Simulating a high-rate liquid xenon calorimeter for the PIONEER Experiment

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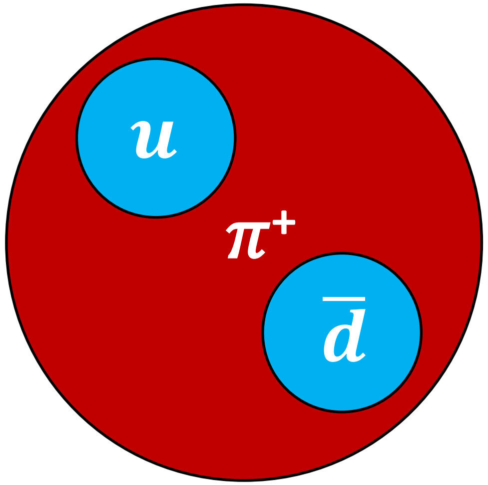
PIONEER Physics: The Why and What

- Lepton Flavour Universality (LFU) – assumed symmetry of the Standard Model (SM) – is this symmetry violated?
  - **Any LFU violation implies new physics!**
- LFU: universal lepton gauge coupling: $g_e = g_\mu = g_\tau$
- **PION**EER – pions! Key particle for LFU measurements



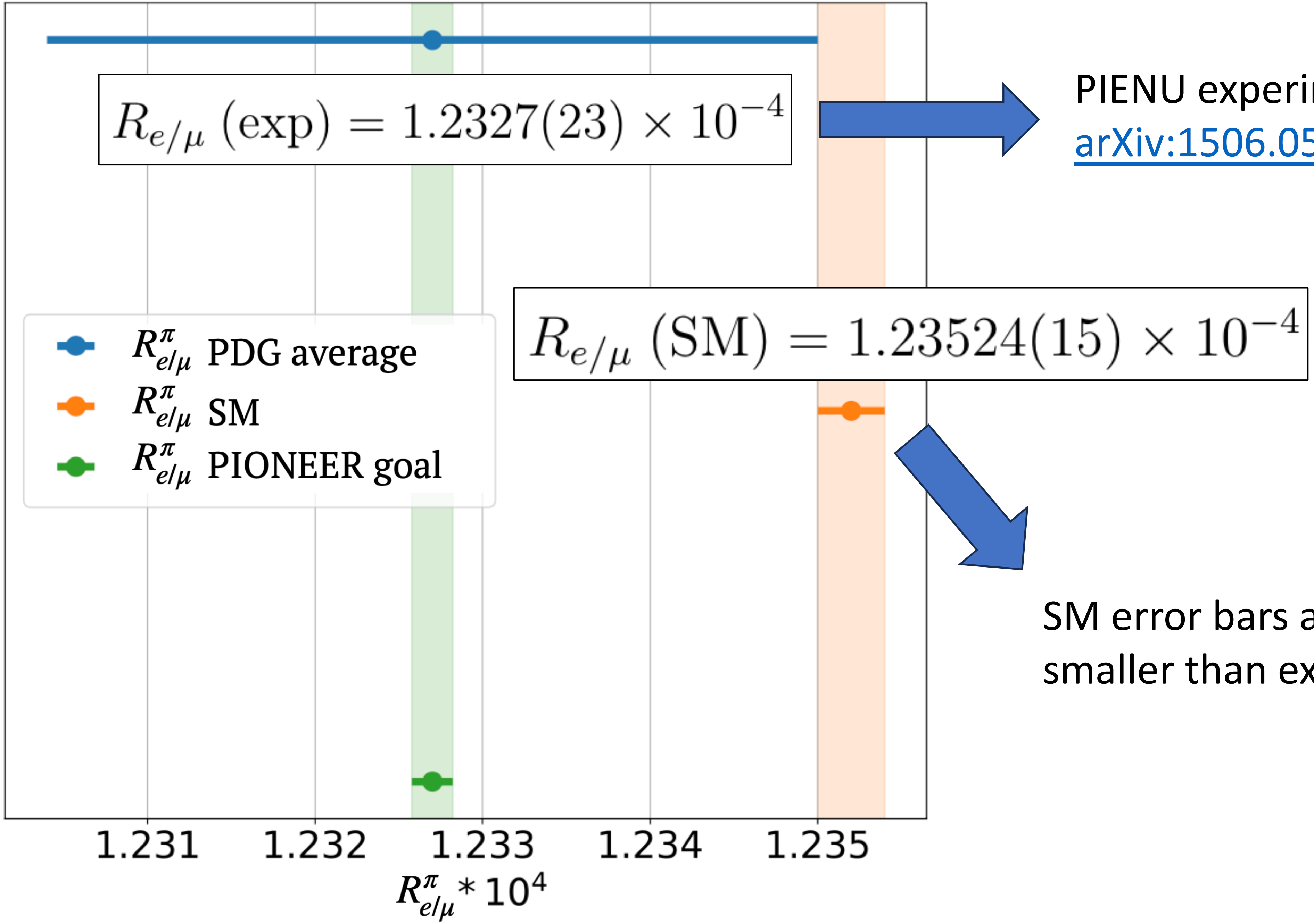
$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

Phase 2 – Pion Beta Decay:
- measure quark mixing parameter $|V_{ud}|$

π^+ Decay Modes

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+\nu_\mu$	(99.98770 ± 0.00004) %	
Γ_2	$\mu^+\nu_\mu\gamma$	$(2.00 \pm 0.25) \times 10^{-4}$	
Γ_3	$e^+\nu_e$	$(1.230 \pm 0.004) \times 10^{-4}$	
Γ_4	$e^+\nu_e\gamma$	$(7.39 \pm 0.05) \times 10^{-7}$	
Γ_5	$e^+\nu_e\pi^0$	$(1.036 \pm 0.006) \times 10^{-8}$	
Γ_6	$e^+\nu_e e^+ e^-$	$(3.2 \pm 0.5) \times 10^{-9}$	
Γ_7	$e^+\nu_e\nu\overline{\nu}$	$< 5 \times 10^{-6}$	90%

