Jet measurements in pp collisions from ATLAS

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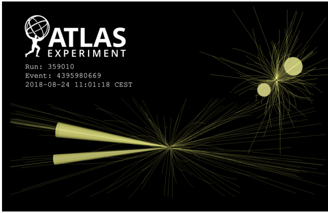
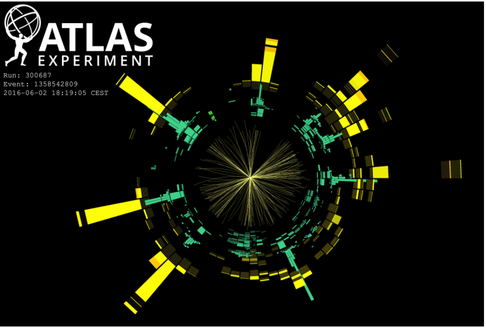
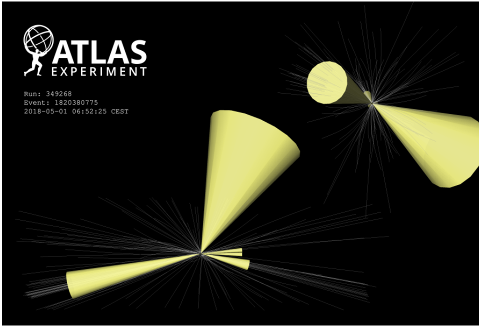
- Transverse energy-energy correlation TEEC and its angular asymmetry ATEEC
  ATLAS, arXiv:2301.09351
- Strong coupling $\alpha_s(Q)$ extraction from (A)TEEC
- Event isotropy in multijet events
  CONF-STDM-2022-056







More jet measurements at ATLAS Public page

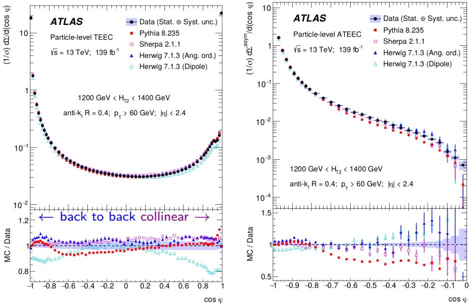
ATLAS TEEC and ATEEC measurements

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

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

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

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

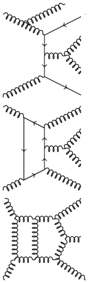


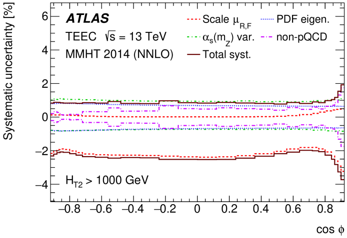
ATLAS, arXiv:2301.09351

- Both TEEC and ATEEC are sensitive to gluon radiation and strong coupling constant $\alpha_s(Q)$

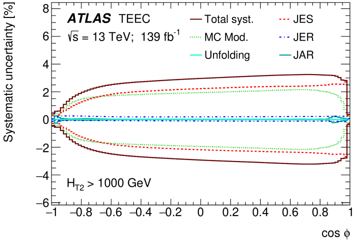
(A)TEEC analysis details

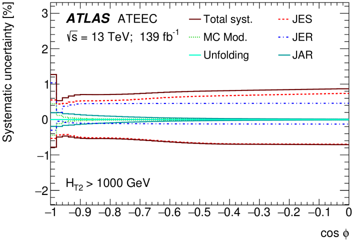
- Proton-proton collisions $\sqrt{s} = 13$ TeV, 139 fb^{-1}, FullRun2 Dataset, Unfolded data to particle level, (57.5 M events after selection)





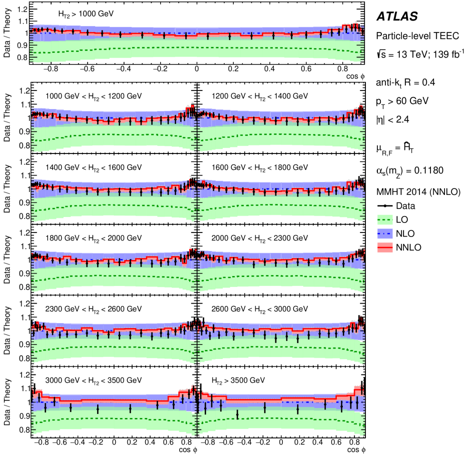
- Anti-k$_T$ $R = 0.4$ calibrated particle-flow jets
  - $p_T > 60$ GeV
  - $|\eta| < 2.4$
  - $H_{T,2} = p_{T,1} + p_{T,2} > 1$ TeV
- Extended energy range, improved experimental precision
  - Dominated by JES+JER and MC modeling
- NNLO pQCD calculations applied for the first time in $2 \to 3$ jets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

