Diffusion deconvolution method and fiducialization for the CYGNO experiment

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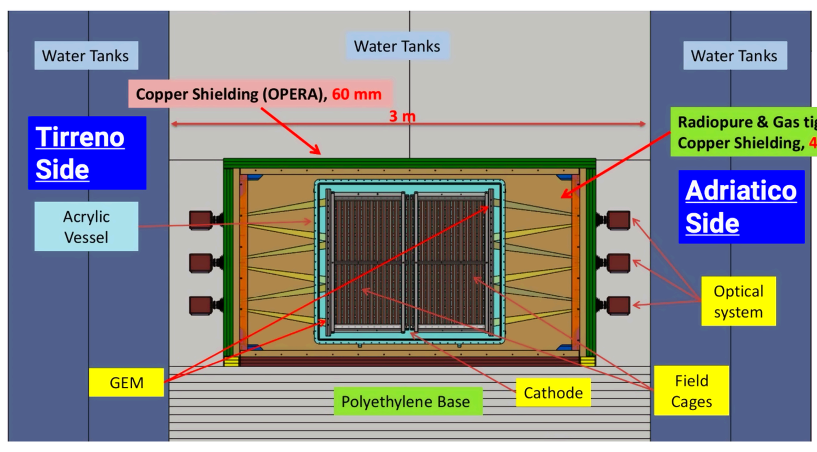
Part of this project has been funded by the European Union's Horizon 2020 research and innovation programme under the ERC Consolidator Grant Agreement No 818744

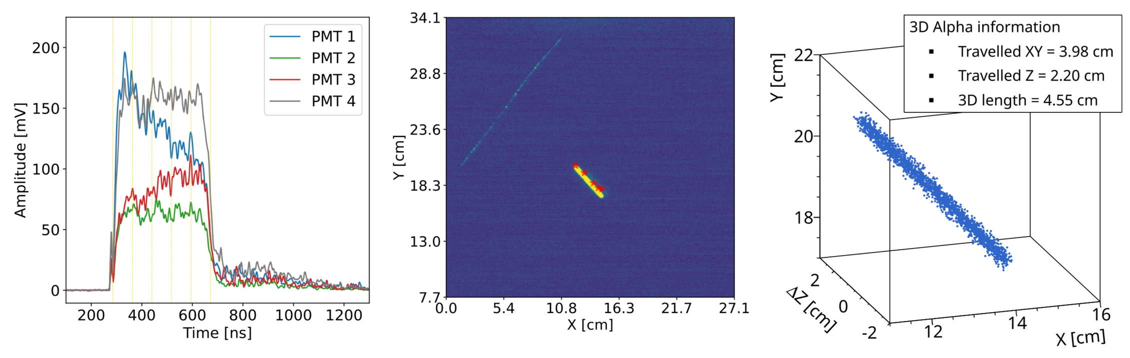
1. THE CYGNO EXPERIMENT

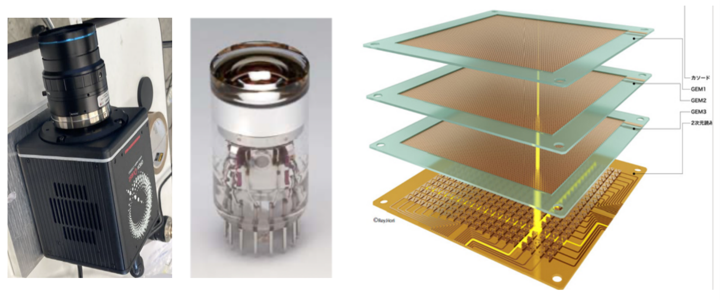
THE DETECTOR CONCEPT

Directional detector for rare event searches at low energies such as Dark Matter and solar neutrinos [1]

- Gaseous Time Projection Chamber
- He : CF_4 (60:40) mixture with scintillating properties
- Ionisation signal amplification via triple GEM stack
- Optical readout comprised of PMTs and qCMOS camera for 3D track reconstruction [2]

