Light-only Liquid Xenon experiment:

Energy and position reconstruction

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On behalf of LoLX collaboration

CAP Congress

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Canadian Association of Physicists

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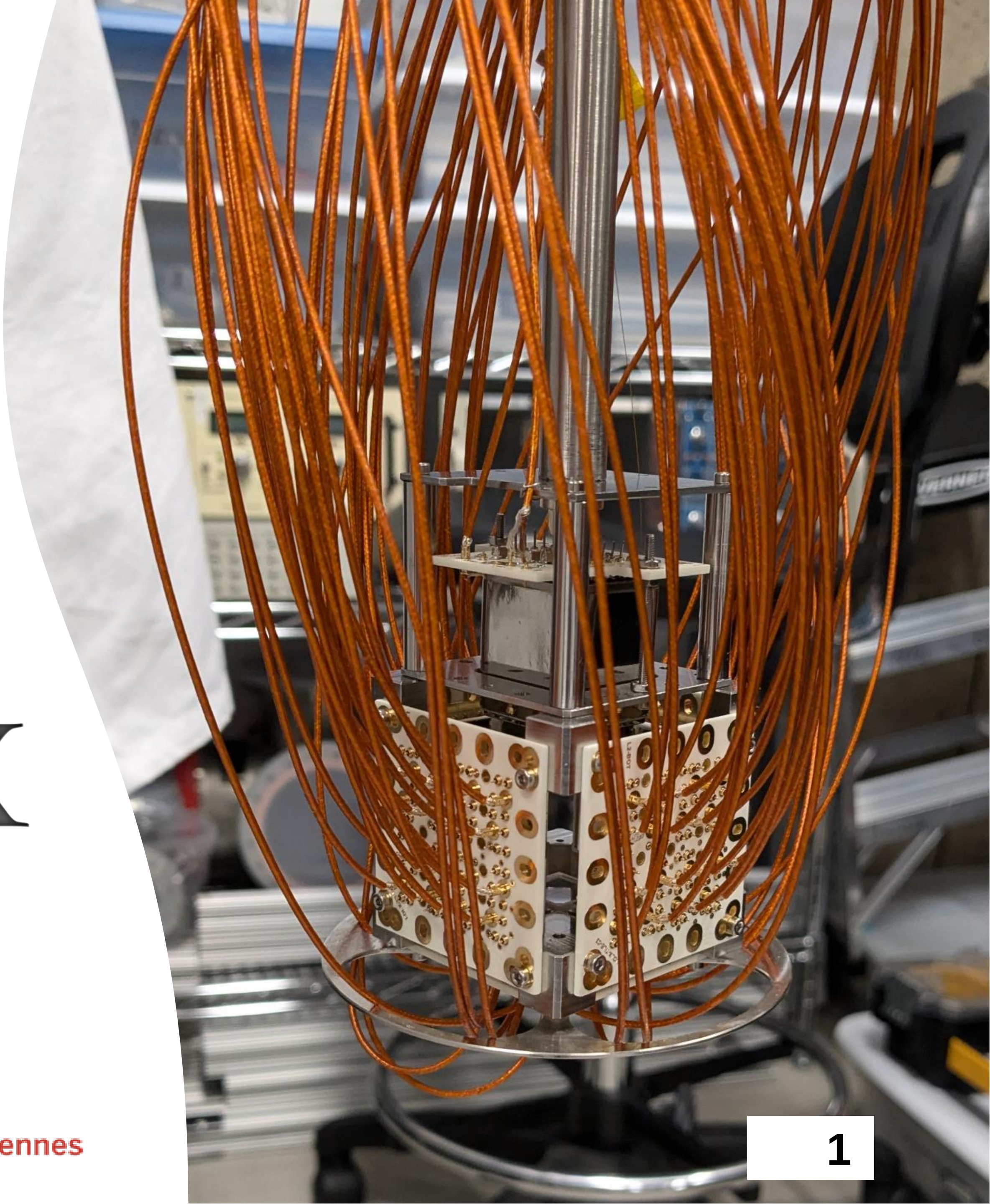
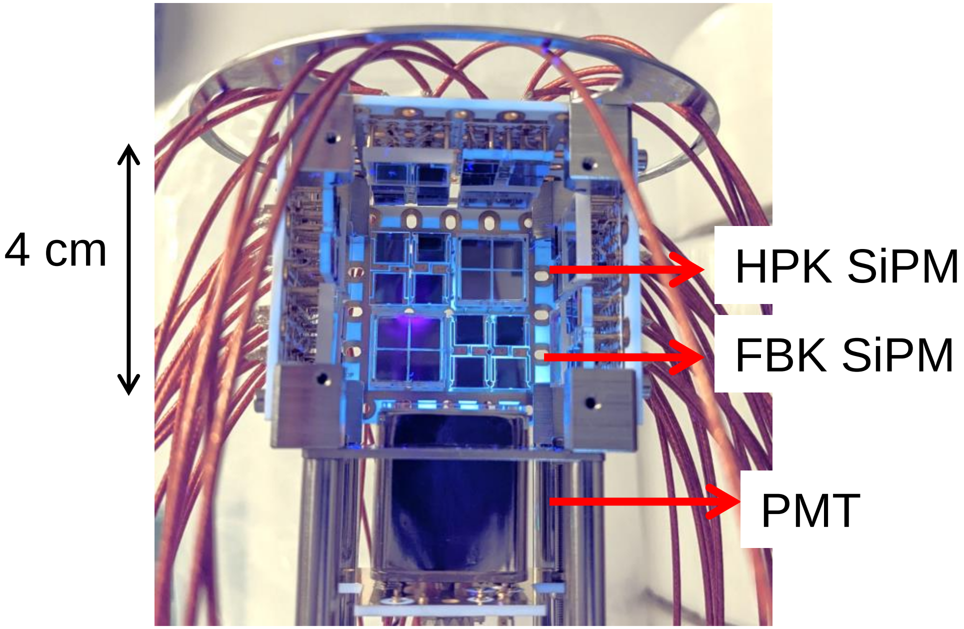
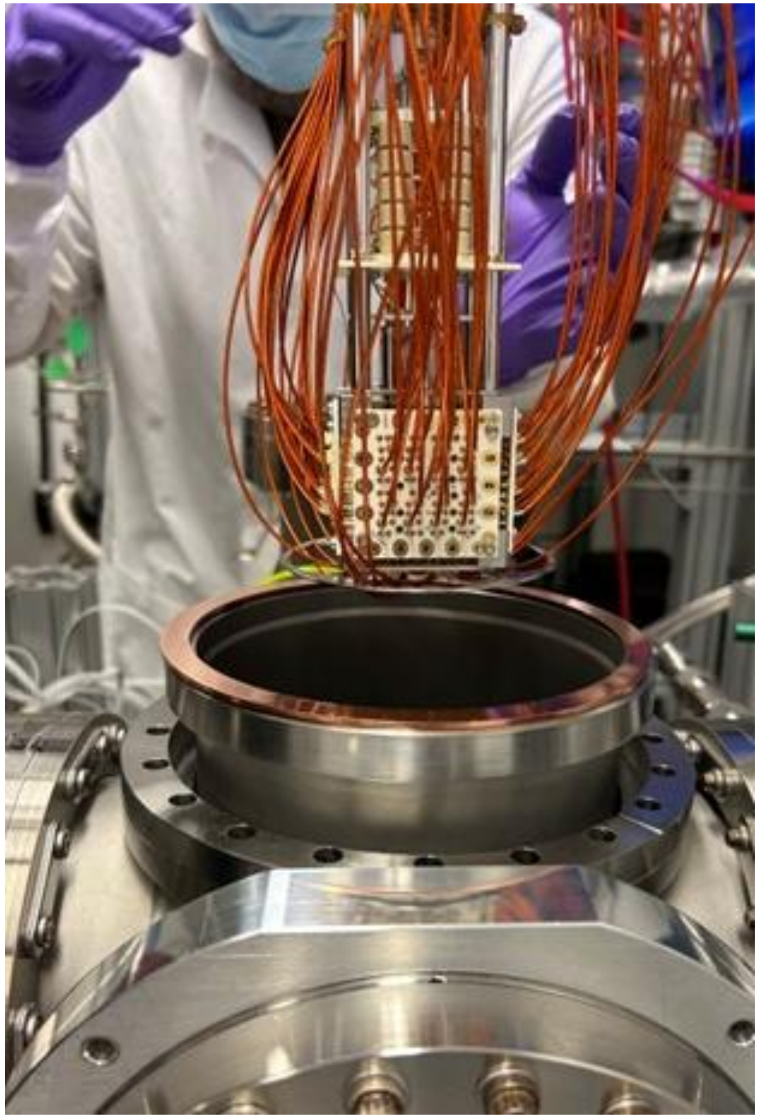


What is LoLX?

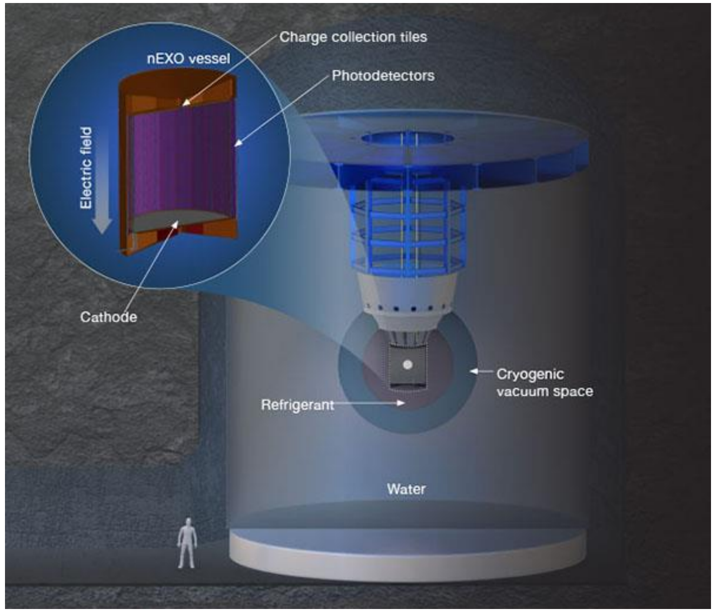
- LoLX: **L**ight-**O**nly **L**iquid **X**enon experiment.
  - Modular cube array of photosensors immersed in liquid xenon (LXe).
  - Built at TRIUMF by Science & Technology group.
  - Operated at McGill University, Brunner Neutrino Lab (BνL).
  - R&D for nEXO and PIONEER.



