PIONEER: A next-generation rare pion decay experiment

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Supervisors: Chloé Malbrunot & Doug Bryman

CIPANP 2025

(unofficial logo)

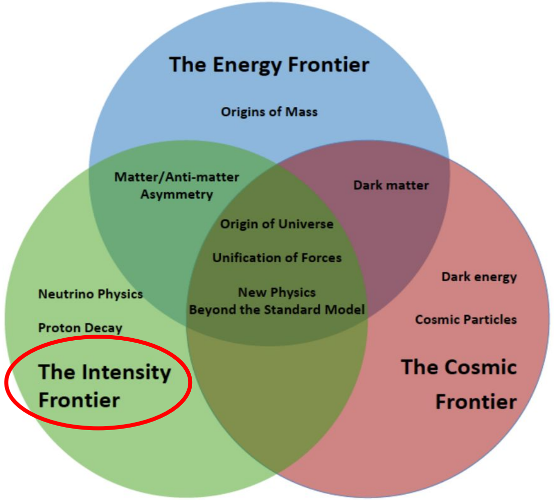


Figure from Fermilab

- A rare pion decay experiment in the intensity frontier
    - With a broad energy range of new possible physics
- Currently being designed and prototyped
- At PSI (The Paul Scherrer Institute), Switzerland
  → The highest intensity pion beam
- Our collaboration is currently ~ 80 scientists from 25 universities & national labs in Canada, the US, Japan and Switzerland, and actively growing

Phase 1 goal: lepton flavour universality (LFU)

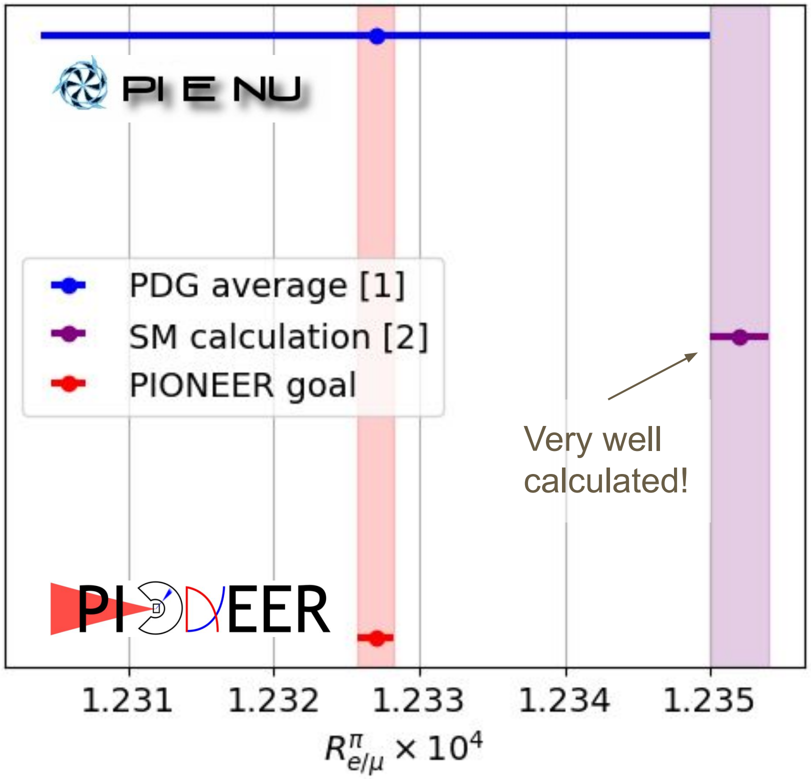
Measure the pion decay ratio:

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

$$= 1.2327(23) \times 10^{-4} \text{ (Exp)}$$ [1]

Best test of the hypothesis that leptons have identical weak interaction strengths

- Known precisely (0.01%) theoretically in the Standard Model (SM) [2]
- Current measurement (PIENU experiment at TRIUMF [3]) has 15x larger error bars than theory
- PIONEER goal is a 0.01% measurement

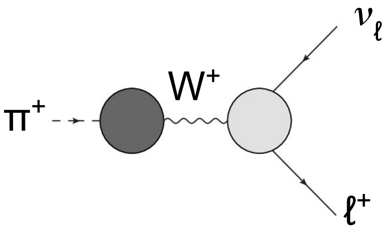


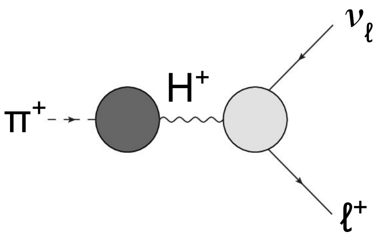
[1] PDG 2022, https://pdg.lbl.gov/
[2] Cirigliano & Rosell 2007, https://doi.org/10.1103/PhysRevLett.99.231801
[2] Aguilar-Arevalo, et al. 2015 https://doi.org/10.1103/PhysRevLett.115.071801

Beyond the Standard model (BSM)

Our goal precision will also make us sensitive to high mass scale BSM physics, particularly as π → eν is helicity-suppressed (V-A).

Such as new pseudoscalars couplings - Example: charged Higgs





$$1 - \frac{R^{\text{New}}_{e/\mu}}{R^{\text{SM}}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m^2_\pi}{m_e(m_d+m_\mu)} \sim \left(\frac{1\ \text{TeV}}{\Lambda_{eP}}\right)^2 \times 10^3$$

$$(P = \pi^\pm)$$

Our 0.01% measurement → energy scale (Λ_{eP}) ~ 3000 TeV

And many others:

- New scalar couplings
- Leptoquarks

As well as exotics searches:

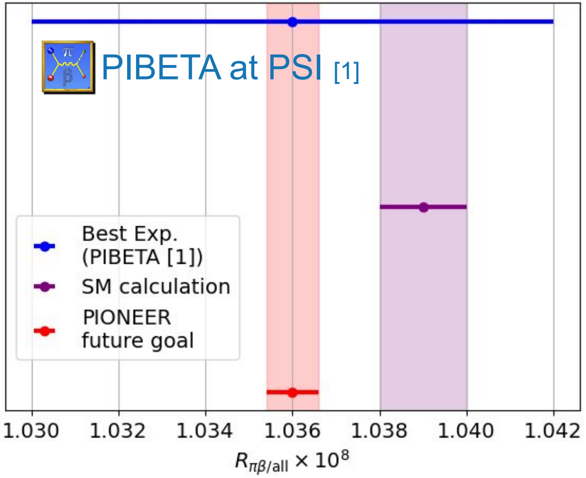
- Sterile massive neutrinos
- ALPs

Campbell 2005, https://doi.org/10.1016/j.nuclphysb.2004.12.015

Phase 2: testing CKM unitarity

Measure the pion beta decay branching ratio:

$$R_{\pi\beta/\text{all}} = B(\pi^+ \to \pi^0 e^+ \nu)$$
$$= 1.036(6) \times 10^{-8} \text{ (Exp.) [1]}$$



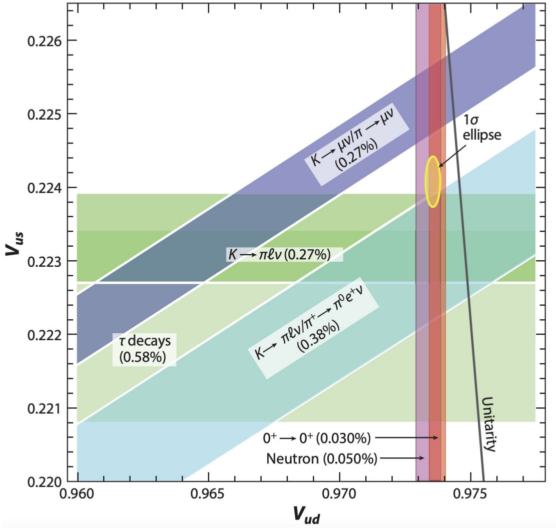
This can be used to extract the quark mixing parameters:

$|V_{us} / V_{ud}|$

- An improvement by 3x on $\delta R_{\pi/\beta}$ would shed light on the $|V_{us} / V_{ud}|$ plane

$|V_{ud}|$

- No nuclear structure contribution compared to other extraction methods



Constraints on V_{ud} and V_{us} extracted from different decays [2].

[1] Počanić 2004, https://doi.org/10.1103/PhysRevLett.93.181803
[2] Bryman 2022, https://doi.org/10.1146/annurev-nucl-110121-051223

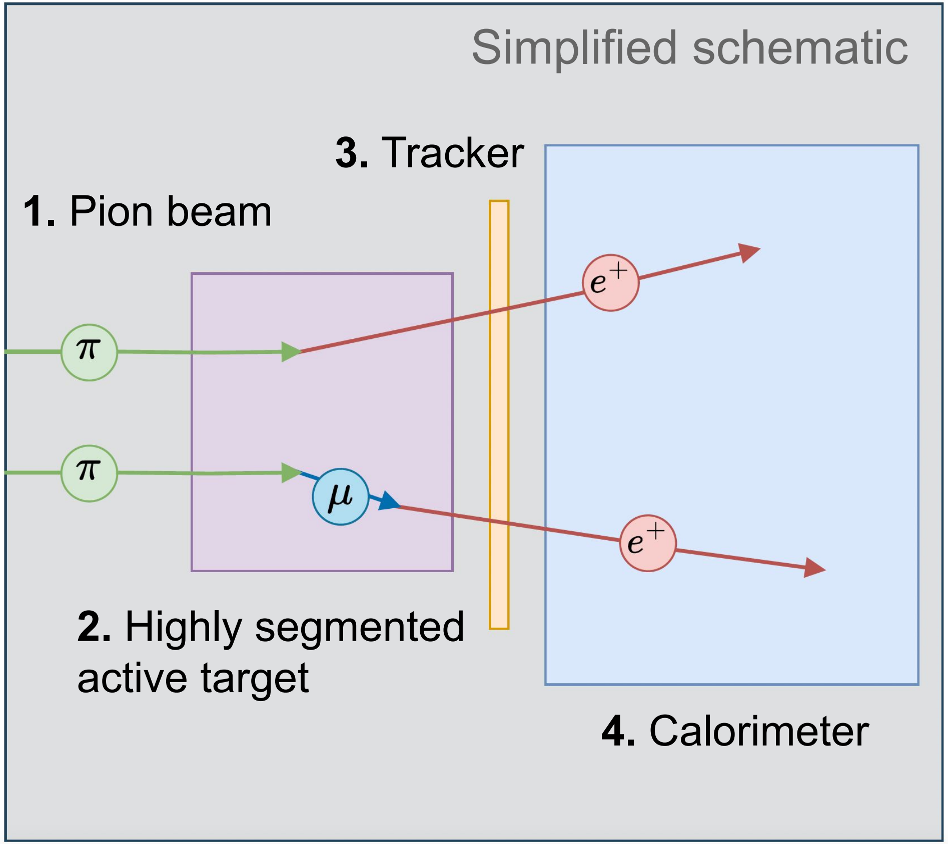
Measurement Strategy

We want to count the number of each type of decay.

