Uncertainties and challenges in jet reconstruction in ATLAS

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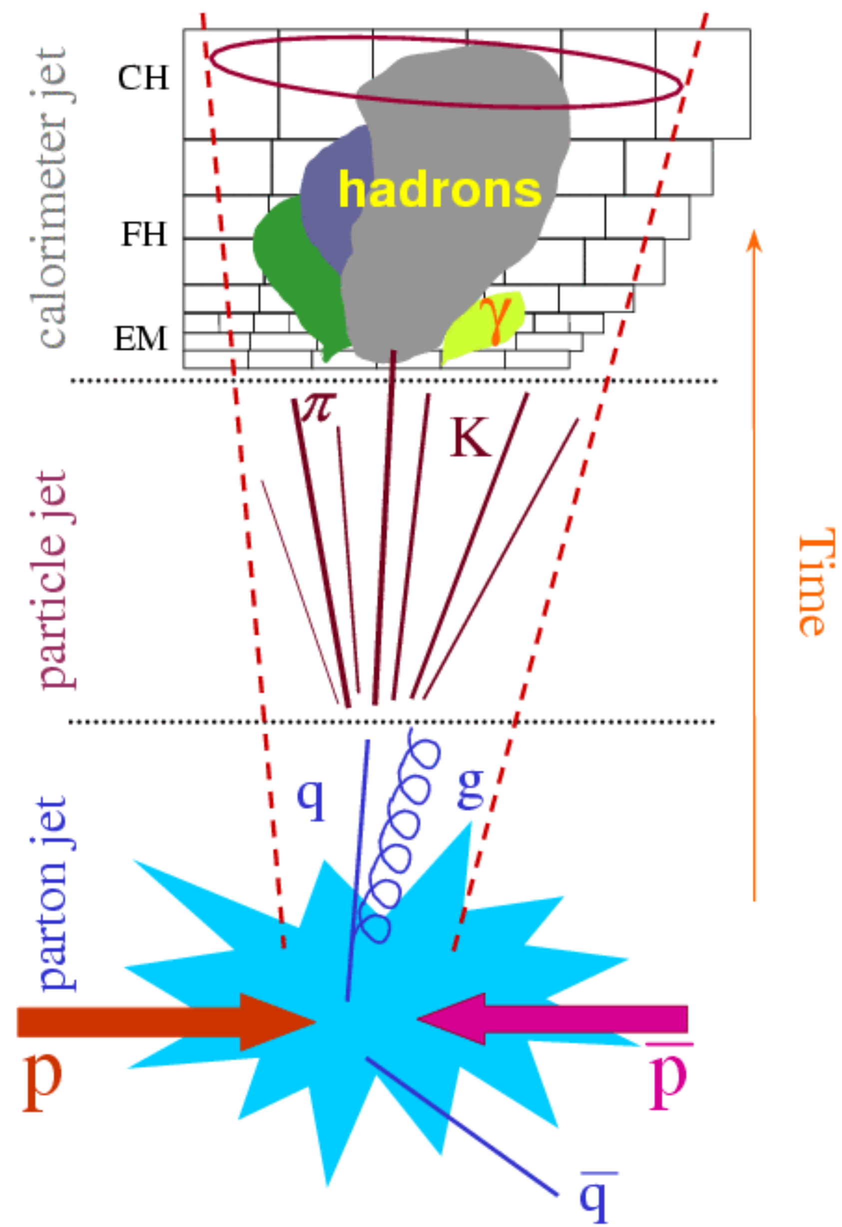
Introduction

- Jets are a useful tool to represent the hadronic energy present in a given proton-proton collision event at the LHC.
- Inelastic proton-proton collisions result in production of quarks and gluons which undergo parton showering and hadronization, as they cannot exist in isolation due to color confinement.
  - Observed as collimated streams of particles depositing energy in the calorimeters, reconstructed as jets.
- Jets are important to almost all analyses at ATLAS
  - Reconstructed and used in order to enhance signal selection in an analysis either by vetoing them or by requiring their presence
- Given their importance, it is essential to calibrate the jet energies to the correct scale and to properly take into account the uncertainties on these calibration procedures.
- In this talk, the different jet reconstruction and calibration procedures and the performance of these methods will be discussed.



Which jet algorithm to use?

- Recommendations based on experience from CDF and D0 experiments:
  - Most commonly used algorithm for reconstructing jets on ATLAS is the anti-kt algorithm.

- Theoretical considerations:
  - Infrared and collinear safety.
  - Invariance under boost.

- Experimental considerations:
  - Independent of detector technology.
  - Control over pile-up effects with increasing luminosity.
  - Should capture well, the decay of the initiating particle.
  - Should be easy to calibrate.
  - Not very computing intensive.

Types of jets used in ATLAS

- Jets on ATLAS can be reconstructed from various inputs:
  - Standard calorimeter jets built from topoclusters.
  - Track jets built using the tracking information.
  - pFlow and TrackCaloCluster jets are examples of jets that use both tracking and calorimeter information.
  - Particle-level jets: Reference for the simulation-based jet calibration.

- Most commonly used jets are reconstructed using the anti-kt algorithm, radius parameters can be:
  - R=0.4: Used in almost all analyses on ATLAS using quark/gluon-initiated jets.
  - R=1.0: Used mainly to capture decay products of hadronically decaying massive particles like a top quark or W/Z/H boson (boosted topologies).
  - Variable-radius (variable-R) jets are also increasingly being used at high pT regimes where it is shown that the hadronic decay products are contained in a smaller area than R=1.0.

topoclusters

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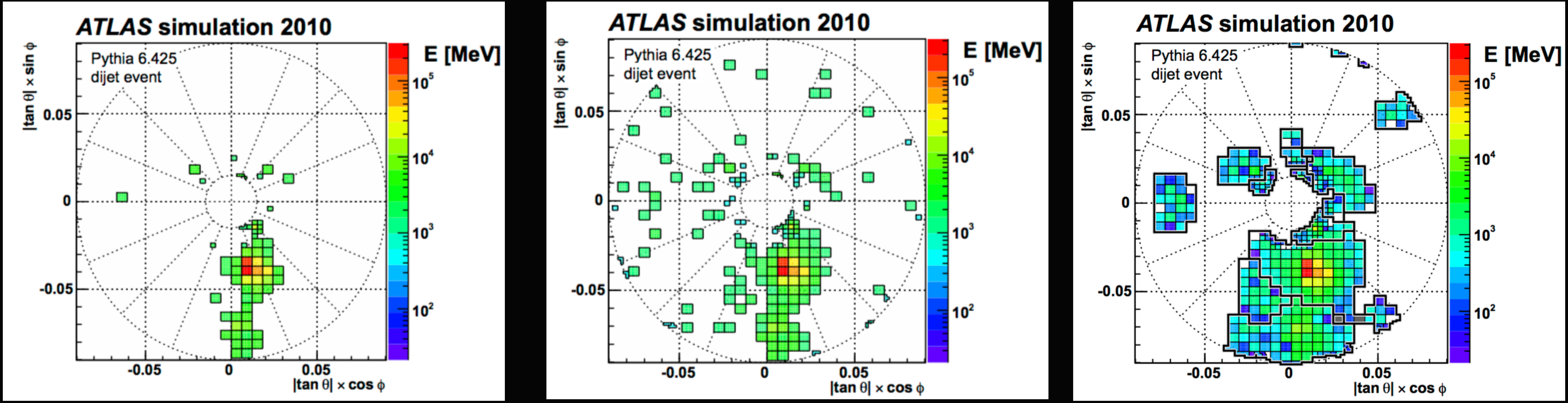
- Jets can be reconstructed from 3D topological clusters of calorimeter cells (topoclusters)
  - Calibrated or uncalibrated topoclusters (LC and EM scale).
- Cells are clustered together based on their signal significance or ratio of the cell signal to the average (expected) noise.

$$\varsigma_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise,cell}}^{\text{EM}}}$$



Cells with signal Significance > 4 seed topoclusters

Cells with signal significance > 2 control topocluster growth

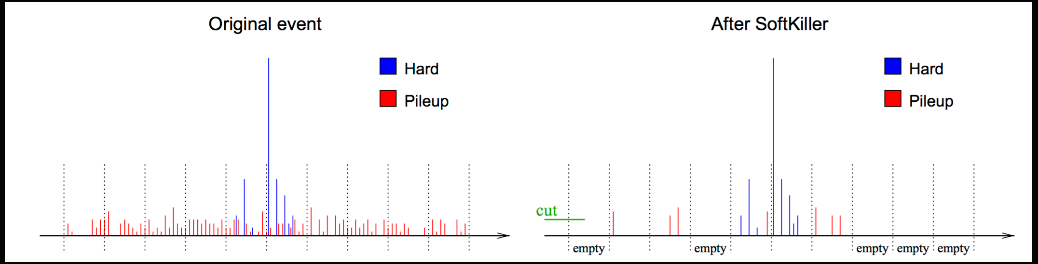
All clustered cells: topoclusters surrounding layer

Stages of topocluster formation: Based on signal significance of calorimeter cells

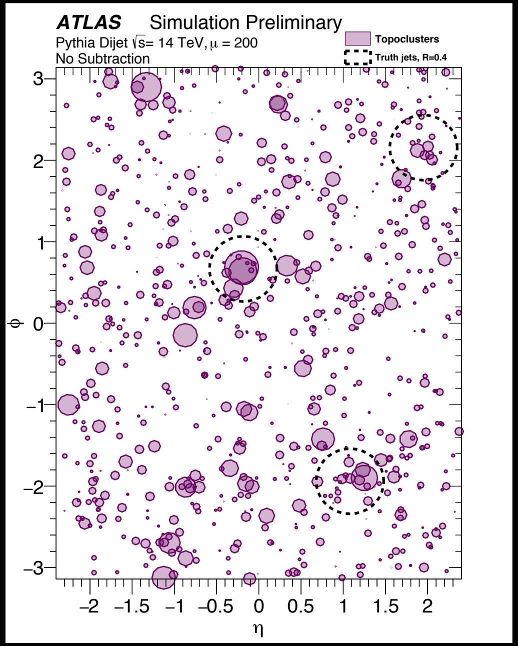
Cluster-level subtraction to mitigate pile up

ATLAS-CONF-2017-065 Eur. Phys. J. C (2015) 75:59

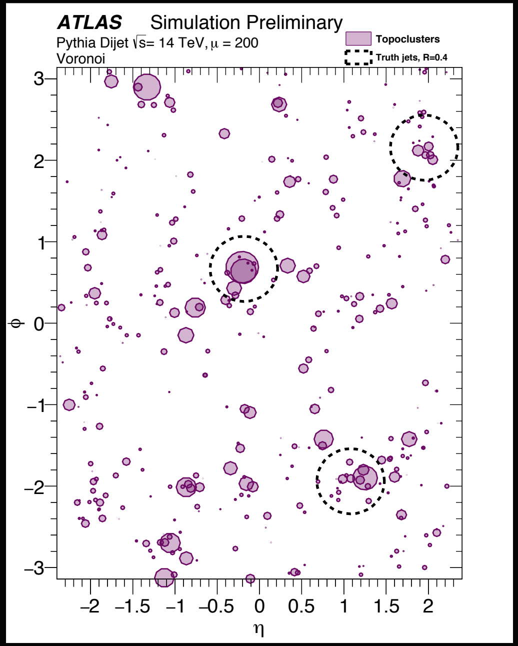
- Constituent subtraction (CS): “ghost particles” (E = ε)" added uniformly in an event and clustered alongside cells: Number of clustered ghosts is proportional to the area.
  - Topoclusters are corrected based on Nghost and event pile-up density (Rho).
- Voronoi area: eta-phi area closest to each cluster:
  - Rho subtracted from each cluster according to voronoi area.
  - All clusters with low significance above noise are removed.
- Softkiller (SK):
  - Clusters below an event-specific pT cut after CS or VS are rejected to further remove pileup.
- CS+SK found to be the best performing one.



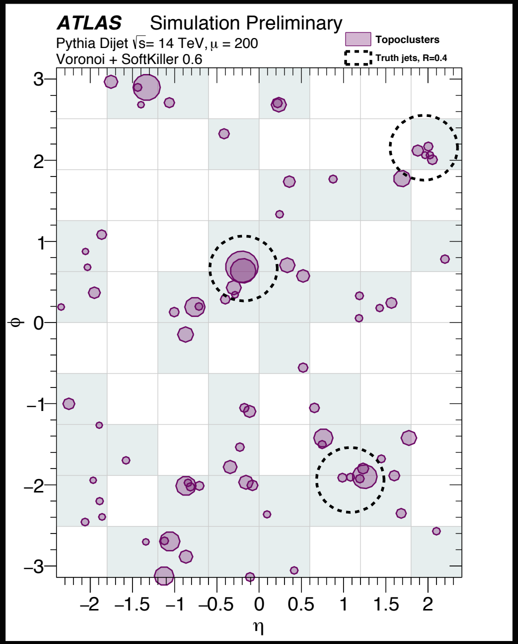
No subtraction



After Voronoi subtraction



After Voronoi + SoftKiller subtraction



particle-flow jets

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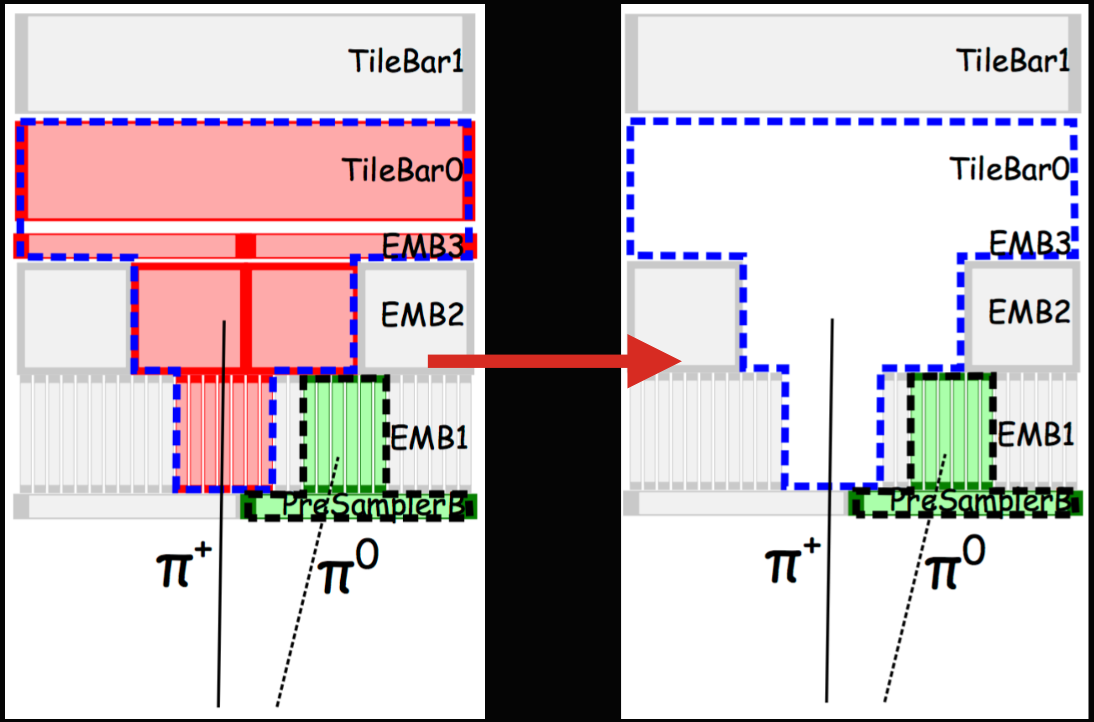
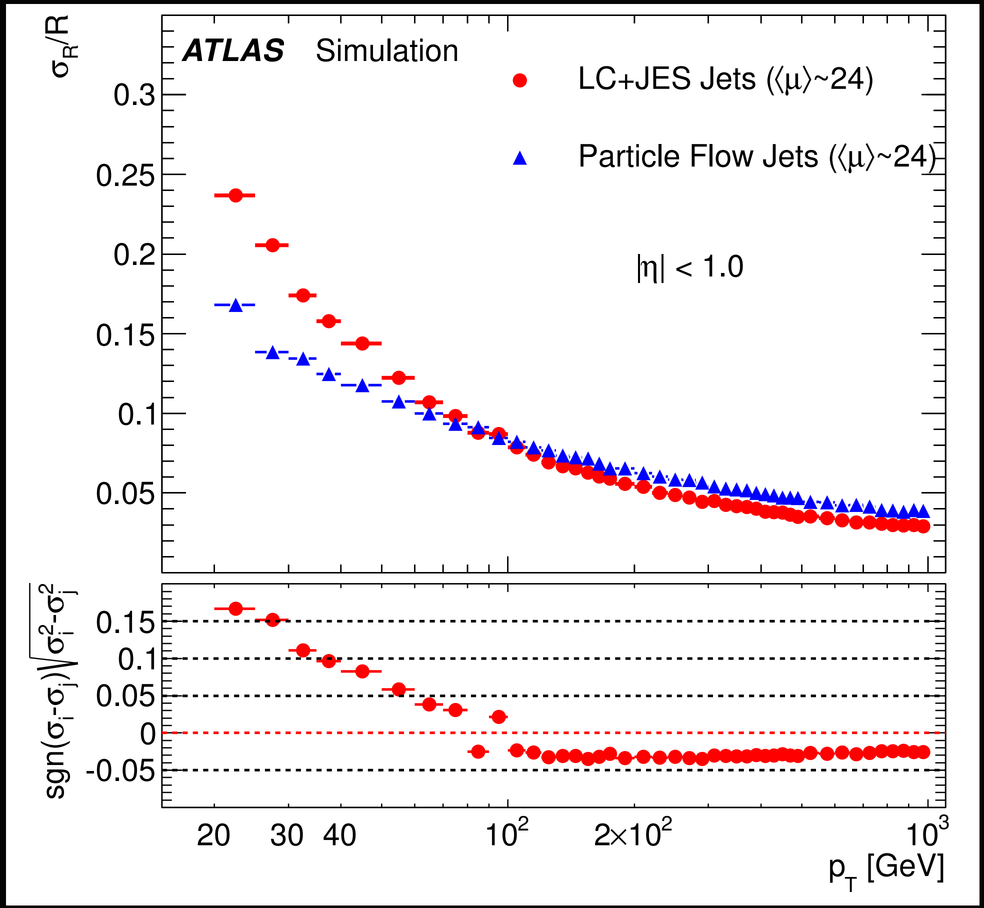
- Tracks matched to topoclusters, removing charged energy while keeping neutral component. Subtraction of energy is done cell-by-cell
- Reconstructed using the anti-kt algorithm with radius parameter 0.4: inputs are topo-clusters surviving the energy subtraction step and the selected track
- Improved resolution at low pT compared to LC+JES jets due to better tracker resolution at low pT





