Point Cloud Deep Learning Methods for Pion Reconstruction in the ATLAS Experiment

Piyush Karande, on behalf of ATLAS Team

ML4Jets Nov 4th, 2022

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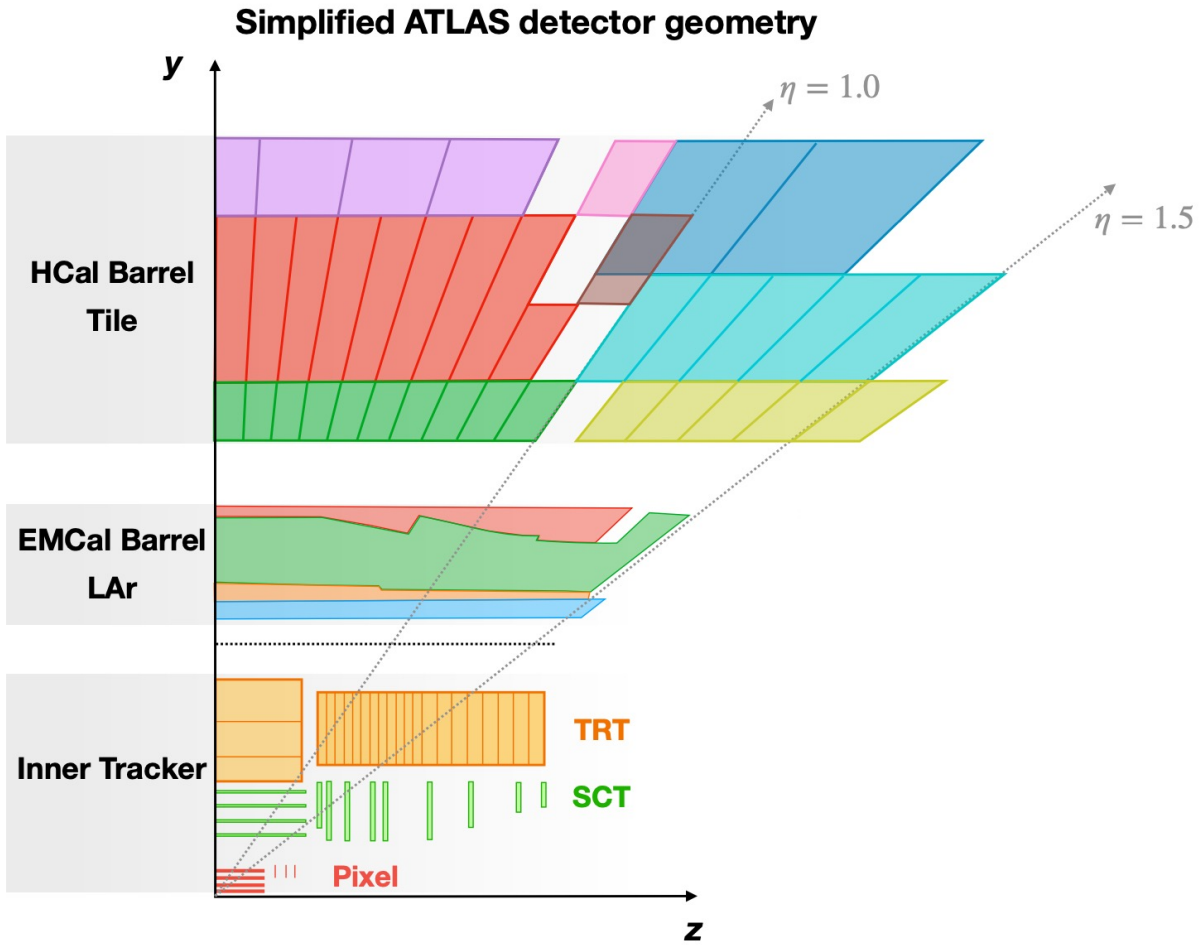
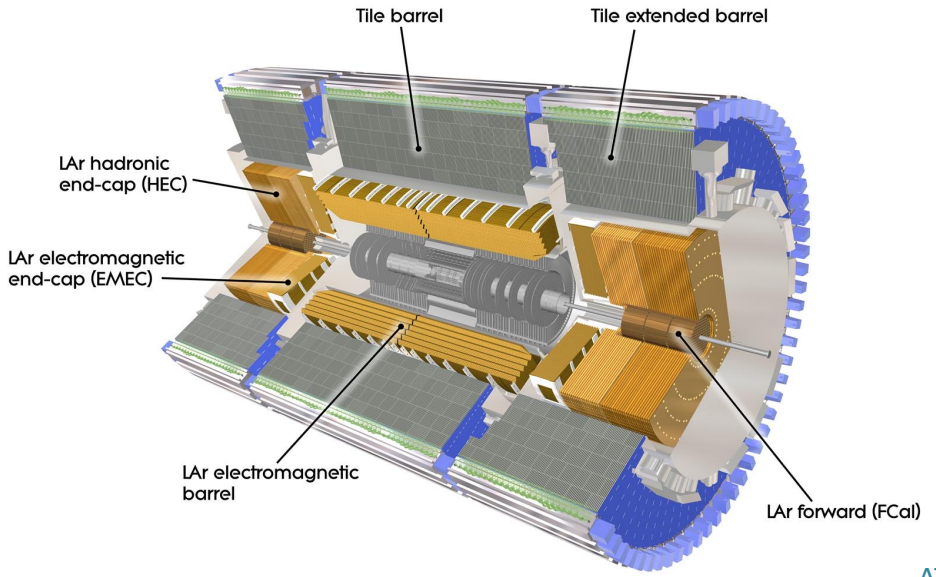
Lawrence Livermore National Laboratory

ATLAS Detector Geometry



Calorimeter Layer	$\Delta\eta$ Granularity	$\Delta\phi$ Granularity	Interaction Lengths
EMB1	$0.025/8 = 0.003125$	$\pi/32 \approx 0.1$	$\approx 4X_0$
EMB2	0.025	$\pi/128 \approx 0.025$	$\approx 16X_0$
EMB3	0.05	$\pi/128 \approx 0.025$	$\approx 2X_0$
Tile0	0.1	$\pi/32 \approx 0.1$	$\approx 1.5\lambda$
Tile1	0.1	$\pi/32 \approx 0.1$	$\approx 4\lambda$
Tile2	0.2	$\pi/32 \approx 0.1$	$\approx 2\lambda$



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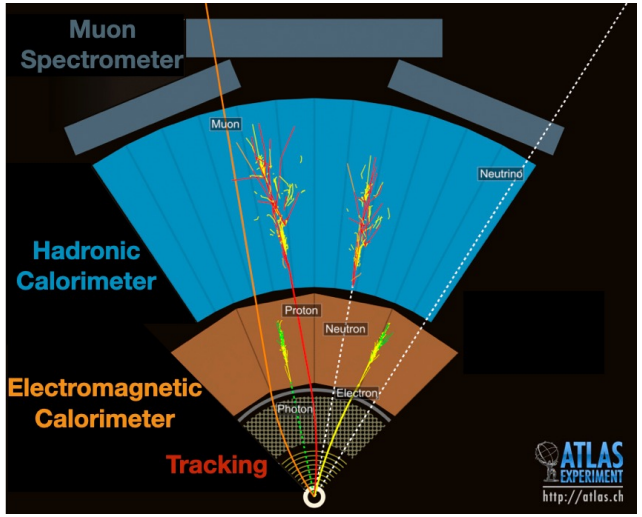
Dataset and ML Problem

- Dataset:
  - Simulated single pion showers (π^0 and π^+)
  - Topo-clusters: 3D clusters of calorimeter cells
  - Standard calibration approaches: Electromagnetic (EM) scale and Local Cell Weighting (LCW)



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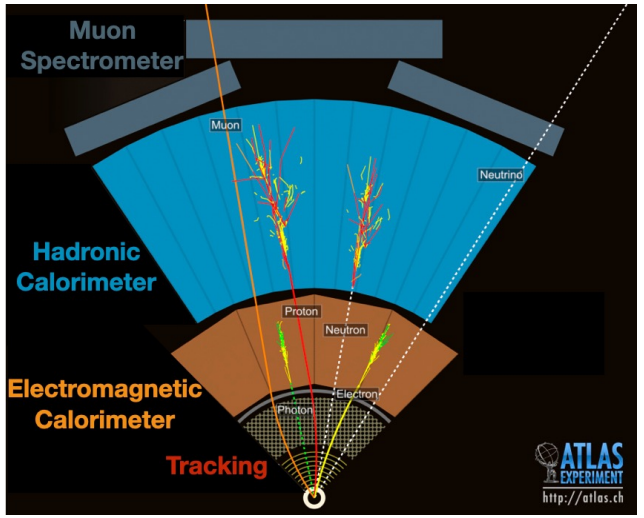
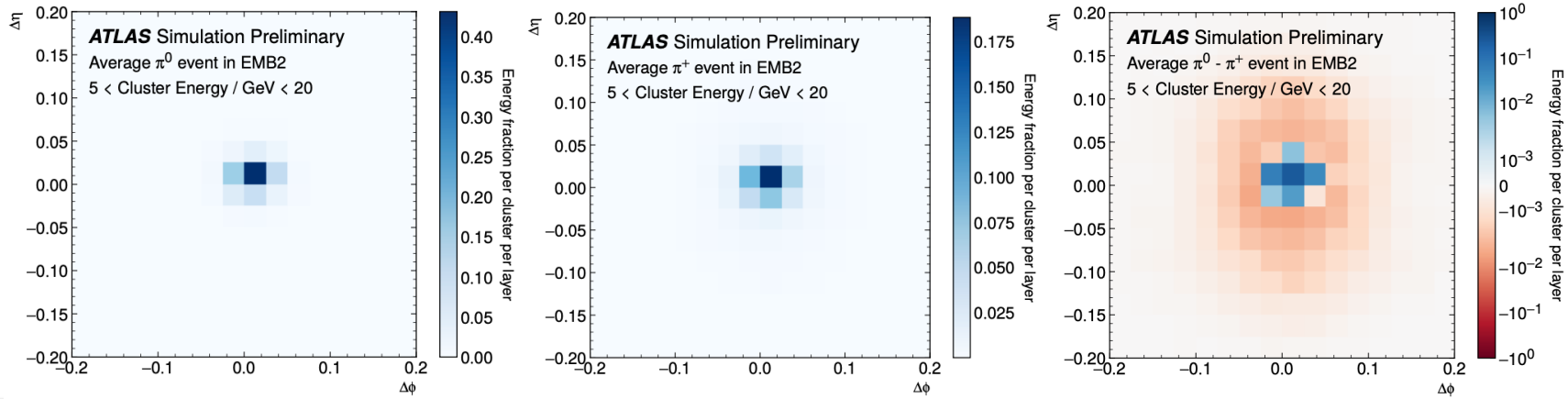
Dataset and ML Problem

- Dataset:
  - Simulated single pion showers (π^0 and π^+)
  - Topo-clusters: 3D clusters of calorimeter cells
  - Standard calibration approaches: Electromagnetic (EM) scale and Local Cell Weighting (LCW)
  - Previous ML approach: image representation of topo-clusters across the layers of calorimeter
- ML Problems:
  - Pion classification: π^0 or π^+
  - Energy regression: pion energy



Neutral pions | **Charged pions** | **Difference**



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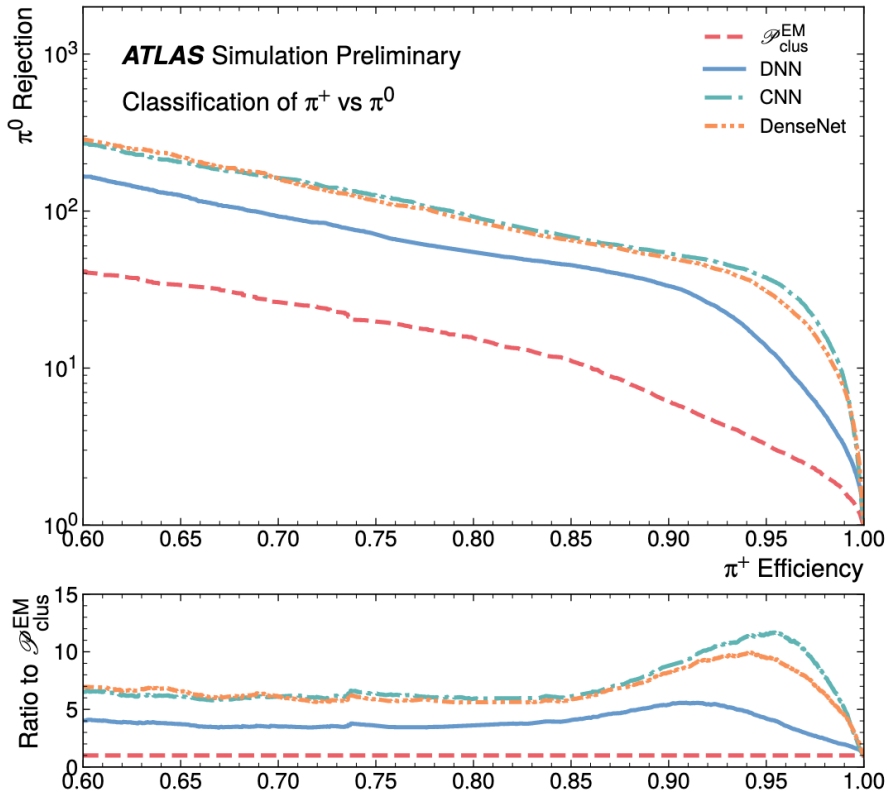
Results: Image-based approach

- Image-based methods outperform the baseline classification and energy calibration methods.

