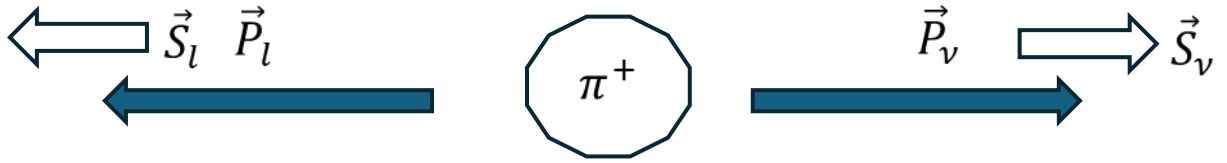
PIONEER
A
Precision Experiment



Jaydeep Datta, Shubham Dutta

Lepton Flavor Universality

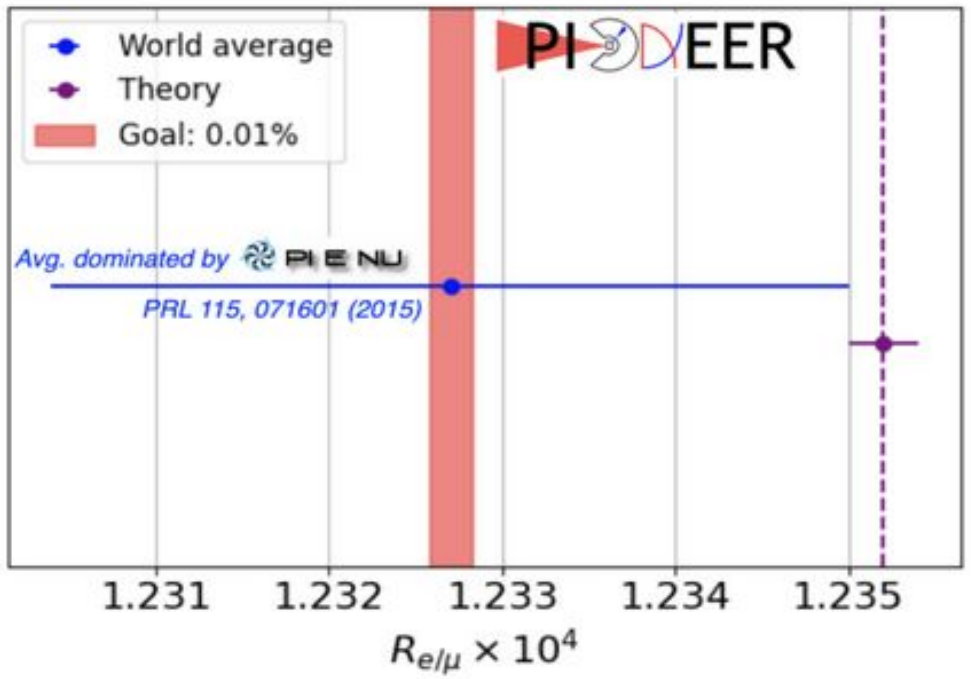
- Standard Model (SM) predicts that all the leptons couple to the Gauge bosons in the same way

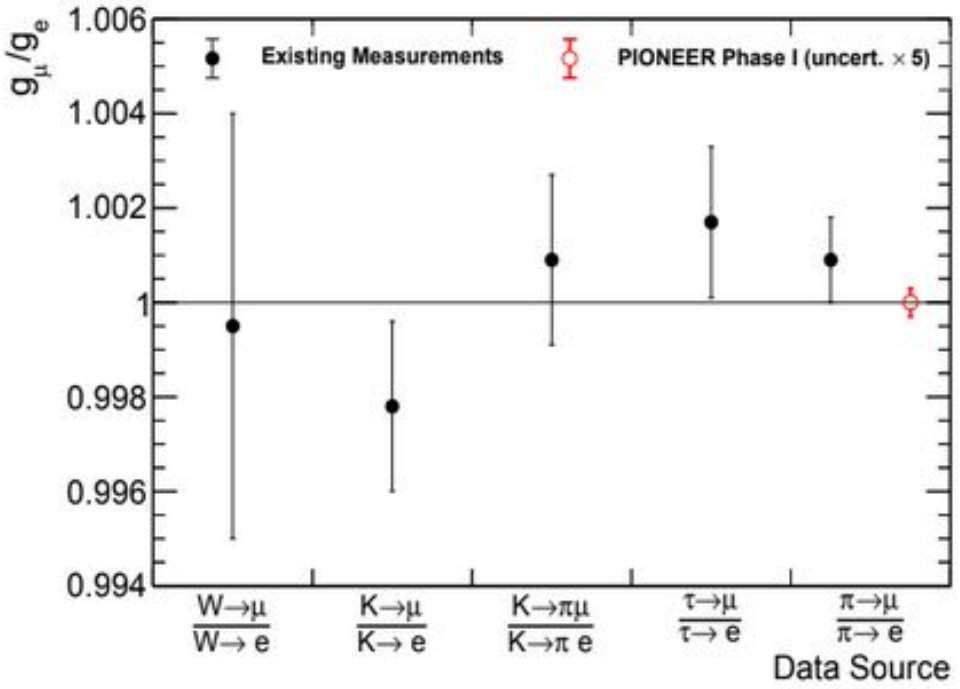


Wrong helicity of lepton suppress decay rate, $\Gamma = \frac{G_F^2 |V_{ud}|^2 f_\pi^2}{8\pi} m_\pi m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2$

- $R_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))} = \frac{m_e^2(m_\pi^2 - m_e^2)}{m_\mu^2(m_\pi^2 - m_\mu^2)}$
- $R_{e/\mu}\,(SM)$ = (1.23524 ± 0.0002)*10^{-4} but experimentally measured (1.2344 ± 0.0023 (stat) ± 0.0019 (syst))*10^{-4} (PIENU experiment).

