Inclusive Jet Measurements with the ATLAS Experiment at LHC

Peter Loch[a,b]

(for the ATLAS Collaboration)

[a]Department of Physics, University of Arizona, Tucson, Arizona, USA

[b]CERN, Geneva, Switzerland

Study of QCD with Jets in ATLAS at the LHC

From inclusive jet cross section measurements …

- Strong interaction in a wide dynamic range
  - QCD at highest orders of calculations
- Structure of the proton at very high momentum transfers
  - Access to parton density functions (PDFs)

… to tests of emission modeling …

- Hard emissions – hadronic event shapes with jets
  - Test of predictions with multi-jet final states
- Soft emissions – looking inside jets
  - See talk by Jennifer Roloff on *Measurements of jet substructure and jet fragmentation using the ATLAS detector*
    - Strong interactions and hadron physics (this track) III, Thursday, July 30, 2020, 12:35pm

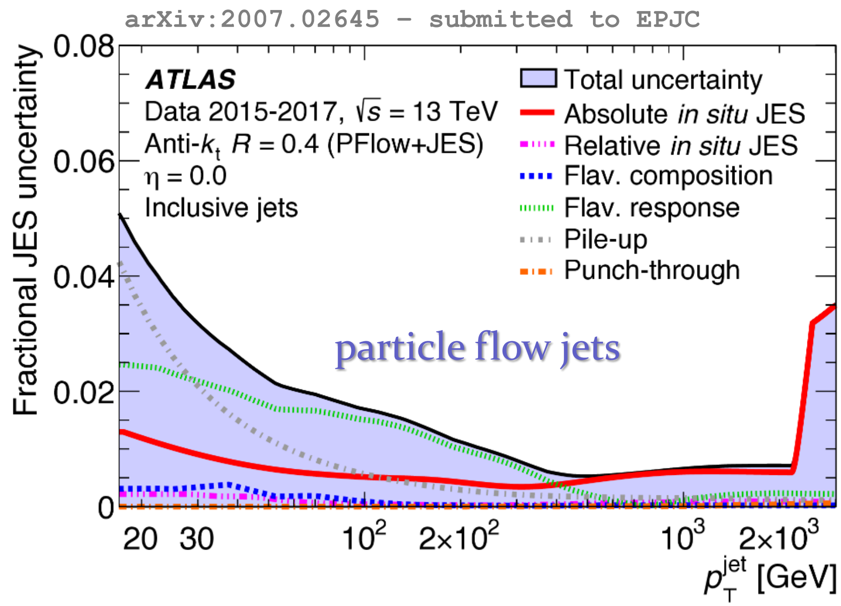
… and the running of the strong coupling constant

- Measurement of running α_s with energy-energy correlations
  - Testing confinement at highest (TeV) scales

Jet Measurements in ATLAS

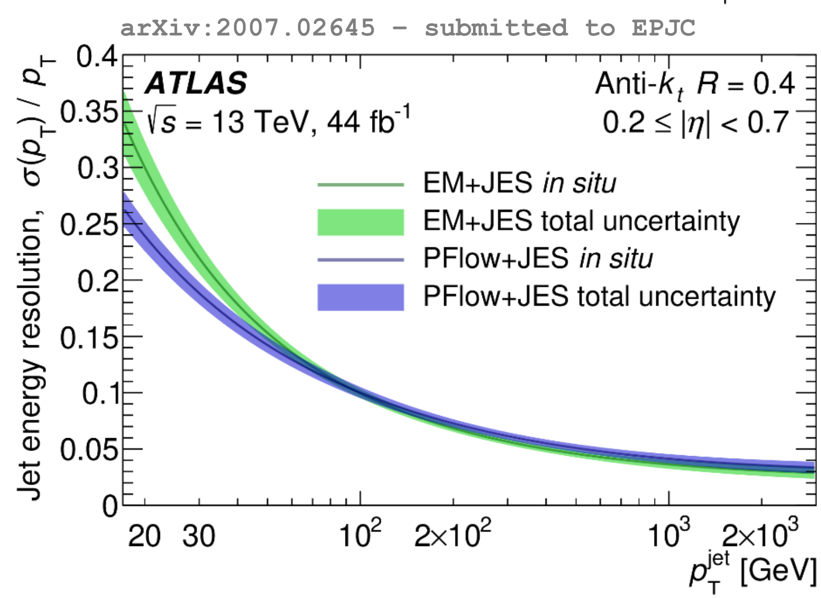
Standard jets for physics in LHC Run 2

- Anti-k_t jets with distance parameter $R = 0.4$
  - Use calorimeter signals or particle flow objects (combined calorimeter signals & tracks)
- High precision reconstruction
  - $\mathcal{O}(1\%)$ total jet energy scale uncertainties
  - More details in talk by Eva Hansen on *Jet reconstruction and calibration in ATLAS*
    - Operation, Performance and upgrade of present detectors IV, Friday, July 31, 2020, 9:50am



Standard Model precision measurements

- Run 2 first year measurements
  - Inclusive jet and dijet cross section corresponding to $\int \mathcal{L}dt \approx 3.2\,\mathrm{fb}^{-1}$ of collected data
- Full Run 2 data set ($\int \mathcal{L}dt \approx 139\,\mathrm{fb}^{-1}$)
  - Hadronic event shapes
  - Strong coupling constant α_S