Classification



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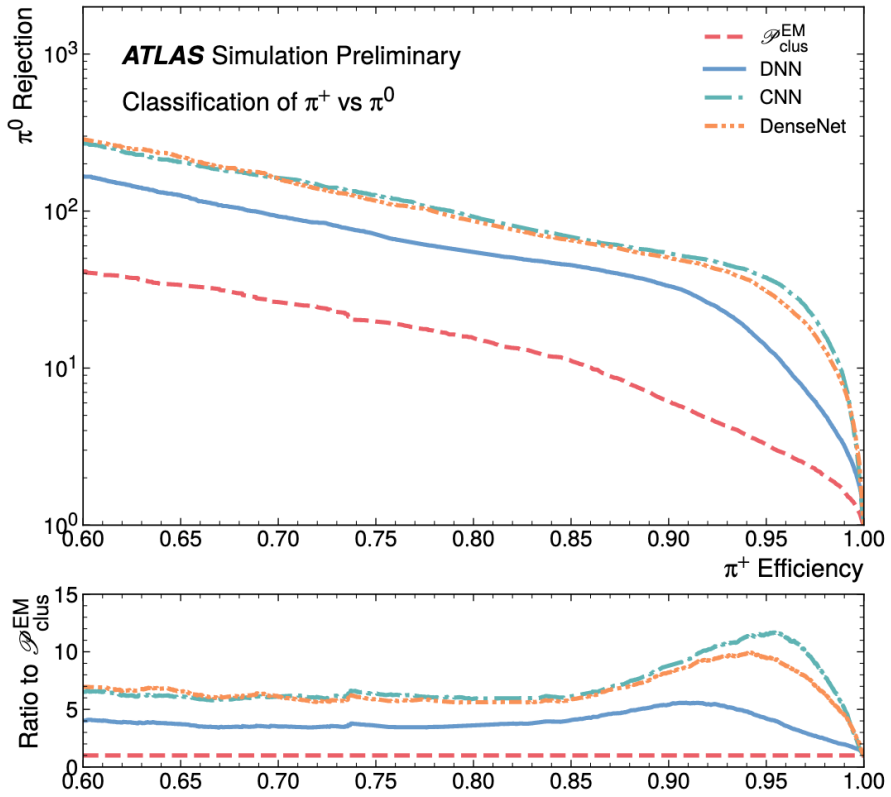
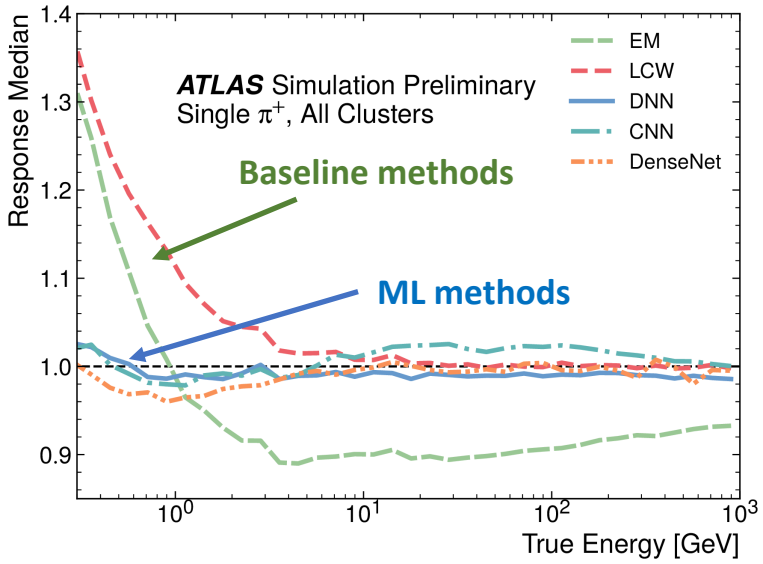
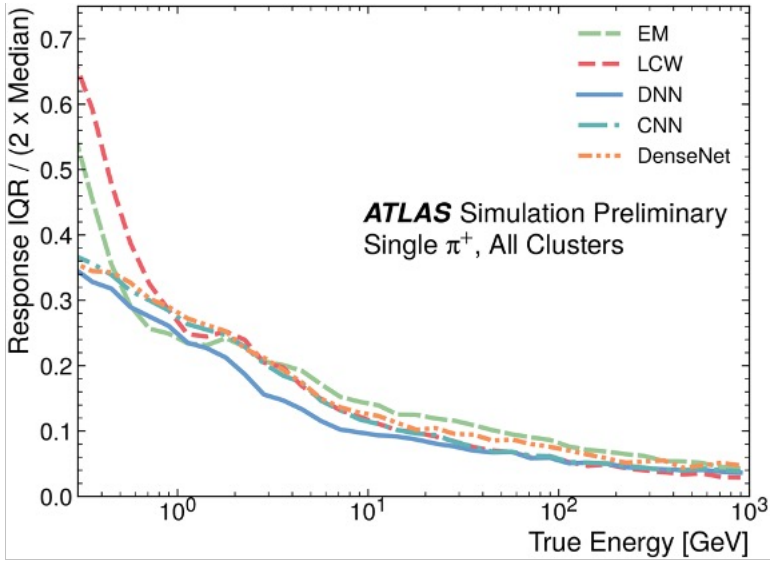


Regression

Response



Inter-Quantile Range (IQR)



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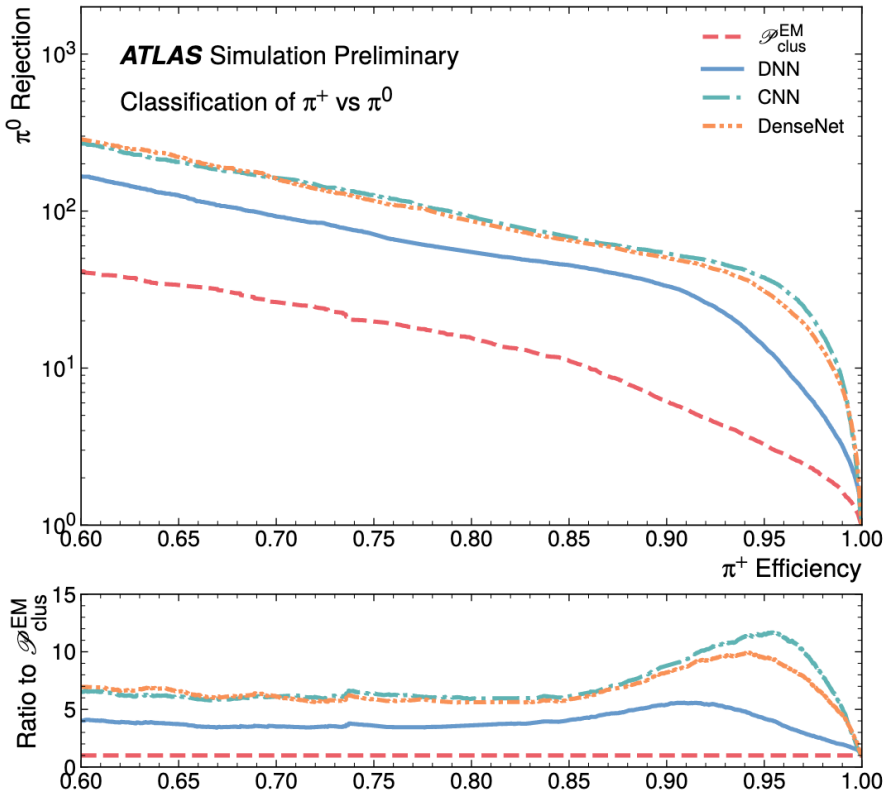
Results: Image-based approach

- Image-based methods outperform the baseline classification and energy calibration methods.
- Drawbacks: Sparse images of varying dimensions, restricted η range (|η| < 0.7) due to changes in detector geometry.

Classification



Regression

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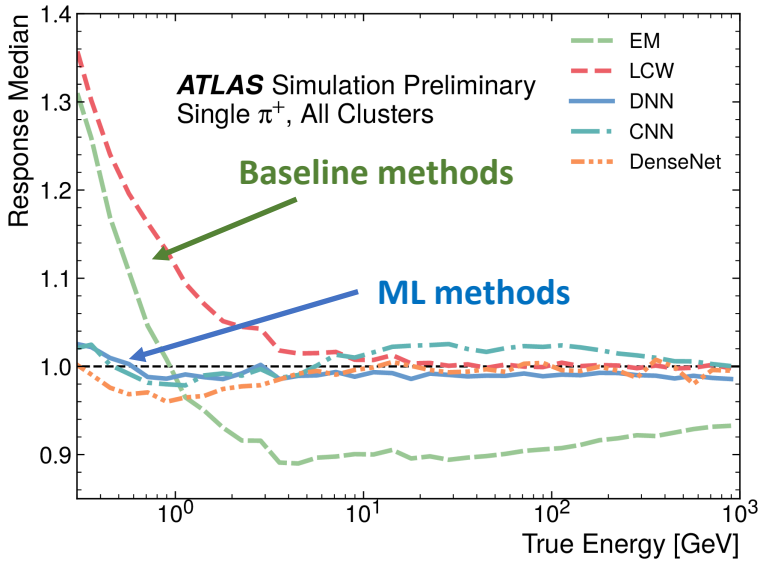

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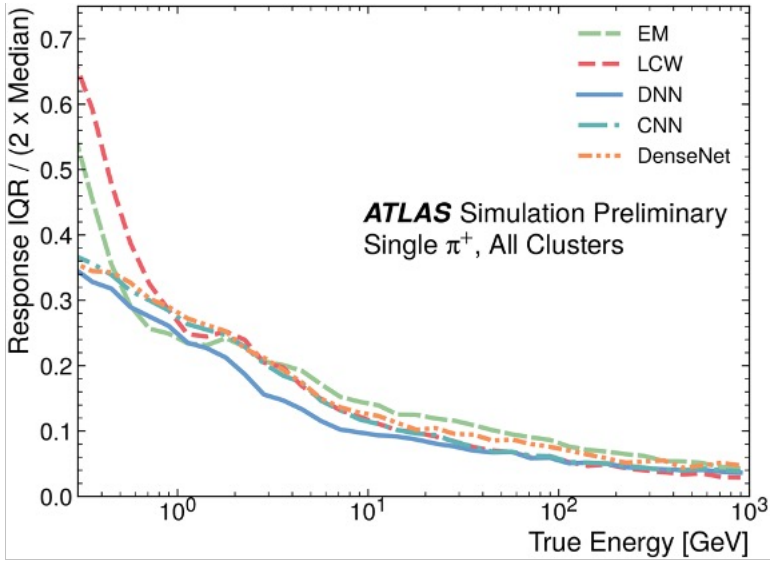

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Graph Neural Network Approach

- Representing topo-clusters as graphs is more suited to handle its non-uniform 3D structure compared to a series of calorimeter images
- More flexibility to include different calorimeter layer geometries/granularities
- Improved ability to perform cluster classification and energy calibration out to forward regions

