



Progress towards a liquid xenon calorimeter for the PIONEER Experiment



Dr. Ben Davis-Purcell, TRIUMF

2025 CAP Congress

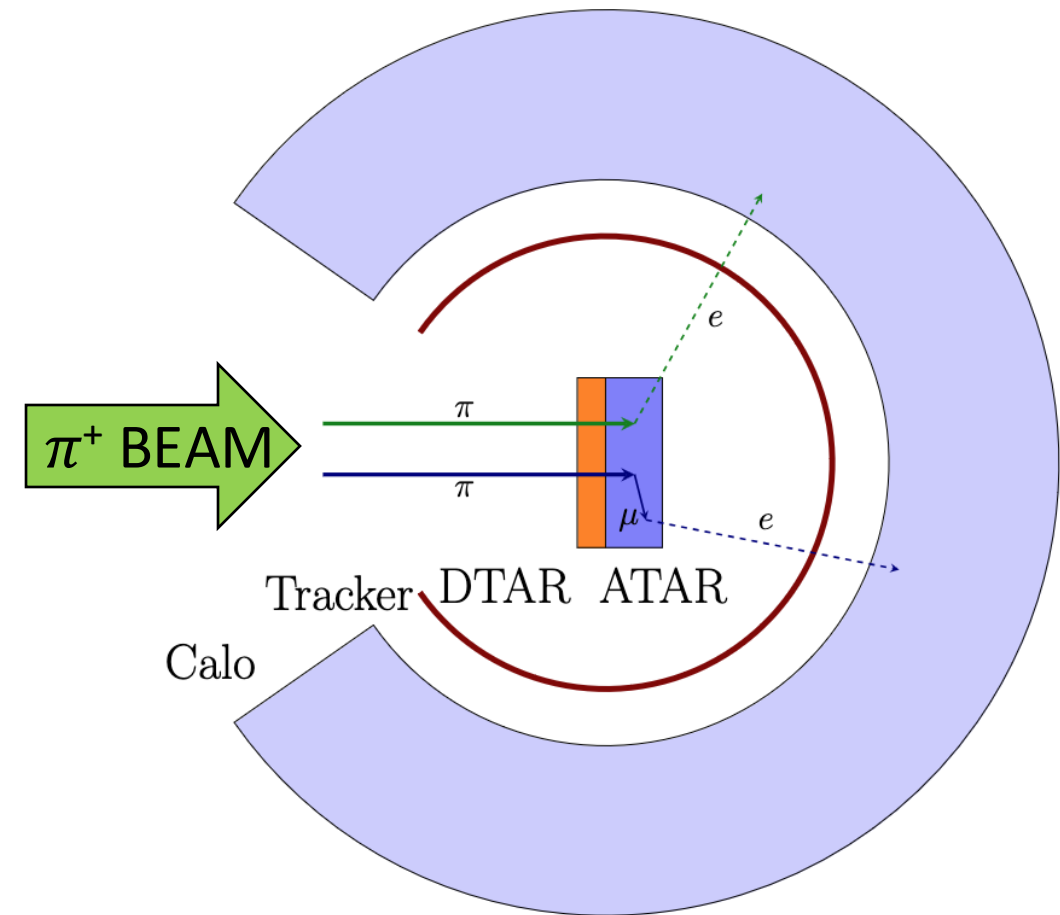
June 11, 2025



PIONEER Experiment Conceptual Overview

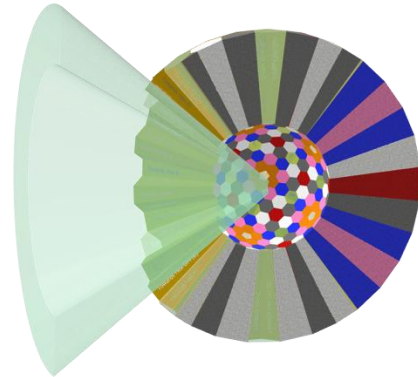
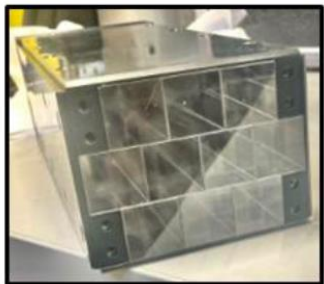
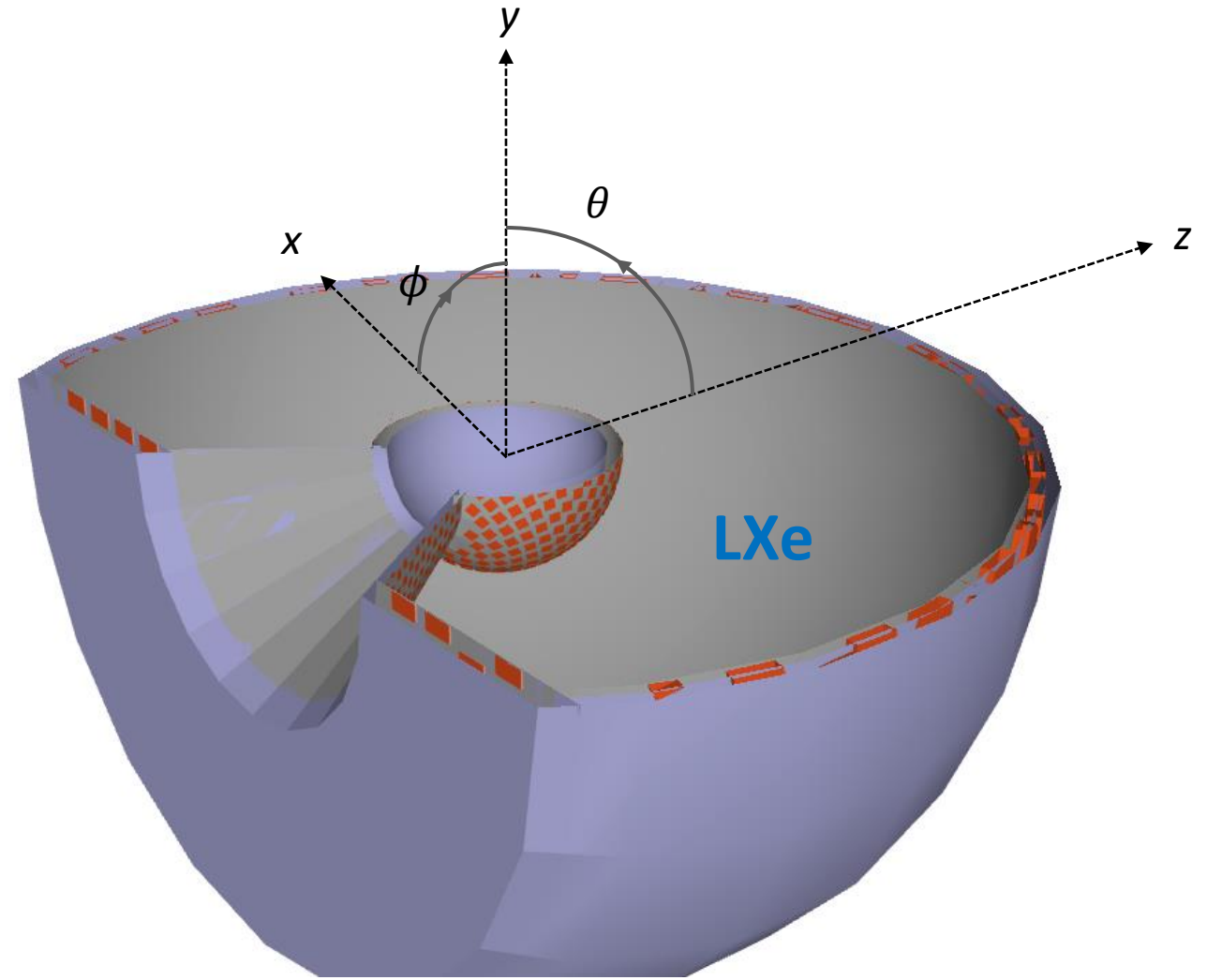
Reminder: $R_{e/\mu}^{\pi} = \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))} \approx 1.23 \times 10^{-4}; \frac{\delta_{exp}}{\delta_{SM}} = \frac{0.187\%}{0.012\%} \approx 15$

- 300 kHz high intensity pion beam at PSI
- Degrader TARget – slows pions
- Active TARget – stops pions and classifies events using topology and energy deposition
- Tracker – auxiliary detector to determine topology of exiting positron
- **Calorimeter (Calo) – measures positron energy, position and timing**



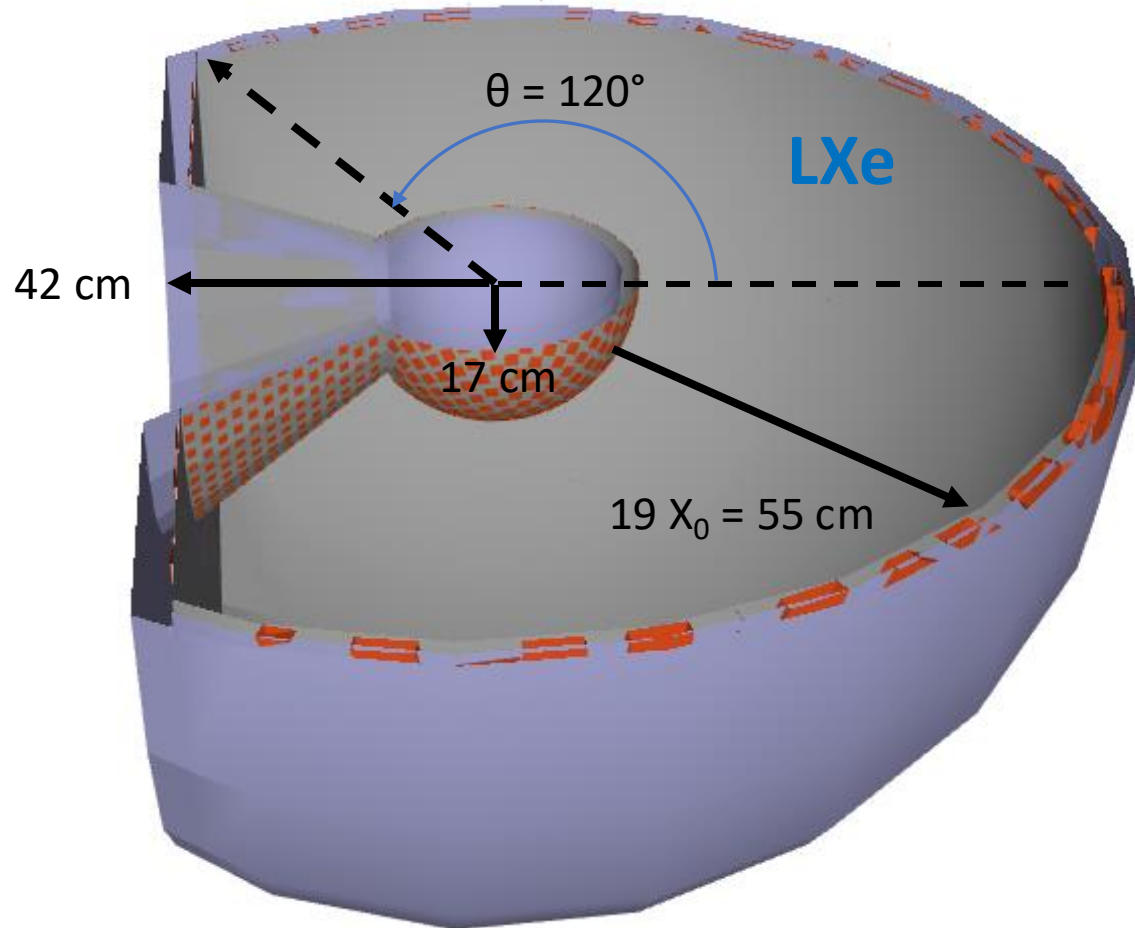
PIONEER Calorimeter

- Requirements:
 - Large radiation length
 - Good energy resolution
 - Precision timing
 - Pileup rejection
- Investigating 2 options:
 - Liquid xenon (LXe)
 - Crystal design with LYSO



- highly segmented (>300 crystals)
- more compact than LXe design (shorter radiation length)

Liquid Xenon Calorimeter



- Fiducial volume: $\theta = [0, 120]^\circ$
- 42 cm = distance to final beamline quadrupole magnet that focuses the pion beam on target

Optical simulation built in GEANT4 to study and optimize detector.

