Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ Reconstruction 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

Roadmap for this Talk

Jet reconstruction in ATLAS

Basic signals and reconstruction sequences

Small-*R* & large-*R* jets calibration

MC-based calibration

In situ calibration methods for jets in data

$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction

Signal ambiguity resolution

Selected performance

Conclusions and outlook

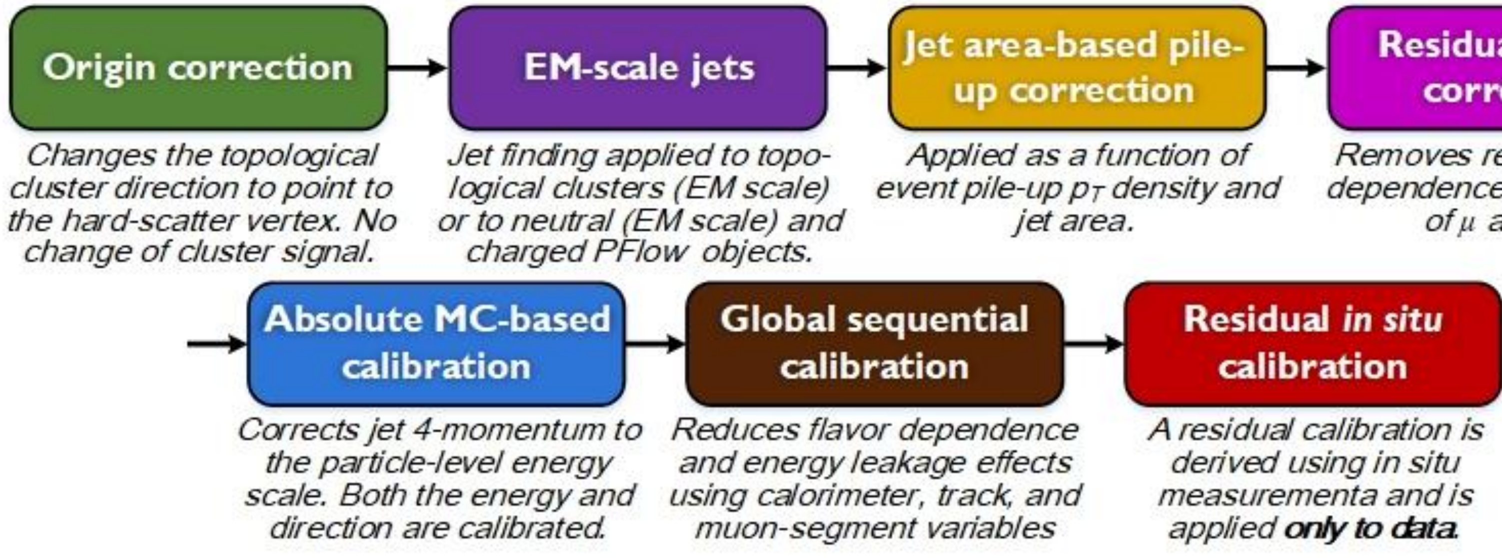
Small-R Jet Reconstruction in ATLAS

Anti-k_t jets with $R = 0.4$

Two choices for input signals

- Calorimeter only: clusters of topologically connected cells (topo-cluster) with signals on a basic electromagnetic (EM) scale – **EMTopo jets**
- Calorimeter and Tracking: particle flow signals (PFlow) combining reconstructed tracks with EM-scale topo-clusters – **EMPFlow jets**
- Clustering uses four-momentum recombination

Jet energy scale (JES) calibration sequence



calibrates p_{T} - $(E, \vec{p})$ rescaled

Large-R Jet Reconstruction in ATLAS

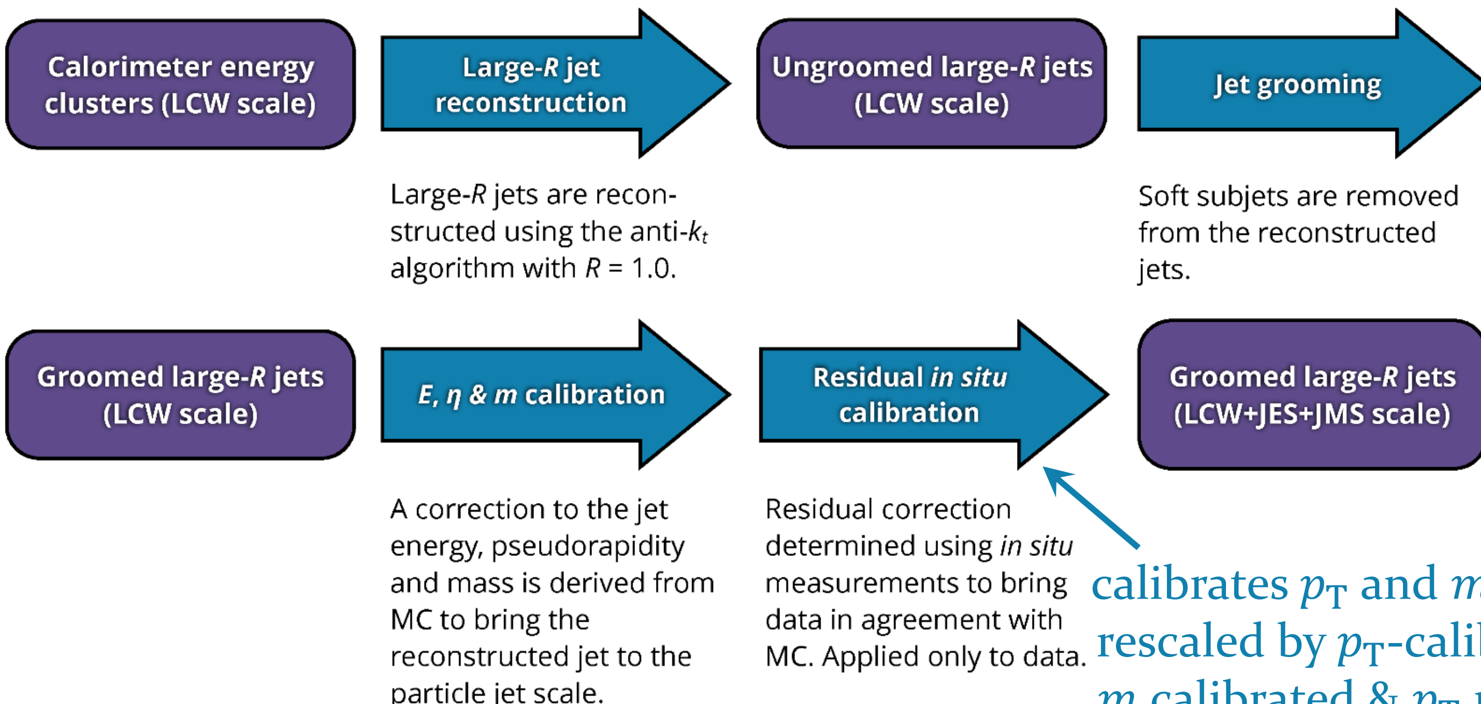
Anti-k_t jets with $R = 1.0$

Input signals

Calorimeter only: clusters of topologically connected cells (topo-cluster) with signals on a locally calibrated hadronic (LCW) scale – **LCTopo jets**

Clustering uses four-momentum recombination

JES and jet mass (JMS) calibration sequence

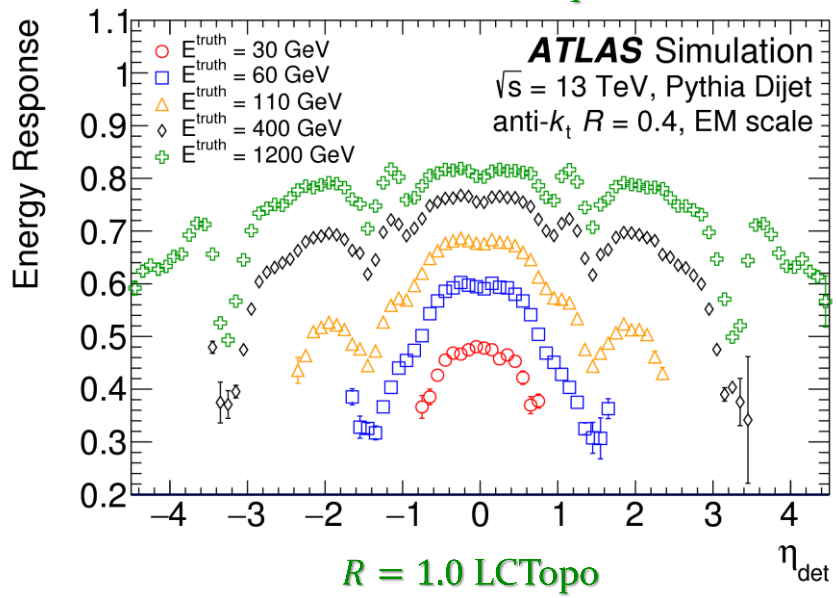


calibrates p_{T} and m – first $(E, \vec{p})$ rescaled by p_{T}-calibration, then m calibrated & p_{T} rescaled with E unchanged

