Light-only Liquid Xenon experiment:
Energy and position reconstruction with SiPMs PDE model

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On behalf of LoLX collaboration

LIDINE 2025

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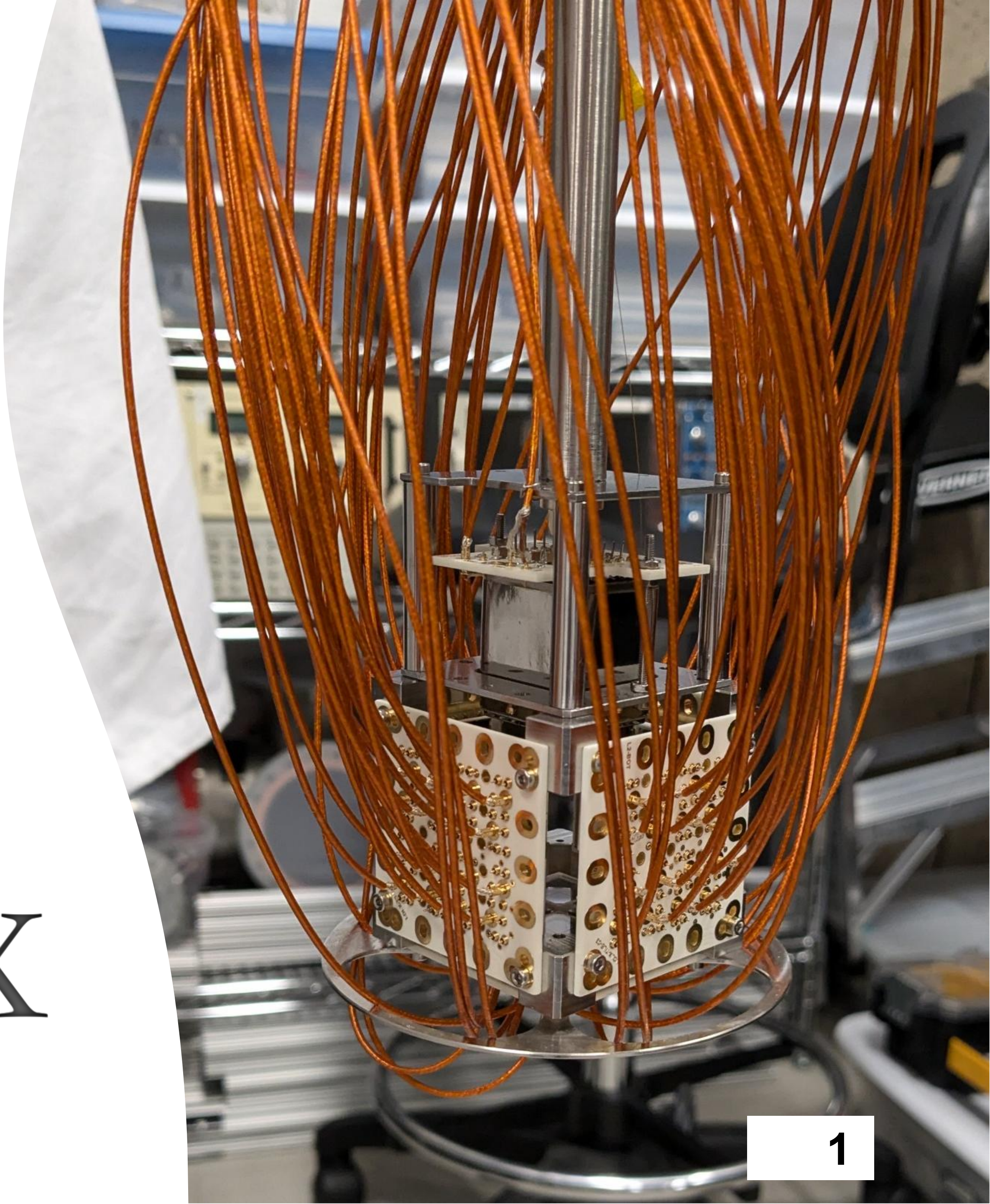
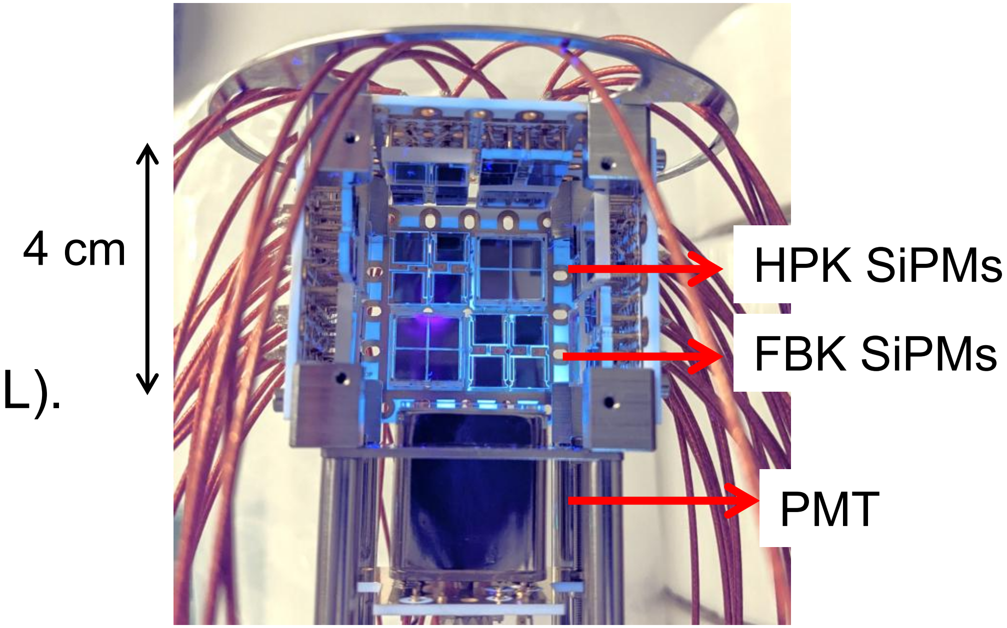
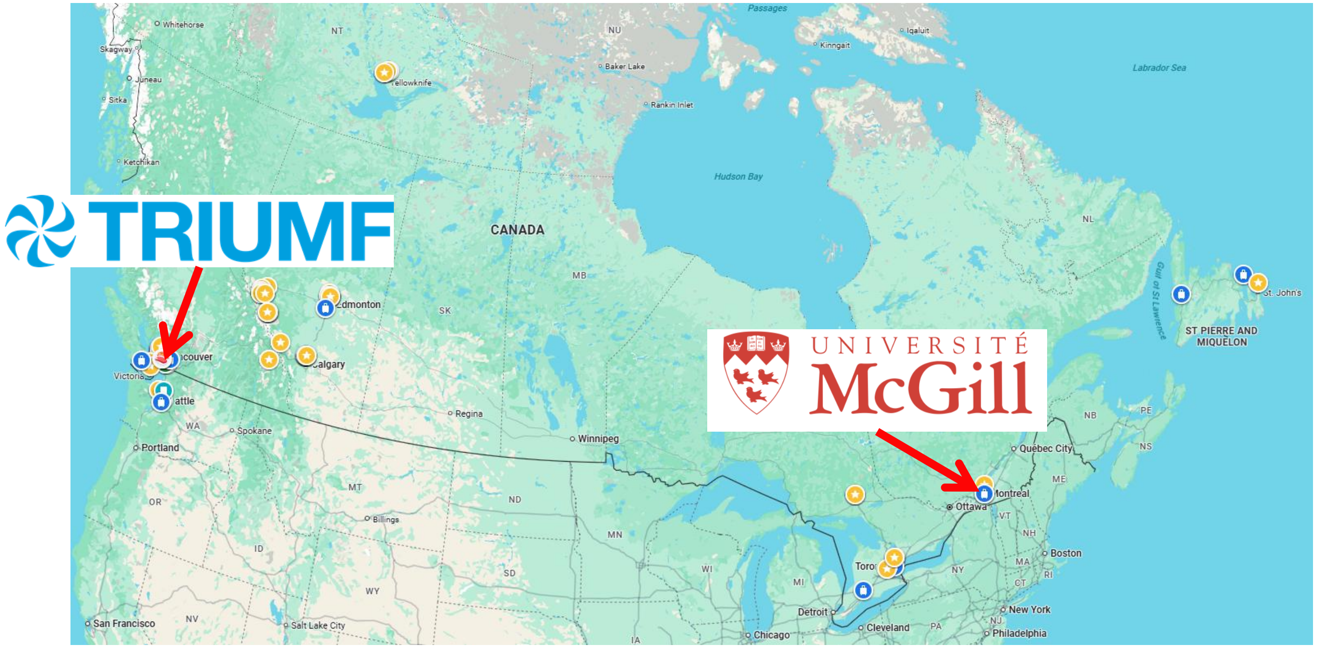


What is LoLX?

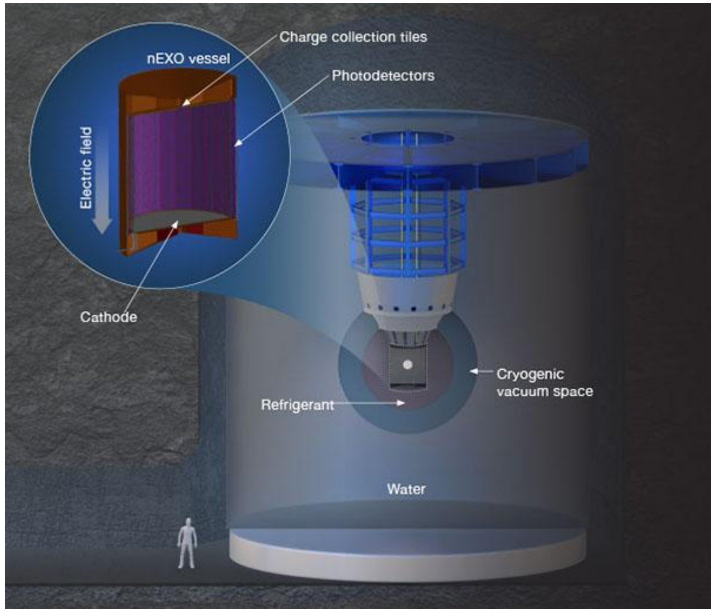
- LoLX: **L**ight-**O**nly **L**iquid **X**enon experiment.
  - Modular cube array of photosensors immersed in liquid xenon (LXe).
  - Built at TRIUMF by Science & Technology group.
  - Operated at McGill University, Brunner Neutrino Lab (BνL).



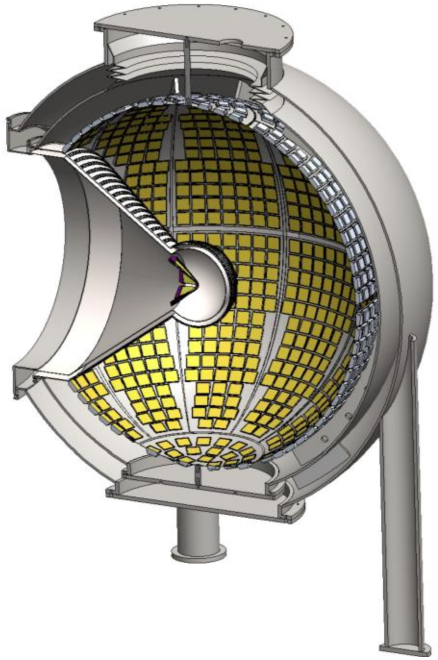


Goals

- **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.
    - Available at arXiv:2510.15270 .
  - External cross-talk study.
    - Published on EPJ C: 2502.15991.
    - Lei's presentation on Wednesday.
  - Long term stability operation.