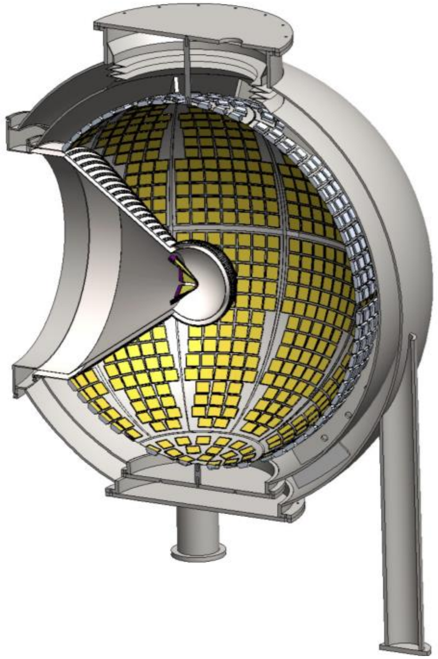


Goals

- **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.
      - Accepted by EPJ C.



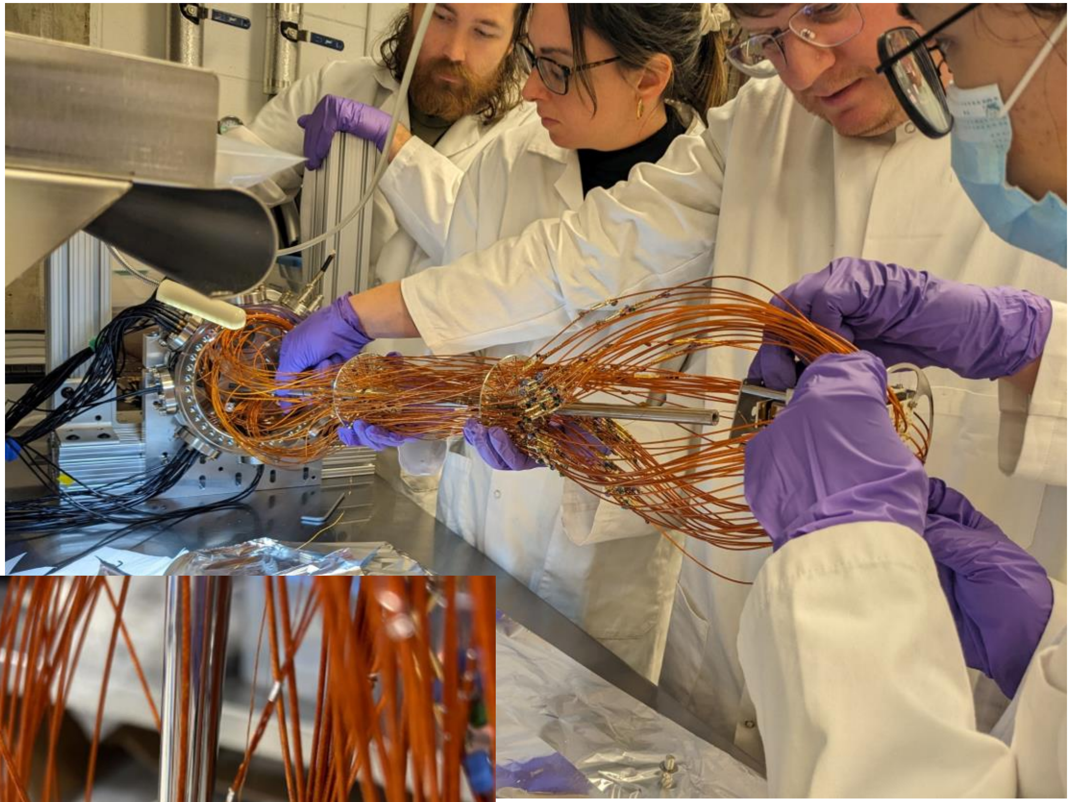
nEXO:
Neutrinoless double beta decay search

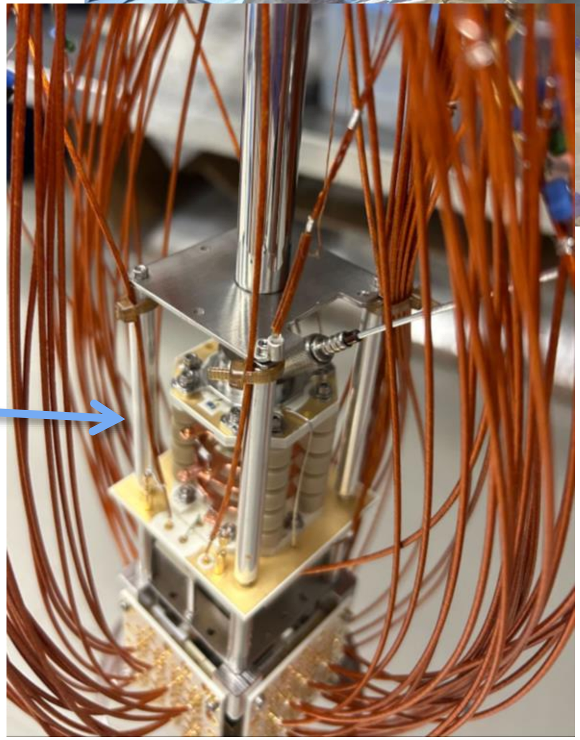


PIONEER:
Lepton flavor universality

LoLX runs

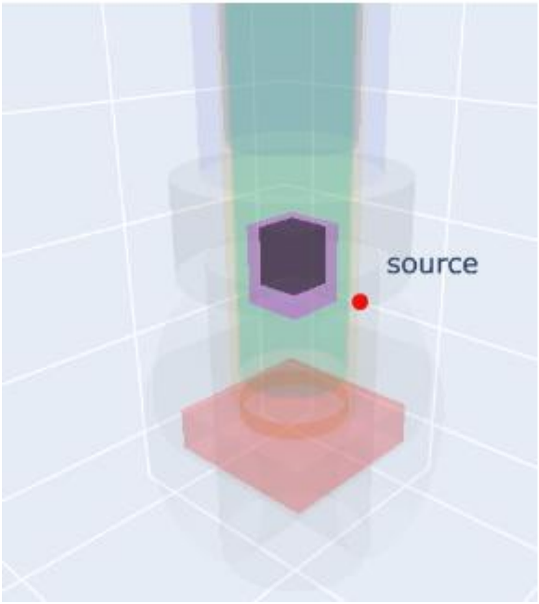
- August 2023 – Run 1, Commissioning:
  - Laser calibration and background runs
  - External gamma sources.
    - $^{22}\mathrm{Na}$, $^{133}\mathrm{Ba}$, $^{137}\mathrm{Cs}$
- January 2025 – Run 2, Engineering:
  - Same source data.
  - Swapping HPKs from another batch.
  - Adding xenon purity monitor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



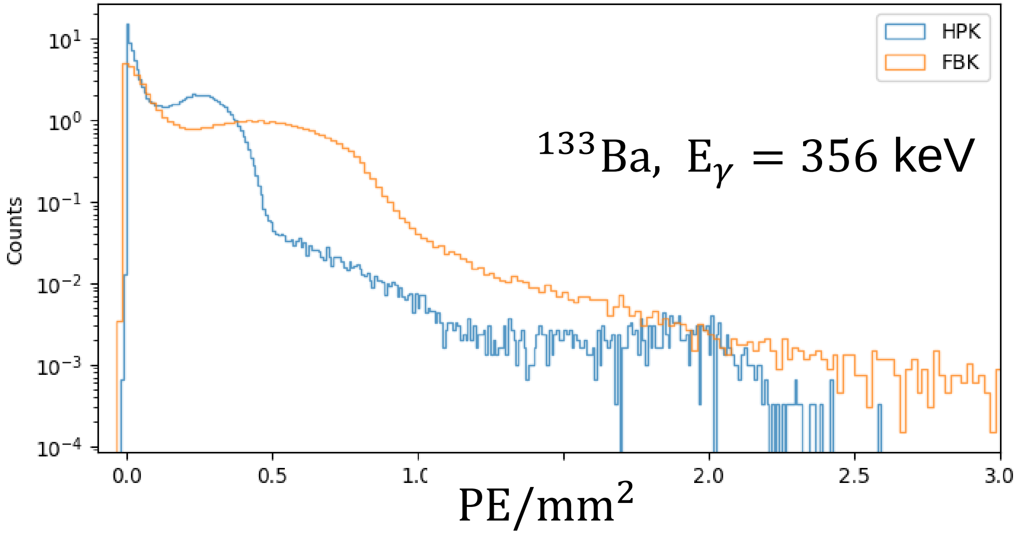


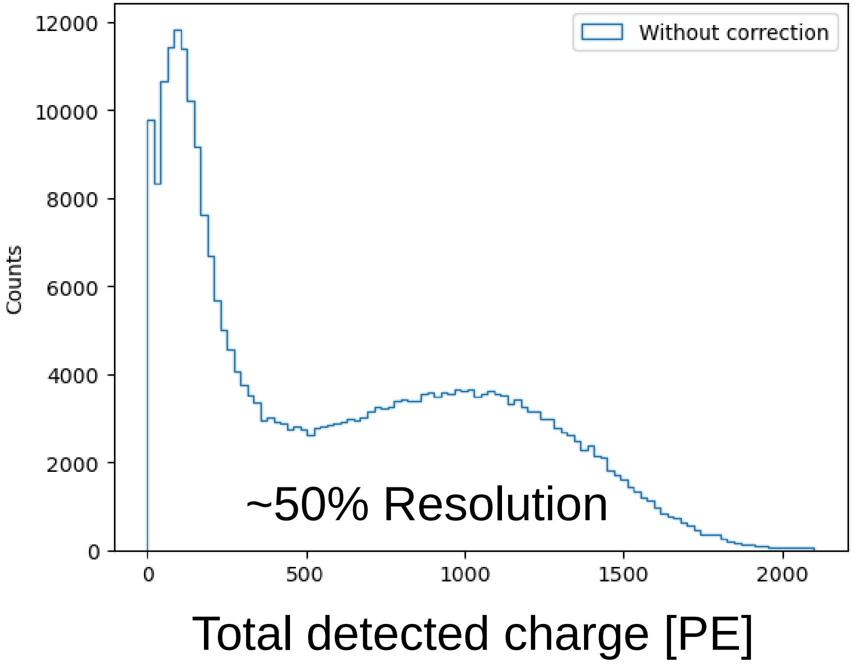
Challenges in LoLX data

- 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.