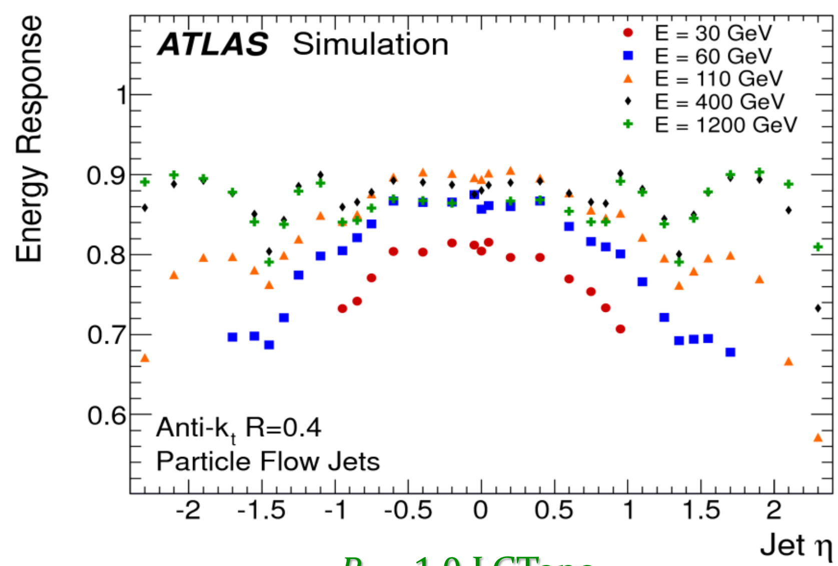
Response Before MC-based Calibration

$R = 0.4$ EMTopo

Phys.Rev.D 96 (2017) 072002



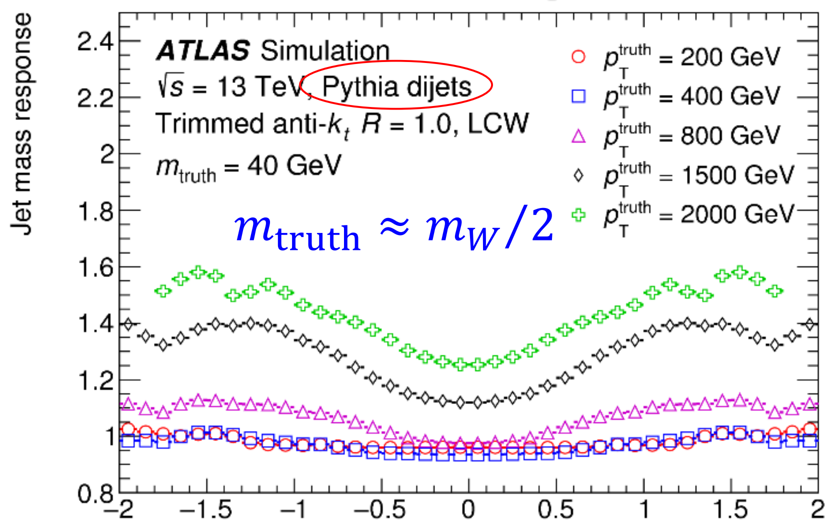
$R = 0.4$ EMPFlow



Eur.Phys.J.C 77 (2017) 466

$R = 1.0$ LCTopo

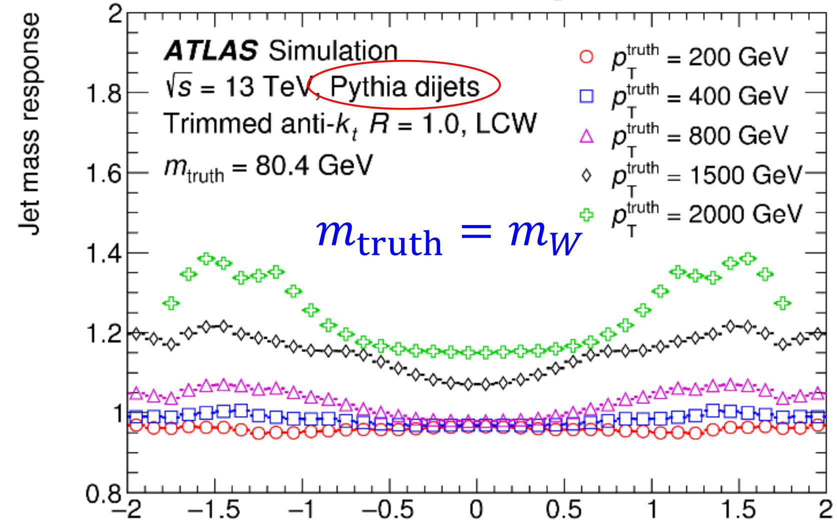
Eur.Phys.J.C 79 (2019) 135



$m_{\mathrm{jet}} \approx (10-20)\% \times p_{\mathrm{T,jet}}$ for q/g jet (NLO, $R = 1.0$)

Large-R jet η_{det}

$R = 1.0$ LCTopo



Eur.Phys.J.C 79 (2019) 135

$2m_{\mathrm{jet}}/p_{\mathrm{T,jet}} < R$ collects boosted particle decay products into jet of size R

Large-R jet η_{det}

Prog.Part.Nucl.Phys.60:484-551 (2008)

In situ Jet Calibration (Data Only)

In-situ calibration

(1) Relative η-intercalibration

- Dijets with central jet balancing probed (forward) jet – removes η-dependent data/MC response variations

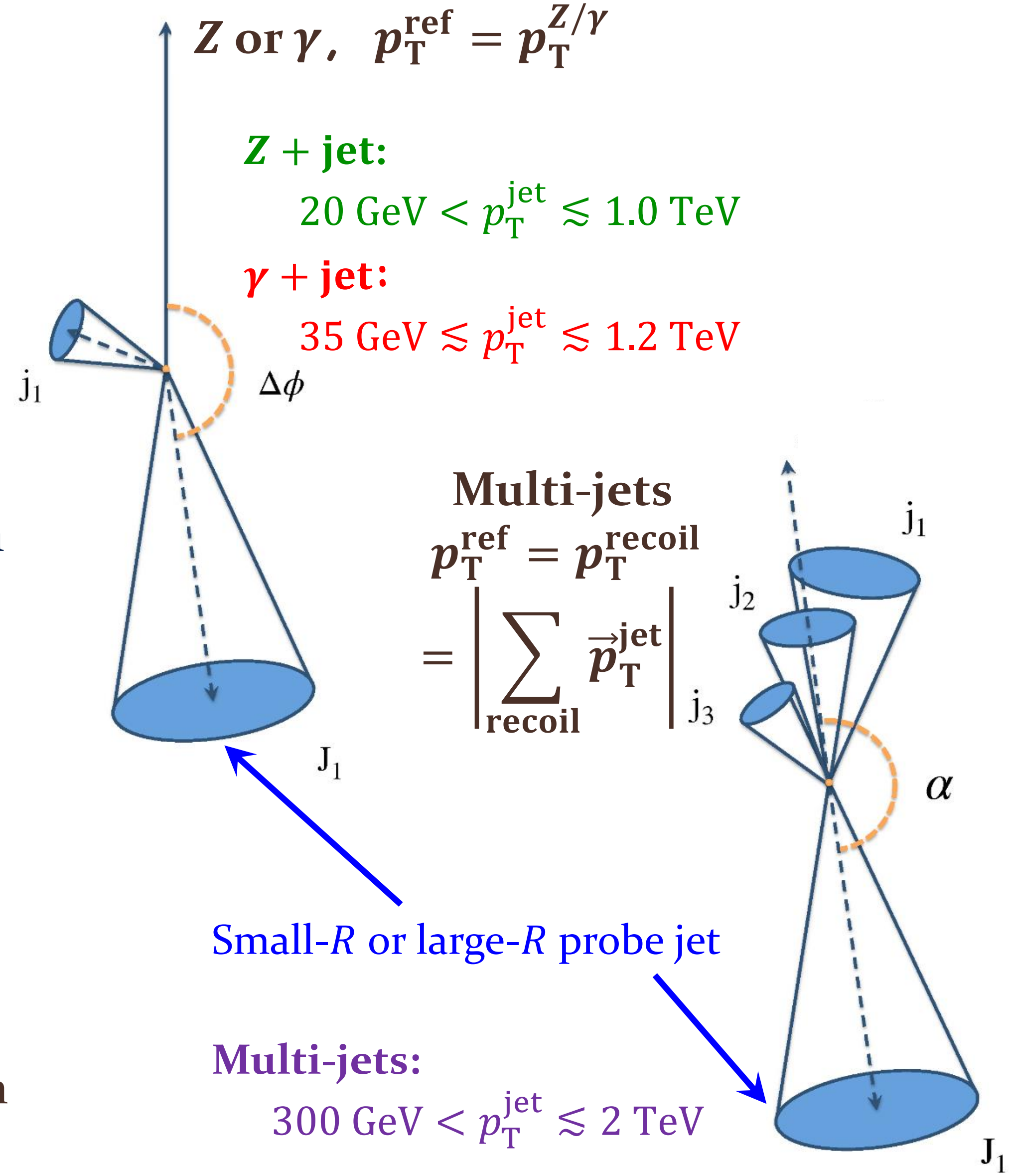
(2) Full response calibration

- Combining various final states for full phase space coverage – scales central response of data to MC