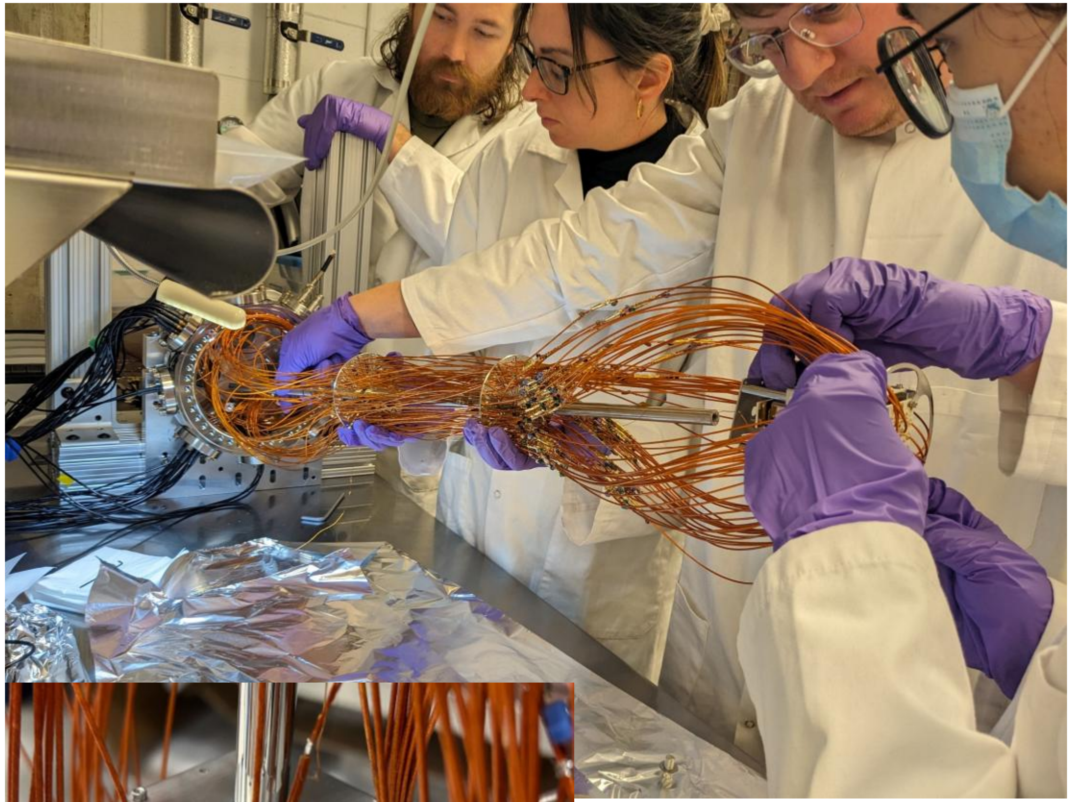
nEXO:
Neutrinoless double beta decay search

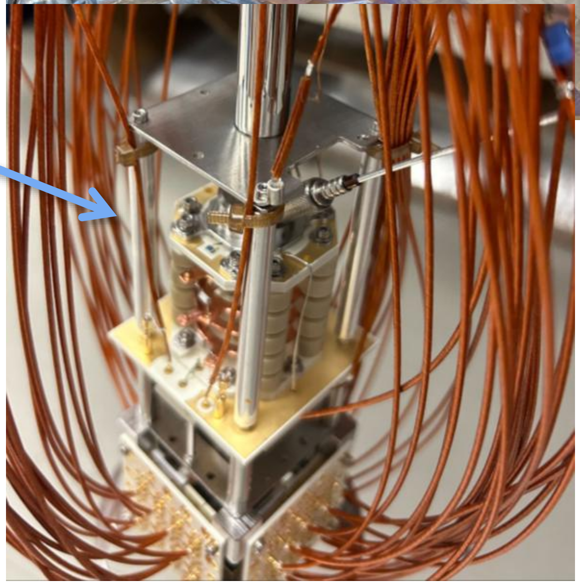


PIONEER:
Lepton flavor universality

LoLX runs

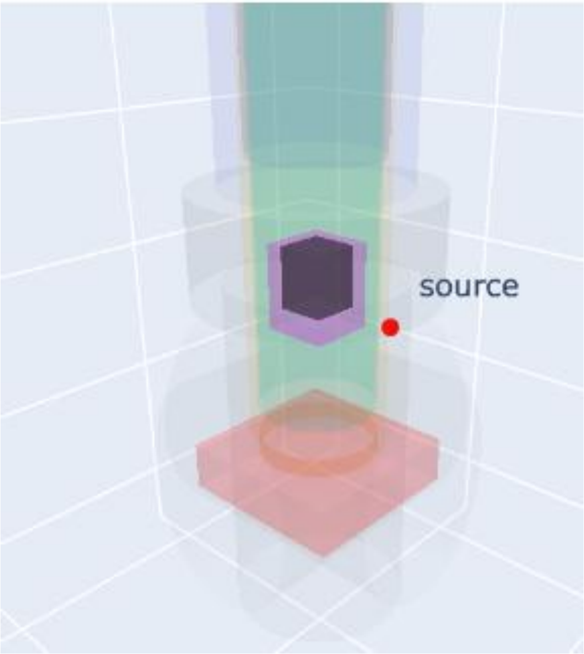
- LoLX runs:
  - Laser calibration and background runs.
  - External gamma sources.
    - $^{22}\mathrm{Na}$, $^{133}\mathrm{Ba}$, $^{137}\mathrm{Cs}$
  - Xenon purity monitor (PUMA) testing.
- 2026 (Planning) – physics runs:
  - Internal $^{181}\mathrm{Hf}$ source.
  - ^{90}Sn beta source for study Cherenkov.

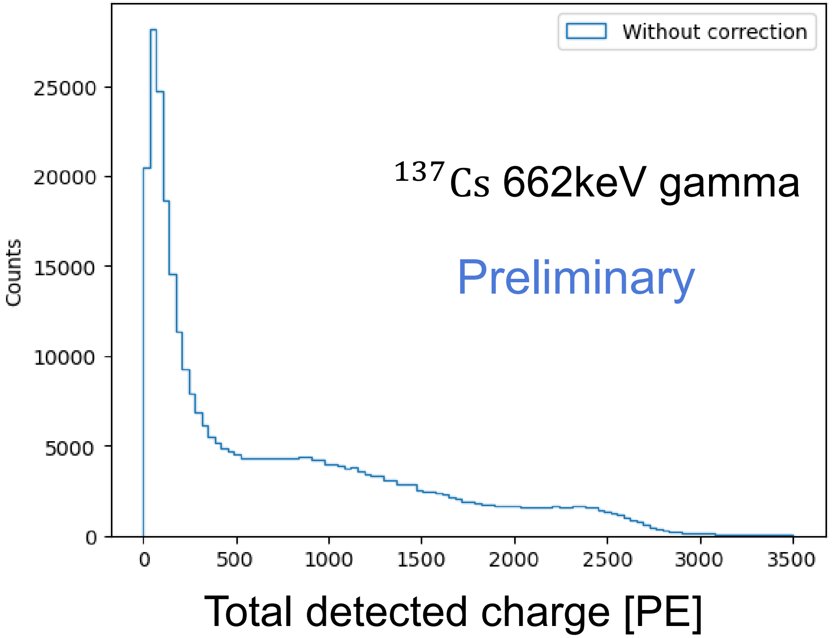


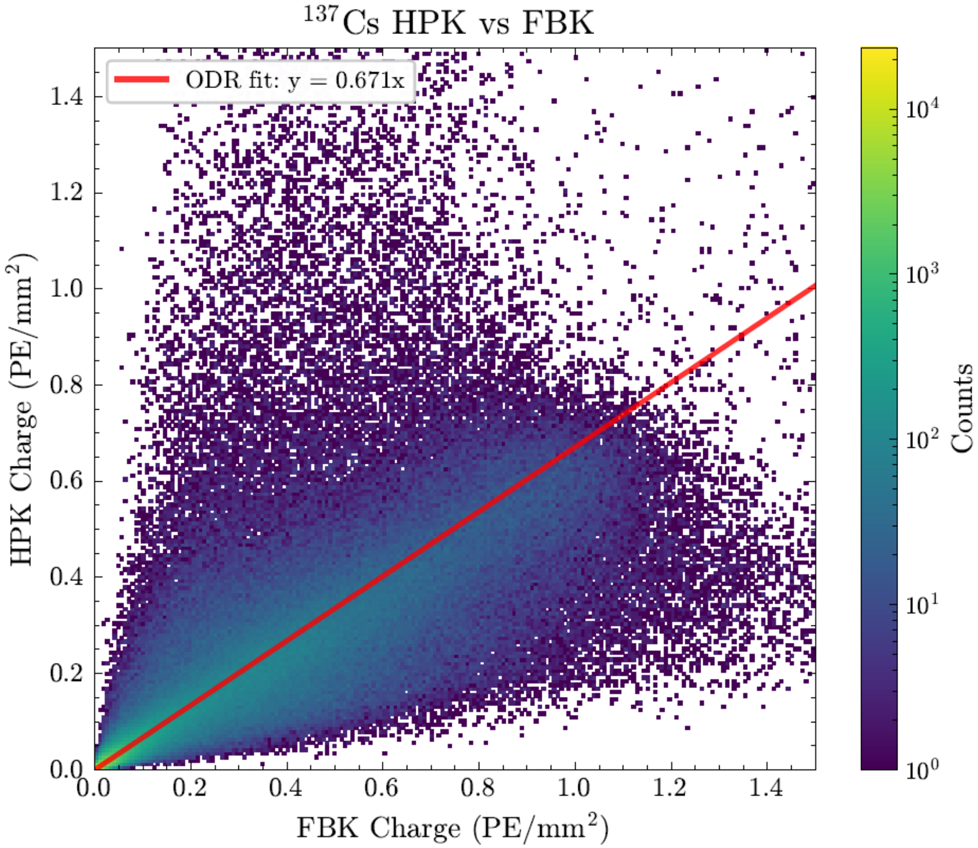


Challenges in LoLX data

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







arXiv:2510.15270

Wavelength and angular dependent PDE model

- SiPM PDE model arXiv:2508.16005v1.
  - Optical effects, avalanche probabilities.
- What does it mean for our experiment, and potential to yours:
  - PDE is convoluted with photon transport efficiency in the event level.
  - External cross talk impacts differently for *FBK HD3* and *HPK VUV4*.

FF: Fill factor.
$T(\lambda,\theta)$: Transmission.
$iPDE(\lambda,V_{OV})$: Internal PDE.
AOI: angle of incidence.

