Development of Position Reconstruction in the LUX-ZEPLIN Outer Detector

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LUX-ZEPLIN

- LUX-ZEPLIN (LZ) is the world's most sensitive direct dark matter detection experiment, aiming to discover Weakly Interacting Massive Particles (WIMPs).

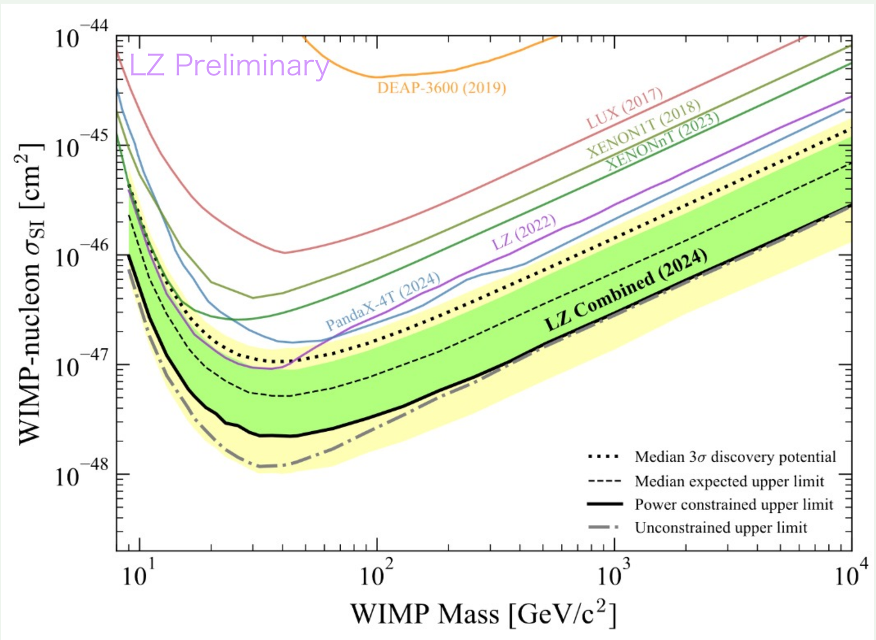

Figure 1: Combined WS2022 + WS2024 power constrained sensitivity limit (black line) for spin-independent WIMP cross-sections vs WIMP mass. The 1σ and 2σ sensitivity bands are shown in green and yellow. [1, 2]

- LZ utilises:
  - Dual-phase liquid Xe (LXe) time projection chamber (TPC).
  - LXe skin veto detector.
  - Gd-loaded liquid scintillator (GdLS) outer detector (OD).

Time Projection Chamber

- 7t of liquid xenon (LXe), gas phase with 8mm of gaseous xenon (GXe).
- Primary scintillation (S1) and ionisation e⁻'s produced by interactions with LXe.
- Secondary scintillation (S2) signal from electroluminescence.

