



REactor neutrino **LI**quid xenon
Coherent elastic **S**cattering

Delayed Electron Mitigation in the RELICS Experiment with Deep Neural Network based Position Reconstruction

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RELICS Collaboration

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RELICS

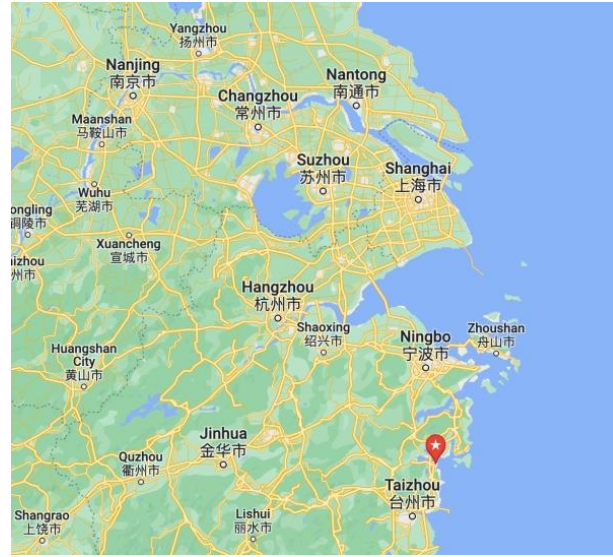
REactor neutrino LIquid xenon COherent SCattering experiment

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2.$$

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

$$Q_W \propto N \implies \frac{d\sigma}{dT} \propto N^2$$

1. Constrain on θ_W
2. Explore:
Nonstandard neutrino interactions
3. Potential application:
Nuclear reactor monitoring

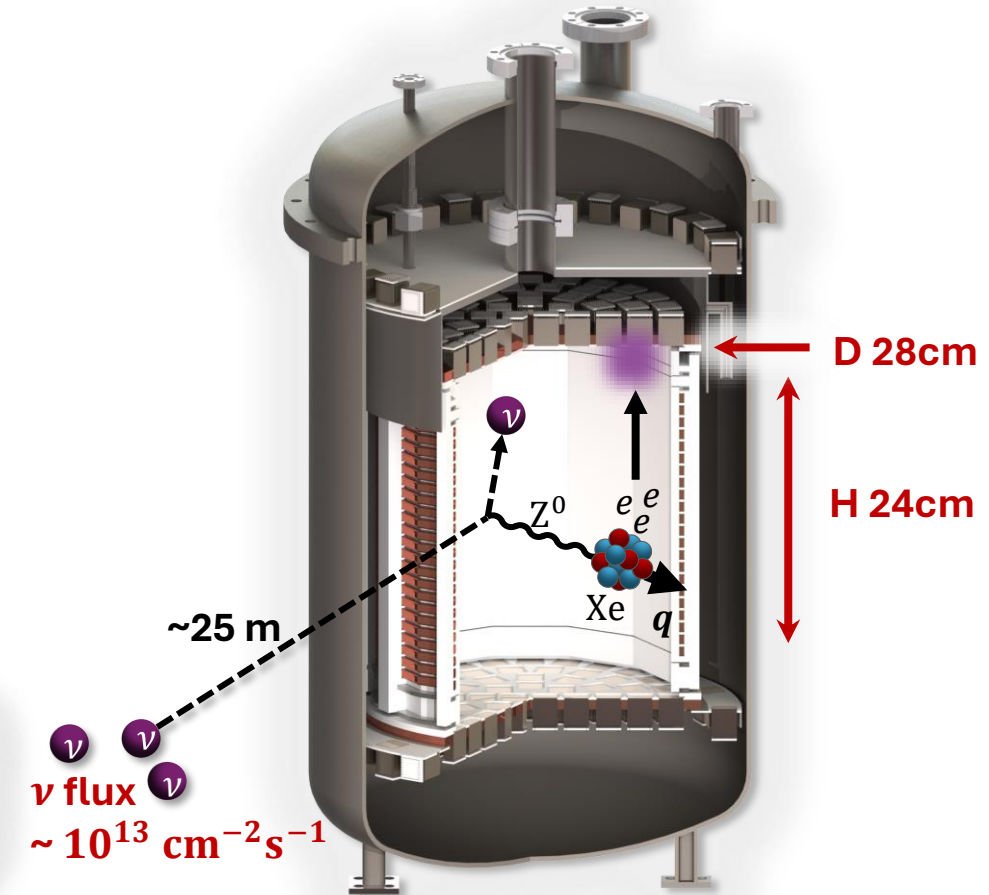


- **Liquid Xenon Time Projection Chamber (LXeTPC) technology**

1. 3D vertex reconstruction
2. Background reduction

Low energy threshold

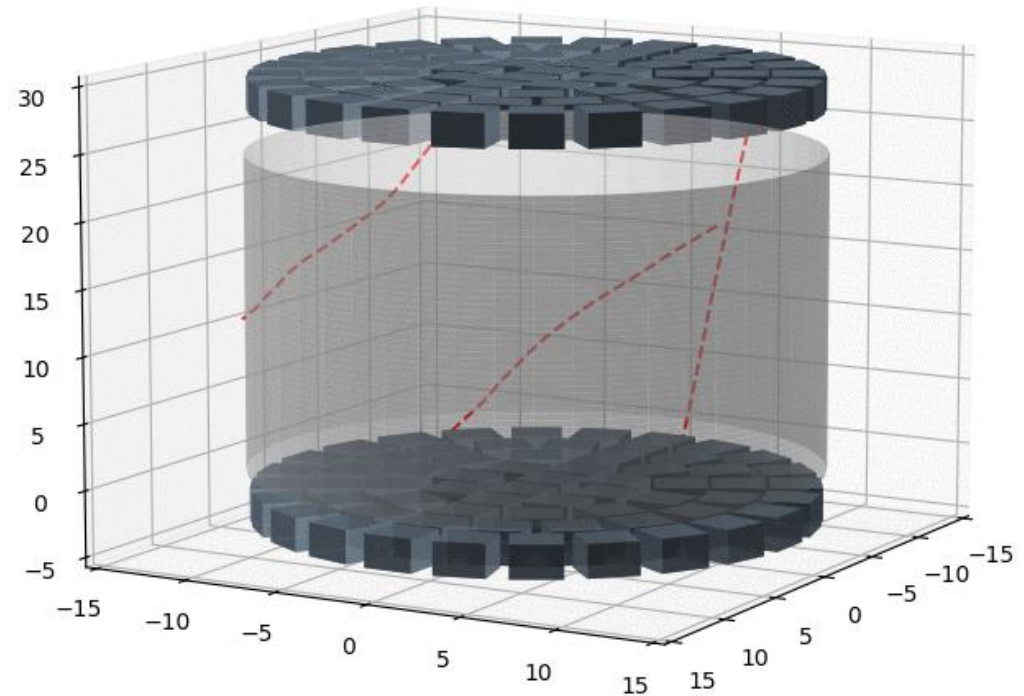
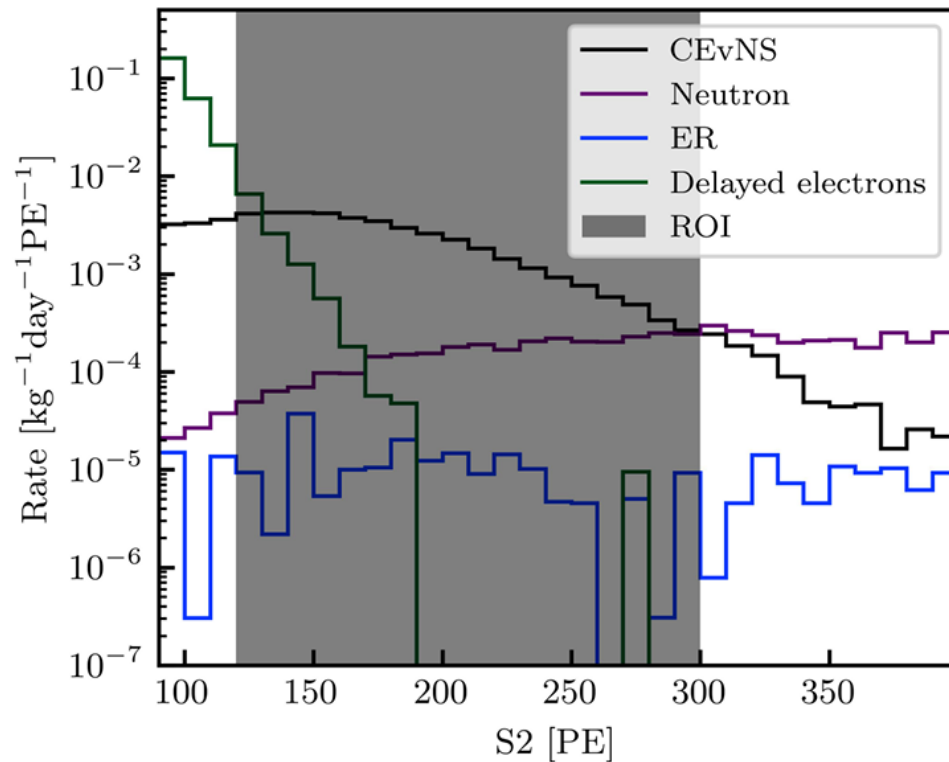
(nuclear recoil energy $\sim 1\text{keV}_{nr}$)



Delayed Electrons(DEs) from Cosmic Muon

- Major challenge: DE caused by **High Rate of Cosmic Muon Events**

Muons passing through the LXeTPC : **Large energy deposition**



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Reactor neutrino liquid xenon coherent elastic scattering experiment

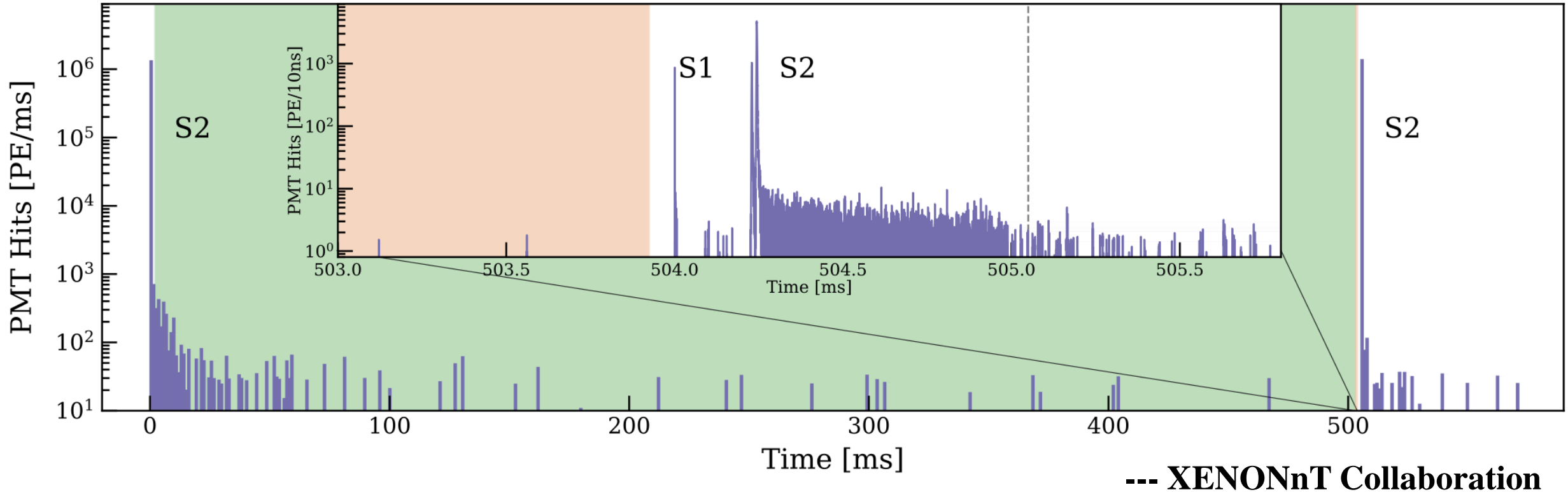
PDF

Chang Cai¹, Guocai Chen², Jiangyu Chen³, Rundong Fang⁴, Fei Gao^{1*}, Xiaoran Guo^{5,6}, Jiheng Guo⁴, Tingyi He^{7,8}, Chengjie Jia^{1,4} et al. (RELICS Collaboration)

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Delayed Electrons(DEs)



Such background has been observed

by large LXeTPCs experiments searching for dark matter particles

XENON1T: <https://doi.org/10.1103/PhysRevD.106.022001>

PandaX 4T: <https://doi.org/10.1103/PhysRevLett.130.261001>

LUX: <https://arxiv.org/abs/2004.07791>

Pile-up DEs and CEvNS

Muon tracks and DEs:

Strongly correlated in: (\mathbf{x}, \mathbf{y}) and \mathbf{t} (emission time)

