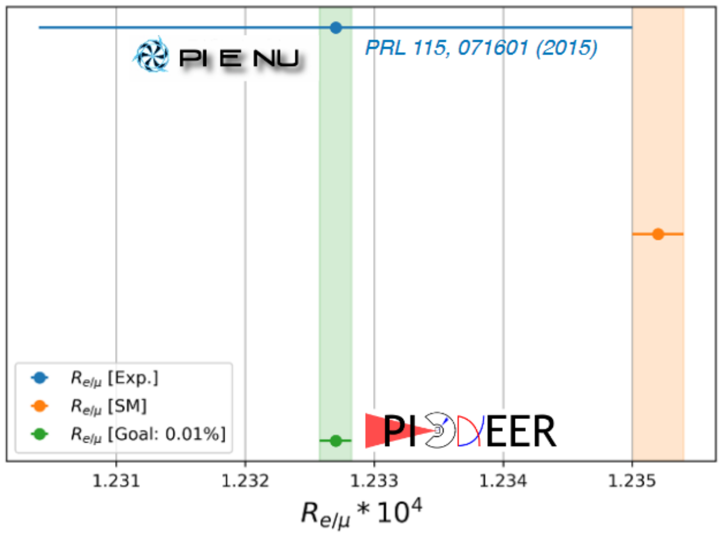
PIONEER

A next generation rare pion decay experiment

P. Kammel for the PIONEER collaboration



https://arxiv.org/abs/2203.01981

A. Adelmann,[1] W. Altmannshofer,[2] S. Ban,[3] O. Beesley,[4] A. Bolotnikov,[5] S. Braun,[4] T. Brunner,[6] D. Bryman,[7,8] Q. Buat,[4] L. Caminada,[1] J. Carlton,[9] S. Chen,[10] M. Chiu,[5] V. Cirigliano,[4] S. Corrodi,[11] A. Crivellin,[1,12] S. Cuen-Rochin,[13] J. Datta,[14] B. Davis-Purcell,[8] K. Dehmelt,[14] A. Deshpande,[14,5] A. Di Canto,[5] L. Doria,[15] J. Dror,[16] P. Fischer,[17] S. Foster,[9] K. Frahm,[17] P. Garg,[14] G. Giacomini,[5] L. Gibbons,[18] C. Glaser,[19] D. Goeldi,[17] S. Gori,[2] T. Gorringe,[9] C. Hamilton,[8] S. Heinekamp,[1,17] C. Hempel,[8] D. Hertzog,[4] S. Hochrein,[17] M. Hoferichter,[20] S. Ito,[21] T. Iwamoto,[3] P. Kammel,[4] E. Klemets,[8,7] K. Labe,[18] J. Labounty,[4] U. Langenegger,[1] Y. Li,[5] C. Malbrunot,[8,6] A. Matsushita,[3] S. M. Mazza,[2] S. Mehrotra,[14] S. Mihara,[22] R. Mischke,[8] A. Molnar,[2] T. Mori,[3] T. Numao,[8] W. Ootani,[3] J. Ott,[2] K. Pachal,[8] D. Pocanic,[19] X. Qian,[5] D. Ries,[1] R. Roehnelt,[4] T. Rostomyan,[1] B. Schumm,[2] P. Schwendimann,[4] A. Seiden,[2] A. Sher,[8] R. Shrock,[14] A. Soter,[17] T. Sullivan,[23] E. Swanson,[4] V. Tishchenko,[5] A. Tricoli,[5] T. Tsang,[5] B. Velghe,[8] V. Wong,[8] M. Worcester,[5] E. Worcester,[5] C. Zhang,[5] and Y. Zhang[5]

[1] *Paul Scherrer Institute* [2] *University of California Santa Cruz* [3] *The University of Tokyo* [4] *University of Washington* [5] *Brookhaven National Laboratory* [6] *McGill University* [7] *University of British Columbia* [8] *TRIUMF* [9] *University of Kentucky* [10] *Tsinghua Universtiy* [11] *Argonne National Laboratory* [12] *University Zurich* [13] *Tecnologico de Monterrey* [14] *Stony Brook University* [15] *Johannes Gutenberg University* [16] *University of Florida* [17] *ETH Zurich* [18] *Cornell University* [19] *University of Virginia* [20] *University of Bern* [21] *Kitakyushu College* [22] *KEK* [23] *University of Victoria*

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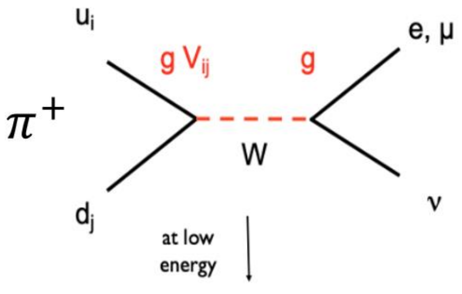
Universality, Unitarity and Rare Pion Decay

Charged currents are mediated by the exchange of W boson between left-handed fermions

- The gauge coupling is the same for all fermions



$$G_F^\beta \sim \frac{g^2 V_{ij}}{M_W^2} \sim G_F^\mu V_{ij}$$

PIONEER Phase I

Lepton Flavor Universality

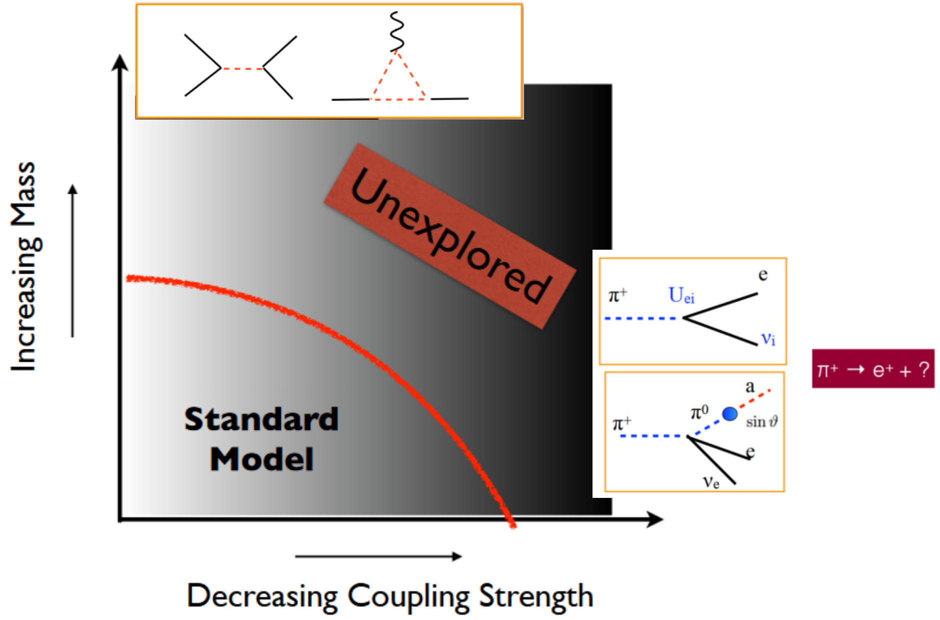
$$[G_F^\beta]_e \,/\, [G_F^\beta]_\mu = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

