Status of PIONEER@PSI

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PIONEER Collaboration

Workshop on "Flavour changing and conserving processes" 2022

September 24, 2022

Pion decays back then

Theory of the Fermi Interaction

R. P. Feynman and M. Gell–Mann
California Institute of Technology, Pasadena, California
(Received September 16, 1957)

Experimentally[16] no $\pi \rightarrow e + \nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.

Pion decays now

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

$$= (1.23524 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%) \quad \text{(SM)}$$
$$= (1.2327 \pm 0.0023) \times 10^{-4} \quad (\pm 0.187\%) \quad \text{(exp.)}$$

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- One of the most precisely known observable involving quarks in the SM!
- Experimental uncertainty 15x larger than theoretical!

A new experiment

Physics cases for a new R^{π} measurement:

- Testing Lepton Flavor Universality
  - Several tensions in flavour sector
  - μ g-2, B decays, CKM unitarity

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  - R^{π} extremely sensitive to new (pseudo)scalar couplings (e.g. charged Higgs, heavy neutrinos, ...)

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  - μ g-2, B decays, CKM unitarity
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Physics cases for a new π beta decay measurement:

- Testing CKM unitarity via V_{us}/V_{ud}
- Direct determination of V_{ud}

PIONEER

Goals:

- measure R^{μ} to 0.01 % relative precision (Phase I)
- measure BR($\pi^+ \rightarrow \pi^0 e^+ \nu$) to 0.2 % (Phase II)
- measure BR($\pi^+ \rightarrow \pi^0 e^+ \nu$) to 0.06 % (Phase III)

PIONEER

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Needs high intensity π^+ beam (Phase 1: $3 \times 10^5\,\mathrm{s}^{-1}$, Phases II/III: $2 \times 10^7\,\mathrm{s}^{-1}$)

PIONEER

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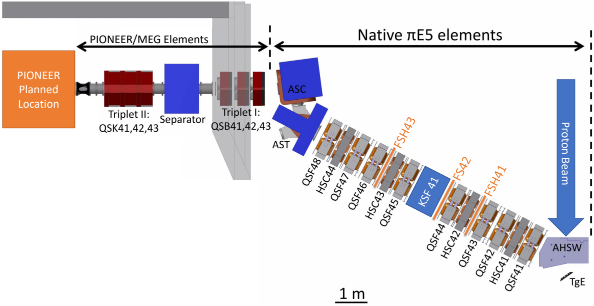
Phase I approved to run at PSI
(Proposal: https://arxiv.org/abs/2203.01981)

Beam Requirements

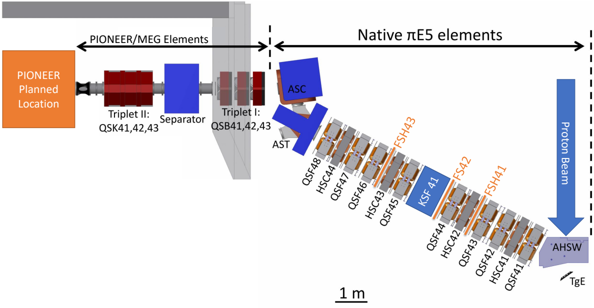
- Momentum: 65 MeV/c
- Rate: $> 300\,000\ \pi^+/s$
- Beam Size: $\sigma_x, \sigma_y < 10\,\mathrm{mm}$
- Momentum Bite: $dp/p < 2\,\%$
- Contamination: $< 10\,\%\ e, \mu$

PiE5 @ PSI



P. Schwendimann

PiE5 @ PSI



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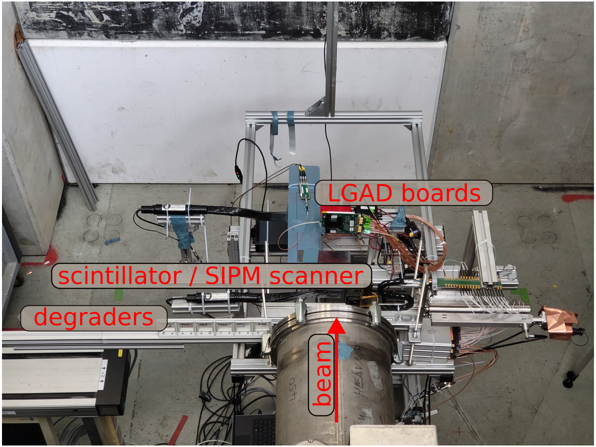
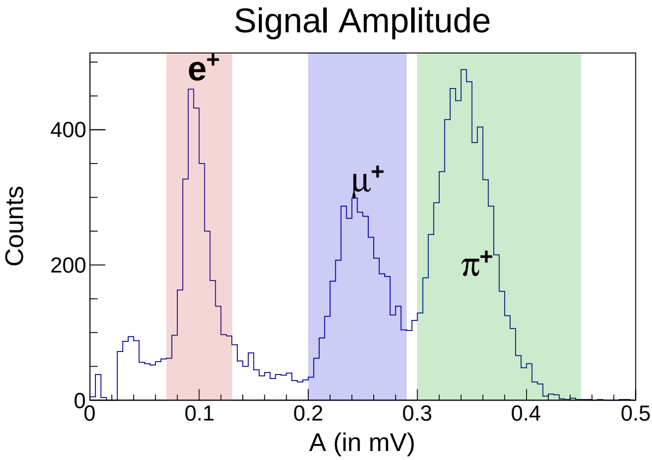
Currently in shared use by MEG II and Mu3e experiments

