New techniques for reconstructing and calibrating hadronic objects with ATLAS

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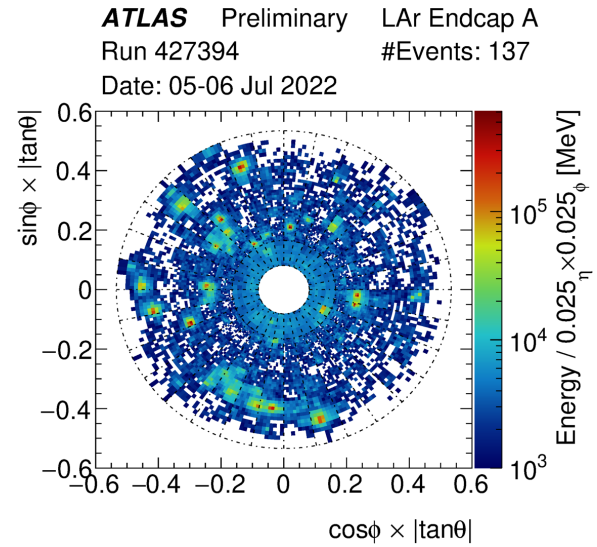
ATLAS EXPERIMENT

MAX-PLANCK-INSTITUT FÜR PHYSIK

Overview

- Developments in the reconstruction and calibration of hadronic signals and missing transverse momentum
  - ✓ legacy p_T^{miss} performance
  - ✓ testing response to b-jets
  - ✓ improvements in reconstruction of calorimeter signals…
  - ✓ …and in their calibration

- Boosted object identification and other ML-based results: see talk by Jad!



ATLAS public plots

➤ A complete list of new ATLAS results for BOOST23 is available here

The legacy of Run 2

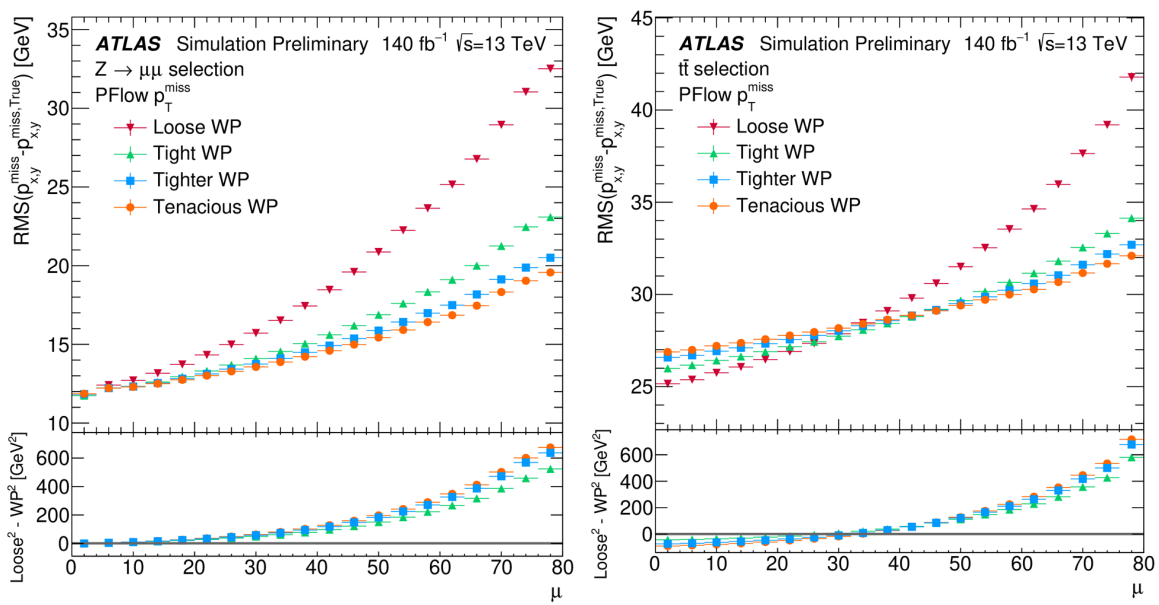
Missing transverse momentum (p_T^{miss})

- Estimate p_T of invisible particle through momentum conservation in *x-y* plane
- Negative sum of reconstructed and calibrated physics objects plus un-associated tracks (soft term)
  - ➤Using tracks was new to Run 2
  - Ambiguity resolution procedure to avoid double counting

$$\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}} = -\left| \underbrace{\sum_{\substack{\text{selected}\\\text{electrons}}} \boldsymbol{p}_{\mathrm{T}}^{e} + \sum_{\substack{\text{accepted}\\\text{photons}}} \boldsymbol{p}_{\mathrm{T}}^{\gamma} + \sum_{\substack{\text{accepted}\\\tau\text{−leptons}}} \boldsymbol{p}_{\mathrm{T}}^{\tau} + \sum_{\substack{\text{selected}\\\mu}} \boldsymbol{p}_{\mathrm{T}}^{\mu} + \sum_{\substack{\text{accepted}\\\text{jets}}} \boldsymbol{p}_{\mathrm{T}}^{\mathrm{jet}}}_{\text{hard term}} + \underbrace{\sum_{\substack{\text{unused}\\\text{tracks}}} \boldsymbol{p}_{\mathrm{T}}^{\mathrm{track}}}_{\text{soft term}} \right|$$

JETM-2023-002

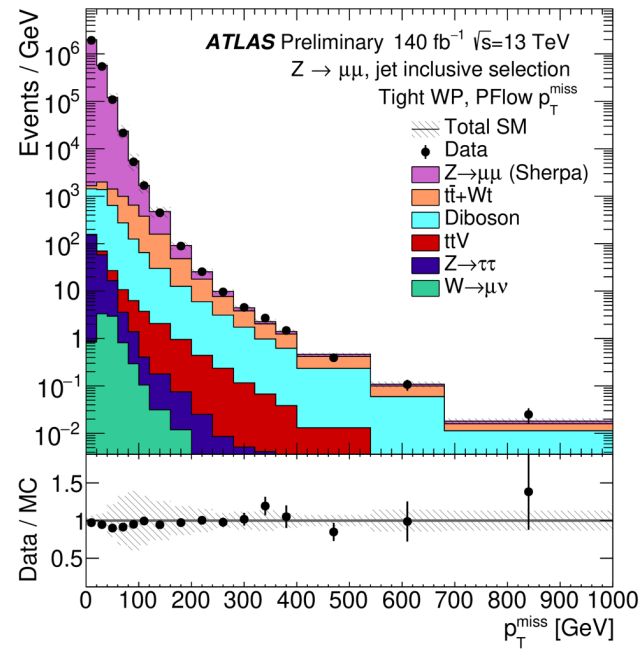
- Choice of multiple working points
  - Based on different jet selections
  - Best performing WP depends on final state's jet multiplicity