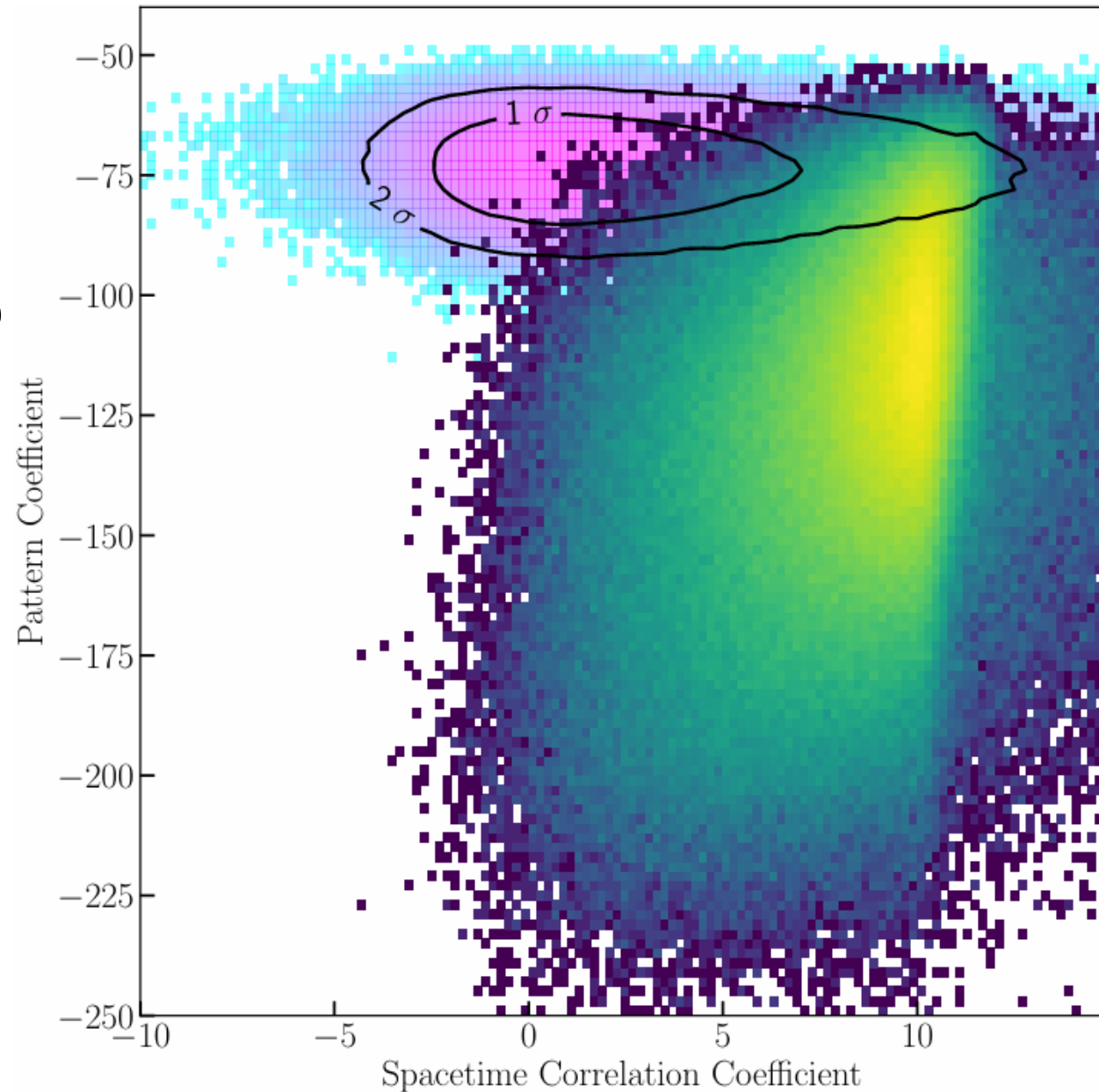
CEvNS within ROI

46.5% (scores over 0)

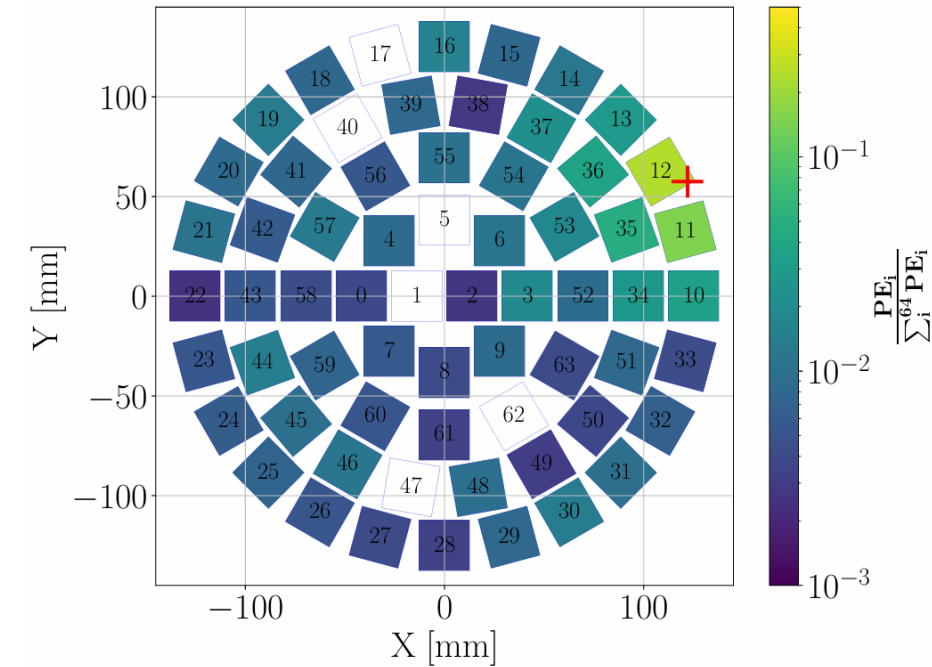
Pile up DEs within ROI

0.005%

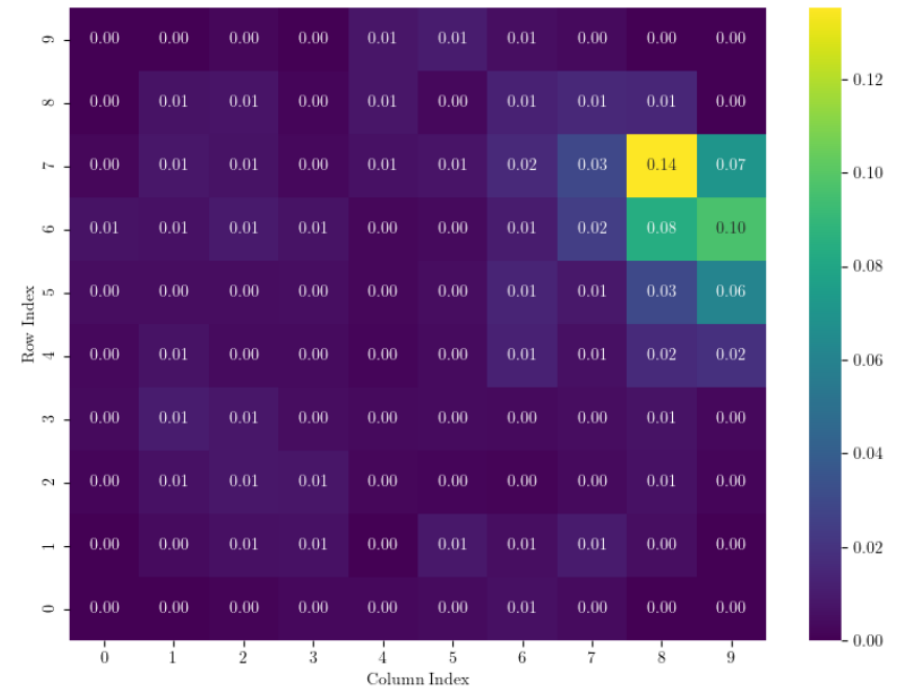
Expected (\mathbf{x}, \mathbf{y}) resolution: 20mm



Position Reconstruction



Convert simulated PMT pattern into 10*10 matrix

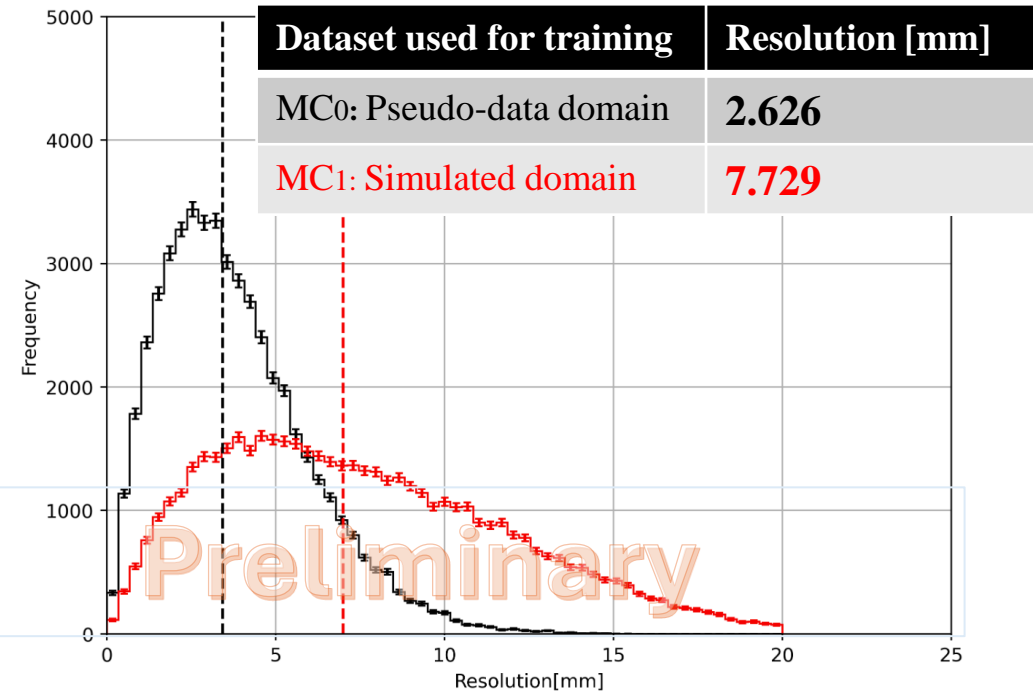


- **Deep Residual Network** for Position Reconstruction
- Use the **Real Position (x, y)** as training label
- **Regression Task:**
Input Matrix → **Predicted (x, y)**

Problems with MC-based Simulations:

- Neural network training **heavily relies on simulated data**

Dataset	S2 Generation Method	Reflectivity of Teflon
MC ₀	Garfield++	0.99
MC ₁	Point like	0.70

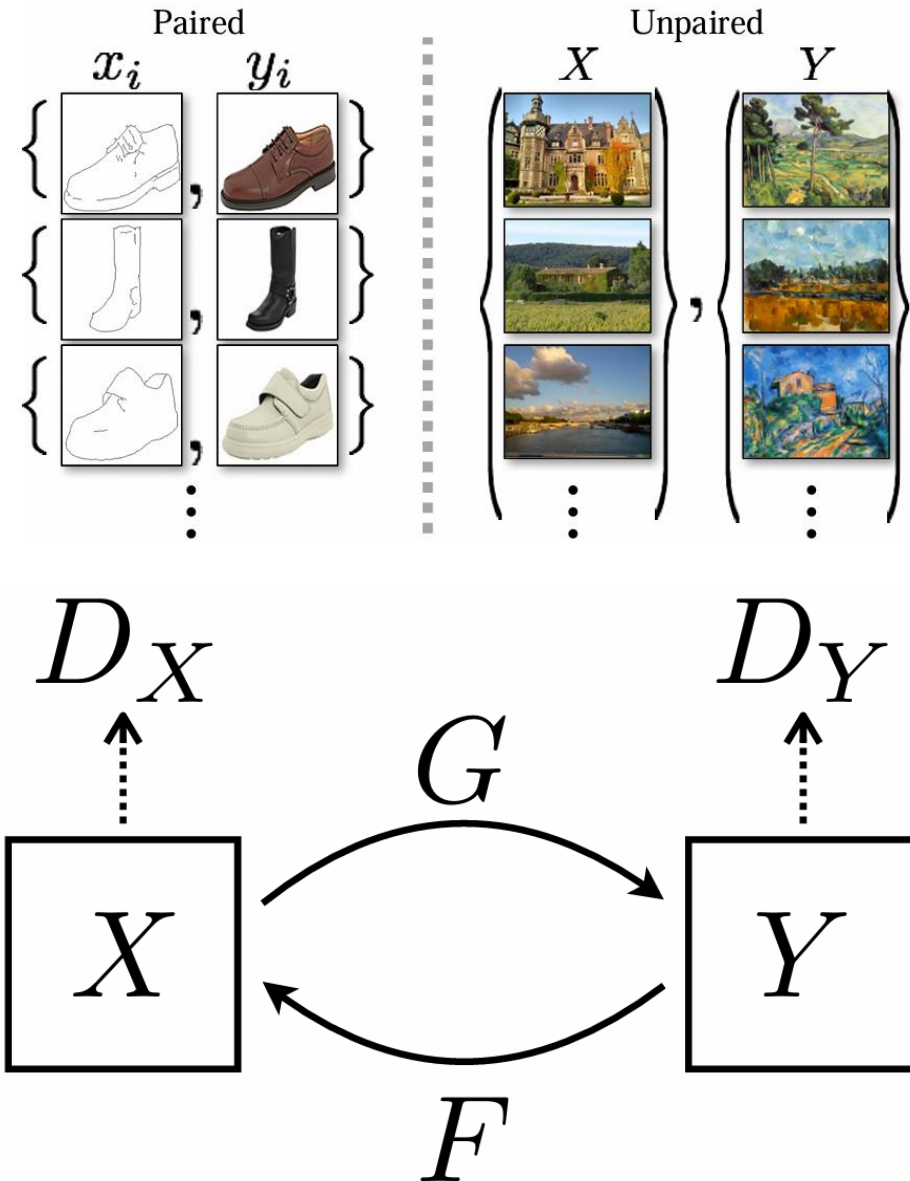


The resolution is calculated by:

$$|\vec{R} - \vec{R}_0| = \sqrt{(x_{rec} - x_{true})^2 + (y_{rec} - y_{true})^2}$$

Apply **Unsupervised Domain Adaptation(DA)** to align the distribution of simulated data with that of real data.

