Reconstruction and Calibration of Small Radius Jets in the ATLAS Experiment for LHC Run 2

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Roadmap for this Talk

Introduction to the ATLAS experiment

- Brief detector description

Jet inputs & finding

- Topological cell clusters in the ATLAS calorimeter
- Particle flow objects

Jet energy scale calibration

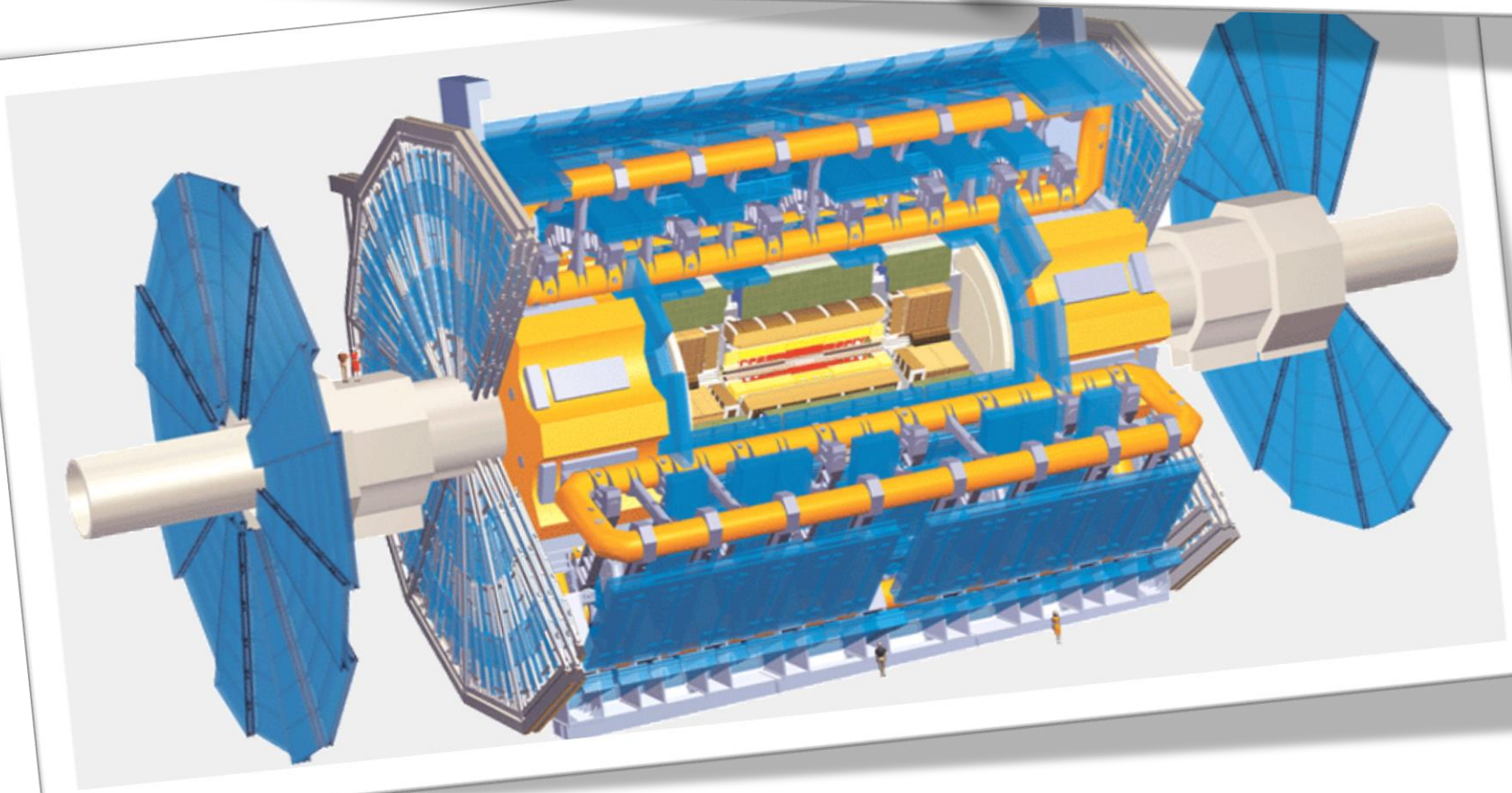
- Pile-up corrections
- MC-based calibration
- *In situ* calibration methods for jets in data

Combined calibration and systematic uncertainties

- Combining *in situ* calibrations
- Sources contributing to jet energy scale uncertainties
- Systematic uncertainties

Conclusions and outlook

The ATLAS Experiment



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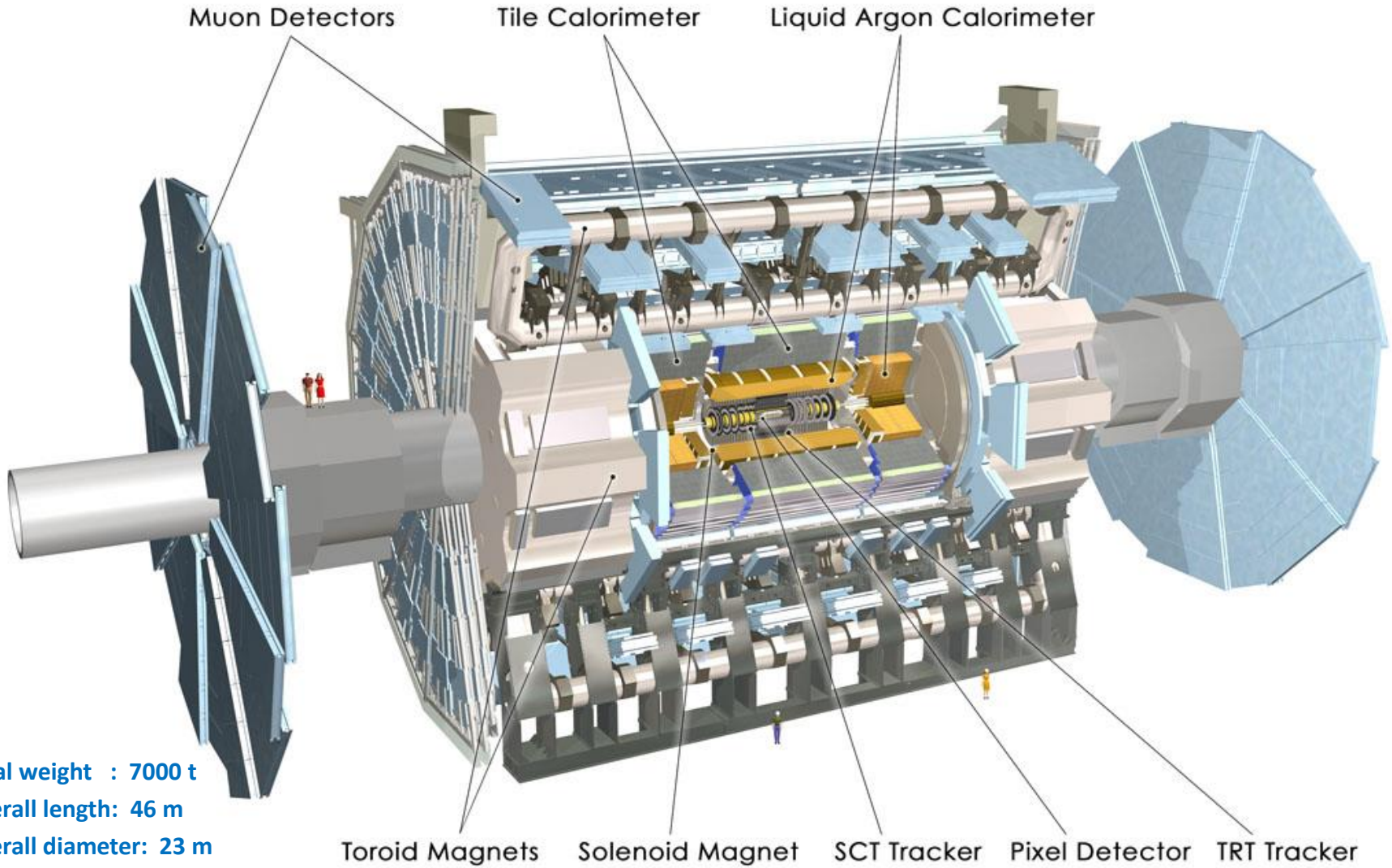
A multi-purpose detector system



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

Detectors for Jet Reconstruction & Calibration

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Calorimeters (Calo)

- Provides principal signals for jet kinematics and substructure measurement
  - Full coverage within $|\eta| < 4.9$ with depth $\gtrsim 10\ \lambda_{\text{int}}$
- Highly segmented for energy flow measurements
  - High granularity in $\Delta\eta \times \Delta\varphi = 0.025 \times \pi/128$ (central EM)
  - Up to seven depth layers (samplings)

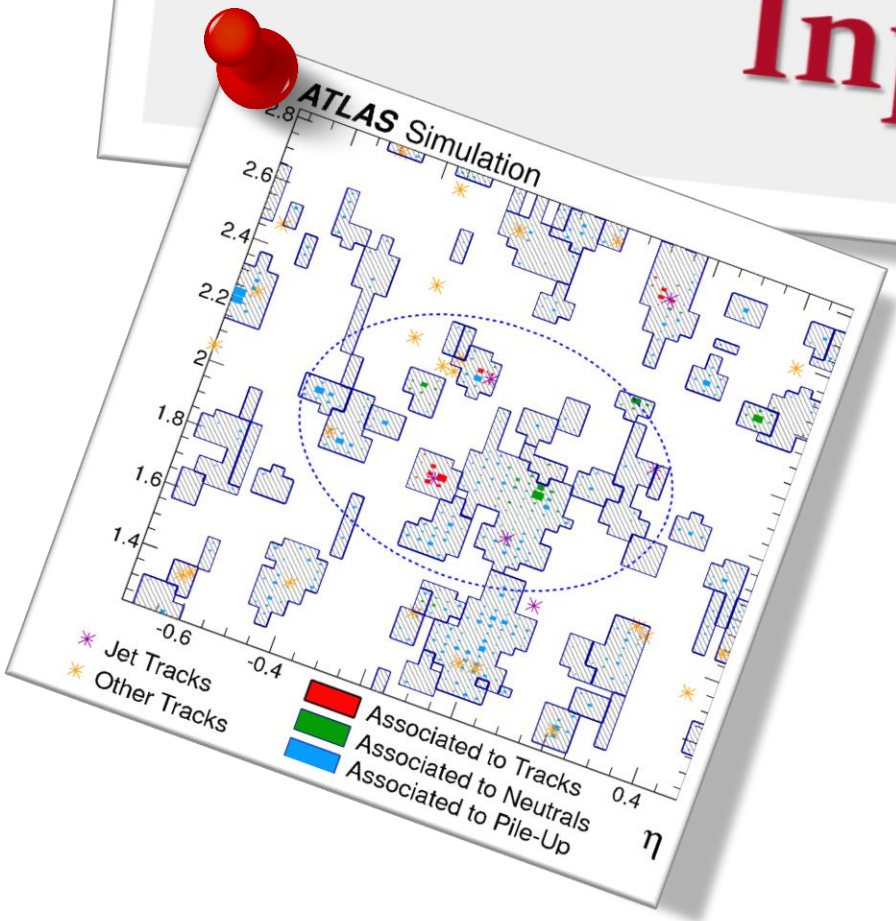
Inner detector (ID)

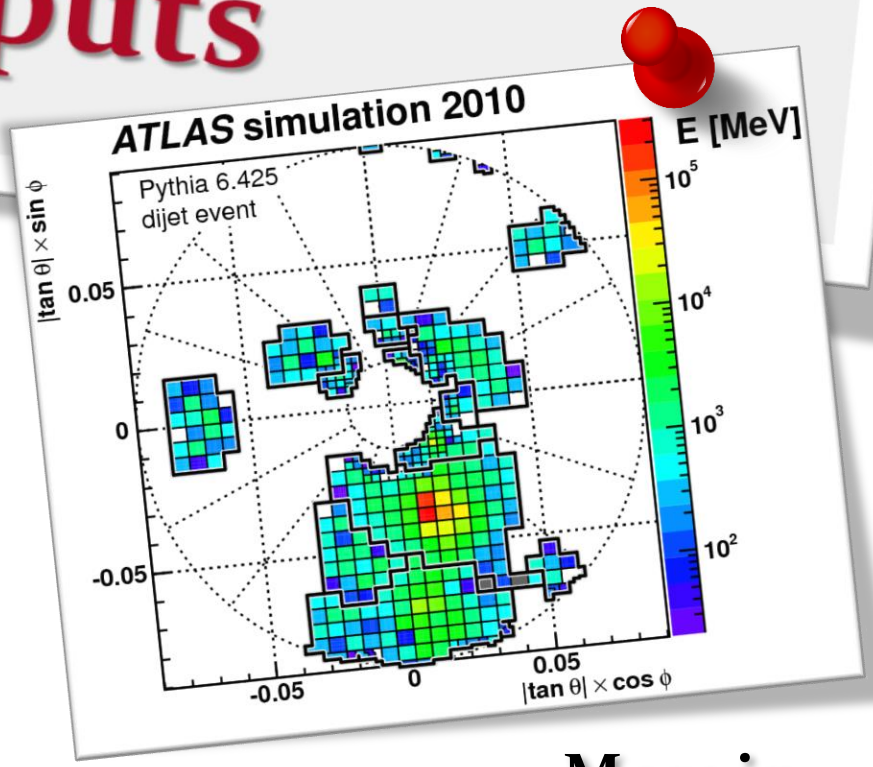
- Provides charged particle tracks and vertices
  - Coverage $|\eta| < 2.5$
- Jet energy calibration refinement
  - Provides vertex for jet origin correction/jet vertex association/jet vertex tagging (JVT)
  - Flavor/fragmentation sensitive response measures – mitigation of jet flavor response dependencies
- Particle flow
  - Replace charged response in calorimeter with kinematics from well-measured tracks

Muon spectrometer (MS)

- Provides track segments
  - Proxy for energy leakage behind a jet

Jet Reconstruction Inputs





More in Jennifer Roloff's talk!