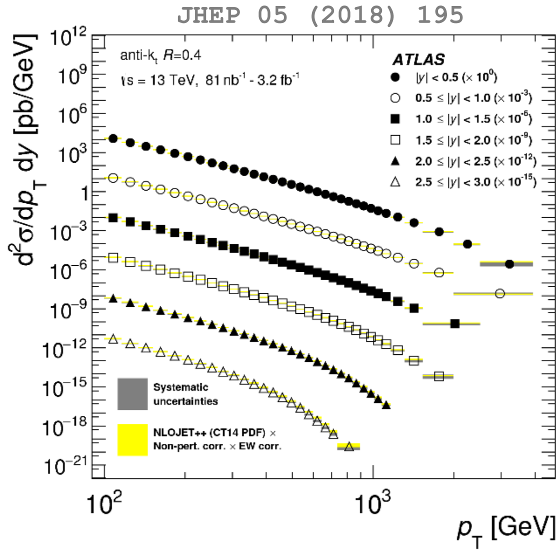


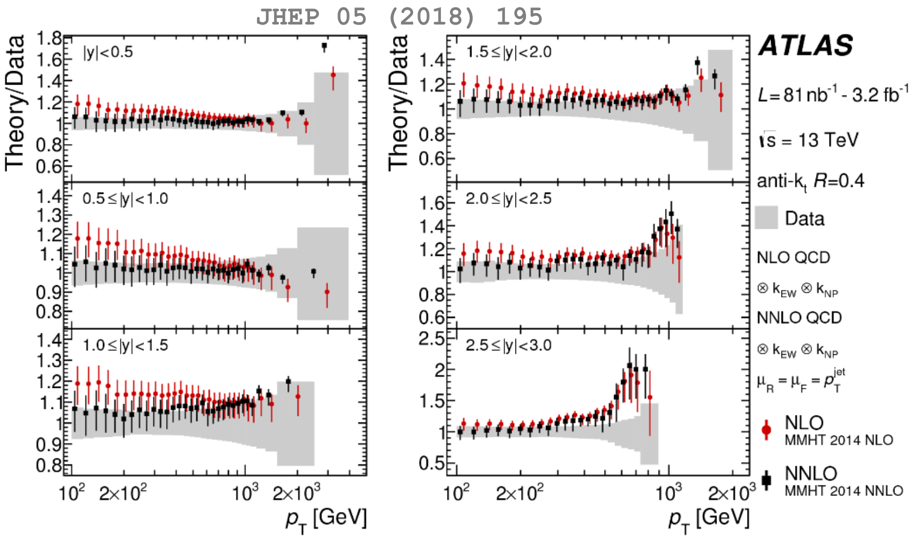
Inclusive Jet Production

Inclusive jet and di-jet cross section

JHEP 05 (2018) 195

- Data collected from pp collisions at $\sqrt{s} = 13$ TeV in 2015
  - Inclusive jet cross section measured in terms of jet transverse momentum with 100 GeV $< p_{\mathrm{T}}^{\mathrm{jet}} <$ 3.5 TeV and $|y^{\mathrm{jet}}| < 3$
  - Inclusive dijet production cross section measured in terms of the invariant mass of the two leading jets 900 GeV $< m_{\mathrm{jj}} <$ 9 TeV and $y^* = \left|\left(y_{\mathrm{lead}}^{\mathrm{jet}} - y_{\mathrm{sublead}}^{\mathrm{jet}}\right)/2\right| < 3$
- Comparison to QCD predictions
  - NLO & NNLO calculations with non-perturbative QCD and electroweak corrections and various PDFs
  - Comparison to theory favors QCD @ NNLO for $|y^{\mathrm{jet}}| < 2$





Hadronic Event Shapes with Jets

Event shapes with jets

arXiv:2007.12600 [hep-ex]

- Proxy for energy flow shapes in collision event
  - Measurement tests prediction power of fixed-order calculations, parton shower modeling, etc.
- Clear expectation values for given topology
  - Shapes vanish for $2 \rightarrow 2$ processes with perfect forward-backward (back-to-back in transverse plane) symmetry – at maximum for uniform energy (transverse momentum) distribution
- Probe for multi-jet energy flow at highest scales
  - $\mathcal{O}(\text{TeV})$ for $\sqrt{s} = 13$ TeV
  - Evaluated in multi-jet final states ($n^{\text{jet}} \geq 2$) as function of hardness of interaction
    - Representative observable for interaction activity is $H_{\text{T2}} = p_{\text{T}}^{\text{lead}} + p_{\text{T}}^{\text{sublead}}$

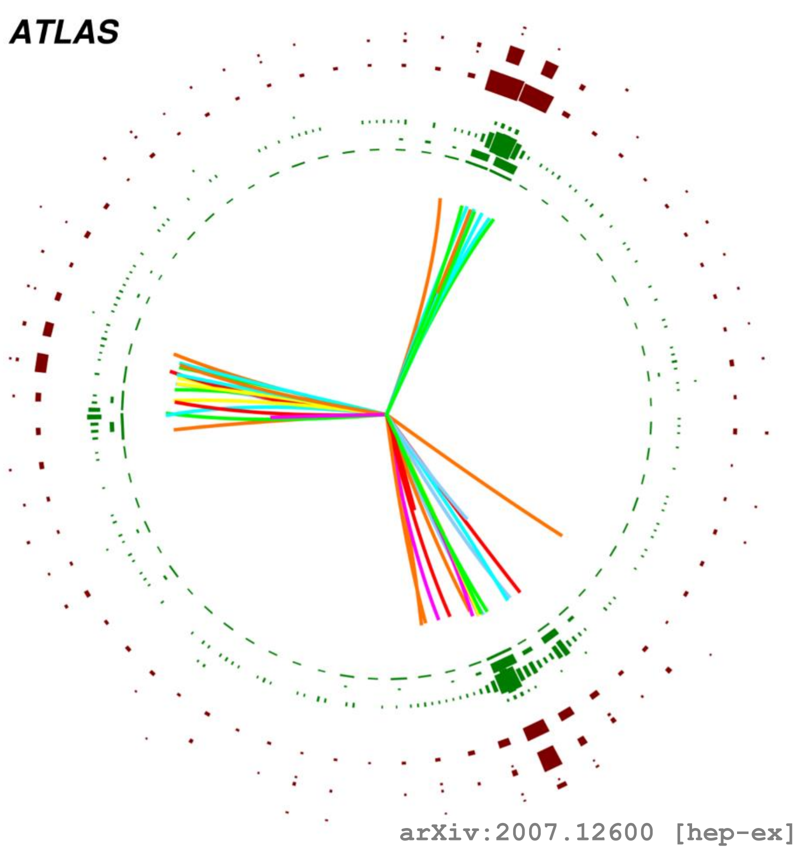
Measurement

- Jet and event selection
  - Consider only fully calibrated anti-k_t jets with $R = 0.4$ clustered from particle flow objects with $p_{\text{T}}^{\text{jet}} > 100$ GeV, $|\eta^{\text{jet}}| < 2.4$
  - Multi-jet events with $n^{\text{jet}} \geq 2$,
  - $H_{\text{T2}} > 1$ TeV selected
- Presentation of results
  - Differential cross-sections as ratio to fiducial cross section $\sigma(n^{\text{jet}} \geq 2)$
    - $1/\sigma(n^{\text{jet}} \geq 2)\, d\sigma/d\{T_{\perp}, T_m, S_{\perp}, A, C, D\}$ in $(H_{\text{T2}}, n^{\text{jet}})$ bins*
  - Unfolded data is compared to various Monte Carlo generators

