



Light-only Liquid Xenon experiment: Energy and position reconstruction

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On behalf of LoLX collaboration

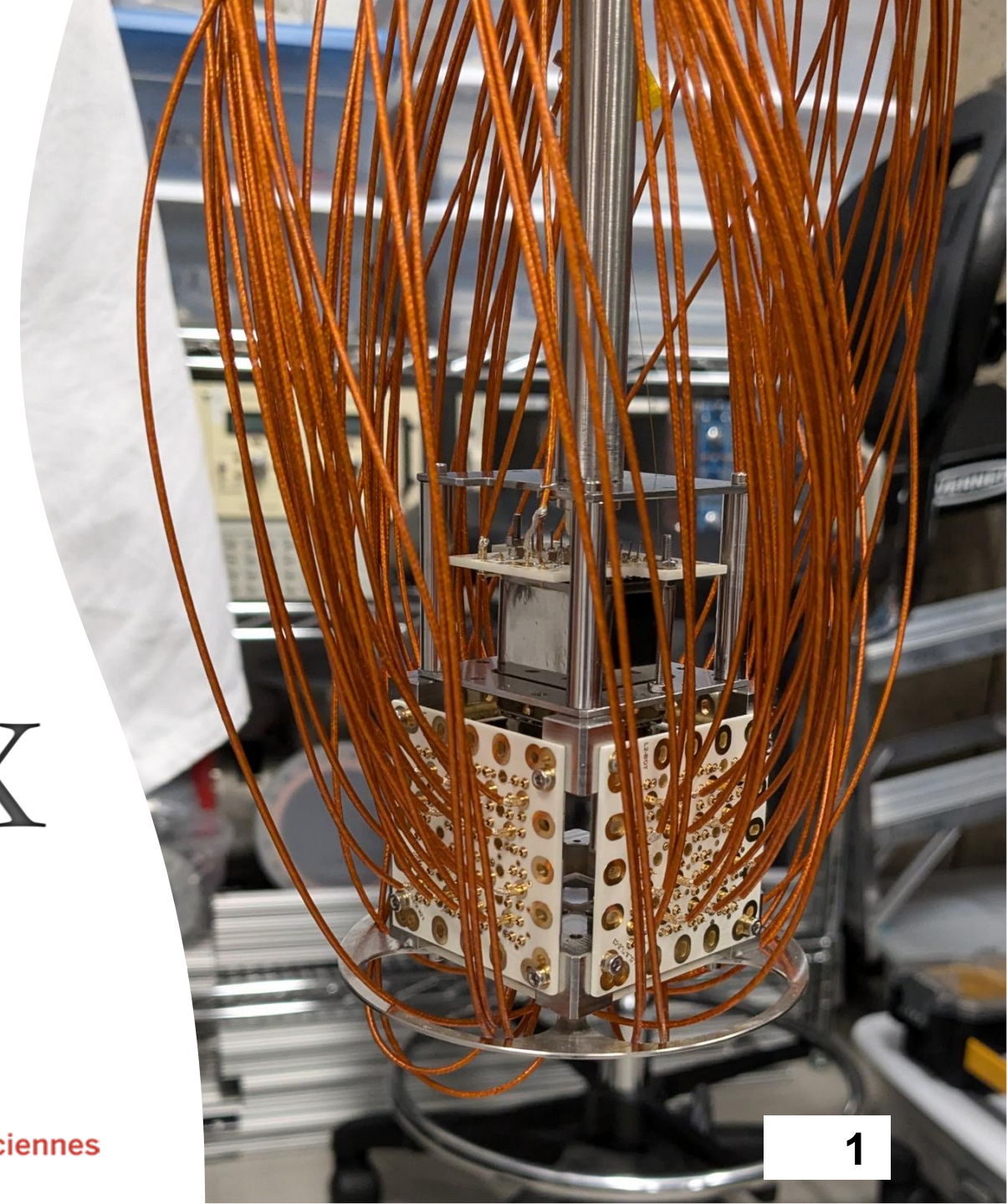
CAP Congress

2025.06.09



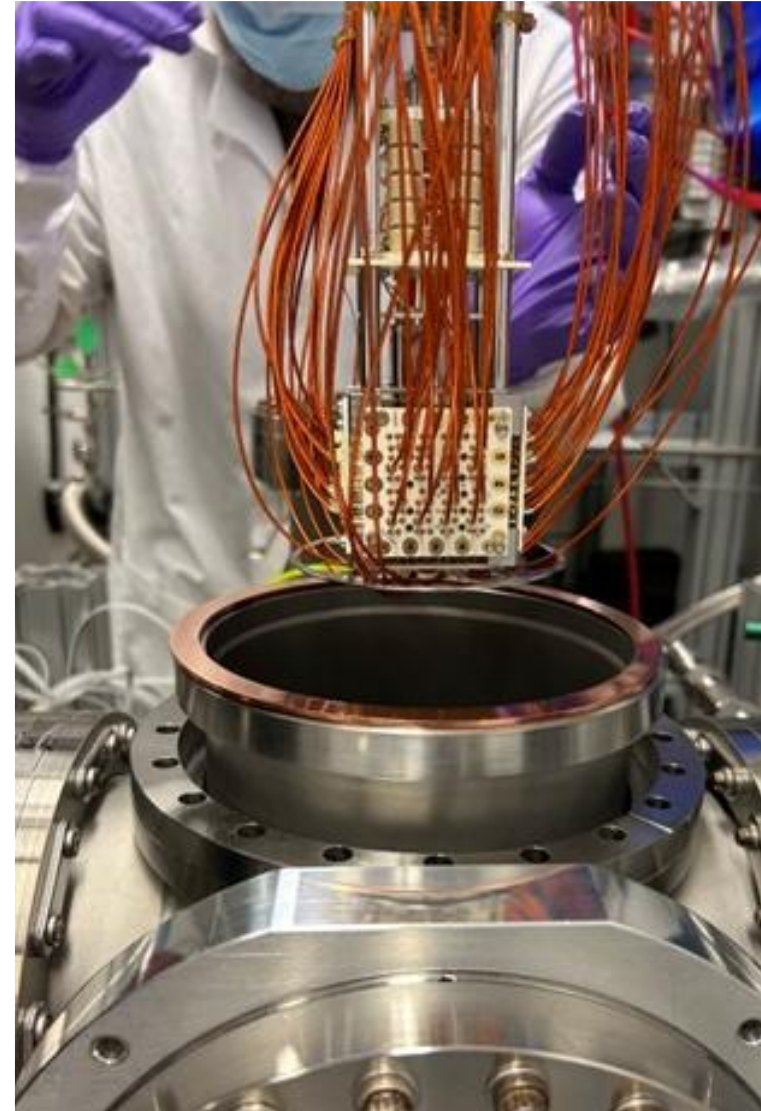
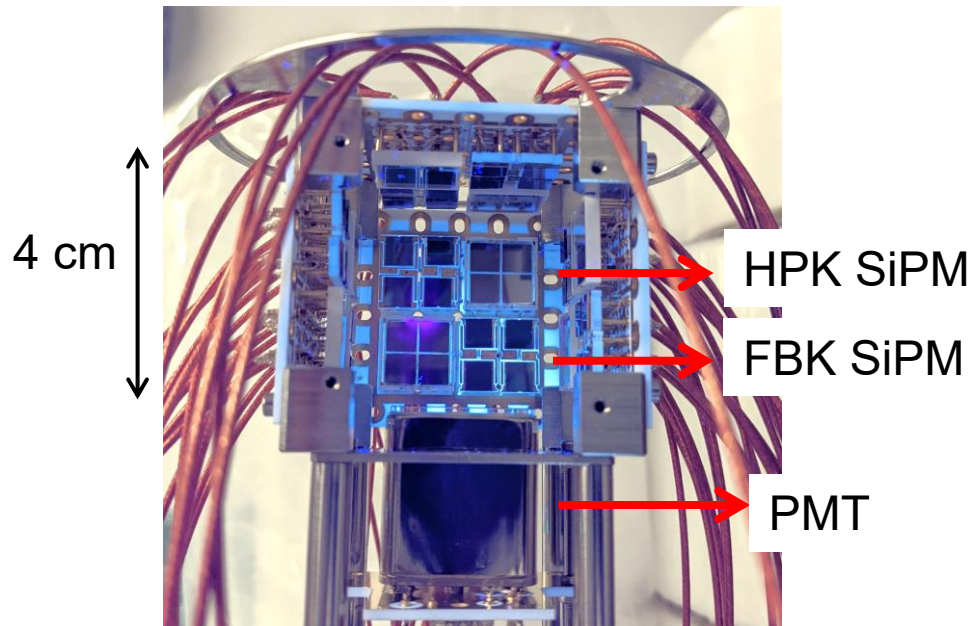
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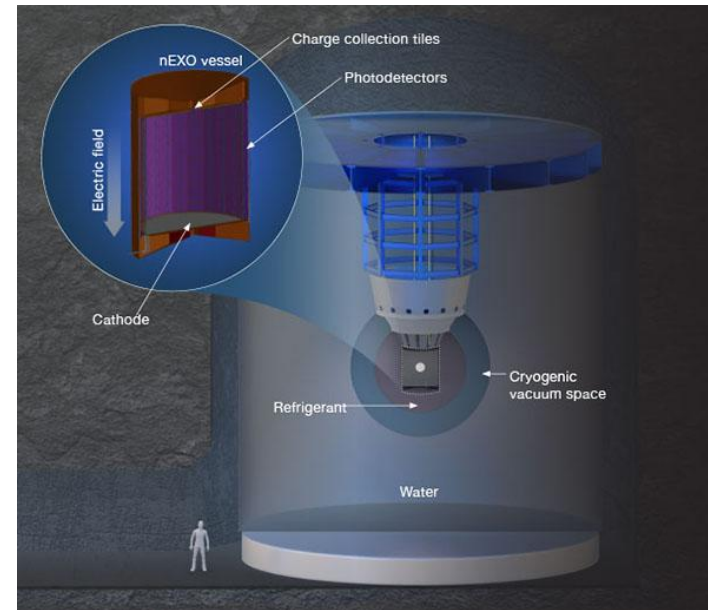
What is LoLX?

- LoLX: **L**ight-**O**nly **L**iquid **X**enon experiment.
 - Modular cube array of photosensors immersed in liquid xenon (LXe).
 - Built at TRIUMF by Science & Technology group.
 - Operated at McGill University, Brunner Neutrino Lab (BvL).
 - R&D for nEXO and PIONEER.

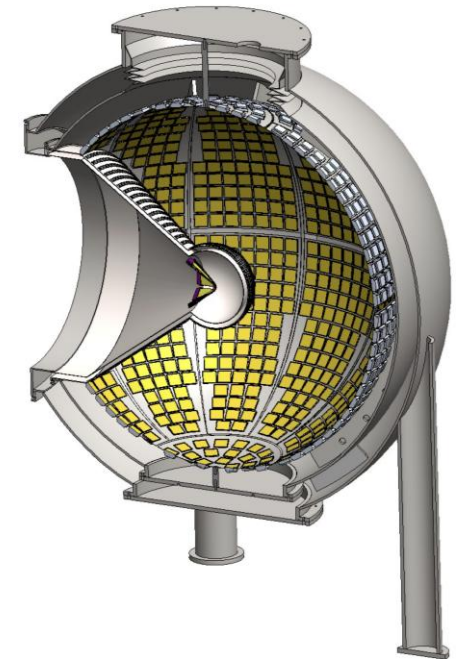


Goals

- **Study light production of LXe.**
 - **Study light yield and energy resolution.**
 - Scintillation and Cherenkov light.
- Develop and validate simulation model with experimental data.
 - Inform future experiments, such as nEXO, and PIONEER.
- SiPMs performance in LXe.
 - Photon detection efficiency.
 - Long term stability operation.
 - Cross-talk study.
 - We recently published!
 - Available on arXiv: [2502.15991](https://arxiv.org/abs/2502.15991).
 - Accepted by EPJ C.



