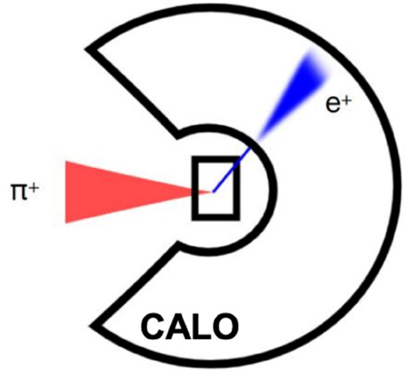
PIONEER: A next-generation rare pion decay experiment

David Hertzog / University of Washington



- Physics Goals
- Experimental Concept and Innovative Solutions
- Technical Progress and Status

* (non -official logo)

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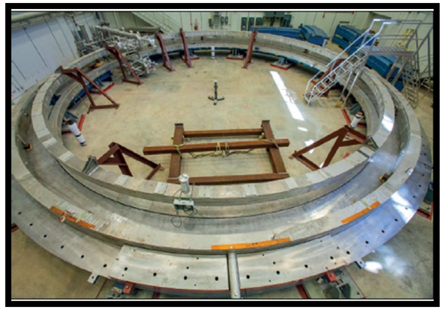
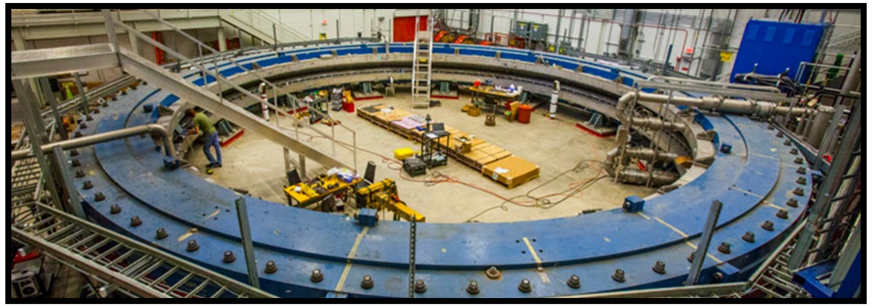
Some of us at a recent meeting in TRIUMF

Next Generation Muon (g-2)

Goal δa_μ ~ 140 ppb





FCCP in 2015 !! It all turned out quite well

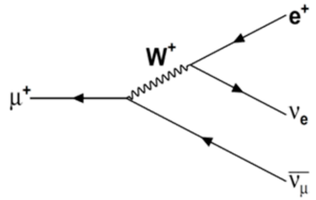
David Hertzog, University of Washington

for the E989 Muon (g-2) Collaboration

Lepton Flavor Universality

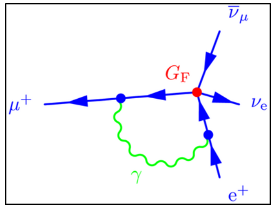
The weak interaction bare gauge couplings among leptons are the same e / μ / τ

- The weak-interaction "strength" is associated with the Fermi Constant, $\mathbf{G_F}$
- Muon decay provides the most precise measurement
  - Technically it determines $\mathbf{G_\mu}$, which is usually just called $\mathbf{G_F}$ … because we believe in LFU



G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

$$\boxed{\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}\left(1 + q\right)}$$



PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (2013)

Questioning the validity of what others took to be true…

PHYSICAL REVIEW D, VOLUME 60, 093006

Fermi constants and "new physics"

William J. Marciano

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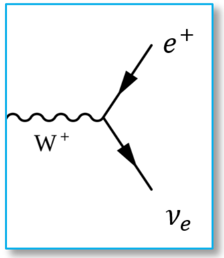
(Received 25 March 1999; published 7 October 1999)

Physics Case I: Precision Test of Lepton Flavor Universality

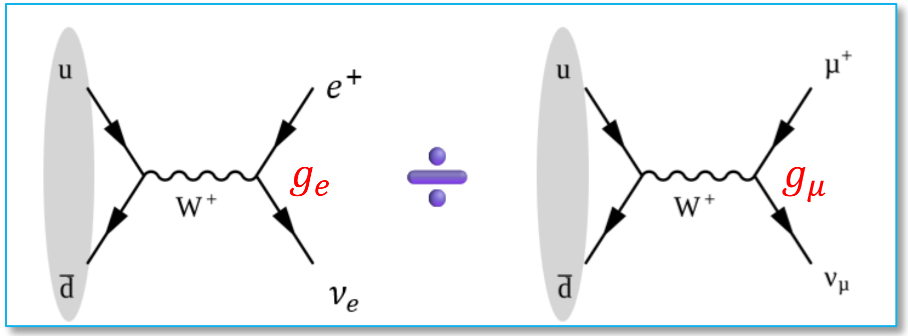
- Gauge coupling the same for all flavors
  - PIONEER will test this fundamental principle to 0.01%



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

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

PIENU at TRIUMF
Cirigliano & Rosell



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

  - The SM prediction is very precise!
    - →15x more so than experiment
    - Strong helicity suppression

$$R_{e/\mu} = \frac{\Gamma[\pi \to e\nu(\gamma)]}{\Gamma[\pi \to \mu\nu(\gamma)]} = \left|\frac{g_e}{g_\mu}\right|^2 \frac{m_e^2}{m_\mu^2} \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 (1 + \mathrm{EW\ corrections}) = 1.23524(015) \times 10^{-4}$$

LFU

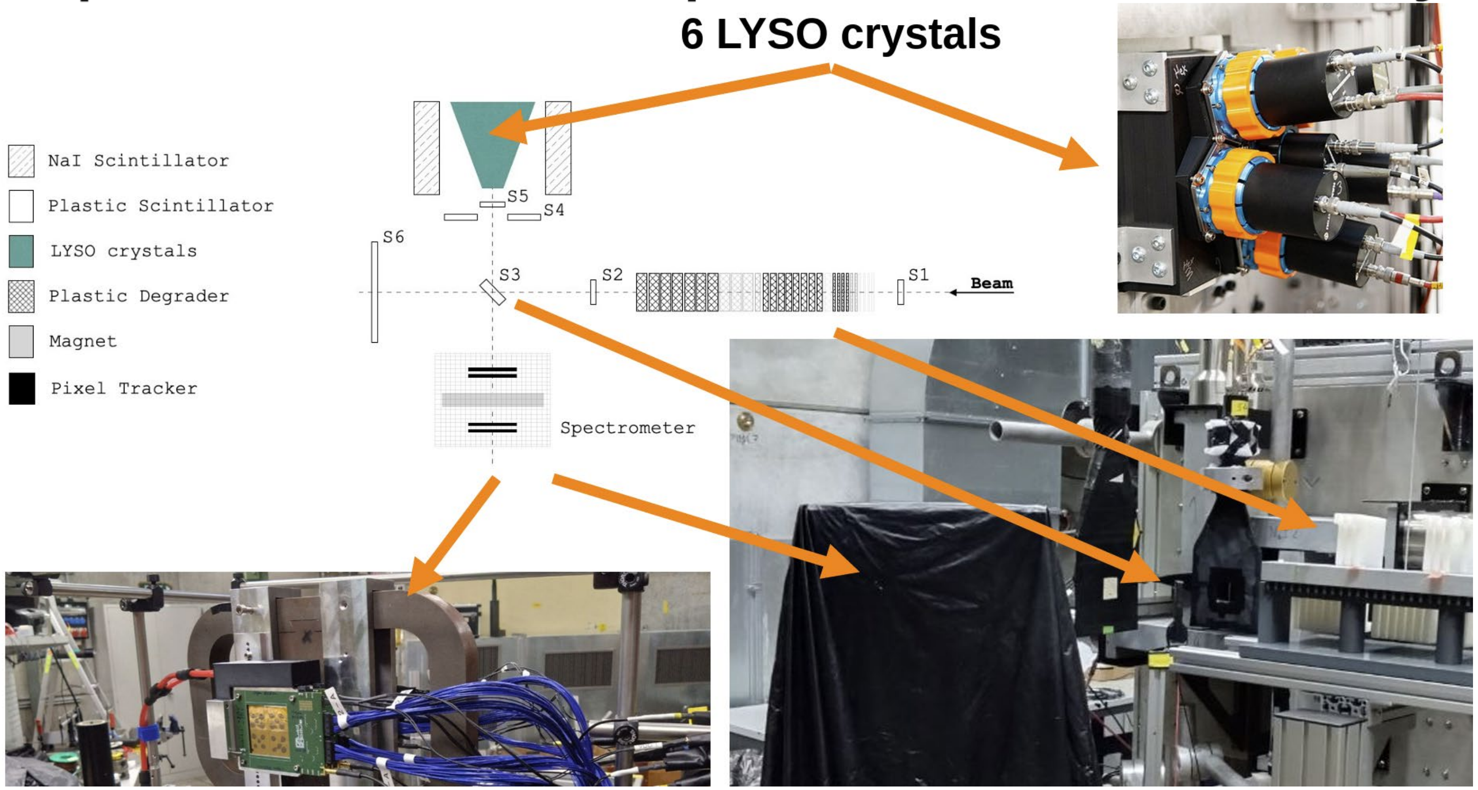
'Helicity suppression' term: ~2.3 x10^{-5}

Phase space term: ~ 5.5

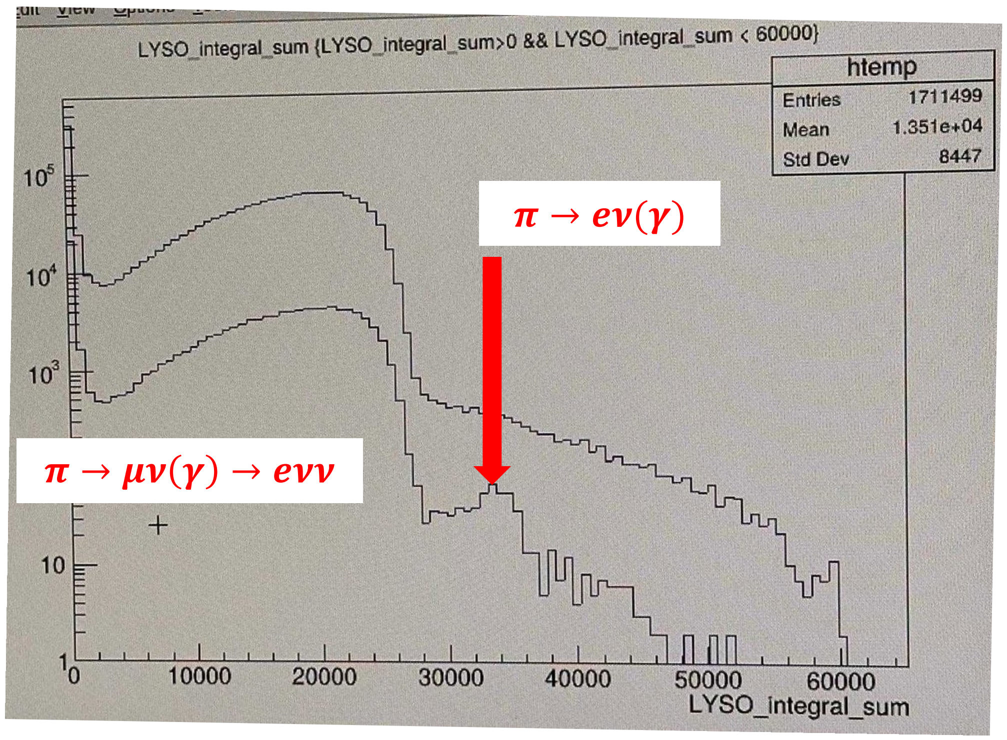
Fully computed at NLO
O(10^{-4}) uncertainties at NNLO

The π → e ν decay was first discovered in 1958, but these days, one can even make a rough measure as a "Student Exercise"

Experimental Setup for $\pi^+ \rightarrow e^+\nu$ Study



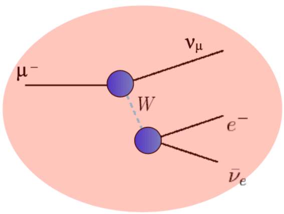
September 2025



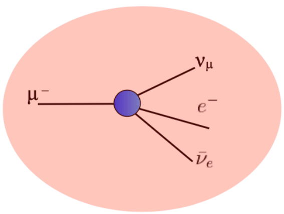
Univ. Heidelberg, Mainz, and ETH Zurich Practicum at PSI

In our case, we aim for 10^{-4} precision on this rare $\sim10^{-4}$ branch

- Most sensitive test of LFU
- Many BSM scenarios exist, SMEFT
  - $Wl\nu$ coupling, 4-fermion operators



Vertex corrections



4-fermion contact interaction

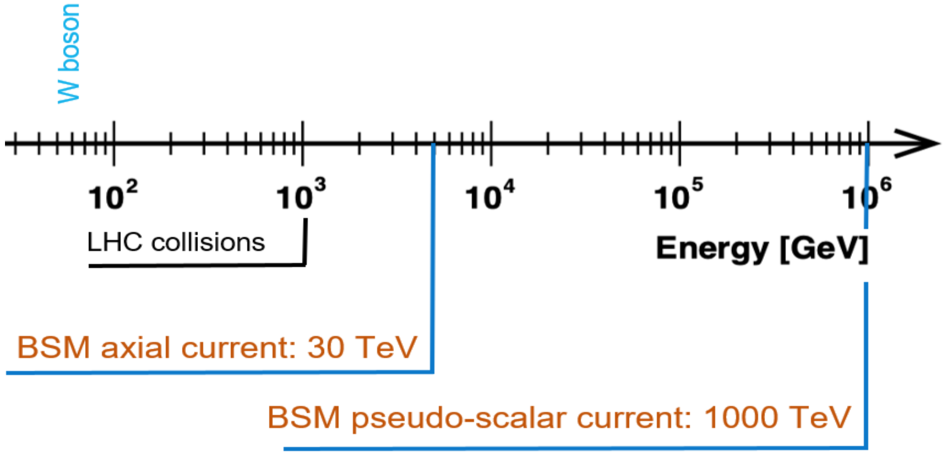
Best constraints on **modified *W* couplings**