CKM Unitarity

PIONEER Phase II

new physics searches



- PIONEER will test these fundamental properties for both leptons and quarks

- and will also search for weakly coupled particles

Additional motivation from existing flavor anomalies

- Muon g-2
- Cabibbo angle anomaly
- hints in B decays

Physics Case I: Precision Test of Lepton Flavor Universality

- Pion decay ratio $R_{e/\mu} = \frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}$

$R_{e/\mu}(Exp) = 1.23270(230) \times 10^{-4}$ (0.18%)
$R_{e/\mu}(SM) = 1.23524(015) \times 10^{-4}$ (0.01%)

$$\frac{g_\mu}{g_e} = 1.0010 \pm 0.0009$$

PIENU at TRIUMF
Cirigliano & Rosell

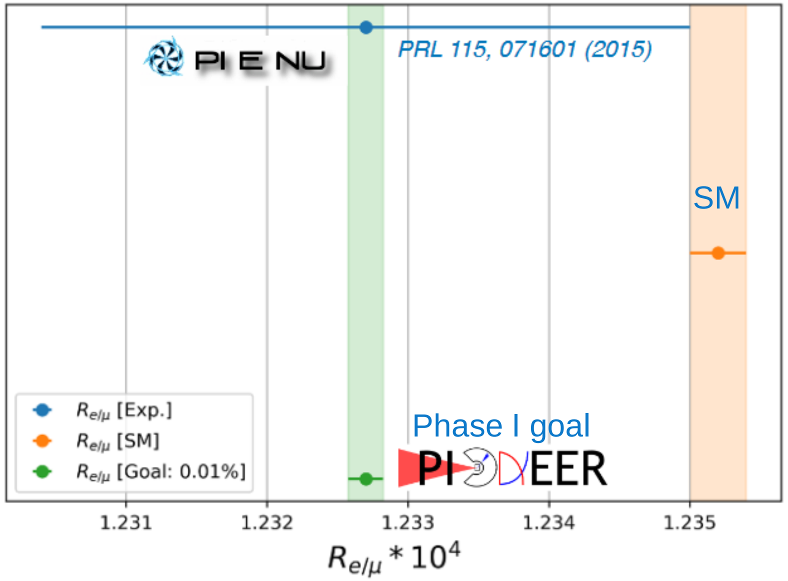
- Very high precision SM prediction theory 15x more precise than experiment

$$R_{e/\mu} = \frac{\Gamma[\pi \to e\nu(\gamma)]}{\Gamma[\pi \to \mu\nu(\gamma)]} = \left|\frac{g_e}{g_\mu}\right|^2 \frac{m_e^2}{m_\mu^2} \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 (1 + \text{EW corrections})$$

LFU | **helicity suppression** | phase space | 0.01 % uncertainty in NNLO EFT calculation

- Clean, generic way to search for new physics reaching 0.01% precision level for the first time

- PIONEER goal



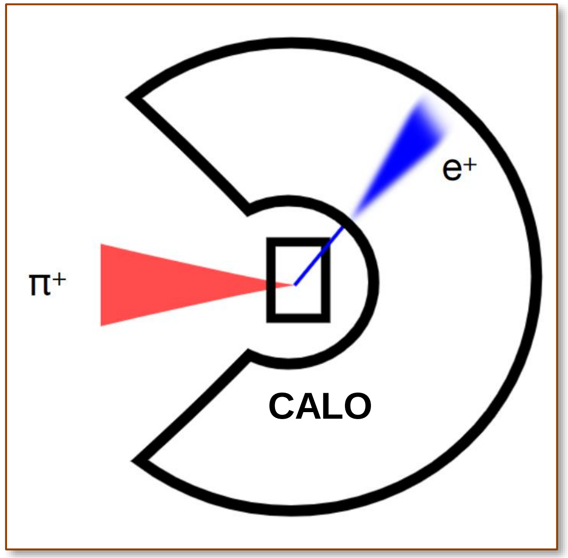
- PIONEER physics reach
  - unprecedented LFU sensitivity 10^{-4}
  - many BSM scenarios exist
    - $Wl\nu$ coupling, 4-fermion operators
  - sensitive to high mass scales
    - ~30-1000 TeV pseudoscalar
    - ~ 30 TeV axial-vector

Basics of $R_{e/\mu} = \frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}$ measurement