Topo-cluster

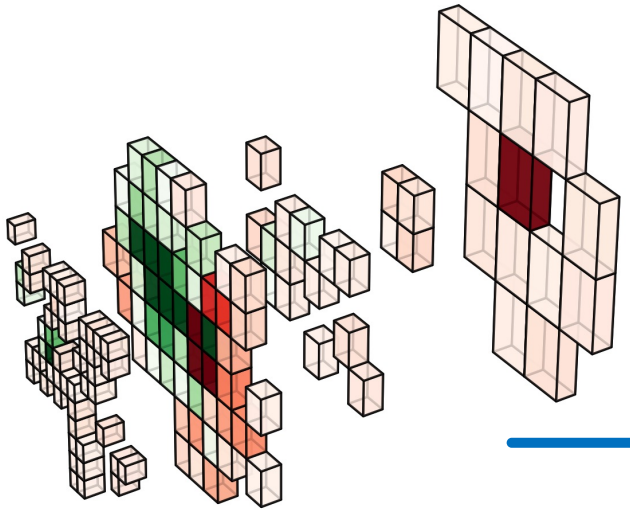
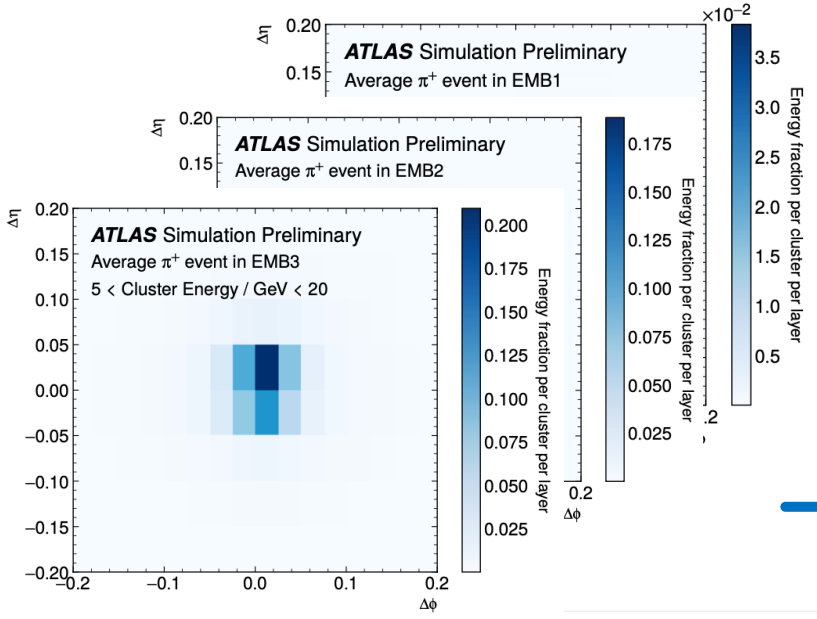
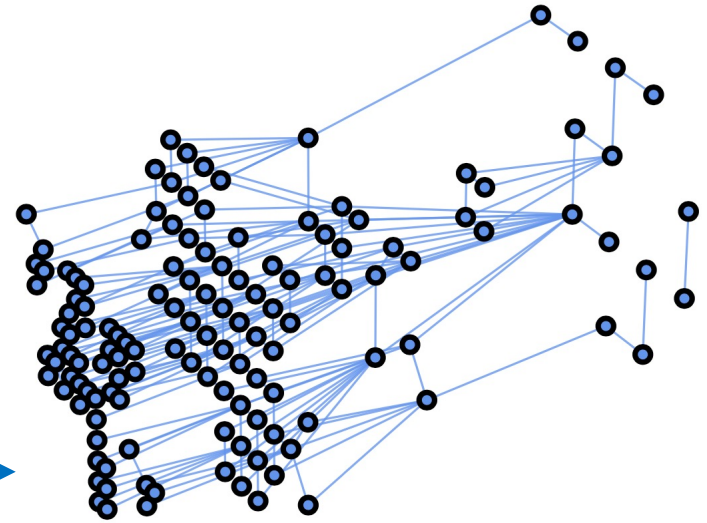


Image-based representation



Graph-based representation



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Topo-Cluster Graph Representation

- **Nodes**: Cells from the topo-cluster with features such as
  - cell energy
  - sampling layer
  - cell location (η, φ)
  - cell size
- **Edges**: One-hot encoded vector defining geographical connections between nodes
- **Global Node**: total cluster energy
- **Target**: pion type (π^0 or π^+) and calibrated cluster energy

GNN Model

Graph Nets library by DeepMind[1]

- Highly customizable graph blocks
- Lightweight
- Not actively developed or widely used

[1]github.com/deepmind/graph_nets

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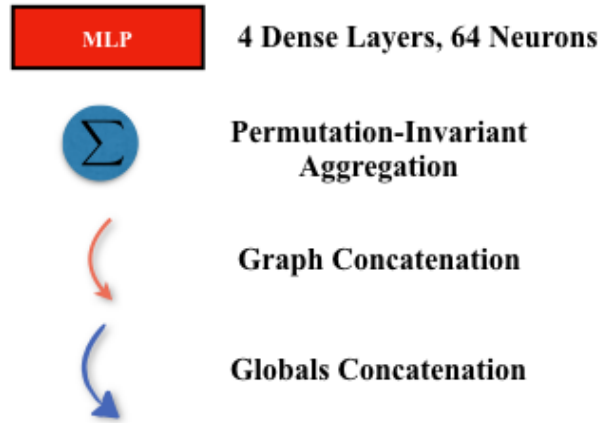
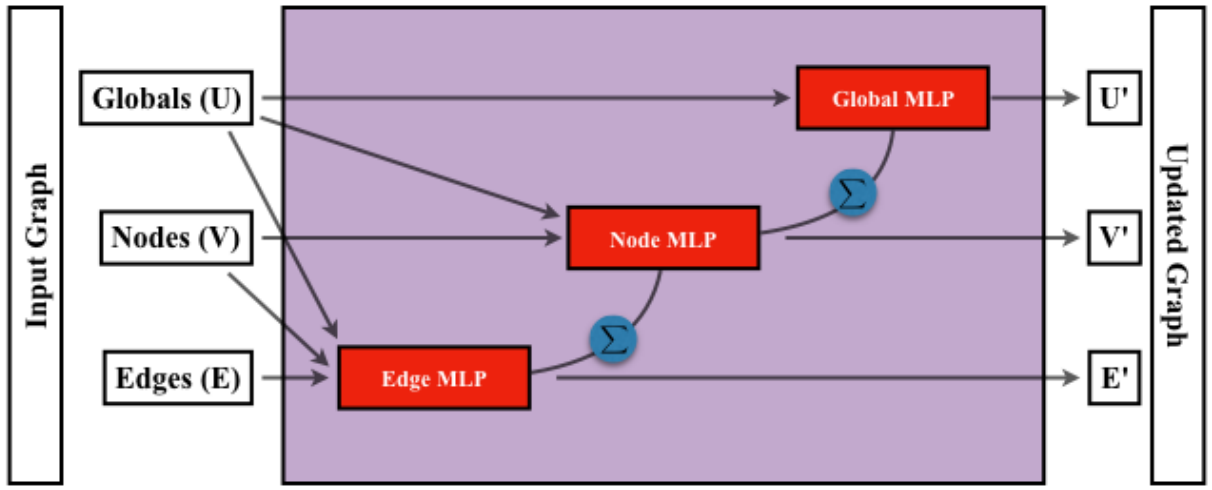


FullGNN Block



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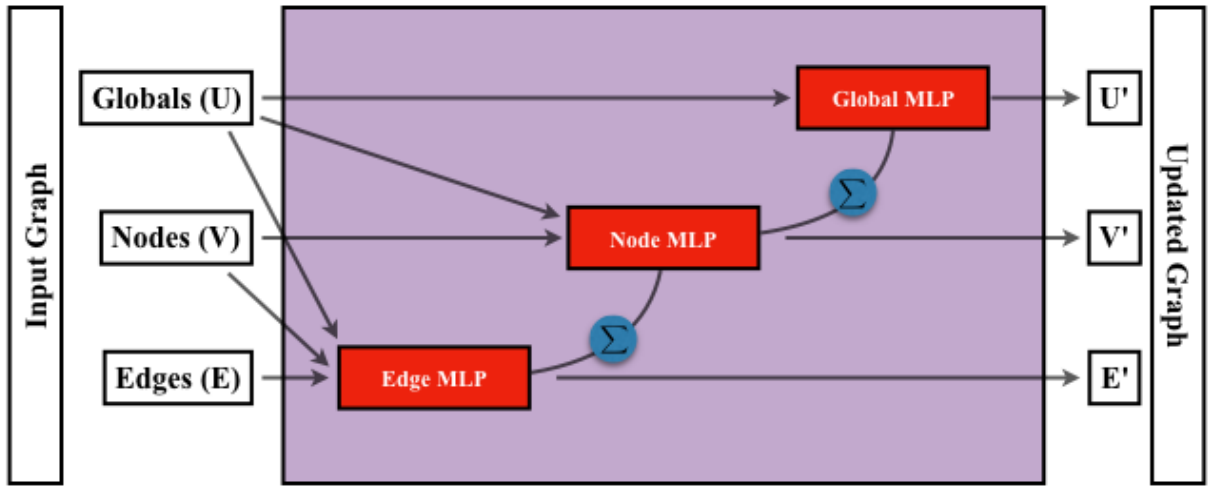
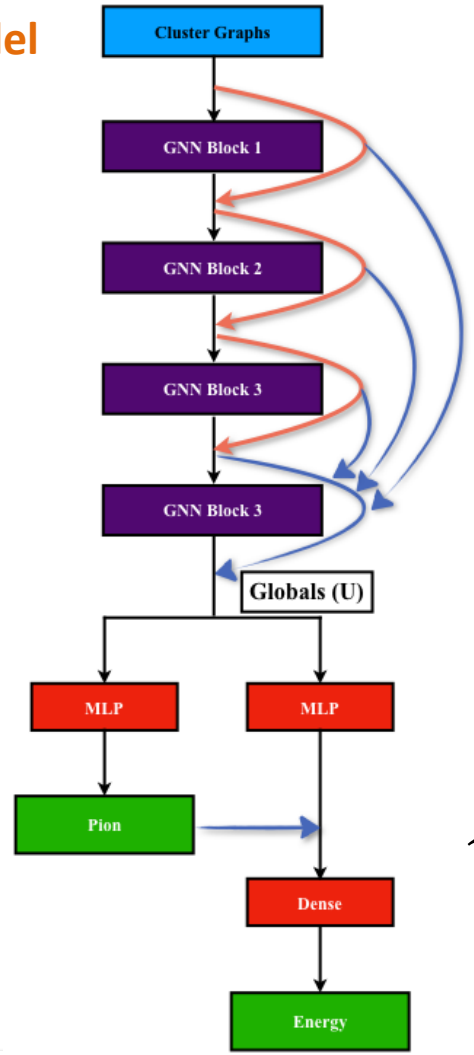
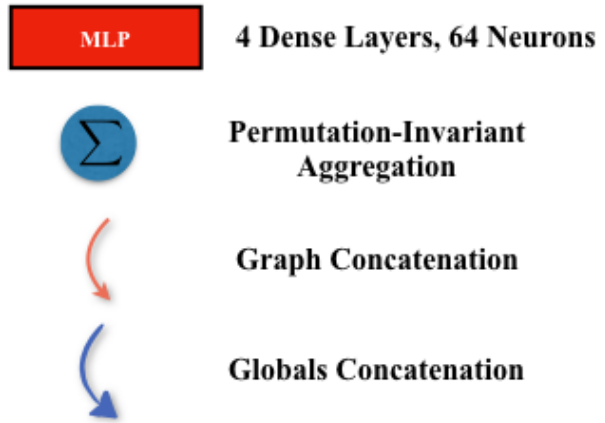


Model





$$\mathcal{L} = \alpha\mathcal{L}_{Reg} + (1-\alpha)\mathcal{L}_{Class}$$

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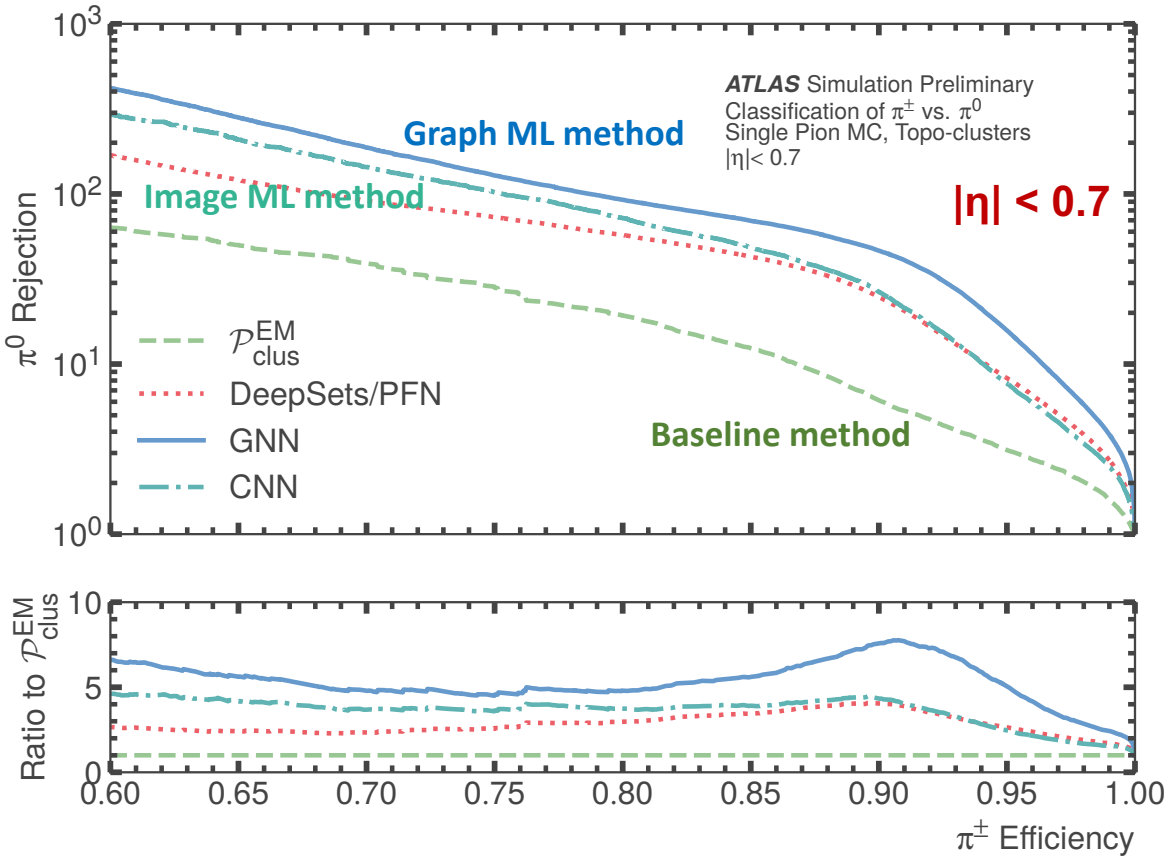
GNN Results: Classification