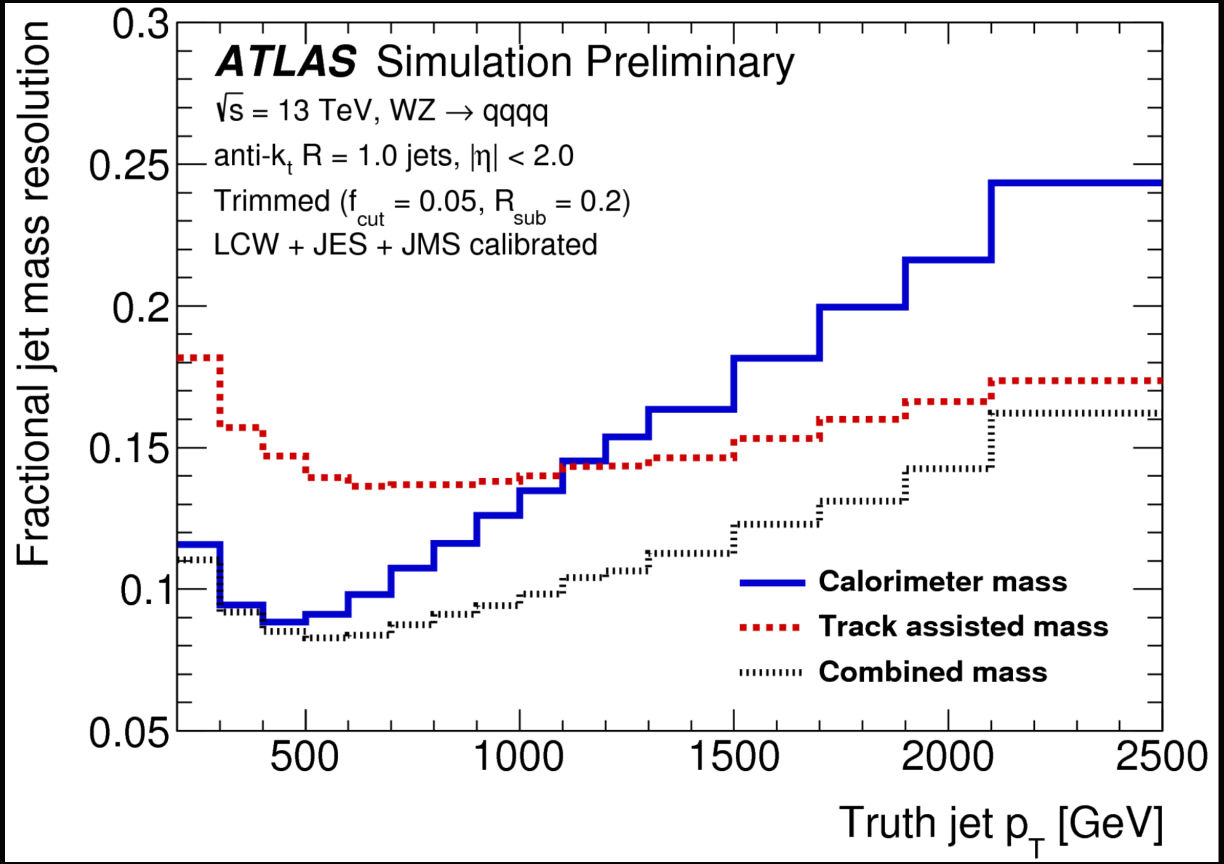
Improvements in jet mass reconstruction for R=1.0 jets

JETM-2017-002

Mass is a commonly used variable in the identification of hadronically decaying massive particles such as top and W/Z/H.

Calorimeter mass: Resolution degrades at high pt, shower size (1/pT) becomes comparable to calo granularity

$$m^{\text{calo}} = \sqrt{\left(\sum_{i\in J} E_i\right)^2 - \left(\sum_{i\in J} \vec{p}_i\right)^2}$$



Track-assisted mass: Tracking information can be used to maintain performance beyond the calo granularity limit. Pt(calo)/Pt(track) corrects for neutral energy not accounted for in track jet reconstruction.

$$m^{\text{TA}} = \frac{p_{\text{T}}^{\text{calo}}}{p_{\text{T}}^{\text{track}}} \times m^{\text{track}}$$

Combined mass uses an inverse resolution weighted combination of mCalo and mTA

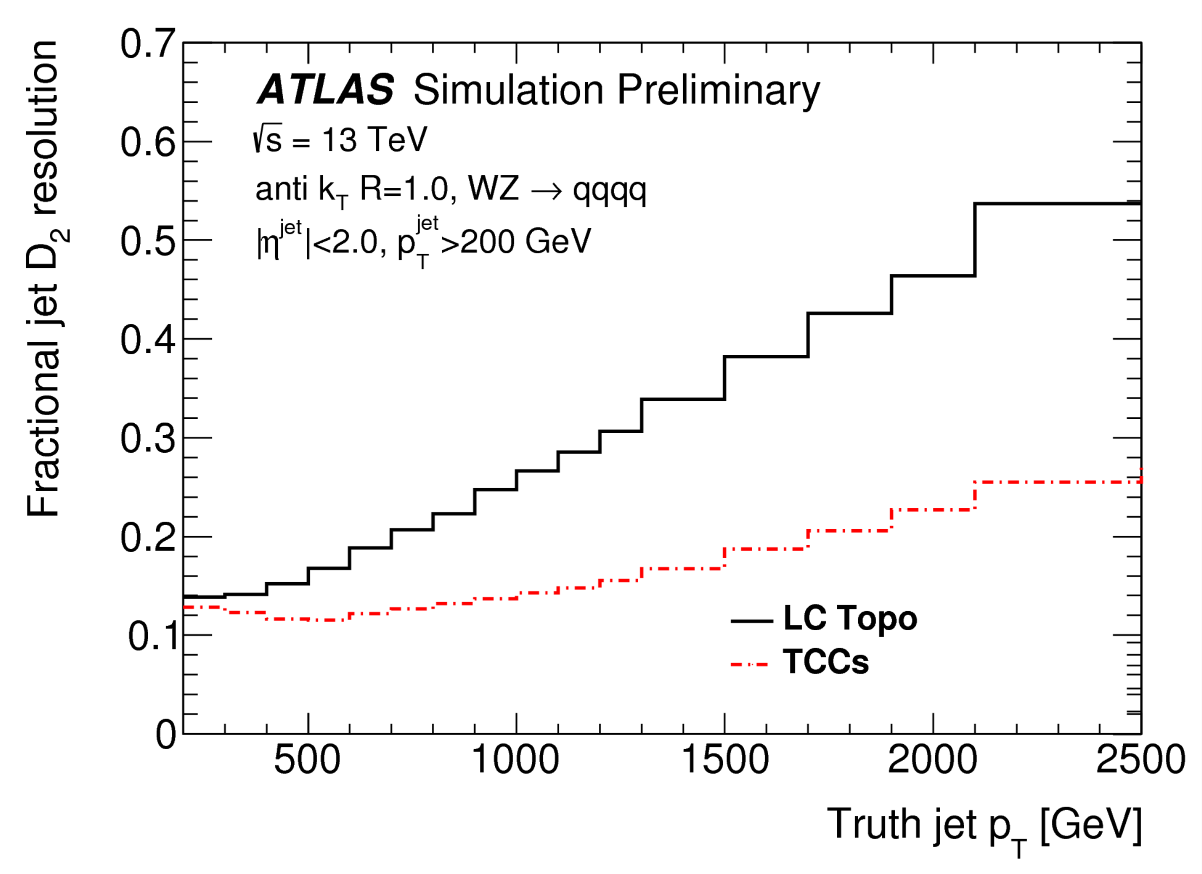
$$w_{\text{det}} = (\sigma[m_{\text{det}}])^{-2}$$

$$m_{\text{comb}} = \left(\sum_{\text{TA,calo}} w_{\text{det}} m_{\text{det}}\right) \Big/ \left(\sum_{\text{TA,calo}} w_{\text{det}}\right)$$

Track-Calo cluster (TCC) jets

ATL-PHYS-PUB-2017-015 ATLAS-CONF-2018-016

- Define a jet using spatial coordinates of the tracker and the energy scale of the calorimeter: Use superior angular resolution of tracker and energy resolution of calorimeter
- Neutral TCCs (unmatched topo-clusters) jets have a similar pile-up dependence to standard topocluster jets, additional pile up removal techniques applied.
- Improved resolution of large-R jet mass for very high pT and substructure observables sensitive to the substructure of a W/Z-boson jet.



variable-R (VR) jets

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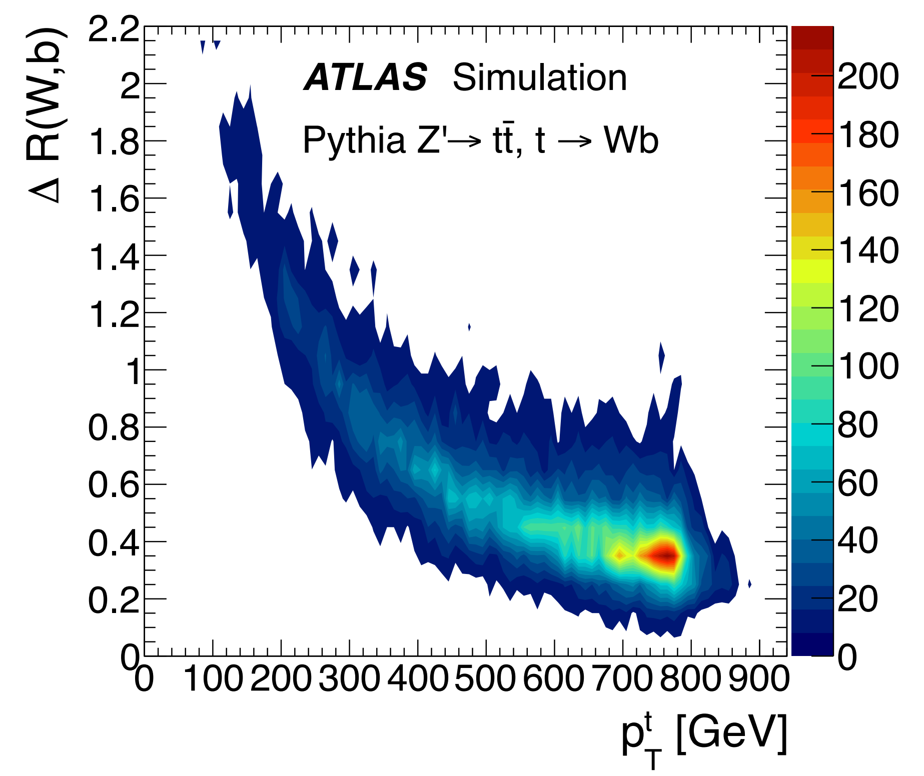
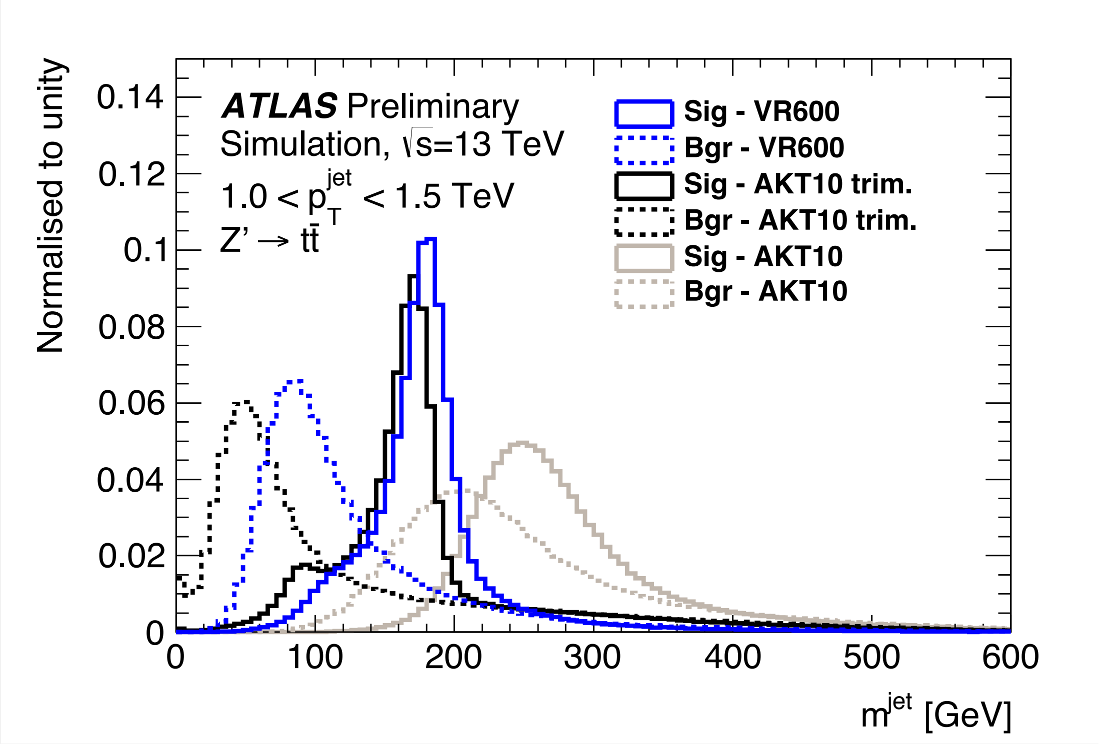




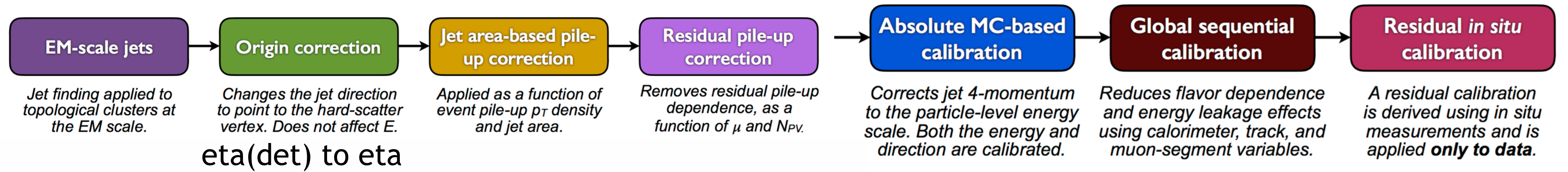
- For high pT jets (top jets in left plot) R < 1 is sufficient.
- For VR jets, radius parameter scales with 1/pT

$$R_0 \longrightarrow R_{eff}(p_{T,i}) = \frac{\rho}{p_{T,i}}$$

- ρ determines how fast the effective jet size decreases with jet pT.
    - Min and max R values prevents the jets from becoming too large at low pT and from shrinking below the detector resolution at high pT

Calibration procedure for R=0.4 (small-R) and R=1.0 jets (large-R)

Phys. Rev. D 96 (2017) 072002



EM-scale jets → **Origin correction** → **Jet area-based pile-up correction** → **Residual pile-up correction** → **Absolute MC-based calibration** → **Global sequential calibration** → **Residual *in situ* calibration**

Jet finding applied to topological clusters at the EM scale.

Changes the jet direction to point to the hard-scatter vertex. Does not affect E.

eta(det) to eta

Applied as a function of event pile-up p_T density and jet area.

Removes residual pile-up dependence, as a function of μ and N_{PV}.

Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.

Reduces flavor dependence and energy leakage effects using calorimeter, track, and muon-segment variables.

*A residual calibration is derived using in situ measurements and is applied **only to data**.*

R=0.4 jets

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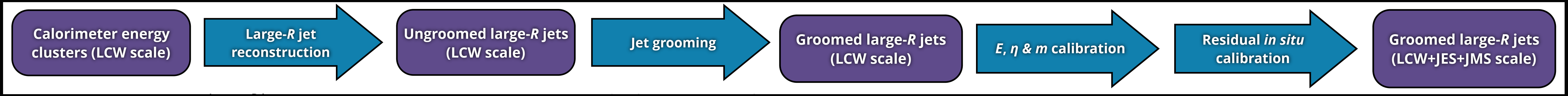


Calorimeter energy clusters (LCW scale) → **Large-*R* jet reconstruction** → **Ungroomed large-*R* jets (LCW scale)** → **Jet grooming** → **Groomed large-*R* jets (LCW scale)** → **E, η & m calibration** → **Residual *in situ* calibration** → **Groomed large-*R* jets (LCW+JES+JMS scale)**

Large-R jets reconstructed using the anti-kt algorithm with R = 1.0.

removes pile-up and the underlying event

reconstructed jet E,eta and m corrected using MC to the particle jet scale

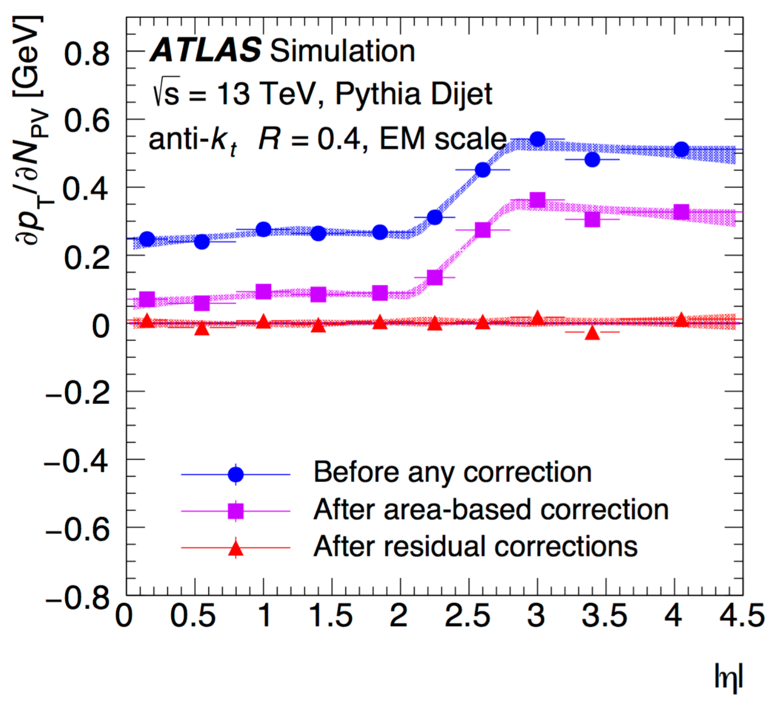
Residual correction applied to data

R=1.0 jets

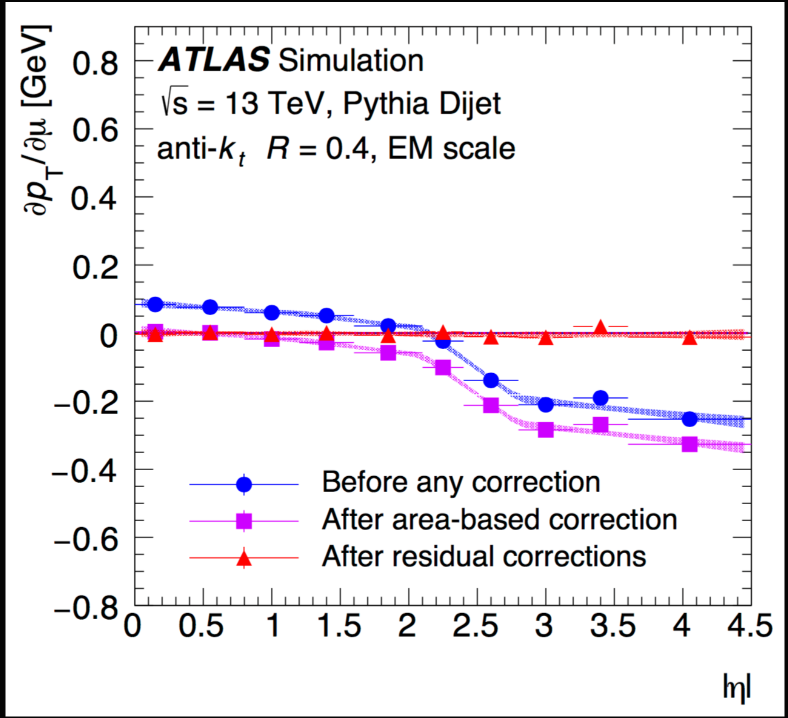
Pile-up correction for R=0.4 jets

Phys. Rev. D 96 (2017) 072002

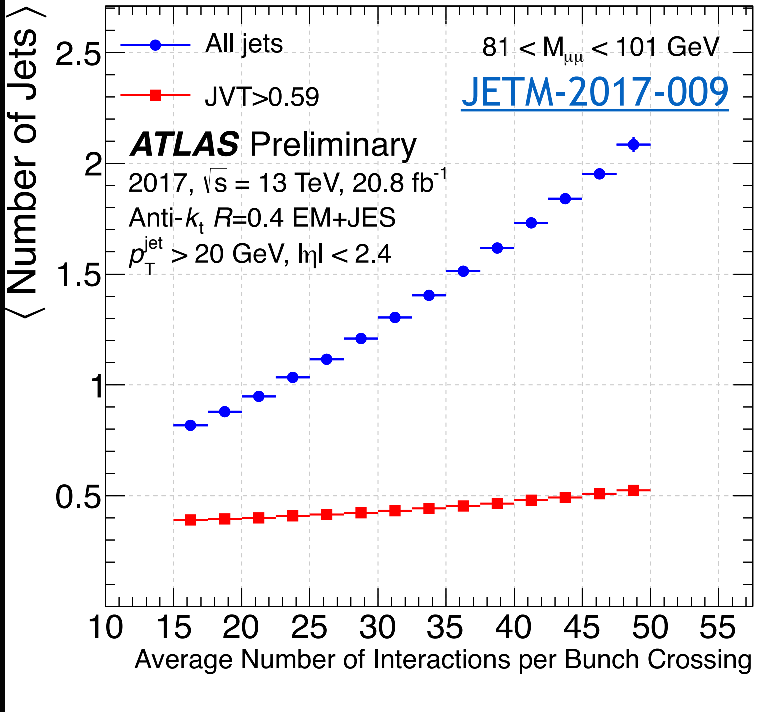
- Particles from pile-up collisions can add additional jets that are not from the hard-scatter
- Can overlap with hard scatter jets, altering their energy
- Effect of pile-up reduced by applying per-jet corrections based on pile-up density in the event and JVT (connects jets to pile-up vertices using tracking information) cuts for small-R jets.