	m(MeV)	τ(ns)
π	139.6	26.03
μ	105.7	2197

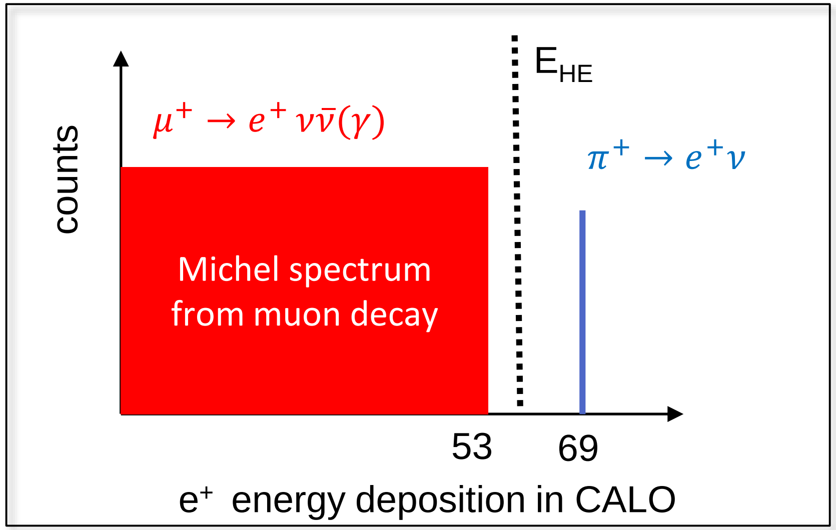
Pion stops in the target

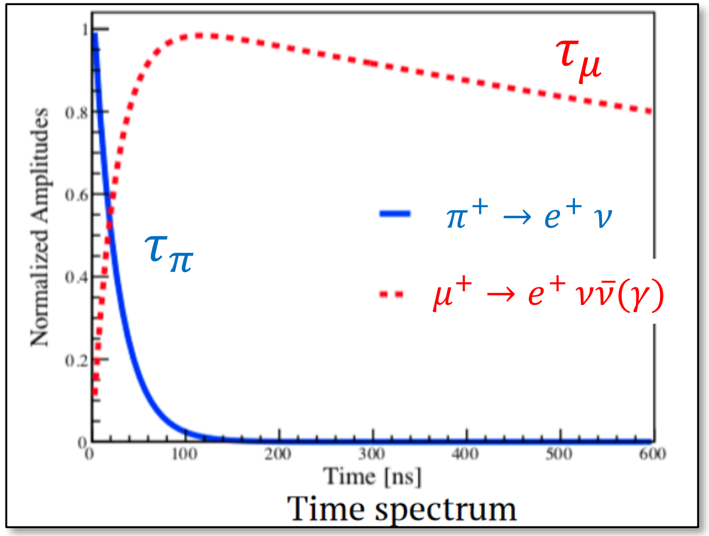
- $\pi^+ \to e^+\nu(\gamma)$ $\mathbf{1.23\times10^{-4}}$
- E_e = 69.8 MeV



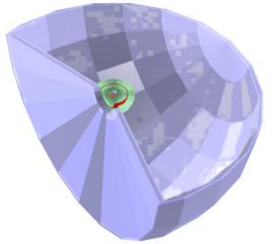
Pion stops in the target

- $\pi^+ \to \mu^+\nu(\gamma)$ **99.99%**
  $\mu^+ \to e^+\nu\bar{\nu}(\gamma)$ **100 %**
- E_e = 0.5-52.8 MeV





Reality with state-of-the art detector

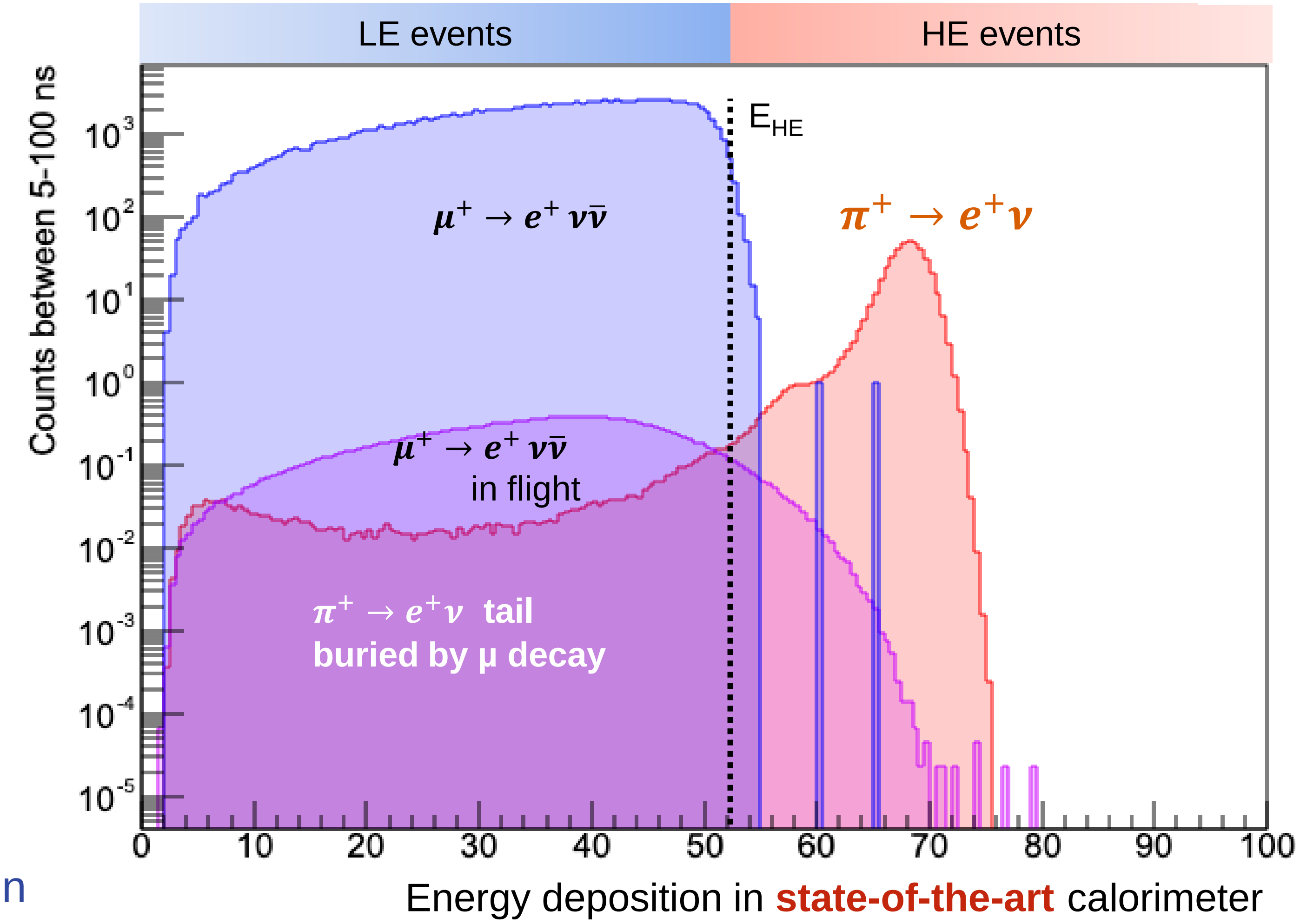


Separate energy spectrum
at E_{HE} ~ 52 MeV

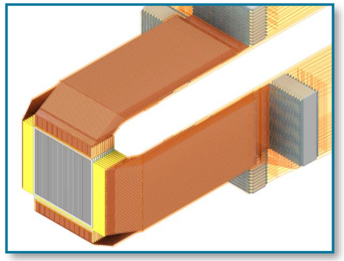
$$R_{e/\mu} \sim \frac{HE\ events}{LE\ events} \ ?$$