Phase I Goal of PIONEER



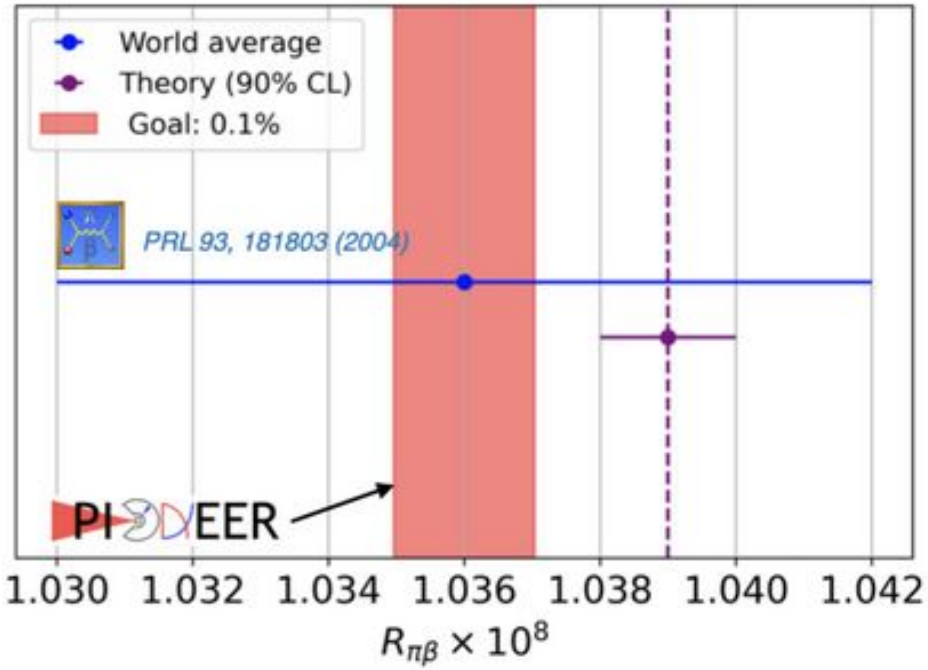


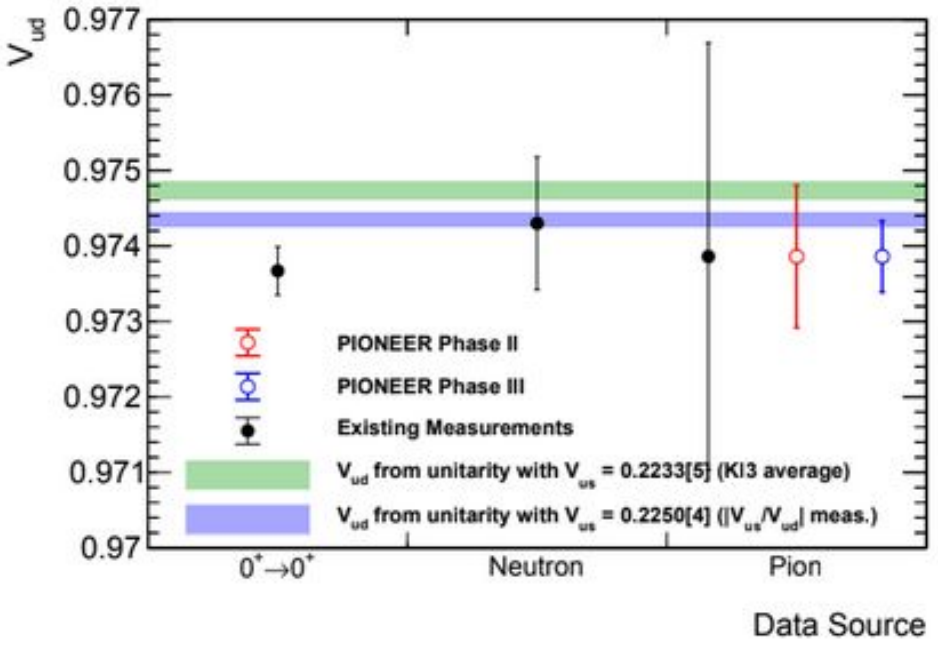
Best measurement and SM prediction of $R_{e/\mu}$ [Ref: arXiv 2504.06375]

Unitarity test of CKM matrix

- Quark mixing is explained by Cabibbo Kobayashi Masakawa (CKM) matrix.
- SM demands $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- Experimentally measured $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \approx 0.9985 \pm 0.0005$
- Pion beta decay, $\pi^+ \longrightarrow \pi^0 + e^+ + \nu_e$, has a decay rate $\Gamma_{\pi\beta} = \frac{G_F^2 |V_{ud}|^2 (m_{\pi^+} - m_{\pi^0})^5}{30\pi^3} f(m_e/(m_{\pi^+} - m_{\pi^0}), (m_{\pi^+} - m_{\pi^0}))(1 + \delta_{RC})$
- $\frac{\Gamma_{\pi\beta}^{SM}}{\Gamma_{all}^{SM}} = (1.036 \pm 0.004\ (stat) \pm 0.005\ (syst)) * 10^{-8}$ [Ref: PRL 93, 181803]

Phase II and III Goal of PIONEER



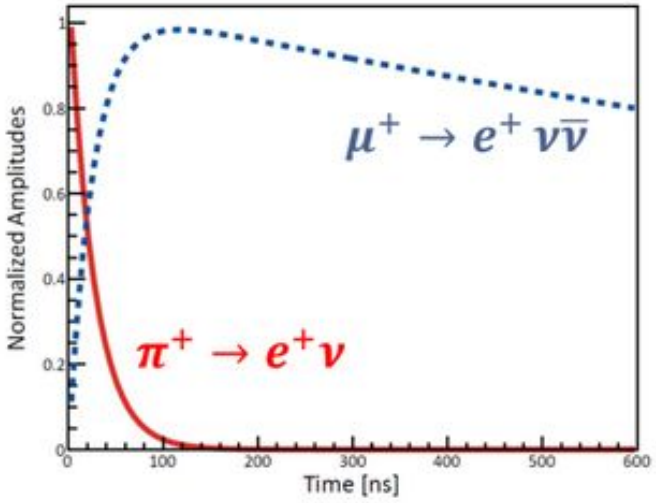


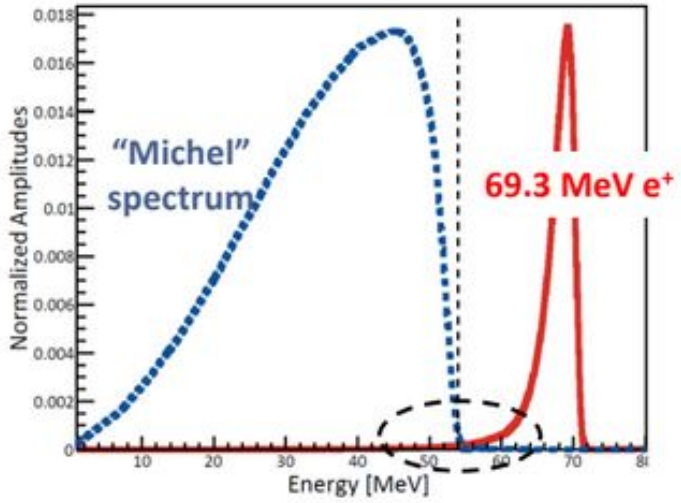
Best measurement and SM prediction of $R_{\pi\beta}$ [Ref: arXiv 2504.06375]