Final state selection

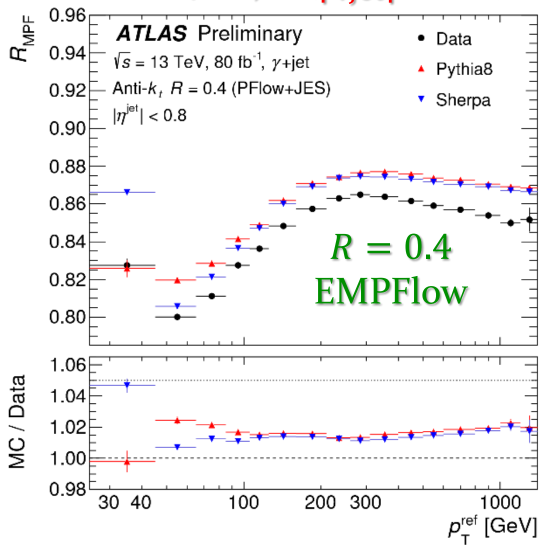
Same topologies data & MC

- Back-to-back reference and probe
- Suppression of events with additional jet(s) above threshold



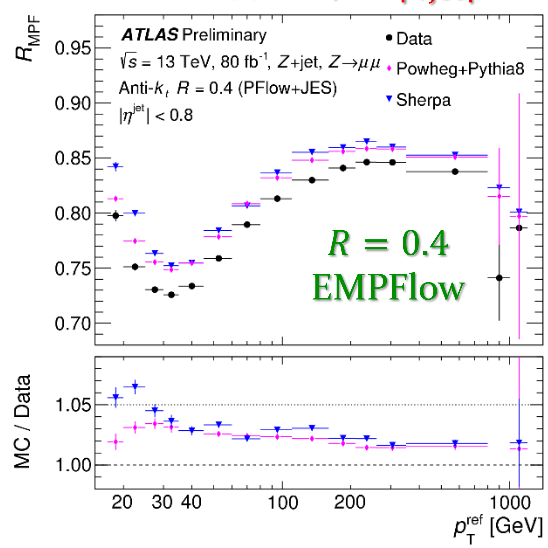
In situ Jet Energy Scale

MPF γ + jet ($|\eta_{\text{jet}}| < 0.8$)



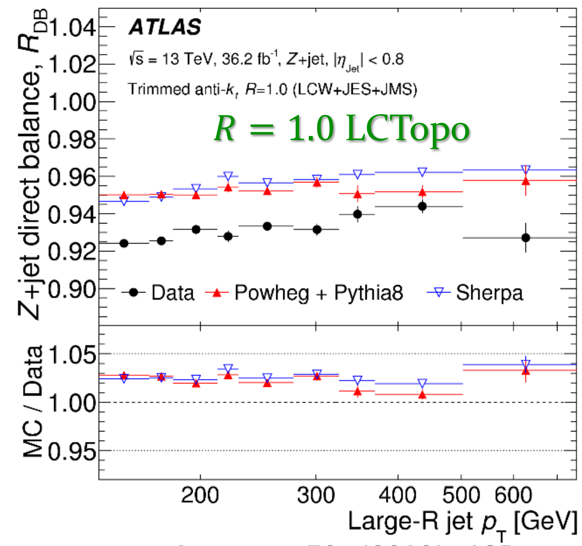
ATLAS JETM-2019-02 (Fig.1)

MPF ($Z \to \mu\mu$) + jet ($|\eta_{\text{jet}}| < 0.8$)



ATLAS JETM-2019-02 (Fig.2b)

DB Z + jet ($|\eta_{\text{jet}}| < 0.8$)



Eur.Phys.J.C 79 (2019) 135

In situ corrections relative to MC

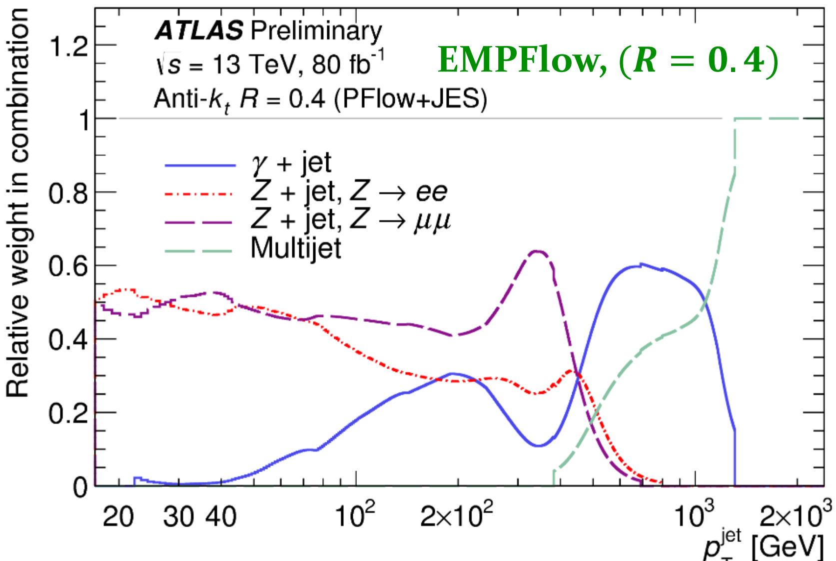
- Derived from DB or MPF
  - Depends on phase space coverage and precision
  - $r_{in\ situ} = p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}}^{\mathrm{ref}}\,(p_{\mathrm{T}}^{\mathrm{ref}})$ – **direct balance** (DB)
  - $R_{\mathrm{MPF}} = 1 + \left(\vec{p}_T^{\,\mathrm{ref}} \cdot \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)/\left|\vec{p}_T^{\,\mathrm{ref}}\right|^2$ – **missing projection fraction** (MPF)
- Calibration functions
  - (Powheg+)Pythia8/data ratio reflects nominal calibration function for data – near flat (~2%) correction for $p_{\mathrm{T}}^{\mathrm{jet}} > 40$ GeV both for small- and large-*R* jets
  - Differences to other MC generators and variations of topology selections contribute to systematic uncertainties

Extracting Jet Calibration for Full Phase Space

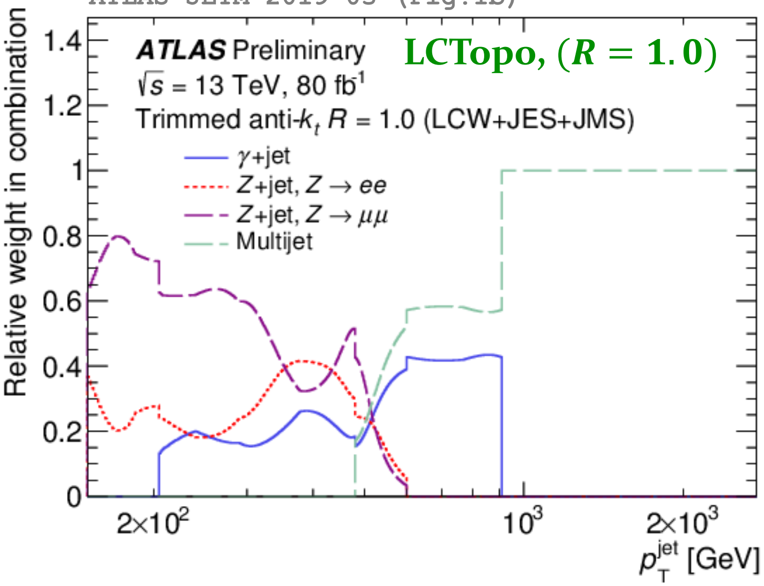
Combination of results

- Various final states and methodologies
  - Most precise configuration gets highest weight
- Contribution weights
  - Some dependency on jet definition, collected luminosity (statistical precision), algorithm choice (MPF,DB) and detector signal choice
  - Statistical limitations towards phase space limits