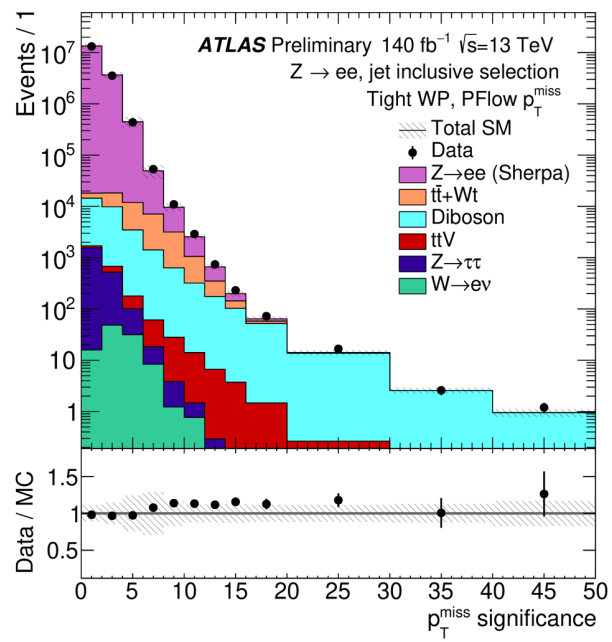
JETM-2023-002

p_T^{miss} performance in Run 2

- Legacy performance studies
- $Z \longrightarrow ee/\mu\mu$ final state: investigate fake p_T^{miss} background from e.g. detector acceptance of pile-up



- p_T^{miss} significance
  - Discriminant between fake p_T^{miss} and that from real invisible particles
  - In Run 2, object oriented version was used
    - ➤likelihood-based significance built from resolution of physics objects in p_T^{miss} definition
    - ➤First introduced in ATLAS-CONF-2018-038
    - ➤Separation power improved by about 25% with respect to previous definition

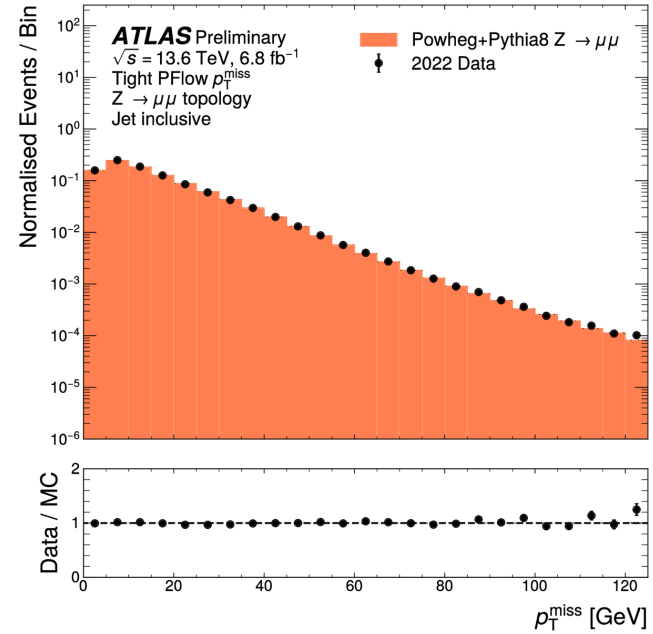


- Both p_T^{miss} and its significance are well described

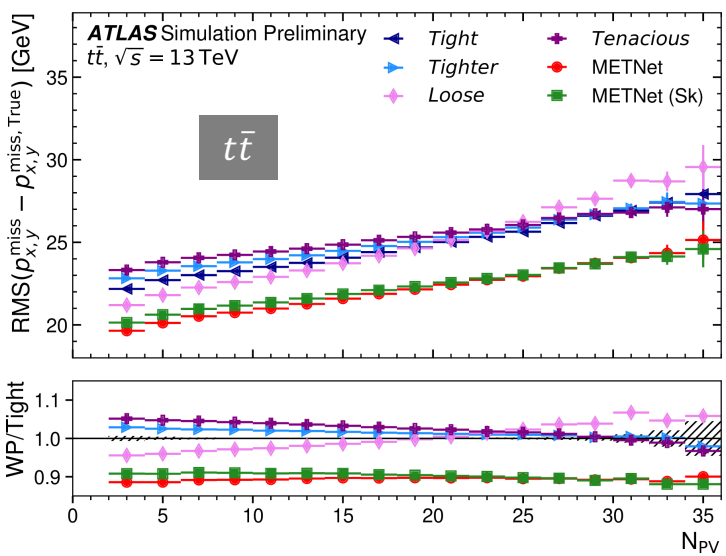
Run 3 and future prospects

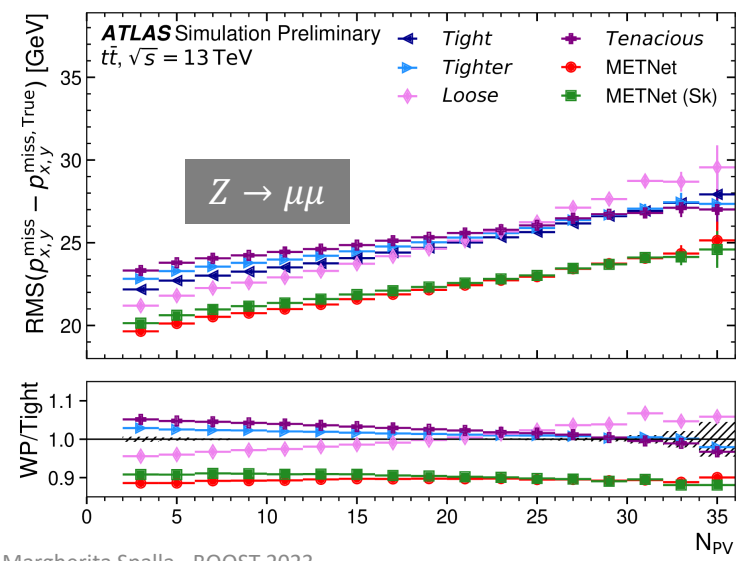
- p_T^{miss} in early Run 3

JETM-2022-009



- NN-based combination of multiple p_T^{miss} working points (method published in 2021)