Test beam time May 2022



Test beam results I



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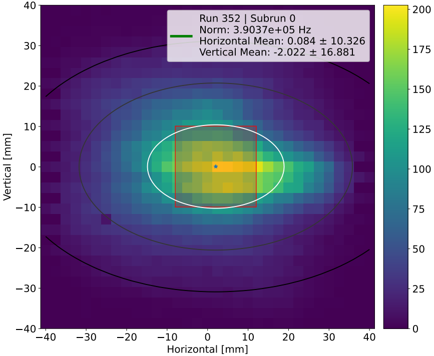
Test beam results II



Pions

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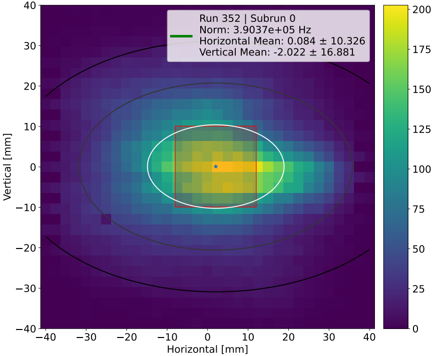
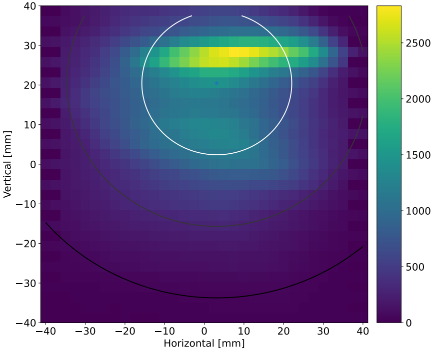
Test beam results II



Pions



Full beam

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- Momentum: 65 MeV/c: ✓
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Some more work to be done on beamline

$$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$: how is it measured?

($\mu \to e\nu\bar{\nu}$)

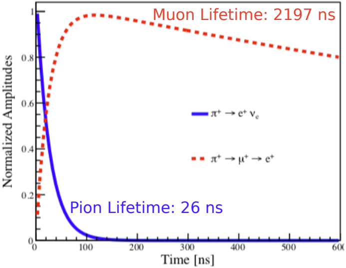
What π decay to "normally": $B(\pi^+ \to \mu^+\nu(\gamma)) = 0.999877 \pm 0.0000004$

Helicity suppressed decay: $B(\pi^+ \to e^+\nu_e(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}$

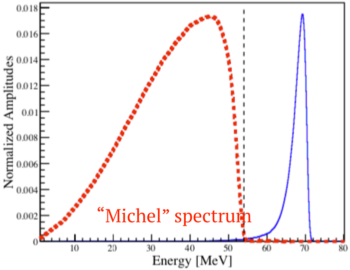
Pion β decay: $B(\pi^+ \to e^+\nu_e\pi^0) = (1.036 \pm 0.006) \times 10^{-8}$

Measure precisely e^+ energy spectrum and $t_{e^+} - t_{\pi^+}$

$\Longrightarrow$ different time and energy spectra - discrimination between the two decays



