Pacific Northwest NATIONAL LABORATORY

Graph Neural Networks for Angle Reconstruction in the ZDC

April 27, 2023

U.S. DEPARTMENT OF ENERGY BATTELLE

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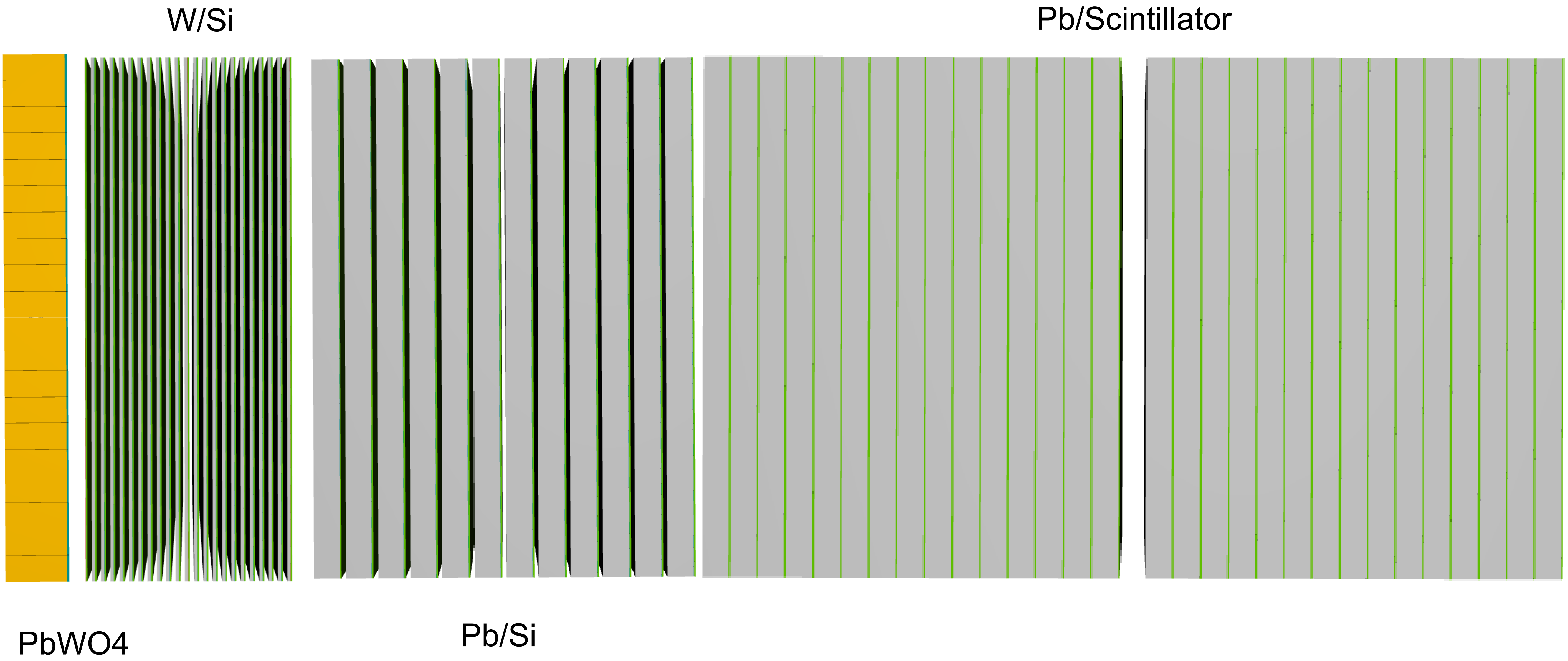
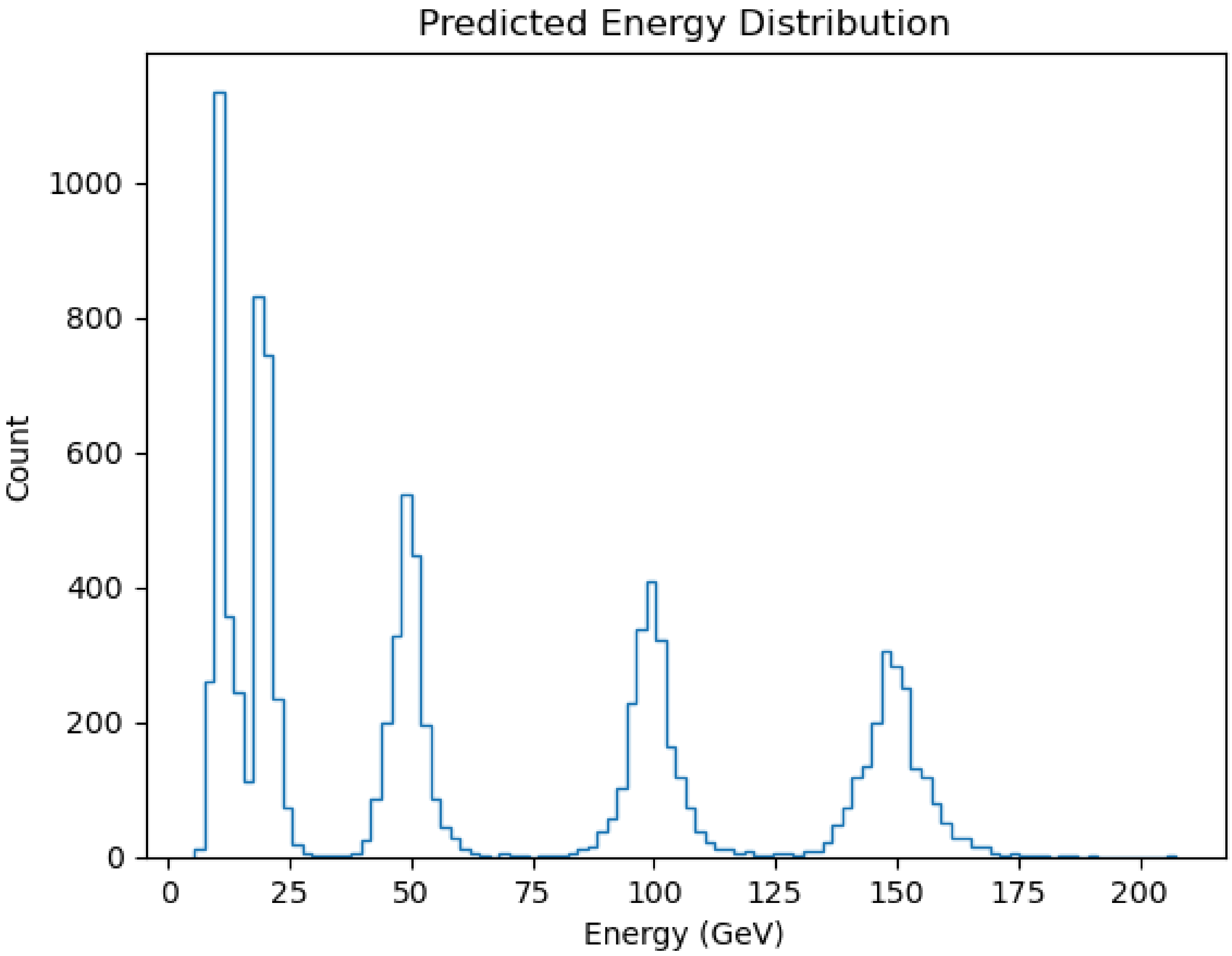
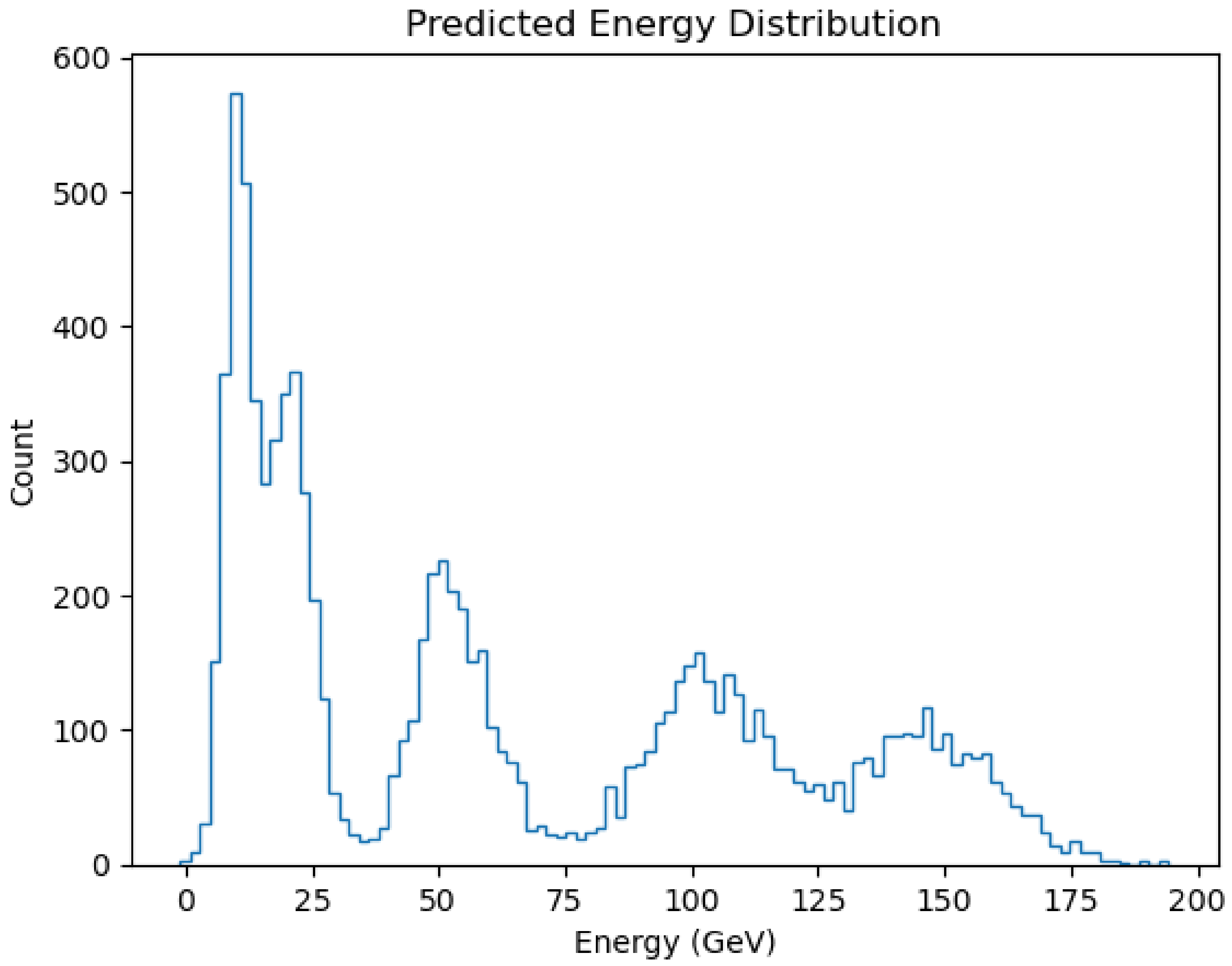
Current ZDC Design