Measurement Technique

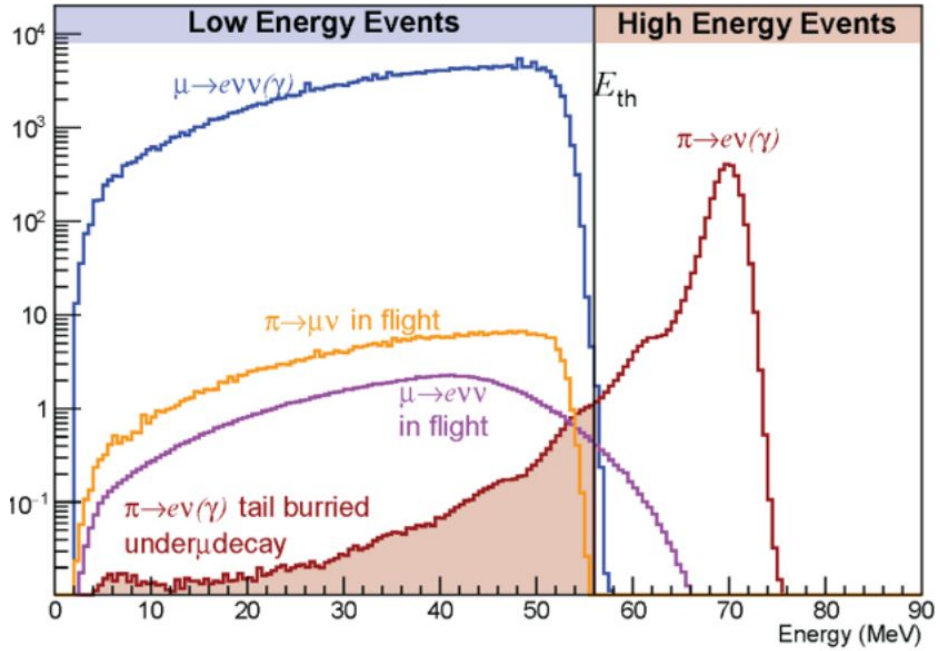
- $\pi^+ \longrightarrow e^+ + \nu_e$; E_e: 69.3 MeV
- $\pi^+ \longrightarrow \mu^+ + \nu_\mu$; P_μ: 4 MeV
- $\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$; E_e: 0 - 53 MeV
- We can measure the energy of the positron carefully and count the ratio of the two decay channels
- $\pi^+ \longrightarrow \pi^0 + e^+ + \nu_e$; $P_\pi \sim 0$ MeV
- $\pi^0 \longrightarrow \gamma + \gamma$; $E_\gamma \sim 67.5$ MeV
- Measure two photons at 180° and a small energy deposition for e^+ annihilation

Experimental Challenge





Theoretical expectation of energy spectrum and decay time distribution. [Ref: Talk given by David Hertzog at PSI BVR]



Energy spectra of positrons coming from different sources. [Ref: arXiv 2504.06375]

Detector Design

CALORIMETER

We need a very good calorimeter

ACTIVE TARGET (ATAR)

To identify pion decaying in flight we need a target which will stop the pions, also can measure the energy, track direction and the time, an Active TARget (ATAR).

TRACKER

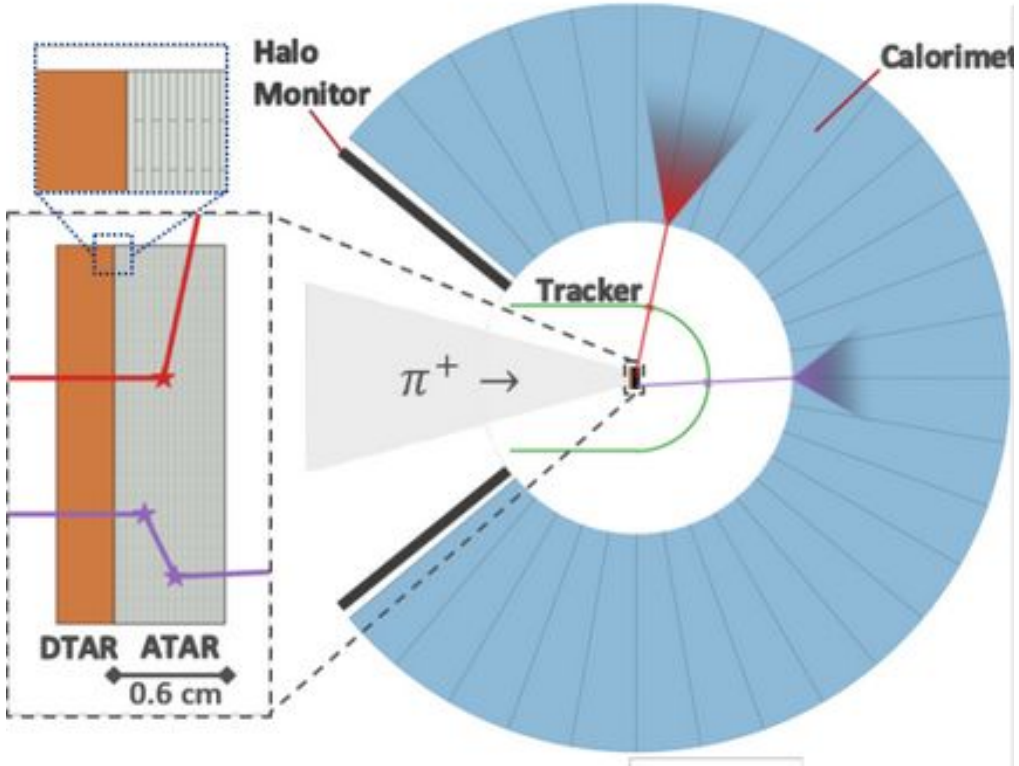
To track particles missed by ATAR, need Tracker