Cycle-GAN



- **Two generators:**

1. **G:** $X \rightarrow Y$ (simulated domain \rightarrow data domain)
2. **F:** $Y \rightarrow X$ (data domain \rightarrow simulated domain)

- **Two discriminators :**

1. **D_Y** : Are the input matrices from data domain?
2. **D_X** : Are the input matrices from simulated domain?

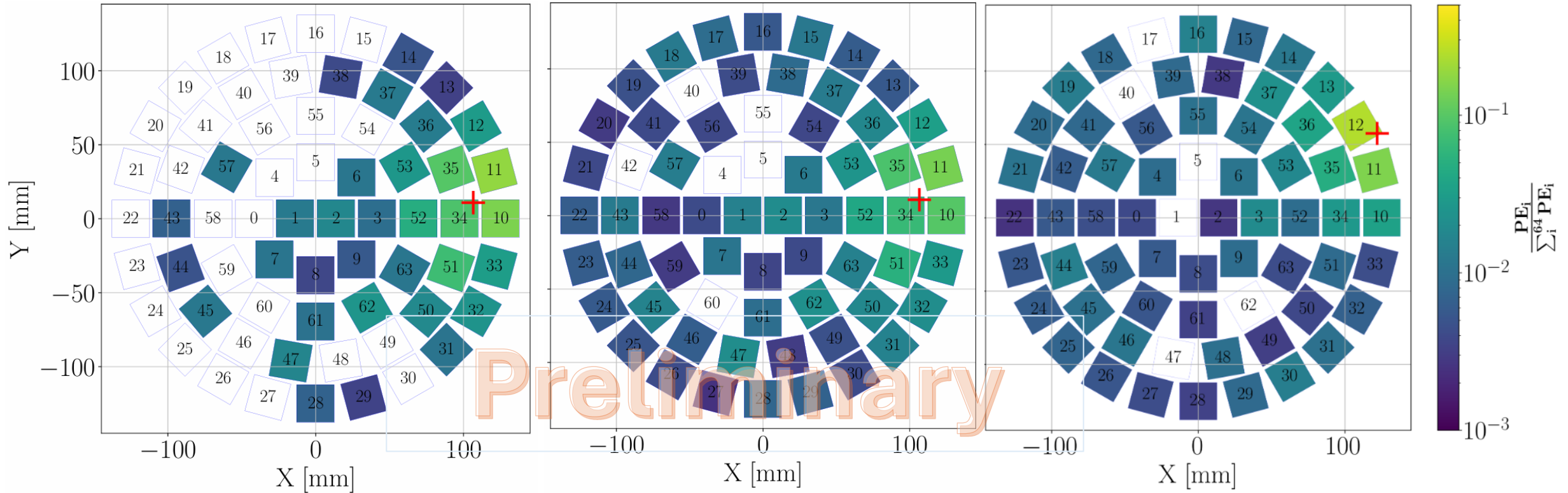
Cycle consistency loss:

Constrain the GAN to:

$$\mathbf{x} \rightarrow \mathbf{G}(\mathbf{x}) \rightarrow \mathbf{F}(\mathbf{G}(\mathbf{x})) \approx \mathbf{x}$$

Domain Adaptation(DA)

Dataset	S2 Generation Method	Reflectivity of Teflon
MC ₀	Garfield++	0.99
MC ₁	Point like	0.70

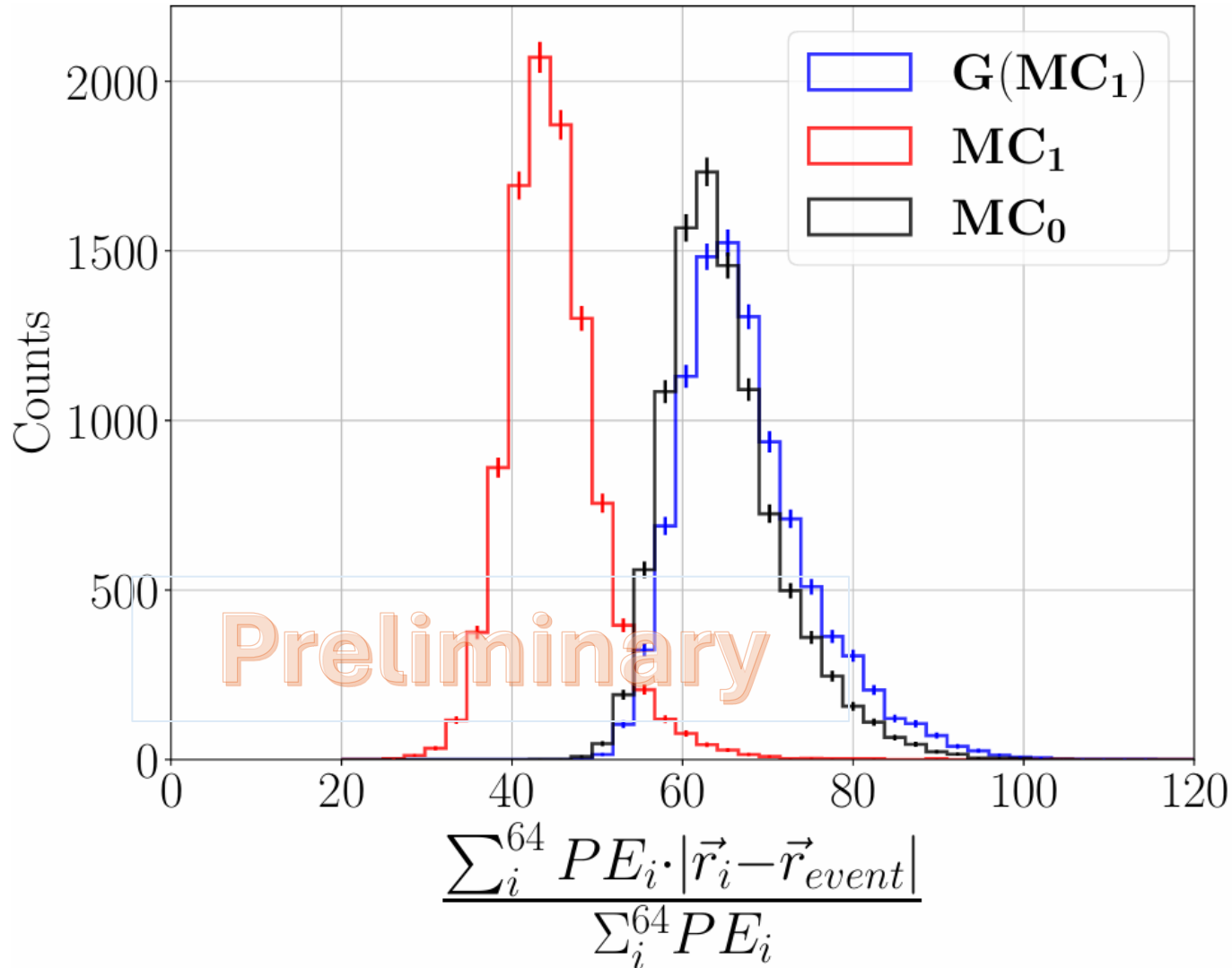


(a) : Pattern From MC₁
MC₁: Simulated domain

(b) : Pattern After DA
Using the trained generator G
to generate a new Dataset G(MC₁)

(c) : Pattern From MC₀
MC₀: Pseudo-data domain

Data Distribution Before and After DA



PMT center Position

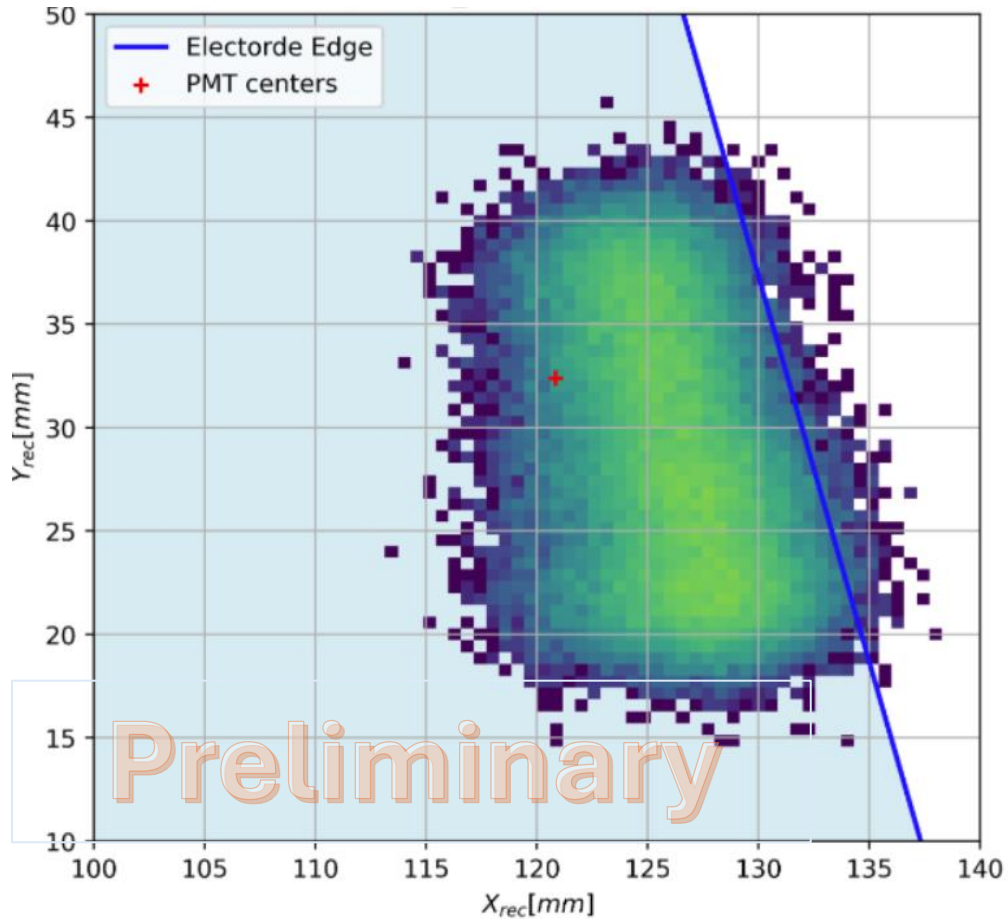
$$\frac{\sum_i^{64} PE_i \cdot |\vec{r}_i - \vec{r}_{event}|}{\sum_i^{64} PE_i}$$

Real Position(simulated)

Dataset	S2 Generation Method	Reflectivity of Teflon
MC ₀	Garfield++	0.99
MC ₁	Point like	0.70

RELICS TPC

Events reconstruction near the TPC edge

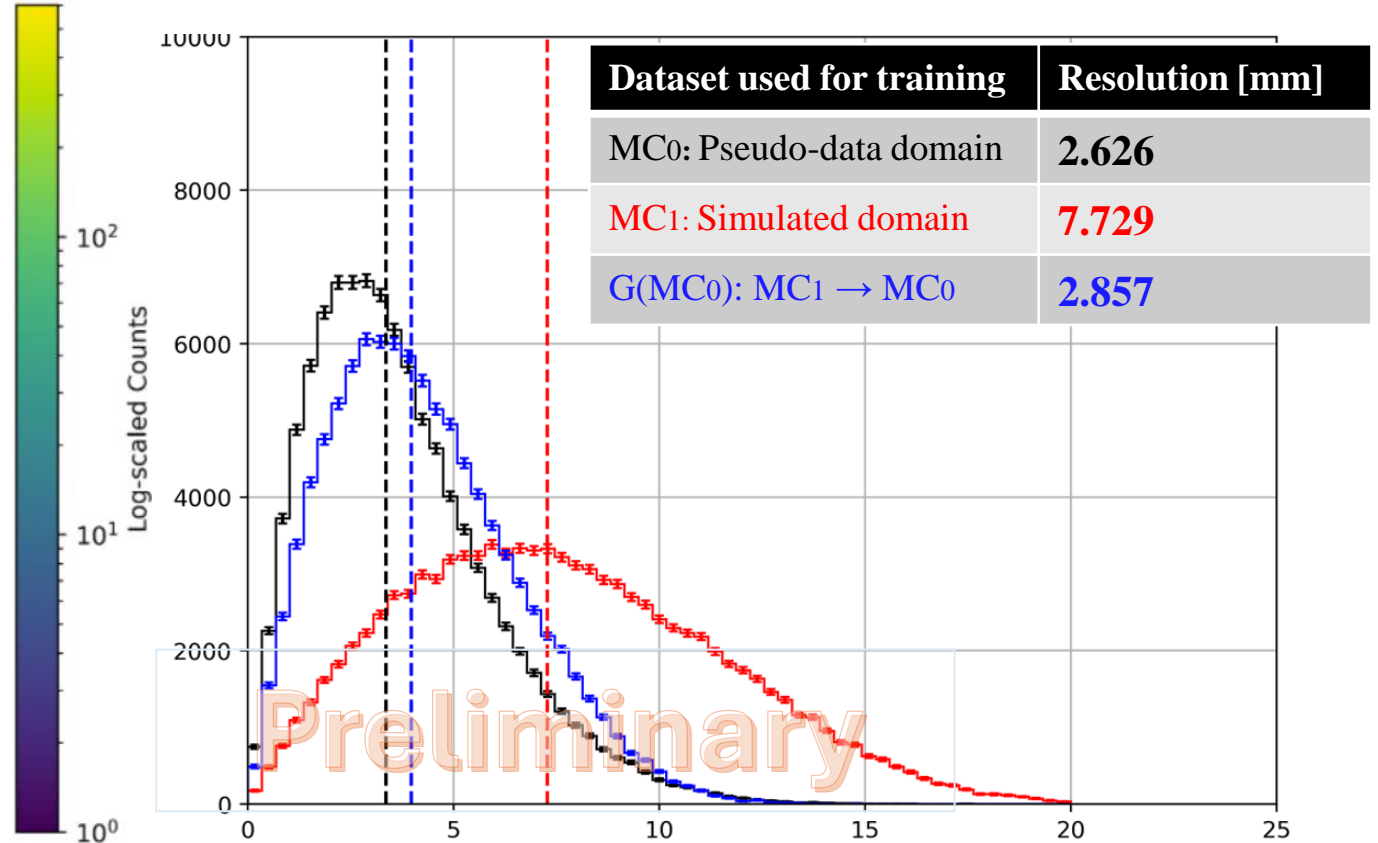


Distribution of reconstructed events

The resolution is calculated by:

