The LUX-ZEPLIN Outer Detector: Performance and Position Reconstruction with Machine Learning Algorithms

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LUX-ZEPLIN (LZ)

Dark matter direct-detection experiment

- Aiming to detect Weakly Interacting Massive Particles (WIMPs)

7t dual phase LXe time projection chamber (TPC)

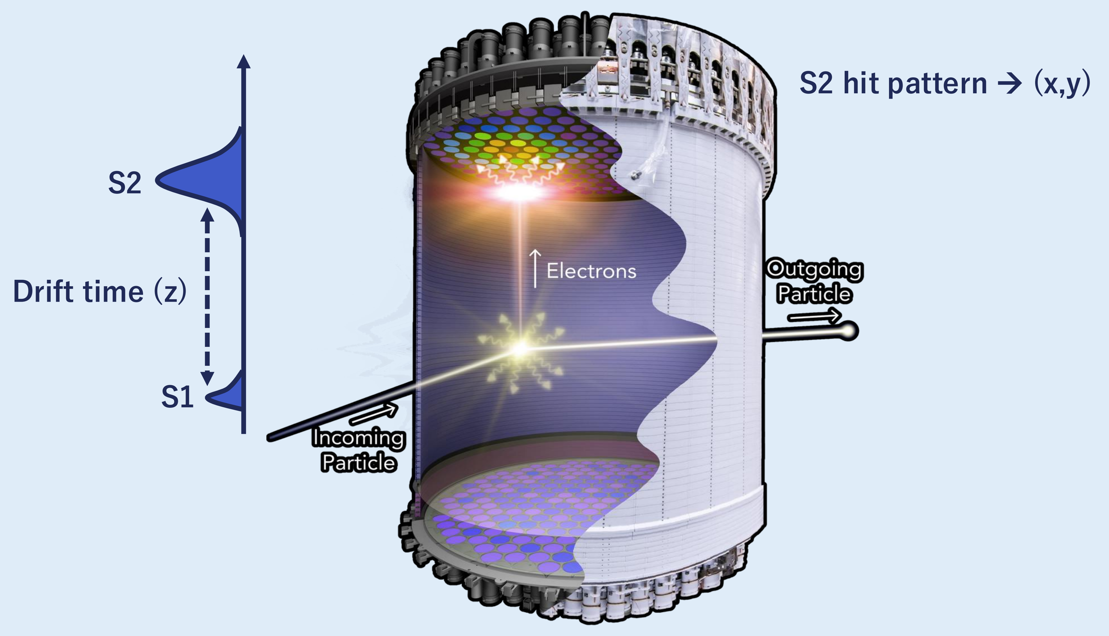


Figure 1: Schematic of a particle interacting in the LZ TPC

Two observable signals per interaction

- Prompt scintillation (S1)
- Delayed electroluminescence from extracted electrons (S2)

S2/S1 → interaction type

- Small ratio – nuclear recoil (NR) e.g. WIMPs, neutrons
- Large ratio – electron recoil (ER) e.g. β, γ-rays

LZ Outer Detector

The **Outer Detector (OD)** surrounds the TPC, enabling the tagging and vetoing of neutrons

OD comprised of 10 segmented UV-transparent acrylic tanks [1]

- 17t Gd-loaded liquid scintillator (GdLS)
- Surrounding tank of 228t of ultra-pure water
- 120 8" Hamamatsu R5912 PMTs