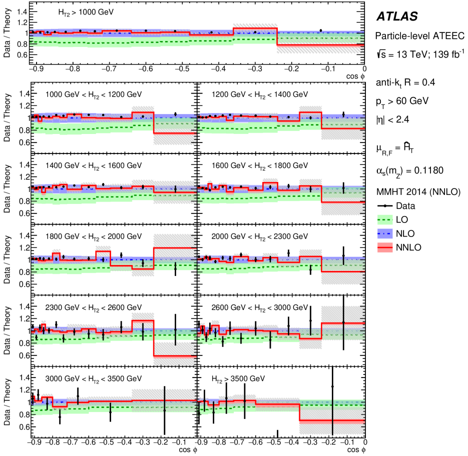




(A)TEEC Data to Theory comparison

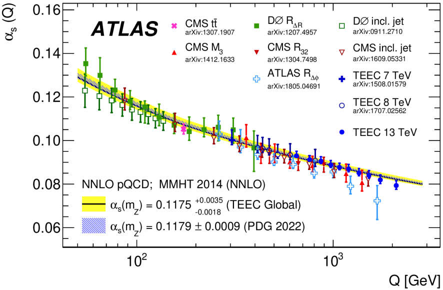
- Measurement done in 1 inclusive $H_{T,2}$ bin and 10 exclusive $H_{T,2}$ bins
- NLO calculation applied in previous Eur. Phys. J. C 77 (2017) 872 publication
- NNLO calculation as state-of-art
  - Very good description of data
  - Significant improvement with above $|cos(\phi)| > 0.8$
  - Significant reduction of theoretical uncertainties

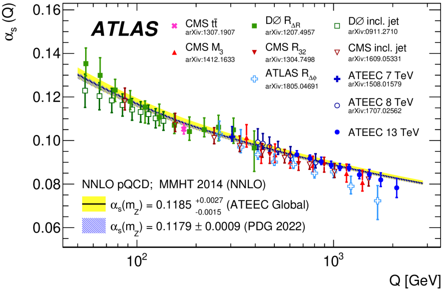




Strong coupling $\alpha_s(Q)$ extraction

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





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

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

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

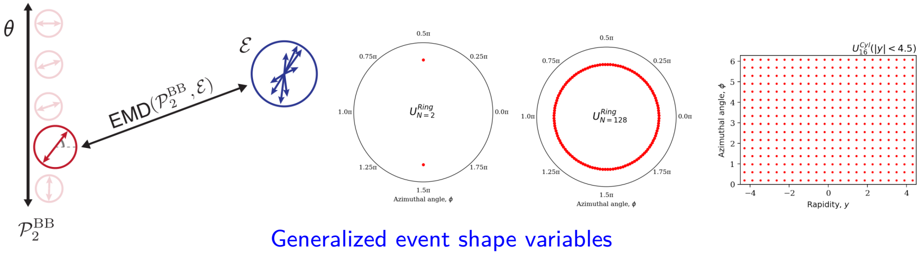
$$\rho = 0.86 \pm 0.02(\text{exp.})$$

Good agreement with other measurements and RGE prediction

No deviation from RGE suggesting new coloured fermions

ATLAS Multijet event isotropy

- Standard event shape variables (Thrust, Sphericity) interpolates between back-to-back and well balanced three jet event
- 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

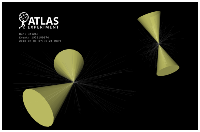
Infrared and collinear safe variables by construction

Event isotropy analysis details

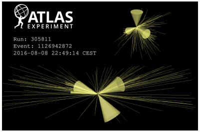
- Proton-proton collisions, $\sqrt{s} = 13$ TeV, 139 fb^{-1}, FullRun2 Dataset, Unfolded data to particle level, CONF-STDM-2022-056
- Anti-k$_{\mathrm{T}}$ $R = 0.4$ calibrated particle-flow jets
  - $N_{jet} \geq 2$
  - $p_{\mathrm{T}} > 60$ GeV
  - $|y| < 4.5$
  - $H_{T,2} = p_{T,1} + p_{T,2} \geq 400$ 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 I^2_{Ring}