Comparison with Image-based approaches



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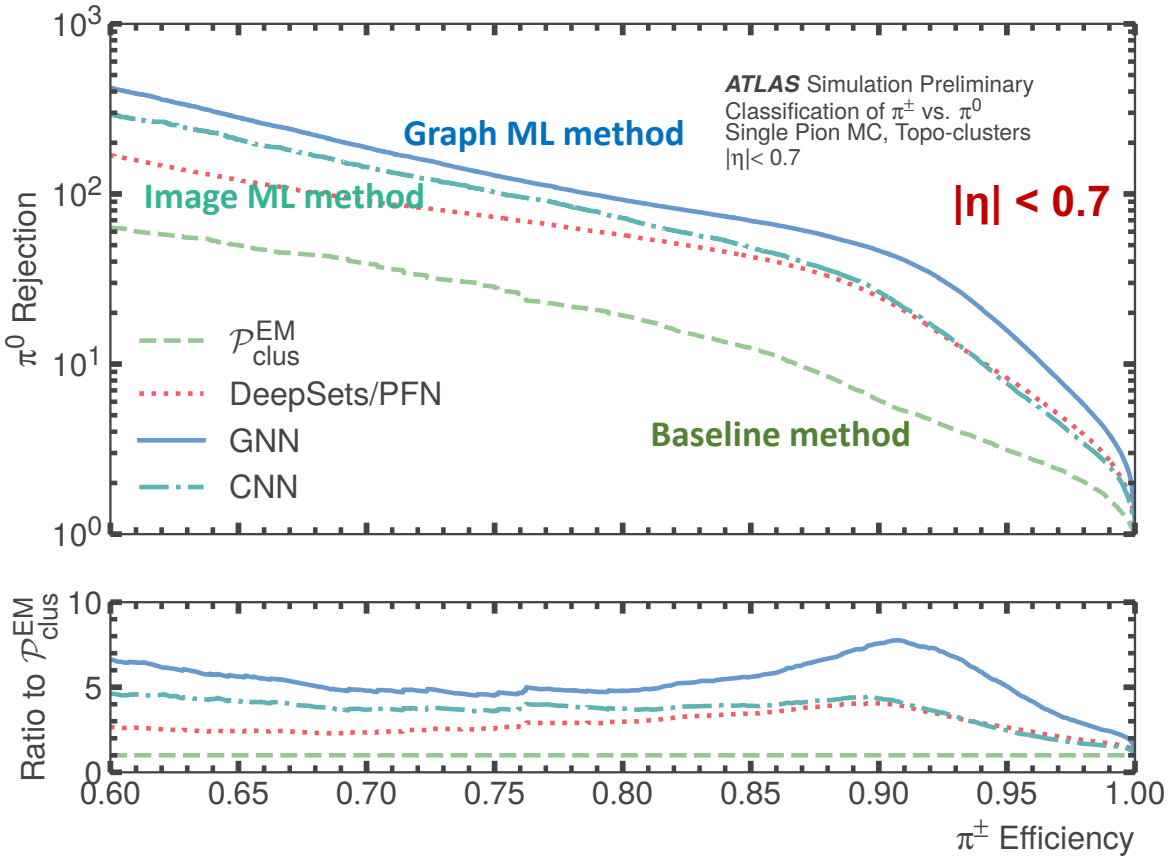
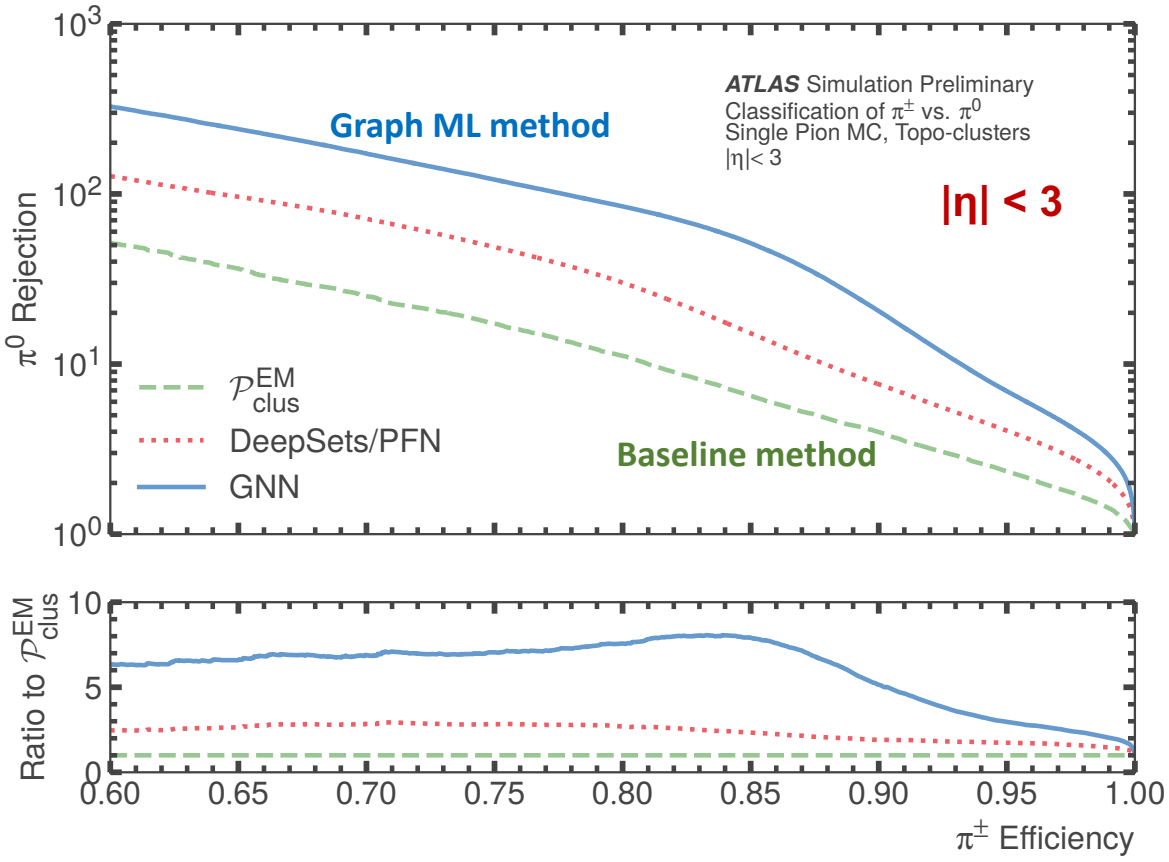


Performance on expanded Detector Regions



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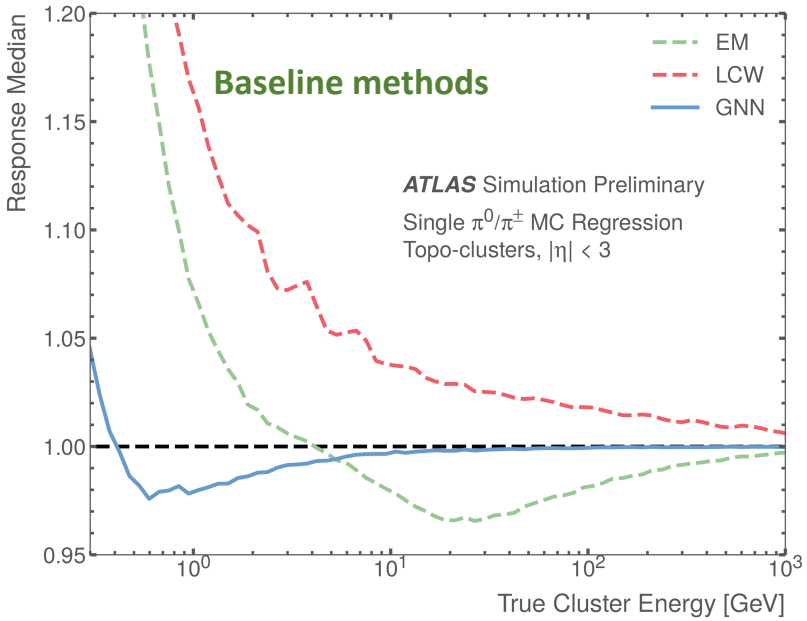
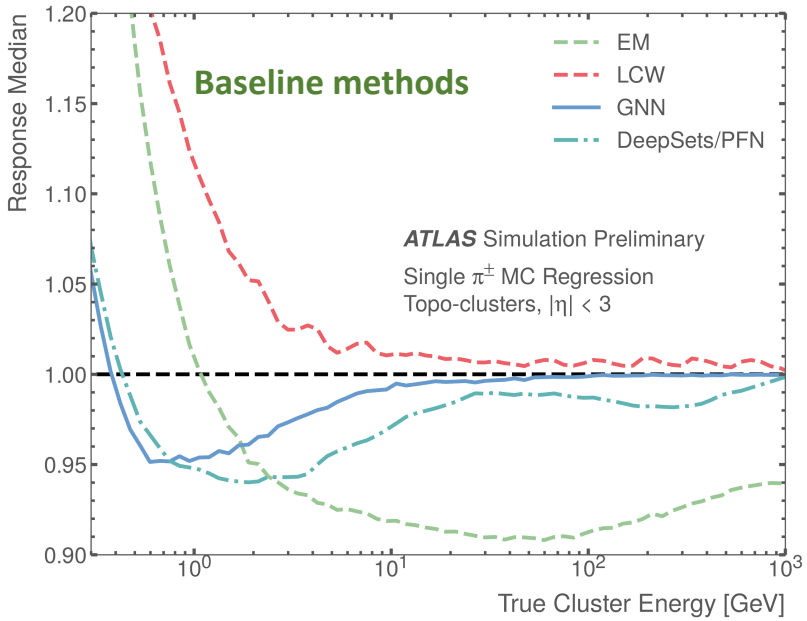
GNN Results: Regression

Response Medians

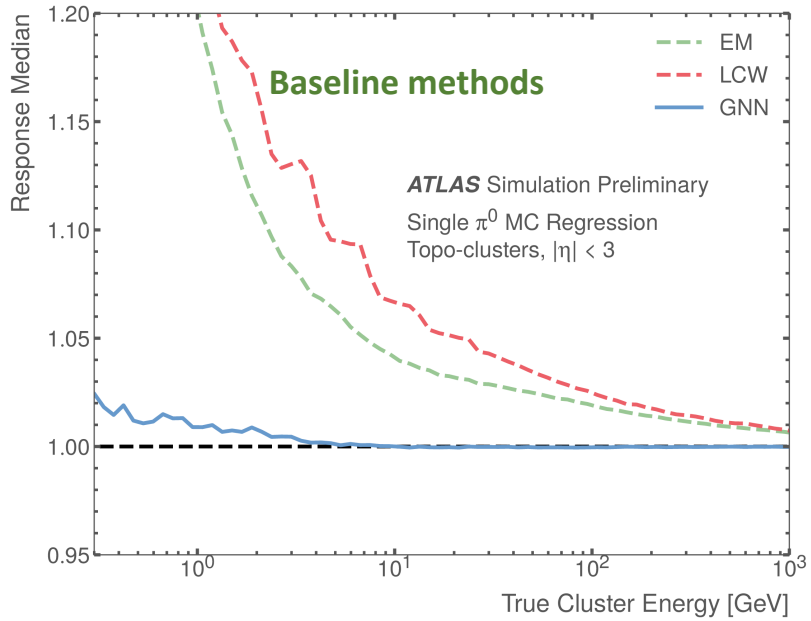
Mixed Neutral and Charged Pions



Charged Pions



Neutral Pions



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GNN Results: Regression

Significant improvement in the cluster energy response using the GNN model compared to EM and LCW scales

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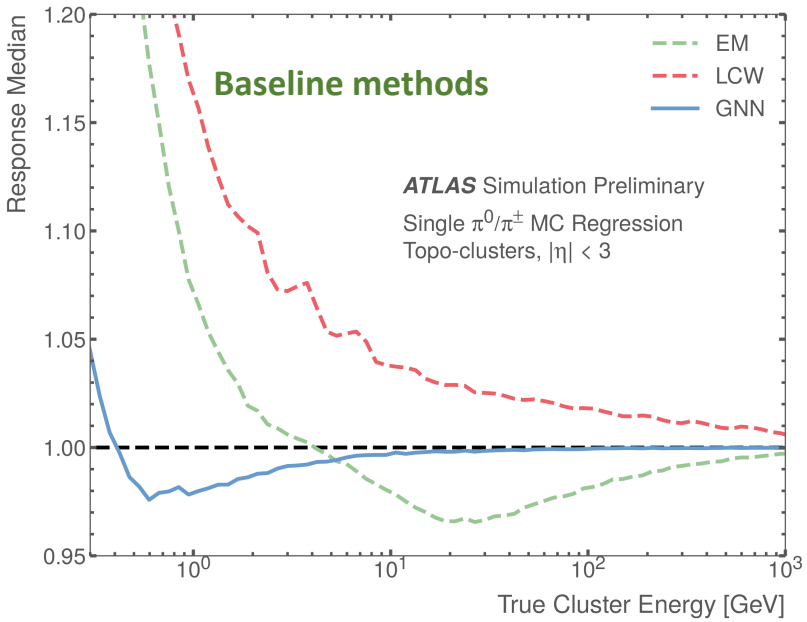

