New Techniques for Jet Reconstruction and Calibration at ATLAS

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and TRIUMF
- on behalf of the -
ATLAS Collaboration

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See ATLAS Collaboration, arXiv:2303.17312 [hep-ex]
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(unless otherwise noted, figures are from this note)

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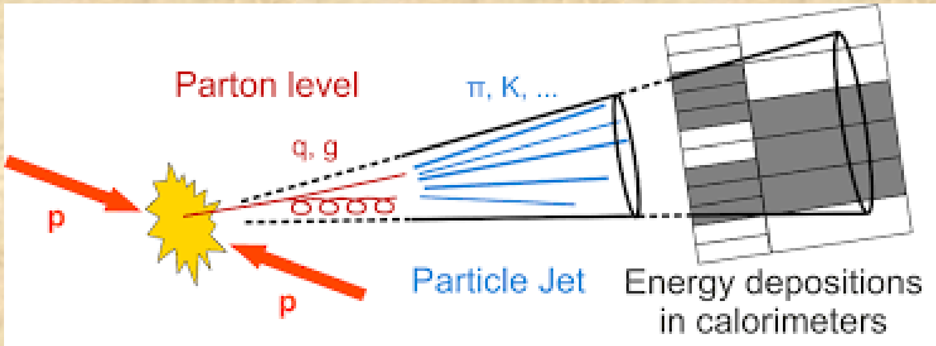
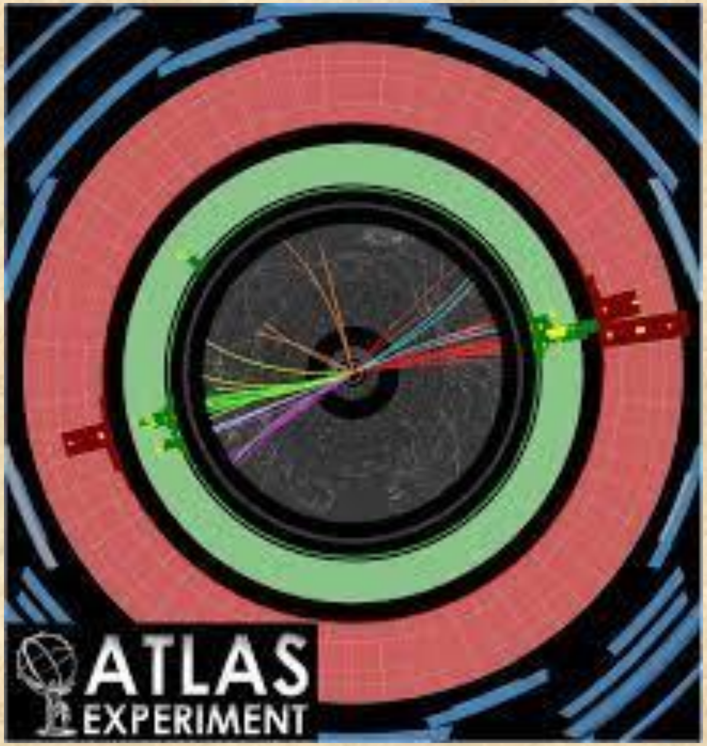
Introduction

• *Jets are ubiquitous in high-energy pp collisions. Critical to understand them for all physics analyses.*

• *Collimated streams of particles (mostly hadrons) created by quarks and gluons emerging from the collisions.*



ATLAS
dijet event



Introduction

• *Jets are ubiquitous in high-energy pp collisions. Critical to understand them for all physics analyses.*

• *Collimated streams of particles (mostly hadrons) created by quarks and gluons emerging from the collisions.*

• *Reconstruction and calibration are particularly difficult in the presence of large pileup (multiple interactions superimposed on the hard scattering of interest).*

• *Large-R jets capture the products of boosted particle decays (e.g. W, Z, top); determination of jet mass and substructure now important, in addition to energy.*

• *ATLAS has done numerous studies with Run-2 data to fine tune the reco and calibration of jets to improve physics results.*

=> some of this here in this talk

Inputs to Jet Reconstruction

- *Calorimeter Clusters: Energy deposited in the calorimeter*
- *Particle Flow Objects (PFlow): Tracks are measured better in the Inner Detector at lower energies (< 100 GeV). Replace calo clusters with tracks & subtract predicted energy deposits from the clusters. Keep neutral PFOs unchanged => ATLAS Standard*

Inputs to Jet Reconstruction

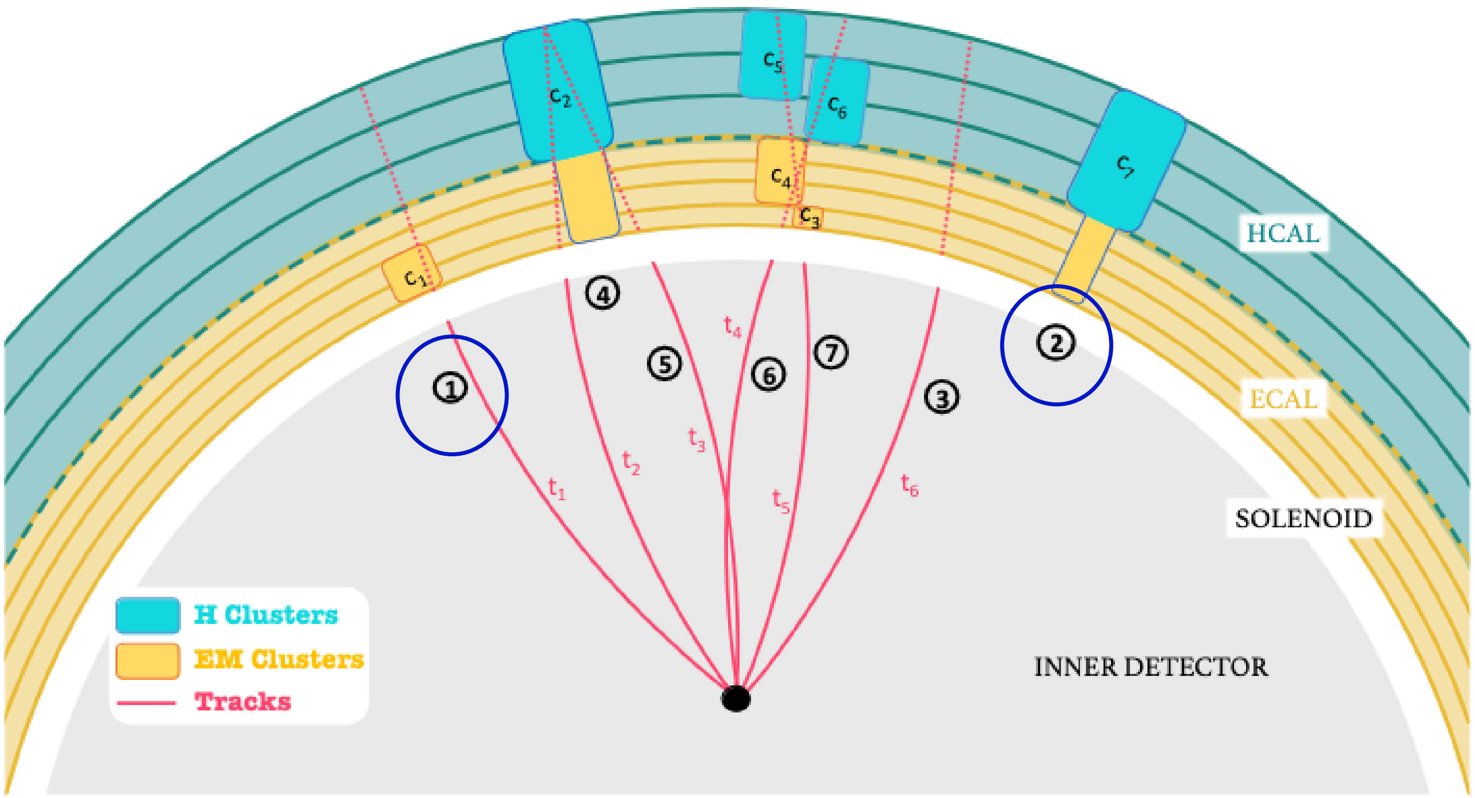


Figure 3: A schematic demonstrating the creation of seven TCC objects representing ① a simple track-cluster match, ② a topo-cluster without a matching track, ③ a track without a matching cluster, ④ and ⑤ are each tracks matching a single cluster but sharing that cluster's energy, and ⑥ and ⑦ showing a much more complex scenario with multiple track-cluster matches. Details on the exact reconstruction procedure and the seven TCC 4-vectors are provided in the text.