Absolute PDE: $APDE(\lambda,\theta,V_{OV}) = FF \cdot T(\lambda,\theta) \cdot iPDE(\lambda,V_{OV})$

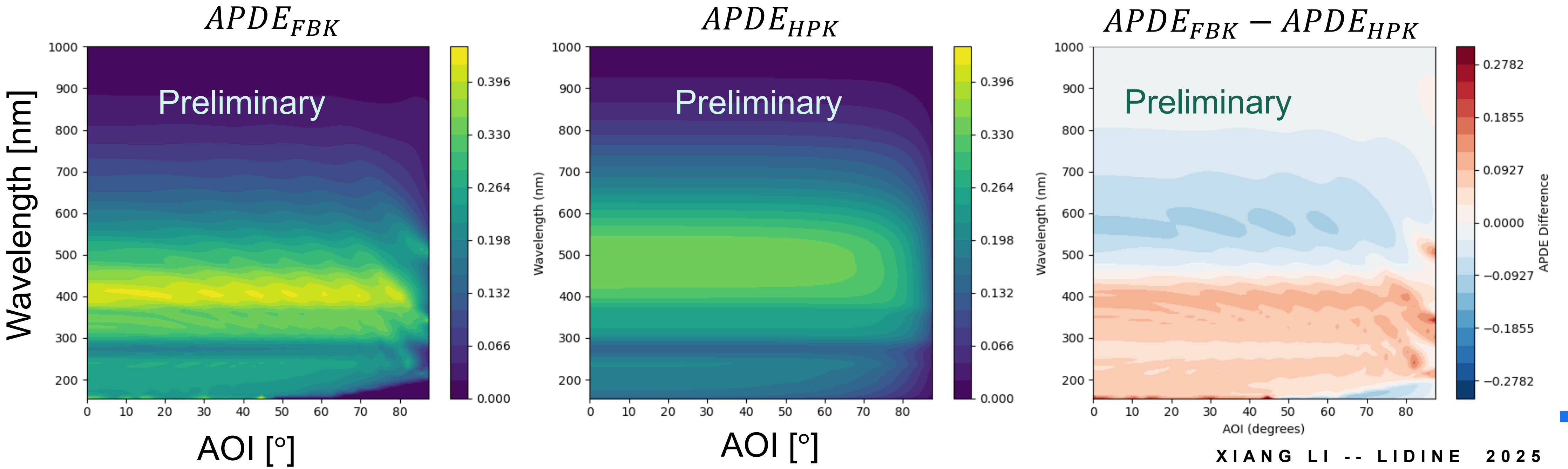
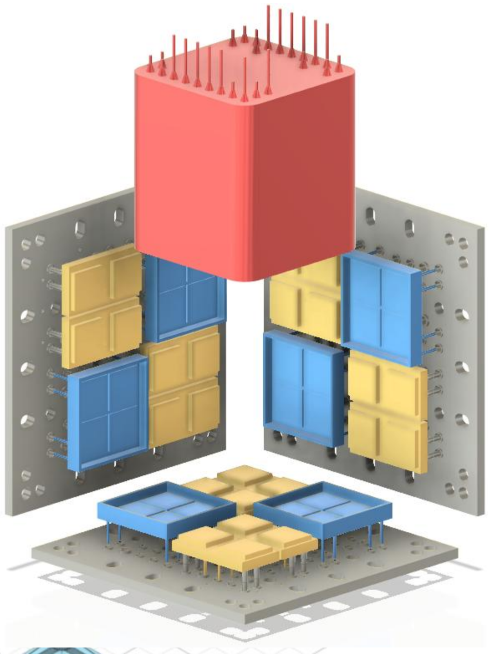
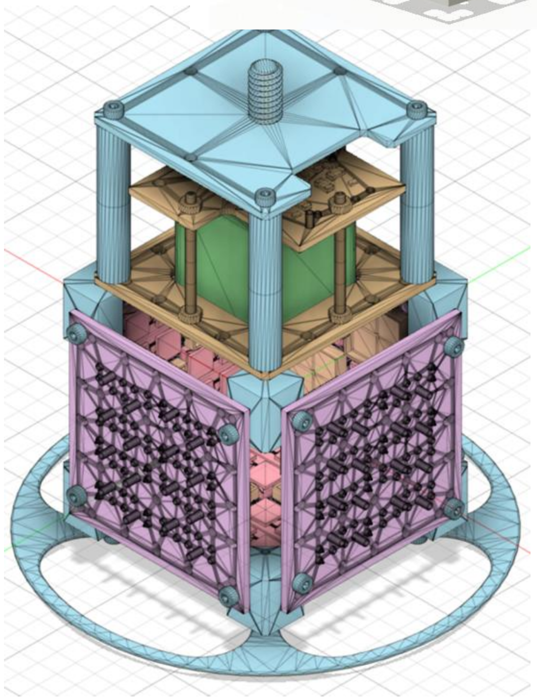


Figure shows PDE in Lxe with 3V overvoltage.

Chroma – GPU Optical Simulation

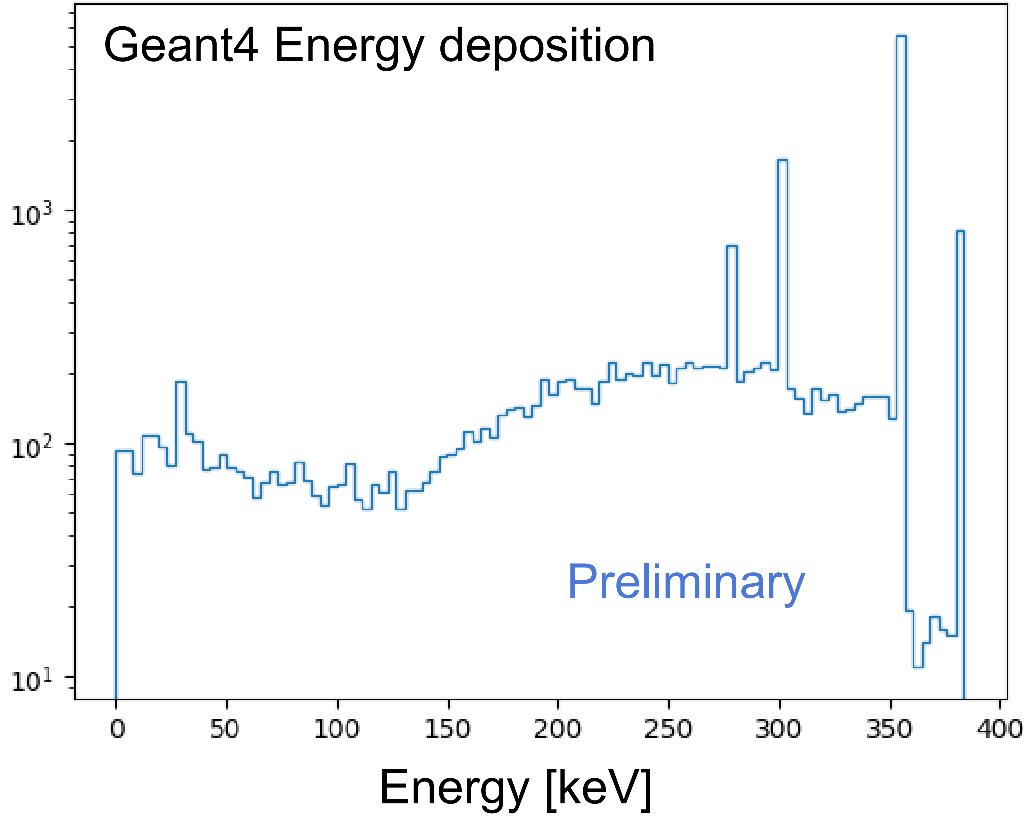
- Chroma is an optical photon simulation for particle physics detectors.
- GPU-based photon transport simulation.
  - Development in Python (core simulation in CUDA-C).
  - ~200x faster than G4OpticalPhoton.
- Does:
  - Take the energy deposition in GEANT4 as input.
    - Or other user defined photon generators.
  - Optical Photon Transport.
    - Refractive index, wavelength shifter, scattering, attenuation length…
  - Photon Detection.
    - Angular and wavelength dependent SiPM model (arXiv:2508.16005v1) based on measurement at TRIUMF.
    - Fully customized detection logic.

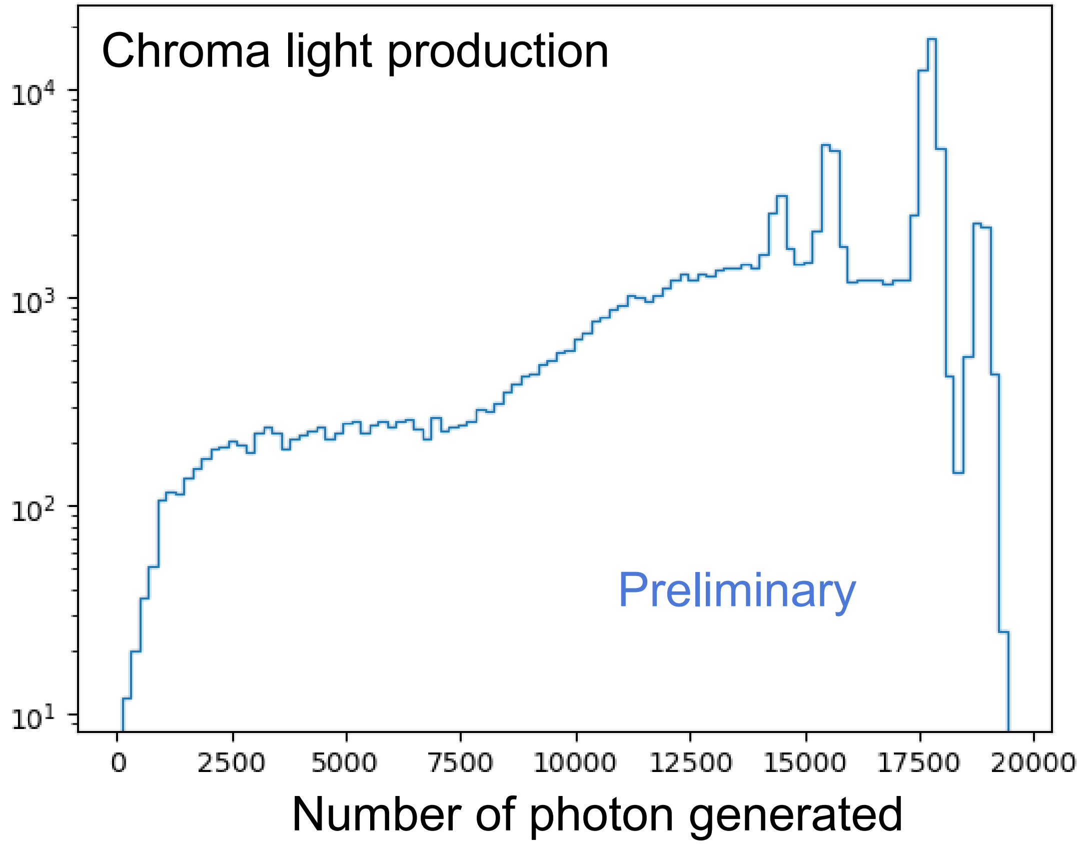




Geant 4 and Chroma

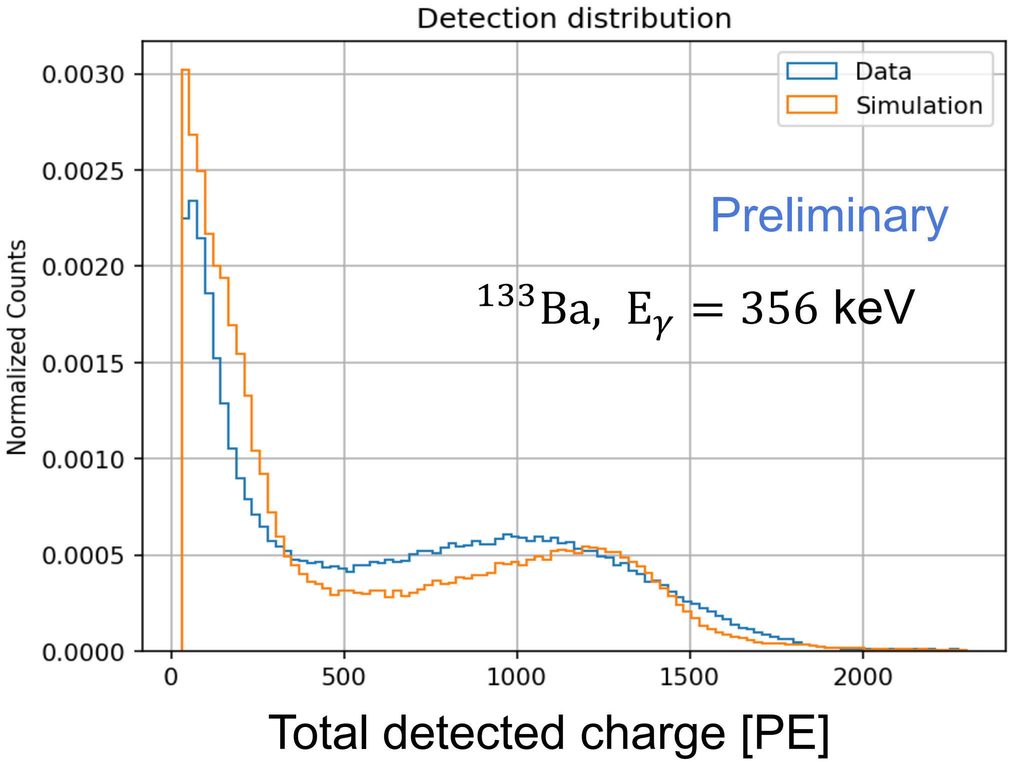
- Energy deposition in GEANT4 vs light production in Chroma.
  - Light yield base on NEST model.
    - NEST: [Noble Element Simulation Technique](#).
- Ba-133 source example:

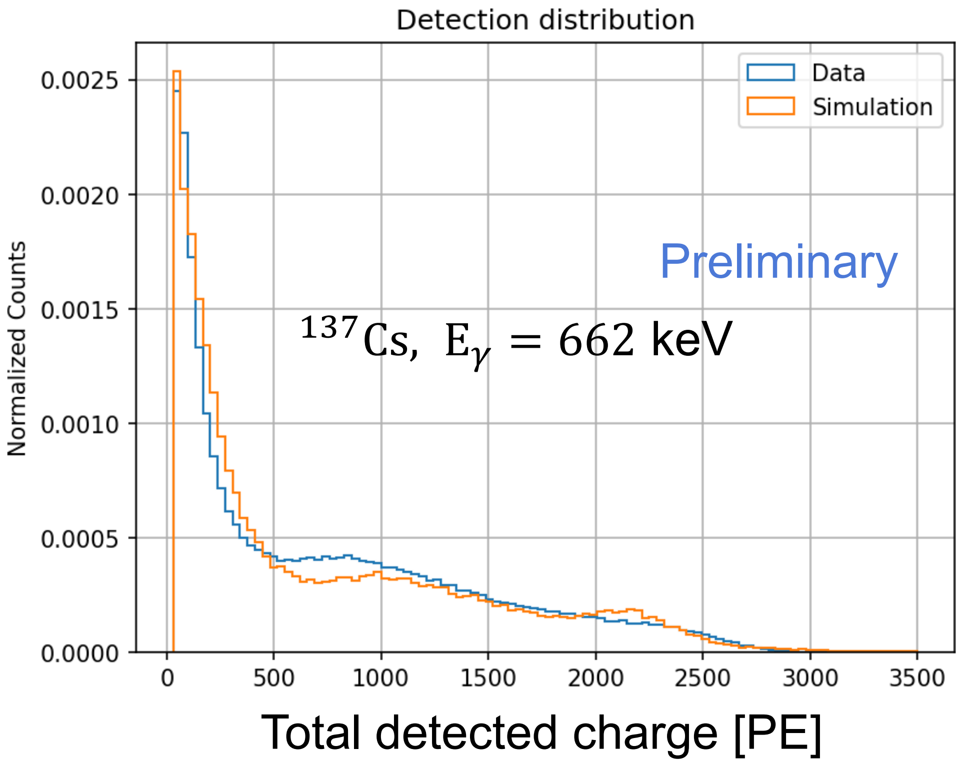




Simulation data compare

- 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 ~356keV.
  - NEST photon generator.
  - Scintillation photons with real wavelength distribution.
- Feedforward neural network (FNN).

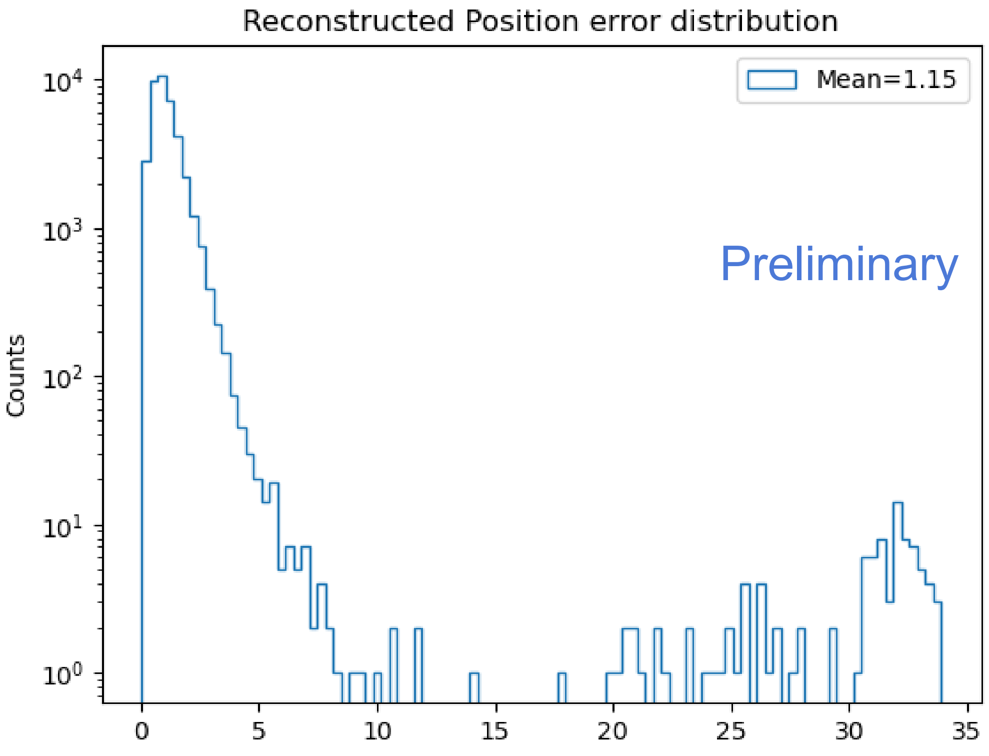
Hit patterns $\xrightarrow{\text{NN1}}$ Position $\xrightarrow{\text{NN2}}$ Photon collection efficiency ($\boldsymbol{PCE}$)

$$N_{recon} = \frac{\sum Q_i}{\sum PCE_i}$$

- $\boldsymbol{Q}$ $[Q_1 \ldots Q_{27}]$: Number of PE detected by each channels (array of 27 channels).
- $\boldsymbol{PCE}$ $[PCE_1 \ldots PCE_i]$:Photon collection efficiency for each channel (array of 27 channels).
  - Include all optical effects, transport efficiency and photon detection efficiency.

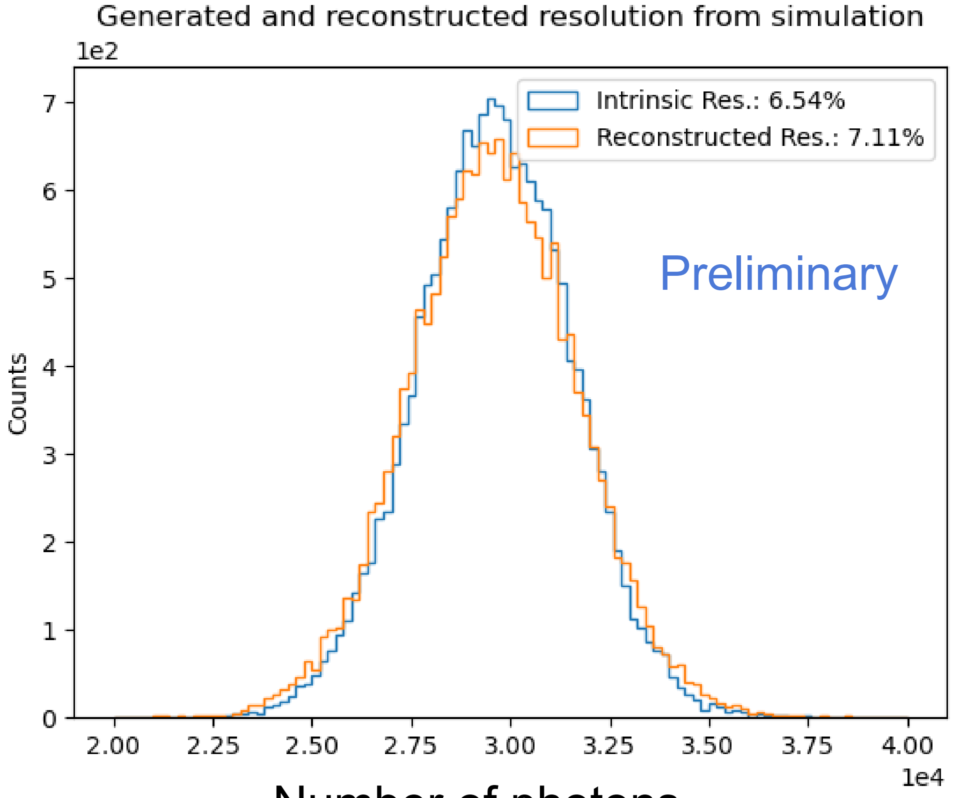
Validation within simulation – Electron gun

- Validated simulation with electron gun energy 662 keV using NEST generator.



Euclidean distance error [mm]

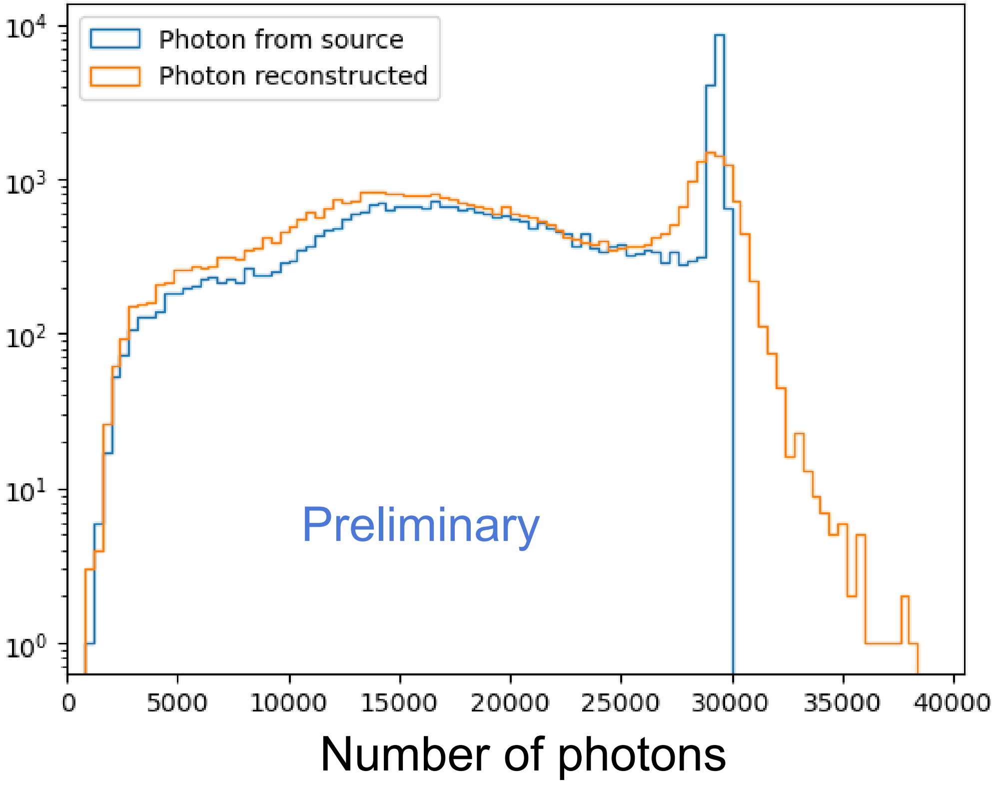
Fiducial cut events outside of 34mm cube.