In-time pile-up correction



Out-of-time pile-up correction

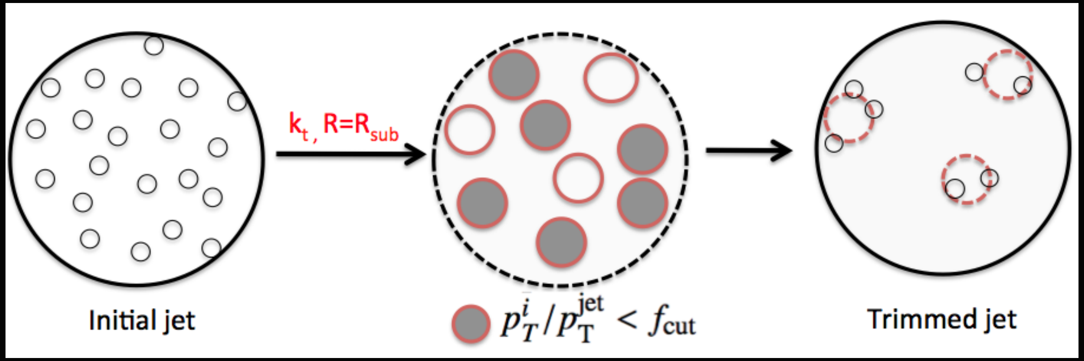


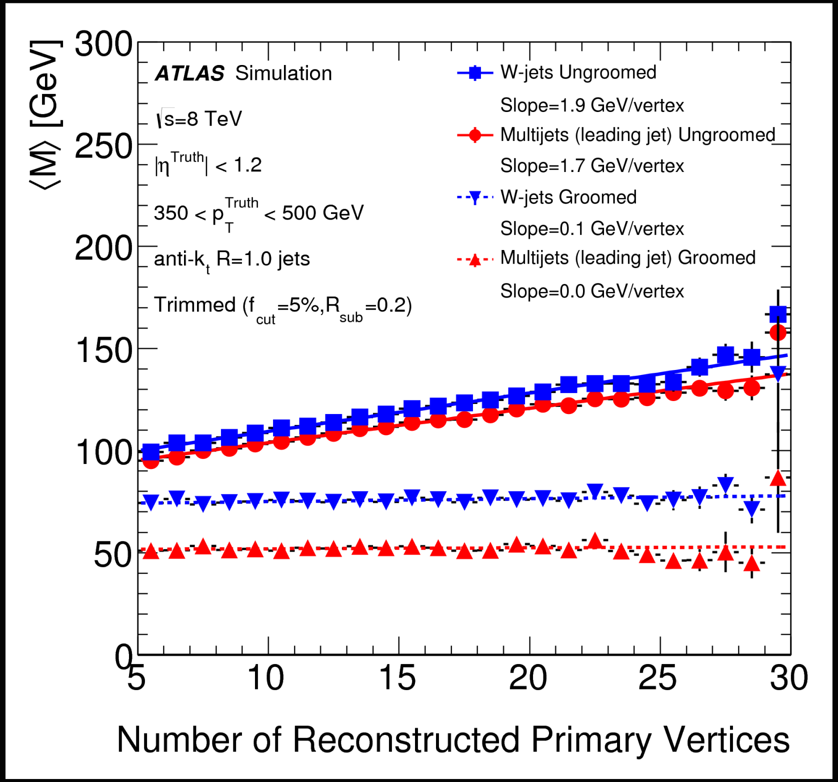
Pile-up correction for R=1.0 jets: “grooming”

ATL-PHYS-PUB-2015-033

- Large-R jets due to a larger area are more susceptible to pile-up effects.
- Grooming techniques are applied to correct for these effects which can alter substructure features.
- The trimming procedure with parameters of fcut = 5% and Rsub = 0.2 is used on ATLAS.
  - Constituents of the original anti-kt jet are reclustered using the kt algorithm with a distance parameter of Rsub.
  - Resulting kt sub-jet is removed if the pT is less than fcut of the large-R jet pT.
  - Jet is rebuilt from the remaining constituents.

- Soft drop grooming has also been studied and found to have good performance.

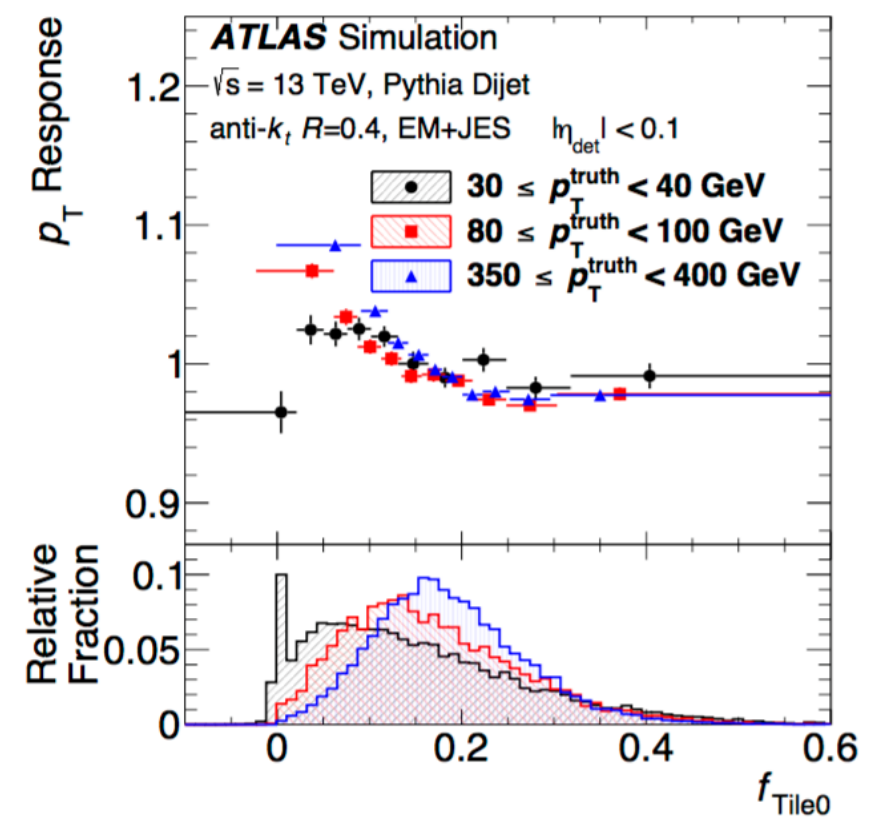


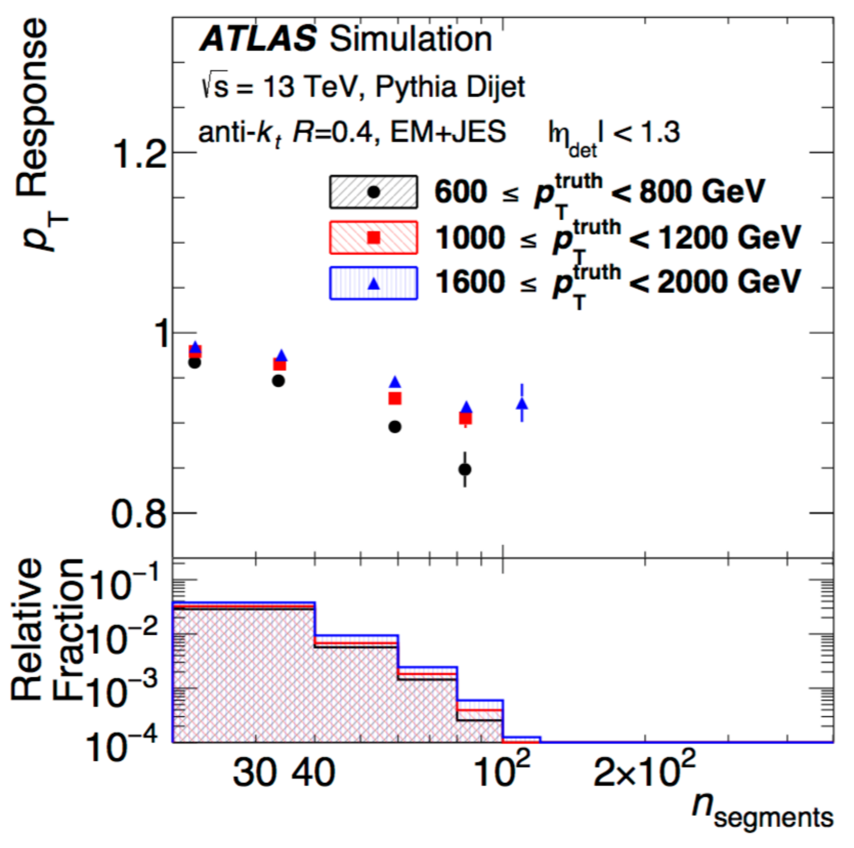


Grooming techniques can improve the reconstruction of the jet mass helping discriminate for e.g. a W-boson initiated jet from a light quark/gluon jet, the distribution for which will peak at lower masses.

Global sequential calibration (GSC) for R=0.4 jets

- Correct jet response according to jet shower depth, track variables and muon punch-through to characterize fluctuations in the jet particle composition, distribution of energy within the jet.
- This correction applied in MC improves jet energy resolution and jet flavor dependence.
- Average JES is unchanged





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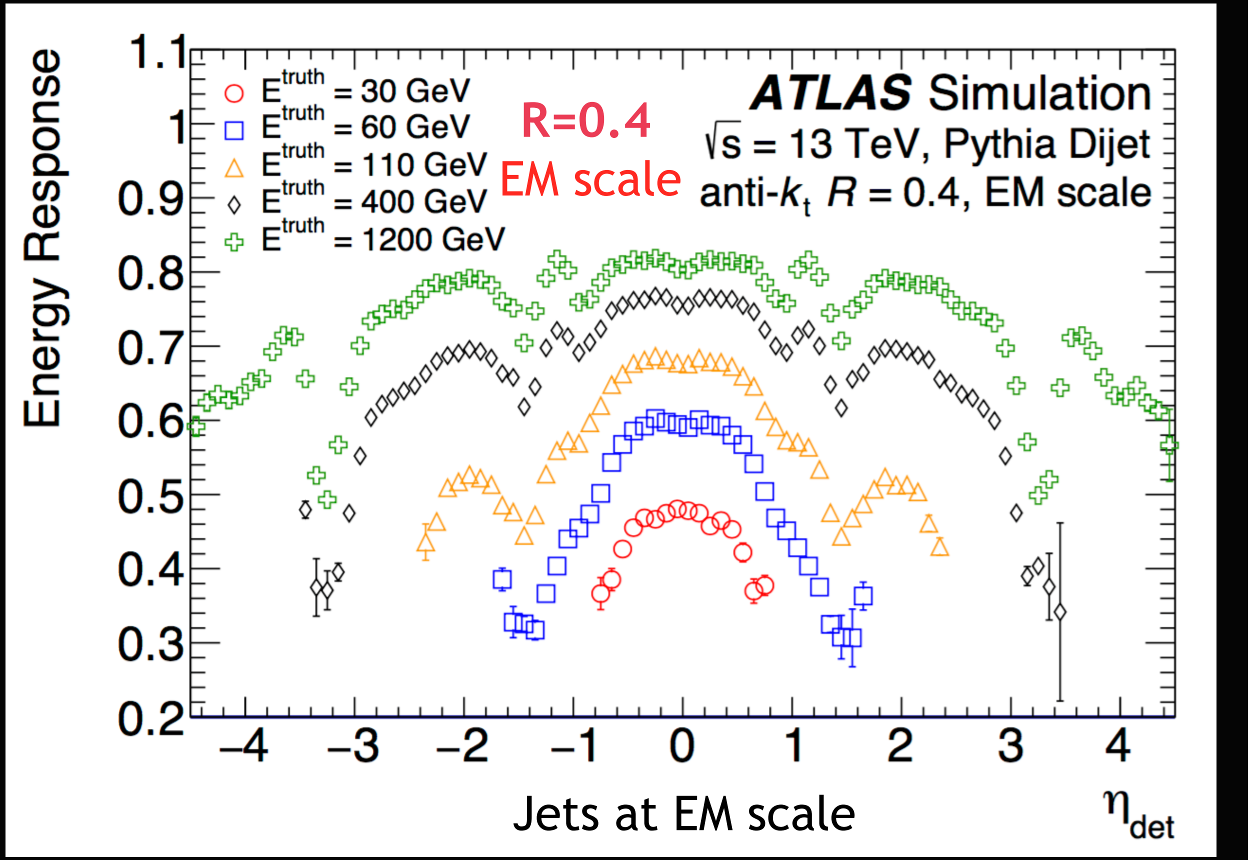
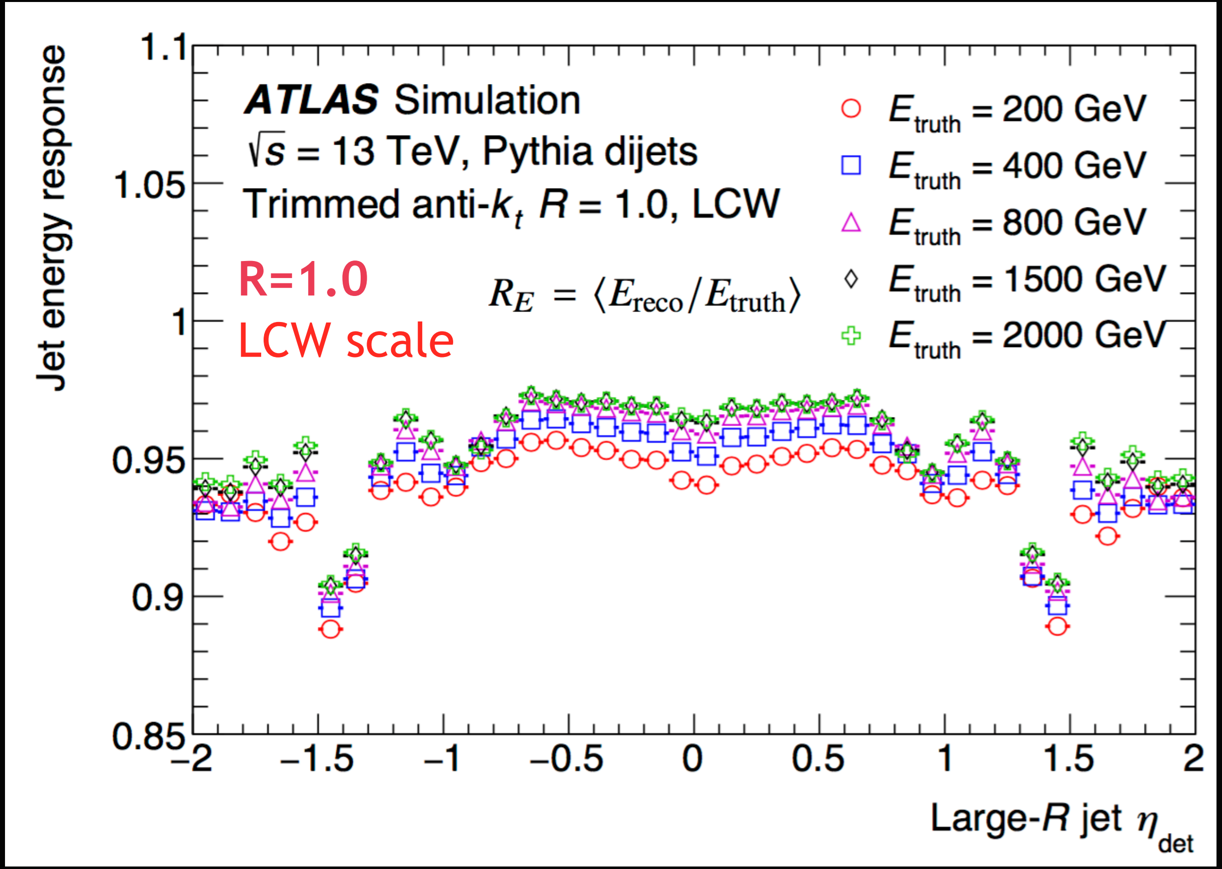
Simulation based energy response correction

Phys. Rev. D 96 (2017) 072002 CERN-EP-2018-191

- Average response determined from a Gaussian fit to the core of the response distribution $R_E = \langle E_{\mathrm{reco}} / E_{\mathrm{truth}} \rangle$
- JES correction factor cJES is determined as a function of the jet energy and pseudorapidity ηdet.
- Large-R jet energy, mass, eta, and pT after applying the correction factor (Phi is not changed)

$$E_{\mathrm{reco}} = c_{\mathrm{JES}}\, E_0, \quad m_{\mathrm{reco}} = c_{\mathrm{JES}}\, m_0, \quad \eta_{\mathrm{reco}} = \eta_0 + \Delta\eta, \quad p_{\mathrm{T}}^{\mathrm{reco}} = c_{\mathrm{JES}}\, |\vec{p}_0| / \cosh(\eta_0 + \Delta\eta)$$