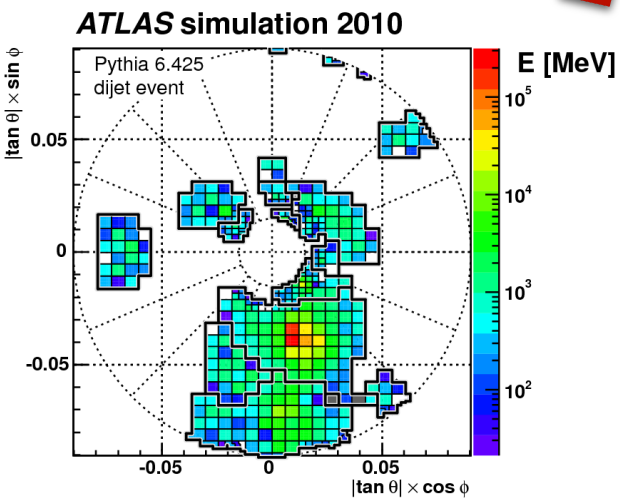




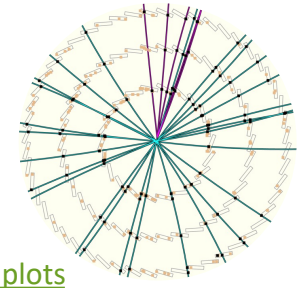
ATL-PHYS-PUB-2021-025

Hadronic signal reconstruction

Eur. Phys. J. C 77 (2017) 490



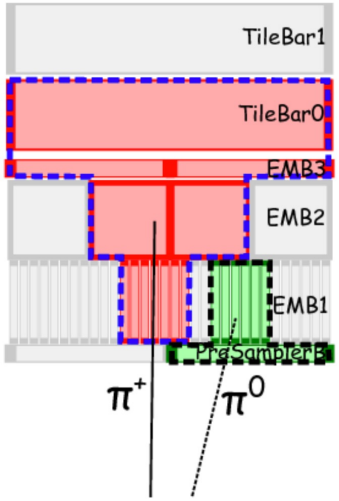
Topo-clusters:
cluster connected calorimeter cells around cells with high signal-to-noise ratio



ID Tracks

ATLAS public plots

Particle-flow objects

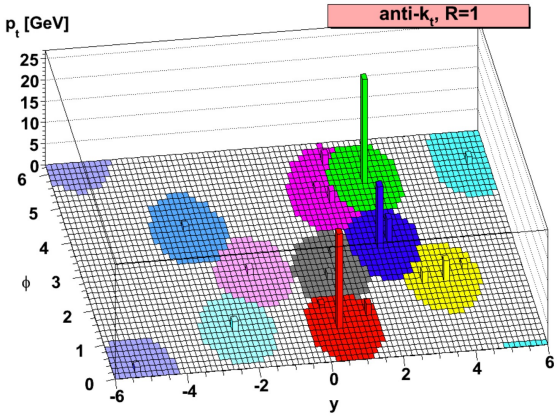


Eur. Phys. J. C 77 (2017) 490

- ✓ More recent approach also exploits tracks' angular resolution in dense environment: Unified Flow Objects

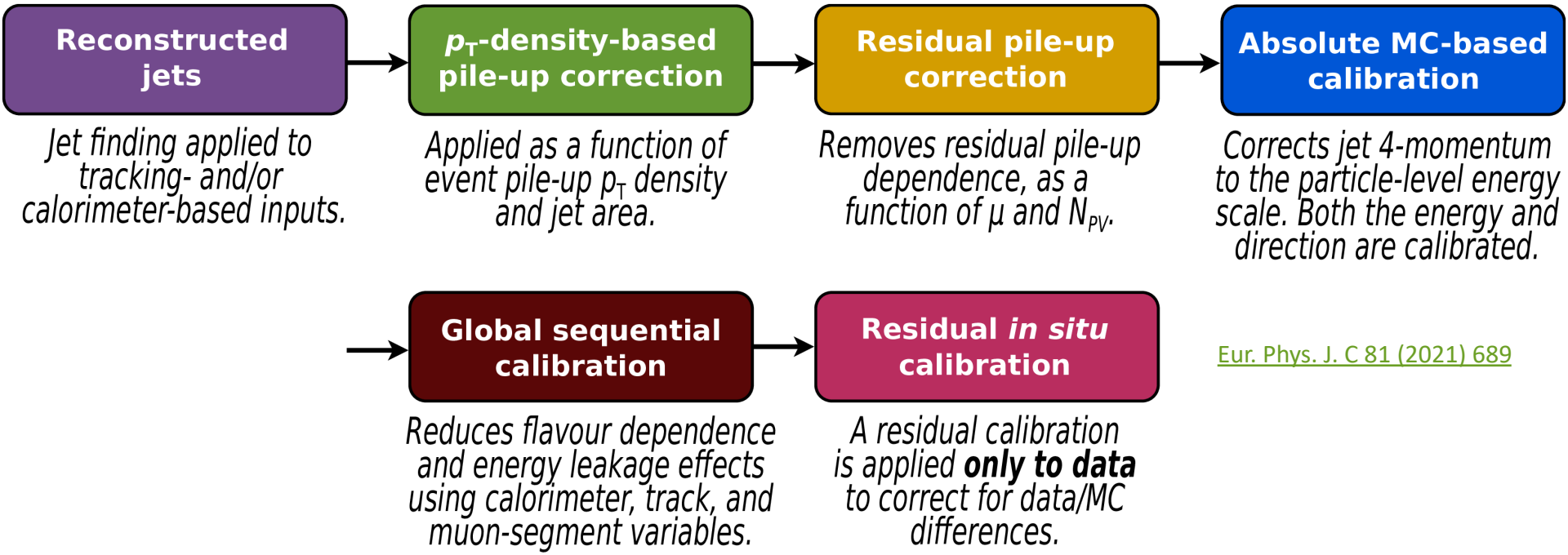
Jets build with anti-k_t algorithm.
R=0.4 or 1.0

- ✓ In this talk, focus on R=0.4



JHEP 2008 (2008) 063

The jet calibration chain



Eur. Phys. J. C 81 (2021) 689

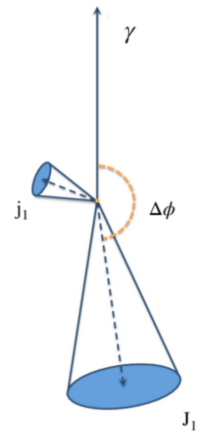
- Many new techniques developed building on Run 2 expertise [arXiv:2303.17312]
  - e.g. improved pile-up correction, Neural-Network based Global Calibration (GNNC), *in-situ* correction for b-jets
  - Very important input to Run 3 calibration