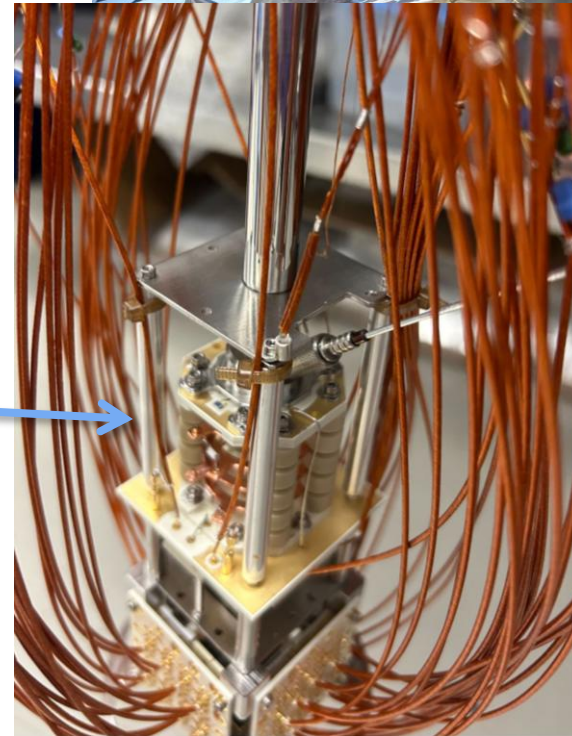
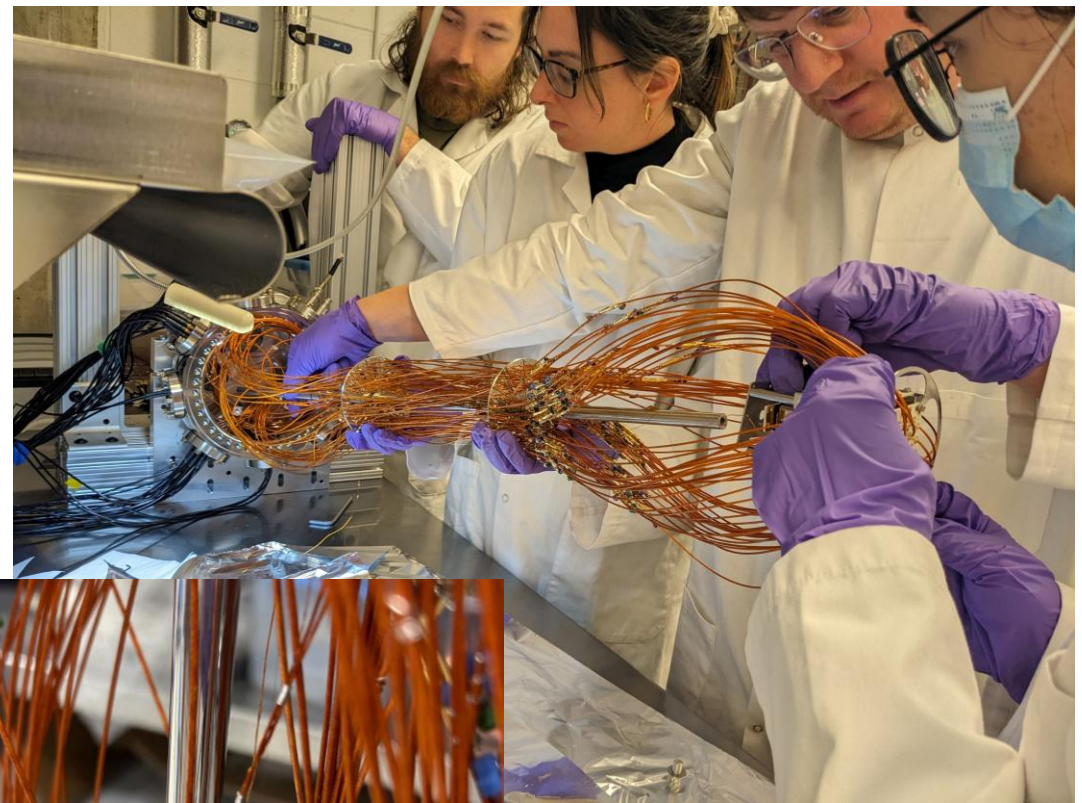
nEXO:
Neutrinoless double beta decay search



PIONEER:
Lepton flavor universality

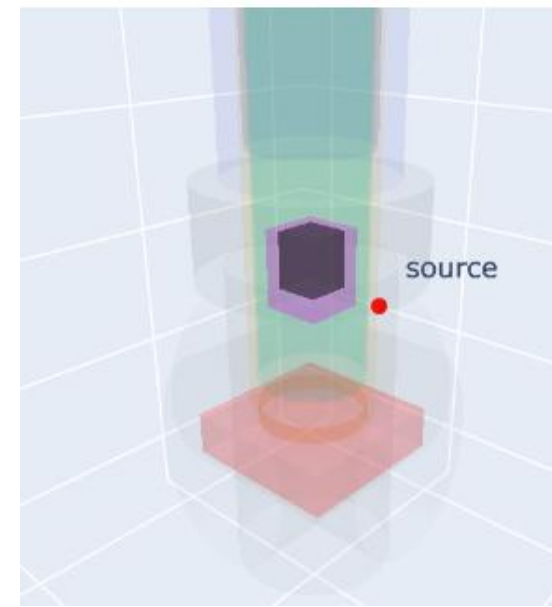
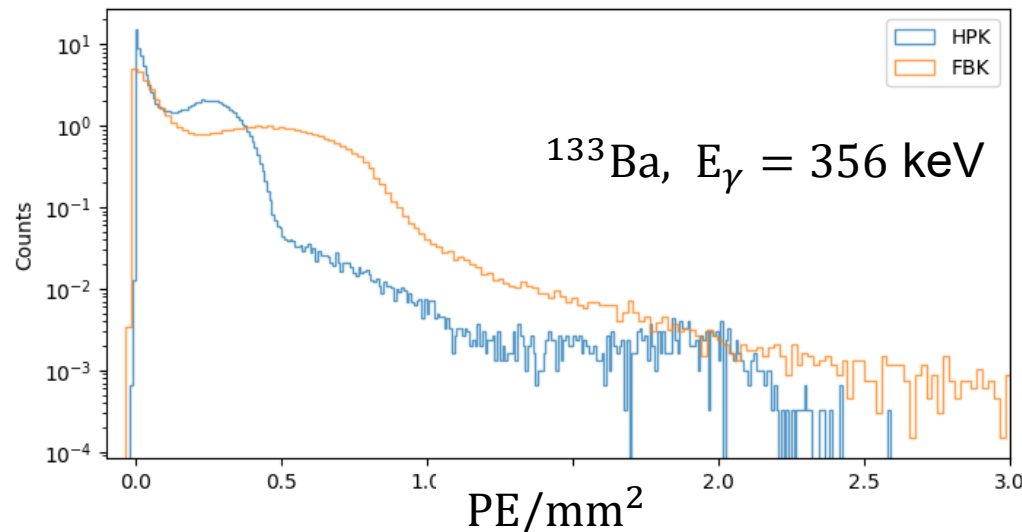
LoLX runs

- August 2023 – Run 1, Commissioning:
 - Laser calibration and background runs
 - External gamma sources.
 - ^{22}Na , ^{133}Ba , ^{137}Cs
- January 2025 – Run 2, Engineering:
 - Same source data.
 - Swapping HPKs from another batch.
 - Adding xenon purity monitor (PUMA).
- Fall 2025 (Planning) – Run 3, physics:
 - Internal ^{181}Hf source.
 - Wavelength filters.

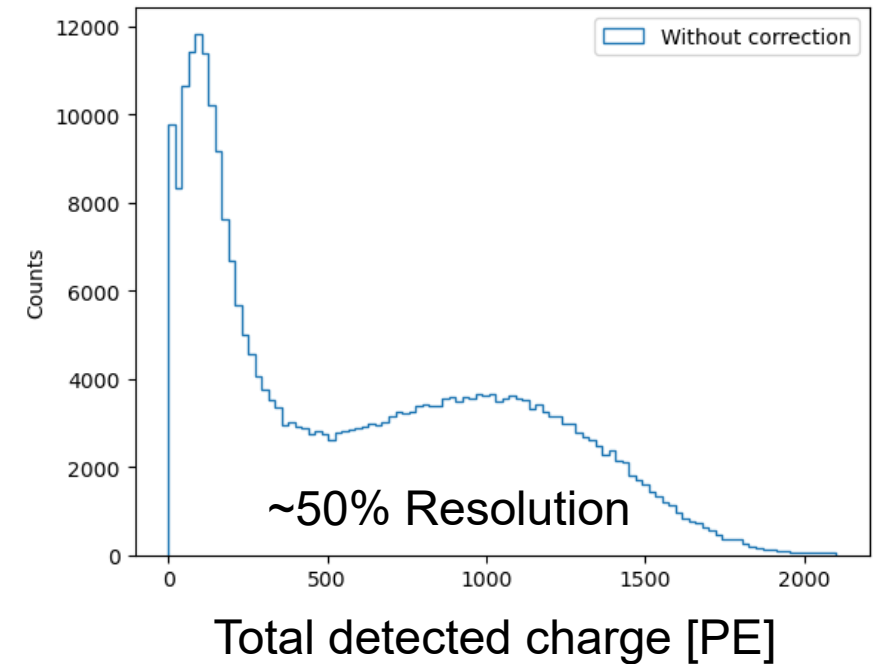


Challenges in LoLX data

- We want to study the energy resolution of using SiPMs in xenon.
- Position dependent light collection efficiency smears energy resolution.
- Photon detection efficiency (PDE) difference three photosensor types (FBK, HPK, PMT).
 - SiPMs performance in liquid xenon is one of study goals.