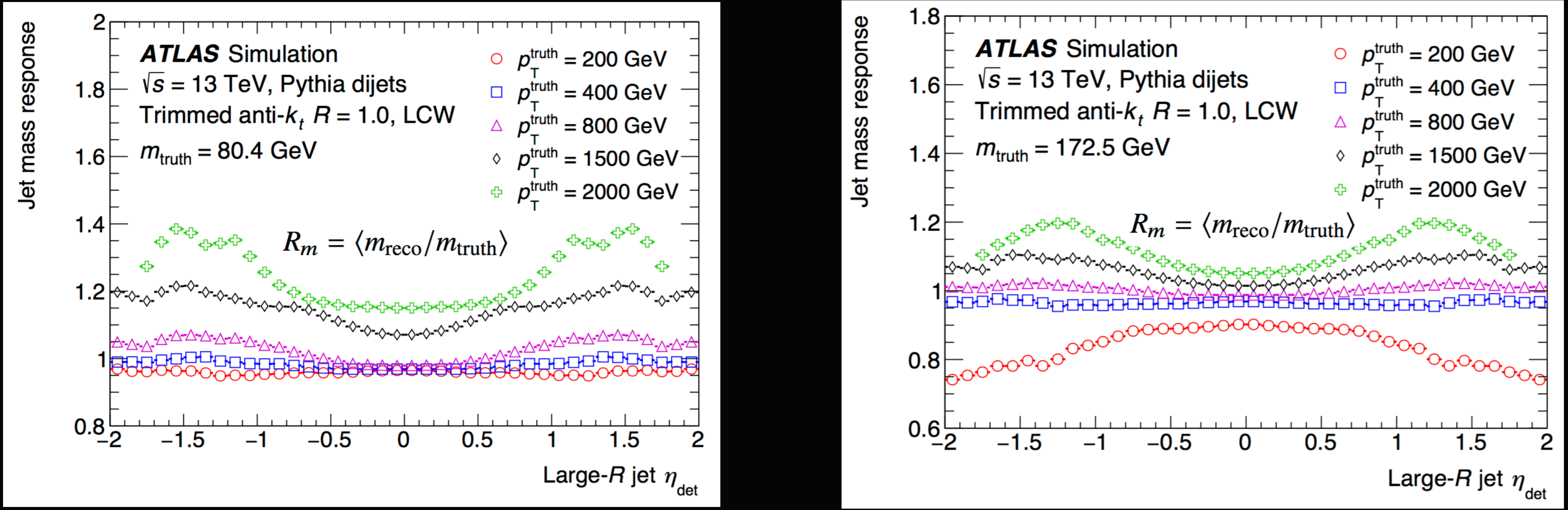


Simulation based mass response correction for R=1.0 jets

CERN-EP-2018-191

- Jet mass more sensitive to soft, wide angle radiation and topocluster merging and splitting than pT. Jet mass response measured in dijet events for different truth pT: $R_m = \langle m_{\mathrm{reco}}/m_{\mathrm{truth}} \rangle$
- Correction (cJMS) applied after Jet energy response correction, large-R jet energy kept fixed and pT allowed to vary. cJMS varies from ~1-1.5.

$$E_{\mathrm{reco}} = c_{\mathrm{JES}}\,E_0, \quad m_{\mathrm{reco}} = c_{\mathrm{JES}}\,c_{\mathrm{JMS}}\,m_0, \quad \eta_{\mathrm{reco}} = \eta_0 + \Delta\eta, \quad p_{\mathrm{T}}^{\mathrm{reco}} = c_{\mathrm{JES}}\sqrt{E_0^2 - c_{\mathrm{JMS}}^2\,m_0^2}/\cosh(\eta_0 + \Delta\eta).$$



Mass response for two representative values of the truth mass: W boson mass (left) and top quark mass (right)

Data-based correction: Eta-intercalibration

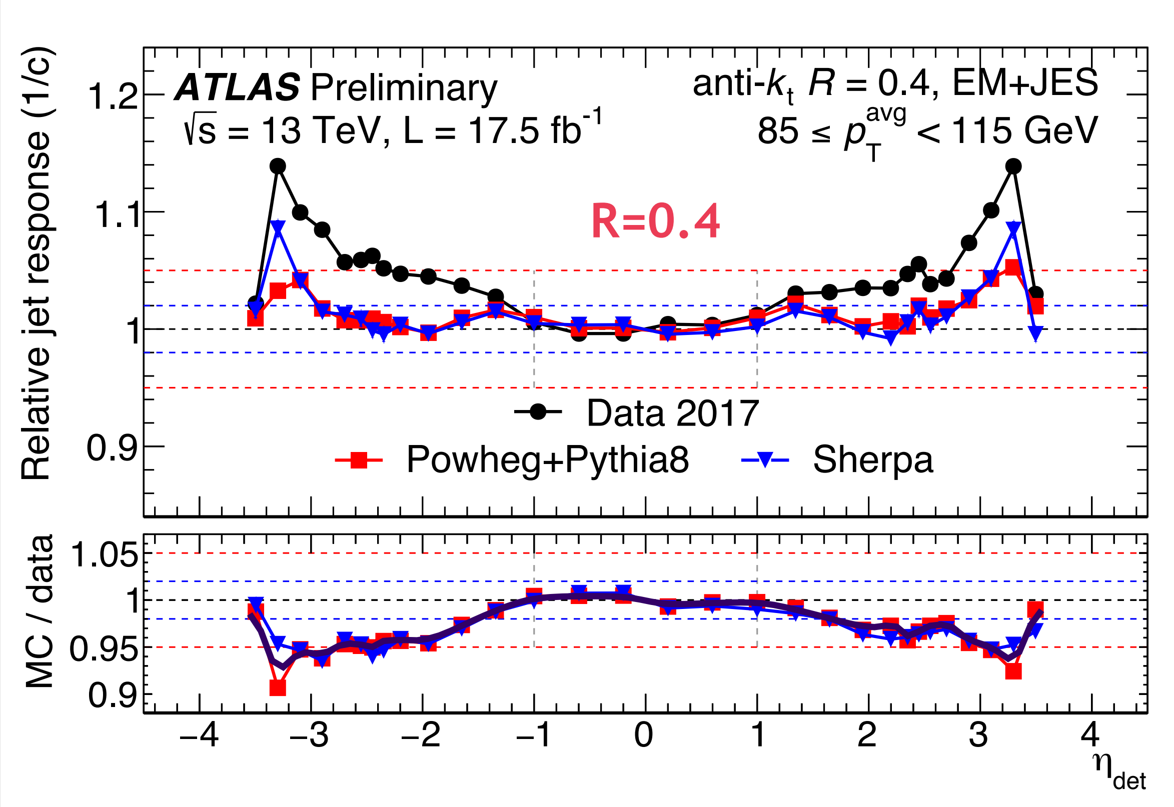
JETM-2017-008 CERN-EP-2018-191

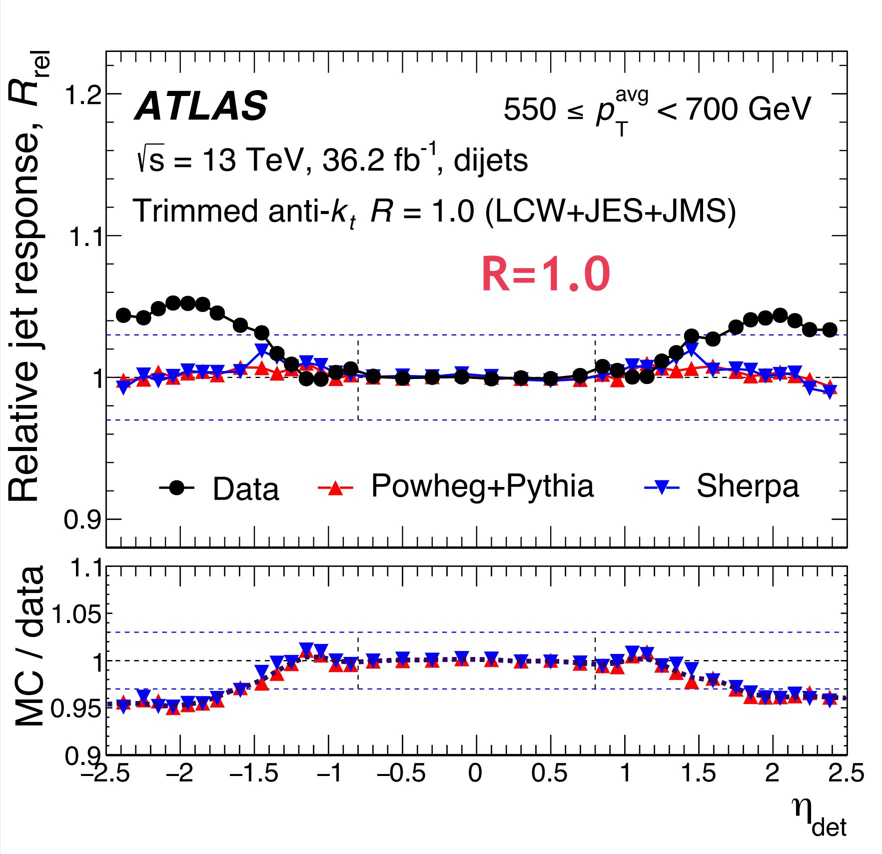
$$\mathcal{A} = \frac{p_{\mathrm{T}}^{\mathrm{probe}} - p_{\mathrm{T}}^{\mathrm{ref}}}{p_{\mathrm{T}}^{\mathrm{avg}}}$$

$$\left\langle \frac{p_{\mathrm{T}}^{\mathrm{probe}}}{p_{\mathrm{T}}^{\mathrm{ref}}} \right\rangle \approx \frac{2 + \langle \mathcal{A} \rangle}{2 - \langle \mathcal{A} \rangle}$$

- Correct for the average pT asymmetry between central (eta<0.8) reference jets and forward (eta>0.8) probe jets with DeltaPhi > 2.5 as a function of η(probe) based on the agreement between data and MC.

- Relative jet response with respect to the reference region is studied given that the asymmetry is Gaussian. ⟨A⟩: mean value of the Gaussian asymmetry distribution for a bin of pTavg and ηdet.





Data-based correction: Residual energy scale correction

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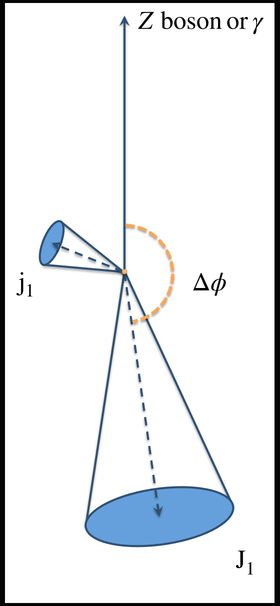
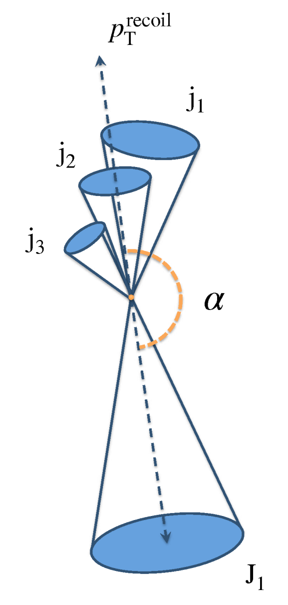
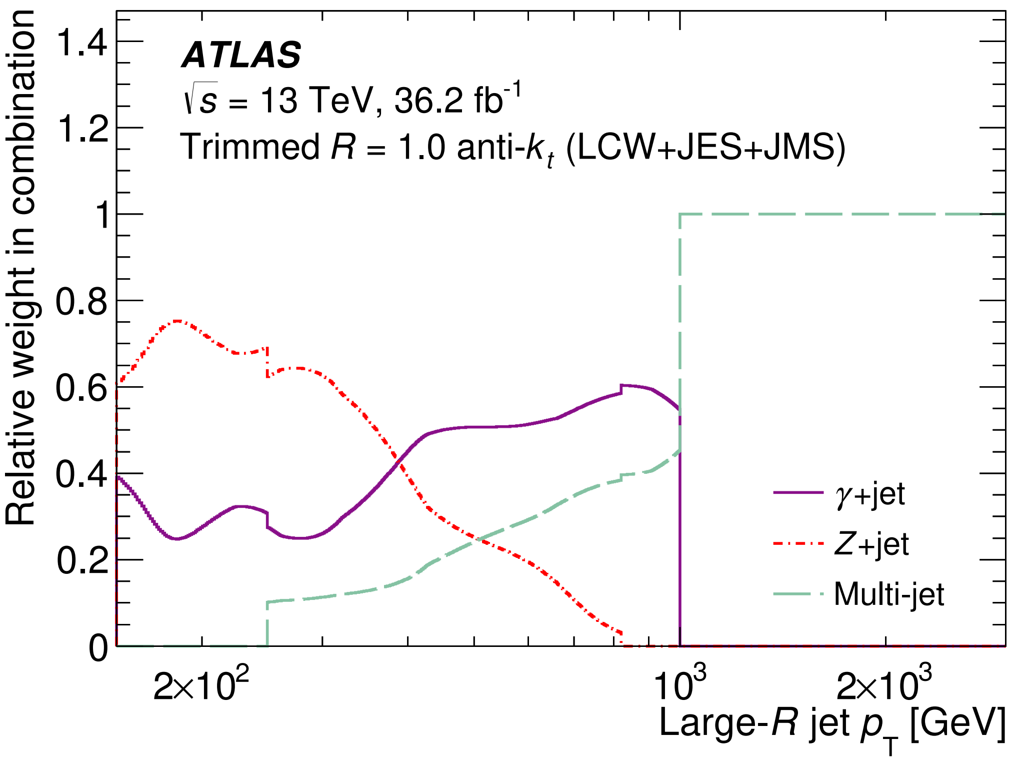
- Measure differences in average pT balance between the jet and reference object in data and MC after the MC-based calibrations.
- Require jet to recoil against a well measured reference object
  - Gamma+jet, Z+jet and Multijet have different pT reaches
  - Multijet: pT balance between jet and recoiling system of calibrated small-R jets





Relevance of a calibration reference:
- Energy scale uncertainty
- Trigger rate and purity
- Production cross-section



Weights for each measurement are derived by chi-square minimization using statistical and systematic uncertainties of finely-binned scale measurements

Residual energy scale correction

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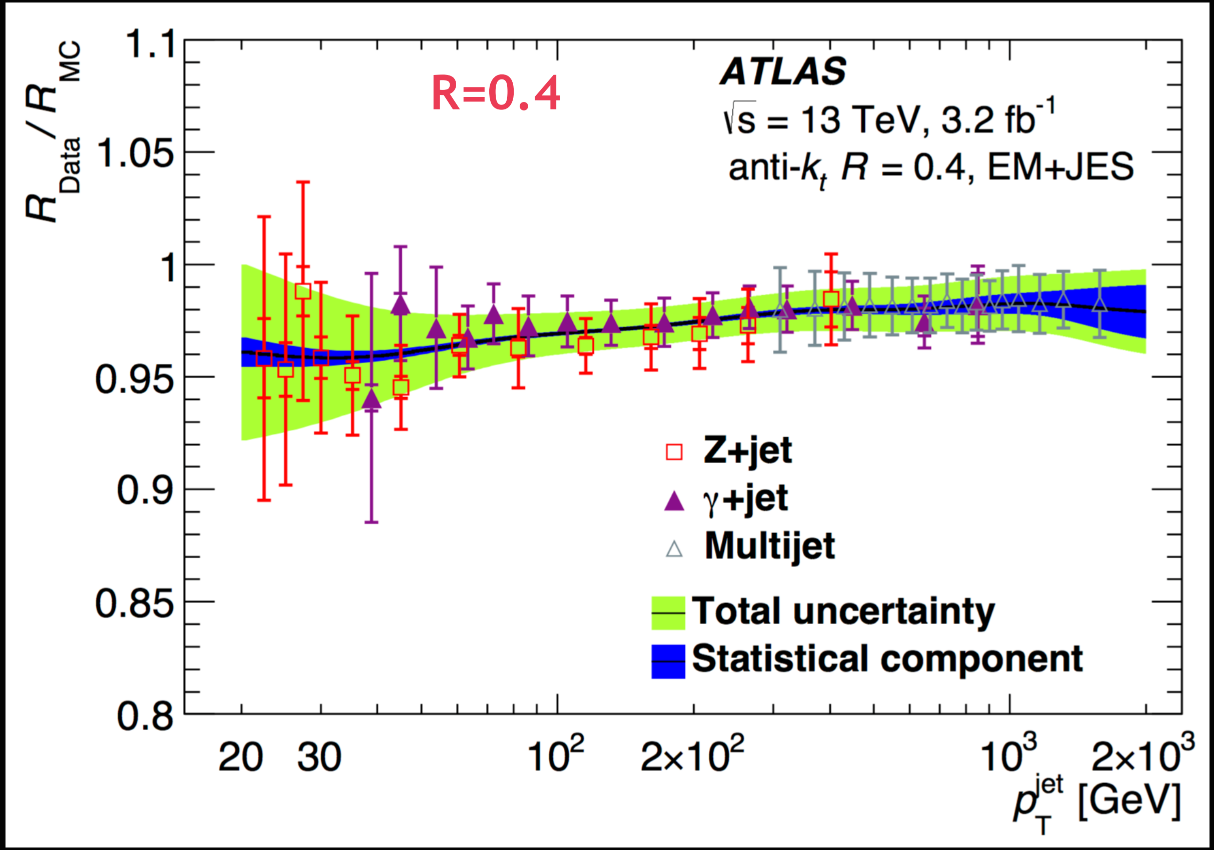
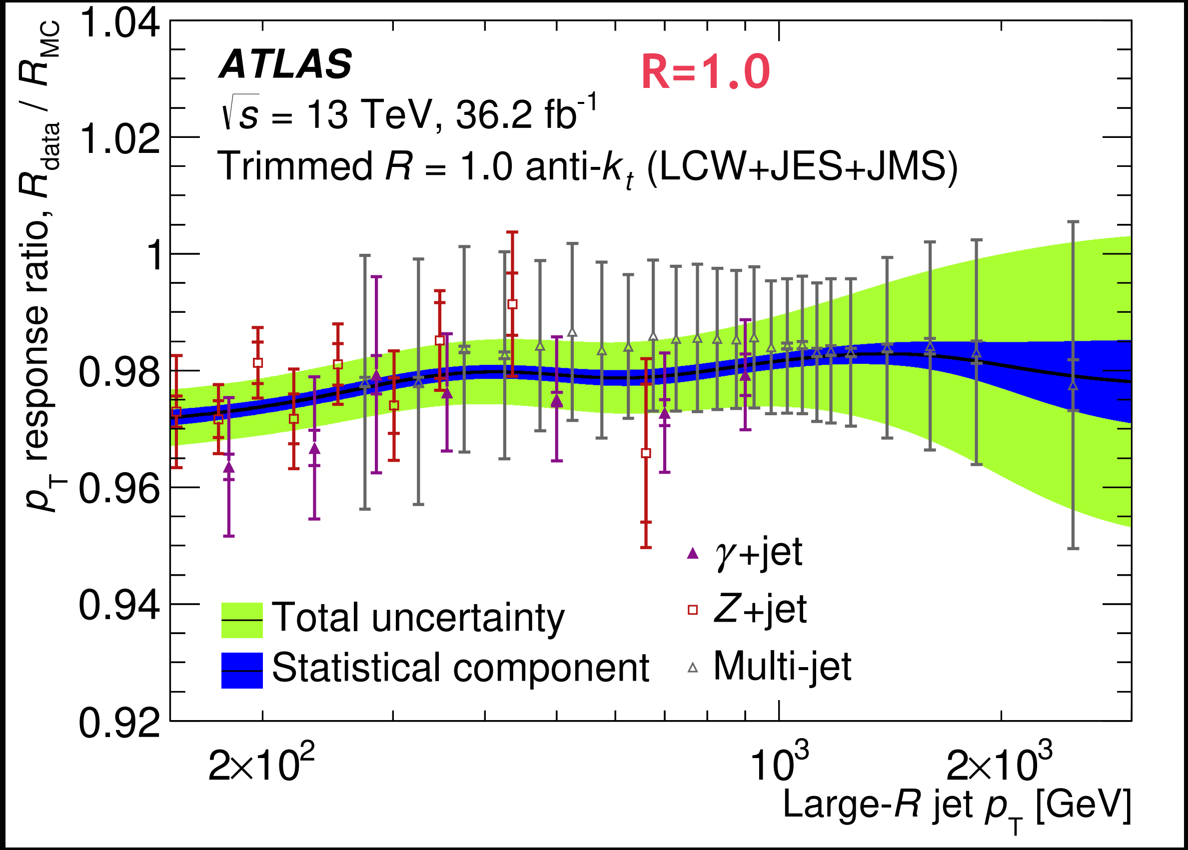
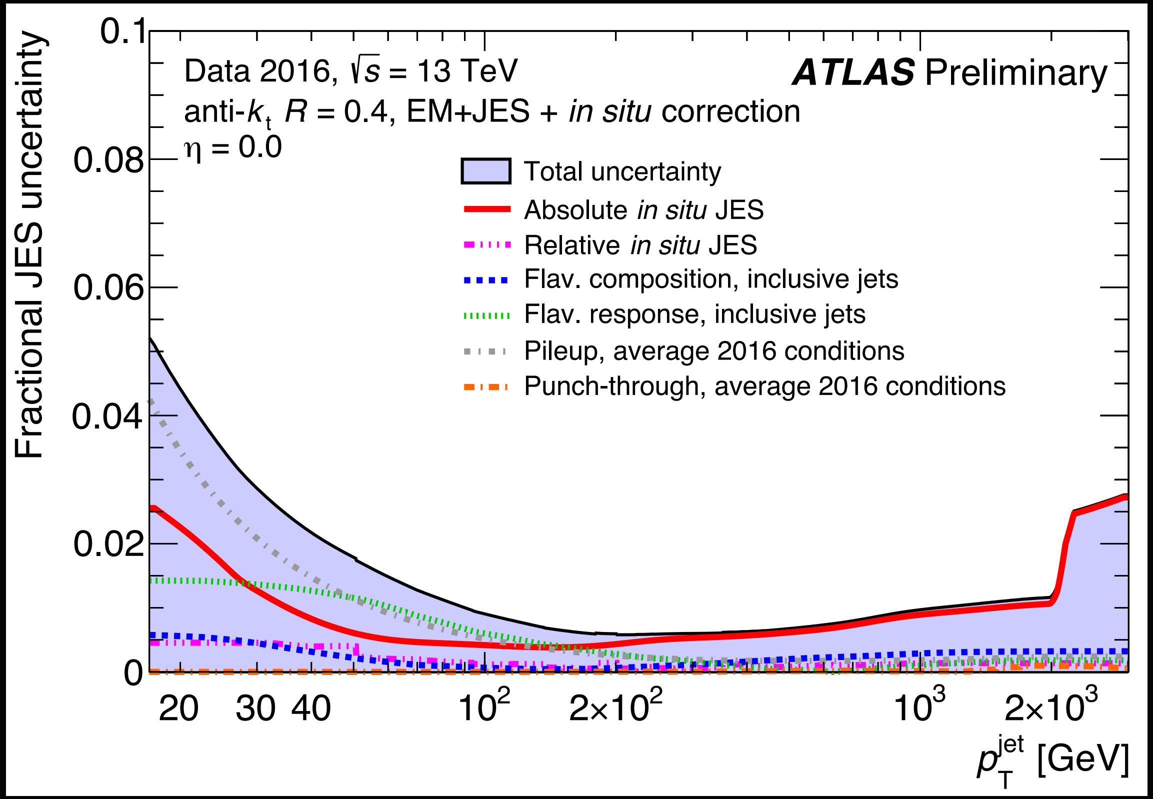