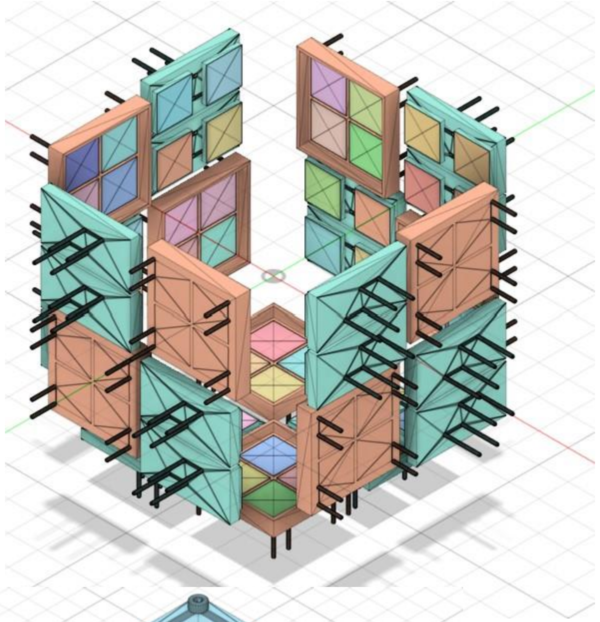


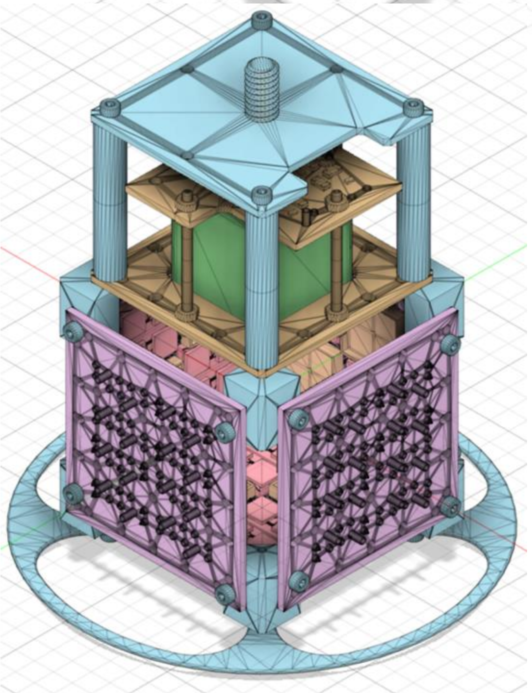
^{133}Ba 356keV gamma source





Chroma – GPU Optical Simulation

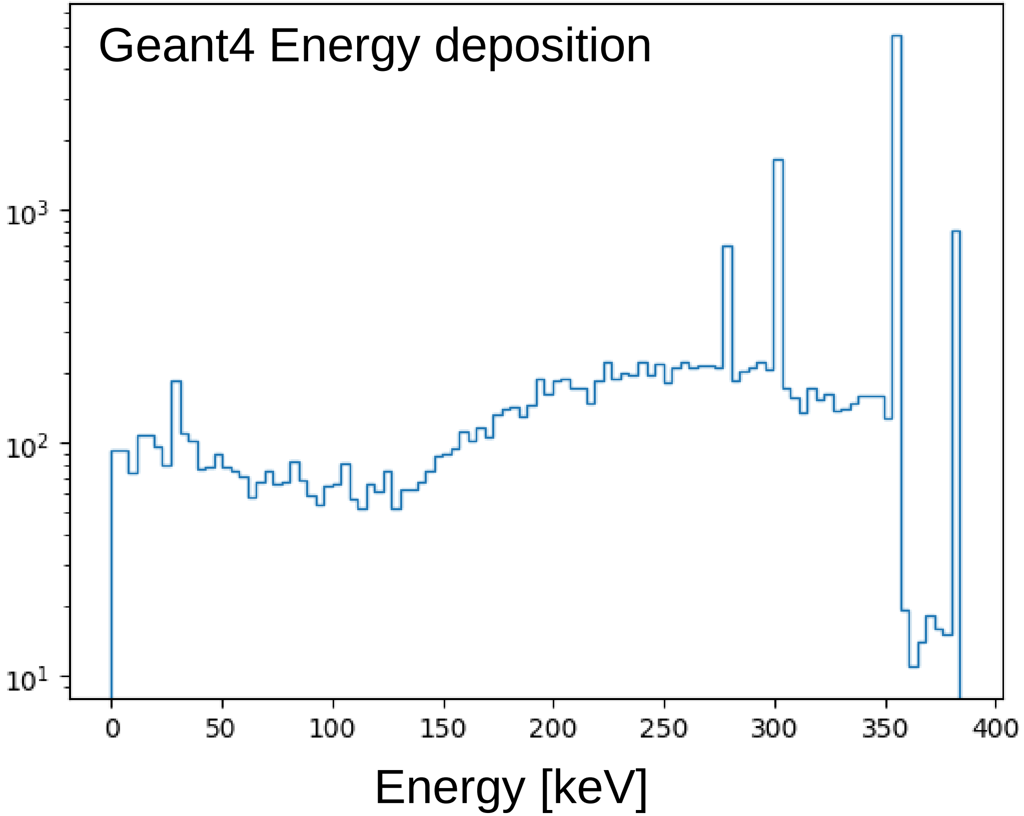


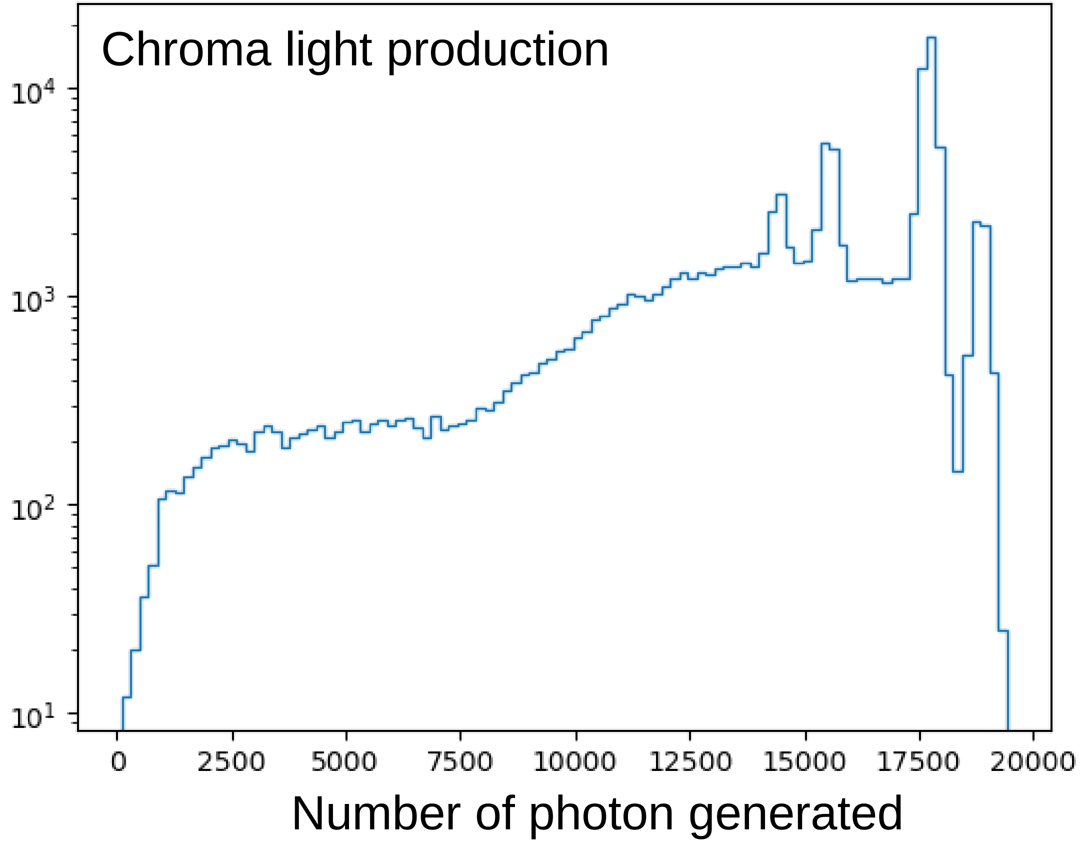


- Chroma is an optical photon simulation for particle physics detectors.
- GPU-based photon transport simulation.
  - Development in Python (core simulation in CUDA-C).
  - ~100 times faster than G4OpticalPhoton.
- Does:
  - Take the energy deposition in GEANT4 as input.
    - Or other user defined photon 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

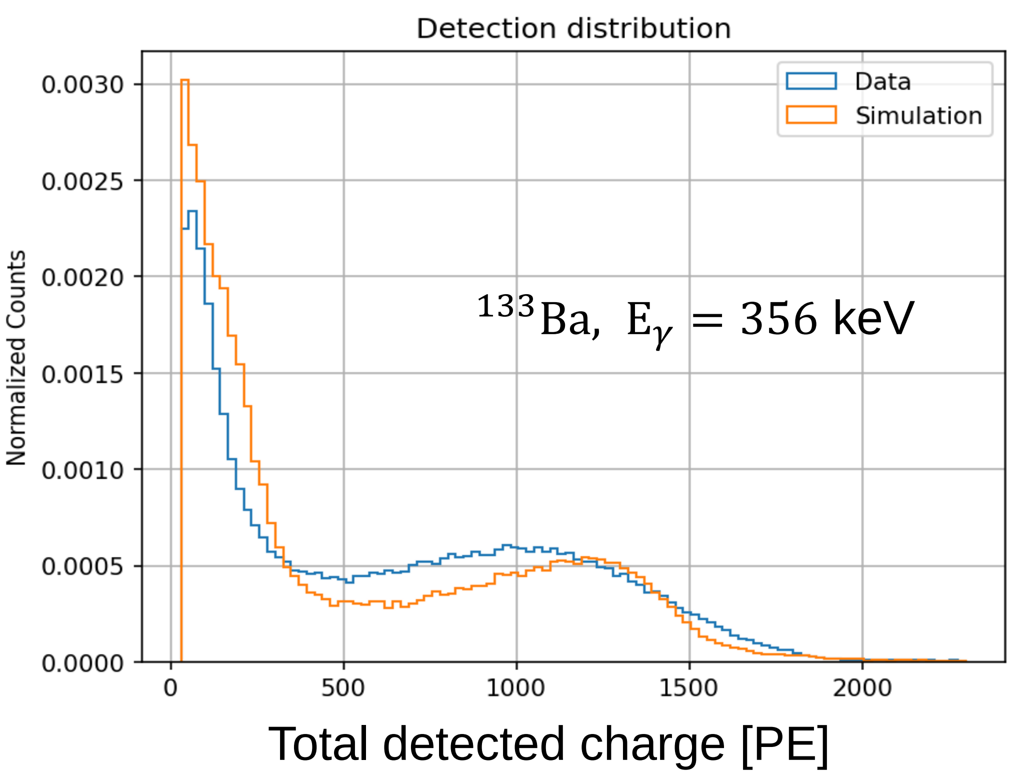
- Energy deposition in GEANT4 vs light production in Chroma.
  - Light yield base on NEST model.
    - NEST: Noble Element Simulation Technique.
- Ba-133 source example:

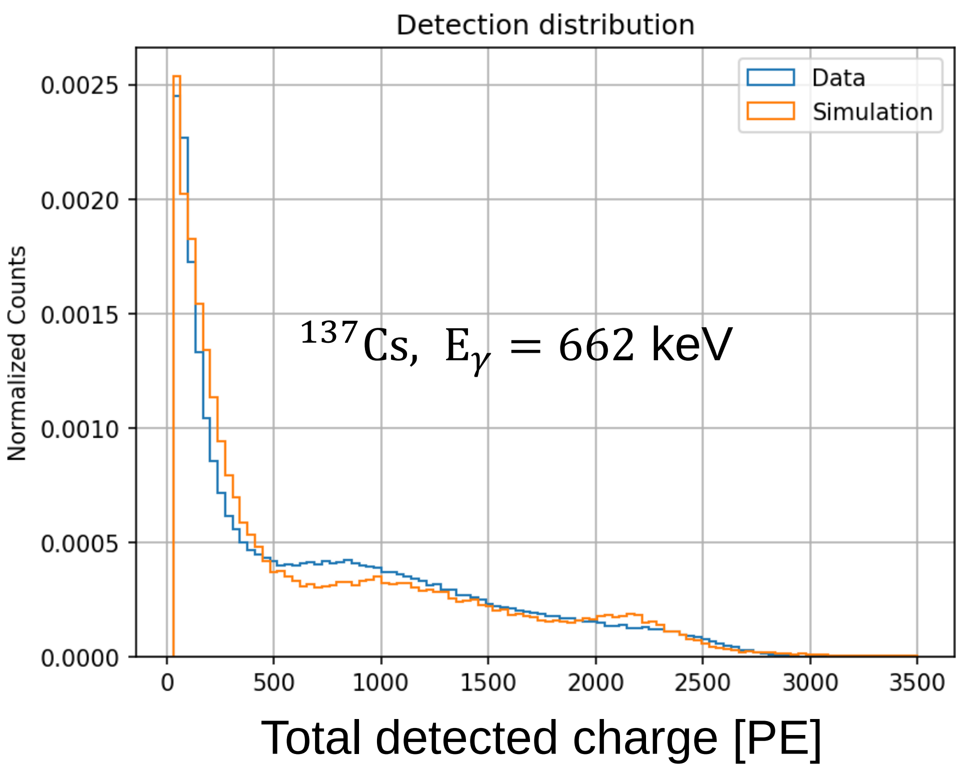




Simulation data compare

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

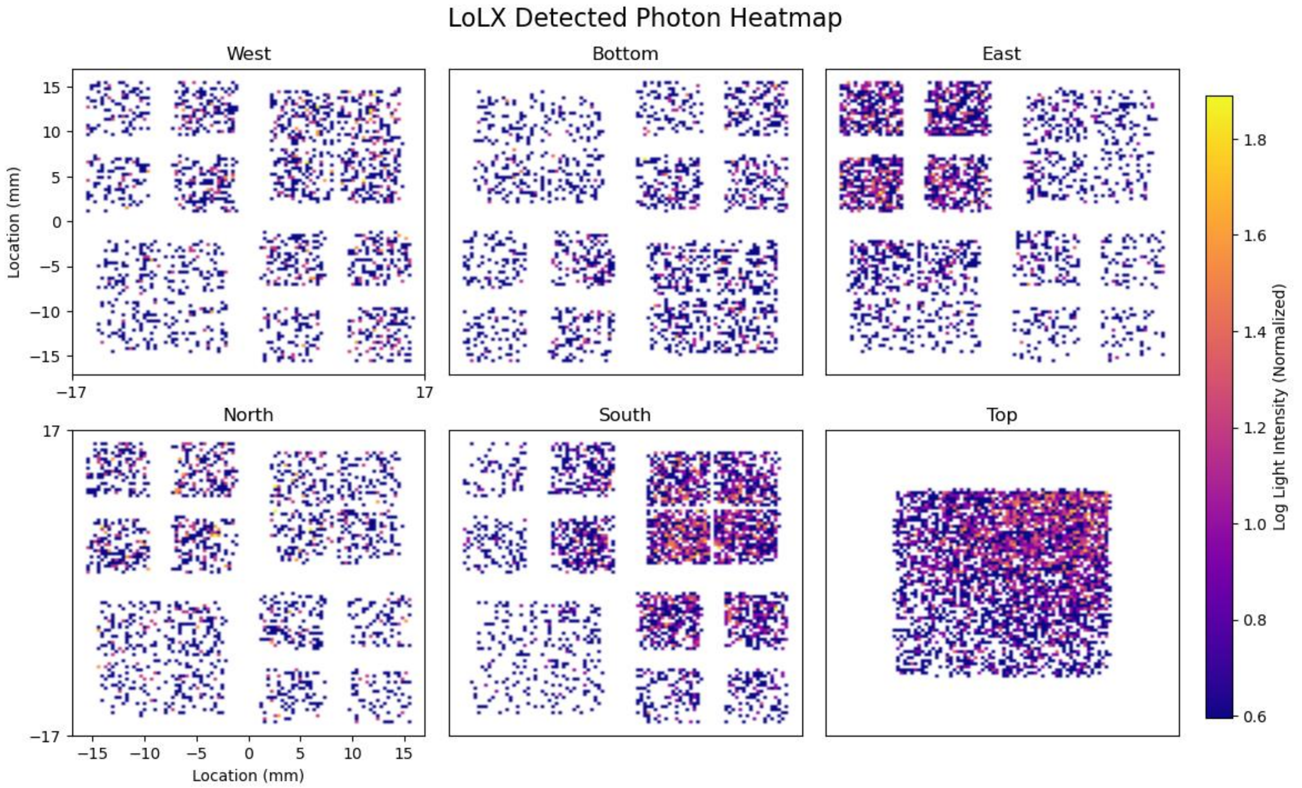




Position and energy reconstruction

- Simulation with electron gun energy ~356keV.
  - NEST photon generator.
    - NEST: Noble Element Simulation Technique.
  - Scintillation photons with real wavelength distribution.
- Feedforward neural network (FNN).

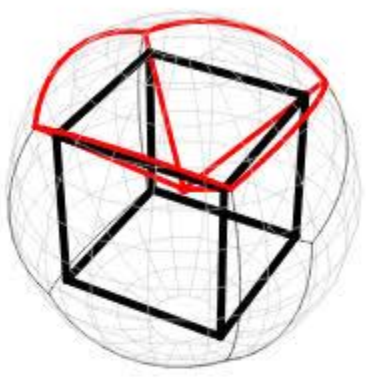
$\boldsymbol{Q} = [Q_0 \ldots Q_i]$: charge detection distribution in each channels



NN1 mapping

NN 2 mapping

$\boldsymbol{r}_s = [x, y, z]$

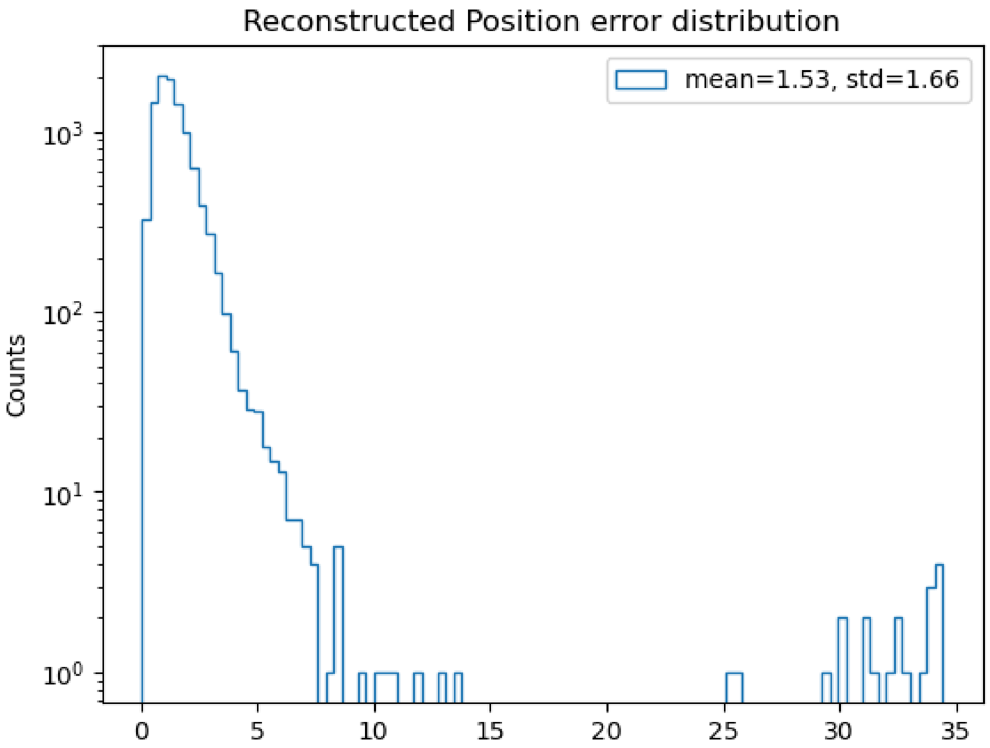


$\boldsymbol{PCE}(x, y, z)$: photon collection efficiency

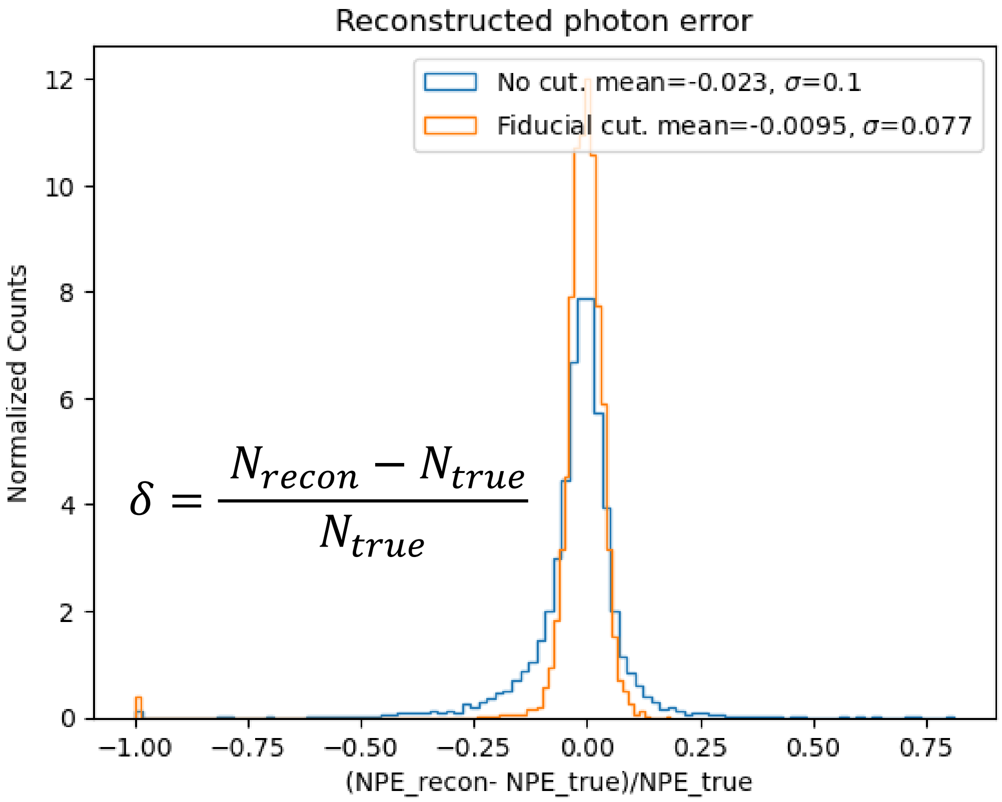
$\boldsymbol{PCE} = \boldsymbol{Q}/N_{gen}$, It includes photon transport efficiency and photon detection efficiency.