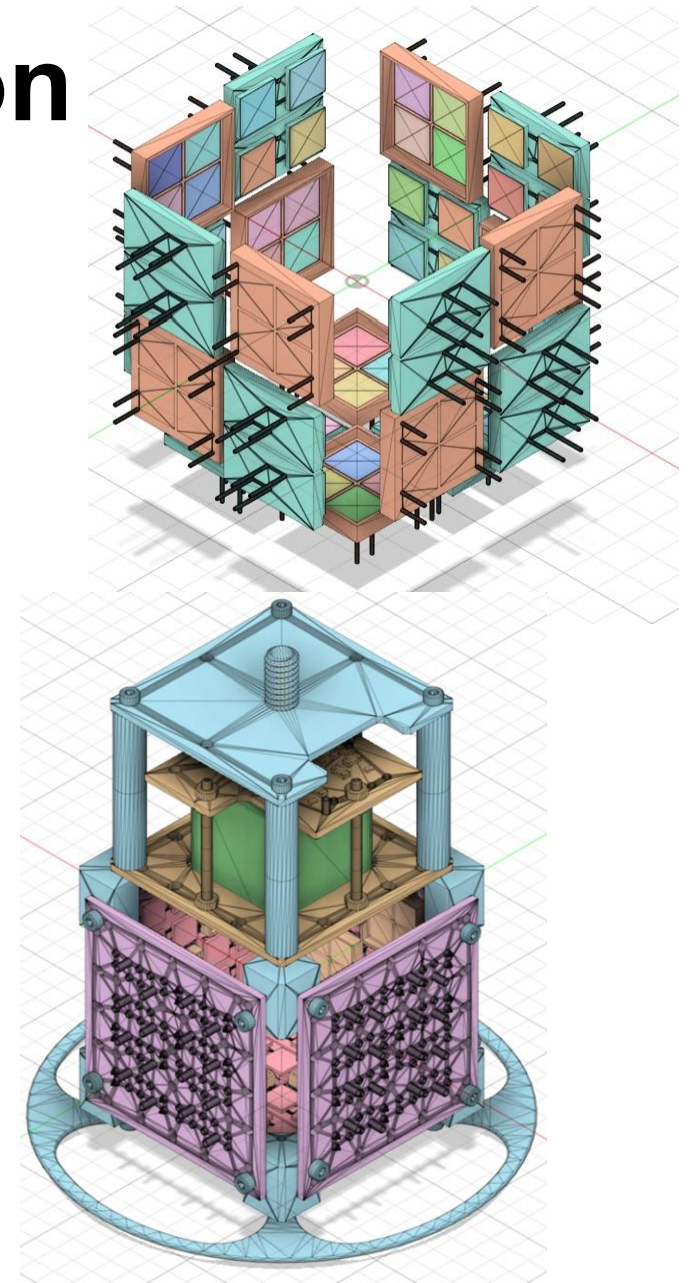


^{133}Ba 356keV gamma source



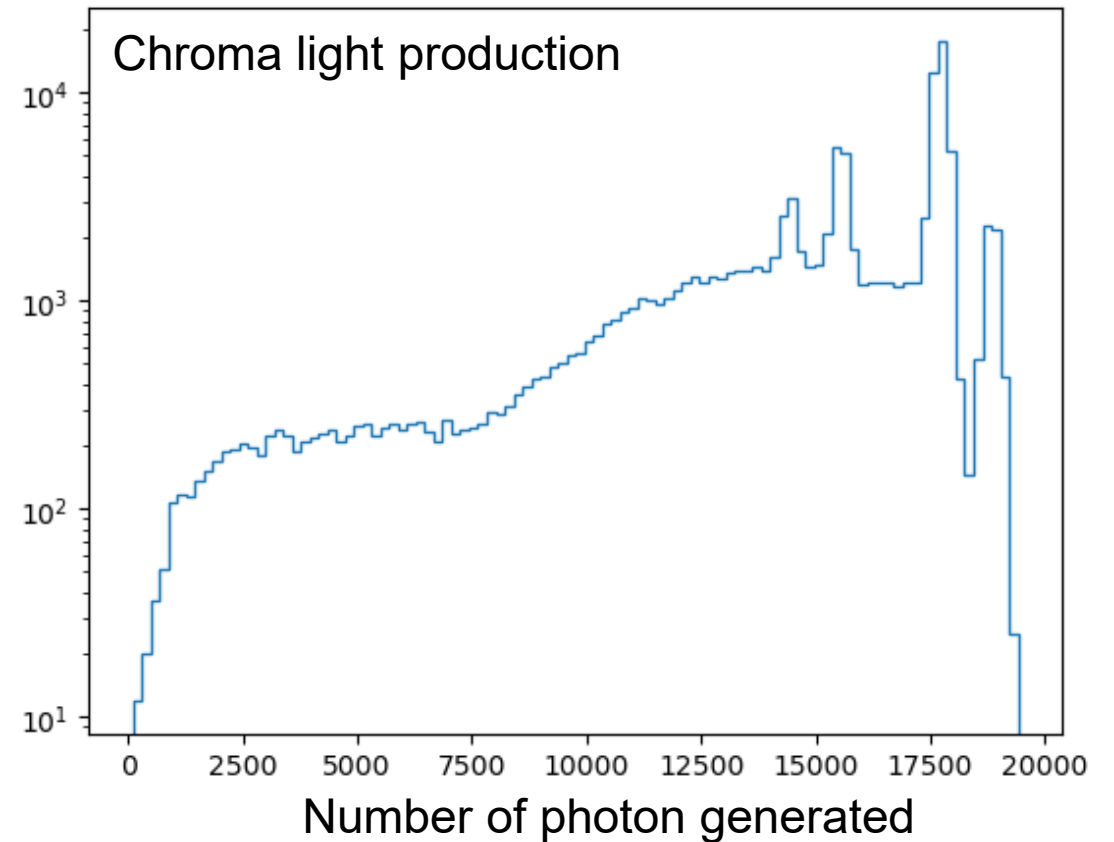
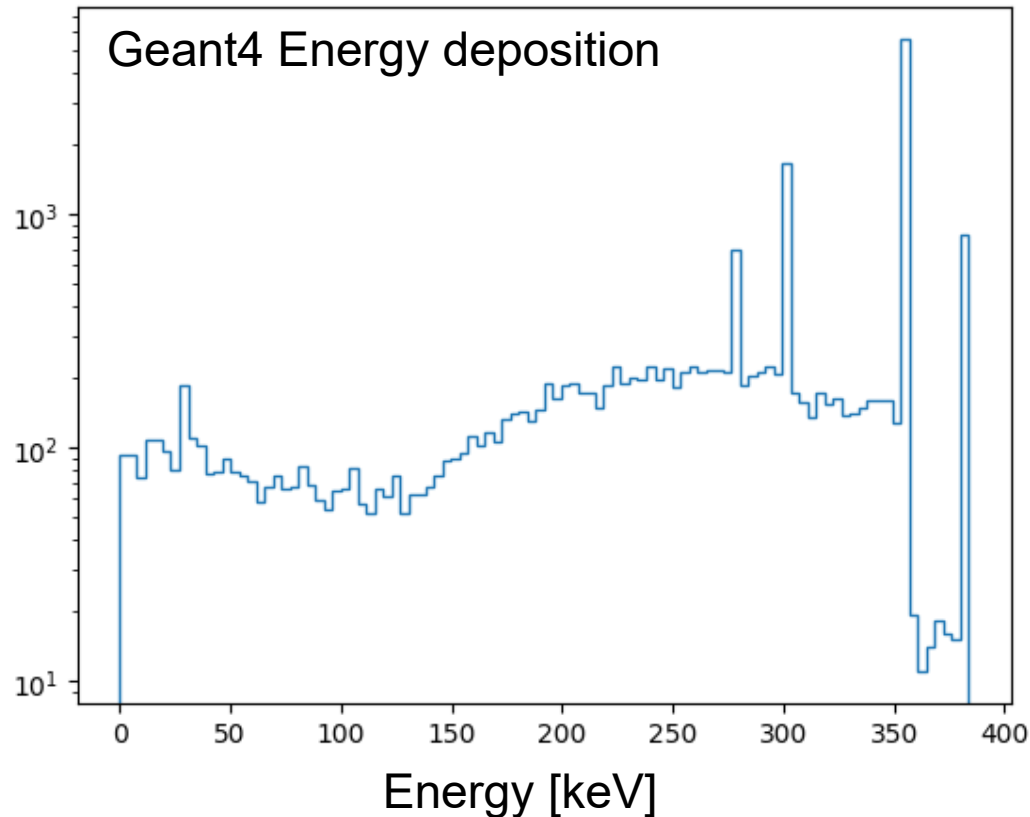
Chroma – GPU Optical Simulation

- Chroma is an optical photon simulation for particle physics detectors.
- GPU-based photon transport simulation.
 - Development in Python (core simulation in CUDA-C).
 - ~100 times faster than G4OpticalPhoton.
- Does:
 - Take the energy deposition in GEANT4 as input.
 - Or other user defined photon generators.
 - Optical Photon Transport.
 - Refractive index, wavelength shifter, scattering, attenuation length...
 - Photon Detection.
 - Angular and wavelength dependent SiPM photon detection efficiency based on measurement at TRIUMF.
 - Fully customized detection logic.



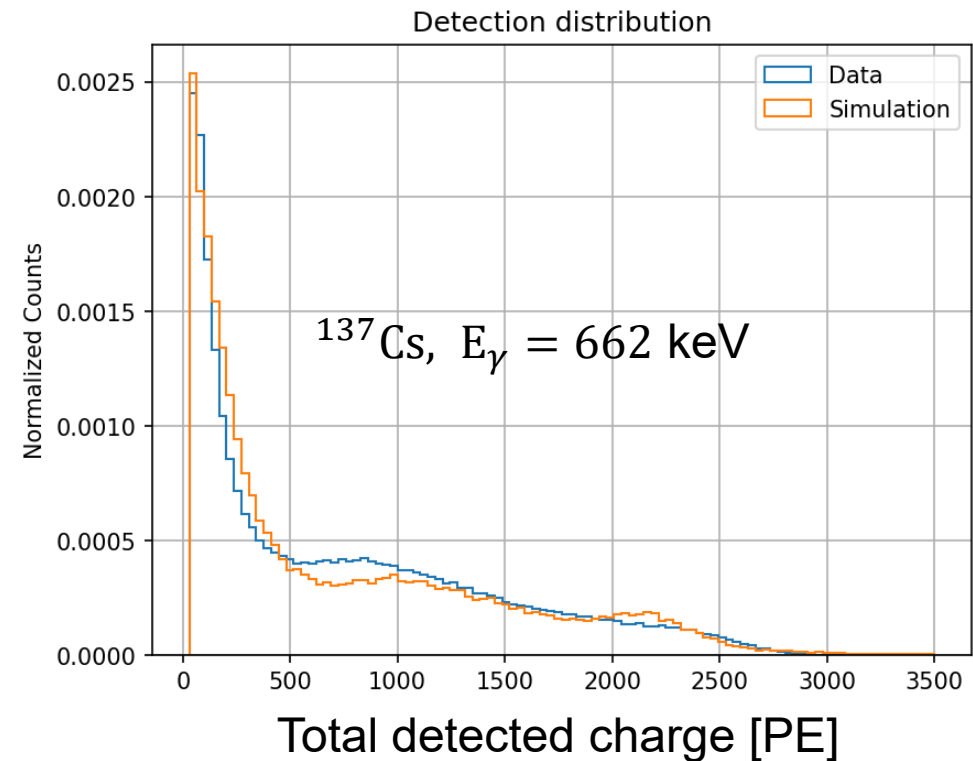
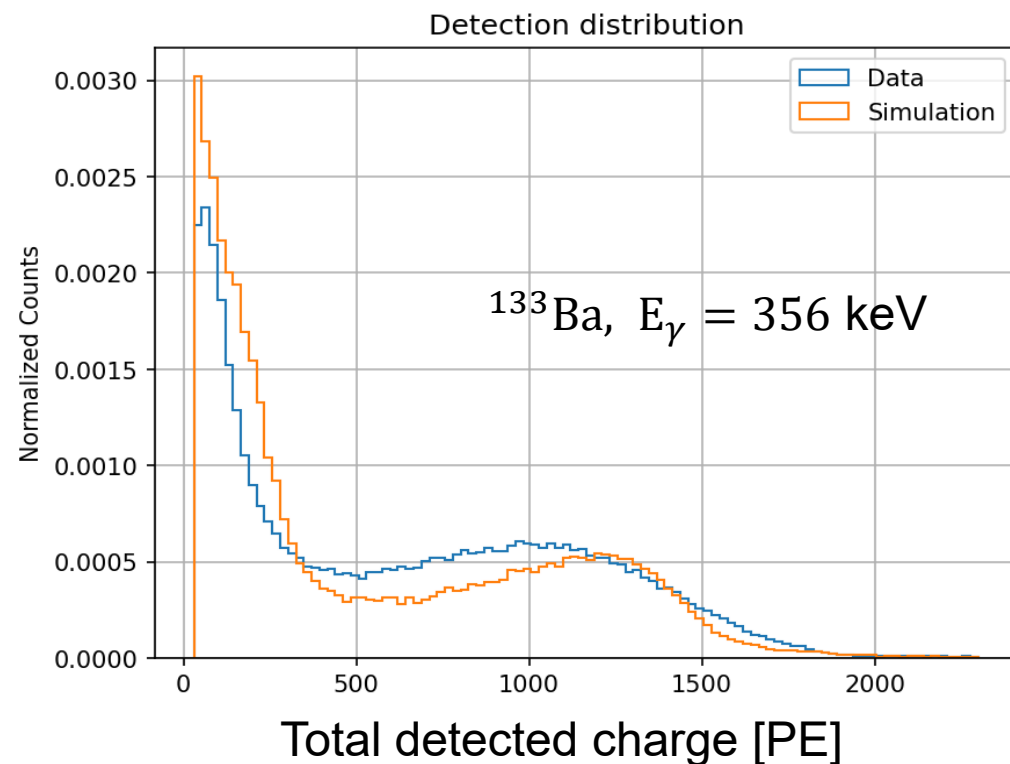
Geant 4 and Chroma