Energy Calibration (Neural Network)

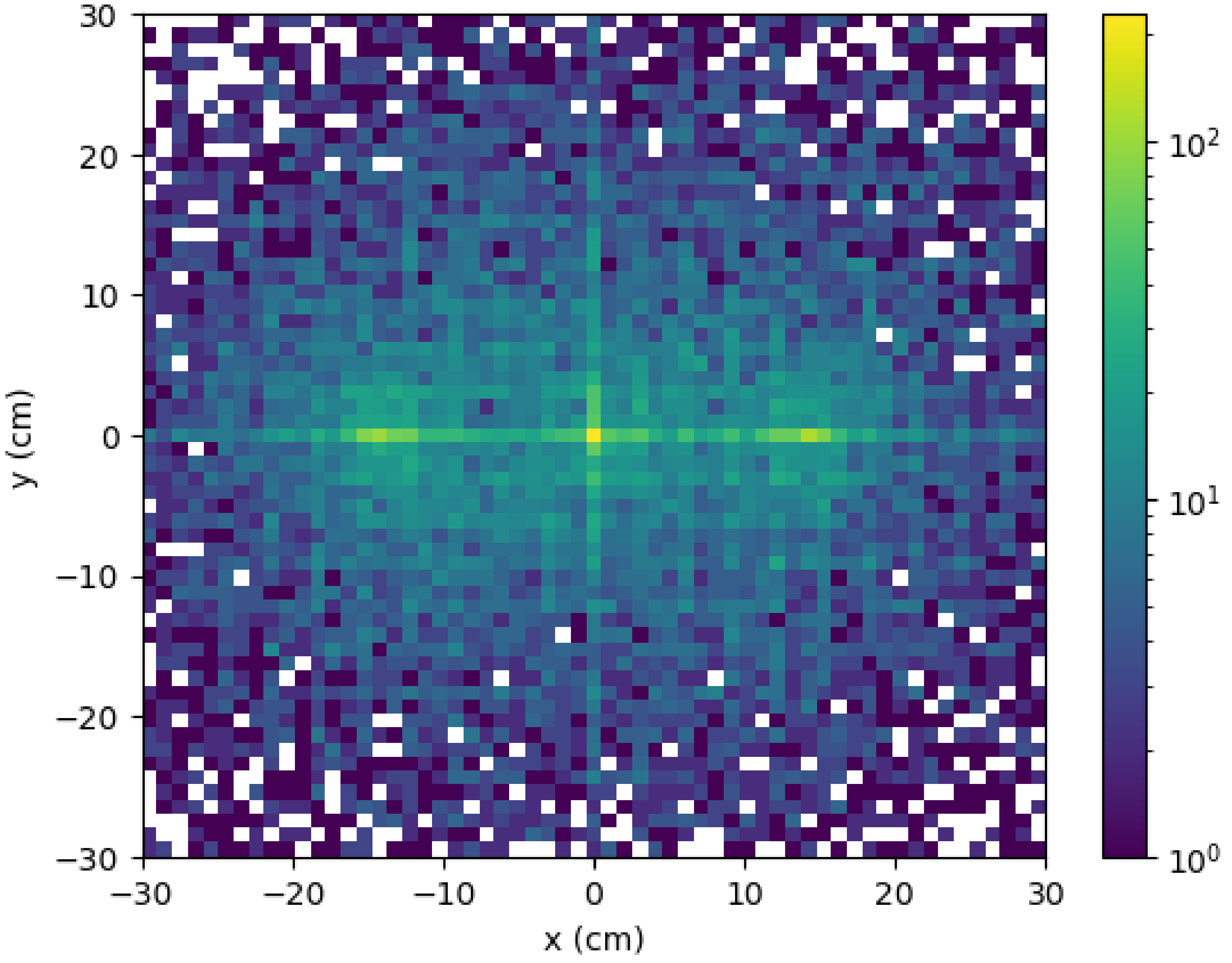


Energy Calibration (Graph Neural Network)

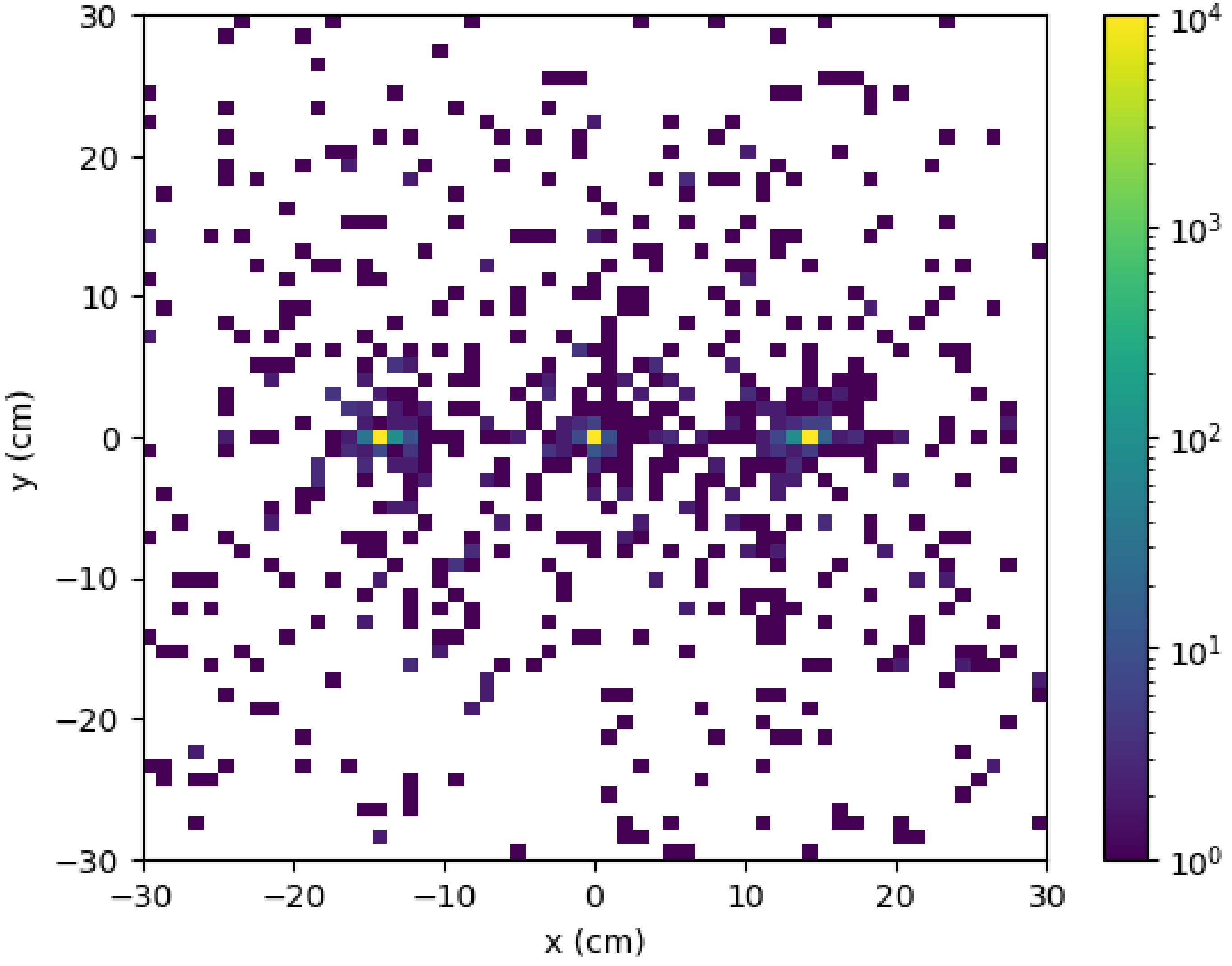


Transverse Distributions

Hits in 1st SiPix Layer (neutron) (-4 mrad, 0 mrad, 4 mrad)