Take aways:

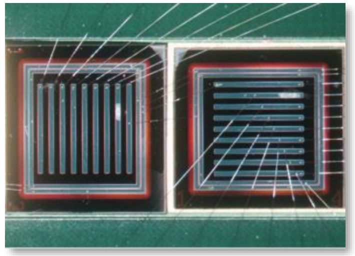
- significant rad. tail for $\pi^+ \to e^+ \nu$
  - reduce tail with deep CALO to O(1%)
  - measure tail in e^+ beam and in situ
- time spectra remain powerful for separation of event types
- information beyond CALO critical to suppress background @ 10^{-4} precision

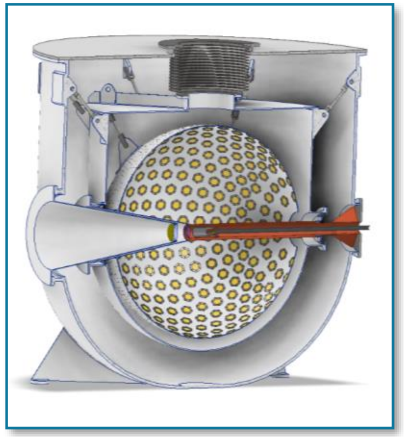


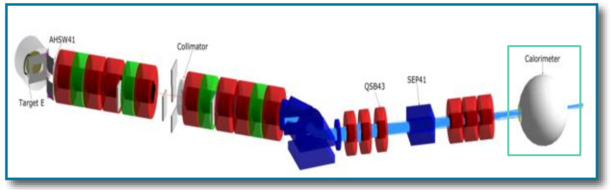
PIONEER strategy and components



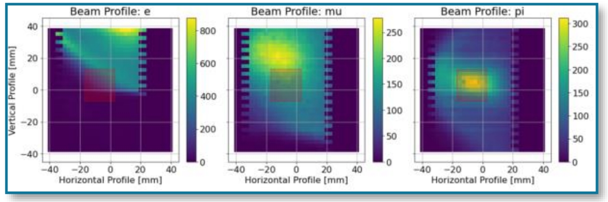
High granularity active target
(ATAR) made of LGAD sensors
BNL, UCSC, UW

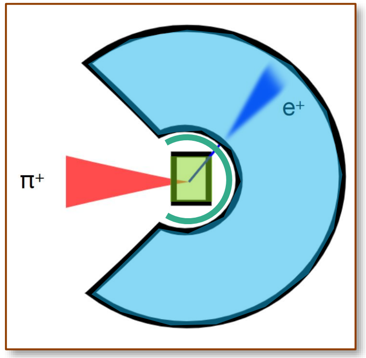




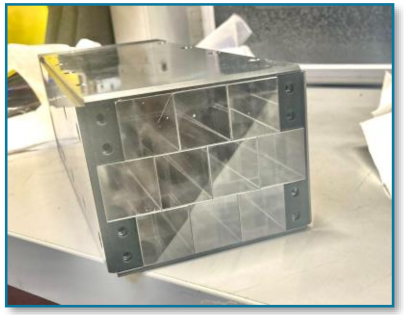


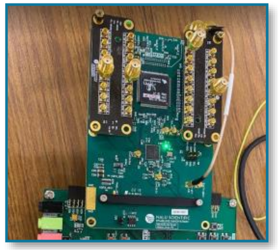
Develop PIONEER beamline,
beam design and machine learning
ETH, PSI, UW





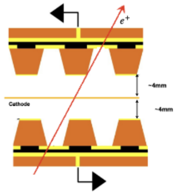
Fast, deep calo
Liquid Xe or LYSO
KEK, TRIUMF,UBC,
U.Tokyo, UW





FE and digitizer electronics
~500 channel CALO
~5000 channel ATAR
Cornell, UK, UCSC, UW
SBIR with companies planned

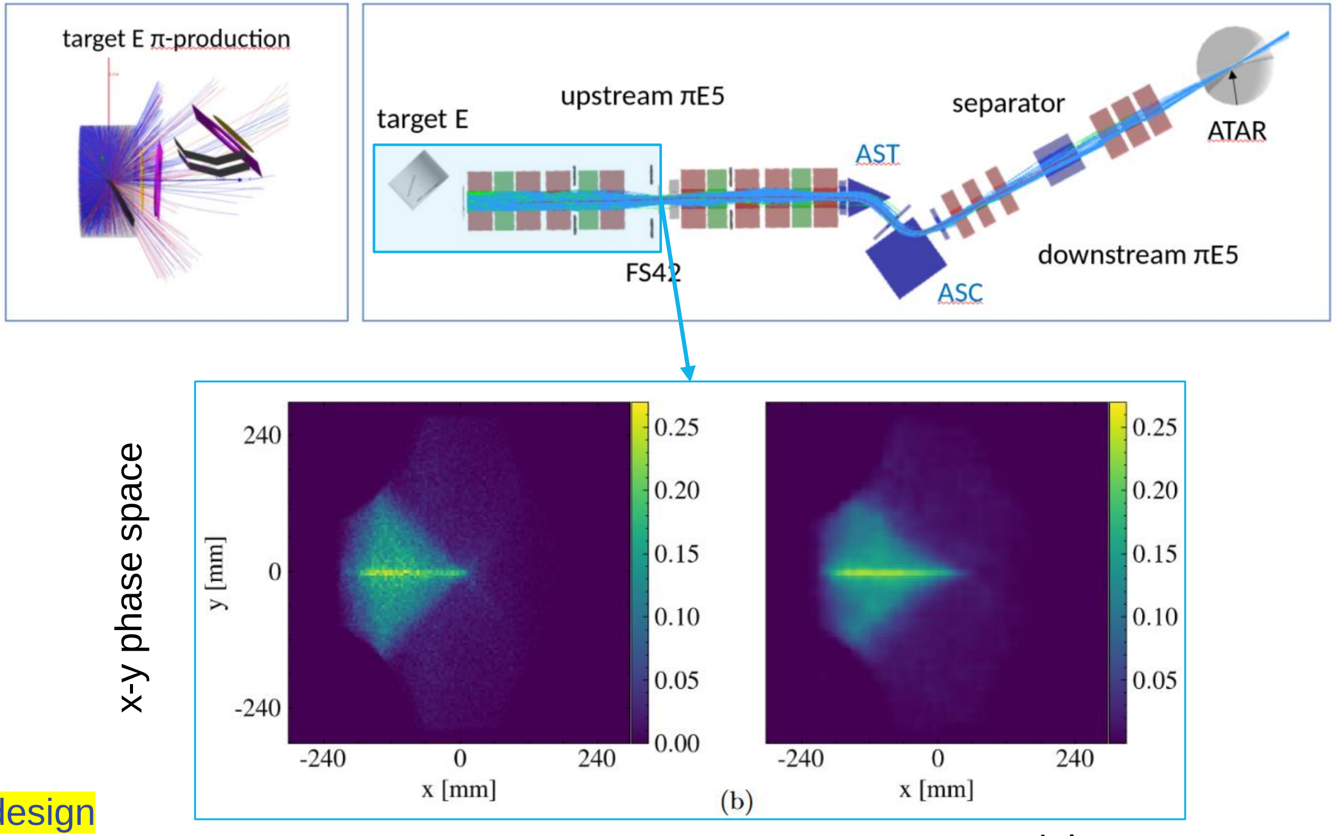
Tracker
μ-RWELL technology R&D
Stony Brook