ATL-PHYS-PUB-2017-15

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Inputs to Jet Reconstruction

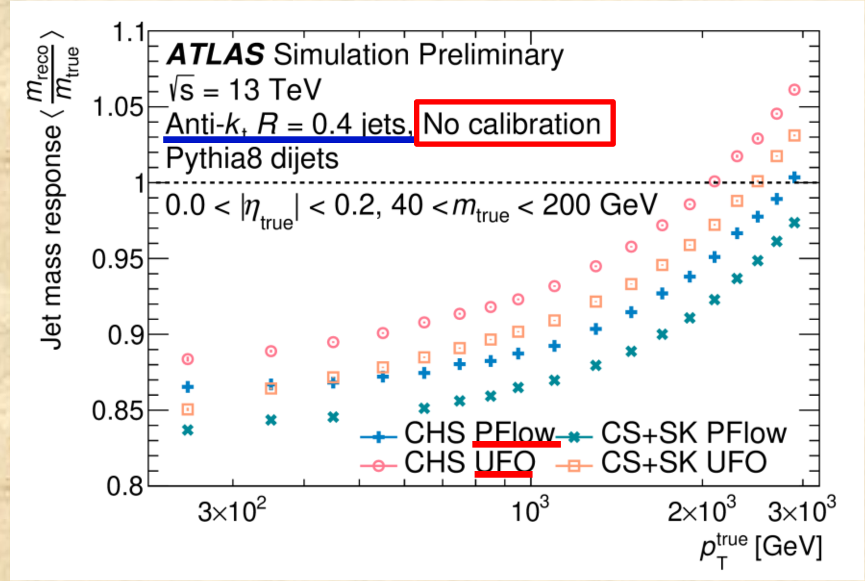
- *Track Calo Clusters:* *Produce new 4-vectors that use the energy from the calorimeter & angles from matched tracks: (p_T, η, ϕ). Clusters shared by more than one track are split. Also have neutral TCCs.*
  Much better jet mass and substructure measurement.

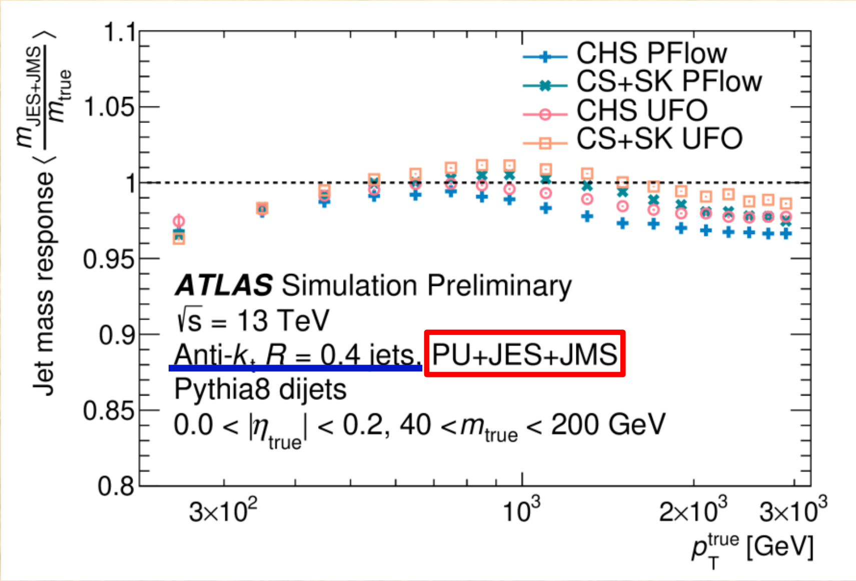
- *Unified Flow Objects (UFO): Start with standard PFlow; remove pileup vertices. Then apply a modified TCC cluster splitting at high energy (don't consider tracks used for Pflow and ignore pileup vertices). Especially improve the jet mass and substructure variables.*

  => new ATLAS standard

Inputs to Jet Reconstruction

- *Jet reco using various constituent objects; PFOs vs UFOs*
- *Improved jet-mass response; even better with large-R jets.*





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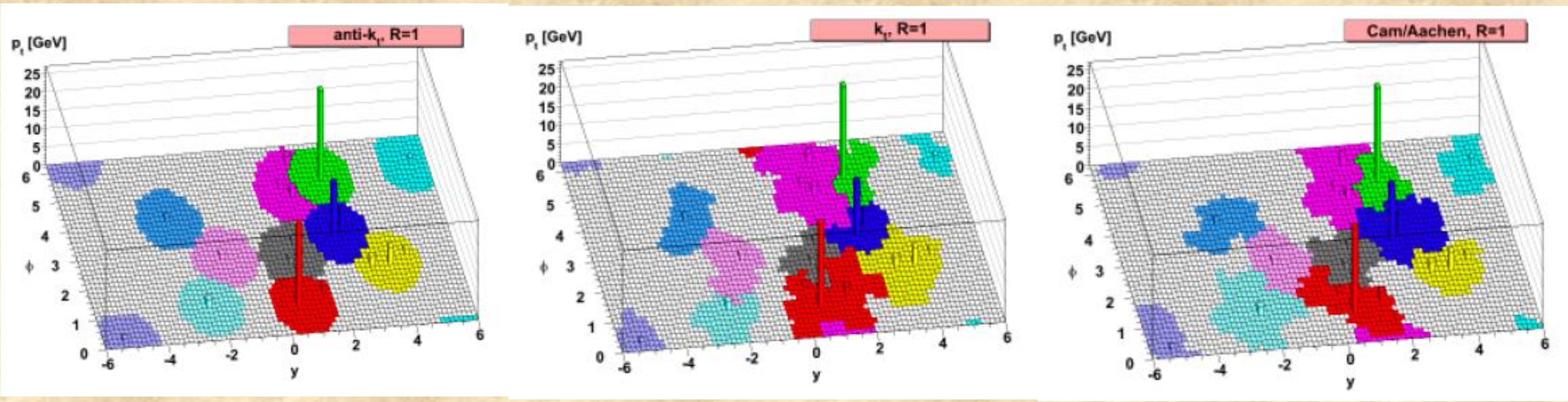
CHS, SK, CS are constituent-level pileup mitigation techniques; effectively remove low-energy particles before jet reco

(see backup slides)

Jet Reconstruction Algorithm

- *ATLAS uses the anti-k_T recombination scheme with a radius of R= 0.4 and R= 1.0, the latter for boosted decaying objects.*
  R is the radius in the (y,ϕ) plane.