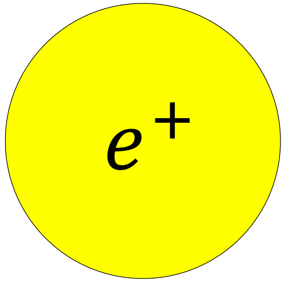
Source: PDG



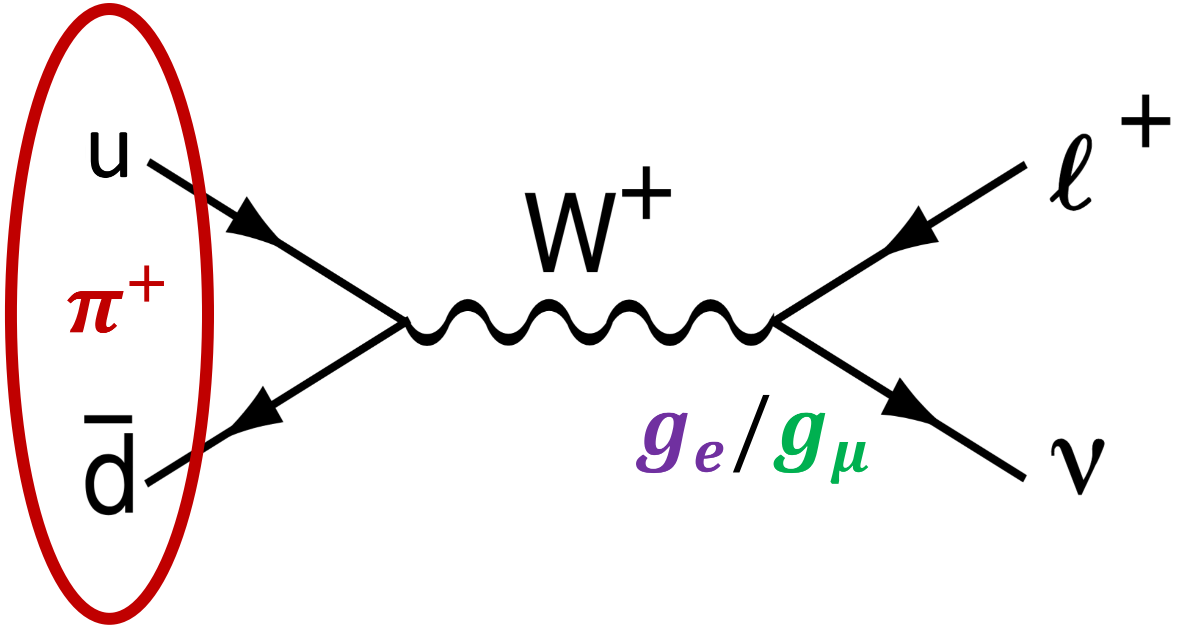
PIENU experiment
arXiv:1506.05845

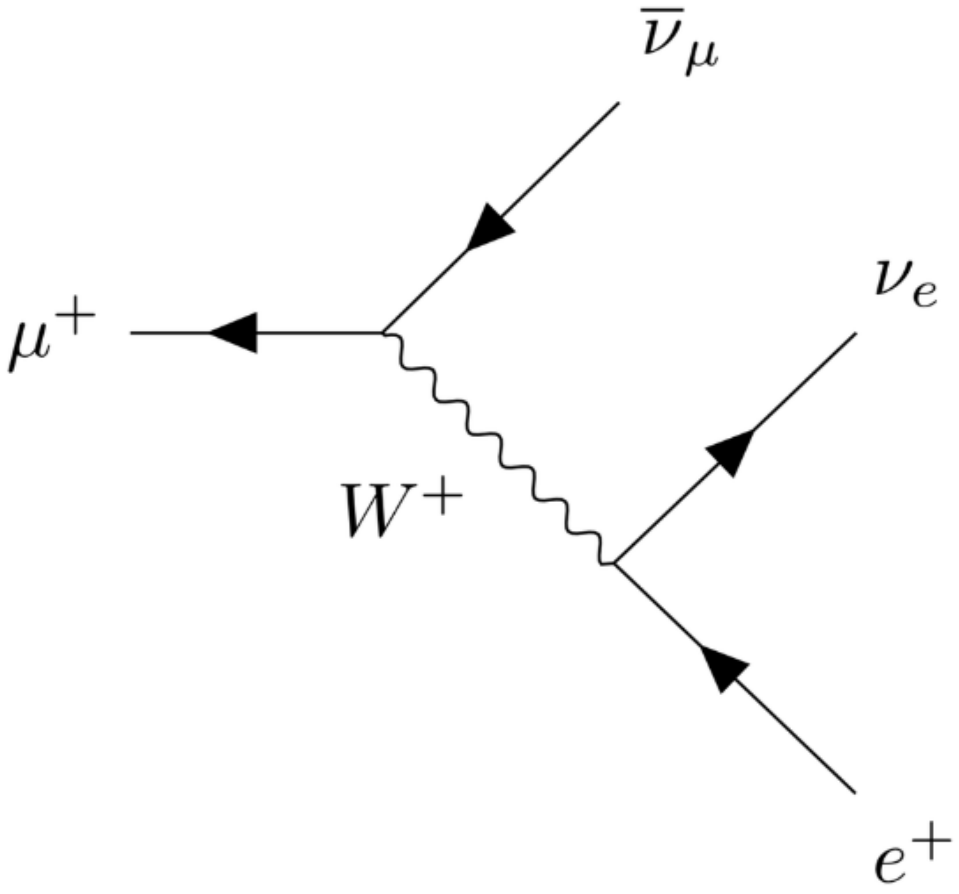
SM error bars are 15x smaller than experiment

What are we measuring?