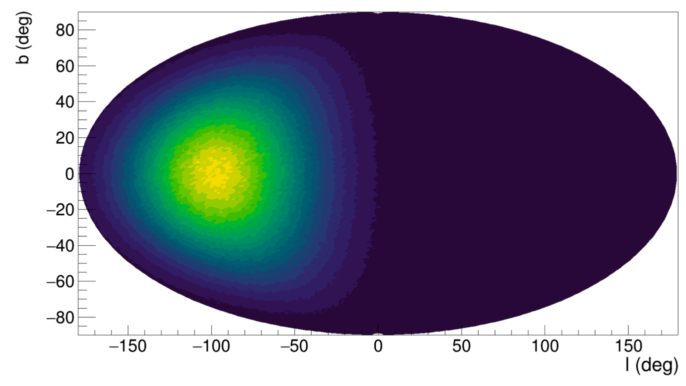






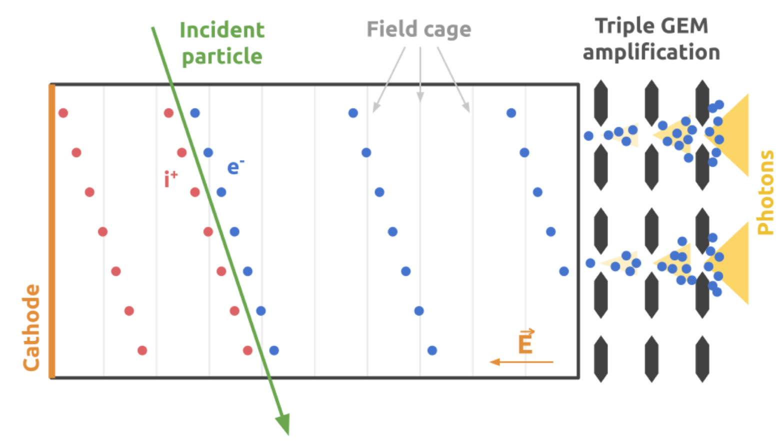
HOW TO BE A DIRECTIONAL DETECTOR?

Direction and sense of the recoil reconstructed from track topology combining PMT and Camera information