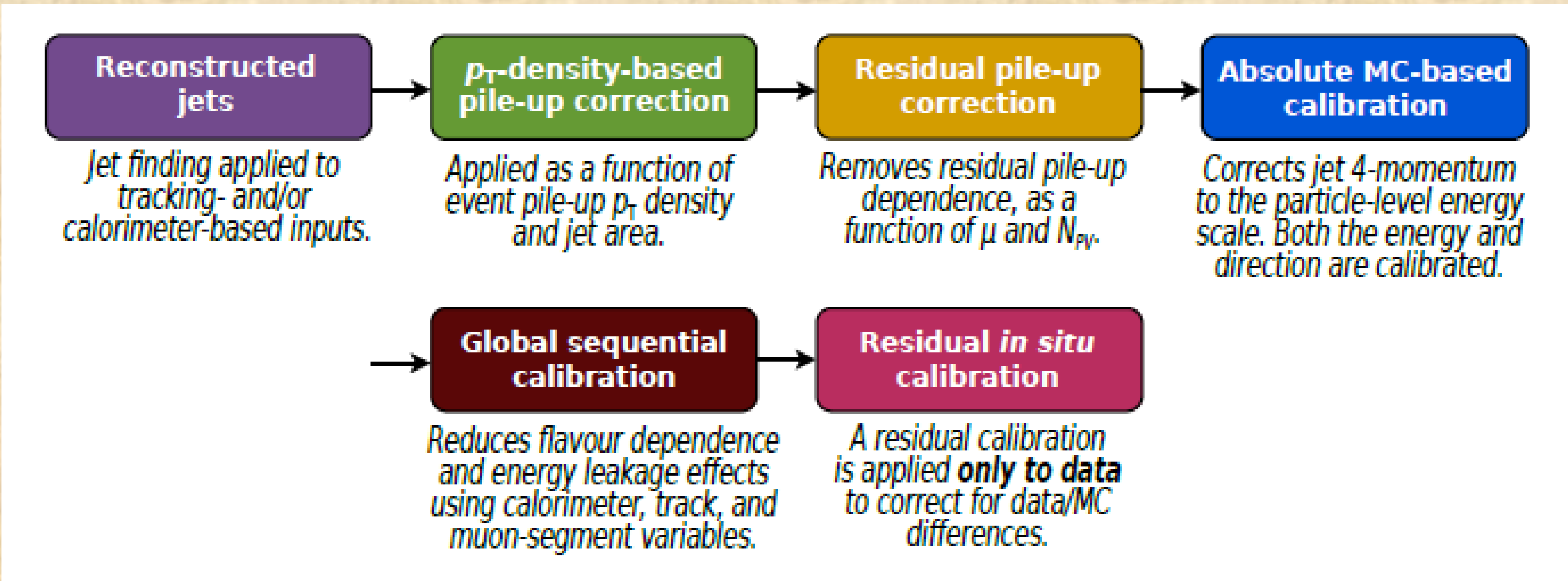
- *Also use the k_T and Cambridge-Aachen algorithms for large-R jet grooming (e.g. trimming, pruning, and soft-drop)*



M. Cacciari & G. Salam; JHEP04 (2008) 063

The Calibration Chain

• *ATLAS uses a <u>Monte-Carlo based calibration scheme</u> that is adjusted using in-situ measurements*



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Pileup Mitigation

- *Default:* use an *area-based subtraction* of pileup activity in a jet

$$p_{\mathrm{T}}^{\mathrm{area}} = p_{\mathrm{T}} - \rho \times A$$

- A: jet area determined using ghost tracks.
- ρ: estimated pileup energy density (median of all jets reconstructed with the k_T algorithm with R= 0.4).
  Pileup is assumed to be uniform in the detector
  New: "pile-up sideband" algorithm
  (ignore hard scatter vertex)

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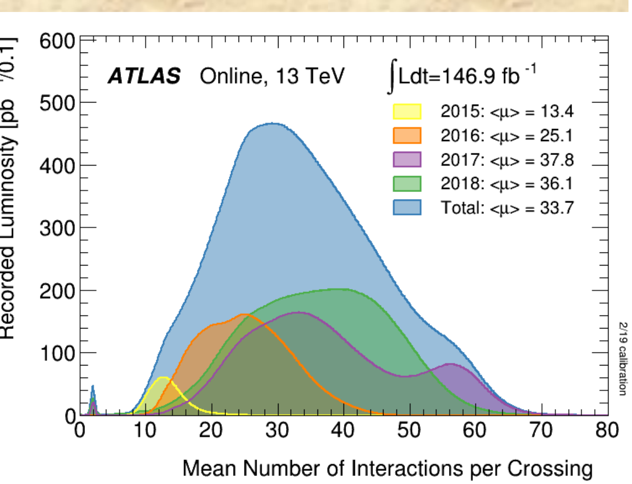
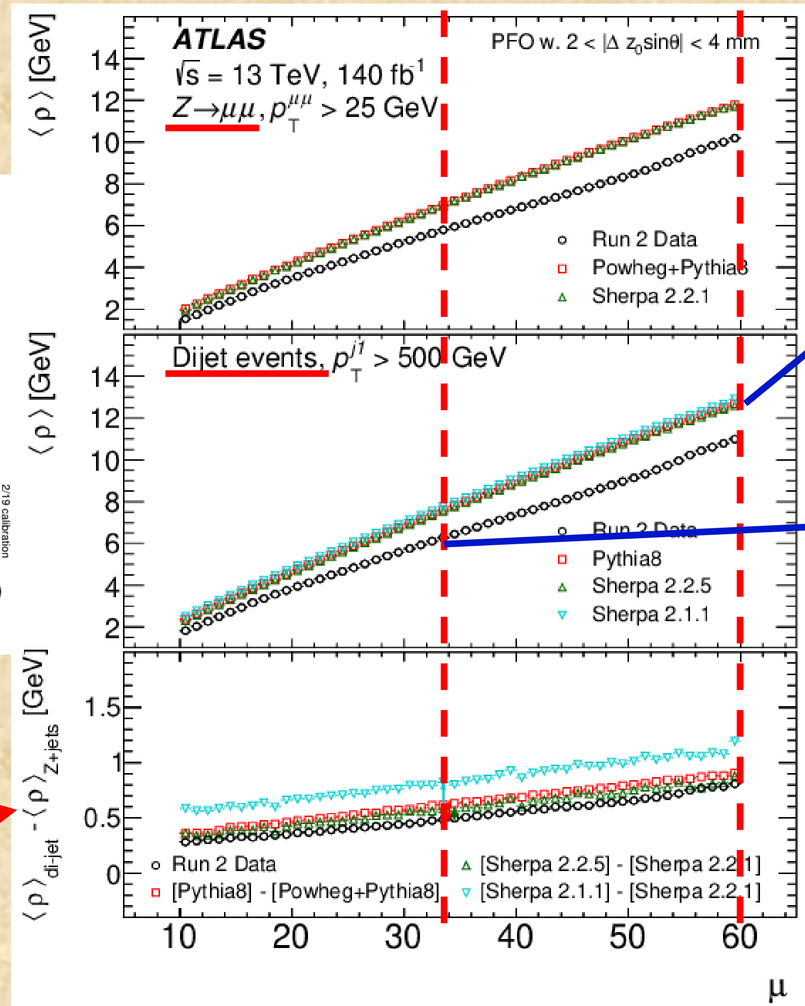
Pileup Mitigation

μ is the average # of interactions (N_{PV}) per beam crossing





R= 0.4 => 5.5 GeV
R= 1.0 => 35 GeV

R= 0.4 => 3 GeV
R= 1.0 => 19 GeV

Topology Bias:
The calo response depends on how busy the event is

Pileup Mitigation

- *Residual pileup correction: plot the pileup corrected energy as a function of N_{PV} and μ => not flat!*
- *1D correction:* $p_{\mathrm{T}}^{\mathrm{1D\ residual}} = p_{\mathrm{T}}^{\mathrm{area}} - (\partial p_{\mathrm{T}}/\partial N_{\mathrm{PV}}) \times (N_{\mathrm{PV}} - 1) - (\partial p_{\mathrm{T}}/\partial \mu) \times \mu.$

Does not account for the correlation between N_{PV} and μ

Pileup Mitigation

- *Residual pileup correction:* *plot the pileup corrected energy as a function of* N_{PV} *and* μ *=> not flat!*
- *1D correction:* $p_T^{\text{1D residual}} = p_T^{\text{area}} - (\partial p_T/\partial N_{PV}) \times (N_{PV} - 1) - (\partial p_T/\partial \mu) \times \mu.$