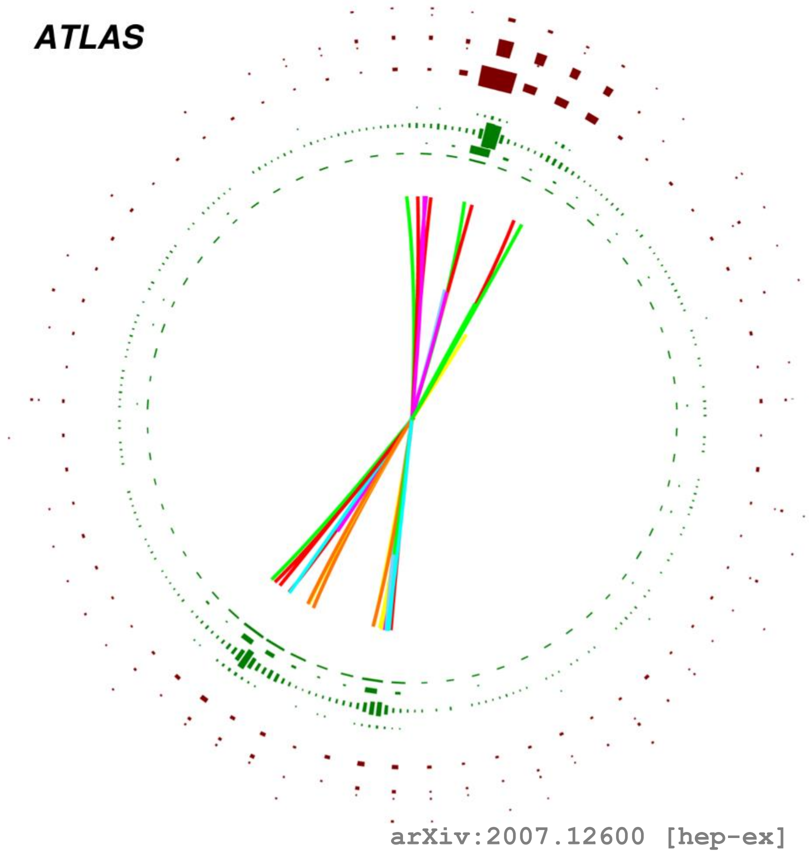
*see additional material for description of all used event shape observables

Hadronic Event Shapes with Jets

Examples: transverse thrust & transverse sphericity

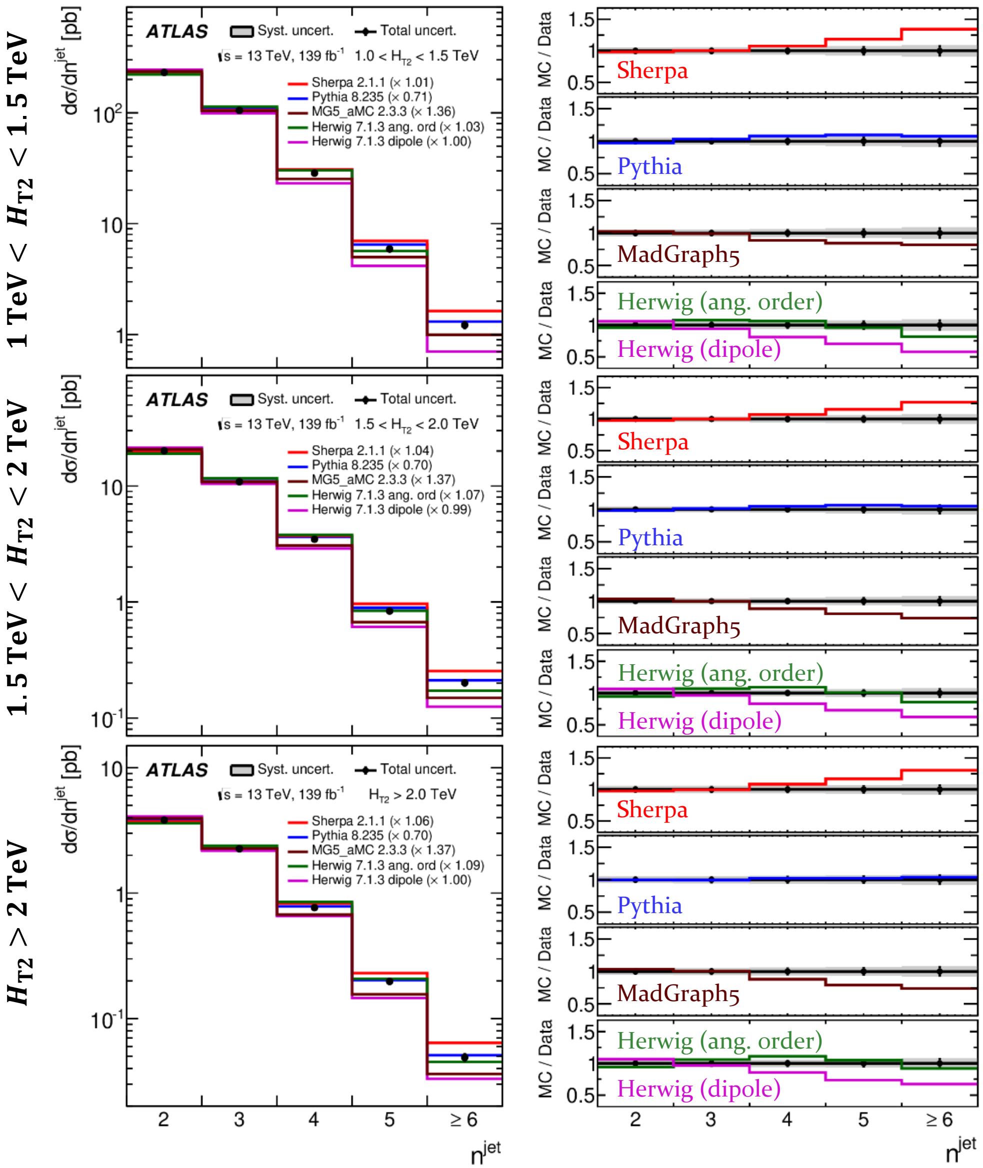


$n^{\mathrm{jet}} = 3$, high values of $\tau_{\perp} = 1 - T_{\perp}$ and $S_{\perp}$



$n^{\mathrm{jet}} = 5$, low values of $\tau_{\perp}$ and $S_{\perp}$

Modeling of Jet Multiplicities



arXiv:2007.12600 [hep-ex]

Fiducial cross section

Measured as function of n^{jet}

Evaluated in same three regions of H_{T2} used for event shape measurements – provides normalization

Modeling $d\sigma/dn^{\mathrm{jet}}$ shapes

Pythia 8.235

$2 \rightarrow 2$, LO accuracy

Generally good agreement for all n^{jet}

Sherpa 2.2.1

$2 \rightarrow \{2, 3\}$, LO accuracy (multi-leg)

Overestimation (increasing) for $n^{\mathrm{jet}} > 4$

Herwig 7.1.3 (angular ordered PS)