For more information see presentation by S. Piacentini

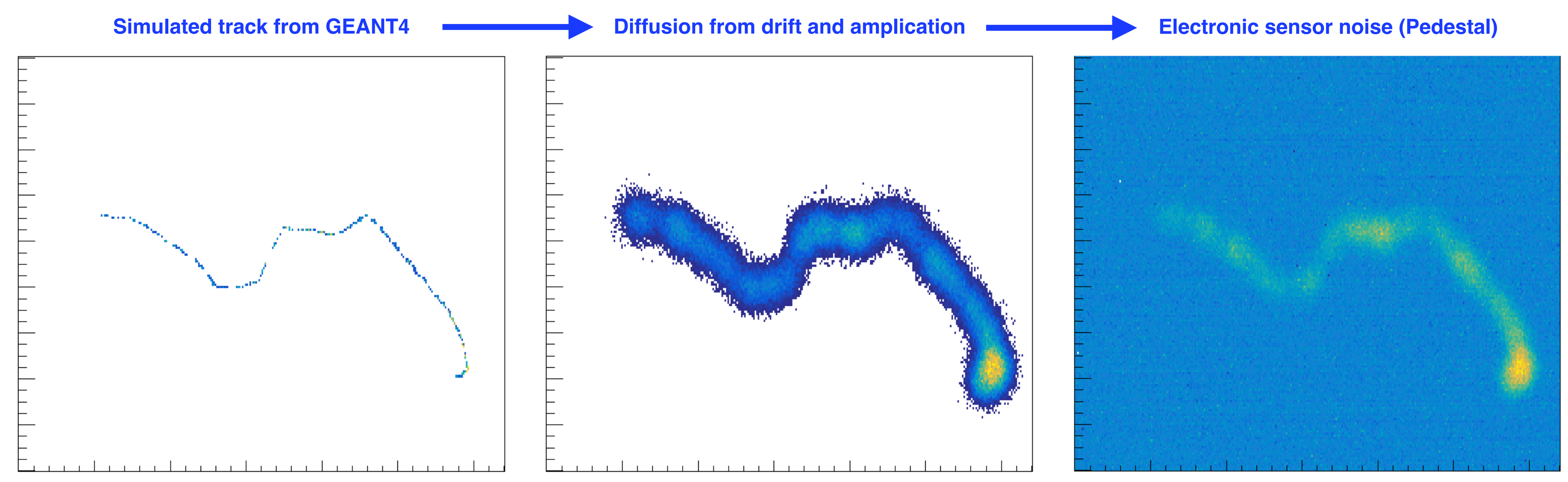
2. THE IMAGE FORMATION PROCESS



OPTICAL SIGNAL PRODUCTION:

1. Incident particle interacts with target in the detector
2. Primary ionisation electrons produced
3. Primary electrons drifted onto the anode plane
4. Electrons initiate avalanches in the GEMs
5. Photons emitted due to CF_4 scintillation
6. Light collected by optical readout

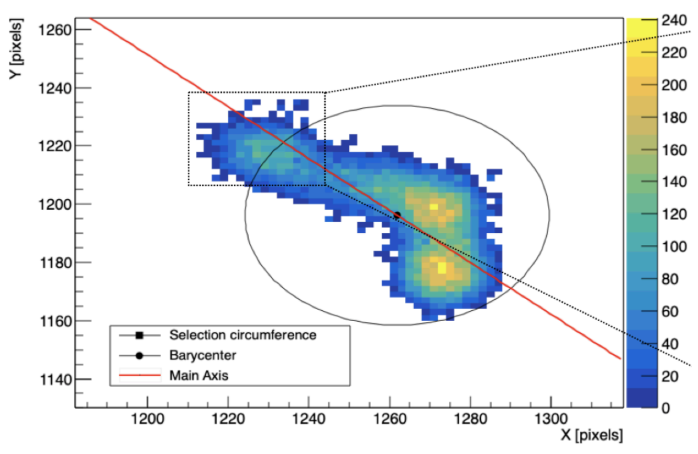
SIMULATION PIELINE [3]

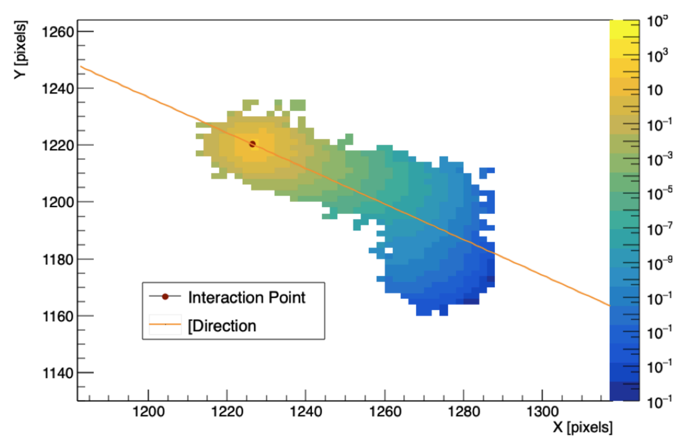


3. 2D - DIRECTIONAL ANALYSIS

Directionality algorithm adapted from X-Ray polarimetry [4, 5]

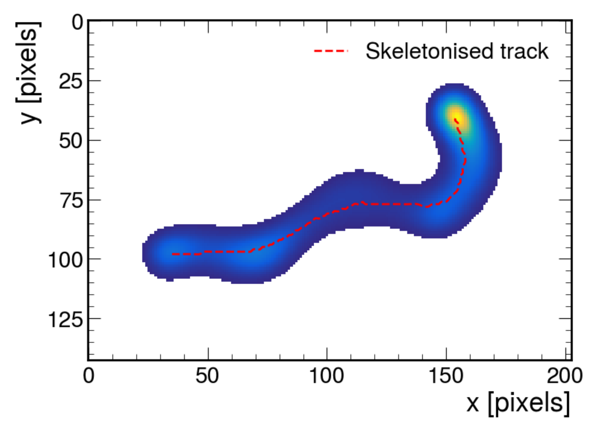
- Find the barycenter
- Mask the center of the track
- Impact Point is the barycenter of the remaining track