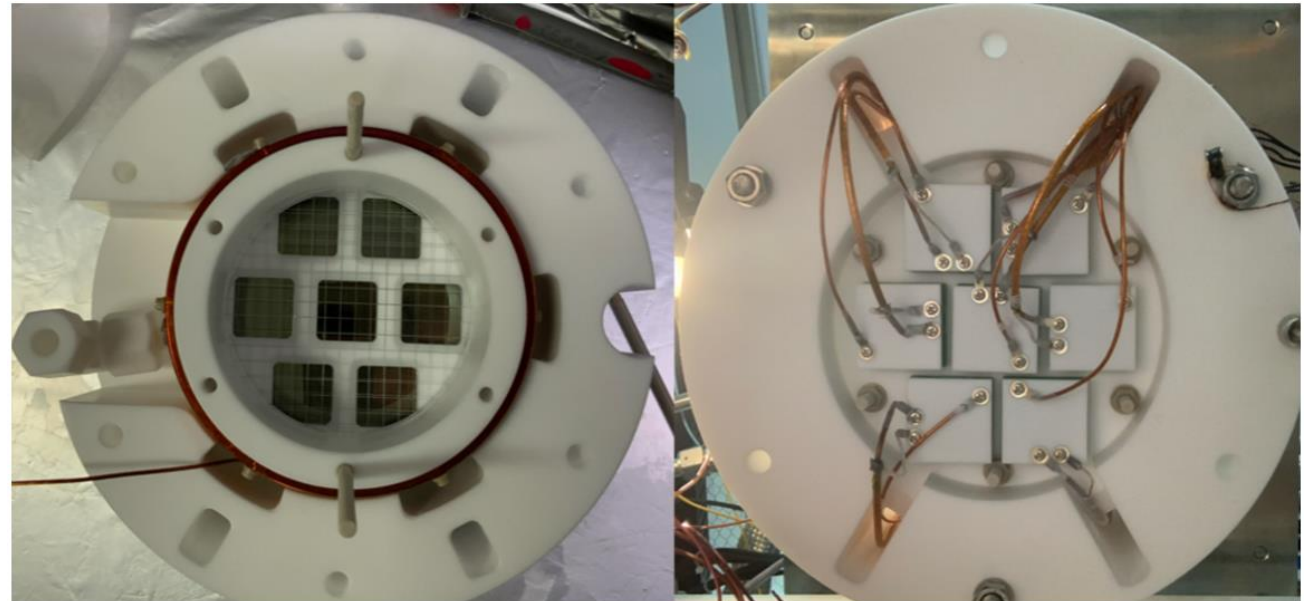
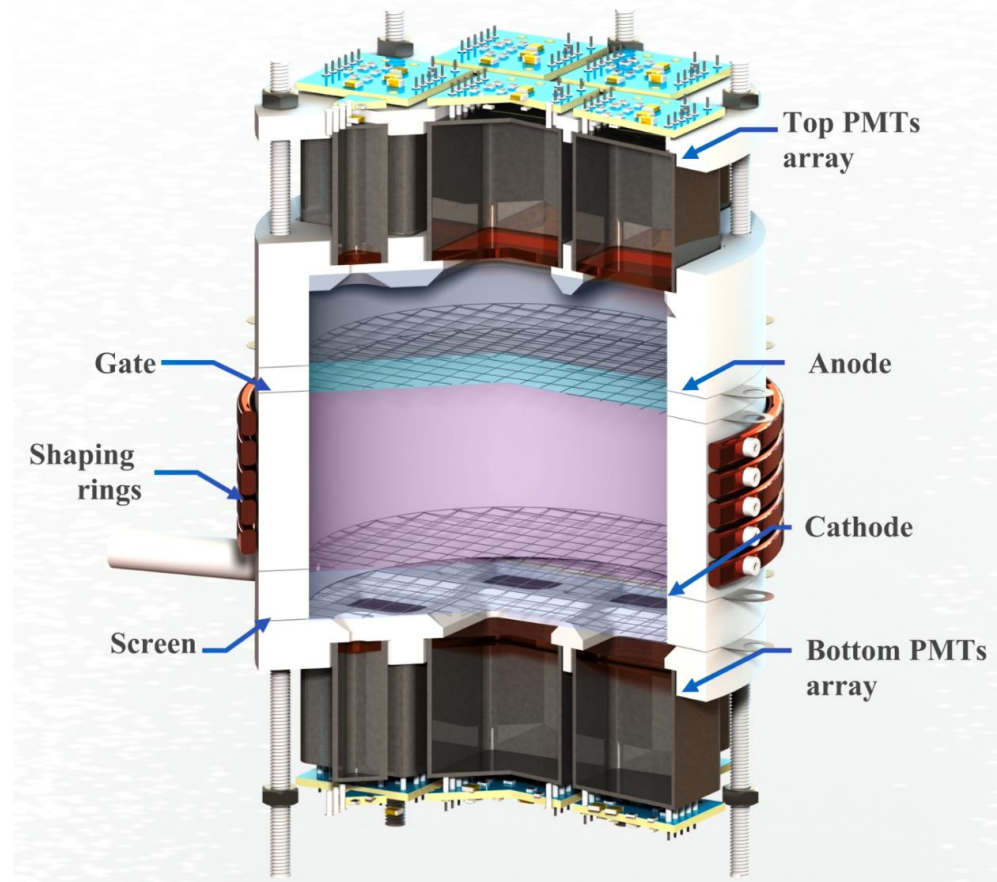
$$|\vec{R} - \vec{R}_0| = \sqrt{(x_{rec} - x_{true})^2 + (y_{rec} - y_{true})^2}$$

Different models validated on Pseudo-data domain (MC0)



Distribution of resolution
in $100 < R < 140$ [mm]

RELICS Prototype

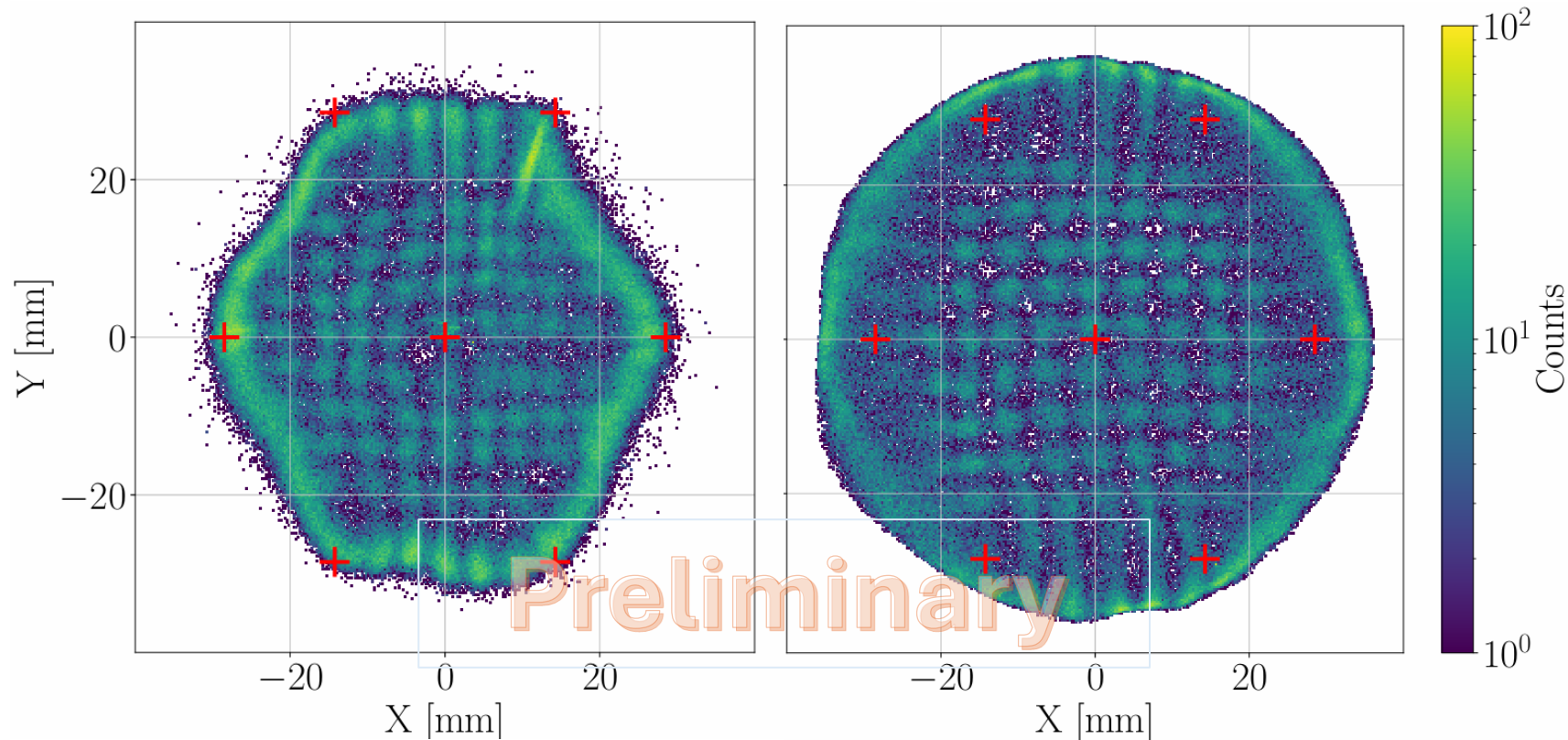


- The prototype for RELICS is a more compact TPC.
- Two arrays of 7 PMTs(R8520-406 PMTs) for each on top and bottom

Distribution of Ar37 Events After Reconstruction

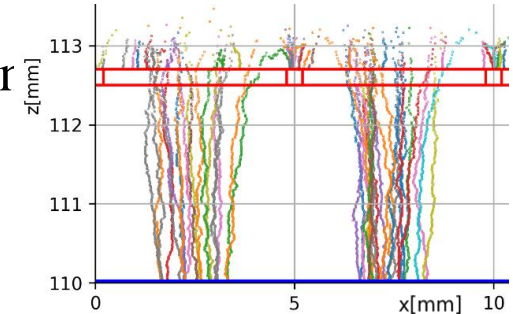
Calibration source: Ar37

Injected into the gas circulation system, considered to be a uniform distribution