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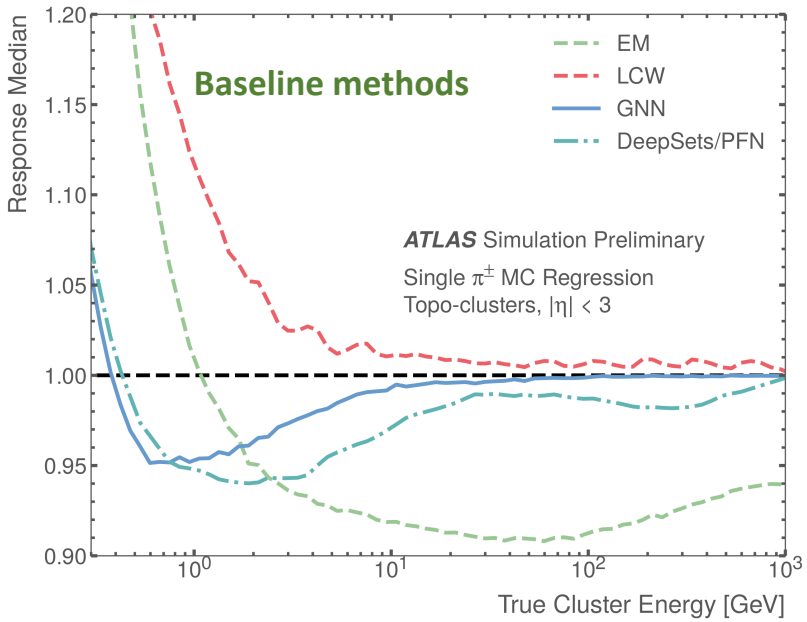

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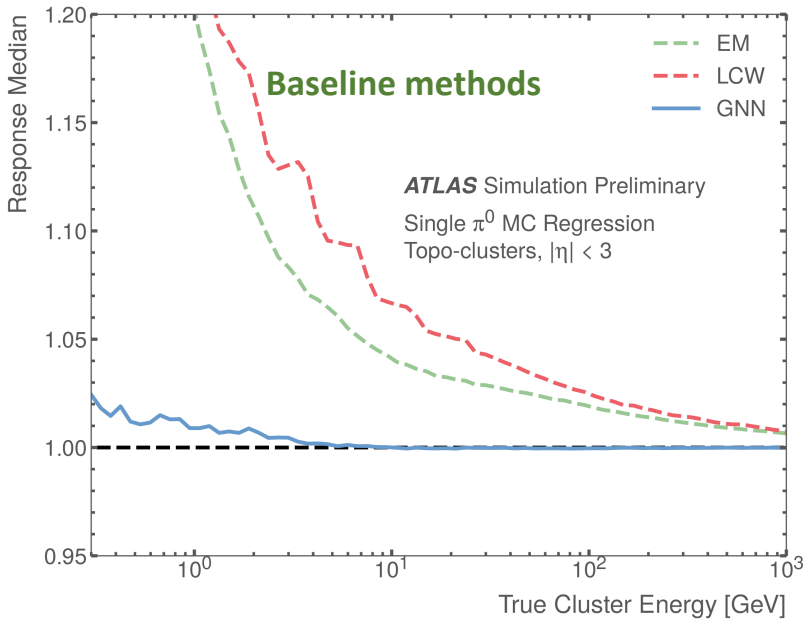

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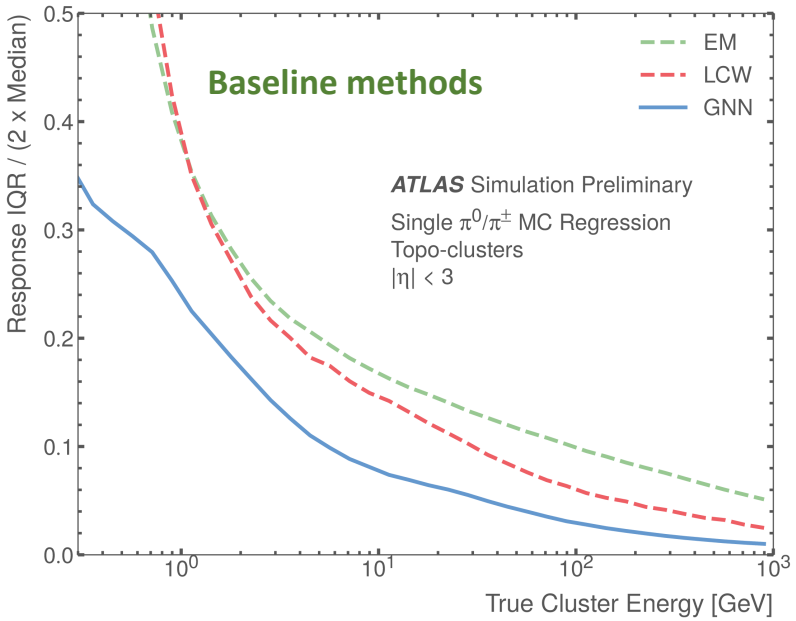
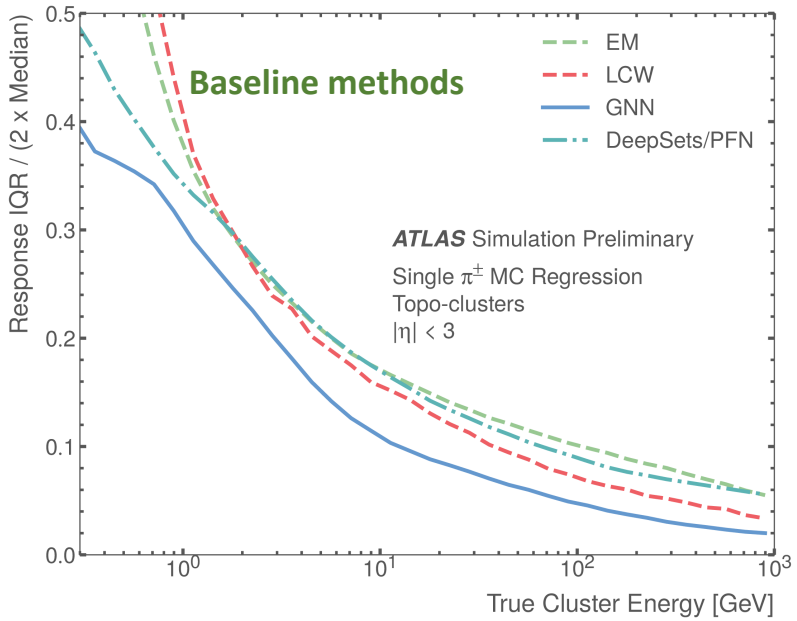


Inter-Quantile Range (IQR) Charged Pions



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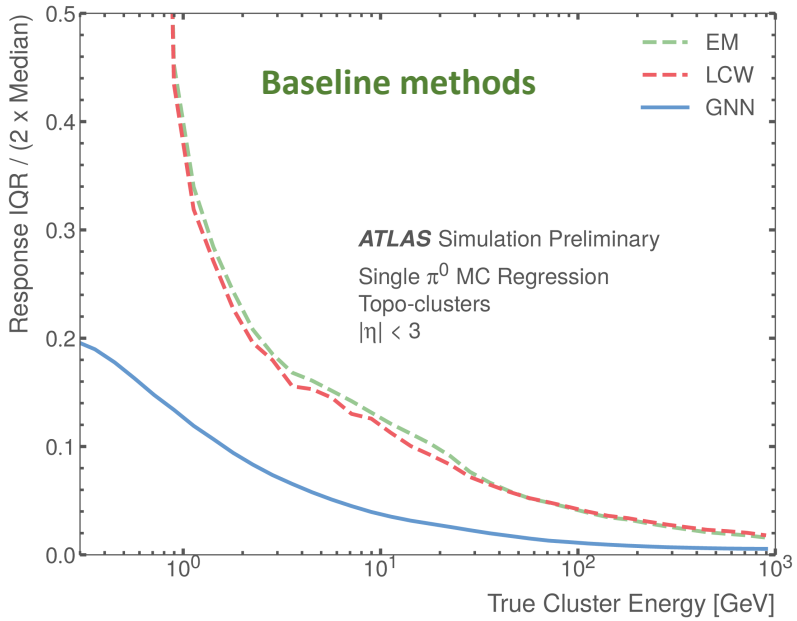

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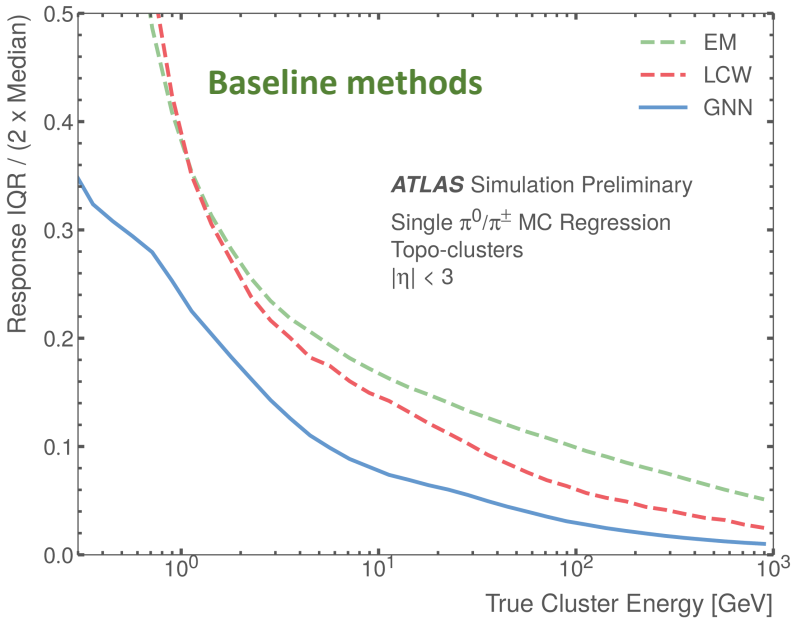
GNN Results: Regression

Significant improvement in the cluster energy resolution using the GNN model compared to EM and LCW scales

Mixed Neutral and Charged Pions



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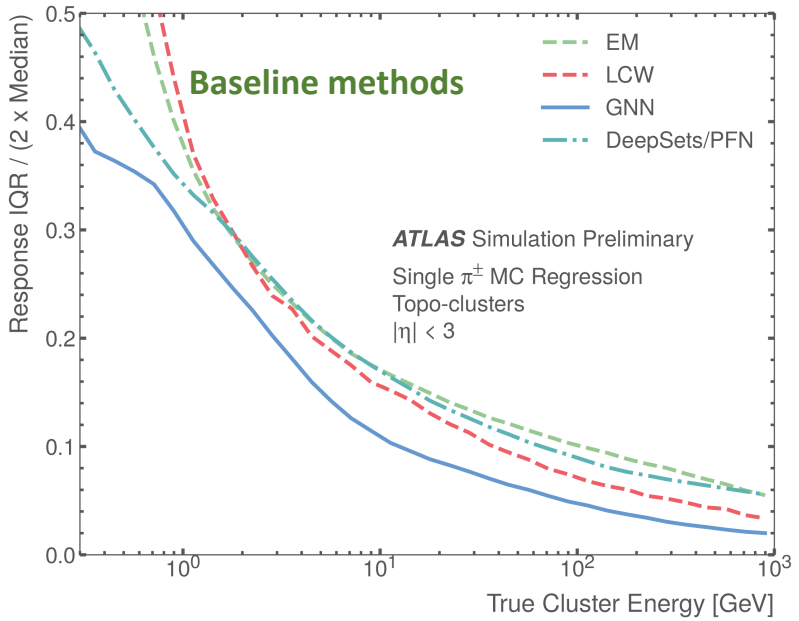

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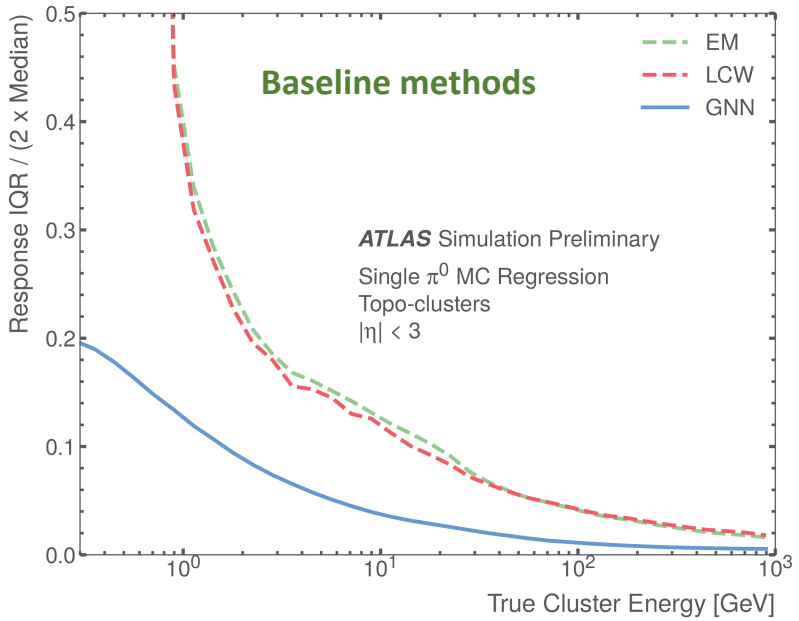