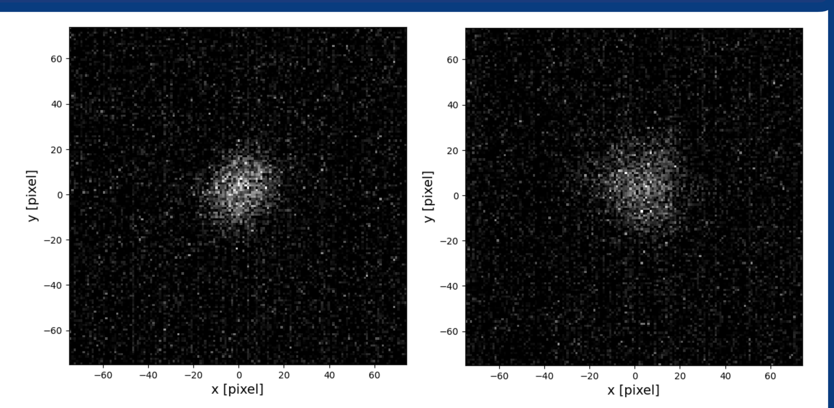
- Find the principal axis with a PCA
- From the skewness of the projection discriminate Head-Tail
- Attenuate track exponentially
- Direction is found as the new PCA axis

- Algorithm struggles on complex track topologies
- Skeletonisation investigated as alternative
- Projection on skeleton is topology independent
- Impact point reconstruction less sensitive to sensor noise



4. DECONVOLVING DIFFUSION

- Tracking performance in CYGNO limited by electron diffusion
- Diffusion due to electron drift and amplification stage at the GEMs
- At $\mathcal{O}(10\,\mathrm{keV})$ energy the track is dominated by diffusion envelope → tracking becomes impossible