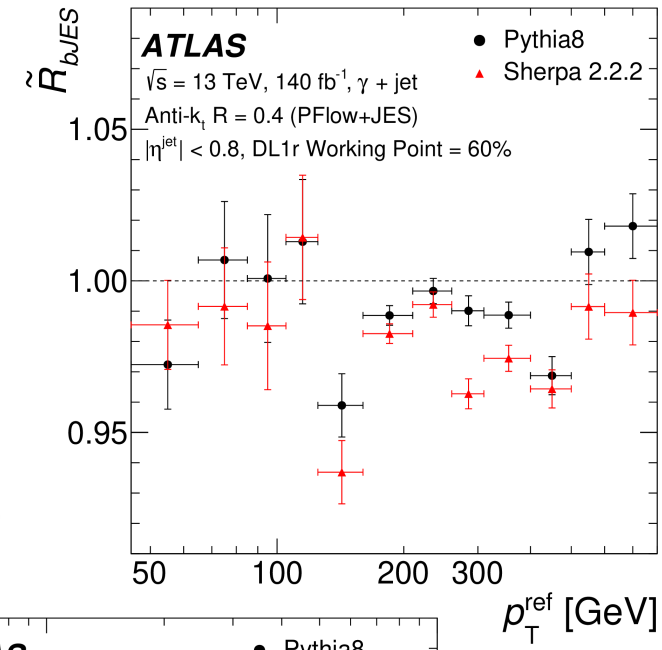
b-jet calibration using Run 2 data

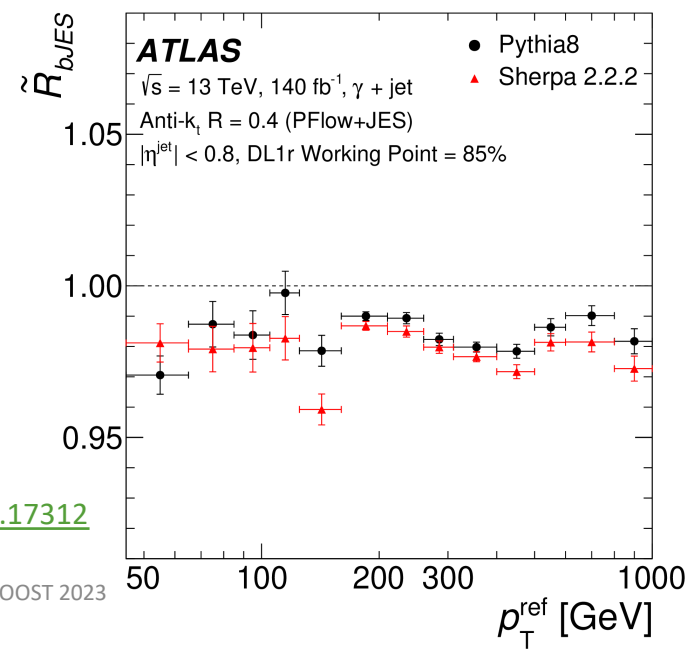
→ **Residual *in situ* calibration**

- Dedicated in-situ correction for b-tagged jets
  - Direct balance method used: jets tested against well measured γ
- b-jets correction found to differ from the one for inclusive jets
- Very interesting area worth exploring in more depth

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







arXiv:2303.17312

New for Run 3

Calorimeter topo-clusters

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- Building method based on cell energy significance E/σ_E
  - Topo-cluster seed: cell passing $|E|/\sigma_E>4$
  - Neighbouring cells iteratively collected
- Improvement: further suppress *out-of-time pile-up* using calorimeter time measurement

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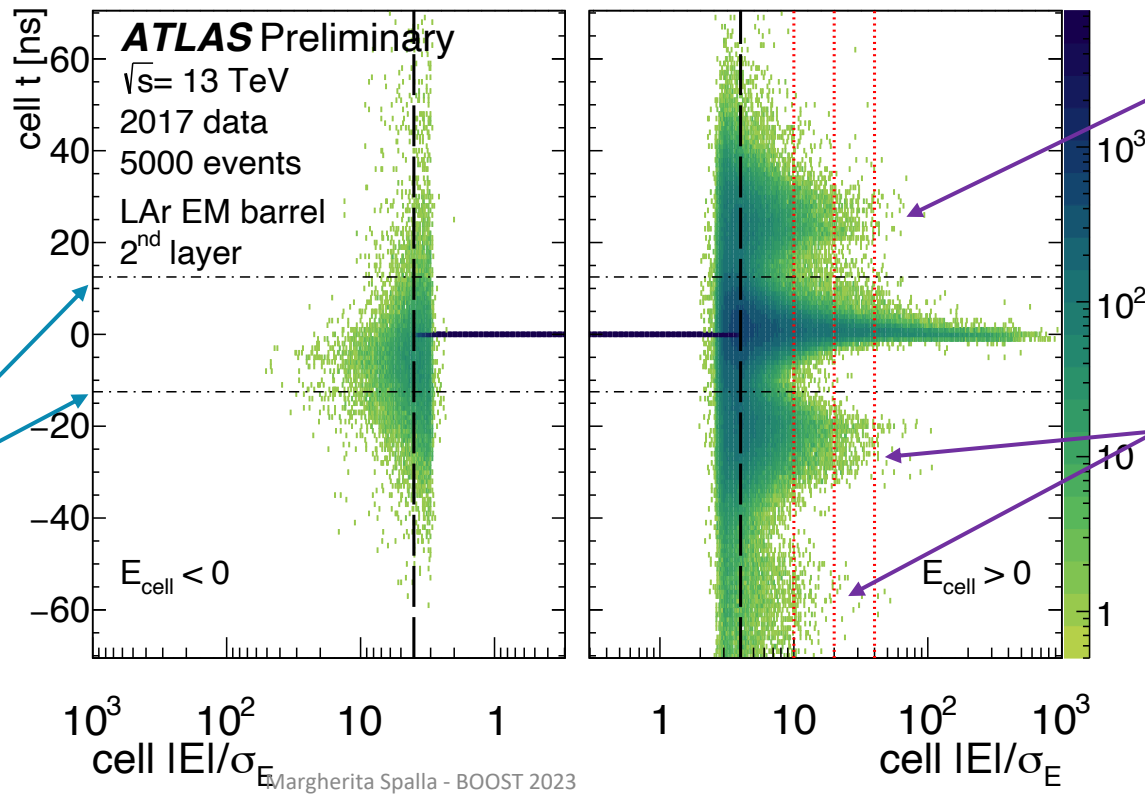
- Time resolution is good for large enough E significance

±12.5 ns



Next bunch crossing

Previous bunch crossings

The cell 'time cut'

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- Requirement for seeding a cluster modified to:

$$\begin{cases} |E_{\text{cell}}|/\sigma_E > 4 \\ |t_{\text{cell}}| \leq 12.5 \text{ ns} \end{cases} \quad \text{OR} \quad |E_{\text{cell}}|/\sigma_E > X_{\text{UL}}$$

  - Cells passing $|E_{cell}|/\sigma_E>4$ but failing $|t_{cell}|<12.5$ ns are also vetoed from being collected as neighbouring cells