$2 \rightarrow 2$ NLO accuracy, $2 \rightarrow 3$ LO

Good description with slight underestimation for $n^{\mathrm{jet}} \geq 6$

Herwig 7.1.3 (dipole PS)

$2 \rightarrow 2$ NLO accuracy, $2 \rightarrow 3$ LO

Good description for low n^{jet}, underestimation for higher n^{jet}

MadGraph5_aMC 2.3.3

$2 \rightarrow \{2, 3, 4\}$ NLO accuracy

Good description for low n^{jet}, underestimation for higher n^{jet}

Modeling normalization

Well predicted at low n^{jet}

Only small differences between models

Large spread in normalization at high n^{jet}

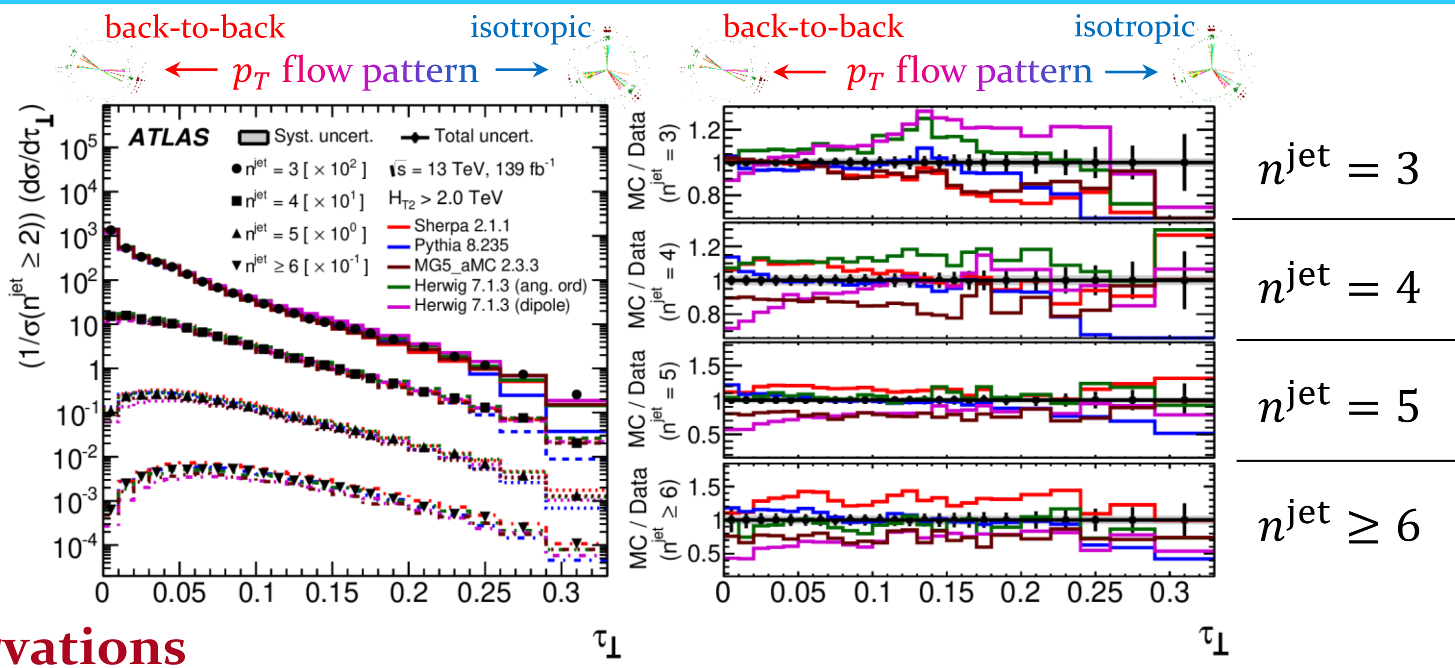
Sherpa predicts 30% more than data

Herwig (dipole PS), MadGraph predict 30% less

Transverse Thrust with Jets

arXiv:2007.12600 [hep-ex]

$H_{T2} > 2$ TeV



Observations

Evolution with increasing hardness of interaction

- More events with more isotropic flow at softer interactions (lower H_{T2})
- Increasing H_{T2} yields increased contribution from events with close to back-to-back flow patterns

Comparisons to models

Evaluation of predictions

- Generally fewer isotropic events in MC than in data at low n^{jet} – better agreement at higher jet multiplicities

Shapes of cross sections

- None of the considered MC generators gives good description in full phase space
- Similar distribution shapes at high n^{jet} from all considered model

Measurement of Strong Coupling

Transverse energy-energy correlations (TEEC)

TEEC function in multi-jet events

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

with $E_{\mathrm{T}} = \sum_i E_{\mathrm{T},i}$

Associated azimuthal asymmetries (ATEEC)

Measures difference between forward ($\cos\phi > 0$) and backward ($\cos\phi < 0$) parts of TEEC

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

Measurement

Determine α_s from evolution of TEEC/ATEEC with varying hard scale

$H_{\mathrm{T2}} = p_{\mathrm{T}}^{\mathrm{lead}} + p_{\mathrm{T}}^{\mathrm{sublead}}$ serves as proxy for hard interaction scale Q

Jets

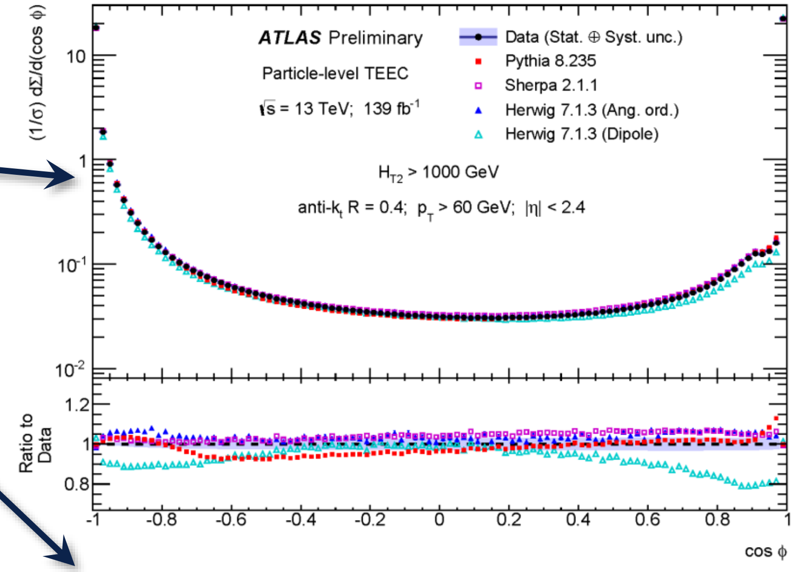
Anti-k_t jets with $R = 0.4$ from particle flow objects ($p_{\mathrm{T}} > 60$ GeV, $|\eta| < 2.4$)