- Energy deposition in GEANT4 vs light production in Chroma.
 - Light yield base on NEST model.
 - NEST: [Noble Element Simulation Technique](#).
- Ba-133 source example:



Simulation data compare

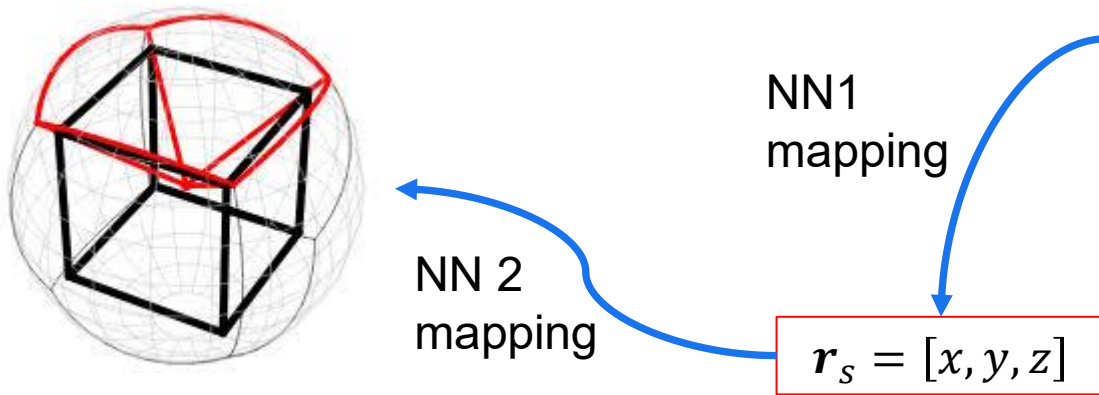
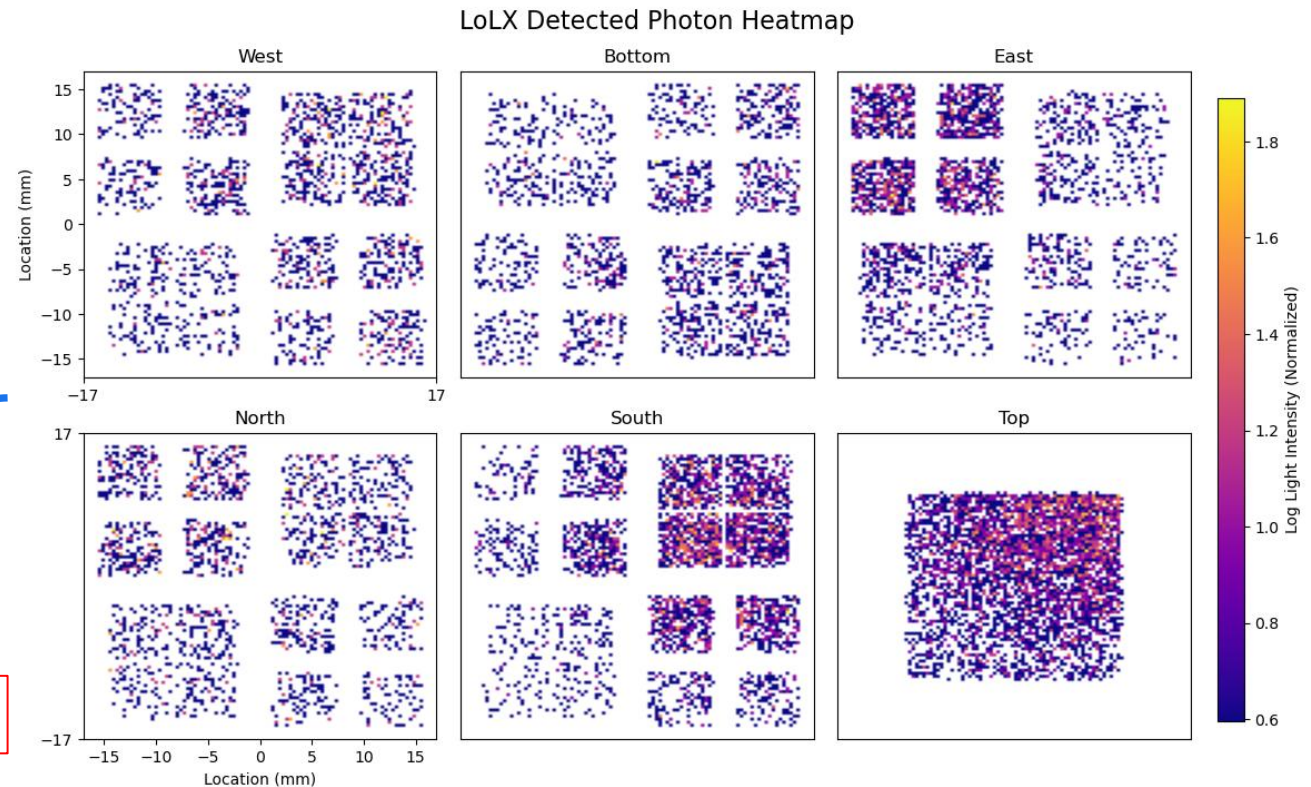
- Simulation also shows the similar feature with low energy resolution.
- Sum all the channels without correction.



Position and energy reconstruction

- Simulation with electron gun energy $\sim 356\text{keV}$.
 - NEST photon generator.
 - NEST: [Noble Element Simulation Technique](#).
 - Scintillation photons with real wavelength distribution.
- Feedforward neural network (FNN).

$Q = [Q_0 \dots Q_i]$: charge detection distribution in each channels

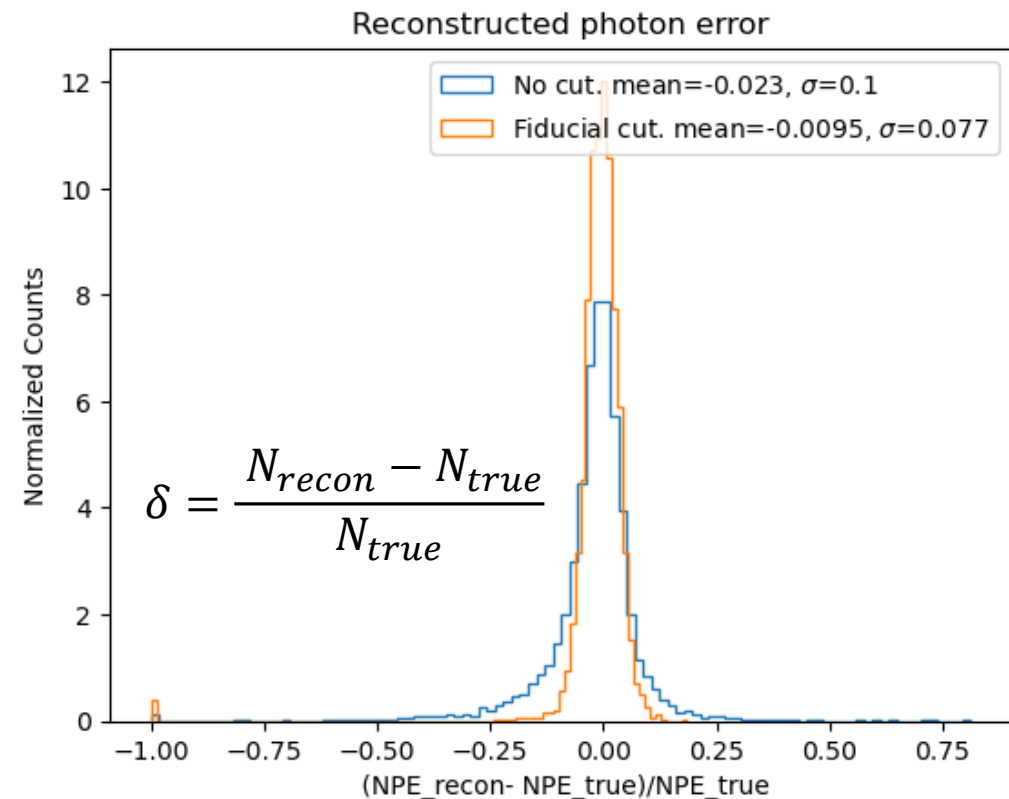
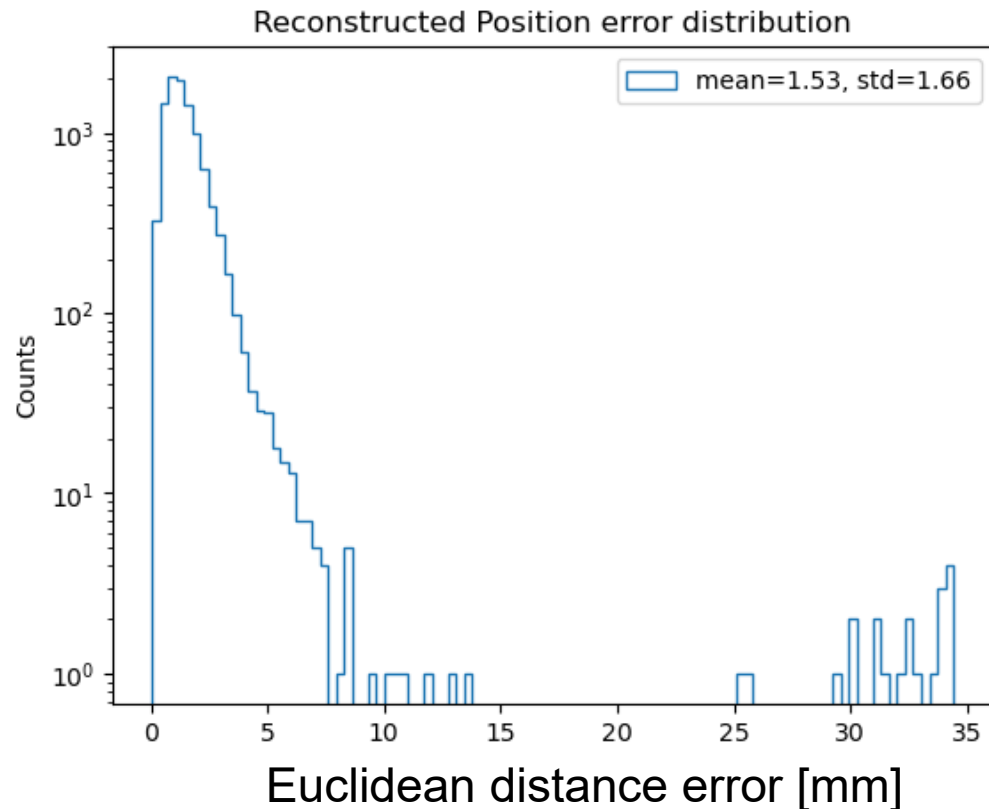


$PCE(x, y, z)$: photon collection efficiency

$PCE = Q/N_{gen}$, It includes photon transport efficiency and photon detection efficiency.