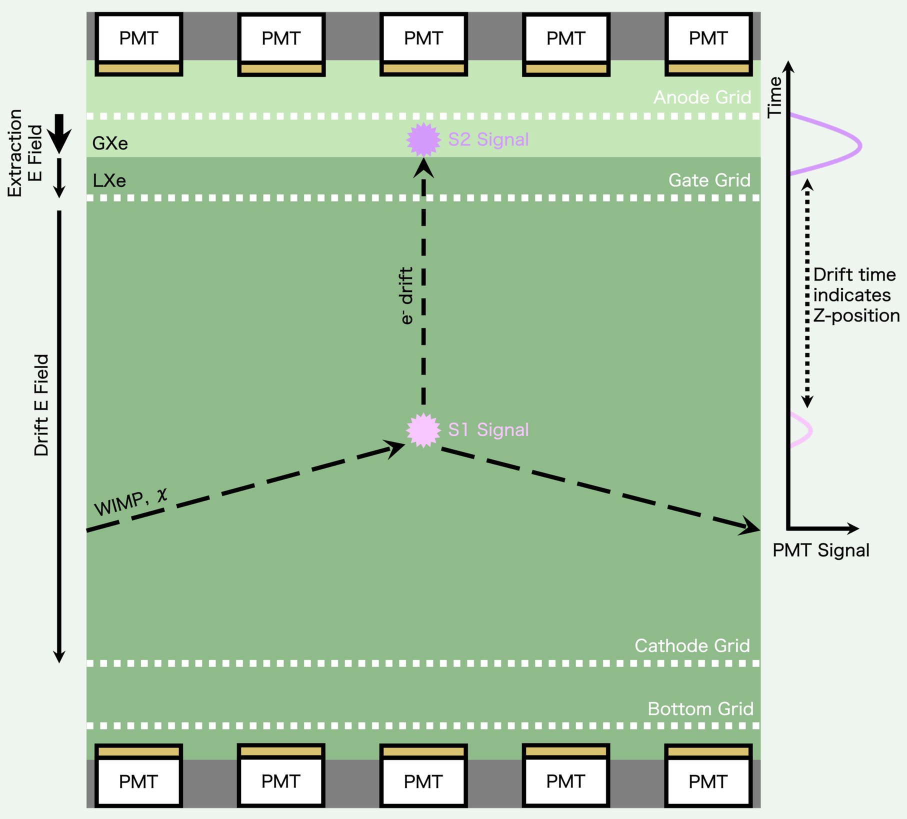

Figure 2: Schematic Diagram of the LZ TPC.

- Particle discrimination – S1:log(S2).
- 3D position reconstruction:
  - (X,Y) from S2 hit pattern.
  - Z from drift time.

Outer Detector

- 17t of GdLS across 10 tanks of varying geometry.
- Cylindrical array of 120 PMTs. [3]
- Primary focus:
  - Veto single scatter neutrons with an efficiency of 89±3%.
  - Characterise the neutron background.