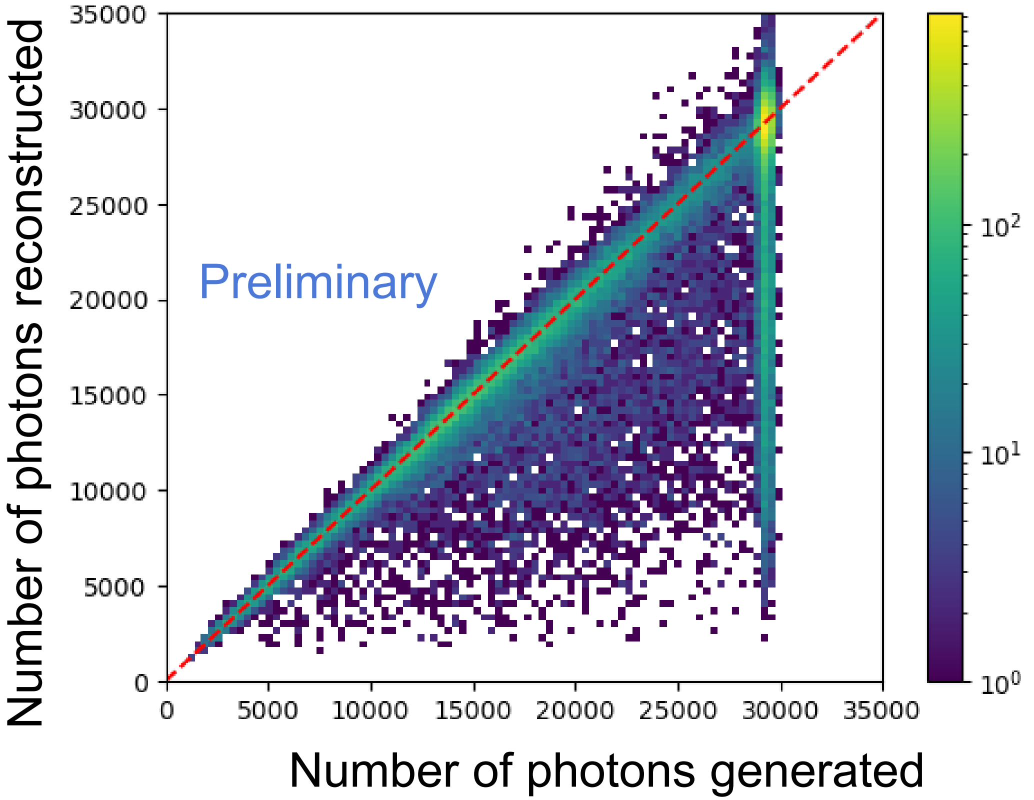


Number of photons

Validation within simulation – Gamma ray

- Geant 4 produced Cs-137 decay gamma ray (662keV).
- Chroma handles optical photons base on the energy deposition.

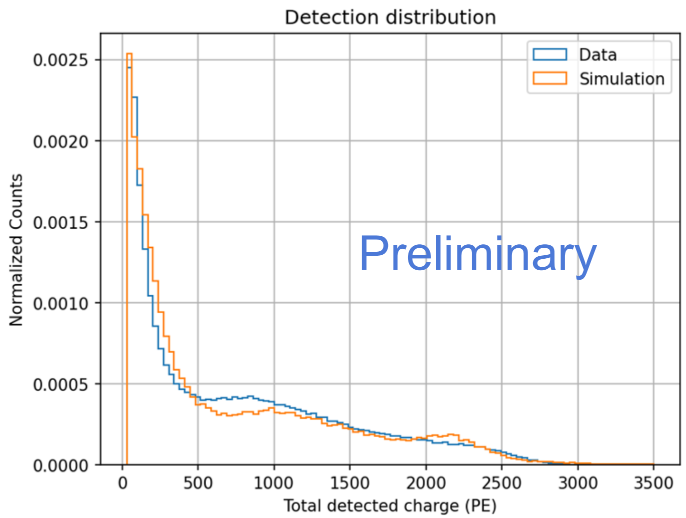




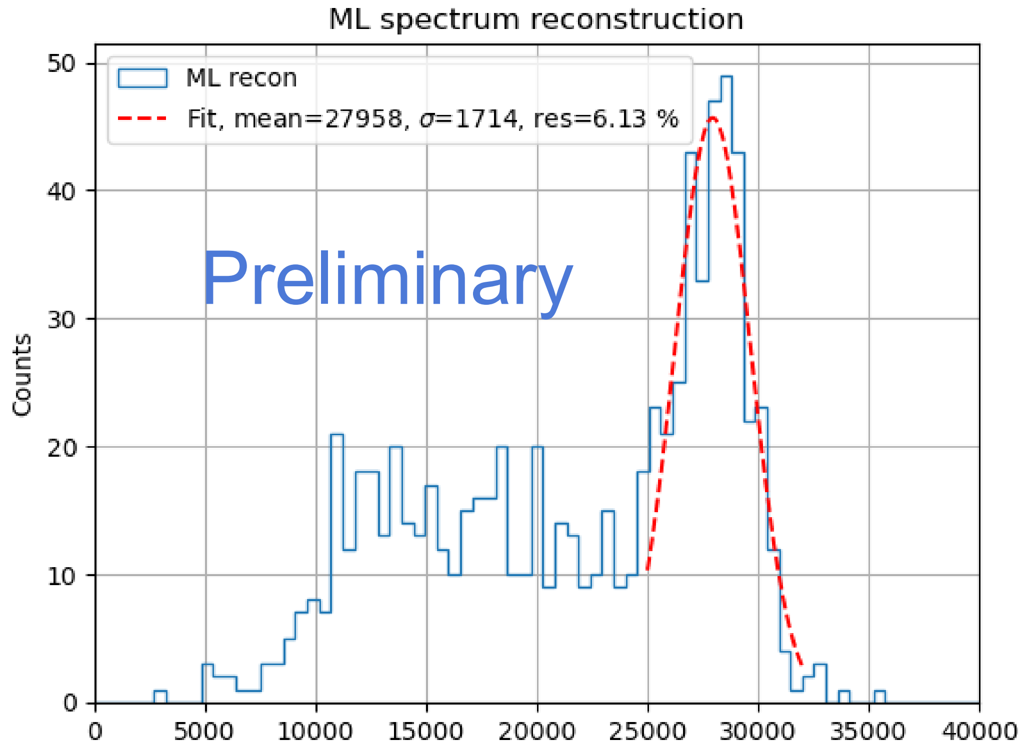
Likelihood and fiducial cut applied:
Likelihood<0.95, events outside of 34mm cube.

Reconstruction on real data

- Cs-137 (662 keV gamma) data reconstruction.
  - Light yield (LY): $42.2 \pm 3.8\ ph/keV$.
    - NEST γ-ER LY: 55 ~ 65 ph/keV
    - NEST β-ER LY: 40 ~ 50 ph/keV
      - https://doi.org/10.3389/fdest.2024.1480975
  - Measure Resolution: $6.1 \pm 0.6\%\ (\sigma/\mu)$
    - A Minamino (2010), XMASS report: $5.2\ \pm\ 0.2\ \%$.
      - https://doi.org/10.1016/j.nima.2010.03.032



ML reconstruction

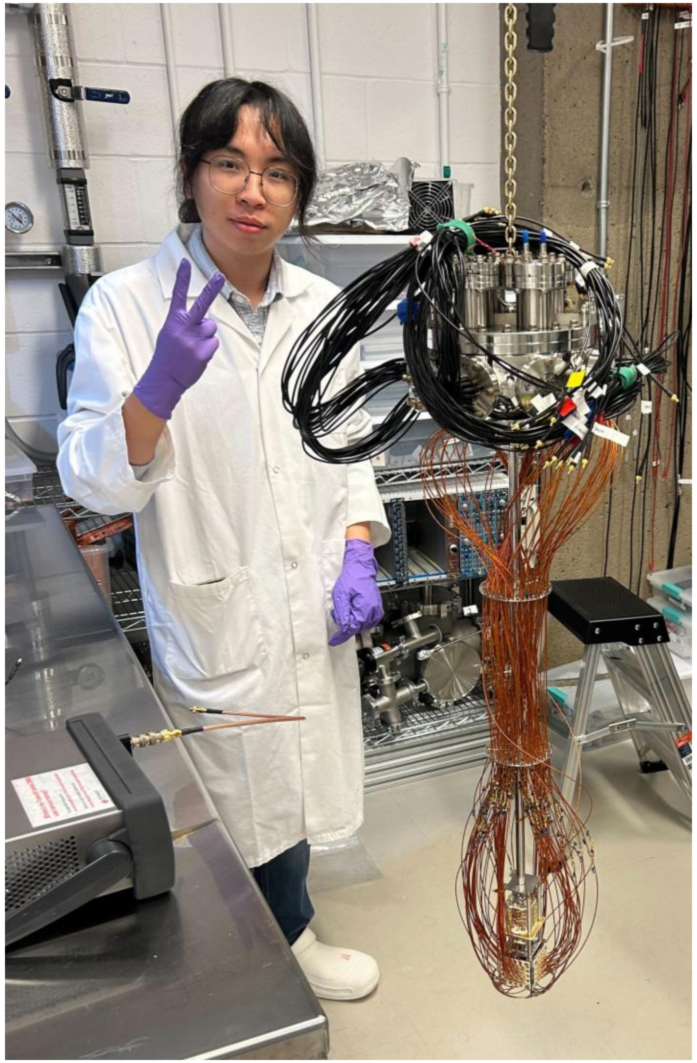


Likelihood and fiducial cut applied:

Likelihood<0.95, events outside of 34mm cube.

Summary

- Conclusion:
  - We validate the PDE model by using the LoLX data.
  - Energy resolution agree with XMASS.
- Next steps:
  - This work is still work in progress.
    - Implement dark counts, cross-talk into the simulation model.
    - Constrain the intrinsic LXe resolution value with all source of fluctuation from instrument.
  - Next runs:
    - Fixed-position internal $^{181}\mathrm{Hf}$ gamma source will be implemented.
    - Internal beta source with wavelength filter.



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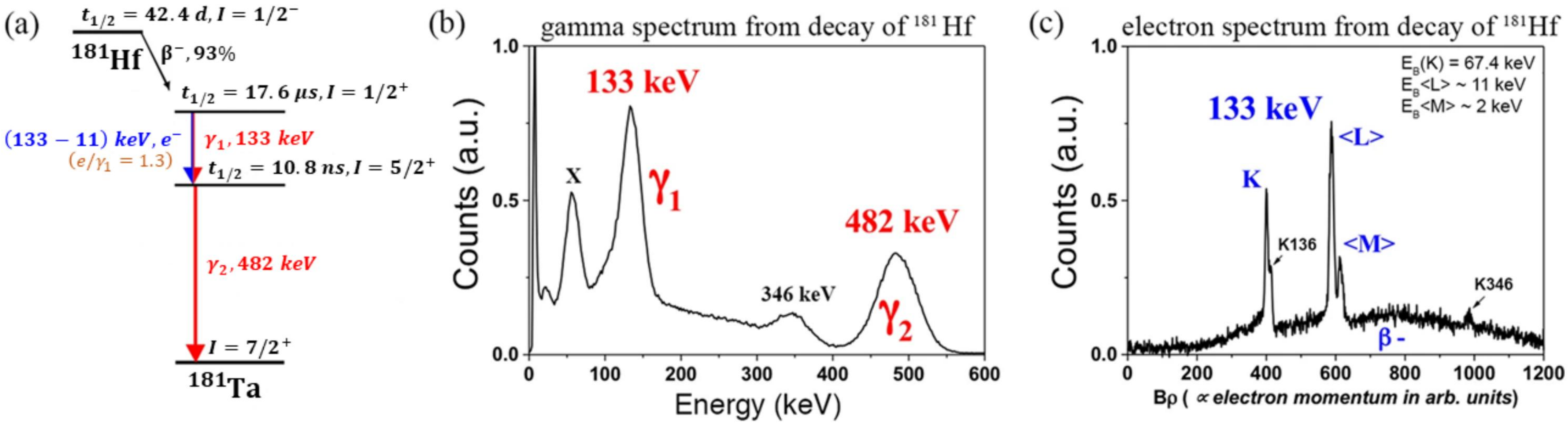
Thank you!
Question?