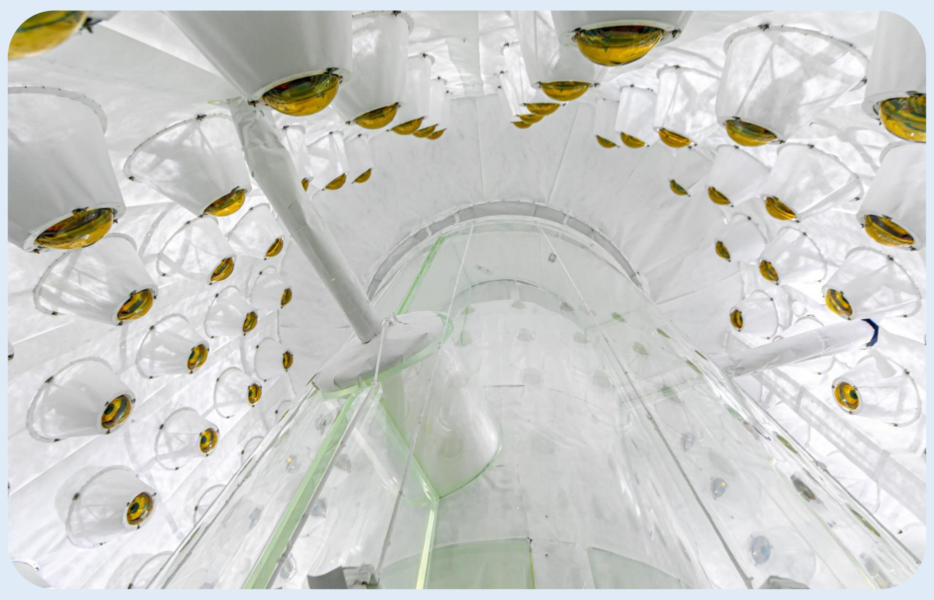


Figure 2: LZ OD pre-GdLS and water tank fill

Neutrons in the OD capture on ^{155}Gd/^{157}Gd or H

- Gd-n: 4-5 γ cascade, ΣE = 7.9 to 8.5 MeV
- H-n: single 2.2 MeV γ

Veto System Principle

Veto system operates through two OD timing windows

- Prompt window – vetoes γ-rays and proton recoils
- Delayed window – tags and vetoes neutrons captured on H/Gd

Table 1: Selection criteria for each veto window

Selection criteria	Prompt Window	Delayed Window
$\Delta t = t_{OD} - t_{S1,\,SS\,NR}$	$\pm 0.3\ \mu s$	$[0.3, 600]\ \mu s$
PMT coincidence	5	5
Pulse area	> 4.5 phd (~30 keV)	> 32 phd (200 keV)