Validation within simulation – Electron gun

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



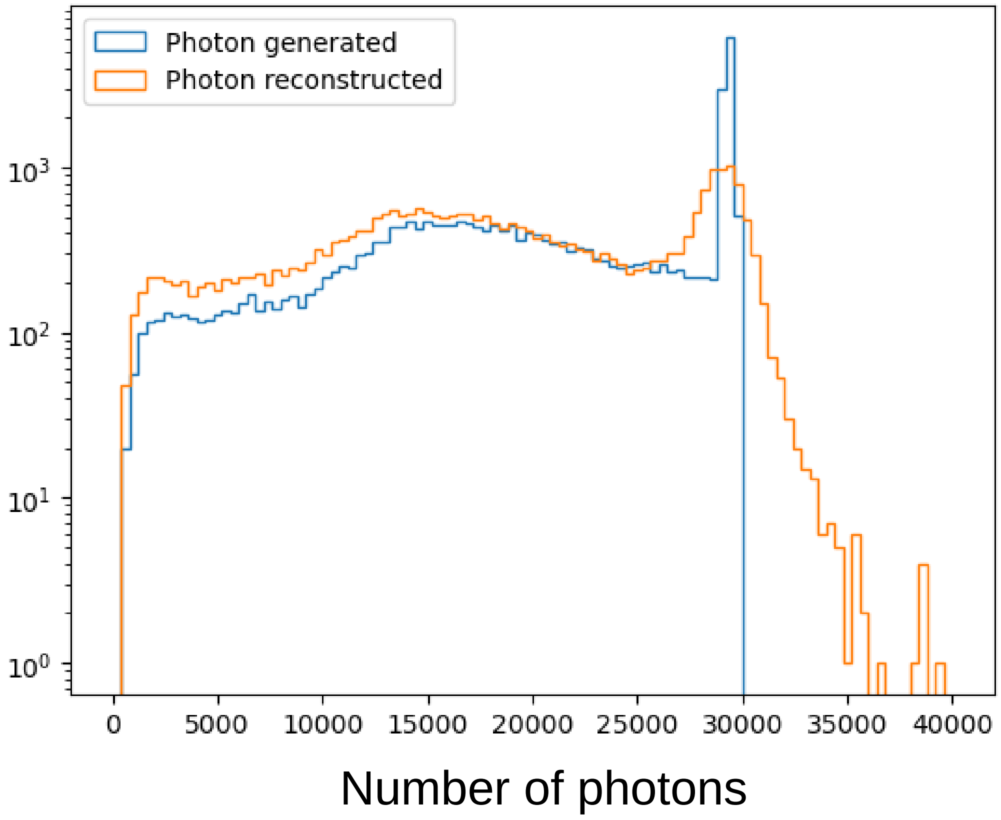
Euclidean distance error [mm]

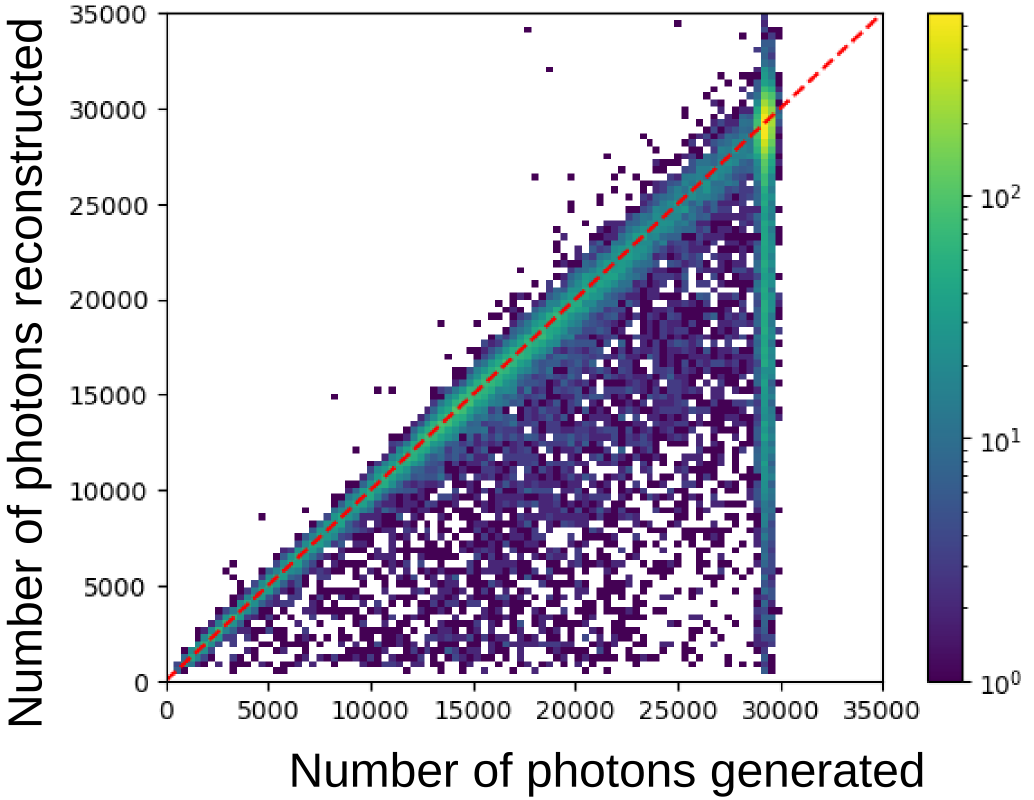


$$\delta = \frac{N_{recon} - N_{true}}{N_{true}}$$

Validation within simulation – Gamma ray

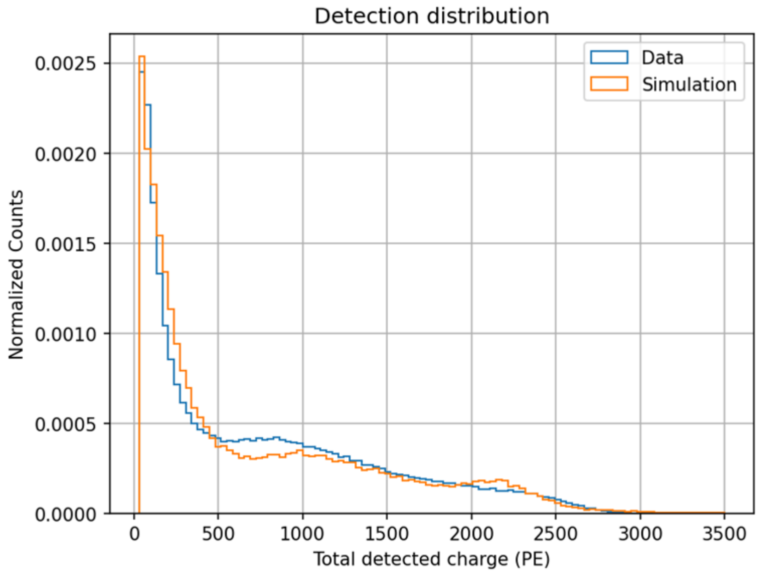
- Geant 4 general particle source (GPS) produced Cs-137 decay gamma ray.
- Chroma handles optical photons base on the energy deposition.



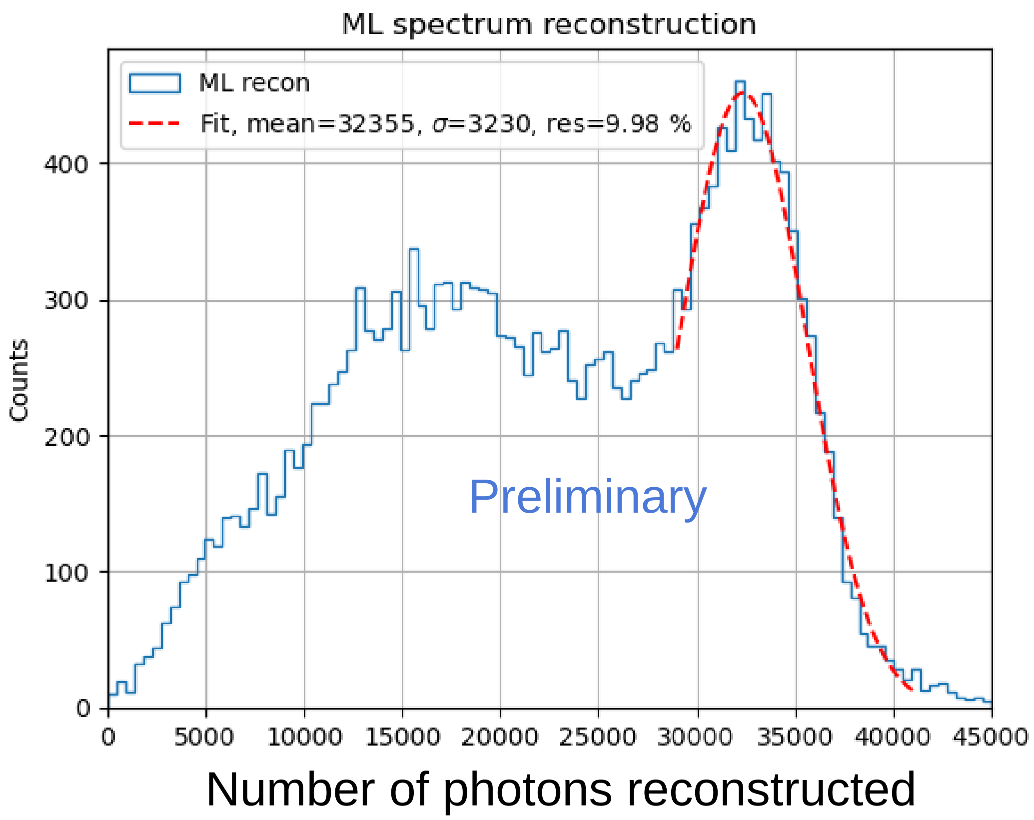


Reconstruction on real data

- Cs-137 (662 keV gamma) data reconstruction.
  - Light yield (LY): $48.88 \pm 4.88\ ph/keV$.
    - M Szydagis, *et al.*, (2022) NEST report $\mathrm{Ly} = 40{\sim}60\ ph/keV$ at O(10^2 keV)
    - https://doi.org/10.3389/fdest.2024.1480975
  - Resolution: $9.98 \pm 0.25\%$.
    - A Minamino (2010), XMASS report: 5.6 ± 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 consistence with the literatures value.
  - The results shows the energy resolution has massively improve.
- 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 $^{181}\mathrm{Hf}$ gamma source will be implemented.
    - Internal beta source with wavelength filter.