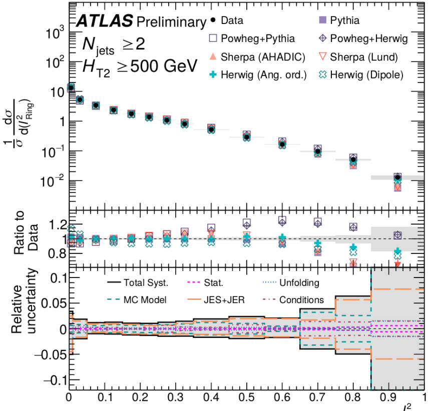
- Unfolded data compared to several state-of-art MC model
- Good agreement in non-isotropy region (dijet like events) for LO and NLO
- More isotropic events more differences observed in different MC
- More isotropic events described better with MC NLO matrix elements (Powheg, Herwig) than LO (Pythia, 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)



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



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

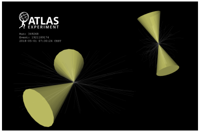


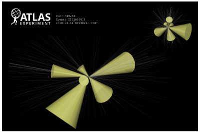
← Balanced dijet event

Symmetric multijet event →

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

- Cross-section falls down by 6 order of magnitudes → increased dynamic range
- Different isotropic patterns than for I^{2}_{Ring}



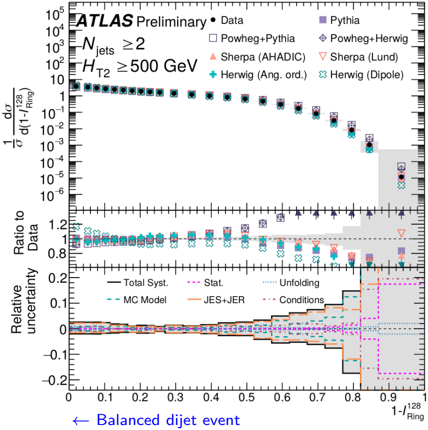


$1 - I^{128}_{\text{Ring}} = 0.83$

- 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



← Balanced dijet event

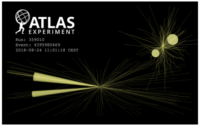
Symmetric multijet event →

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

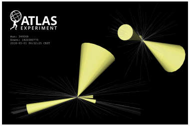
- Unique shape for $1 - I^{16}_{\mathrm{Cyl}}$ observable
- Peak position correlated with average number of jets

- No MC describes $1 - I^{16}_{\mathrm{Cyl}}$ variable accurately
- Pythia, Powheg+Pythia, Powheg+Herwig are consistent and overestimate data at high $1 - I^{16}_{\mathrm{Cyl}}$ values
- No differences for Sherpa AHADIC (cluster-based) and Lund (string-based) hadronization models

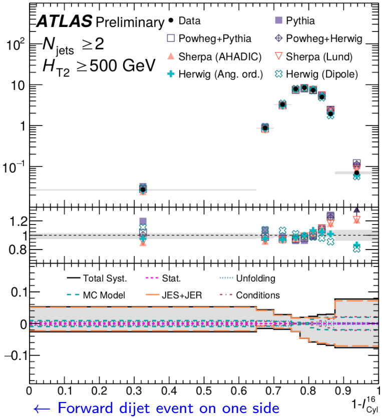
- Dominant sys. unc.
  - JES+JER
  - MC Model



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



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



← Forward dijet event on one side of the detector

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

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

Thank you for your attention.

Back-up

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

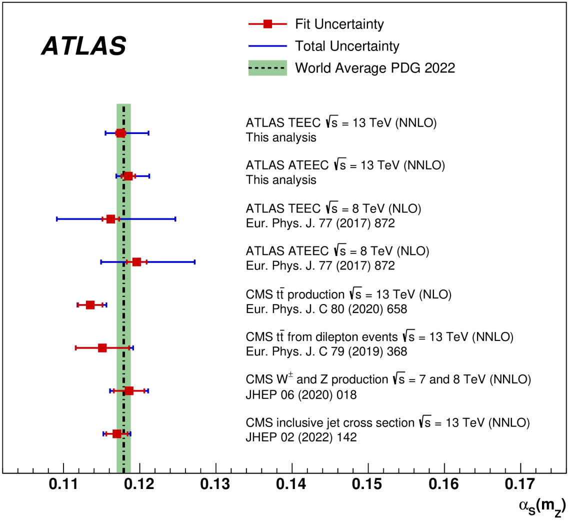
- χ^2 function for $\alpha_s = \alpha_s(m_Z)$ extraction
- considering correlations of sys. unc., nuicent