Small R Jet Reconstruction in ATLAS

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Jet definition

- Anti-k_t jets† with $R = 0.4$ from FastJet‡
  - Clustering uses four-momentum recombination

Jet input signals

- Standard calorimeter jets
  - Clustered from topologically connected cell clusters (topo-cluster)
- Particle flow jets
  - Clustered from combined track/topo-cluster signals (PFlow objects)

Jet energy scale (JES) calibration

- MC-based
  - Pile-up suppression
  - Energy calibration and direction correction
- *In situ* calibration: relative
  - η-intercalibration using p_{T} balance in dijet events
- *In situ* calibration: absolute
  - Calibrate data to MC using p_{T} balance in γ/Z + jet(s), and multi-jet final states

†M. Cacciari, G.P. Salam, G. Soyez JHEP 0804 (2008) 063

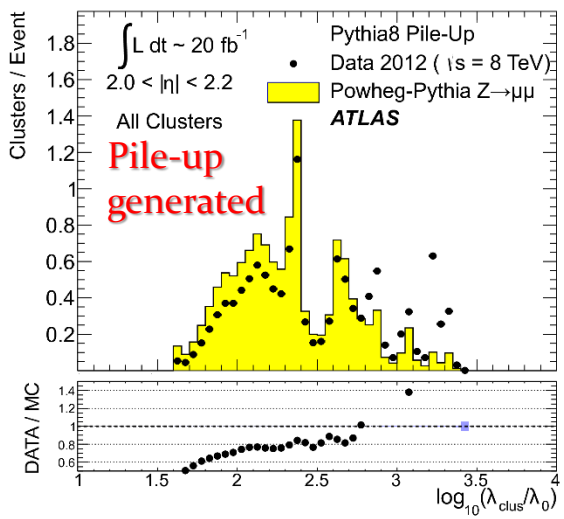
‡M. Cacciari, G.P. Salam, G. Soyez Eur.Phys.J. C72 (2012) 1896

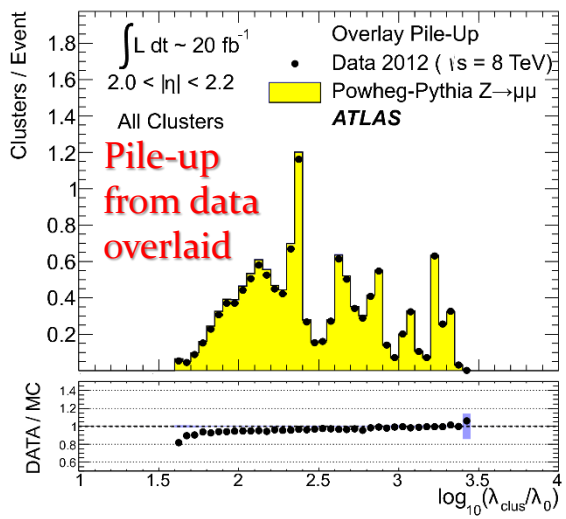
Jet Reconstruction Inputs: Topo-cluster

Topological clustering

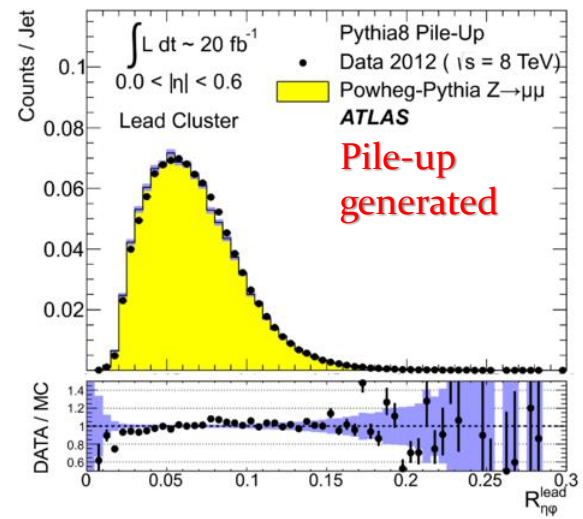
- Collects signals from individual or close-by particles into 3-dimensional *energy blobs*
  - Connect cells by following spatial signal significance patterns with seed and growth control
- Massless pseudo-particle representation
  - Recombines (weighted) cell energies to four-momentum $P_{\text{clus}} = (E_{\text{clus}}, \eta_{\text{clus}}, \varphi_{\text{clus}}, m_{\text{clus}} = 0)$
  - Cluster direction with respect to nominal collision vertex
- Cluster signal on basic (EM) or locally calibrated (LCW) scale
  - For jets in this talk $P_{\text{clus}} = P_{\text{clus}}^{\text{EM}} = \left(E_{\text{clus}}^{\text{EM}}, \eta_{\text{clus}}^{\text{EM}}, \varphi_{\text{clus}}^{\text{EM}}, 0\right)$
  - LCW uses cluster shapes – pile-up modeling issues a concern

arXiv:1603.02934 (to appear in EPJC)





Topo-cluster depth location measure $\log_{10}(\lambda_{\text{clus}}/1\text{ mm})$



Leading topo-cluster size $R_{\eta\varphi}^{\text{lead}}$

Jet Reconstruction Inputs: PFlow Objects

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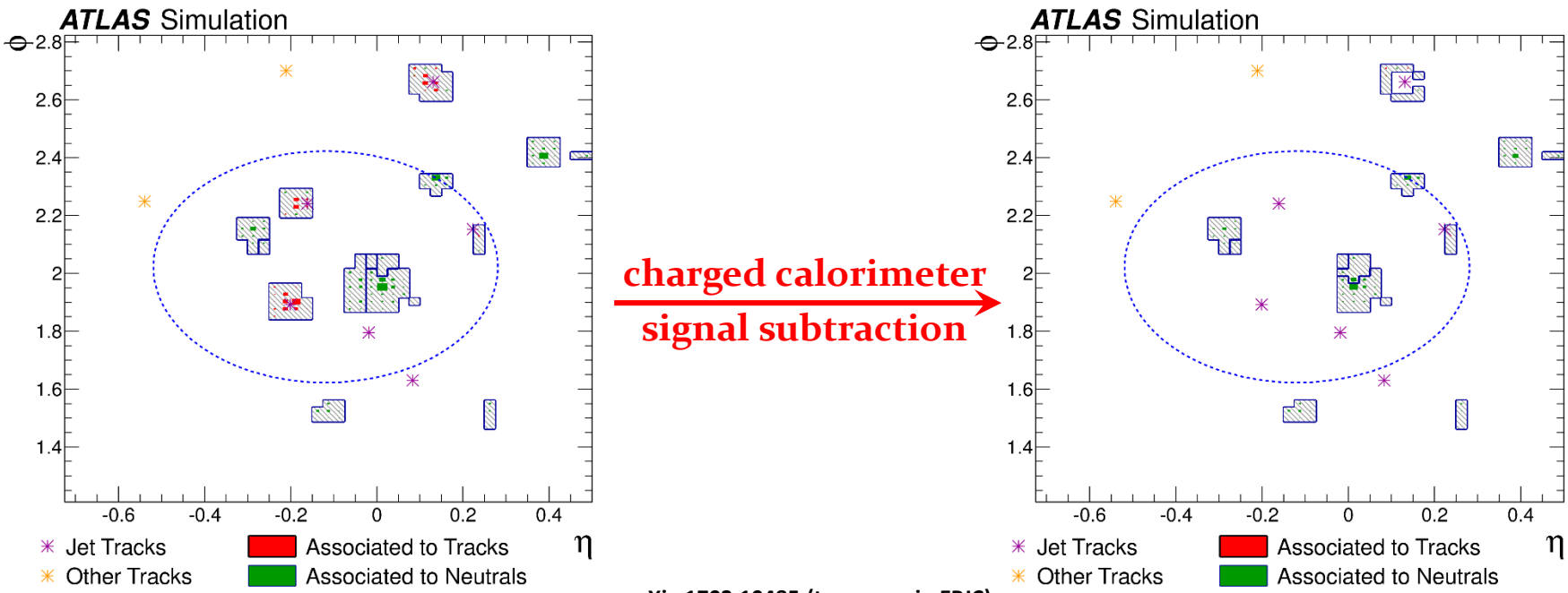
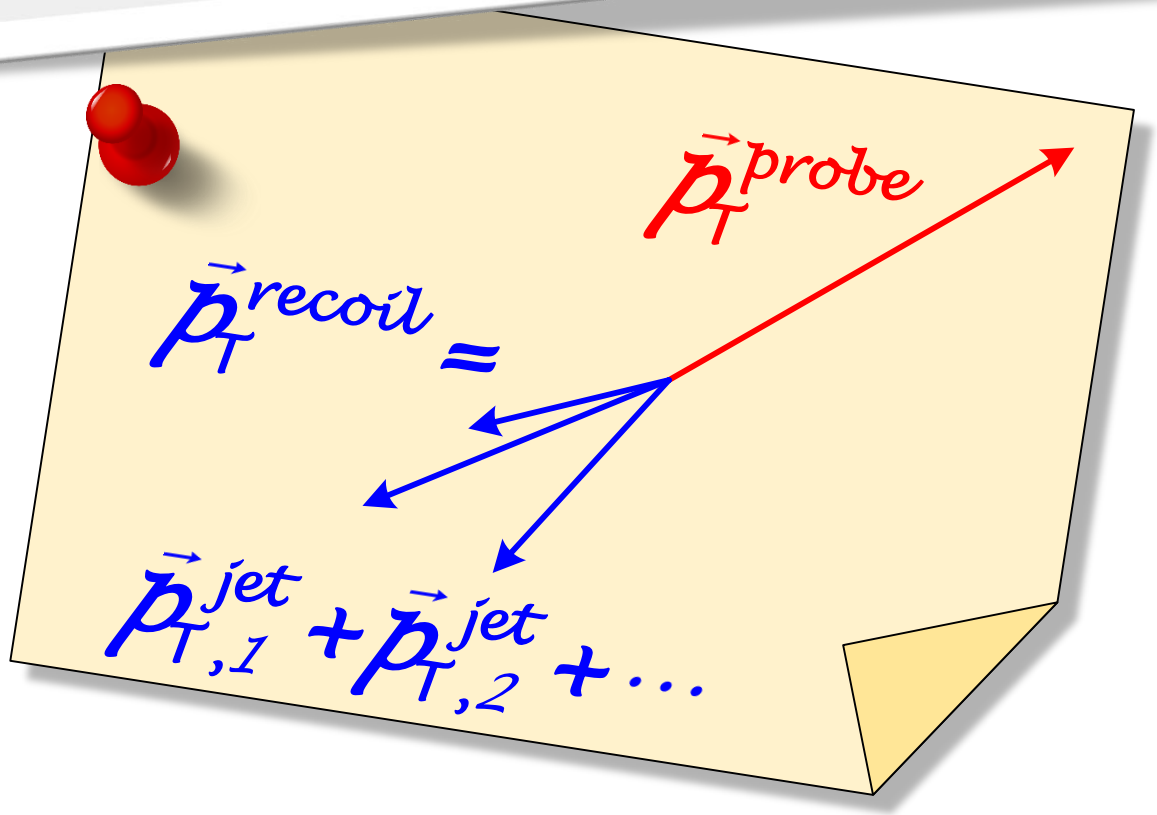
Particle flow objects

- Using reconstructed tracks for charged response
  - Match tracks with topo-clusters and remove calorimeter signal associated with track – fully (whole cluster) or partial (cells from cluster)
  - Yields charged (matched and unmatched tracks) and neutral (original or modified topo-clusters) PFlow objects
- ID Track selection
  - High quality tracks with $N_{\text{hits}}^{\text{SD}} \geq 9$, no missing pixels, $|\eta| < 2.5$, 500 MeV $< p_{\text{T}} <$ 40 GeV
  - Tracks not associated with electron or muon candidates
- Topo-clusters
  - EM scale (LCW possible)



arXiv:1703.10485 (to appear in EPJC)