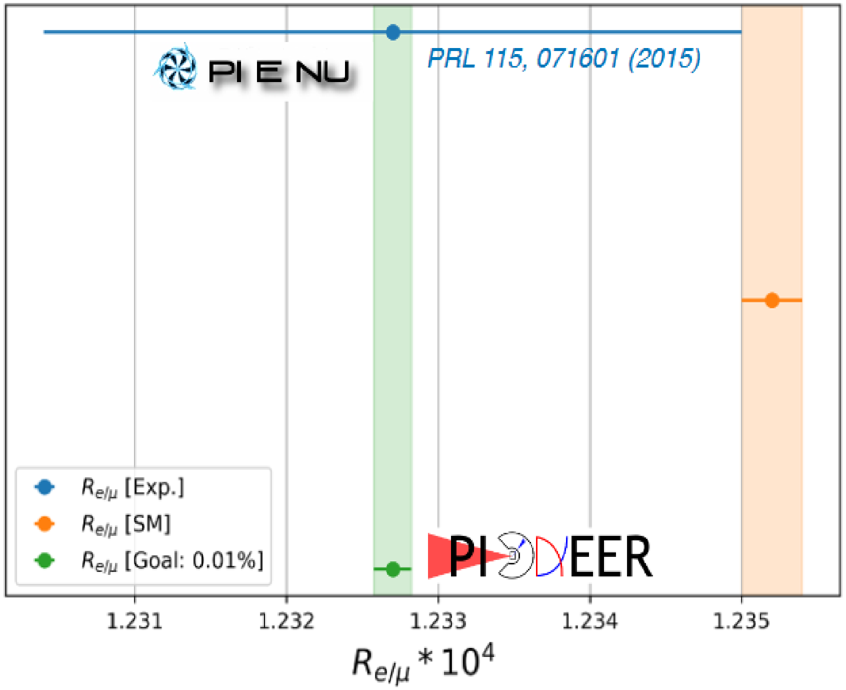
$$\mathcal{L} = -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L\nu_j W_\mu\left(\delta_{ij}+\varepsilon_{ij}\right)$$

$$\frac{R^{\mathrm{SM}}_{e/\mu}}{R^{\mathrm{exp}}_{e/\mu}} = 1+\varepsilon_{\mu\mu}-\varepsilon_{ee} = 1.0010(9)$$

- sensitive to very high mass scales

also T and S currents

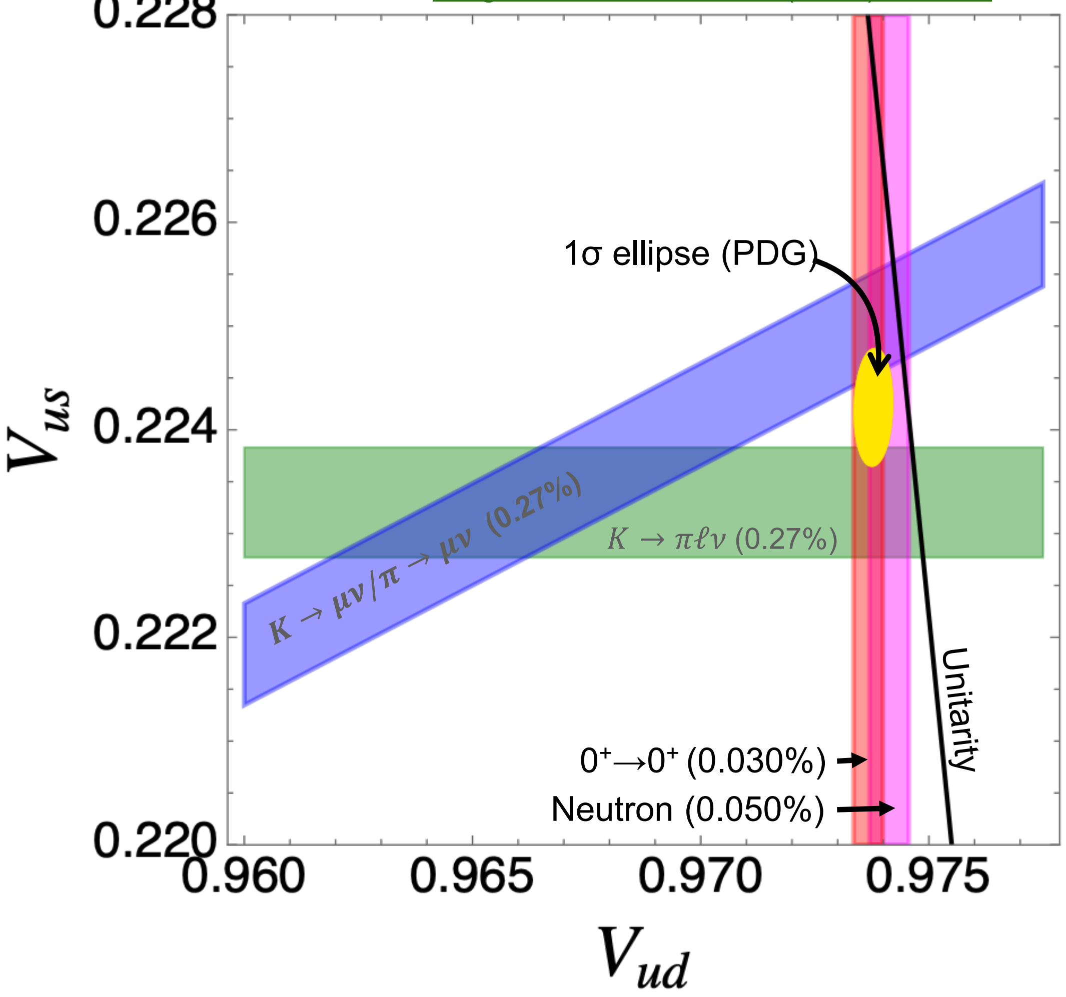




Physics Case II: Testing CKM Unitar $|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$

- Tensions in the first row CKM unitarity test

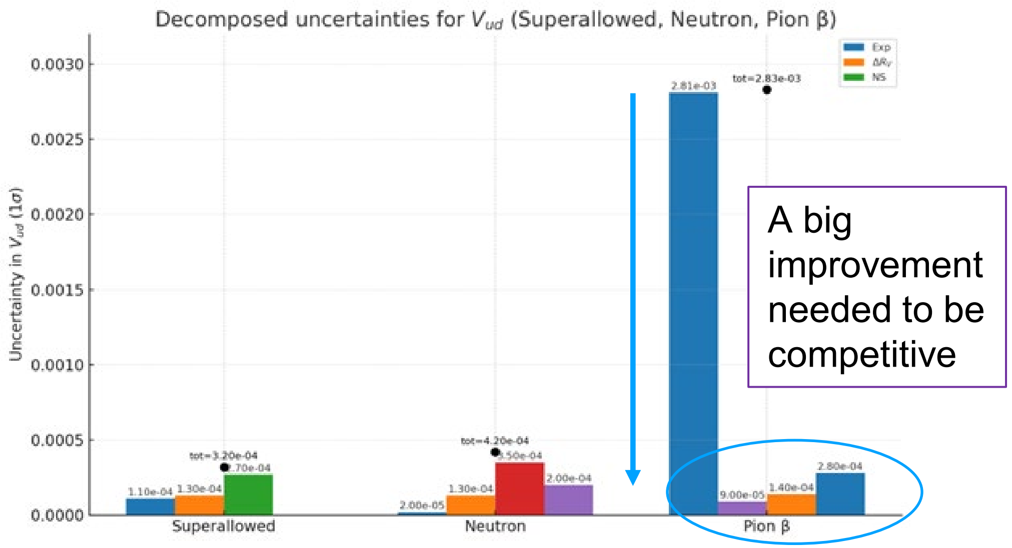
[Cirigliano et al. PLB 838 (2023) 137748](https://doi.org/10.1016/j.physletb.2023.137748)



- Cabibbo Anomaly: 2-3 σ discrepancy
  - V_{ud} and Unitarity,
  - V_{us} measurements disagree

- Pion beta decay $\pi^+ \to \pi^0 e^+ \nu(\gamma)$
  - provides theoretical cleanest determination of $|V_{ud}|$ as dominant uncertainties from hadronic and nuclear structure

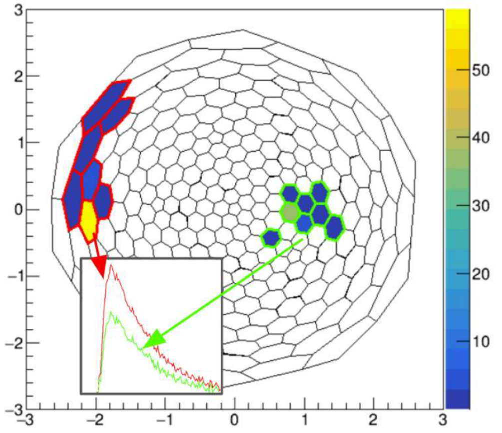
PiBeta doi.org/10.1103/PhysRevLett.93.181803

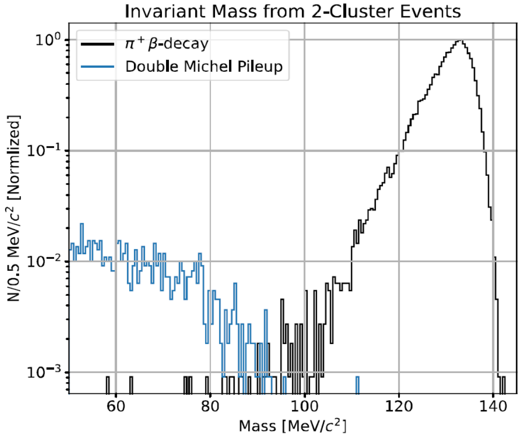


These are actually smaller

PiBeta concept with PIONEER's LYSO calorimeter option

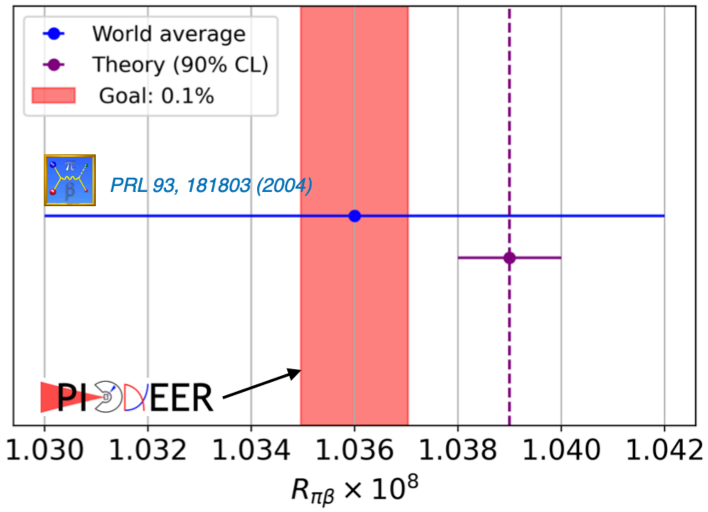
- Method



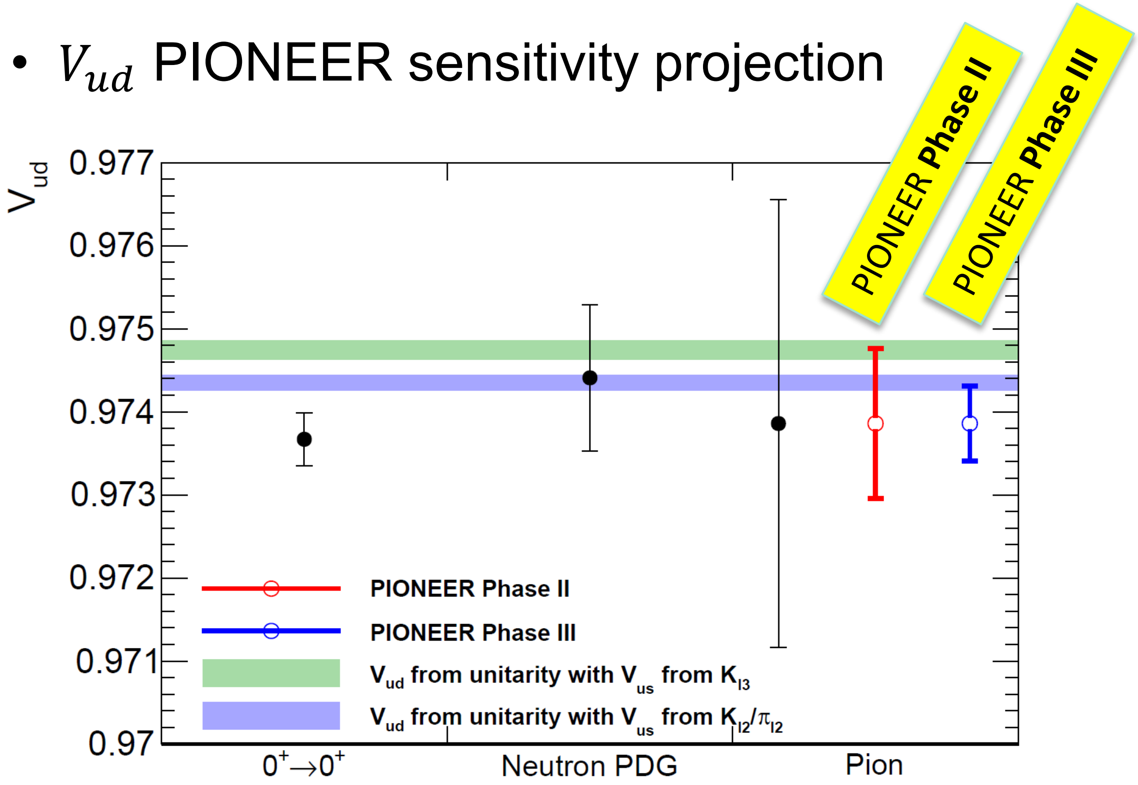


  - two back-to-back gammas $\pi^0 \rightarrow \gamma\gamma$
  - high beam rate required: 10^7 π/s @ 85 MeV/c

- Phase III goal



- V_{ud} PIONEER sensitivity projection



PDG24

  - 3 and 6-fold improved measurement (Phase II,III)
  - Simplest beta decay process in theoretical pristine $\bar{q}q$ system
  - Competitive probe with completely different error budget

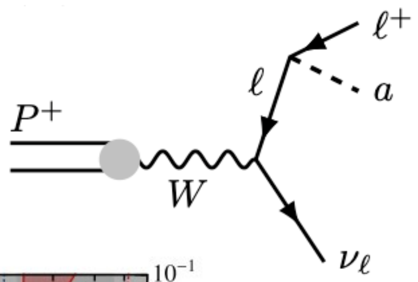
Physics Case III: Search for Weakly Coupled Physics:

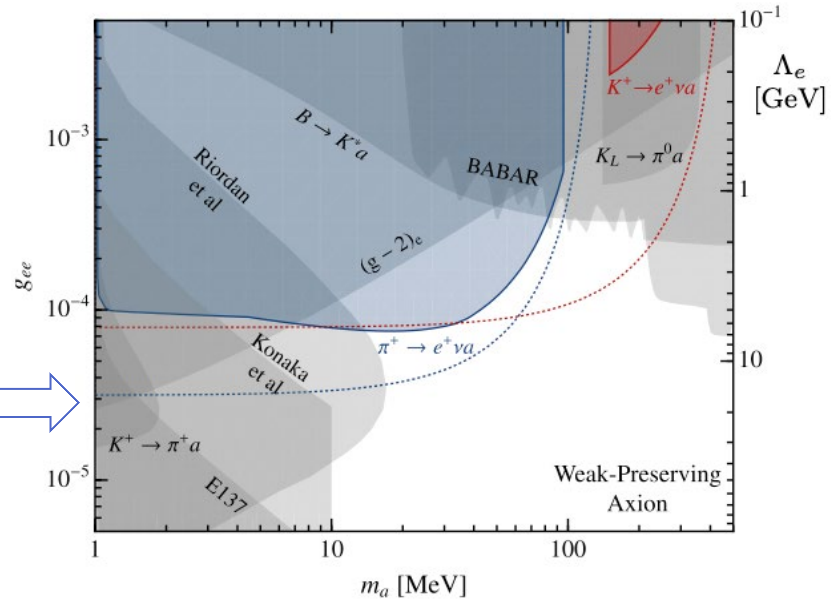
PIONEER will collect an unprecedented set of pion decays (surpassing existing sample by at least a factor 10)