Lessons learned from past year:

- 1) Homogeneous photosensor coverage > maximal photosensor coverage
- 2) Can scale by geometric coverage to improve energy resolution
- 3) Good position resolution achievable with light from inner photosensors
- 4) Slightly reducing detector size allows for shortened beam travel without sacrificing energy resolution

Will link to these lessons throughout talk

LXe Calo Photosensors

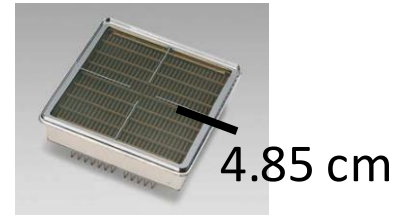
- VUV (~ 175 nm peak), high quantum efficiency
- **Homogeneous photosensor coverage**

110 Wall PMTs

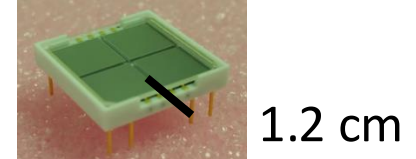
600 Inner SiPMs

Square photosensors:

PMTs



SiPMs

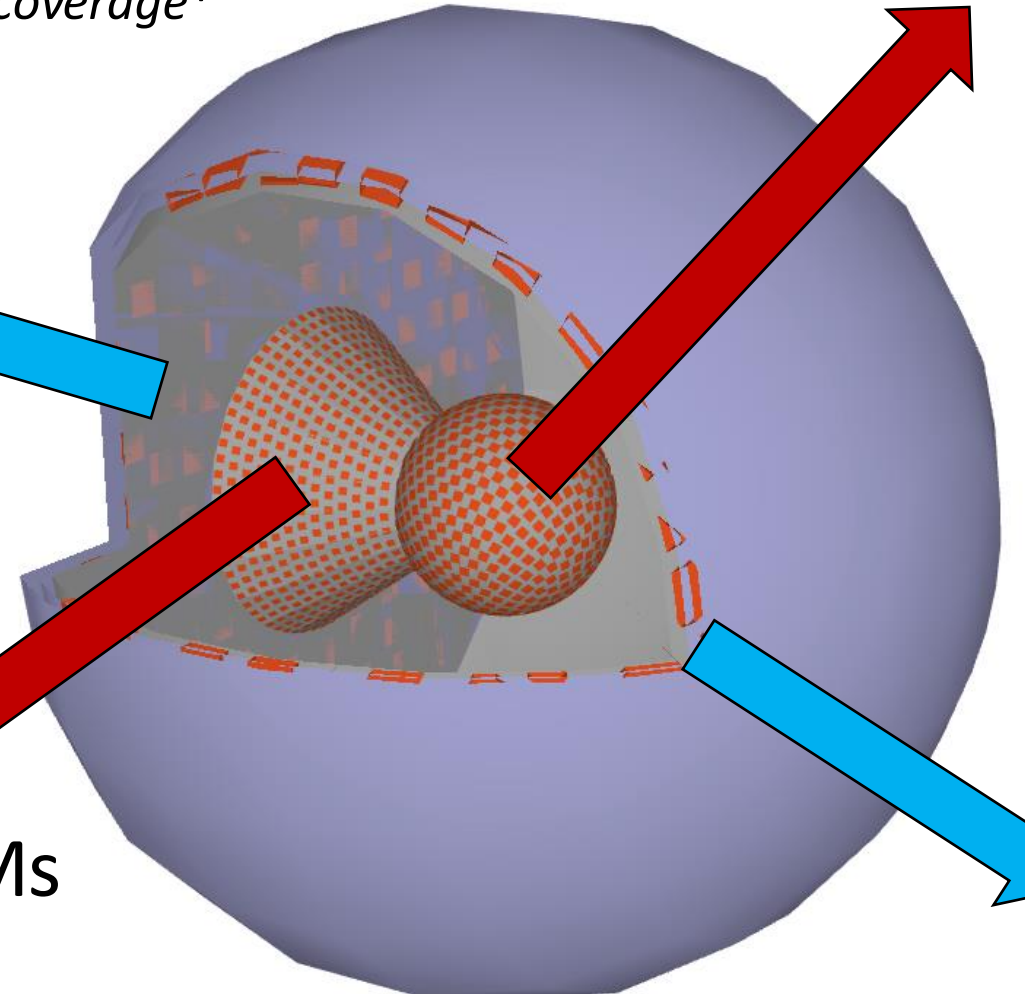


- “Chip on film” technology

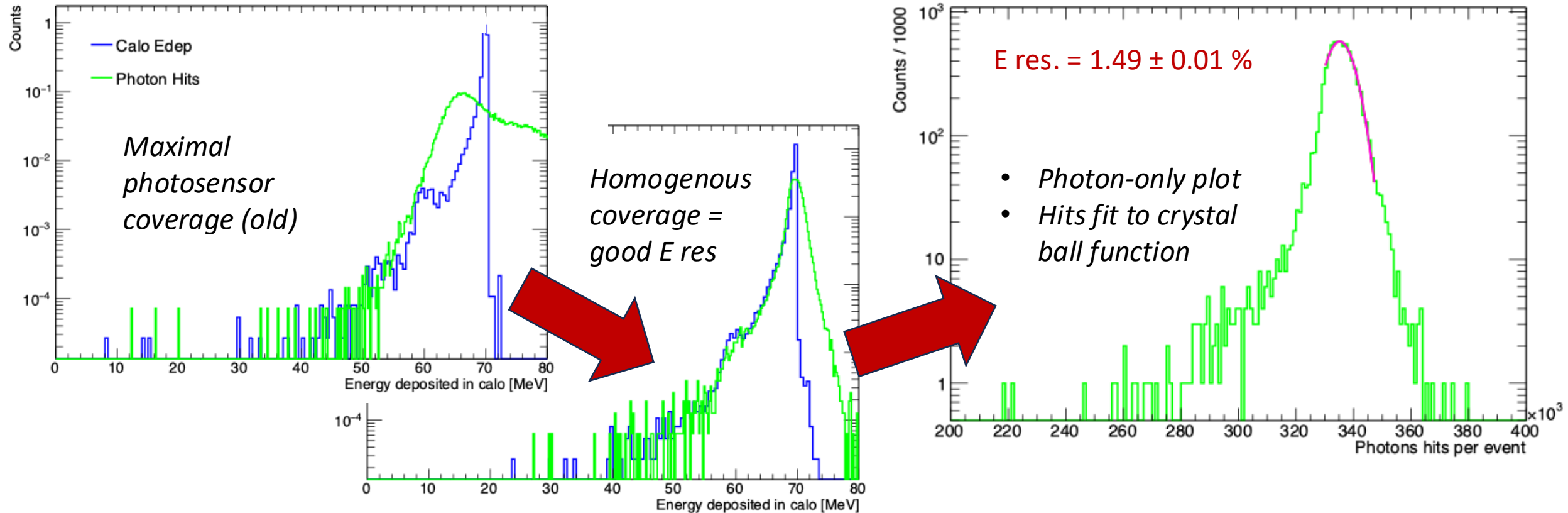
650 Cone SiPMs

550 Outer PMTs

*Flattened entrance \rightarrow PMTs
at beam entrance wall*



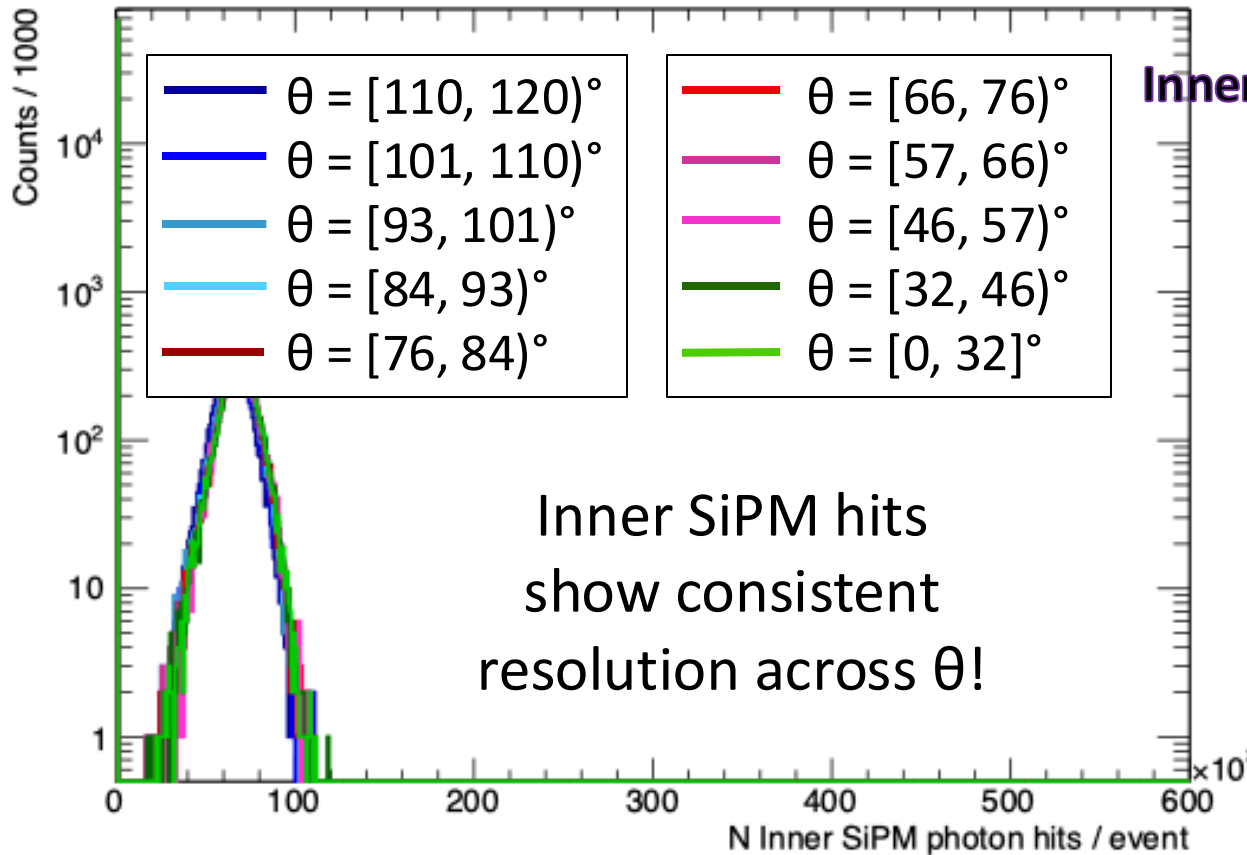
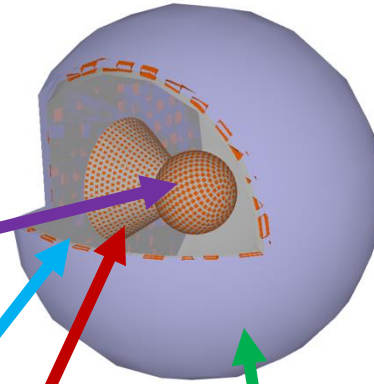
Energy Resolution