- Look at positrons emitted from stopped pion decays
- Many detector systematics cancel in the ratio

Improvements compared to past measurements (PIENU, PEN):

- Central tracking target
- Increased acceptance



The energy spectrum

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

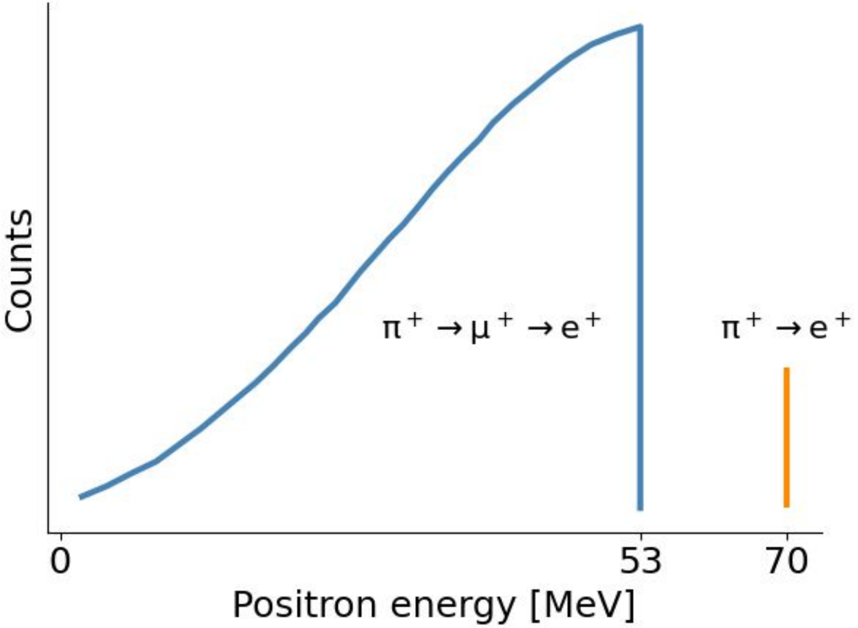
We want to count the number of each type of decay, so we measure the positron energy & time spectra to discriminate between the decays.

Pion to positron: π → e

- Two body decay
- Positron energy: 69.8 MeV
- Timing based on τ_π ~ 26 ns

Pion to muon: π → μ → e

- Three body decay
- Positron energy: 0.5-52.8 MeV
- Timing based on decay chain, where τ_μ ~ 2200 ns



What we measure

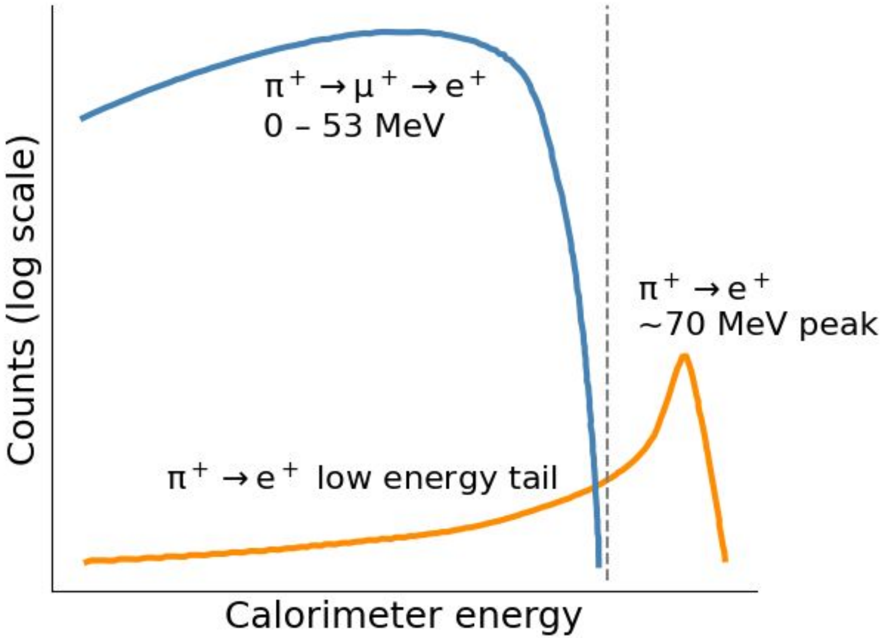
$$R^{\pi,\,raw}_{e/\mu} = \frac{N_{\text{high E}}}{N_{\text{low E}}}$$

In the calorimeter, the spectra overlap, so a threshold is used to separate out low and high energy events.

What makes this difficult: the low energy $\pi \rightarrow e$ tail is buried under the Michel spectrum

This tail comes from:

- Photonuclear interactions
- Finite energy and timing resolution of the calorimeter
- Electromagnetic shower leakages
- Radiative decays
- Upstream dead material …

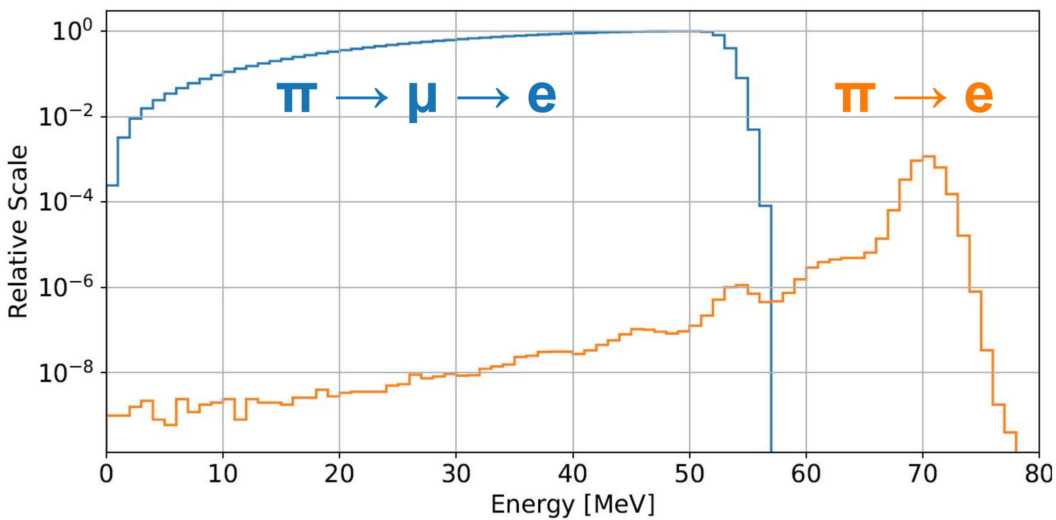


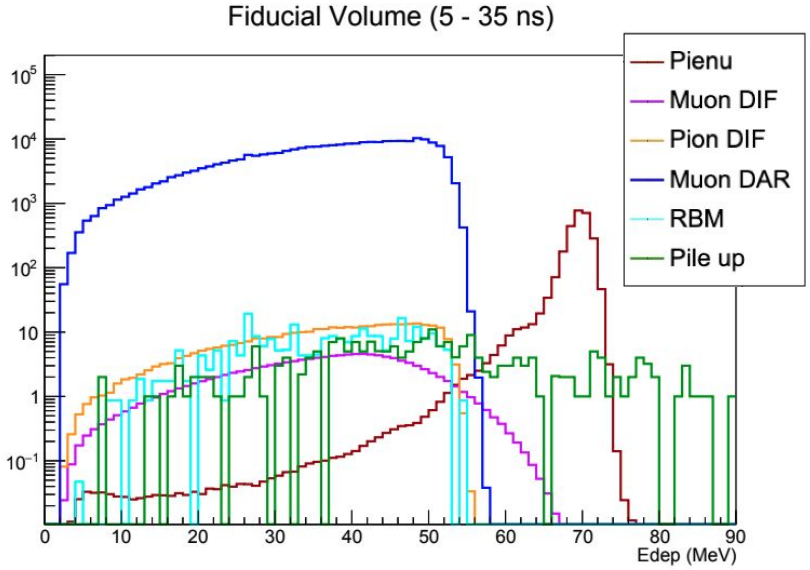
Guiding principles for the experiment

$$R^{\pi}_{e/\mu} = \frac{N_{\text{high E}}}{N_{\text{low E}}} \times (1 + C_{\text{tail}}) \times R^{\epsilon}$$

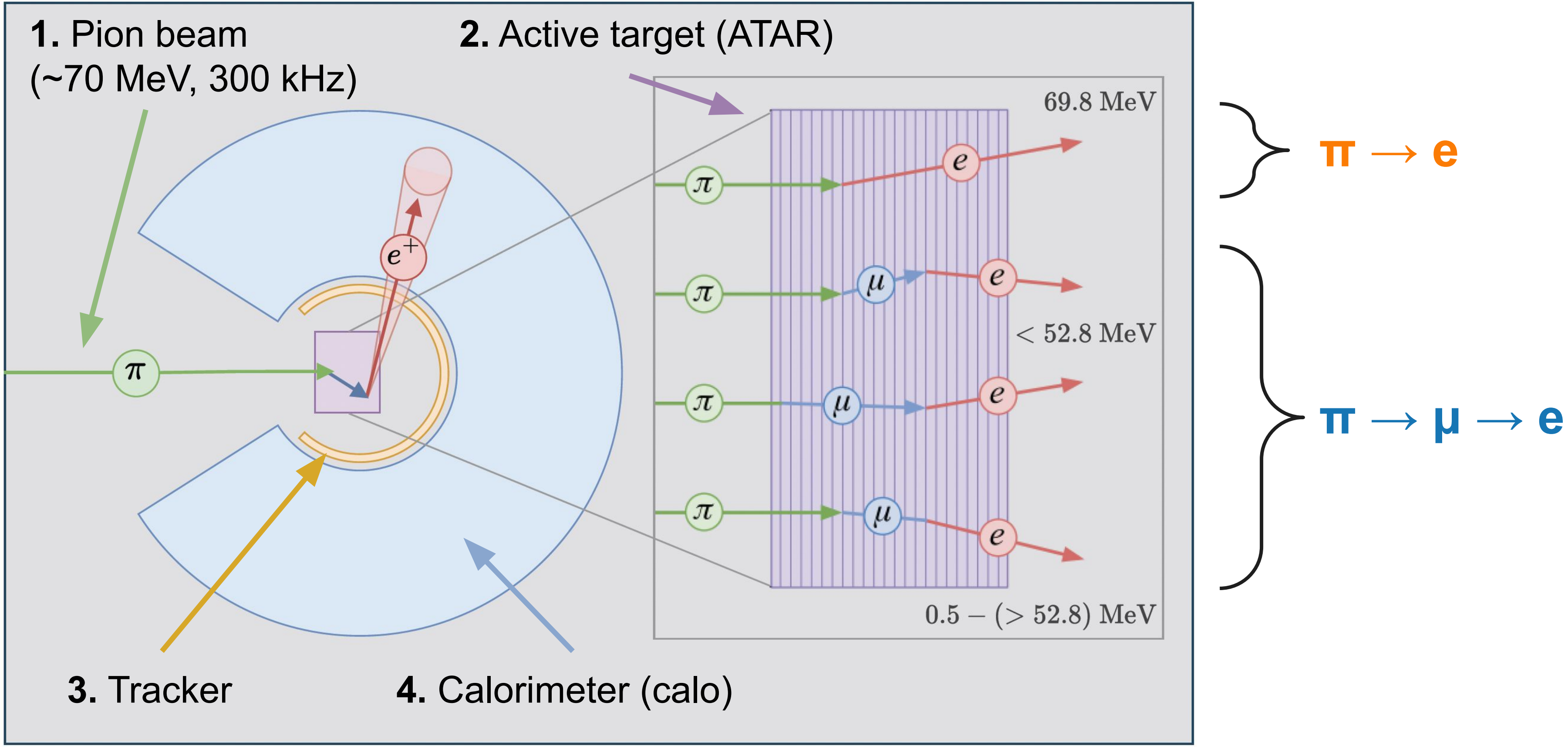
- Large statistics of pion decay events
- Minimize the low energy tail
- Precisely measured low energy tail

As it isn't just the tail (C_{tail}) we have to account for, but many backgrounds and the acceptance correction (R^{ϵ}).