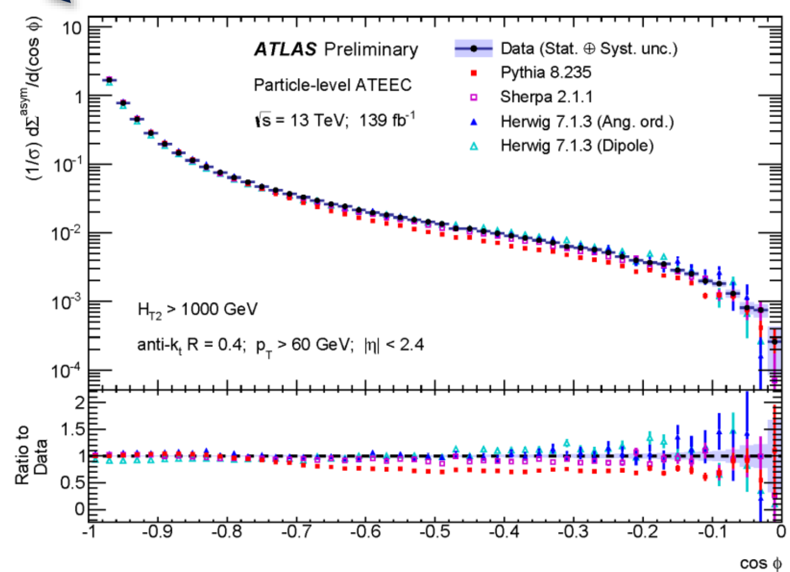
Events

Two leading jets with $H_{\mathrm{T2}} > 1$ TeV

Results

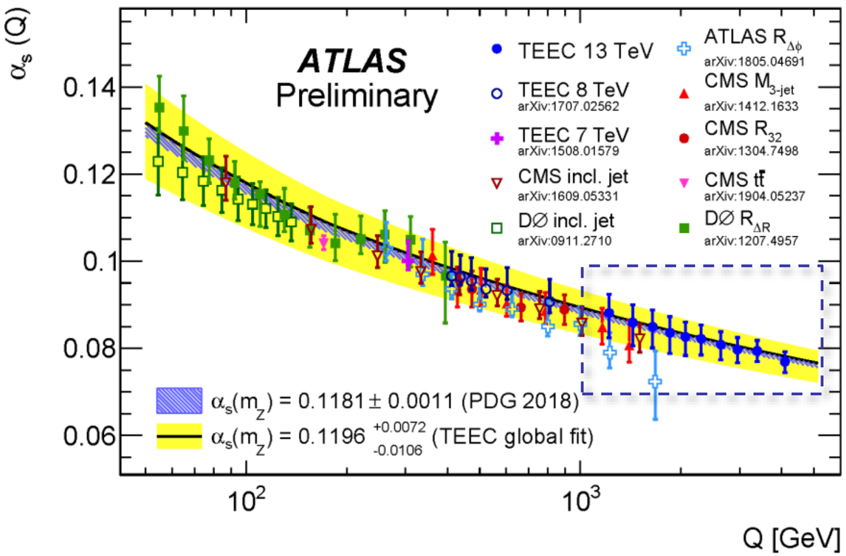
Data unfolded to particle level

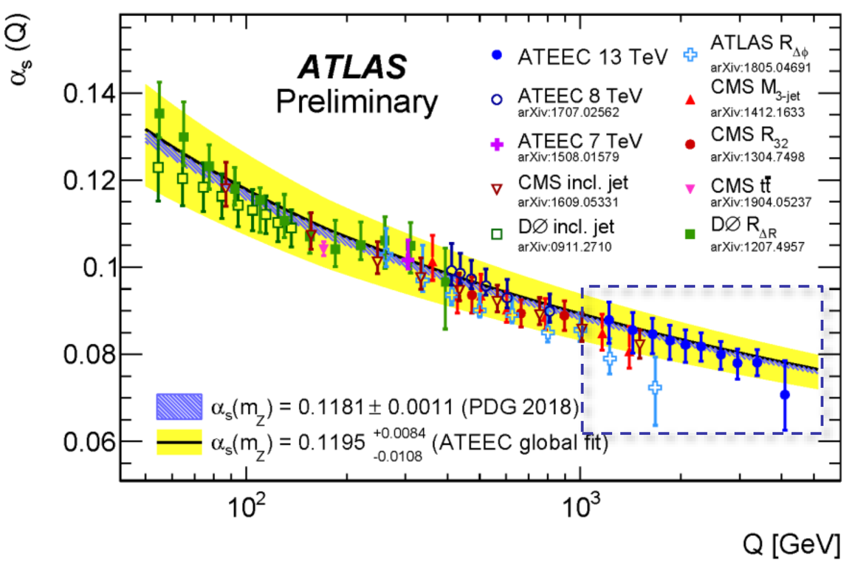




ATLAS-CONF-2020-025

Evolution of α_s with Momentum Transfer





ATLAS-CONF-2020-025

Determination of α_s

- Fit theoretical predictions to measured (A)TEEC distributions
  - Inclusive $\alpha_s(m_Z)$ from global fit
    - $H_{T2} > 1$ TeV
  - Local $\alpha_s(m_Z)$ fits in bins of H_{T2}
  - Evolution $\alpha_s(m_Z) \rightarrow \alpha_s(Q)$ uses NLO solutions to RGE

Running α_s measurement using (A)TEEC

- Tests RGE predictions at the highest energy scales ever
  - Running of $\alpha_s(Q)$ for $Q > 1$ TeV observed in data agrees very well with predictions
- Inclusive measurement
  - Compares very well to world average $\alpha_s(m_Z)$ within uncertainties

Conclusions & Outlook

Inclusive jet measurements

- Early cross section measurement
  - First results to test QCD calculations at NNLO
- Increased precision in jet reconstruction in ATLAS in LHC Run 2
  - Full Run 2 analysis is under way to provide inclusive jet and dijet cross sections at significantly increased precision over the accessible full phase space

Hadronic event shapes

- Observable deficiencies in modeling of event shapes reconstructed from hard ($p_T^{jet} >$ 100 GeV) jets
  - Room for improvement of modeling/calculation of final states with ≥ 3 hard emissions

Measurement of running α_s

- Extension of measurement to TeV scales
  - Very good agreement of NLO $\alpha_s(Q)$ prediction with measurement