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

LoLX Collaboration: Canada-US-Italy- Nigeria

Back up

- $^{181}\mathrm{Hf}$ 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 $T_{1/2} = 17.6\ \mu s$ after beta, decay from $I = 1/2^+$ to $I = 5/2^+$
  - 482 keV gamma emission with $T_{1/2} = 21.1\ ns$ from $I = 5/2^+$ to Ta181 ground state.



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

Hf181 simulation

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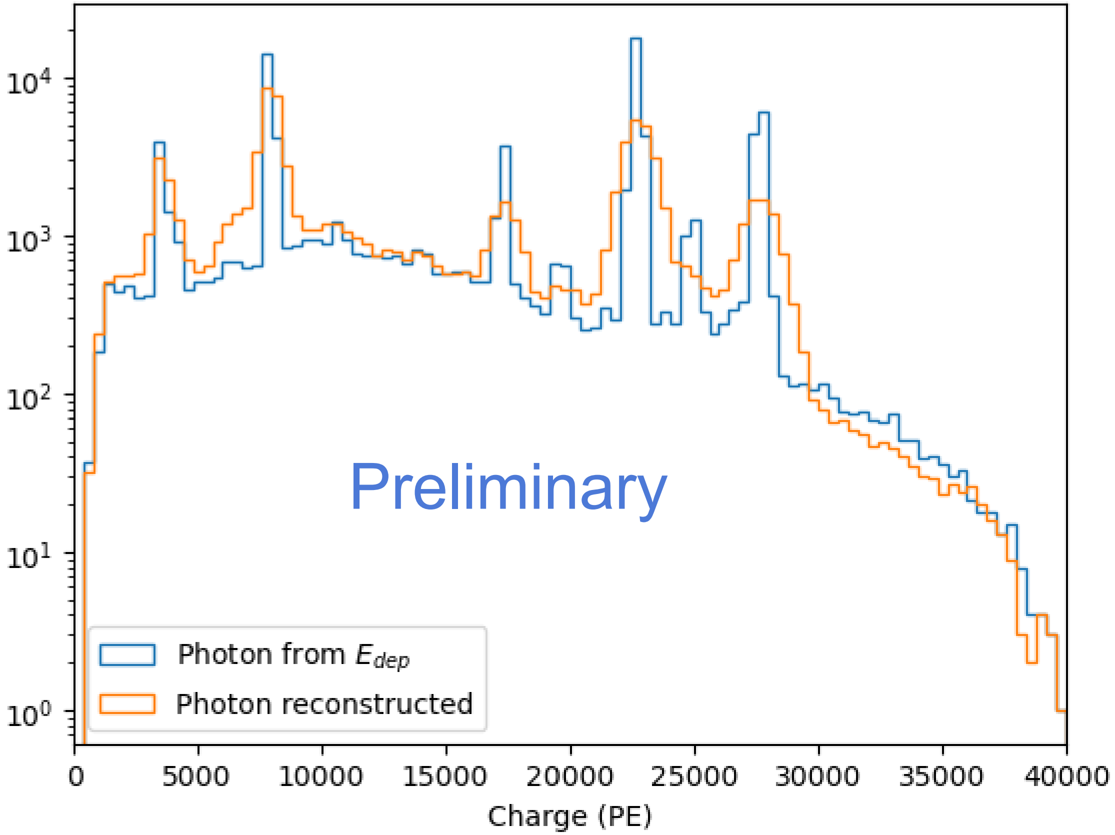
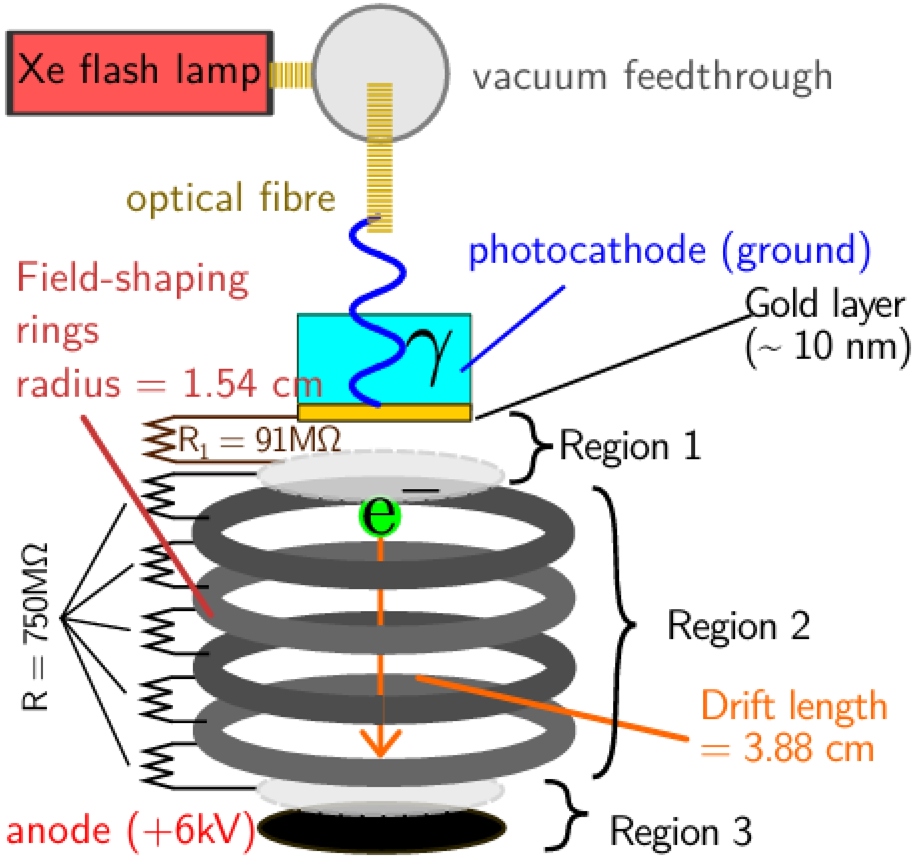


Credit to E. Klemets' work:

How PUMA works

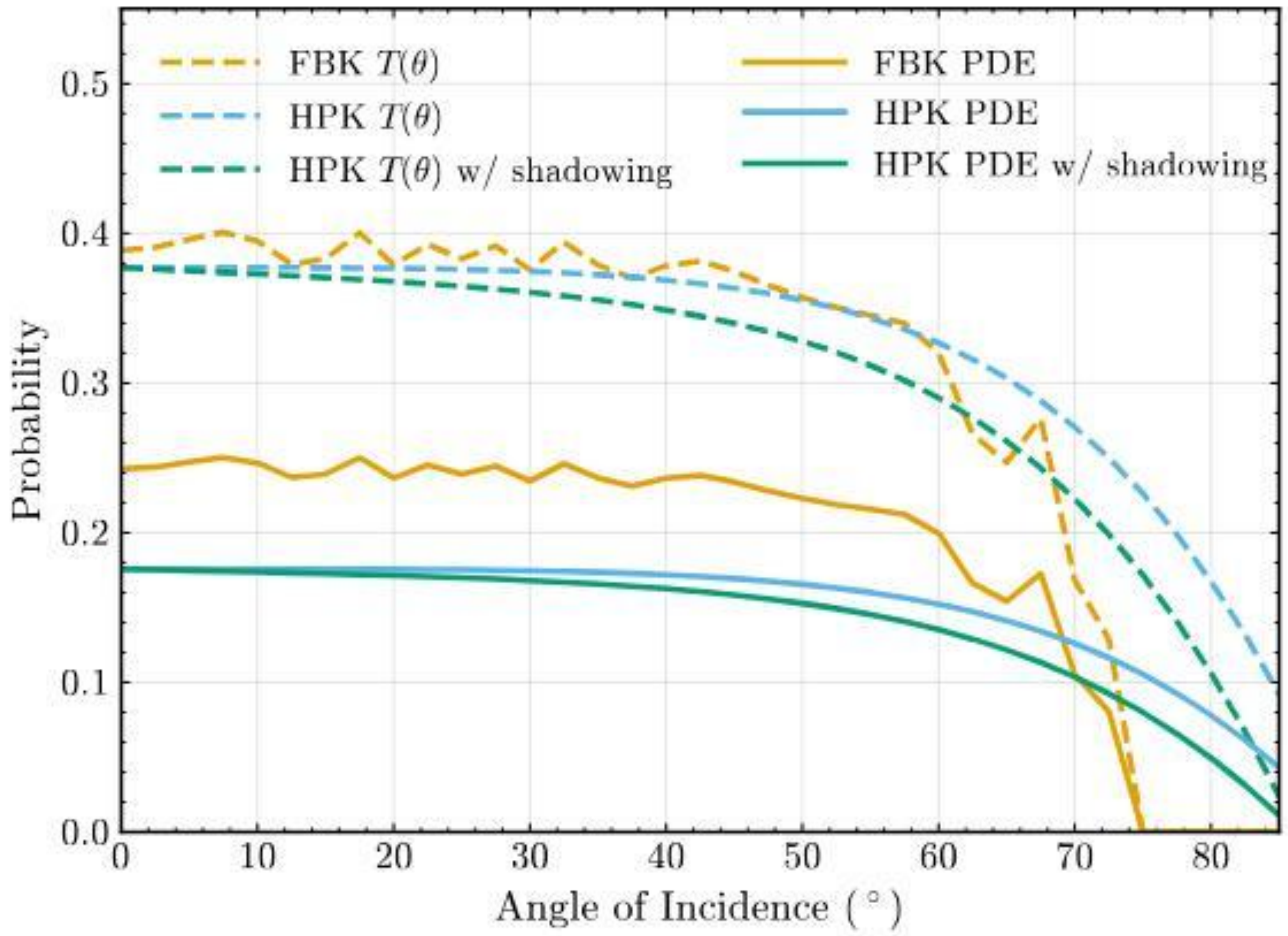
- UV light from Xe lamp hits a photocathode (10 nm layer of gold on a MgF_2 window) and creates electrons
  - → cathode signal (Q_c)
- Electrons drift ~ 4 cm through a uniform electric field (takes time t_d)
  - Created by 4 copper rings at HV
  - Shielded from anode/cathode by fine grids
- Bottom anode measures charge of remaining electrons
  - → anode signal (Q_a)



