Redefining Performance: New Techniques for ATLAS Jet Calibration

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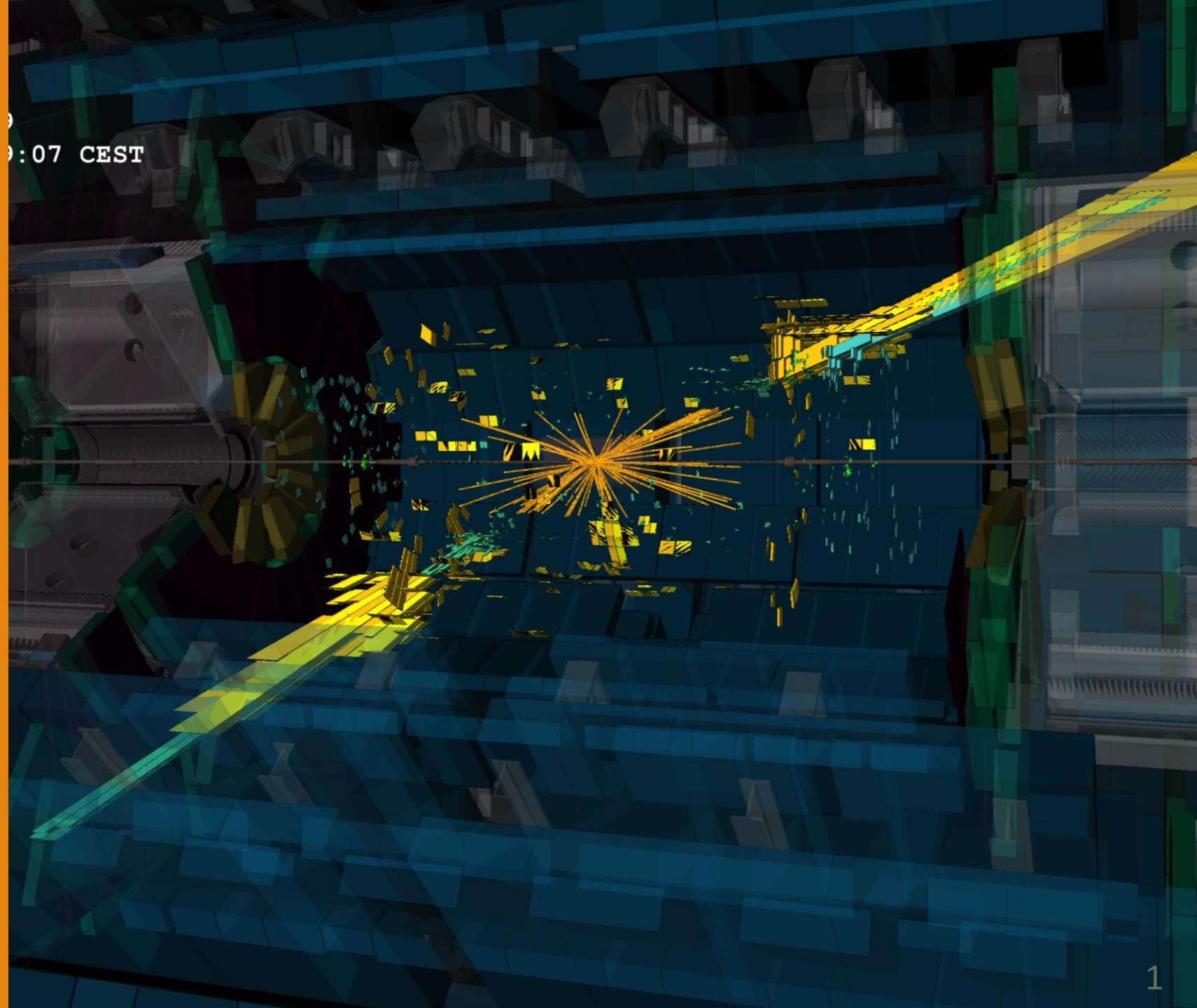
LPNHE/CNRS
On behalf of the ATLAS Collaboration

HEP2023

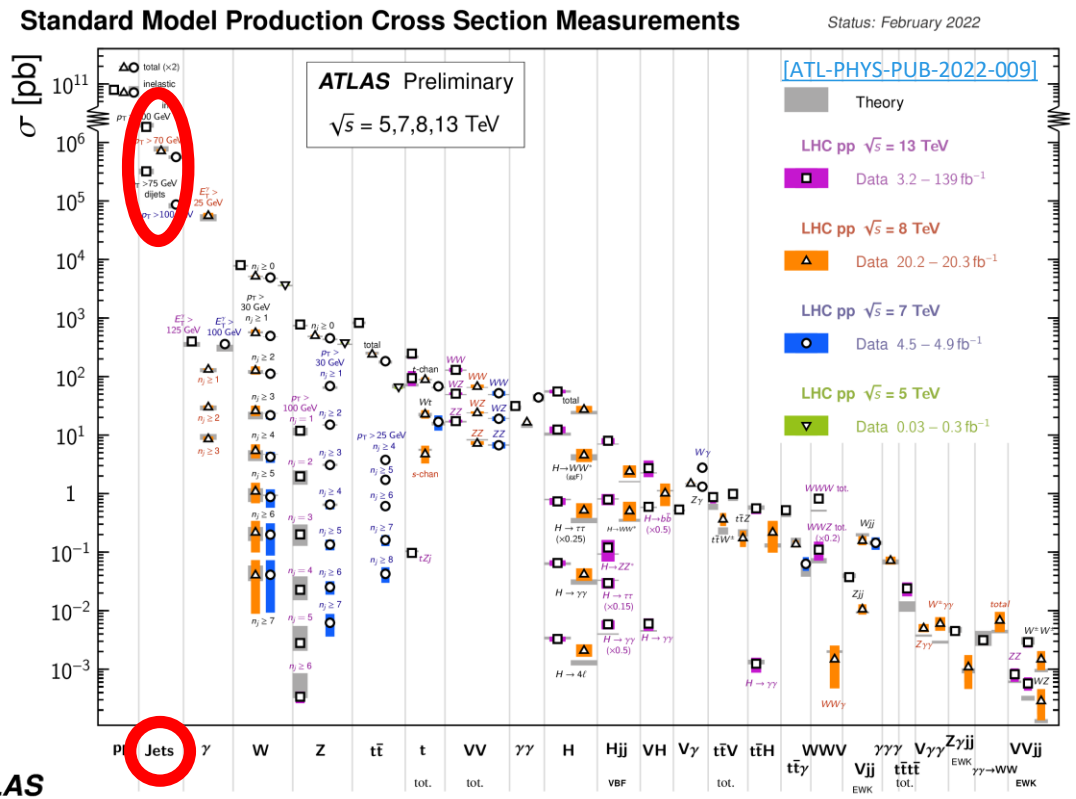
January 12th, 2023



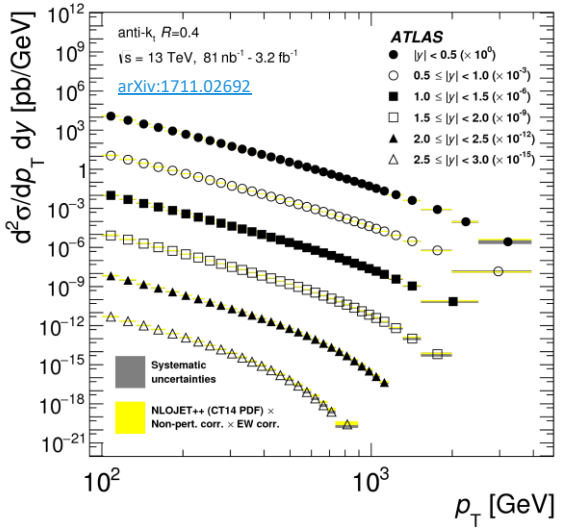
Importance of Jets at LHC

LHC: **Particle accelerator at CERN**, 27 km circumference
→ currently produce **proton-proton collisions** at a center-of-mass energy of **13.6 TeV**

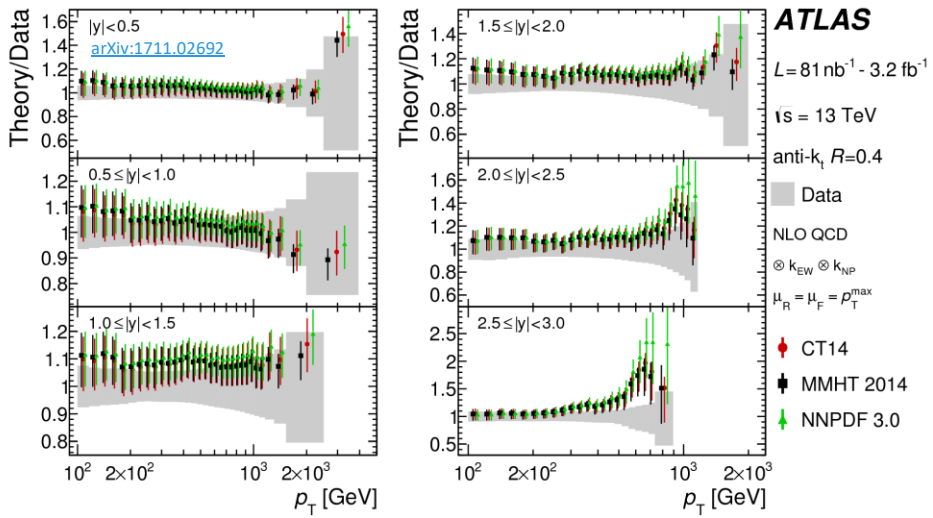
Quarks and gluons, resulting in "**jets**" in the detector, are by far **the dominant production at LHC**



Jet production cross-section



Data-theory tension



Jets are used both in:
- **precision measurement** of standard model processes
- **beyond the standard model** searches

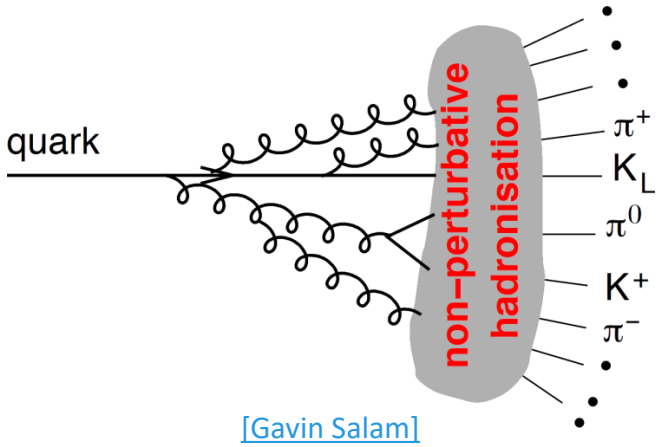
→ **Precision is crucial**

Jet Production and Detection in ATLAS

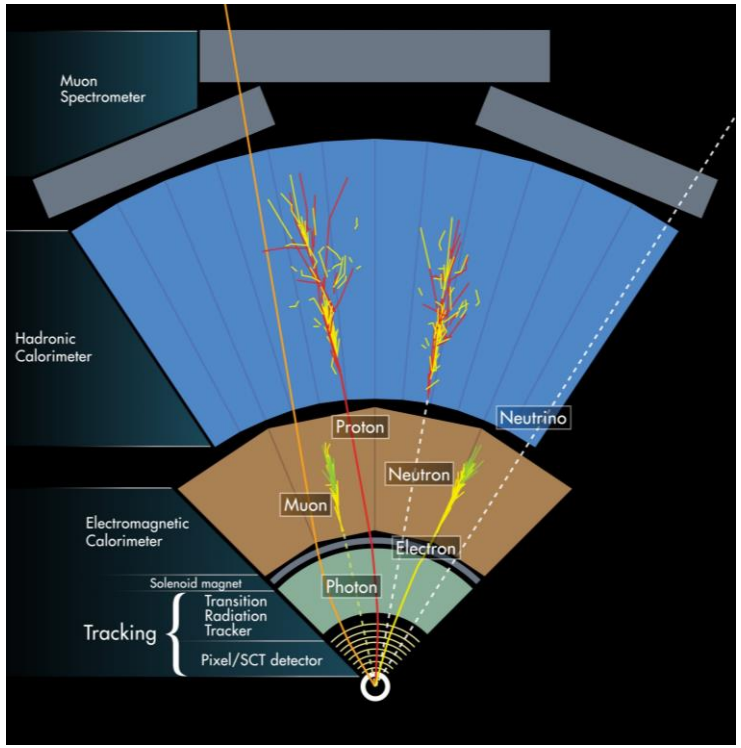
ATLAS: multi-purpose **particle detector**

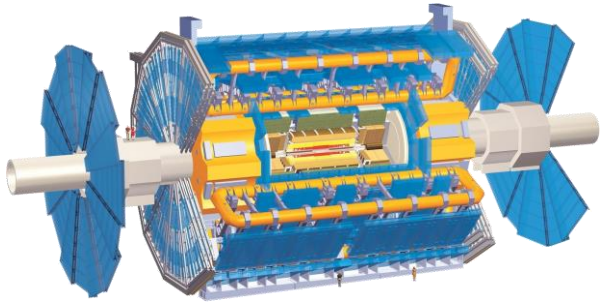
Jet: collimated **spray of hadrons** produced by the **hadronization of a quark or a gluon**