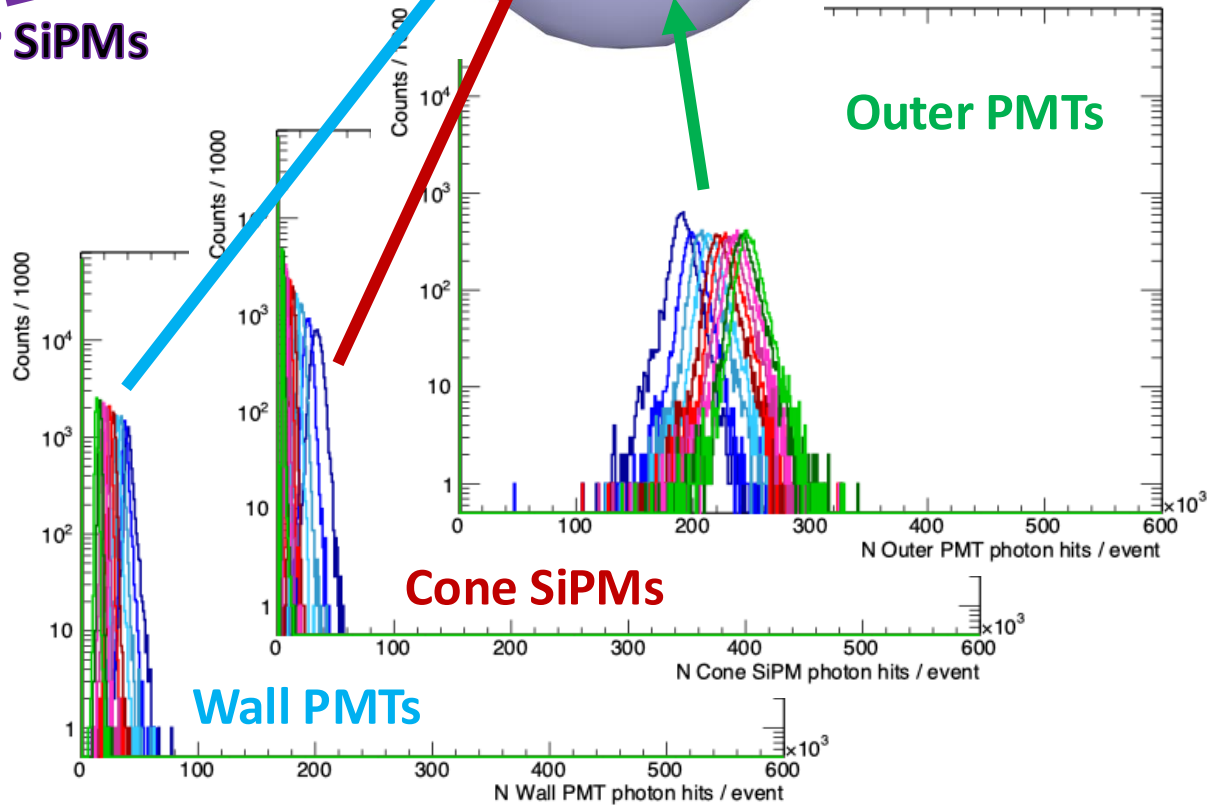
- Results from GEANT4 simulations of $\pi \rightarrow e\nu$ decays
- Energy resolution = σ/μ of crystal ball fit
- Can achieve 1.5% energy resolution!

More Detail: Measuring Optical Photon Hits

- Positron from pion begins to shower (initiated by bremsstrahlung) when it hits LXe (or enough dead material)
- Shower photons detected by the photosensors on 1 of 4 surfaces: **Inner SiPMs**, **Outer PMTs**, **Cone SiPMs**, **Wall PMTs**

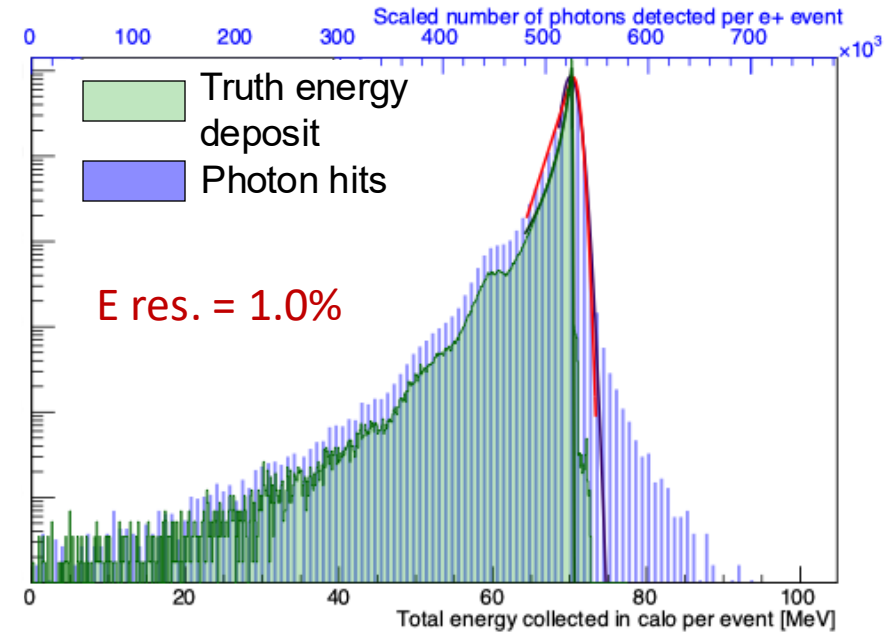
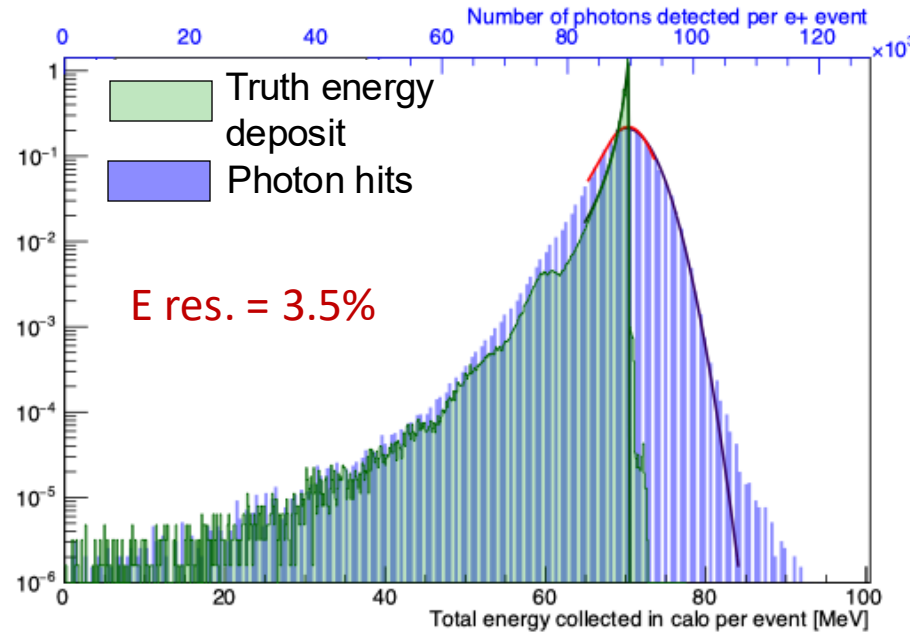
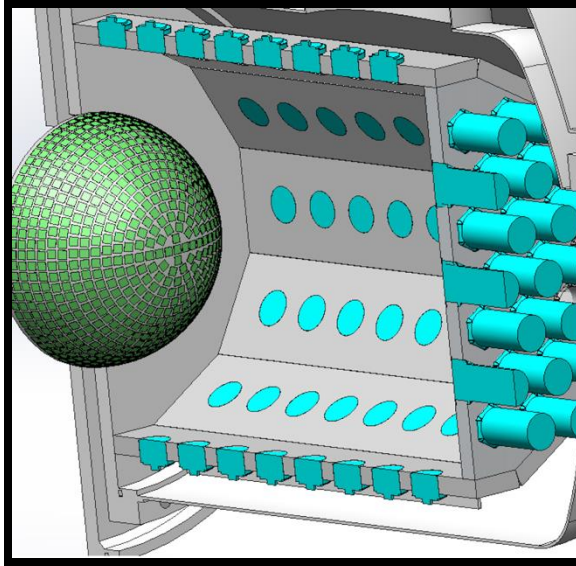


Inner SiPMs

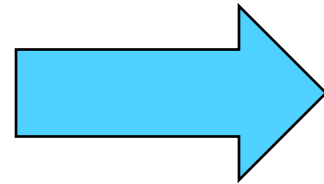


LXe Prototype: *Photon Hit Scaling*

work by Emma Klemets,
UBC/TRIUMF PhD student

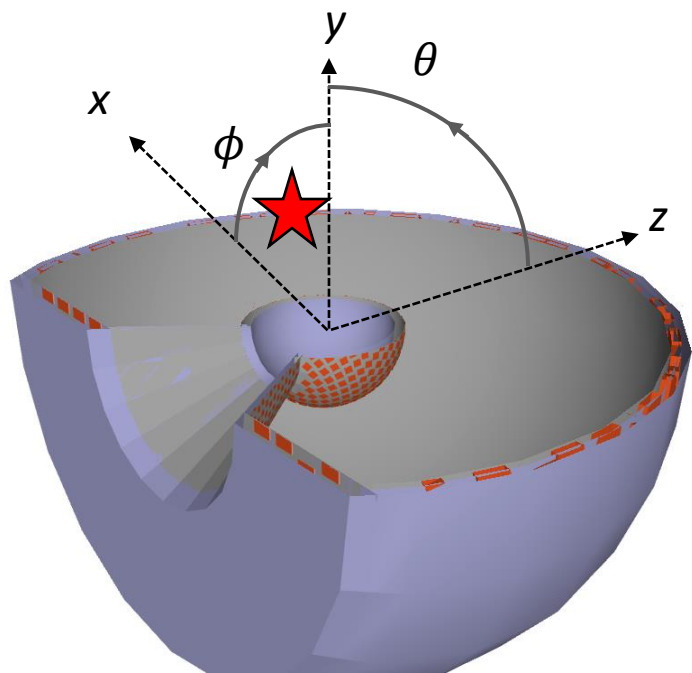


- large LXe prototype detector under development – set to run at PSI in 2026
- cylindrical geometry and PMT limitations means photosensor coverage is not homogeneous



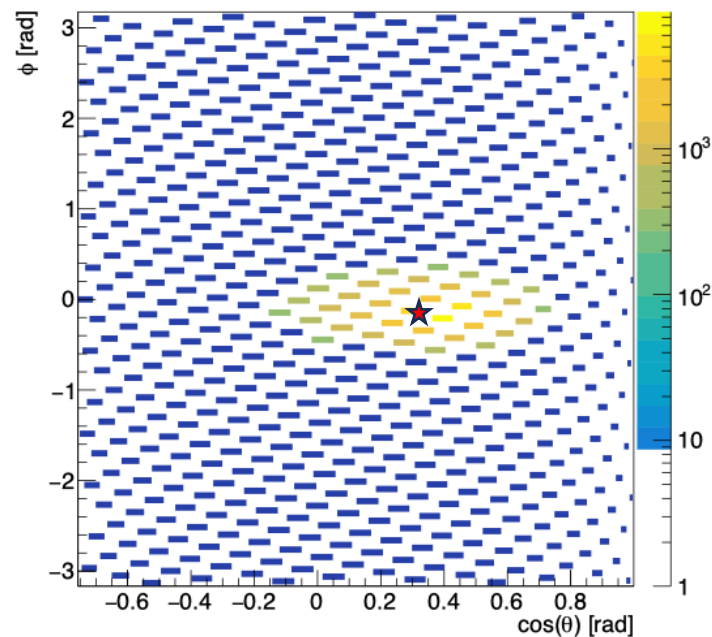
- Scale hits per surface by (Face Surface Area) / (Photosensitive Surface Area)
- Energy resolution improves from 3.5% to 1%!