ICHEP2020 – more from jets in ATLAS

- Recent results from QCD
  - Bogdan Malaescu, *Latest results from top, electroweak and Standard Model*
    - Plenary talk, Wednesday, August 5, 2020, 11:00am
- Jet measurements
  - Helena Santos: *Jet measurements in heavy ion collisions with the ATLAS experiment*
    - Heavy ions I, Tuesday, July 28, 2020, 6:06pm
- Determination of PDFs
  - Mark Sutton: *Determination of the parton density functions of the proton with the ATLAS data*
    - Strong interactions and hadron physics I (this session), July 28, 2020, 8:30pm

Additional Material

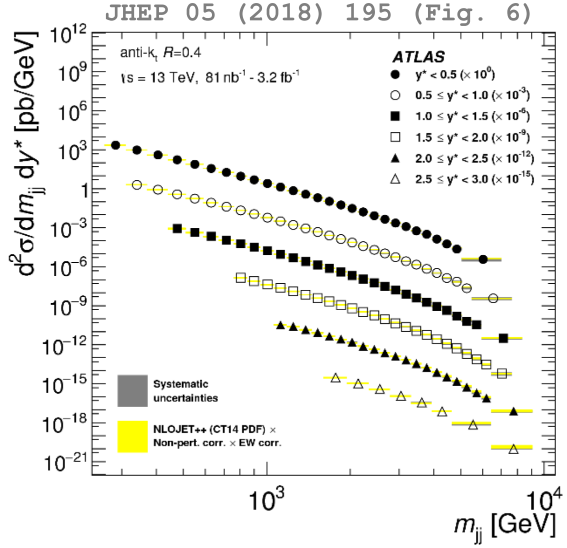
Inclusive Dijet Production

Inclusive jet and di-jet cross section

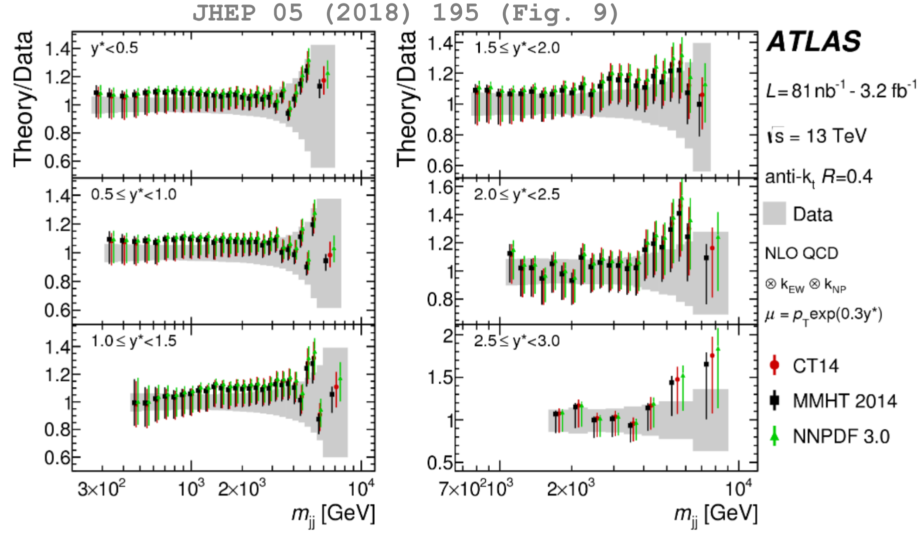
JHEP 05 (2018) 195

- Data collected from pp collisions at $\sqrt{s} = 13$ TeV in 2015
  - Inclusive jet cross section measured in terms of jet transverve momentum with 100 GeV $< p_{\mathrm{T}}^{\mathrm{jet}} <$ 3.5 TeV and $|y^{\mathrm{jet}}| < 3$
  - Inclusive dijet production cross section measured in terms of the invariant mass of the two leading jets 900 GeV $< m_{\mathrm{jj}} <$ 9 TeV and $y^* = \left|\left(y_{\mathrm{lead}}^{\mathrm{jet}} - y_{\mathrm{sublead}}^{\mathrm{jet}}\right)/2\right| < 3$
- Comparison to QCD predictions
  - Various PDF sets considered – acceptable agreement with NLO calculation with initial analysis using only about 2.5% of full dataset
  - Various PDF sets considered

JHEP 05 (2018) 195 (Fig. 6)



JHEP 05 (2018) 195 (Fig. 9)



Hadronic Event Shapes With Jets

Event shapes with jets

- Proxy for energy flow (shapes) in collision event
  - Measurement tests prediction power of fixed-order calculations, parton shower modeling, etc.
- Clear expectation values for given topology
  - Shapes vanish for $2 \rightarrow 2$ processes with perfect forward-backward (back-to-back in transverse plane) symmetry – at maximum for uniform energy (transverse momentum) distribution
- Probe for multi-jet energy flow at highest scales
  - $\mathcal{O}(\mathrm{TeV})$ for $\sqrt{s} = 13$ TeV
  - Evaluated in multi-jet final states ($n^{\mathrm{jet}} \geq 2$) as function of $H_{\mathrm{T2}} = p_{\mathrm{T}}^{\mathrm{lead}} + p_{\mathrm{T}}^{\mathrm{sublead}}$

Event shape	Name	Comments
$T_{\perp}$	Transverse thrust	$\tau_{\perp} = 1 - T_{\perp}$, $0 \leq \tau_{\perp} < 1 - 2/\pi$, $\tau_{\perp} \nearrow \Rightarrow$ back-to-back topology
T_m	Transverse thrust, minor component	$0 \leq T_m < 2/\pi$, $T_m \nearrow \Rightarrow$ increased energy flow outside of plane spanned by thrust and beam axes
$S_{\perp}$	Transverse sphericity	from eigenvalues $\{\mu_k\}$ of transverse sphericity tensor $\mathcal{M}_{xy}$, $S_{\perp} = 2\mu_2/(\mu_1 + \mu_2)$, $0 \leq S_{\perp} \leq 1$, $\downarrow$ back-to-back, $\uparrow$ isotropic
A	Aplanarity	from eigenvalues $\{\lambda_k\}$ of sphericity tensor $\mathcal{M}_{xyz}$, $A = \frac{3}{2}\lambda_3$, $0 \leq A \leq 1$, $A \nearrow \Rightarrow$ event less planar
C	3-jet observable	$C = 3(\lambda_1\lambda_1 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$, $C = 0$ for $n^{\mathrm{jet}} < 3$, $0 < C \leq 1$ for $n^{\mathrm{jet}} > 2$
D	4-jet observable	$D = 27(\lambda_1\lambda_2\lambda_3)$, $0 \leq D \leq 1$, $D = 0$ if all jets are in same plane

