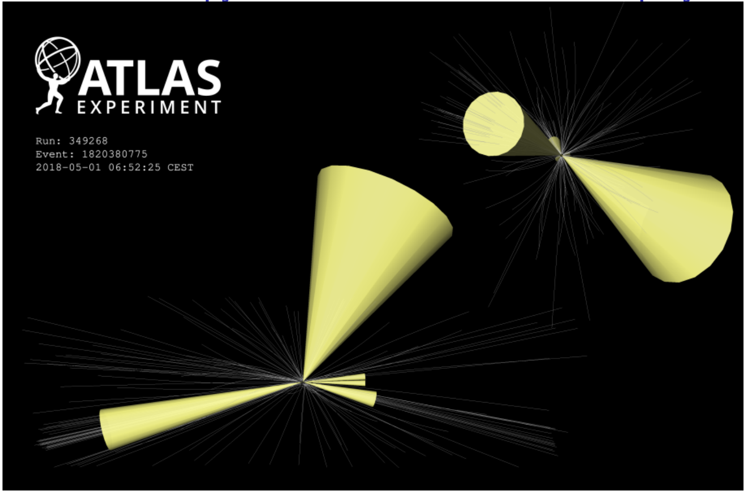
$N_{jet} = 3,\ I^2_{\text{Ring}} = 0.99$

Event isotropy measurement - Event display 2



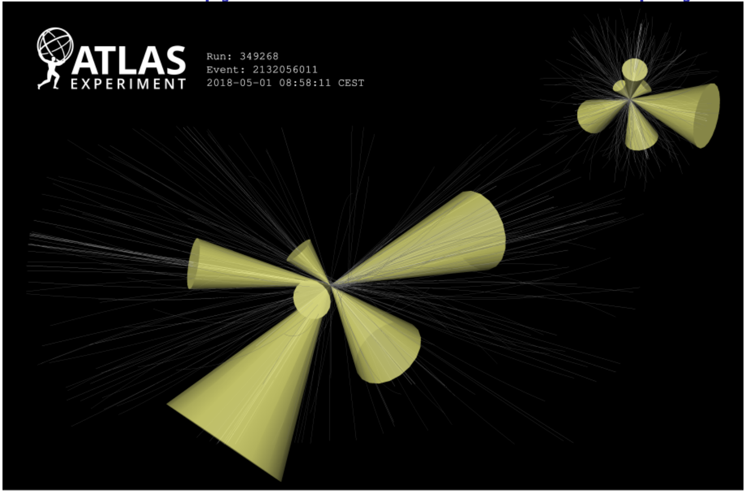
$$N_{jet} = 2,\ 1 - I^{16}_{\mathrm{Cyl}} = 0.48$$

Event isotropy measurement - Event display 3



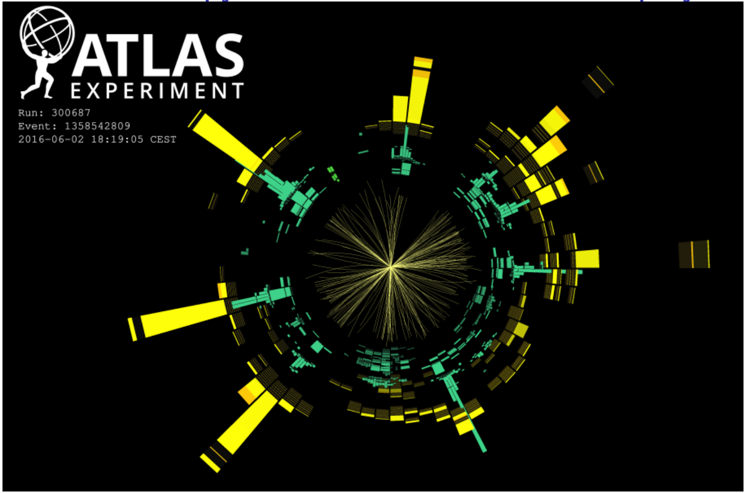
$$N_{jet} = 3,\ 1 - I^{16}_{\mathrm{Cyl}} = 0.91$$

Event isotropy measurement - Event display 5



$$N_{jet} = 6,\ 1 - I^{128}_{\text{Ring}} = 0.83$$

Event isotropy measurement - Event display 6



$N_{jet} = 12,\ 1 - I^{128}_{\text{Ring}} = 0.92$

Conclusion

ATLAS (A)TEEC measurements:

- Transverse energy-energy correlations and its angular asymmetry (A)TEEC evaluated
- Running $\alpha_s(Q)$ extracted from TEEC and ATEEC correlations profiting from new NNLO pQCD calculations
- Extracted $\alpha_s(Q)$ in good agreement with RGE prediction

ATLAS Isotropy measurements:

- Novel isotropy observables allow testing more features of QCD radiation and new insight to MC tuning
- No MC is able to describe all the new isotopy variables