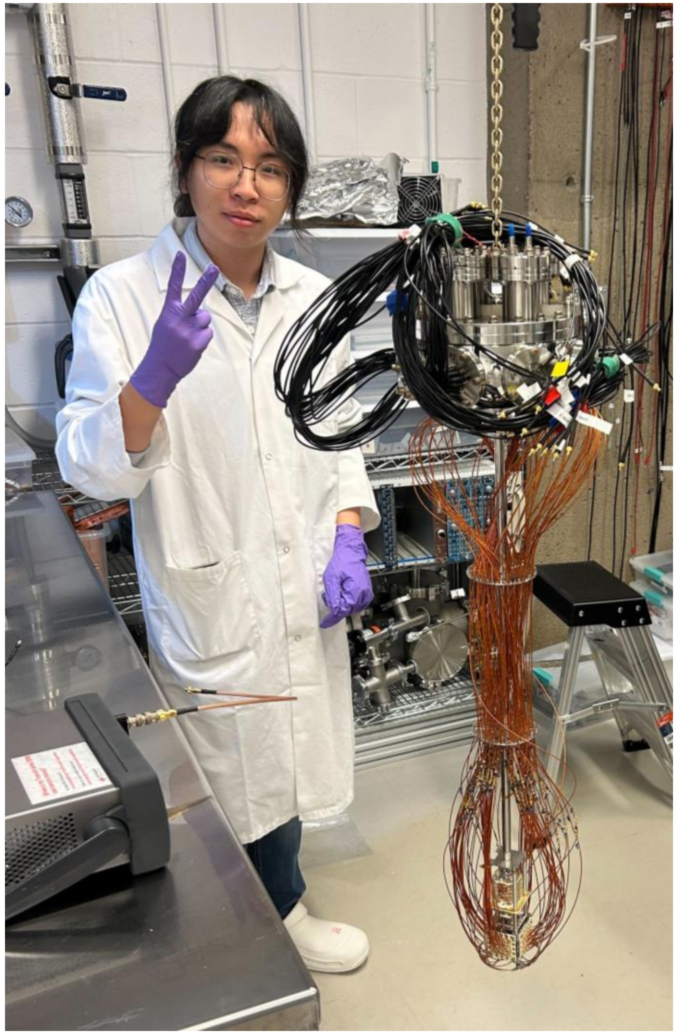


Photo by: D. Gallacher. 2024 Oct

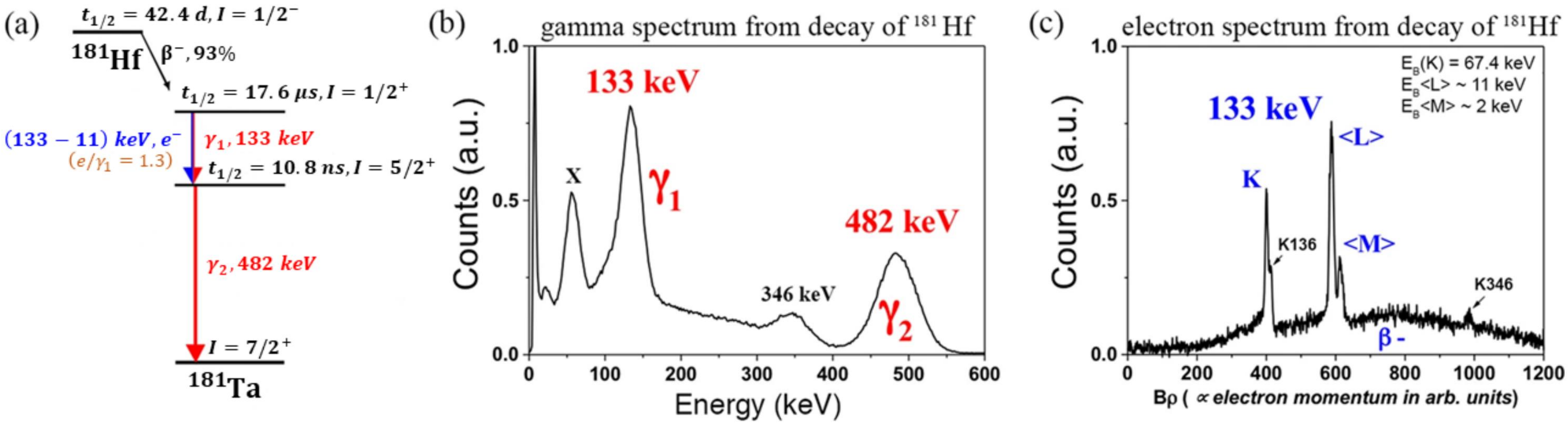
Thank you!
Question?

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

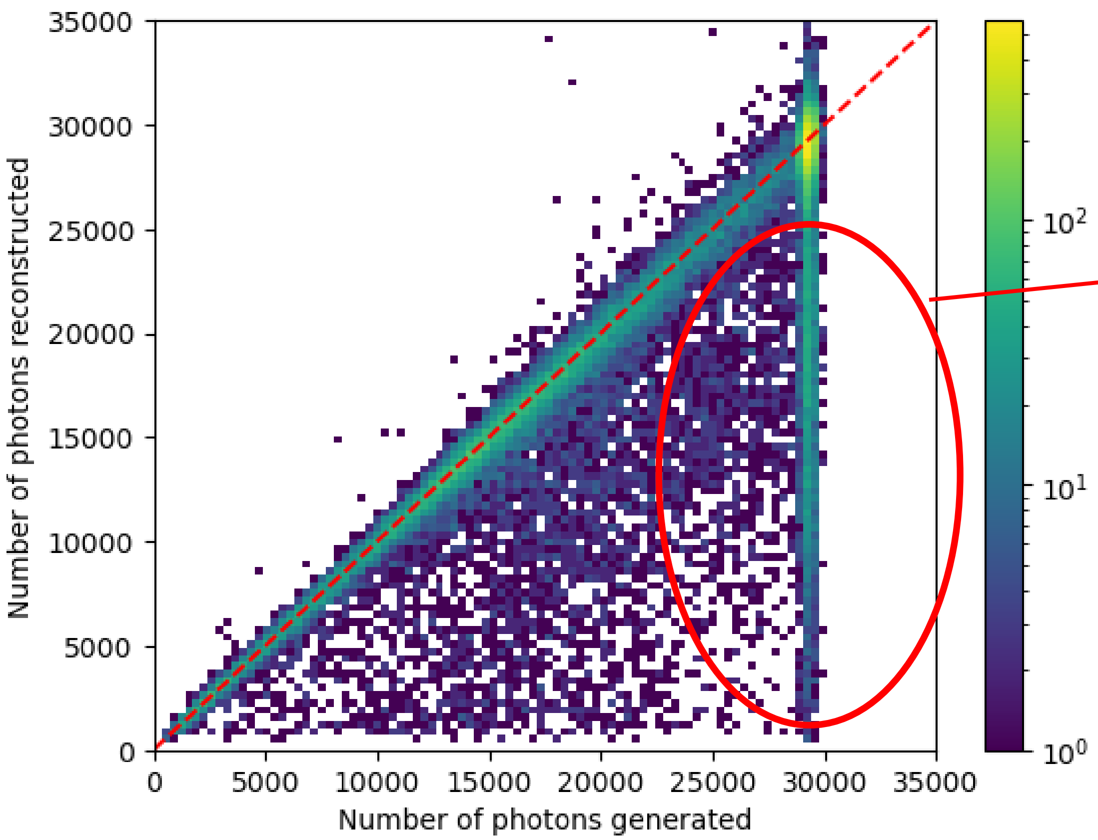
- $^{181}\mathrm{Hf}$ source. Beta decay with end point energy 414 keV, mean energy 120keV.
  - Beta decay from Hf181 to Ta181 $I = 1/2^{+}$ state.
  - 133 keV gamma emission with $T_{1/2} = 17.6\ \mu s$ after beta, decay from $I = 1/2^{+}$ to $I = 5/2^{+}$
  - 482 keV gamma emission with $T_{1/2} =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



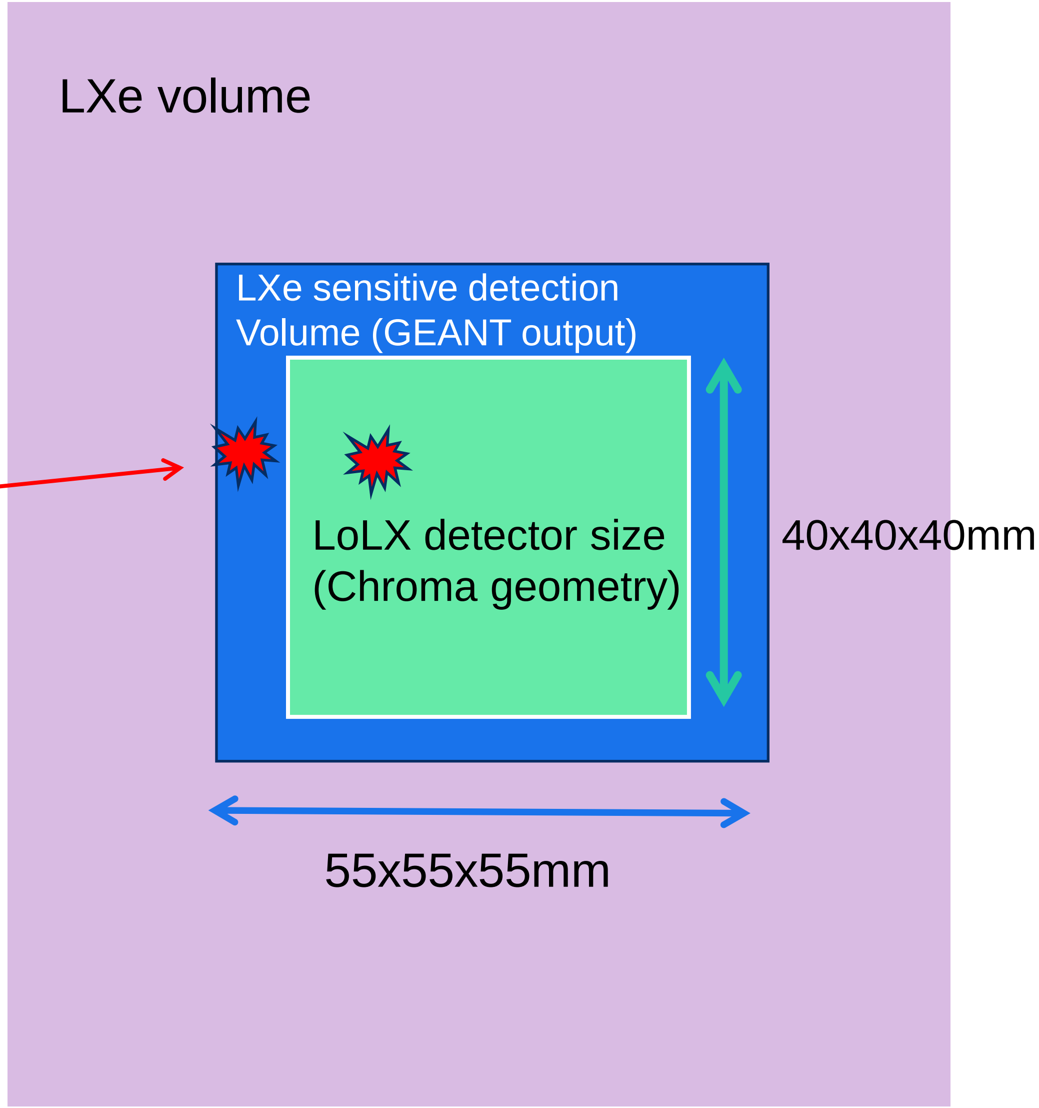
Ian Chang Jie Yap (2022): https://doi.org/10.3390/cryst12070946

Multi-sites events

Multi-sites energy deposition due to Compton scattering.



