Particle Flow Algorithm (PFA) for forward region jet reconstruction with the ATLAS ITk detector setup at the HL-LHC

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Outline

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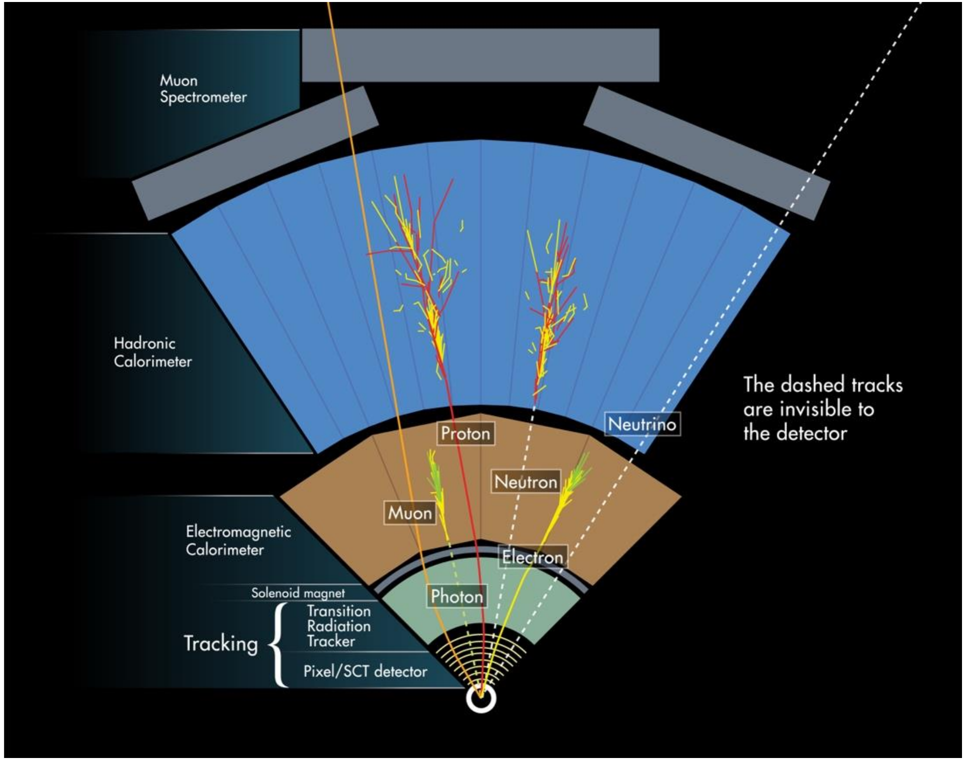
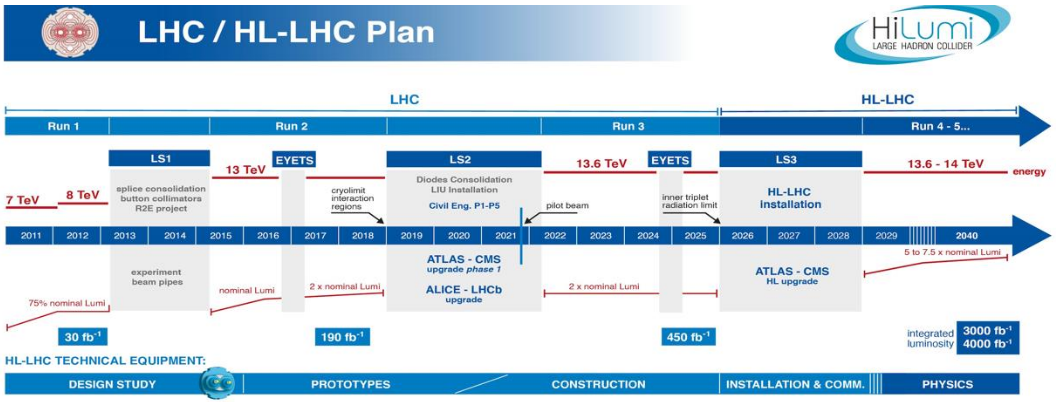
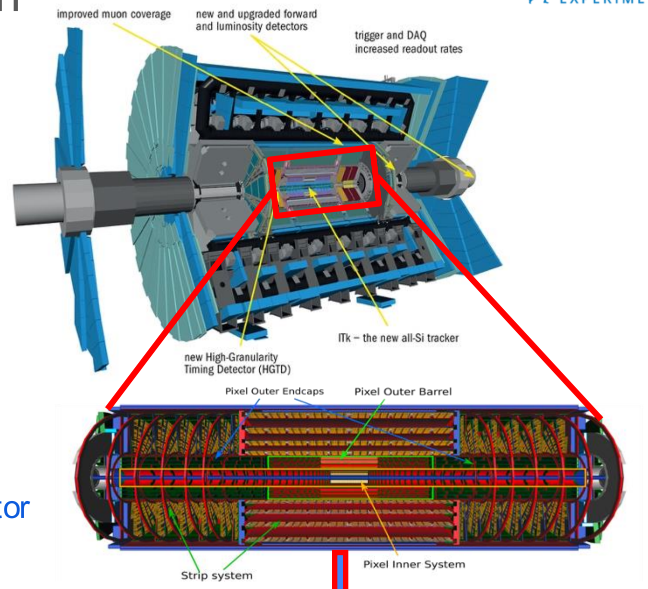
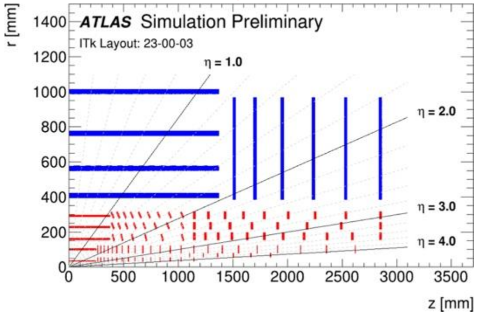
- ❑ Particle flow algorithm
- ❑ Forward region strategy
- ❑ Analysis Framework
- ❑ Results
- ❑ Summary and outlook