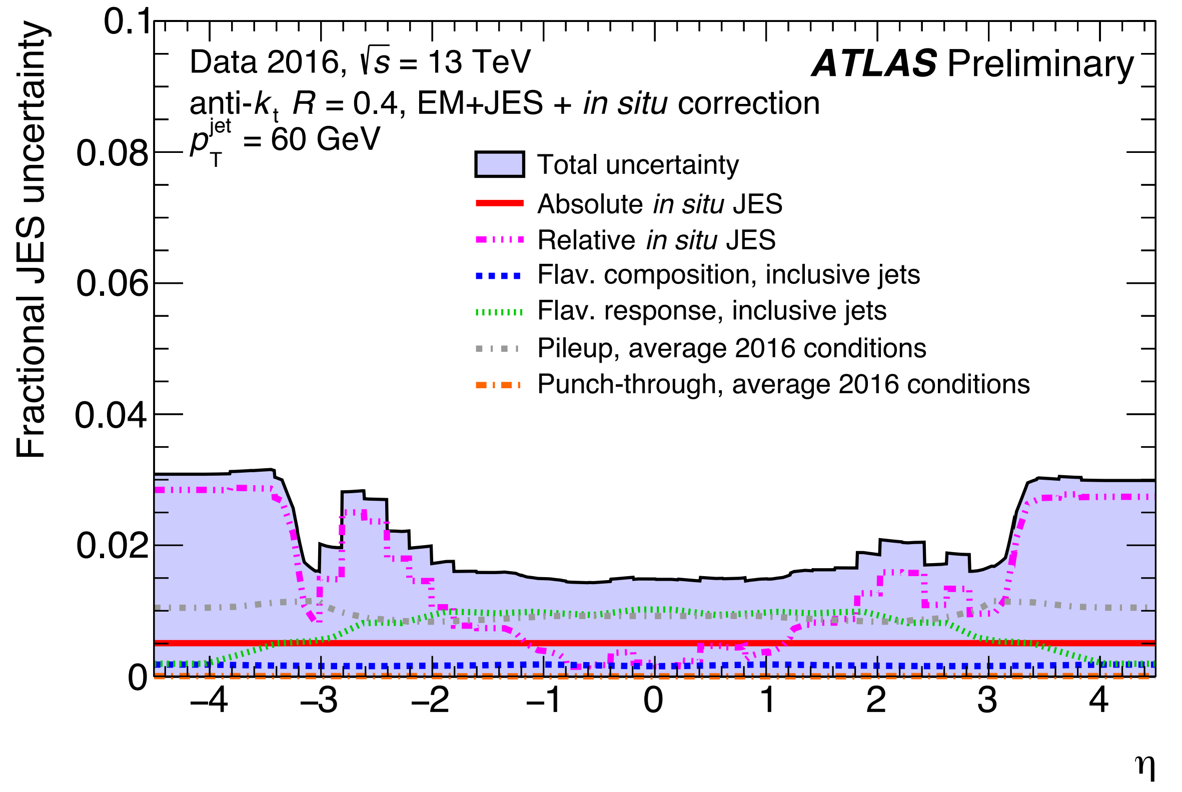


R=0.4 jet energy scale uncertainties

JETM-2017-003

- The full JES uncertainties contain in situ uncertainties and additional uncertainties for the modeling of pile-up, flavor composition and response differences between generators, and single particle response at the highest pT.
- At low pT: the pile-up uncertainties > flavor response of gluon jets > photon energy scale > single particle uncertainties.
- At high |eta| modeling issues of the balance between forward and central jets dominate.



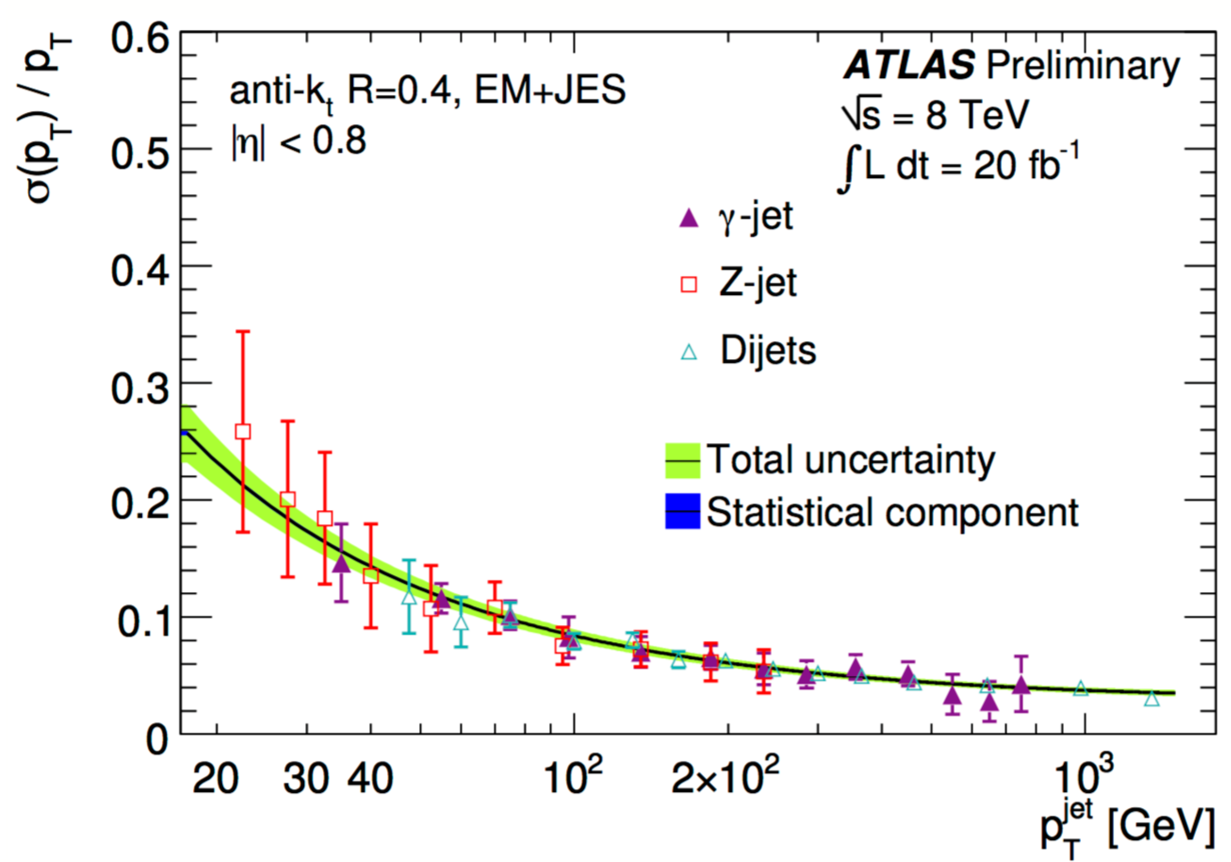


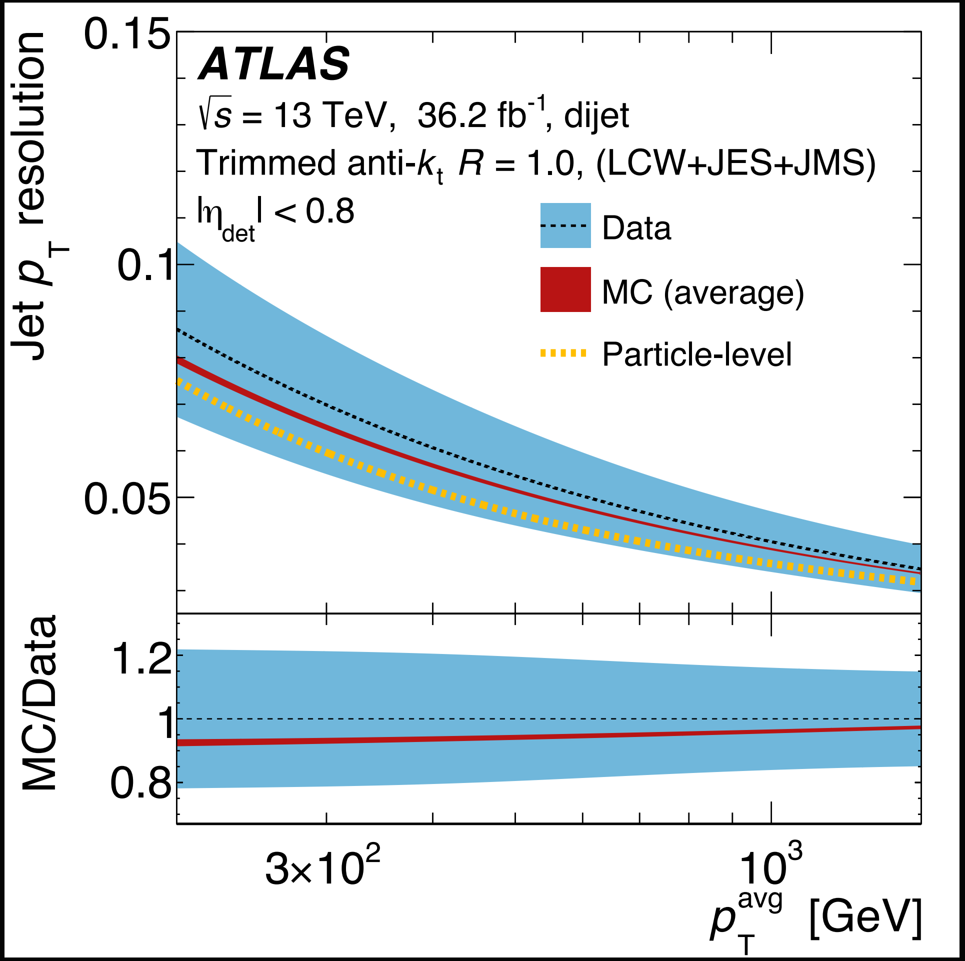
pT resolution

ATLAS-CONF-2015-037 CERN-EP-2018-191

For R=0.4 jets, insitu pT resolution is studied by combining measurements in gamma+jet, Z+jet and Dijet events.
For R=1.0 jets, dijet events are used.

$$JER \equiv \left(\frac{\sigma[p_T]}{p_T}\right) = \sigma_{A,det}/\sqrt{2}$$





R=1.0 jets: Rtrack method for uncertainties on mass and pT response

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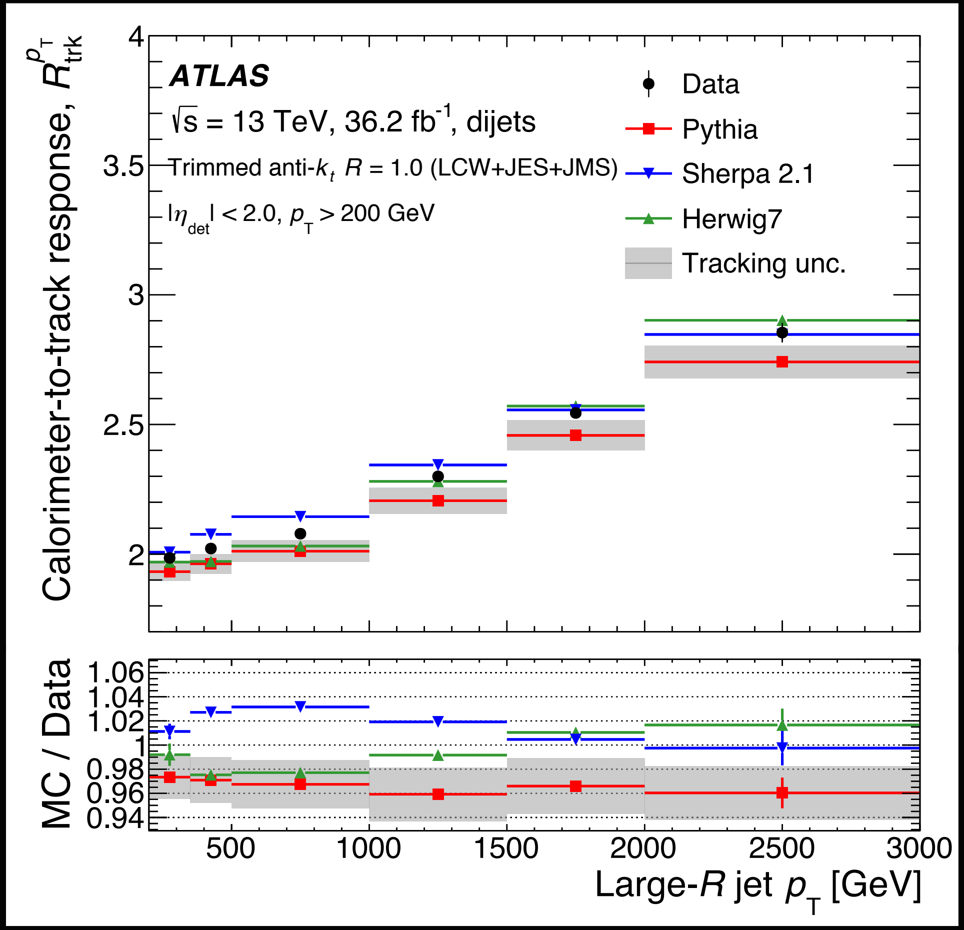
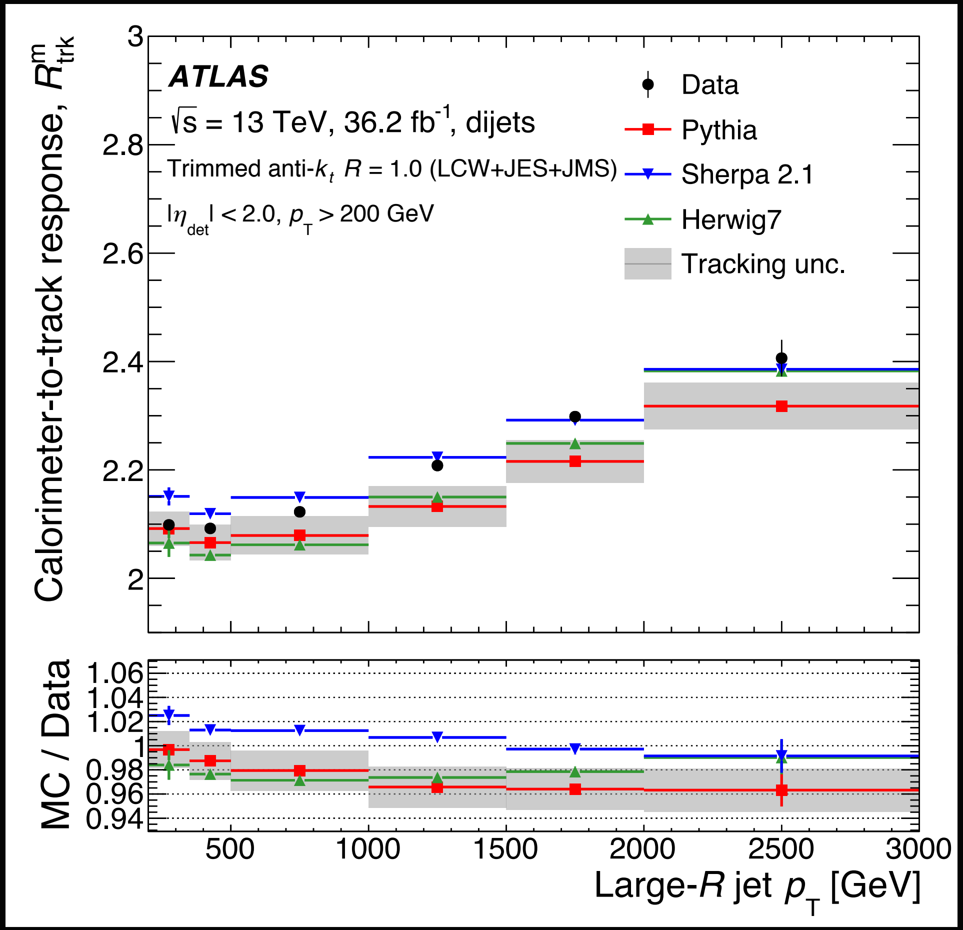
- Average calorimeter-to-track jet response is proportional to the average calorimeter-to-truth jet response.

$$R_{\text{trk}} = \left\langle \frac{p_{\text{T}}^{\text{calo}}}{p_{\text{T}}^{\text{track}}} \right\rangle$$

- Comparing Rtrk in simulation and data is a way to validate the modeling of large-R jets in data:
  - Any deviation from 1 is taken to be a scale uncertainty in the measurement.
- This method is used to determine uncertainties on pT, mass and substructure information of R=1.0 jets.