Does not account for the correlation between N_{PV} *and* μ

- *3D correction:* $p_T^{\text{3D residual}} = p_T^{\text{area}} - \Delta p_T^{\text{area-truth}}(N_{PV}, \mu, p_T^{\text{area}})$

  - *Corrects for* N_{PV} *and* μ *at the same time AND*
  - *Corrects back to the particle/truth level*
    => i.e. includes pileup AND detector effects (shifts the JES)

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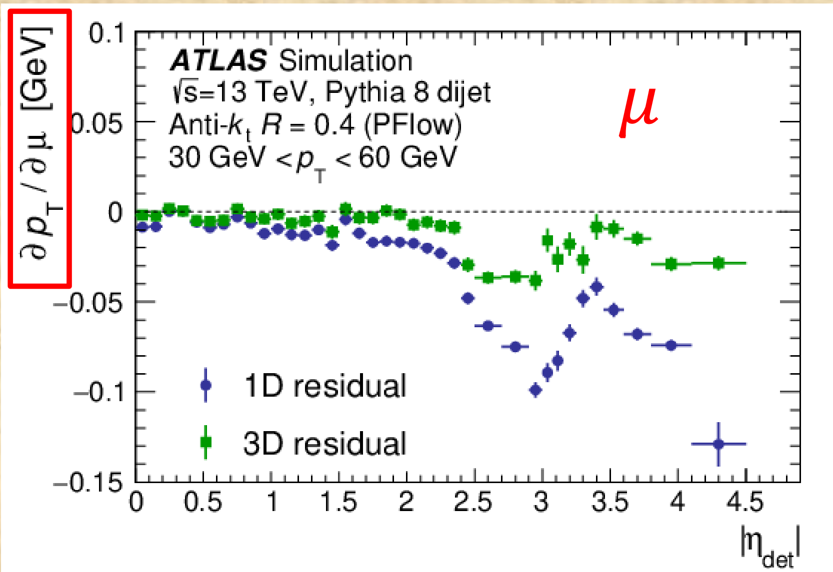
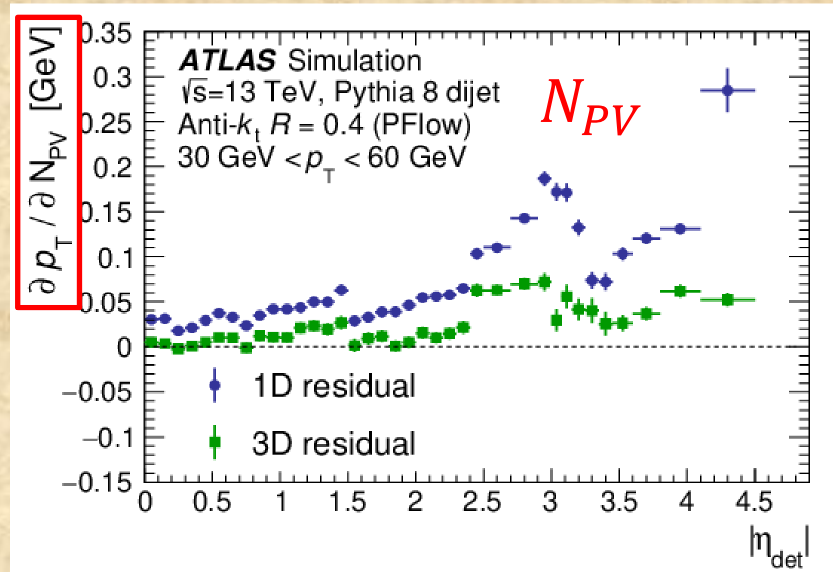
Pileup Mitigation

Comparison of 1D and 3D residual pileup corrections





=> *move to the 3D correction*

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Global Property Calibration

- *Jet resolution can be improved by examining jet properties.*
- *Correct for shower fluctuations (parton & calo showers)*
- *Correct for differences between quark- and gluon-induced jets*
  - *quark jets have fewer, higher energy constituents*
  - *gluon jets have more, lower energy constituents because there is more QCD radiation*
- *Parameters used sequentially: Global Sequential Correction (GSC)*
  - *number & total p_T of tracks*
  - *depth and width of the calorimeter shower*
  - *punch through to the muon spectrometer*

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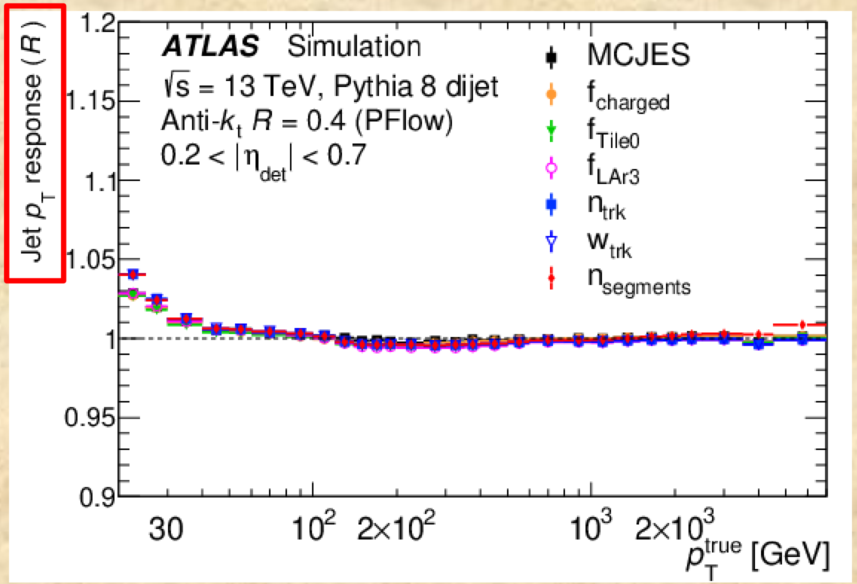
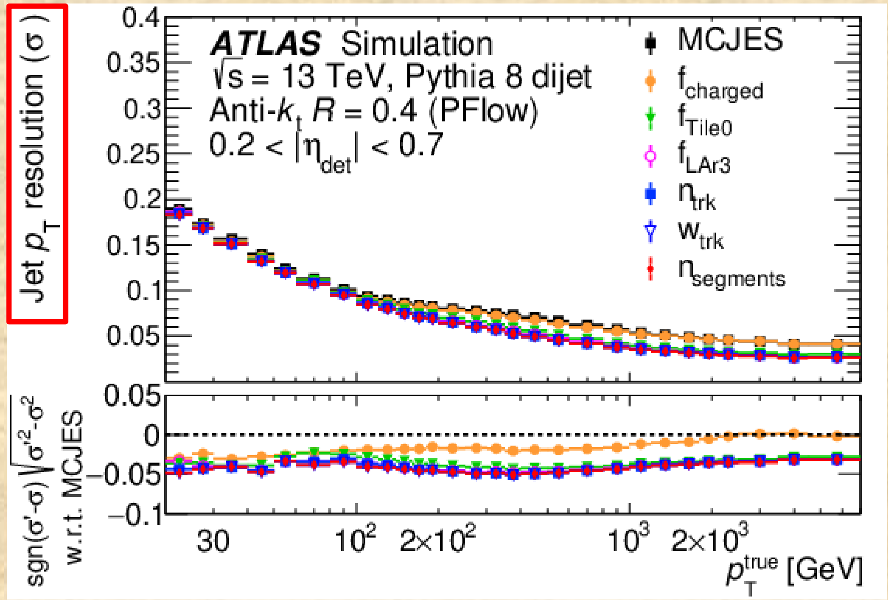
Global Property Calibration

- *The GSC should not change the Jet Energy Scale (JES), but should improve the Jet Resolution (JER).*