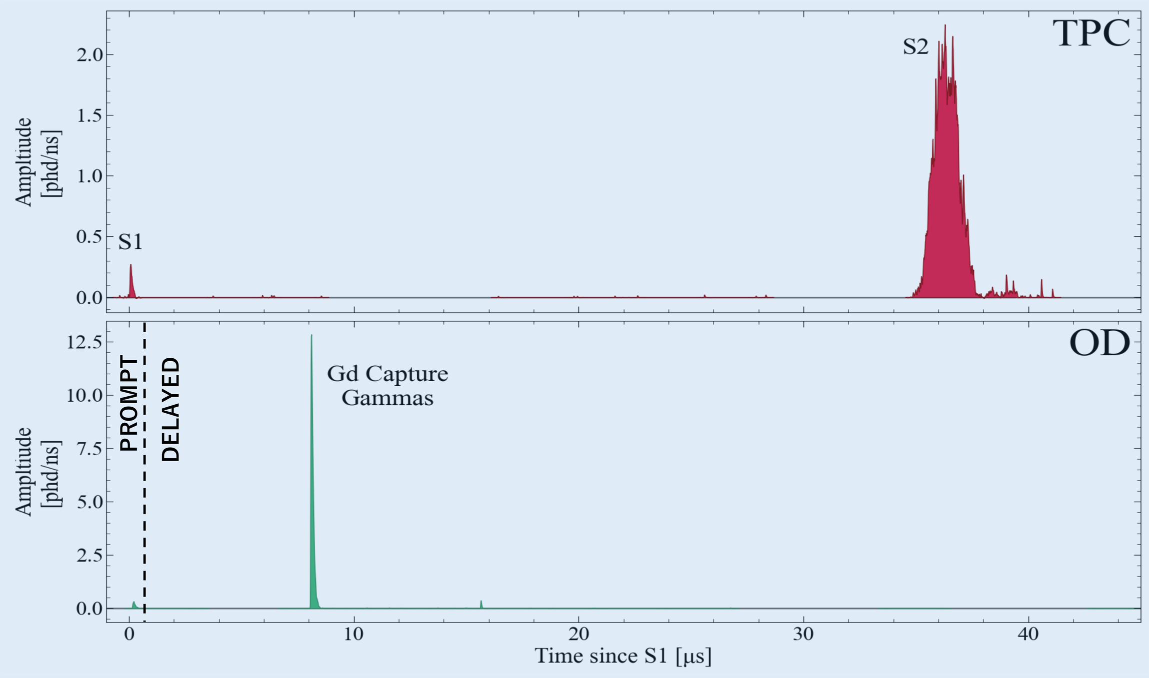


Figure 3: Coincident single scatter neutron event waveforms in TPC and OD

LZ Neutron Veto

Total OD background rate of ~43 Hz in WS2024

Neutron sources used to evaluate tagging efficiency, ε

- Deployed at fixed heights in calibration tubes
- OD pulse tagged in either veto windows

$$\varepsilon = \frac{N_{\text{Pass Cuts+Veto Tagged}}}{N_{\text{Pass Cuts}}} = 89 \pm 3\%$$

Spurious OD coincidences introduce a false-veto probability, P_{fv}

$$P_{fv} = 1 - e^{-Rt} = 2.84 \pm 0.10\%$$

where R is the background rate and t is the veto time-window

Veto-tagged data used to constrain neutron background

$0.04^{+2.43}_{-0.04}$ neutrons in skin/OD tagged sideband → provides constraint of $0.0^{+0.2}$ neutrons in WS2024 science dataset

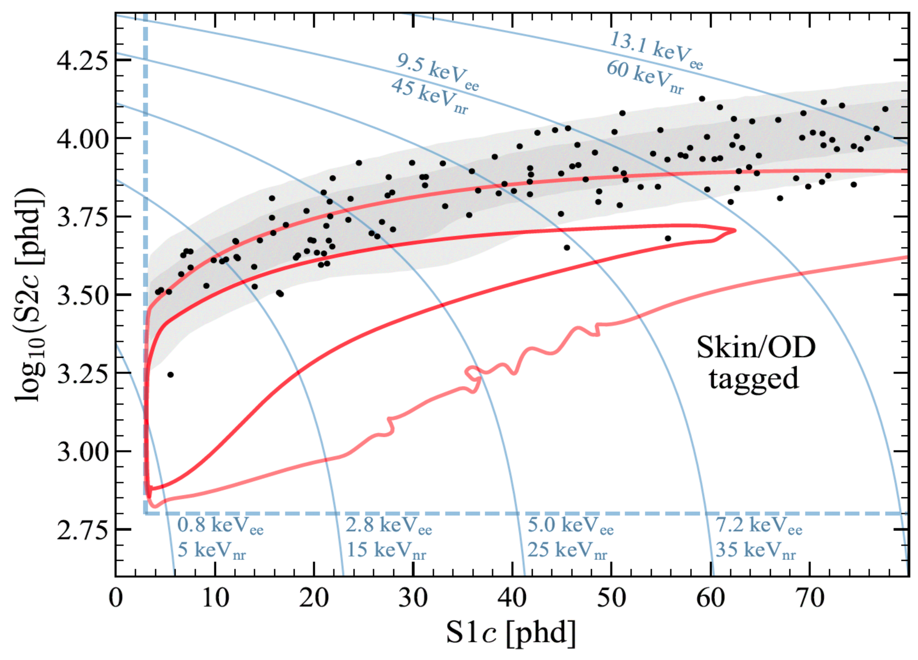
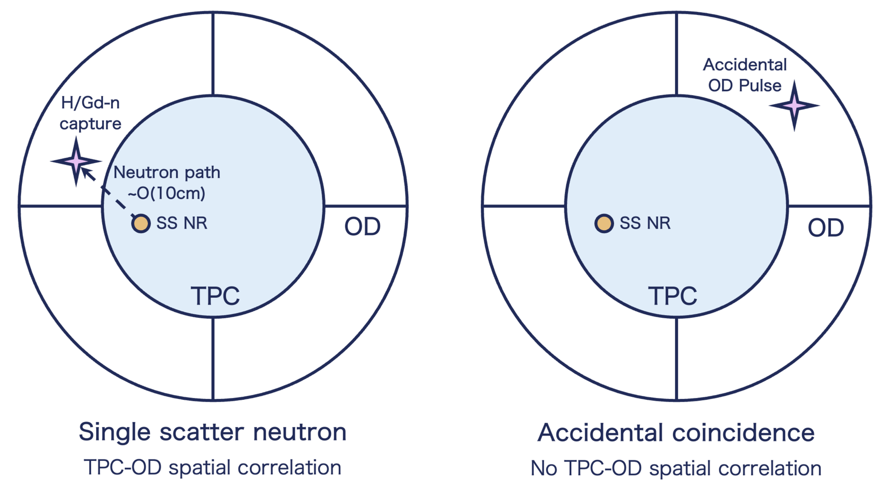