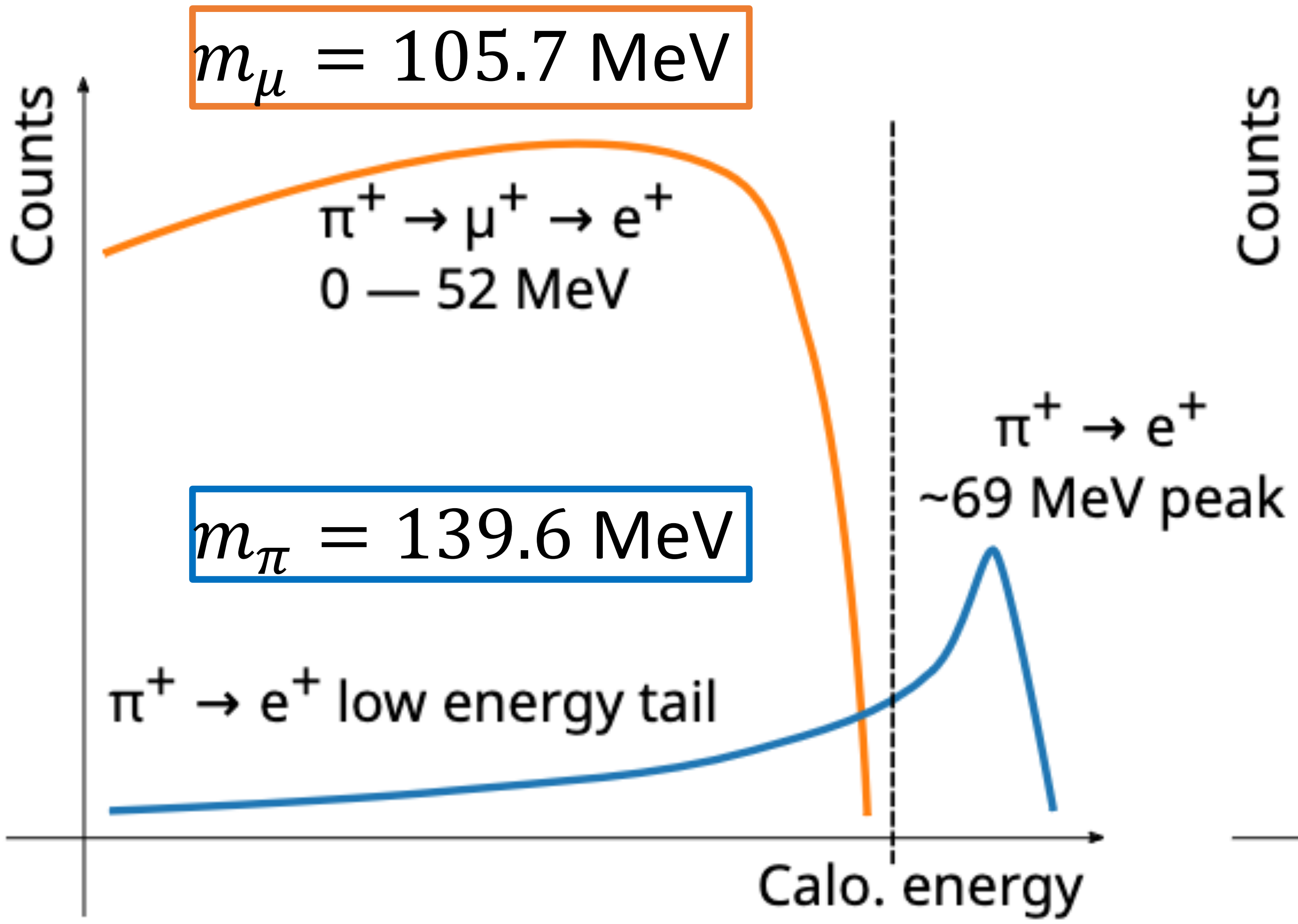
- Only measure the positron



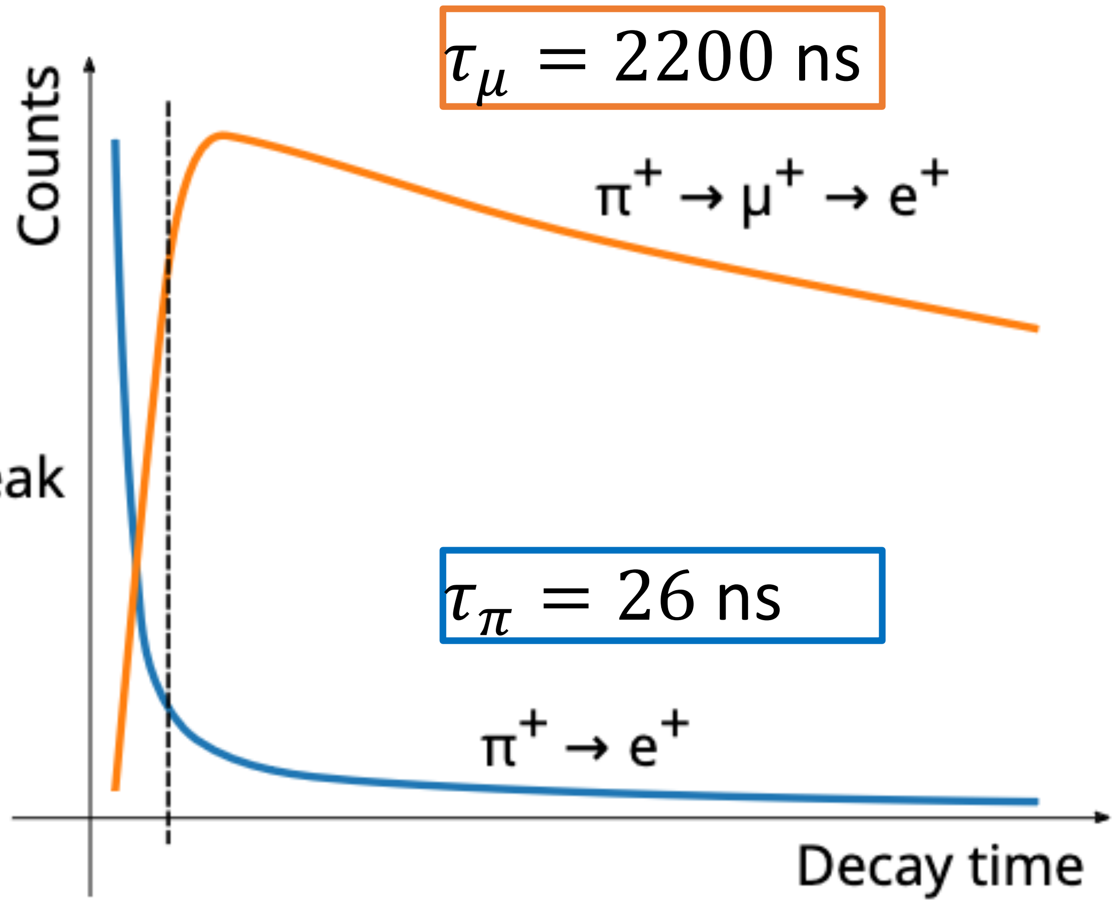


What are we measuring?

Energy

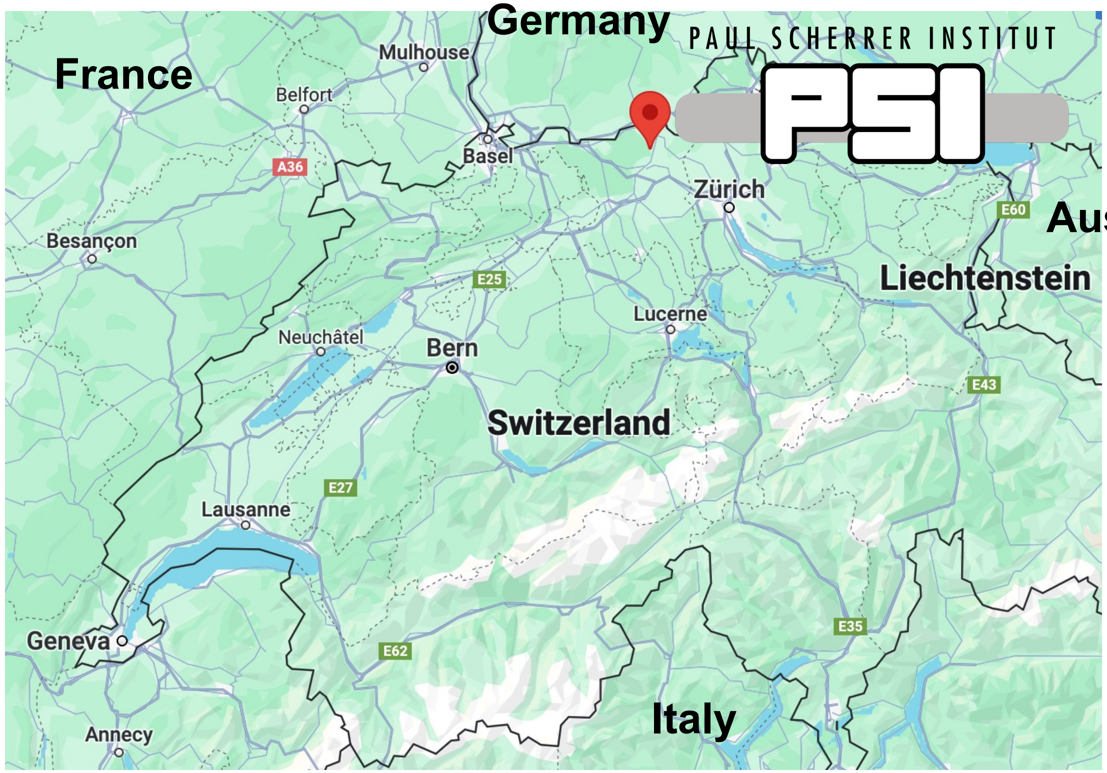


Time



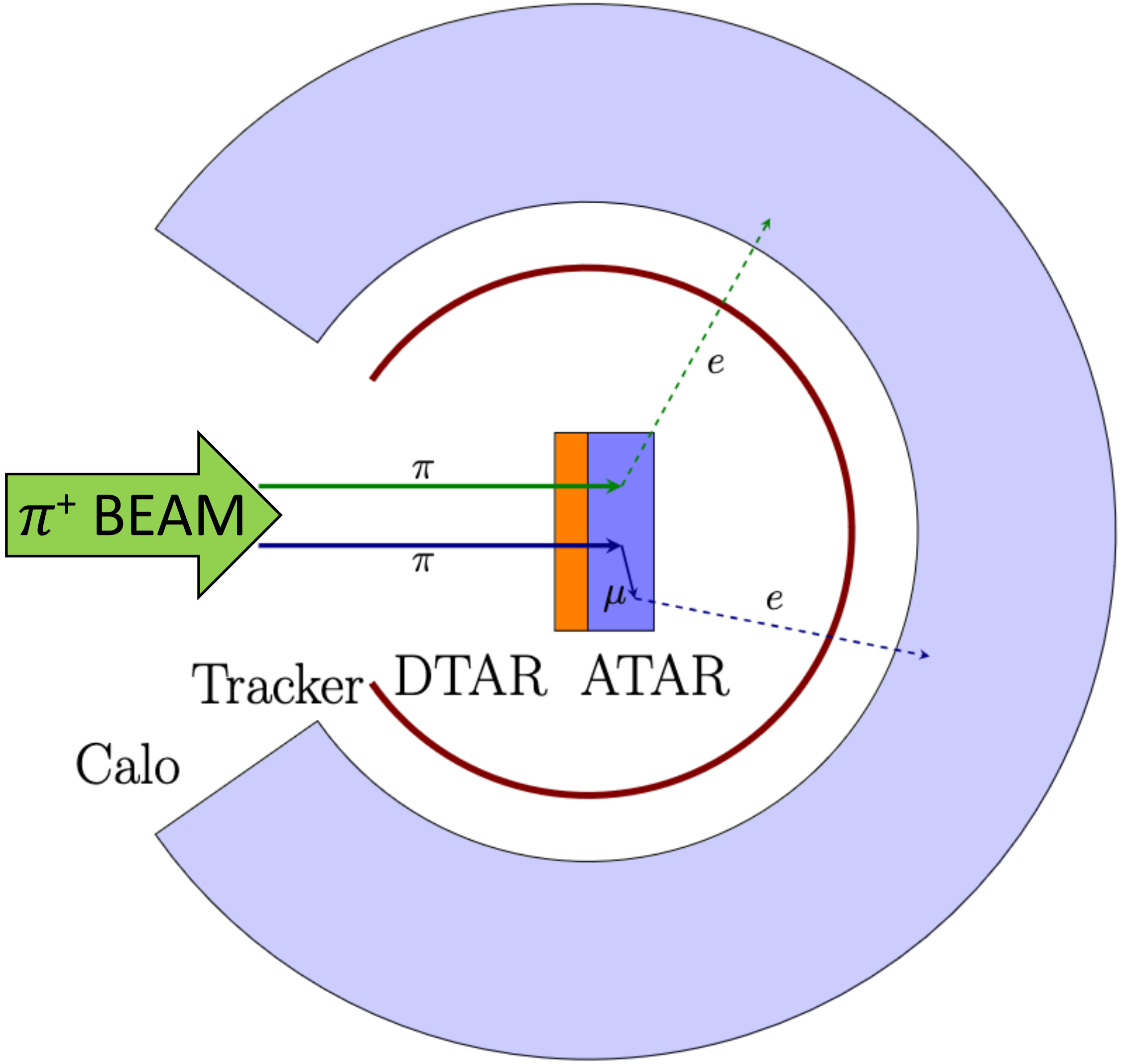
Where?

- Requirement: high intensity, high rate pion beam with good momentum resolution
  - ➢ Paul Scherrer Institut (PSI) beamline meets these requirements!