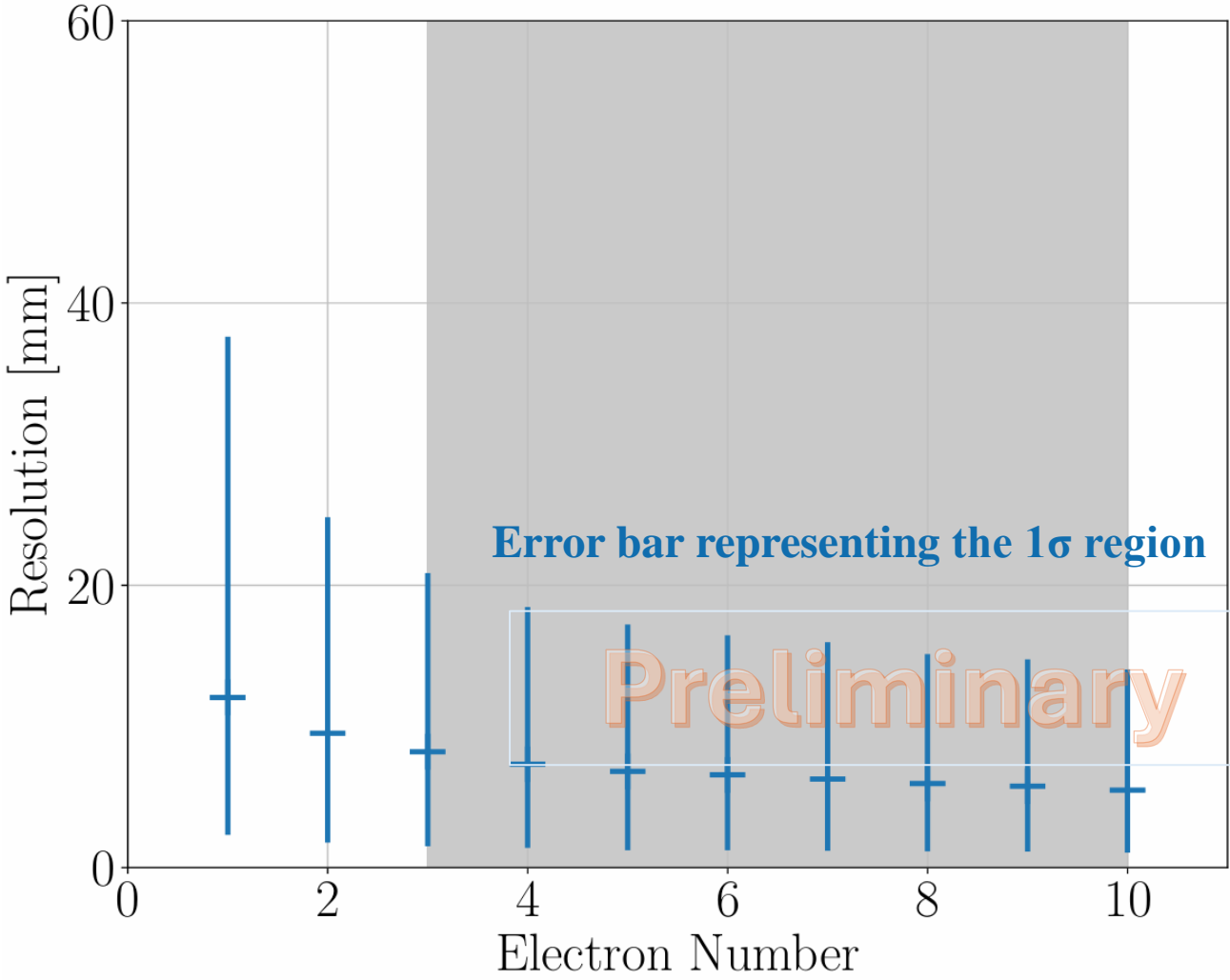
**Reconstructed with DNN
trained with simulated domain**

**Reconstructed with DNN
trained with simulated domain after DA**



- **Hot Spot:** Higher electric field in the center of electric grid, matches the pitch(5 mm)
- **Better performance:** Edge events tend to be distributed nearer to the boundary of the cylindrical TPC

Reconstruction Resolution in ROI



RELICS region-of-interest(ROI) :
[3, 10] electrons
Shaded in gray

An average resolution of 6.478 mm
with [3.106, 11.117] mm as the 1σ region.
is obtained

Summary

- Under the assumption of a 20 mm spatial resolution, the DE signal was suppressed by **4-orders** of magnitude.
- Training-testing bias caused by discrepancies between simulated and actual detector optical parameters can lead to reduced reconstruction accuracy.
- After applying CycleGAN for domain adaptation, the position resolution near the edge of the TPC is **improved by 63%**
- An average Resolution of **6.478 mm** for Position Reconstruction is achieved

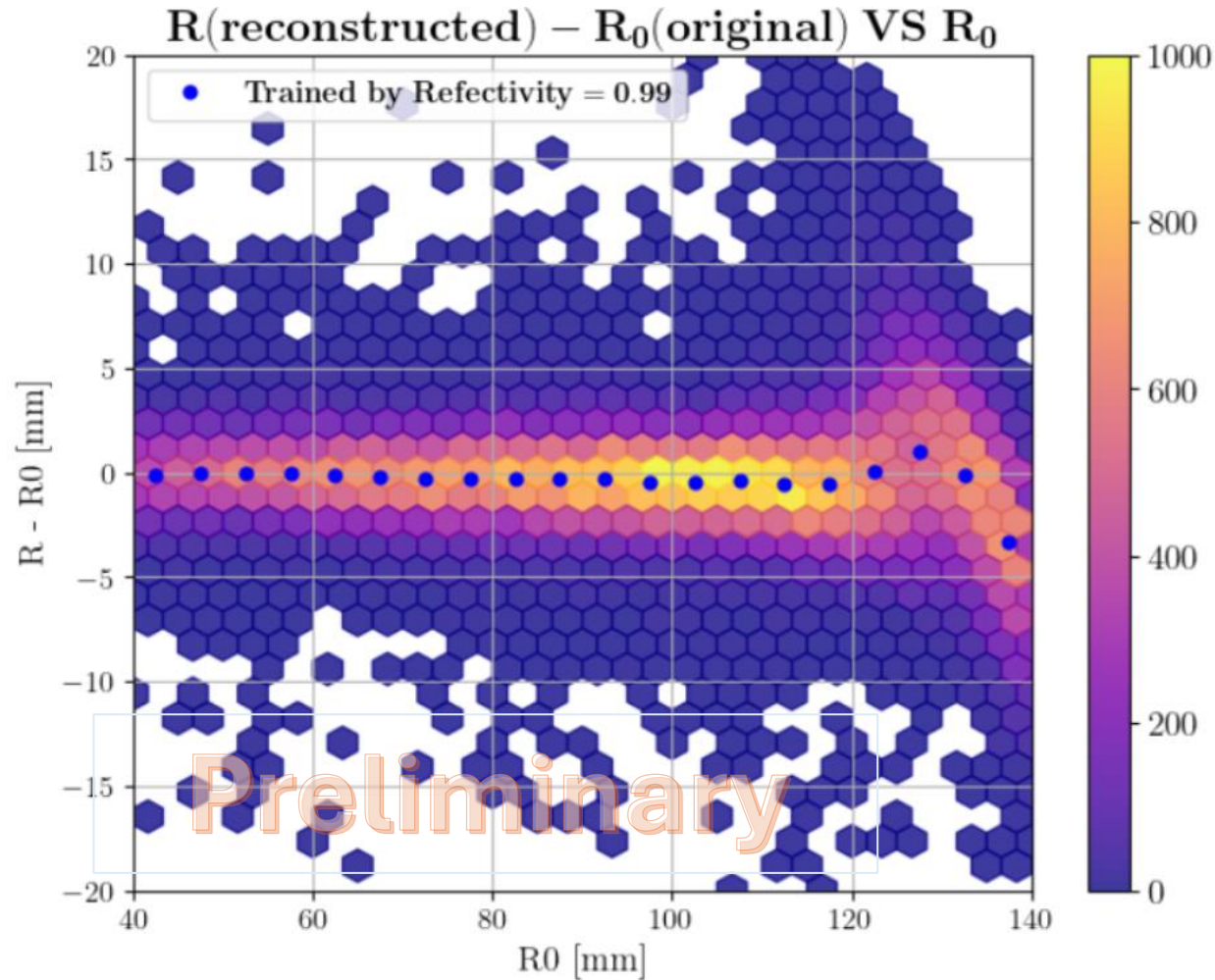


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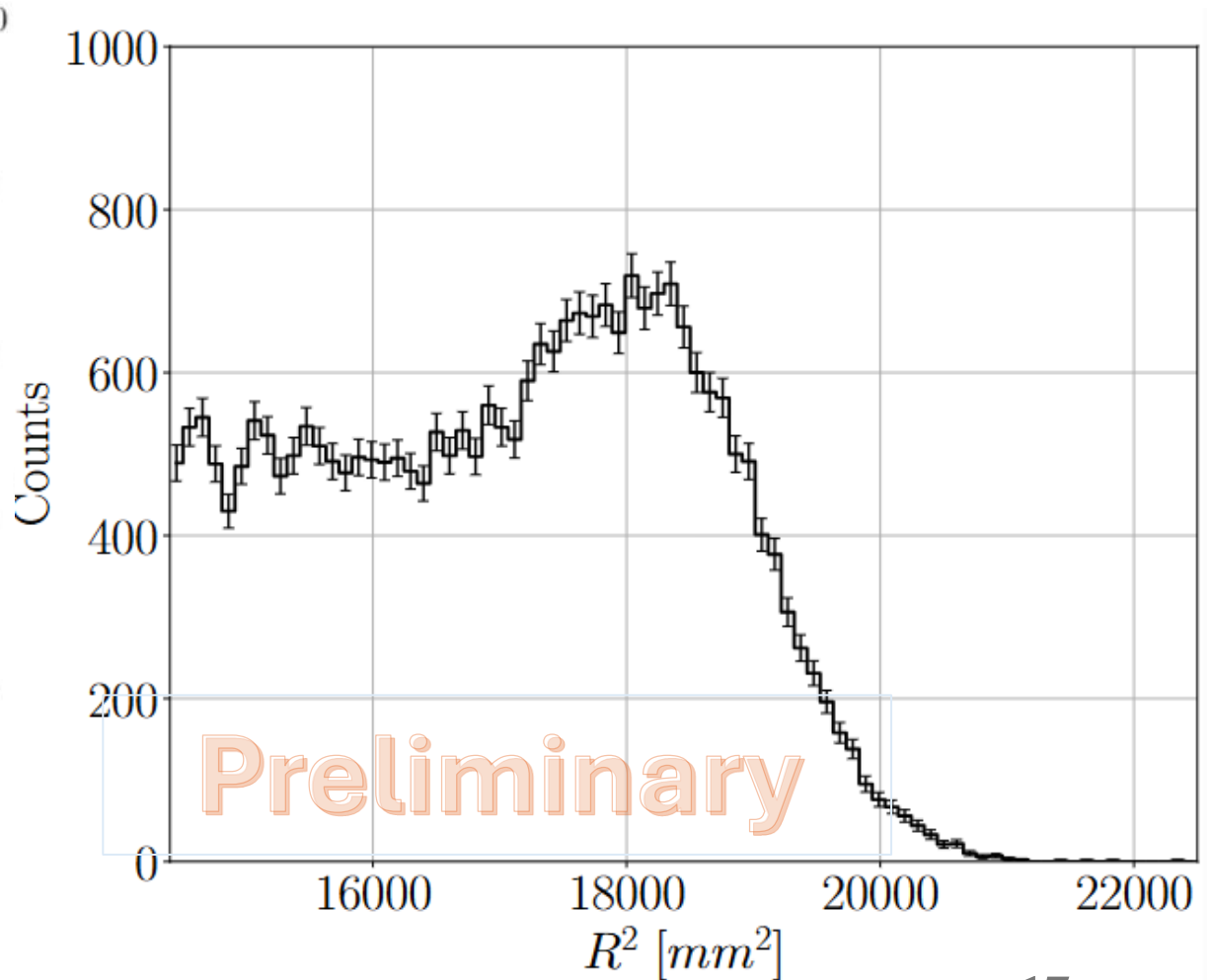
**Thank you
for your attention!**