Overview of the experimental setup



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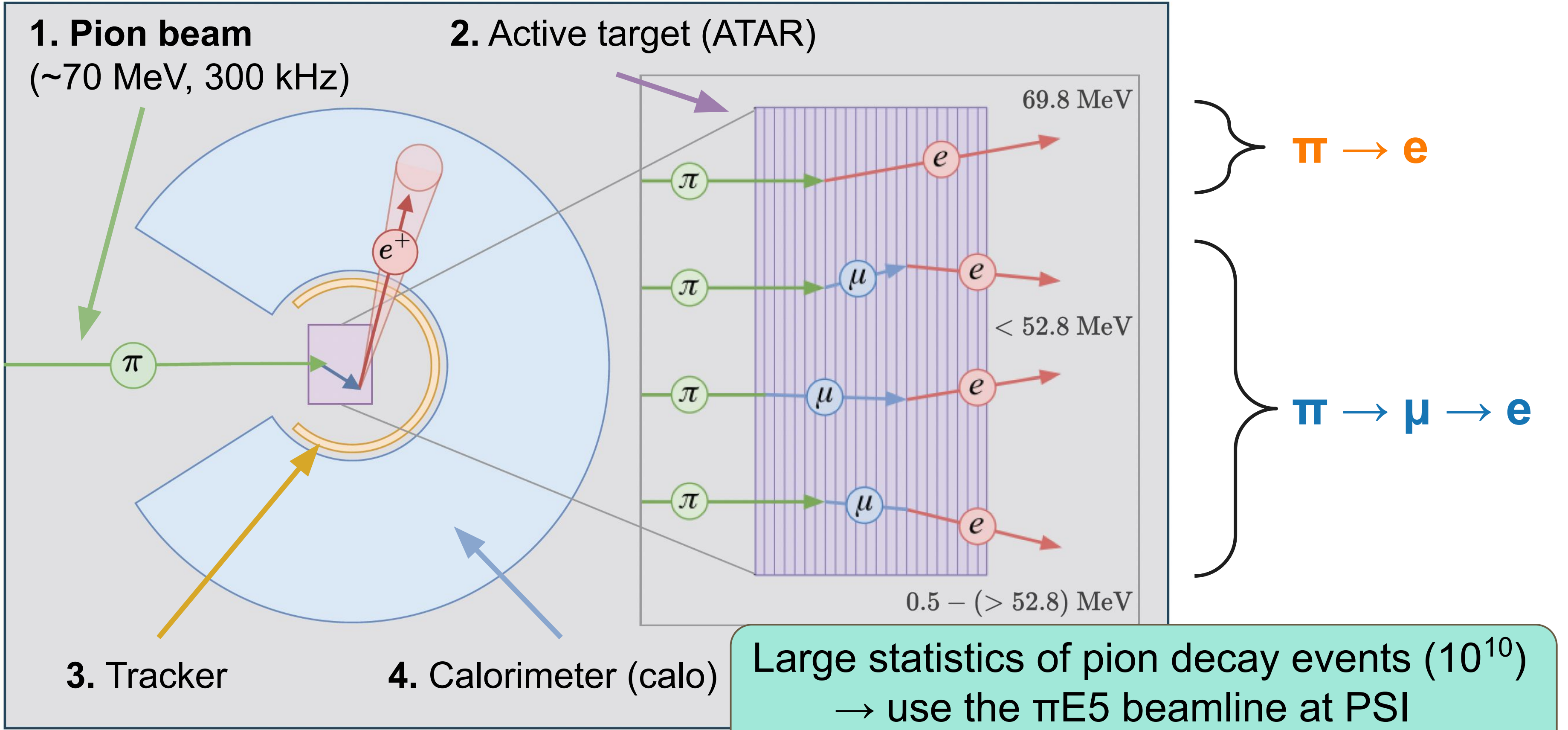
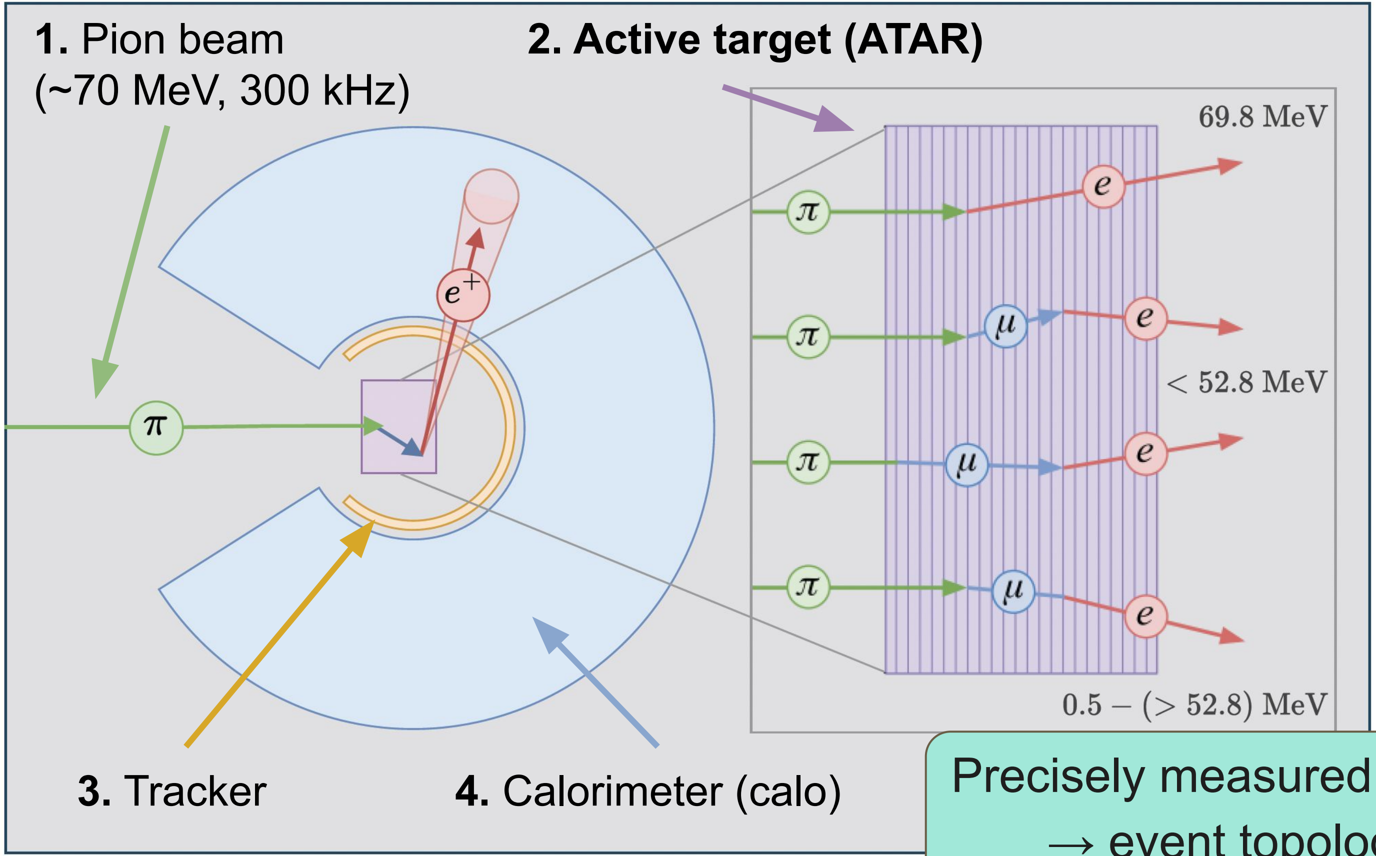


Large statistics of pion decay events (10^{10})
→ use the πE5 beamline at PSI

Overview of the experimental setup



π → e

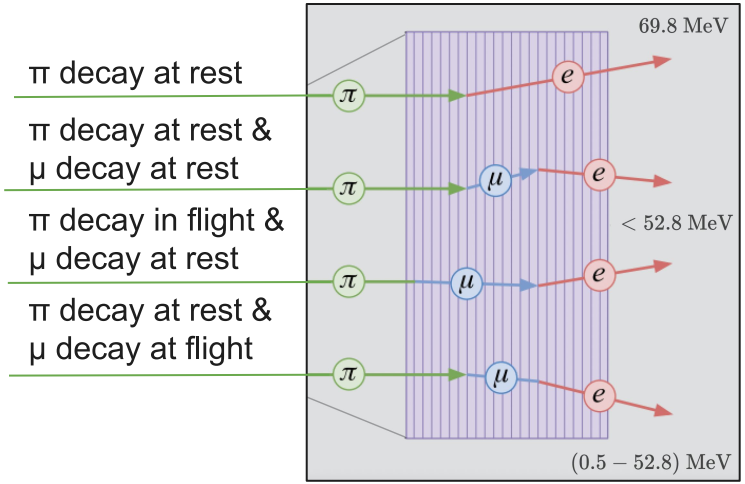
π → μ → e

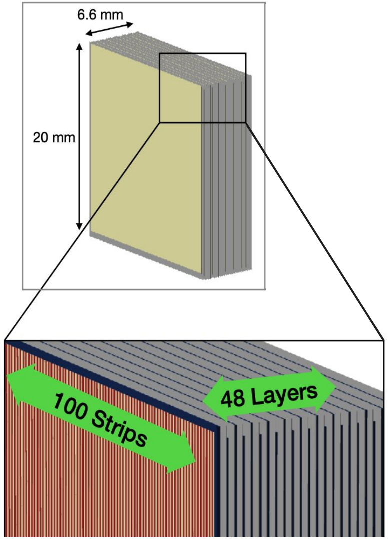
Precisely measured low energy tail
→ event topology

The ATAR

A 5D (x,y,z,t,E) tracking system at the heart of PIONEER that will:

- Define the pion stopping region
- Provide high resolution timing information
- Lead to track reconstruction