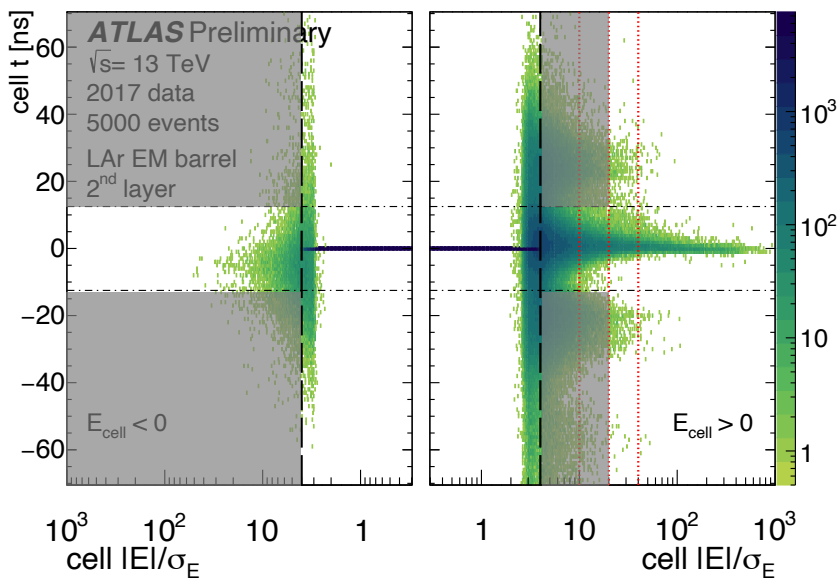
- Cut switched off for E significance greater than x_{UL} to avoid rejecting phase space potentially sensitive to Long-Lived-Particles signals with higher significance

ATLAS-CONF-2023-042

  - Multiple x_{UL} tested:

$$X_{\text{UL}} = 10, 20 \text{ and } 40$$

- Multiple cuts compared on both data and MC
- X_{UL} = 20 ultimately preferred

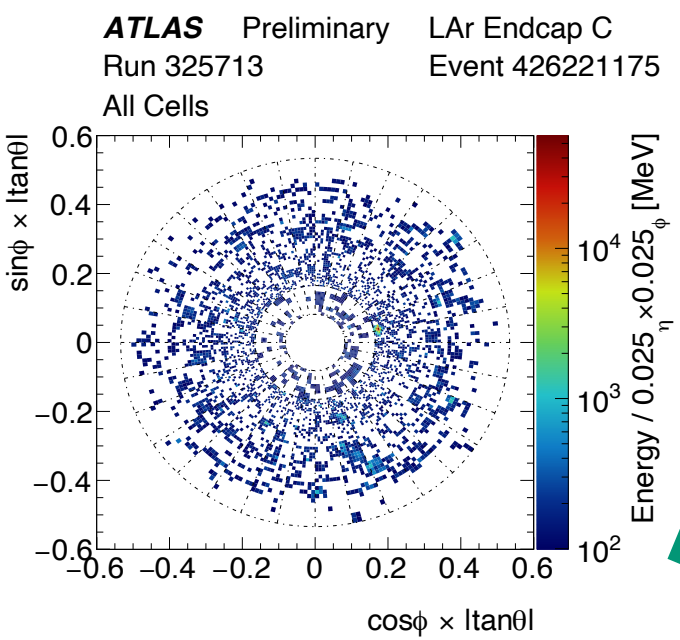


The *time cut*: an example

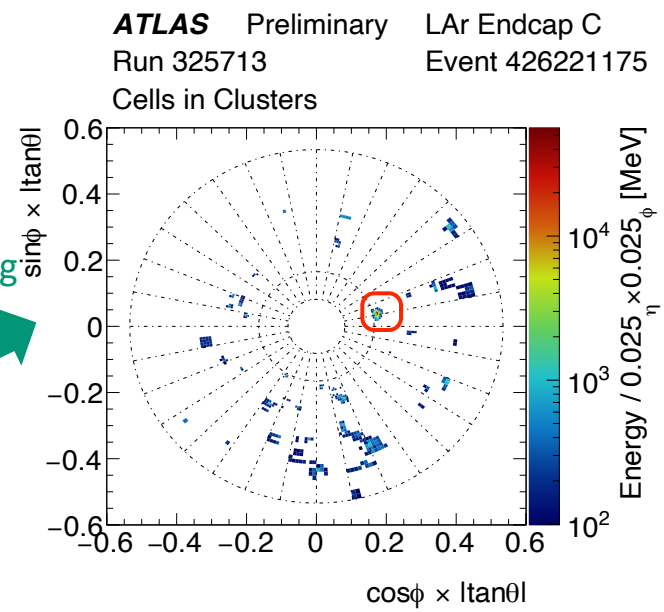
ATLAS Public Plots

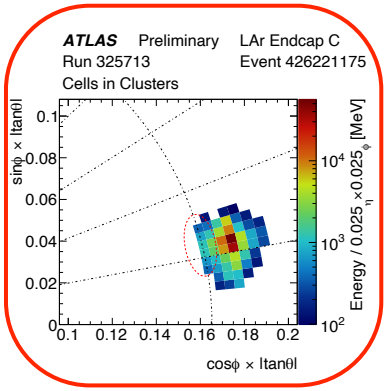
- One event from Run 2

Calorimeter cells

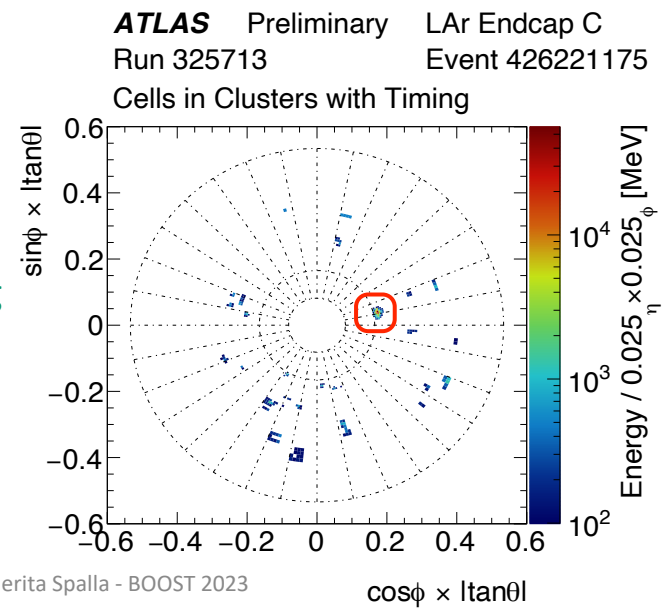


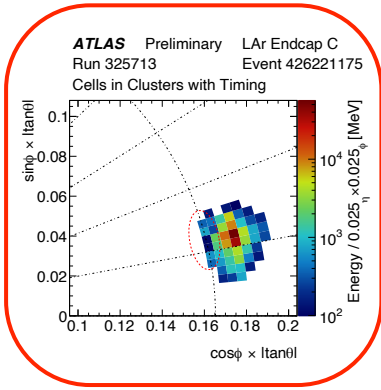
standard topo-clustering





topo-clustering with time cut





- Spurious contributions are removed
- Signal cluster becomes cleaner

The *time cut* performance

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- Suppresses out-of-time jets while preserving in-time signals
  - About -60% at p_T=20 GeV