Motivation: Upgrading PFA for HL-LHC Forward Region







- ATLAS Phase II upgrades (Inner tracker (Itk) + high granularity timing detector (HGTD)) extend tracking to |η| ≈ 4.
- Forward region suffers from coarse granularity and extreme pile-up at High Luminosity – Large Hadron Collider (HL-LHC) (μ ≈ 200).
- Particle Flow Algorithm (PFA) uses track information to subtract charged energy from calorimeters.
- HGTD adds timing precision (~30 ps) to suppress pile-up in the forward region.
- Forward PFA is critical to unlock full physics potential of HL-LHC.

Particle Flow Algorithm (PFA)

Why it matters?

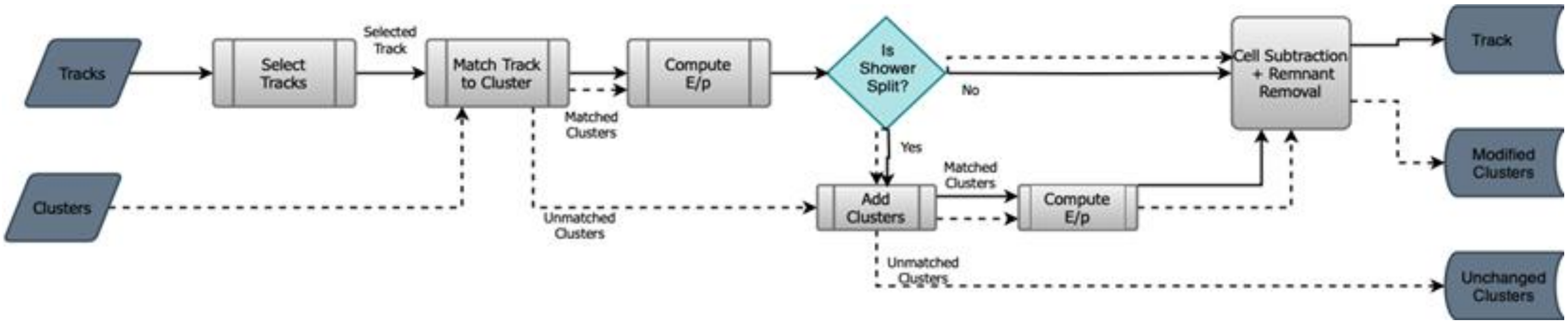
- ITk extends tracking to |η| ≤ 4 → enabling PFA in forward regions for the first time.
- HGTD adds precise timing → improves track–cluster matching under pile-up (μ ≈ 200).
- Cluster align with forward calorimeter geometry → make energy subtraction feasible despite coarse granularity.
- Together, these upgrades unlock forward-region PFA → critical for robust jet and MET reconstruction at HL-LHC.

Purpose:

- Enhance event reconstruction and improve energy resolution for hadronic objects by combining tracker and calorimeter information.

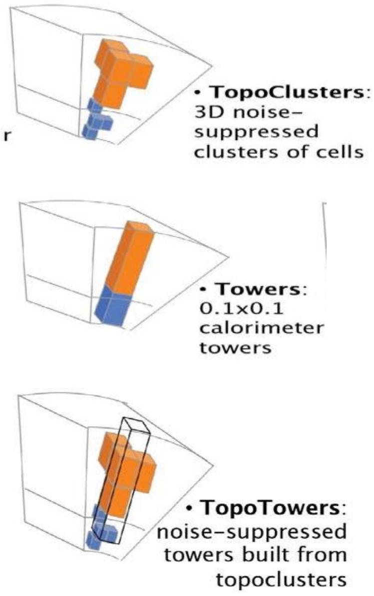
Key Features:

- **Track–Cluster Integration:** Merges inner detector and calorimeter information.
- **E/p Matching:** Subtracts charged track energy from calorimeter to prevent double-counting.
- **Shower Splitting Correction:** Recovers energy from fragmented clusters.



Forward region strategy: Clusters (TopoClusters & Topotowers)

Feature	Topocluster	Topotowers
Formation	3D topological clustering (cell significance, spatial connections)	Fixed-size η-φ towers (predefined grids)
Granularity	Dynamic, optimized for isolated showers	Static, coarser in forward regions
Noise Suppression	High (cell-level thresholds)	Moderate (tower-level averaging)
Use Case	Precision tracking in central η (<2)	Robustness in high-η, high-pileup regions



- ❏ Forward calorimeters have coarser granularity → topotower better match geometry.
- ❏ Reduced computational complexity for HL-LHC pile-up conditions (avg. μ = 200).
- ❏ Simplified energy subtraction in Particle Flow Algorithm (PFA).