Figure 4: Veto-tagged events in WS2022+WS2024 dataset. Red contours describe regions containing 68% and 95% of tagged neutron events [2].

Delayed veto dominated by non-neutron accidentals

For a neutron, the TPC NR and OD capture are spatially correlated:



OD position reconstruction enables improved neutron tagging and accidental discrimination

Complex OD geometry limits analytical position reconstruction

→ new method developed using machine learning techniques

Outer Detector Position Reconstruction

Convolutional neural network (CNN) → **predict positions and energy deposited (R, θ, Z, E) in OD**

- Trained on full optical simulation of 0-9 MeV γ-rays in GdLS

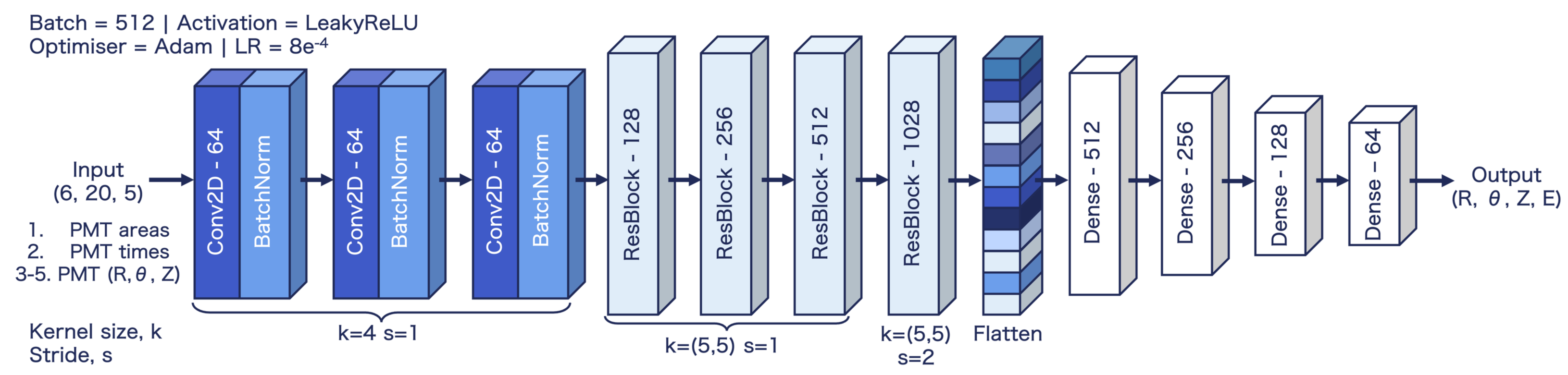


Figure 5: ResNet CNN for OD position and energy reconstruction

At E_{dep} = 2 MeV, (σ_θ, σ_Z) = (0.06 rad, 14 cm) → (1.0%, 3.6%) of OD dimensions

