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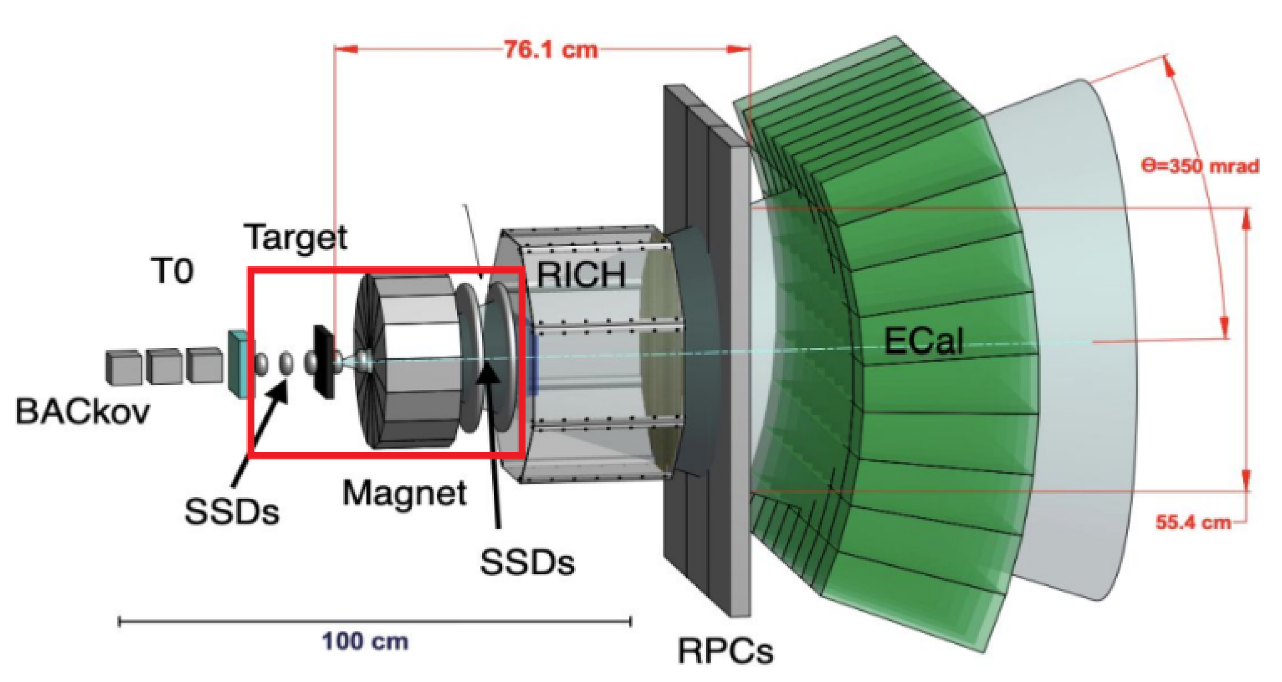
Track reconstruction using graph neural networks in the EMPHATIC experiment

Aayush Bhattarai[1] for the EMPHATIC Collaboration
[1]Department of Physics, University of Notre Dame, Notre Dame, IN, USA