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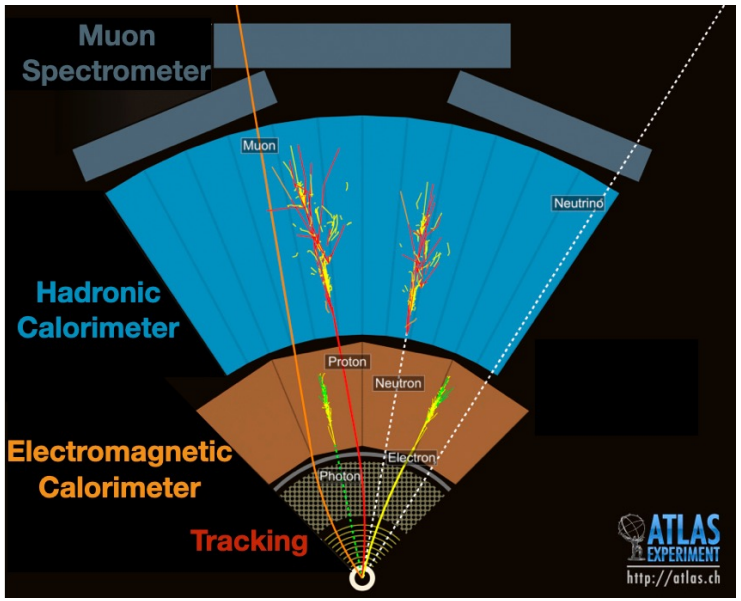
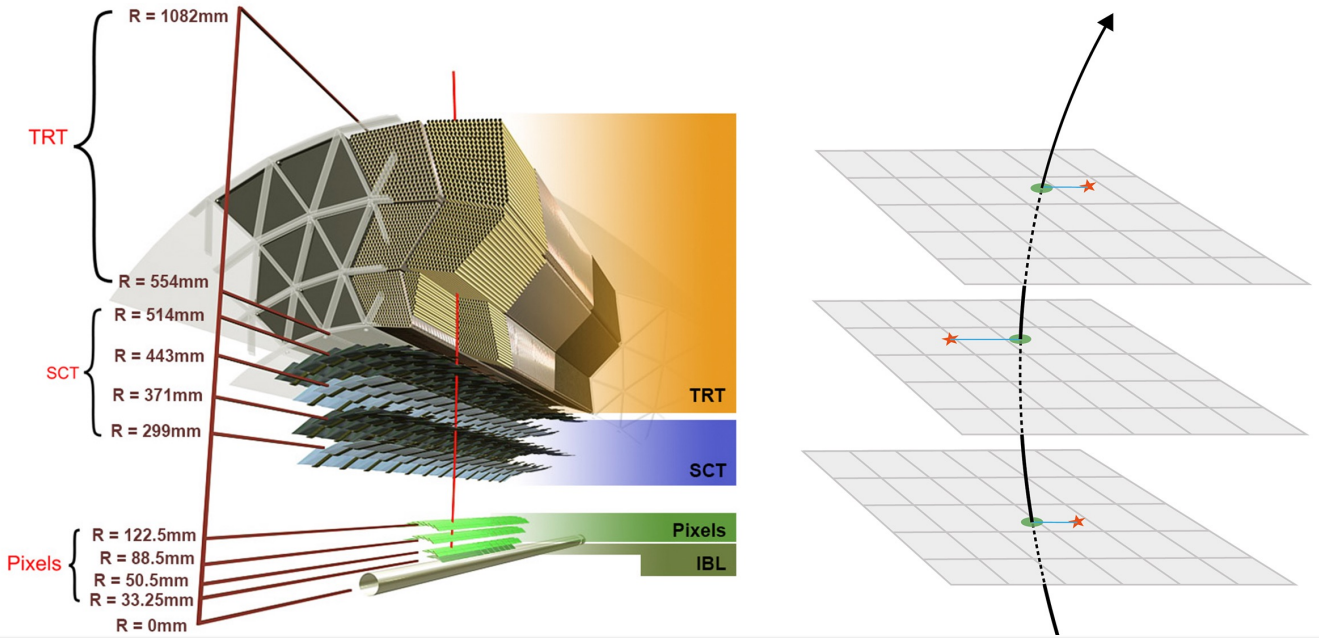
Inclusion of Tracker

- Allows for more accurate prediction of charged pion energy
- Predict particle energies and not cluster energies
- Extra information included: track momentum (track p_T) and track η

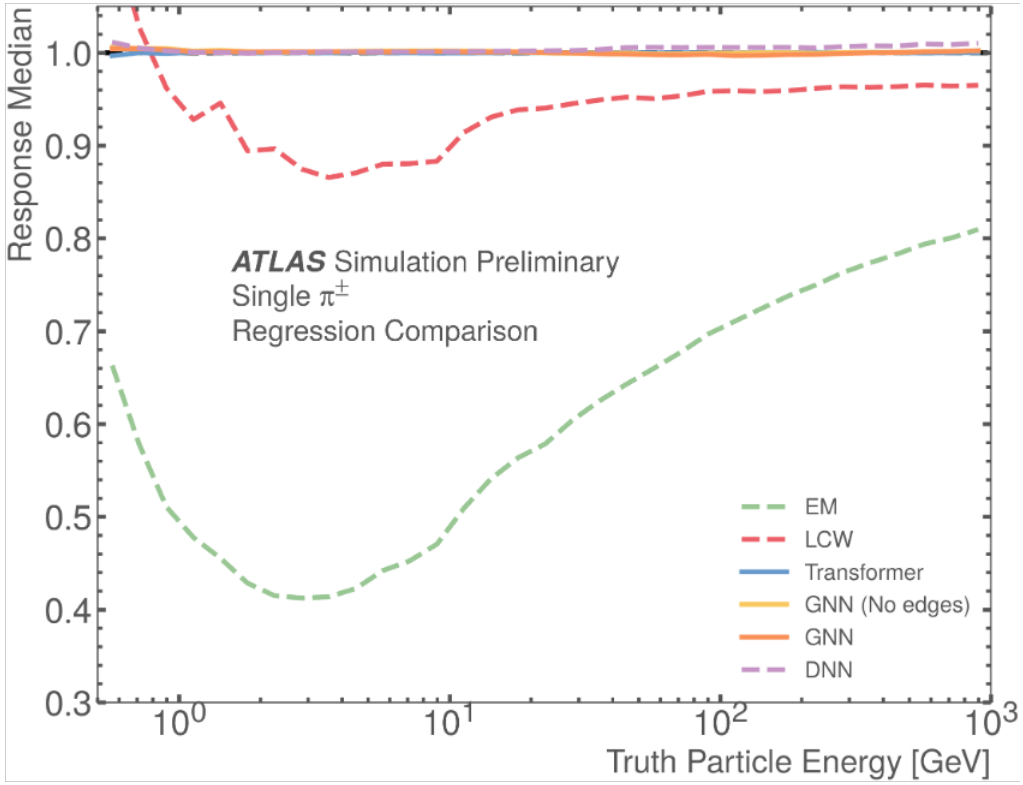
ATLAS Detector Schematic



ATLAS Inner Tracking Detector



GNN Results: Track Regression Response



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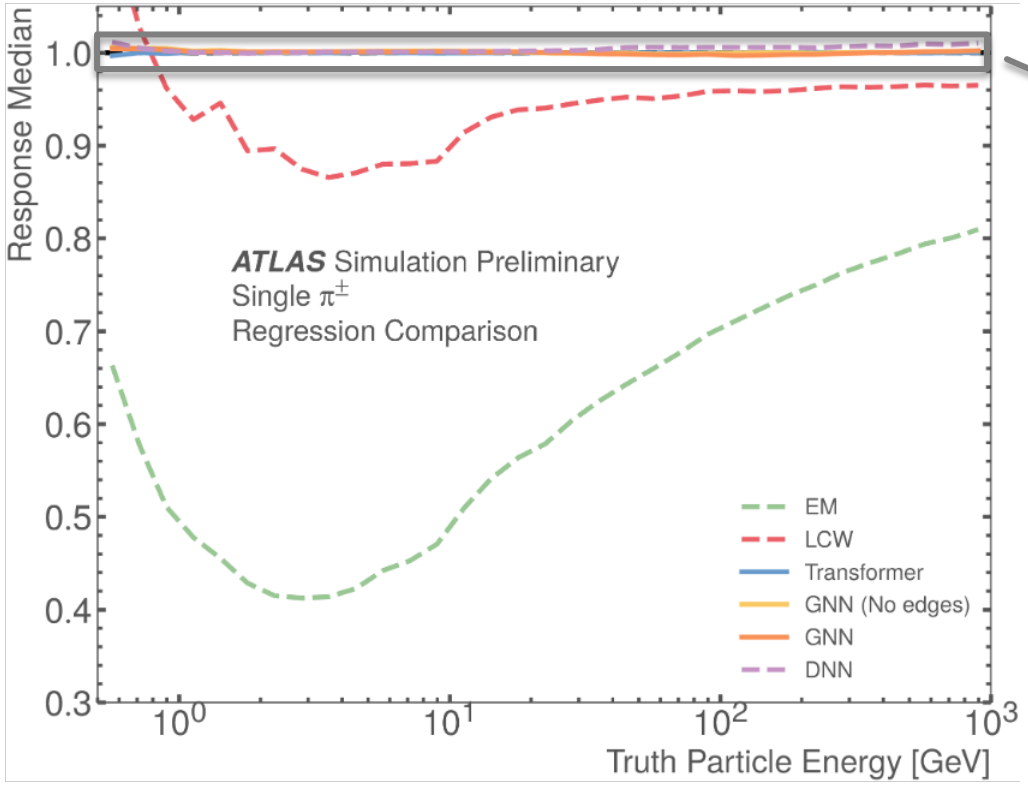