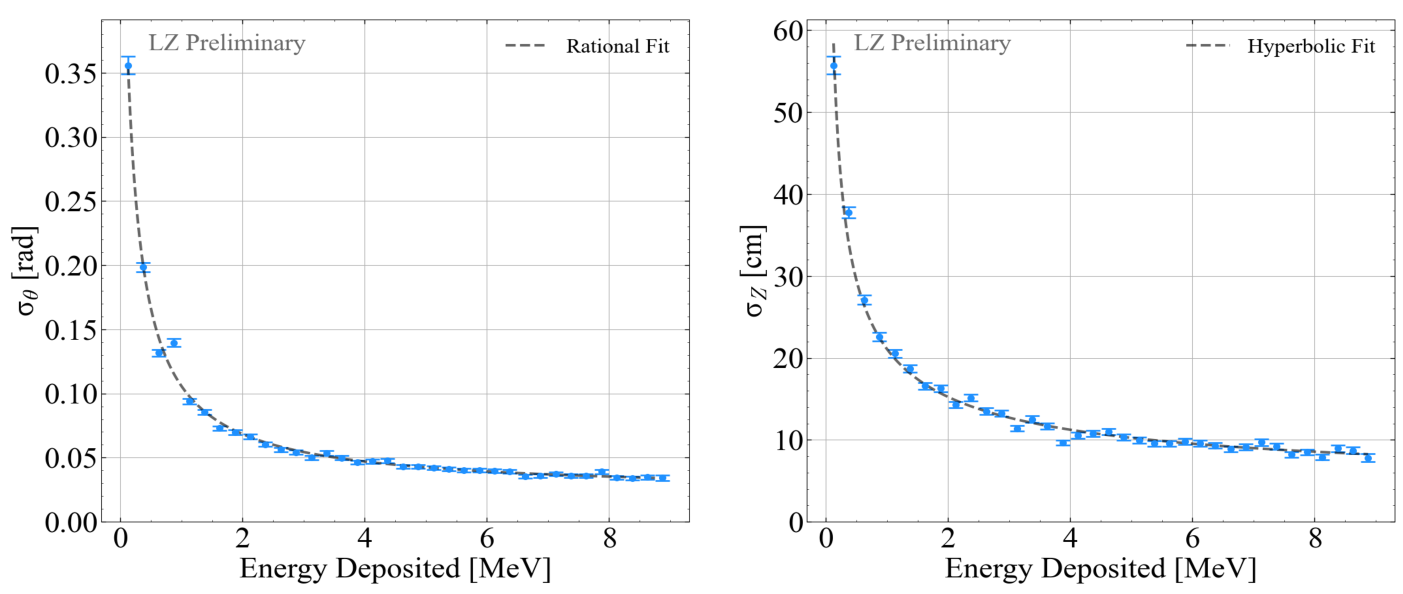


Figure 6: (θ,Z) resolution as a function of energy deposited in the side GdLS tanks from simulated 0-9 MeV γ-rays.

CNN reconstruction aligns with geometry and source deployment heights in calibration data

- Limited radial reconstruction from fixed-radius PMT coverage
- Small source offset from γ-transport and reconstruction effects