HYPOTHESIS

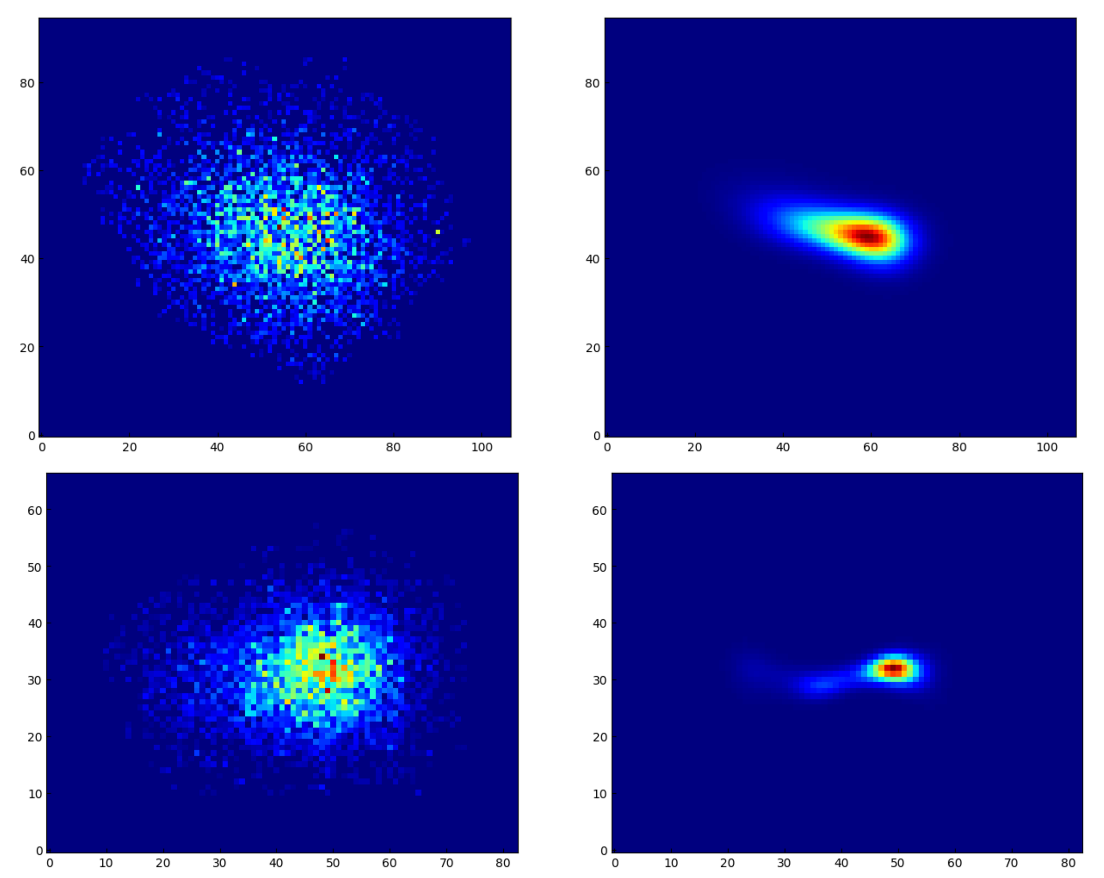
$$O = H \circledast I + n$$

Observation (O), Primary ionisation density (I), Point Spread Function (H), Noise (n)

- Convolution is a multiplication in Fourier Space
- Sensor noise prevents simple inversion
- Bayesian approach to deconvolution [6]

$$\hat{I} = \arg\min_{I} \left(\frac{\|O - HI\|^2}{2\sigma^2} - kS(I) \right) \quad \text{with } k \in \mathbb{R}$$

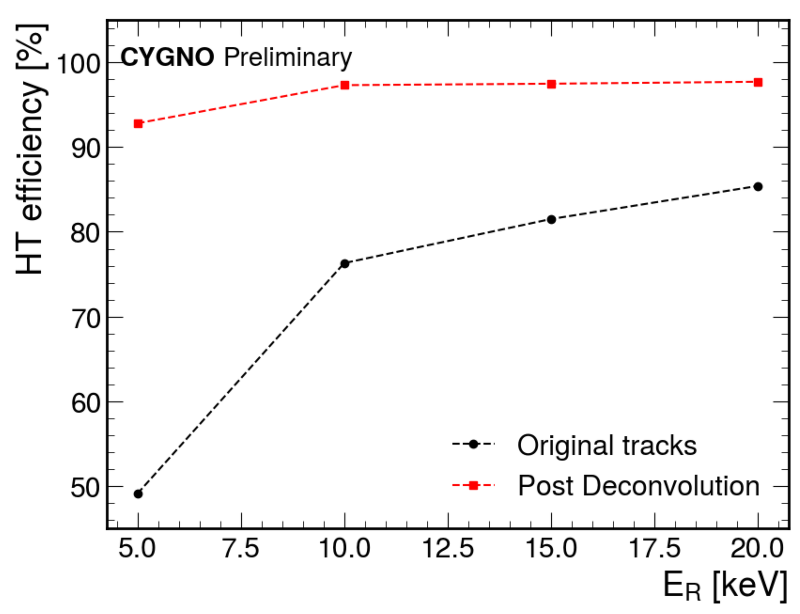
$S(I)$ is the Shannon-Jaynes entropy $\quad S(I) = \sum_{ij}^{N} \left[I_{ij} - P_{ij} - I_{ij} \ln\left(\frac{I_{ij}}{P_{ij}}\right) \right]$