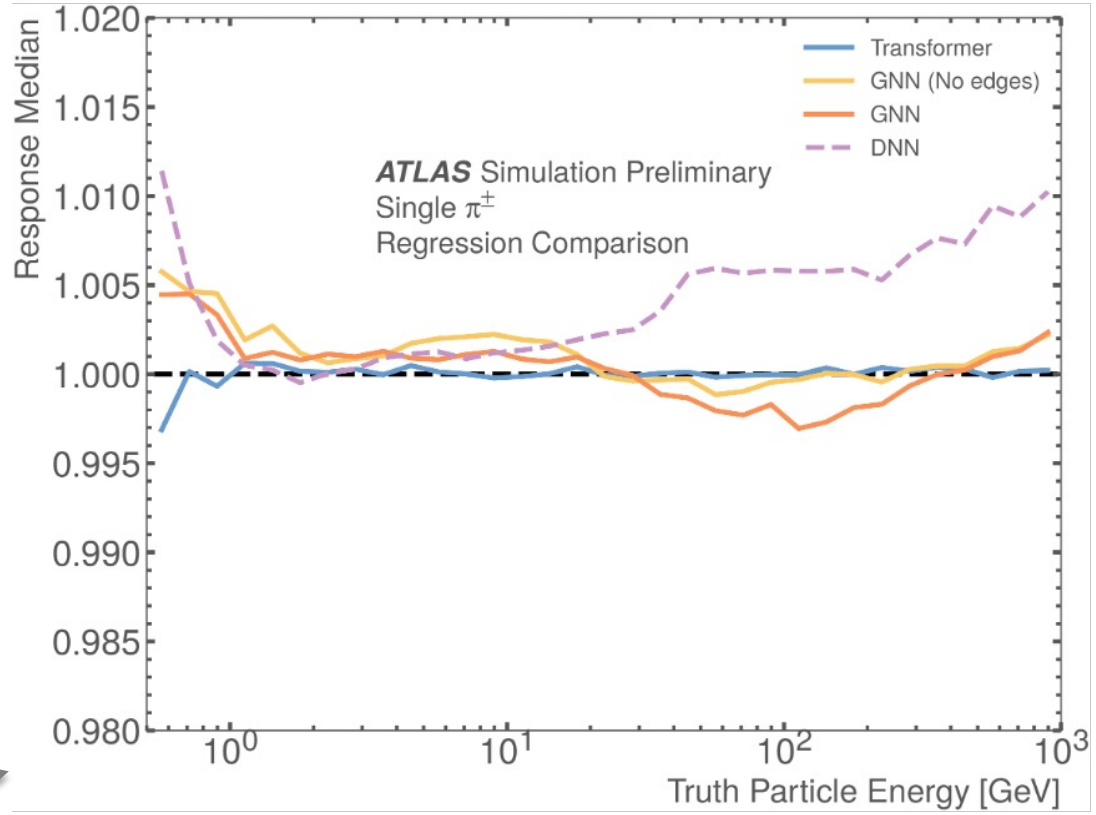

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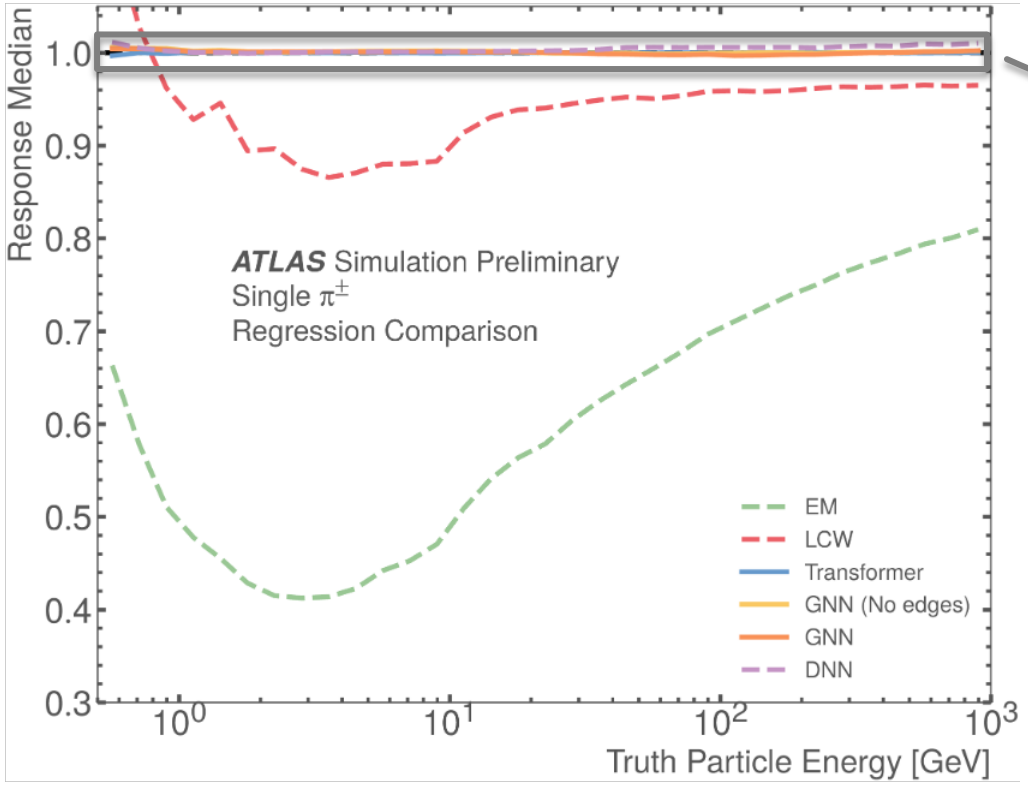
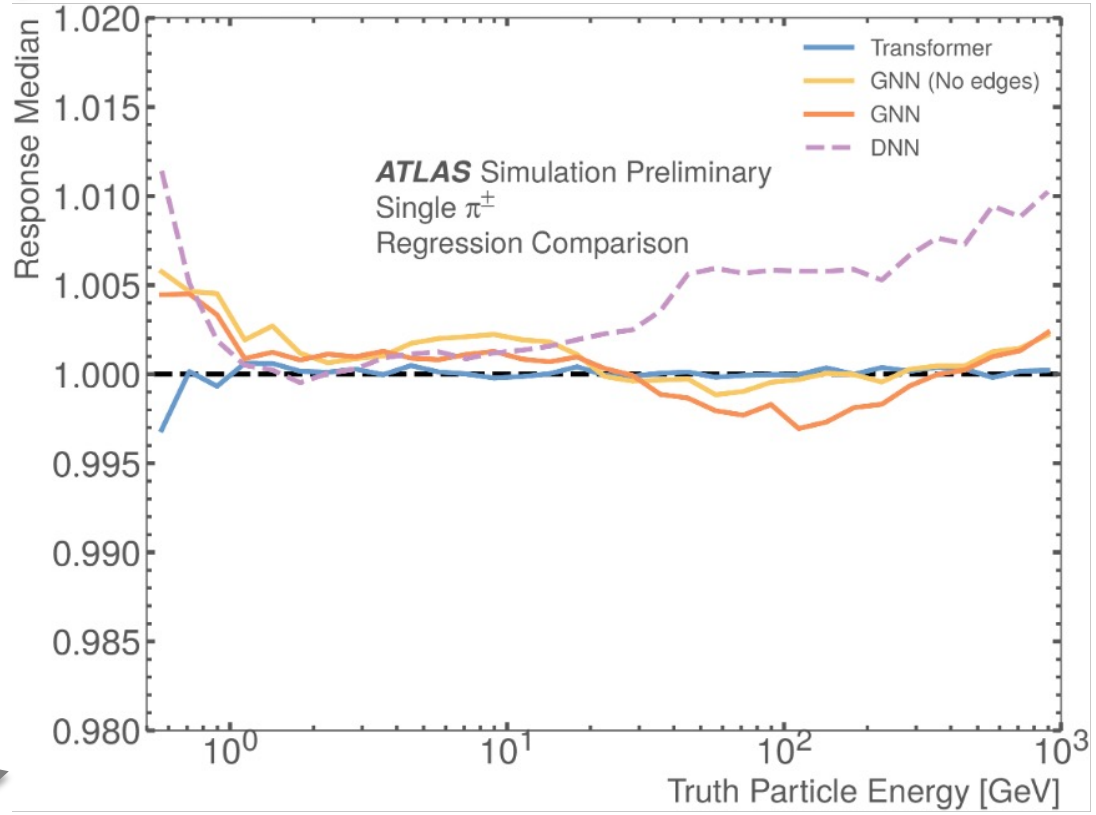
GNN Results: Track Regression Response

Models accurately predict true particle energies when compared to LCW and EM scales by using track information





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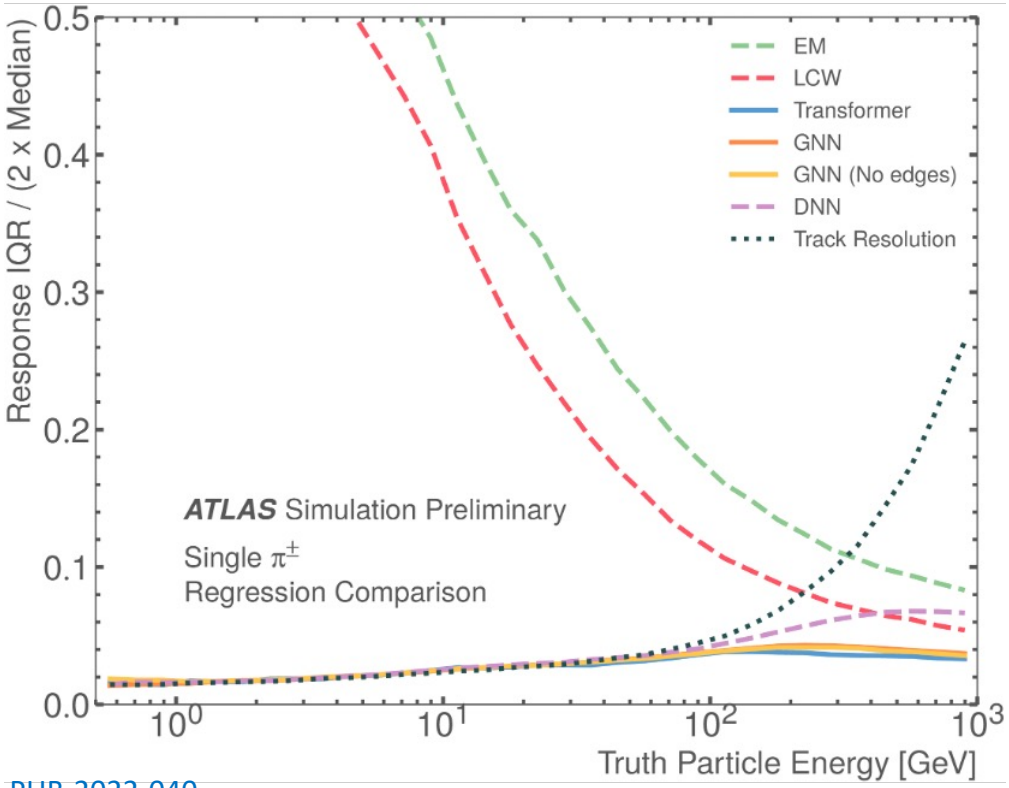

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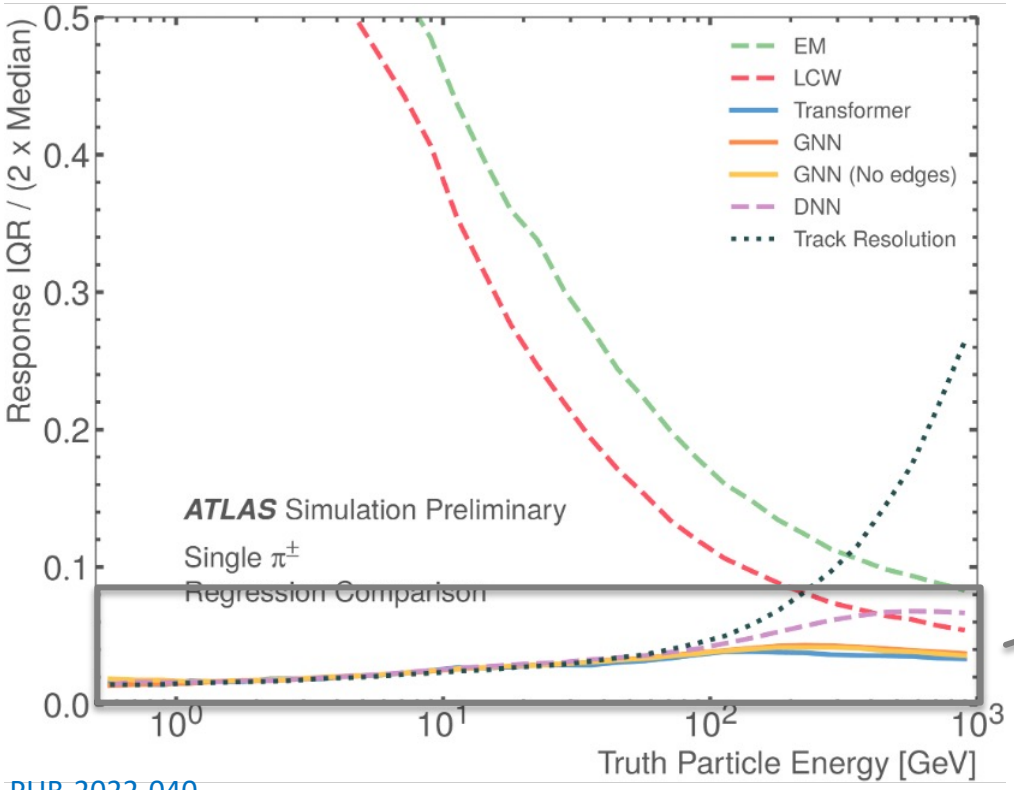