HALO MONITOR

For monitoring beam remnants Halo monitor

DTAR

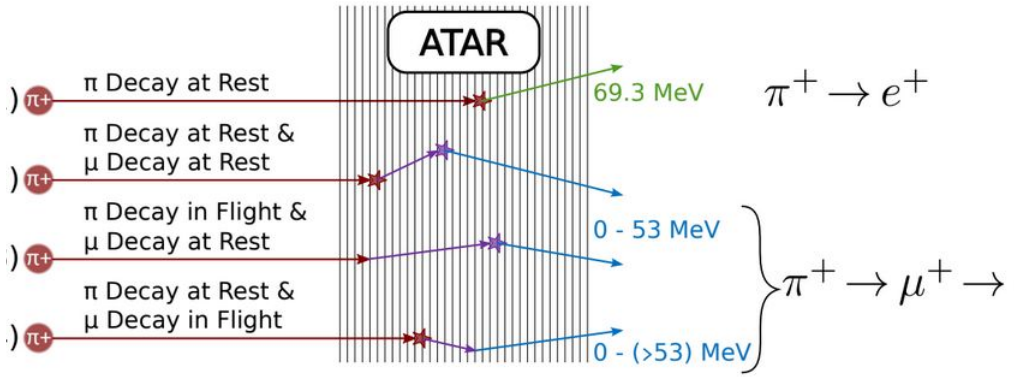
For beam timing and slowing down pions, DTAR



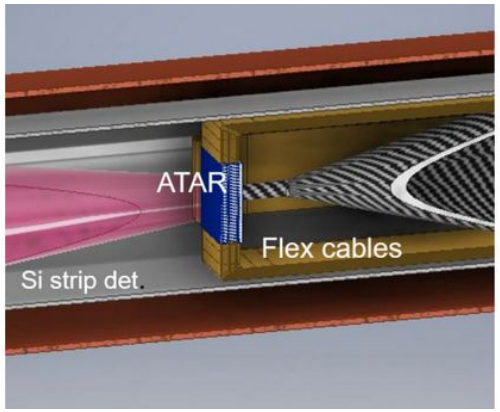
Schematic diagram of the PIONEER experiment, Ref: arXiv 2504.06375

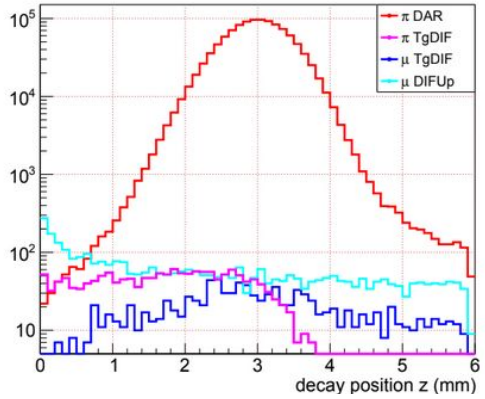
Active TARget (ATAR)

DECAY MODES IN ATAR



CAD & SIMULATION



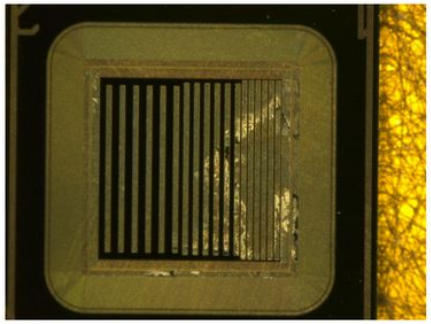


DETECTOR TECHNOLOGY

- **Low Gain Avalanche Detector (LGAD) chosen for ATAR technology**
- Cross section of 2 cm × 2 cm, thickness of 6 mm
- 200 μm pitch, 100 strips, each strip 120 μm thick

[Ref: arXiv 2504.06375, arXiv 2111.05375]

AC-LGAD PROTOTYPE



Prototype of AC-LGAD

LYSO Calorimeter

MATERIAL COMPOSITION

Lutetium Yttrium Orthosilicate (LYSO) Crystal

- By weight: **73%** Lutetium, **18%** Oxygen, **6%** Silicon, **3%** Yttrium
- Negligible amount of Cerium as dopant

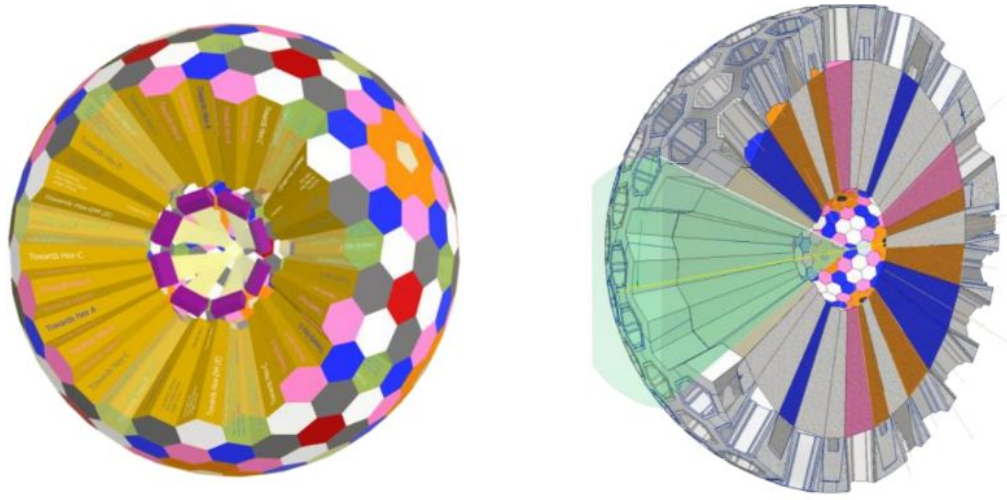
PROPERTIES & PERFORMANCE

- **X_0:** 1.14 cm | **RM:** 2.07 cm | **Decay time:** 40 ns
- **Light yield:** 30,000 γ/MeV | **λpeak:** 420 nm
- **Energy resolution:** 1.5% at 70 MeV
- **Time resolution:** 74 ps

[Ref: arXiv 2409.14691]

GEOMETRY & FEATURES

- **311 crystals** of 8 different shapes
- Non-hygroscopic, radiation hard, negligible temp dependence
- Has intrinsic background radiation; segmented volume helps but introduces design complexity