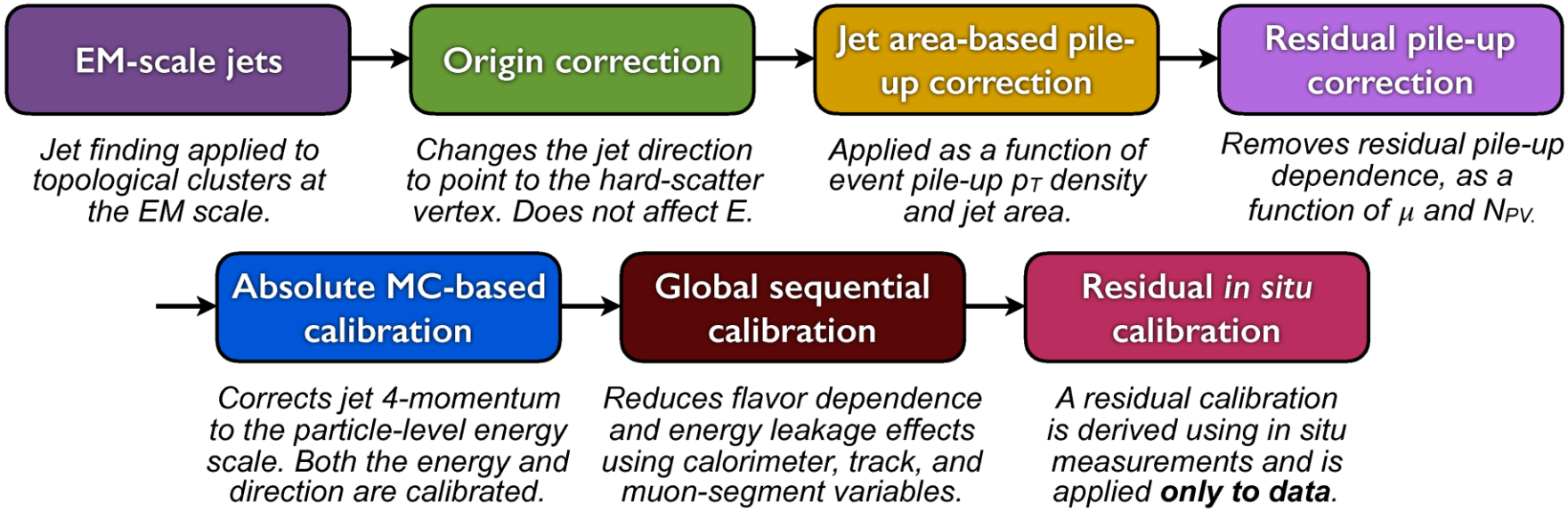
Jet Energy Calibration



Calibration Sequence

Calorimeter jets (Run 2) arXiv:1703.09665 (submitted to PRD)

Jets are reconstructed in $|\eta| < 4.5$ with $p_T > 7$ GeV and subject to Jet Vertex Tagging



PFlow jets (Run 1) arXiv:1703.10485 (to appear in EPJC)

Very similar sequence

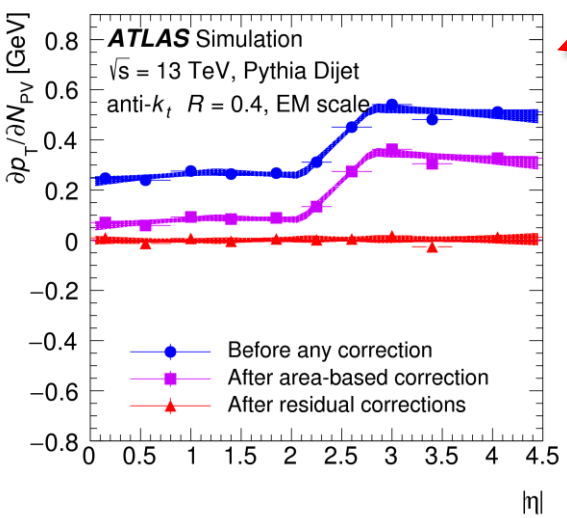
- Slight modifications in e.g. the pile-up suppression
- Origin correction modified – use charged PFlow from primary vertex and neutral PFlow with (η, φ) recalculated with respect to primary vertex

Pile-up Corrections

Jet-area-based pile-up subtraction

- Run 1 ($\sqrt{s}$ = 8 TeV, 50 ns bunch crossing) versus Run 2 ($\sqrt{s}$ = 13 TeV, 25 ns bunch crossing)
  - Pile-up noise increased > 10% – higher noise thresholds in topo-cluster formation
  - Modified topo-cluster algorithm does not allow seeds in pre-samplers – restricts jet formation from low-energy pile-up
- Similar strategies
  - Transverse momentum density ρ from k_t jets clustered from EM-scale topo-clusters within $|\eta| < 2$
    - Similar ρ values than for Run 1 – higher center-of-mass energy effect is offset by higher topo-cluster thresholds and better online suppression due to larger out-of-time pile-up
  - Residual corrections needed particularly in forward region

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}}^{\mathrm{reco}} - \rho \times A - \alpha \times (N_{\mathrm{PV}} - 1) - \beta \times \mu$$

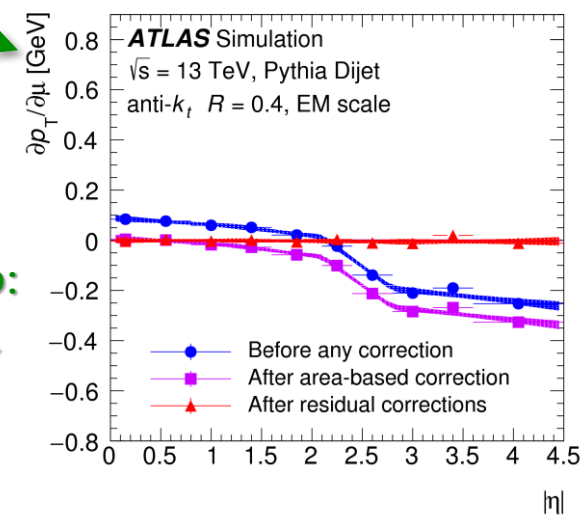


In-time pile-up:

N_{PV} averaged over μ

Out-of-time pile-up:

μ averaged over N_{PV}



arXiv:1703.09665 (submitted to PRD)

Absolute JES Calibration (MC-based)

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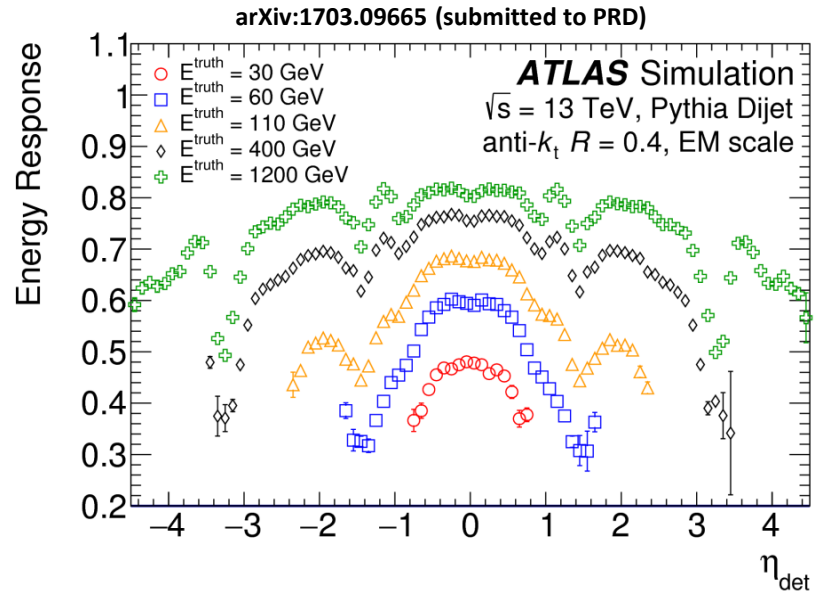
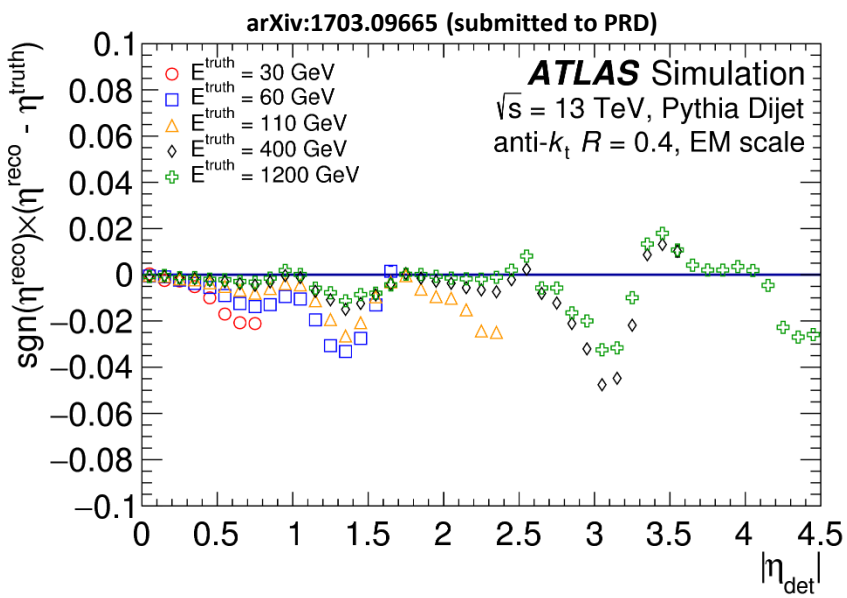
Calibrates reconstructed jet four-momentum to particle level

- Determines energy response R for matched isolated truth and calorimeter jets
  - $R = E_{\text{jet}}^{\text{reco}} / E_{\text{jet}}^{\text{truth}}$ as function of $(E_{\text{jet}}^{\text{truth}}, \eta_{\text{det}})$
- Corrects for η mis-reconstruction
  - Mainly observed in transition regions with different responses due to technology or geometry changes
  - $\Delta\eta = \eta^{\text{reco}} - \eta^{\text{truth}}$ as function of $(E_{\text{jet}}^{\text{truth}}, |\eta_{\text{det}}|)$
    - $\eta^{\text{reco}} \neq \eta_{\text{det}}$ due to origin correction
- Numerical inversion and calibration
  - $R(E_{\text{jet}}^{\text{truth}}, \eta_{\text{det}}) \longmapsto R^{-1}(E_{\text{jet}}^{\text{reco}}, \eta_{\text{det}})$
  - $\Delta\eta(E_{\text{jet}}^{\text{truth}}, |\eta_{\text{det}}|) \longmapsto \Delta\eta(E_{\text{jet}}^{\text{reco}}, |\eta_{\text{det}}|)$





In situ Jet Calibration (Data Only)

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Account for jet response differences in data and MC simulations

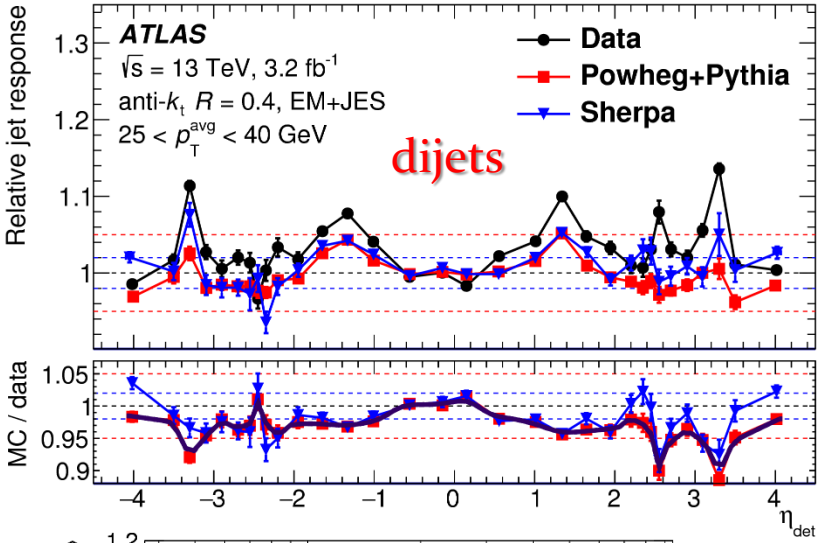
- Multiple sources for discrepancies
  - Imperfect detector geometry setup and response simulation including electromagnetic and hadronic interactions
  - Modeling of particle jets including hard scatter, underlying event, pile-up
  - Differences in jet formation
- Using p_T balance between well-measured reference objects and probed jet
  - $r_{in\ situ} = p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}}^{\mathrm{ref}}\,(p_{\mathrm{T}}^{\mathrm{ref}})$
- Define data-MC differences in terms of double ratios and derive calibrations for data only
  - $\mathcal{R}(p_{\mathrm{T}}^{\mathrm{ref}}) = \langle r_{in\ situ}^{\mathrm{data}}/r_{in\ situ}^{\mathrm{MC}}\rangle(p_{\mathrm{T}}^{\mathrm{ref}}) \longmapsto c = \mathcal{R}^{-1}(p_{\mathrm{T}}^{\mathrm{jet}})$ by numerical inversion

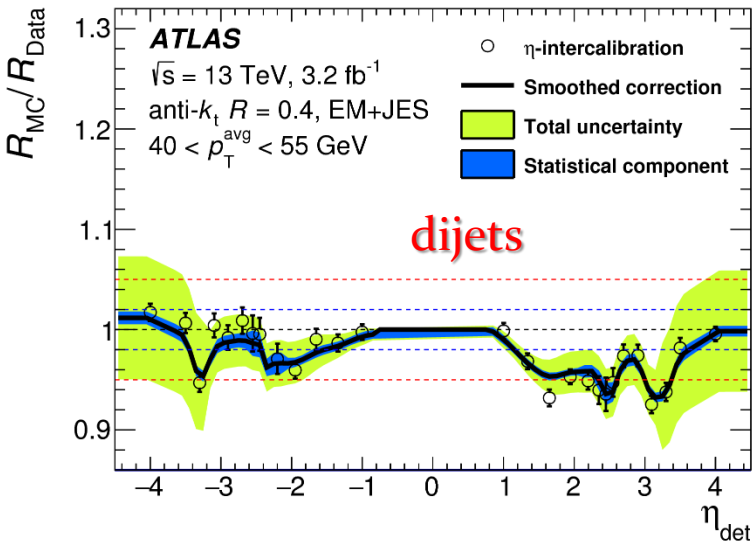
Final states for in-situ (data) calibration