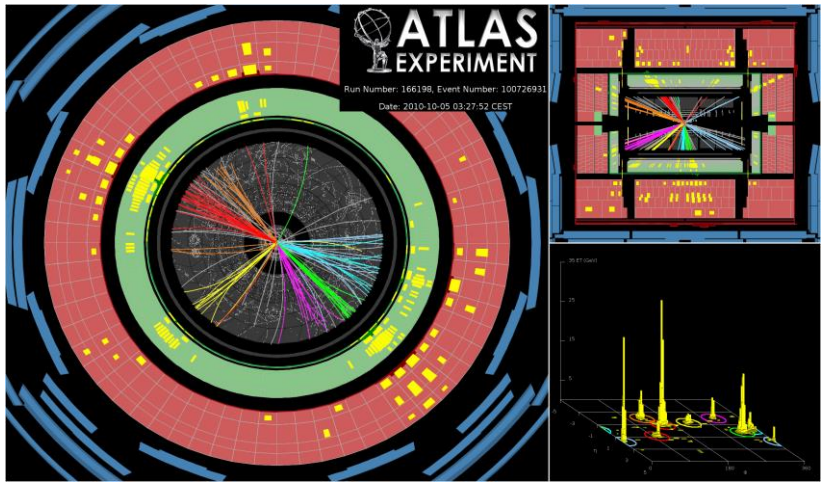
→ Produce **tracks** in the trackers and **energy deposits** in the calorimeters, that are **clustered together** to obtain the properties of the initial quark or gluon



[Gavin Salam]





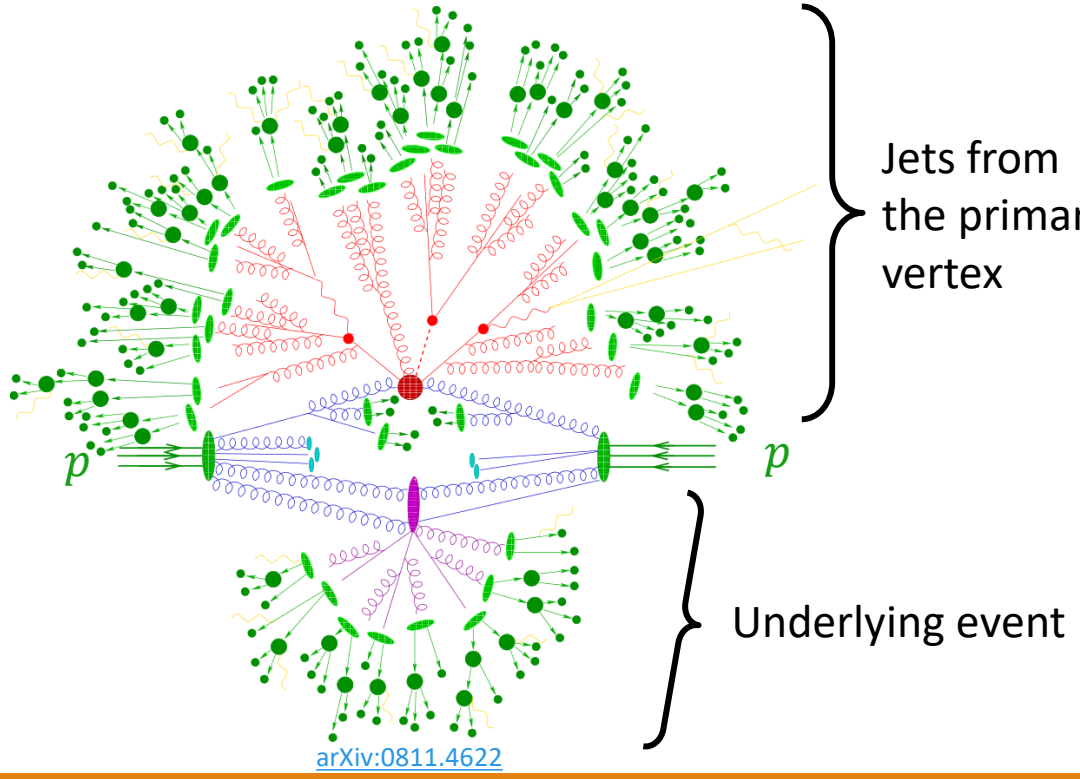


Pileup

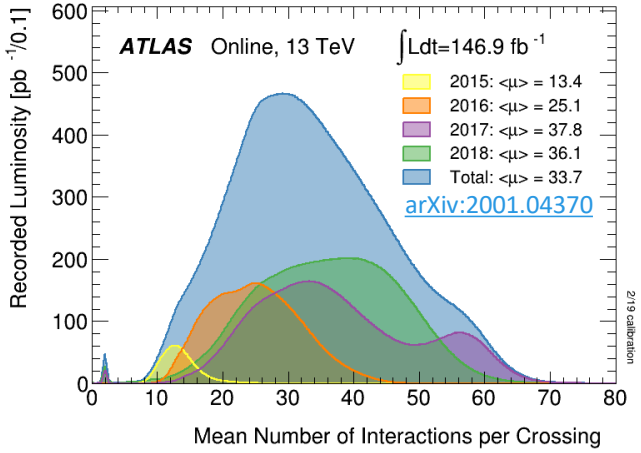
Pileup: all the effects of other interactions other than the hard scatter
→ **Challenge** for the jet reconstruction and calibration

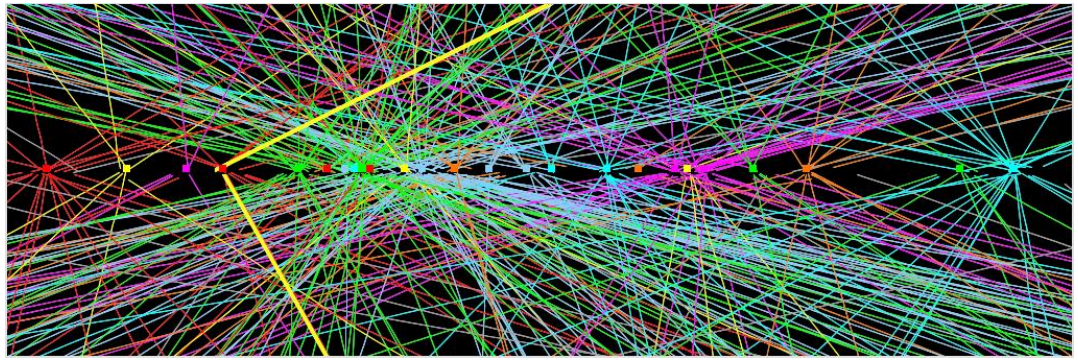
In-time pileup: underlying event, other collisions in the same bunch crossing

Out-of-time pileup: collisions in other bunch crossings



arXiv:0811.4622





Jet Reconstruction in ATLAS used during Run 2

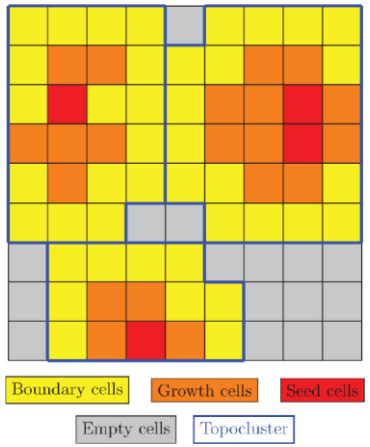
Step 1: Building particle-like **clusters** from the energy deposits and the tracks

Topological clusters

arXiv:1603.02934

Connect group of calorimeter cells

1) Seed: cell with $|E| > 4\sigma$
2) Growth: adjecent cells with $|E| > 2\sigma$
3) Additional layer
4) Splitting algorithm (local maxima)



[Deepak Kar]

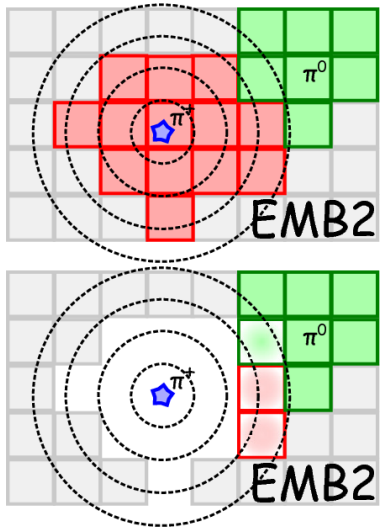
Particle flow objects (PFOs)

arXiv:1703.10485

Combine track and cluster information

→ Better resolution at low p_T, pileup separation

1) Select good tracks
2) Subtract them from the topo-clusters



Step 2: Building **jets** from clusters/PFOs

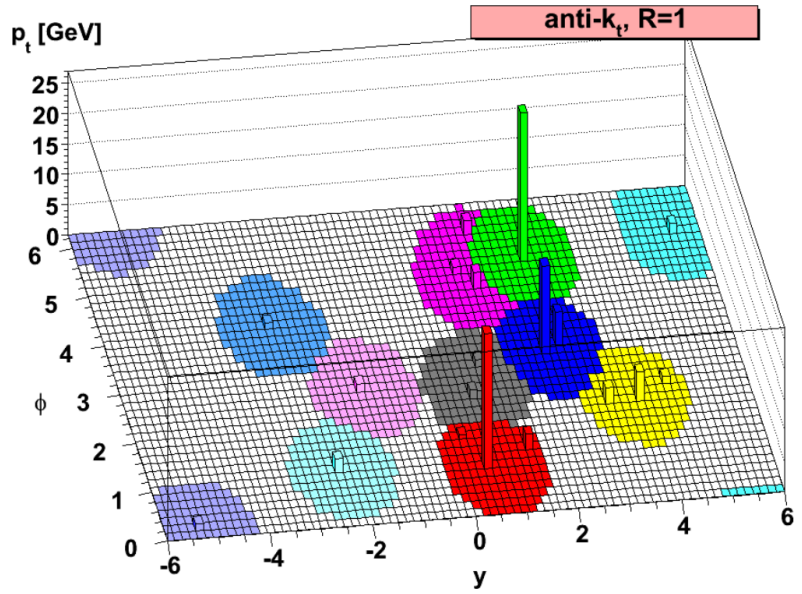
Anti-k_t algorithm

arXiv:0802.1189

Sequentially **gather nearby constituents**

Small radius jets: parameter $R = 0.4$

Large radius jets: parameter $R = 1.0$



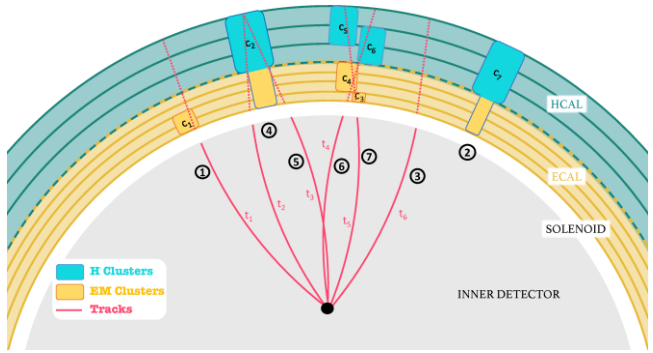
Unified Flow Objects

Track-CaloClusters (TCC)

[ATL-PHYS-PUB-2017-015]

Use **tracks** to **split up large clusters** based on the energy flow and their direction.

→ **Improvement of the mass resolution at high-p_T**

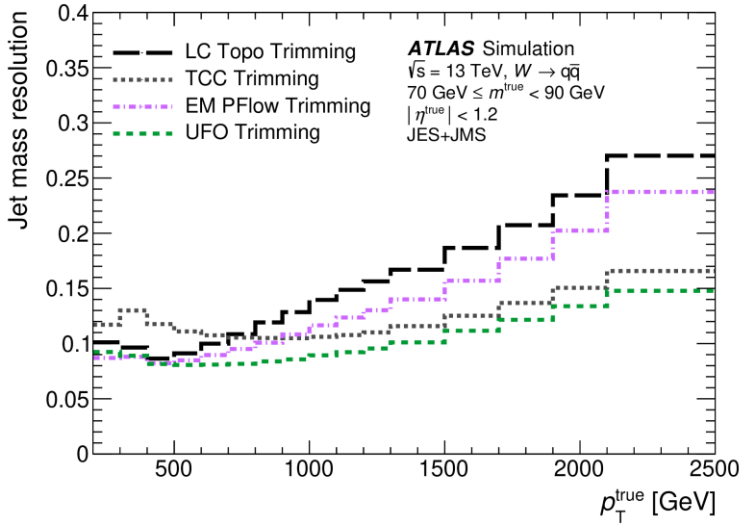


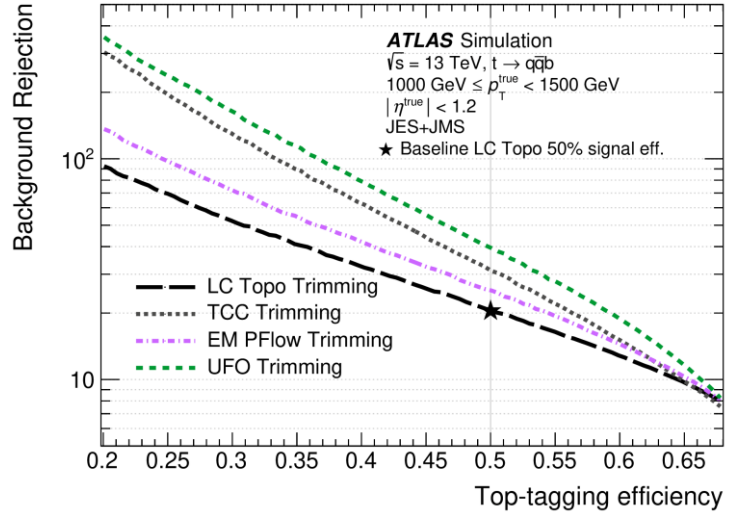
Unified Flow Objects (UFOs)

arXiv:2009.04986
[ATL-PHYS-PUB-2022-038]

Apply TCC technique to split PFOs
→ Low p_T: good pileup subtraction from PFOs
→ High p_T: large clusters are split

→ **Best mass resolution across p_T**
→ **Best background rejection** for a simple top-tagger at both low and high p_T





Results shown here for large radius jets ($R = 0.1$); results for small radius jets in backup.