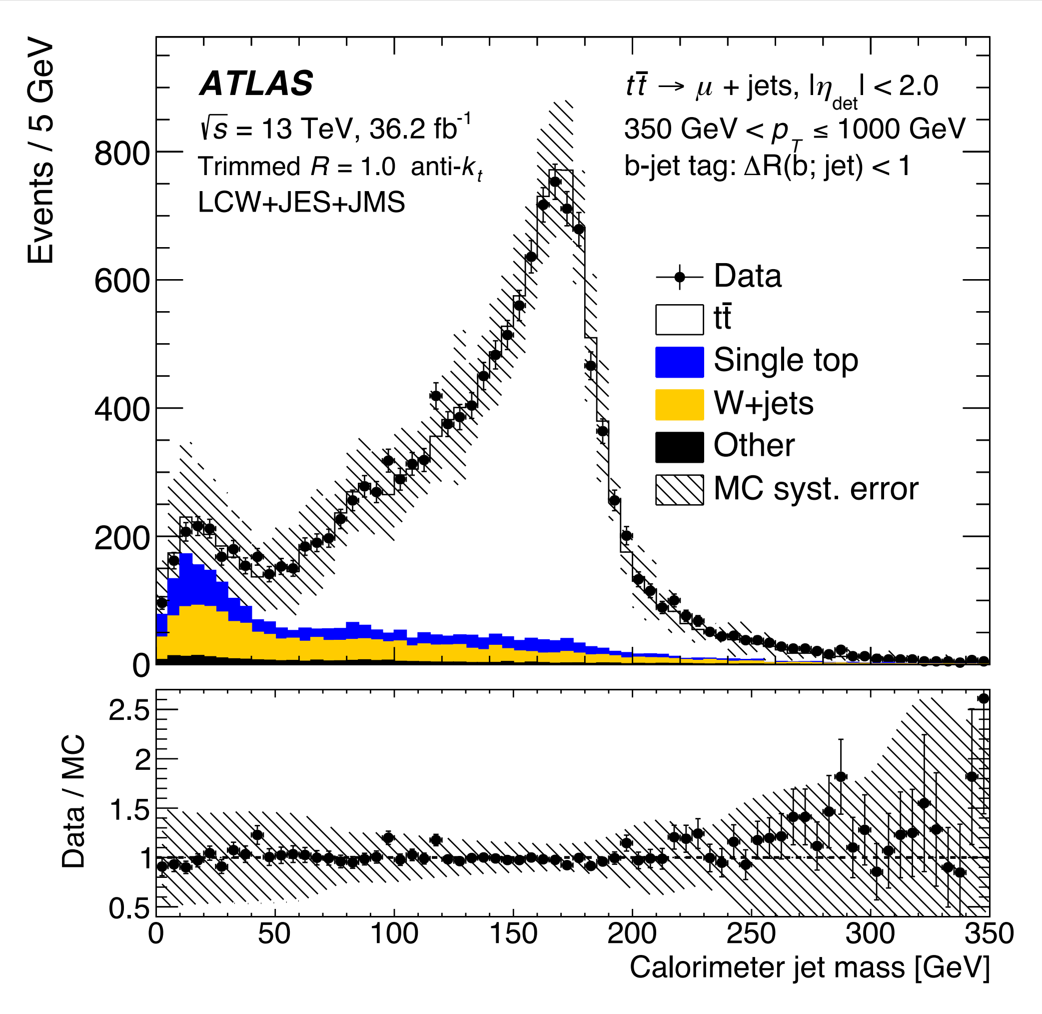


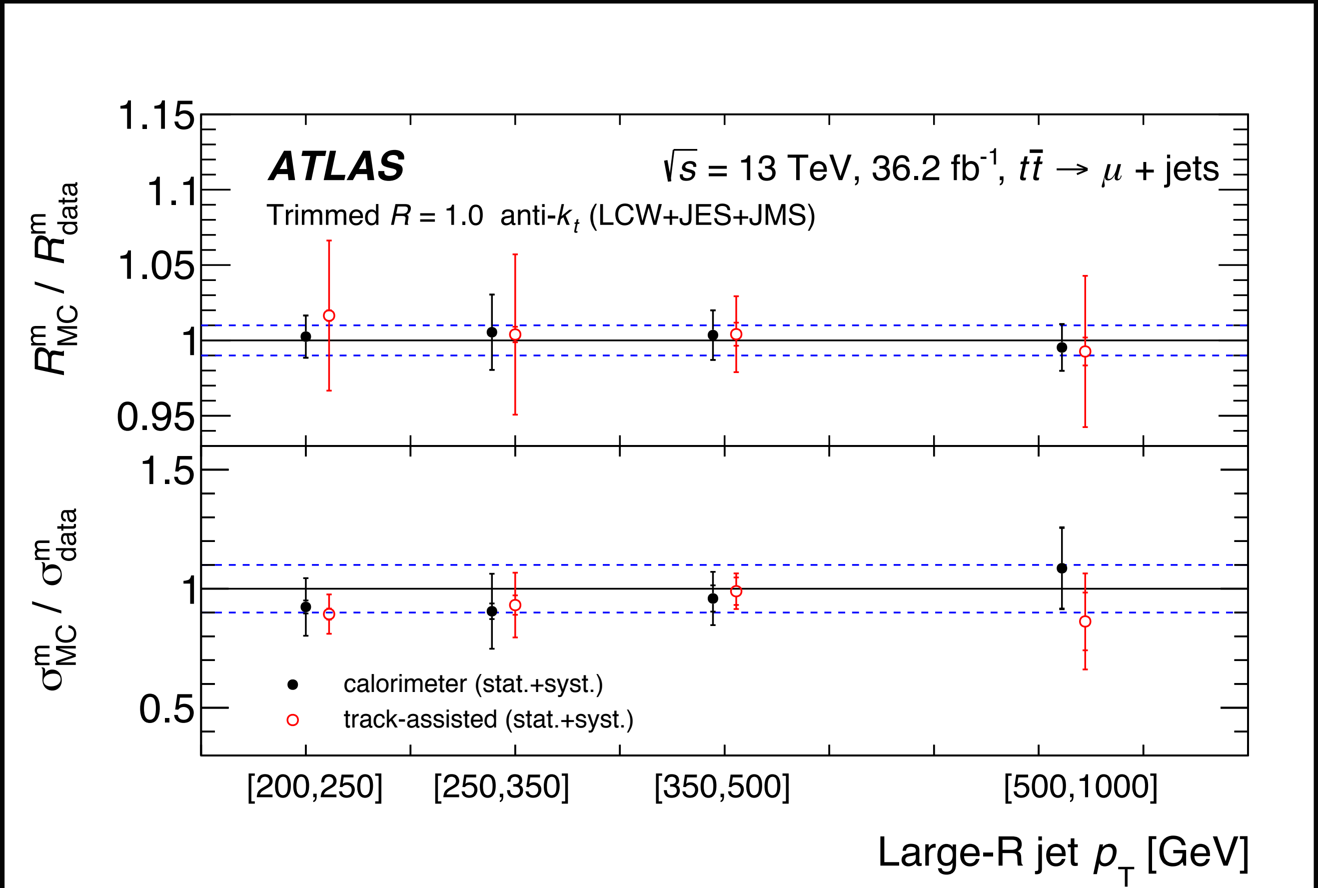
Breakdown of uncertainties on pT and mass response for large-R jets with values of m/pT ≈ 0.2 using the Rtrk method

R=1.0 jets: Forward folding method for jet mass scale and resolution

CERN-EP-2018-191

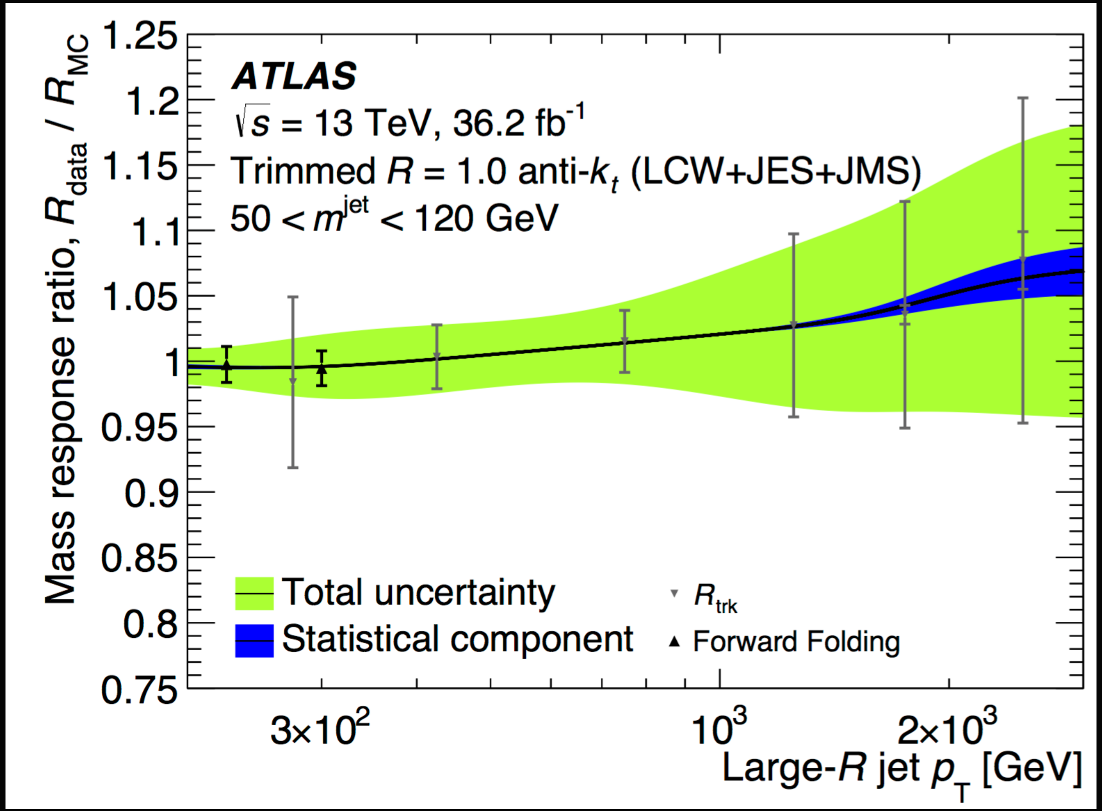
- Produces simulation predictions of the jet mass spectrum with variable response and resolution.
- Ratio of the mass response in data and simulations (s = Rmdata/RmMC) and of the mass resolution in data and simulations (r = σmdata/σmMC) are extracted from the jet mass spectrum.
- Done by folding particle-level jets with a response function.



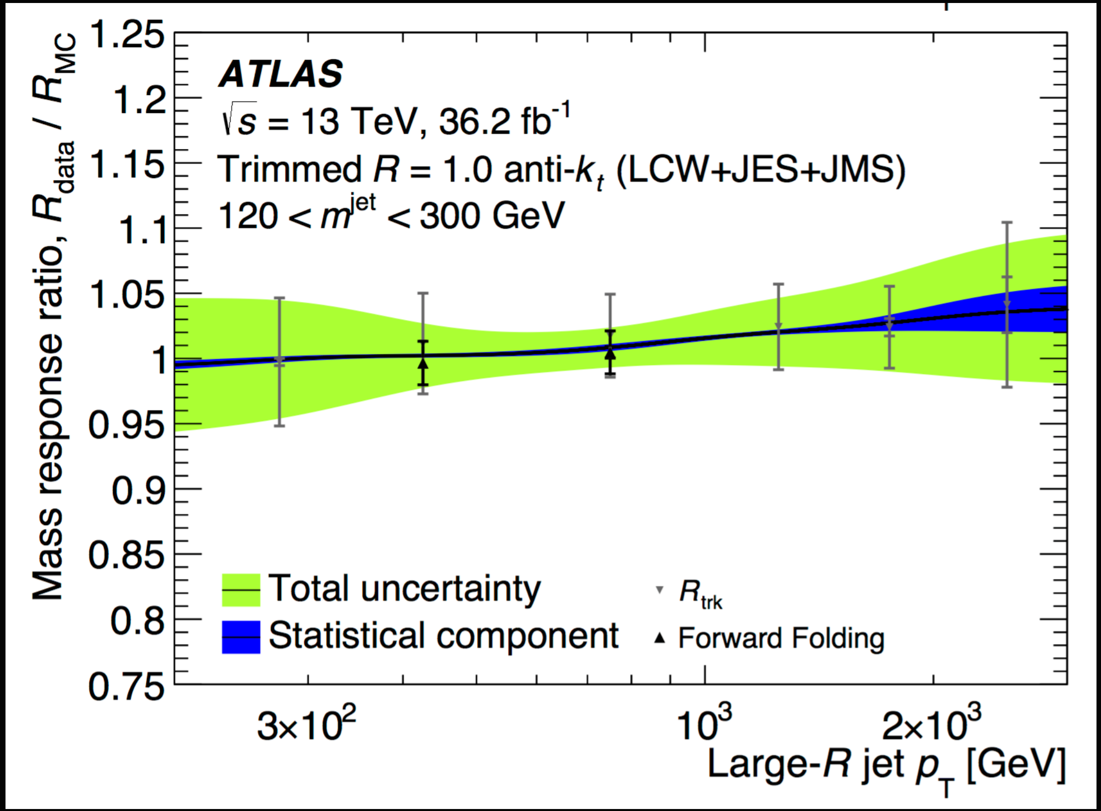


R=1.0 jets: Combined (Rtrk and fwd folding) measurement of Jet mass scale

- Forward folding provides four measurements for pT < 1 TeV.
- Rtrk method extends the measurement to ~ 2 TeV.
- Found to be consistent with one.



Fit in W mass range



Fit in top mass range

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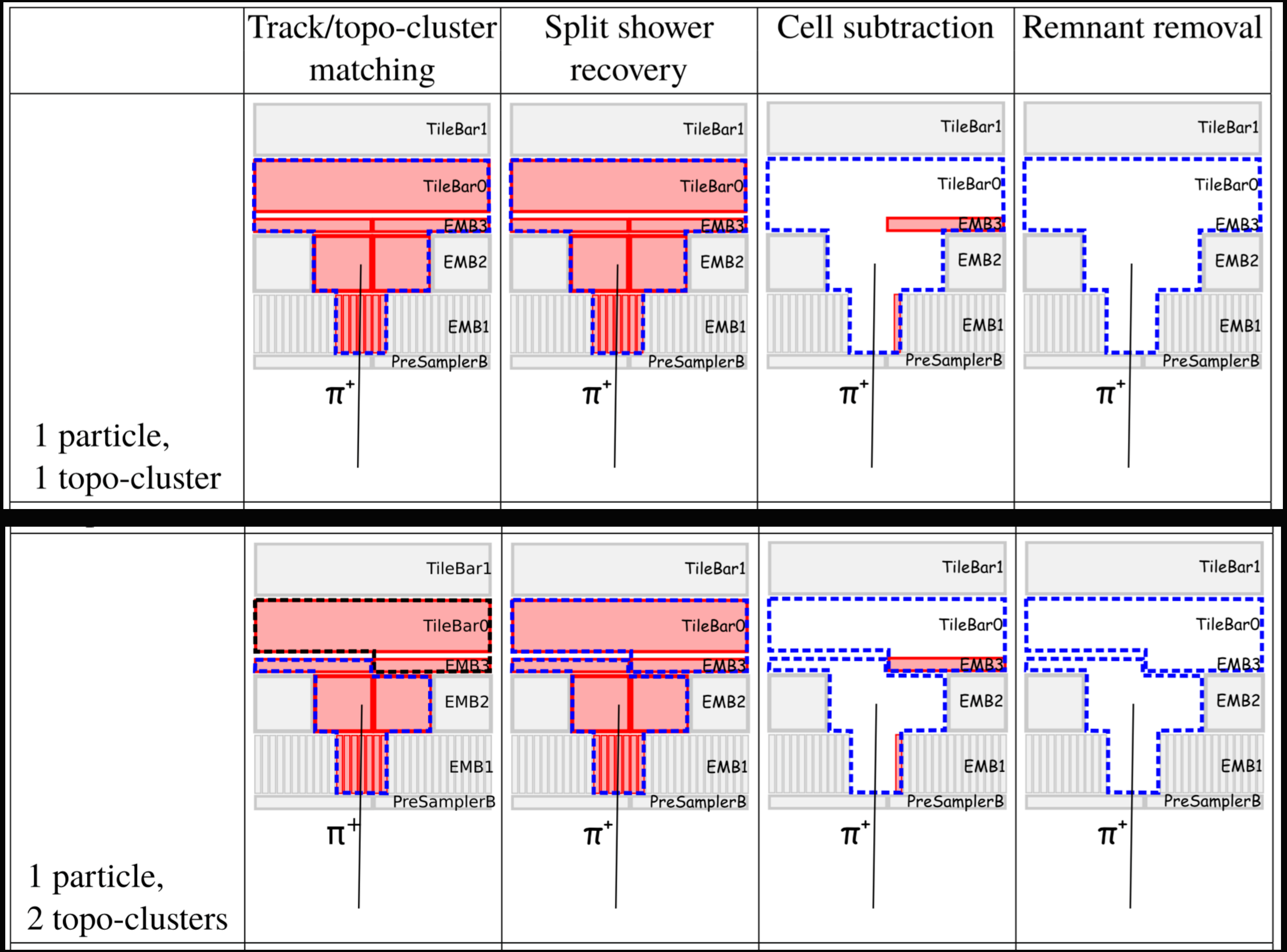
Summary

- Jets can be used to study quark-gluon initiated jets or to reconstruct hadronic decays of massive particles like top, W/Z and Higgs.
- Jets can be reconstructed from various inputs
  - Using tracking information can improve pT or substructure resolution.
- Several in situ calibration methods are used to measure the response of the ATLAS detector to small-R and trimmed large-R jets.
- For R=0.4 jets, the uncertainty on the jet energy scale derived from data is < 1% for 0.1 < pT < 1 TeV in the central region
- For R=1.0 jets:
  - Uncertainty on the jet energy scale derived from data is 1–2% for pT from 150 GeV to 2 TeV.
  - Jet mass scale precision varies from 2% to 10% over the same pT range.
  - The in situ JES calibration, derived from light quark and gluon jets, is found to fully correct the energy and mass scales of high pT W bosons and top quarks to within the precision of the present measurement (1–3%).
- Effort continues to measure JES more precisely using the larger full Run 2 dataset.