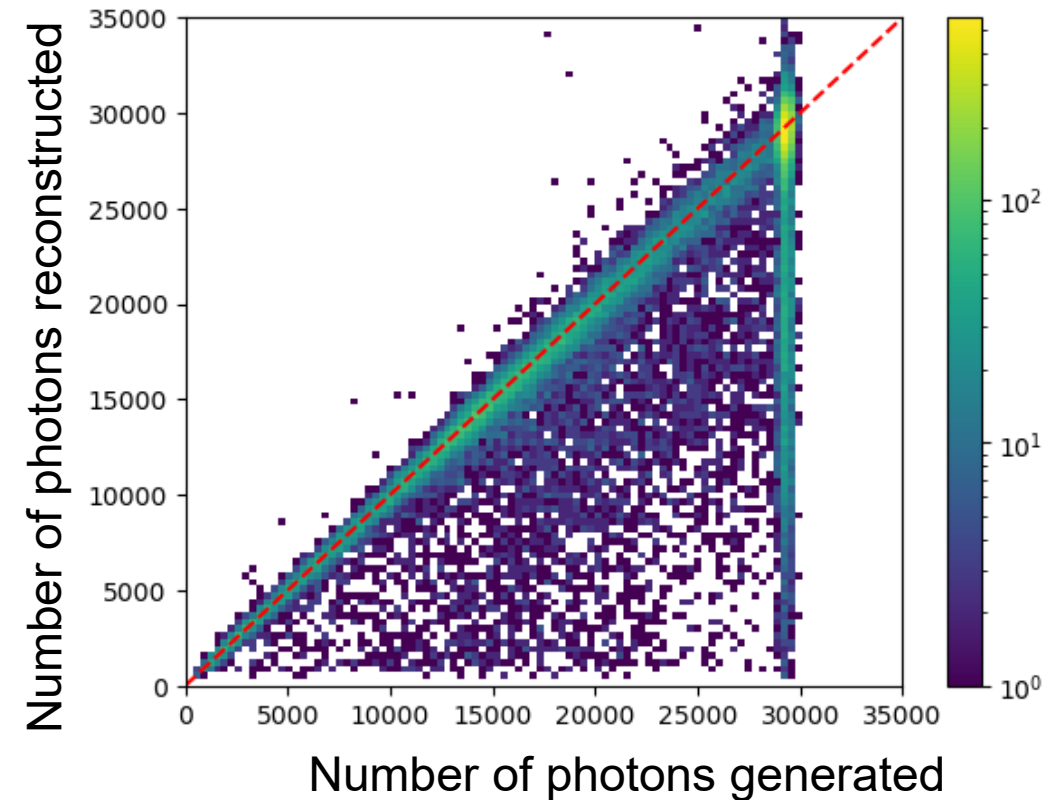
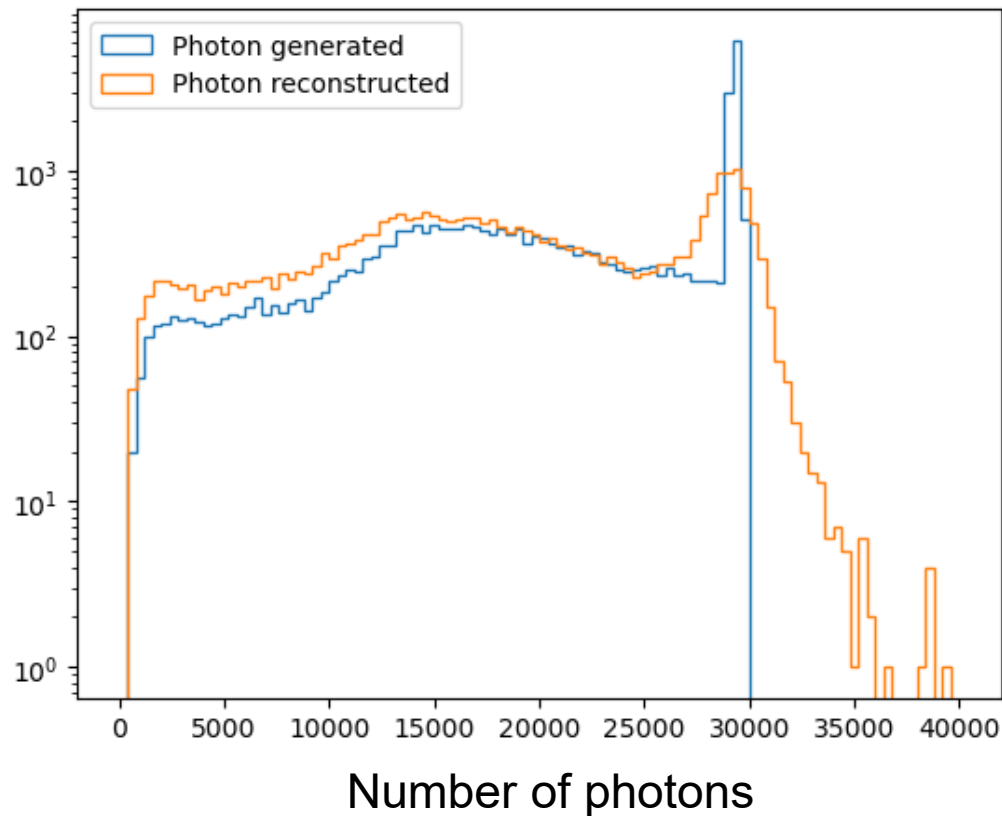
Validation within simulation – Electron gun

- Validated simulation with electron gun energy 662 keV using NEST generator.
- Fiducial cut events outside of 34mm cube.



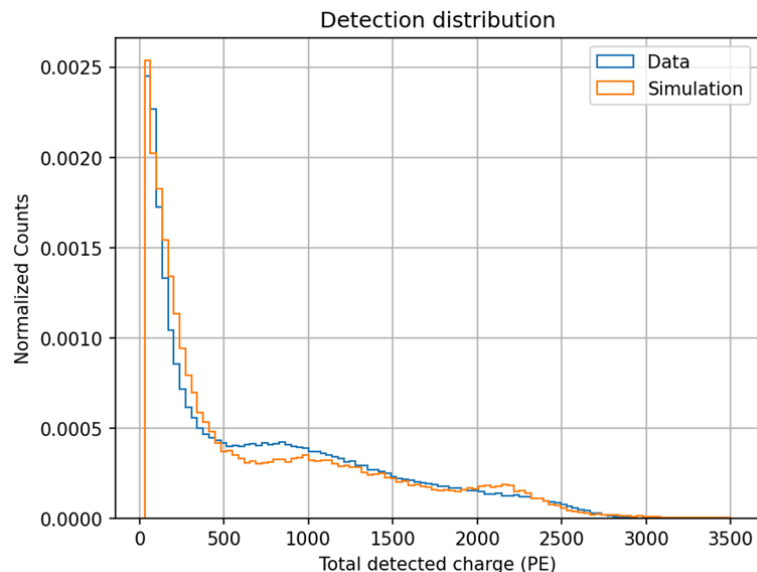
Validation within simulation – Gamma ray

- Geant 4 general particle source (GPS) produced Cs-137 decay gamma ray.
- Chroma handles optical photons base on the energy deposition.

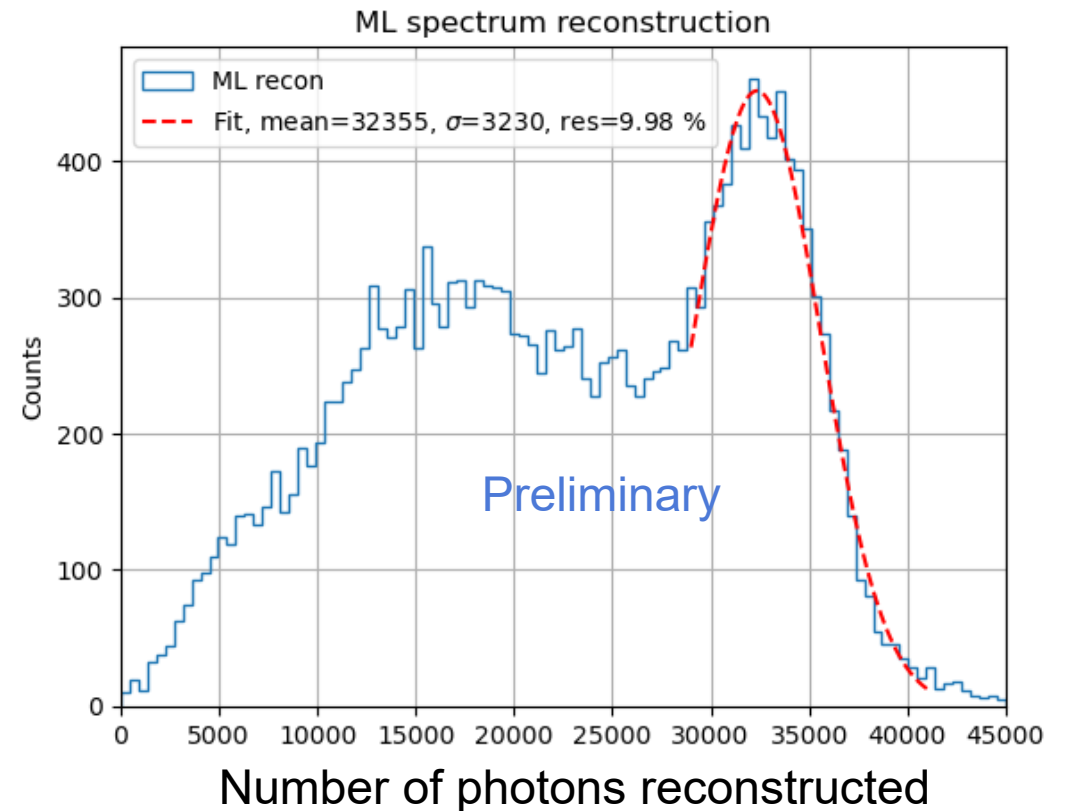


Reconstruction on real data

- Cs-137 (662 keV gamma) data reconstruction.
 - Light yield (LY): $48.88 \pm 4.88 \text{ ph/keV}$.
 - M Szydagis, *et al.*, (2022) NEST report $Ly = 40\sim 60 \text{ ph/keV}$ at $O(10^2 \text{ keV})$
 - <https://doi.org/10.3389/fdest.2024.1480975>
 - Resolution: $9.98 \pm 0.25\%$.
 - A Minamino (2010), XMASS report: $5.6 \pm 0.2 \%$.
 - <https://doi.org/10.1016/j.nima.2010.03.032>



ML reconstruction



Likelihood and fiducial cut applied:
Likelihood < 0.8, events outside of 34mm cube.

Summary

- Conclusion:
 - Light yield estimate is consistent with the literature's value.
 - The results show the energy resolution has massively improved.
- Next steps:
 - This work is still work in progress.
 - Separate multi-site events.
 - Implement dark counts, after pulsing, cross-talk into the simulation model.
- Next runs:
 - Fixed-position internal ^{181}Hf gamma source will be implemented.
 - Internal beta source with wavelength filter.