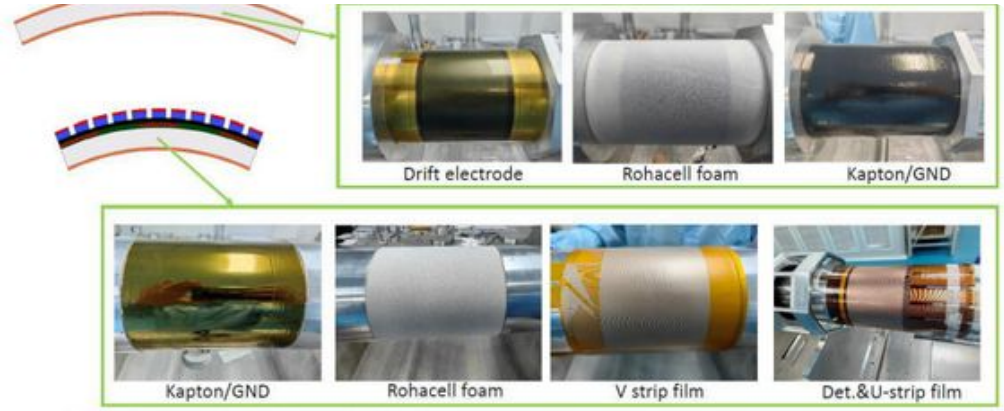
Schematic diagram of the LYSO Calorimeter. [Ref: arXiv 2504.06375]

Tracker

TRACKER SPECIFICATIONS

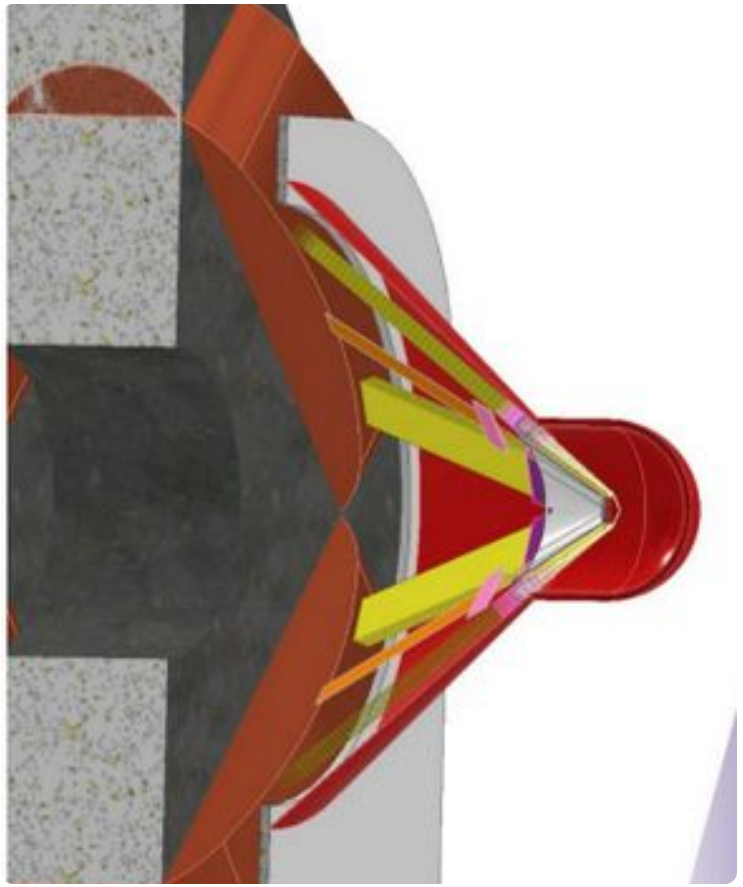
- **Technology:** uRGroove based tracker, MPGD
- **Spatial Resolution:** ~ 100 μm | **Time Resolution:** ~ 5 ns
- **Material Budget:** Low material budget ~ 0.4% X_0
- **Configuration:** Single volume layout possible

CYLINDRICAL uRGROOVE TRACKER



Cylindrical uRGroove tracker [Ref: Talk presented by Siqi He at Pisa Meeting 2024]

SCHEMATIC DIAGRAM



Schematic diagram of the tracker

Tracker Simulation

G4PAI Ionization Model

MODULE NAME

G4PAI

- For MPGD Geant4 has specific ionization module, named G4PAI
- The model is only applicable for relativistic particles
- Only applied for positrons

Simulation Workflow for Other Particles

1 **Energy Deposition**

For other particles, energy deposition is divided by W value of the gas mixture:

Mean Primary Electrons: $N = \Delta E / W$

2 **Primary Electron Generation**

Primary number of electrons generated from Gaussian distribution with mean N:

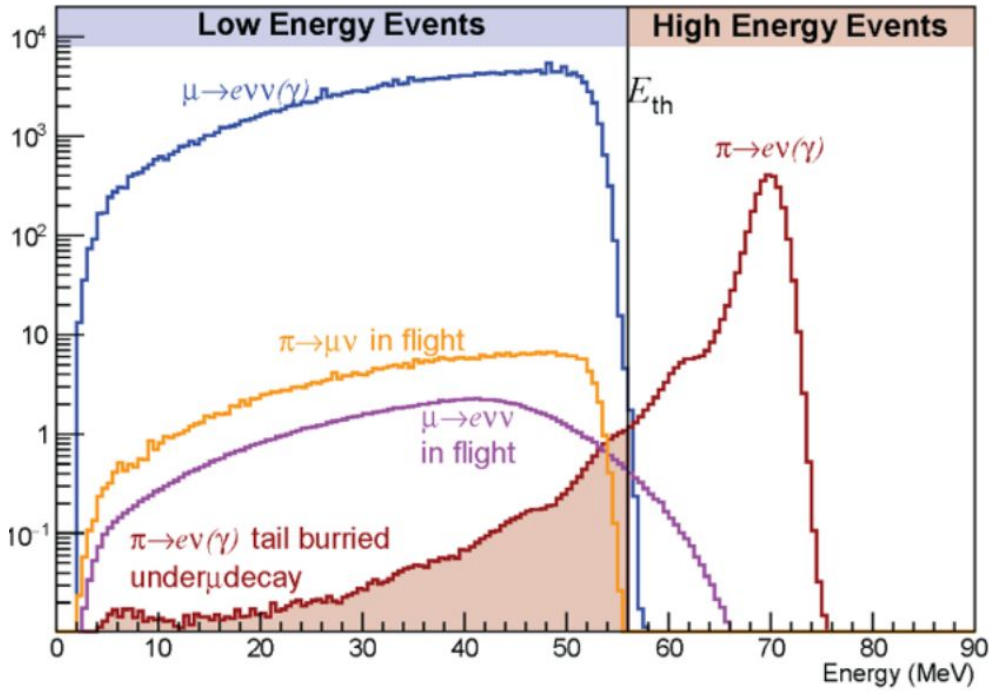
Standard Deviation: $\sigma = \sqrt{(F \cdot N)}$ | **Fano Factor:** $F = \sigma^2 / N$