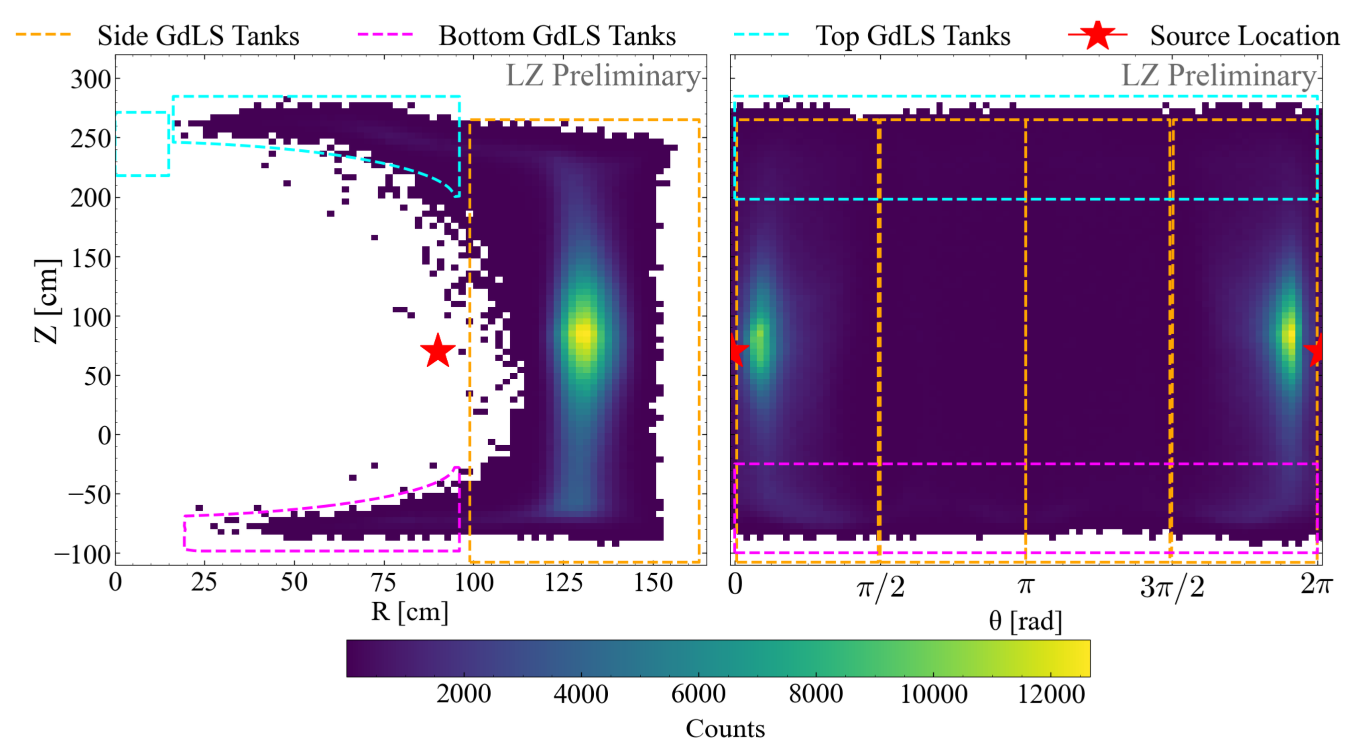


Figure 7: CNN reconstructed positions for a ^{228}Th source at a height of 70cm. Clustering aligns with deployed height.

Spatially Dependent Neutron Veto

Spatial dependence in the neutron veto suppresses the probability of false-vetoes

Neutron calibrations are used to evaluate spatial-veto performance

1. Select TPC-OD coincident SS NRs
2. Reconstruct OD pulses with CNN position reconstruction approach
3. Compute TPC-OD separation ($\Delta\theta$, ΔZ)
4. Define 3σ neutron acceptance area, $A_{3\sigma}$