Excellent opportunity to search for feeble interactions producing new particles in the pion decay

Will appear as a modification of the energy spectrum lineshape in the calorimeter spectra (bump or shape)

Recent development with
Lepto-philic axion-like particles





W. Altmannshofer, J. Dror, and S. Gori
Phys. Rev. Lett. **130**, 241801

PI E NU

Many signatures explored by TRIUMF PIENU

$$\pi \to e\nu_H$$
$$\pi \to \mu\nu_H$$
$$\pi \to \ell\nu_\ell\nu\bar{\nu}$$
$$\mu \to eX$$
$$\pi \to e\nu X$$

Physical Review D 97(7) 072012 (2018)
Physics Letters B 798 134980 (2019)
Phys. Rev. D 102, 012001 (2020)
Phys. Rev. D 101, 052014 (2020)
Phys. Rev. D 103, 052006 (2021)

Goal of PIONEER
Increase reach of the global search program for feeble interactions
(ie ALPs, heavy neutrinos, …) by an order of magnitude in the 10—100 MeV range

PSI *Approved* Proposal Jan. 2022

PSI Ring Cyclotron Proposal R-22-01.1
PIONEER: Studies of Rare Pion Decays

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Has become a high-priority experiment at PSI

Since the proposal, we have been very actively designing and simulating the experiment

I will share some progress

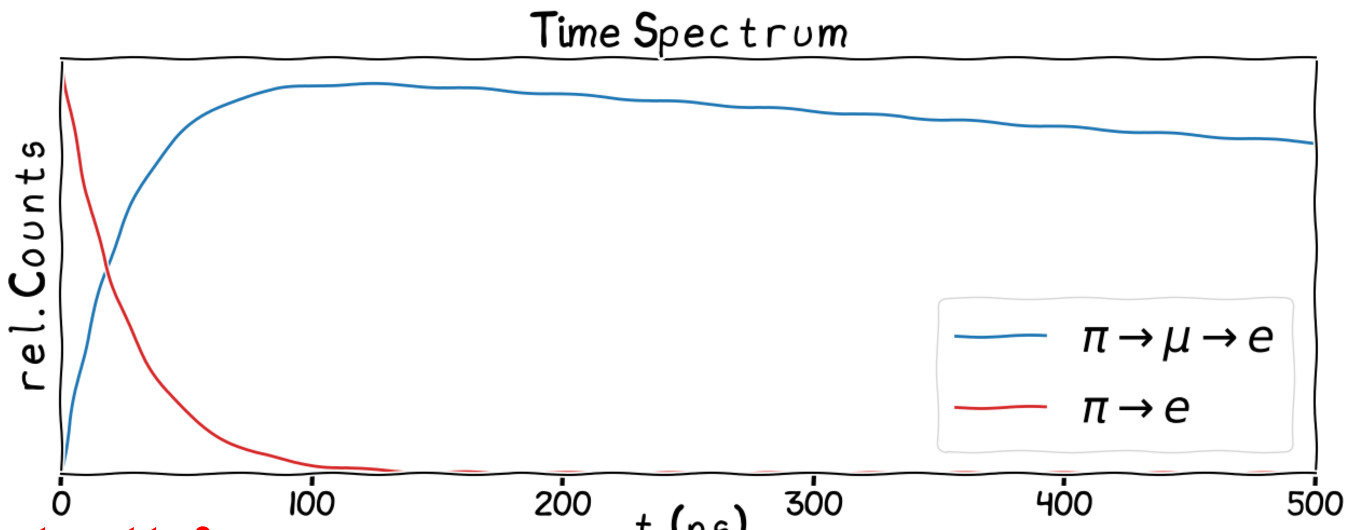
Pion decay (at rest) related to measuring

$$\frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

Reminders

$\tau_{\pi+}$ = 26 ns $\quad m_{\pi^+} \approx 140$ MeV

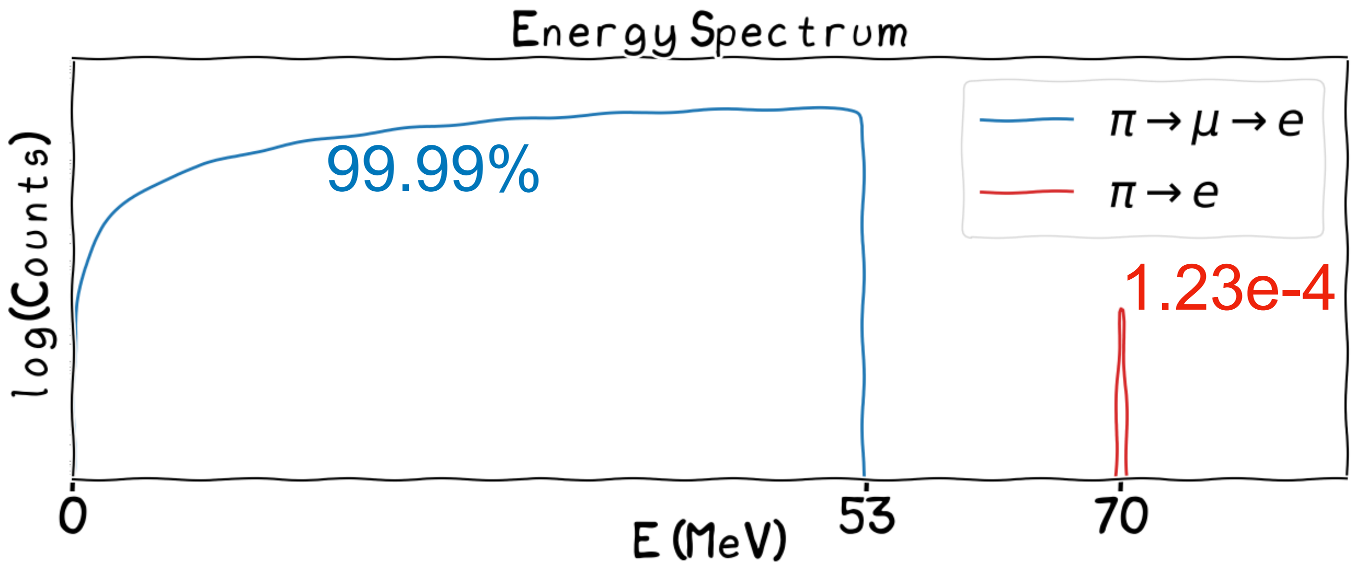
$\tau_{\mu+}$ = 2197 ns, $m_{\mu^+} \approx 106$ MeV



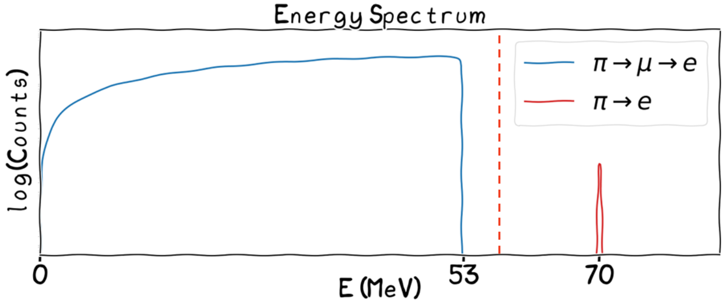
π⁺ stop at t =0

$\pi^+ \to \mu^+\nu \quad E_e < \frac{m_\mu}{2} \approx 53$ MeV

$\pi^+ \to e^+\nu \quad E_e = \frac{m_\pi}{2} \approx 70$ MeV

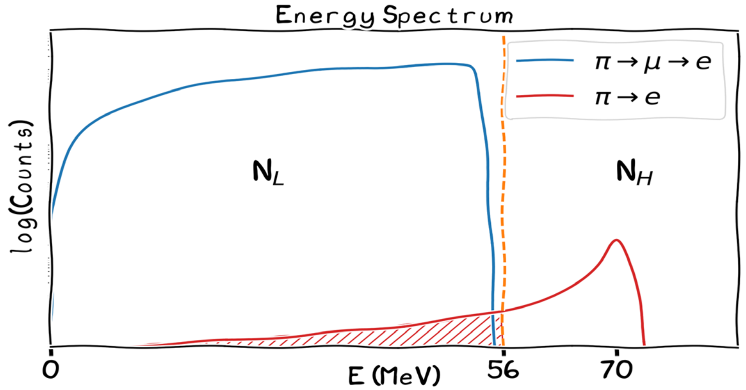


The ideal and realistic e⁺ energy spectrum:



Define $E_{thr} = 56\,MeV$ and count events above and below threshold

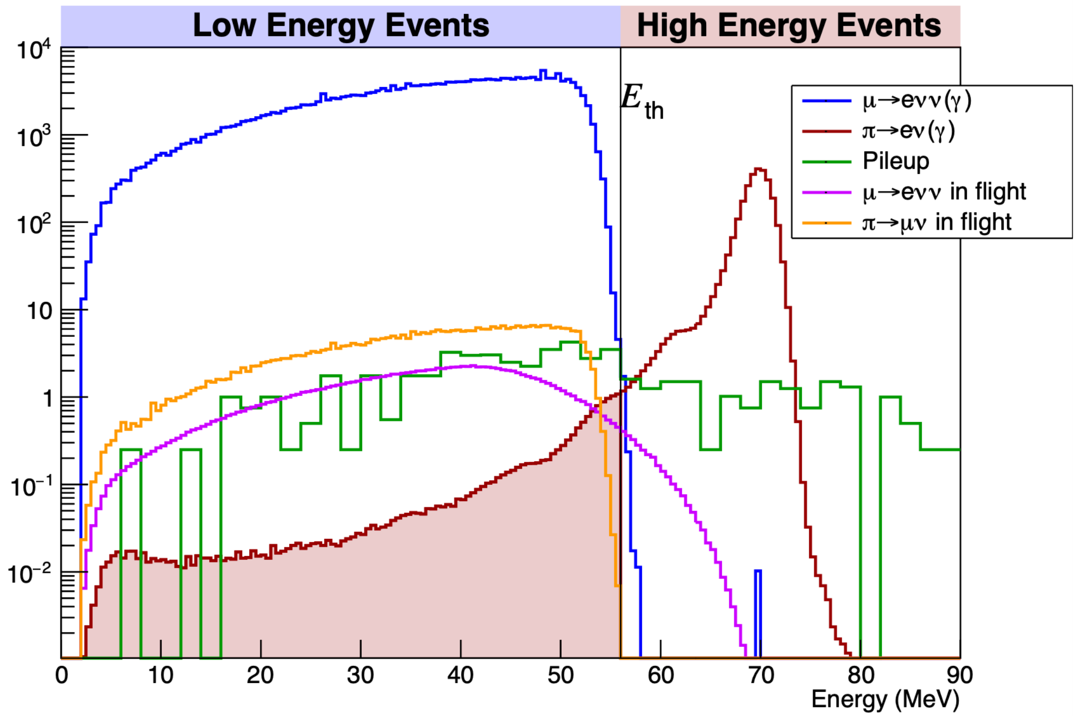
$$R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))} \approx \frac{N_H}{N_L}$$



Finite resolution and incomplete energy collection in the calorimeter result in a **tail**

$$R_{e/\mu} = \frac{N_{\pi-e}(E > E_{th})}{N_{\pi-\mu-e}} \times (1 + c_{tail}) \times \boldsymbol{R^{\epsilon}}$$

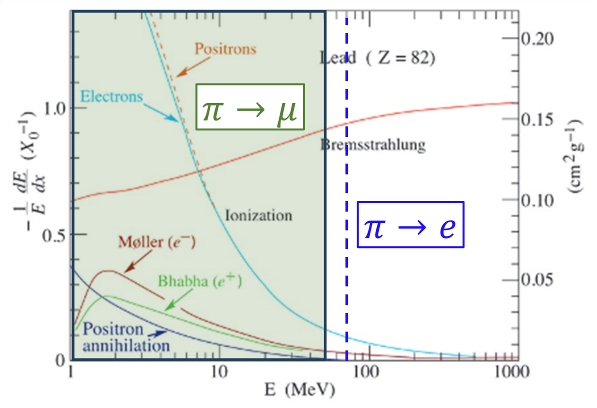
Realistic e⁺ spectrum in the time window (5 – 35) ns after π stop



- The **$\pi \to e$ tail**: *0.5% systematic correction*
- **Muon decays in flight** can boost positrons to the high energy region: *0.1% correction*
- **Some muon stops confused as pions:** *0.1% - 0.2% correction*
- ***Pileup from old muons:*** *must mitigate*

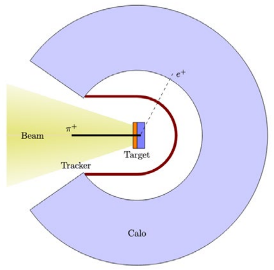
Why so challenging?