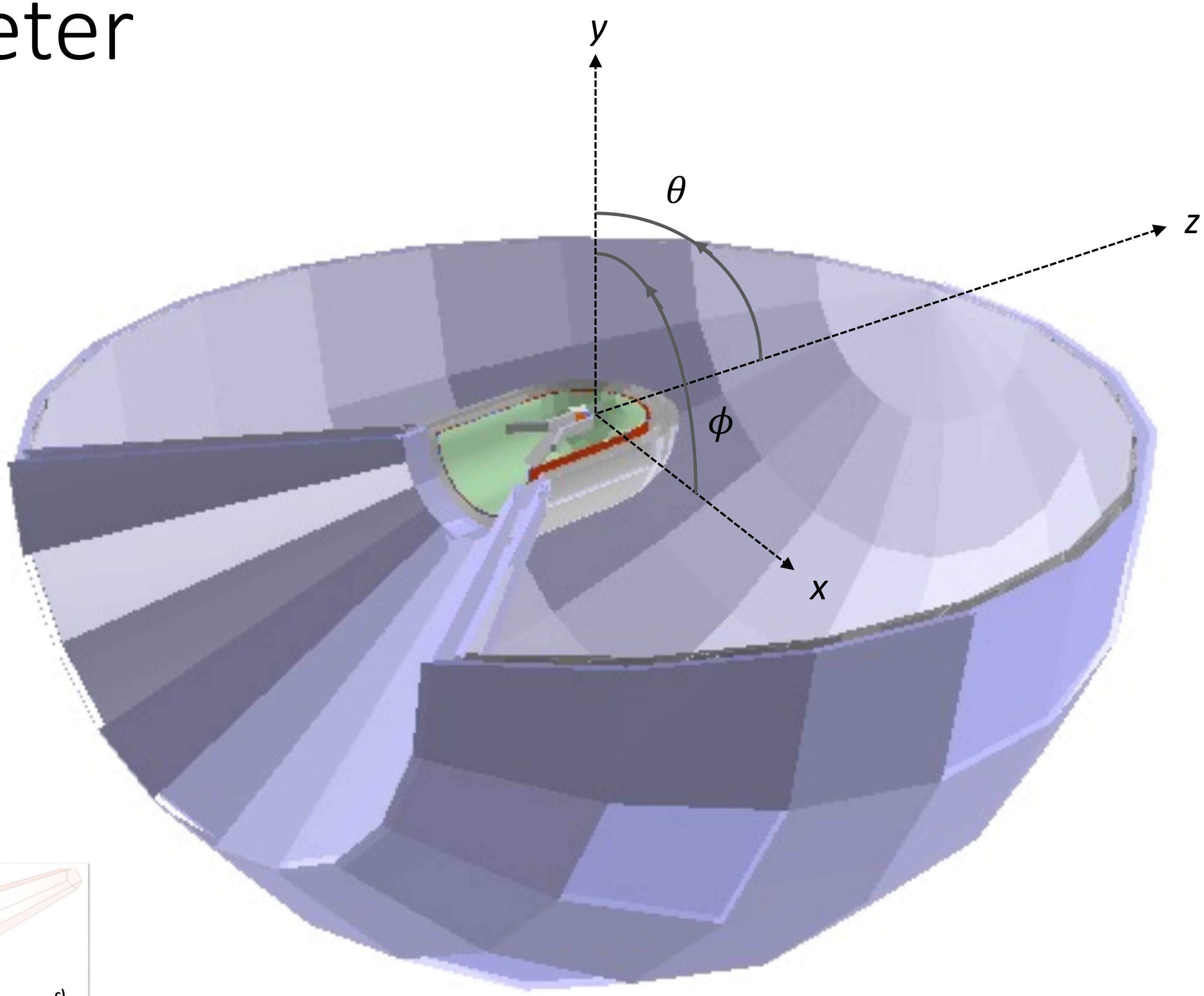
How? (PIONEER Experiment conceptual overview)

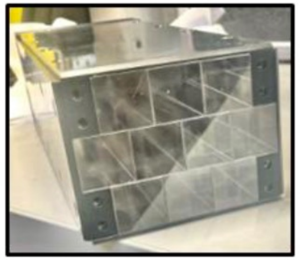
- 300 kHz high intensity pion beam
- Degrader (DTAR) – slows pions
- Active TARget – stops pions and classifies events using topology and energy deposition
- Tracker – auxiliary detector to determine topology of exiting positron
- Calorimeter (Calo) – measures positron energy and timing
- See talks by Dr. Chloé Malbrunot (Tuesday @ 10:30) and Dr. Doug Bryman (Thursday @ 17:00)

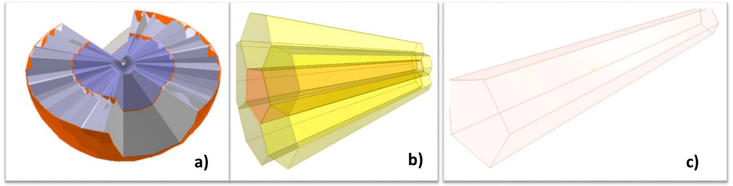


PIONEER Calorimeter

- Requirements:
  - Large radiation length
  - Good energy resolution
  - Precision timing
- 2 options:
  - Liquid xenon (LXe)
  - “Classic” crystal design with LYSO





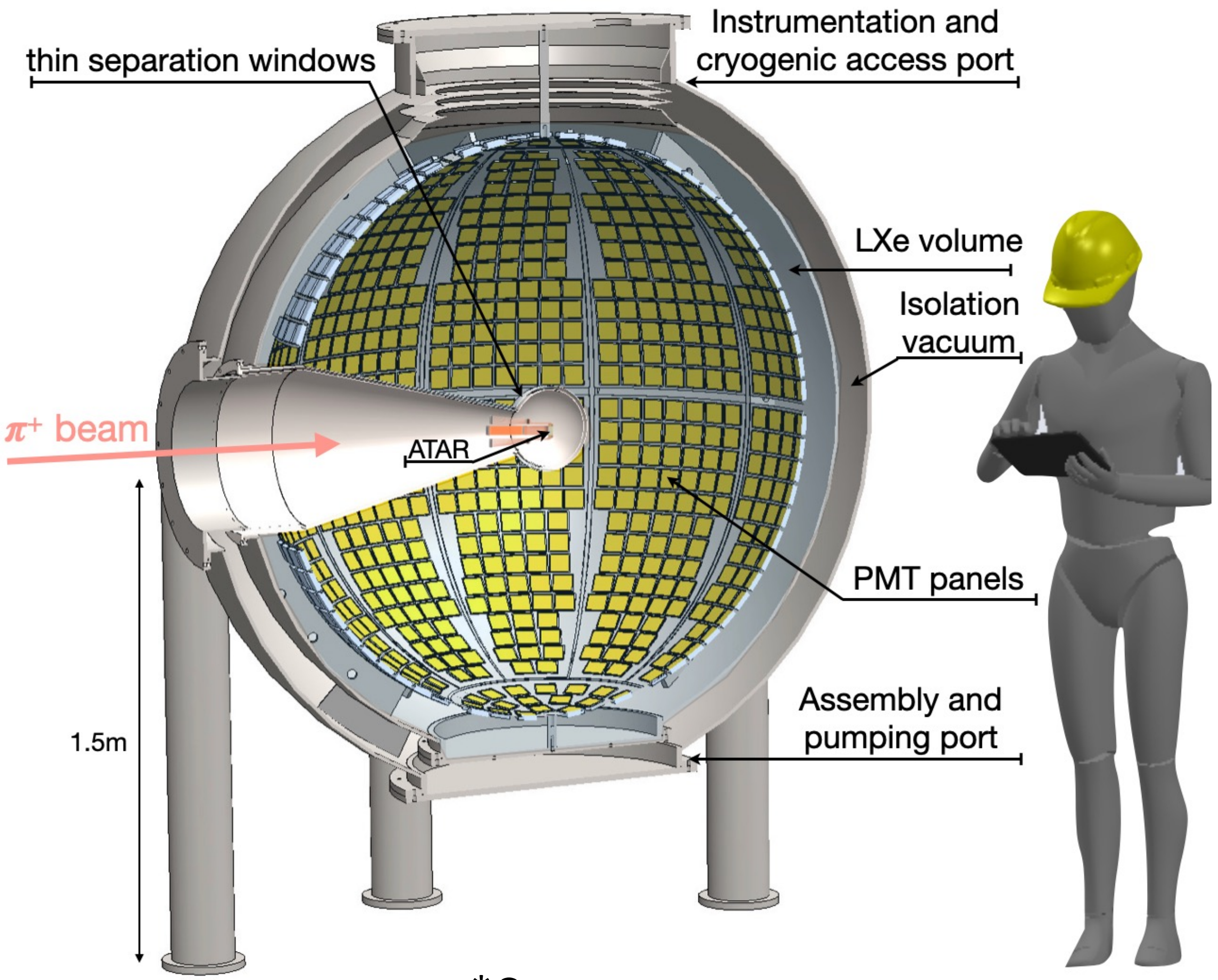


Focus @ TRIUMF: Liquid xenon calorimeter

Questions: (Challenges to overcome)

- How are photons distributed in the detector?
  - ex. are we biased by our geometry?
- How do we identify pileup events?
  - ex. beam pions and muons that miss the target, slow muons
- What is the effect of dead material?