Beam: piE5 @ PSI - World's Brightest Stopped Pion Beam

- Progress 2023
  - PIONEER requirements and test beam 2022 results
    - Rate: 300k π/s stopped in ATAR: ok at 65 MeV/c
    - Momentum bite: Δp/p <2%: marginal
    - Spot size: <2 cm FWHM: not achieved
    - μ,e less than 10% π: needs second focus extension
  - improved understanding and optimization
    - non-linear effects due to large phase space
    - beamline model with G4BL
    - novel promising machine learning approach (Adelmann et al)
- Plans 2024
  - machine learning
    - extend machine learning to full beam line
    - optimization of beam properties
    - prepare experimental verification
  - beam design
    - 2nd focus extension
    - better focus
    - retune for smaller Δp/p <2%

request PSI support in design



G4BL

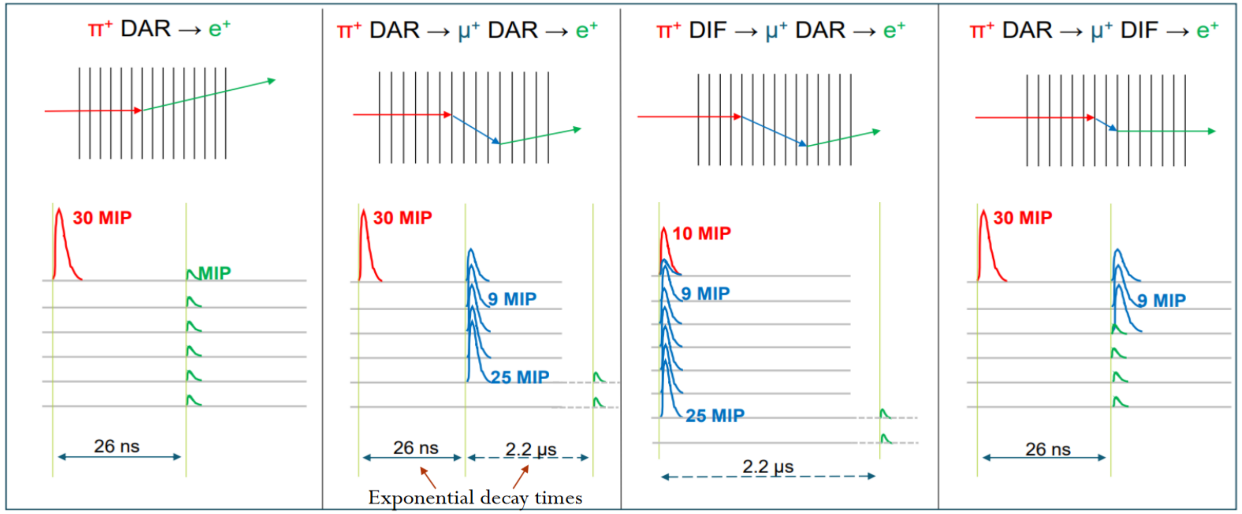
surrogate model
~ 10^4 faster

P. Fischer, Semester Project ETH

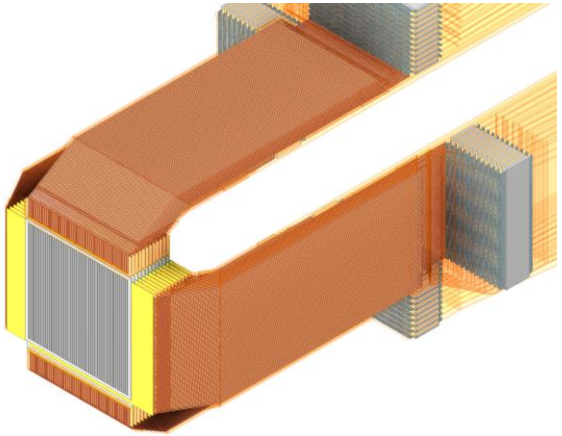
Active Target ATAR 5-D tracker is key to separate events

- Motivation
  - DAR decay at rest
  - DIF decay in flight

R_π ~ 4 mm, R_μ~ 0.8 mm



- Specs
  5-D tracker can provide rich information (x, y, z, t, E)
  - 20 x 20 x 5.76 mm
  - 48 sensor layers with 120 μm thickness, 200 μm strips
  - Δt ~ 200 ps, pulse pair 2 ns
  - $\sigma_E < 10\ \%$

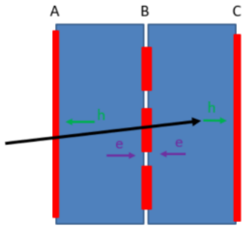


Early PIONEER design of Si detector stack

- Baseline Technology
  Low Gain Avalanche Diodes LGADs
  - High granularity sensors under development
    - AC LGADs most common
    - TI (trench isolated) LGADs favorable for PIONEER
  - Non-linear for large dE/dx due to gain saturation
    - PIN diodes explored as alternative