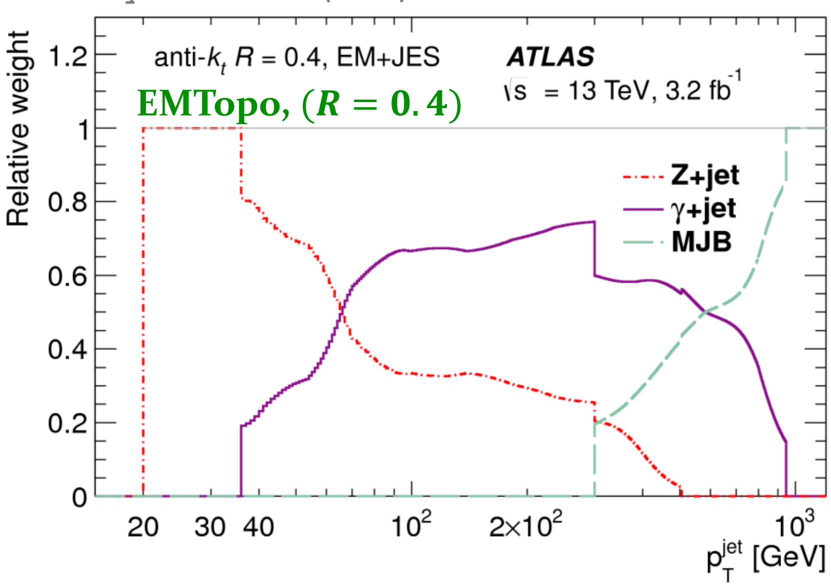
ATLAS JETM-2019-02 (Fig.4)



ATLAS JETM-2019-05 (Fig.1b)



Phys.Rev.D 96 (2017) 072002

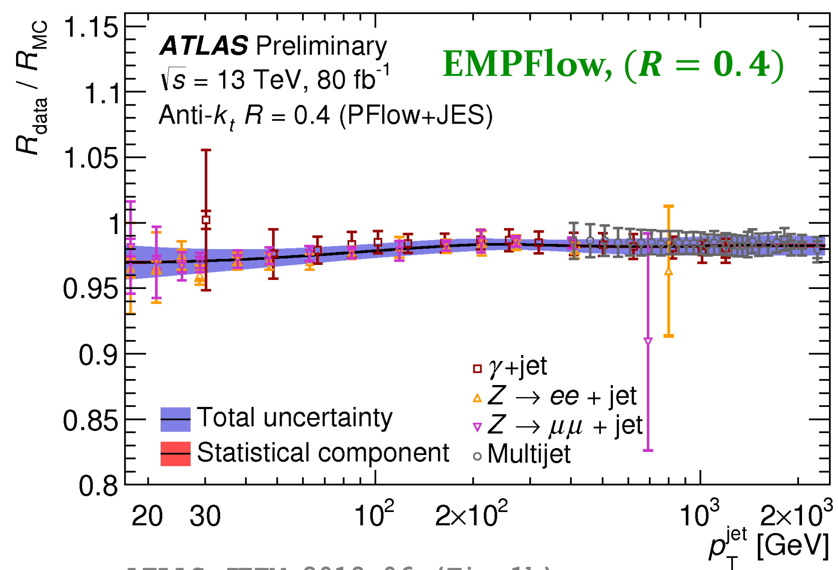


Extracting Jet Calibration for Full Phase Space

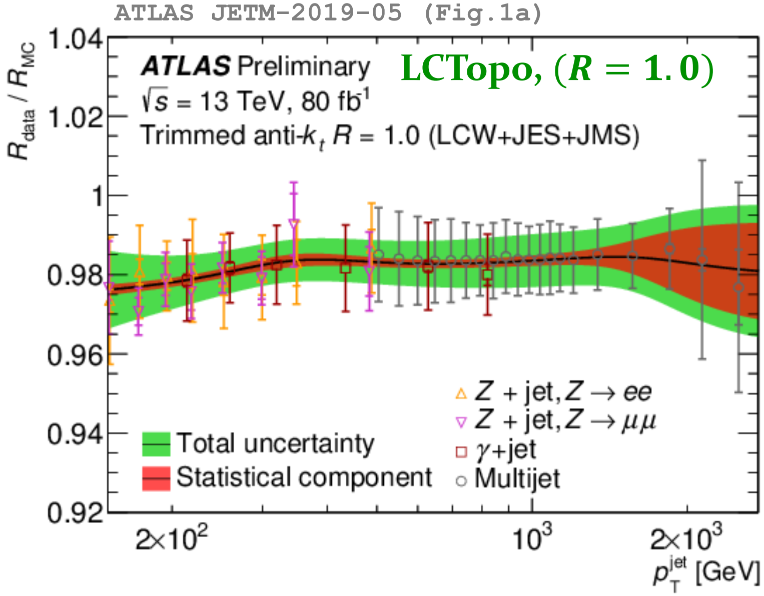
Combination of results

- Various final states and methodologies
  - Most precise configuration gets highest weight
- Calibration functions
  - From response curves from weighted combination
  - Gaussian Kernel smoothing
  - Calibration and uncertainties very comparable between small-R and large-R jets

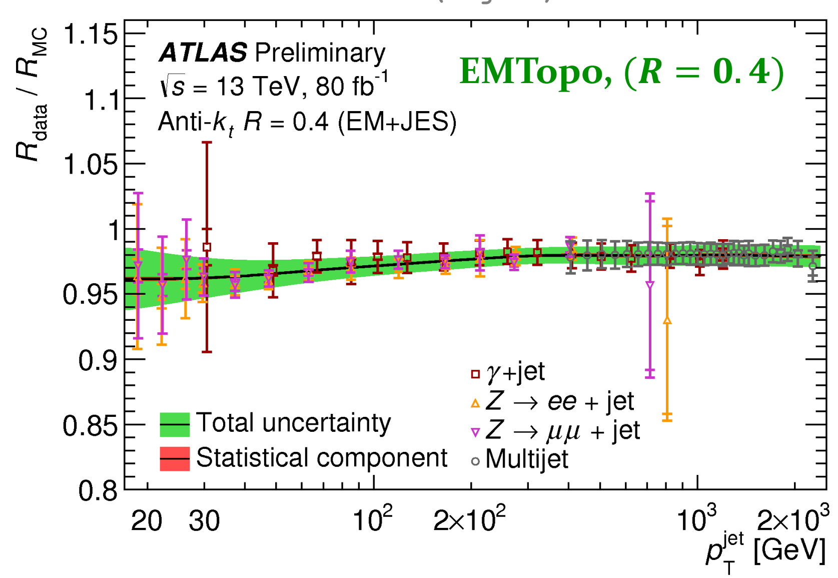
ATLAS JETM-2018-06 (Fig.1a)



ATLAS JETM-2019-05 (Fig.1a)



ATLAS JETM-2018-06 (Fig.1b)



Relative Jet Energy Resolution

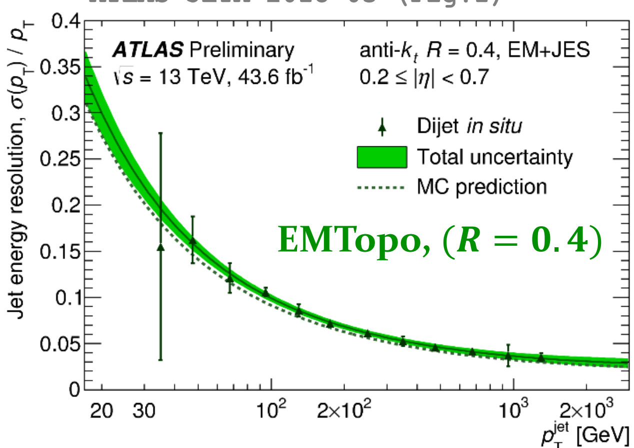
Measured with p_T asymmetry in di-jet balance

PFlow shows expected improvements at low p_T

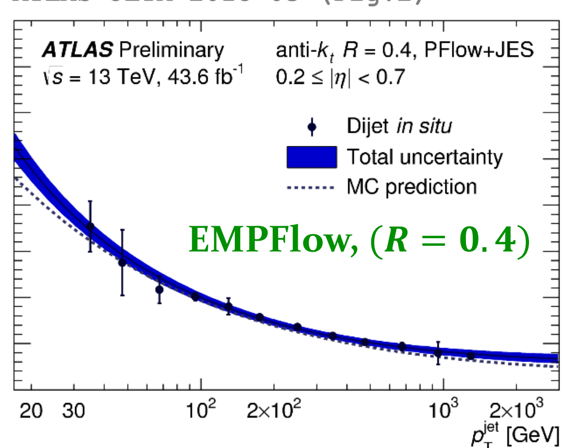
Significantly reduced fluctuations from pile-up