Analysis Framework

Data Processing

- Monte Carlo sample used are single pions
- Convert ESD (full event details) → AOD (physics-optimized objects).
- Forward region: Add **TopoTowers** to AOD for coarse granularity.
- Generate n-tuples for $^{E}/_{p}$ distributions.

Energy Subtraction

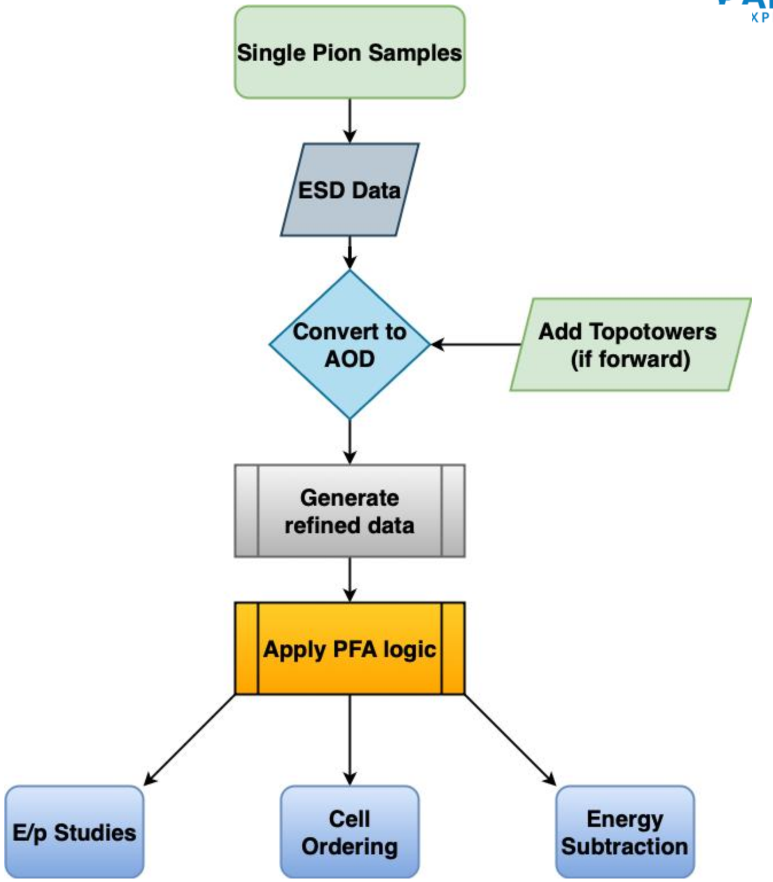
- Cell-based algorithm removes charged energy from calorimeters.
- Mitigates double-counting in track-cluster overlaps.

E/p Studies

- Analyze single-pion samples binned by:
  - Calorimeter layer.
  - Track energy (0–100 GeV).
  - Pseudorapidity ($|\eta| < 4$).

Cell Ordering

- Prioritize energy subtraction by density (highest → lowest).
- Critical for forward showers in coarse calorimeters.



E/p Calibration Methodology

- Key Definitions
  - E/p Ratio:
    - *E* = Calorimeter energy deposit in $\Delta R < 0.2$ cone around track.
    - *p* = Track momentum (inner detector).
    - $\langle {}^{E}/_{p} \rangle$ = Mean ratio, binned by E_{track}, η, LHED (Layer of Highest Energy Deposit).
- Fitting Strategy
  - Gaussian Fit to *E/p* distributions in each bin:
    - Range: Mean±RMS.
    - Validation:
      - If |Hist mean−Gauss mean|>0.1 → Use histogram mode (if mode > 0.1) or mean (if mode < 0.1).
      - Fit Quality: χ^2/NDF < 2.0 (central) / < 3.0 (forward)
- Energy Density Profiling *(For shower subtraction)*
  - Per ring ($\Delta\eta \times \Delta\varphi = 0.05 \times 0.05$):

    $$\langle E_{density} \rangle = {}^{\sum E_{cell}}/_{ring\ Area} \rangle$$
  - Priority: Subtract highest-density cells first

Binning Scheme for E/p Studies

Layer	Description
EMB	Electro-Magnetic Barrel calorimeter
EME	Electro-Magnetic Endcap calorimeter
Tile	Tile calorimeter
FCal	Forward calorimeter