*Not to scale



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 $\boldsymbol{q} = [q_0 \dots q_i]$, 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.

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

  - 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!

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

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

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

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, $q_{i,norm}(r_{recon}) = \frac{q_i}{\sum q_i}$
  - Same $q_{i,norm}$ in page 10.

Likelihood vs number of photon

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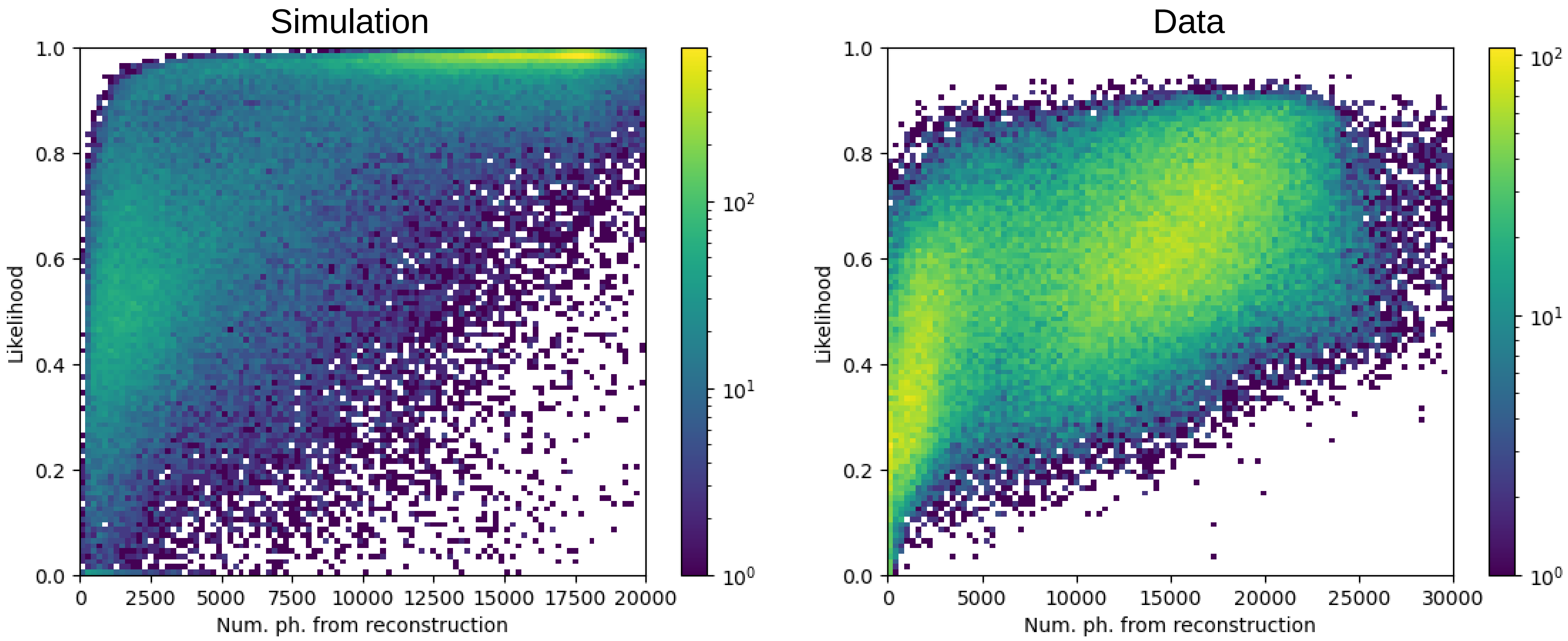
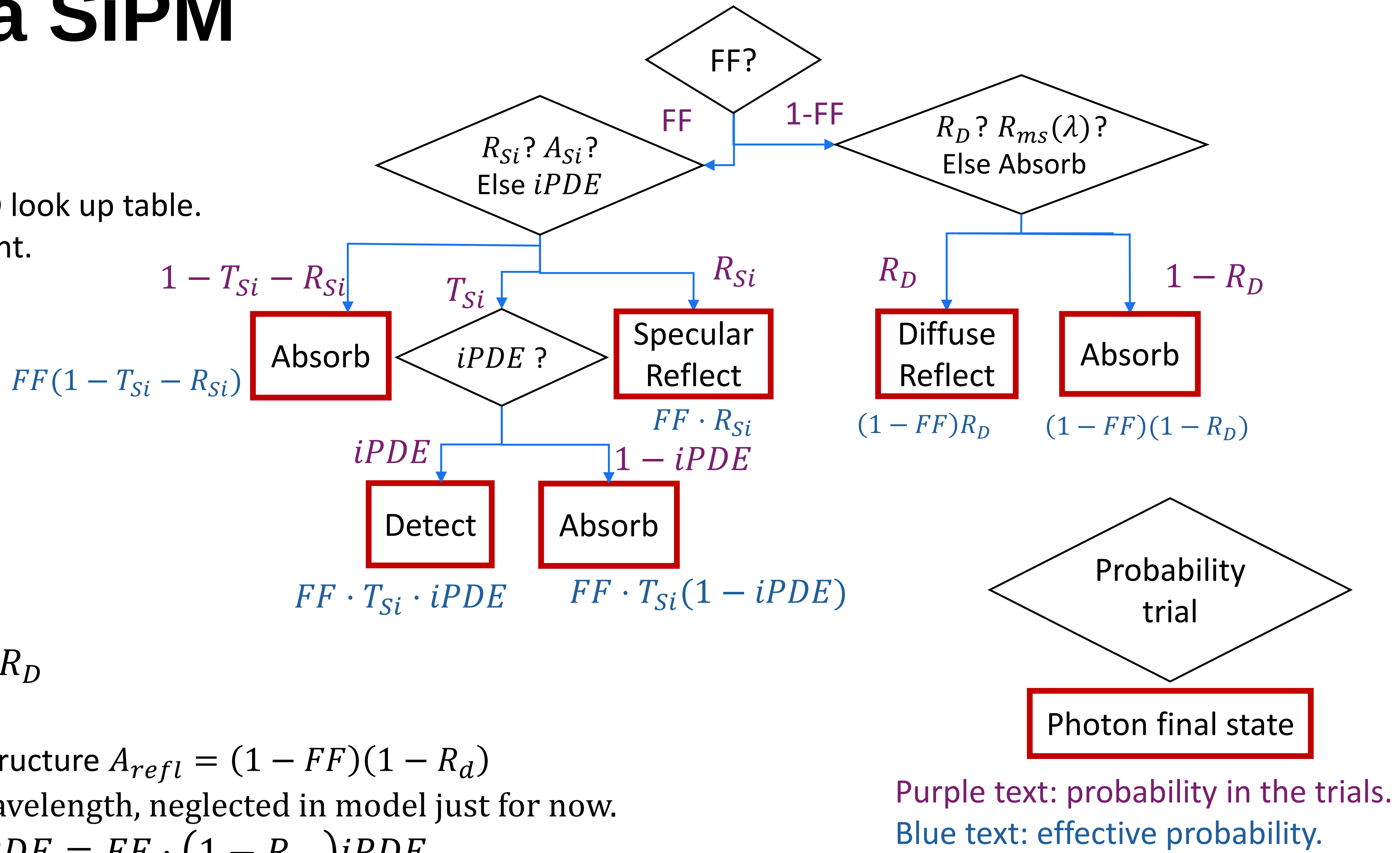