Significantly reduced uncertainties at low p_T

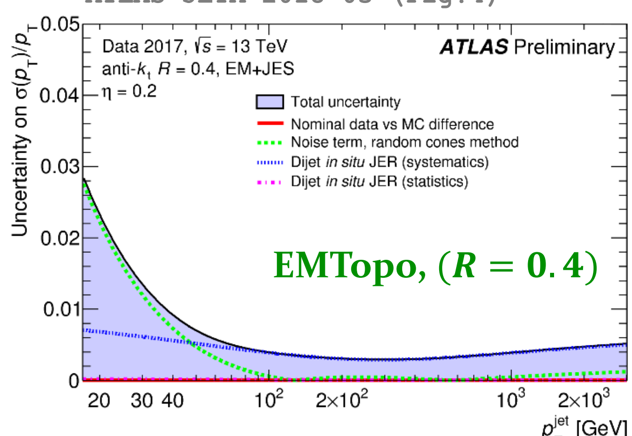
ATLAS JETM-2018-05 (Fig.1)



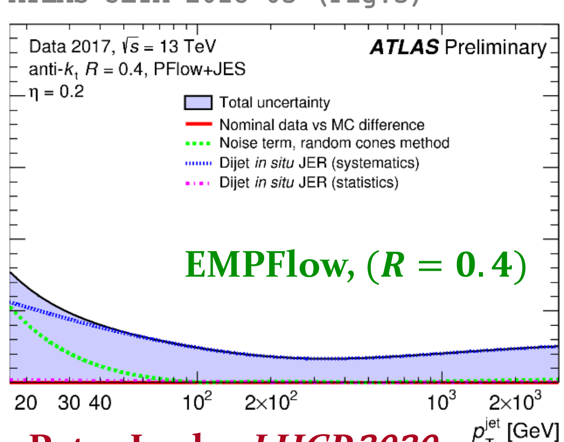
ATLAS JETM-2018-05 (Fig.2)



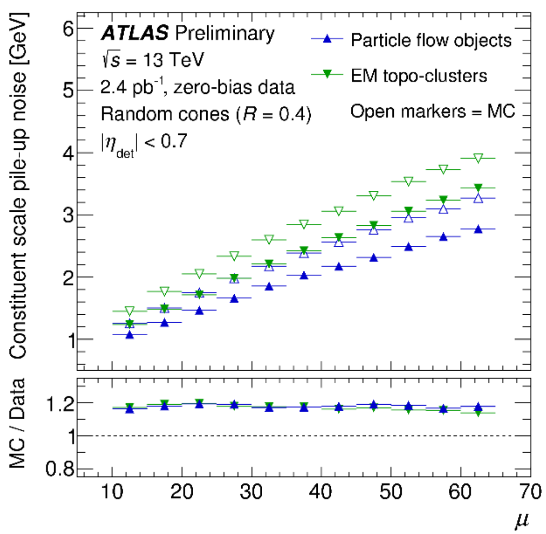
ATLAS JETM-2018-05 (Fig.4)



ATLAS JETM-2018-05 (Fig.5)



ATLAS JETM-2019-01 (Fig.2b)



Imperfect pile-up modeling – larger fluctuations in MC simulation than in data

Object-based approach

- Fully reconstructed and calibrated particles and jets
  - Require signal ambiguity resolution to avoid double counting
- Soft signals
  - Signals below reconstruction threshold(s) still contribute to the event p_{T} flow – can be important for $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution, bias and significance

Signal ambiguity resolution

- Priority ranking of object contributing to $E_{\mathrm{T}}^{\mathrm{miss}}$
  - Higher priority to object with higher reconstruction quality
  - Analysis goals determine the ranking and particular object selections
- Reasons for rejection of lower priority objects for $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction
  - A – use of same detector signal
  - B – association with detector signals used for reconstruction of accepted objects
  - C – other significant phase space overlap with accepted object

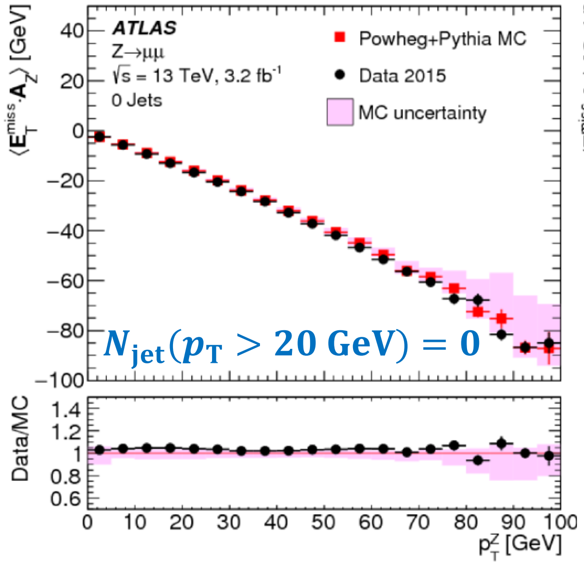
Soft signal collection

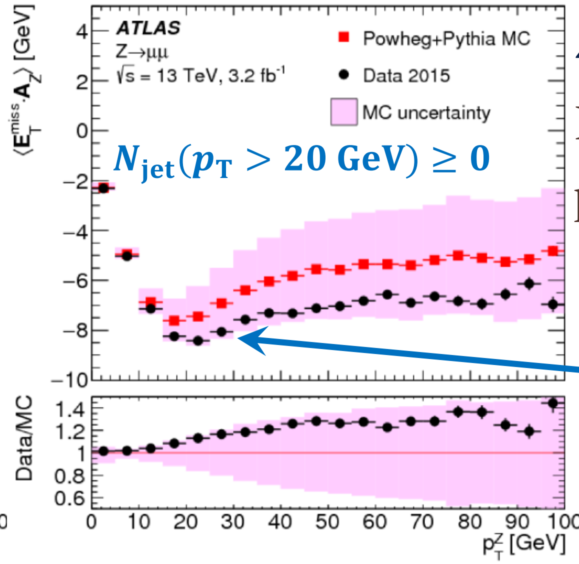
- Signals not associated or used by accepted objects
  - Basic signals or signal remnants from rejected objects – e.g., accepted electron removes only part of jet
  - Topo-clusters in Run 1 – now primary vertex tracks due to higher stability to increased pile-up

$E_{\mathrm{T}}^{\mathrm{miss}}$ Response

Eur.Phys.J.C 78 (2018) 903
(all figures)

Response & resolution

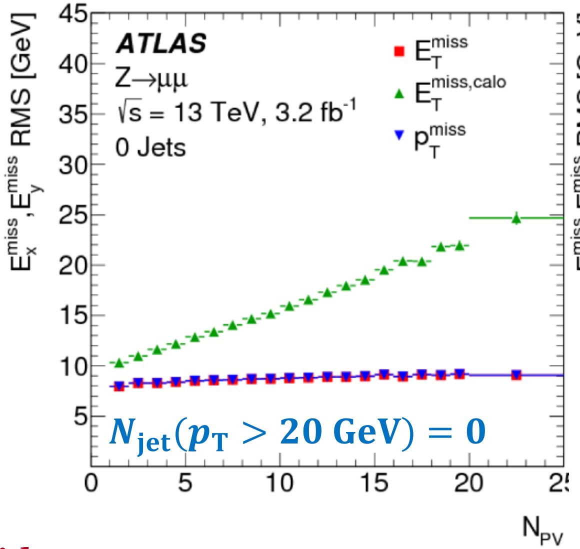


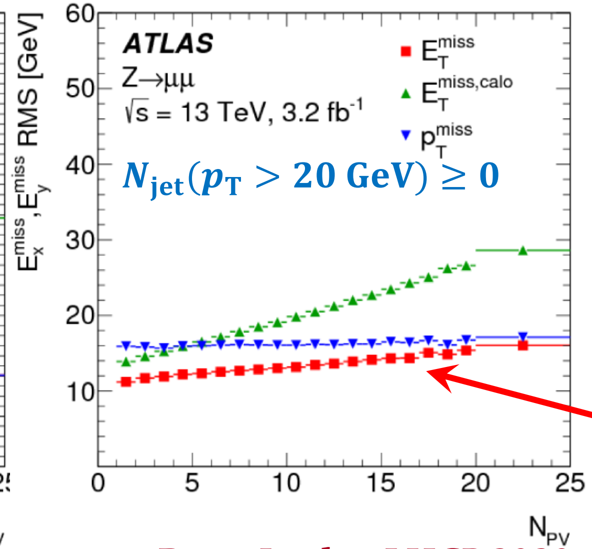


$Z \to \ell\ell + (0, \ldots, N_{\mathrm{jet}})$ jet(s)