- Identify the 1 in 10^4 π->e decays, with a misidentification factor below 1 part in 10^4

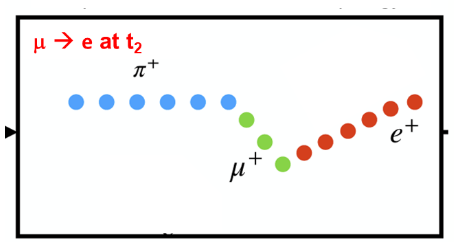


- While the decay times and positron energies are different, the physics processes in the detectors are energy dependent
  - scattering, annihilation, Bhabha probabilities

- Need high statistics,
  - Large and uniform acceptance
  - High beam rate (pileup)



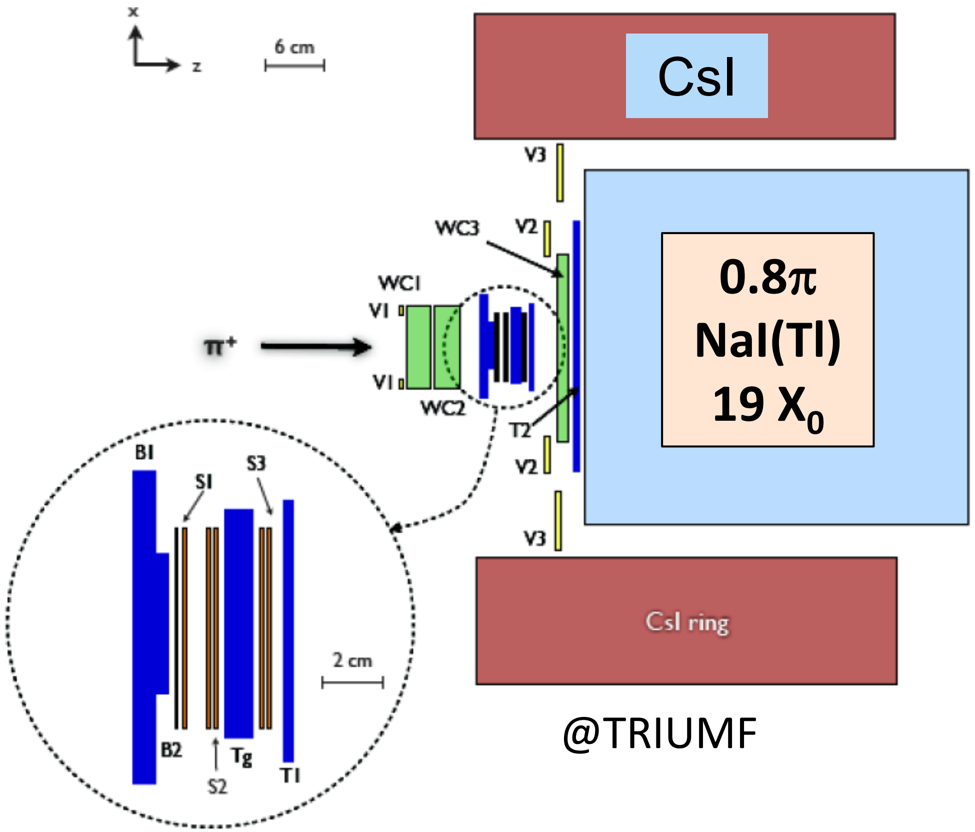
- Strategy
  - Innovative imaging target and high-resolution, fast calorimeter
  - MC – data comparisons in great detail

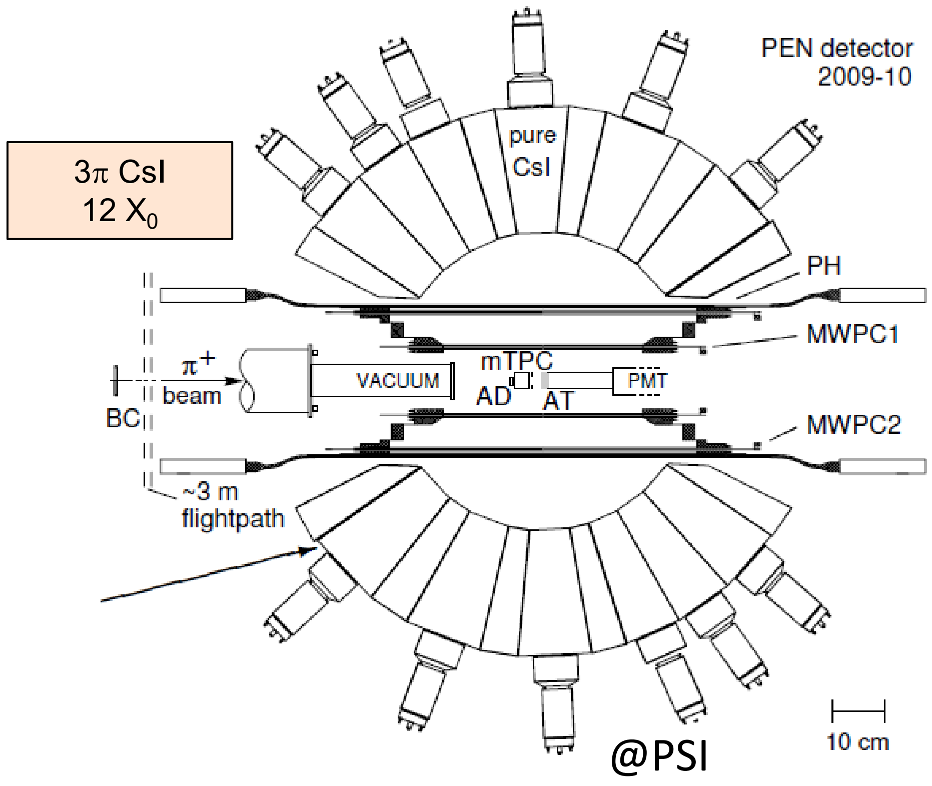


- Analyses are being developed in advance with highly realistic simulation framework
  - Classic "Rule Based"
  - Advanced Machine Learning techniques

Two previous-generation Pion Decay Experiments: PIENU and PEN/PIBETA

Limitations and lessons learned to design “next-gen”





- NaI: excellent resolution, but slow so rate limited
- Shower leakage in single crystal depends on angle
- Small overall acceptance

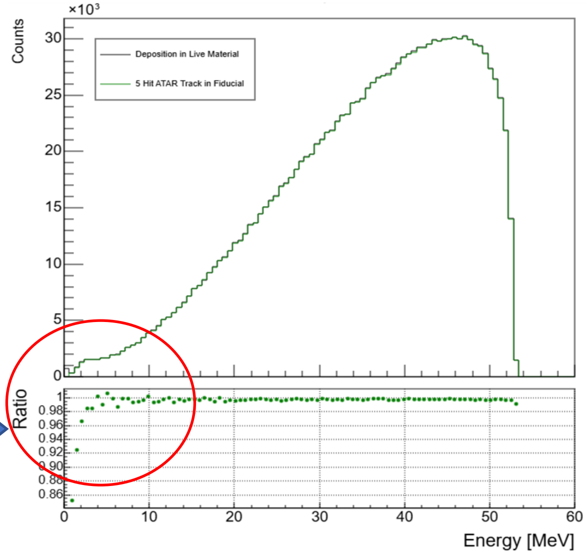
- Calorimeter depth too small to resolve tail
- Uneven crystal performance

In any analysis, one must determine from a Master Formula:

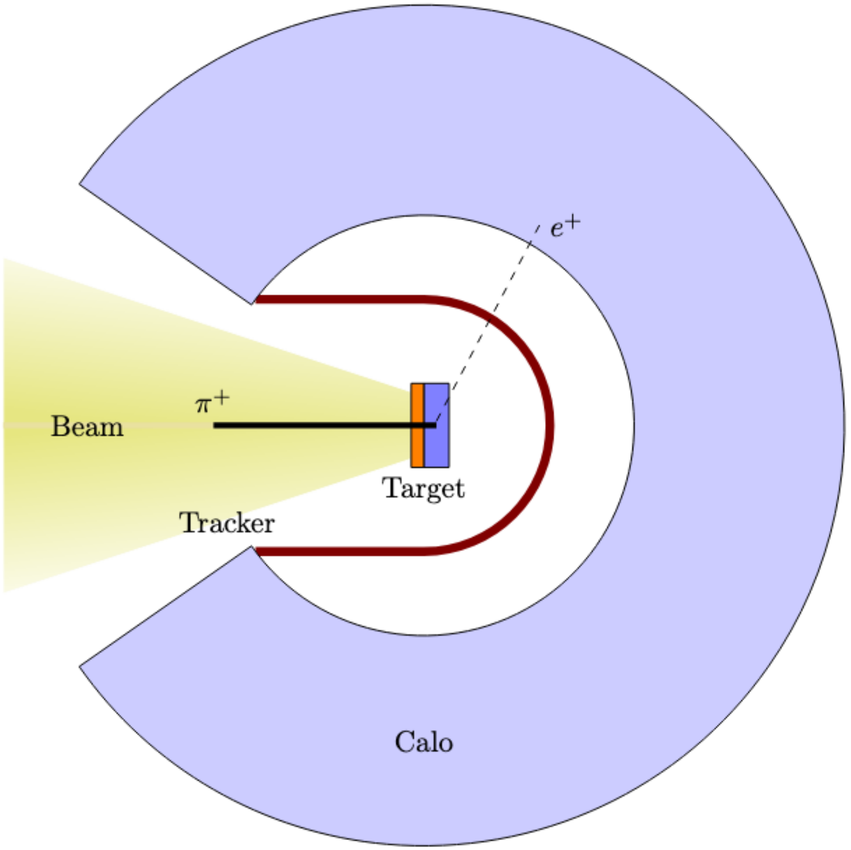
$$R_{e/\mu} = \frac{N_{\pi-e}(E > E_{th})}{N_{\pi-\mu-e}} \times (1 + c_{tail}) \times R^{\epsilon}$$

All vs polar angle θ

- $N_{\pi-e}(E > E_{th})$ = Counts in the "high bin" … above ~56 MeV
- $N_{\pi-\mu-e}$ = Counts in the "low bin" (Michel decays) … below ~56 MeV
- c_{tail} = $\pi^+ \to e^+$ events that deposit less than 56 MeV in the Calo
- R^{ϵ} = the acceptance ratio (vs θ). Quite critical because the positron energies from $\pi^+ \to e^+$ and $\pi^+ \to \mu \to e^+$ events differ significantly (especially at the low end)



PIONEER experimental strategy:

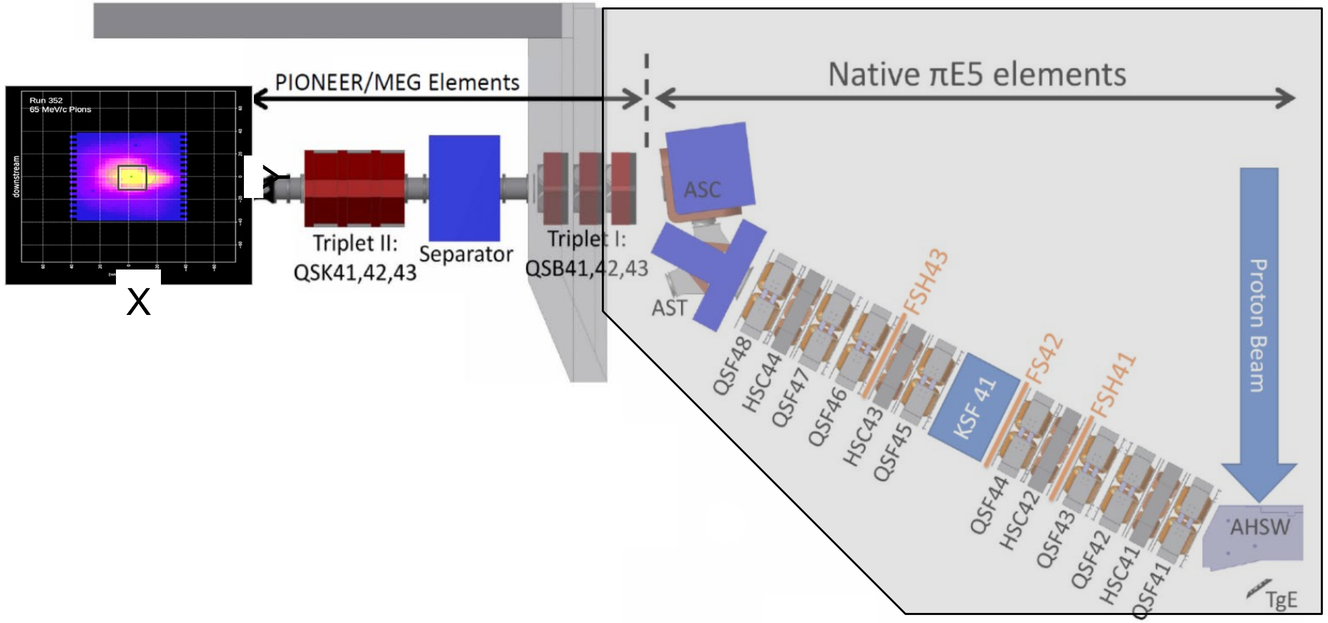


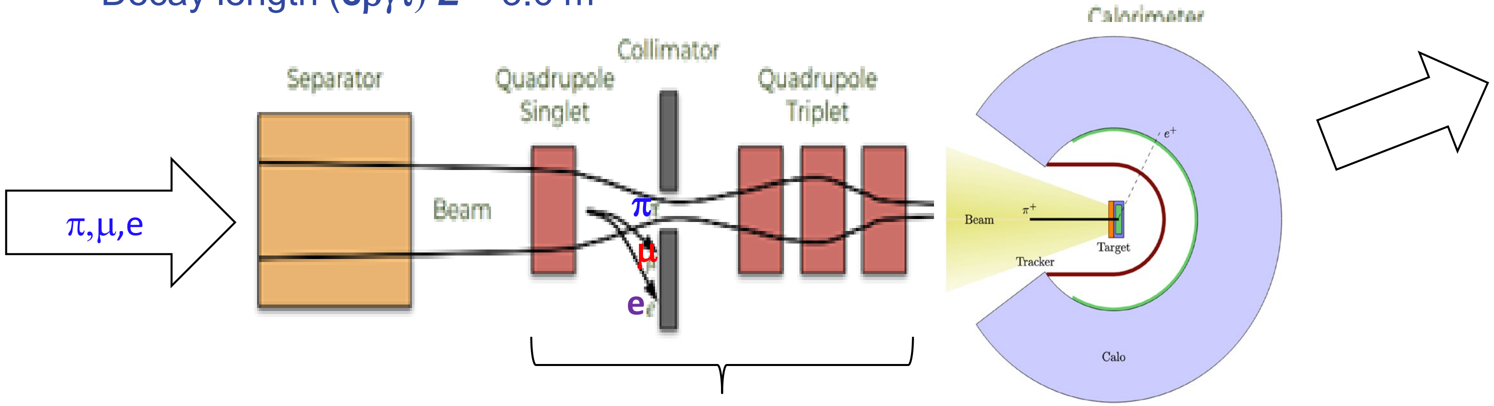
Generic diagram

- 65 MeV/c DC positive pion beam @ 300 kHz
- Stop in a segmented imaging target
- Measure positron energies from $\pi \to e$ and $\pi \to \mu \to e$ with a high-resolution calorimeter
- Record "region of interest" both before and after the stop

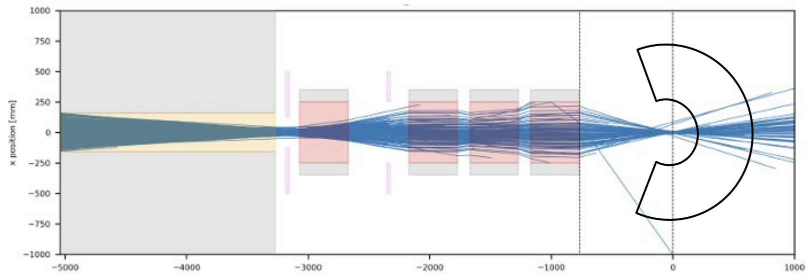
Approved to use the high-rate pion piE5 beam at PSI