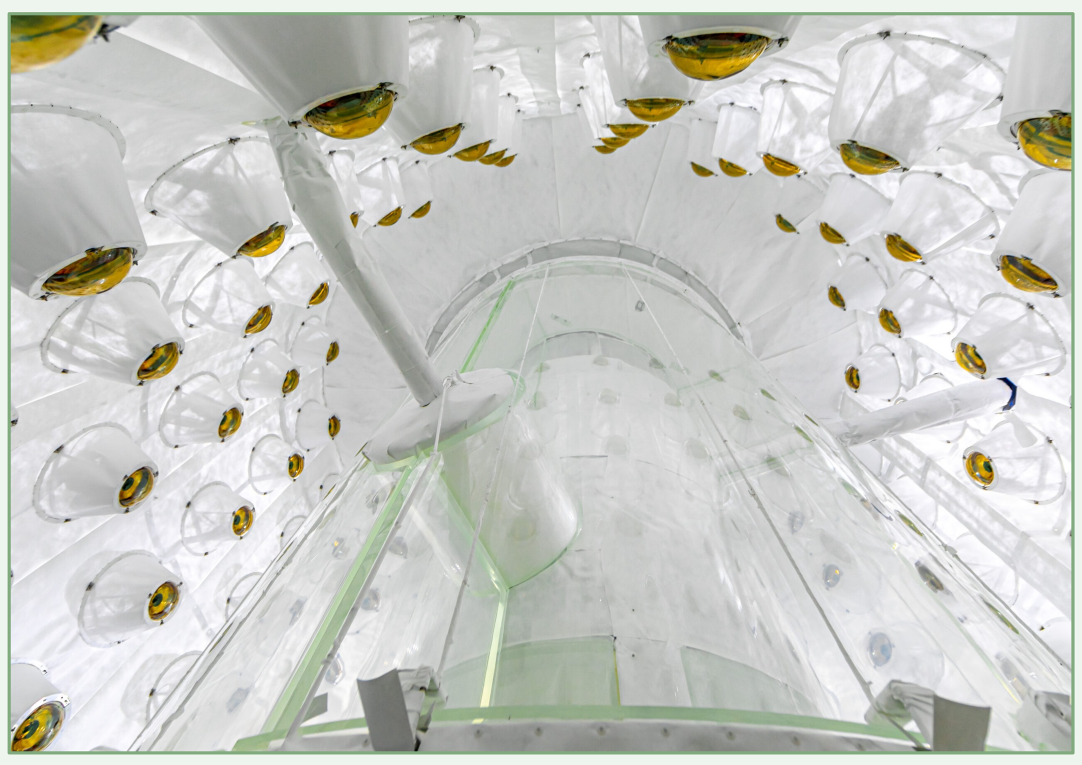

Figure 3: Fully assembled LUX-ZEPLIN Outer Detector

Outer Detector Position Reconstruction

- Current OD position reconstruction uses a centre of gravity (CoG) method.
  - Positions are being largely mis-reconstructed.
- Motivation:
  - Additional quantities for background discrimination.
  - Light collection efficiency mapping.
  - Equivalent energy thresholds.
  - Reduced neutron veto dead-time.
- A **machine learning approach** has been investigated, utilising **convolutional neural network (CNN)** algorithms.

