# Status of the PIONEER Experiment

**Sean Foster (Amherst College),**
***on behalf of the PIONEER Collaboration***

**MENU 2026**
**Friday October 23, 2026**

# PIONEER Collaboration

- PIONEER is a next-generation rare pion decay experiment.
- Approved to take place at the Paul Scherrer Institute, near Zurich, Switzerland.
- ~80 collaborators from 20+ institutions across the globe.




- Newer additions (not pictured):
  - Amherst College, University of Hawai'i at Mānoa, Sorbonne Université, Université Paris-Saclay, Rensselaer Polytechnic Institute

# Outline

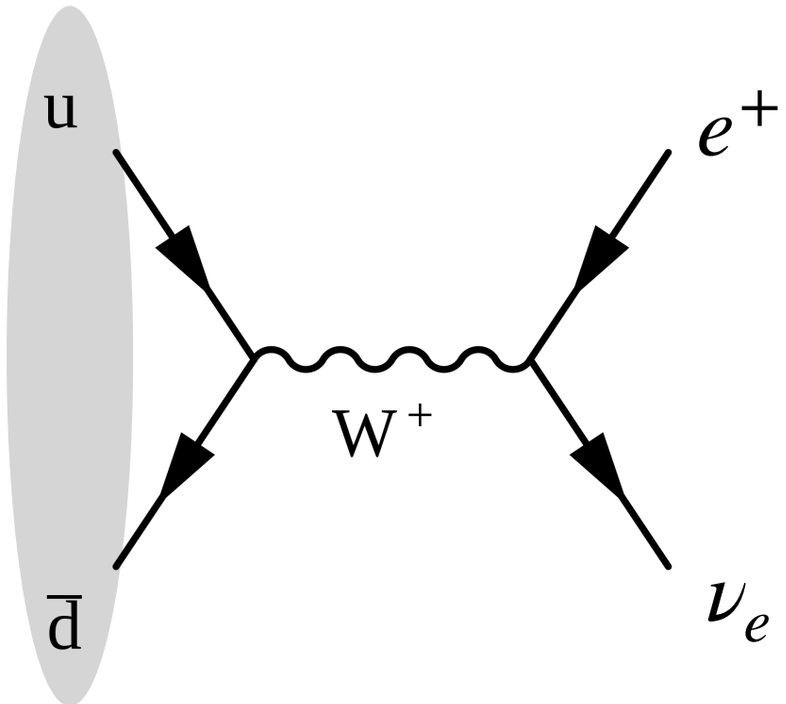
- Physics Goals of the PIONEER Experiment
- The Measurement Principle
- The PIONEER Experiment
- Summary and Conclusions

# Physics Goals of the PIONEER Experiment

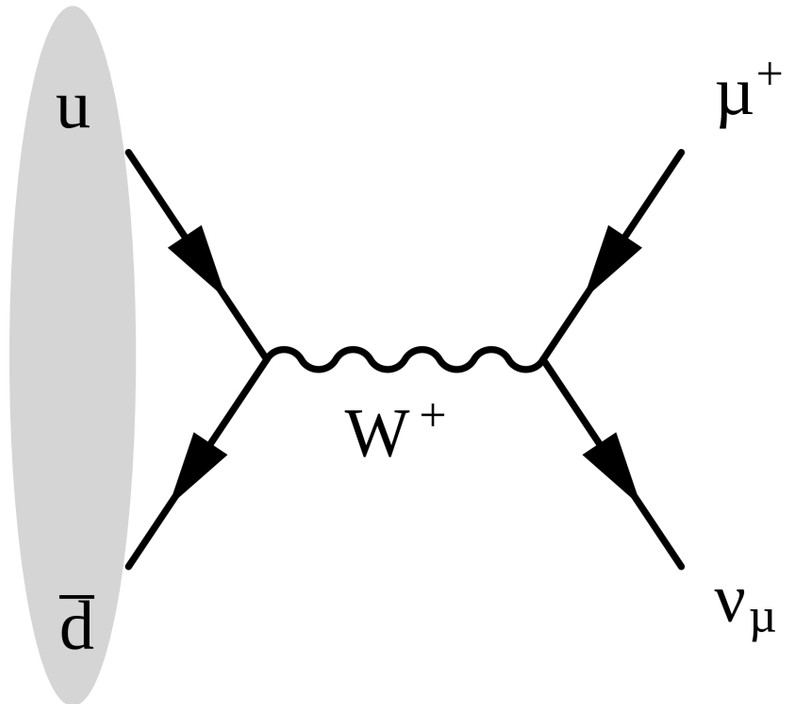
# Rare pion decays

- Rare pion decays were important in the discovery of the V-A structure of the weak interaction.