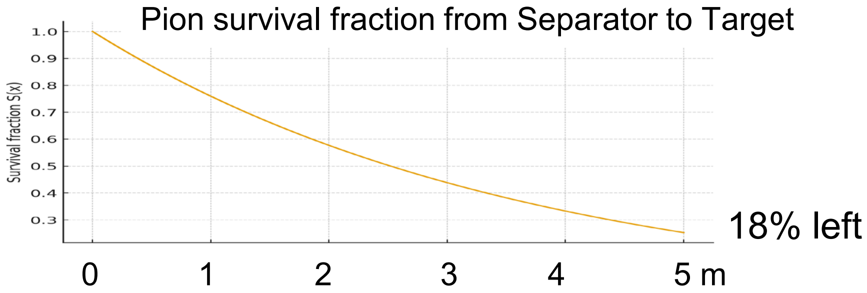
- piE5 @ PSI - World's Brightest Stopped Pion Beam
  - Now: Fundamental **muon** physics: MEG II, Mu3e
- Our 2023 measurements of existing beam
  - Rate: 300k π/s stopped in ATAR: **ok at 65 MeV/c**
  - Momentum bite: Δp/p <2%: **marginal**
  - Spot size: <2 cm FWHM: **not yet achieved**
  - μ,e less than 10% π: **needs second focus extension**
- Pions at 65 MeV/c have
  - β = 0.42
  - Decay length ($c\beta\gamma\tau$) L = 3.6 m



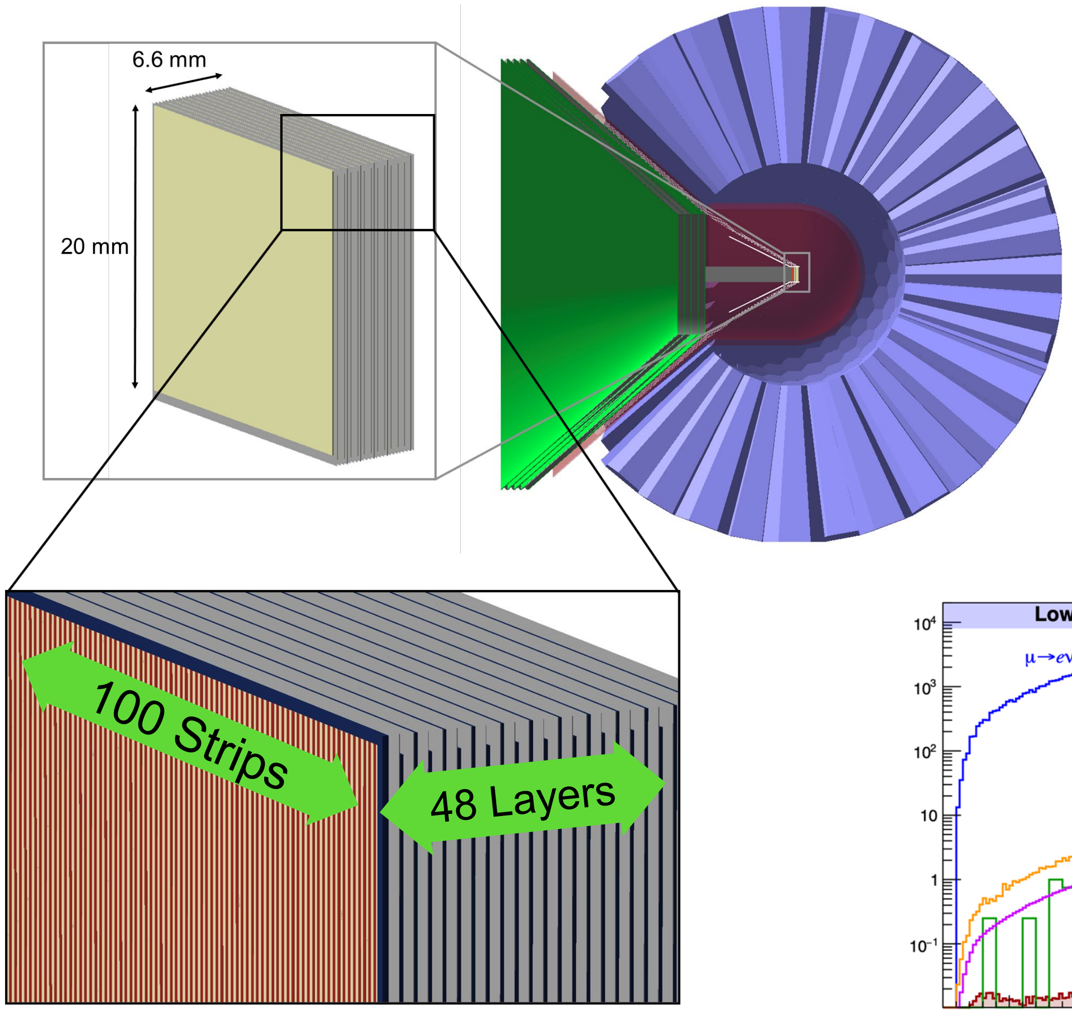


A challenging work in progress to design these elements





Key development for PIONEER: LGAD-based *Active TARget*

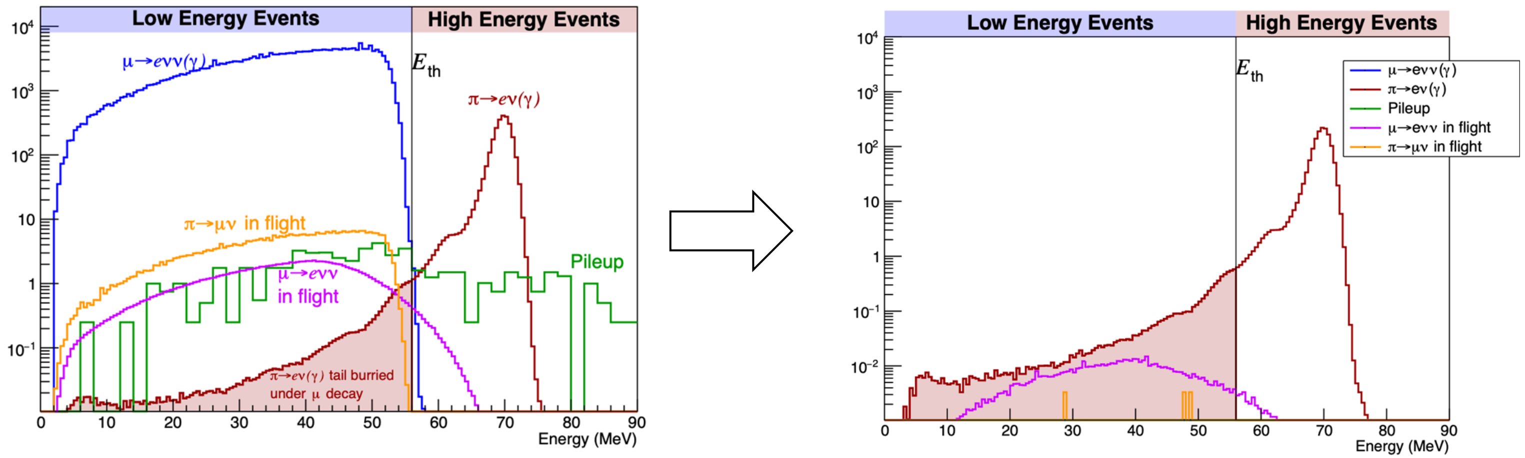


Highly segmented and instrumented.

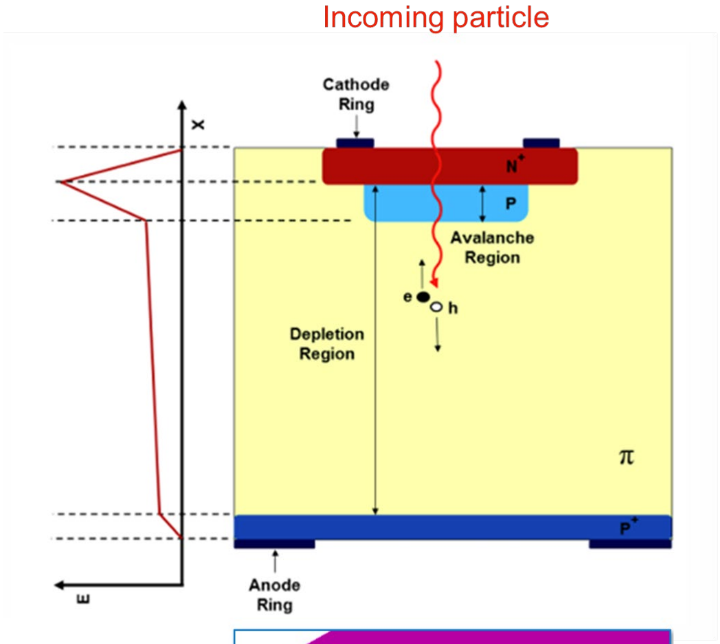
- 48 planes of 20 mm x 200 μm x 120 μm strips
- 4800 channels

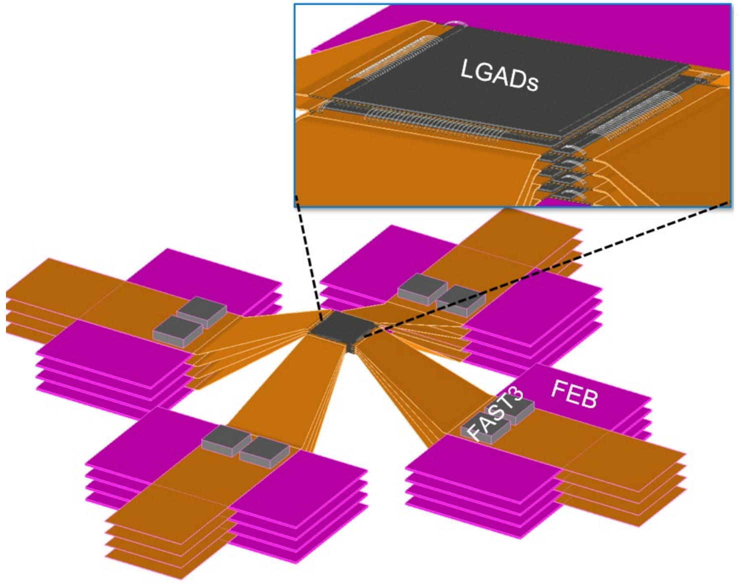
ATAR provides 5D track information

- 3D position (*x,y,z*).
- Time: 100 ps single hit / few ns pulse pair resolution
- Energy in each strip: MIPs to heavily ionizing pion and muon tracks distinguished



(TI)* Low Gain Avalanche Diodes (LGAD)





Silicon Diodes: *p-n* junction separated by an intrinsic layer (undoped)

LGADs: additional highly doped layer generates a very high electric field → avalanche effect

Signal amplification allows for thin sensors and very good timing resolution

Gain mechanism can saturate for large energy deposit and introduces an angle dependency. We are studying this carefully

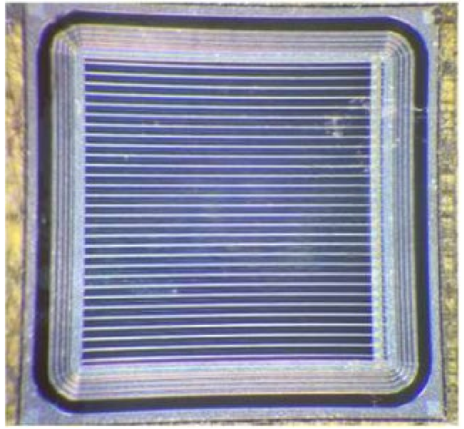
ATAR Demonstrator: *16-planes to be tested in 2026 with TI-LGAD sensors from FBK, FAST3 amplifiers, and SAMPIC 6 GSPS digitizers*

*trench-isolated to avoids cross talk to neighboring strips

The ATAR has a deep connection to Italy !

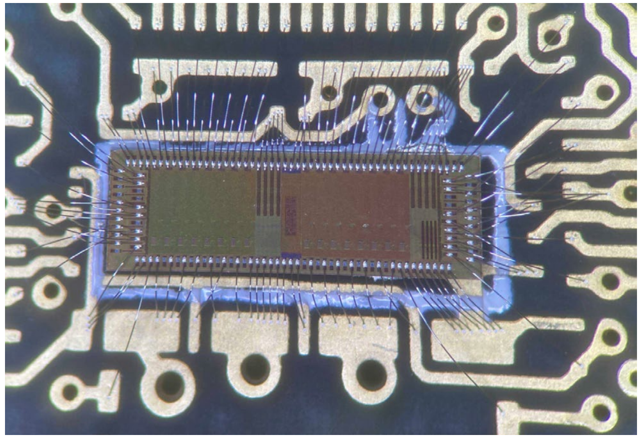
TI LGADs

FONDAZIONE
BRUNO KESSLER



FAST3 amplifier

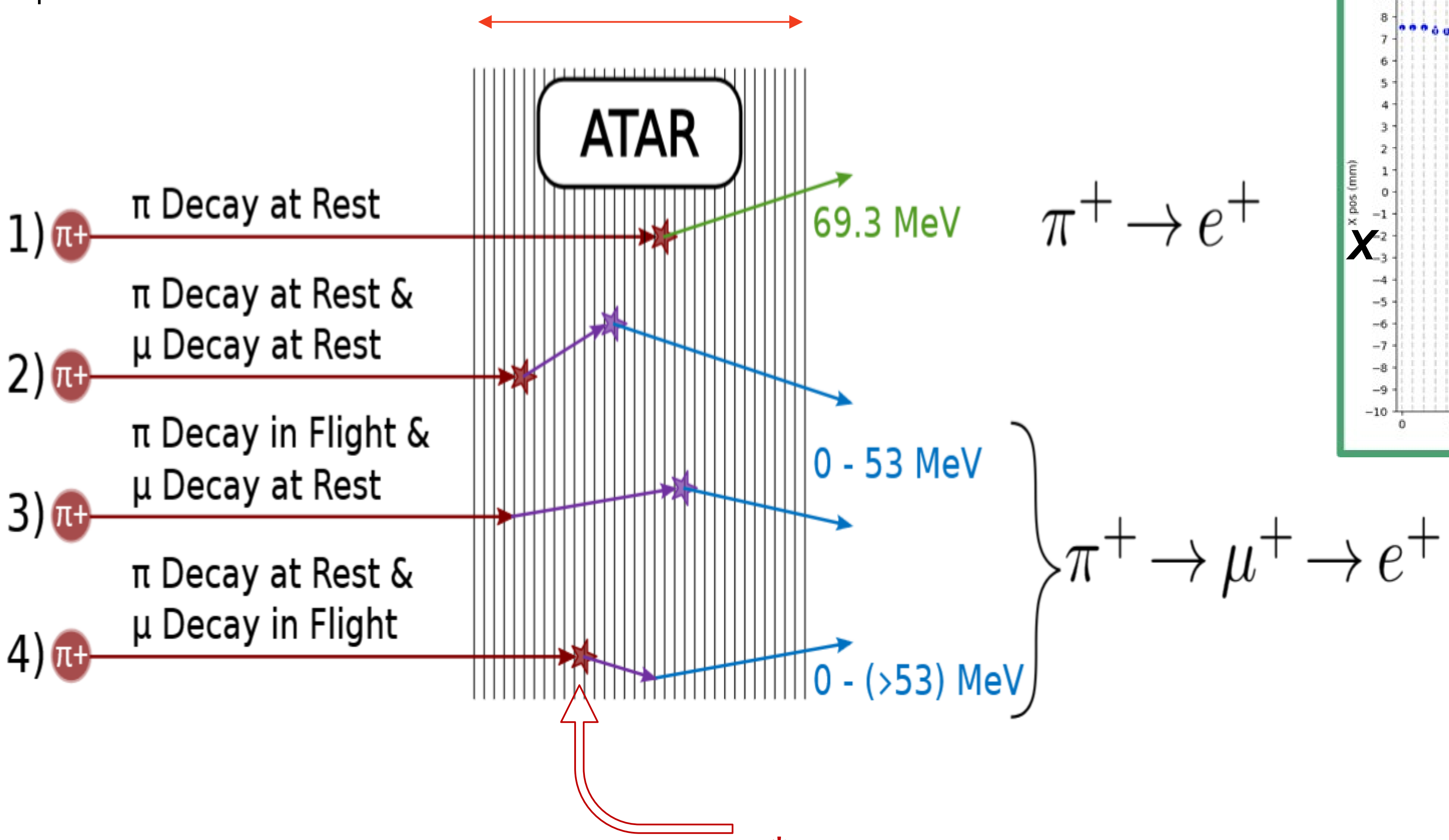
INFN
TORINO
Istituto Nazionale di Fisica Nucleare
Sezione di Torino