- Relative η-intercalibration with all MC calibrations applied
  - Dijets with well measured central jet balancing probed (forward) jet
- Absolute response calibration combining various references for full phase space coverage
  - $Z + \mathrm{jet}\ p_{\mathrm{T}}$ balance for $20\ \mathrm{GeV} < p_{\mathrm{T}}^{\mathrm{jet}} \lesssim 500\ \mathrm{GeV}$ (no GSC due to MPF method)
  - $\gamma + \mathrm{jet}\ p_{\mathrm{T}}$ balance for $35\ \mathrm{GeV} \lesssim p_{\mathrm{T}}^{\mathrm{jet}} \lesssim 950\ \mathrm{GeV}$ (MC calibrations + η-intercalibration)
  - Multi-jet balance for $300\ \mathrm{GeV} \lesssim p_{\mathrm{T}}^{\mathrm{jet}} \lesssim 2\ \mathrm{TeV}$ (all calibrations applied)

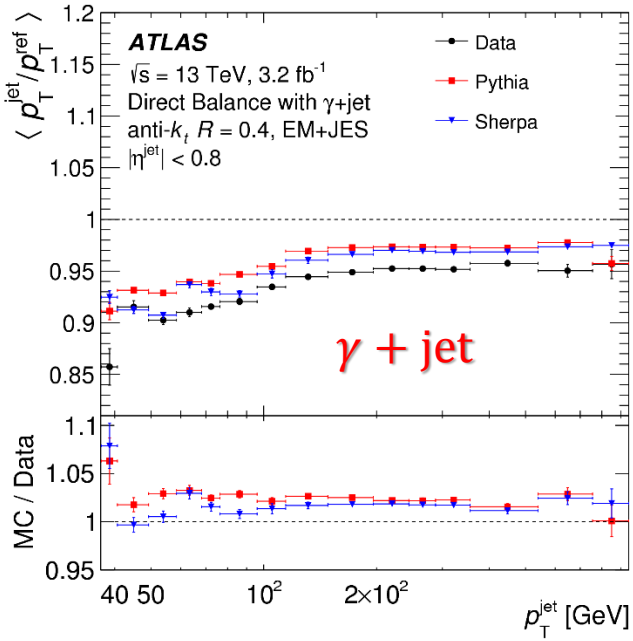
Relative & Absolute *In-situ*

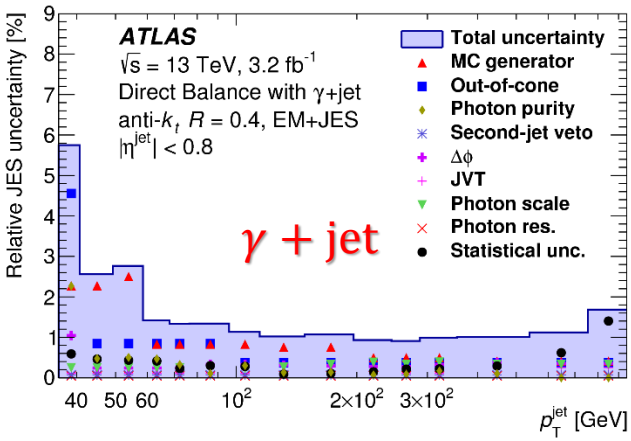
Relative – η-intercalibration in dijet final states





Absolute – well-measured reference objects (Z/γ)

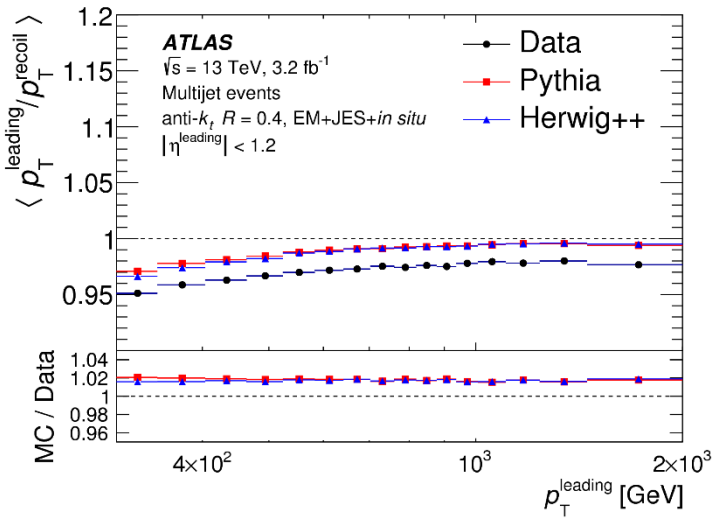


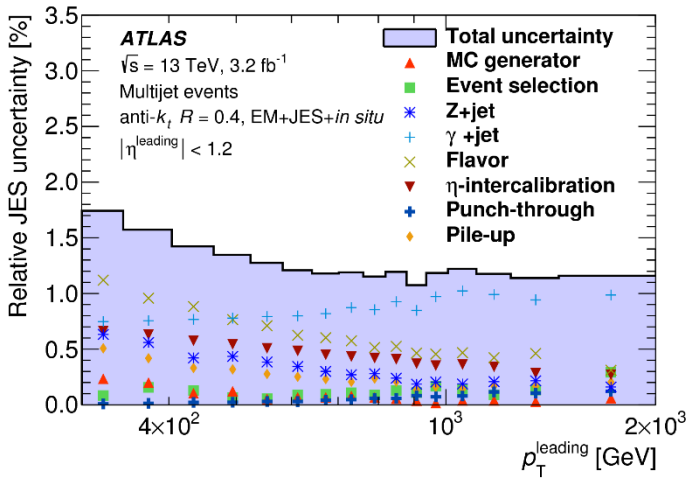


In situ Multijet Balance (MJB)

Calibration of high p_T jets in data

- Balance high p_T leading jet beyond reach of γ/Z + jet domain against multiple fully calibrated lower p_T subleading jets
  - Subleading jets form recoil system for leading jet
  - Fully calibrated subleading jets require $p_T^{\text{sublead}} < 950$ GeV – limits p_T of leading jet to about 2 TeV
- Requirements for clean back-to-back topology
  - Reject events with second jet carrying considerable fraction of recoil p_T (> 80%) to avoid dijet-like signatures
  - Recoil back to back – azimuthal distance α^{MJB} between leading jet and recoil $|\alpha^{\text{MJB}} - \pi| < 0.3$ rad
  - Leading jet isolated/recoil focused – azimuthal distance between leading and nearest recoil jet with $p_T > 0.25 \times p_T^{\text{lead}}$ at least 1 rad



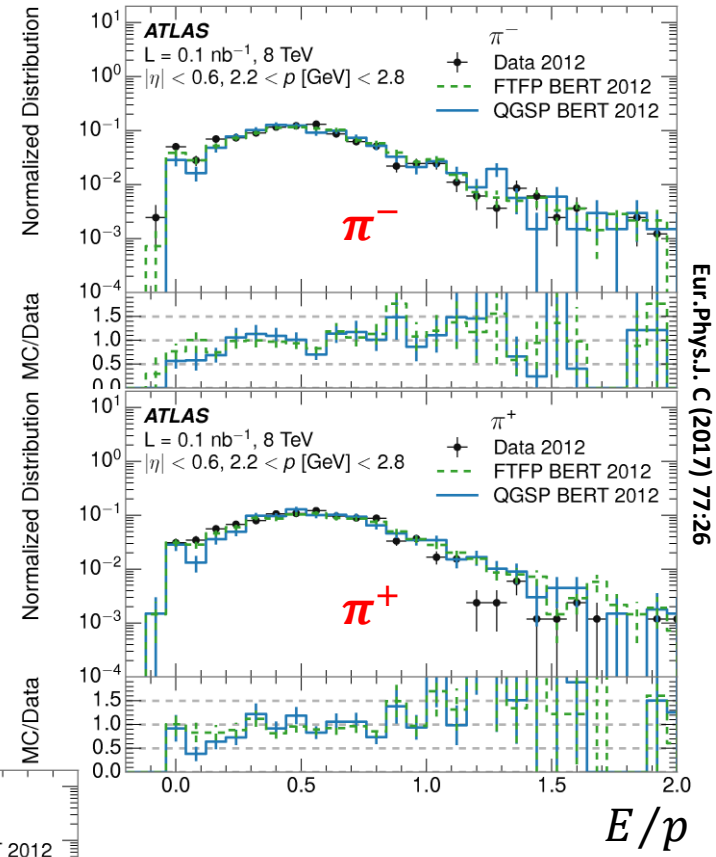


arXiv:1703.09665 (submitted to PRD)

Calibration of Very High-p_T Jets

Jet response de-composition

- Hadronic energy flow inside jet
  - Test beams provide $\pi^{\pm}$ response uncertainties for 10 GeV $\leq p \leq$ 350 GeV
  - In-situ E/p measurements provide response uncertainties for charged hadron response
- Track-CaloClusters
  - Improve structural measurements so far – improvements for overall kinematics expected
  - See Steven Schramm's poster & (related) **ATL-PHYS-PUB-2017-016** on high p_T tracks in jets



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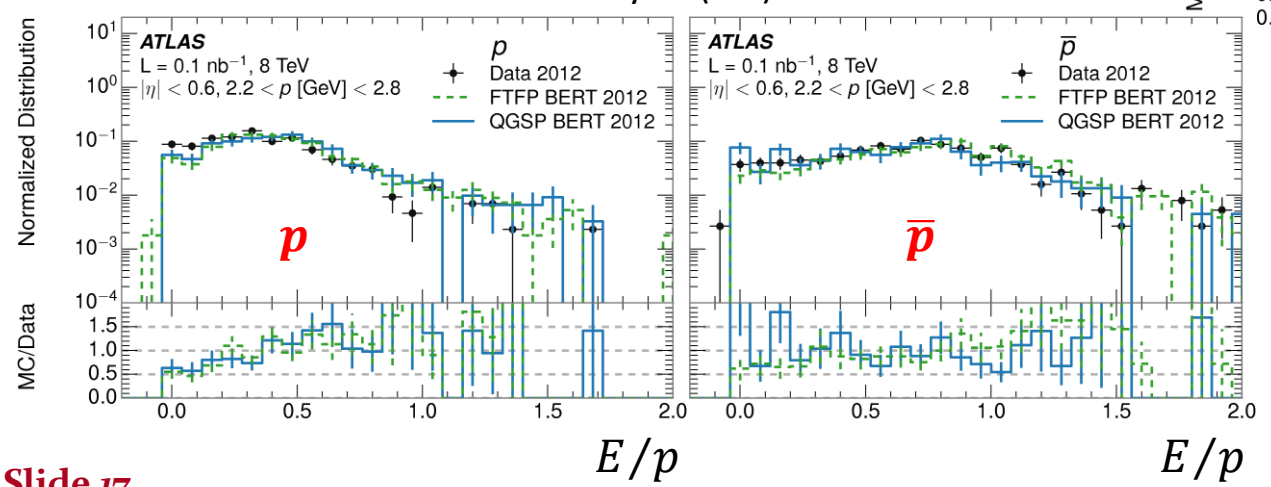


Reconstructed from:

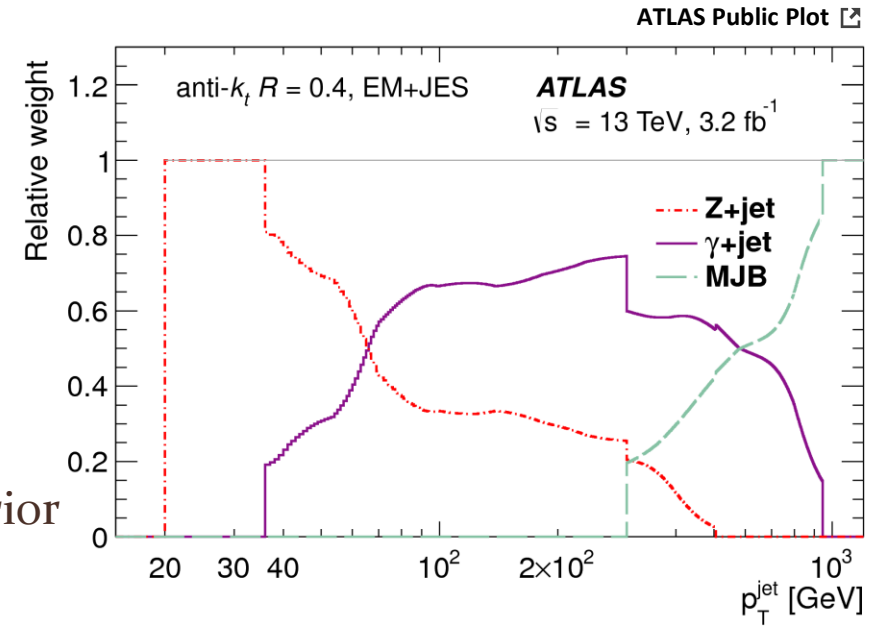
$$K_S^0 \to \pi^+\pi^-$$
$$\Lambda \to \pi^- p$$
$$\bar{\Lambda} \to \pi^+ \bar{p}$$

Combined Calibrations & Systematic Uncertainties

In situ Combinations

Kinematic overlap

- Absolute and orthogonal Z + jet, γ + jet, and MJB calibrations populate overlapping regions in jet p_T
  - Relative and exclusive η-inter-calibration applied to data jets prior to absolute calibration