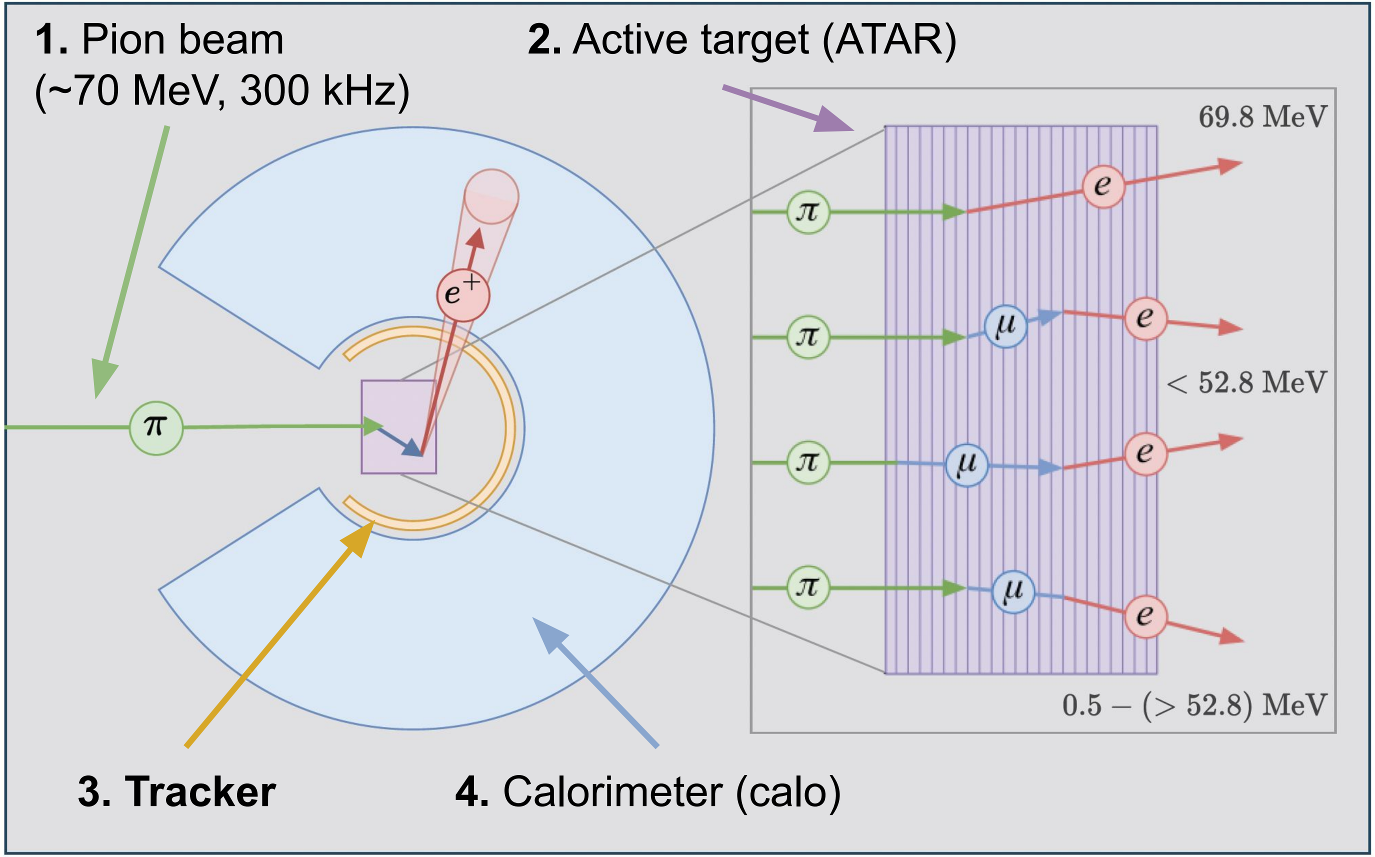
Design requirements:

- Large dynamic range: keV - MeV for minimum-ionizing particles to π/μ stopping
- Good time resolution: < 100 ps
- Sufficient granularity: < 200 μm
- Minimal dead material & cross talk

New technology: LGADs (low gain avalanche diodes)

Publications: Mazza 2021, https://doi.org/10.48550/arXiv.2111.05375 ;
Mazza 2023, https://doi.org/10.22323/1.420.0015

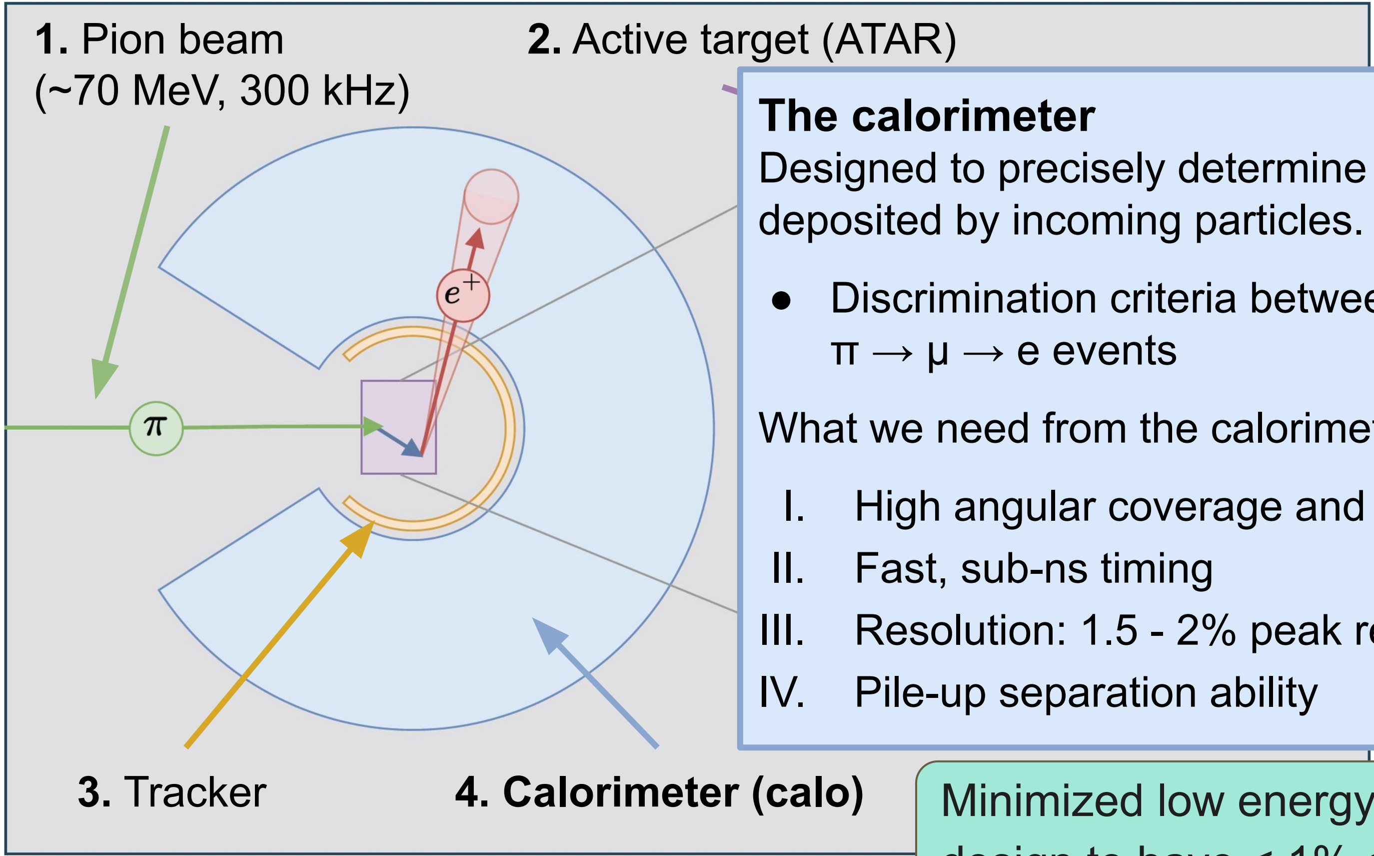
Overview of the experimental setup



π → e

π → μ → e

Overview of the experimental setup



The calorimeter
Designed to precisely determine the energy deposited by incoming particles.

- Discrimination criteria between π → e and π → μ → e events

What we need from the calorimeter is:

I. High angular coverage and uniformity
II. Fast, sub-ns timing
III. Resolution: 1.5 - 2% peak resolution
IV. Pile-up separation ability

Minimized low energy tail→ calorimeter design to have < 1% events in the tail

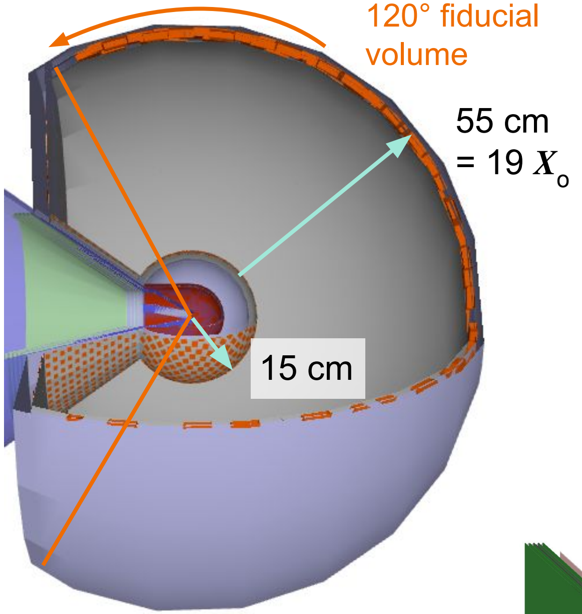
PIONEER is exploring 2 calorimeter options

Common features

- High light yield (> 30,000 γ/MeV)
- "Fast", 40 ns decay time
- Both promise < 2% resolution
- Both promise good timing

Differences

- LYSO is segmented by design
- LXe is a single volume
- Density
- Data load per event
- LYSO is slightly radioactive



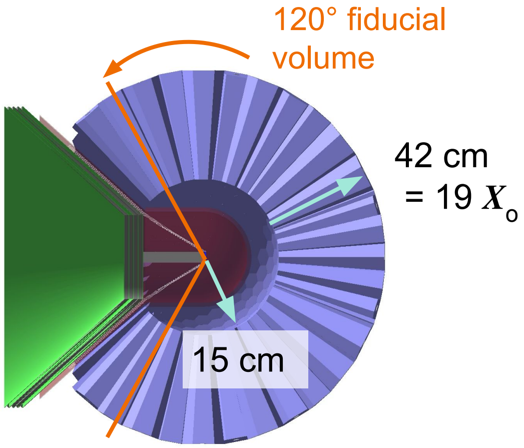
Liquid xenon (LXe)

4.5 tons of LXe

LYSO crystals

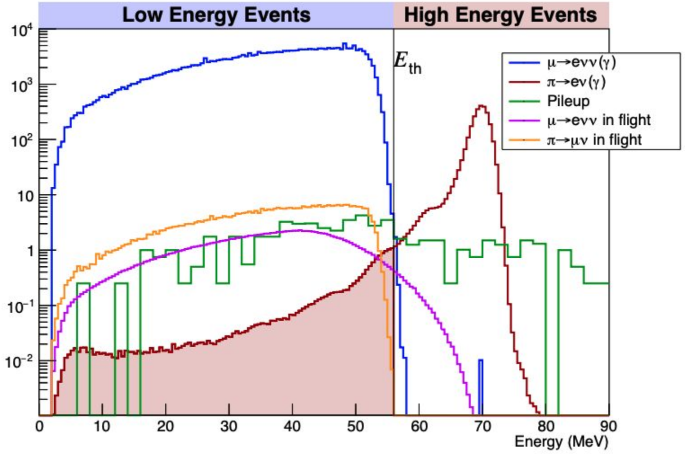
(Lutetium-yttrium oxyorthosilicate, $Lu_{2(1-x)}Y_{2x}SiO_5$)