Small-R Jet Energy Scale Calibration used in ATLAS during Run 2

Pileup corrections → **Absolute MC-based calibration** → **Global sequential calibration** → **Residual *in situ* calibration**

1) Correction based on the **pileup density** and the **jet area**

2) Remove residual pileup dependency

Energy and direction are corrected to **particle-level** scale based on MC simulations.

Response:

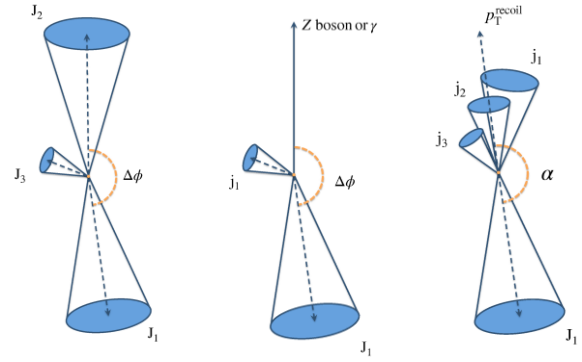
$$\mathcal{R} = \frac{E^{detector}}{E^{particle}}$$

The scale depends on visible **features of the jets**, like the **quark/gluon nature**.

The **resolution can be improved** by removing these dependencies thanks to MC simulations.

MC does not perfectly represent data

→ *In situ* corrections needed using different event topologies.

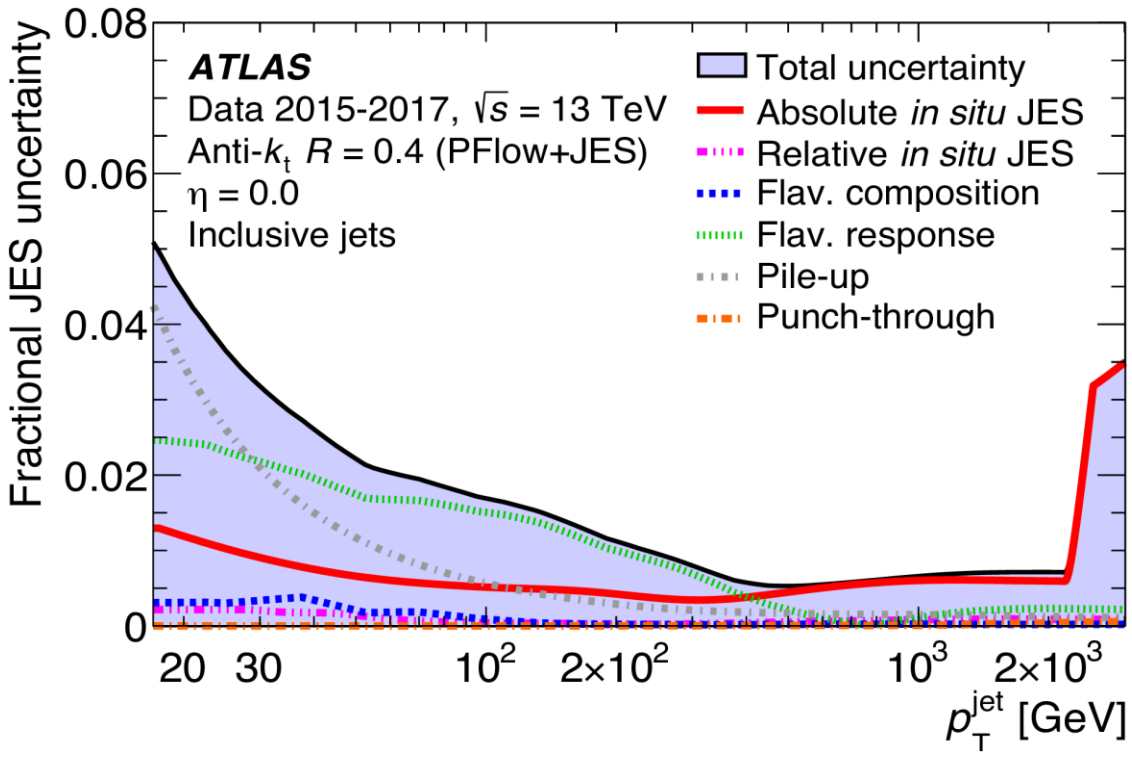


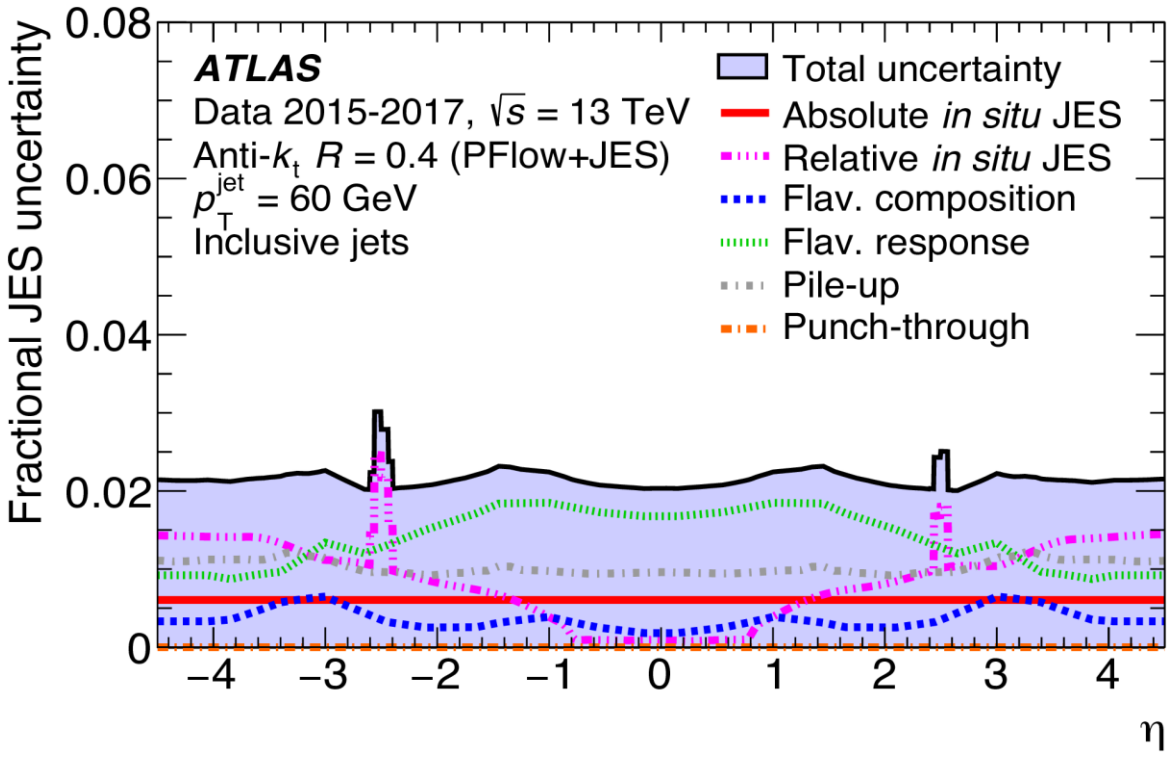
Backup: small-R JES calibration more in depth

The Uncertainties on the Jet Energy Scale

Improvements of some dominant uncertainties:

Flavour uncertainties (slides 15-17) | η-intercalibration (slide 12) | E/p (high-p_T) (slide 13) | Pileup (backup 1, 2)





Global Neural Network Calibration

The Global Sequential Calibration (**GSC**) **sequentially** corrects for the response dependency on six variable so does not exploit correlations.

The Global Neural Network Calibration (**GNNC**) uses a **Deep Neural Network (DNN)** trained to predict the p_T response. **It can use more correlated variables**. Architecture and inputs in backup.

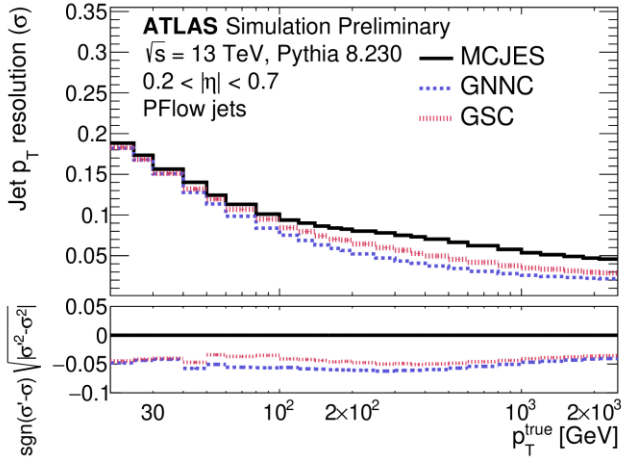
→ **The Jet Energy Resolution (JER) is improved by $15 - 25$ %** on average compared to the GSC.

→ **The responses of quark-initiated jets is closer to unity → Reduction of the flavour uncertainties.**

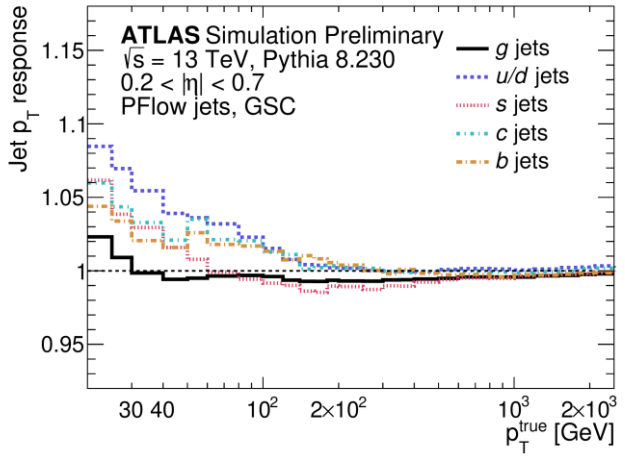
(→ see slide 15)

The *in situ* studies allow to validate the improvements in the calibration chain (see backup)**.**

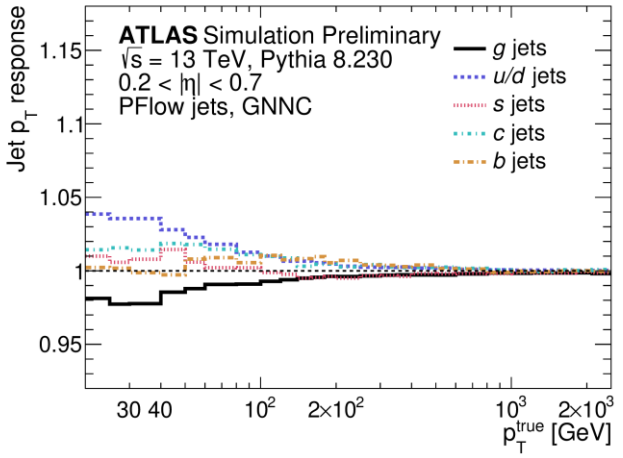
Resolution



Response: MC JES + GSC

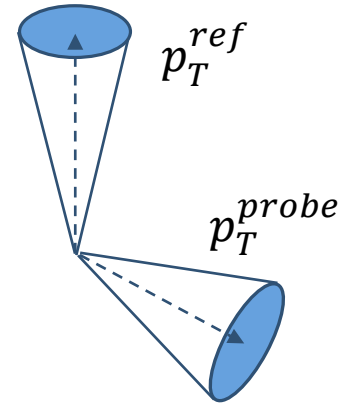


Response: MC JES + GNNC



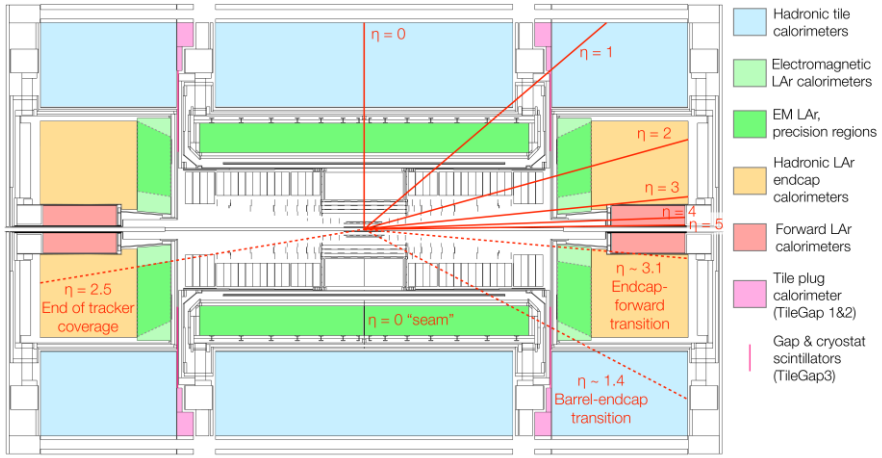
η-intercalibration Uncertainty Reduction

***In situ* η-intercalibration:** make the calibration homogeneous across the whole η range using dijet events and transverse momentum conservation: $c = p_T^{ref} / p_T^{probe} \approx 1$.