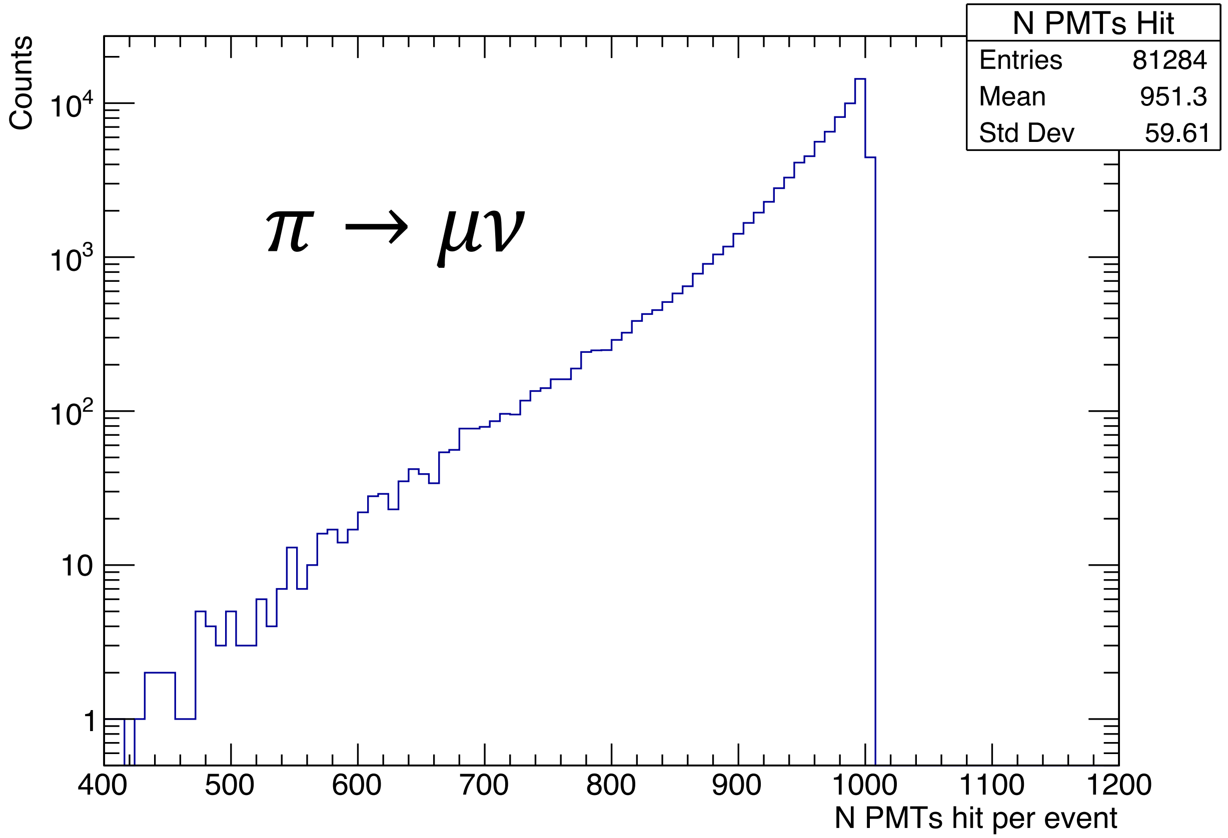
- Full experiment simulation built in GEANT4 (with optics!) to study and optimize the detector