Back up

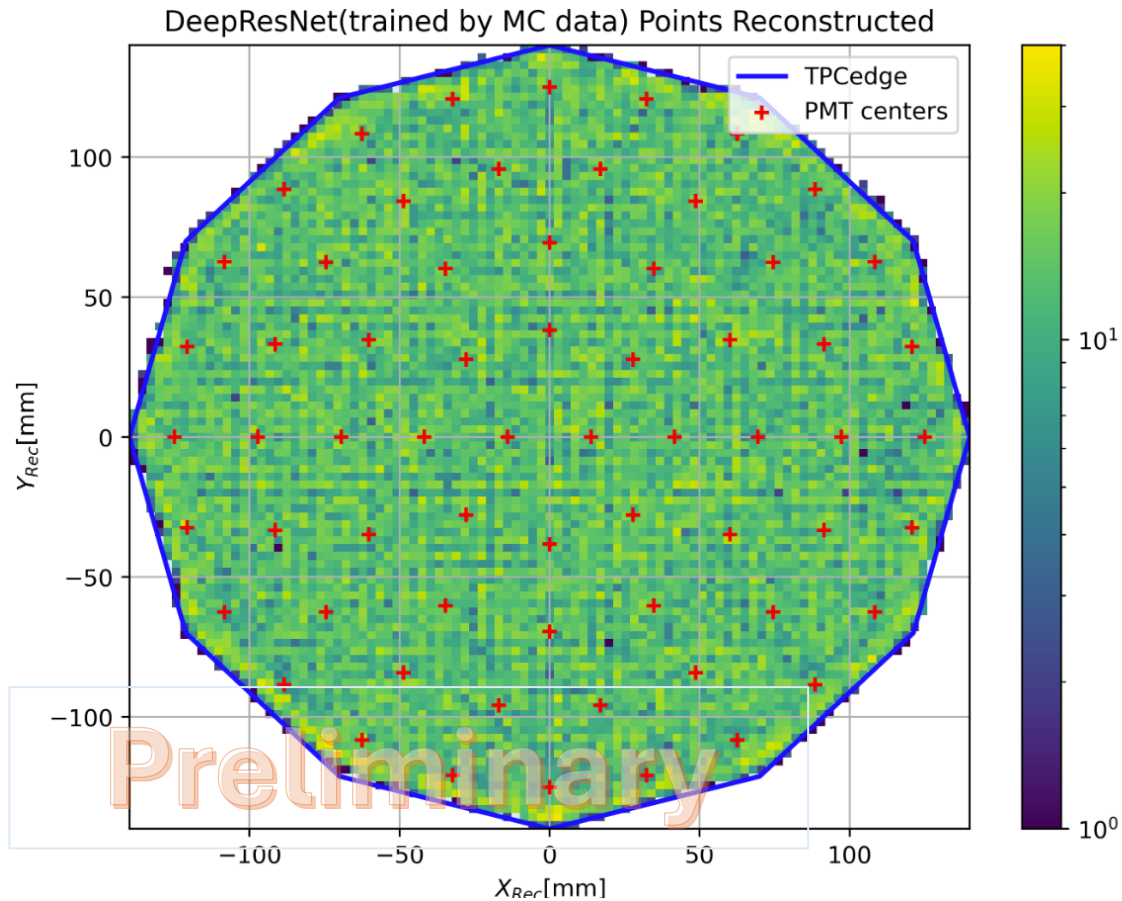
Bias



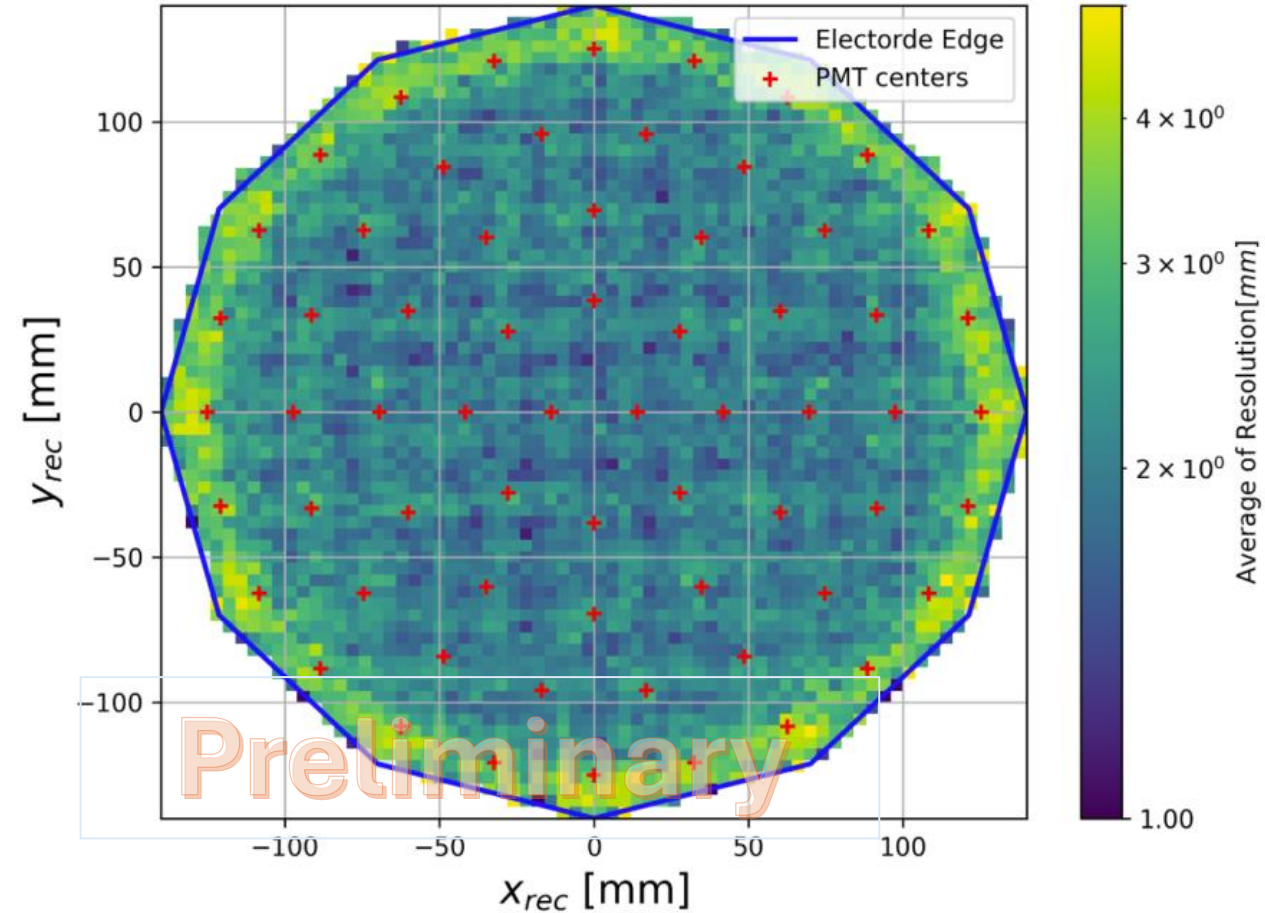
Events Reconstructed form a uniform distribution



Reconstructed from a uniform distribution

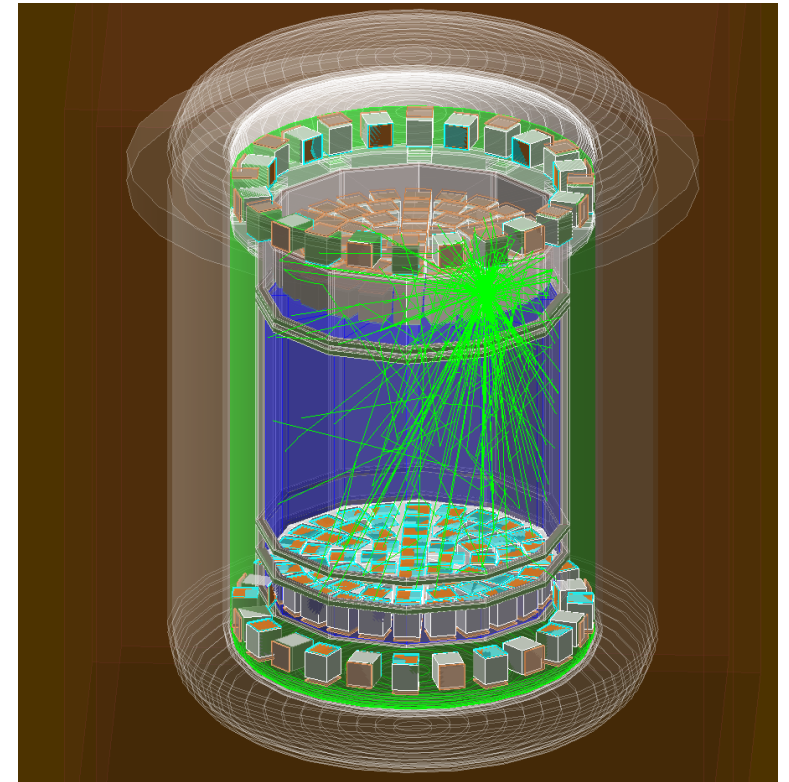
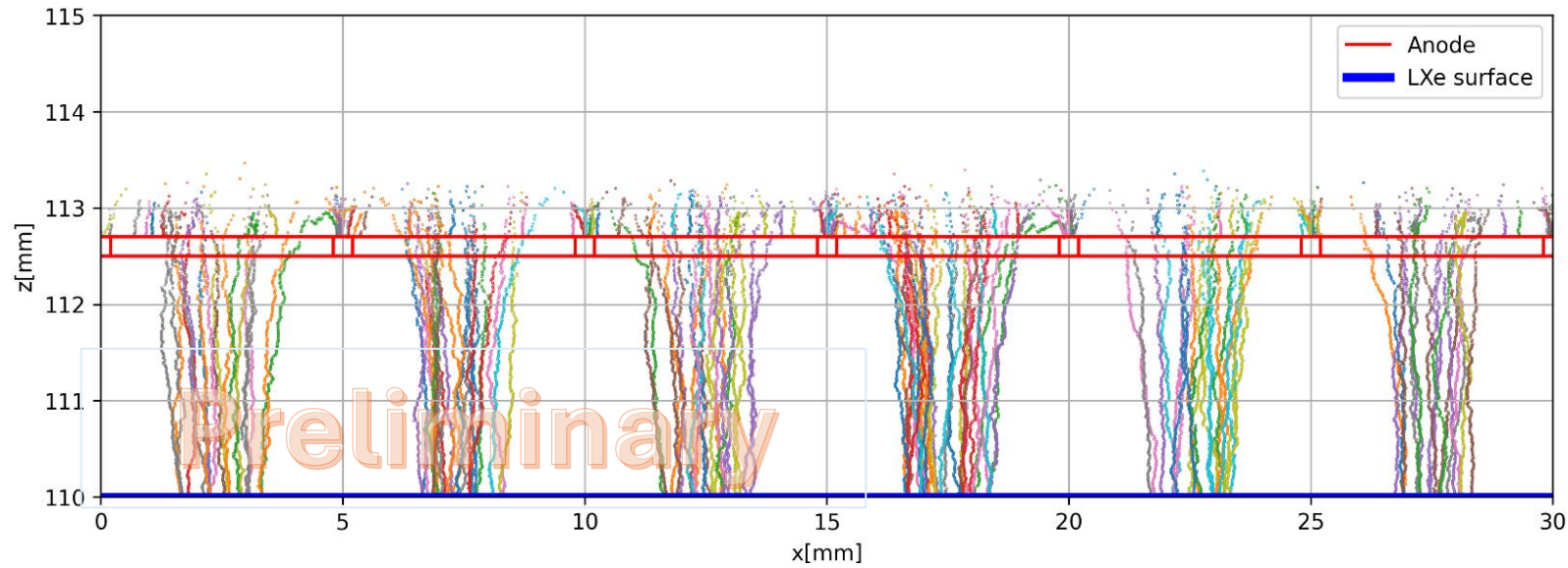


The reconstructed position distribution in the XY plane

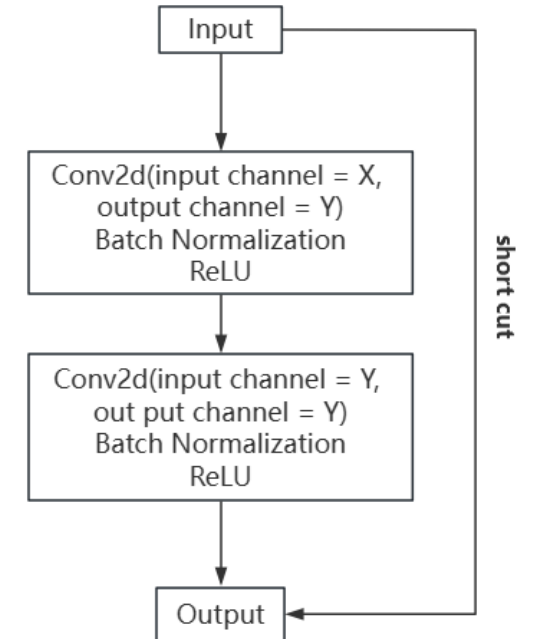
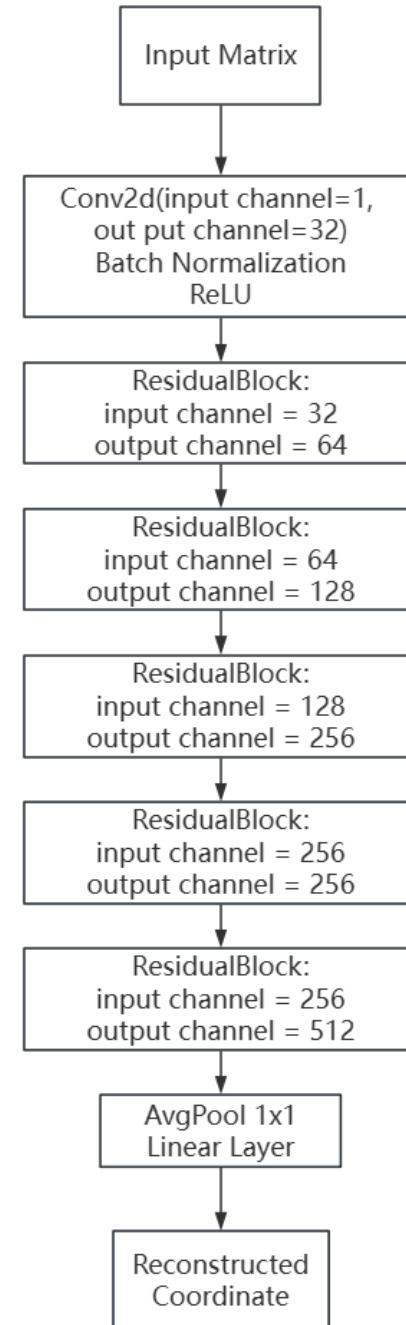
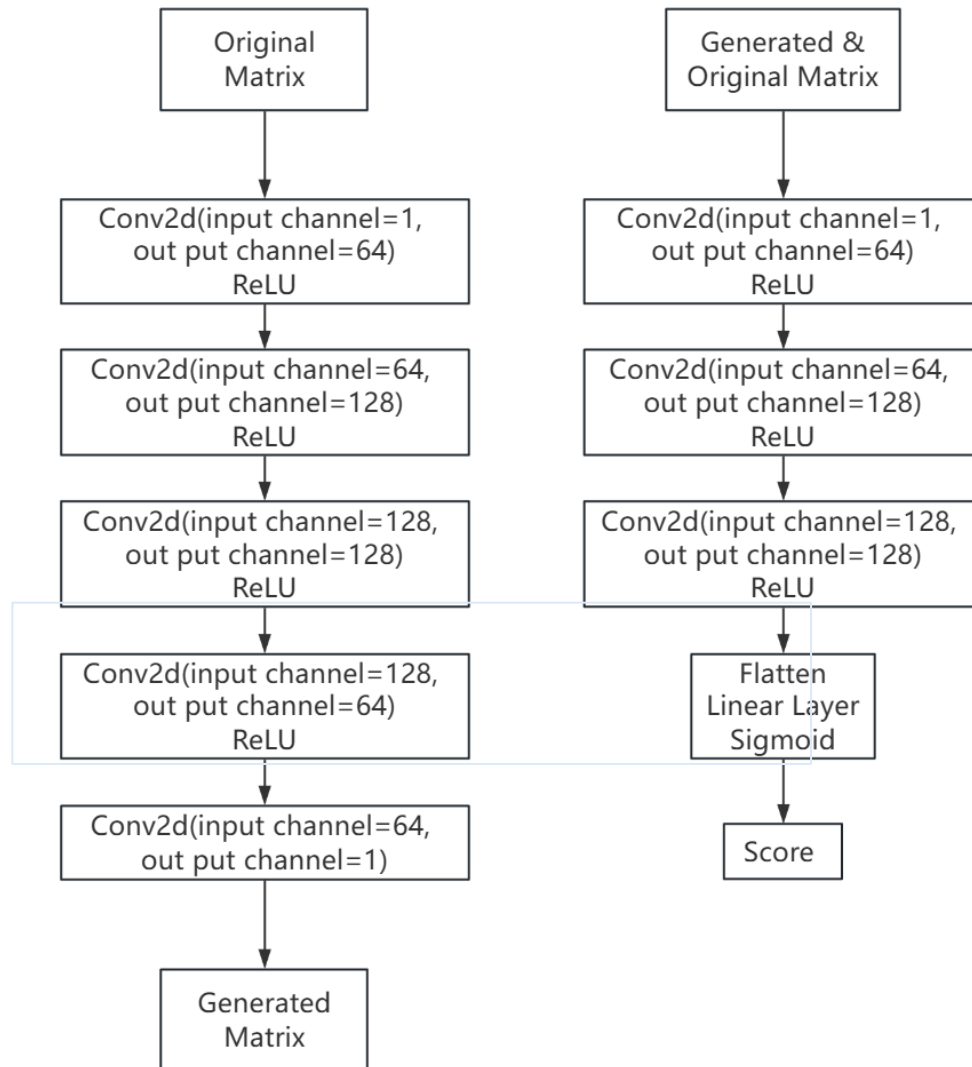