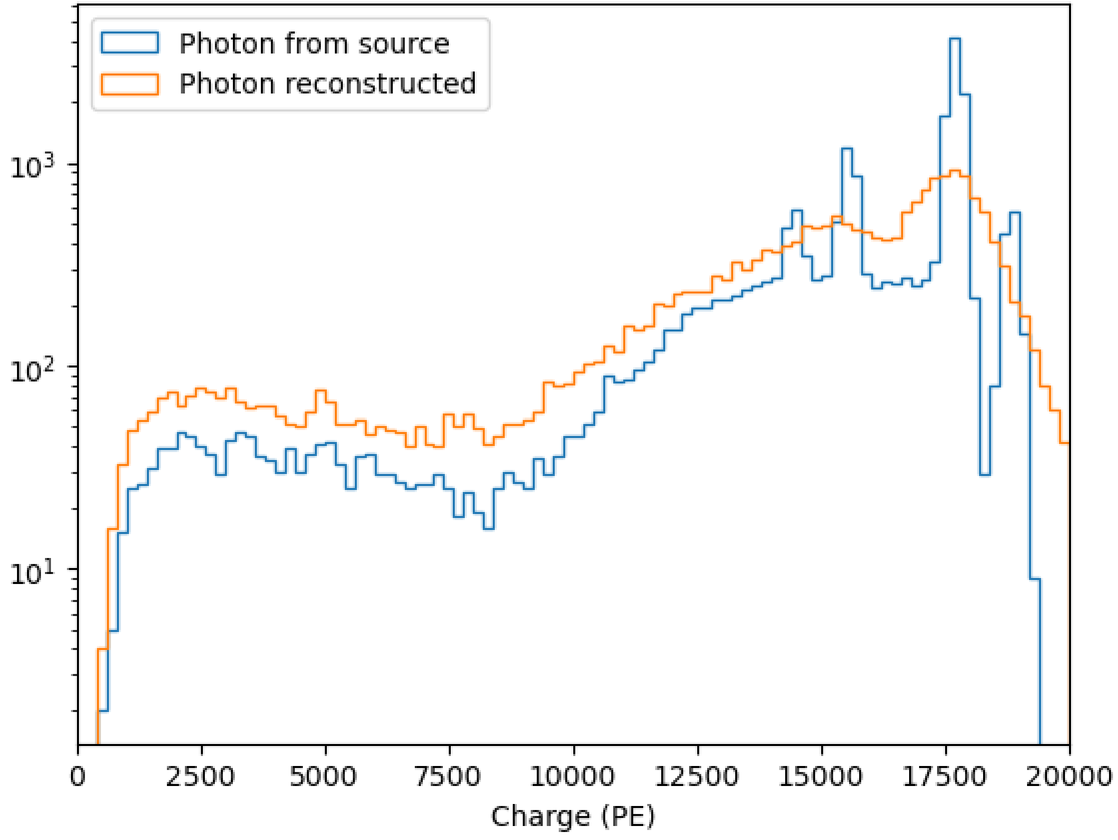
Chroma SiPM

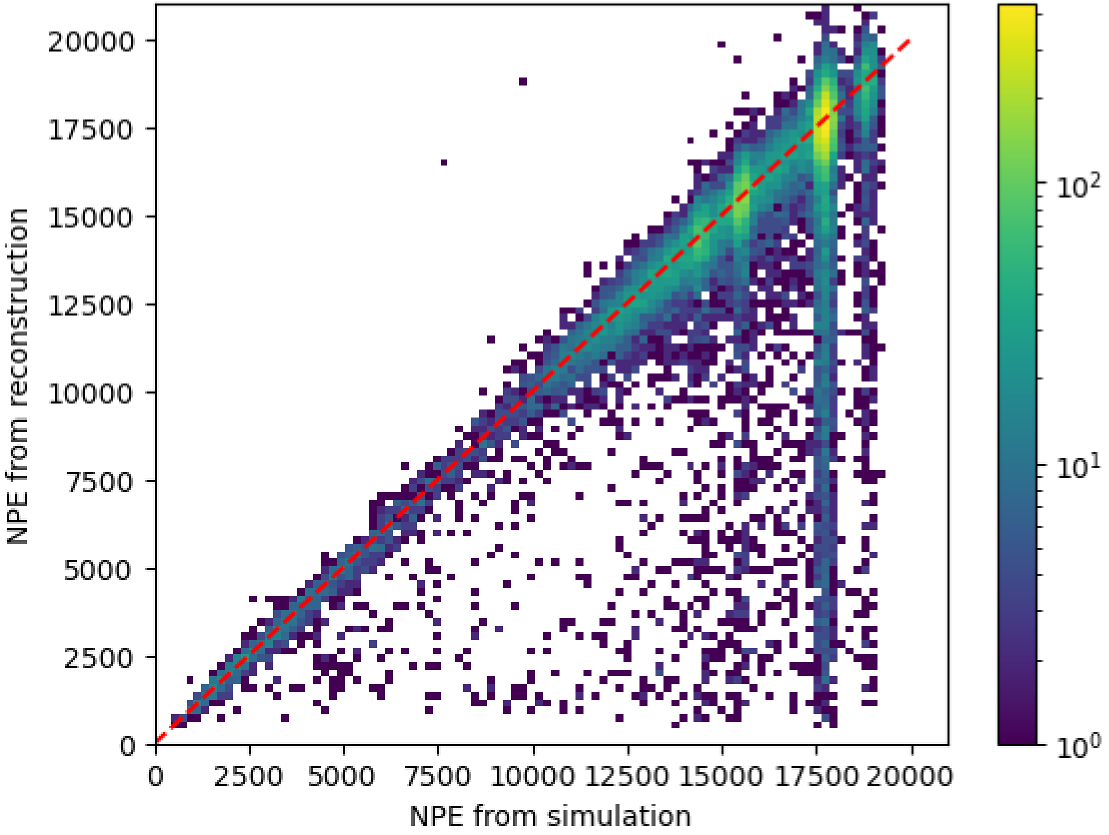
- Input:
  - $T_{si}, R_{Si}, iPDE,$: 2D look up table.
  - R_D, FF: Fix constant.



- 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.
- $PDE = FF \cdot T_{Si} \cdot iPDE = FF \cdot (1 - R_{sp})iPDE$

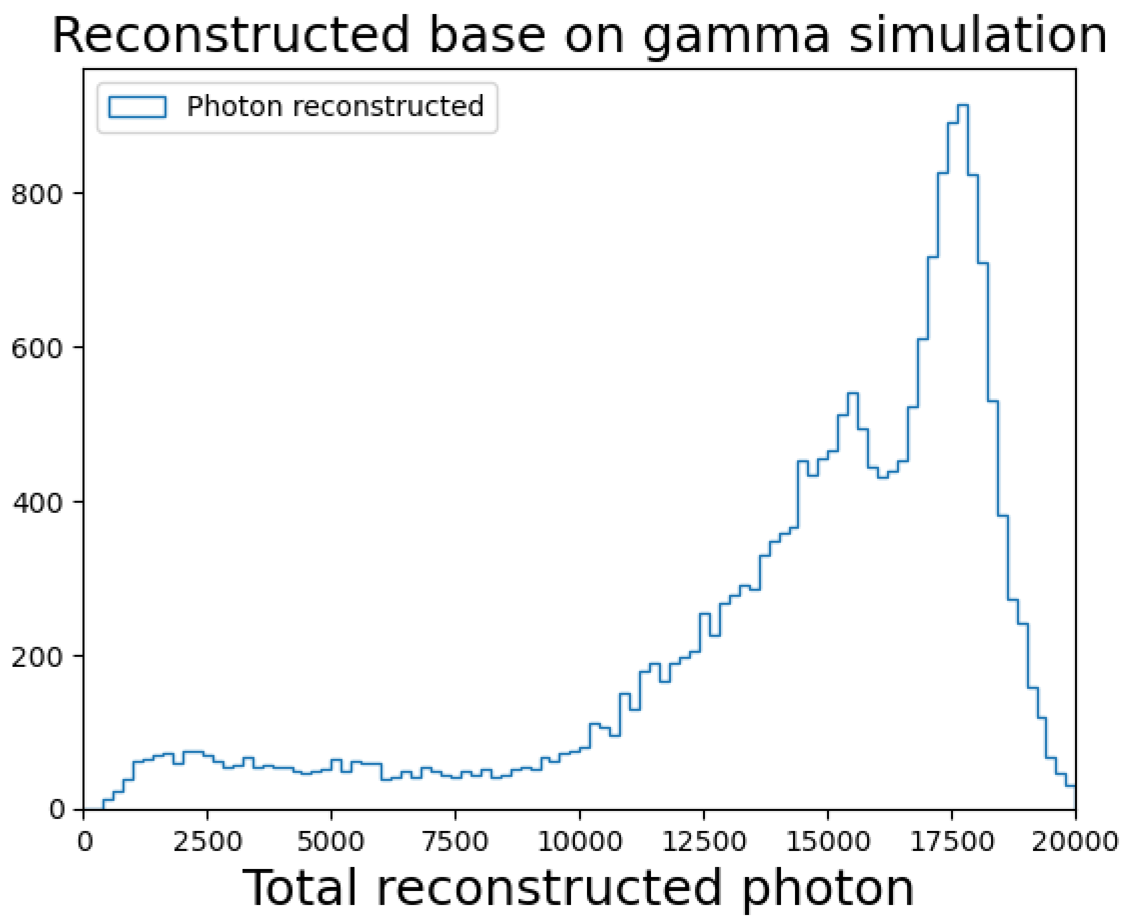
Ba-133 Simulation

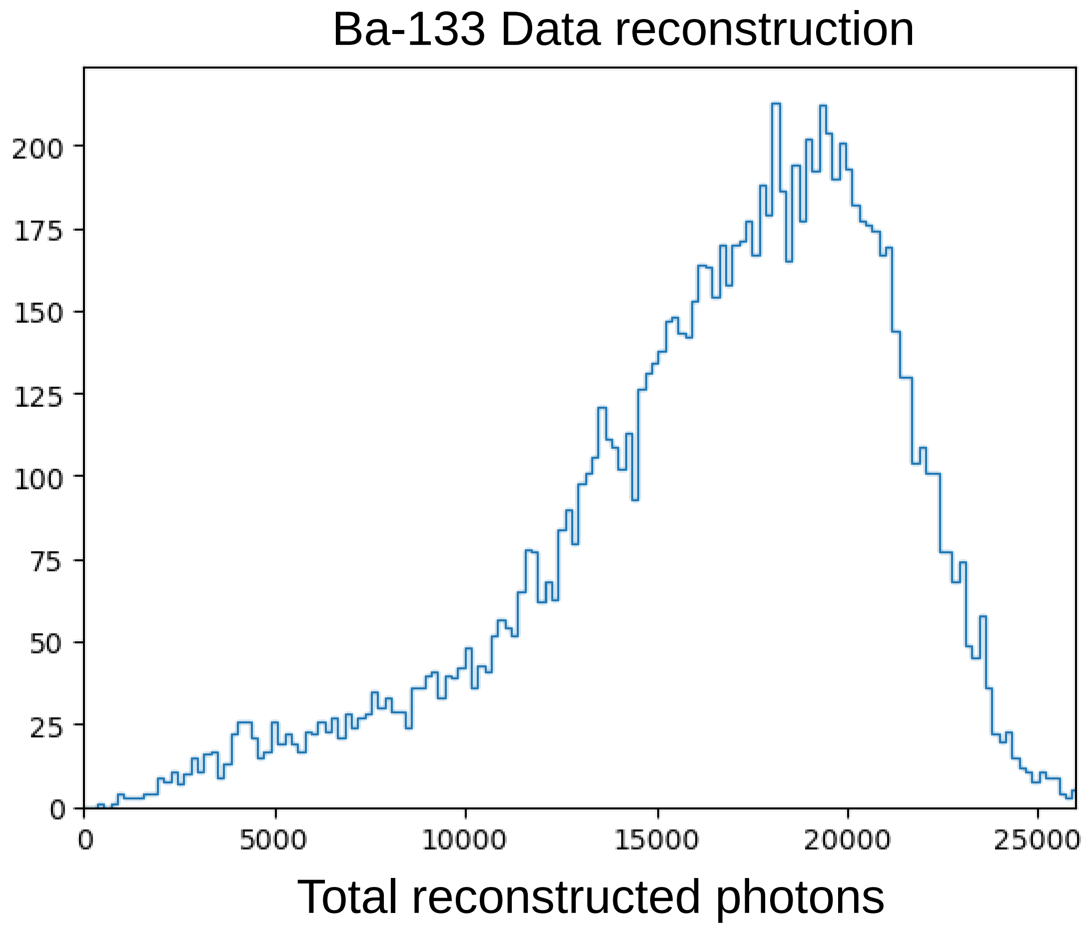




Ba-133 Simulation data compare

- Same Cut apply on likelihood and fiducial volume.





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.