3 **Gain Factor Multiplication**

Multiplied this number with a gain factor chosen from gaussian

Analysis Technique

- $R_{e/\mu} = \frac{N_{\pi\to e}\,(E>E_{th})}{N_{\pi\to\mu\to e}} * (1 + c_{tail}) * R^{\epsilon}$
- $\frac{\Delta R_{\{e/\mu\}}}{R_{\{e/\mu\}}} = 0.01\%$
- Required c_{tail} with a precision of 1 %
- R^{ϵ}, ratio of pion decaying to positron and pion decaying to muon and to positron acceptance, with precision < 0.01%



Different contribution to positron spectra

Fast Response Reconstruction

Algorithm Overview

CURRENT STATUS

Detailed Reconstruction

• Full detail reconstruction starting from pulse shape is currently under active development.

INTERIM SOLUTION

Fast Response Model

• Operational fast response reconstruction algorithm used for immediate physics studies and cross-checks.

Reconstruction Pipeline & Methodology

1 **Geant4 Energy Deposition**

Extract energy deposited at every step in each of the detector volumes, along with exact spatial coordinates and timing info.

2 **Gaussian Parameter Smearing**

Apply simple Gaussian smearing functions to the exact position and timing details to emulate detector response resolution.

3 **Truth Data Storage & Validation**

Store Monte Carlo truth information alongside reconstructed data to perform cross-checks and evaluate analysis methods.

Reconstruction & Readout Timing

Beam & Data Acquisition

BEAM RATE

300 kHz (~1 pion per 3.3 μs)

TRIGGER & STORAGE

Upon receiving a trigger, data from all detector sub-systems are stored simultaneously for full event processing.

READOUT METHODOLOGY

To accurately analyze the spectrum tail, events are reconstructed inside defined time windows, referred to as **readouts**.

Decay Kinetics & Window Selection

π

Pion Lifetime

26 ns

μ

Muon Lifetime

2.2 μs

OPTIMAL TIME WINDOW SELECTION

600 ns Window

- Includes **almost all pion decays** (~23 lifetime intervals).
- Effectively suppresses background by capturing **very few muon decays**.

Reconstruction Methodology

ATAR Reconstruction

HIT MERGING

Energy depositions in a silicon strip in 2 ns time window are merged as one hit.

Position assigned by strip & average time.

TRACKLET FORMATION

Two consecutive hits within 1 ns window are clubbed together to form a tracklet.

Tracker Reconstruction

PRIMARY ELECTRON CLUSTERING

In each layer, all primary electrons within 1 cm distance from their closest neighbour are clubbed as one hit.

SMEARING & RESOLUTION

Average ρ, φ, z, and t are calculated.

Smeared using Gaussian function with 100 μm standard deviation.

Calorimeter

CRYSTAL ENERGY CLUSTERING

Energy deposited in one crystal are clubbed and then smeared.

Provides total energy measurement and detector resolution modeling across crystal volumes.

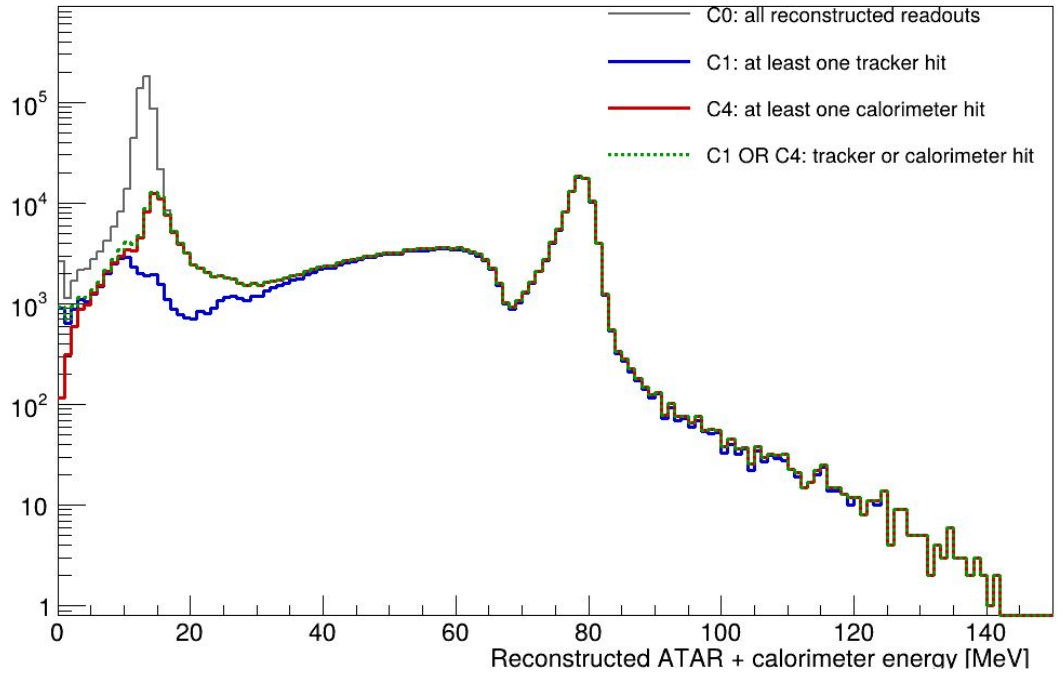
Hit Requirement Cut

TIMING WINDOW: As muon decays late, in a 600 ns window pion will decay to muon, but muon will not decay.

Selection Efficiency & Survival Summary

Selection	Readouts	True π→e (kept / %)	True π→μ (kept / %)	π→e Purity
C0: All (No selection)	752,608	111,007 100.00%	639,383 100.00%	14.75%
C1 Tracker hit	232,748	99,479 89.62%	132,066 20.66%	42.74%
C4 Calorimeter hit	292,784	103,484 93.22%	187,092 29.26%	35.34%
C1 OR C4 Tracker or Calo	298,755	105,302 94.86%	191,245 29.91%	35.25%

Reconstructed Energy Distribution Spectrum



Tracker for PID?

ENERGY RANGE BEHAVIOR

At this energy range, **pion** and **muon** are not minimum ionizing particles, but **positron** is.