- Overall <u>reduces disk size by about -6% per event</u>
  (including effect on other physics objects not described here)

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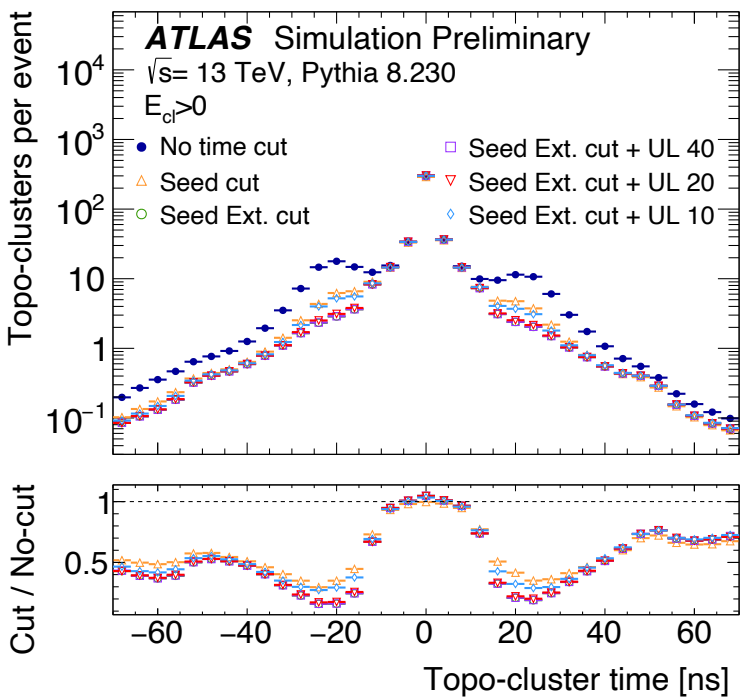
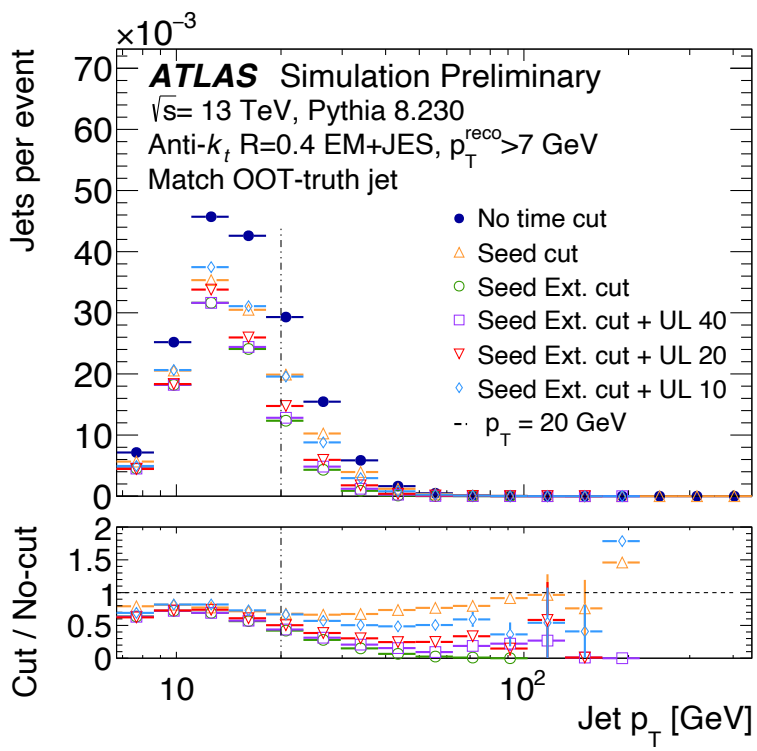




✓ Preferred option: x_{UL}=20

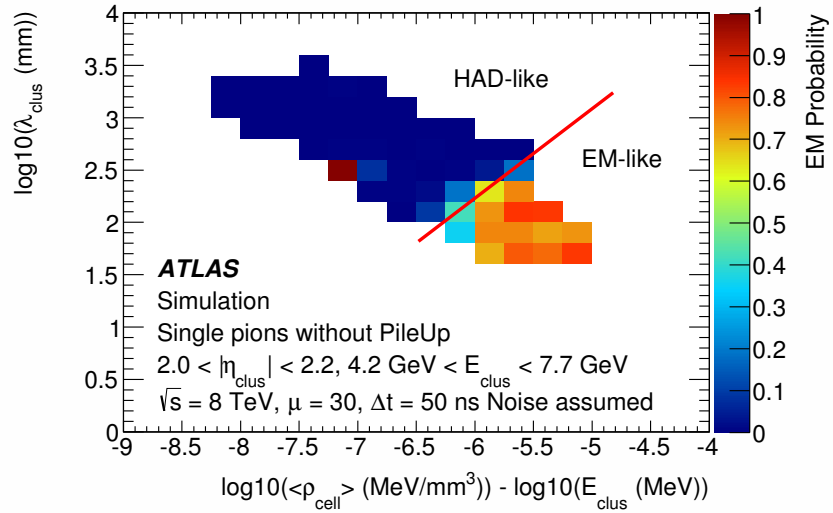
Moving towards the future

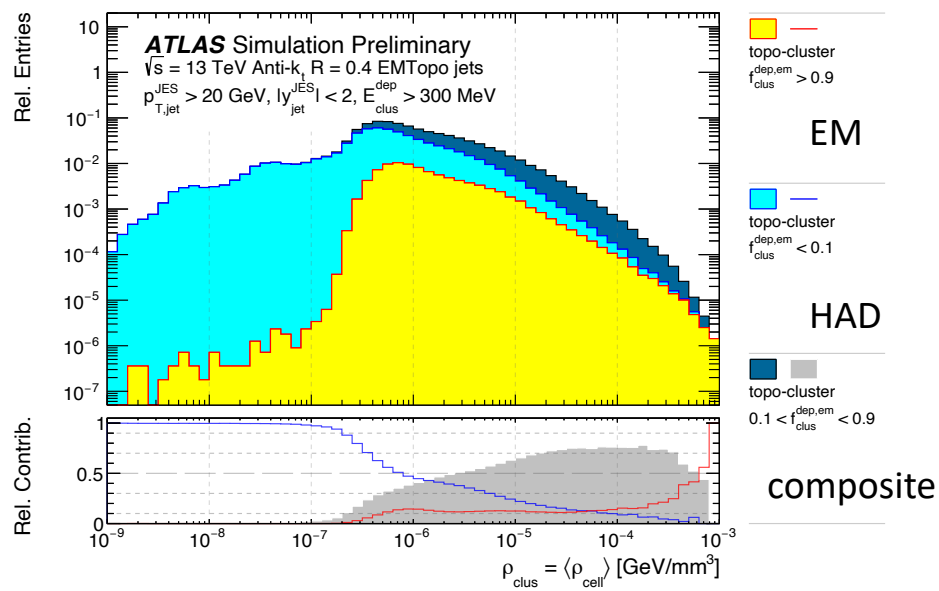
Eur. Phys. J. C77 (2017) 490

Topo-cluster calibration

- Calibrating cluster: correct for energy losses and calorimeter non-compensation
- Current version (Local hadronic Cell Weighting or LCW)
  - has been used widely for boosted analysis, e.g. jet sub-structure
  - LCW: identification of EM vs HAD clusters and calibration based on look-up table
- Wide interest in ML-based alternatives
  - Earlier results have looked at point-cloud + GNN approaches using cells and tracks