Full Calo Hit Map

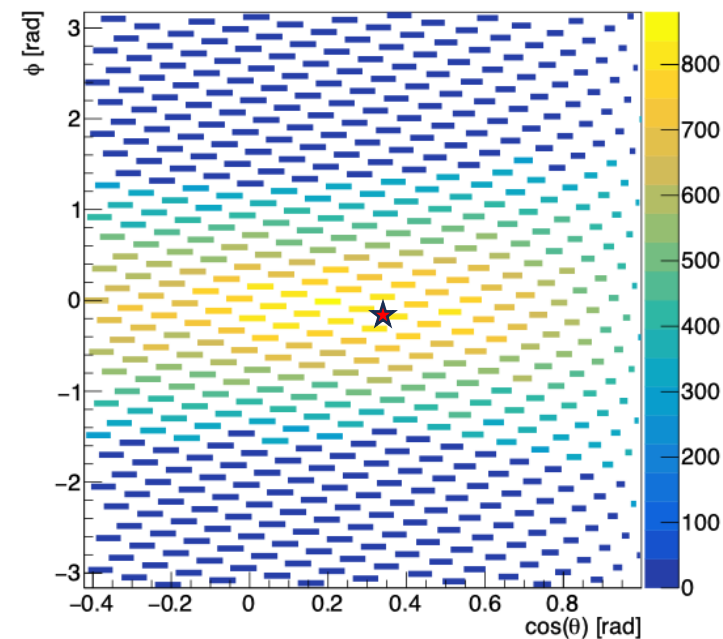


- Sample event: photons light up the detector!
- ★ marks the “truth” position of where the positron begins to shower
- Clustering \rightarrow position reconstruction