PRIMARY ELECTRONS

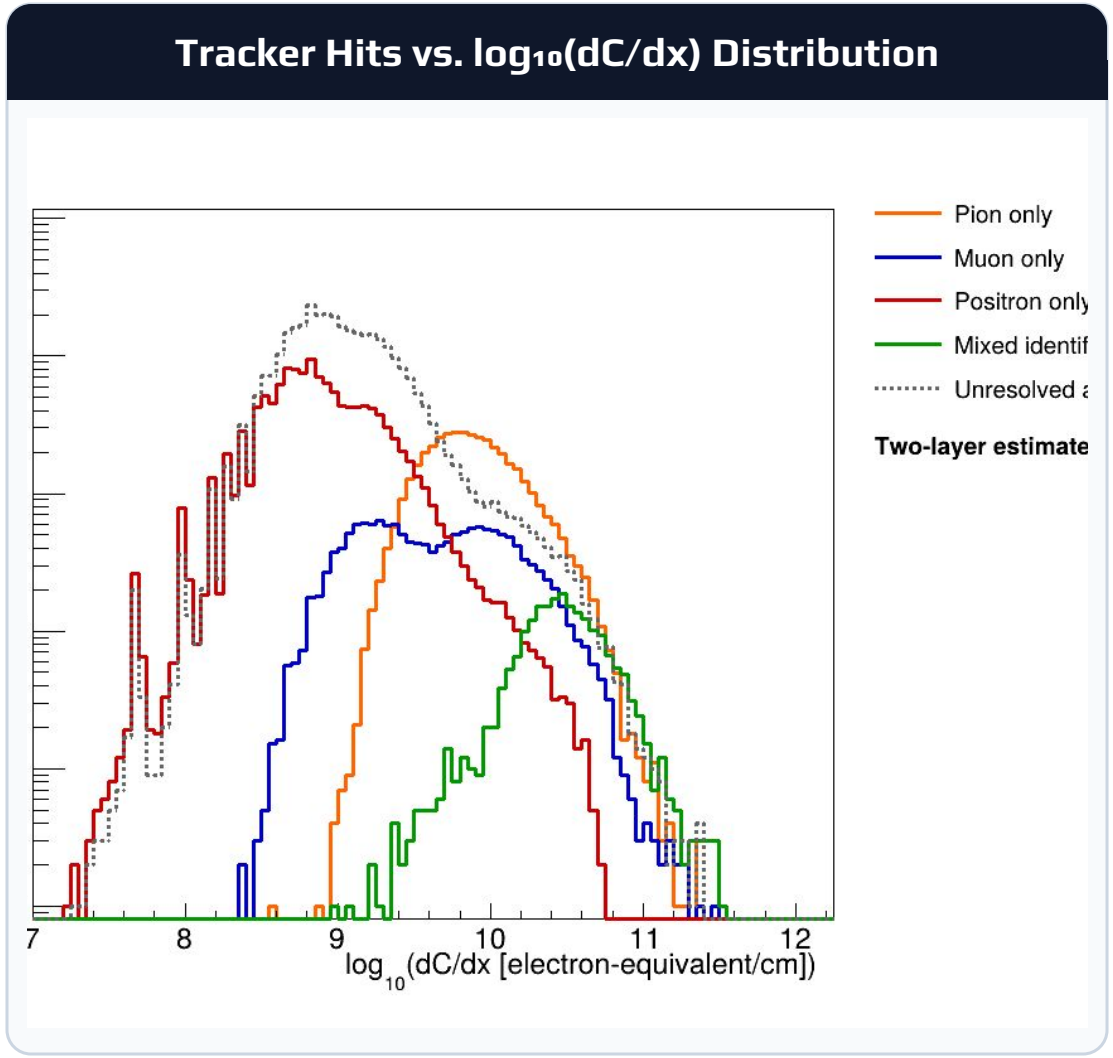
In the tracker, the number of primary electrons will be different for different particle types.

PATH LENGTH AMBIGUITY

However, different path lengths traversed inside the tracker can end up giving the same total number of primary electrons.

SOLUTION

Defined dC/dx to resolve path length degeneracy.



Correlation with ATAR?

TRACKER dC/dx LIMITATION

The dC/dx cut for tracker will not be of much help because of significant signal overlap.

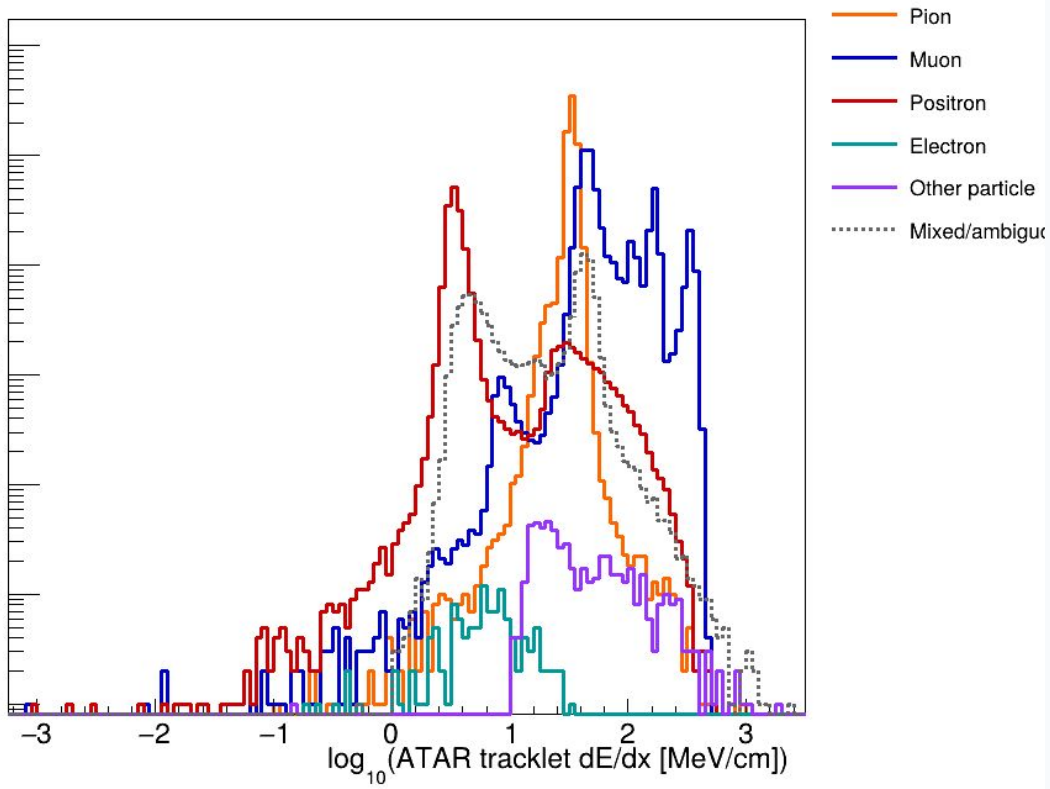
TRACKLET CORRELATION

When more than one hit is observed in tracker, it could be correlated with a different tracklet in ATAR.