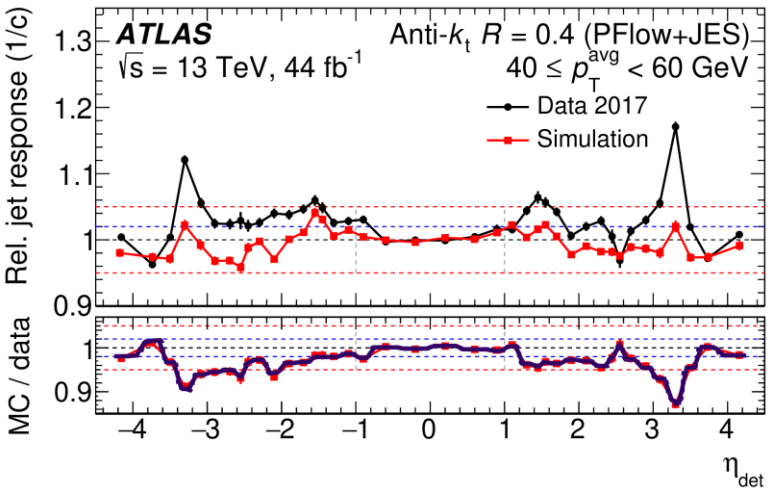


Modelling differences affect:
- the dijet balance (extra radiations like a third jet, out-of-cone radiations)
- the detector response (through the jet composition and substructure)

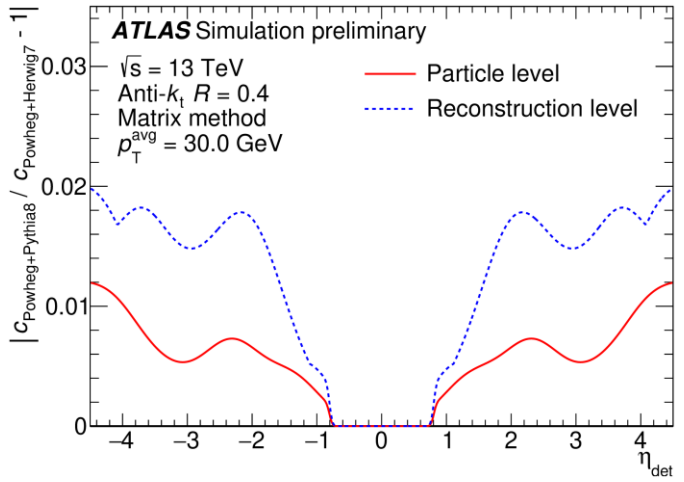
→ Possible **double-counting of detector effects with the flavour uncertainty.**
→ Solution: separating physics effects from detector effects
→ **Factor 2 reduction** of the modelling uncertainty below 40 GeV, which was dominant



Calibration



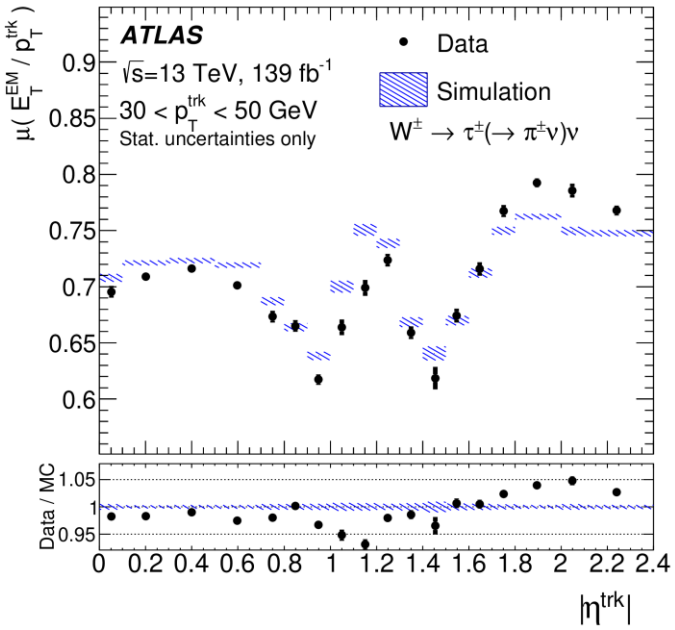
Modelling uncertainty

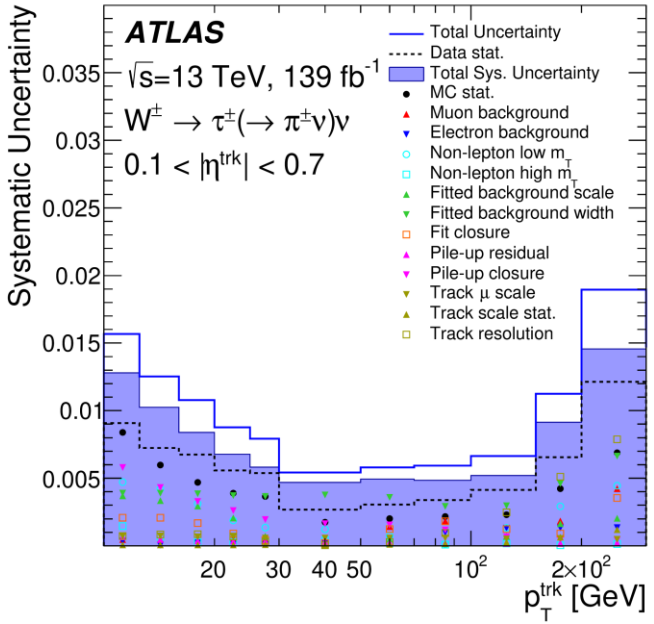


E/p Calibration Using $W^{\pm} \to \tau^{\pm}(\to \pi^{\pm}\nu_{\tau})\nu_{\tau}$ Events

$W^{\pm} \to \tau^{\pm}(\to \pi^{\pm}\nu_{\tau})\nu_{\tau}$ events provide **highly-energetic isolated charged pions**

Gaussian fit of the $E^{calorimeter}/p_T^{tracker}$ distribution in data and MC





→ **Calorimeter response** obtained in a very **wide range** $(10 < p_T < 2000$ GeV and $|\eta| < 2.4)$

→ **Excellent precision → High p_T uncertainties improvement**

→ **Improvement over the combined test-beam data previously used**

More E/p results

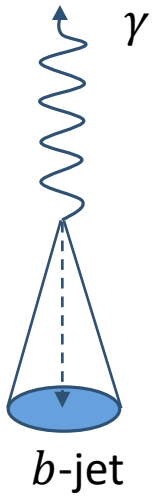
[JETM-2022-008]

b Quark Jet Energy Scale in γ+jet Balance

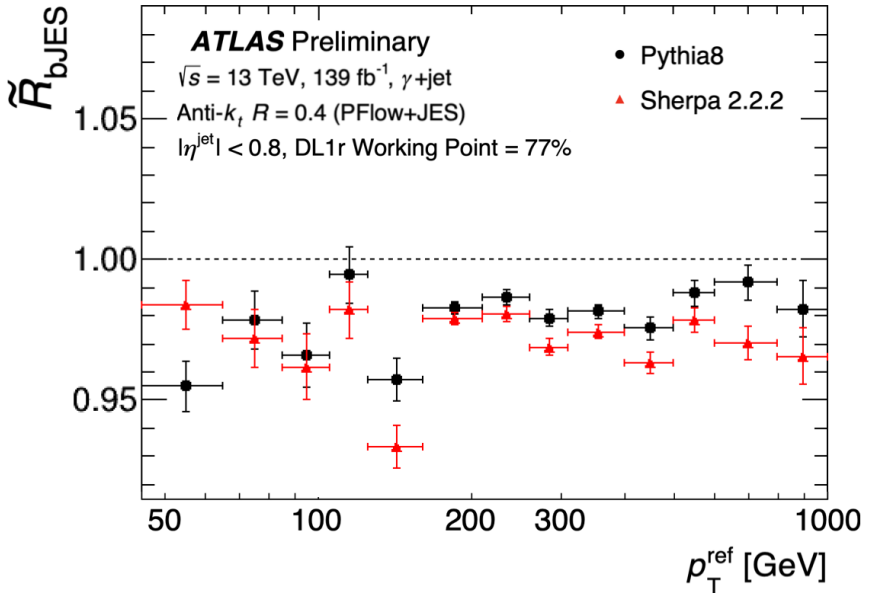
γ+jet balance: exploit the transverse momentum balance between a jet and a reference photon.

The MC-to-data response ratio is obtained for two selections: inclusive, and **b-tagged jets**.

$$\tilde{\mathcal{R}}_{bJES} = \frac{\mathcal{R}^{MC}_{b-tagged}/\mathcal{R}^{data}_{b-tagged}}{\mathcal{R}^{MC}_{inclusive}/\mathcal{R}^{data}_{inclusive}}$$



The **energy scale of b-tagged jets with respect to that of inclusive jets** is determined in with a **precision of about 1.5 to 2 %** on a broad phase-space range.



→ **Will improve measurements of:**
- **Top mass**
- **Bottom Yukawa ($VH, H \to b\bar{b}$)**

[b-JES for different b-tagger working points in backup]

The Flavour Uncertainty

Different MC generators, different hadronization models

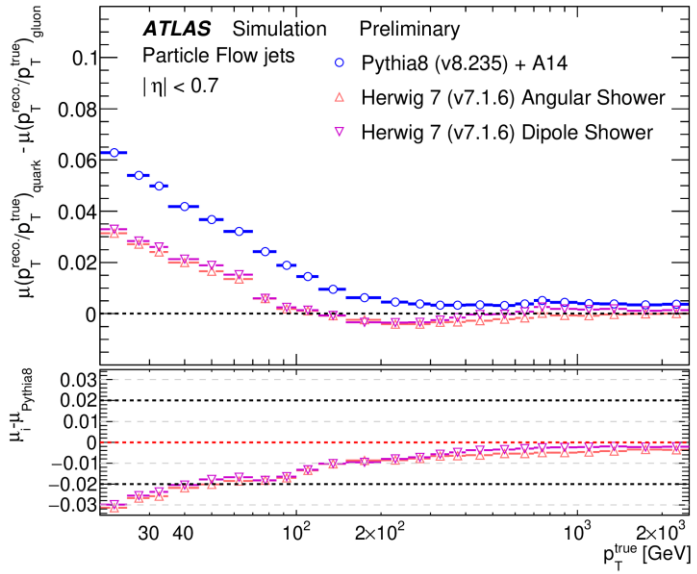
→ **Different fragmentation pattern and hadron content**

→ Different detector responses

→ **Flavour uncertainty**

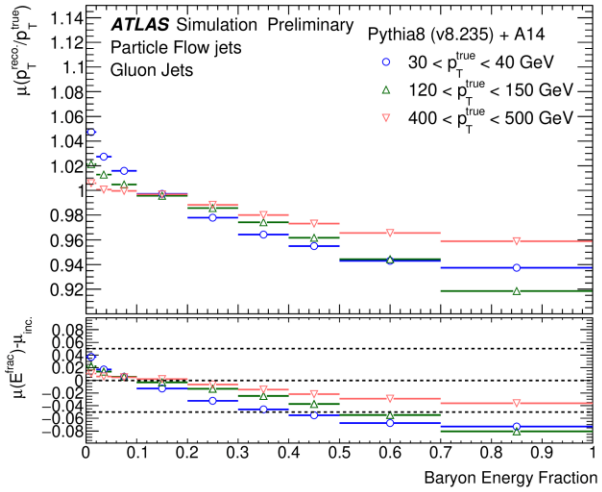
Origin: non-compensating nature of the calorimeters.
Response of π^0 and $\pi^{\pm}$ are very different. Response of pions, kaons, baryons are different too.