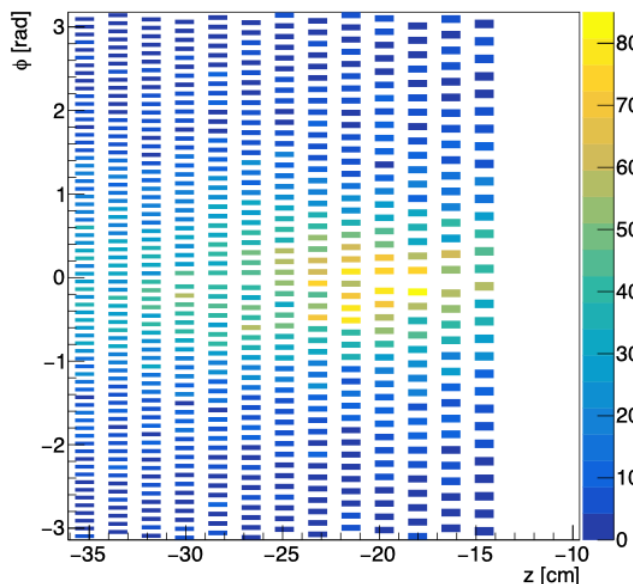
Inner Sphere SiPMs



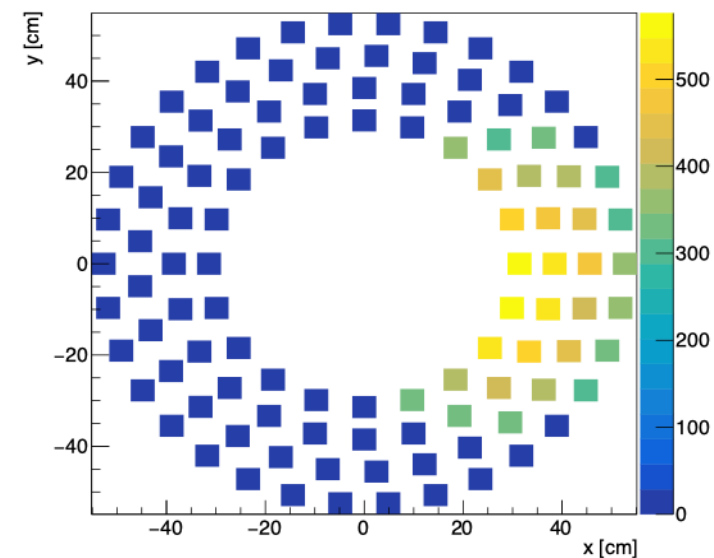
Outer Shell PMTs



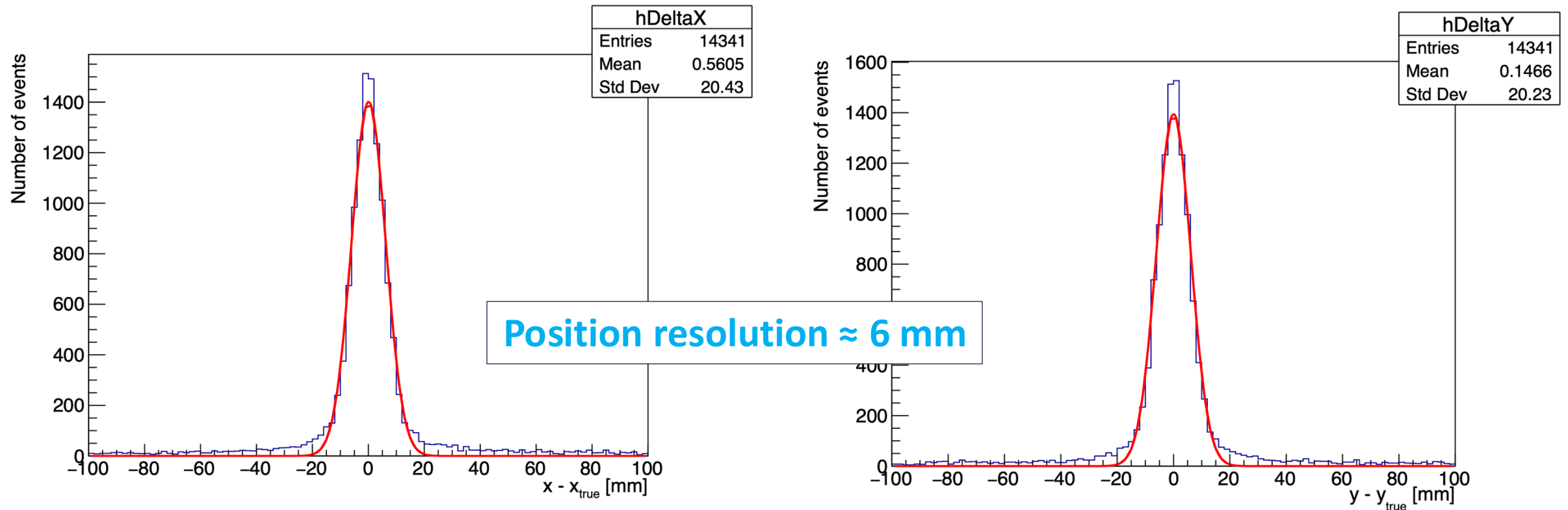
Entrance Cone SiPMs



Entrance Wall PMTs



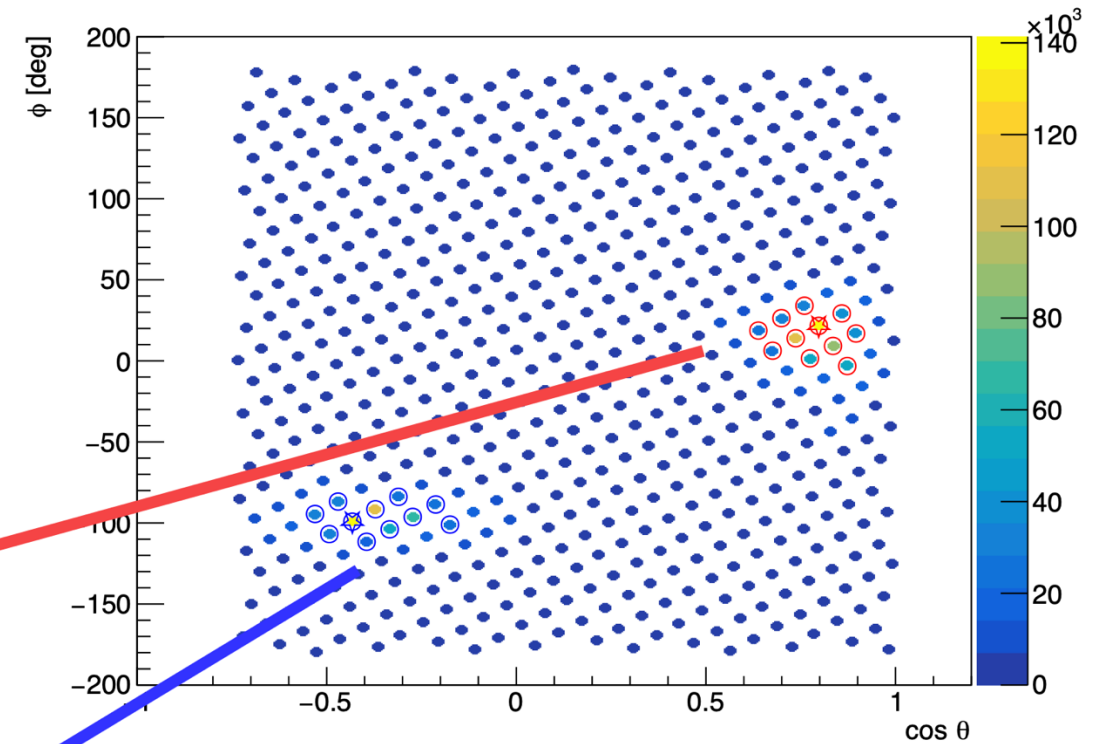
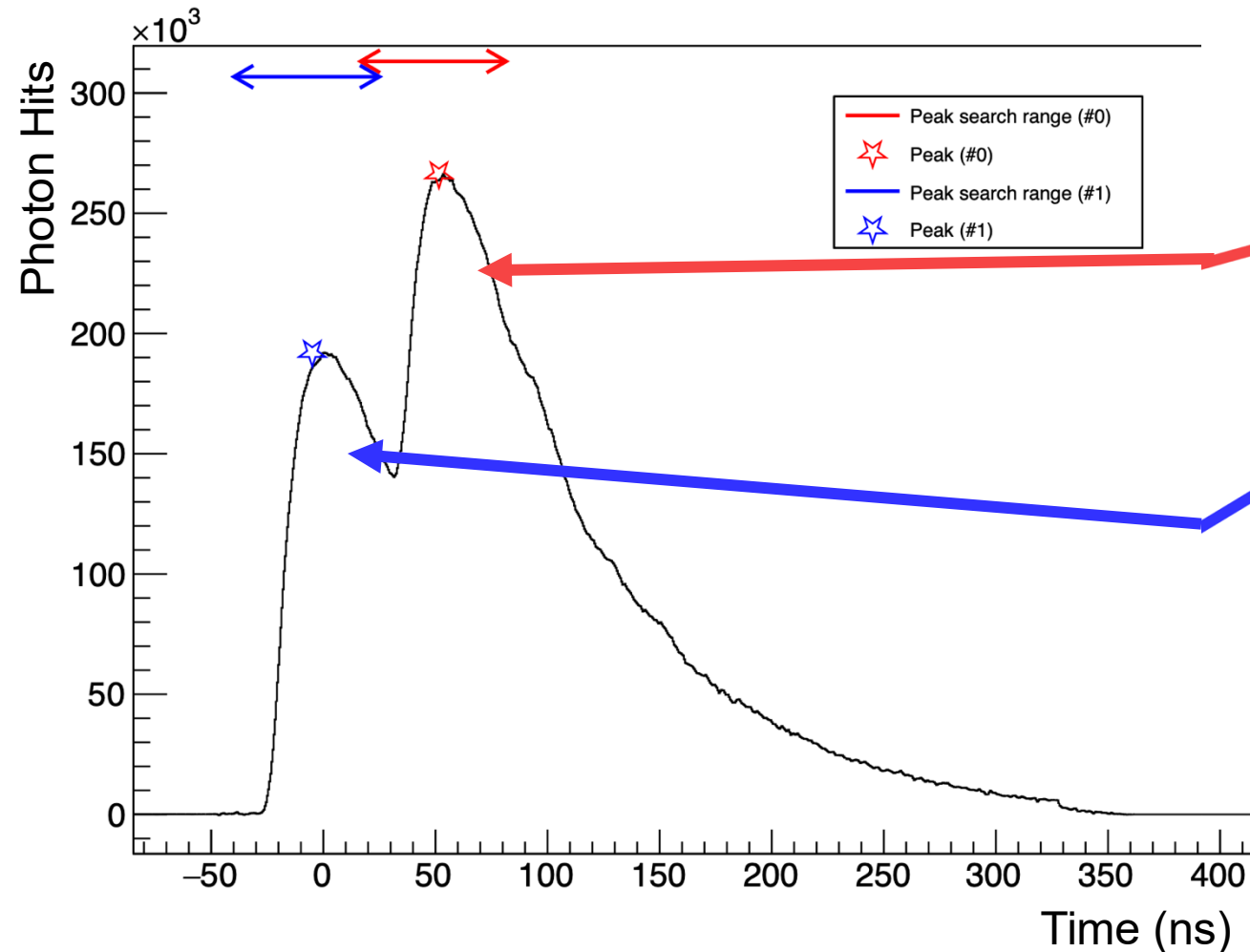
Position Reconstruction



- Photon hit clusters built using clustering algorithm
- *Silicon photomultipliers on inner surface key factor for good position resolution*

Pileup Identification (work in progress)

work by Ayaka Matsushita, UTokyo PhD student

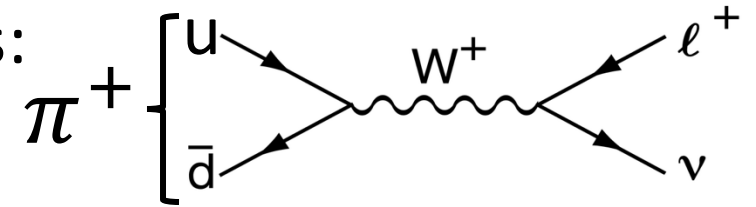


- Multiple clusters within time window can be identified as pileup
- Summed waveforms created and time shifted
- Assigning separate summed waveforms to respective energy deposits:
 - radiative modes must be summed while rejecting pileup events

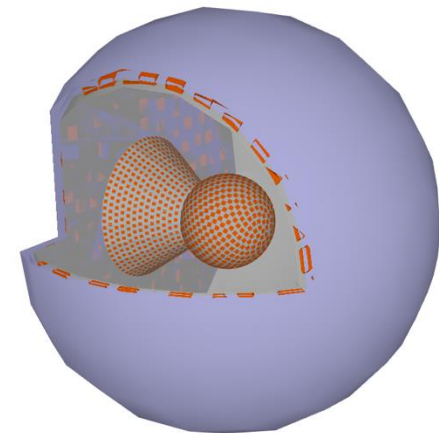
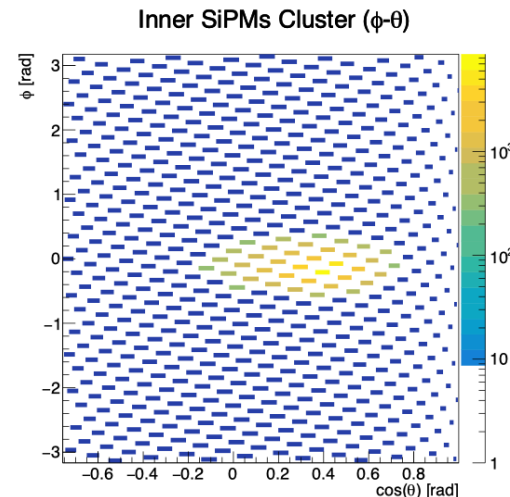
Summary

- PIONEER: precision rare decay experiment that will study lepton flavour universality by measuring pion decays:

- $R_{e/\mu}^{\pi} = \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))}$ with uncertainty $O(0.01\%)$

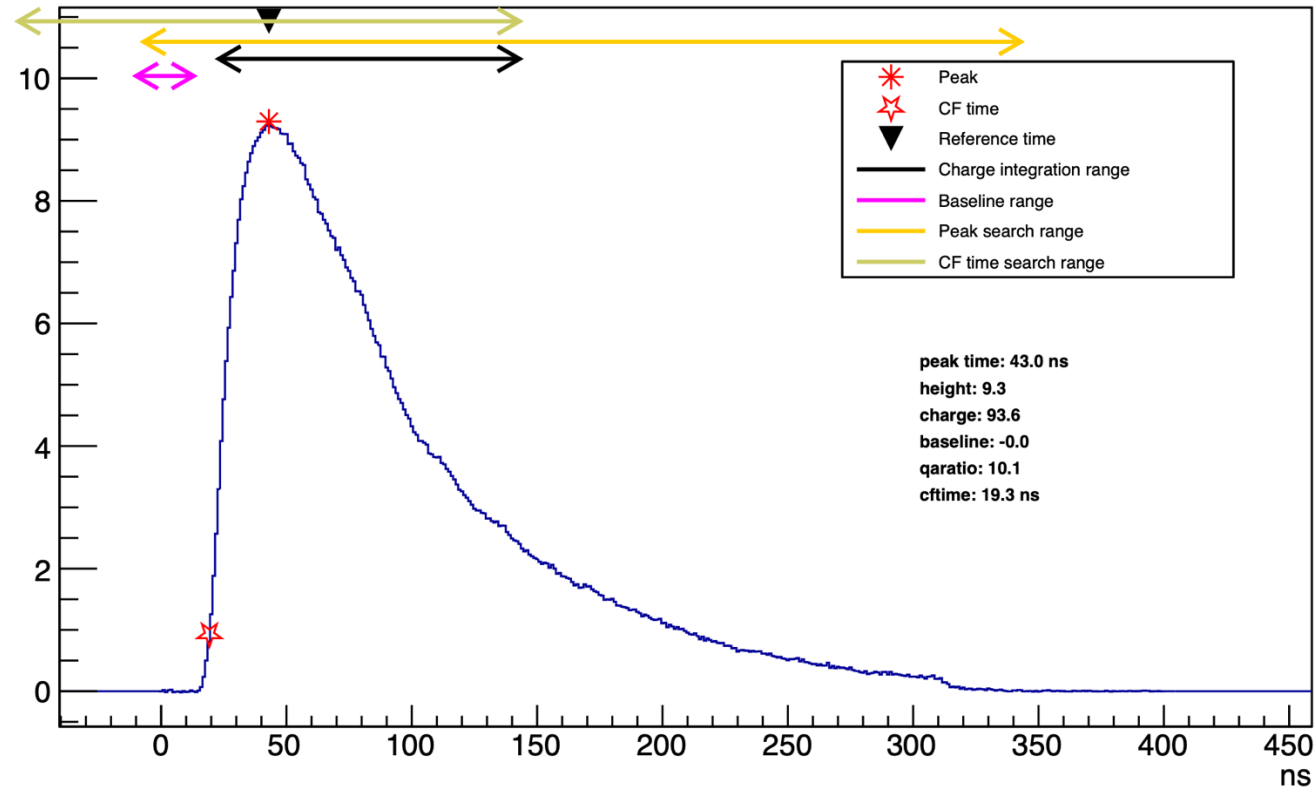


- Significant progress made towards understanding the effectiveness of a high-rate liquid xenon calorimeter
- Critical simulation step of understanding pileup currently underway