From P. Comerford, Co-op report 2024

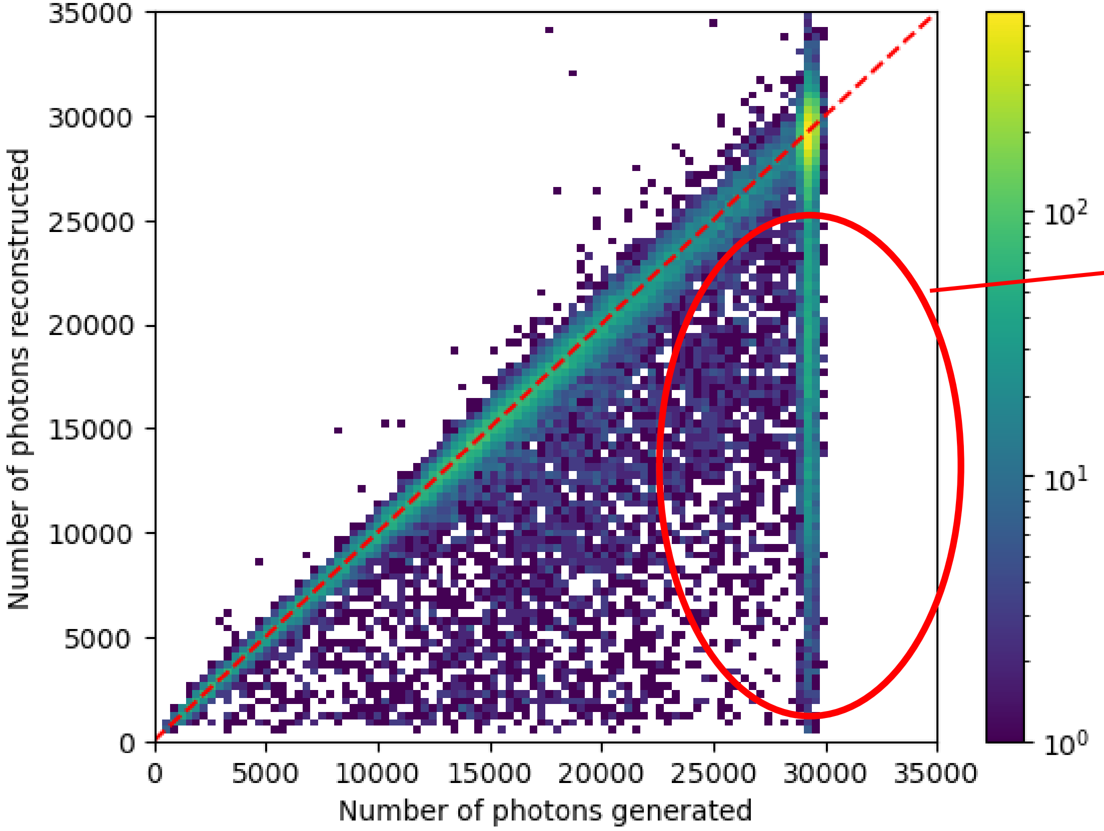
Angular PDE for LXe

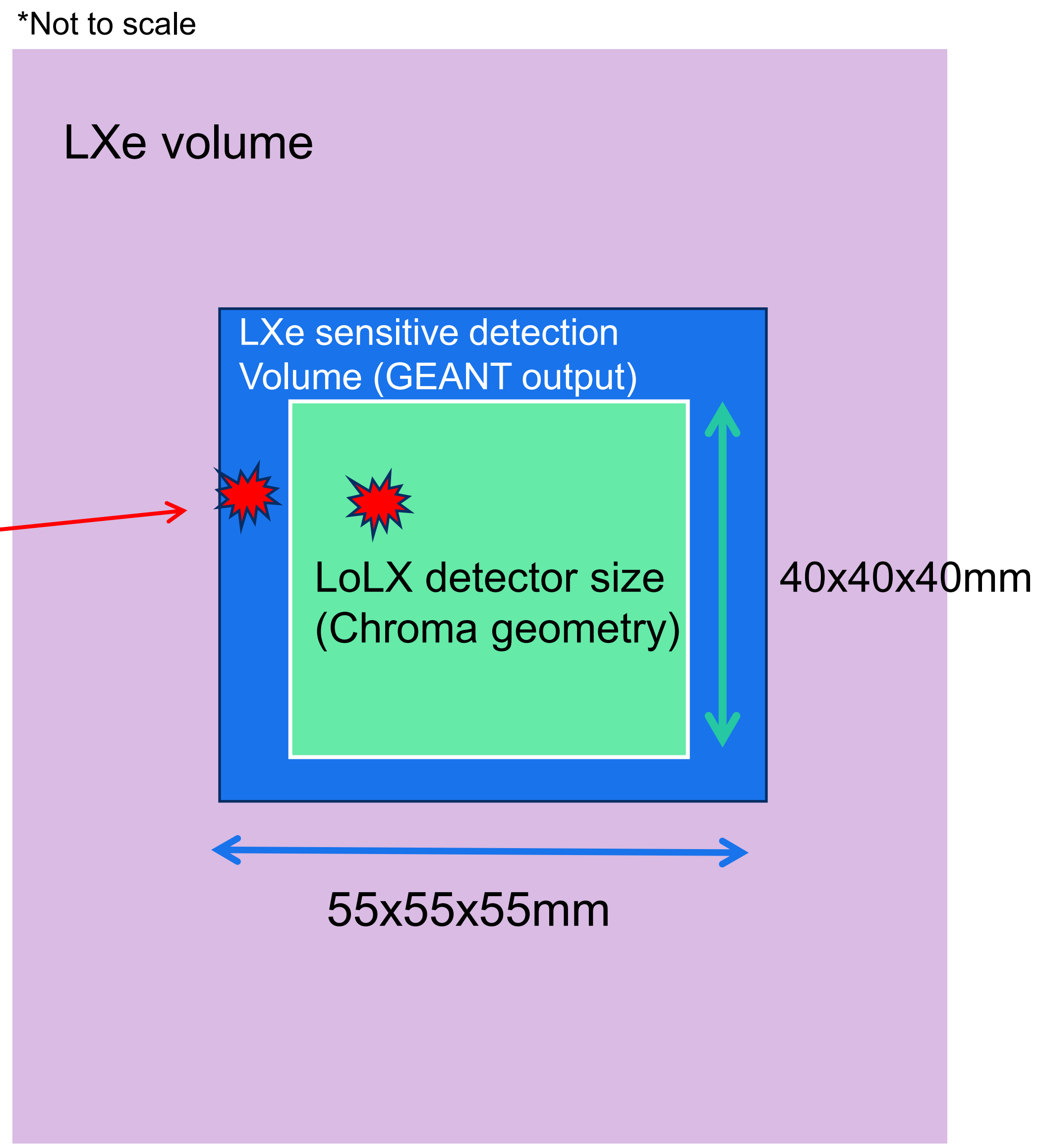
arXiv:2510.15270



Multi-sites events

Multi-sites energy deposition due to Compton scattering.





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.

$$\boldsymbol{r_s} \mapsto \boldsymbol{q}$$

  - Where $\boldsymbol{q} = [q_0 \ldots q_i]$, 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.

$$\boldsymbol{q}_{norm} \mapsto \boldsymbol{r_s}$$

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

Reconstruction steps

Apply the ML neural network

$$\boldsymbol{Q}_{obs} \Rightarrow \boxed{\boldsymbol{q}_{norm} \mapsto \boldsymbol{r}_{s,recon} \mapsto \boldsymbol{q}} \Rightarrow N_{s,recon}$$

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

$$\boxed{q_{i,norm} = \frac{q_i}{\sum q} = \frac{Q_i}{\sum Q_i}} \qquad \boxed{q_i = \frac{Q_i}{N_{gen}}}$$

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

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

Likelihood function

- KL-divergence base NLL function:

$$L(\boldsymbol{r_s}) = \sum_i p_i \ln \frac{p_i}{q_{i,norm}(\boldsymbol{r_s})}$$

  - 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, $q_{i,norm}\,(r_{recon}) = \frac{q_i}{\sum q_i}$

Likelihood vs number of photon

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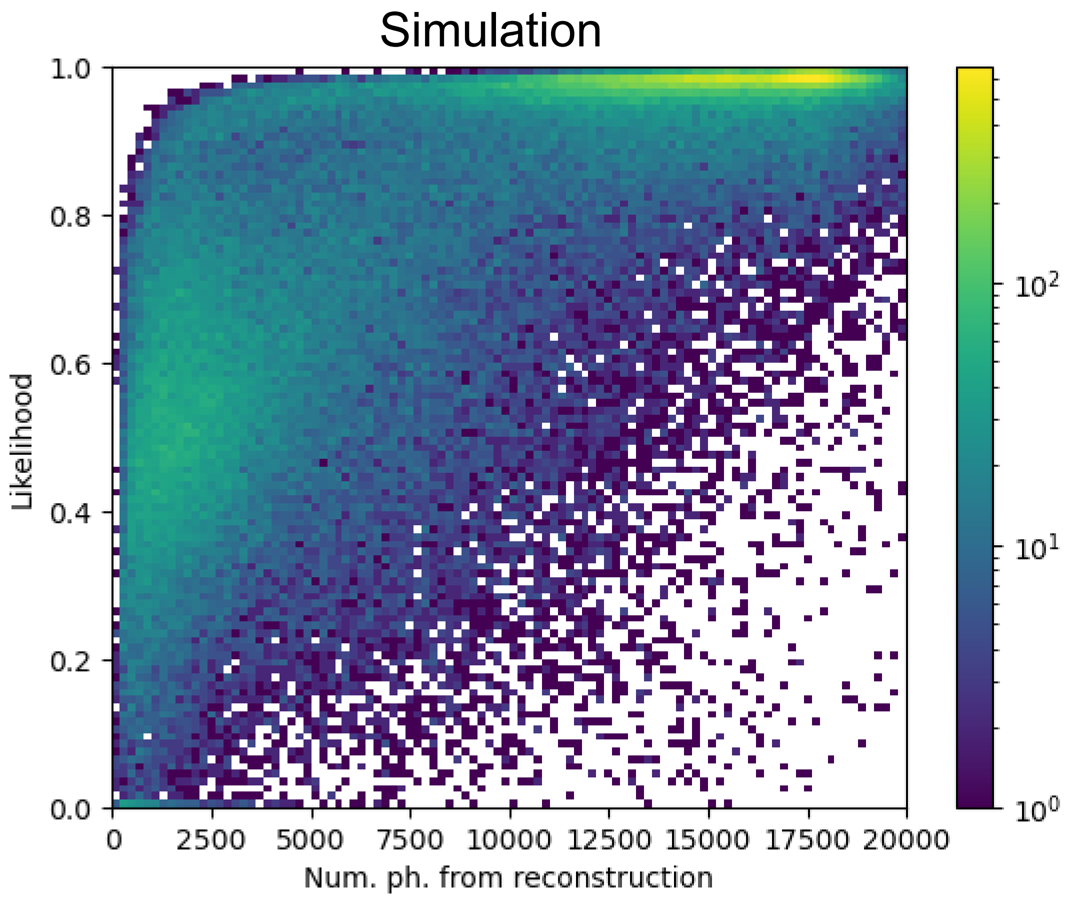
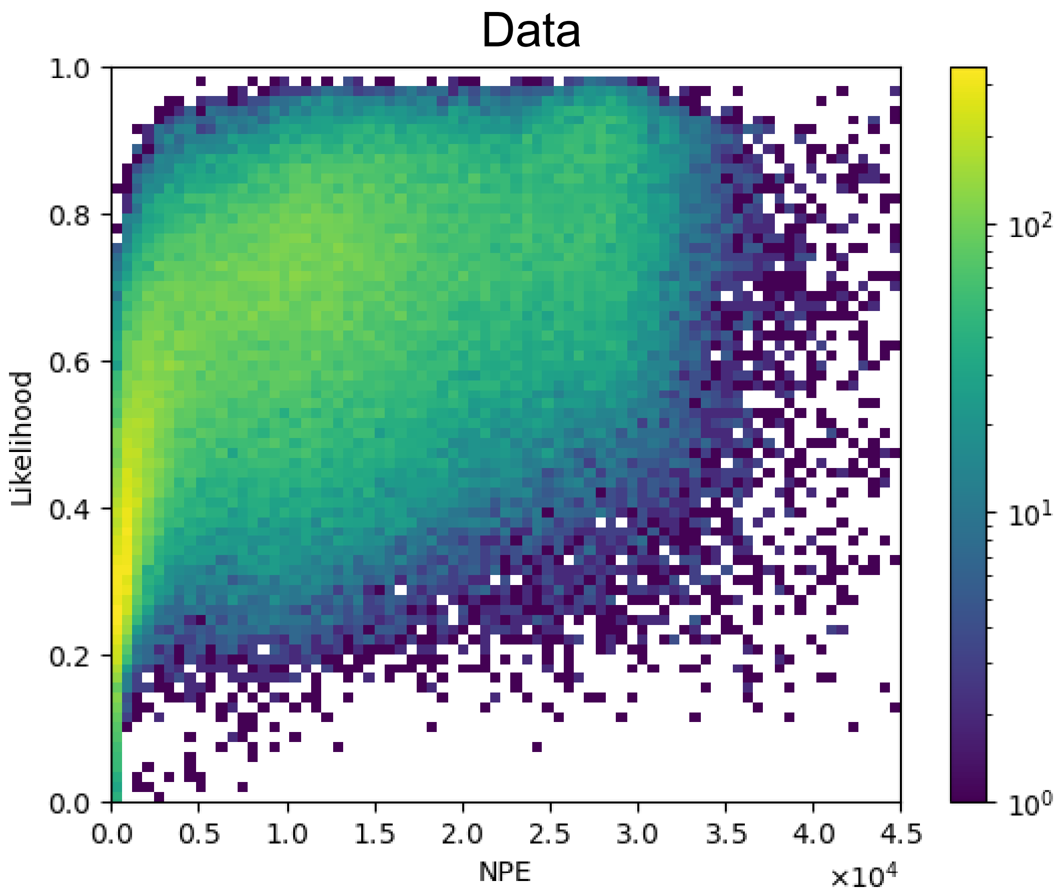
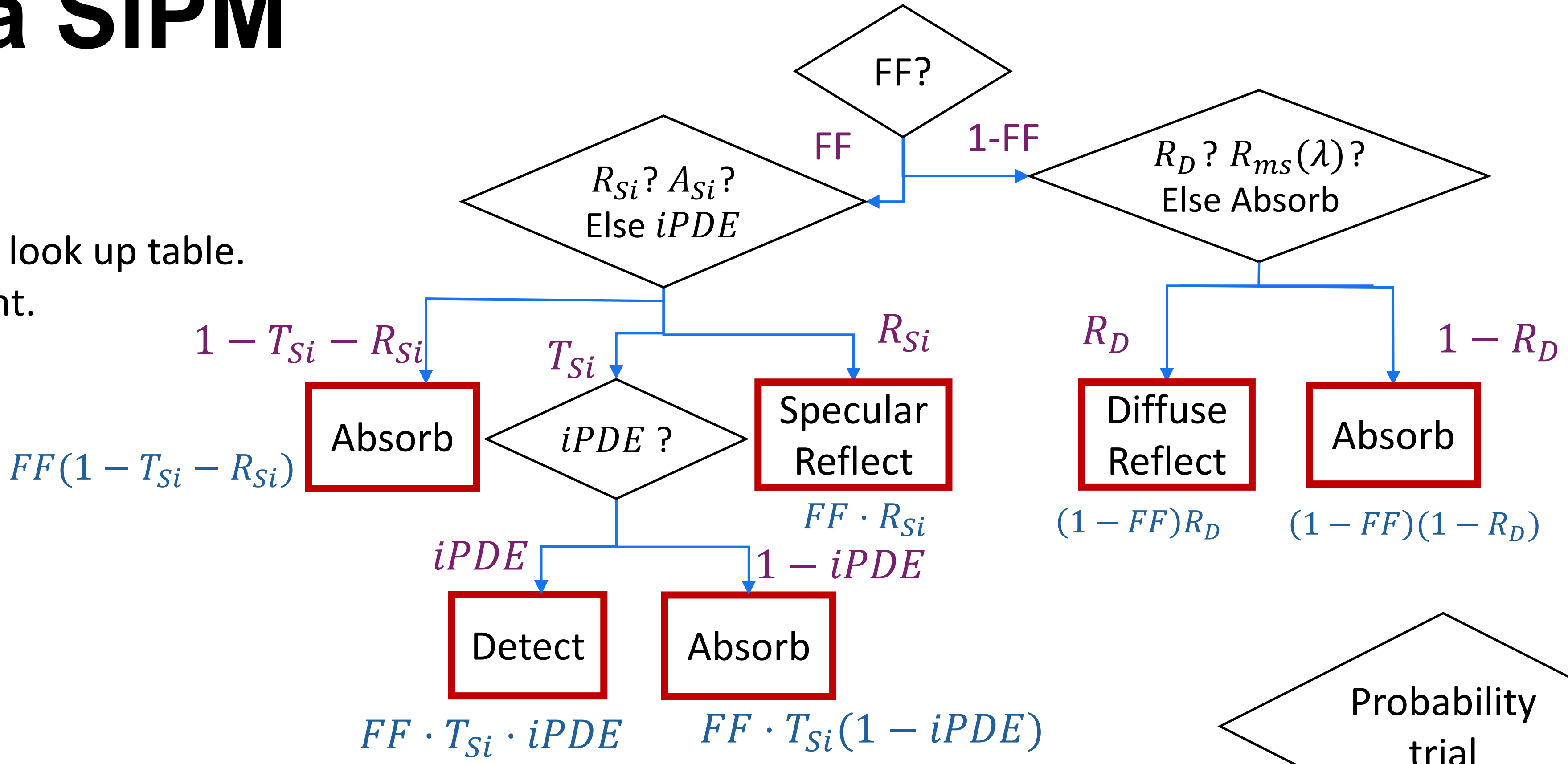