Reconstructed $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ is projected onto $\mathbf{p}_{\mathrm{T}}^{Z}$

Turn on of jets in recoil improves recoil reconstruction ($p_{\mathrm{T,jet}} > 20$ GeV)





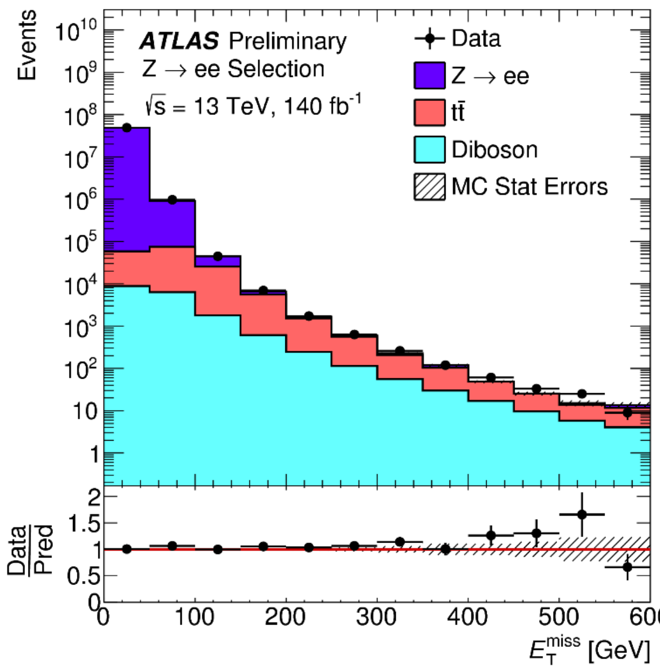
Pile-up stability

Soft term using tracks performs well – soft calorimeter signals strongly affected by pile-up

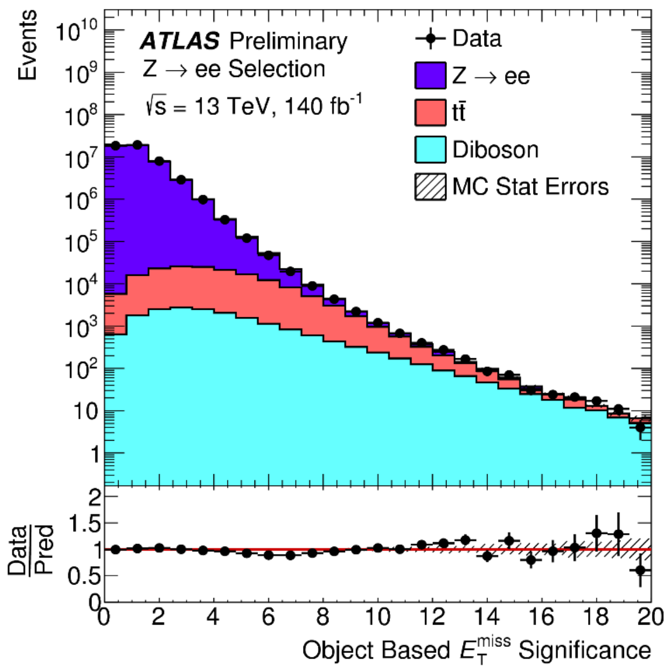
Jets in recoil improve resolution but introduce a pile-up dependence

E_T^{miss} in Data & Simulations in LHC Run 2

ATLAS JETM-2019-03 (Fig.1)



ATLAS JETM-2019-03 (Fig.2)



Good agreement observed

- E_T^{miss} spectrum
  - Important for e.g. phase space selections
- E_T^{miss} significance (ATLAS-CONF-2018-038)
  - Relates observed E_T^{miss} to accumulated signal fluctuations in underlying objects – including correlations
  - Important tool for e.g. searches for non-interacting or weakly interacting particles

Conclusions & Outlook

Jets in ATLAS in LHC Run 2

- Following principal approaches developed in Run 1
  - MC-based calibrations followed by *in situ* data-only calibrations
- Similar small and large R jet performance
  - Uncertainties at $\mathcal{O}(1\%)$ comparable to Run 1
  - Well controlled and precise measurement of overall jet kinematics
  - Effects from increased pile-up in Run 2 appropriately mitigated using well-established tools
- PFlow jets
  - Improved pile-up suppression for $p_{\mathrm{T}} \lesssim 100$ GeV – similar or higher precision
  - New standard and basis of the final precision recommendations for physics analysis
- Further improvements
  - Several projects looking at one-step calibration approaches and the application of machine learning in jet calibration
  - Improved pile-up mitigation techniques considering correlations between the out-of-time signal remnants and the in-time pile-up signals

Conclusions & Outlook

$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction

- Object-based approach carried from Run 1 to higher luminosity
  - Works very well even at highest luminosities (so far)
  - Extension to PFlow – mainly affects jets
  - Investigation of Machine Learning in reconstruction
  - Improved fJVT measure removes pile-up jets outside of tracking acceptance more efficiently

Selected Resources & Latest Developments

Recent and relevant publications

ATLAS Coll., *Jet energy scale and resolution in Run 1*, arXiv:1910.04482 (to appear in Eur.Phys.J.C)

ATLAS Coll., *Large-R jet in-situ calibration*, Eur.Phys.J.C 79 (2019) 135

ATLAS Coll., *Performance of missing transverse momentum reconstruction in 2015 data*, Eur.Phys.J.C 78 (2018) 903

ATLAS Coll., *Jet reconstruction and performance using particle flow with the ATLAS detector*, Eur.Phys.J.C 77 (2017) 466

ATLAS Coll., *ATLAS jet energy scale in early Run 2*, Phys.Rev.D 96 (2017) 072002

Conference & public notes

ATLAS Coll., *Simultaneous jet energy scale and jet mass scale calibration using generalized numerical inversion*, ATLAS-PHYS-PUB-2020-001

ATLAS Coll., *Pile-up-suppressing missing transverse momentum using image de-noising*, ATLAS-PHYS-PUB-2019-28

ATLAS Coll., *Object-based missing transverse momentum significance in the ATLAS detector*, ATLAS-CONF-2018-038

ATLAS Coll., *Missing transverse momentum performance in 13 TeV data*, ATLAS-CONF-2018-23

Additional Material

Small-R Jet Reconstruction in ATLAS

Anti-k_t jets with $R = 0.4$

- Two choices for input signals
  - Calorimeter only: clusters of topologically connected cells (topo-cluster) with signals on a basic electromagnetic (EM) scale – **EMTopo jets**
  - Calorimeter and Tracking: particle flow signals (PFlow) combining reconstructed tracks with EM-scale topo-clusters – **EMPFlow jets**
  - Clustering uses four-momentum recombination

Jet energy scale (JES) calibration sequence

- MC-based
  - **Pile-up suppression:** removes diffuse emissions from pile-up into jet (jet-area-based – pile-up represented as median p_{T} density of given event
  - **Energy calibration** and **direction correction:** scales the reconstructed jet energy to the truth expectation and corrects small directional deflections
  - **Global sequential calibration:** reduces jet-by-jet response variations introduced by jet flavor, fragmentation and longitudinal energy leakage
- *In situ* calibration: data only – relative to MC
  - **η-intercalibration using p_{T} balance in dijet events:** corrects data-MC response ratio variations in calorimeter regions, relative to central region
  - **p_{T} balance in γ/Z + jet(s) & multi-jet final states:** calibrates data to jet response in MC simulations – removes residual data-MC differences