Introduction & Motivation

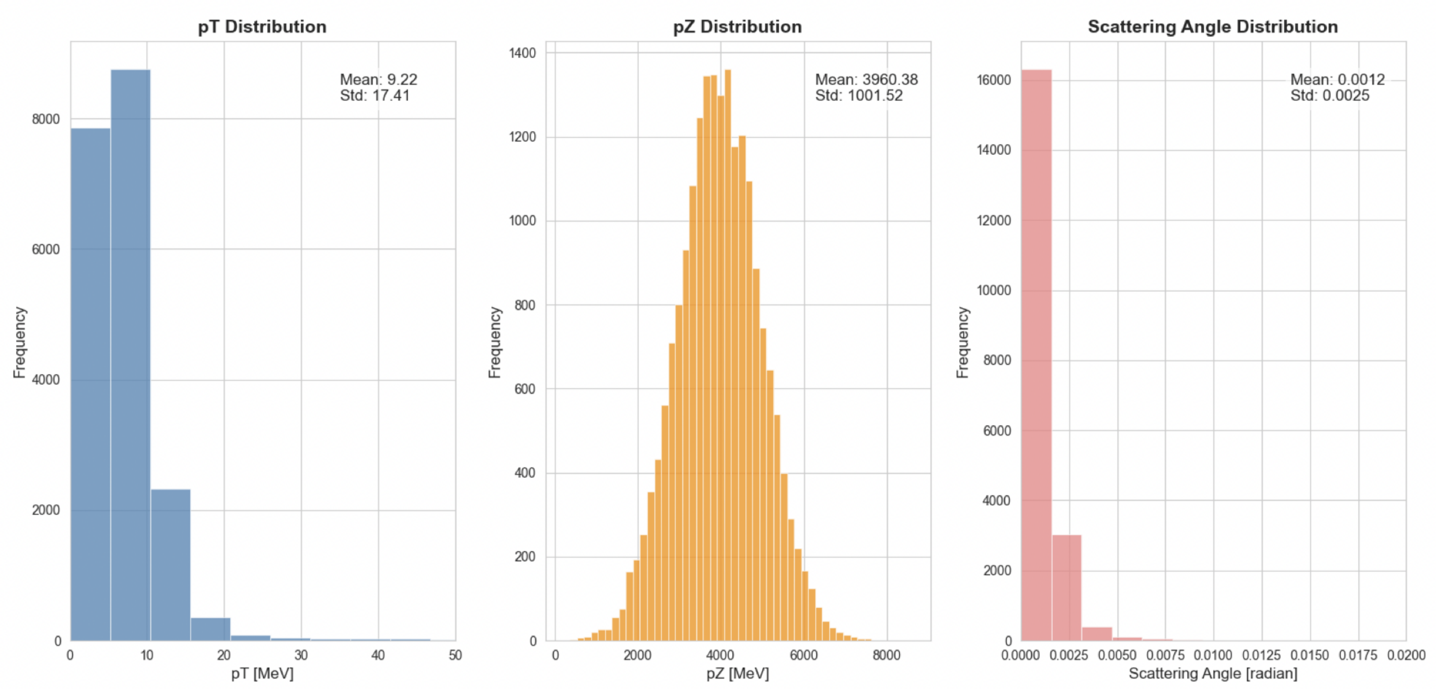
- **EMPHATIC** is a compact experiment designed to measure hadron production and scattering cross sections
- These measurements help reduce neutrino flux uncertainties by improving hadron interaction modeling in the neutrino production target and secondary beamline
- Track reconstruction is critical for extracting particle momentum and scattering angles from detector data in high-energy and nuclear physics.
- We apply Graph Neural Networks (GNNs) to predict a proton's transverse momentum p_T, longitudinal momentum p_z, and scattering angle θ at the target, directly from simulated SSD hits.



Top view of the EMPHATIC experiment setup

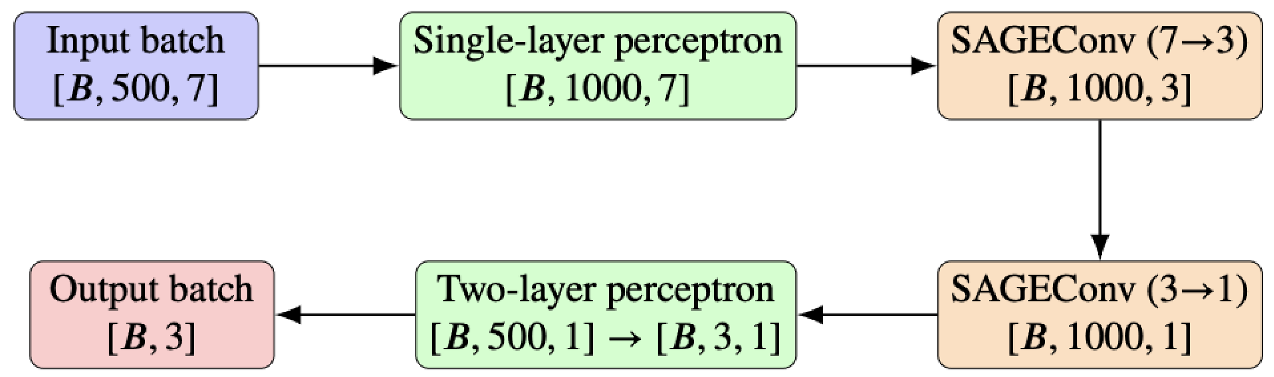
Simulation Dataset

- A "hit" is a recorded signal as a charged particle passes through a sensor element, identified by the sensor's unique location in the spectrometer.
- Generated using Geant4 simulations of the EMPHATIC detector
- Selected events contain a single proton with no daughter particles
- Labels for training: p_T, p_z, and scattering angle θ at the target