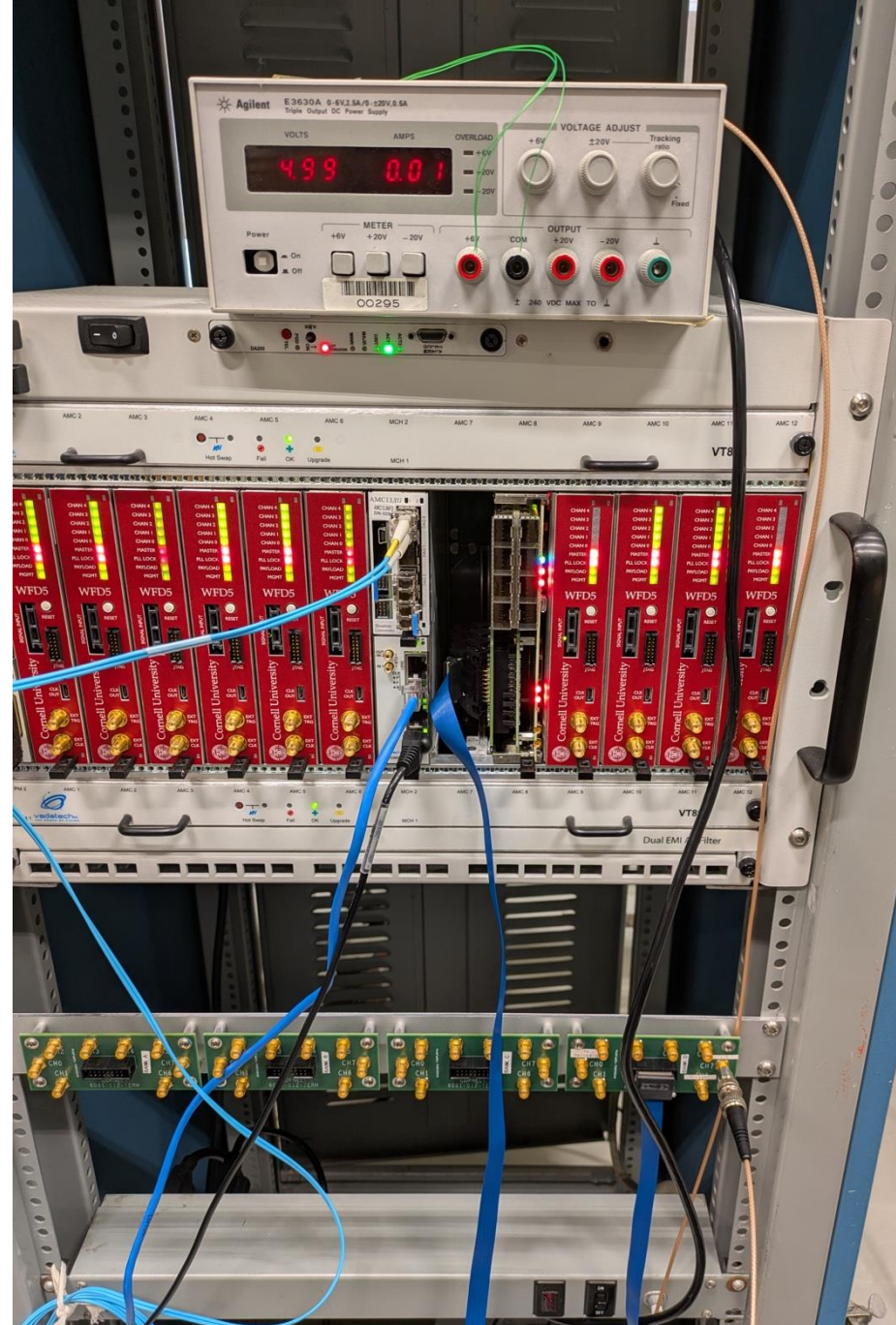
Backup

Photosensor Waveforms



- Photosensor waveform reconstruction built using templates from MEG Experiment
- Photon hits used to scale waveforms

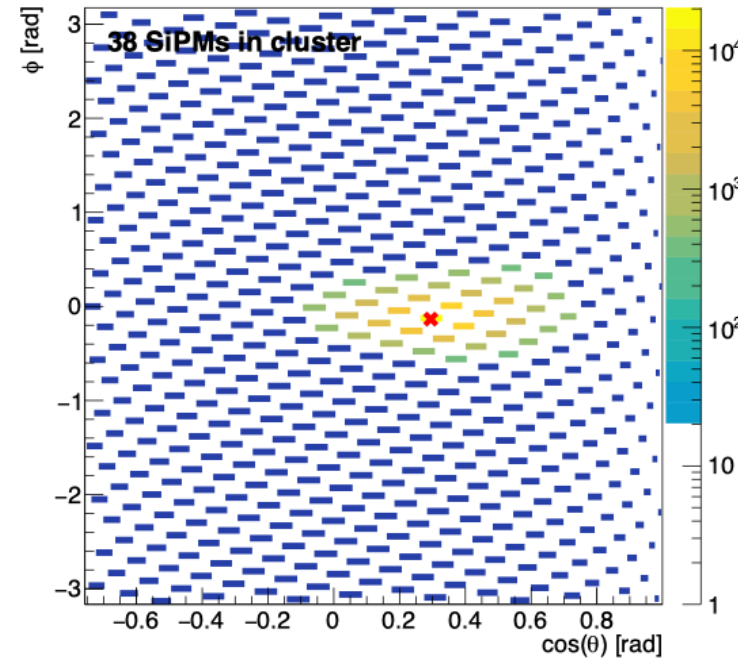
DAQ @ TRIUMF



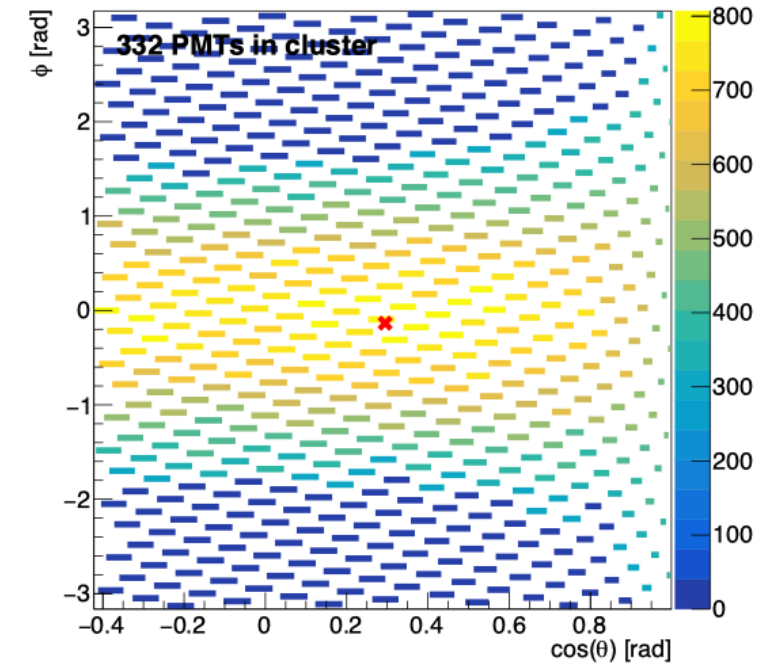
Clustering

- Build cluster of photosensors (PMs) based on a hit threshold and number of nearest neighbour PMs to search
- Nearest neighbours based on photosensor proximity to initial seed

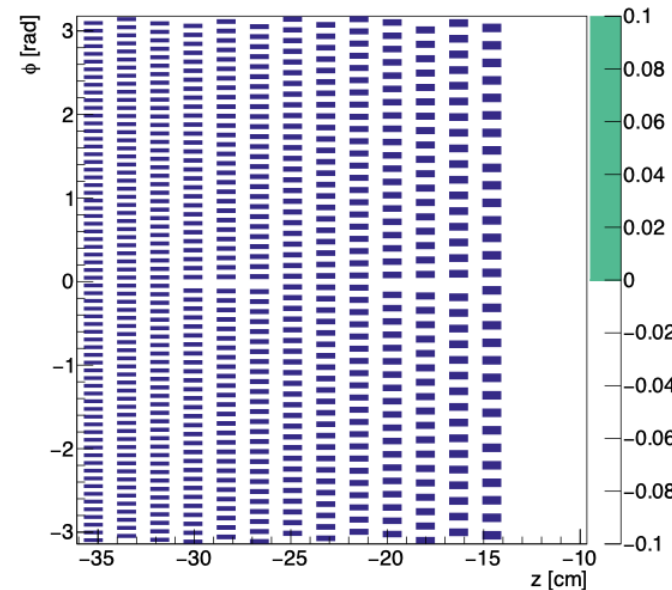
Inner SiPMs Only Cluster (ϕ - θ)



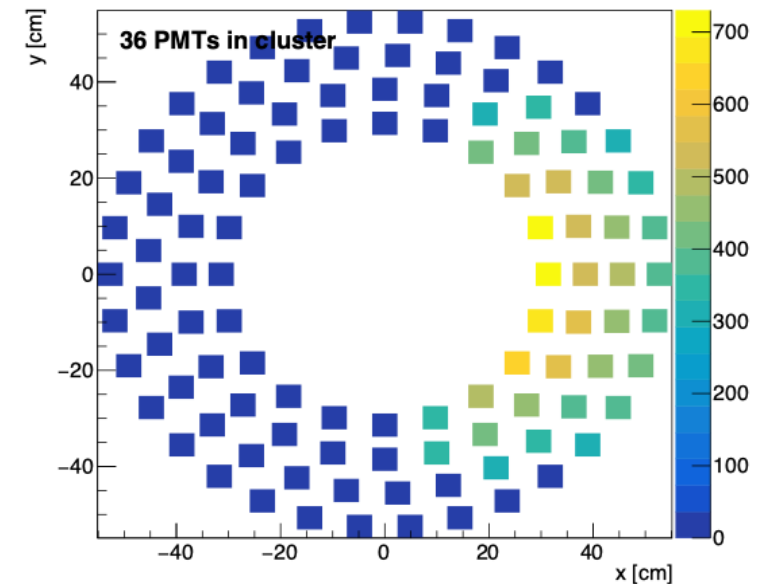
Outer PMTs Only Cluster (ϕ - θ)

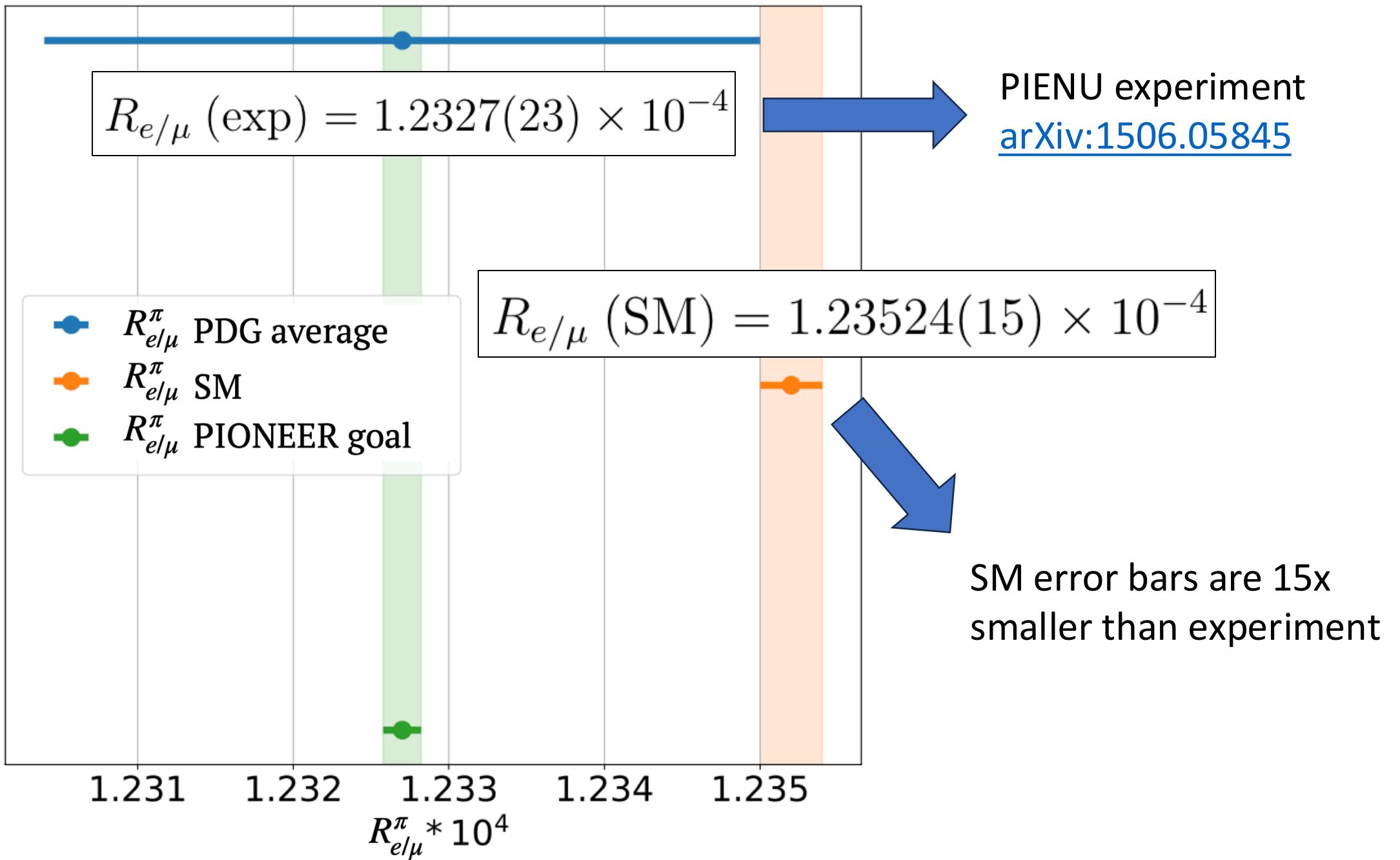


Cone SiPMs Cluster (ϕ -z)