The total deviation distribution in the XY plane

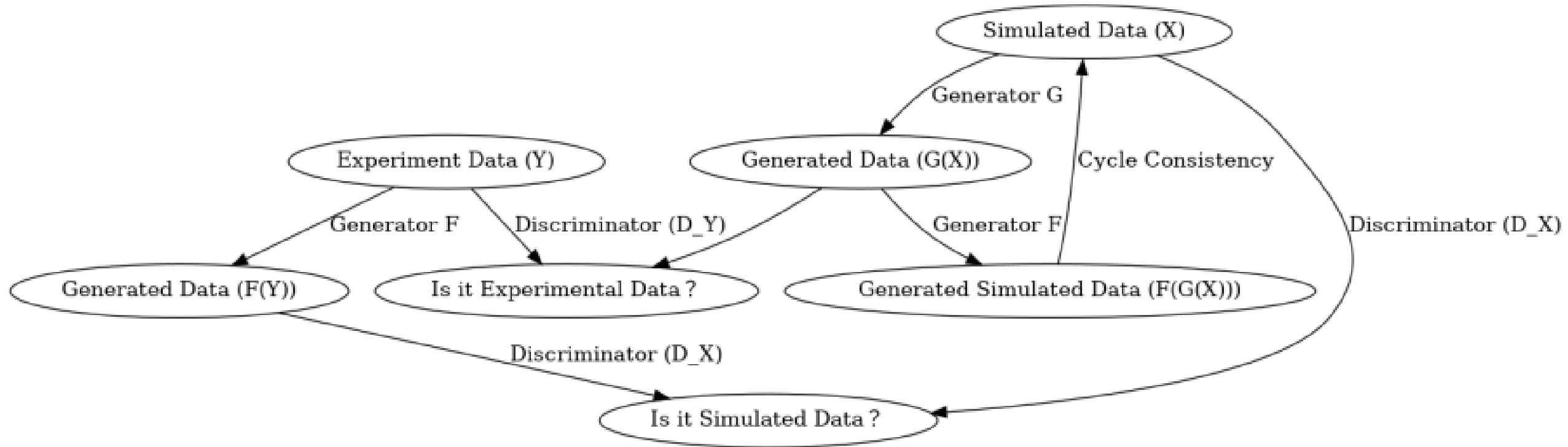
S2 simulation



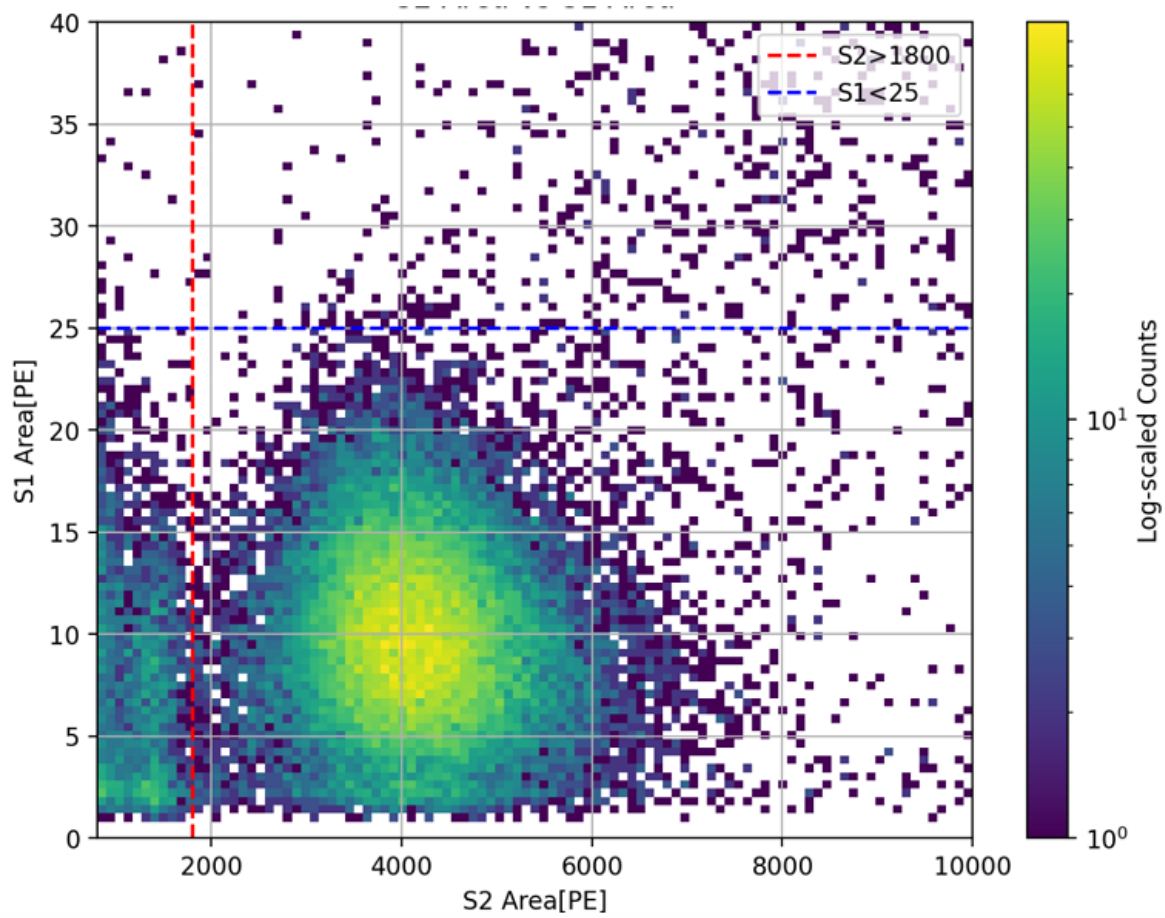
Network structure



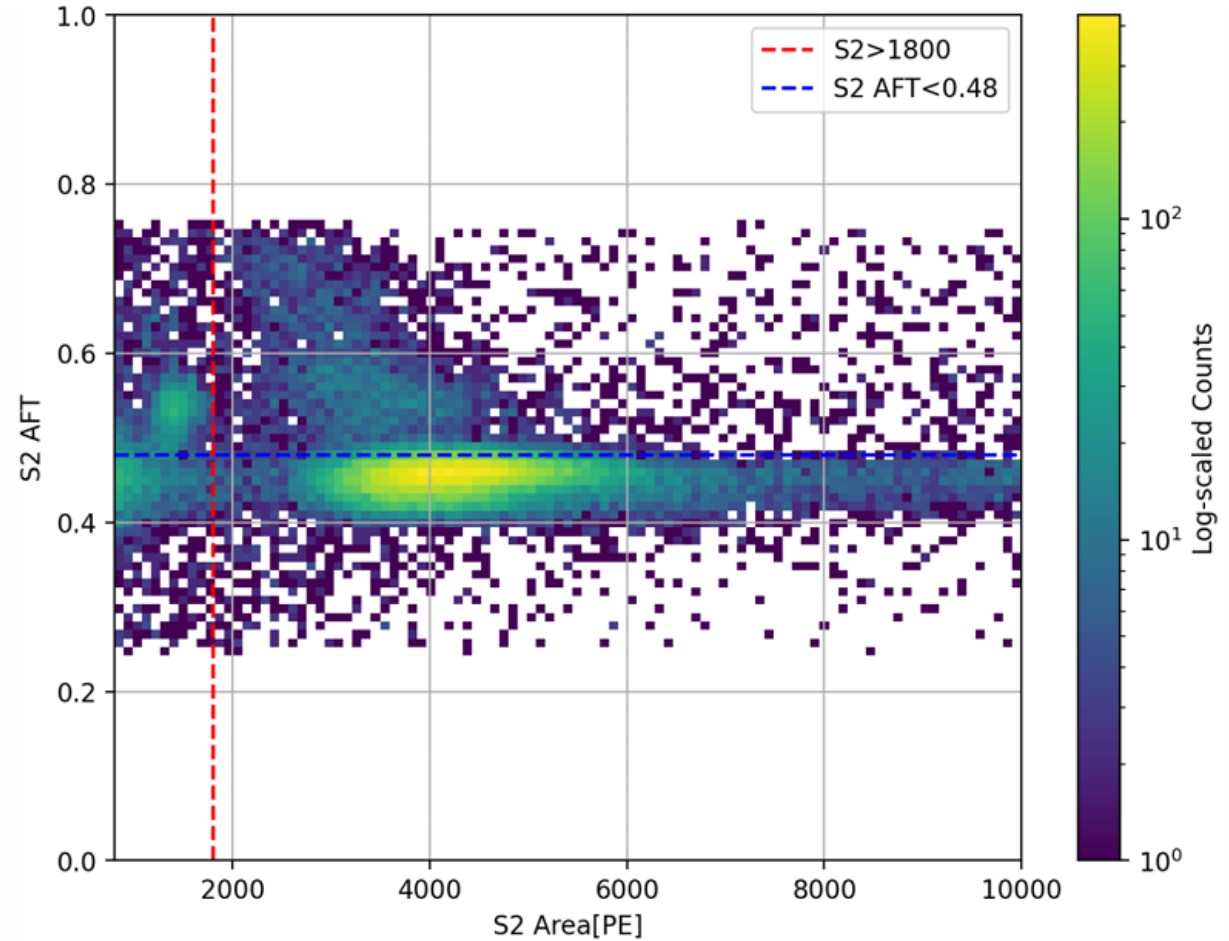
CycleGAN



Ar37 Events



S1 VS S2

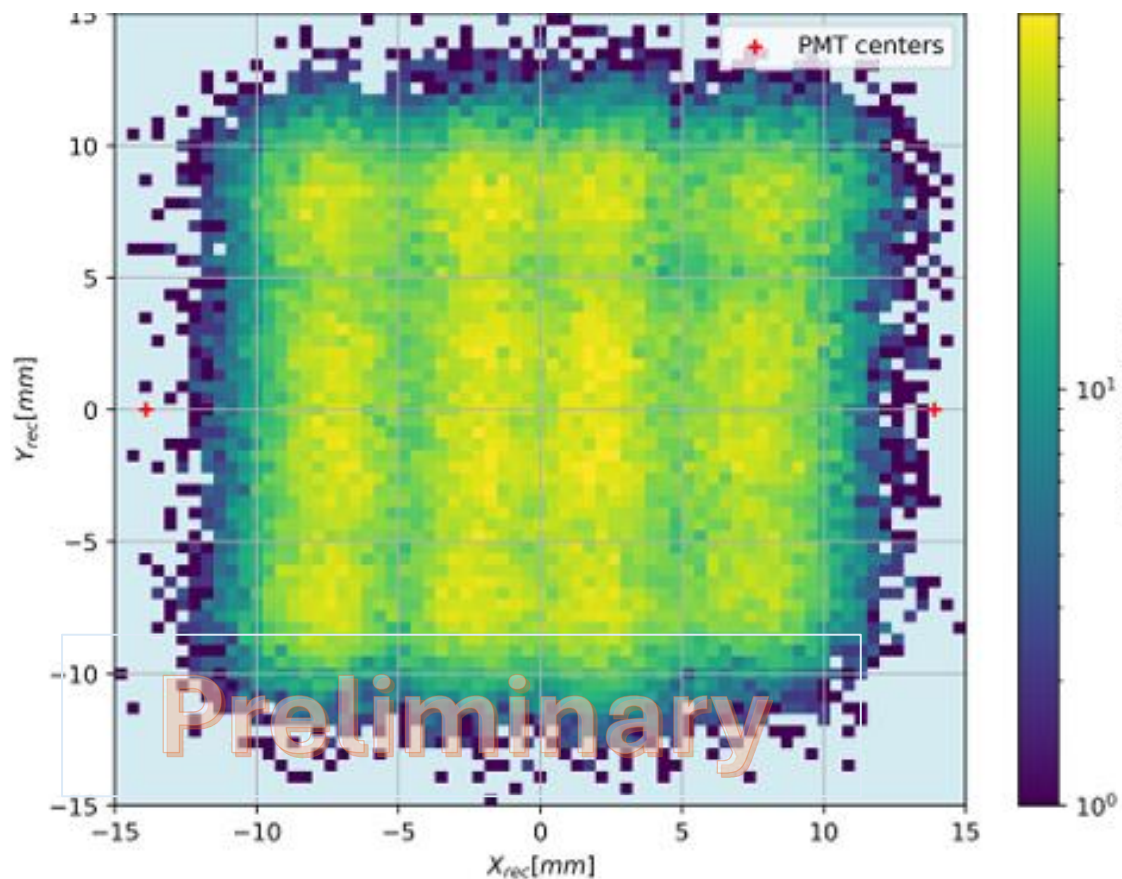


S2 AFT VS S2 Area

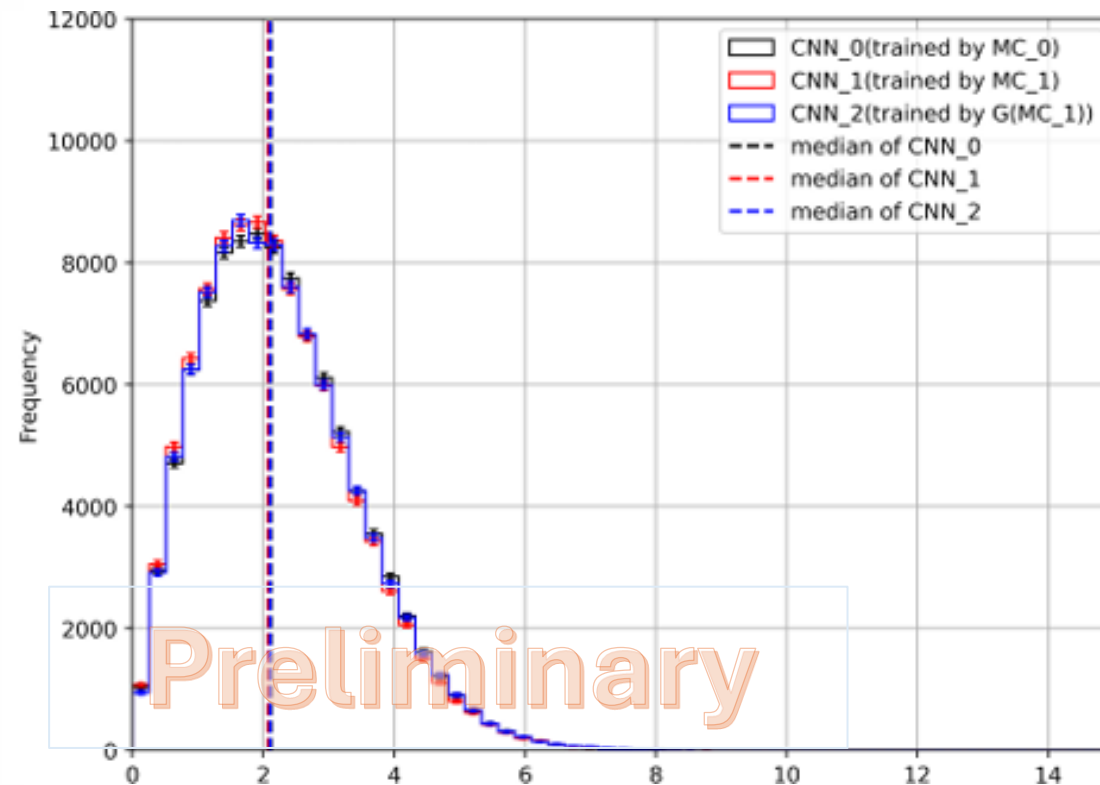
RELICS TPC (center area)

The total deviation is calculated by:

$$|\vec{R} - \vec{R}_0| = \sqrt{(x_{rec} - x_{true})^2 + (y_{rec} - y_{true})^2}$$



Distribution of reconstructed events



Distribution of total deviation

Space-time Correlation

$$C_{Space-time} = \log \left(\sum_i P_i \right)$$

- **Muon tracks** and **DEs**:

Strongly correlated in: (\mathbf{x}, \mathbf{y}) and \mathbf{t} (emission time)

PDF of DEs:

$$P_i = N_i \times (t - t_i)^{-\gamma} \times \frac{1}{2\pi \cdot \sigma^2} e^{-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma^2}}$$