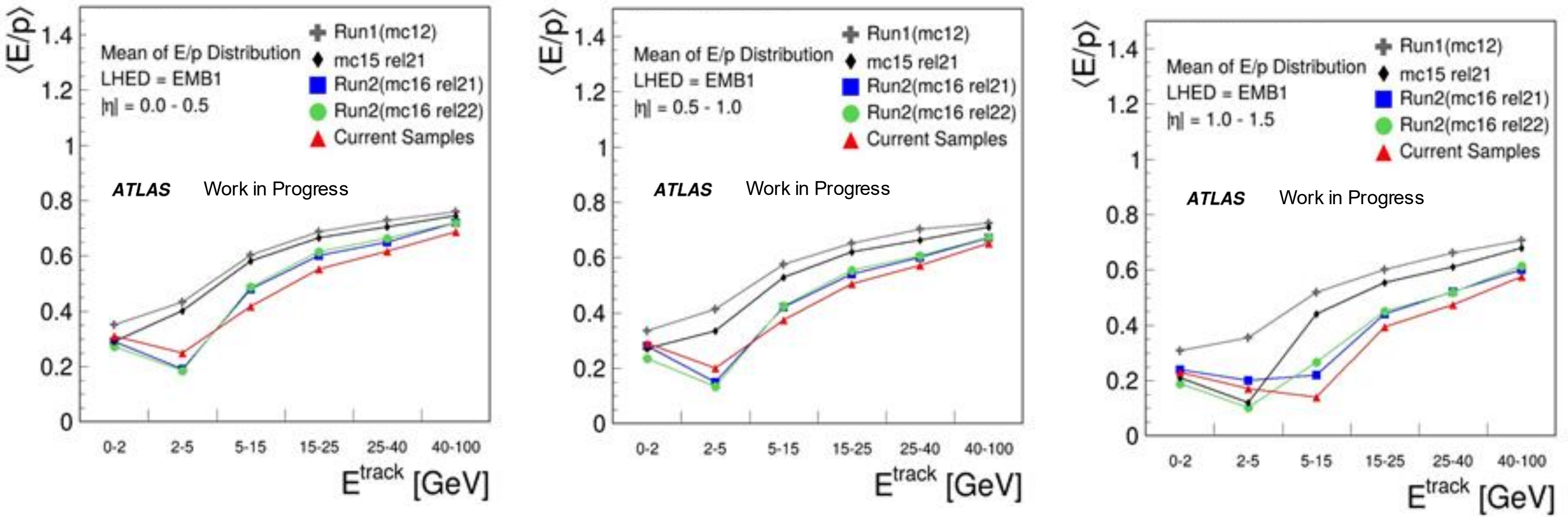
Calorimeter Layers

Variable	Bin edges
η_{track}	0; 0.5; 1.0; 1.5; 2.0; 2.5; 3.0; 3.5; 4.0
E_{track} $[GeV]$	0; 2; 5; 15; 25; 100
$LHED$	EMB1; EMB2; EMB3; EME1; EME2; EME3; HEC; Tile; FCal

Binning Variables

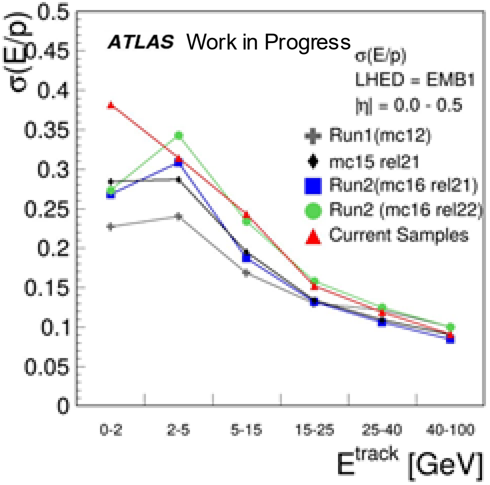
Forward Region: Coarse η bins for |η|>2.5 due to calorimeter granularity.
Low Energy: Focused bins below 5 GeV (critical for pile-up suppression).

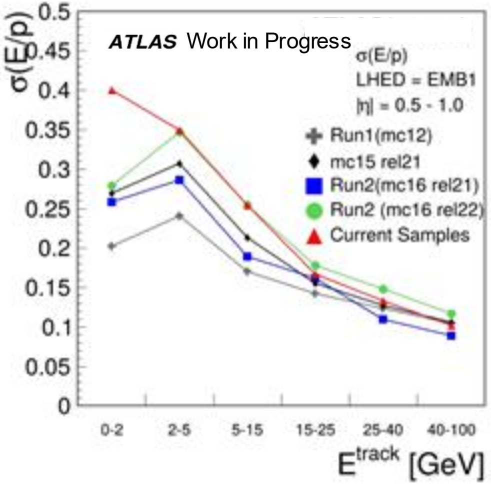
Central region results: Mean of E/p distribution (LHED=EMB1, η=[0-1.5])

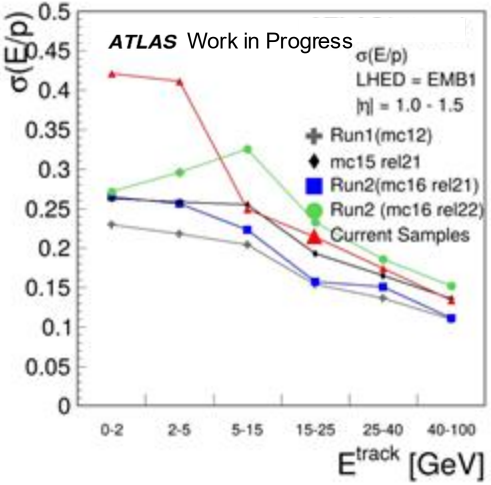


- For all samples, the mean E/p value generally increases with increasing transverse momentum (E_{TRACK})
- In the lower momentum bins, the mean E/p values are significantly below 1 for all samples.
- As the transverse momentum increases, the mean E/p values for most samples approach a plateau, generally between 0.6 and 0.7, due to energy loss in calorimeter material

Central region results: Sigma E/p distribution (LHED=EMB1, η=[0-1.5])