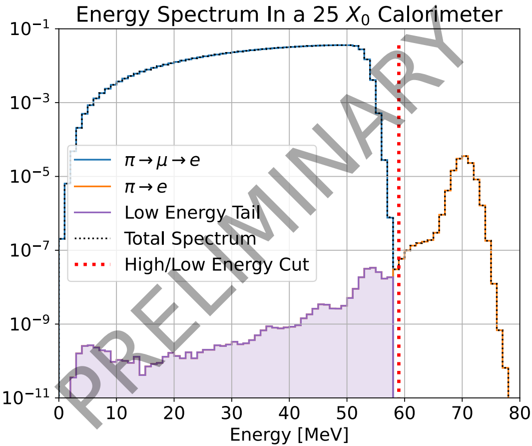
Time spectrum



e^+ energy spectrum

C. Malbrunot

The low energy tail



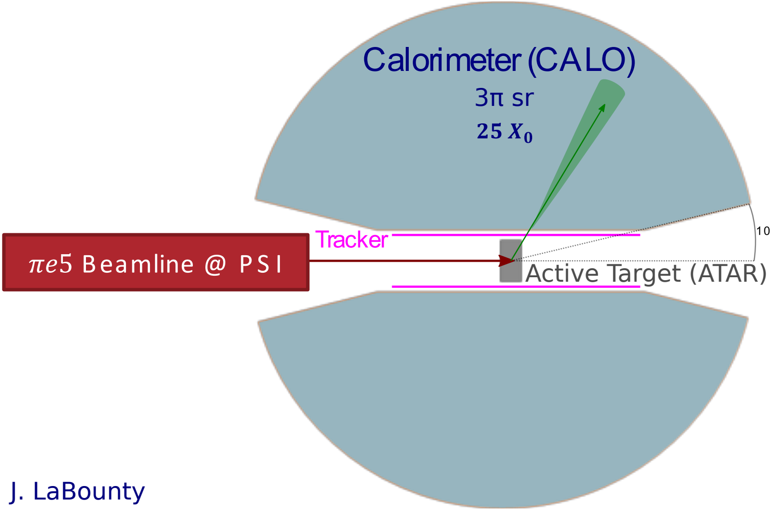
The low energy tail II

Main systematic effect:
Low energy tail of positron spectrum from $\pi \rightarrow e\nu$

Caused by:

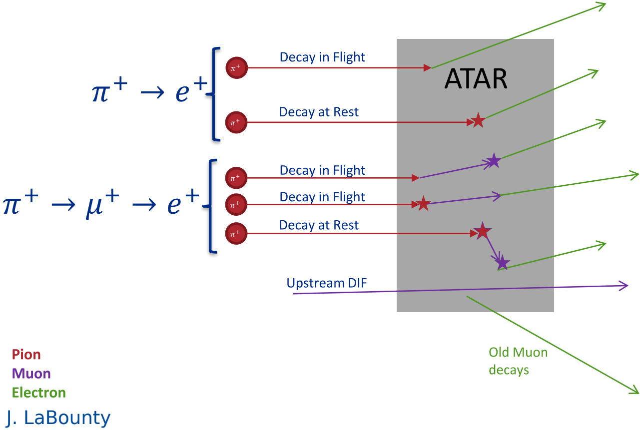
- finite energy resolution
- energy loss in dead material
- shower leakage
- geometrical acceptance
- radiative decays
- PIENU experiment: photo-nuclear interactions (^{127}I(γ,n))
- ...

Apparatus overview



J. LaBounty

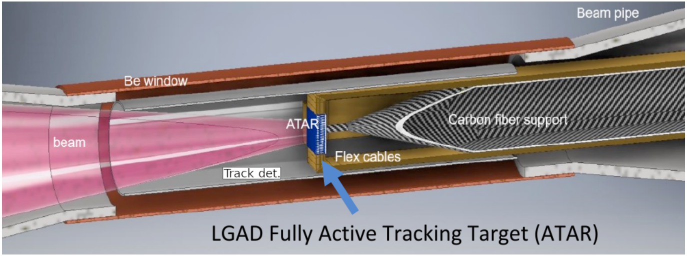
ATAR



- High longitudinal segmentation
- As little material as possible
- Fast collection time
- Large dynamic range

ATAR Hardware (preliminary)

- Stack of low gain avalanche diodes (LGADs)
- 48 layers, 120 μm thickness per layer
- 100 strips per layer, 20 mm length, 200 μm pitch
- 20 mm x 20 mm area
- read out using flex cables to the side, then back
- Development led by UC Santa Cruz

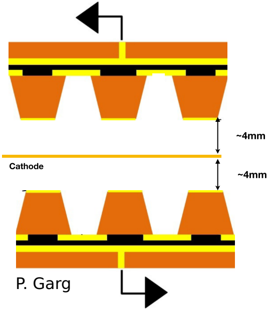


Tracker

- Correlation of ATAR hit to CALO shower
- High speed
- As little material as possible

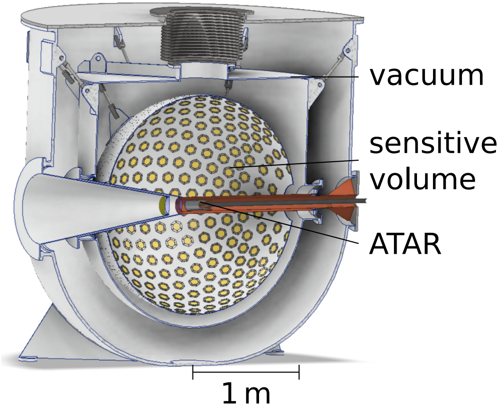
Preliminary concept:

- Cylindrical 2-layer Resistive Micro Well (μRWELL)
- Development led by Stony Brook University



P. Garg

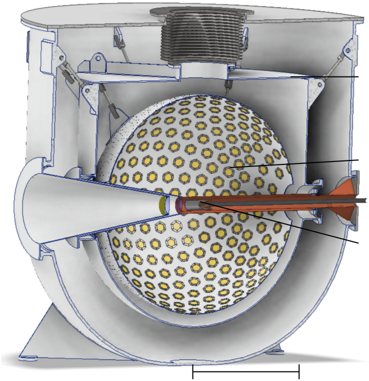
Liquid Xenon Calorimeter



Liquid Xenon:

- fast (∼40 ns decay)
- homogeneous
- high resolution

Liquid Xenon Calorimeter



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Conceptual design:

- 9 t of lXe
- ∼1000 channels

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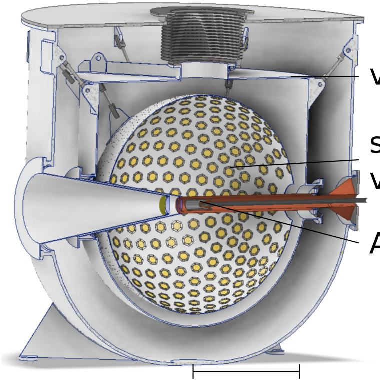

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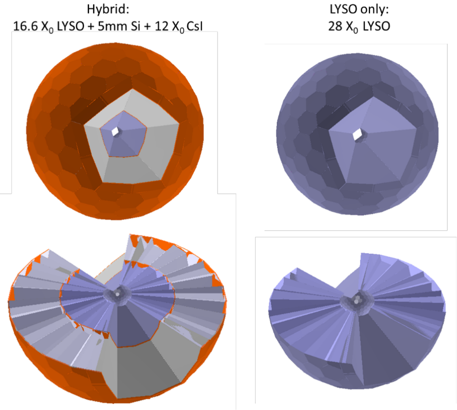
Challenges:

- 9 t of lXe!
- Price!
- Segmentation
- VUV photo sensors

CALO crystal alternative

LYSO or combined LYSO/CsI

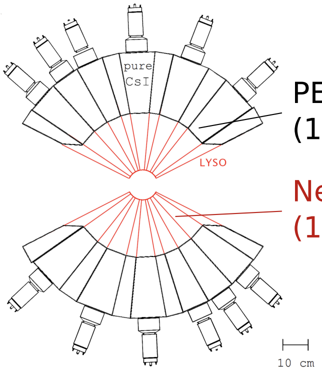


<u>Advantages</u>:
- Not cryogenic
- fast response
- “natural segmentation”

<u>Question marks</u>
- energy resolution
- possible to make long crystals?
- cost

C. Malbrunot

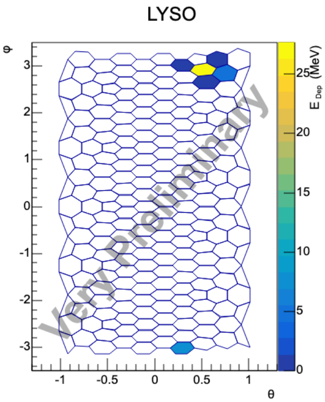
Why the hybrid idea?

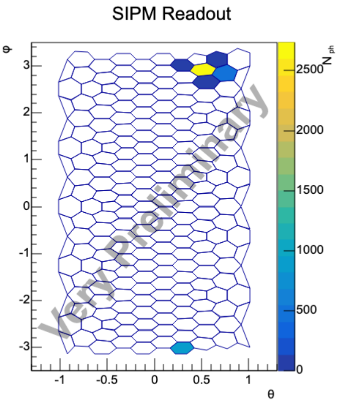


- PEN calorimeter still at PSI
- LYSO length more realistic
- inner volume possibly large enough for ATAR, Tracker + LYSO

P. Schwendimann

Simulations





43 MeV/c Positron as seen in LYSO

P. Schwendimann

PIONEER Collaboration

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[25] University of Victoria
[26] Inst. Div, BNL

more collaborators welcome!

Summary

- Pion decay: long history of challenging the SM
- PIONEER: Major new pion decay experiment pushing state of the art technology into low energy precision physics
- Goals:
  - R^π at 0.01 %
  - Pion beta decay at 0.06 % (in 2 steps)
- Approved to run at PSI, first test beam time just finished
- Time scale: 10-15 years
- New collaborators welcome!