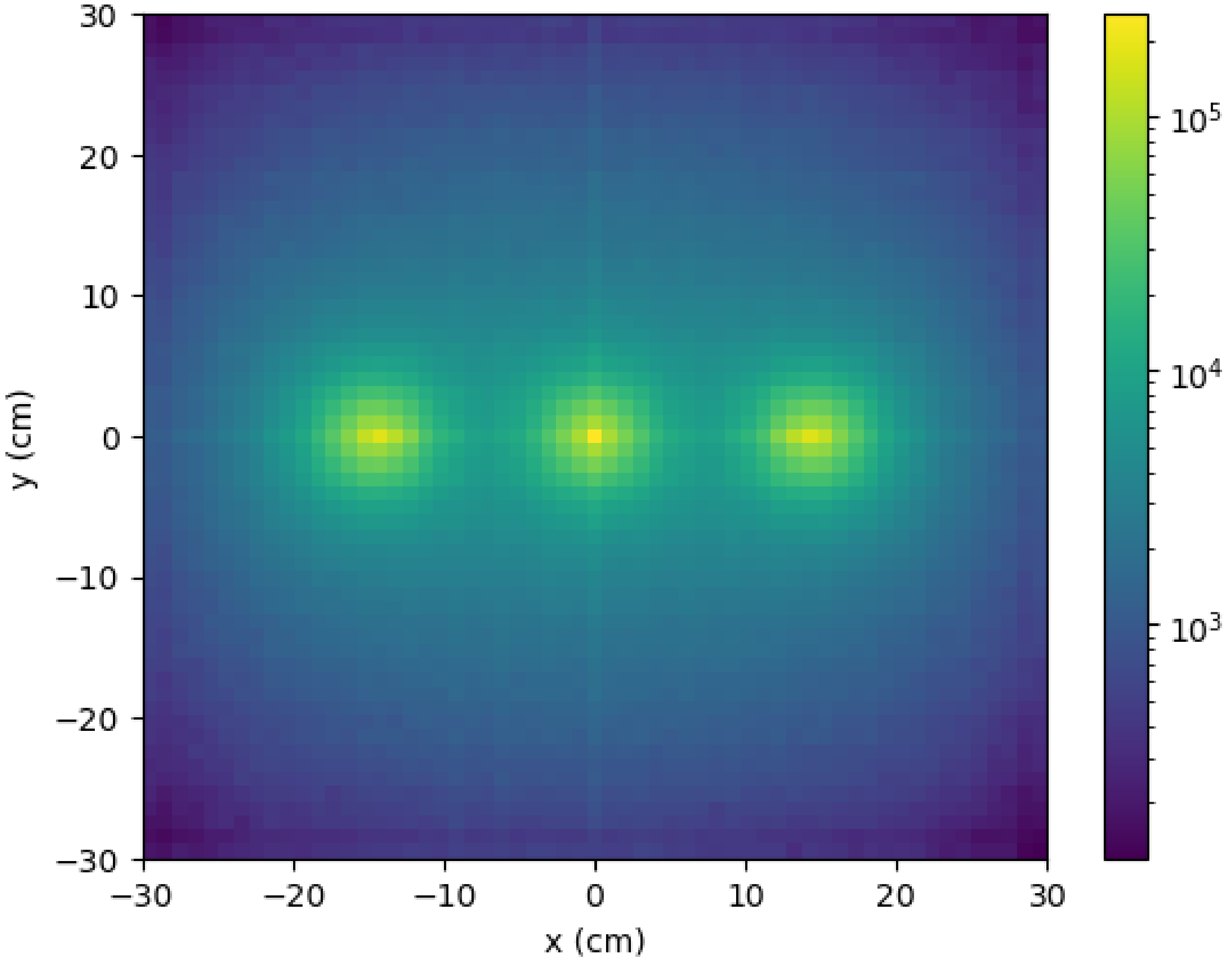


Hits in 1st SiPix Layers (μ-) (-4 mrad, 0 mrad, 4 mrad)

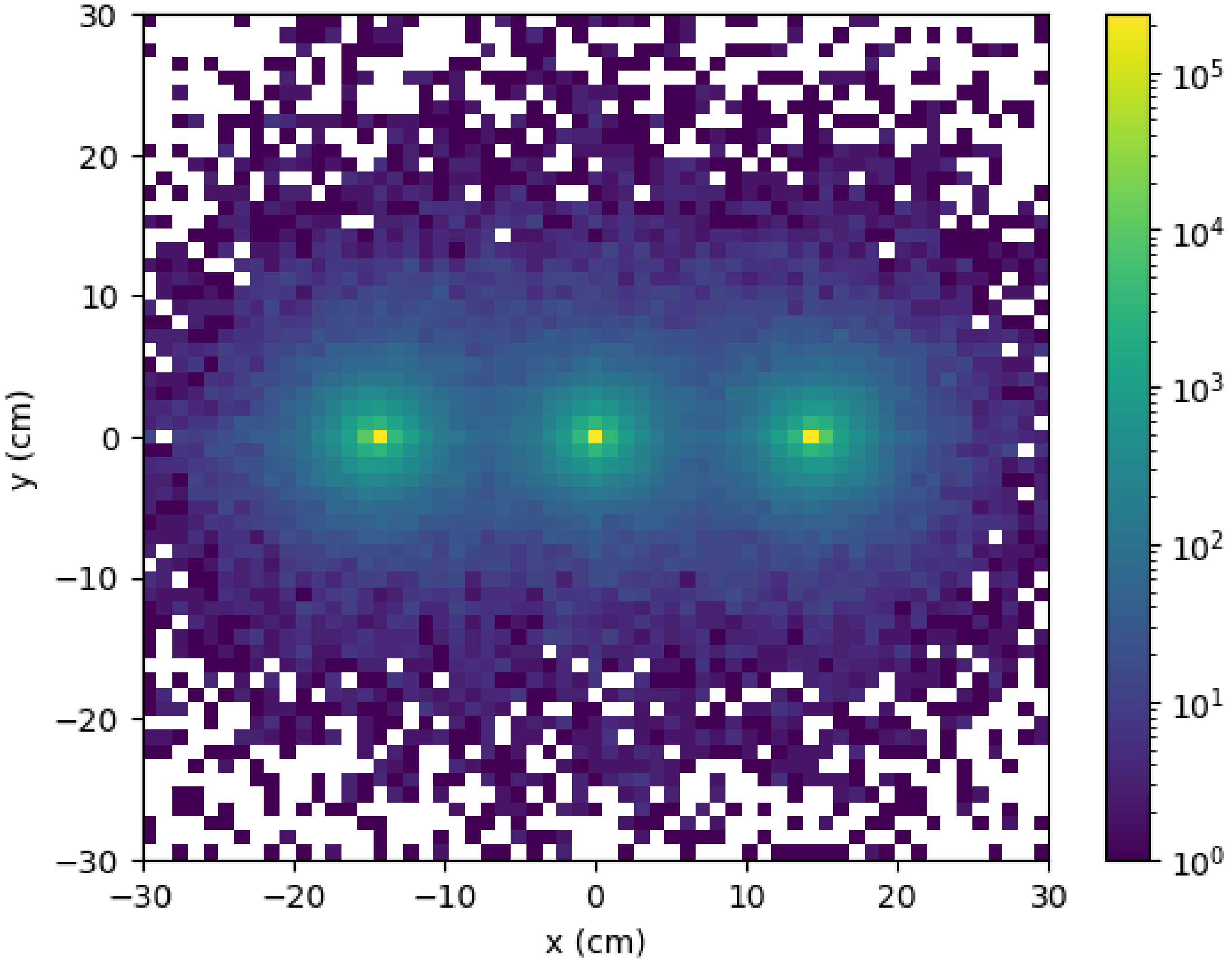


Transverse Distributions

Hits in W/Si Layers (neutron) (-4 mrad, 0 mrad, 4 mrad)