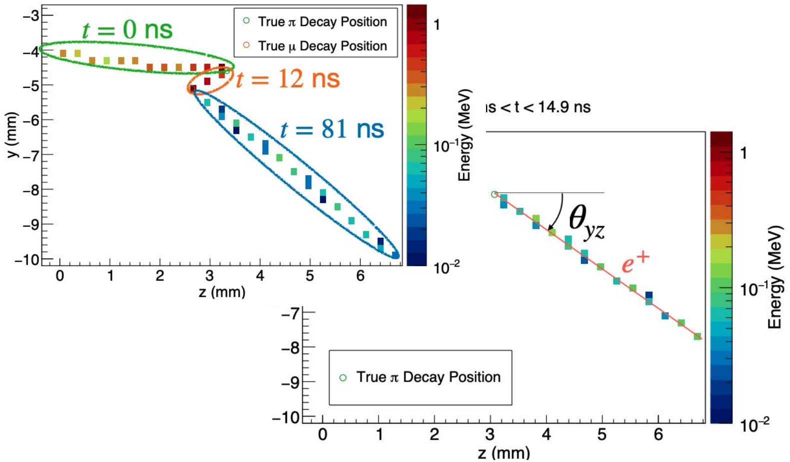
Lattice of 311 crystals



The PIONEER simulation framework

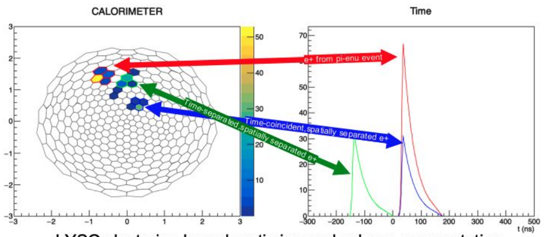
- Geant4 Monte Carlo basis
- Very active development on implementing detector responses, event mixing, reconstruction algorithms…



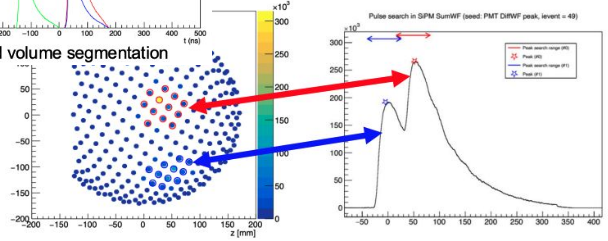


Track reconstruction using ATAR simulation

Energy clusters formation in the calorimeter



LYSO clustering based on timing and volume segmentation



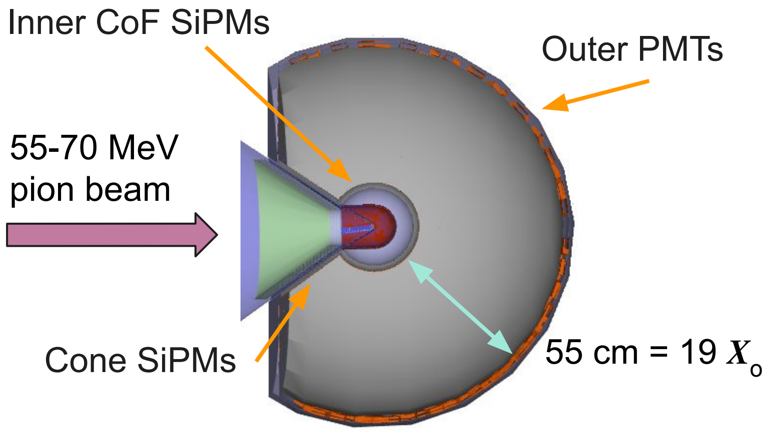
LXe clustering based on timing and energy profile in neighboring SiPMs

LXe Calorimeter

Joint effort between Canadian & Japanese groups

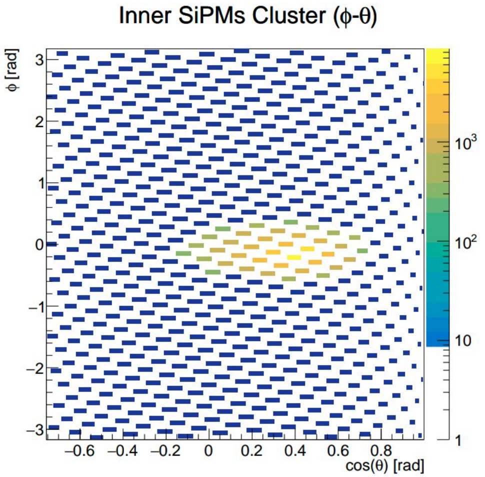
The PIONEER simulation framework

- Geant4 Monte Carlo basis
- Very active development on implementing detector responses, event mixing, reconstruction algorithms…
- LXe specific: work on refining optical photon processing



Key optical features:

- Light only signal: VUV scintillation light
- Thin two layered inner window
  - To be instrumented with Hamamatsu VUV SiPMs in a new chip-on-film (CoF) package
  - Need to limit dead material



Light signal clustering from simulation in progress - crucial for pile up suppression.
By Benjamin Davis-Purcell

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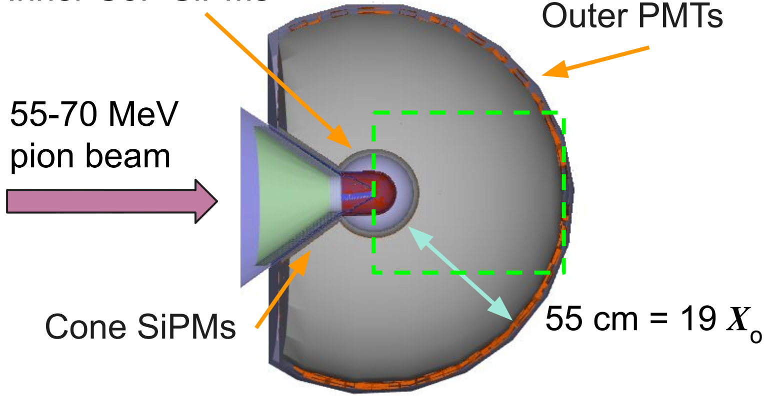

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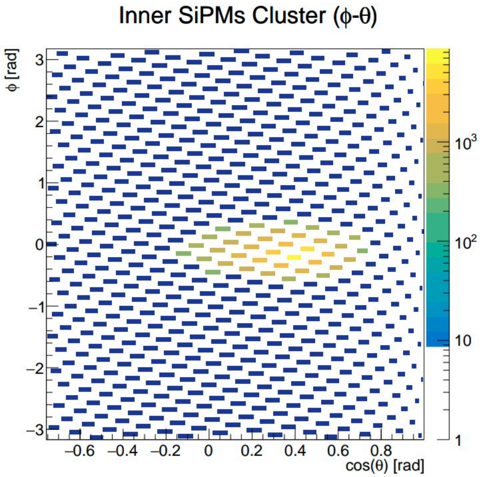


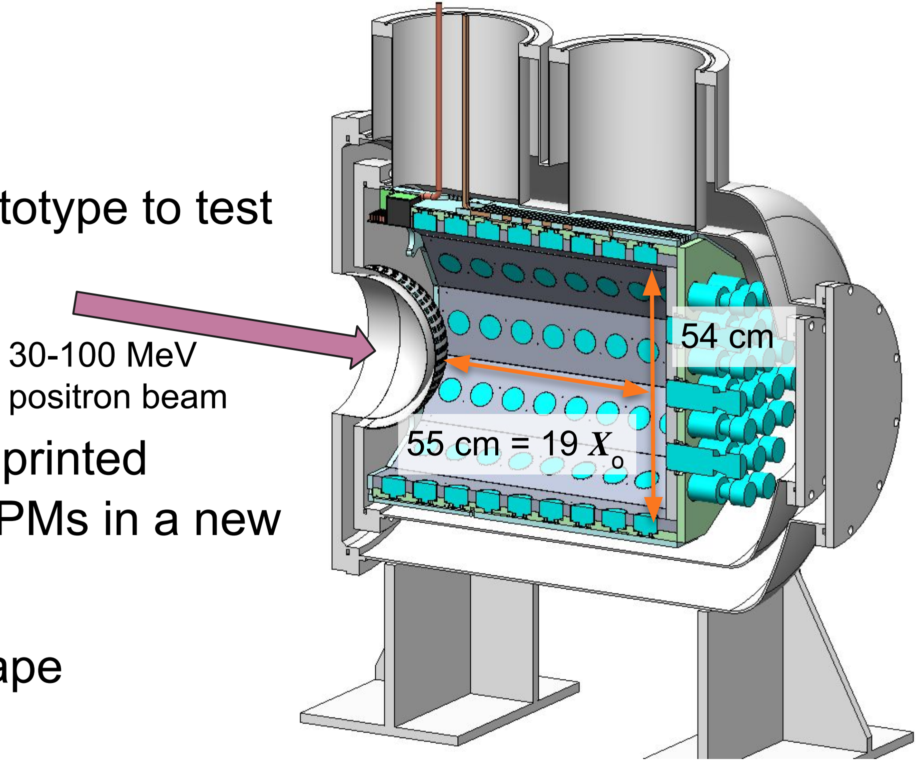
Light signal clustering from simulation in progress - crucial for pile up suppression.
By Benjamin Davis-Purcell

The Large Prototype

We are building a large LXe calorimeter prototype to test the LXe calorimeter option.

Goals:

- Test of new hardware components: 3D printed instrumented window & Hamamatsu SiPMs in a new Chip-on-Film Package
- Measure energy resolution and line shape
  - Compare to simulations
- Study shower leakages, photonuclear effects
- Study pileup suppression



Current large prototype design using ~650 kg of LXe. Nominal design has 133 PMTs and 400 SiPM quads.

Development highlights of the Large Prototype

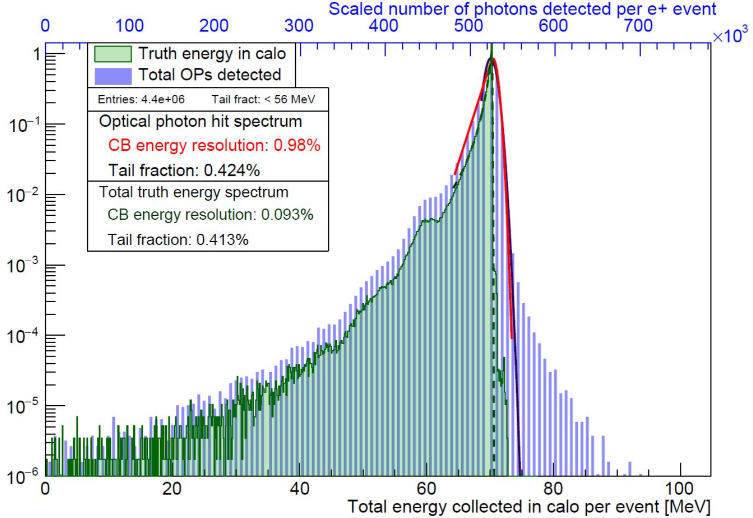
Simulation - Using the PIONEER framework

- Results have been used for design choices
- The simulation will be validated with data from this prototype

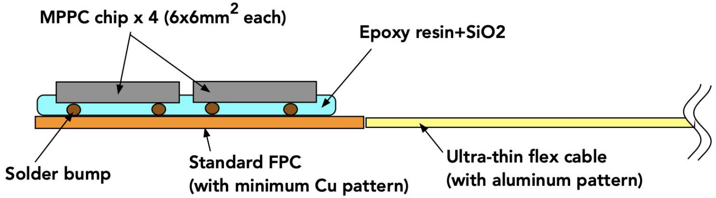
Hardware - Tests for the full LXe calorimeter

Lots of hardware development ongoing at TRIUMF, PSI, KEK, and at the University of Tokyo.

- 3D printed hexagonal tiled semi-sphere
- First tests of the SiPMs in a new Chip-on-Film Package from Hamamatsu



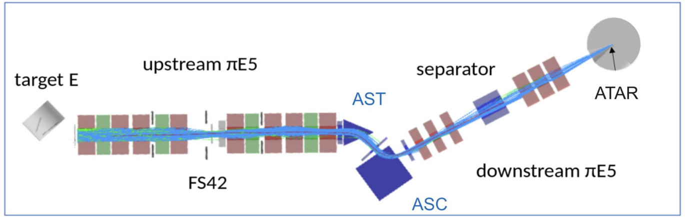
Truth and optical simulated energy spectra of the LXe prototype with Crystal Ball function (CB) fits to peak region, after simple geometric correction.