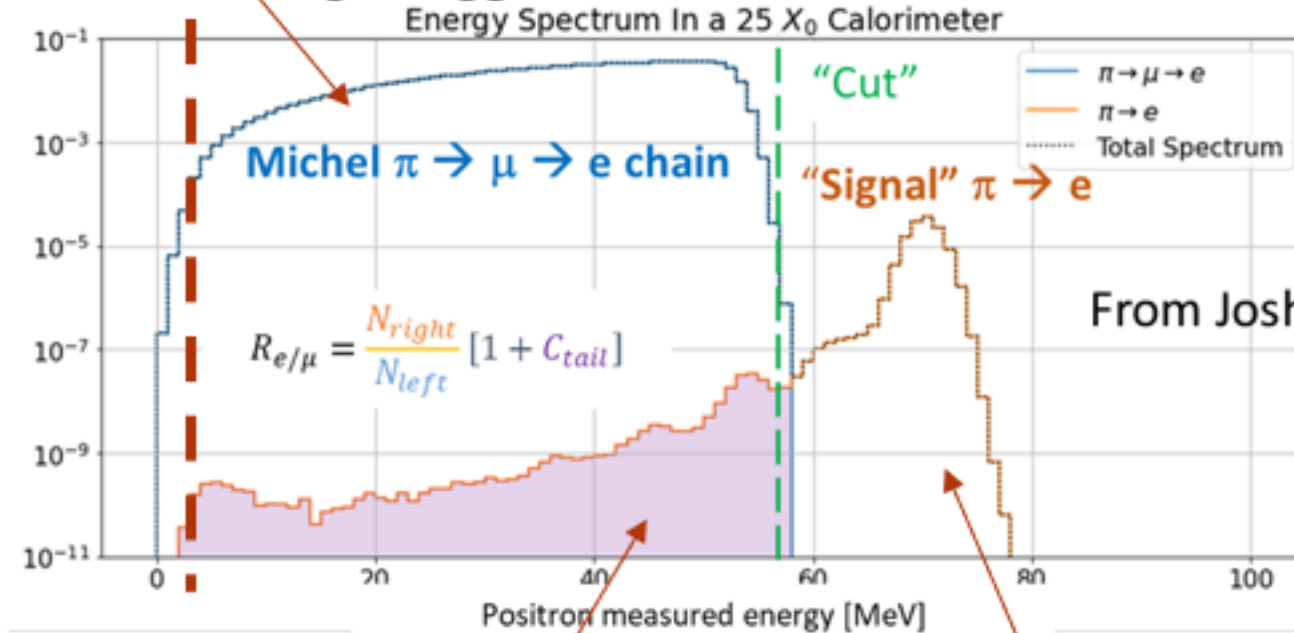
Wall PMTs Only Cluster (y-x)





The Measurement

Easy: low energy trigger



(Dr. Josh LaBounty, UW)

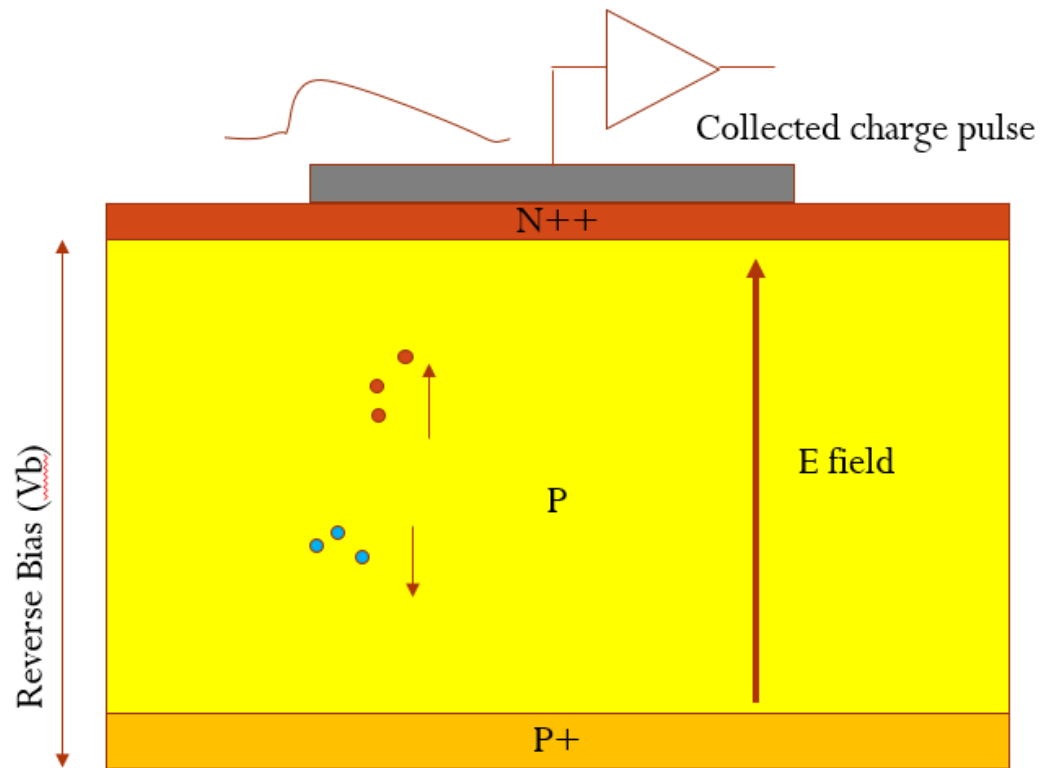
At some point e⁺ won't make it to the Calo

This is the hard part
Tail fraction trigger

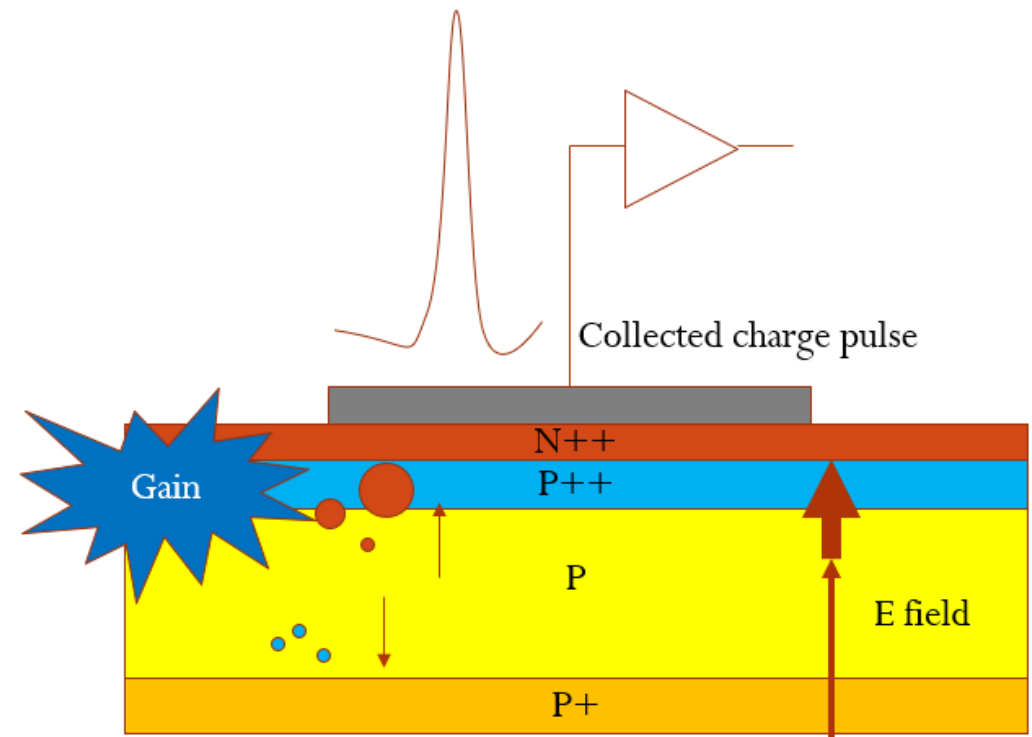
Easy: high energy trigger

ATAR (Active Target)