Event Shape Variables

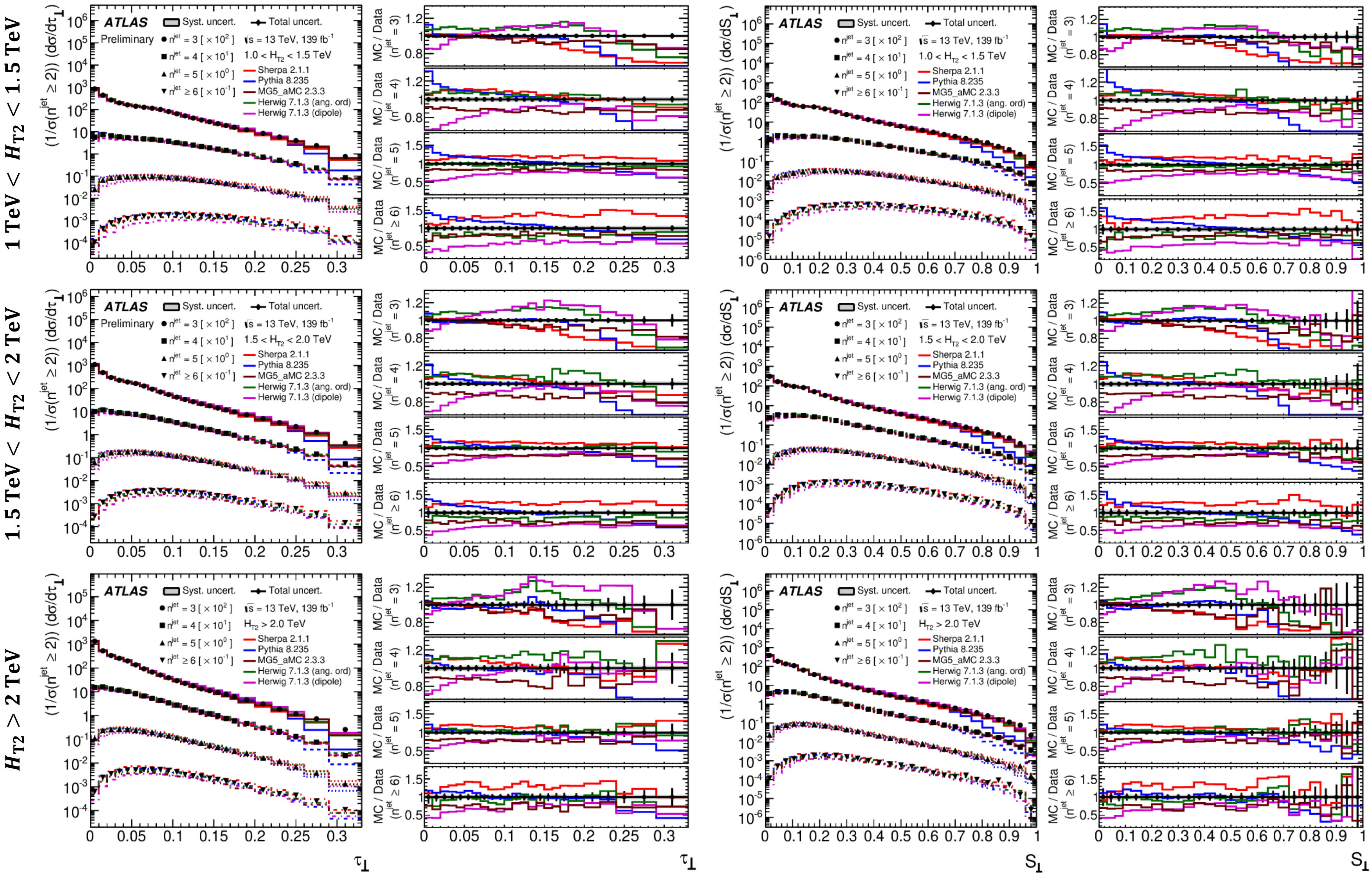
Linearized Sphericity Tensor

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

Transverse Linearized Sphericity Tensor

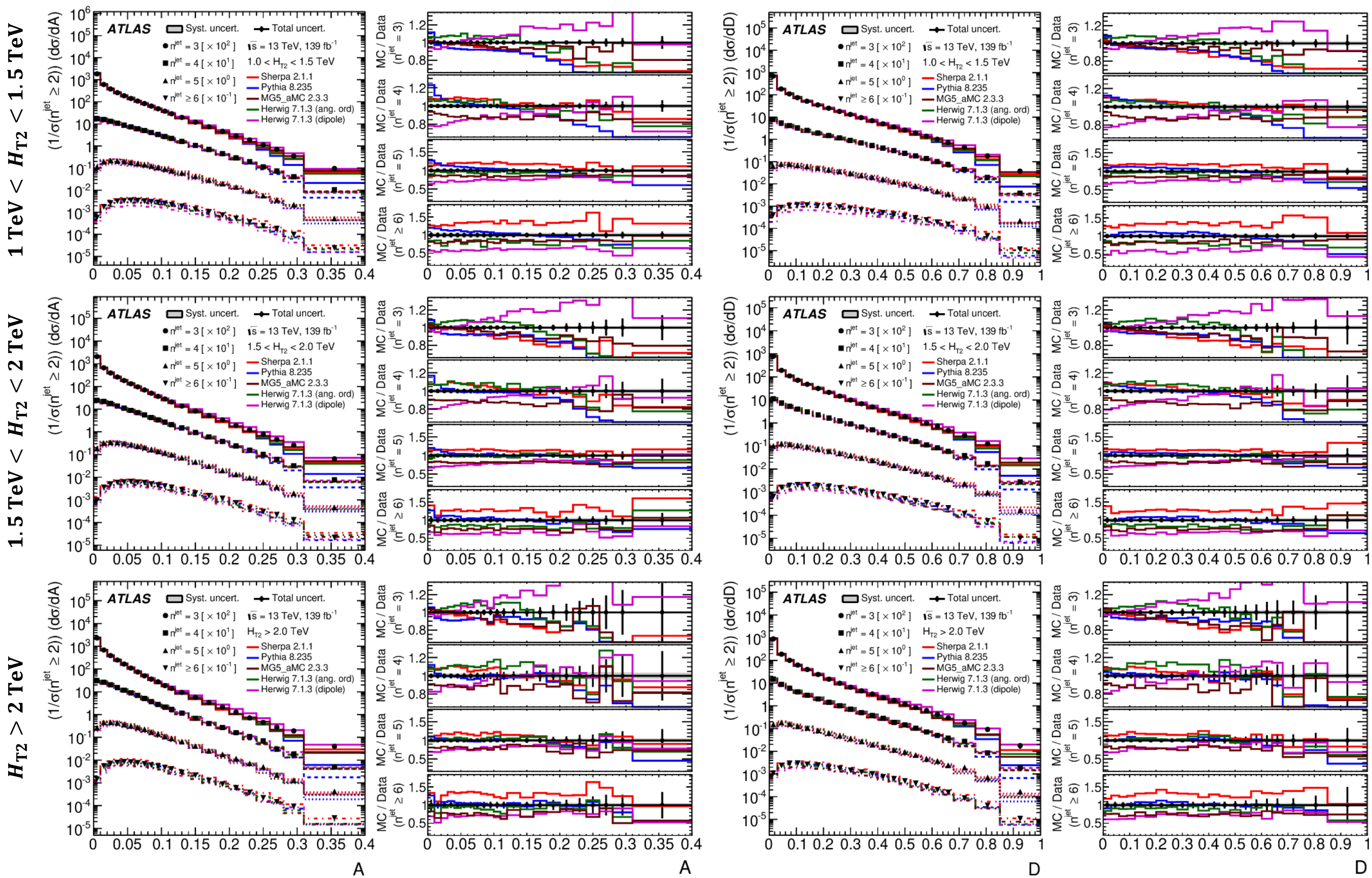
$$\mathcal{M}_{xy} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 \end{pmatrix}$$