$$\text{Accepted area fraction, } F_{accepted} = \frac{A_{3\sigma}}{A_{total}}$$

5. Scale accidental veto coincidences with $F_{accepted}$

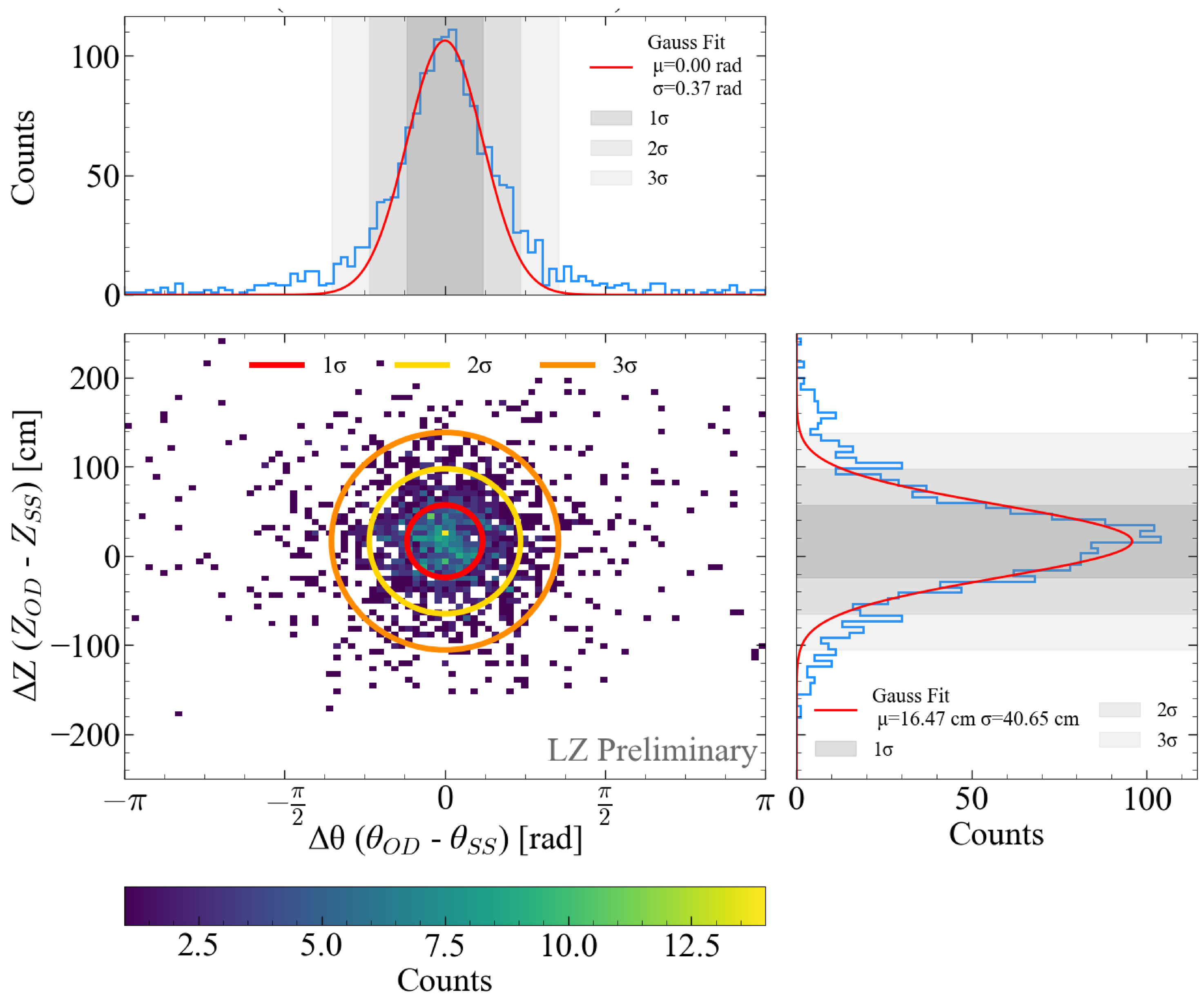


Figure 8: ($\Delta\theta$, ΔZ) distribution for TPC–OD coincident SS NRs from AmLi neutron calibration sources deployed at a height of Z=70cm in each calibration tube, with neutron acceptance contours.

Preliminary geometric studies indicate a 4–8× reduction in false-veto probability, with minimal impact on neutron-tagging efficiency!

- Further studies ongoing to optimise timing, energy and spatial selections for maximum tagging efficiency and accidental background rejection.

References

1. LUX-ZEPLIN Technical Design Report. The LZ Collaboration (2017)
2. Dark Matter Search Results from 4.2 Tonne – Years of Exposure of the LUX-ZEPLIN (LZ) Experiment. The LZ Collaboration. Phys. Rev. Lett. 135 (2024), 011802

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