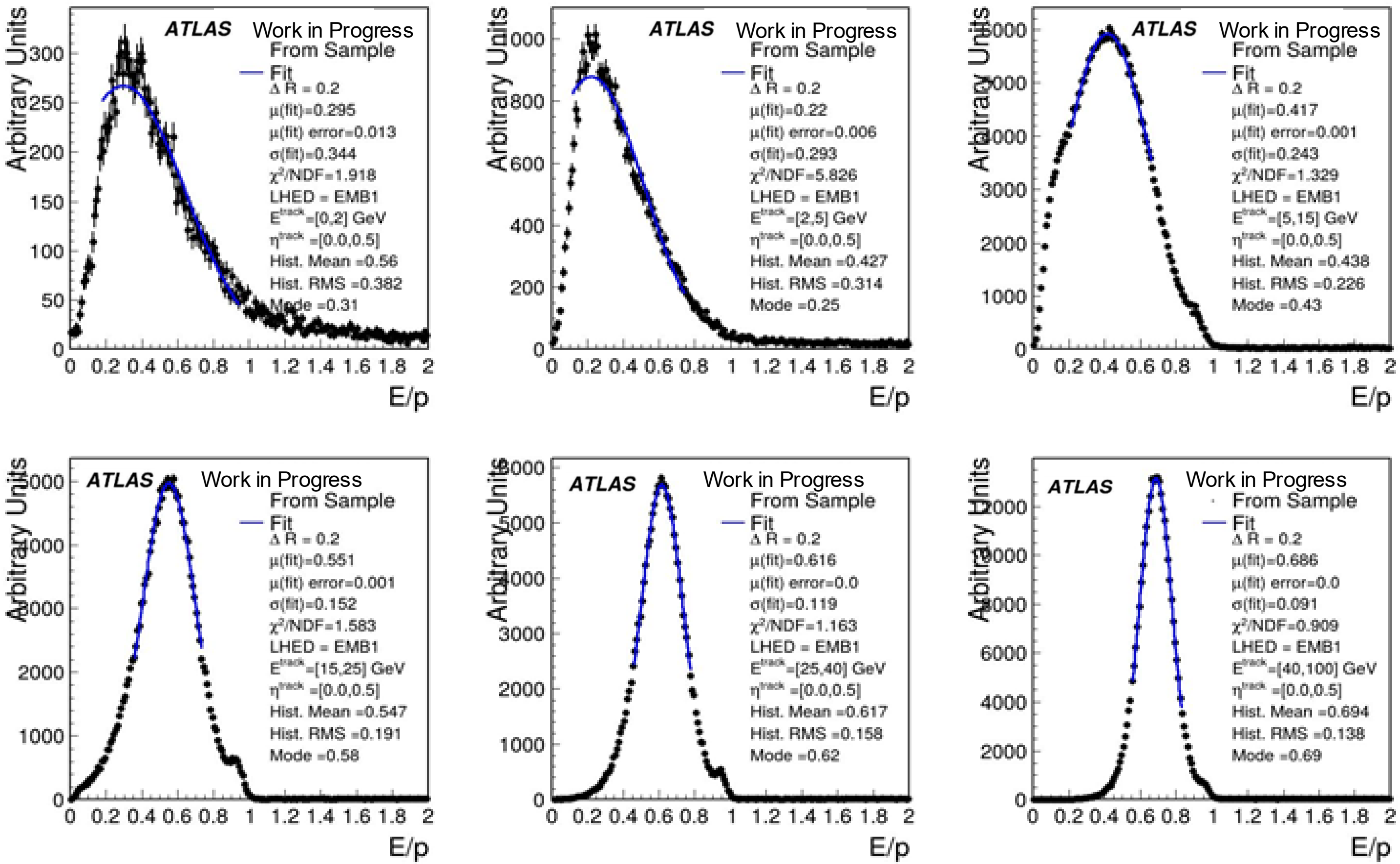




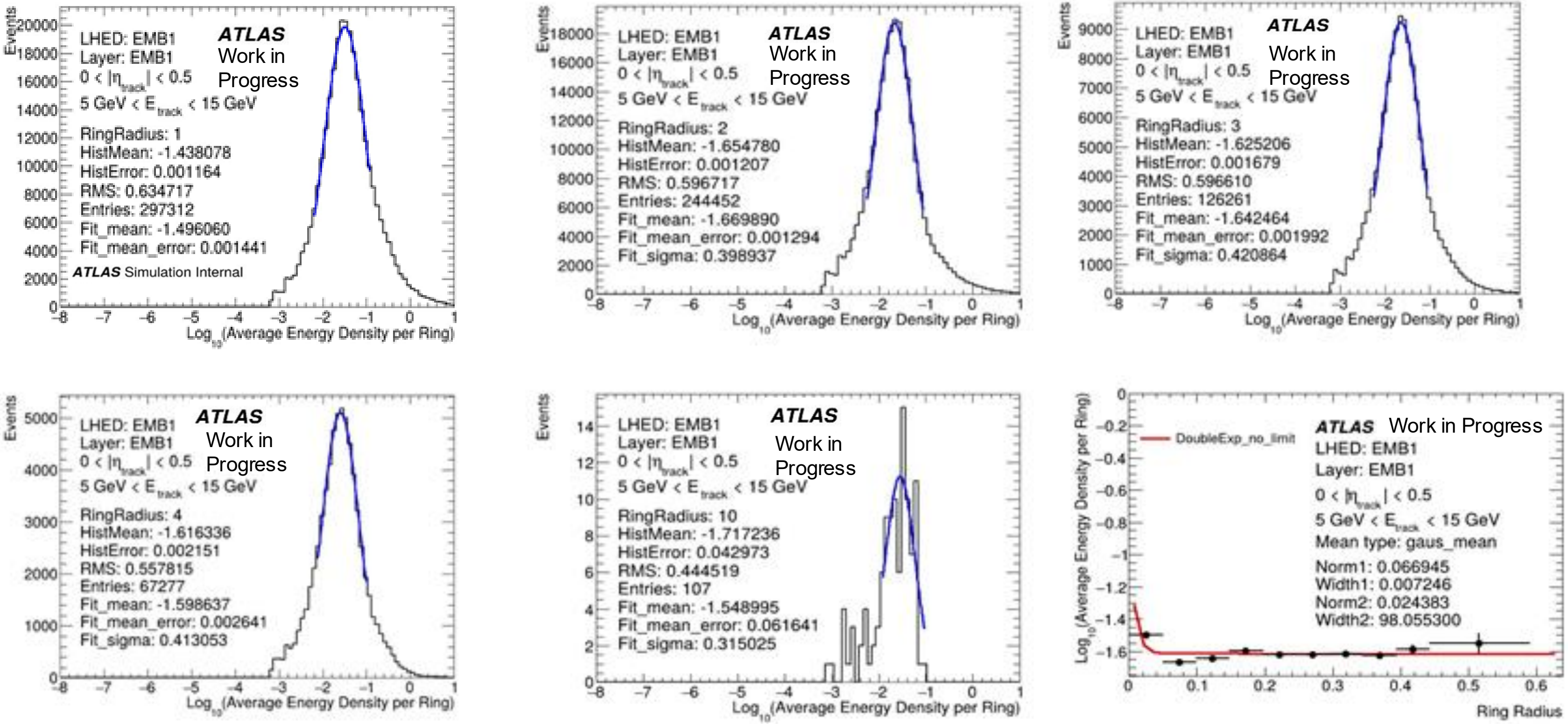


- For most samples, the E/p resolution (σ(E/p)) generally improves (decreases) as the transverse momentum (E_{track}) increases.
- In the lower momentum bins, the resolution tends to be