→ **Important response difference observed between quark and gluon jets**



Response of **Gluon Jets** vs. Baryon Energy Fraction

Dependency of the response on the **baryon energy fraction**



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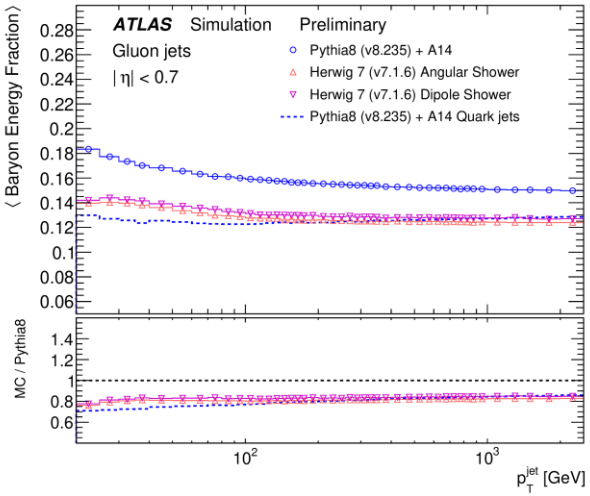
Different baryon energy fraction between Lund string-based and cluster-based **hadronization models**



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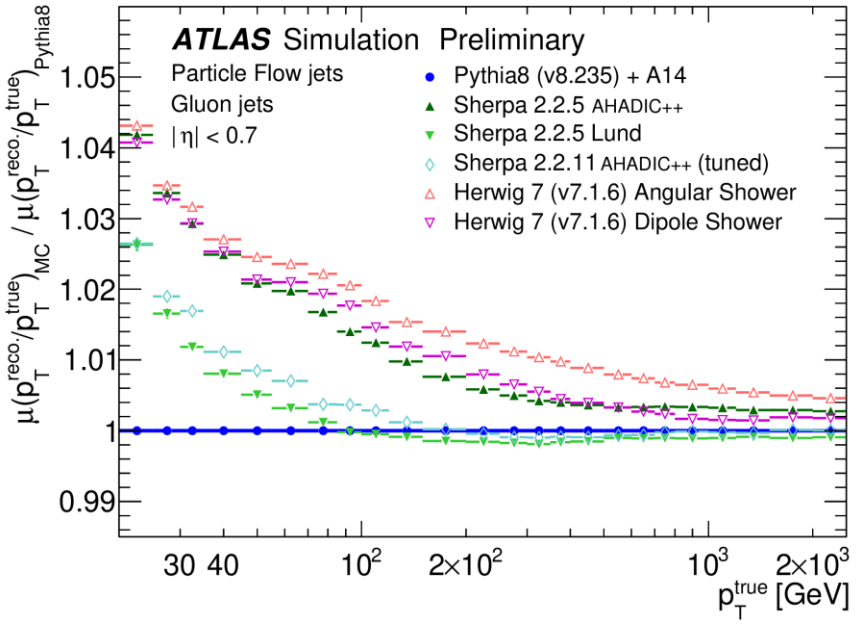
Response difference between the two types of hadronization models



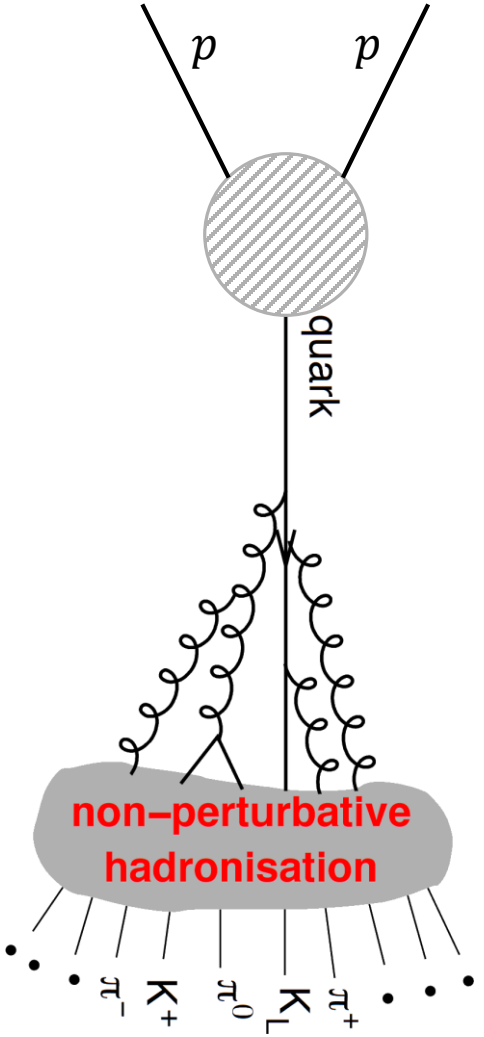
+ Similar observations for kaons, see backup

Fragmentation pattern + hadron content → need to be tuned to experimental measurements

Reweighting the events based on the baryon and kaon energy fractions reduces the differences (backup)

Reduction in the dependence on the generator configuration would result in a significant improvement of the flavour uncertainties.

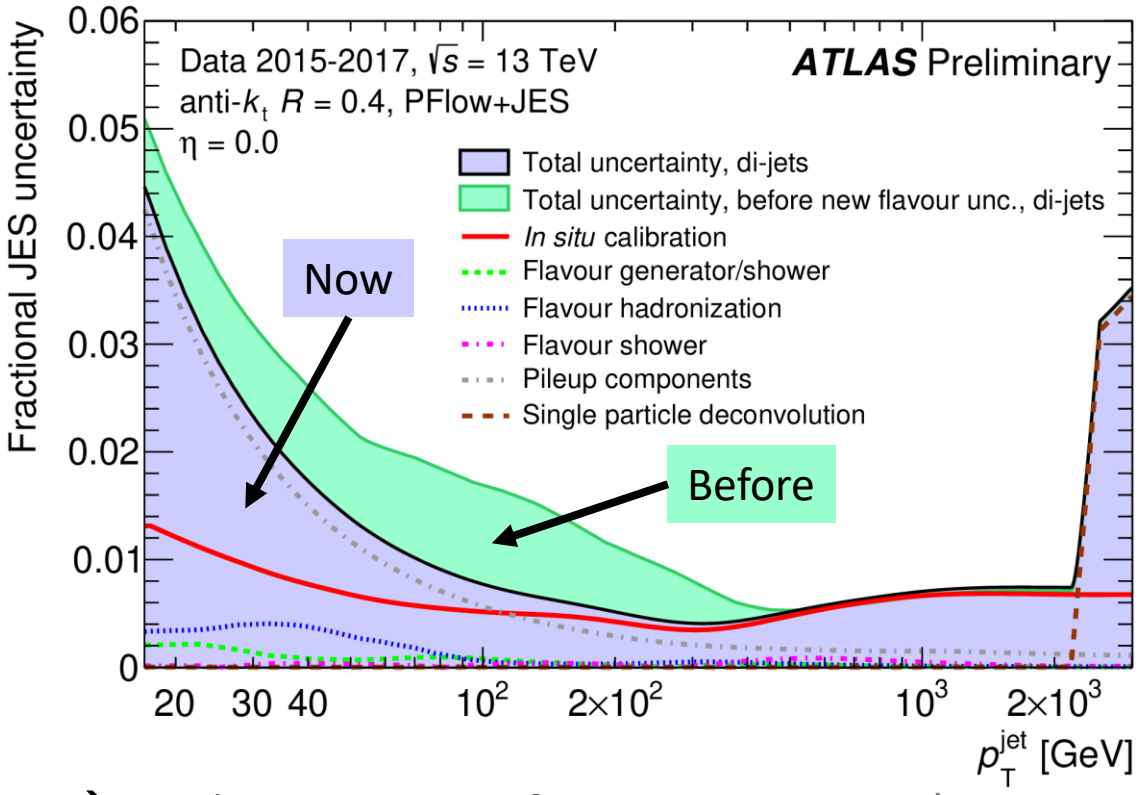
Flavour Uncertainty Decomposition



Matrix element generation
→ Difference of responses between Pythia8 and Sherpa + Lund string hadronization

Shower model
→ Difference of responses between Herwig7 + angular-ordered shower and Herwig7 + dipole shower

Hadronization model
→ Difference of responses between Sherpa + cluster-based hadronization and Sherpa + Lund string hadronization



→ Previous treatment: 2 components: sample composition + response difference of gluon-initiated jets between Pythia8 and Herwig7
→ New treatment: 3 components
→ **Improvement of the overall flavour uncertainty**

Conclusion

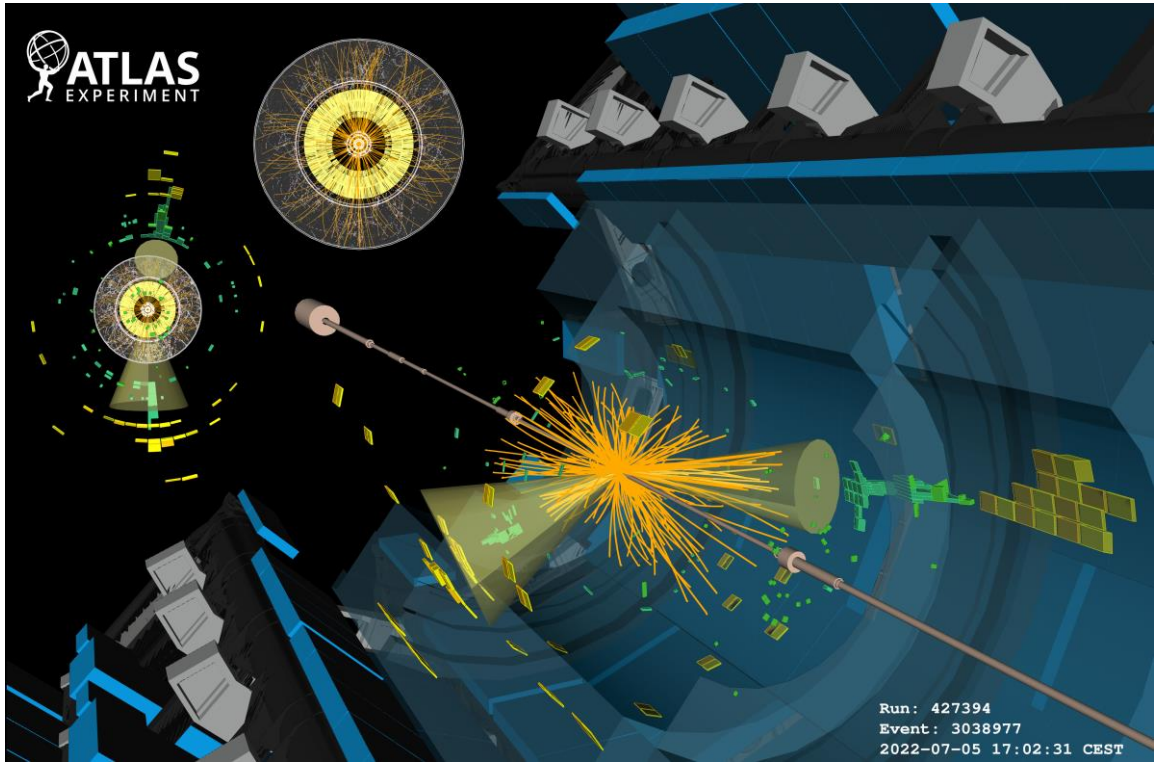
Hadronic objects reconstruction and calibration are important for **precision measurements** and **BSM** exploration at the LHC (and beyond)

Lots of improvements at every step of the definition and calibration of jets, thanks to the exploration of new techniques

→ Also see the use of ML/AI techniques for hadronic object performance (see Reina Camacho's talk)

Run 3 just started: great opportunity to exploit these developments and continue refining our strategies

→ Lot of work ongoing in that direction, stay tuned!



Run 3 dijet event

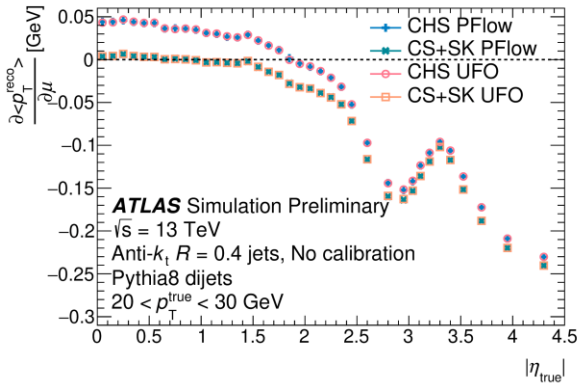
Backup

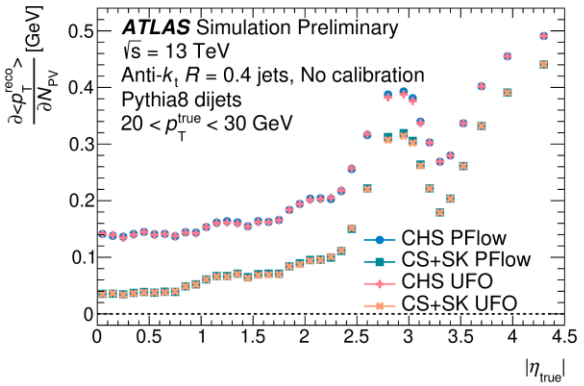
UFOs and CS+SK for small-R jets

CS+SK reduces the pileup dependency (see next slide).

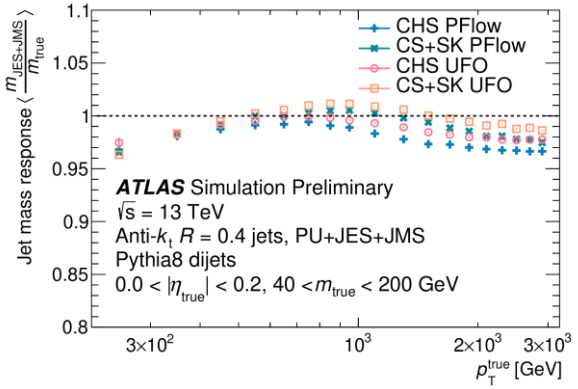
CS+SK UFO → **Better calibration of the jet mass** and **better mass resolution**.
→ Consistent with PFlow jets on other observables.