  (e.g. ATL-PHYS-PUB-2022-040)





ATL-PHYS-PUB-2023-019

cluster signal density

Topo-cluster calibration with Neural-Network

- NN learns the topo-cluster energy response $\mathcal{R}^{EM}_{clus}$
- Trained on topo-cluster moments
  - ➤ Weighted average over cells in the clusters
  - Same approach as LCW
    - ➤ pile-up information (μ, N_{PV}) also considered
  - ✓ Can apply to data formats not including cells (accessible at analysis level)
- Architectures:
  - fully connected Deep Neural Network (DNN)
  - Bayesian Neural Network (BNN)

$$\mathcal{R}^{EM}_{clus} = \frac{E^{EM}_{clus}}{E^{dep}_{clus}}$$

Measured energy, EM scale (i.e. *e* response=1)

Energy deposited in topo-cluster (truth-level)

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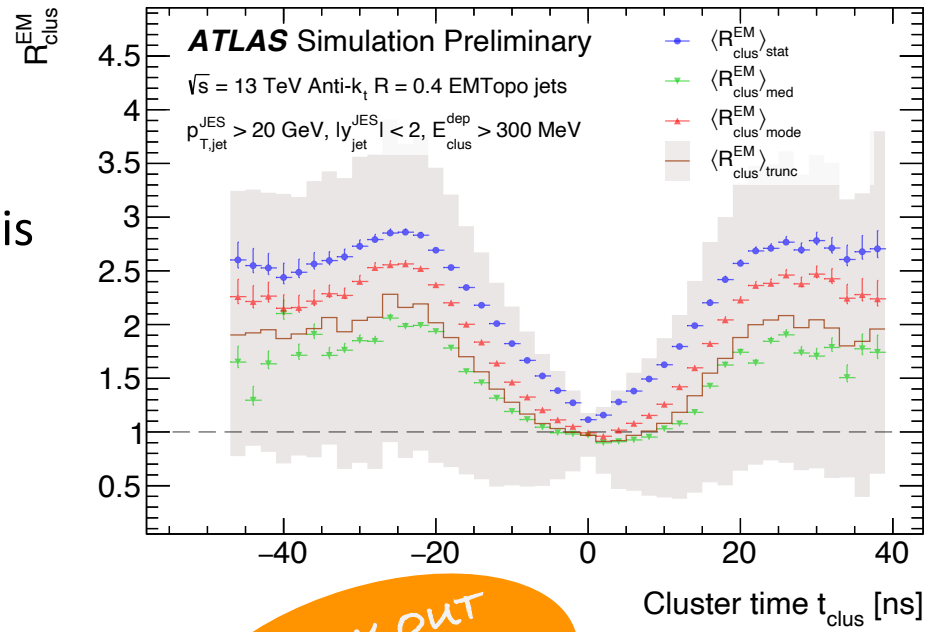

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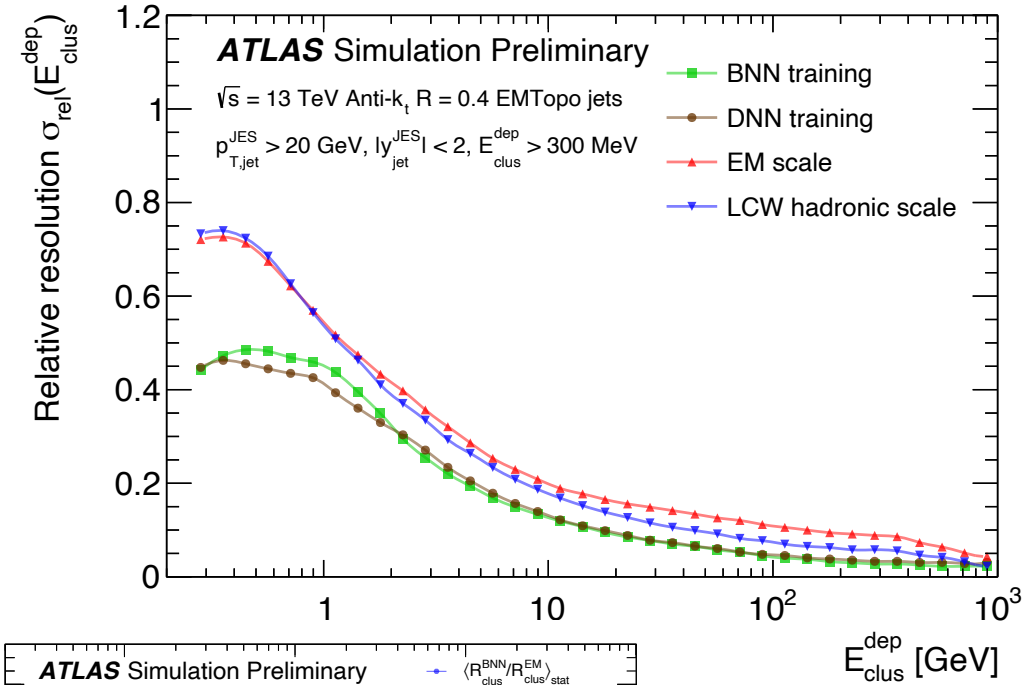
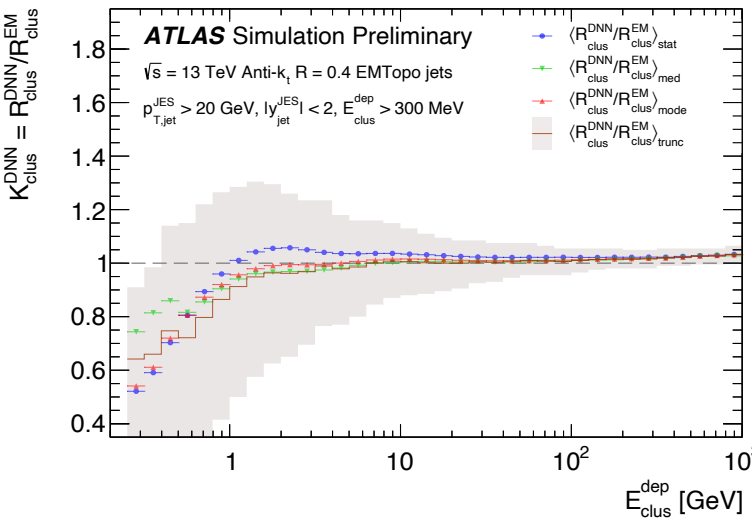
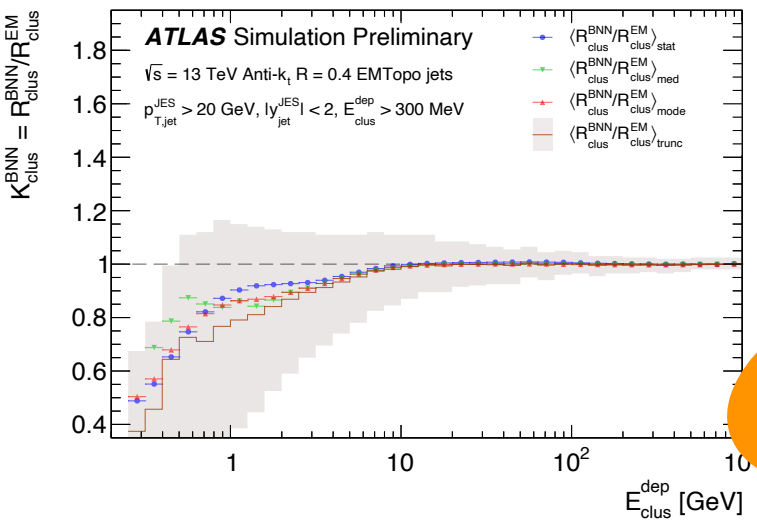
Topo-cluster calibration with Neural-Network (2)