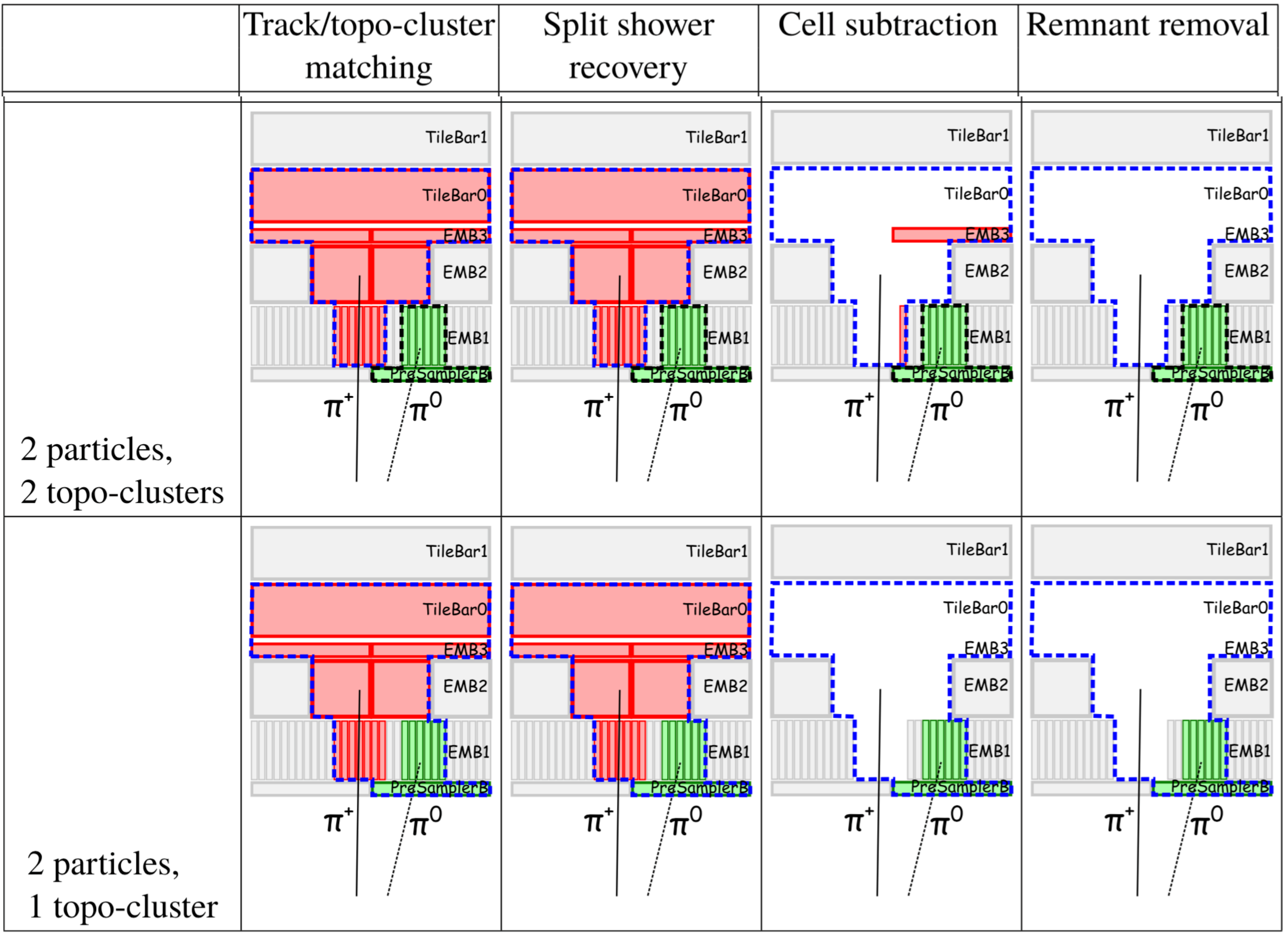
Backup

flow subtraction procedure for different cases (1)



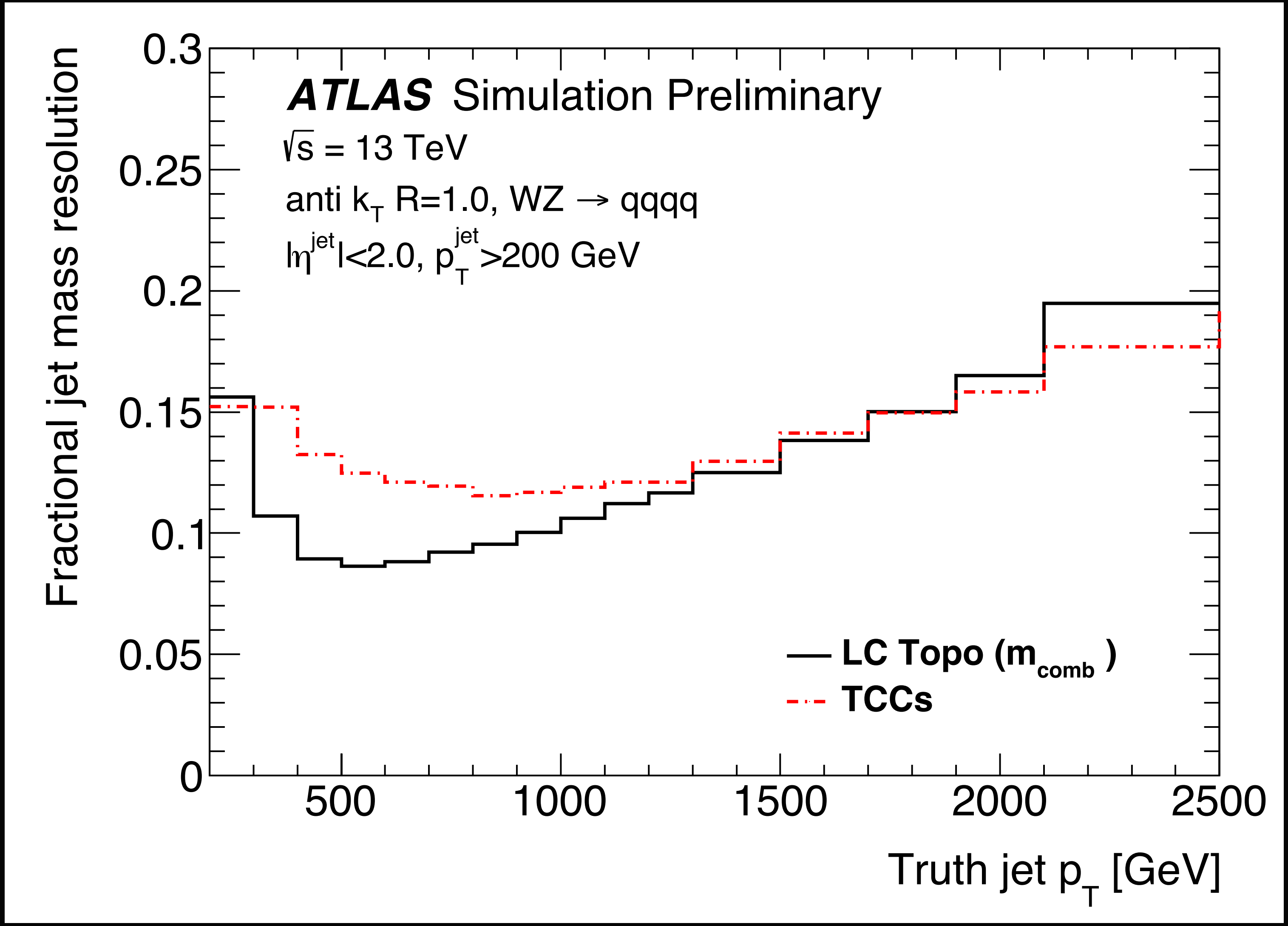
	Track/topo-cluster matching	Split shower recovery	Cell subtraction	Remnant removal
1 particle, 1 topo-cluster				
1 particle, 2 topo-clusters				

flow subtraction procedure for different cases (2)



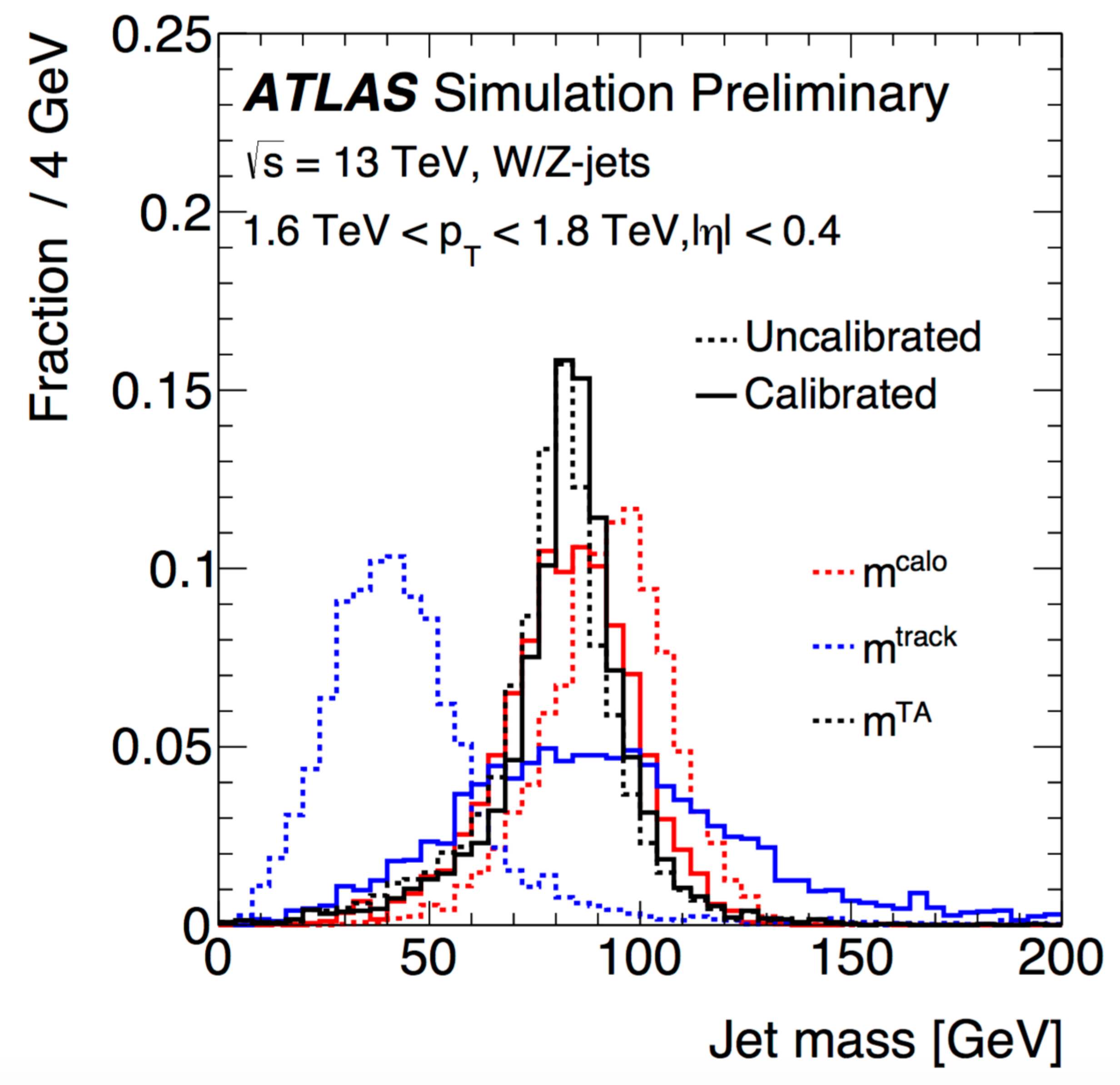
	Track/topo-cluster matching	Split shower recovery	Cell subtraction	Remnant removal
2 particles, 2 topo-clusters				
2 particles, 1 topo-cluster				

TCC mass

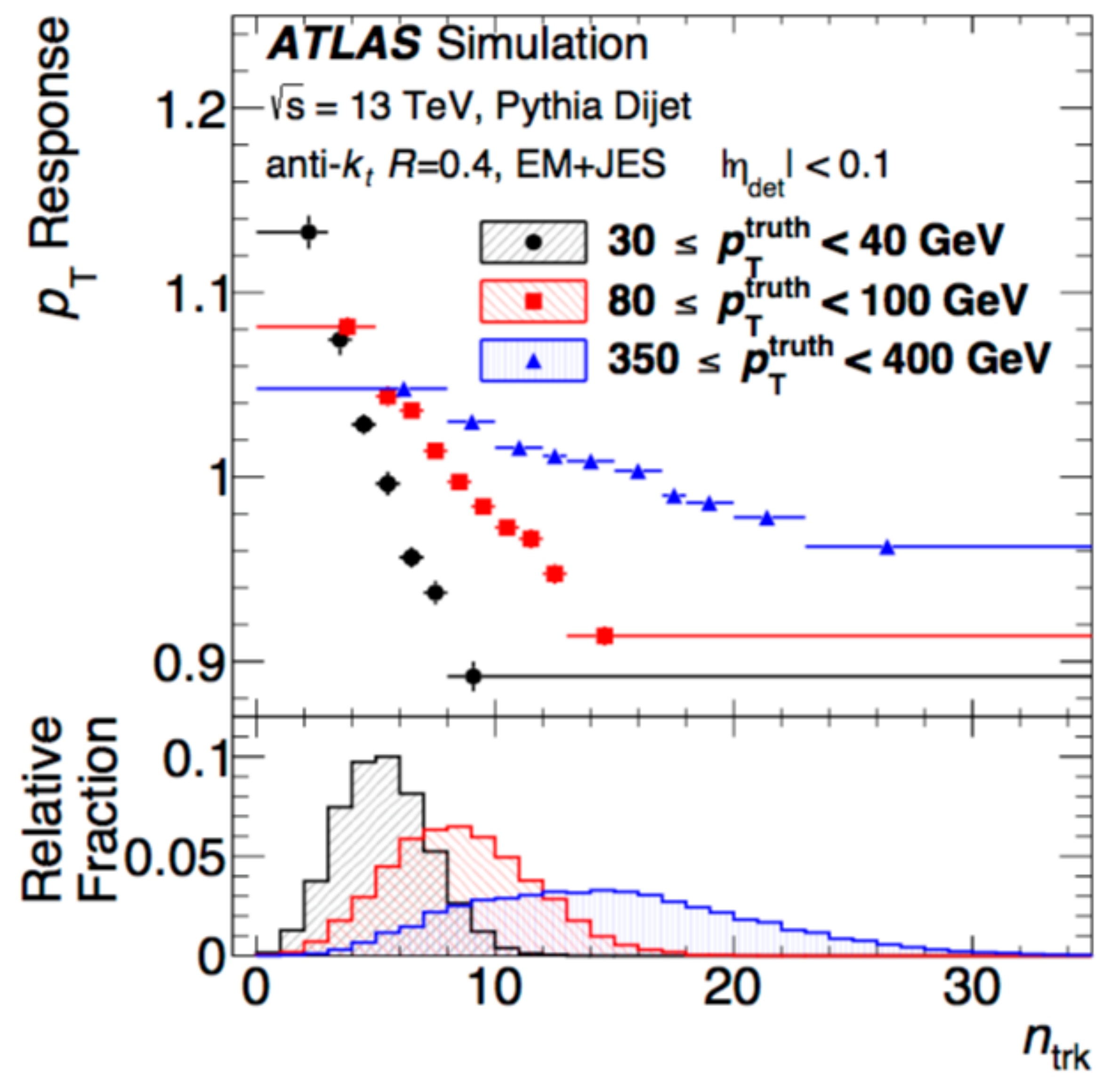


ATLAS Simulation Preliminary
$\sqrt{s}$ = 13 TeV
anti k_T R=1.0, WZ → qqqq
$|\eta^{jet}|$<2.0, p_T^{jet}>200 GeV
LC Topo (m_{comb})
TCCs
Fractional jet mass resolution
0
0.05
0.1
0.15
0.2
0.25
0.3
500
1000
1500
2000
2500
Truth jet p_T [GeV]

Track mass and track-assisted mass



GSC

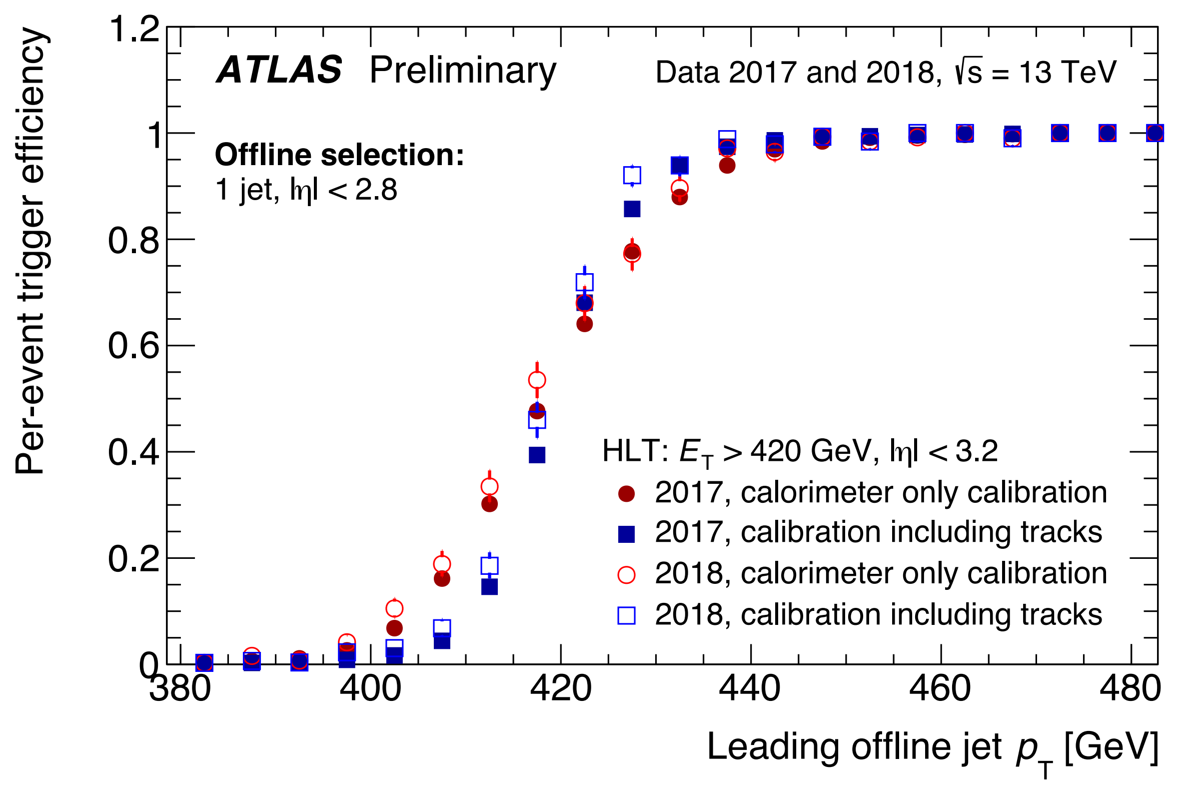

ATLAS Simulation
√s = 13 TeV, Pythia Dijet
anti-k_t, R=0.4, EM+JES
$|\eta_{det}| < 0.1$
$30 \leq p_T^{truth} < 40$ GeV
$80 \leq p_T^{truth} < 100$ GeV
$350 \leq p_T^{truth} < 400$ GeV
p_T Response
1.2
1.1
1
0.9
Relative Fraction
0.1
0.05
0
0
10
20
30
n_{trk}