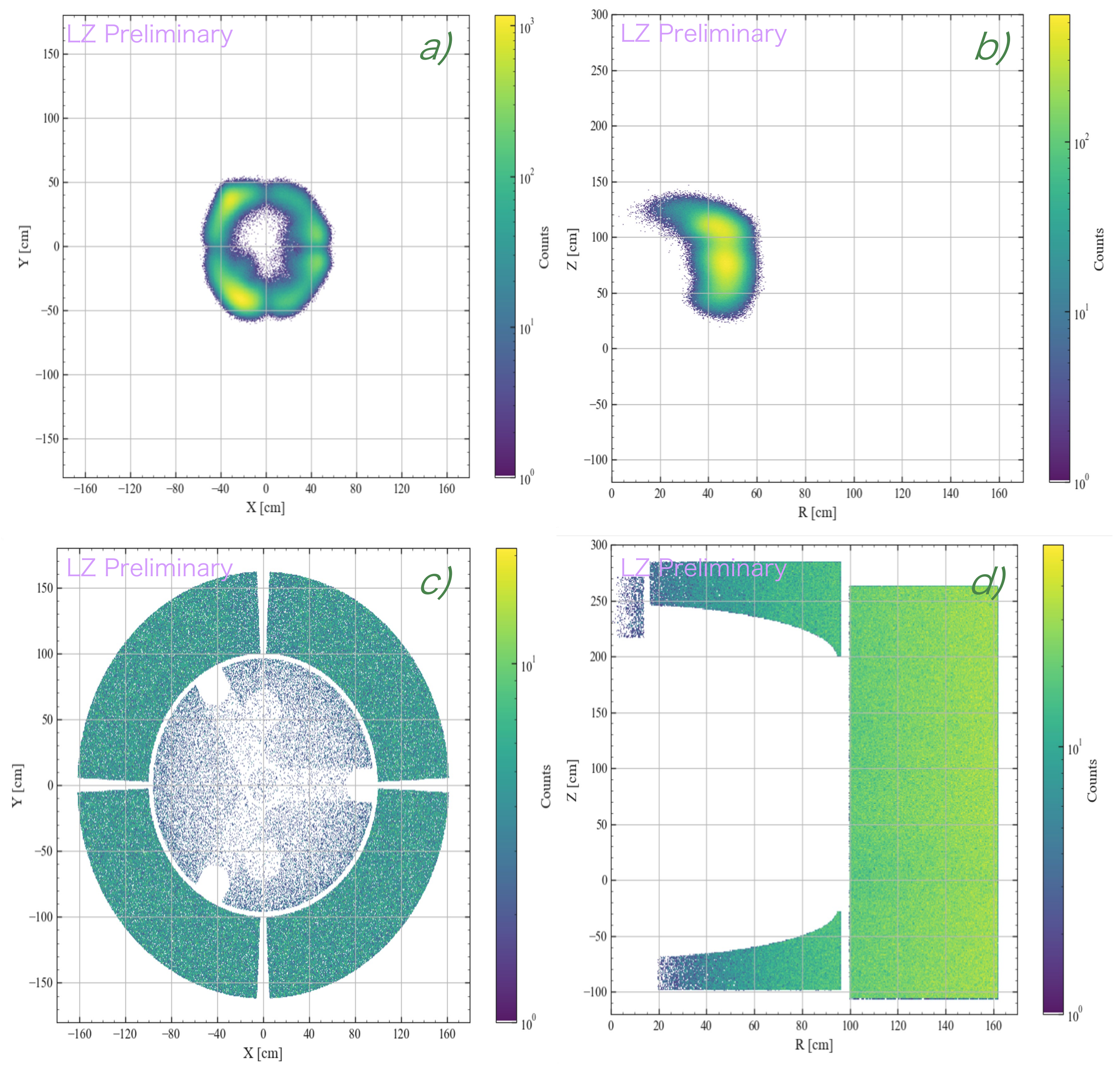

*Figure 4: Event positions in XY (left) and RZ (right) from **a,b)** preWS2024 ²²⁸Th calibration data using CoG method, **c,d)** photon bomb simulations using truth positions.*

Convolutional Neural Networks

- CNN designed to make predictions of event positions in (R, θ, Z) within the OD scintillator tanks.
- Two channel input.
  - OD PMT pulse areas.
  - OD PMT pulse timings.

$$\text{Timing} = \text{Time}_{\text{Channel Peak}} - \text{Time}_{5\%\ \text{Area Fraction}}$$

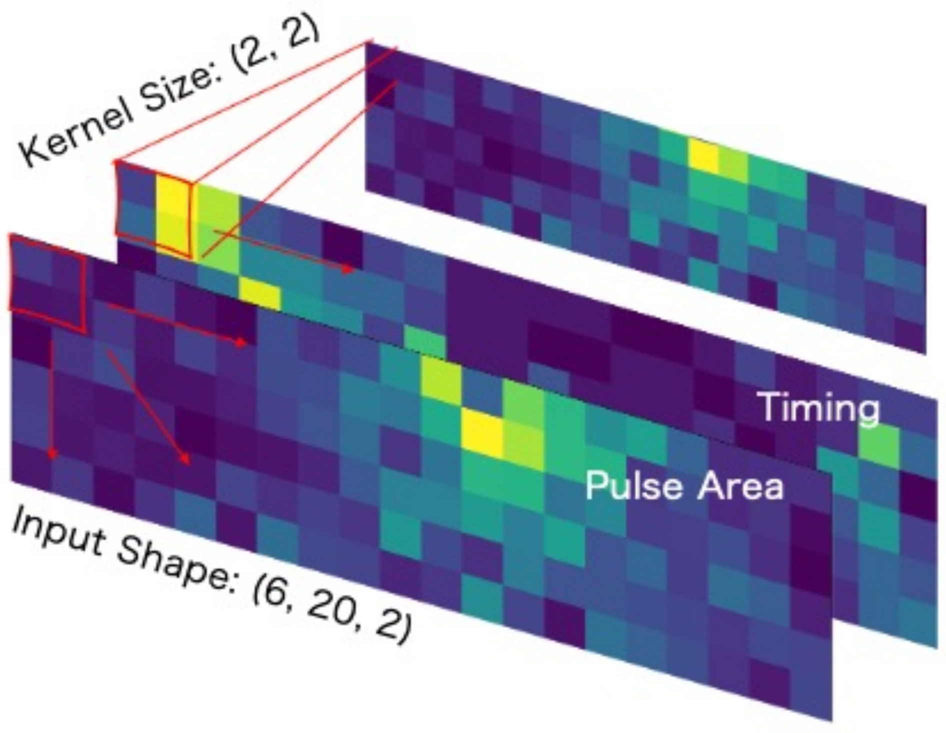

Figure 5: Schematic diagram of CNN. Channel 1 is the PMT pulse area, channel 2 is the respective PMT pulse timing information.