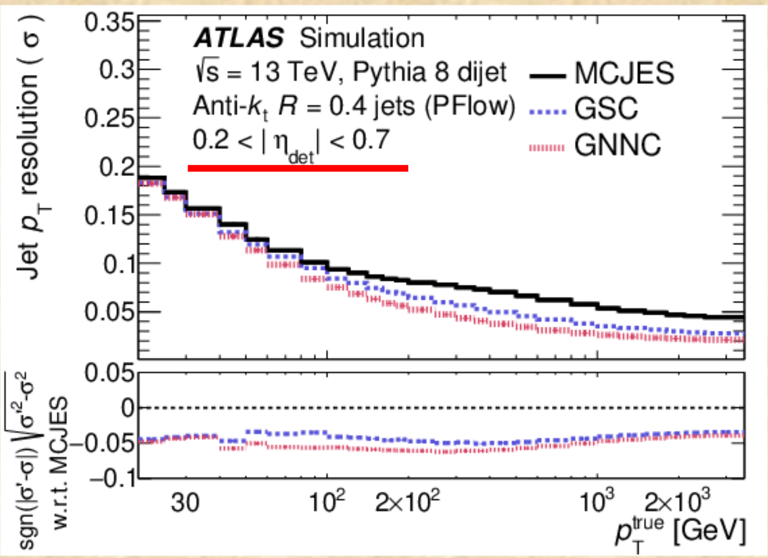


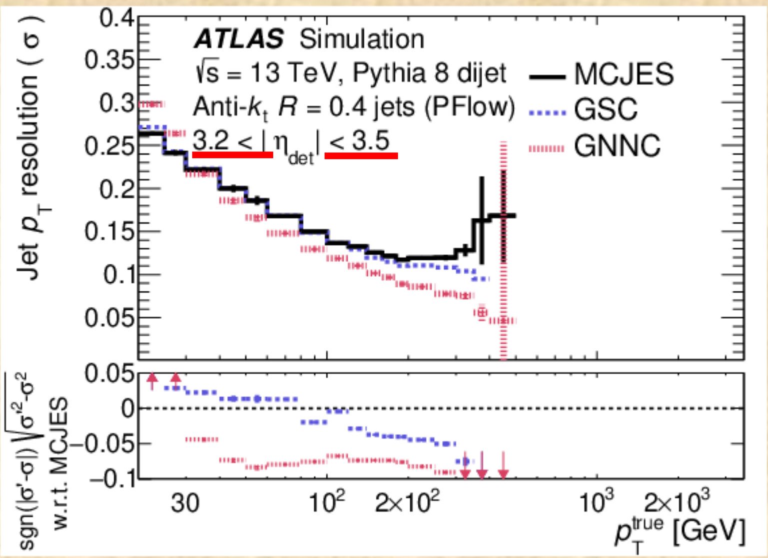
JES unchanged by any of the steps

JER improved above 100 GeV

Global Property Calibration

- *The GSC does not take correlations between jet properties into account, so it is limited in how many variables it can use.*
- *New: A Deep Neural Network (GNNC) is used to improve the situation, especially at high p_T and large eta.*





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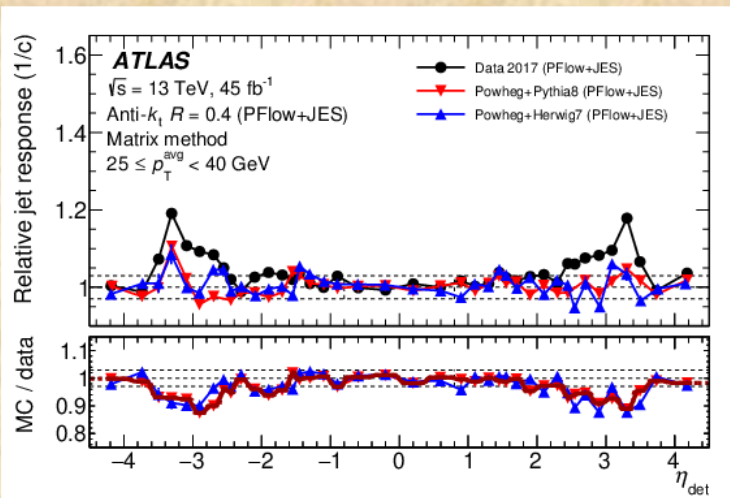
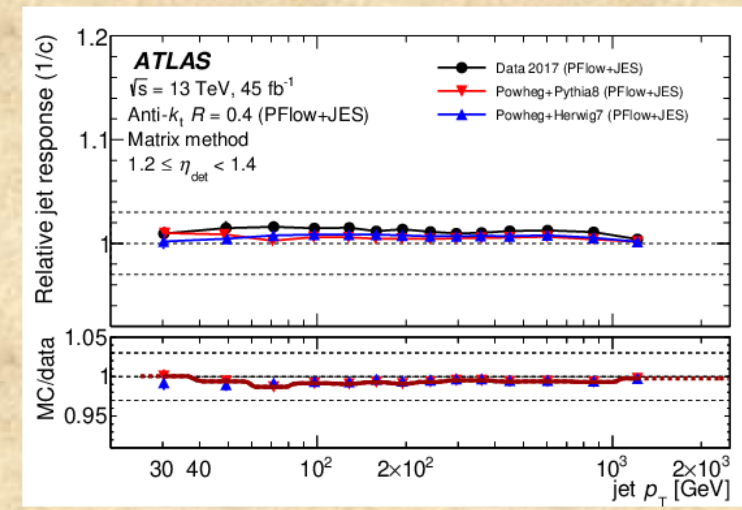
In-situ η inter-calibration

- *Use dijet events to transfer the calibration from the central detector to the forward region.*

$$\mathcal{A} = \frac{p_{\mathrm{T}}^{\mathrm{left}} - p_{\mathrm{T}}^{\mathrm{right}}}{p_{\mathrm{T}}^{\mathrm{avg}}}$$

$$\mathcal{R} = \frac{c^{\mathrm{right}}}{c^{\mathrm{left}}} = \frac{2 + \langle \mathcal{A} \rangle}{2 - \langle \mathcal{A} \rangle} \approx \frac{\langle p_{\mathrm{T}}^{\mathrm{left}} \rangle}{\langle p_{\mathrm{T}}^{\mathrm{right}} \rangle}$$