Large-R Jet Reconstruction in ATLAS

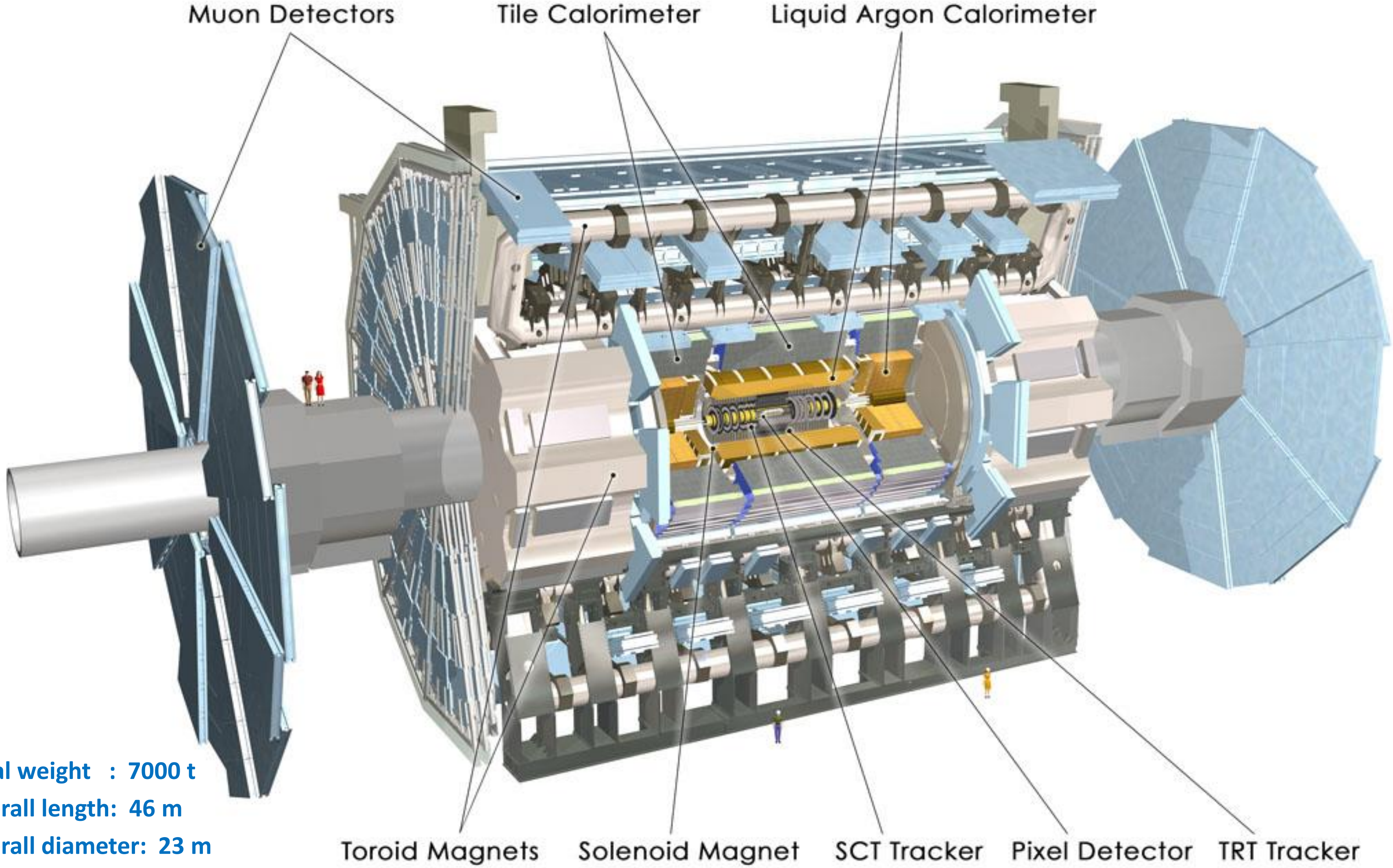
Anti-k_t jets with $R = 1.0$

- Input signals
  - Calorimeter only: clusters of topologically connected cells (topo-cluster) with signals on a locally calibrated hadronic (LCW) scale – **LCTopo jets**
  - Clustering uses four-momentum recombination

JES and jet mass (JMS) calibration sequence

- Pile-up suppression by jet grooming
  - Removing soft subjets by trimming $(p_{\mathrm{T}}^{\mathrm{subjet}}/p_{\mathrm{T}}^{\mathrm{jet}} > f_{\mathrm{cut}} = 5\%, R_{\mathrm{subjet}} = 0.2)$
- MC-based
  - **Energy** and **mass calibration** and **direction correction :** scales the reconstructed jet energy and mass to the truth expectations; corrects small directional deflections (truth particle jet is trimmed as well)
- *In situ* calibration: data only – relative to MC
  - ***In situ* JES similar to small-*R* jets approach:** using p_{T} balance with well-calibrated reference(s)
  - ***In situ* JMS:** applied after *in situ* JES – corrects $m_{\mathrm{jet}}^{\mathrm{data}}$ with scale factors determined by forward-folding $m_{W\to jj}^{\mathrm{MC}}$ and $m_{t\to jjj}^{\mathrm{MC}}$ distributions from MC to data in $t\bar{t} \to (Wb)(Wb) \to (qqb)(\ell\ell b)$ final states

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

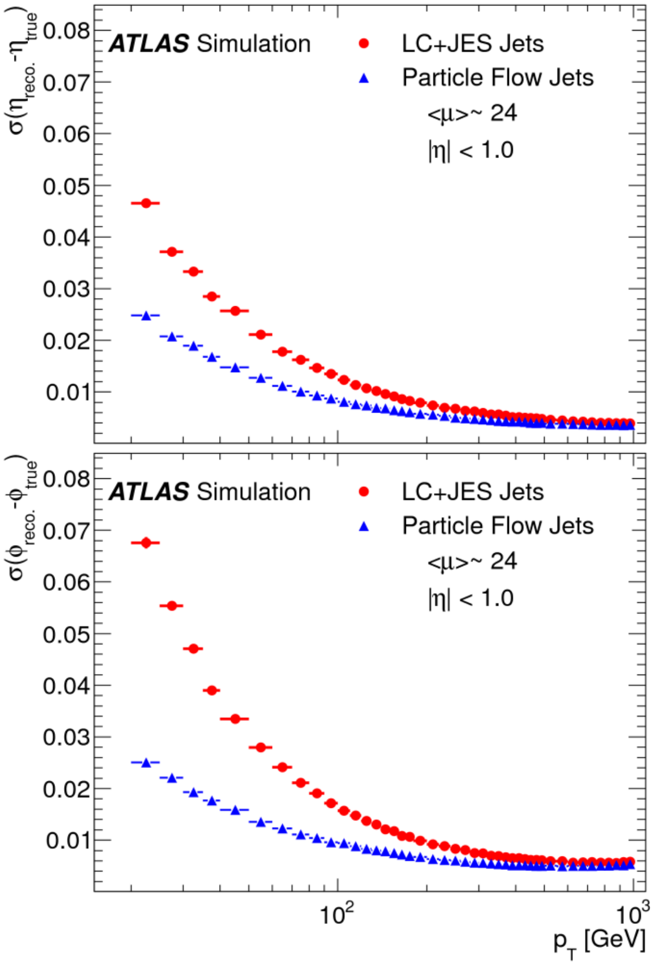
Muon spectrometer

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

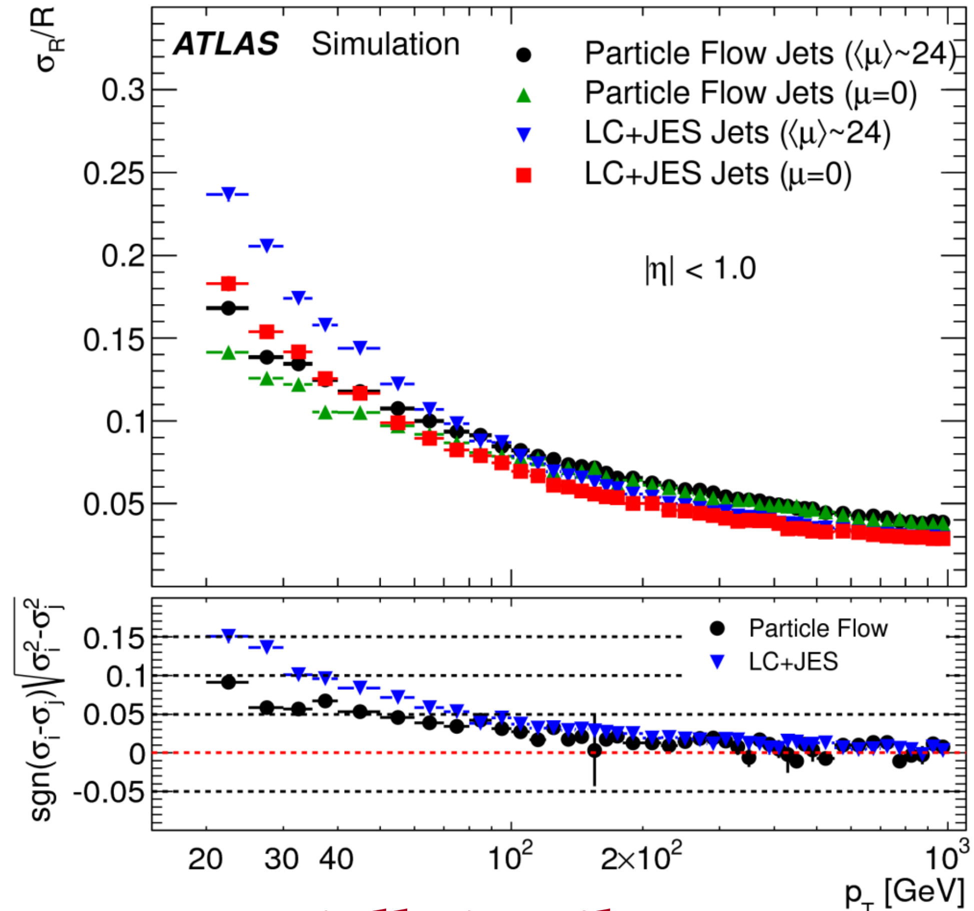
Why Particle Flow Jets?