worse (higher σ(E/p)) and shows more variation between different samples.
- At higher transverse momenta, the resolution generally plateaus or continues to improve slowly.

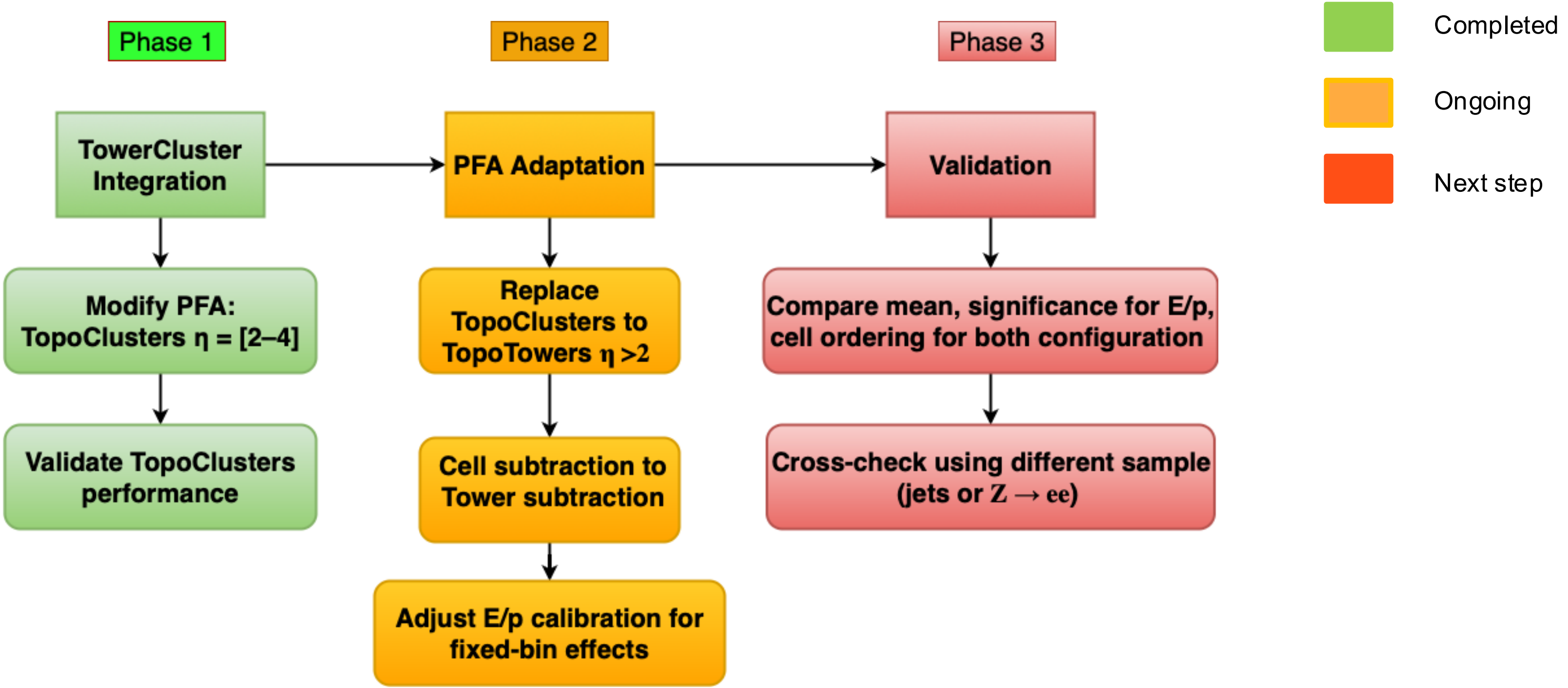
Central region results: Fitting results (LHED=EMB1, η=[0-0.5])