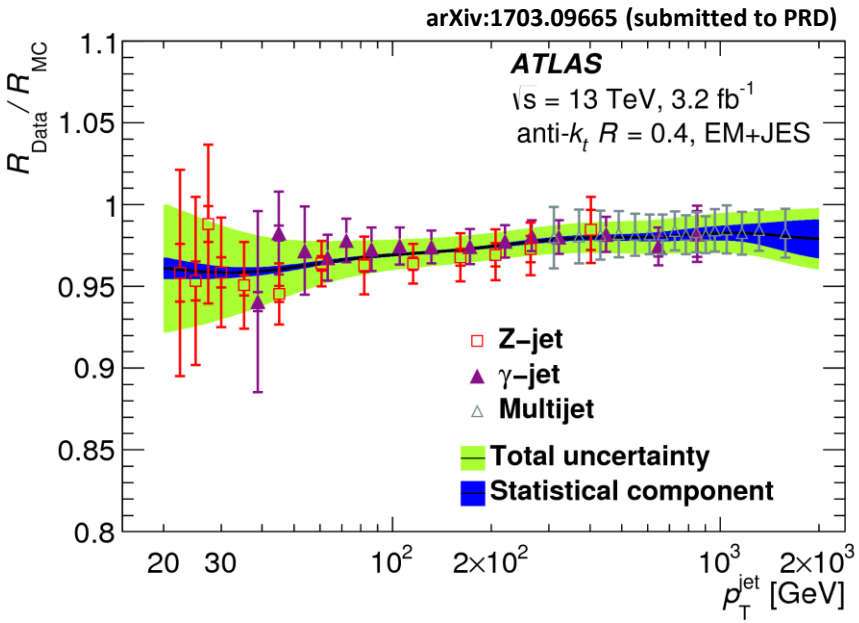
- Combination is characterized by p_T- dependent weight applied to calibrations
  - Requires re-casting calibrations from specific method with individually optimized p_T-binning into a common fine binning
  - Given method's weight is increased in regions of smaller binning and smaller uncertainty – combination favors method with greatest precision in each region
- Combined data-MC ratios are smoothed with sliding Gaussian kernel

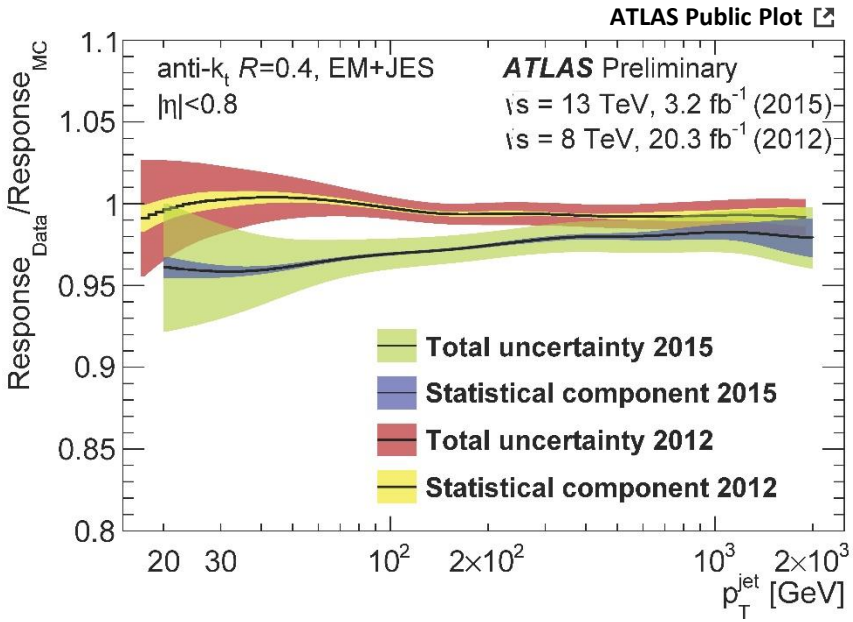
Full JES Calibration

Change of jet response in data and MC

Comparison to 2012 shows lower response in data in 2015

Attributed to change in hadronic shower models in Geant4 and slight down drift of ATLAS Tile Calorimeter PMTs

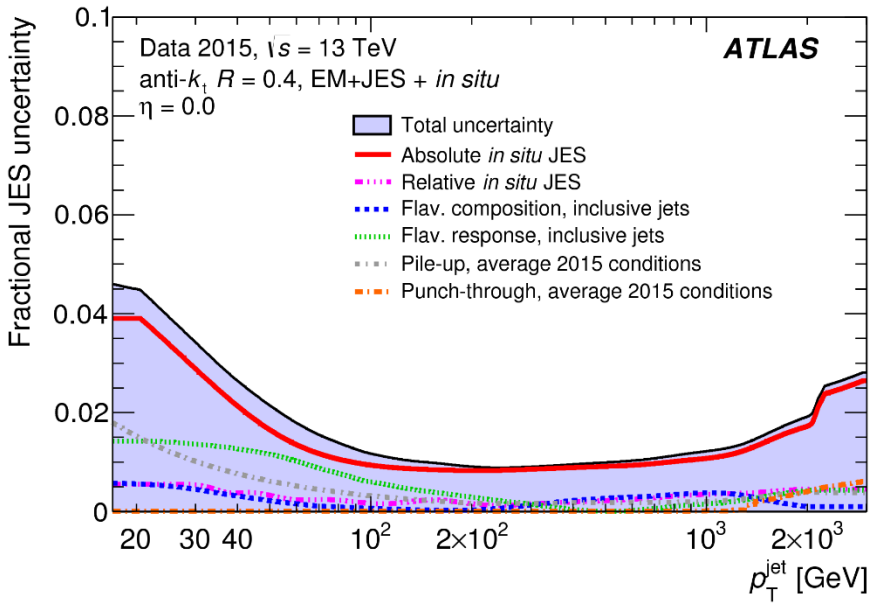


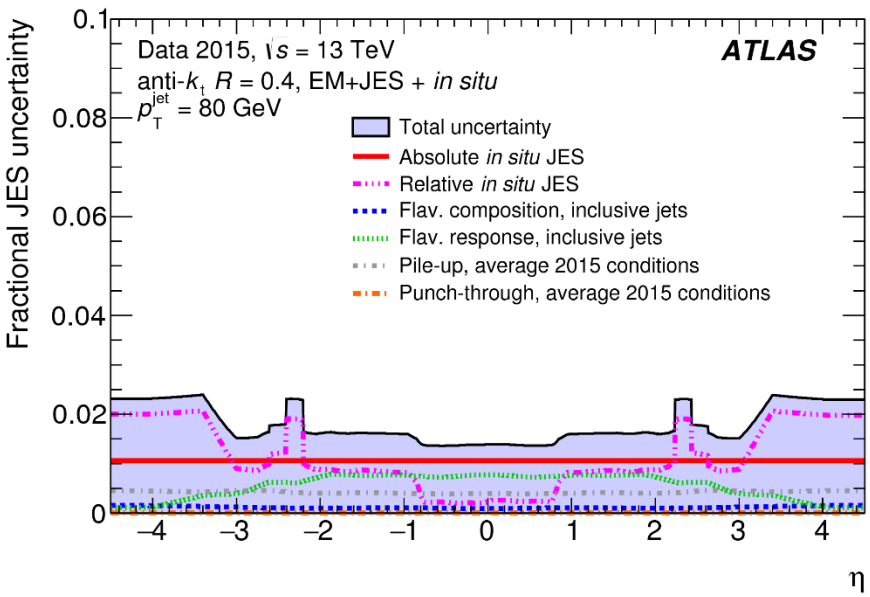


Effect of Geant4 shower simulation mitigated for 2016 Run 2

FTFP_BERT → FTFP_BERT_ATL reverts to QGSP_BERT-like response

Systematic Uncertainties





arXiv:1703.09665 (submitted to PRD)

80 sources involved in total uncertainty

Among those contributions from…

- Reference object uncertainties
- MC non-closure and modeling uncertainties
- Statistical uncertainties for some regions of phase space in some methods
- Method specific uncertainties
- Jet flavor composition and flavor response, *b*-jet response…

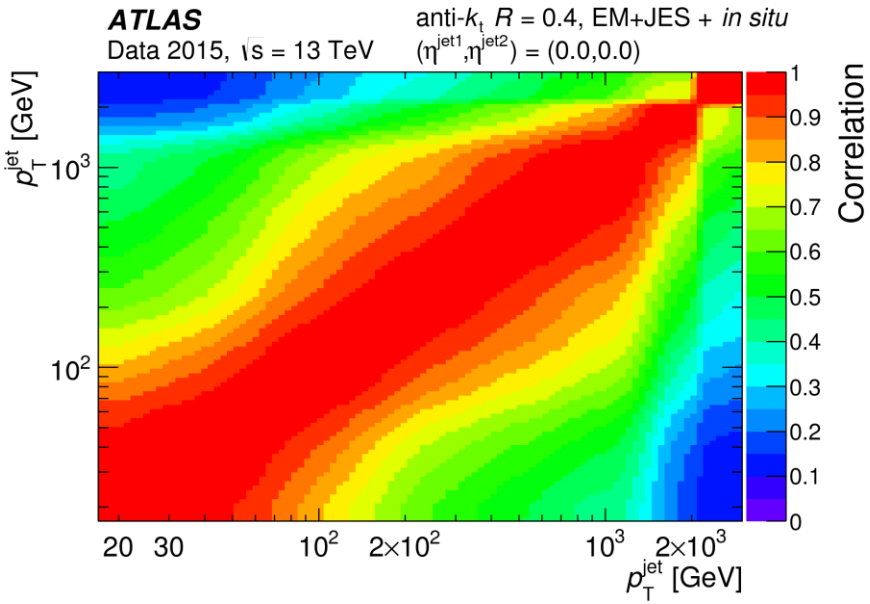
…lead to large jet-jet correlation matrices for p_T reconstruction

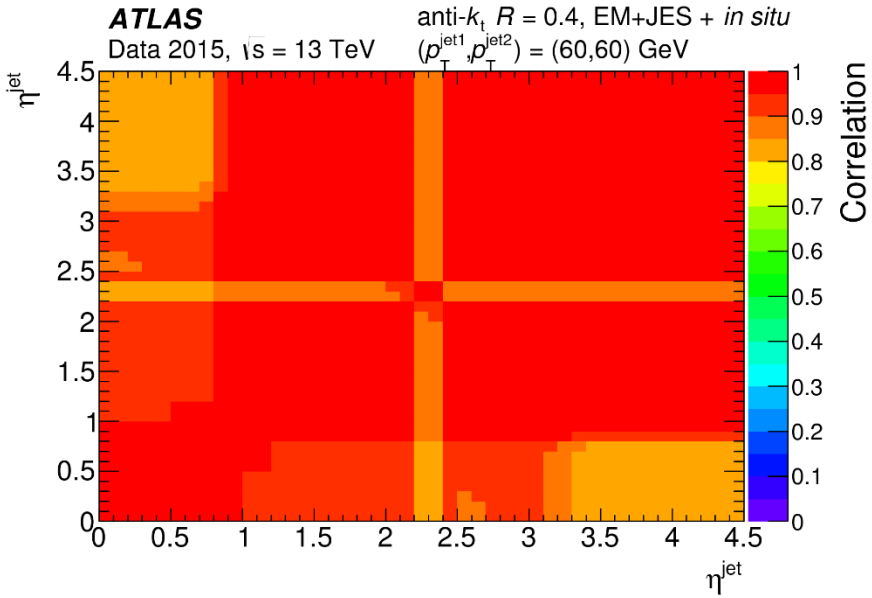
Full list

Correlations in Uncertainties

Full correlations with 80 uncertainties

arXiv:1703.09665 (submitted to PRD)





Large number of uncertainties and correlations hard to manage in analysis context

- Provide a reduced set of nuisance parameters preserving relevant correlations

Reduced set of nuisance parameters (NP)

Reduction of independent *in situ* NP

- Eigen-decomposition of 67 uncertainty sources retains five principal components and combines remaining 62 into one – 19 remaining NPs

Strong reduction in 2015

- Further reduction from 19 NPs to three components by grouping NPs in kinematic regions where they are most relevant – typically grouping in low, medium, high p_T regimes
- Grouping scheme optimized for analyses – chose one with least/no impact of correlation loss

Conclusions

Small *R* calorimeter jet calibration in ATLAS for LHC Run 2

- Following principal approaches developed in Run 1
  - MC-based calibrations followed by *in situ* data-only calibrations
- Adaptations and modifications as needed
  - Different pile-up scenarios
  - Extended phase space at higher $\sqrt{s}$
- Uncertainties at $\mathcal{O}(1\%)$ comparable to Run 1
  - Well controlled and precise measurement of overall jet kinematics
- Additional benefits expected from PFlow jets
  - Improved pile-up suppression for $p_{\mathrm{T}} \lesssim 100$ GeV
  - In commissioning for Run 2 analysis

Applications and extensions

- Jet mass calibration
  - Independent MC-base calibration of jet mass
  - See Joe Taenzer's talk this workshop
- Pre-clustered *fat jets* (large *R* jets)
  - Build fat jets from fully calibrated small *R* jets – constituents are well measured
  - See Jon Burr's talk and Matt LeBlanc's poster this workshop

References

arXiv:1603.02934 (to appear in EPJC)

Material shown in this talk

arXiv:1603.02934 (to appear in Eur.Phys.J. C)

ATLAS Coll., *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1* (2016)

arXiv:1703.10485 (to appear in Eur.Phys.J. C)

ATLAS Coll., *Jet reconstruction and performance using particle flow with the ATLAS detector* (2017)

arXiv:1703.09665 (submitted to PRD)

ATLAS Coll., *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at* $\sqrt{s} = 13\ TeV$ *with the ATLAS detector* (2017)

Eur.Phys.J. C (2017) 77:26 (Eur.Phys.J. C77 (2017) no.1, 26)

ATLAS Coll., *A measurement of the calorimeter response to single hadrons and determination of the jet energy scale uncertainty using LHC Run-1 pp-collision data with the ATLAS detector (2017)*

ATL-PHYS-PUB-2017-016 (embargo lifted soon)

ATLAS Coll., *Modelling of track reconstruction inside jets with the 2016* $\sqrt{s} = 13\ TeV$ *pp dataset (2017)*