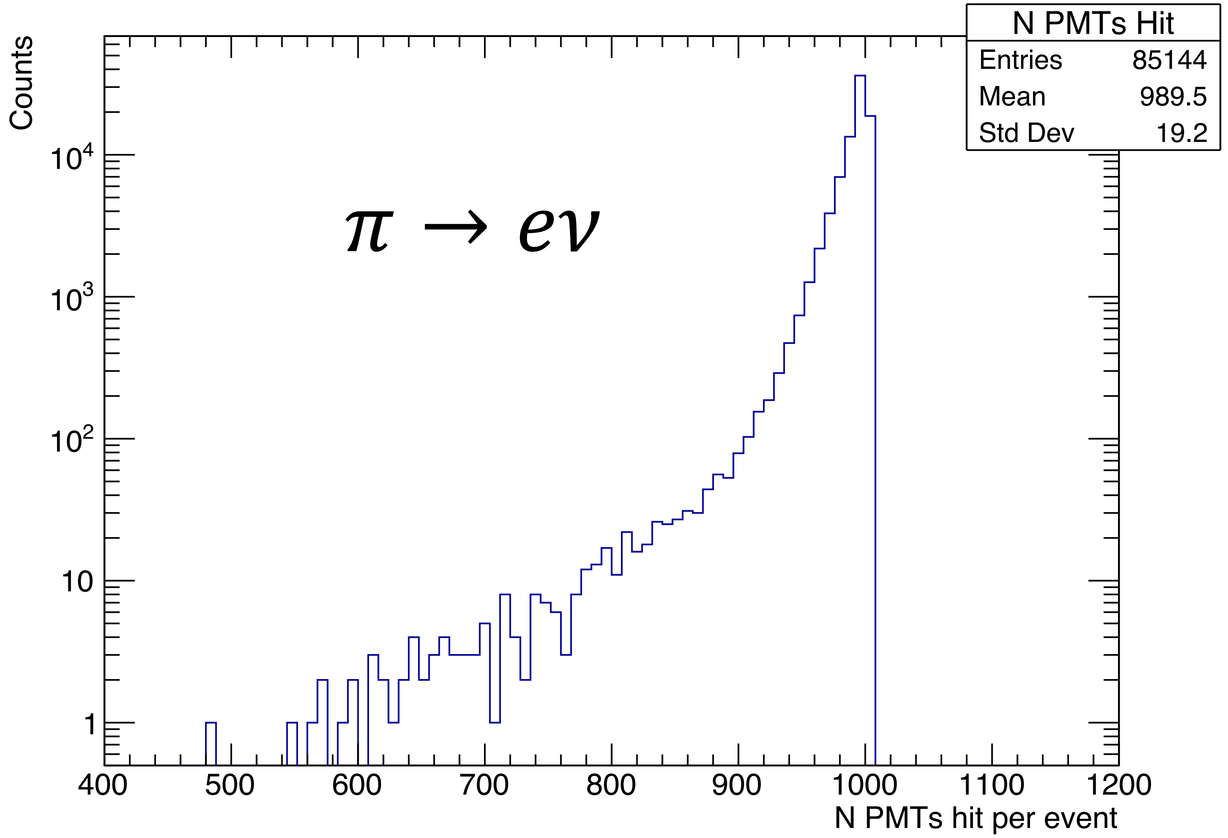


*Current concept

Basic Optics: # of PMTs hit per event

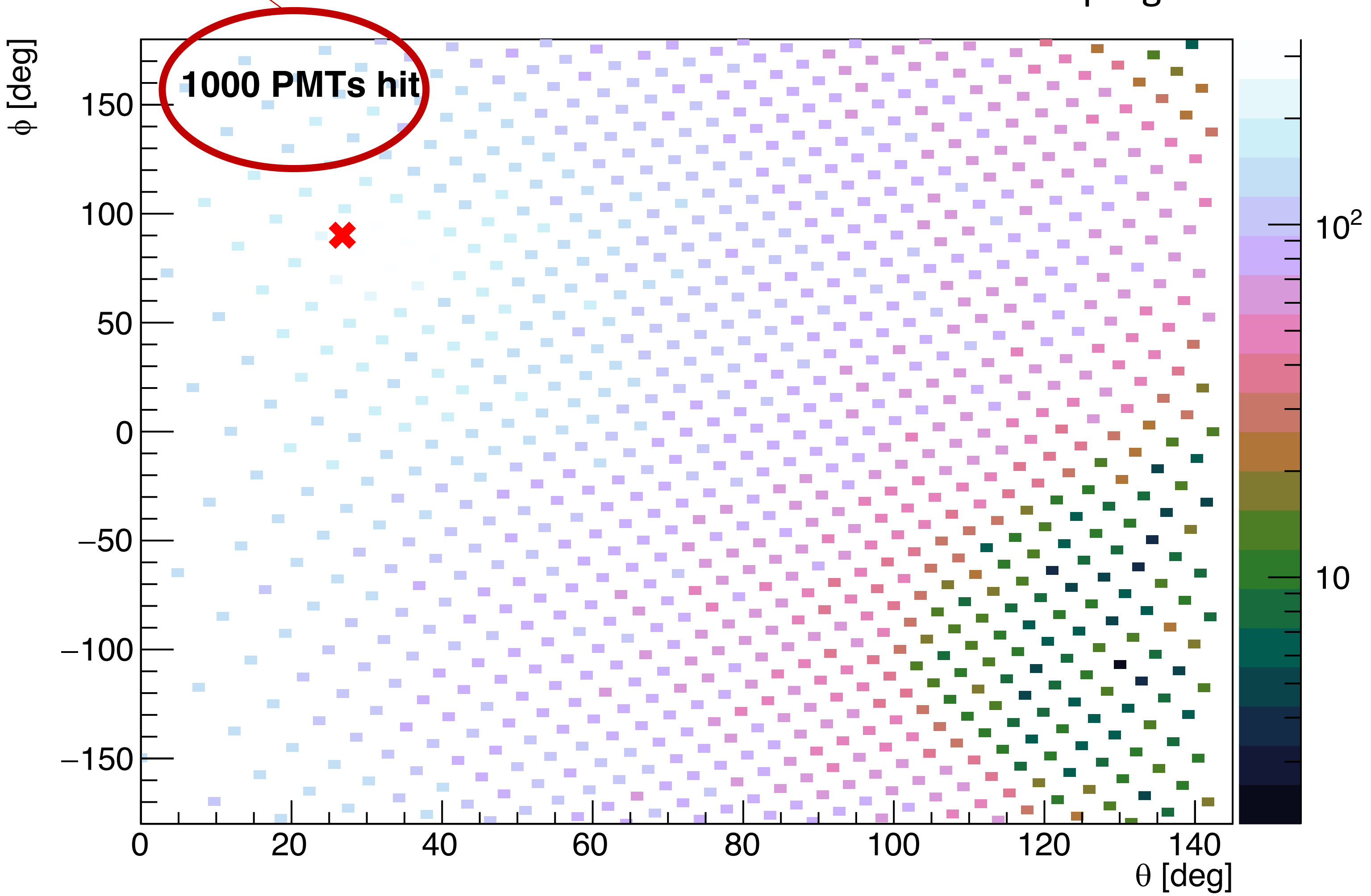
- 100,000 simulated events: decays from rest at center of calo



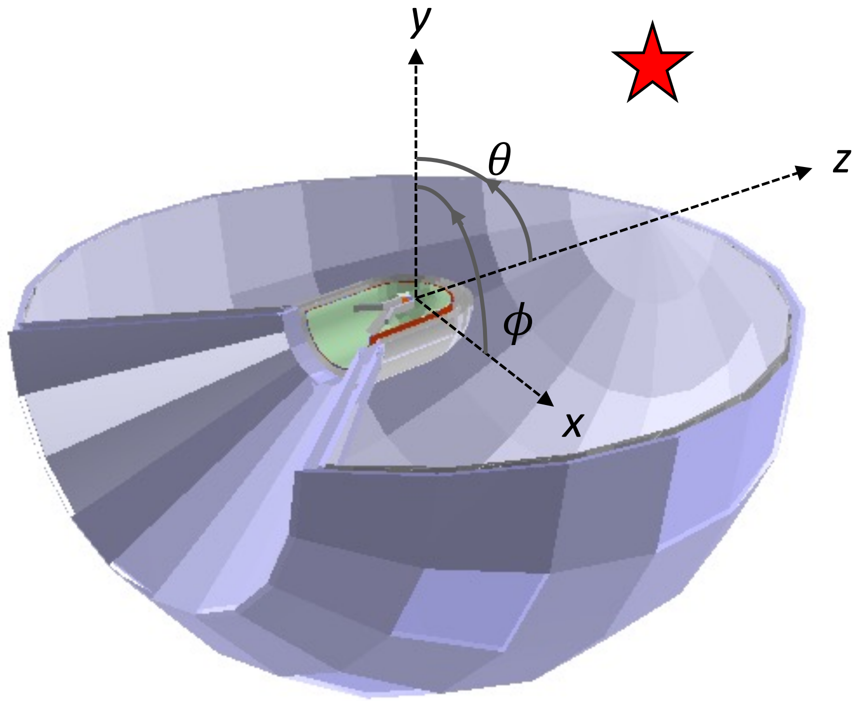


Light distribution in the calo

All 1000 PMTs hit!

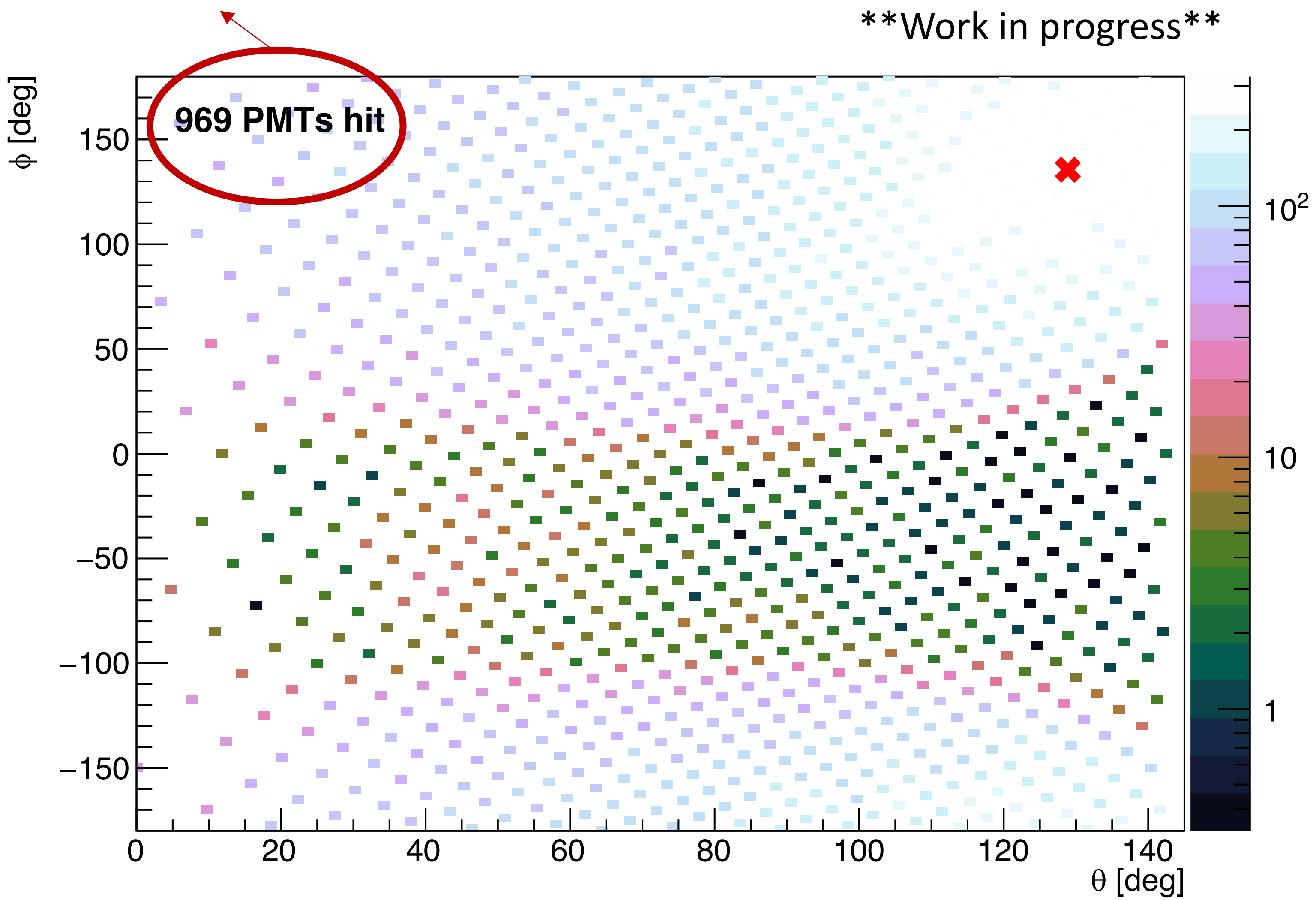


- z-axis: # of photons hitting the PMT
- red cross (or star): position of e^+ hitting the calo