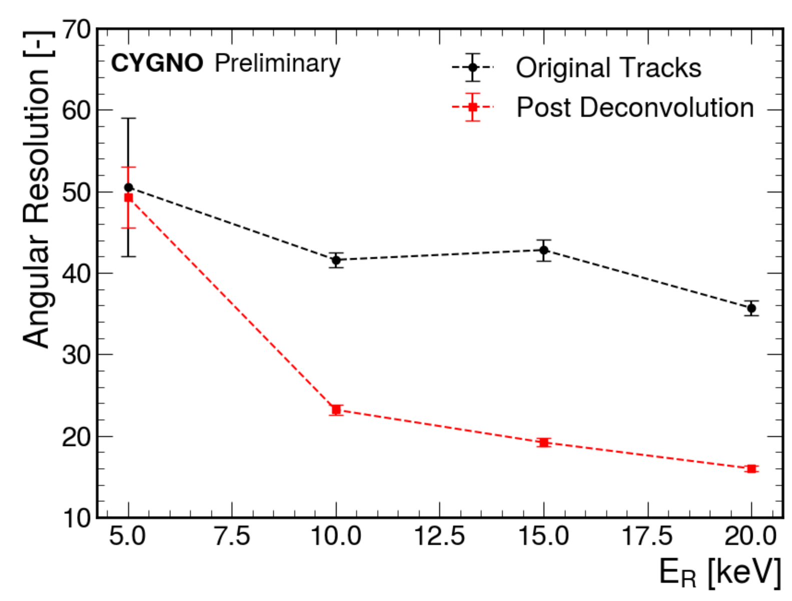


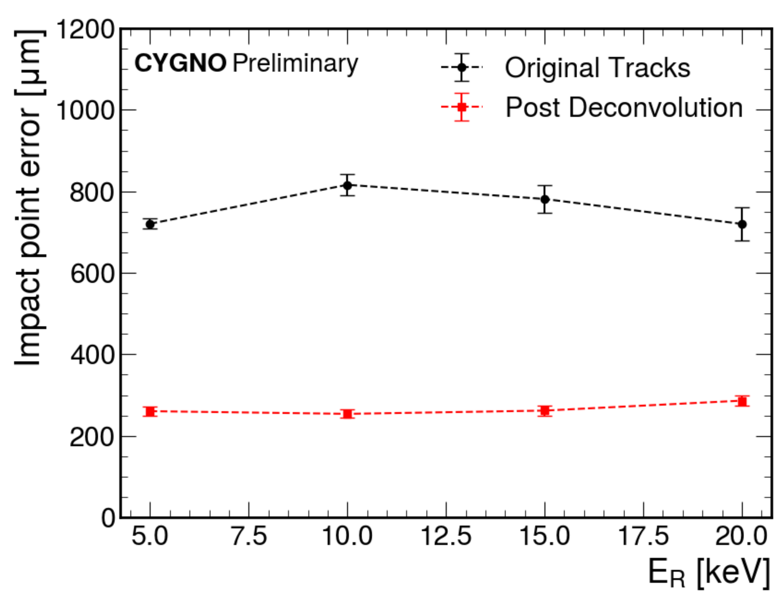
5. TRACKING PERFORMANCE IMPROVEMENT

Preliminary analysis on simulation suggests a drastic improvement in tracking performance

- Impact point reconstruction improved by a factor of 2
- Angular resolution improved doubles above 15 keV
- Head-Tail discrimination efficiency over 90% even at 5 keV