Additional Material

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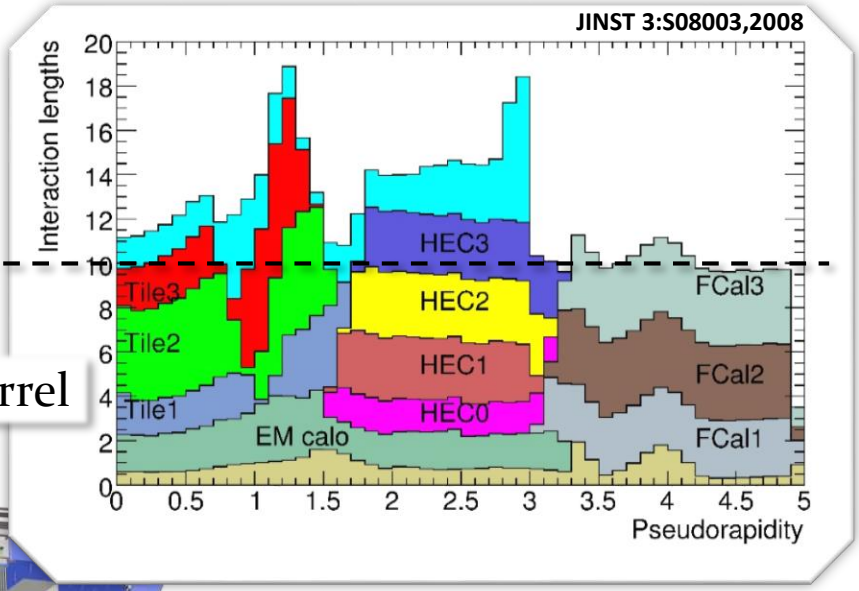
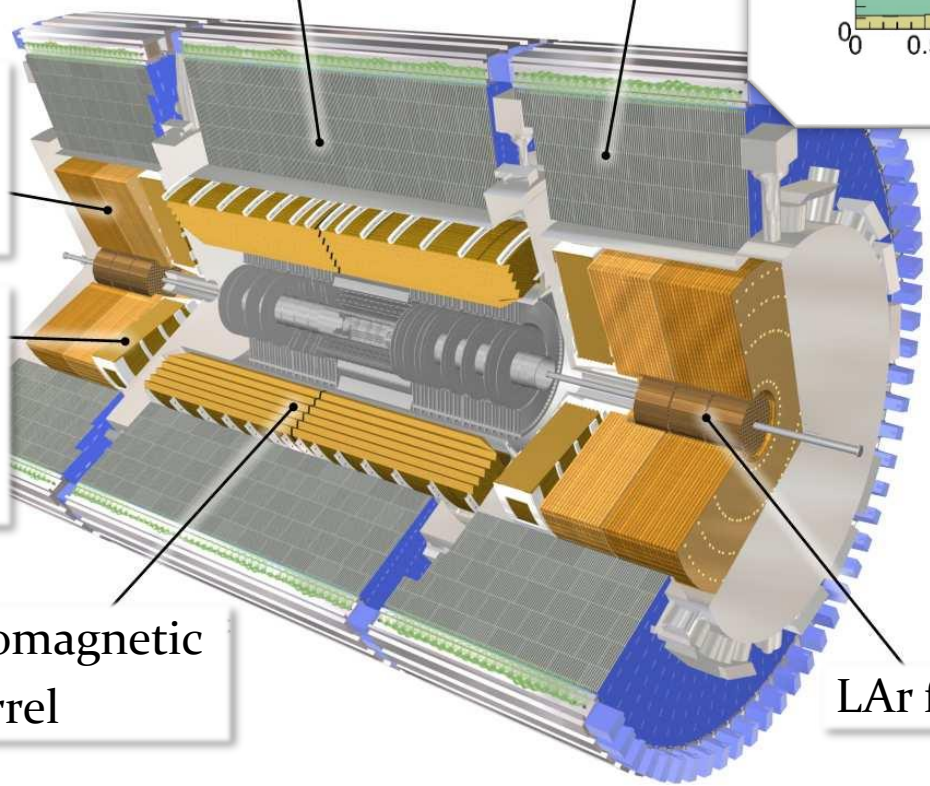
Calorimeter system

$|\eta| < 4.9$, depth $\gtrsim 10\ \lambda_{\text{int}}$





Topo-cluster Shapes in Pile-up

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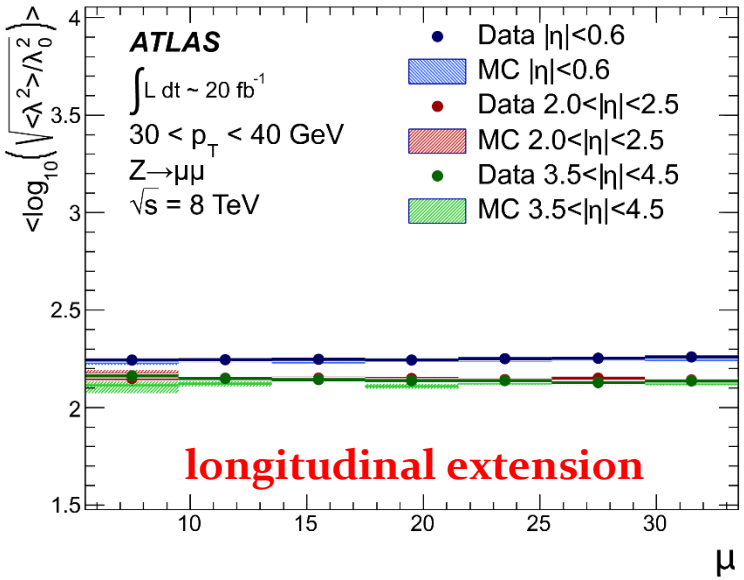
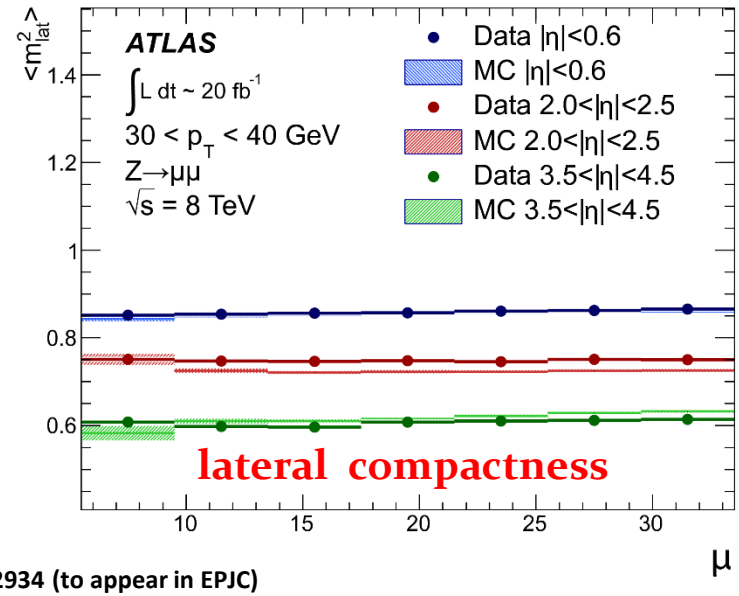
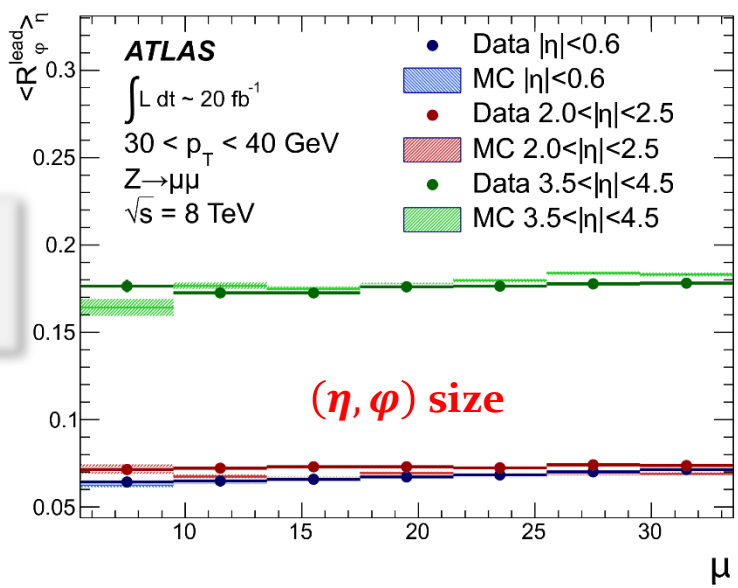
arXiv:1603.02934 (to appear in EPJC)



arXiv:1603.02934 (to appear in EPJC)



arXiv:1603.02934 (to appear in EPJC)

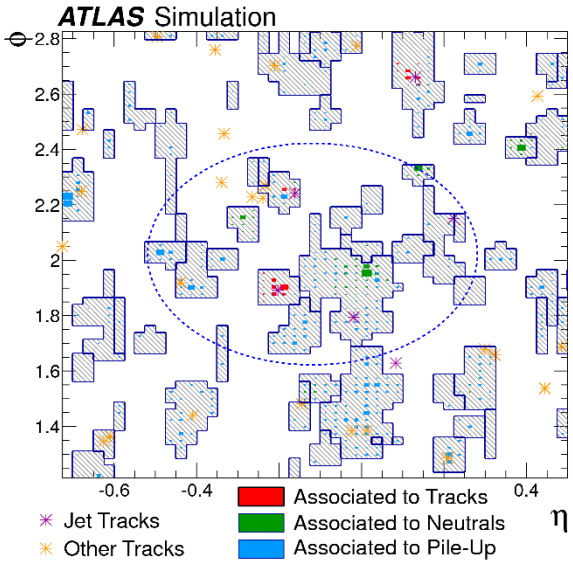


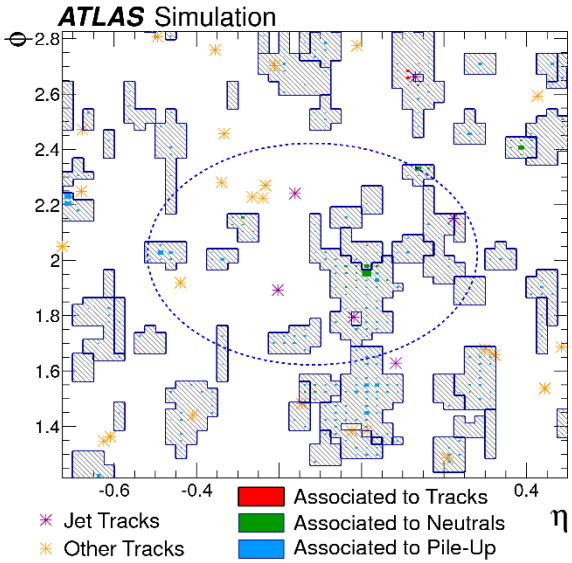
Leading topo-cluster in anti-k_t $R = 0.4$

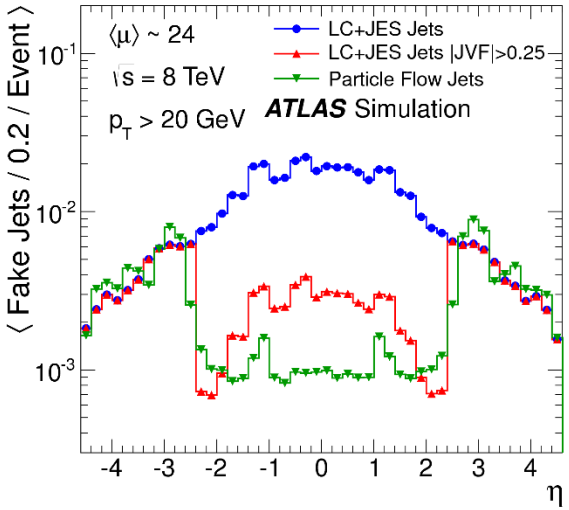
Pile-up Suppression PFlow Jets

Jet-area and track vertex constraint

Before … … after … … fake jet efficiencies



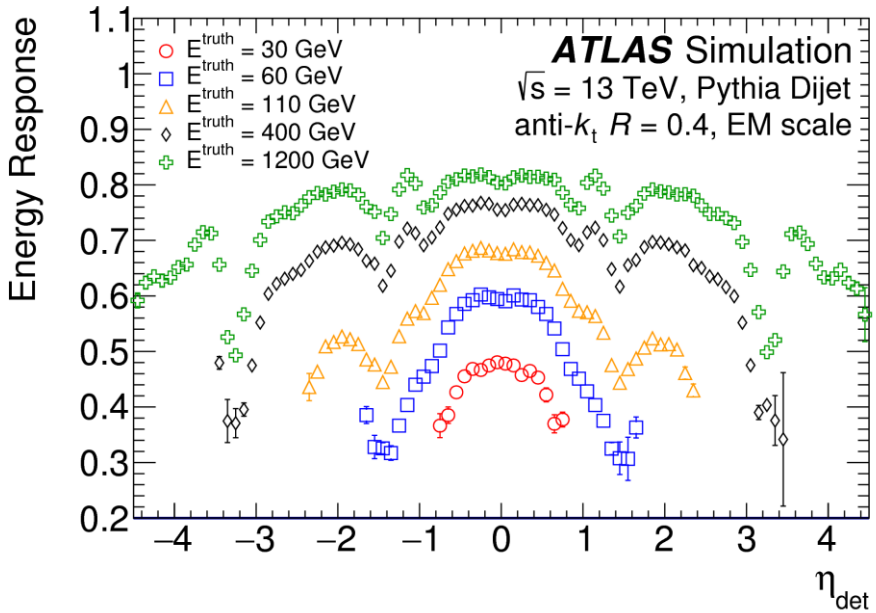




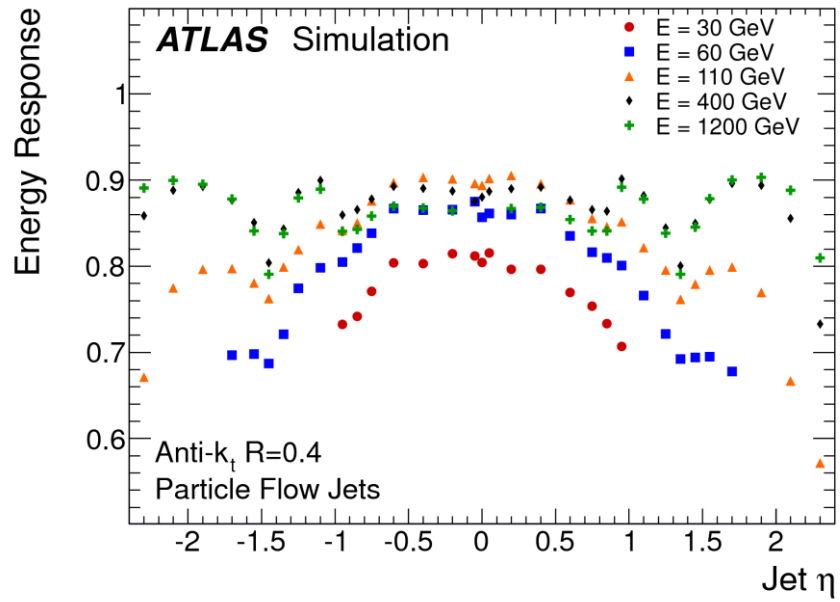
Response PFlow Jets

EM-scale jet response

Calorimeter jets …



… PFlow jets



Enhanced charged hadron response in PFlow jets

Calibration factors $\mathcal{O}(30\%)$ compared to about $\gtrsim 2$ for calorimeter EM-scale jets with $E^{\text{truth}} = 30$ GeV within tracking acceptance $|\eta| < 2.5$