Model Architecture

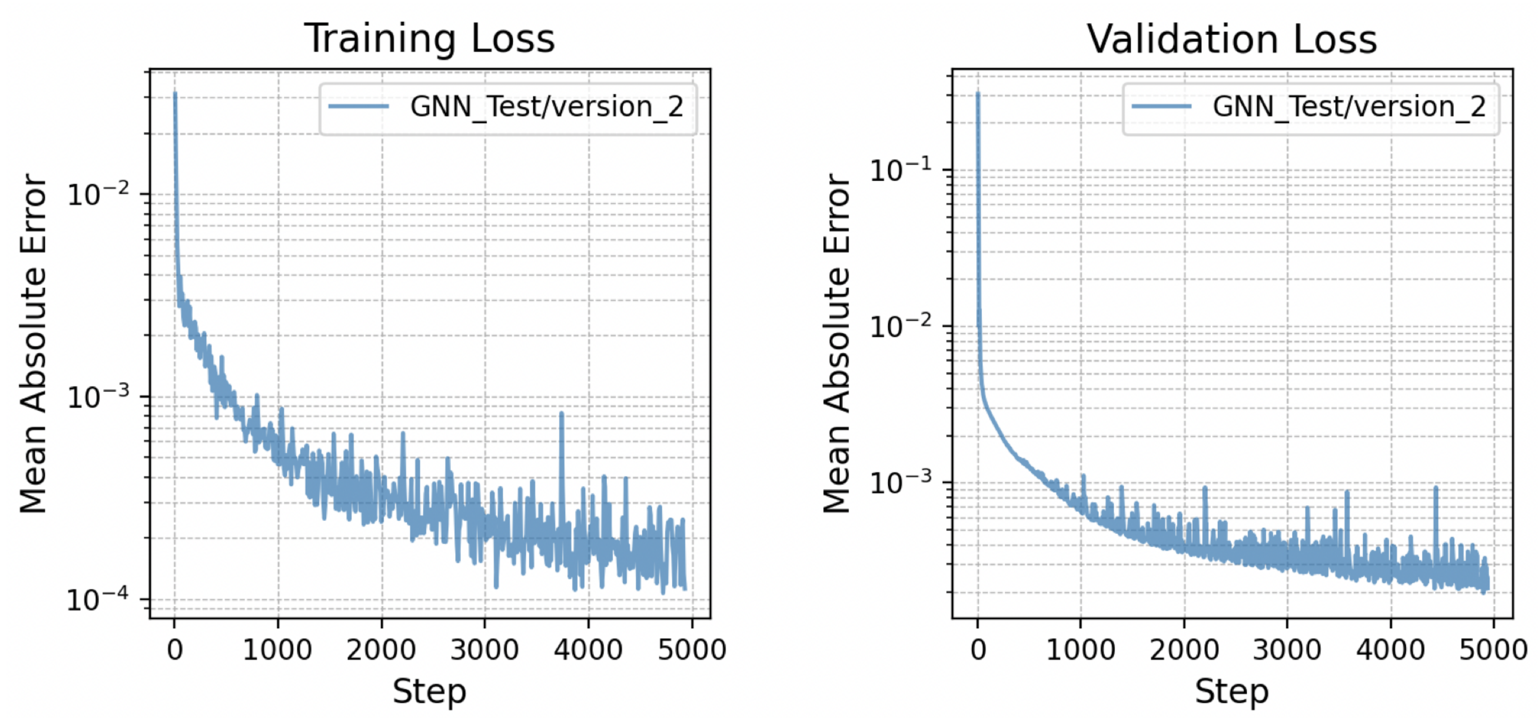
- Graph: hits = nodes, edges = spatial proximity
- Each node encodes the sensor strip's unique location in the spectrometer and its 3 orientation angles
- A hybrid architecture is used: MLP layers for feature transformation + GraphSAGE convolutions for message passing
- The model outputs (p_T, p_z, θ) at the target via a final two-layer perceptron