Hadronic Event Shapes: $\tau_\perp(H_{T2}, n^{jet})$, $S_\perp(H_{T2}, n^{jet})$



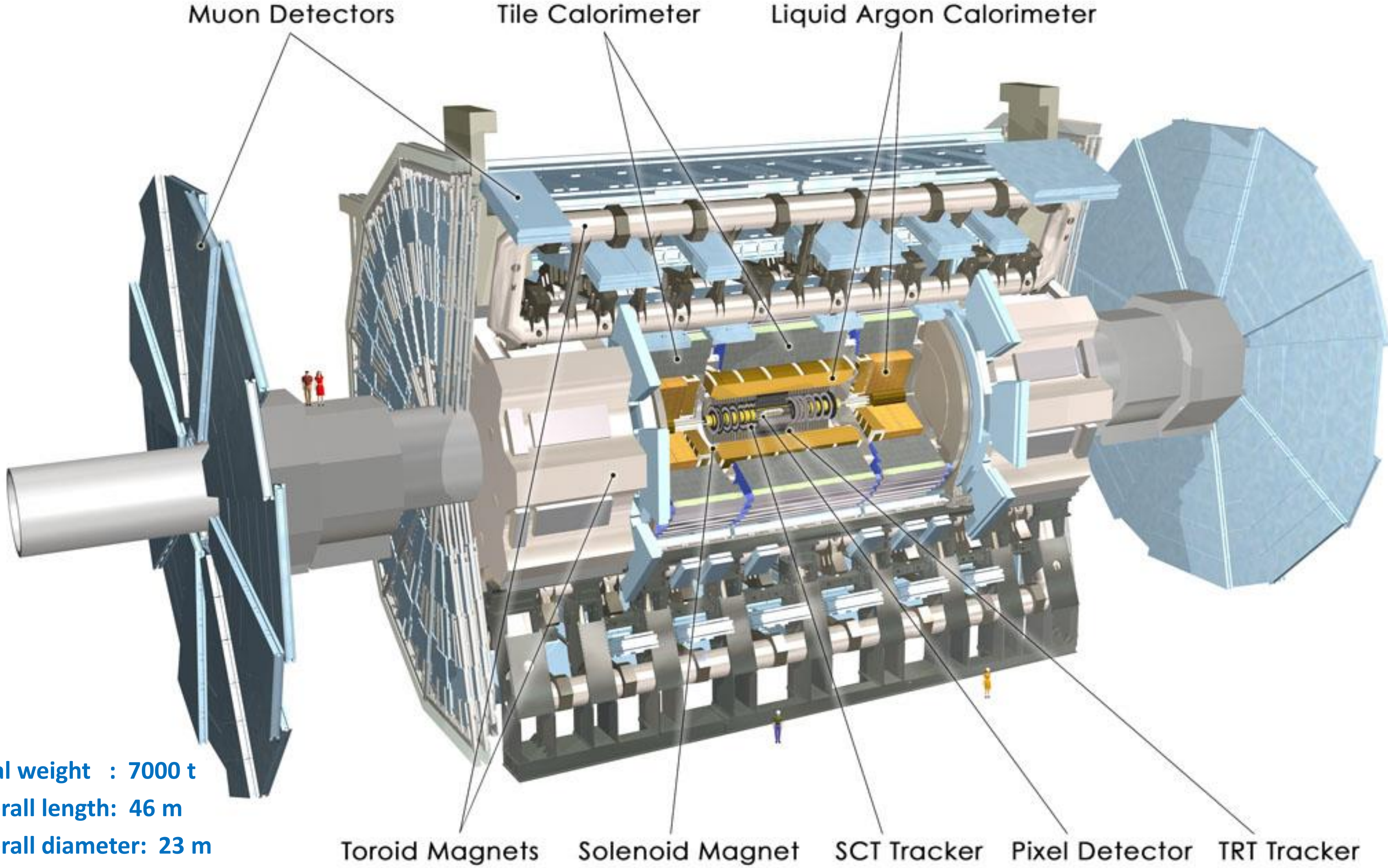
arXiv:2007.12600 [hep-ex]

Hadronic Event Shapes: $A(H_{T2}, n^{jet})$, $D(H_{T2}, n^{jet})$



arXiv:2007.12600 [hep-ex]

A multi-purpose detector system



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + (varying) toroid field

Detectors for Hadronic Final State Reconstruction

Calorimeters

- Provides principal signals for $e^{\pm}/\tau^{\pm}$ and jet kinematics – and other measurements
  - Full coverage within $|\eta| < 4.9$ with depth $\gtrsim 10\ \lambda_{\mathrm{int}}$
- Highly segmented for energy flow measurements (~188,000 cells)
  - High granularity in $\Delta\eta \times \Delta\varphi = 0.025 \times \pi/128$ (central EM)
  - Up to seven depth layers (*samplings*)

Inner detector

- Provides charged particle tracks and vertices
  - Coverage $|\eta| < 2.5$
- Jet energy calibration refinement
  - Provides vertex for jet origin correction/jet vertex association/jet vertex tagging (JVT)
  - Flavor/fragmentation sensitive response measures – mitigation of jet flavor response dependencies
- Particle flow
  - Replace charged response in calorimeter with kinematics from well-measured tracks
- Missing transverse momentum soft contributions
  - Tracks not used or associated with (hard) reconstructed particles and jets

Muon spectrometer

- Reconstructed muons
  - Contribution to missing transverse momentum reconstruction
- Track segments
  - Proxy for energy leakage behind a jet