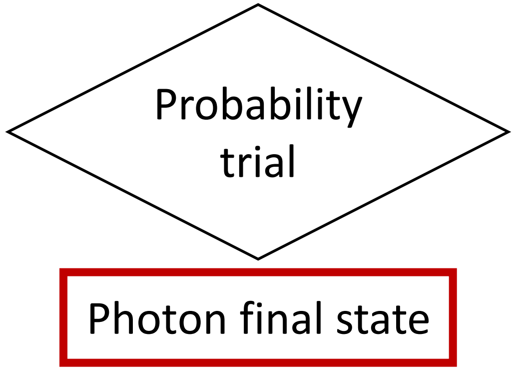
Chroma SiPM

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



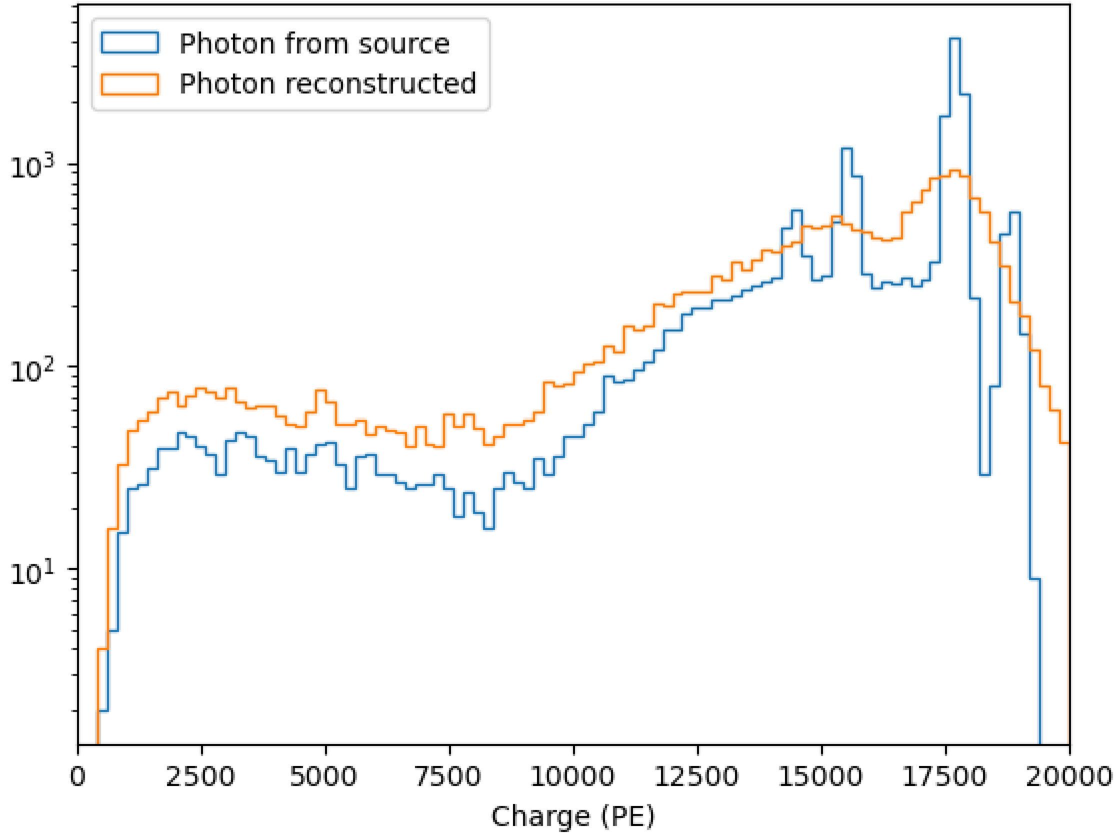
- Effective probabilities:
- $R_{D,eff} = (1-FF)R_D$
- $R_{Sp,eff} = FF \cdot R_{Si}$
  - Absorb in microstructure $A_{refl} = (1-FF)(1-R_d)$
    - For small wavelength, neglected in model just for now.
- $PDE = FF \cdot T_{Si} \cdot iPDE = FF \cdot (1-R_{sp})iPDE$

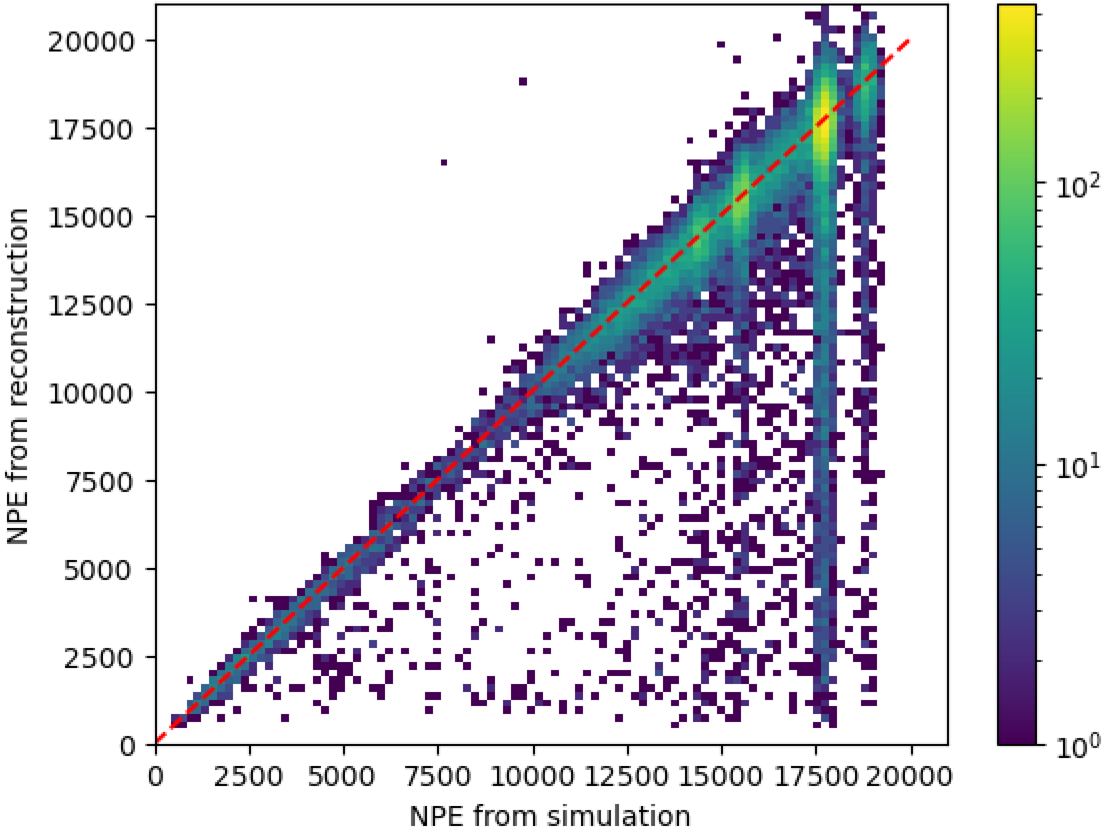
arXiv:2510.15270



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.