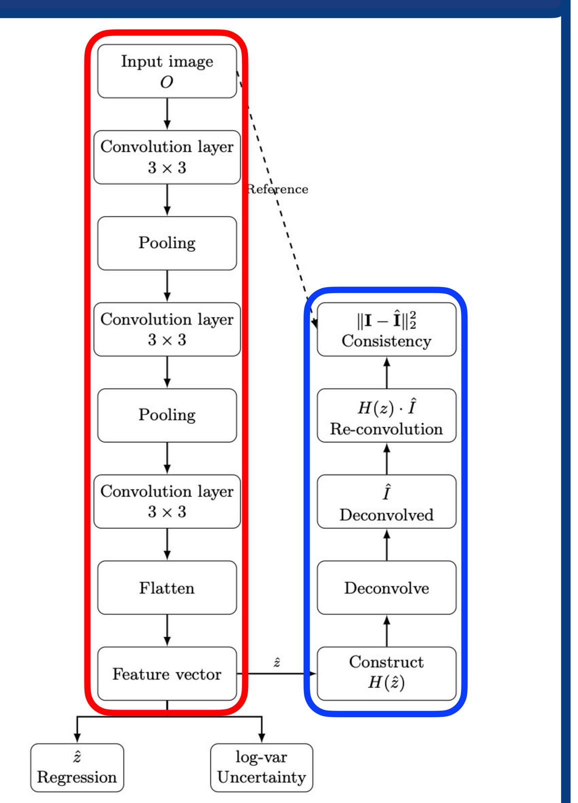


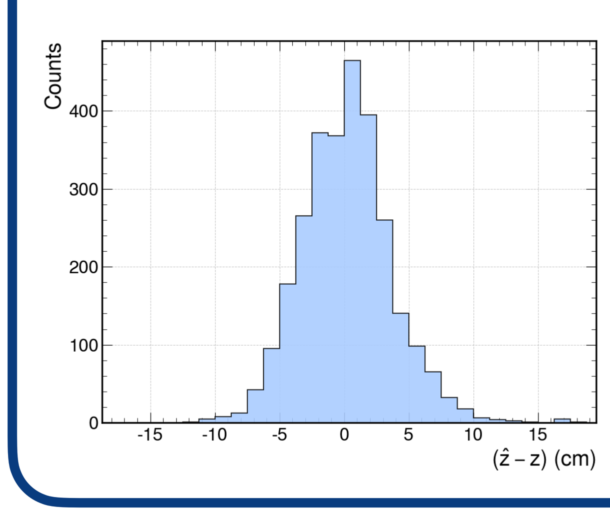
4. DECONVOLUTIONAL MACHINE LEARNING - XPJW-Net

THE IDEA

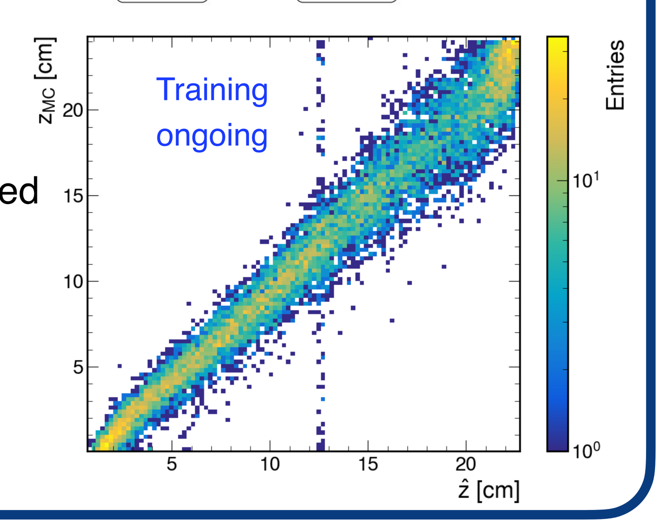
Deconvolution is sensitive to drift distance because of the drift diffusion term

- Construct a machine learning architecture to learn the physics of diffusion through deconvolution
- Encoder network based on the U-Net architecture (XPJ-Net)
- From the feature vector propose a drift coordinate ($\hat{z}$)
- Use this estimate to construct $H(\hat{z})$
- The Wiener network deconvolves the image then reconvolves it with the MC Truth in training
- The network is forced to learn through the physics of diffusion





- Current resolution on real data ≈ 3.4 cm
- Performance limited by poorly labeled dataset
- Training on MC data ongoing
- Current resolution achieved below 1.4 cm



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[1] F. D. Amaro *et al.*, "The CYGNO experiment: a gaseous TPC with optical readout for rare events searches,"arXiv:2603.22595 [physics.ins-det] (2026).

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