In situ Calibrations Overview

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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 + jet (MPF)	$20\ \mathrm{GeV} < p_{\mathrm{T}}^{\mathrm{jet}} \lesssim 500\ \mathrm{GeV}$	n/a	n/a	MC calibrations + η-intercalibration
γ + jet (DB)	$35\ \mathrm{GeV} \lesssim p_{\mathrm{T}}^{\mathrm{jet}} \lesssim 950\ \mathrm{GeV}$	n/a	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

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Residual JES dependencies on features of individual jets

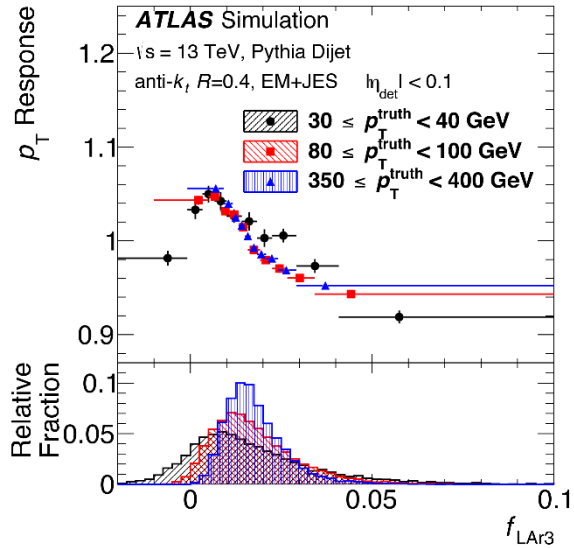
- Jet fragmentation/flavor affects response
  - Calorimeter response sensitive to particle composition and energy flow inside jet – e.g. harder particles in quark-initiated than in gluon-initiated jets
- JES response evaluated for tracking, muon spectrometer and calorimeter based observables
  - Tracks ghost-associated with jet
    - Average p_T-weighted transverse distance $\mathcal{W}_{trk}$ of tracks with $p_T > 1$ GeV in the (η, φ) plane as function of jet p_T (jets with $|\eta_{det}| < 2.5$)
    - Number of tracks n_{trk} associated with jet as function of jet p_T (jets with $|\eta_{det}| < 2.5$)
  - Muon track segments behind jet
    - Number of segments $n_{segments}$ in Muon Spectrometer as function of jet energy (punch-through measure, jets with $|\eta_{det}| < 2.7$)
  - Energy sharing in calorimeter
    - Energy fraction in first sampling of hadronic Tile calorimeter f_{Tile0} (jets with $|\eta_{det}| < 1.7$)
    - Energy fraction measured in third sampling of electromagnetic LAr calorimeter f_{LAr3} (jets with $|\eta_{det}| < 3.5$)
- Calibrations derived independently and applied sequentially
  - Address resolution improvements only – no change of average jet response
  - Derived independently – inclusion of possible correlations does not improve resolution

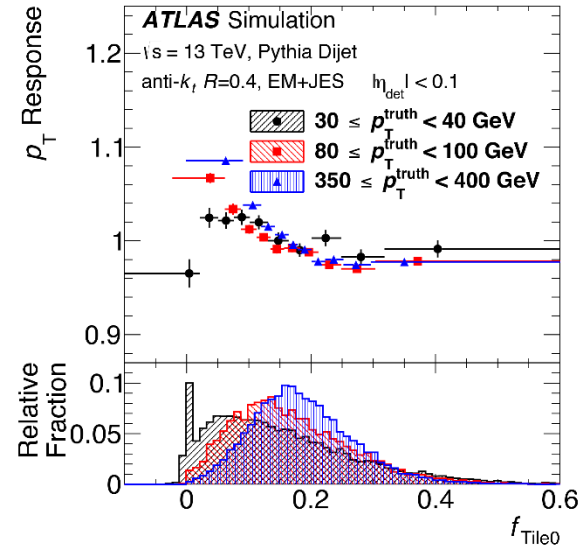
GSC (MC-based)

Application of GSC involves mapping (numerical inversion) of

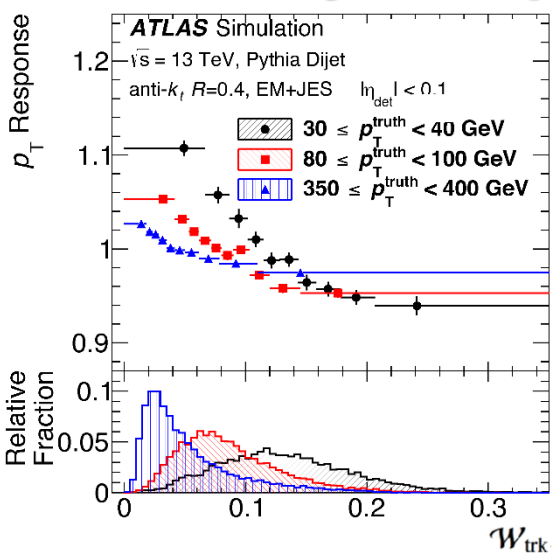
- $p_T^{reco}/p_T^{truth}\,(p_T^{truth}, \eta_{det}) \longmapsto (p_T^{reco}/p_T^{truth})^{-1}(p_T^{reco}, \eta_{det})$ for $\mathcal{W}_{trk}$, n_{trk}, f_{Tile0}, f_{LAr3}
- $E^{reco}/E^{truth}\,(E^{truth}, \eta_{det}) \longmapsto (E^{reco}/E^{truth})^{-1}(E^{reco}, \eta_{det})$ for $n_{segments}$

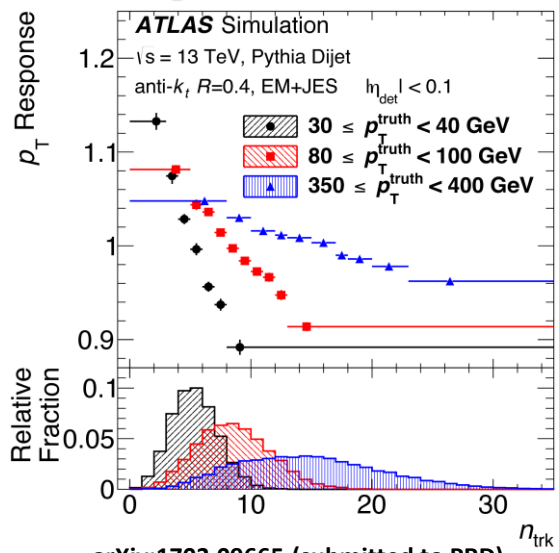
Longitudinal energy sharing (Calo)



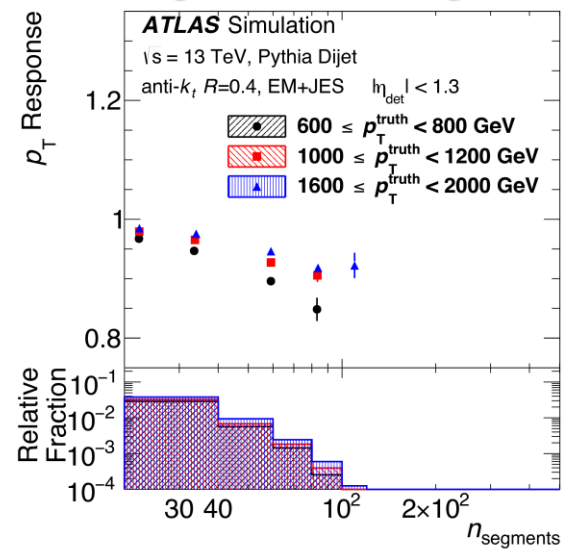


Charged radial spread & composition (ID)





Longitudinal leakage (MS)



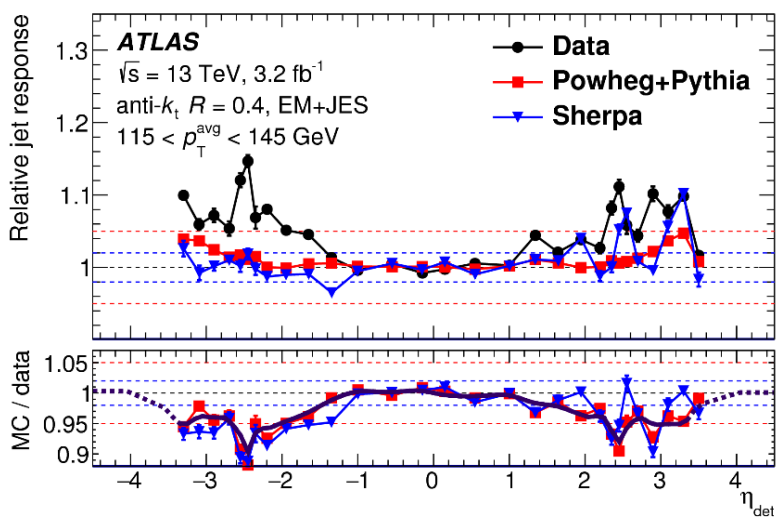
arXiv:1703.09665 (submitted to PRD)

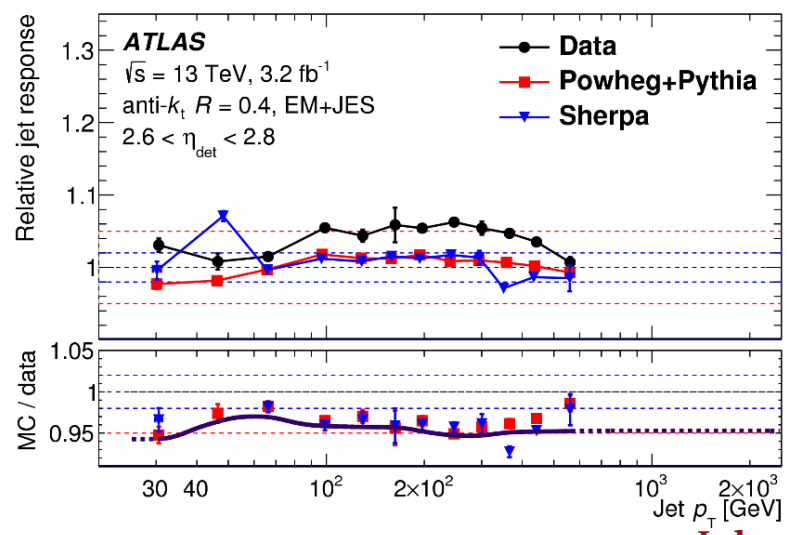
η-intercalibration

Calibrate relative data-MC response variations across η

- Measure for p_T balance
  - $\mathcal{A} = \left(p_T^{probe} - p_T^{ref}\right)/p_T^{avg}$ with p_T^{avg} average p_T of probe reference jet
  - Relative jet response with respect to reference region
  - $\left\langle p_T^{probe}/p_T^{ref}\right\rangle = (2 + \langle\mathcal{A}\rangle)/(2 - \langle\mathcal{A}\rangle)$
- Two different methods
  - Direct balance with central reference $|\eta| < 0.8$, probing $0.8 < |\eta| < 4.5$
  - Matrix method with various reference regions – increased statistical precision

arXiv:1703.09665 (submitted to PRD)