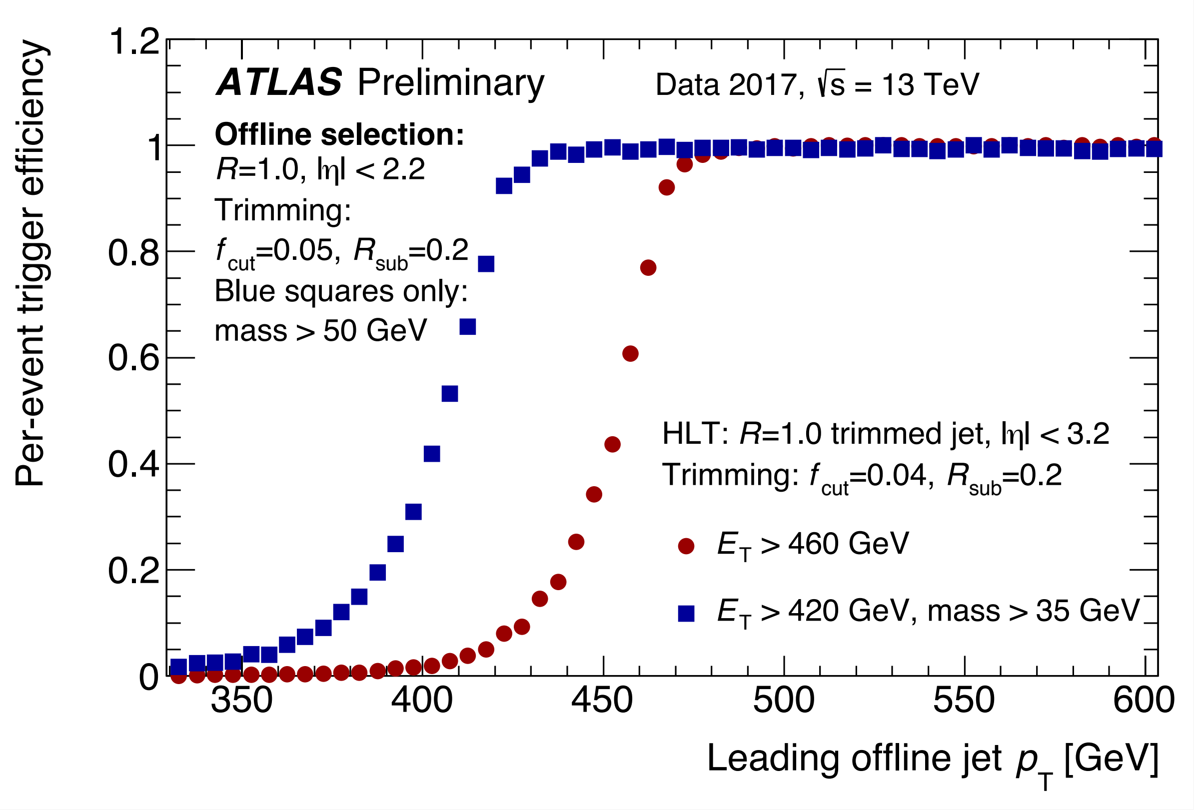
Calibration procedure of calorimeter signals

- Three types of calibration runs for extraction of electronic calibration constants: pedestal, ramp and delay
  - Pedestal: measurement of baseline level and noise properties of the readout electronics
  - ramp: measurement of readout gain
  - delay: measurement of pulse shape as a function of time.
- These special calibration runs are acquired between LHC fills, in absence of collisions

Jet triggers

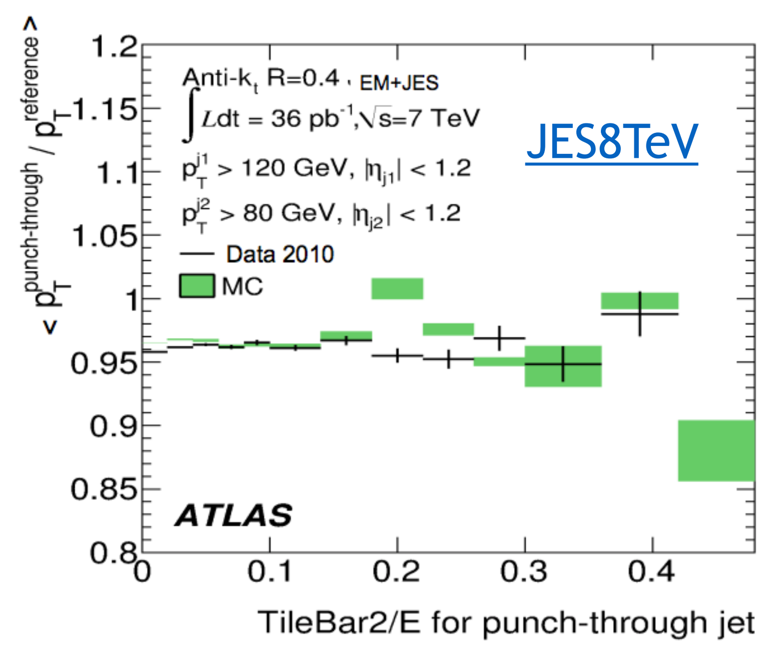
Efficiencies for single R=0.4 and R=1.0 jet triggers as a function of the leading offline trimmed jet pT

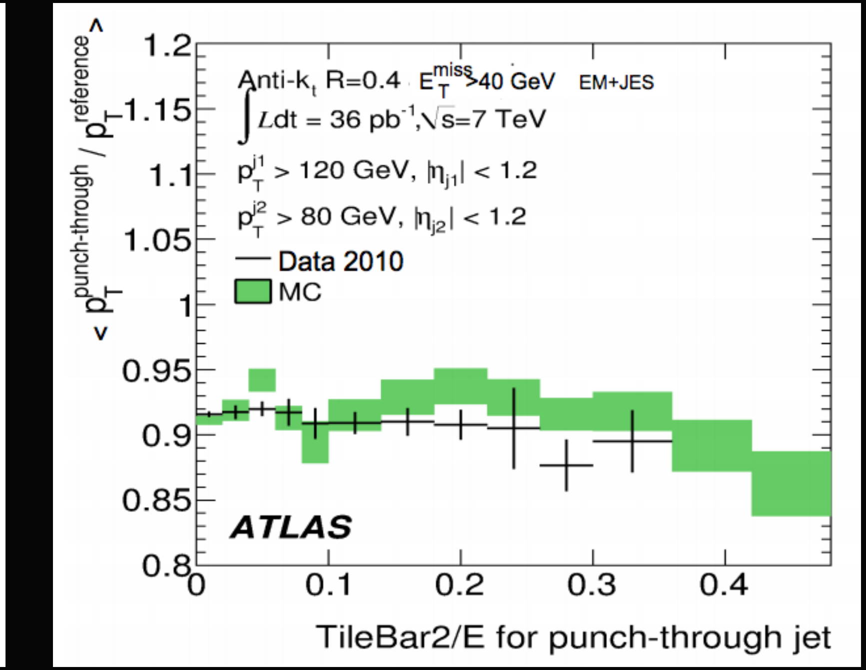


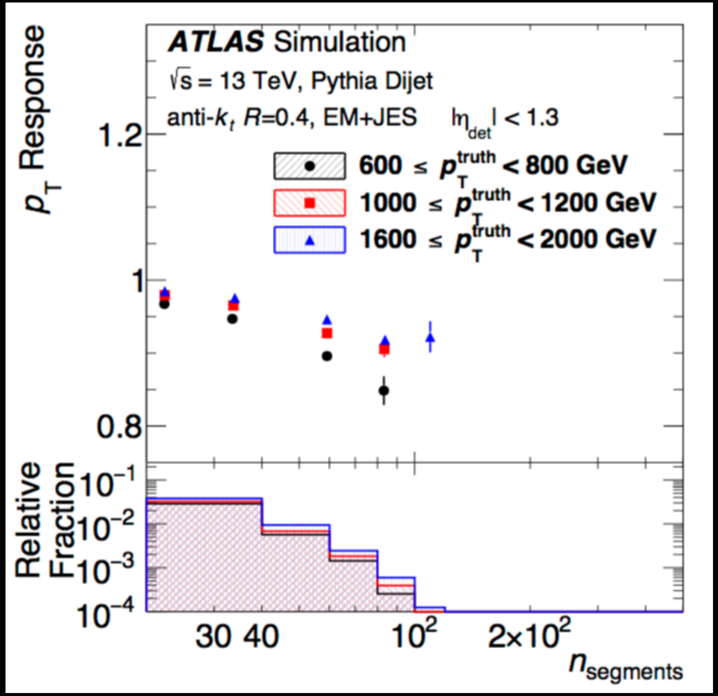


Study of jet punch-through

- nsegments: number of muon track segments ghost-associated with the jet (|eta(det)| < 2.7): targeting jets that are not fully contained in the calorimeter (punch-through jets)
- Jets that deposit energy beyond the hadronic Tile calorimeter and in the muon system
  - Systematic reduction of measured jet energy
  - Can happen in any detector pseudo rapidity region
- Dijet pT balance technique:
  - Asymmetry between transverse momentum of reference jet (pTreference) and punch-through jet as a function of energy deposition of the latter jet
  - Cannot know *apriori* which jet will be affected by punch-through effect
  - Use missing transverse energy (ETmiss) : energy lost beyond calorimeter creates a component of missing transverse energy in the direction of punch-through
    - Jet closest to ETmiss Phi direction selected as punch-through jet

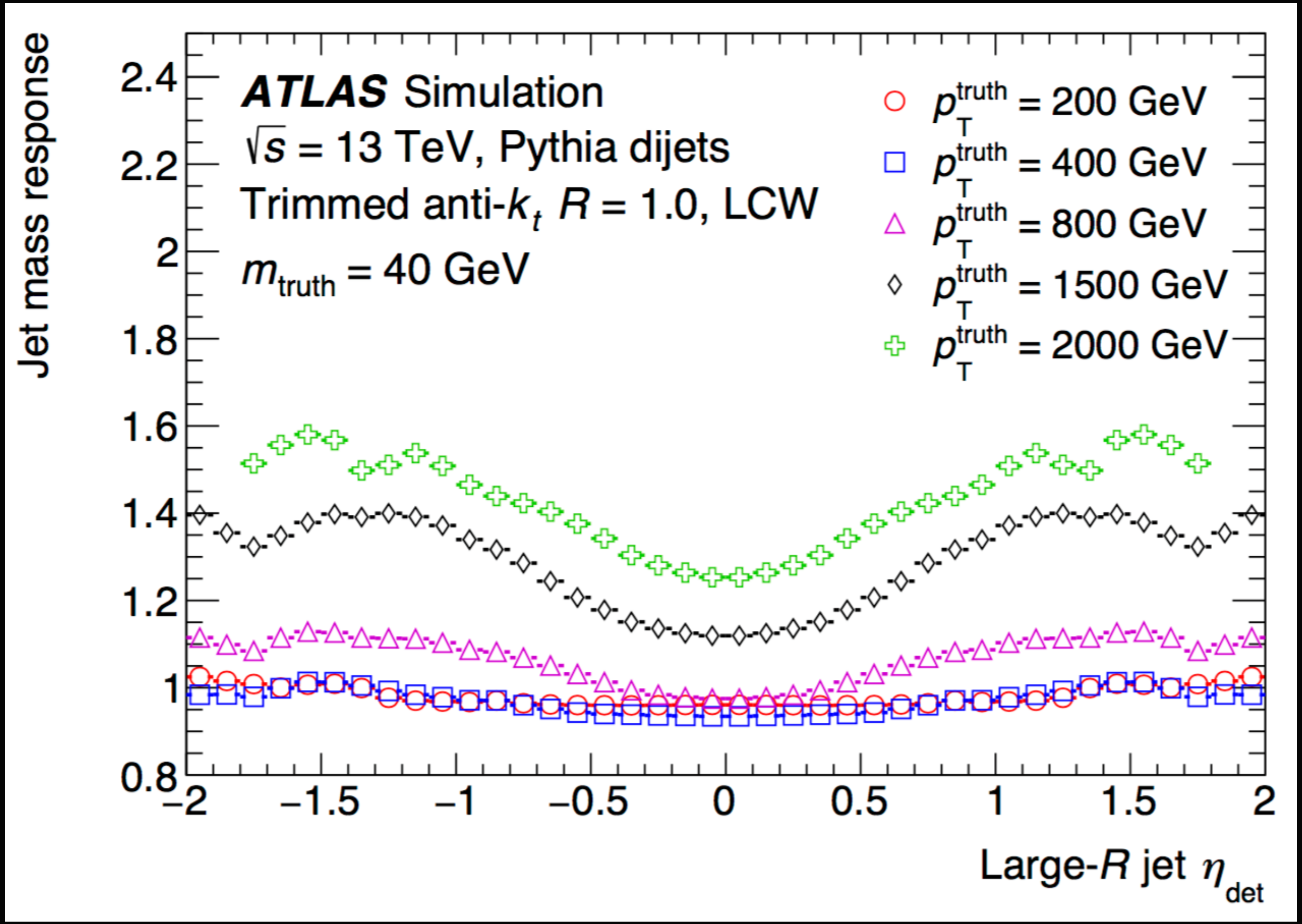






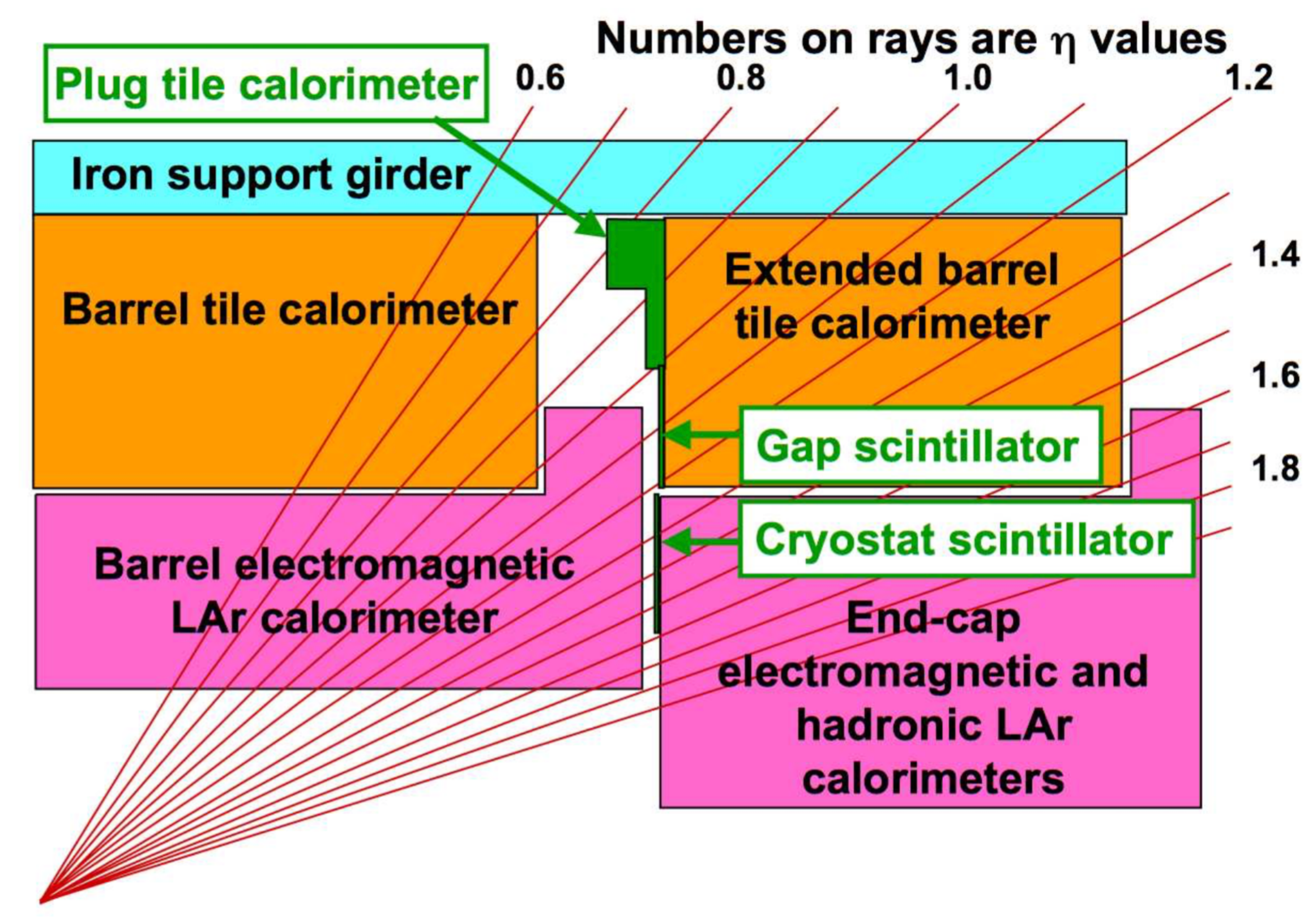
Simulation based mass response correction (m=40 GeV)

- Jet mass more sensitive to soft, wide angle radiation and topocluster merging and splitting and calorimeter geometry than pT.
- Correction (cJMS) applied after Jet energy response correction, R jet energy kept fixed and pT allowed to vary.



m=40 represents a typical value for quark or gluon jets

Calo transition regions



Summary of in-situ calibration factors applied in data

Full calibration applied to jets in data impacts the reconstructed jet energy, mass, eta, and pT:

$$E_{\mathrm{reco}} = c_s \sqrt{E_0^2 + c_{\mathrm{JMS}}\, m_0 \left(c_m^2 - 1\right)}, \quad m_{\mathrm{reco}} = c_s\, c_{\mathrm{JMS}}\, c_m\, m_0, \quad \eta_{\mathrm{reco}} = \eta_0 + \Delta\eta,$$

$$p_{\mathrm{T}}^{\mathrm{reco}} = c_s \sqrt{\left(E_0^2 - c_{\mathrm{JMS}}^2\, m_0^2\right)} \cosh\left(\eta + \Delta\eta\right),$$

Pileup correction: 0.4 jets

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

Uncertainty on R-1.0 jet fractional pT resolution