Eur.Phys.J.C 77 (2017) 466
(all figures)

Angular resolution improvements



Improved jet energy resolution



Better lower p_T performance especially in pile-up

In situ JES Calibration Overview

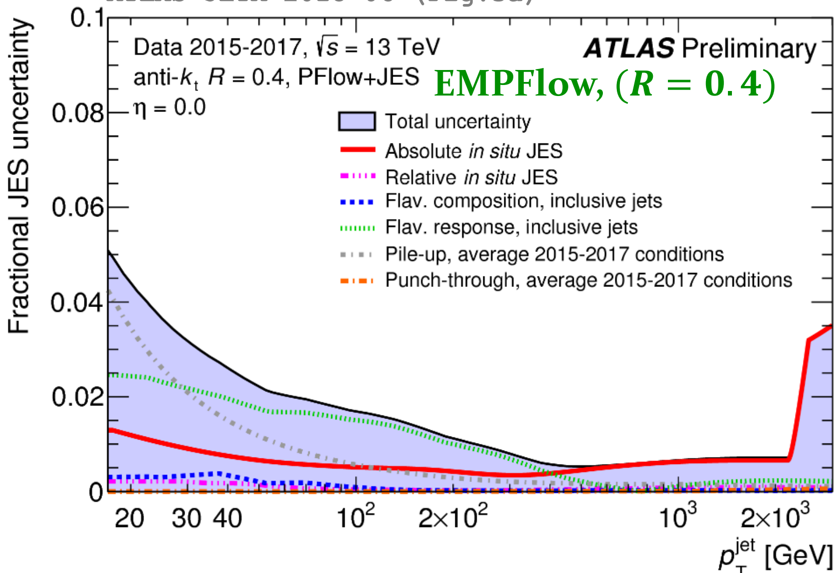
Method	Validity range	Reference jet calibration	Probe jet calibration	Applied to jets with …
η-intercalibration	full accessible $p_{\mathrm{T}}^{\mathrm{jet}}$ range	MC calibrations	MC calibrations	MC calibrations
$Z+\mathrm{jet}$ (MPF)	$20\ \mathrm{GeV} < p_{\mathrm{T}}^{\mathrm{jet}} \lesssim 1.0\ \mathrm{TeV}$	n/a	No probe – full final state response	MC calibrations + η-intercalibration
$Z+\mathrm{jet}$ (DB)			MC calibrations + η-intercalibration	MC calibrations + η-intercalibration
$\gamma+\mathrm{jet}$ (MPF)	$35\ \mathrm{GeV} \lesssim p_{\mathrm{T}}^{\mathrm{jet}} \lesssim 1.2\ \mathrm{TeV}$	n/a	No probe – full final state response	MC calibrations + η-intercalibration
$\gamma+\mathrm{jet}$ (DB)			MC calibrations + η-intercalibration	MC calibrations + η-intercalibration
Multi-jet (MJB)	$300\ \mathrm{GeV} \lesssim p_{\mathrm{T}}^{\mathrm{jet}} \lesssim 2\ \mathrm{TeV}$	full calibration	MC calibrations + η-intercalibration	MC calibrations + η-intercalibration

Extracting Jet Calibration for Full Phase Space

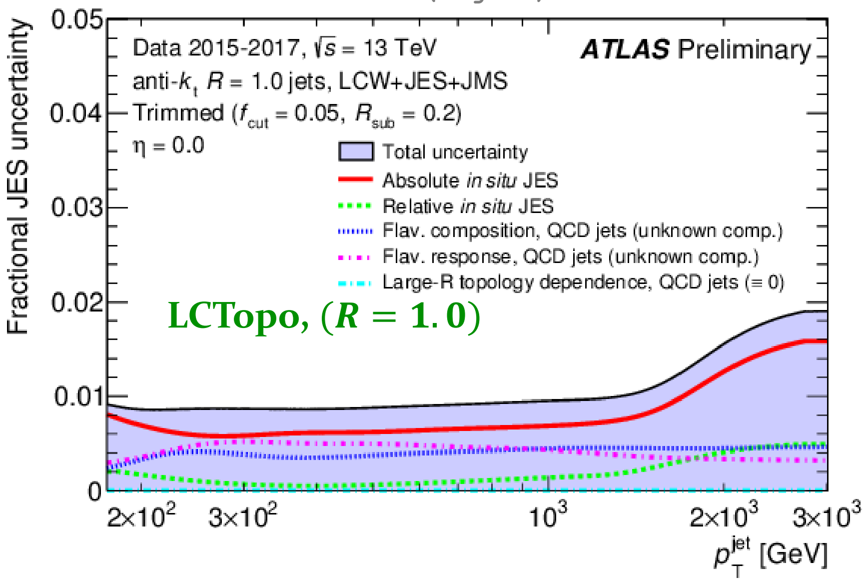
Systematic uncertainties

- Dominant sources
  - Absolute in-situ data-to-MC calibration
  - Flavor response variations and pile-up corrections for low p_T $R = 0.4$ jets
- High precision for $R = 1.0$ jet response
  - Less sensitivity to flavor response (fragmentation)

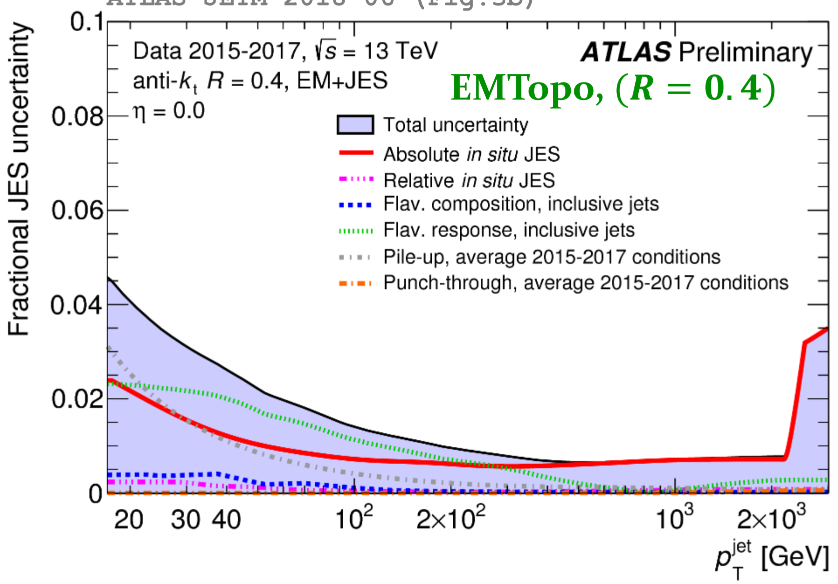
ATLAS JETM-2018-06 (Fig.3a)



ATLAS JETM-2019-05 (Fig.2a)



ATLAS JETM-2018-06 (Fig.3b)



Principal observables

$$E_{x(y)}^{\mathrm{miss}} = -\sum_{i\in\{\text{hard objects}\}} p_{x(y),i} - \sum_{j\in\{\text{soft signals}\}} p_{x(y),j}$$

$$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = (E_x^{\mathrm{miss}}, E_y^{\mathrm{miss}})$$

$$E_{\mathrm{T}}^{\mathrm{miss}} = |\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}| = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$ (E_T^{miss} observation bias!)

$$\phi^{\mathrm{miss}} = \tan^{-1}(E_y^{\mathrm{miss}}/E_x^{\mathrm{miss}})$$

Signal contributions

$$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = \underbrace{\underbrace{-\sum_{\substack{\text{selected}\\\text{electrons}}} \mathbf{p}_{\mathrm{T}}^{e}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},e}} \underbrace{-\sum_{\substack{\text{accepted}\\\text{photons}}} \mathbf{p}_{\mathrm{T}}^{\gamma}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\gamma}} \underbrace{-\sum_{\substack{\text{accepted}\\\tau\text{-leptons}}} \mathbf{p}_{\mathrm{T}}^{\tau_{\mathrm{had}}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\tau_{\mathrm{had}}}} \underbrace{-\sum_{\substack{\text{selected}\\\text{muons}}} \mathbf{p}_{\mathrm{T}}^{\mu}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\mu}} \underbrace{-\sum_{\substack{\text{accepted}\\\text{jets}}} \mathbf{p}_{\mathrm{T}}^{\mathrm{jet}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss,jet}}}}_{\text{hard term}} \underbrace{\underbrace{-\sum_{\substack{\text{unused}\\\text{tracks}}} \mathbf{p}_{\mathrm{T}}^{\mathrm{track}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss,soft}}}}_{\text{soft term}}$$