PURITY ENHANCEMENT

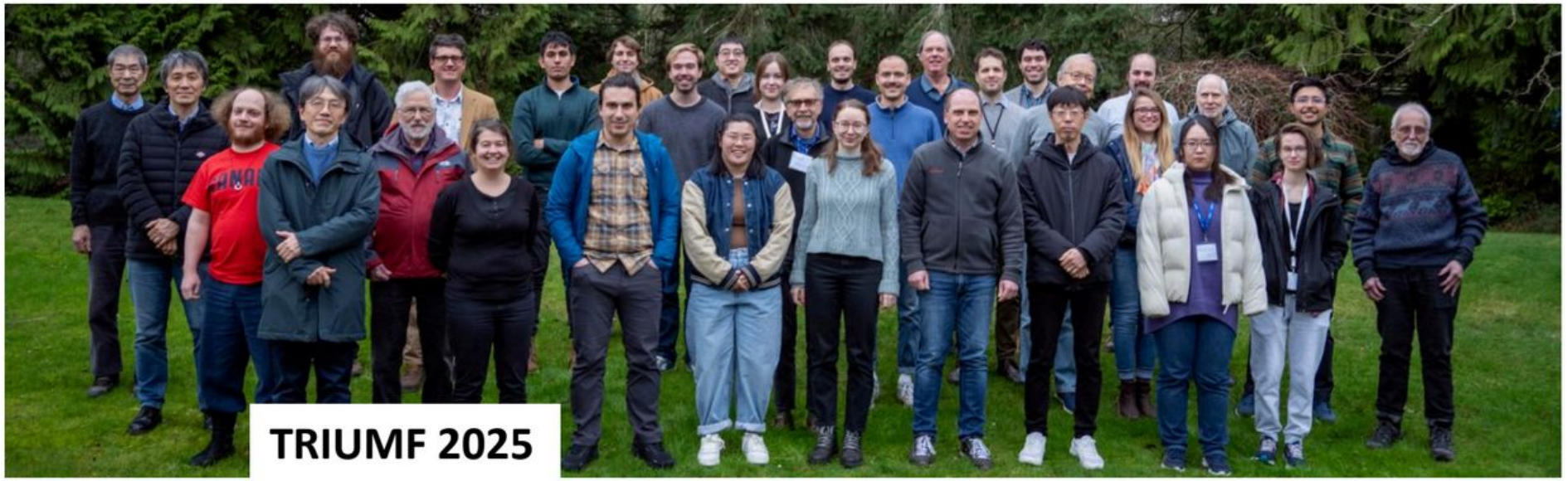
ATAR has the capability to find dE/dx. Correlating them could significantly improve overall particle purity.

$\log_{10}$(ATAR tracklet dE/dx) Distribution



Future Goals

- Tracker and ATAR correlation to improve the purity
- Implement simple BDT to improve the results
- Detector design finalisation



Thank you

Questions?

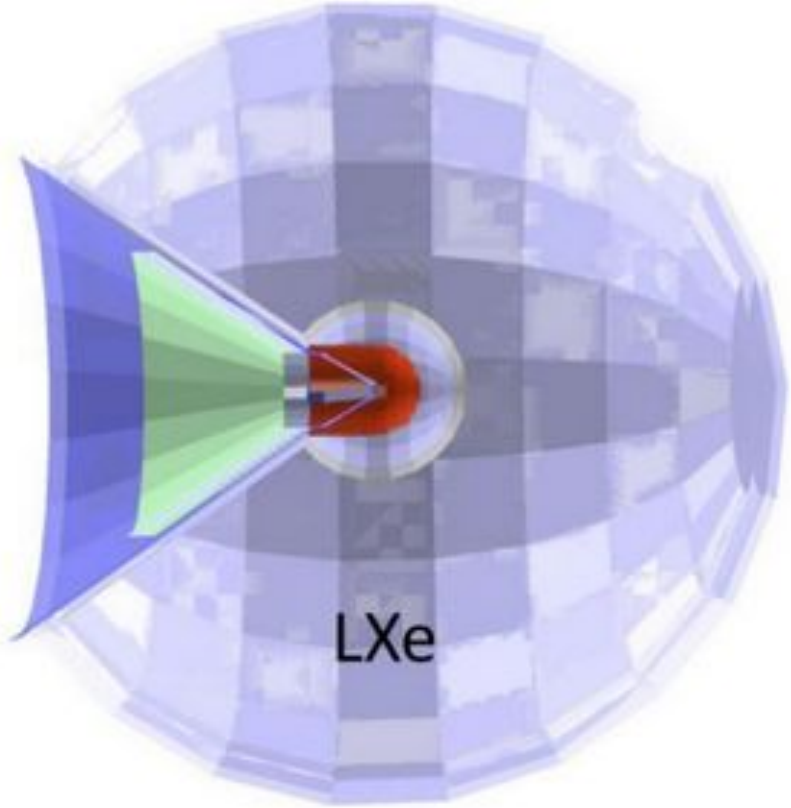
Backup

Calorimeter Requirements

- Energy resolution 1.85% at 70 MeV and 2.2% at 56 MeV
- Timing resolution 200 ps @ 56 MeV
- Spatial resolution 1 cm
- Depth 19 radiation length
- Inner radius is 15 cm
- Must have fast decay ~ 40 ns

Calorimeter LXe

- LXe calorimeter has a uniform one single volume filled with highly pure liquid Xe
- There is no dead zone and can collect all the energy deposited
- Need to deal with pile up and requires a lot of cooling
- It has light yield of ~ 50000 photons/MeV
- Time resolution is 66 to 67 picosecond
- Spatial resolution is 2.5 mm
- Energy resolution is ~ 1.7% at 52.8 MeV



Schematic diagram of the LXe Calorimeter. [Ref: arXiv 2504.06375]

Present status

- The experiment has been approved at PSI
- Technology finalization is going on based on simulation and test beam results
- We are also working on development of analysis software
- Traditional and AI/ML based analysis strategies are being developed