Hits in W/Si Layers (μ-) (-4 mrad, 0 mrad, 4 mrad)



Angle Reconstruction: Methods

- Linear fit between “center of gravity” of hits in first and last layers
  - Cannot reconstruct small angles due to low granularity in Pb/Scint layers
- Linear fit from IP using “center of gravity” in first layer
  - Extremely sensitive to noise (i.e. due to multiple scattering in upstream material)
  - Many particles may pass through the first layer without interacting
- Convolutional Neural Network
  - Spatial neighborhoods do not scale to varying transverse segmentations
  - Inefficient for sparse data
- Graph Neural Network
  - KNN clustering naturally scales for different segmentations
  - Aggregation only utilizes cells with non-zero energy deposition

Linear Fit (Front to Back)

Suppose a particle originates from the interaction point at an angle θ relative to the detector z axis, where θ is the rotation about the y axis. The ZDC has a total length of $162\ \mathrm{cm}$, thus the maximum difference in the transverse position of a particle from the first layer to the last is

$$(\Delta \mathrm{x})_{\mathrm{max}} = 162\ \mathrm{cm} * \tan(\theta)$$

The Pb/Scint layers have a transverse segmentation of $10\ \mathrm{cm} \times 10\ \mathrm{cm}$, thus we have a lower bound on the angular resolution of

$$\arctan\left(\frac{10\ \mathrm{cm}/\sqrt{12}}{162\ \mathrm{cm}}\right) \approx 18\ \mathrm{mrad}$$

(In reality, this value is actually even higher, since the first layer also has a finite spatial resolution of $3\ \mathrm{mm} \times 3\ \mathrm{mm}$)

Linear Fit From IP

Using only the first layer, define the position of the first hit as

$$r_{SiPix} = (\mathrm{x}_1, y_1).$$

Note that for a particle originating at the IP,

$$x_1 = r_{ZDC} * \tan(\theta)\,,$$

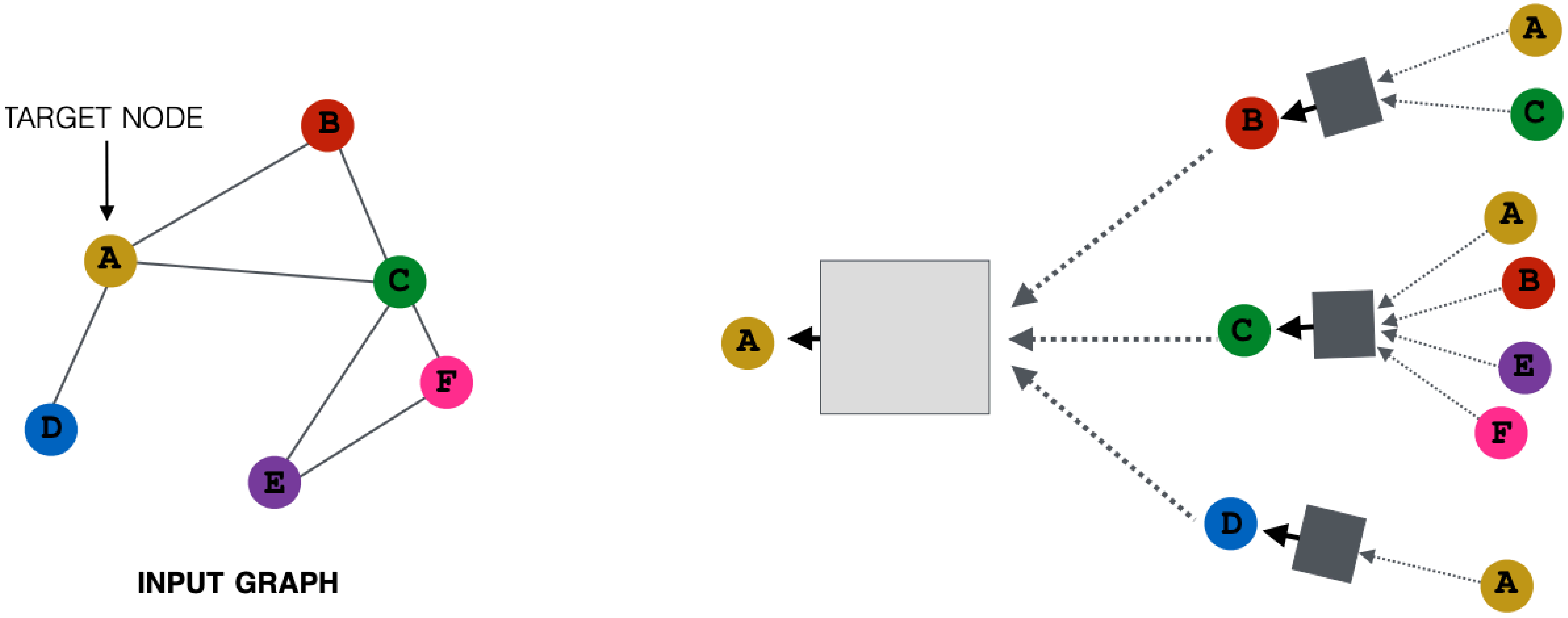
where $r_{ZDC} = 3550\ \mathrm{cm}$ is the distance from the interaction point to the face of the detector. Then

$$x_1 = 3550\ \mathrm{cm}\ * \tan(\theta).$$

The first silicon layer has a segmentation of $3\ \mathrm{mm} \times 3\ \mathrm{mm}$, so we can estimate the (idealized) angular resolution as

$$\arctan\left(\frac{3\ \mathrm{mm}/\sqrt{12}}{3550\ \mathrm{cm}}\right) = 0.0244\ \mathrm{mrad}$$