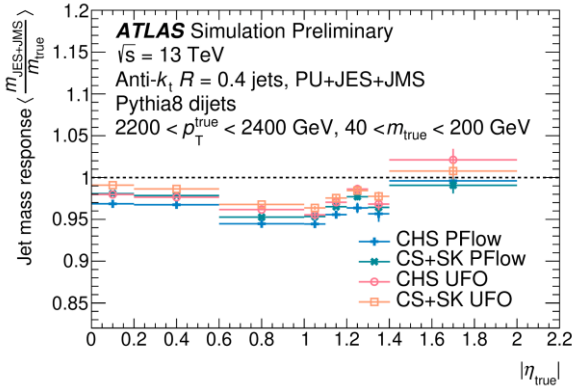
Pileup dependency



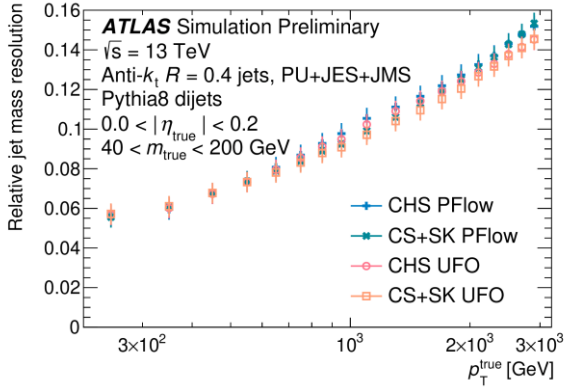


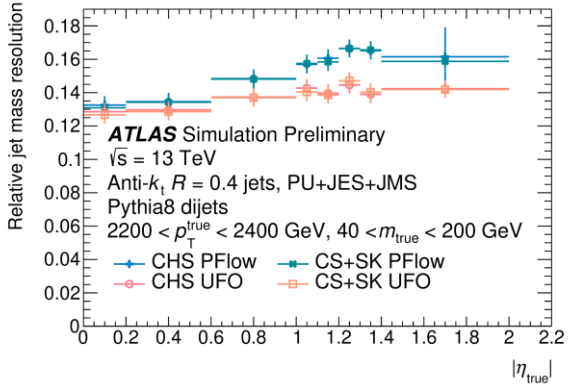
Jet mass





Jet mass resolution





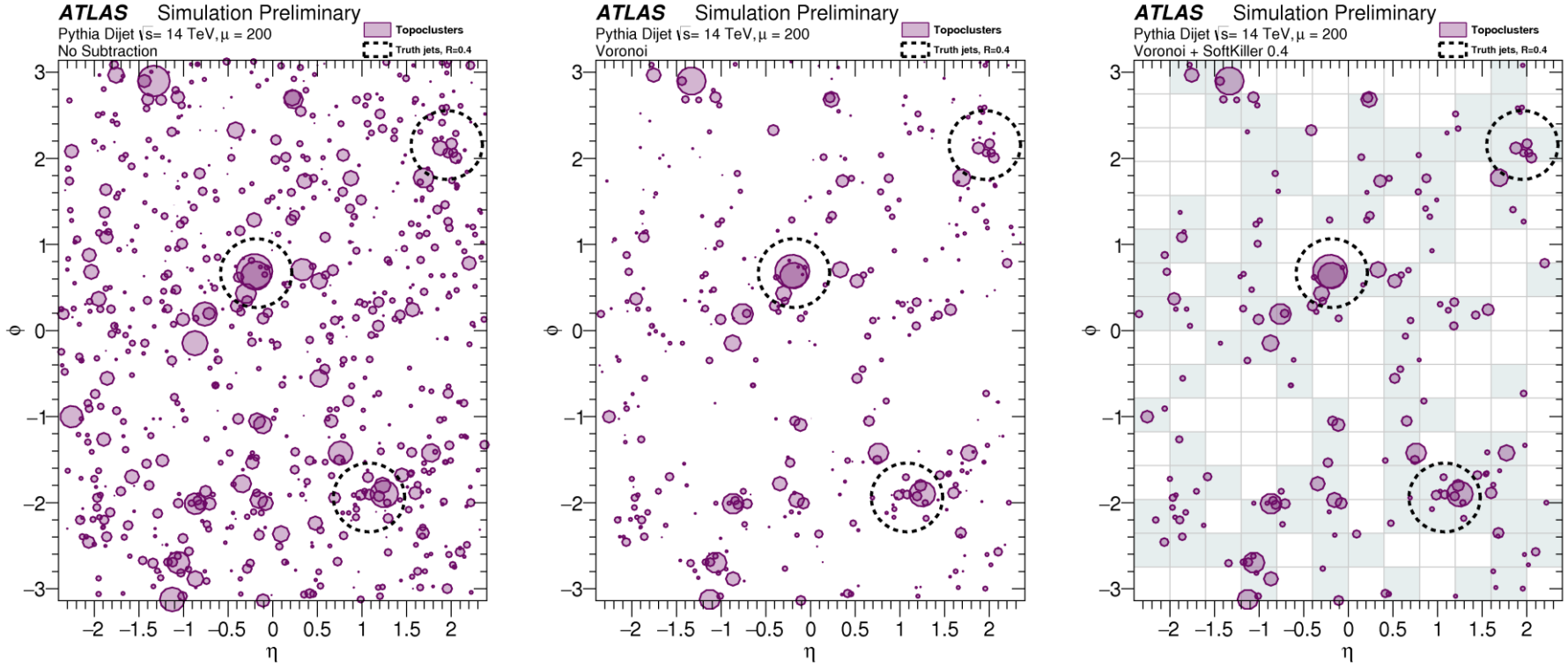
Back to UFO for large-R jets.

CS+SK

Some pileup can be removed prior to jet reconstruction

→ Constituent subtraction (CS): assign an area to each cluster in (η, ϕ) (region where points are closer to that cluster than any other cluster), and subtract the expected pileup for that area.

→ Soft killer (SK): divide the event into a grid and remove the squares below a threshold.



Small-R JES Calibration more in depth

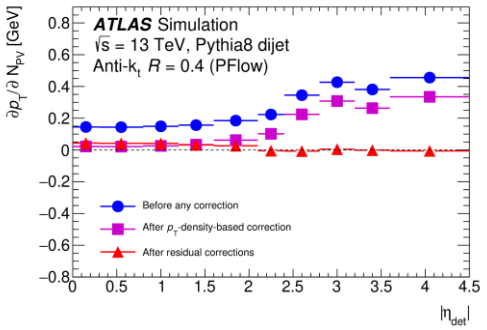
Back to small-R JES calibration

Pileup corrections → **Absolute MC-based calibration** → **Global sequential calibration** → **Residual *in situ* calibration**

1) **Area-based correction** with pile-up density ρ and jet area A.

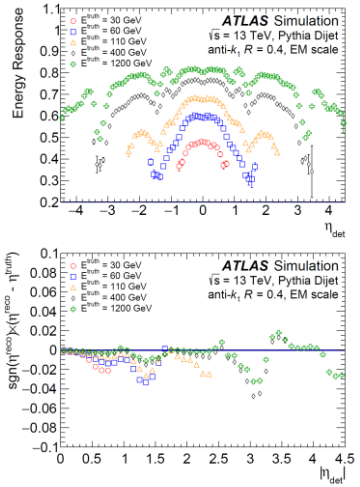
2) **Local MC-based correction**. Characterization:
- In-time pileup: N_{PV}
- Out-of-time pileup: μ

$$p_T^{corr} = p_T^{reco} - \boldsymbol{\rho A} - \alpha(\boldsymbol{N_{PV}} - 1) - \beta\boldsymbol{\mu}$$



1) **Energy** is calibrated to the true jet energy from MC using a smooth multiplicative function in bins of η.

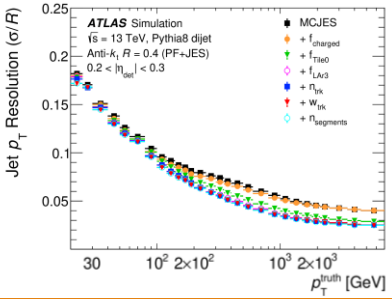
2) **Direction** η receives an additive correction.



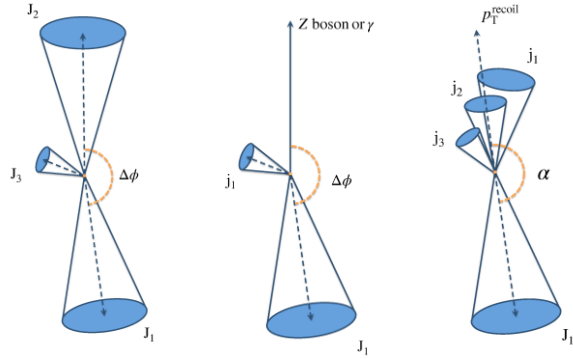
The scale depends on visible **features of the jets**, like the **quark/gluon nature** or the energy in dead material.

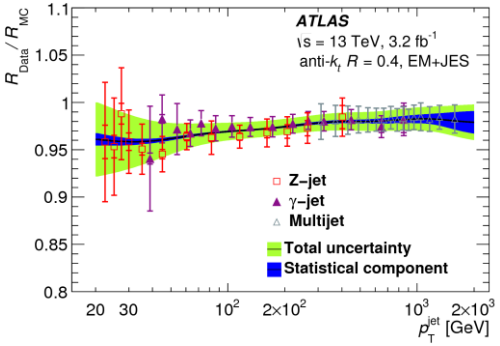
The **resolution can be improved** by removing these dependencies thanks to MC simulations.

This is done sequentially for 6 variables.



MC does not perfectly represent data → *In situ* corrections needed using different event topologies.





Improved Pileup Energy Density Determination

Back to the JES uncertainties

Pile-up energy density $\langle\rho\rangle$ determination:

$$\langle\rho\rangle = \underset{i\in\{jets\}}{\text{median}}\left(\frac{p_{T,i}}{A_i}\right)$$

for two different selections: $Z \to \mu\mu$ and dijet events.

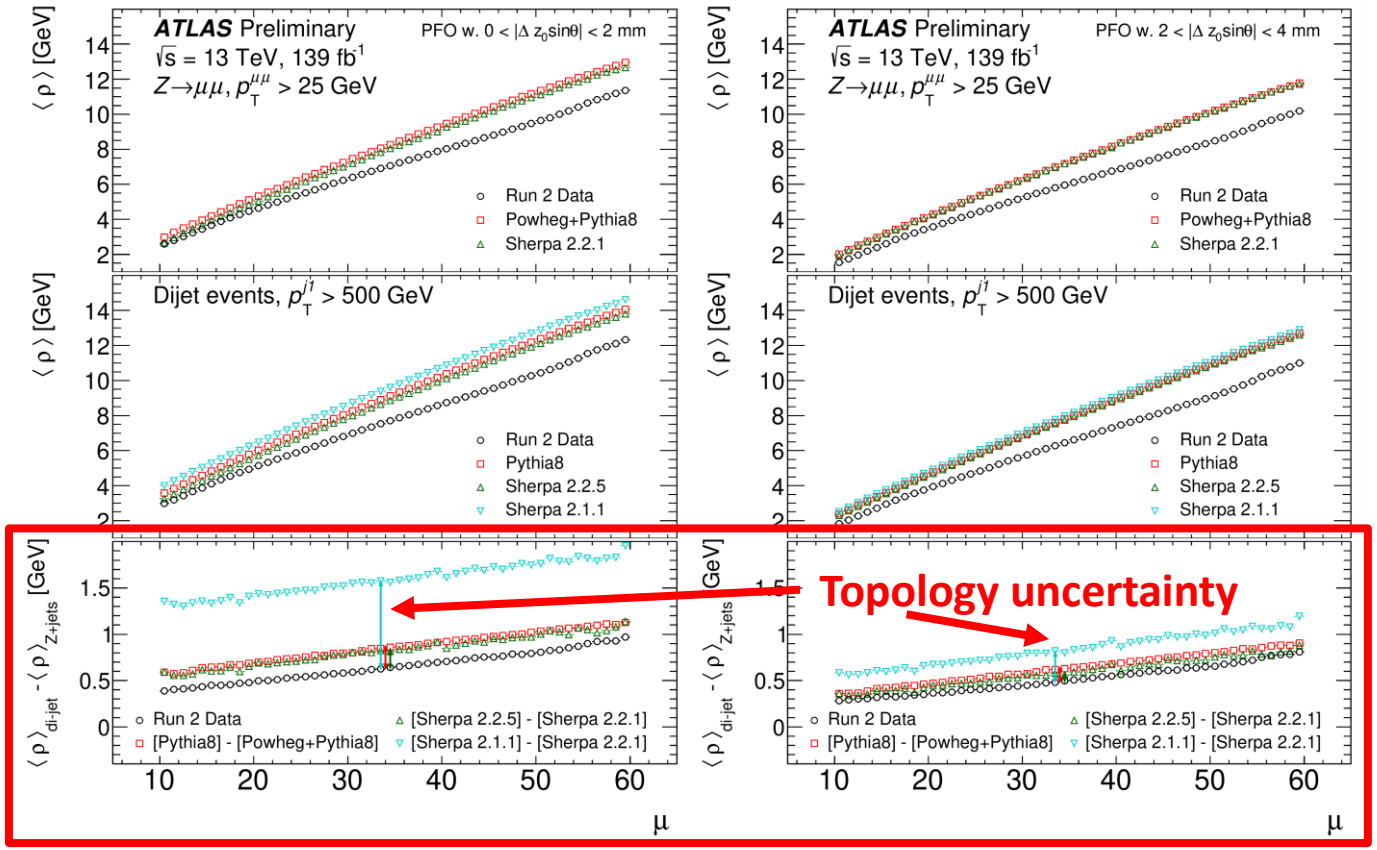
→ Previous determination was including the hard-scatter tracks, shifting $\langle\rho\rangle$ to higher values.
  → **Reduction in the dependency on hard scattering topologies**
  → Improvement on topology uncertainties by a factor of 3

→ **Updated Sherpa Muti-Parton Interaction (MPI)** results in a factor of 4 improvement