Graph Neural Network model architecture

Training

- Framework: PyTorch Geometric + Lightning
- Optimizer: Adam
- Loss function: Mean Absolute Error (MAE)

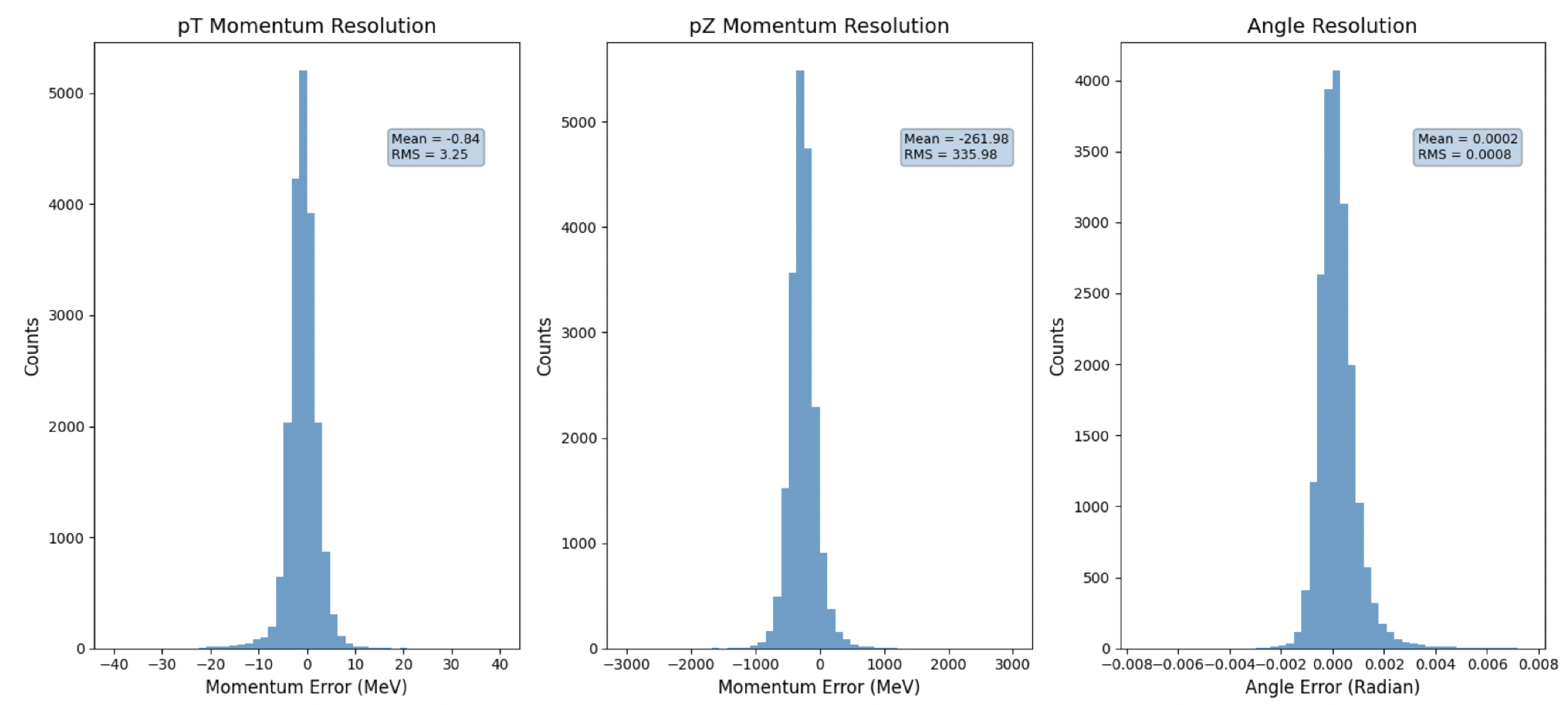


Training and validation loss

- **Training loss:** Error on the training set after each step
- **Validation loss:** Error on unseen data (held-out set)
- Here, both losses decrease and converge to a low MAE without diverging, indicating good generalization