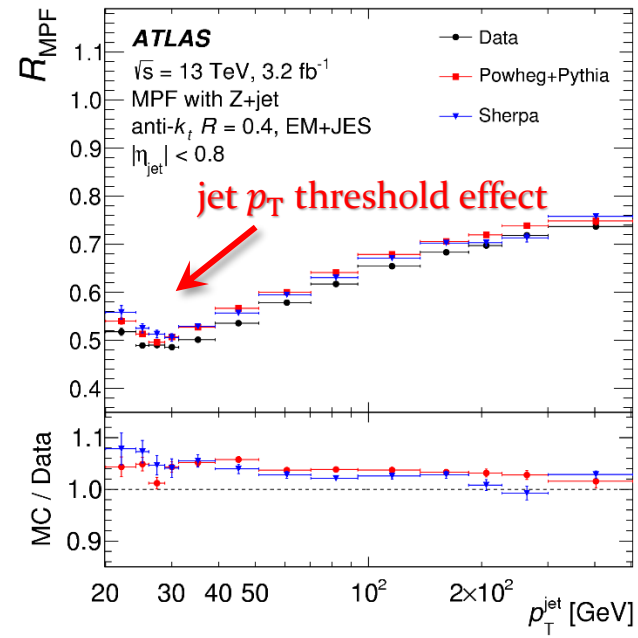


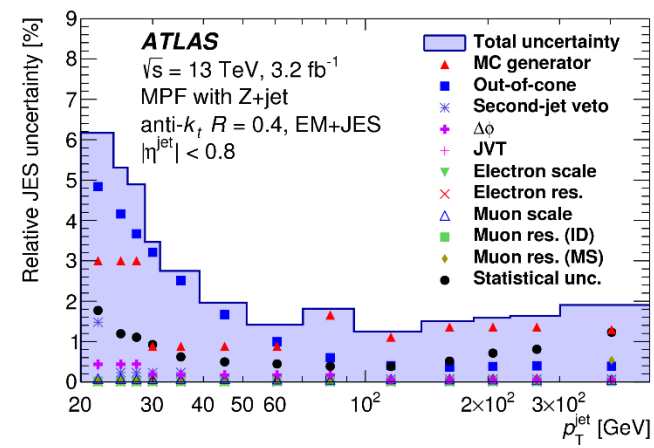


In situ Z + jet p_T Balance

Missing Projection Fraction Method (MPF)

- Utilizes full hadronic recoil response to Z boson p_T^Z
  - Uses jet only for event selection – e.g. back-to-back topology selection $\Delta\varphi(\text{jet}, Z) > 2.8$
  - Response $R_{\text{MPF}} = \left\langle 1 + \left(\vec{p}_T^{\,Z} \cdot \vec{E}_T^{\text{miss}}\right) / \left|\vec{p}_T^{\,Z}\right|^2 \right\rangle$ implies UE and pile-up cancellation due to azimuthal symmetries
  - Requires corrections for topology effects when applied to localized jets – out-of-cone corrections from direct p_T balance and corrections for missing GSC in full hadronic recoil
- Calibration is evaluated as function of p_T^{ref}
  - Numerical inversion applied to double ratio $\langle R_{\text{MPF}}^{\text{data}} / R_{\text{MPF}}^{\text{MC}} \rangle$
  - Applied to jets after η-intercalibration



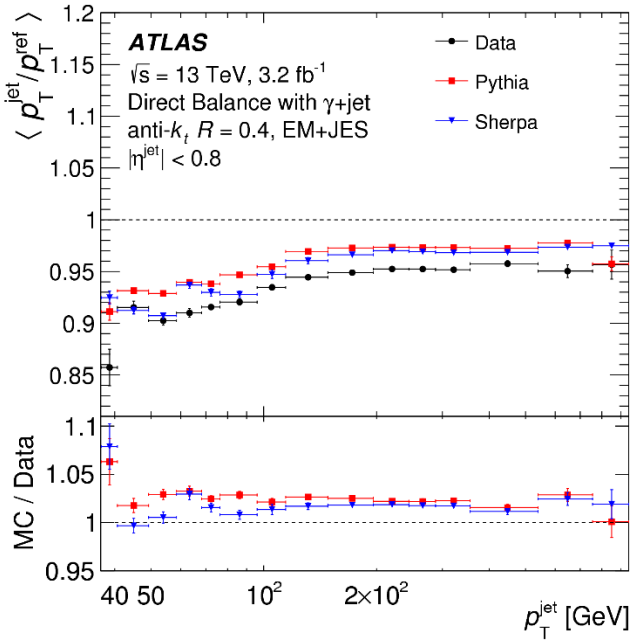


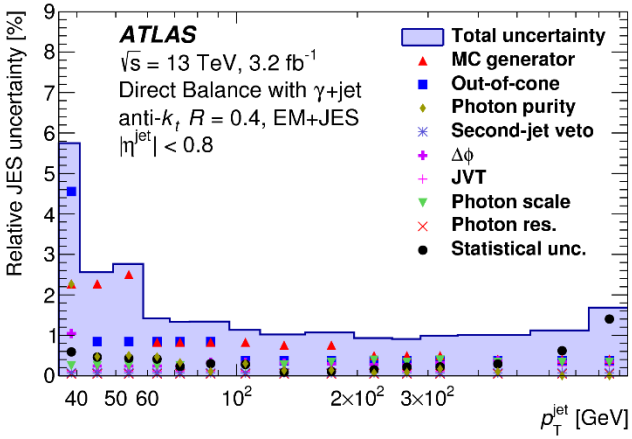
arXiv:1703.09665 (submitted to PRD)

In situ γ + jet p_T Balance

Direct p_T balance (DB)

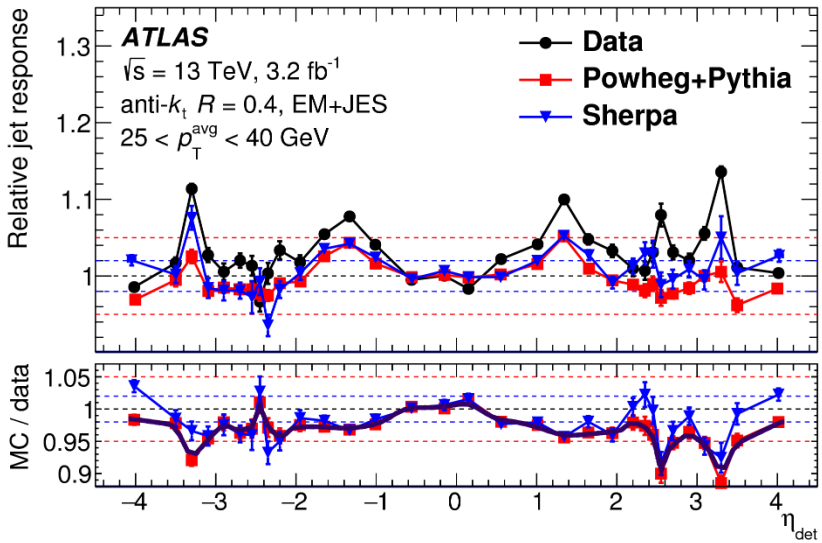
- Uses $r_{DB} = p_T^{probe}/p_T^{ref}$ in γ + jet events
  - Affected by parton radiation – veto against events with second jet with significant $p_T > \max(15\text{ GeV}, 0.1 \times p_T^{ref})$
  - Enforce back-to-back signature with $\Delta\varphi(\text{jet},\gamma) > 2.8$
  - Requires out-of-cone corrections for energy losses due to small R jet finder
  - Probe jets calibrated up to η-intercalibration
- Ignore component perpendicular to jet axis
  - Reference is $p_T^{ref} = p_T^{\gamma} \times \cos(\Delta\varphi)$
- Calibration is evaluated as function of p_T^{ref}
  - Numerical inversion applied to double ratio $\langle r_{DB}^{data}/r_{DB}^{MC}\rangle$
  - Applied to jets after η-intercalibration

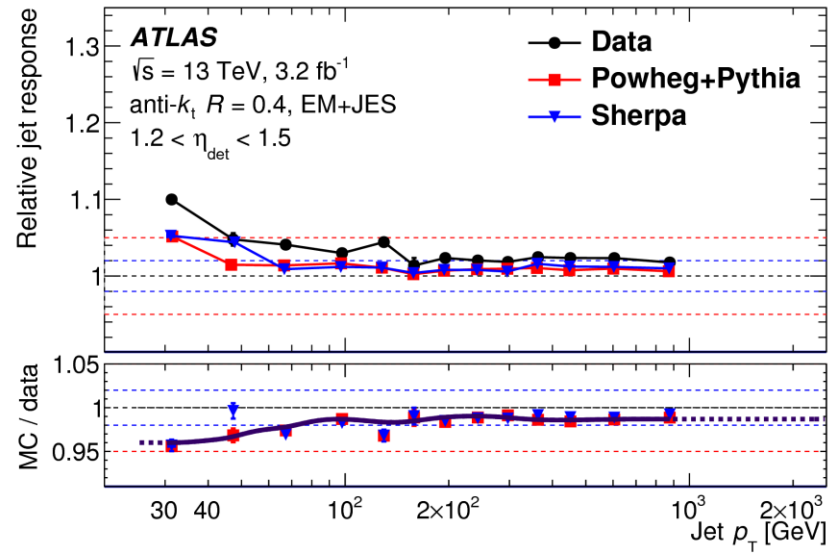


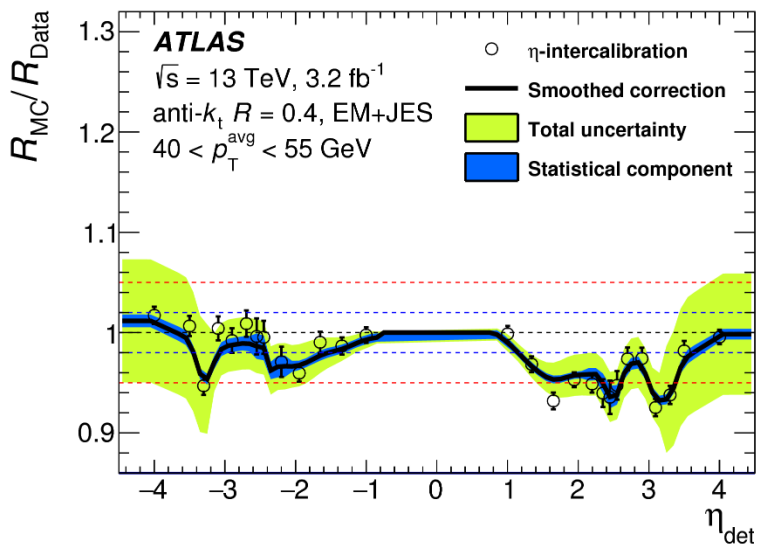


arXiv:1703.09665 (submitted to PRD)

η-intercalibration







Loss of Uncertainty Correlations

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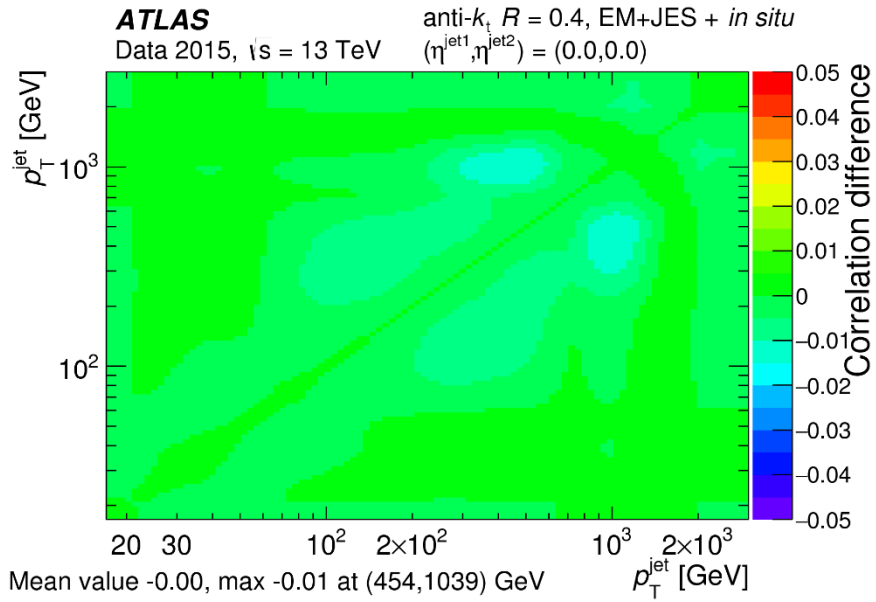
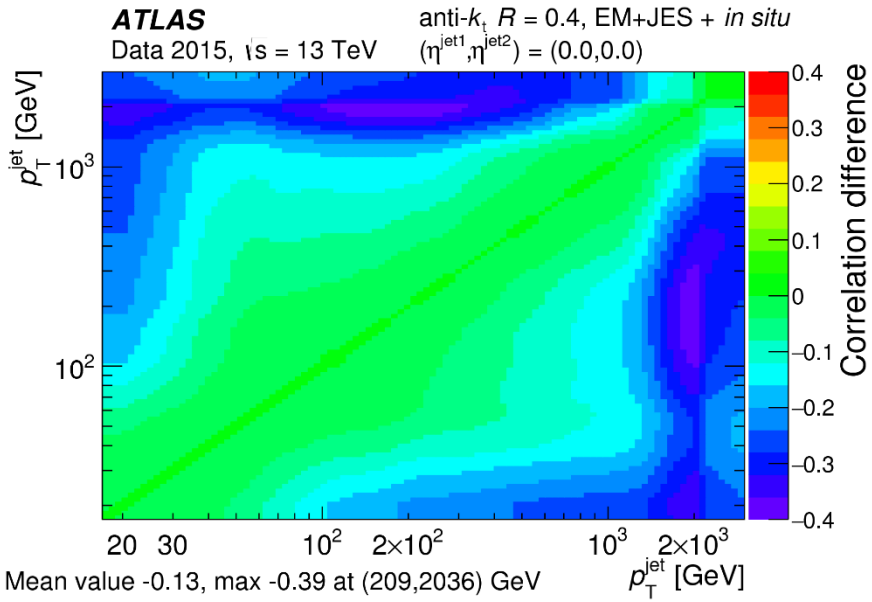
Reduced set of (19) NPs …



… strongly reduced set of NPs