→ **Total improvement of nearly a factor 7 of the topology uncertainty**

Including the hard-scatter tracks

Excluding the hard-scatter tracks



Improved Pileup Residual Correction

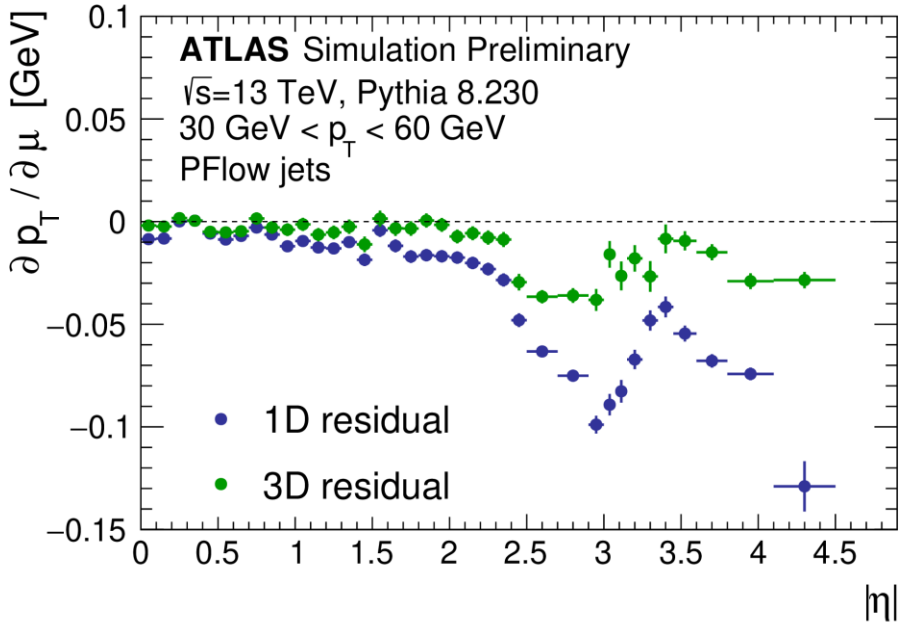
Back to the JES uncertainties

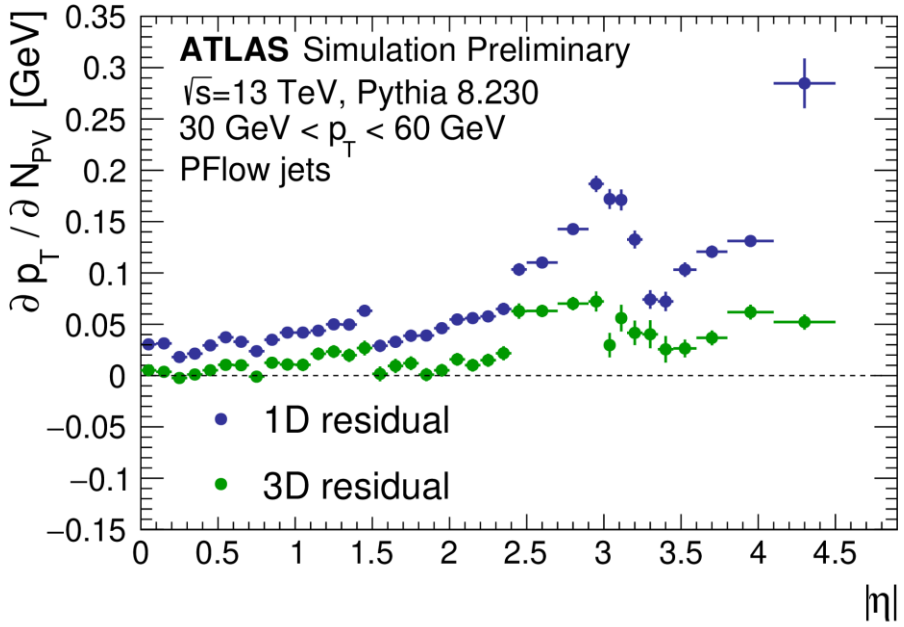
1D residual pileup correction: $p_T^{corrected} = p_T - \alpha(N_{PV} - 1) - \beta\mu$

3D residual correction: $p_T^{corrected} = p_T - \Delta p_T(N_{PV}, \mu, \eta, p_T)$

The 3D residual correction **takes into account correlations between N_{PV}, μ and jet properties**.

→ **Reduction of the pileup dependency above 30 GeV**





GNNC architecture

3 hidden layers with swish activation functions (arXiv:1710.05941), each with 100 nodes, and a single-node output layer with linear activation.

Leaky Gaussian kernel loss function (arXiv:1910.03773), where the target is the jet p_T response.

Back to the GNNC

[JETM-2022-004]

GNNC inputs

Back to the GNNC

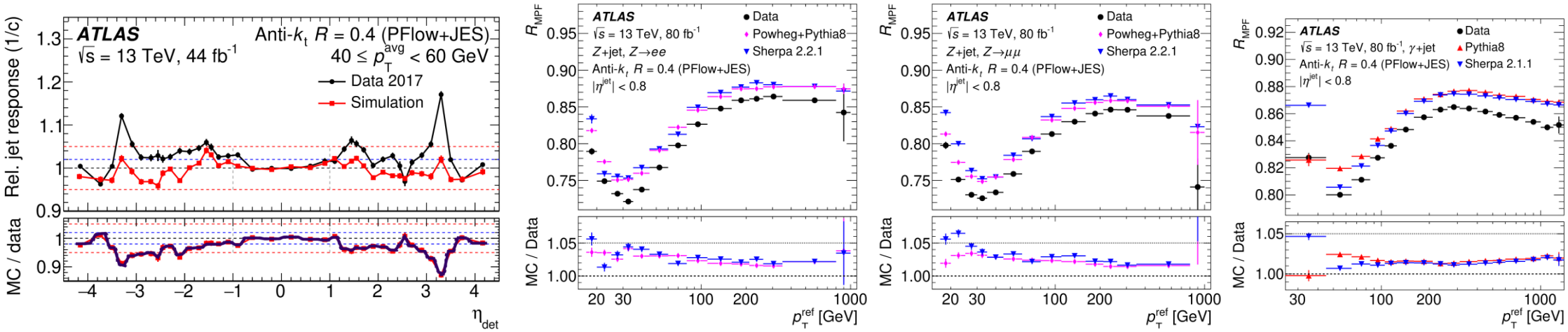
Calorimeter	$f_{\mathrm{LAr},0-3}$	The fraction of energy measured in the 0th-3rd layer of the EM Lar calorimeter
	$f_{\mathrm{TILE},0-2}$	The fraction of energy measured in the 0th-2nd layer of the hadronic tile calorimeter
	$f_{\mathrm{HEC},0-3}$	The fraction of energy measured in the 0th-3rd layer of the hadronic end cap calorimeter
	$f_{\mathrm{FCAL},0-2}$	The fraction of energy measured in the 0th-3rd layer of the forward calorimeter
	$N_{90\,\%}$	The minimum number of clusters containing $90\,\%$ of the jet energy
Jet kinematics	p_T^{JES}	The jet p_T after the MC JES calibration
	η_{det}	The detector η
Tracking	w_{track}	The average p_T-weighted transverse distance in the (η, ϕ) plane between the jet axis and all tracks of $p_T > 1\ \mathrm{GeV}$ ghost-associated with the jet
	N_{track}	The number of tracks with $p_T > 1\ \mathrm{GeV}$ ghost-associated with the jet
	f_{charged}	The fraction of the jet p_T measured from ghost-associated tracks
Muon segments	N_{segments}	The number of muon track segments ghost-associated with the jet
Pileup	μ	The average number of interactions per bunch crossing
	N_{PV}	The number of reconstructed primary vertices

Back to the GNNC

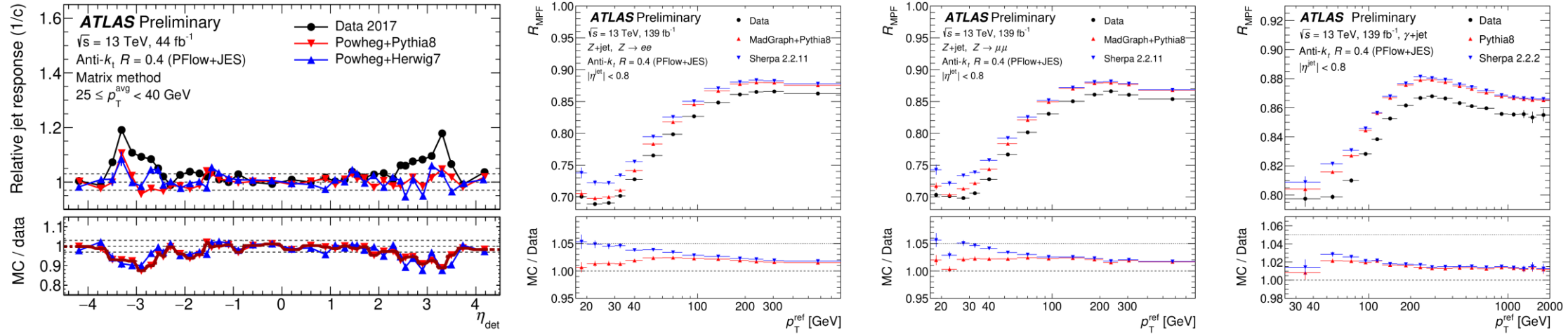
Validation of the MC calibration steps with the *In Situ* Techniques

Improvements in the MC calibration steps are validated thanks to the *in situ* calibration techniques.

Previous *in situ* study
arXiv:2007.02645



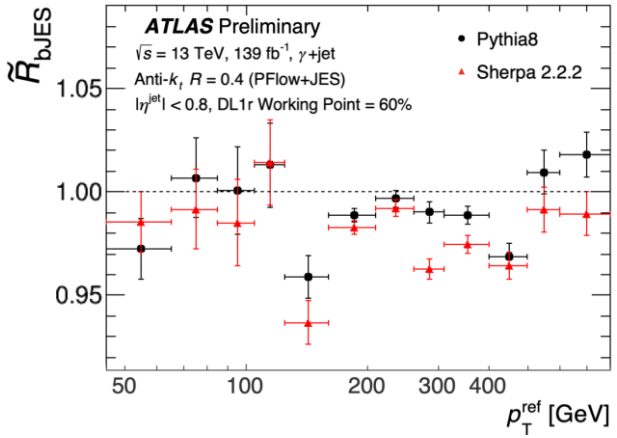
New *in situ* study
[JETM-2022-008]



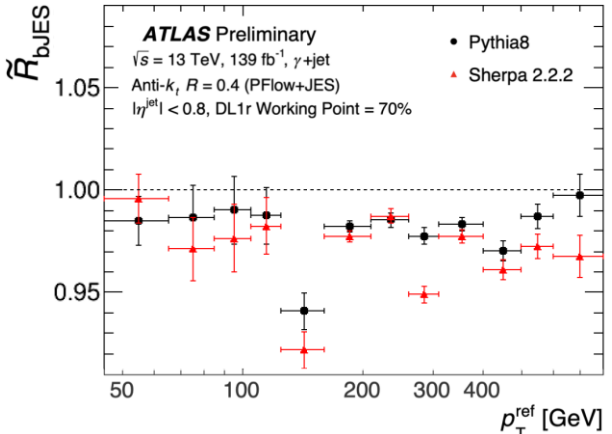
b Quark Jet Energy Scale for Different b-tagging Working Points

Multiple b-tagger working point for different compositions of b quarks, c quarks, light quarks and gluons.