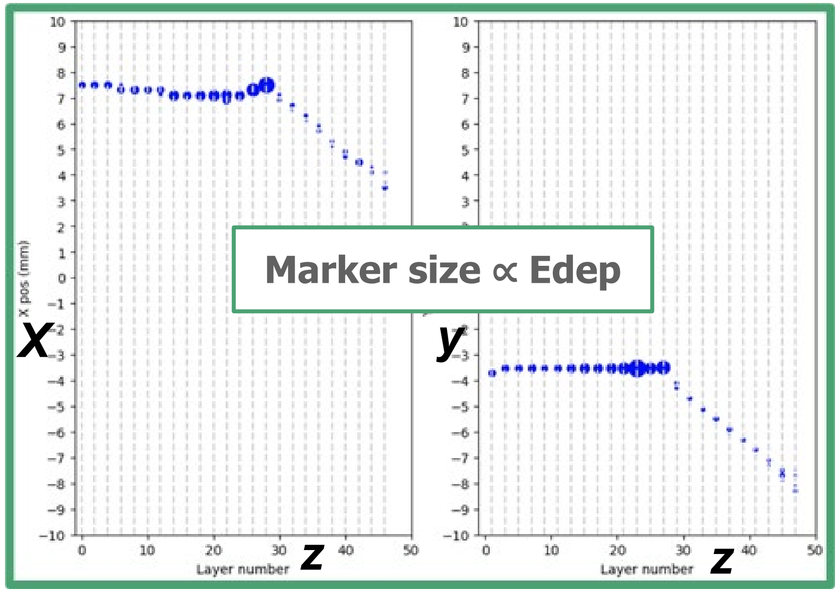
Pion processes in ATAR

R_π (65 MeV/c) ~ 4 mm, (stops in center region)

R_μ (4.1 MeV) ~ 0.8 mm



Example Event Display

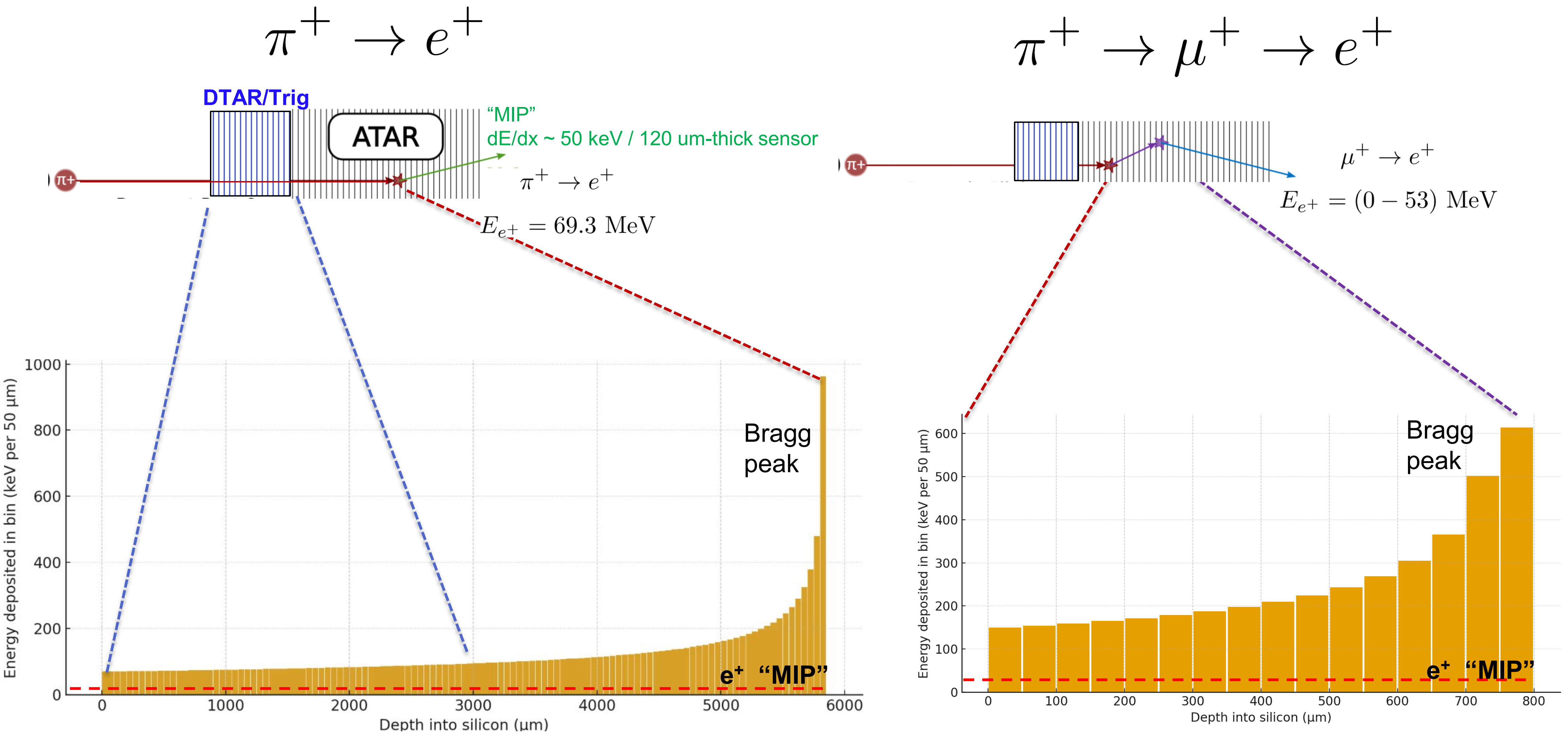


* Represents Bragg peak with large energy deposit

How these processes will appear in ATAR

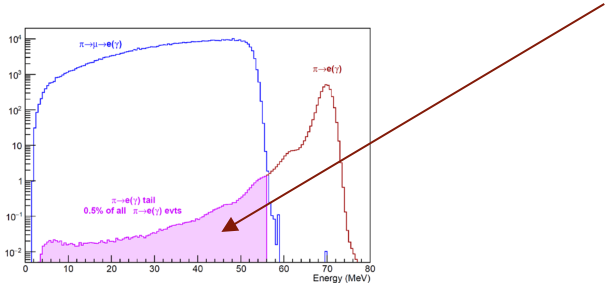
R_π (65 MeV/c) ~ 4 mm, (stops in center region)

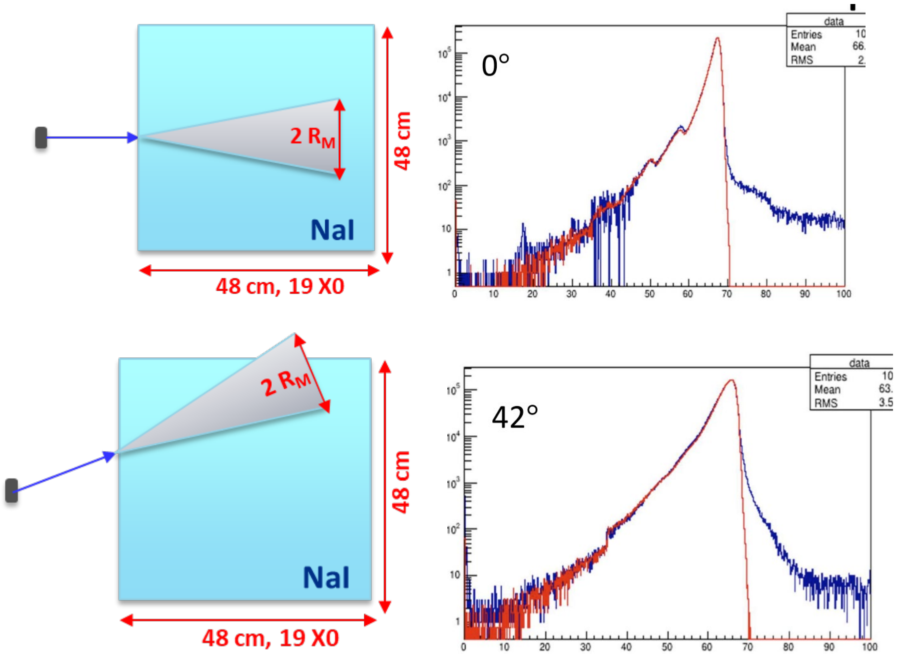
R_μ (4.1 MeV) ~ 0.8 mm



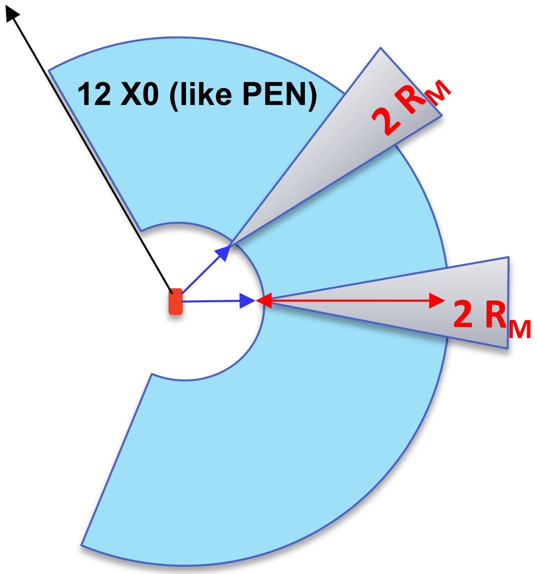
Minimizing the low-side tail is part of Calorimeter design

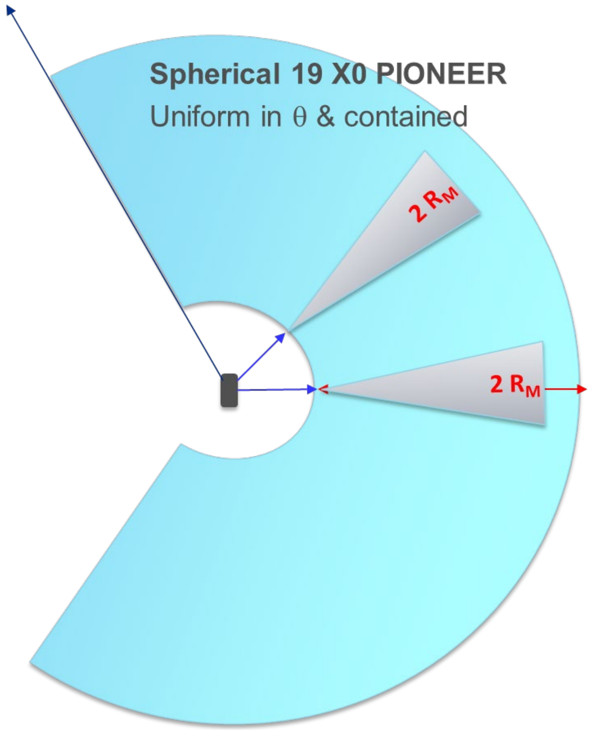
- #X0, depth containment
- R_M: lateral containment





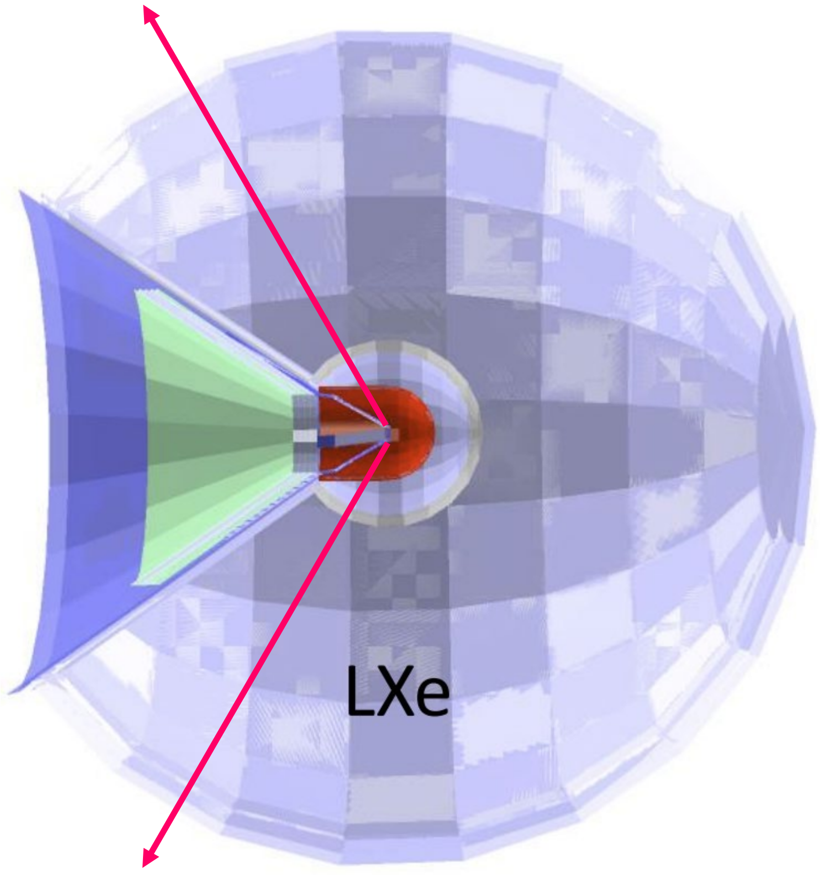
PIENU single large crystal
(their data & simulation)





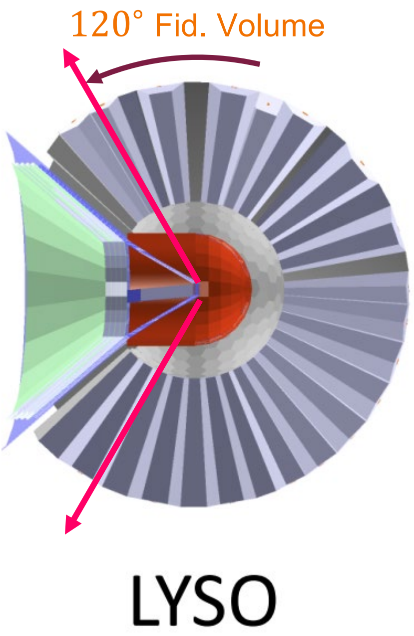
What calorimeter might work in [0 – 70] MeV range?