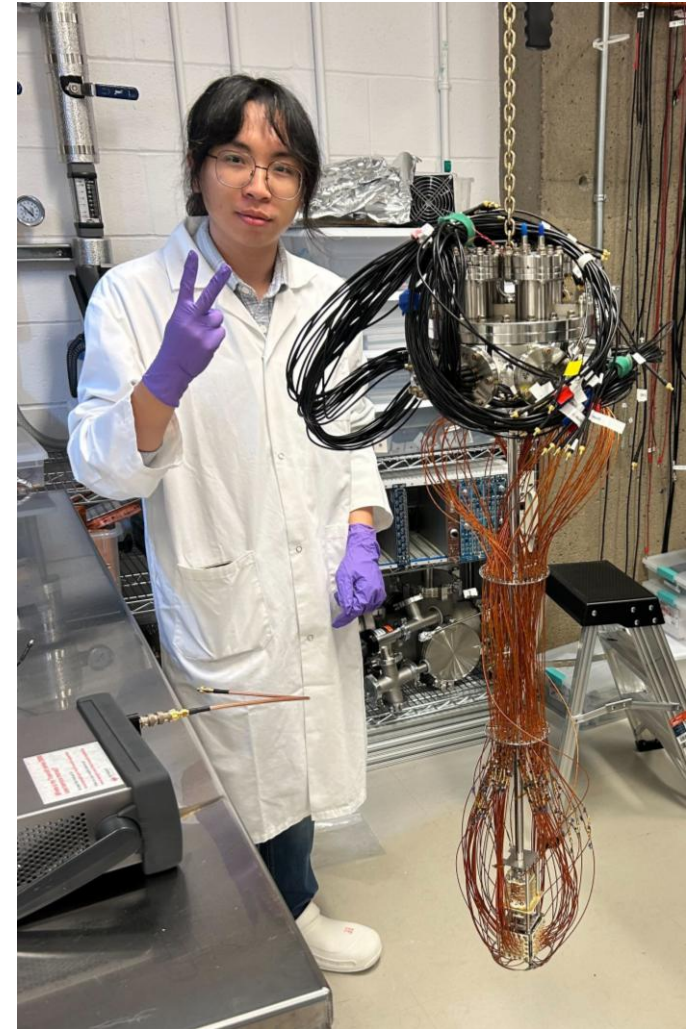


Photo by: D. Gallacher. 2024 Oct

LoLX



Thank you!
Question?



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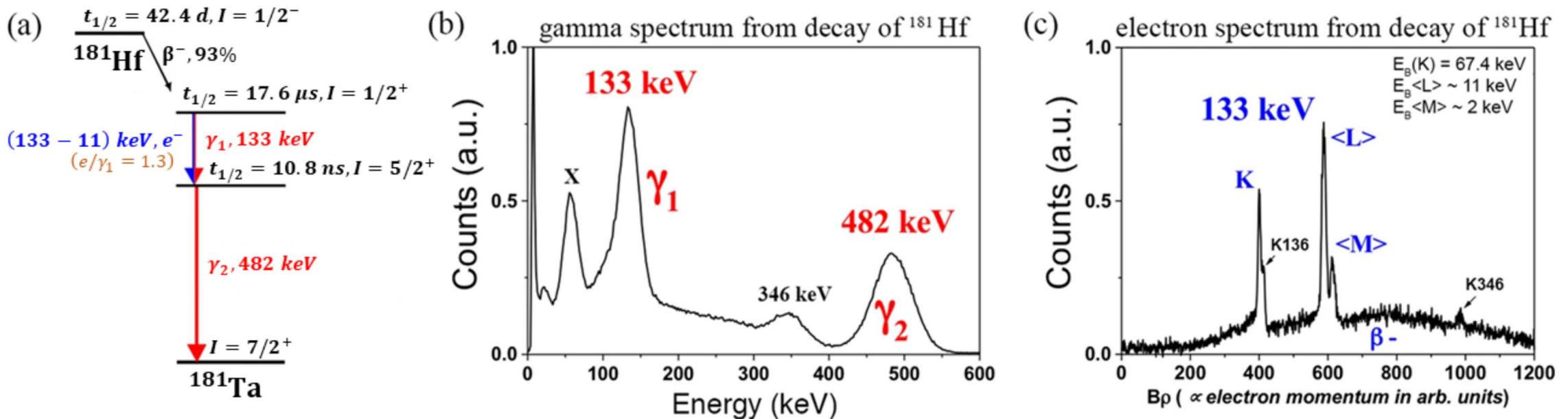


LoLX Collaboration: Canada-US-Italy

This work was supported by the TRIUMF Science and Technology team for engineering assistance, and by the SAP-MRS program through grant funding.

Back up

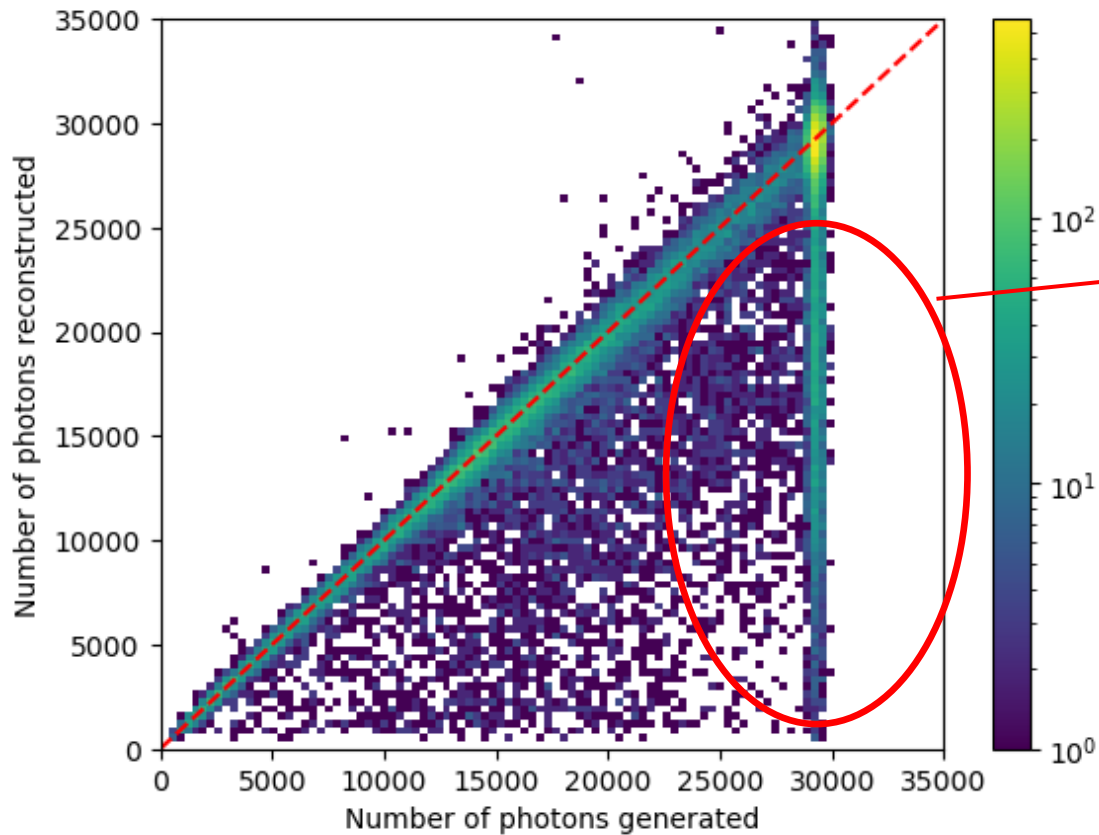
- ^{181}Hf source. Beta decay with end point energy 414 keV, mean energy 120keV.
 - Beta decay from Hf181 to Ta181 $I = 1/2^+$ state.
 - 133 keV gamma emission with $T_{1/2} = 17.6 \mu\text{s}$ after beta, decay from $I = 1/2^+$ to $I = 5/2^+$
 - 482 keV gamma emission with $T_{1/2} = 21.1 \text{ ns}$ from $I = 5/2^+$ to Ta181 ground state.



Ian Chang Jie Yap (2022): <https://doi.org/10.3390/cryst12070946>

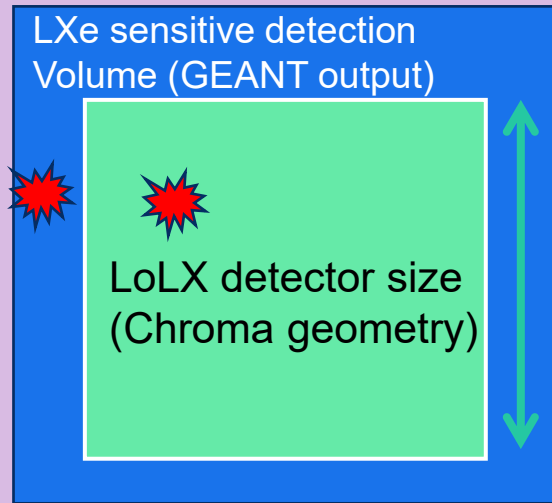
Multi-sites events

Multi-sites energy deposition due to Compton scattering.



*Not to scale

LXe volume



Neural network (NN)

- Feedforward neural network is used.
 - Simple and fast. Good for small detector with few channels.
- NN1: Mapping from source position to DAQ channel charge.

$$\mathbf{r}_s \mapsto \mathbf{q}$$

- Where $\mathbf{q} = [q_0 \dots q_i]$, i is the index in DAQ channels.
- q_i is the fraction of charge observe by channel i .

$$q_i = \frac{Q_i}{N_{gen}}$$

- It is essential because q_i is the link to photon collection efficiency (PCE)

$$PCE = \sum q_i = \frac{\sum Q_i}{N_{gen}}$$

- N_{gen} : Number of photon generated.

- NN2: Mapping from DAQ channels charge to source position.

$$\mathbf{q}_{norm} \mapsto \mathbf{r}_s$$

- Where $q_{i,norm} = \frac{q_i}{\sum q_i} = \frac{Q_i}{\sum Q_i}$

Reconstruction steps

Apply the ML neural network

$$Q_{obs} \Rightarrow \mathbf{q}_{norm} \mapsto \mathbf{r}_{s,recon} \mapsto \mathbf{q} \Rightarrow N_{s,recon}$$

- Where Q_{obs} is the charge in DAQ channel. It can be simulation or real data.
- Important to note that \mathbf{q}_{norm} and \mathbf{q} are different!