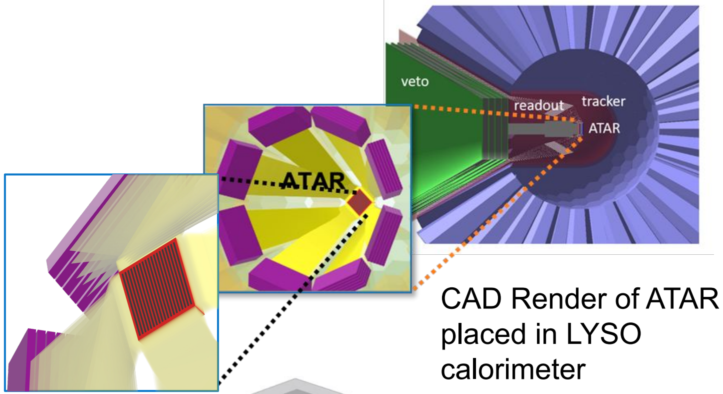
Summary

The PIONEER Experiment at PSI is under development.

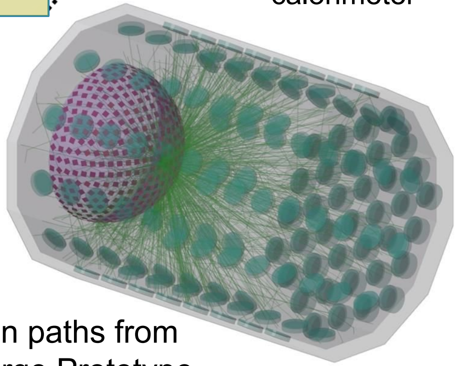
- Multiphase exciting physics goals
- Experimental design to be built around the central tracking target (ATAR)
- Two options for calorimeter technologies
- LYSO prototypes in progress for testing at PSI
- LXe Large Prototype under development at TRIUMF, KEK & PSI



Beamline πE5 at PSI



CAD Render of ATAR placed in LYSO calorimeter


Visualization of photon paths from a simulation of the Large Prototype

TRIUMF

THE UNIVERSITY OF BRITISH COLUMBIA

PIONEER

A next generation rare pion decay experiment

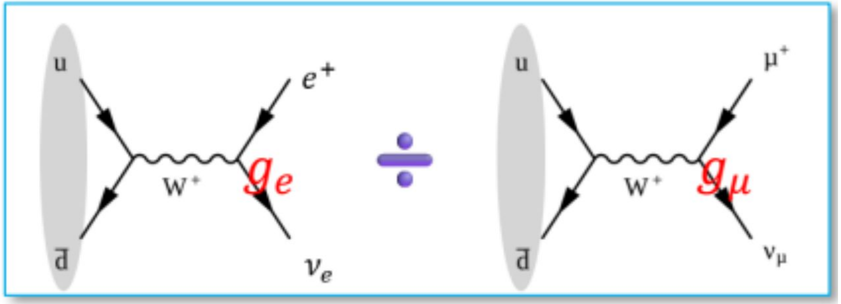
NSERC CRSNG

https://pioneer.triumf.ca

Backups

Why this ratio?

$$R^{\pi}_{e/\mu} = \frac{\Gamma\Big((\pi^+ \to e^+\nu_e) + (\pi^+ \to e^+\nu_e\gamma)\Big)}{\Gamma\Big((\pi^+ \to \mu^+\nu_\mu) + (\pi^+ \to \mu^+\nu_\mu\gamma)\Big)}$$

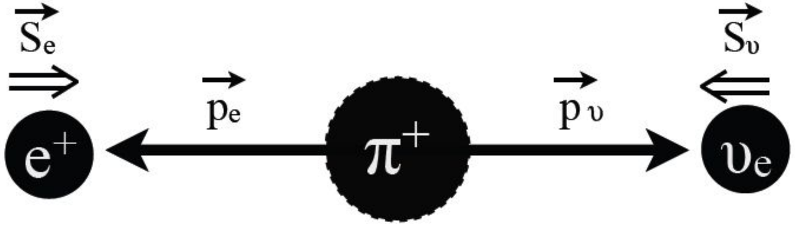


LFU has been tested with many different decays: π, K, τ, W & Z.

There is strong helicity-suppression in π → eν :

$$R^{\pi}_{e/\mu} \sim \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 10^{-4}$$

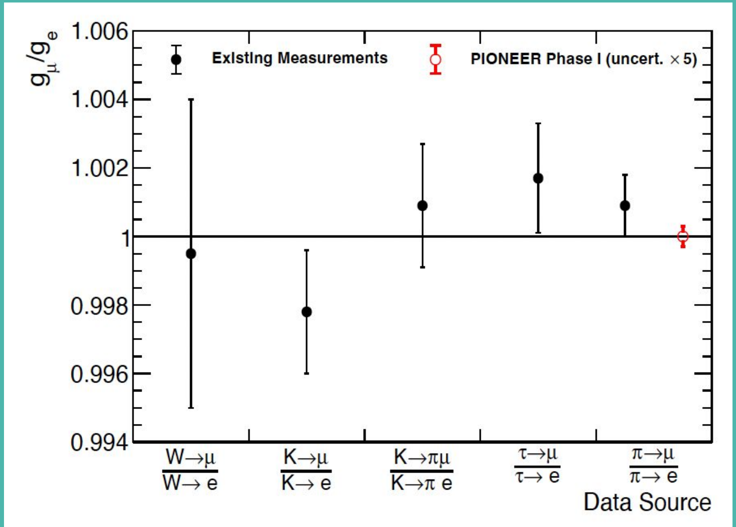
$\sim 10^{-5} \times \sim 5.5$



Comparison to other probes

LFU test

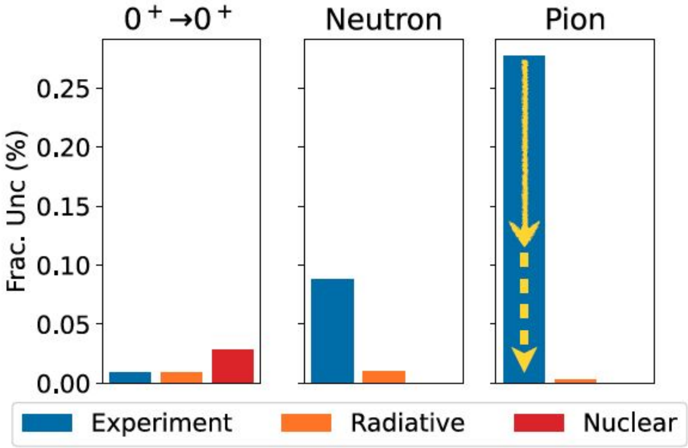
Looking at the weak interaction strength of muons compared to electrons.



Bryman 2022, https://doi.org/10.1146/annurev-nucl-110121-051223
ATLAS Collaboration 2024, https://doi.org/10.1140/epjc/s10052-024-13070-4

Extraction of $|V_{ud}|$

Sources of fractional uncertainty for different experimental methods



$$V_{ud}^{0^+\to 0^+} = 0.97367\,(11)_{\text{exp}}\,(13)_{\Delta_R^V}\,(27)_{NS}\,[32]_{\text{total}}$$

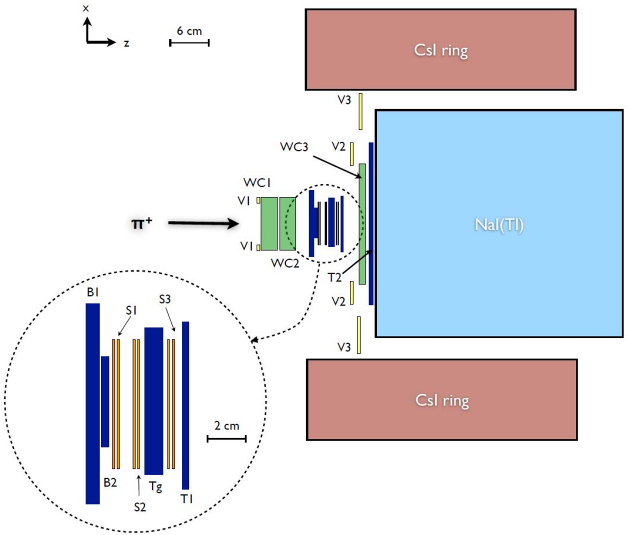
$$V_{ud}^{n,\text{PDG}} = 0.97430\,(2)_{\Delta_f}\,(13)_{\Delta_R}\,(82)_{\lambda}\,(28)_{\tau_n}\,[88]_{\text{total}}$$

$$V_{ud}^{\pi} = 0.97386\,(281)_{\text{BR}}\,(9)_{\tau_\pi}\,(14)_{\Delta_R^\pi}\,(28)_{\Delta_f}\,[283]_{\text{total}}$$

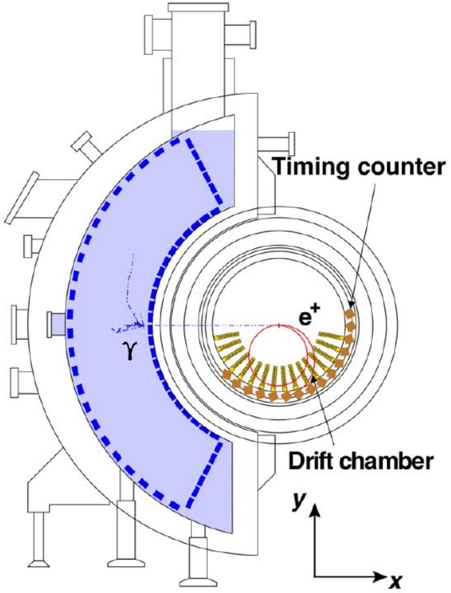
Brodeur et al, 2023, https://doi.org/10.48550/arXiv.2301.03975

Previous related experiments

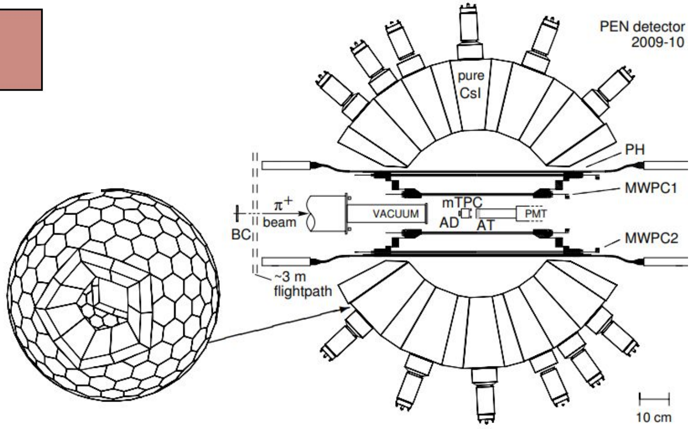
PIENU at TRIUMF - single NaI(Tl) crystal