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

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

- x_i ... ith data point
- F_i ... theoretical prediction
- Δx_i ... stat. unc. in data
- $\Delta \rho_i$ ... stat. unc. in theoretical prediction
- $\sigma_k^{(i)}$ ... relative sys. unc. in bin i for kth source of correlation
- $\vec{\lambda}$ ... nuisance parameters
- $\phi_i(\alpha_s)$ ... analytical function,
  obtained by fitting predicted values of the TEEC (ATEEC) in each ($H_{T,2}$, $\cos\phi$) bin to a third-order polynomial in α_s

α_s extraction - comparison with different analysis



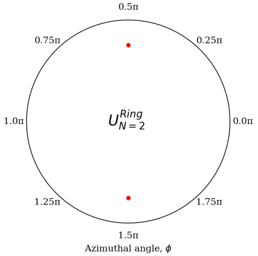
Event isotropy measurement - Energy-Mover's Distance (EMD)

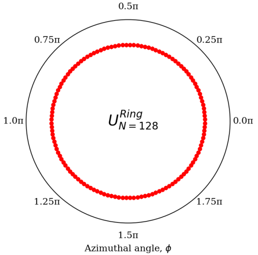
$$EMD_\beta(\mathcal{E}, \mathcal{E}') = \min_{f_{ij} \geq 0} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} \theta_{ij}^{\beta},$$

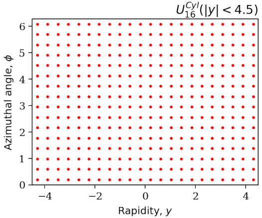
$$\sum_{i=1}^{M} f_{ij} = E'_j, \quad \sum_{j=1}^{M'} f_{ij} = E_i, \quad \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} = \sum_{i=1}^{M} f_{ij} = \sum_{j=1}^{M'} f_{ij} = E_{tot}$$

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)	$w_i^{\text{ring}} = p_{Ti}/p_{T\,\text{tot}}$	$\theta_{ij}^{\text{ring}} = \frac{1}{1-\frac{1}{\sqrt{3}}}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_2^{\text{ring}}$

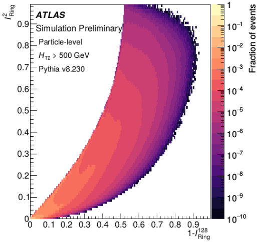
Event isotropy measurement - Referenced geometries

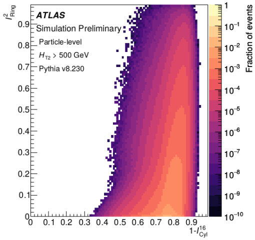


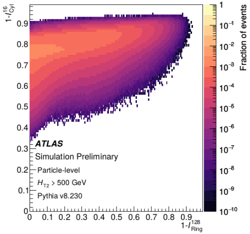




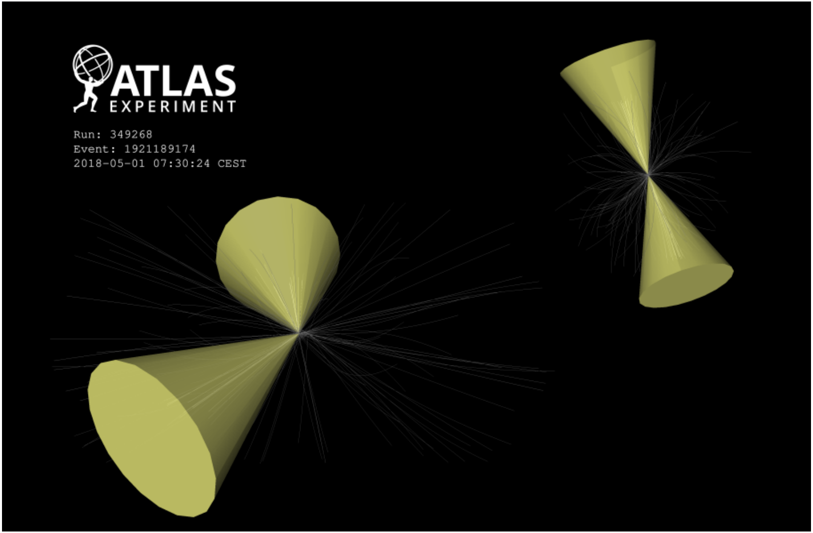
Event isotropy measurement - Correlation for different event isotropy variables