$$q_{i,norm} = \frac{q_i}{\sum q} = \frac{Q_i}{\sum Q_i}$$

$$q_i = \frac{Q_i}{N_{gen}}$$

- $PCE = \sum q_i = \frac{\sum Q_i}{N_{gen}}$

$$N_{s,recon} = \frac{\sum Q_i}{PCE} = \frac{\sum Q_i}{\sum q_i}$$

Likelihood function

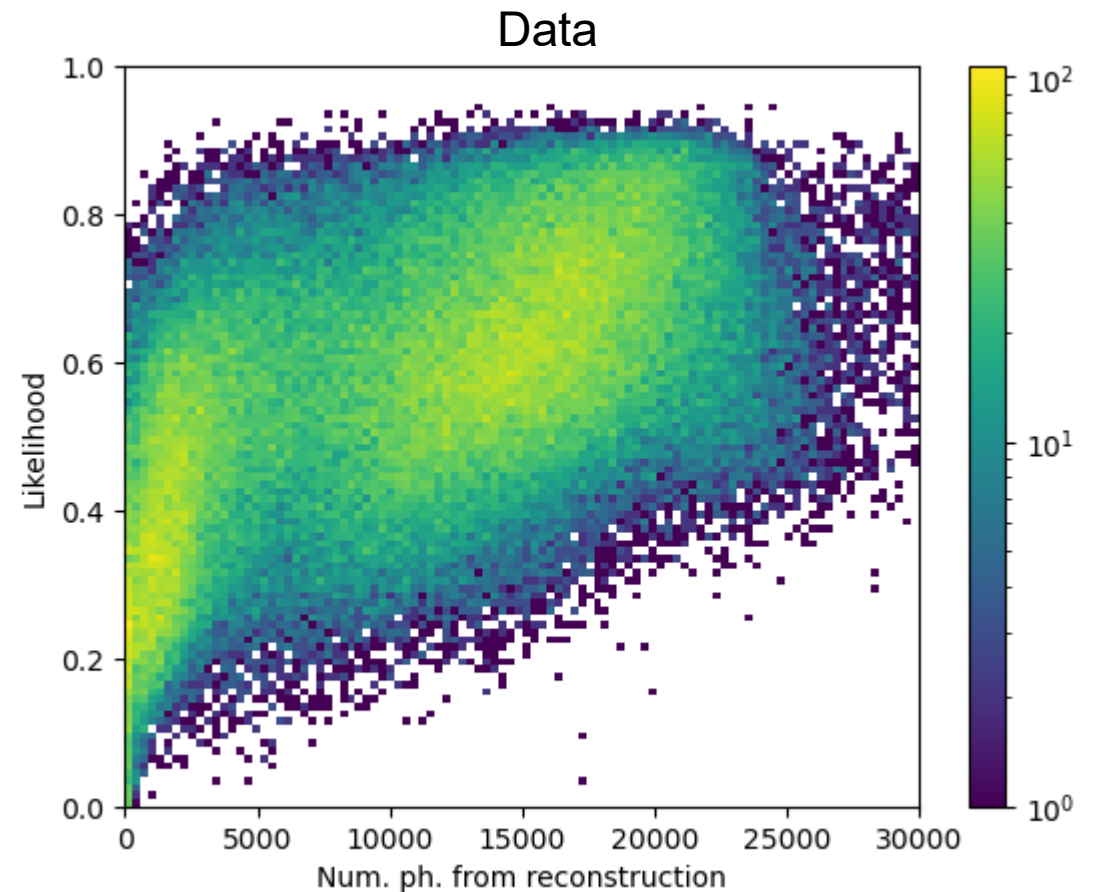
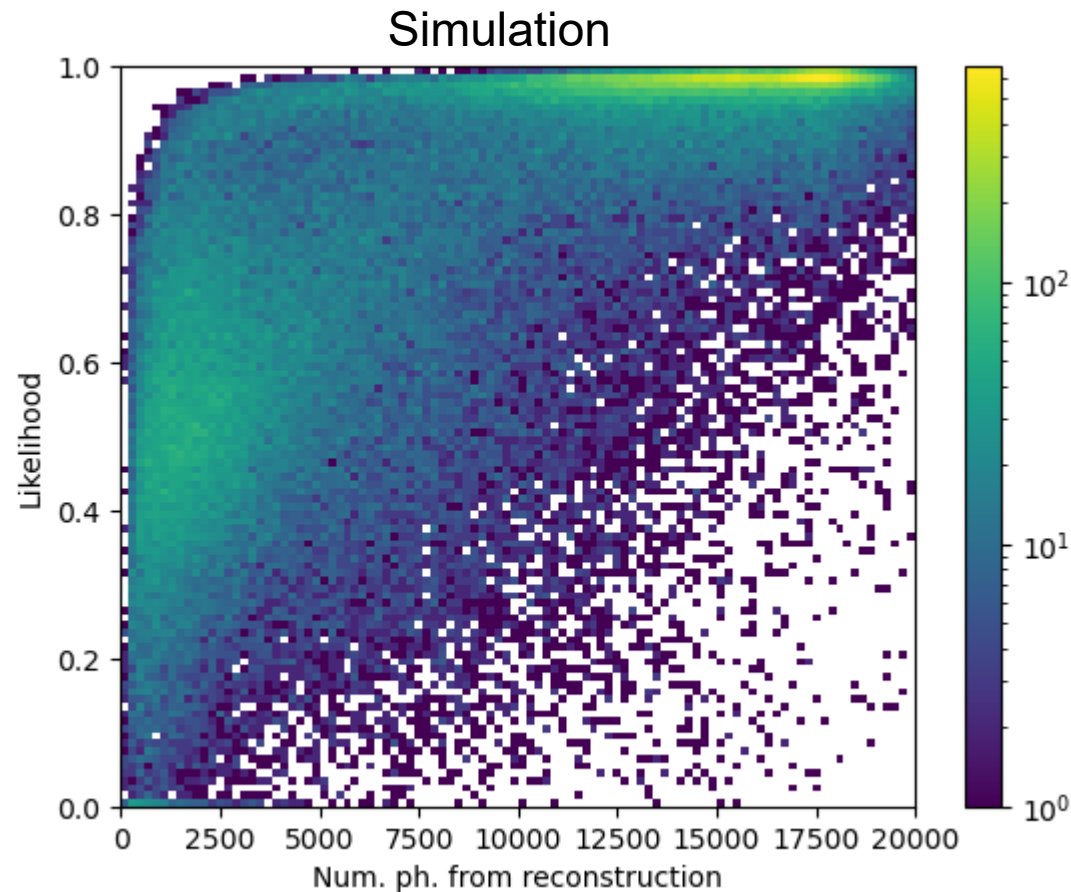
- KL-divergence base NLL function:

$$L(\mathbf{r}_s) = \sum_i p_i \ln \frac{p_i}{q_{i,norm}(\mathbf{r}_s)}$$

- P_i : Charge ratio in each channel in real data.
- Q_i : ML reconstruct charge ratio in each channel.
- From the LoLX data, charge ratio detected in channel i : $p_i = \frac{Q_{i,data}}{\sum_i Q_{i,data}}$.
- Reconstruct photon ratio in channel i , $q_{i,norm}(r_{recon}) = \frac{q_i}{\sum q_i}$
 - Same $q_{i,norm}$ in page 10.