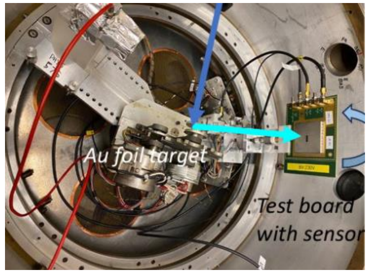
ATAR R&D

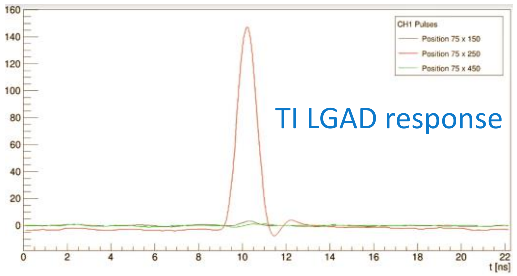
- Development directions
  - optimal customized PIONEER sensor
    - fully depleted 120 µm sensor, double sided with new stacking idea
    - minimal cross talk, small gain saturation, large dynamic range
  - Interface and Electronics
    - frontend chips and board, digitizer for 5000 channels
  - Integration into stack with minimal dead material



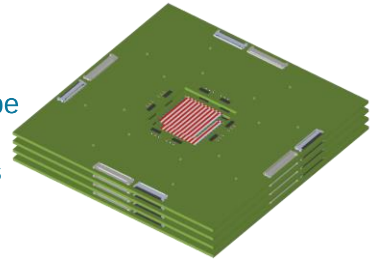
Double sided stacking

CENPA test with protons





ATAR prototype
1/3 sensors
1/9 electronics



- Progress 2023
  - Sensors
    - First production of double-sided strip sensors at BNL
      more information and clean stacking
    - LGAD energy resolution measured in the SSRL X-ray beam line
      (https://dx.doi.org/10.1088/1748-0221/18/10/P10006)
    - LGAD gain saturation studied with protons at CENPA
      (https://indico.cern.ch/event/1184921/contributions/5574780/)
    - New AC-LGAD showed reduced charge sharing
      (https://indico.cern.ch/event/1184921/contributions/5574830/)
  - Electronics
    - First prototype multi-sensor front end board design ready for production
    - Characterization of FAST chip and AS-ROC alternative chip
      (https://indico.cern.ch/event/1255624/contributions/5445271/)

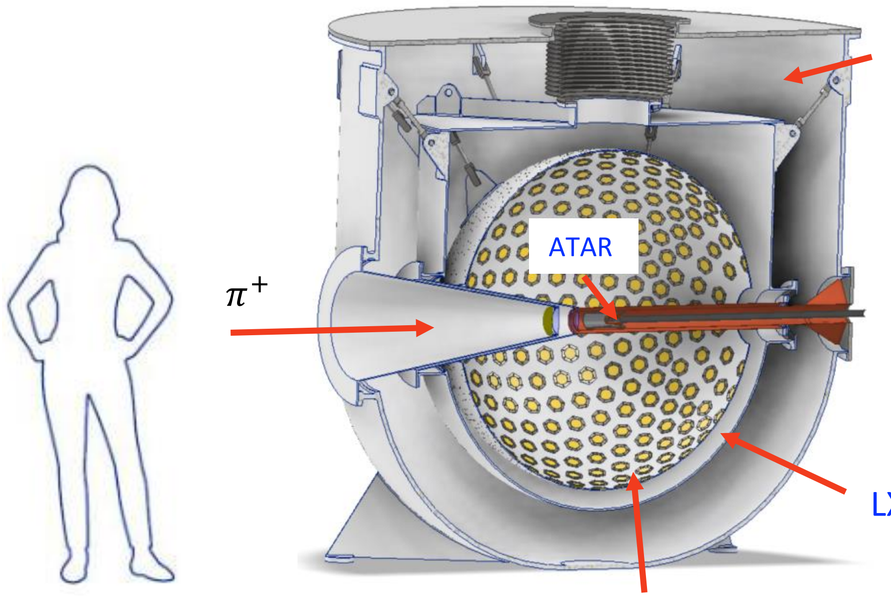
- Goals 2024
  - Sensors
    - Characterization of new BNL sensors and
      new production based on tests and TCAD simulations
    - Characterization of TI-LGADs and thicker LGADs from FBK
    - Acquisition of thin, double-sided Silicon sensors from Micron
    - Study of new LGAD devices with test beams at SSRL and at CENPA
    - Conclude analysis of the PSI test beam data
  - Electronics/Integration
    - multi-sensor FEB testing with sensors, towards sensor stack
    - Double LGAD. Two sensors close packed and insulated by parylene
    - Fabrication of improved flexes after tests and simulation
    - Testing readout chips for low-noise PIN readout

Powerful LXe CALO is Baseline Design

- Specifications
  - i. ~3π coverage, high uniformity
  - ii. fast: sub-ns timing, ~40 ns decay
  - iii. resolution
    - 1.5-2% peak resolution
    - ~20 radiation length X_0 for tail suppression
  - iv. pile-up separation, segmentation ?

  LXe fulfills requirements i-iii
  (demonstrated by MEG 900L calo)

- Conceptual design
  - ~ 7t LXe in vacuum isolated dewar
  - entrance windows Be or Ti
  - service and disassembly possible
  - infrastructure from MEG



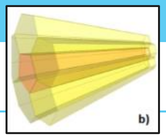
forward cone closed now
- direct e^+ beam calibration
- reduced side leakage

Alternative crystal (LSYO) CALO R&D

simple infrastructure

Detector	Density g/cm^3	dE/dx MeV/cm	X_0 cm	R_M cm	Decay time ns	λ_{max} nm	Light output %
LXe	2.953	3.707	2.872	5.224	~~3, 27,~~ 45	178	100
LSO(Ce)	7.40	9.6	1.14	2.07	40	402	85

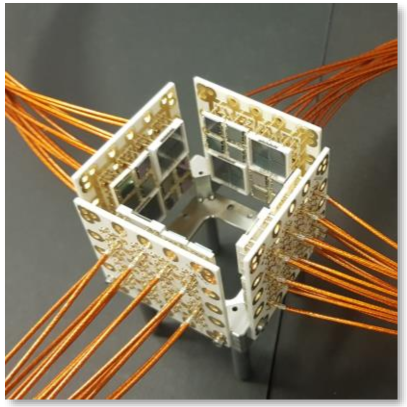
Property	LXe	LYSO
Resolution	1.8%	4% !
Segmentation	R&D	natural
Photosensors	VUV	standard
Experience	MEG	mainly small Xtal for PET