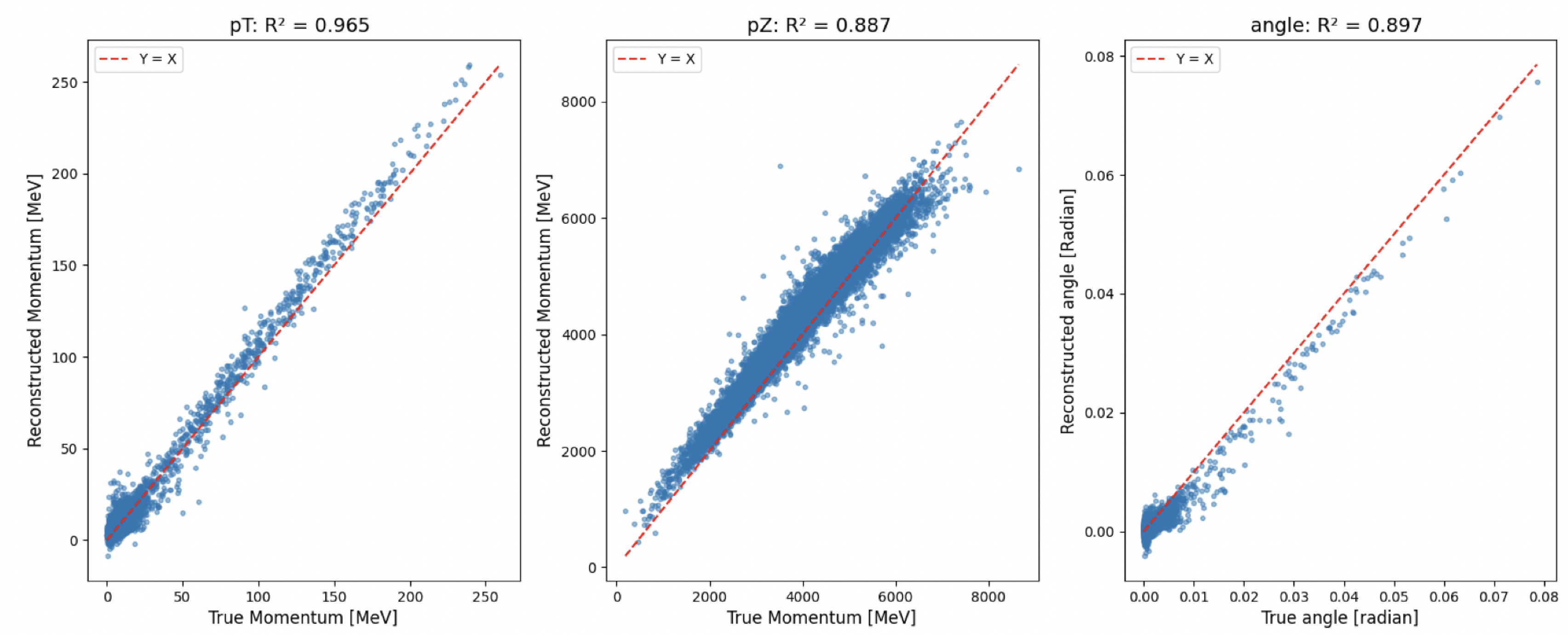
Results

- MAE evaluated on p_T, p_z, and θ
- Stable performance across training checkpoints
- A bias in p_z and asymmetry in θ resolution are observed and are currently under investigation



Momentum and Angle Resolution (True - Reco):

- **Mean:** Average prediction error; near-zero indicates low bias
- **RMS:** Spread of error; lower RMS implies tighter resolution



Reconstructed vs. True Momentum (R^2 Score):

- High R^2 shows strong agreement along the diagonal
- Asymmetry suggests a momentum- and angle-dependent bias (under study); results are promising

Conclusion & Future Work

- GNNs show strong potential for track reconstruction
- Next steps:
  - Identify the source of the observed bias
  - Testing on a range of beam energies and multi-particle events
- *This manuscript has been authored by FermiForward Discovery Group, LLC under Contract No.*