Assumed : power law

LUX: <https://arxiv.org/abs/2004.07791>

Distribution considered as Gaussian

σ is the resolution of Reconstructed Position

Pile-up DEs and CEvNS

$$P = \sum_{ch=0}^{63} \log \left(\frac{\lambda_{ch}^{N_{ch}^{pe}} \times e^{-\lambda_{ch}}}{N_{ch}^{pe}!} \right)$$

$$P_i = N_i \times (t - t_i)^{-\gamma} \times \frac{1}{2\pi \cdot \sigma^2} e^{-\frac{(x-x_i)^2 + (y-y_i)^2}{2\sigma^2}}$$

$$C_{Space-time} = \log \left(\sum_i P_i \right)$$

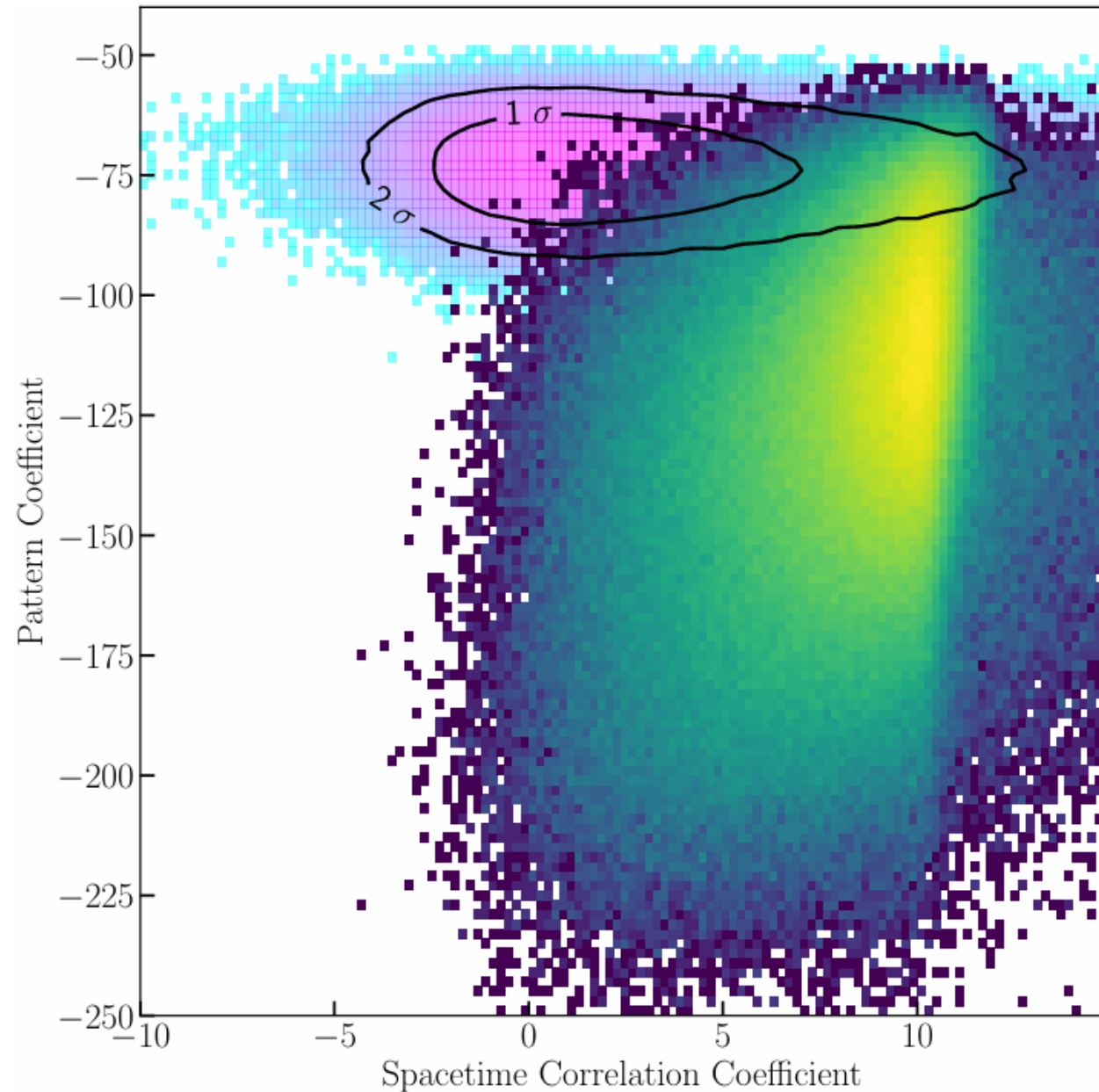
$$Score = P - (k_{st} \cdot C_{space-time}) + k_{area} \cdot S2_{area} + b$$

CEvNS within ROI

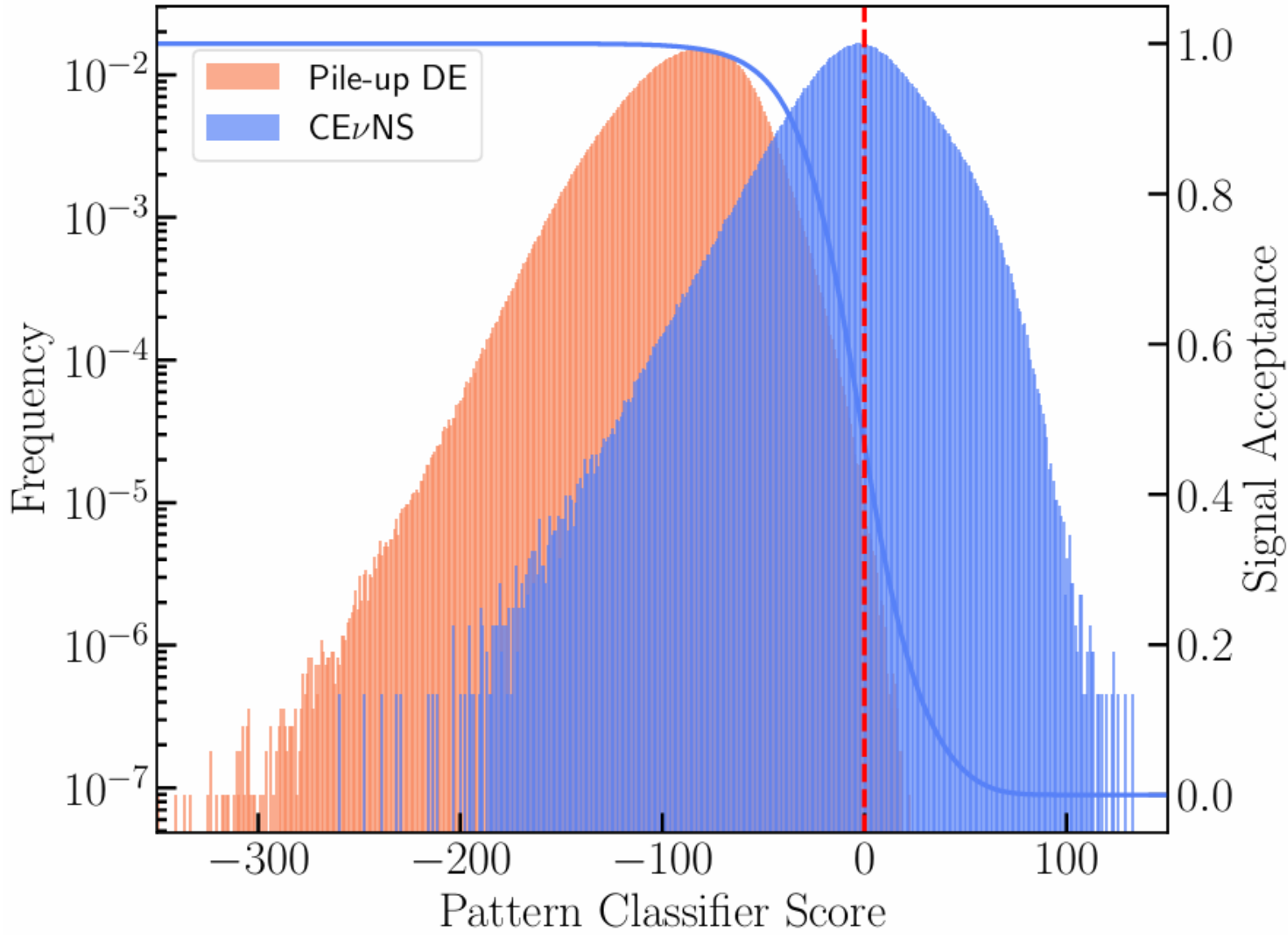
46.5% (scores over 0)

Pile up DEs within ROI

0.005%



Score the events



Distribution of scores
from pattern classifier
Survival rate:

CEνNS within ROI
46.5% (scores over 0)

Pile up DEs within ROI
0.005%