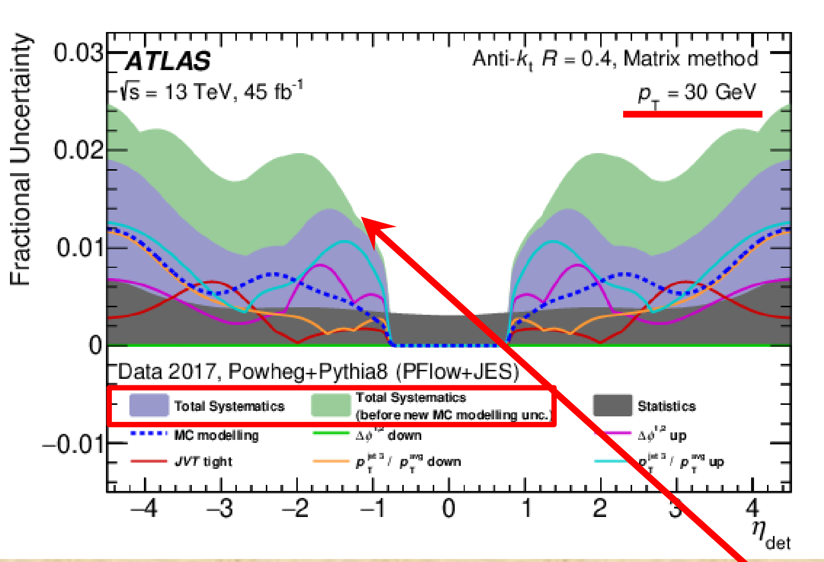


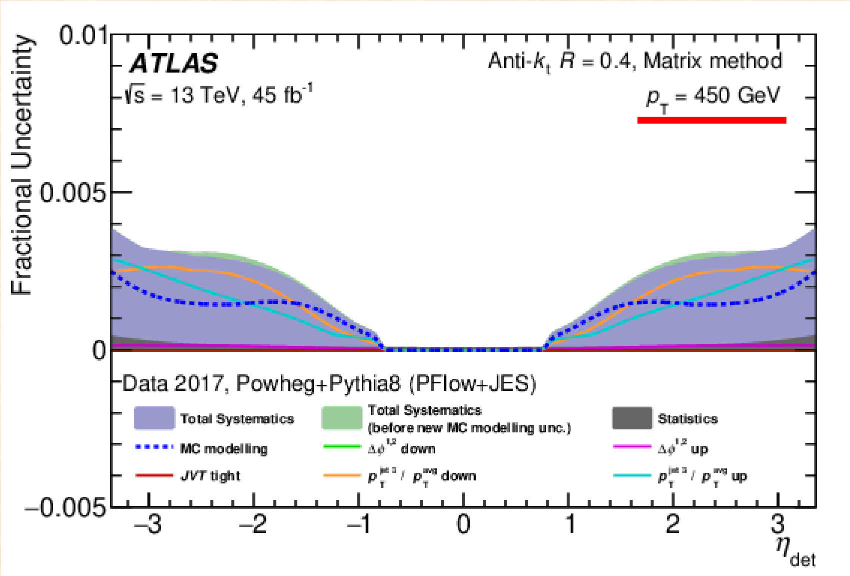


- *New: Studies done at particle and reco level to disentangle physics and detector effects.*

In-situ η inter-calibration

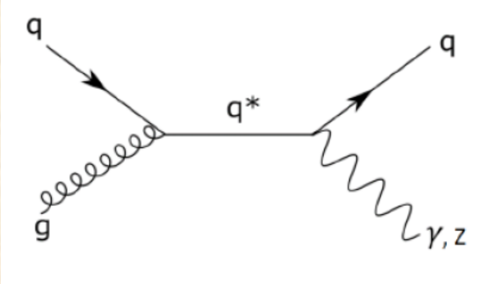
Uncertainties on transferring the jet calibration from the central region to the forward region





Improved MC modelling uncertainties, especially at low pT

In-situ JES – V+jet



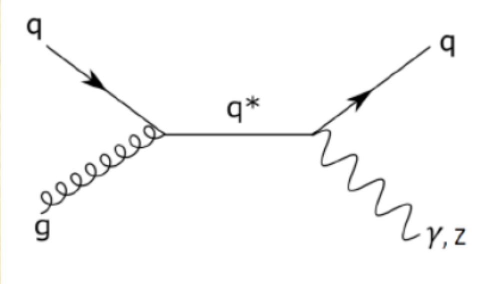
Z/γ+jet events
Z or γ well measured

- *Use the Missing E_T Projection Fraction (MPF) technique because it is less sensitive to pileup and has smaller uncertainties*

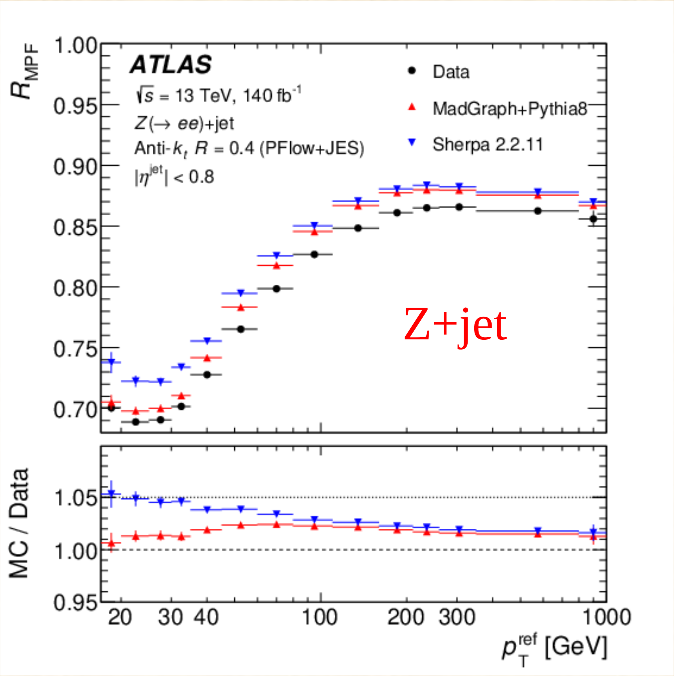
$$\vec{p}_T^{\,ref} + \vec{p}_T^{\,parton} = 0$$

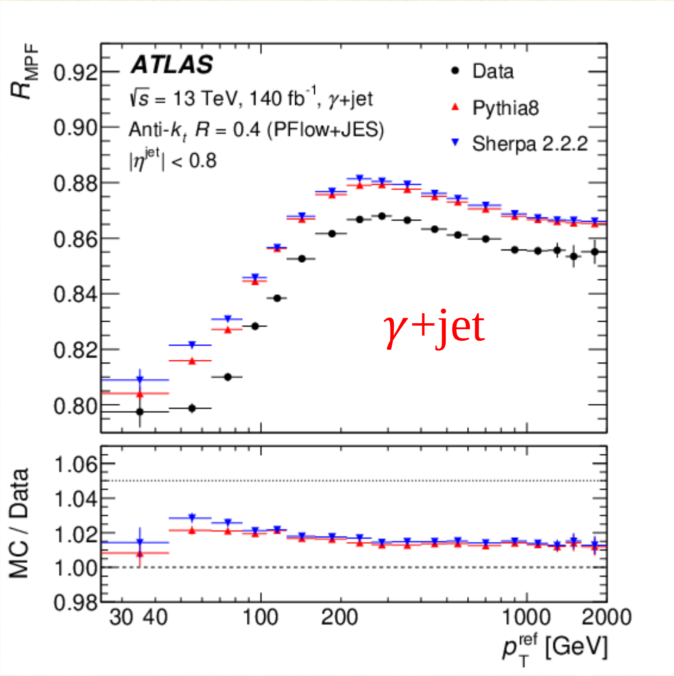
- *R_{MPF} is a measure of E_{meas}/E_{true}*

In-situ JES – V+jet



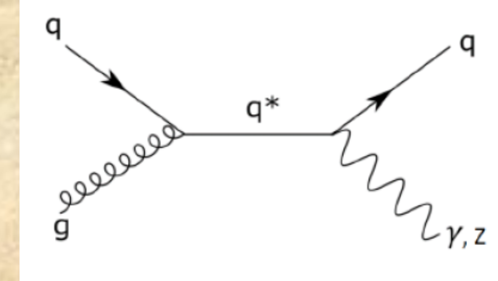
Cuts select events with two final-state objects (limit energy of a 2nd jet, back-to-back in ϕ)