- Custom loss function:

$$\text{Loss} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{|\Delta R_i|}{\sigma_R} + \frac{|\Delta\theta_i|}{\sigma_\theta}P_{\theta,i} + \frac{|\Delta Z_i|}{\sigma_Z}\right)$$

$$P_{\theta,i} = \begin{cases} 1 \text{ if } \theta_{pred,i} \in [-\pi, +\pi] \\ \dfrac{\theta_{pred} - \pi}{\pi} + 1 \text{ if } \theta_{pred,i} \notin [-\pi, +\pi] \end{cases}$$

  - N is the number of samples in a batch.
  - $\Delta y_i = y_{true,i} - y_{pred,i}$.
  - $P_{\theta,i}$ is the angular penalty.
  - σ_x is a pre-defined position resolution.
- Obtained an overall **OD scintillator tank (R, θ, Z) position resolution** of (8.35 cm, 0.16 rad, 12.89cm)

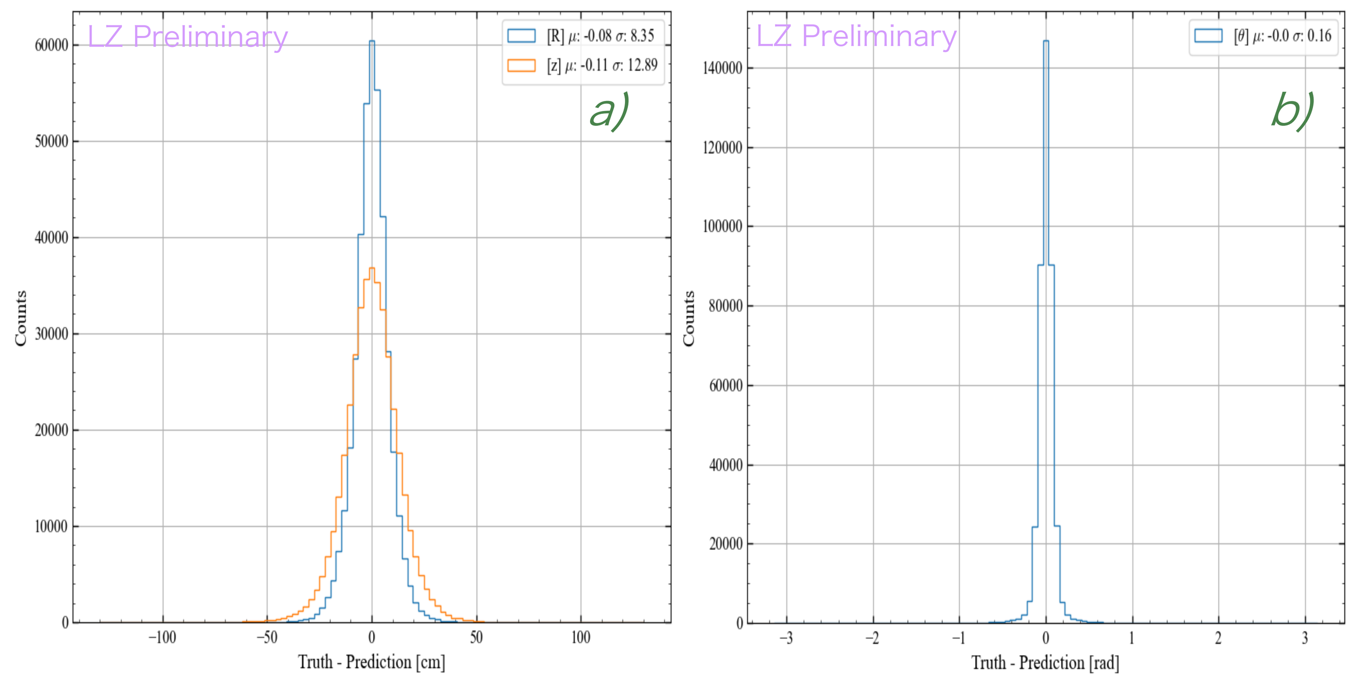

*Figure 6: Plotted differences between the truth and model predicted event positions in **a)** R (blue) and Z (orange), and in **b)** Theta θ (blue). μ is the mean, and σ is the standard deviation describing the position resolution across the LZ outer detector.*

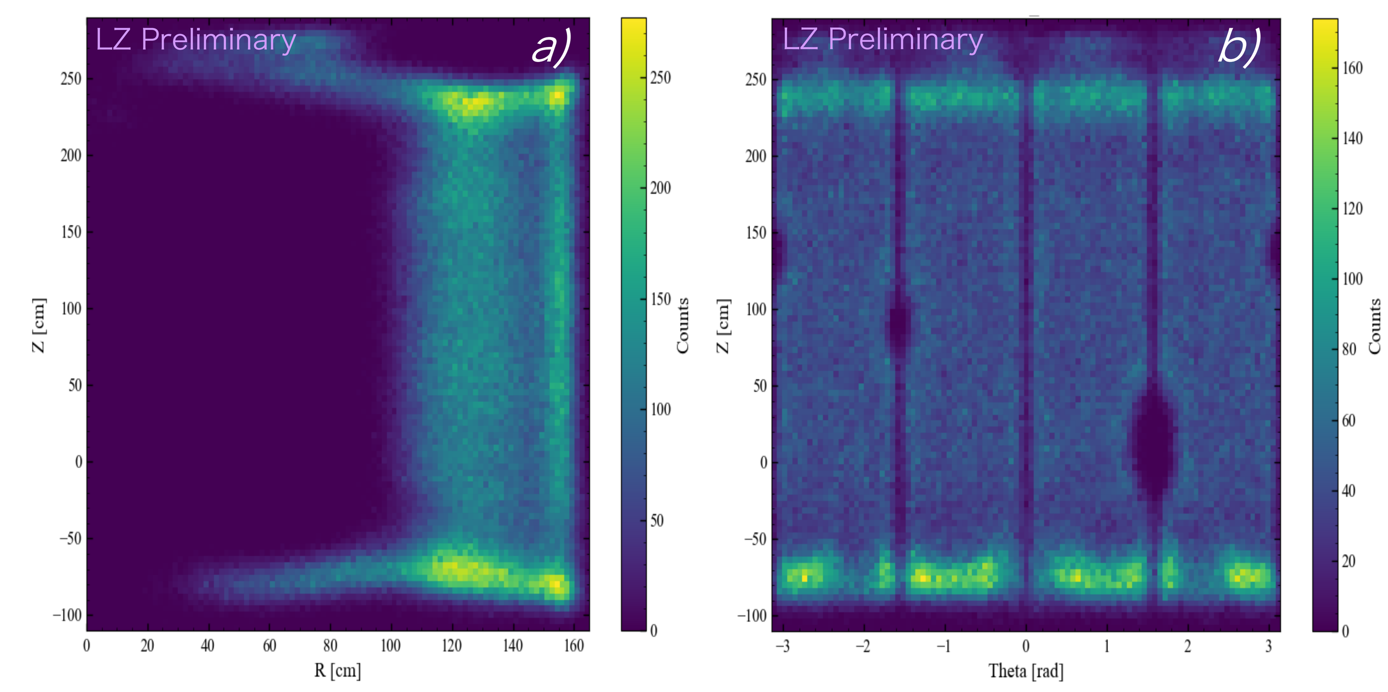

*Figure 7: CNN model predicted positions in **a)** RZ space and **b)** θZ space.*