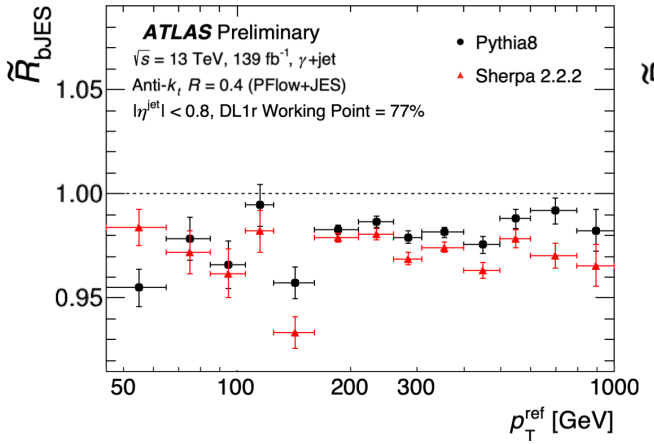
$\approx 90\ \%\ b, \approx 2\ \%\ c$



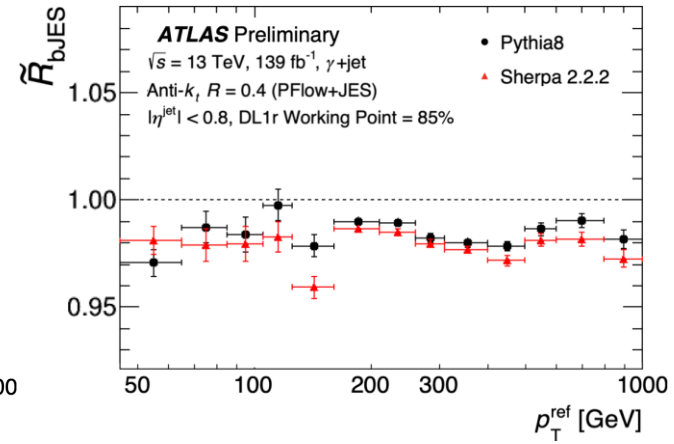
$\approx 80\ \%\ b, \approx 10\ \%\ c$



$\approx 60\ \%\ b, \approx 33\ \%\ c$



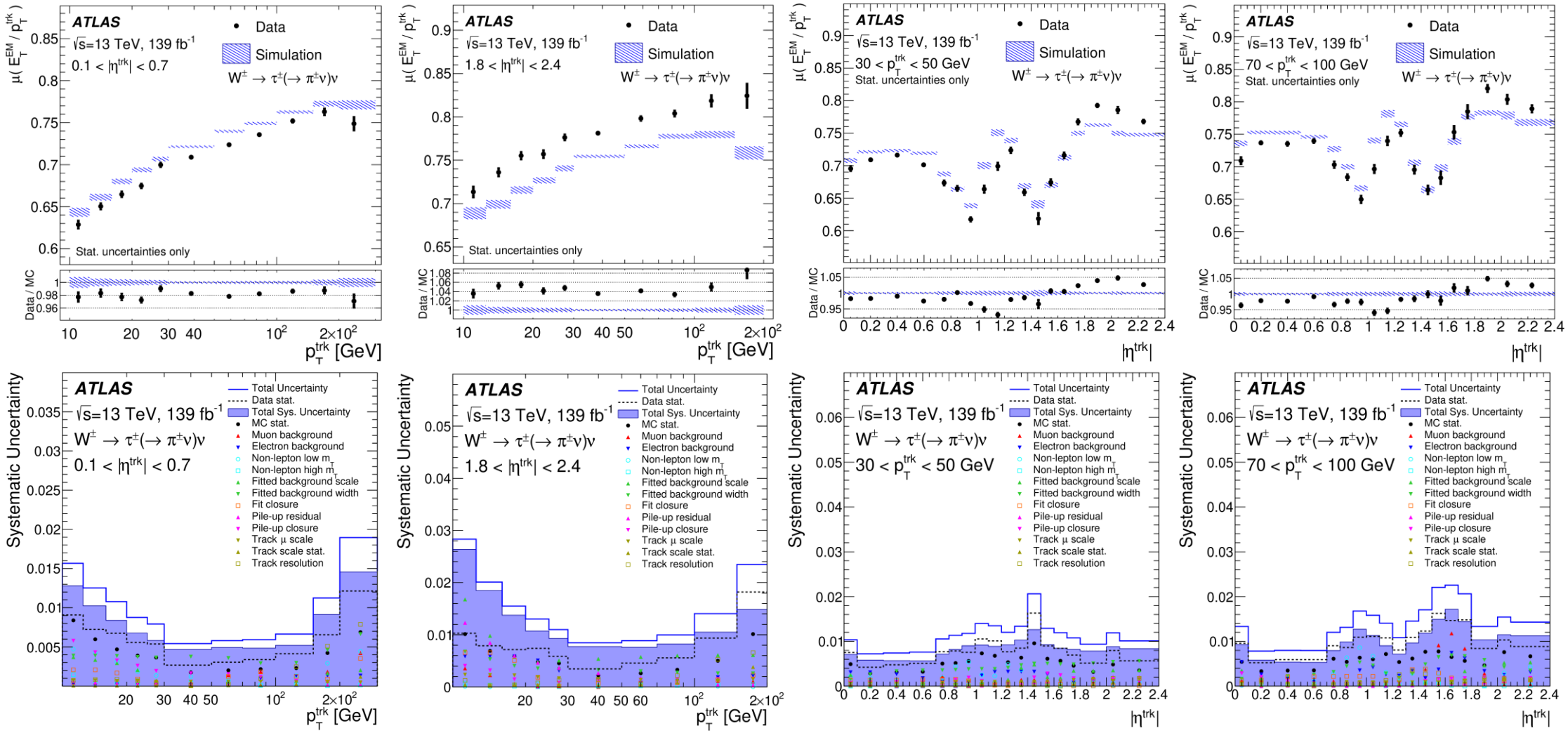
$\approx 37\ \%\ b, \approx 53\ \%\ c$



Back to the b-JES

More E/p results

Back to E/p



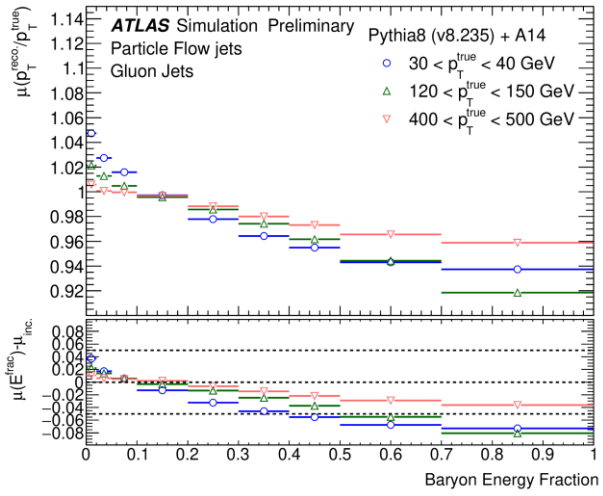
Response of Gluon Jets vs. Baryon and Kaon Energy Fractions

Back to gluon jet response

Pythia8

Pythia8 vs. Herwig7
Lund strings vs. clusters

Baryons



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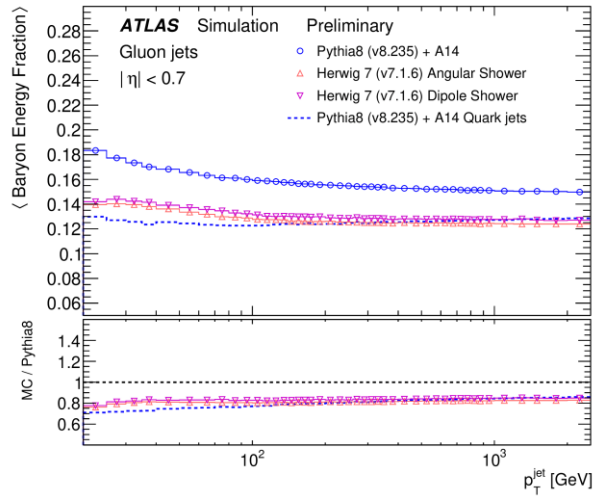
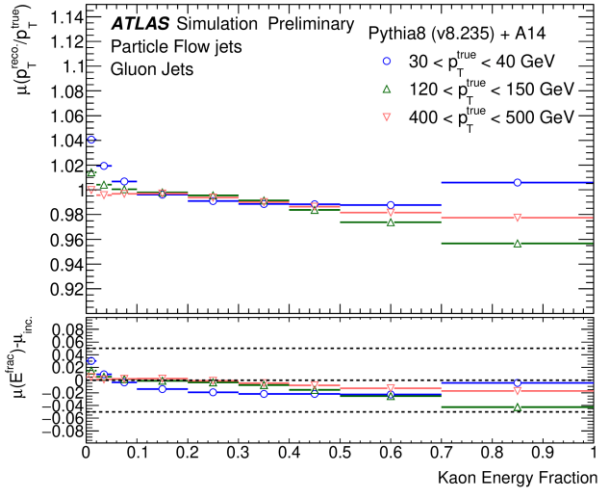


Kaons



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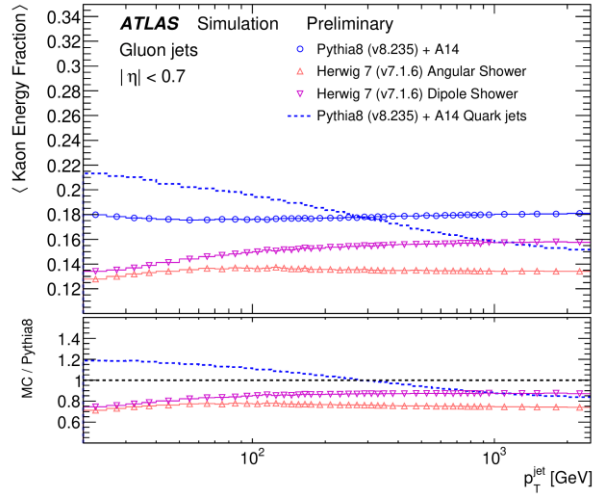
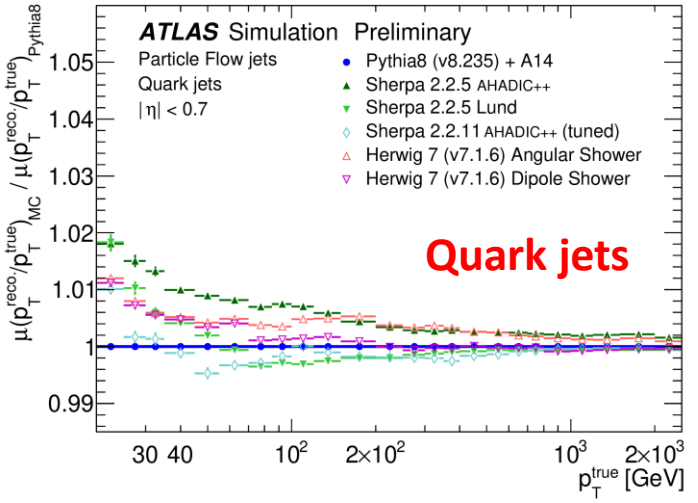
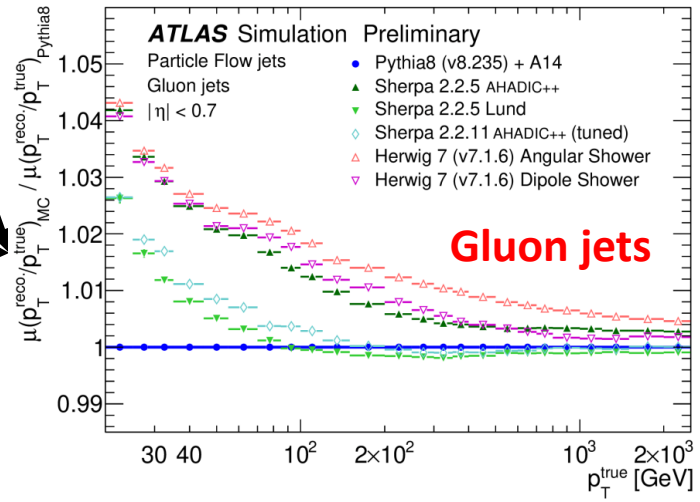




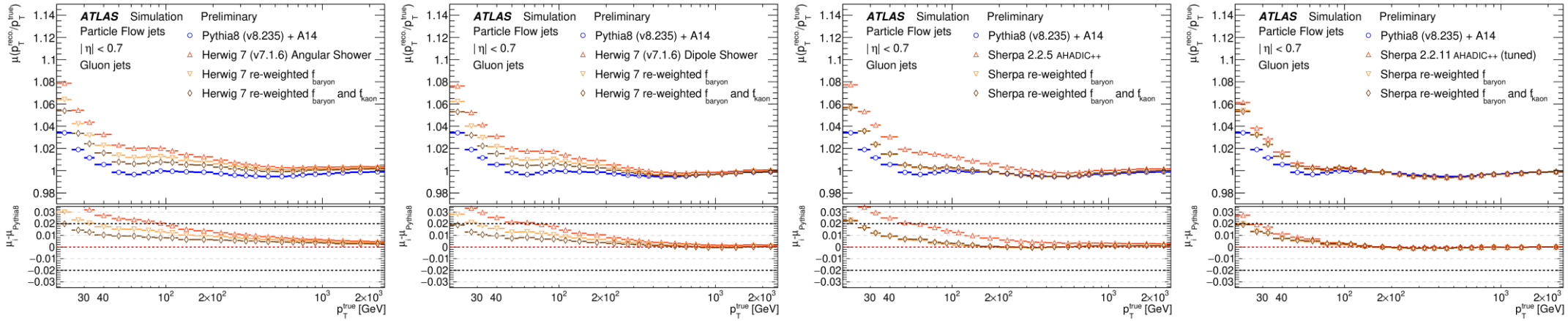


Response After Reweighting of Hadron Content

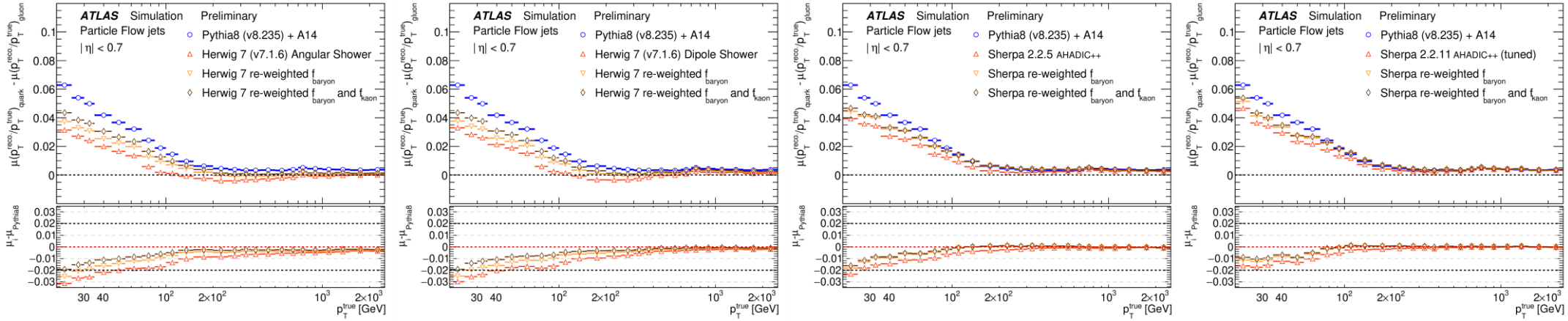
Reweighting the events based on the baryon and kaon energy fractions reduces the differences.

Herwig7 angular | Herwig7 dipole | Sherpa 2.2.5 AHADIC++ | Sherpa 2.2.11 AHADIC++ (re-tuned)

Gluon jets



Quark-gluon jets



Back to response of gluon jets