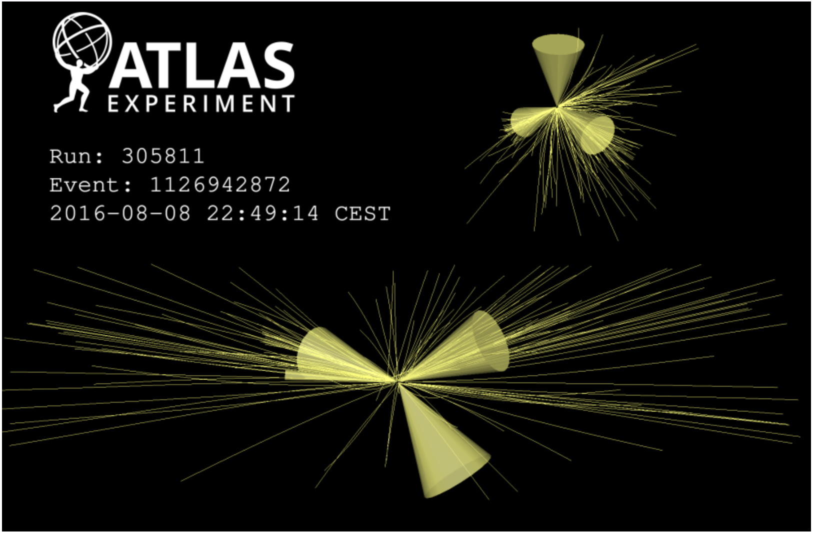


Event isotropy measurement - Event display 4



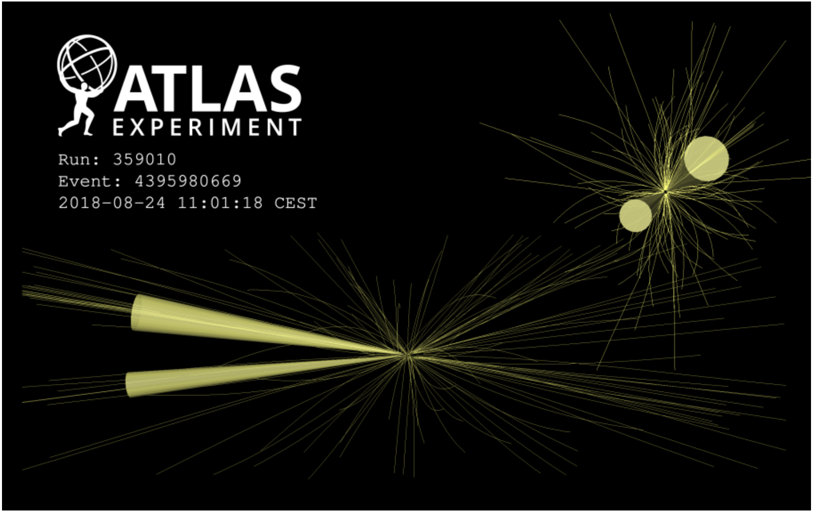
$$N_{jet} = 2,\ I^2_{\text{Ring}} = 0.0001$$