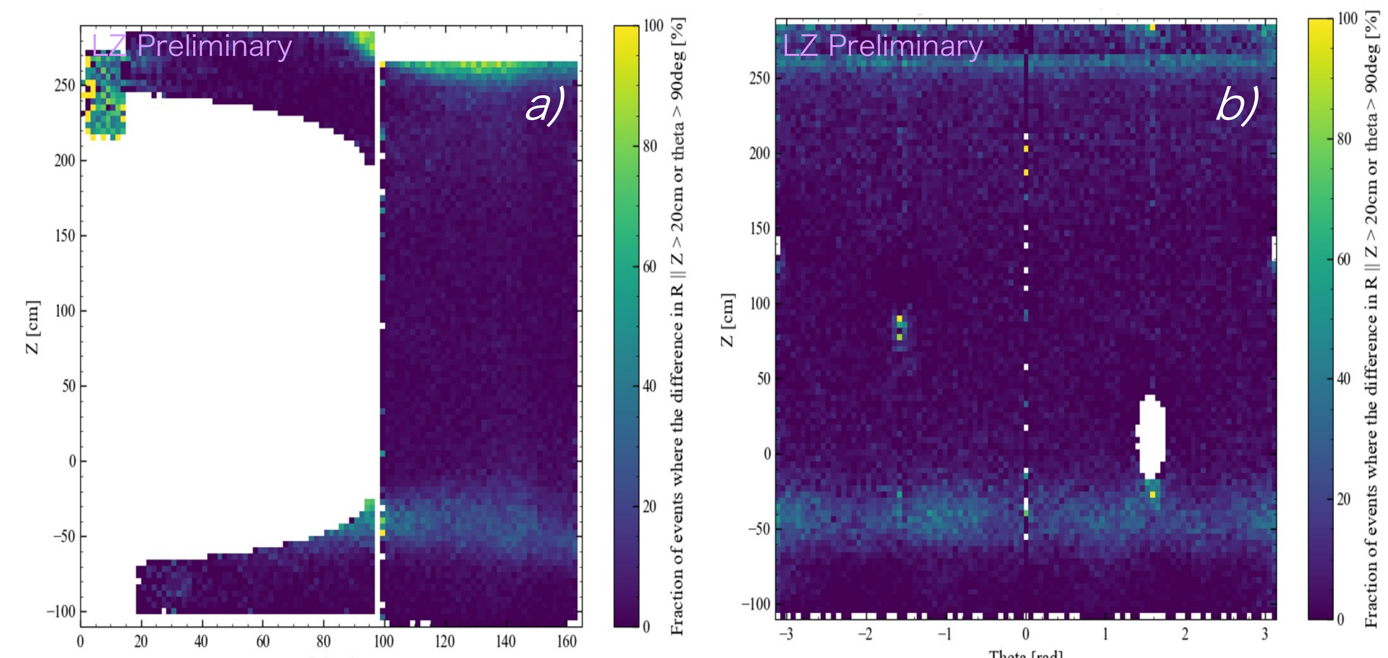

*Figure 8: Fraction of events at their truth position which differ from their corresponding model predicted position by greater than 20cm or 90 degrees (π/2 rad) in **a)** RZ space and in **b)** θZ space. These indicate regions of poor model predictions within the OD.*

Future Work

- Expand training data provided to the CNN.
  - Flat OD gamma simulations.
  - Calibration data.
- Add a fourth output, (R, θ, Z) → (R, θ, Z, E).
  - Energy dependent component loss denominators.

References

1. A. Cottle. 2024. *"New Dark Matter Results from the LUX-ZEPLIN Experiment"*. LIDINE 2024. Sao Paolo, Brazil.
2. S. Haselschwardt. 2024. "*New Dark Matter Results from the LUX-ZEPLIN Experiment*". TeVPA 2024. Chicago, USA.
3. B. J. Mount. et al. 2017. "*LUX-ZEPLIN Technical Design Report*". LUX-ZEPLIN Collaboration. arXiv:1703.09144