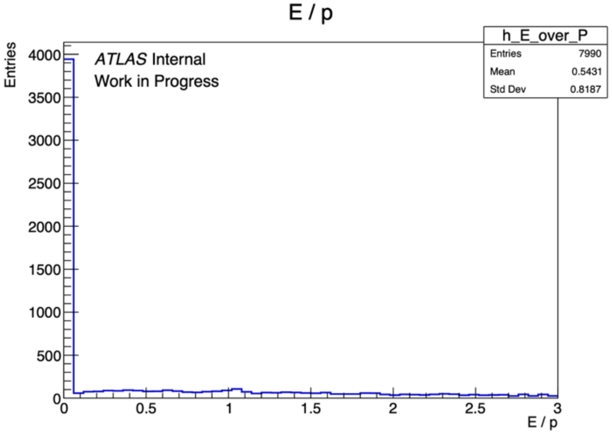
Central region results: Cell Ordering

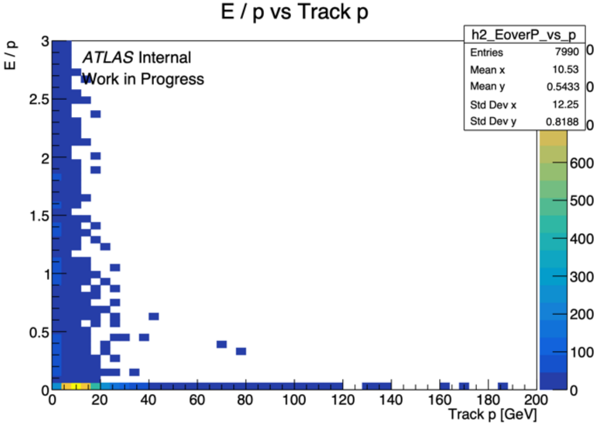


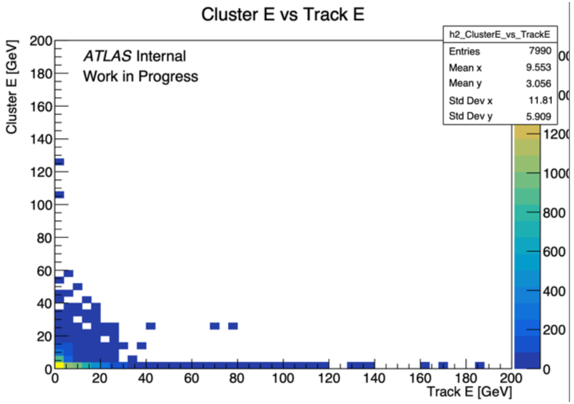
Implementation Roadmap in the Forward region

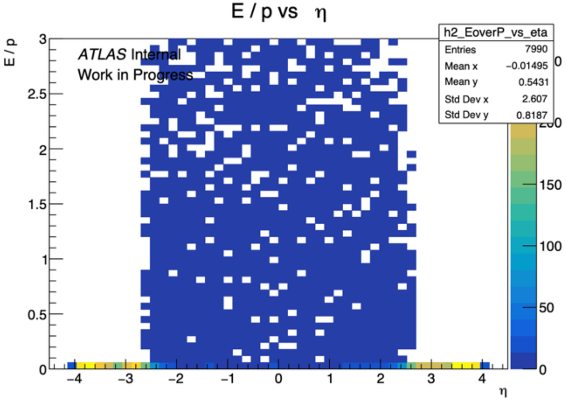


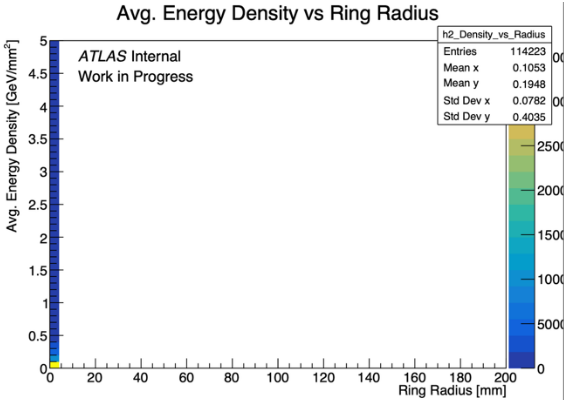
Forward region preliminary results: E/p distribution forward region