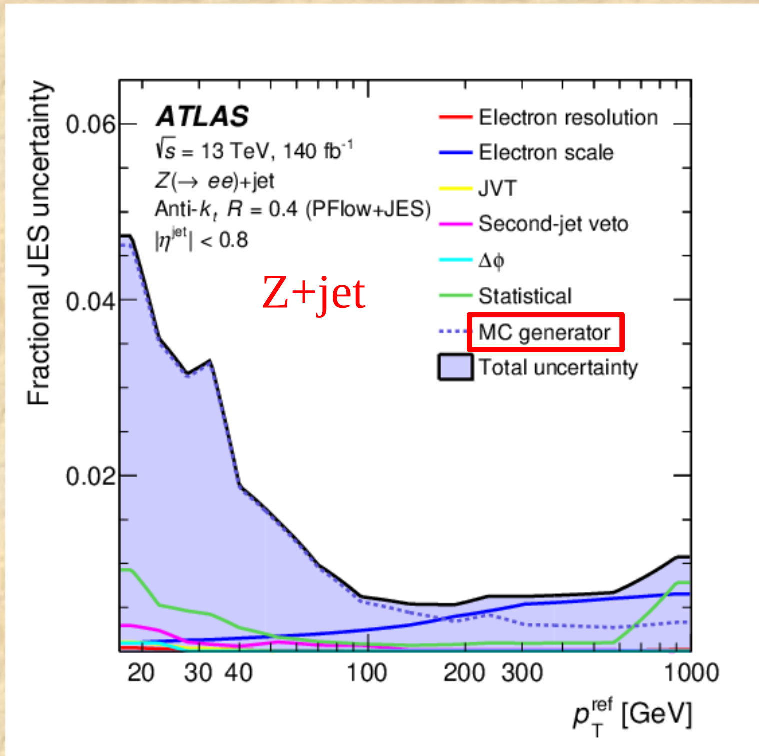


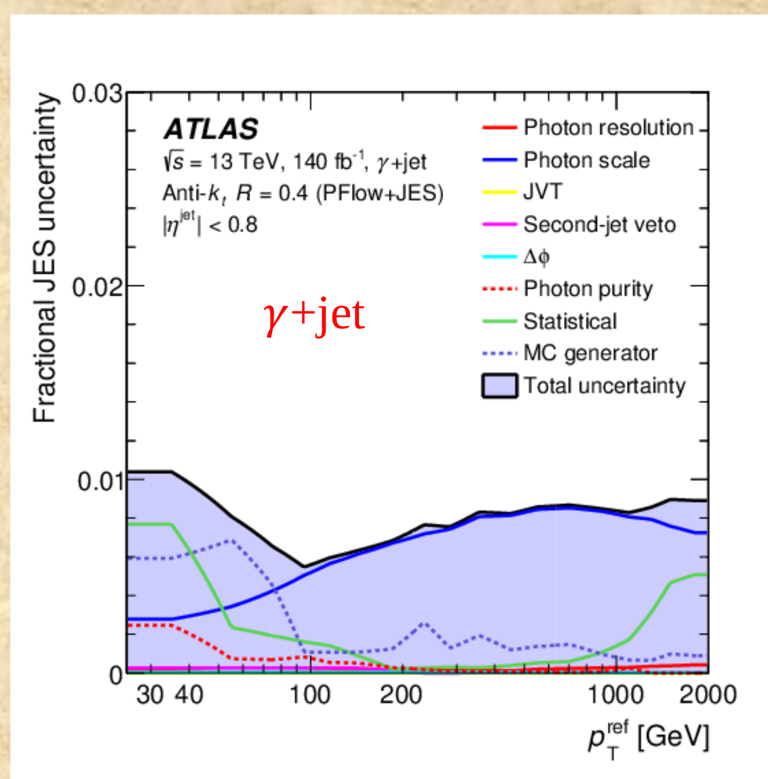
Correct the data for the difference with the MC; and use MC-based calibration

In-situ JES – V+jet



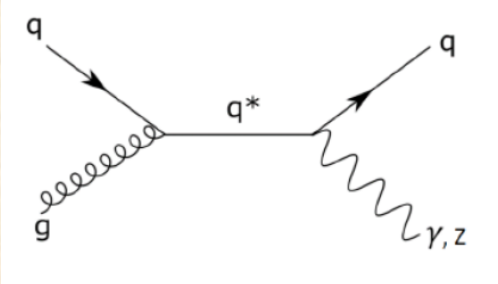
Extensive studies of systematic uncertainties



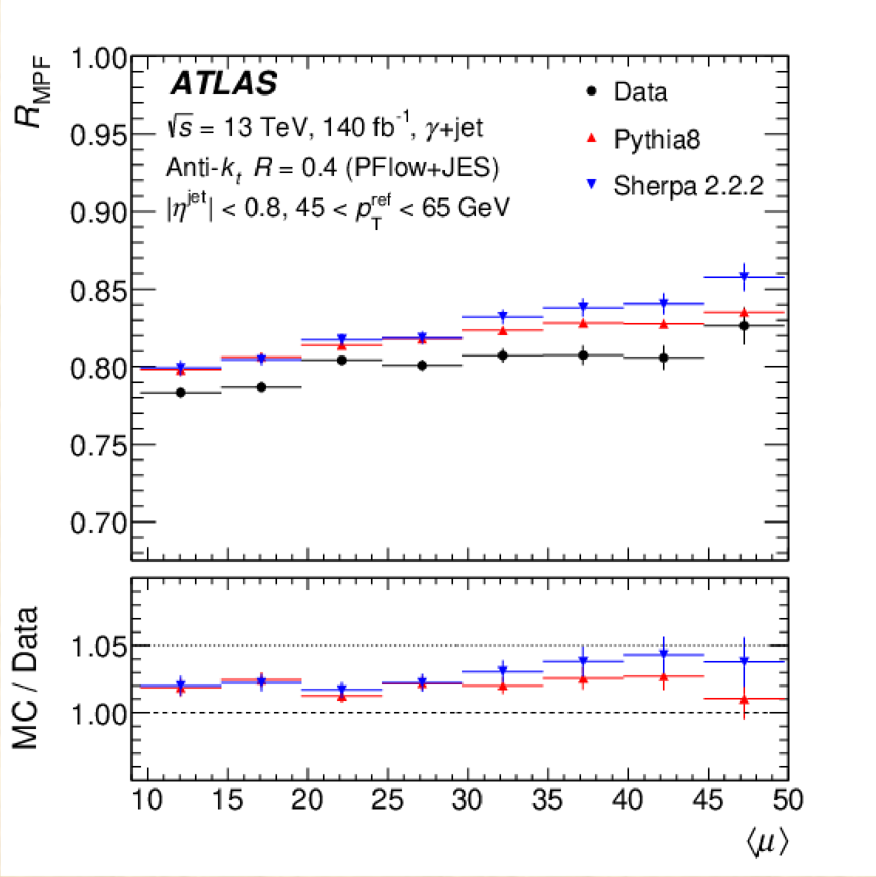


Less than 1% systematic uncertainty over most of the p_T range

In-situ JES – V+jet



The MPF response is mostly insensitive to pileup.
(no pileup correction done in this plot)



Although there is a small slope at μ > 20-25

Conclusion

ATLAS has recently done a large number of studies using a variety of jet reconstruction algorithms, pileup suppression techniques, as well as new DNN tools, which have improved the JES and especially the JER.

- UFOs instead of PFOs (helps most for large-R jets)
- Improved determination of pileup energy density (sideband method)
- CS+SK, pre jet-reco pileup suppression
- 3D residual pileup correction (correlations between N_{PV} and μ)
- Use of a DNN for the Global Sequential Correction (GNNC)
- Reduced MC uncertainties on η-intercalibration
- Flavour Uncertainties (did not cover these)
- in-situ b-quark Jet Energy Scale (did not cover this)
    - Some of these techniques may prove even more useful when the number of interactions per beam crossing increases further later in Run-3 and at the HL-LHC.