- Common features
  - High light yield (>30,000 γ/MeV)
  - “Fast” 40 ns decay time
  - Both aim at resolution <2%
  - Both aim at good timing
- Significant differences (LYSO/LXe)
  - **Segmented → 311 PMTs ~420 nm**
  - **Single volume → 1650 VUV sensors**
  - Density (see scaled pics)
  - Data load (LXe >100 higher)
  - LYSO is slightly radioactive



The original idea

(TRIUMF and Japan exploring)

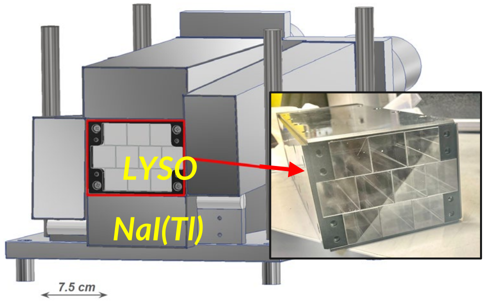


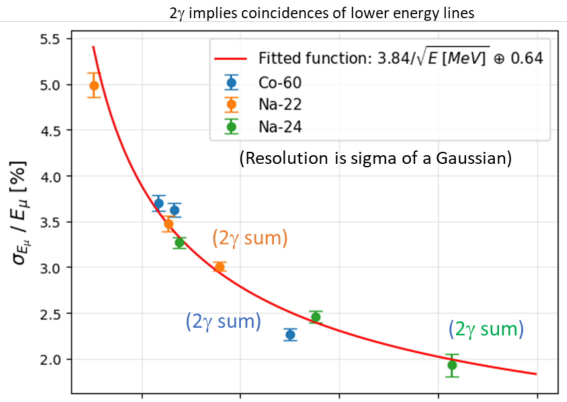
Since then …

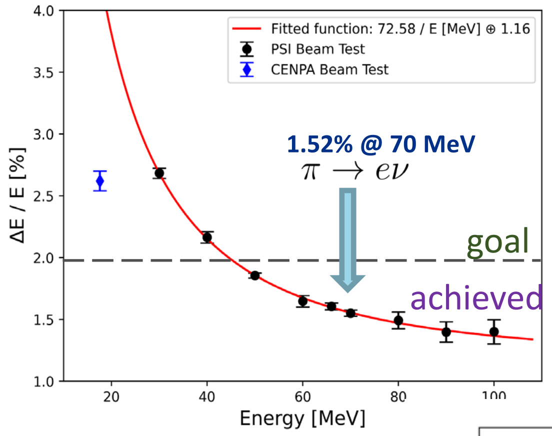
(SJTU, ETH Zurich, **UW** exploring)

LYSO R&D very promising …

- Tested 10-array
  - Nucl.Instrum.Meth.A 1075 (2025), 170320



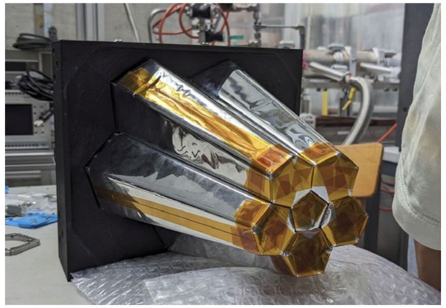


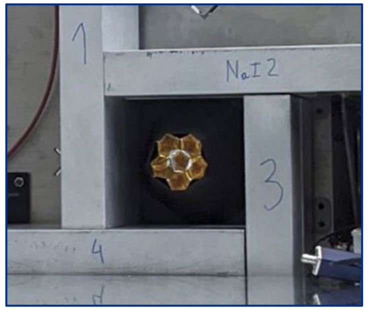


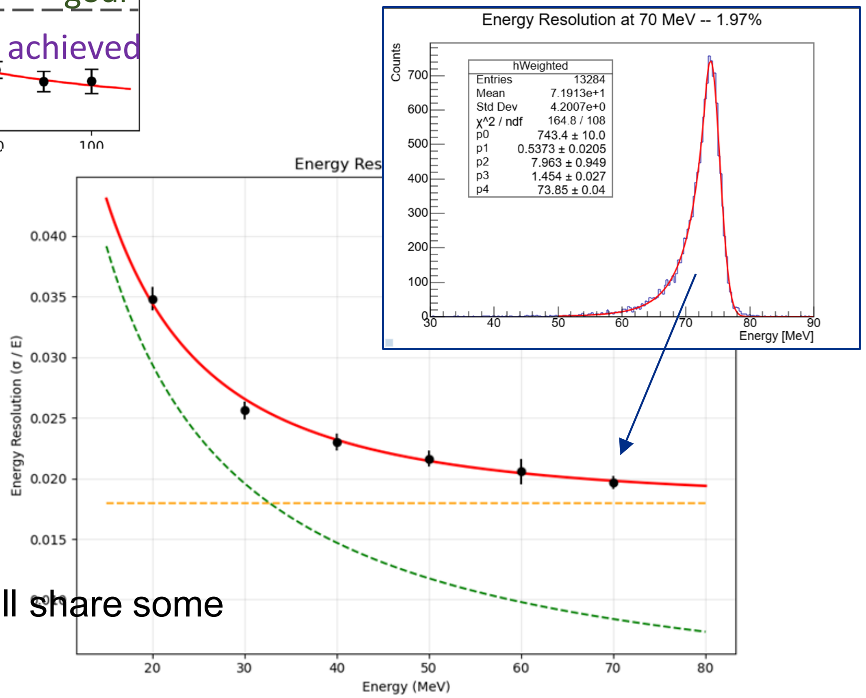
Lutetium–yttrium oxyorthosilicate (LYSO):

- 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

- Tested 6 full-sized, tapered crystals (August, 2025)





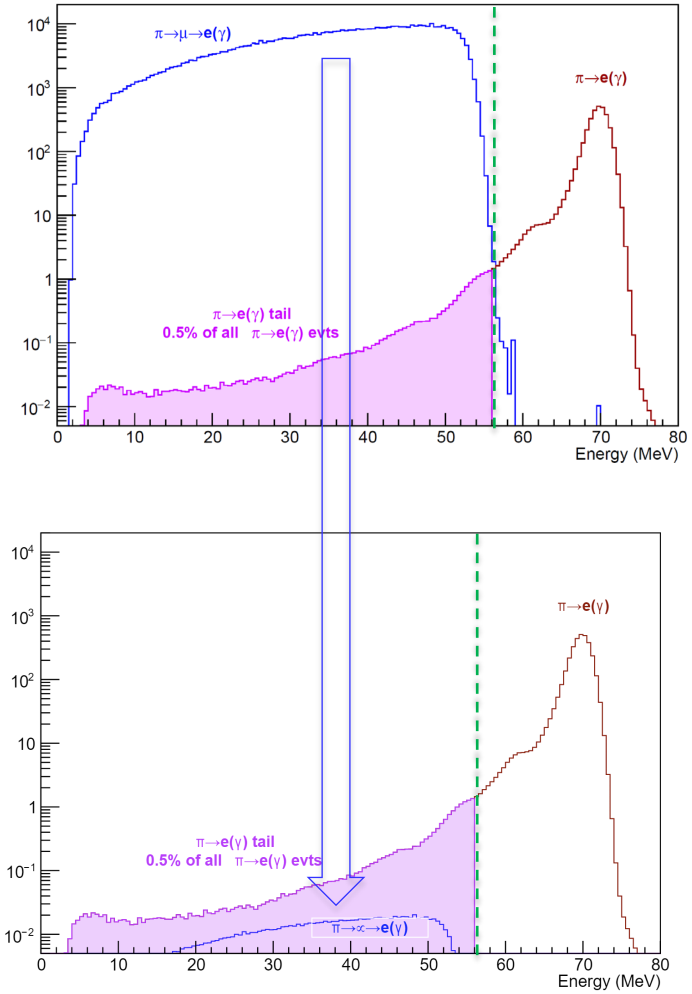


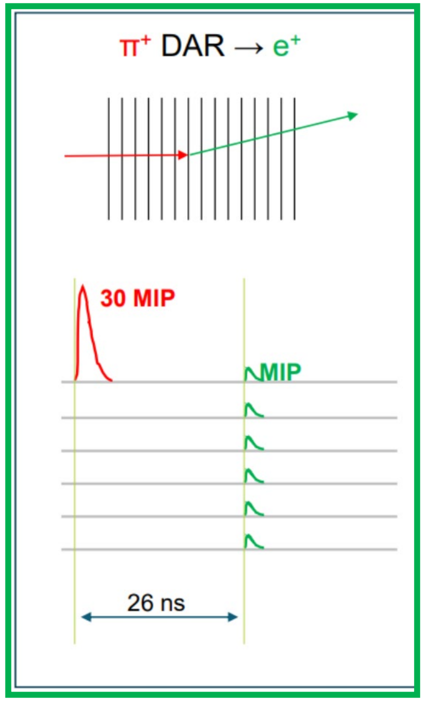
I am sharing work our group is helping to lead on LYSO but PIONEER has not finalic will share some progress we've made with LYSO here (but decision is not made!)

Connection of Calo and ATAR hardware to main systematic: The Tail Correction

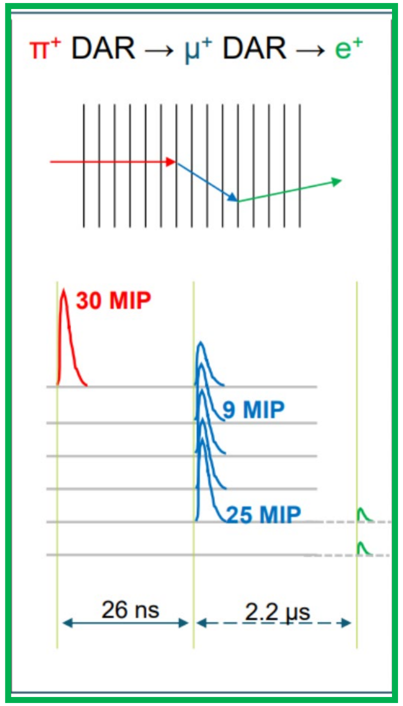
$\pi \rightarrow e$ events with energy below 56 MeV occur $\sim(5 \times 10^{-7})$ of the time

$\pi \rightarrow \mu \rightarrow e$ events with energy below 56 MeV occur 99.9% of the time





Measure to 1%



Suppress by 10^7

Signal $\pi \rightarrow e$ event:

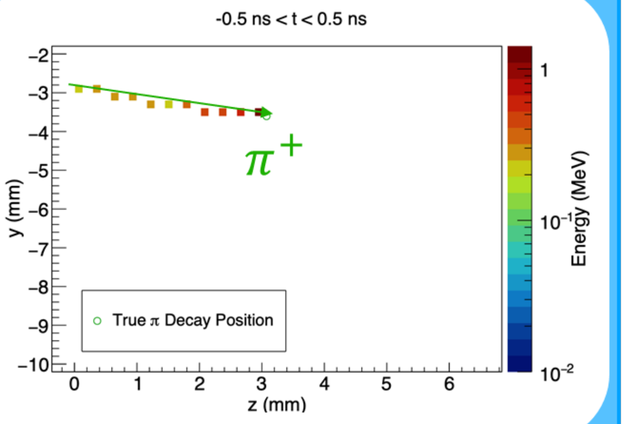
- Highly ionizing pion stop
- MIP positron
- Defined by pion lifetime alone

Background $\pi \rightarrow \mu \rightarrow e$

- Highly ionizing π and μ stops
- MIP positron
- Defined by both muon and pion lifetimes
- Timing and energy alone give 10^4 suppression

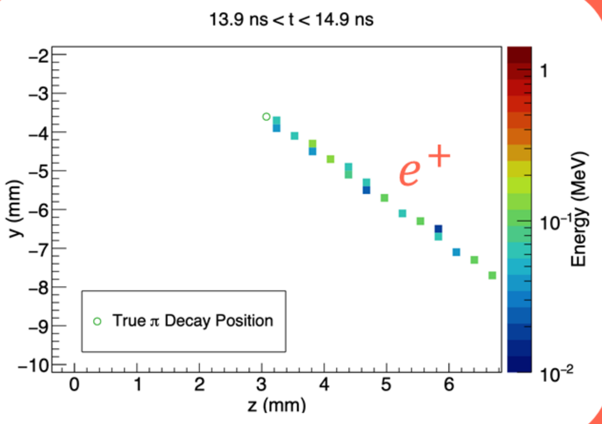
Pivot to our developing analysis methods: 3 essential tasks

Pion Stop Location



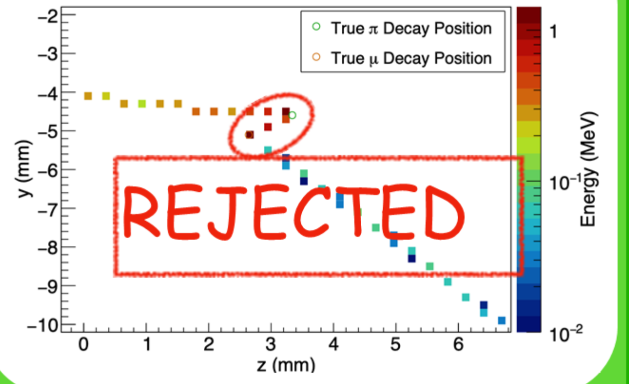
Find the end point of the pion track.
$r_\pi(x_\pi, y_\pi, z_\pi)$