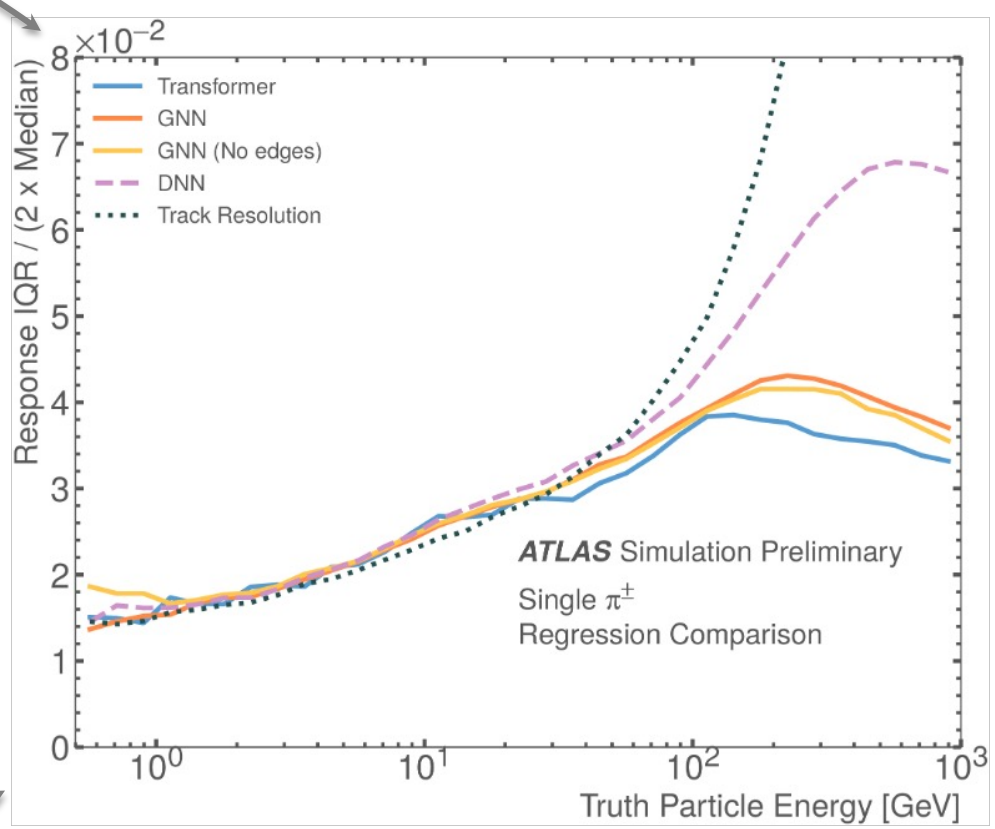

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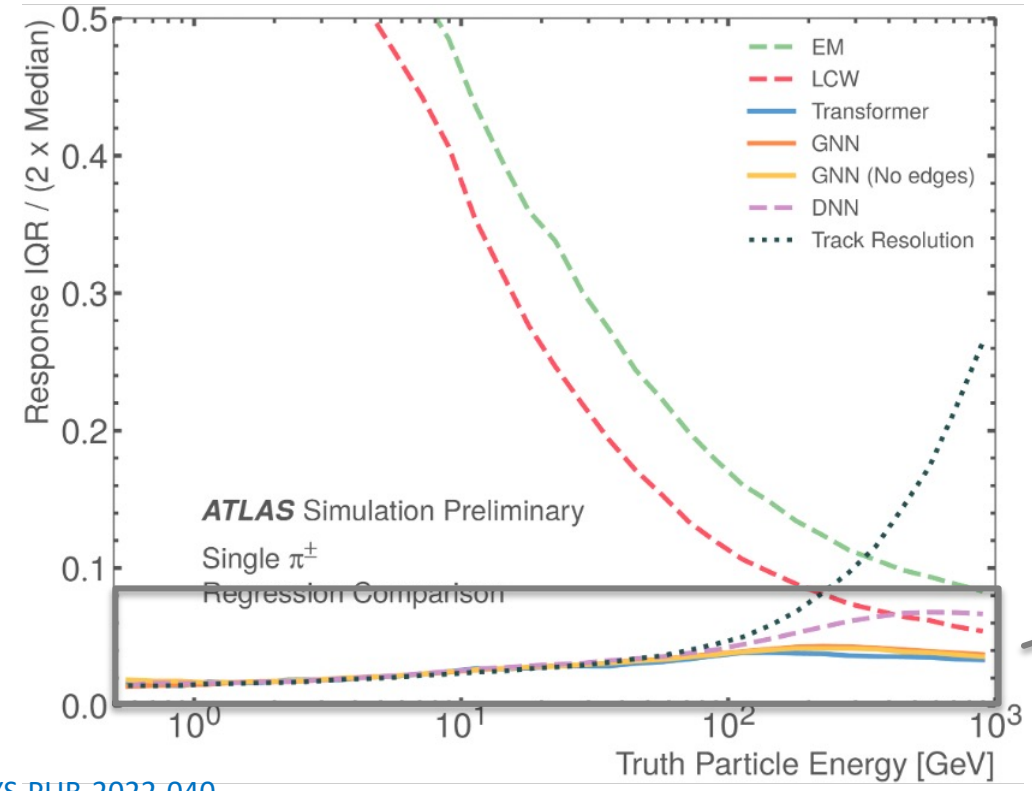
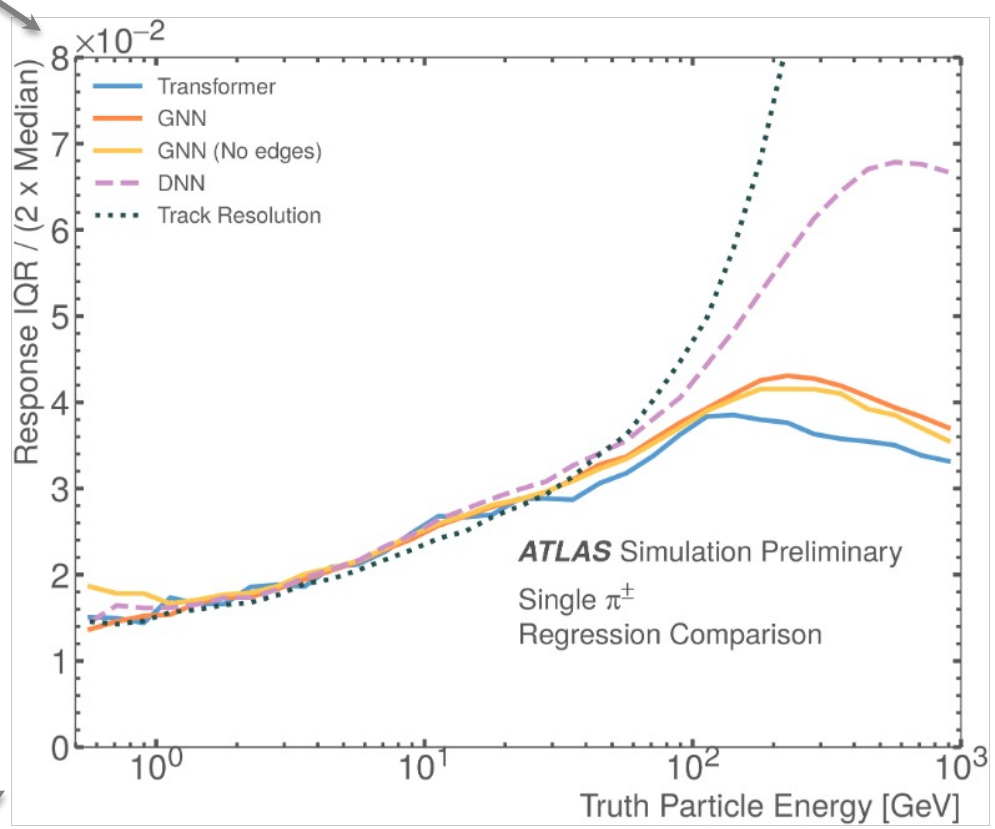
GNN Results: Track Regression Response

Models efficiently combine calorimeter and track information producing precise predictions across whole energy range





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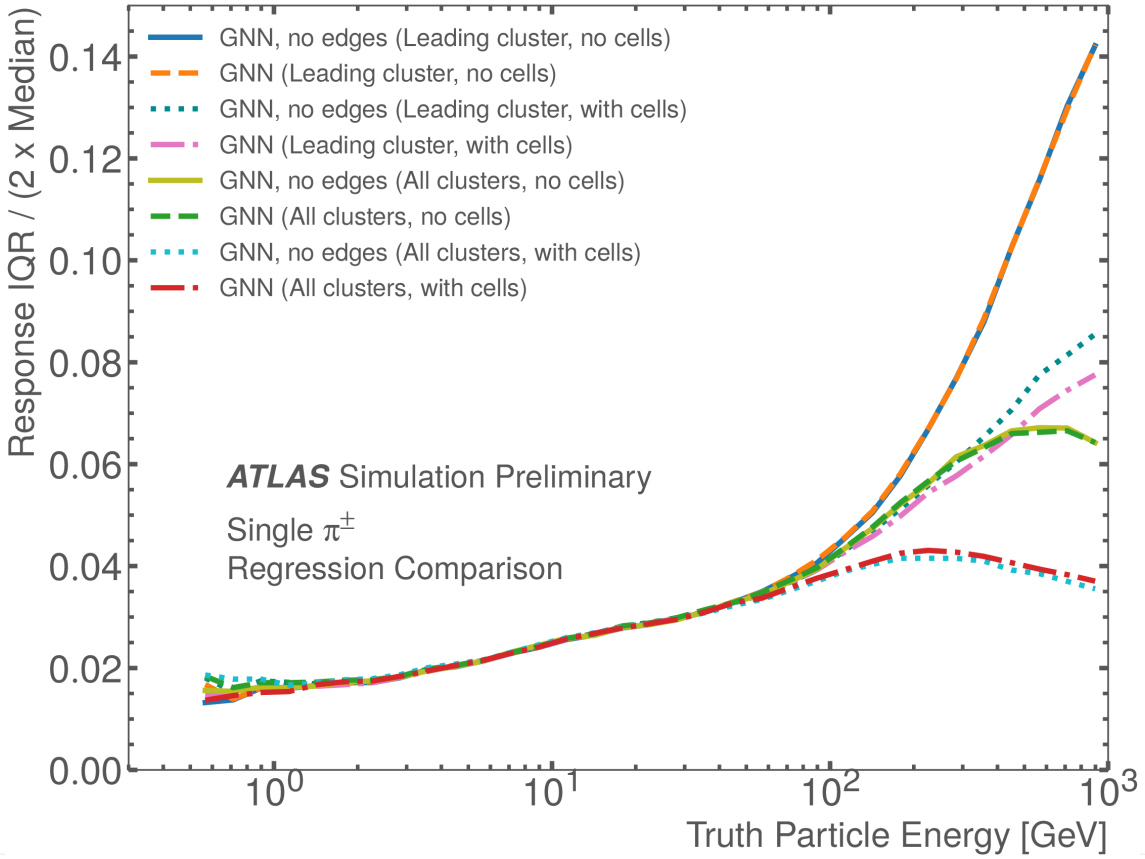
GNN Results: Global and Local Information



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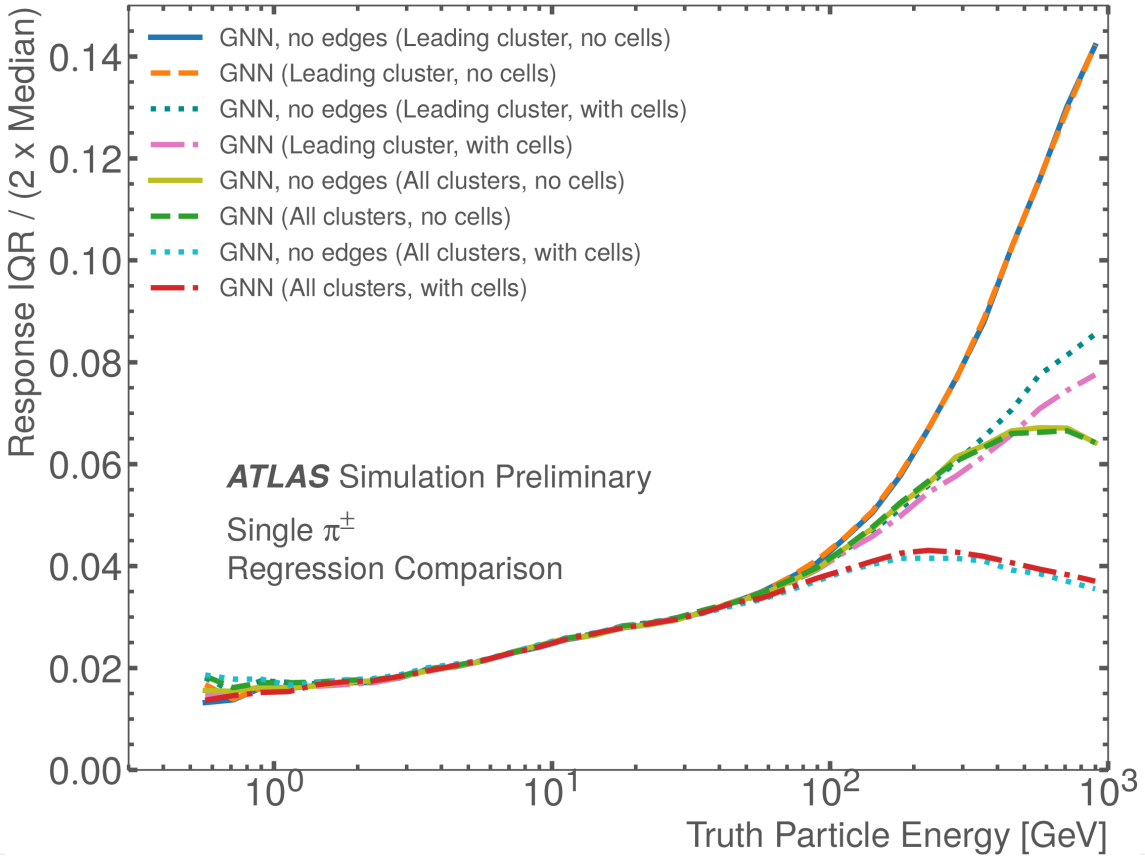
GNN Results: Global and Local Information

- Introduction of cell-level information significantly improves the resolution of models
- Adding edges representing geometric connections between cells is not always helpful



ATL-PHYS-PUB-2022-040

Conclusions

- GNN models were used to represent cluster and particle energies deposited across a large area of the ATLAS detector ($|\eta| < 3$).
- GNN models outperformed the baseline EM scale classifier and the previous image based ML models
- GNN models had significantly more accurate and precise energy calibration of topo-clusters compared to the LCW calibration
- GNN models efficiently integrated information from the calorimeter and tracker resulting in precise prediction of true particle energies.

Thank You!

ATL-PHYS-PUB-2020-018
Deep Learning for Pion Identification and Energy Calibration with the ATLAS Detector
https://cds.cern.ch/record/2724632

ATL-PHYS-PUB-2022-040
Point Cloud Deep Learning Methods for Pion Reconstruction in the ATLAS Experiment
https://cds.cern.ch/record/2825379