- Improved resolution, less dependent on pile-up
- DNN provides a better response estimation than BNN
- Promising proof of principle for further investigation into constituent calibration







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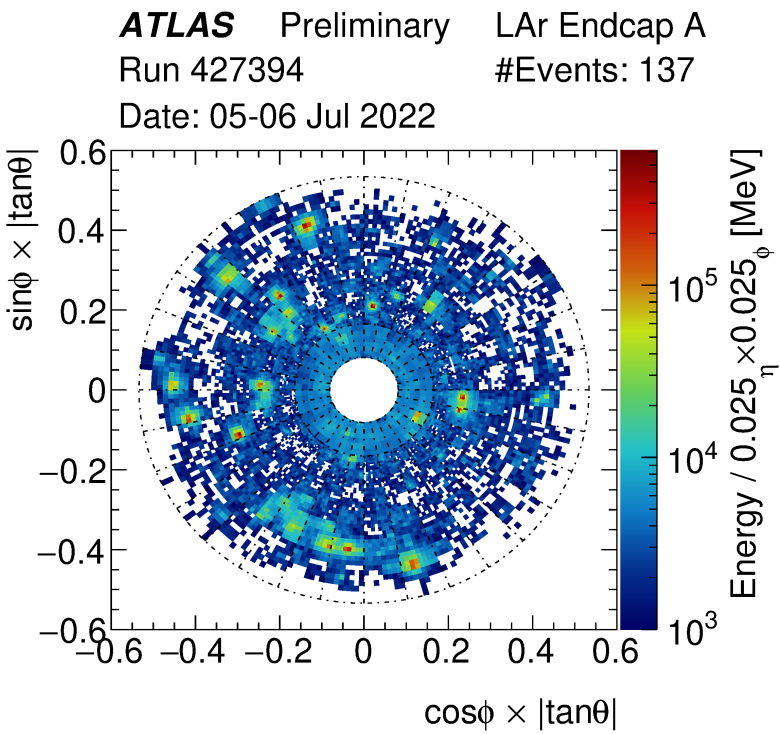
Summary

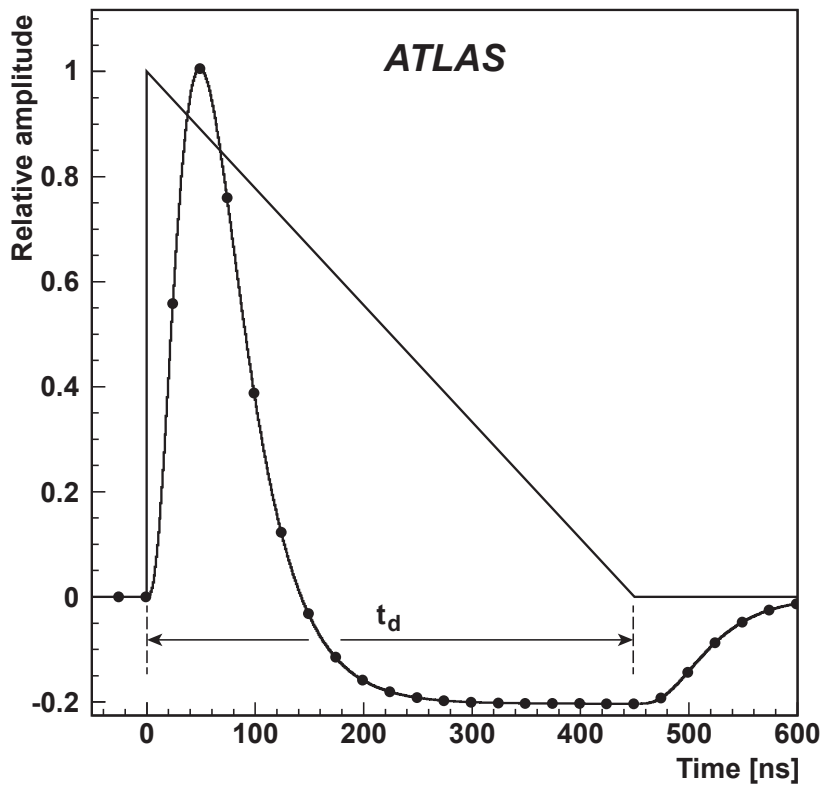
- Multiple improvements building on Run 2 acquired knowledge
  - To be applied during Run 3
  - As well as moving towards HL-LHC
- Reconstruction and calibration of low-level objects getting increasing interest
  - Thanks to ML developments as well as never-before used information
- Stay tuned for more developments to come!



Average view of 137 (sparse!) events in the LAr end-cap.
From ATLAS public plots

Backup

$$A = \sum_{i=1}^{n_{\text{samples}}} a_i S_i, \qquad t = \frac{1}{A} \sum_{i=1}^{n_{\text{samples}}} b_i S_i,$$



Plot from:
Eur. Phys. J. C 77 (2017) 490

ML scheme

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