Progress / Plans on LXe R&D and prototyping

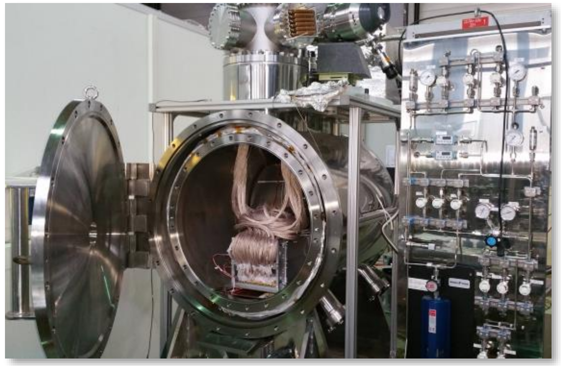
- LoLX @ McGill (2 L)   nEXO
  - small and versatile test LXe test set-up
  - goals
    - photosensor performance (SiPM and VUV PMT)
    - separation of scintillation and Cherenkov light with optical filters

Photosensor assembly built at TRIUMF



- plans 2024
  - upgrade with a recirculation pump and purity monitor
  - add optical filters for IR/Cherenkov detection
  - continue developing Chroma optical photon transport for validation

- MEG large LXe prototype (~120 L)
  - aim for test beam in 2025
  - goals
    - measure energy resolution and detector line shape including contribution of photonuclear reactions
    - study effect of optical coating on energy resolution, optical segmentation, benchmark simulations



envisioned sensitive volume
L= 20 X_0 (~60 cm)
R= 25 cm

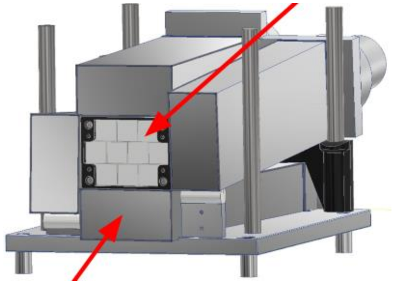
- plans 2024
  - purchase/acquire remaining 80 L of xenon
  - construction of inner photosensor assembly and commissioning (outside of cryostat) at TRIUMF
  - upgrade gas handling, purification and storage system
  - new cryostat windows

Successful LYSO Test Run at PSI

- LYSO Test run at PSI (πM1 Nov 2024)
  - scan 10 crystal array with e^+ beam, 30-100 MeV
  - demonstrate resolution
  - measure backscattering albedo
- Results
  - LYSO energy resolution ~1.8% at 70 MeV
  - Longitudinal uniformity better than 3%

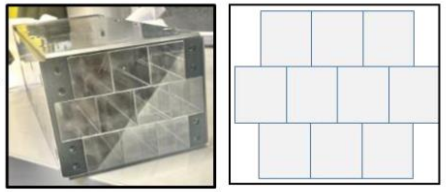
    This would smear the resolution for a LYSO PIONEER CALO by less than 0.25% (so it is a minimal contribution)
- Plans 2024
  - value engineering
    - calo inner radius and X_0
  - tapered prototype
  - realistic costing