Positron Direction



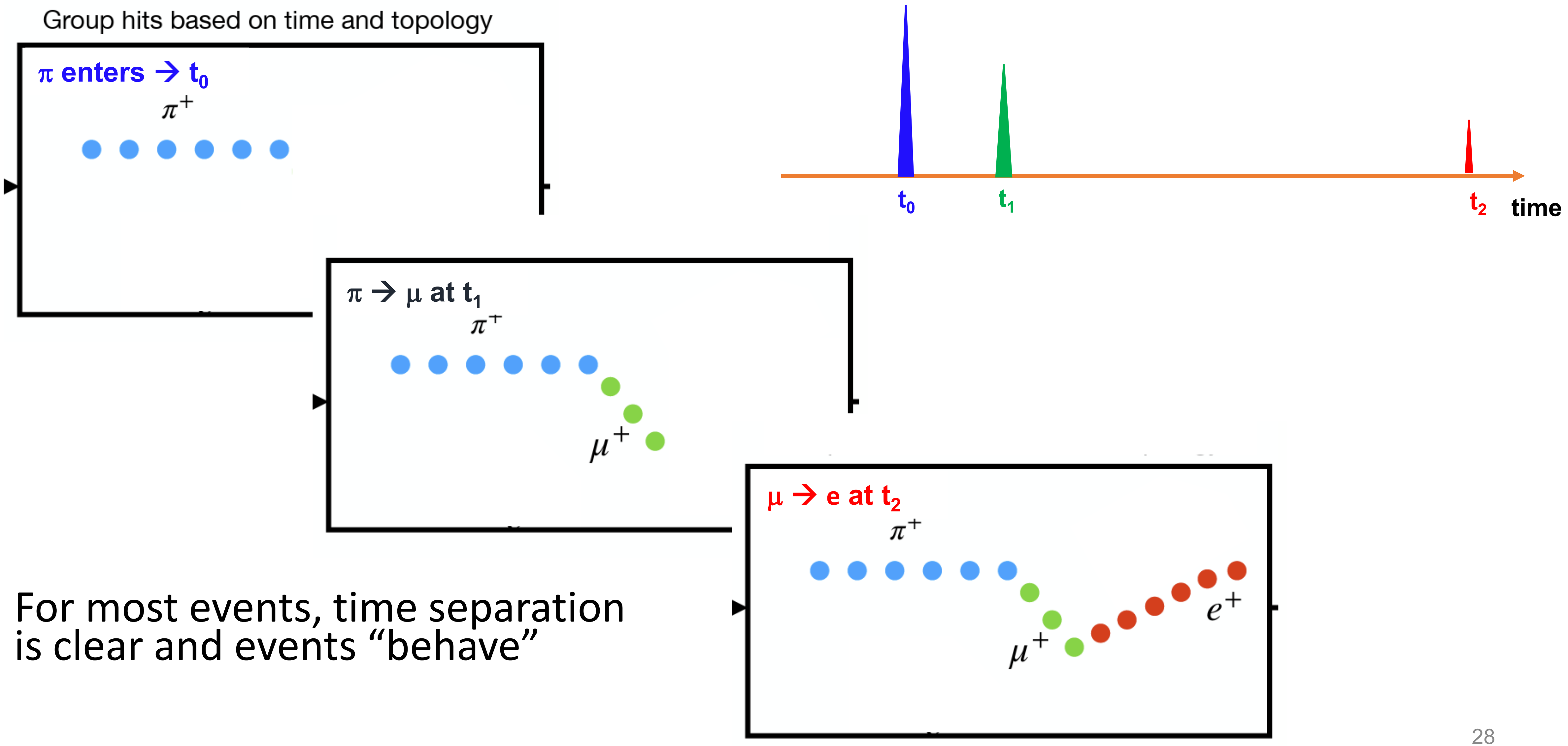
Determine direction of emitted positron
θ_e, ϕ_e

Tail Analysis



Tag $\pi \to \mu \to e$ events. Provide 7 orders of magnitude suppression

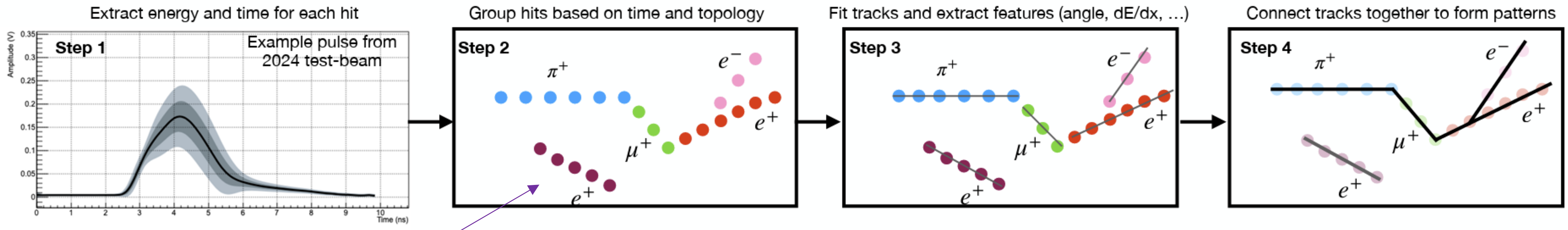
Basic steps involve finding the tracklets



For most events, time separation is clear and events "behave"

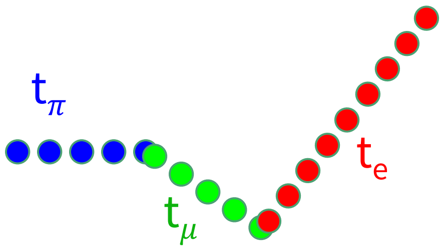
Including the more challenging ones for topological reasons or owing to important sub-dominant processes

In a classic "Rules-based approach"



Do these tracklets all belong to the same sequence?

What about those **old muon** decays?

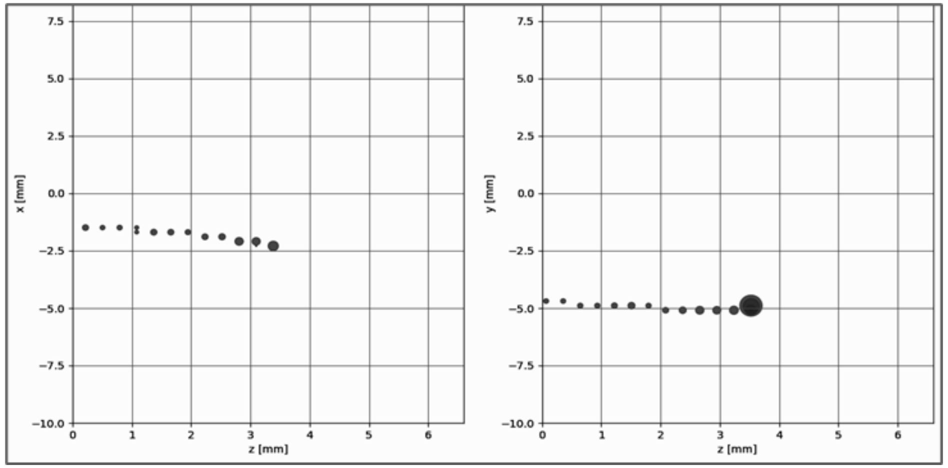


In this approach, we look for
- Time grouped hits
- Patterns to match
- Energy deposits vs expected
- Final directional fits to establish θ/ϕ of positron

And do our best to fit and classify

Omar Beesley (UW)

Advanced AI/ML techniques that adapt to the event topologies based on extensive training



Which particle(s) is responsible for this track?

Neural network without attention:

Here,

- Fixed sets of questions about event
- Likely gives **same time & weight** to each statement.
- But is capable of picking up on details requiring understanding of many things at once

→
This approach struggles with subtle conclusions because of its inflexibility in asking questions and weighting the relevance of different testimonies

“Transformer” based network

Here:

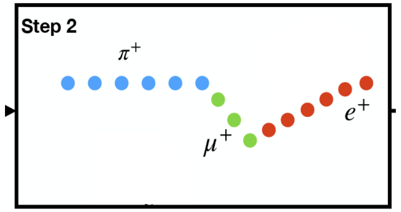
- Adapts questions based on the context of the witness (hits, etc) and what is learned from other hits, etc.
- Weighs the relevance of information based on previous experiences
- Picks up on subtle information requiring details from aspects of the event

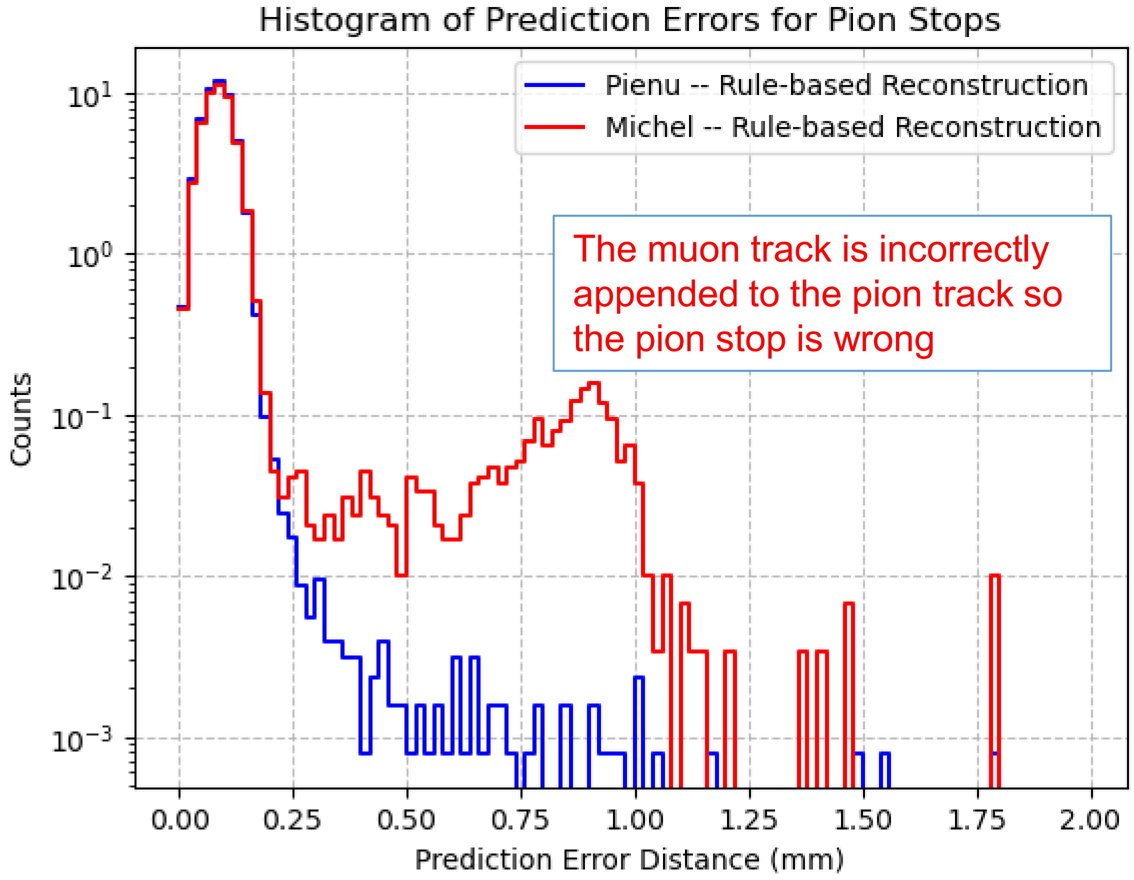
Dynamic weighting: identifying Bragg peaks, grouping time-coincident hits, and leveraging 4D detector data to infer 5D trajectories. Unlike traditional models that rely on distribution moments and outliers, **transformers explicitly learn *relationships between hits***

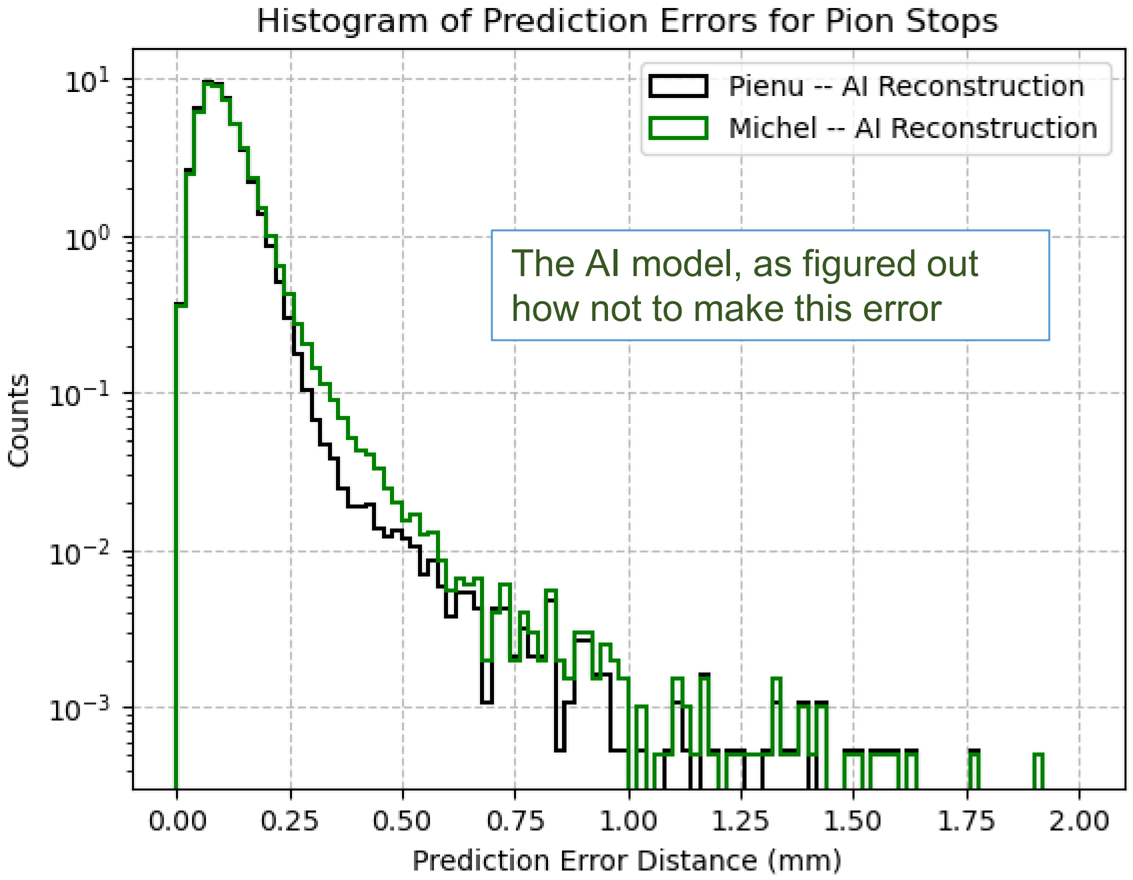
TITLE	CITED BY	YEAR
Attention is all you need A Vaswani, N Shazeer, N Parmar, J Uszkoreit, L Jones, AN Gomez, ... Advances in neural information processing systems 30	202885	2017

Omar Beesley (UW)

An example of how a Rules based approach can differ from our AI/ML approach in the prediction of the Pion stop location in the ATAR for both Pienu and Michel events







Status of PIONEER: A next-gen campaign

- Fundamental R&D on LGADs and Calorimeters
- 2026 Test beam desires
  - piE5 Phase Space
  - 16-Plan ATAR Demonstrator
  - Large LXe prototype (if funding is realized)
- Significant work ongoing on electronics, triggering, digitizers, & DAQ
- PSI shuts down in 2027 and much of 2028.
- We are seeking Euro collaborating groups to join this campaign and take leadership in any of these areas I've mentioned

PIONEER

A next generation rare pion decay experiment