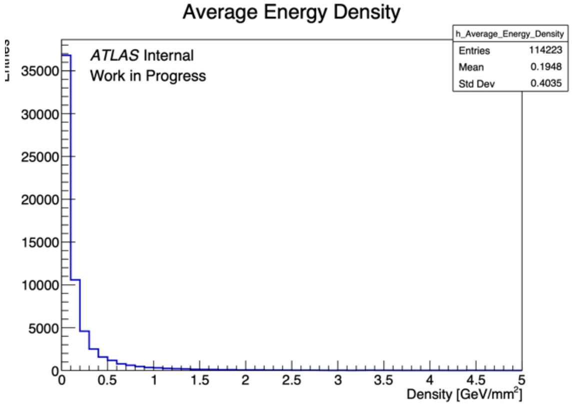




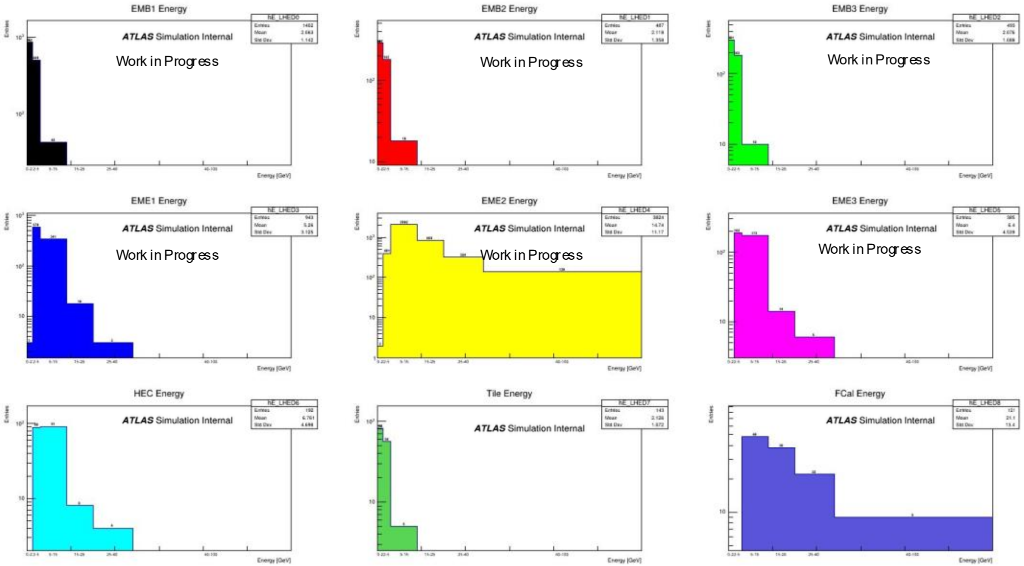


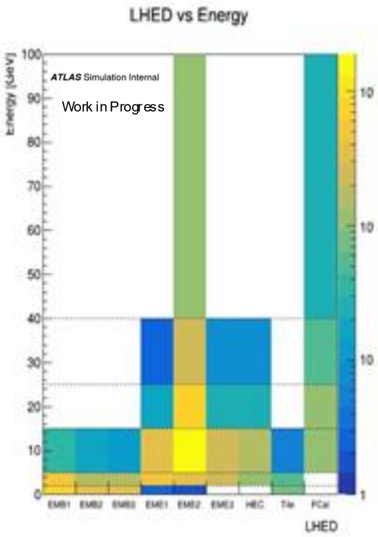






E/p distribution Forward region preliminary results





- ❑ E/p plots are still being validated to ensure the topotowers are implemented correctly
- ❑ FCal indicates there are entries with energies ranging from 5-100 GeV

Summary and outlook

- Extended Particle Flow Algorithm (PFA) to forward region using Topotowers, leveraging ITk coverage ($|\eta \leq 4|$) at the HL-LHC.

- Central region validation shows expected E/p trends: increasing mean, improving resolution with transverse momentum p_T

- Forward region integration:
    - Phase 1 & 2 complete (Topotower input + PFA adaptation).
    - Phase 3 validation in progress (Z→ee, jets).

- Workflow established: E/p binning, LHED-based subtraction, and cell/tower ordering.

- Next Steps:
    - Finalize E/p validation and tower subtraction tuning.
    - Cross-check physics performance, document for ATLAS integration.
    - Explore ML-based or hybrid tower/cluster methods.

- Impact:
  Enables robust jet/MET reconstruction in forward region under extreme pile-up, unlocking full HL-LHC potential.

Kea Leboha!

Pula, nala!

BACK UPS

ΔR

- ΔR is a distance metric in η–φ space (pseudorapidity vs. azimuthal angle), defined as:
  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$
  - Δη: Difference in pseudorapidity (measures "forward/backward" angle relative to beam axis).
  - Δφ: Difference in azimuthal angle (measures "around the beam" direction).
- $\Delta R<0.2$ means we only link a track to calorimeter clusters *within a cone of radius 0.2* around the track's extrapolated position.

Why This Matters in PFA

- Precision Matching
  - Ensures the energy subtracted from calorimeters truly belongs to the charged track.
  - Too large (e.g., $\Delta R<0.4$): Risks including energy from pile-up or nearby particles → double-counting.
    Too small (e.g., $\Delta R<0.1$): May miss parts of the particle's shower → energy loss.
- Pile-Up Resilience
  - At HL-LHC ($\mu\approx200$), the detector is crowded. $\Delta R<0.2$ isolates the core shower while excluding contamination:
    Shower width ~0.1-0.15 in η/φ → $\Delta R<0.2$ safely contains >95% of energy.
- Forward Region Specifics
  - In coarse-grained forward calorimeters (HEC/FCal), showers spread wider.
  - We validated $\Delta R<0.2$ still captures the dominant energy fraction (see cell-ordering plots on Slide 13: energy density drops sharply beyond $\Delta R=0.15$).