Graph Neural Networks

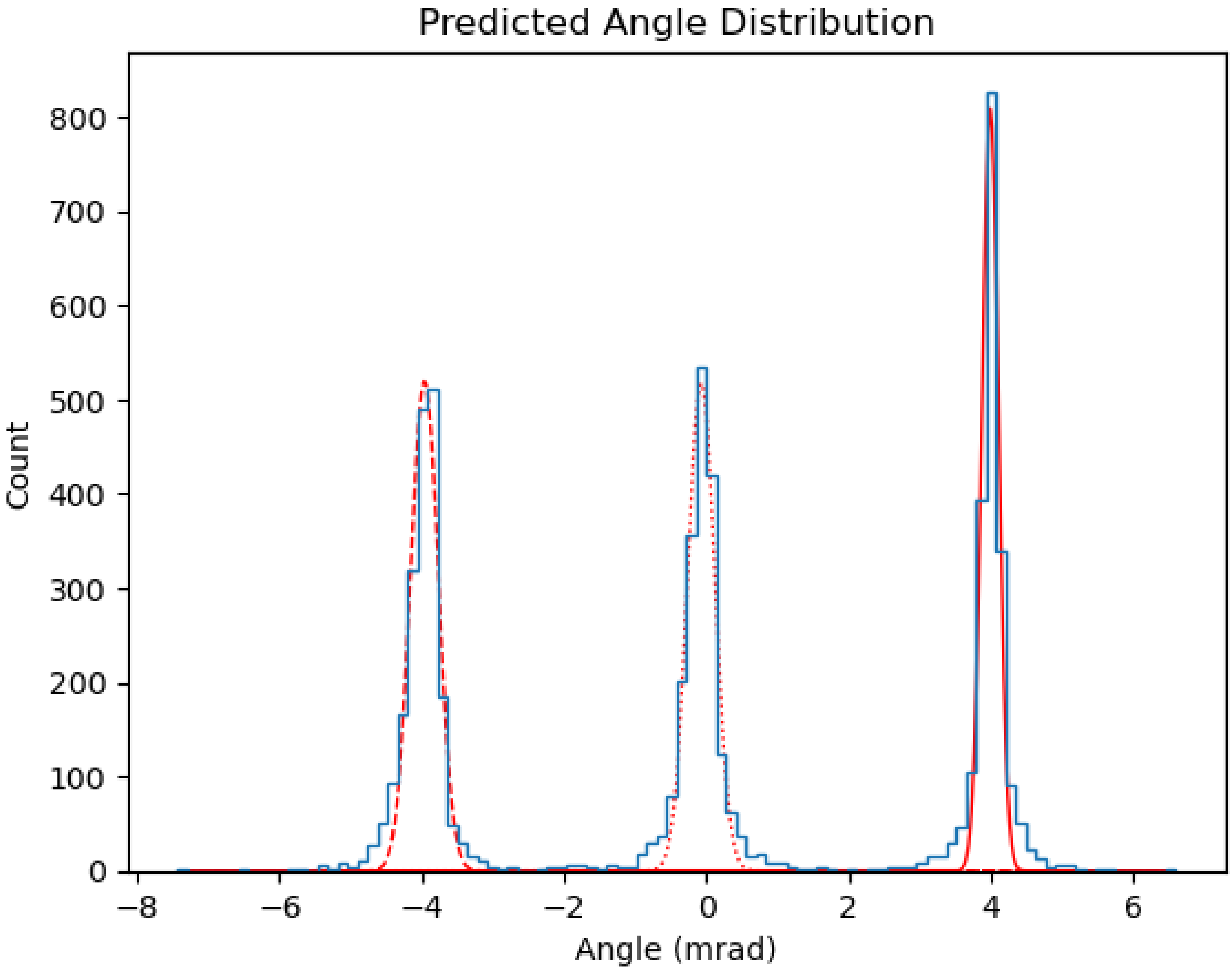


Source: Stanford CS224W

GNN Architecture (GravNet-based)

- Better performance by training separate convolutional filters for each subdetector
- Convolutional layer outputs are concatenated and passed to a single linear hidden layer to reconstruct total shower energy
- F_{IN} = [xID, yID, layerID, hitEnergy]
- Learned space for KNN clustering has dimension 3 (S = 3)
- Learned space for propagated node features has dimension 1 (F_{LR} = 1)

Muon Angle Reconstruction (ZDC Only)



Peak Positions:

μ_1 = -3.96 mrad

μ_2 = -0.07 mrad

μ_3 = 3.99 mrad

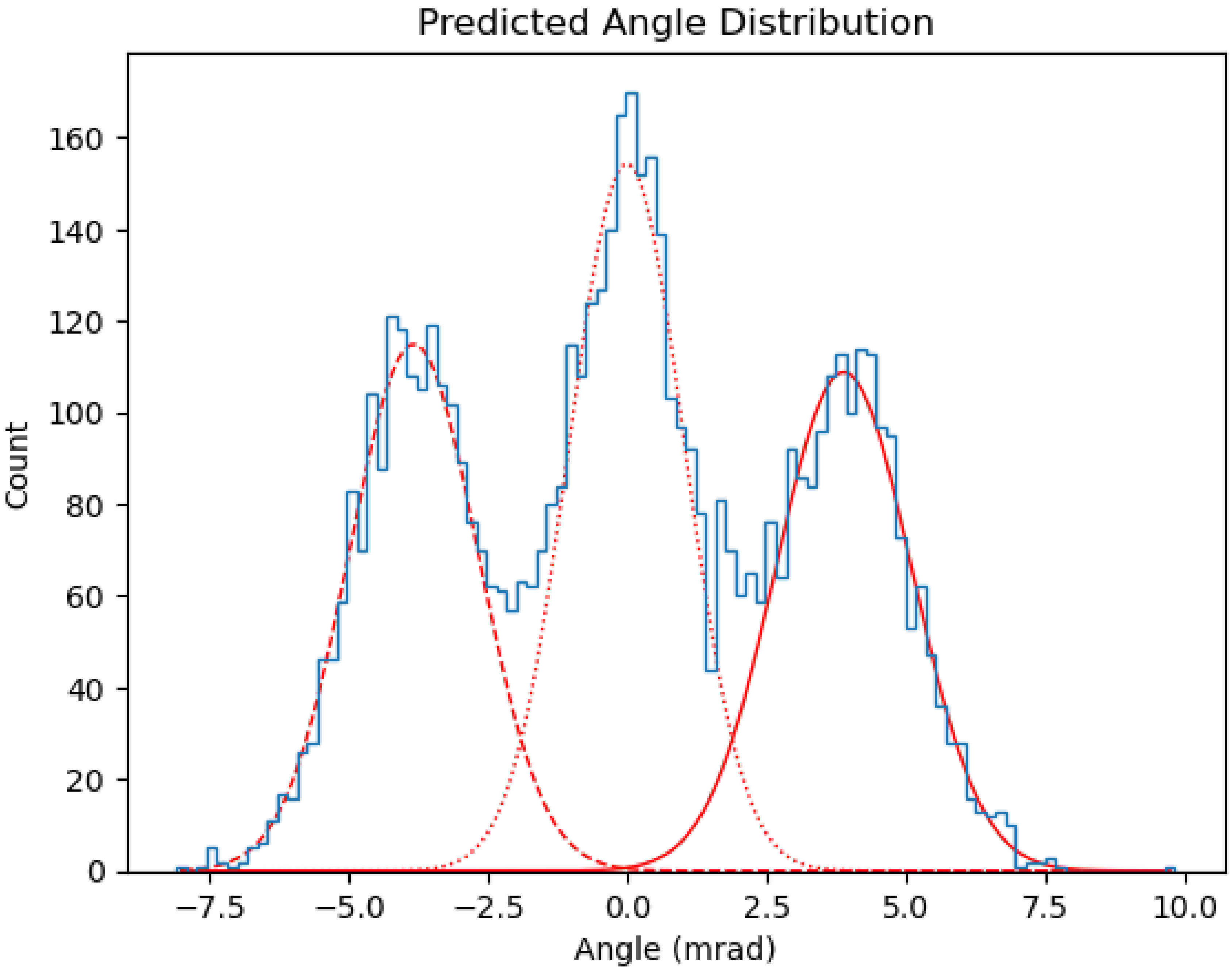
Resolution:

σ_1 = 0.19 mrad

σ_2 = 0.17 mrad

σ_3 = 0.12 mrad

Neutron Angle Reconstruction (ZDC Only)



Peak Positions:

μ_1 = -3.84 mrad

μ_2 = -0.01 mrad

μ_3 = 3.89 mrad

Resolution:

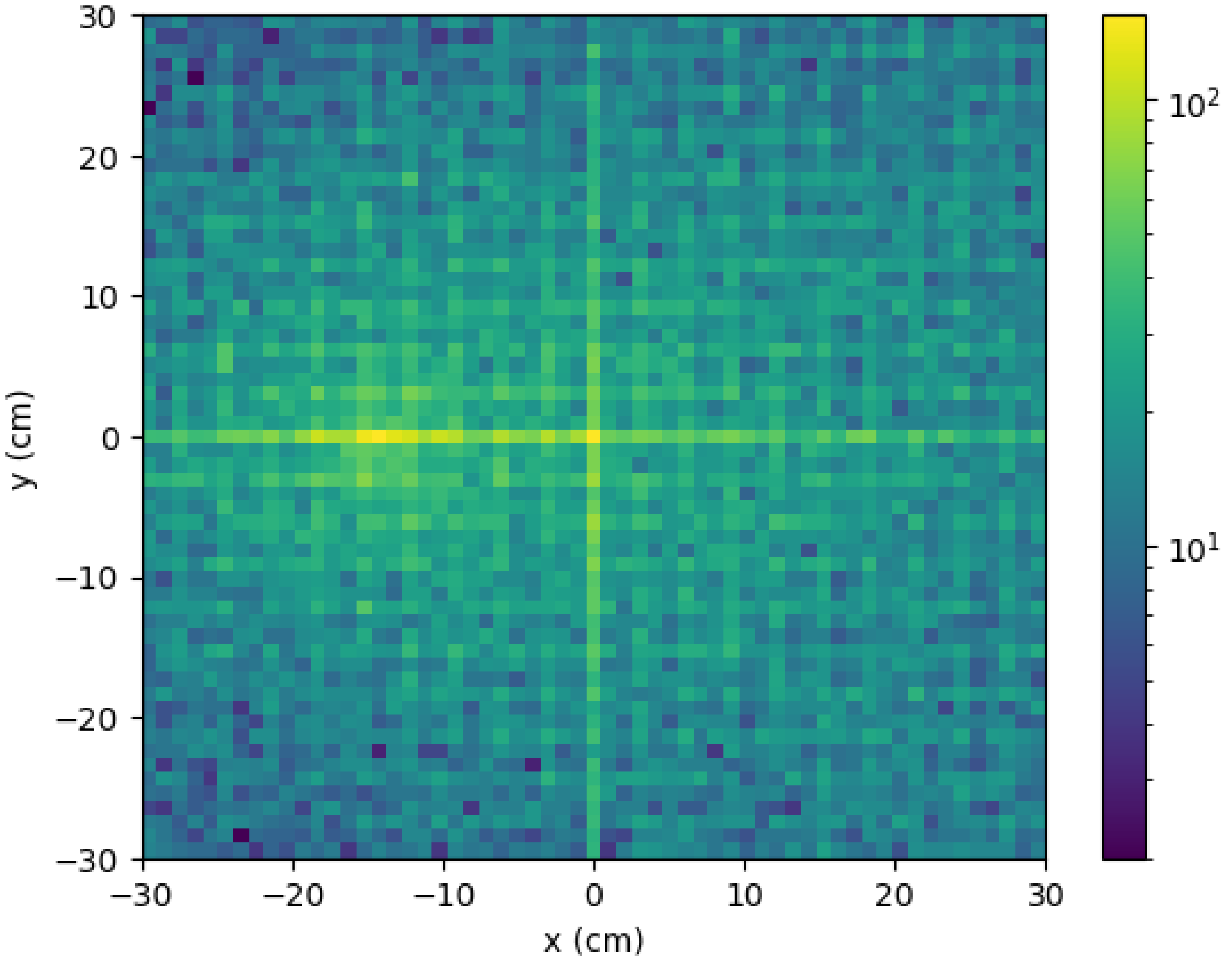
σ_1 = 1.16 mrad

σ_2 = 1.03 mrad

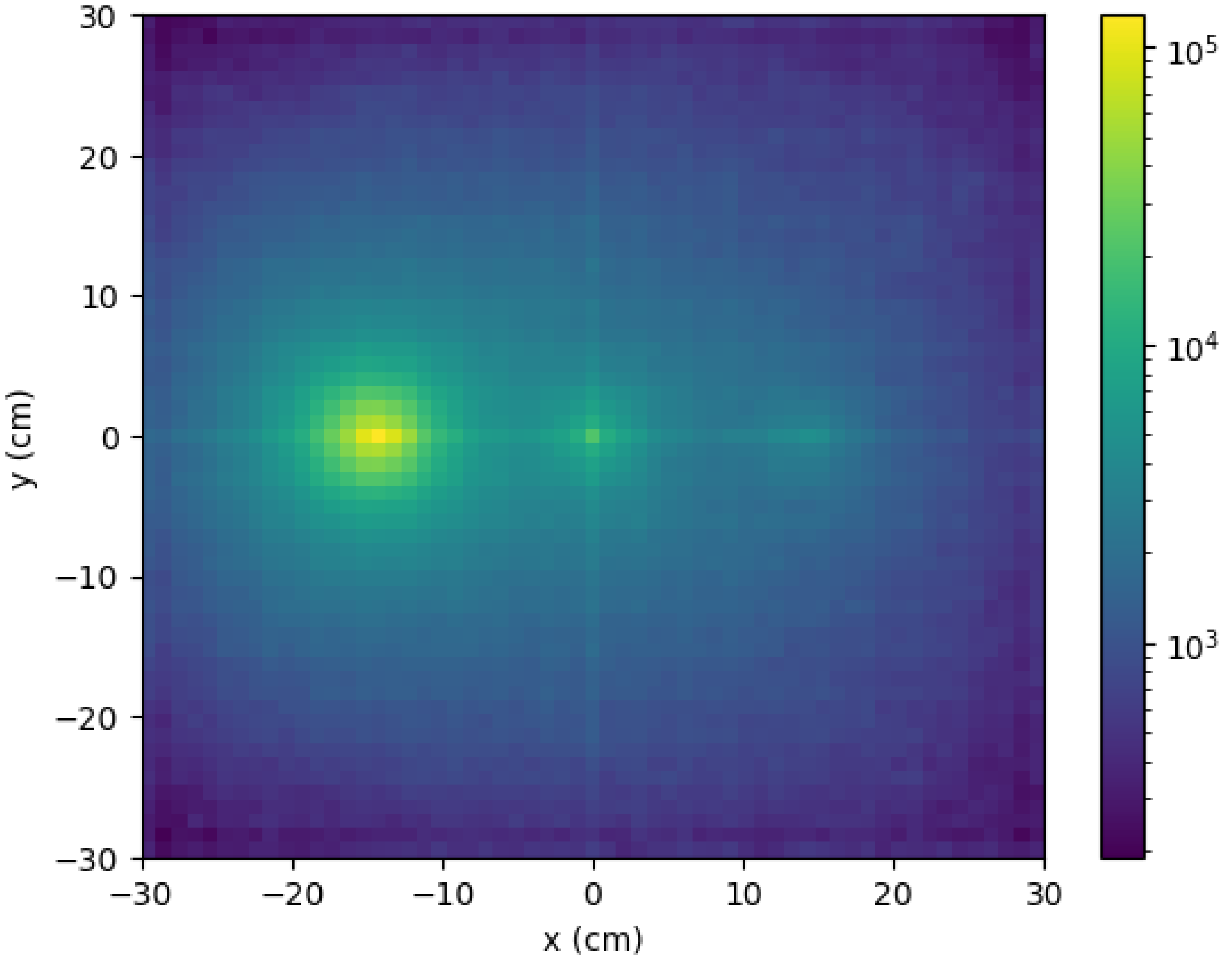
σ_3 = 1.22 mrad

Effects of Upstream Material

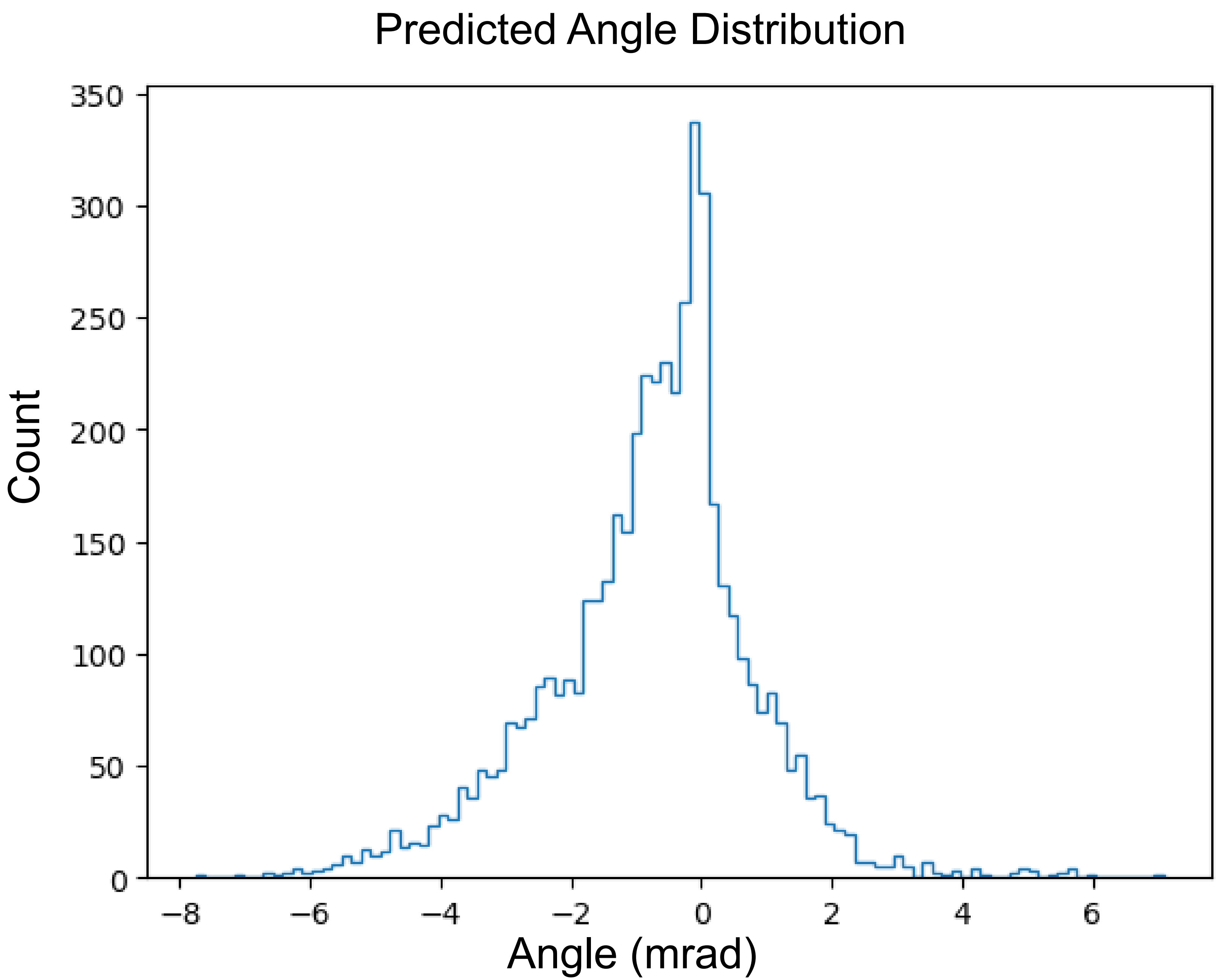
Hits in 1st SiPix Layer (neutron) (-4 mrad, 0 mrad, 4 mrad)



Hits in W/Si Layers (neutron) (-4 mrad, 0 mrad, 4 mrad)



Effects of Upstream Material



Summary & Conclusions

- First implementation of a graph neural network for the reconstruction of small angles (≤4 mrad) in the ZDC
  - Can be adapted to a variety of configurations and geometries due to independent treatment of each component
- Investigation of the effects of upstream material on hadronic showers in the ZDC.
  - Emphasis on how interactions with this material impacts our ability to reconstruct the angles of neutrons from the IP

Future Work

- Fine-tune hyperparameters for better optimization
  - Accounting for differences in material properties between components

- Include hit timing information in node feature embedding
  - Important for shower separation with multiple primary particles

- Further quantify effects of upstream material
  - Informs the design & layout of the far-forward region

https://github.com/demisra/zdc

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Thank you