Light distribution in the calo

969/1000 PMTs were hit by at least 1 photon



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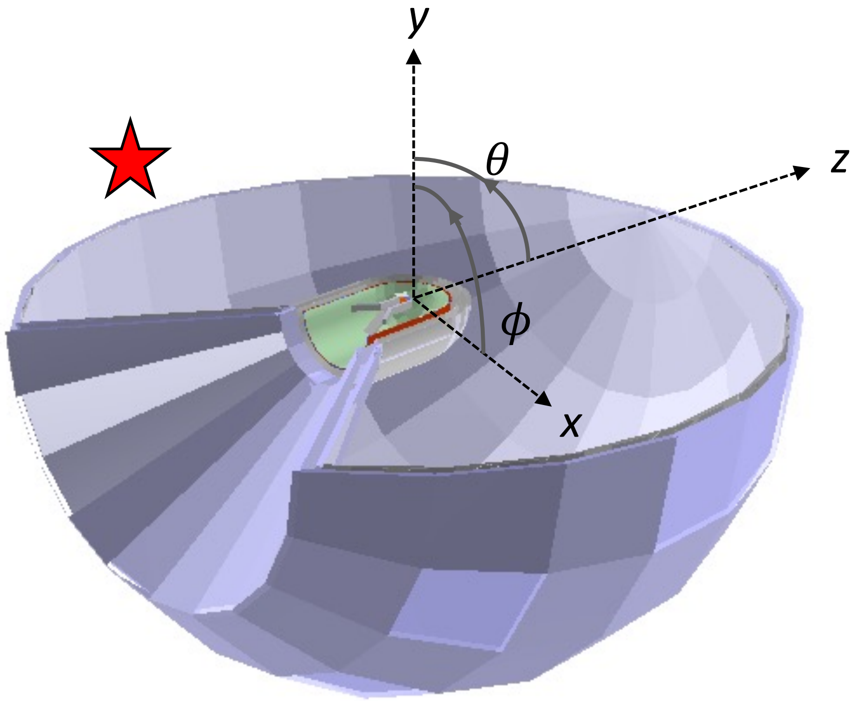
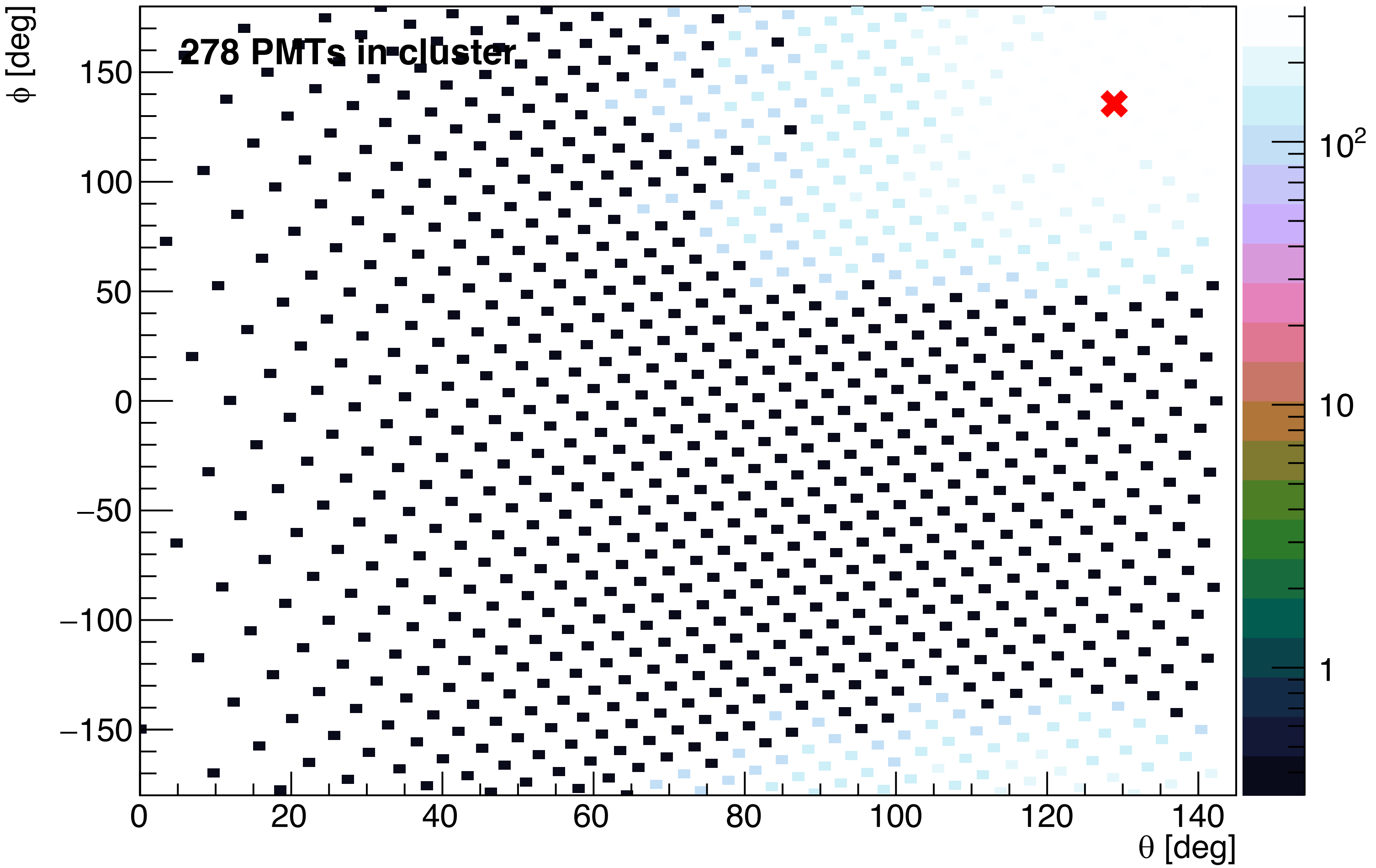


Clustering for pileup identification?

Work in progress

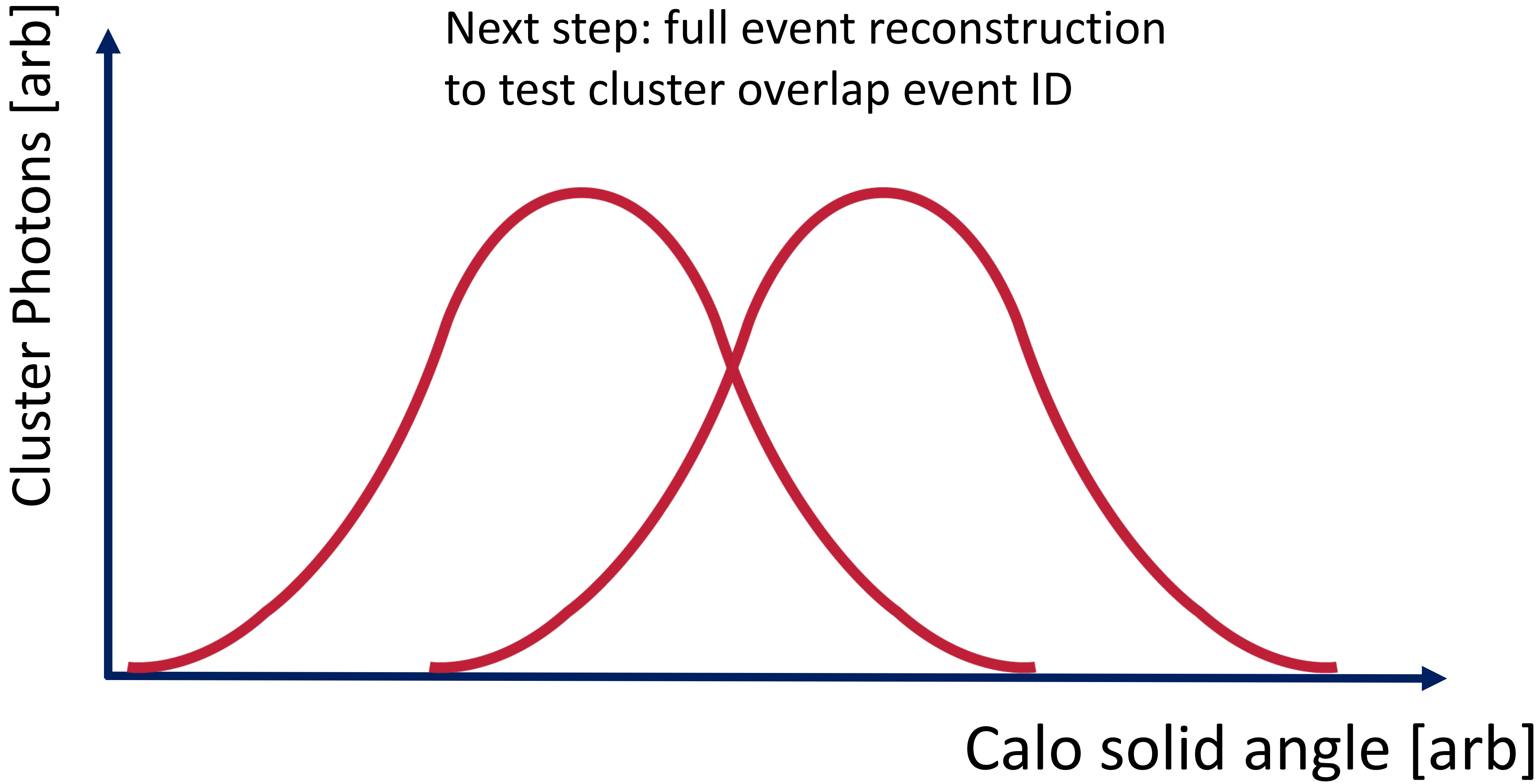


Clustering!