10x LYSO
2.5x2.5x18 cm^3



NaI(Tl) as tail catcher

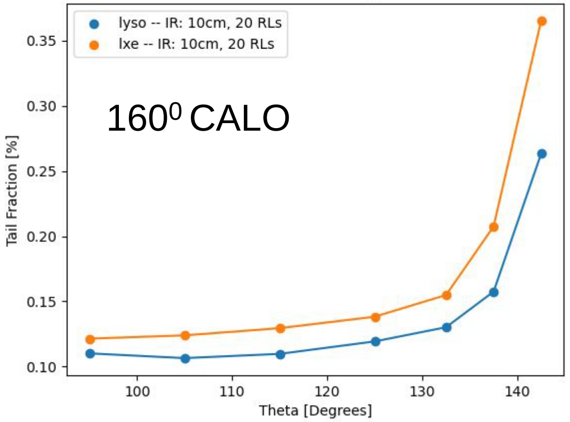
new SICCAS crystals

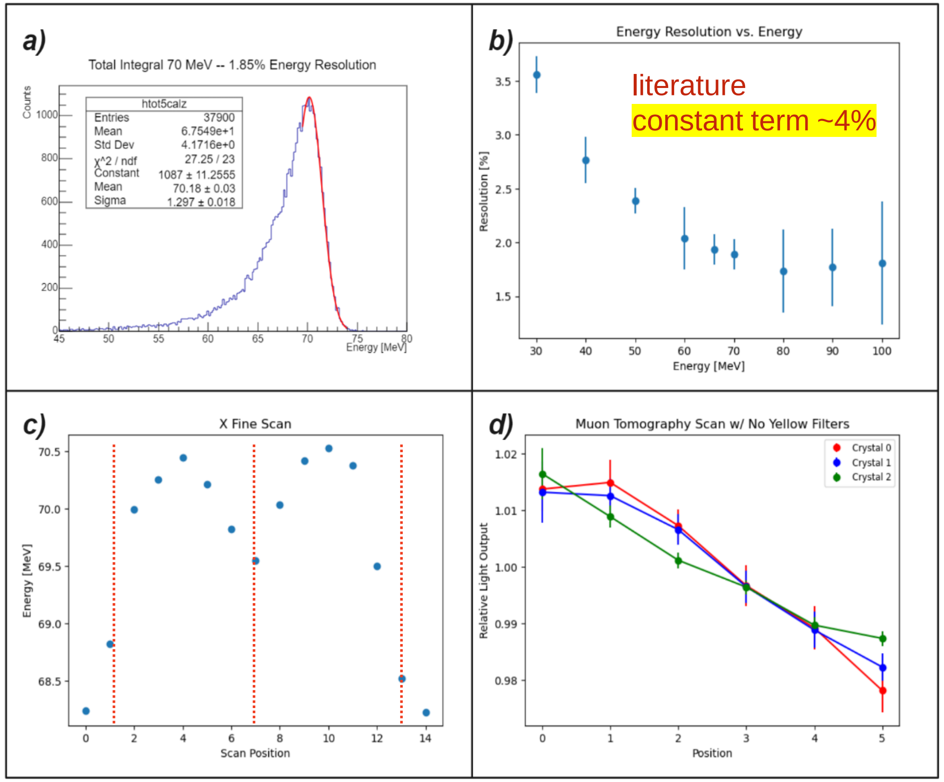


10-element LYSO array

Calorimeter on x-y table with upstream beam telescope

X_0=20 R_i=10 cm



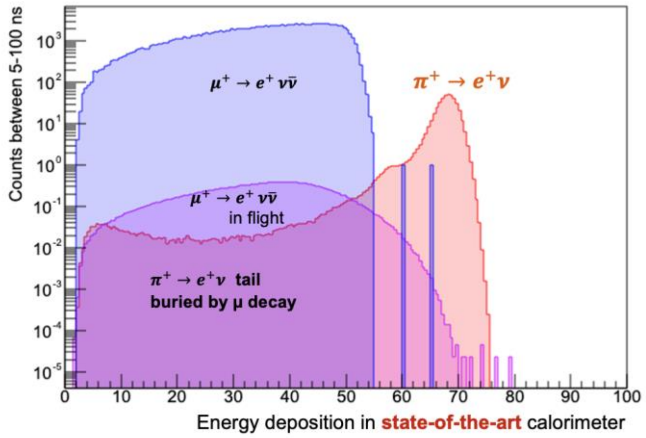


preliminary

Simulation and Analysis: ATAR powerful in background and tail suppression

- $\pi \to e\nu$ tail suppression

daring the impossible



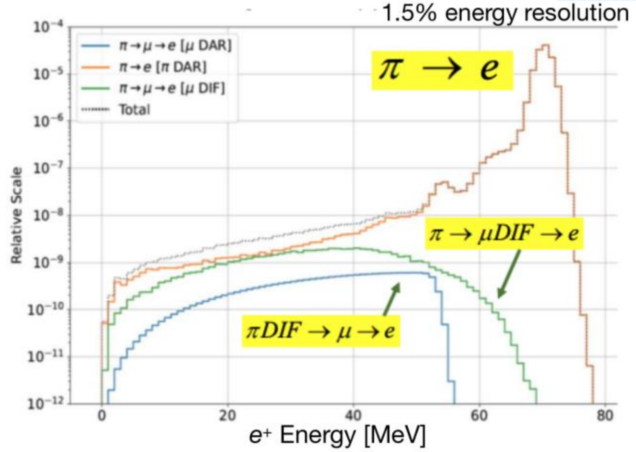
t_e within 2-32 ns
50x suppression

- pion stopping plane position
- plane position with max E
- total energy deposit
- goodness of linear track fit in x- & y-orientation
- individual energy deposits in the last five planes before the pion stopping plane

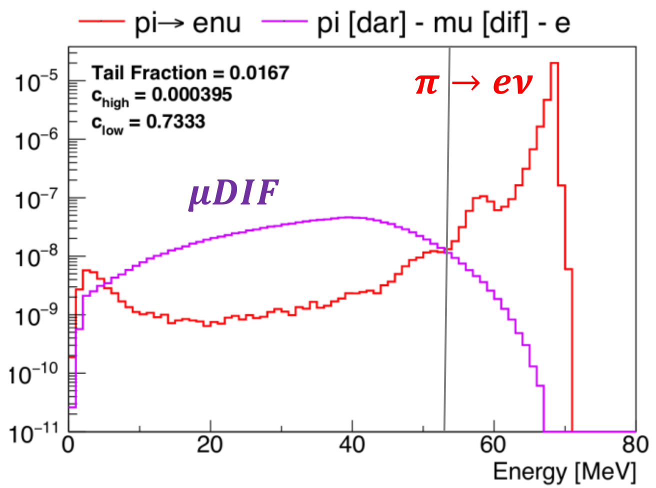
650x suppression

XGBoost

PIONEER analysis, Wong

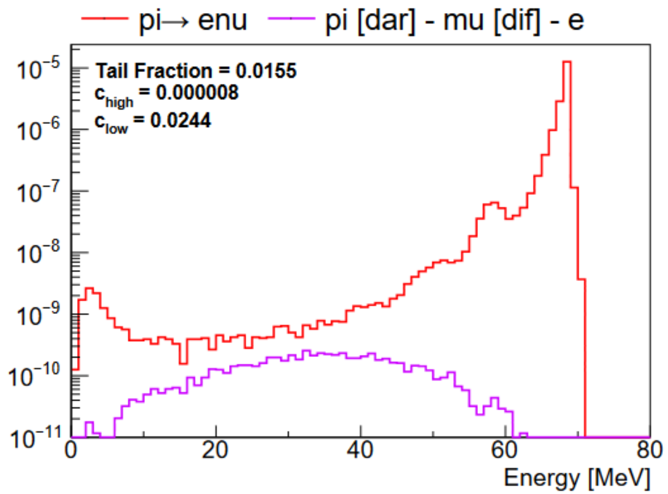


- μ decay in flight suppression



PIONEER analysis, Buat

- ΔE in first μ pixel
- π z-position with dE/dx
- ...



Prelim analyses to be confirmed with full detector model

Summary

PIONEER

- Exiting physics to be explored with PIONEER
  - Lepton Flavor Universality Violation
    - pushing the discovery limit by one order of magnitude
    - probing very high mass scales, up to 1000 TeV
    - possible connection to existing flavor anomalies
  - Typically factor 10 improved sensitivity in Exotic Physics Searches

Important past dates

2022 Approved with high priority by PSI PAC

2022 Snowmass Whitepaper

2022-23 Endorsed and aligned to
Fundamental Symmetries, Neutrons and Neutrino Whitepaper
and NSAC Long Range Plan

- PIONEER status and plans
  - a growing international collaboration (HEP, NP, instrumentation, theory)
  - experimental challenges requiring state-of-the-art technology are actively being investigated
    - Intense and well focused stopped pion beam
    - 5-D tracking in a compact active target
    - Very high resolution, deep and fast EM calorimeter
    - Advanced trigger, digitization, DAQ
    - Simulation is key in design and analysis
  - 2024
    - Continued R&D to validate technology choices and define experimental baseline and alternatives

Exciting times with a brand-new experiment with many concepts still on the drawing board, **and new ideas, expertise and collaborators are very welcome!**