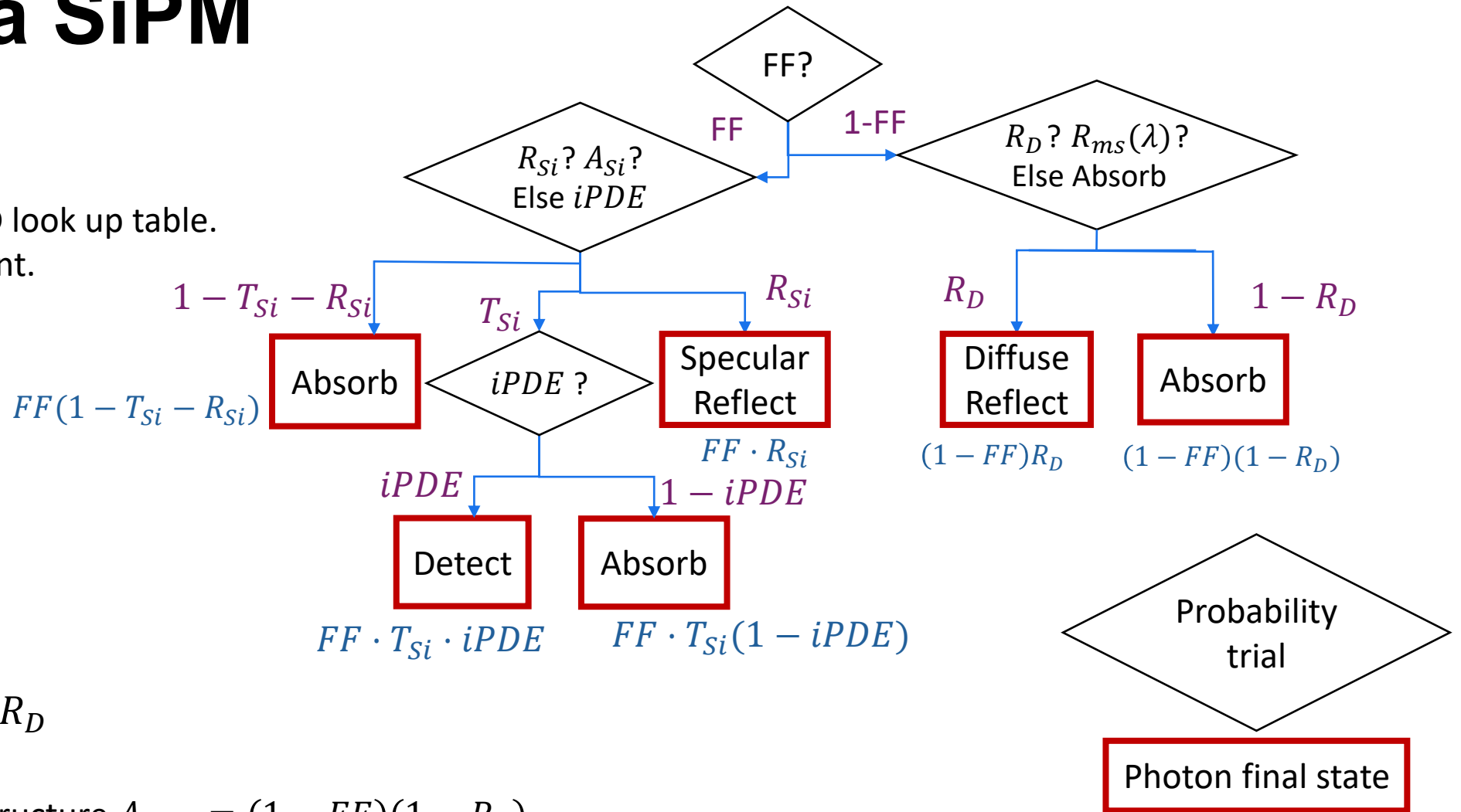
Likelihood vs number of photon

-



Chroma SiPM

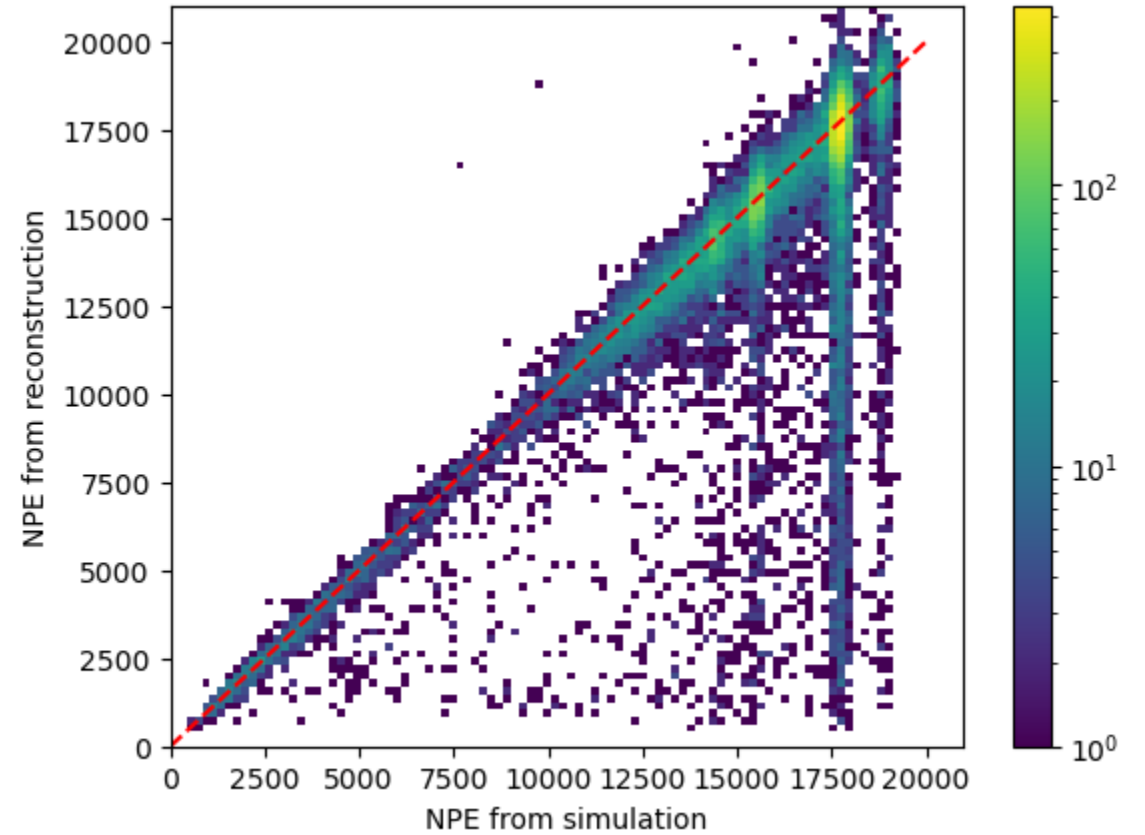
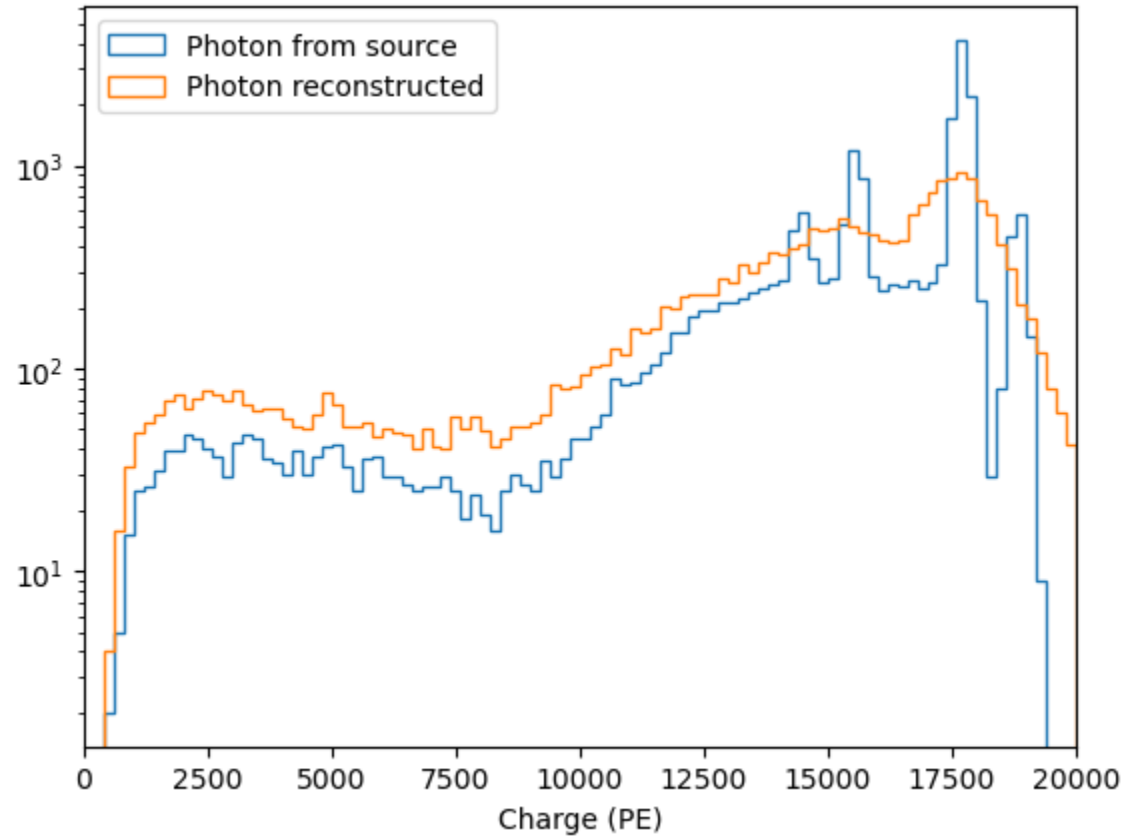
- Input:
 - $T_{Si}, R_{Si}, iPDE$, : 2D look up table.
 - R_D, FF : Fix constant.



- Effective probabilities:
 - $R_{D,eff} = (1 - FF)R_D$
 - $R_{Sp,eff} = FF \cdot R_{Si}$
 - Absorb in microstructure $A_{refl} = (1 - FF)(1 - R_d)$
 - For small wavelength, neglected in model just for now.
 - $PDE = FF \cdot T_{Si} \cdot iPDE = FF \cdot (1 - R_{Sp})iPDE$

Purple text: probability in the trials.
Blue text: effective probability.

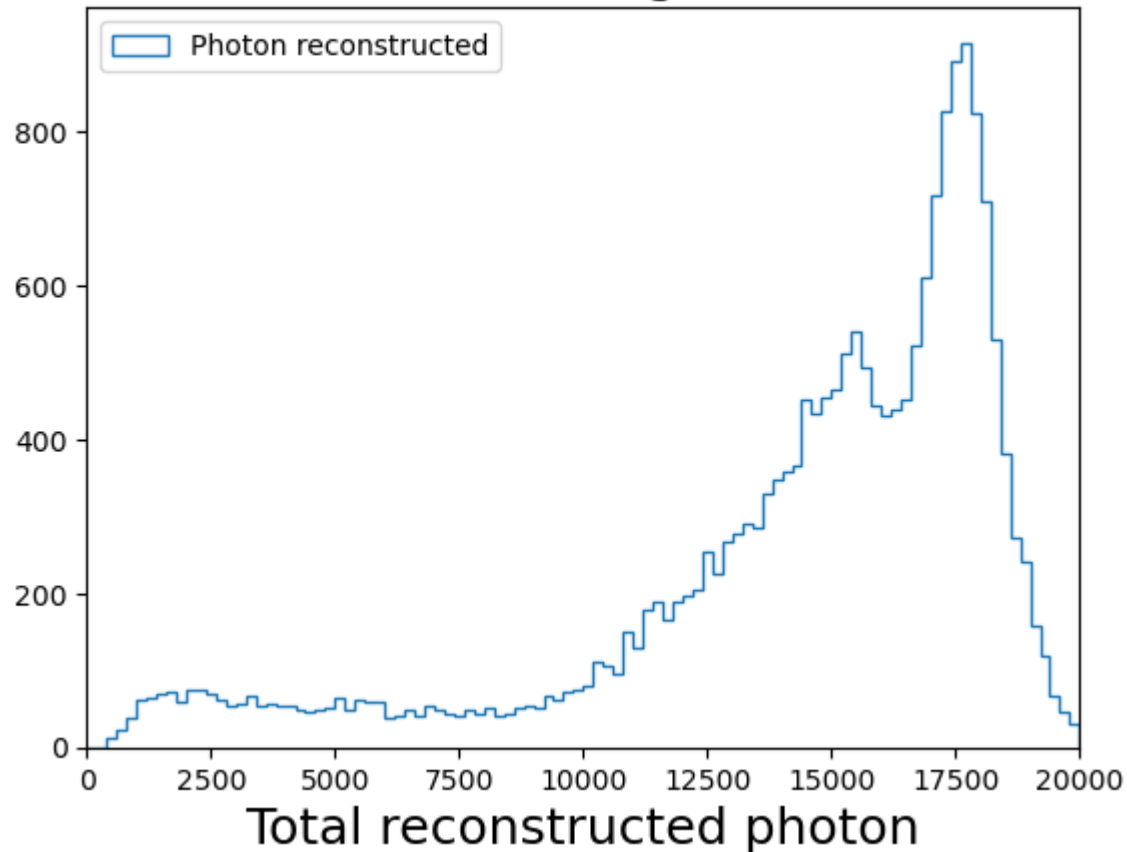
Ba-133 Simulation



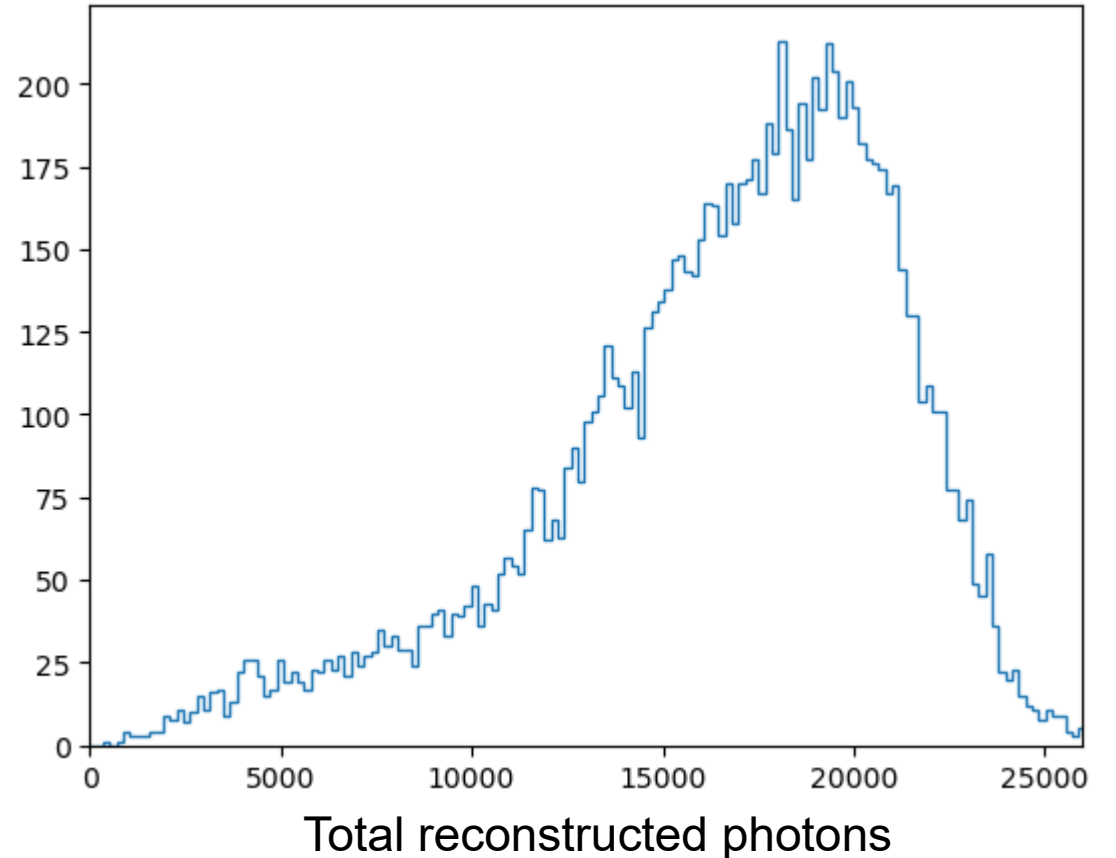
Ba-133 Simulation data compare

- Same Cut apply on likelihood and fiducial volume.

Reconstructed base on gamma simulation



Ba-133 Data reconstruction



Compare LoLX1 and LoLX2



- Problems found in LoLX1:
 - Fluorescence from 3D-printed plastic.
 - Detector light yield is lower than expected.
 - LXe impurity?
 - SiPMs have lower efficiency?
- Improvements:
 - Adding a PMT.
 - Benchmarking SiPMs Photon detection efficiency (PDE).
 - Comparing FBK and Hamamatsu SiPMs performance.
 - Never did it in LXe before, only in vacuum.
 - Installing a purity monitor.
 - Upgrading to a faster DAQ system.