- Seed with max hit in the event
- Select # of nearest neighbours (NN) to search
- Select PMT hit threshold required for PMT NN to be added to cluster
- If PMT is added to cluster, repeat and check each NN
- Check to make sure no PMTs are double-counted

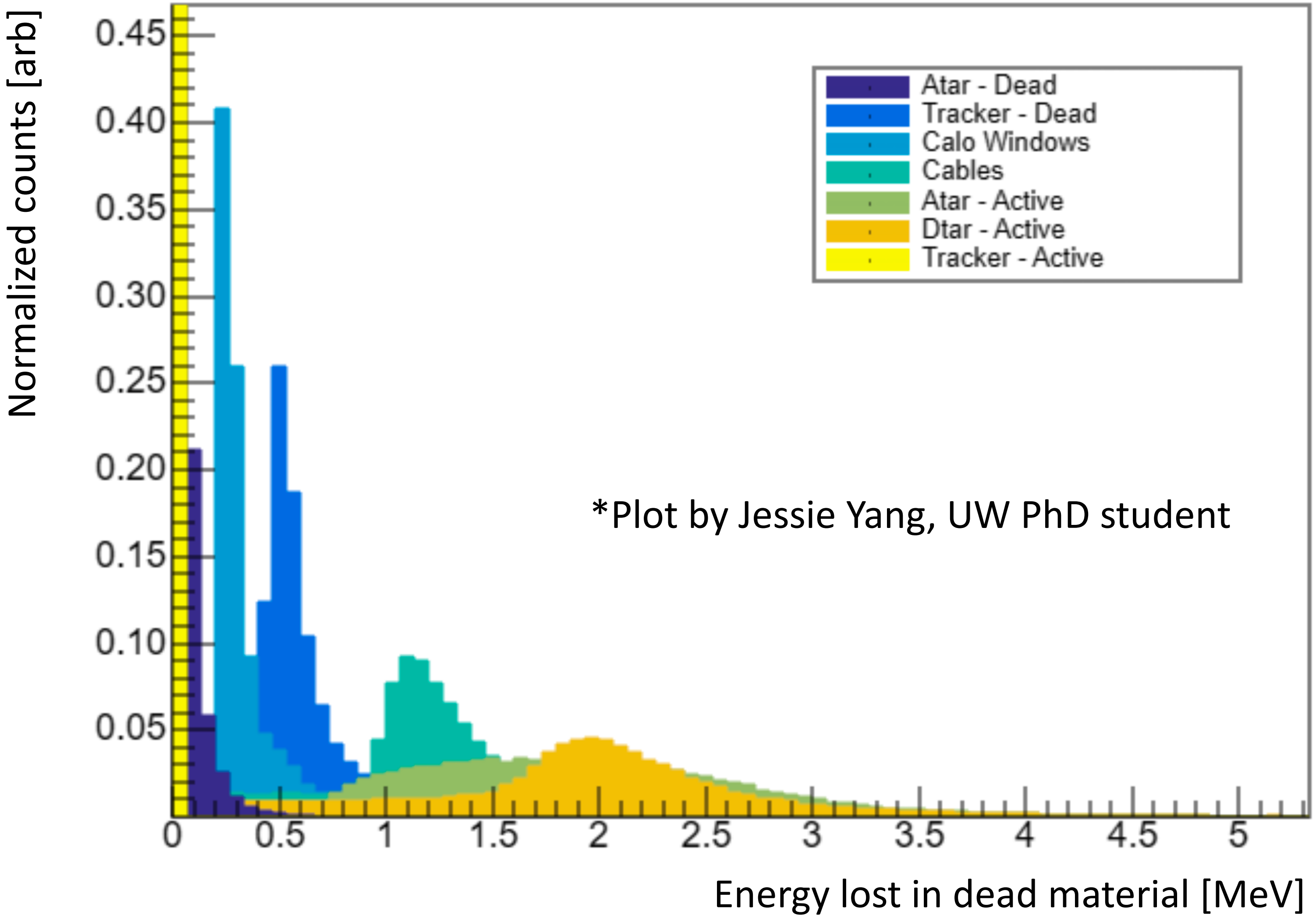
Clustering for pileup identification?

Next step: full event reconstruction to test cluster overlap event ID



Dead Material

Work in progress



- Understanding impact of dead material is critical for the final calo decision – LXe has great energy resolution, but if this is already degraded by dead material, having optimal energy resolution with LXe becomes less important

The Who (PIONEER Collaboration)

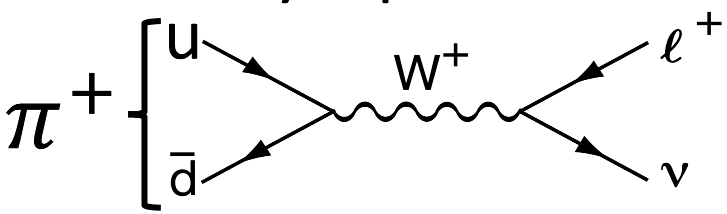
~80 collaborators around the world and still growing!

When?

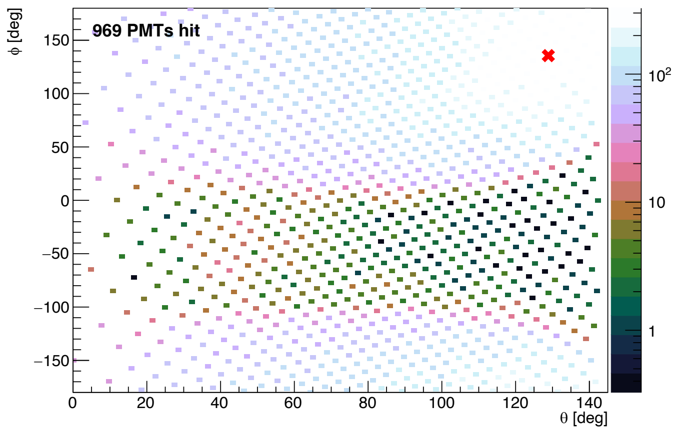
- Collaboration meeting @ TRIUMF Jan. 2025
- LXe prototype tests late 2025
- Full experiment data run #1: 2030

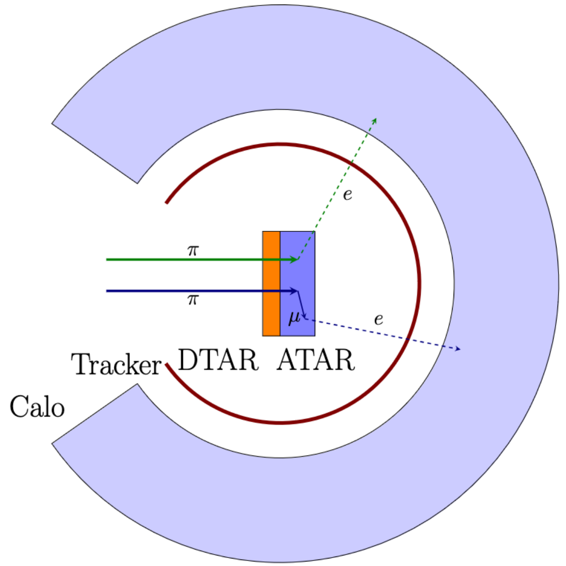
Summary

- PIONEER: precision rare decay experiment that will study lepton flavour universality by measuring pion decays:
  - $R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$ with uncertainty O(0.01%)



- Multiple detector components including active target, calorimeter
- TRIUMF focus: LXe Calo simulation and construction
- Hope to begin data-taking at PSI in 2030!
  - (2025 for LXe prototype)





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