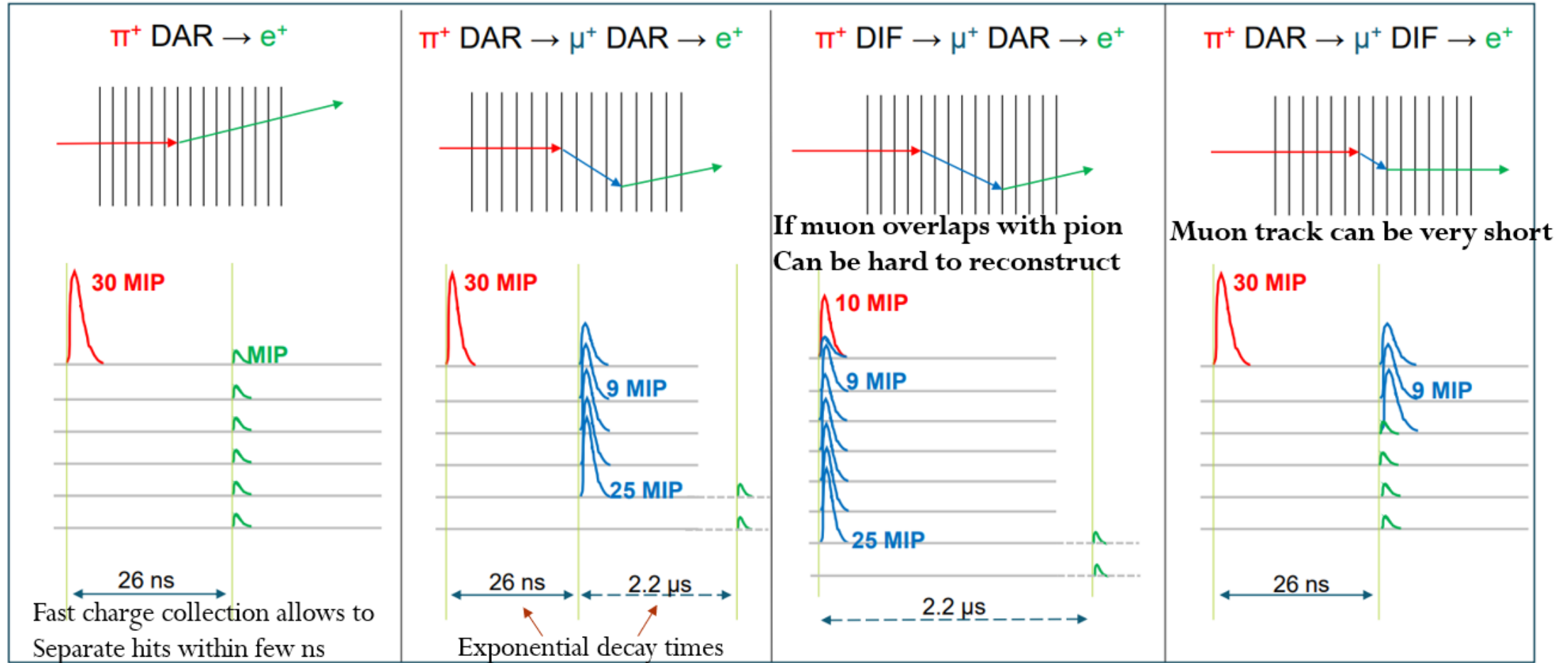
Silicon detector



LGAD

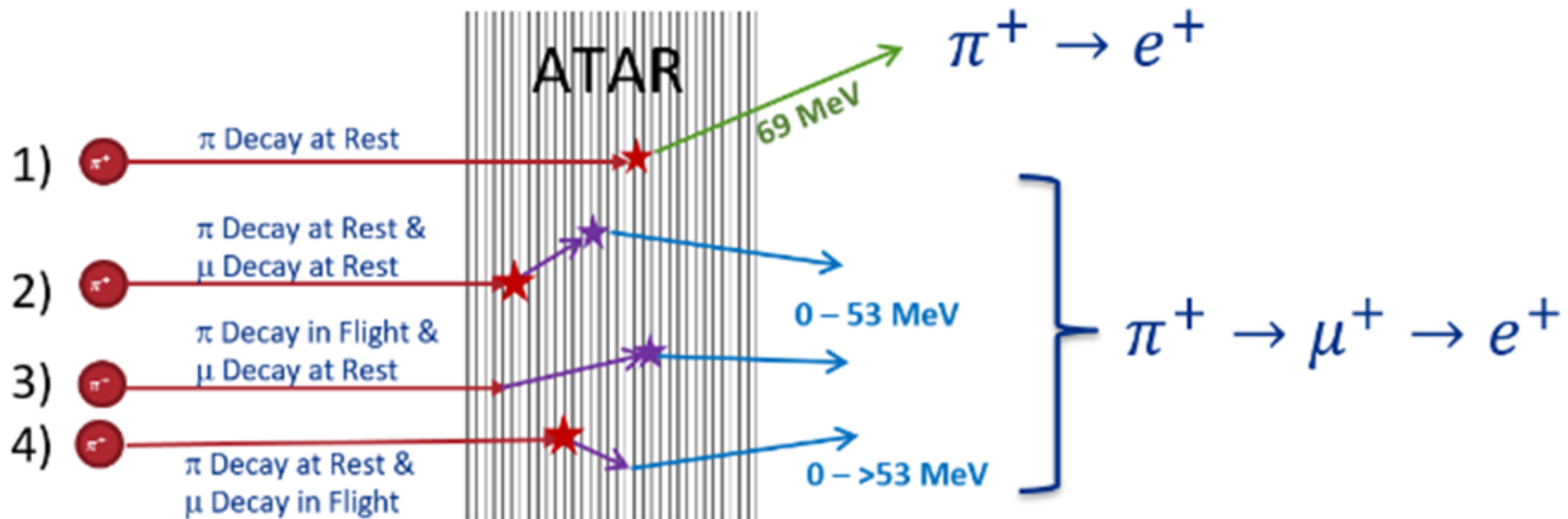


ATAR (Active Target)



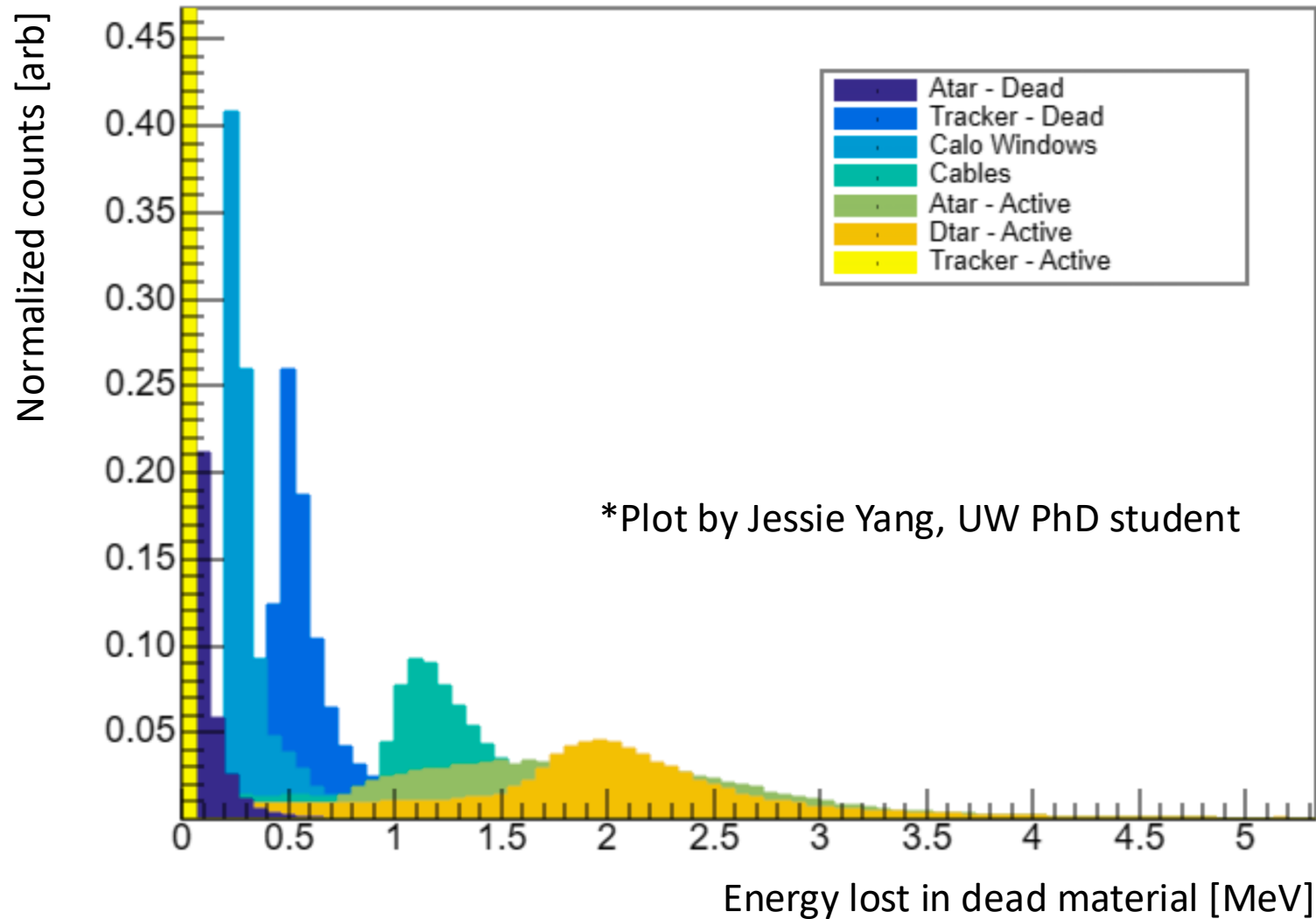
ATAR (Active Target)

- high granularity, fast timing silicon target
- 48 planes of silicon strip sensors alternating between x and y planes
- 100 strips per plane X 48 planes = 4800 channels



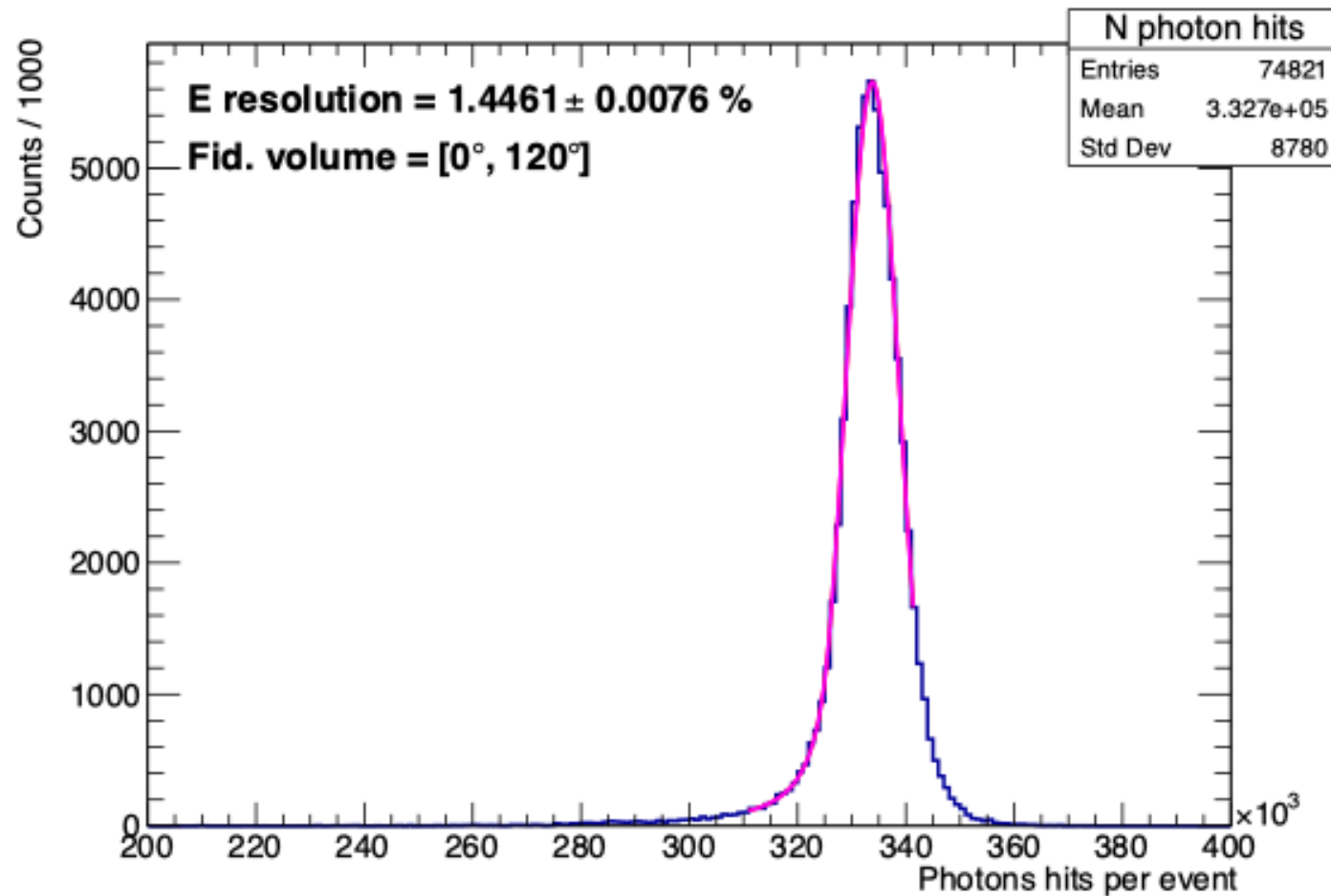
Dead Material

Work in progress



- Understanding impact of dead material is critical for the final calo decision – can obtain good energy resolution with LXe, but becomes less important if already degraded by dead material

Energy Resolution



Can achieve $\sim 1.5\%$ energy resolution!
➤ not a limiting factor for the experiment

- Fit photon hits to a crystal ball function
- Energy resolution = (std. deviation)/(mean)