MEG & MEGII (Mu to Electron Gamma) at PSI - uses LXe



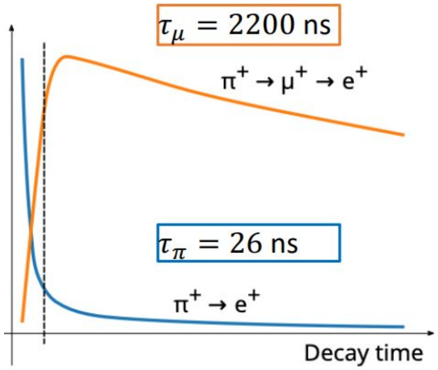
PEN at PSI - 3π coverage array of CsI crystals



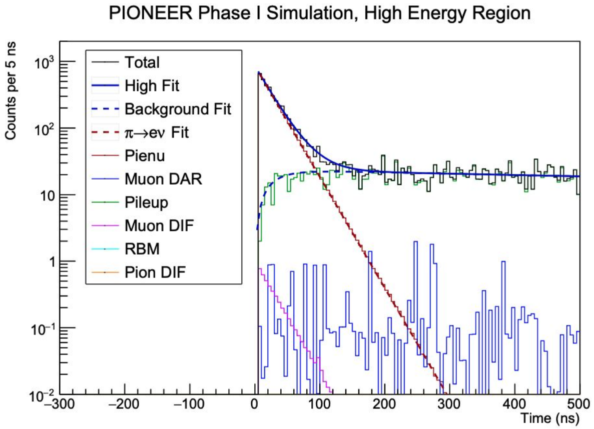
Time spectra & raw BR

$$R^{\pi}_{e/\mu} = \frac{N_{\text{high E}}}{N_{\text{low E}}} \times (1 + C_{\text{tail}}) \times R^{\epsilon}$$

- Following the 'PIENU method', the raw branching ratio, $R^{raw}_{\pi/\square}$, is extracted from the simultaneously fits on the time spectra, split into the low and high energy events
  - These fits account for the different types of decays that end up in the two spectra
- After this, the tail correction, C_{tail} and the acceptance ratio, R^{ϵ}, must also be added in



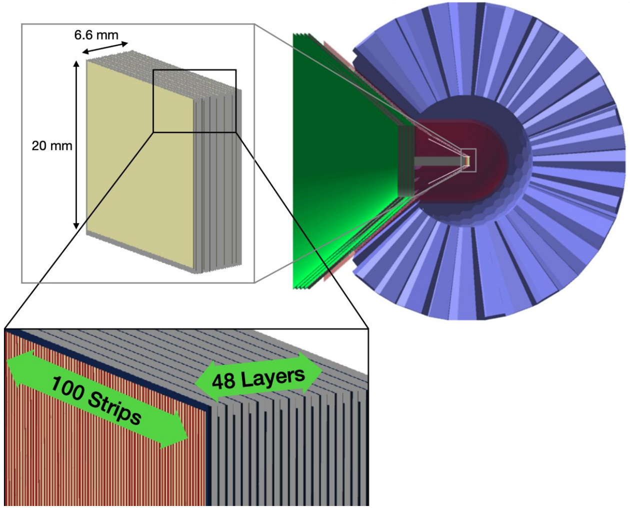
Idealized time spectra for the two types of decays

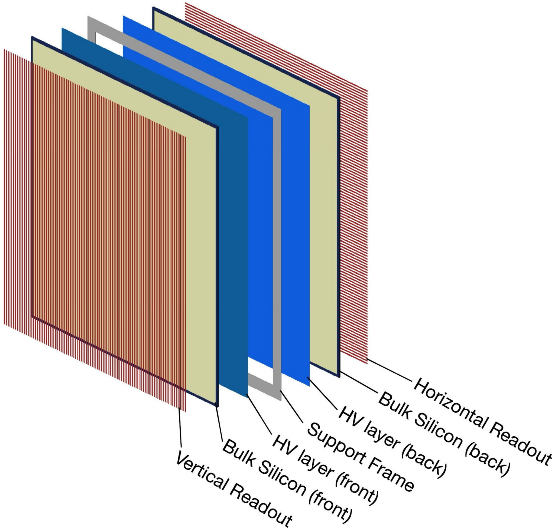


High energy binned events simulated time spectra from Patrick Schwendimann

ATAR details - LGADs

- Each sensitive strip of the ATAR has a size of 20 mm x 200 μm x 120 μm
- Baseline design is 48 stacked planes
- Total of 4800 channels arranged in a criss-crossing pattern





LGADs: Silicon detector with a thin gain-layer

- Gain allows for thin sensors & good timing resolution
- But also saturated for large energy deposits & introduces an angular dependency

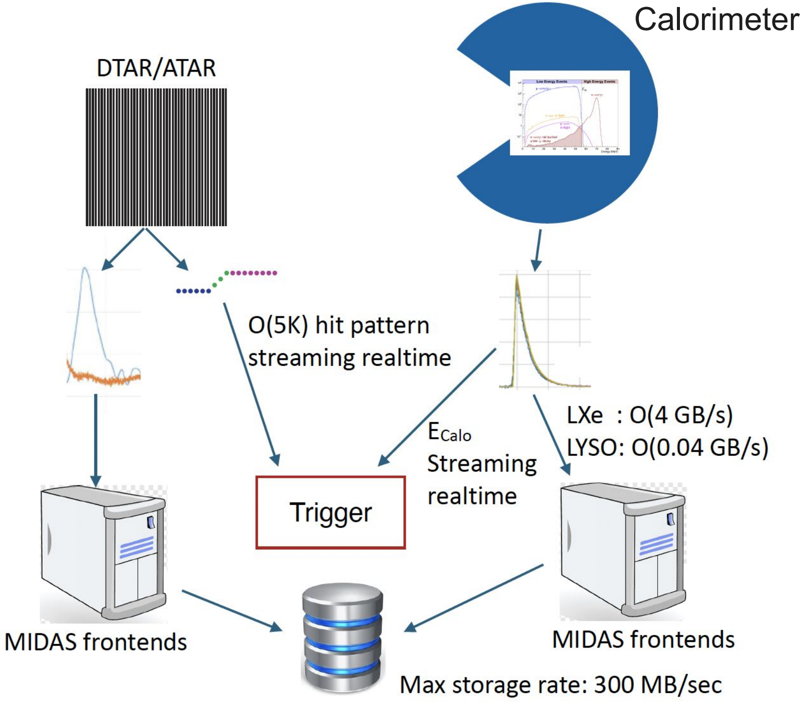
A demonstrator (~10% of the full ATAR) is planned to be tested by the end of 2026 at PSI & then an updated version later tested at TRIUMF in 2027.

Electronics & DAQ

Electronics key requirements

- Low latency for trigger decisions:
    - Few x 100 ns: global trigger for ATAR
- High channel counts:
    - 300-1500 calorimetry channels
    - 4800 channels from ATAR
        - Streaming bit pattern of channels over threshold; sparsified readout
- Flexibility
    - Changes to trigger
    - Evolution of triggering strategies

Plan is to use the CU/CMS Apollo Command Module + ATAR & CALO digitizers under development.



Some challenges

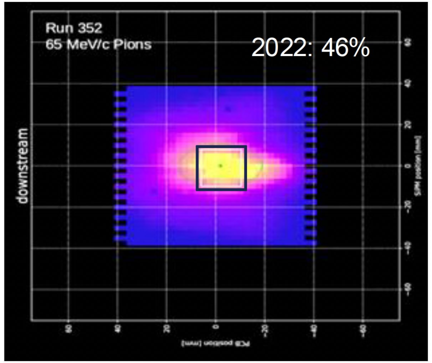
- ATAR digitizer analog buffering
  ⇒ O(few hundred ns) trigger decisions
- LXe event size vs data storage rate
  ⇒ lossy compression (eg., MEG II)

From Lawrence Gibbons

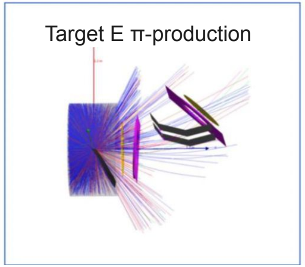
Beam details

PIONEER will use beamline πE5 at PSI

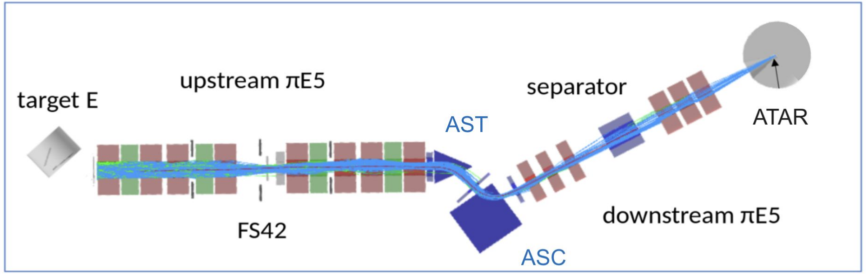
- Beam parameters are critical for the design of PIONEER
- On-going tests of the beamline tuning to learn about intensities, spot sizes, separation, momentum resolution etc.



Beam spot results from 2022 beam test.



Target TgE
- 40 mm polycrystalline graphite
- Pions produced through the interaction of the protons with the target



Beam parameter	PIONEER requirement
Rate of Pions	300 kHz/s from 55-70 MeV/c
Momentum bite (Δp/p)	FWHM < 2%
Spot size of beam	< 2 x 2 cm^2, 0.6 cm deep (or smaller than ATAR)
Particle contamination	μ/e< 10%

LYSO details

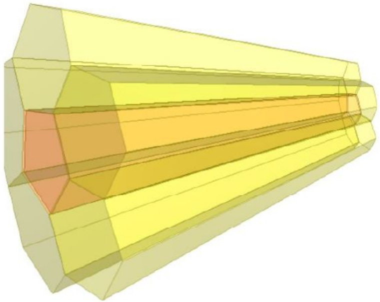
Segmented by design, uniformity depends on response of individual crystals

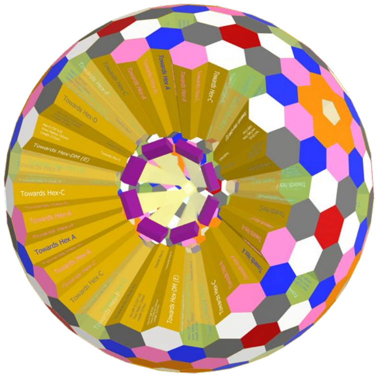
- Efforts lead by groups at the University of Washington, ETH-Zurich and SJTU
- Testing prototypes, with currently promising results
  - Rectilinear (details on next slide)
  - Tapered array to be tested with beam at PSI this summer
- Getting an array of 300+ tapered crystals manufactured is currently possible by a single company

Lutetium–yttrium oxyorthosilicate (LYSO):

- By weight: 73% Lutetium, 18% Oxygen, 6% Silicon, **~0% Cerium (dopant)**, 3% Yttrium
- **X_0 = 1.14 cm , R_M = 2.07 cm**
- Decay time = **40 ns**
- Light yield **30,000 γ/MeV**
- λ_{peak} **420 nm** -> conventional PMTs
- Radioactive (< 1 MeV constant rumble)
- Non hygroscopic, negligible temperature dependence, radiation hard

From David Hertzog





Rectilinear LYSO array test

Ten 2.5 x 2.5 x 18 cm^3 LYSO crystals tested with:

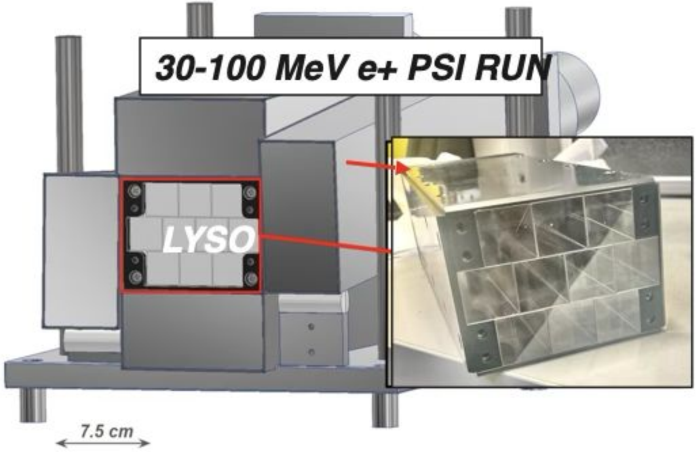
- 30-100 MeV positrons at PiM1 beamline at PSI
- 17.6 MeV gammas at CENPA
  - 2.6% resolution at 17.6 MeV

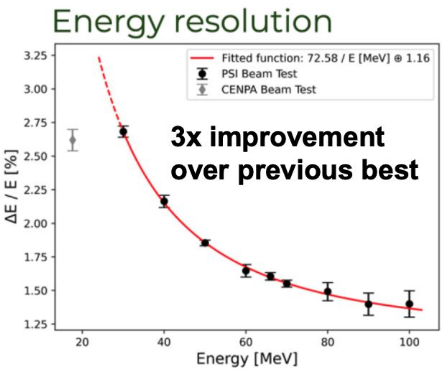
Measurements of:

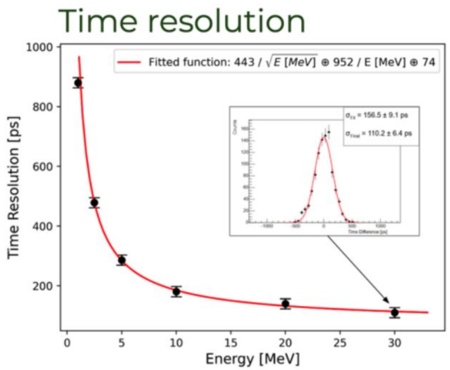
- Longitudinal response uniformity (LRU) using high energy muons: 4% uniformity, PIONEER requires 20%
- Spatial resolution: 6 mm at 70 MeV
- Time resolution: ~100 ps at PIONEER signal energy
- Energy resolution: 1.52% at 70 MeV

Work lead by Omar Beesley

Publication: Beesley 2025, https://doi.org/10.1016/j.nima.2025.170320



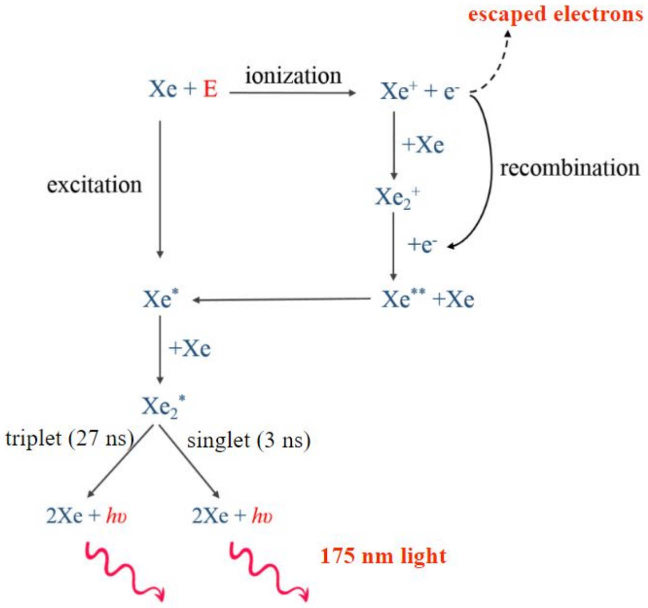




Liquid xenon for calorimetry

Liquid xenon (LXe) - a nobel liquid with good characteristics for use in a calorimeter

- High atomic number & density → high stopping power for radiation
- Very good uniformity & fast response
- Produces both charge carriers & scintillation light → we will use only the light signal



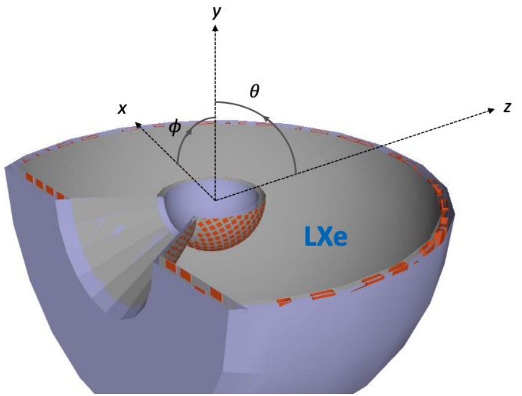
Optical properties of the light signal:

Scintillation yield: ~ 50 000 photons / MeV of deposited energy from a beta particle
→ lots of light produced!

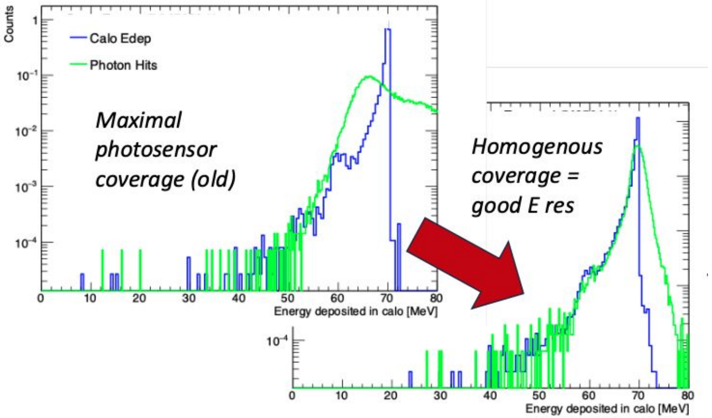
Wavelength: ~ 175 nm → vacuum ultraviolet (VUV) light

LXe overview: Aprile et al.https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.82.2053

Additional LXe calo simulations

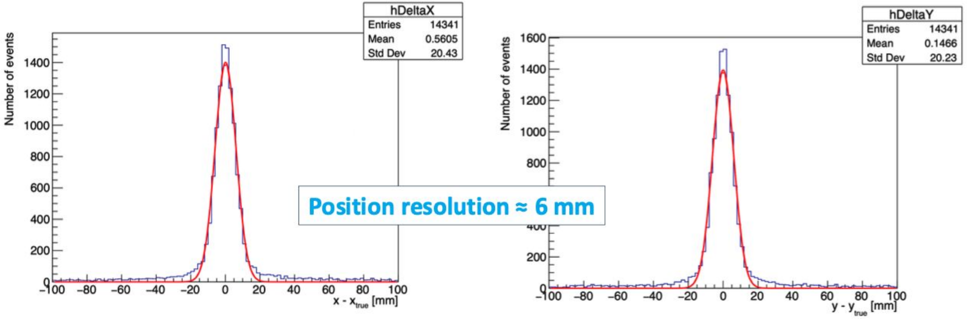


Energy resolution vs sensor coverage



Can achieve resolution of σ/μ=1.5% (Crystal Ball fit). By Benjamin Davis-Purcell

Positron reconstruction & clustering identification in progress



Physics with the prototype

We might be able to do a exotic muon decay search: $\mu^+ \to e^+ e^+ e^- e^+ e^-$

- The SM decay has 2 neutrinos in it, this one would be BSM, involving an on-shell dark Higgs [1]
- Current limit is Br($\mu \to 5e$) < 4 x 10^{-6}
- Requires as uniform PMT coverage as possible

Simulation work is needed to decide the feasibility of this study

Compared to the previous experiment: the PIONEER prototype can improve by $\sim O(10^4 - 10^6)x$ in a 10 day run

Energy resolution 2%: 5x
Scint. Decay time : 5x
Timing resolution 100 ps : (50 x)
Pile-up recognition: 10x
Beam rate 50 kHz : 30 x
Run time 10 days: 10 x
Analysis improvement factor: 3 x
Efficiency factor: 2x

From Doug Bryman

[1] Hostert et al. 2023, https://arxiv.org/pdf/2306.15631

LP simulation analysis details

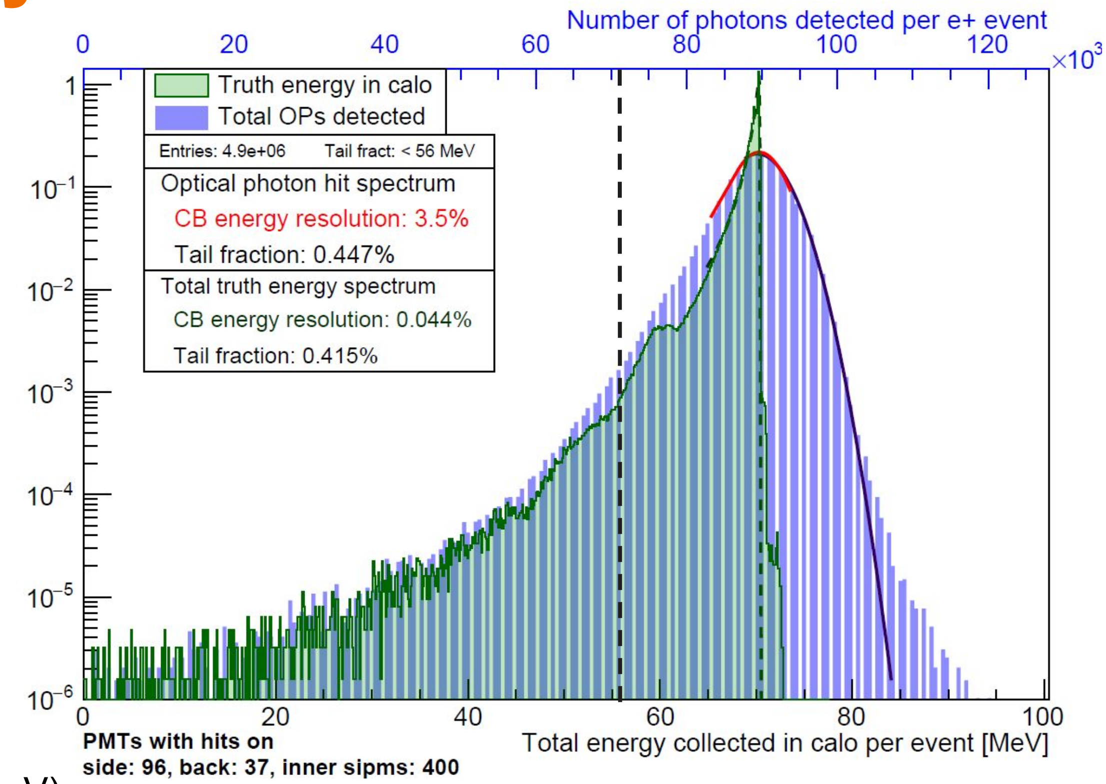
Green: Truth energy deposits in calo
→ Monte Carlo only

Blue: Optical photons detected scaled to match energy peak
→ Still oversimplified compared to real data

Red: Crystal Ball function fit to peak region, resulting in σ & μ values

Energy resolution = σ/μ

$$\text{Tail fraction} = \frac{\sum(\text{events with energy} < 56\text{ MeV})}{\sum(\text{all events})}$$



LP simulation results for $5\text{x}10^6$ positron events