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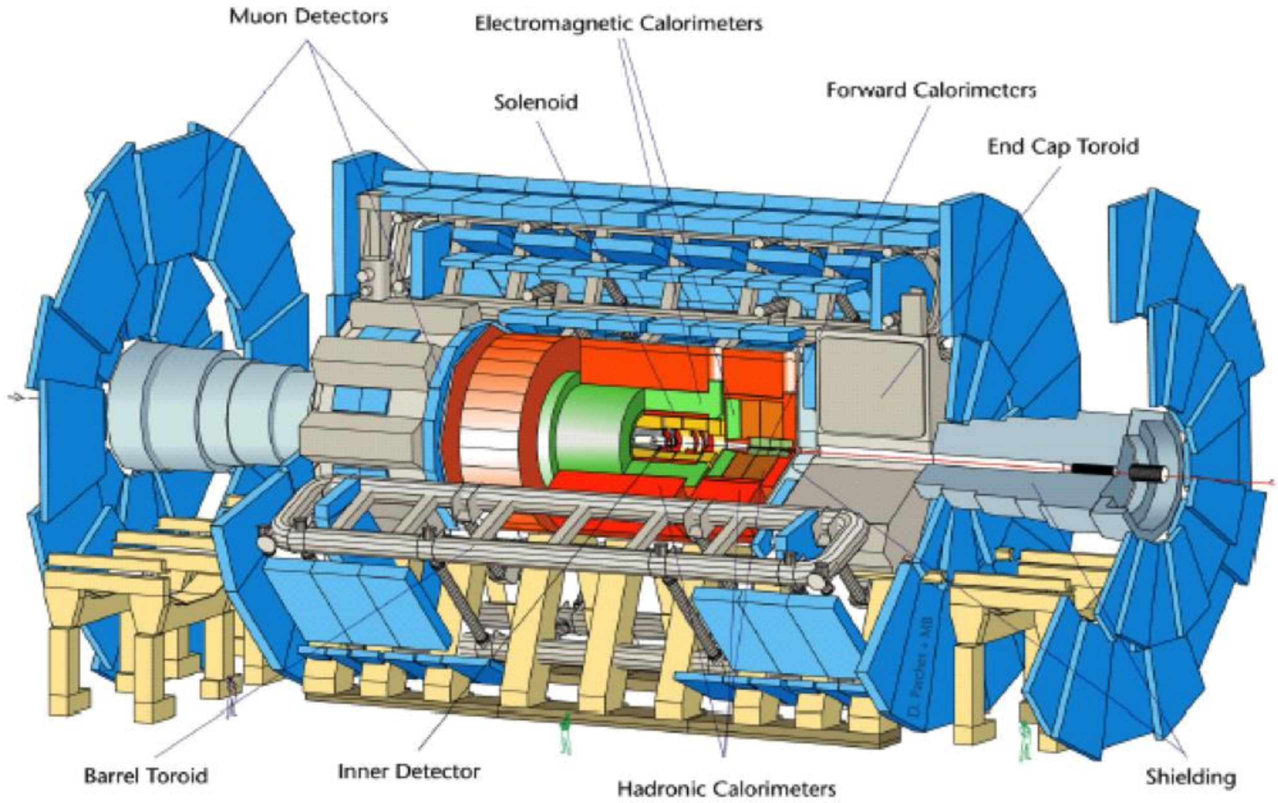
Backup

ATLAS Detector



Diameter	***25 m***
Barrel toroid length	***26 m***
Endcap end-wall chamber span	***46 m***
Overall weight	***7000 Tons***

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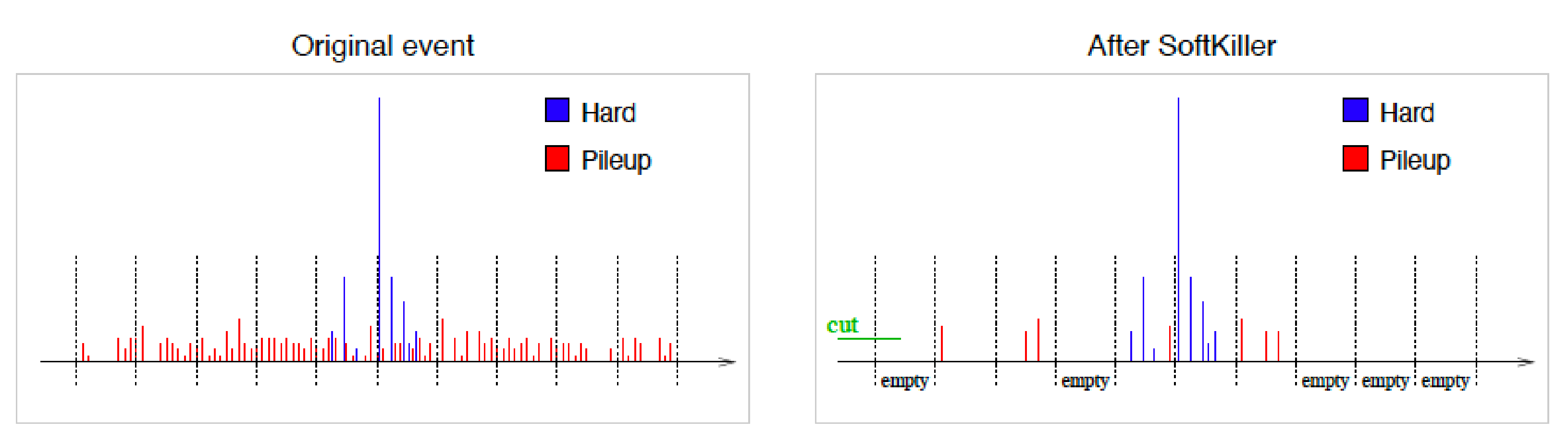
Pileup Mitigation

- *Pileup can also affect the jet reconstruction itself*
  *=> use a mechanism to reduce pileup *before* jet reco*

- *Soft Killer:* *Ignore particles below a dynamic p_T threshold*
  Threshold determined such that ρ is zero



Cacciari, Salam, Soyez; arXiv:1407.04.08

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Pileup Mitigation (pre-reco)

- *Pileup can also affect the jet reconstruction itself*
  *=> use a mechanism to reduce pileup *before* jet reco*

- *Soft Killer (SK): Ignore particles below a dynamic p_T threshold*
  Threshold determined such that ρ is zero

- *Constituent Subtraction: (CS) Flood the detector with "ghost" particles that have very low p_T. Match the ghosts to real particles and subtract their p_T. Ghosts approximate pileup.*
  => modifies constituents by removing pileup contribution

- *Charged-Hadron Subtraction (CHS): Remove tracks that do not come from the primary hard-scattering vertex*

Global Property Calibration

- Jet resolution can be improved by examining jet properties.
- Correct for shower fluctuations (parton & calo showers)
- Correct for differences between quark- and gluon-induced jets
  - quark jets have fewer, higher energy constituents
  - gluon jets have more, lower energy constituents because there is more QCD radiation
- Parameters used in the Global Sequential Correction (GSC):
  - $f_{charged}$: fraction of jet p_T carried by charged tracks
  - f_{Tile0}: fraction of energy in the first Tile layer
  - f_{LAr3}: fraction of energy in the third EM layer
  - N_{track}: # of tracks with p_T > 500 GeV
  - w_{track}: track width
  - $N_{segments}$: # of muon track segments; punch through

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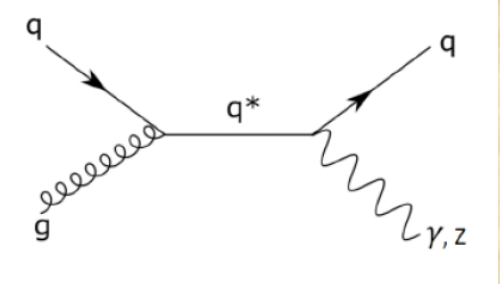
In-situ JES – V+jet



- *Use the Missing E_T Projection Fraction (MPF) technique because it is less sensitive to pileup and has smaller uncertainties*

Z/γ+jet events
Z or γ well measured

$$\vec{p}_T^{\,ref} + \vec{p}_T^{\,parton} = 0$$

- *The reference is well calibrated (R=1), but the hadron response is < 1*
  Results in missing energy in the direction of the recoil

$$\vec{p}_T^{\,ref} + R_{MPF} \cdot \vec{p}_T^{\,recoil} = -\vec{E}_T^{\,miss}$$

$$R_{MPF} = 1 + \frac{\vec{E}_T^{\,miss} \cdot \hat{p}_T^{\,ref}}{\vec{p}_T^{\,ref}}$$

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B-Jet Calibration

- *The top-quark mass is limited by the b-jet JES*
- *b-jets are reconstructed using PFlow objects*
- *Tagged using a multivariate algorithm (DL1r) that relies on impact parameters of tracks and displaced vertices*
- *The Direct Balance method in γ+jet events is used instead of the MPF because we need tagged b-jets*
- *Several working points are studied with different fractions of b and c jets*

B-Jet Calibration