Event isotropy measurement - Event display 1



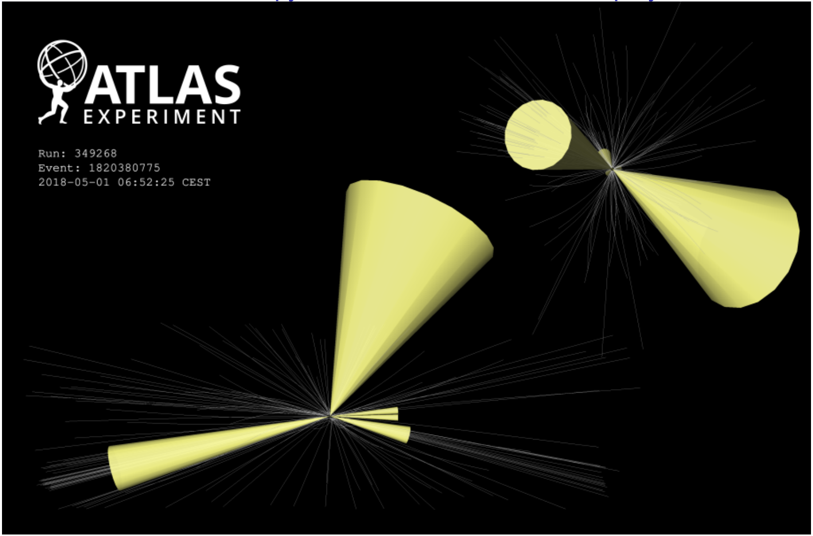
$N_{jet} = 3, \; I^2_{\text{Ring}} = 0.99$

Event isotropy measurement - Event display 2



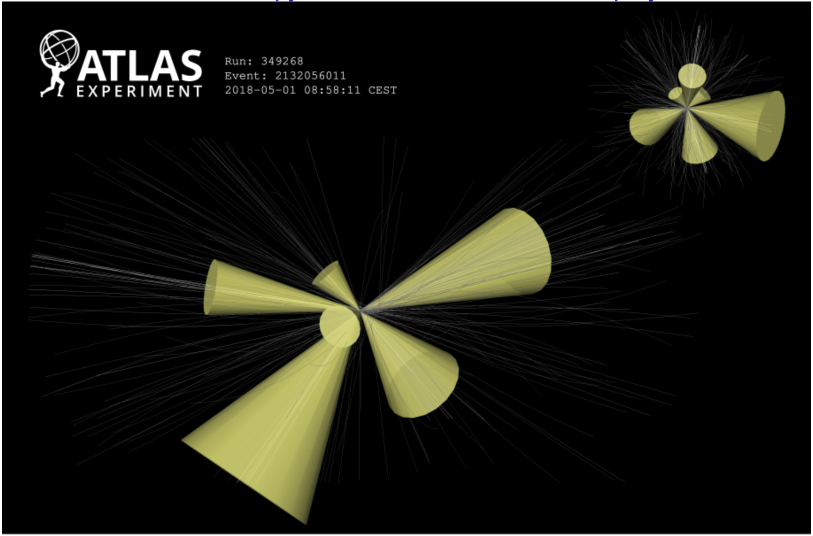
$$N_{jet} = 2,\ 1 - I^{16}_{\mathrm{Cyl}} = 0.48$$

Event isotropy measurement - Event display 3



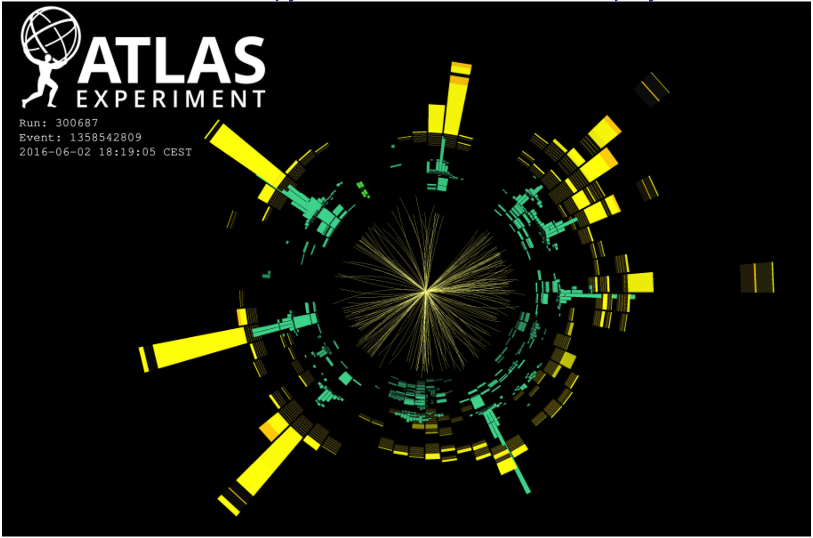
$$N_{jet} = 3,\ 1 - I^{16}_{\text{Cyl}} = 0.91$$

Event isotropy measurement - Event display 5



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

Event isotropy measurement - Event display 6



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