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




÷




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

Lepton flavor universality: 1

'Helicity suppression' term: ~2.3 x$10^{-5}$

Phase space term: ~ 5.5

# **Physics case I:** 0.01% precision test of lepton flavor universality.

**Measure pion branching ratio**

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

**to 0.01%**

$R_{e/\mu}[\text{Exp.}] = 1.23270(230) \times 10^{-4}$

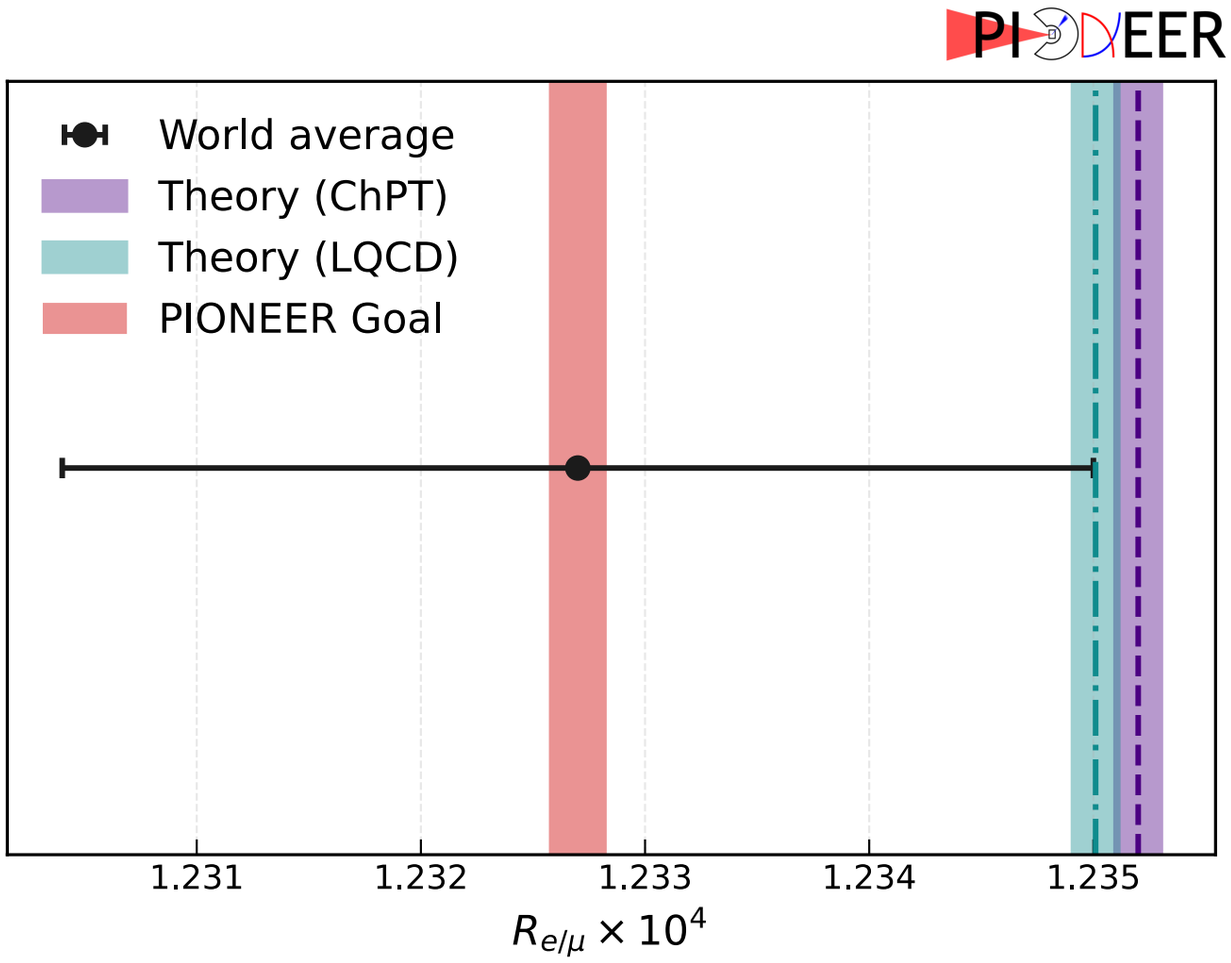
World average PDG PRD 110, 030001 (2024)
Dominated by PIENU, PRL 115, 071801 (2015)

$R_{e/\mu}[\text{SM}] = 1.23524(15) \times 10^{-4}$

Cirigliano & Rosell, PRL 99, 231801 (2007)

$R_{e/\mu}[\text{SM}] = 1.23501(10) \times 10^{-4}$

Boyle et al., arXiv:2607.22358 (2026)

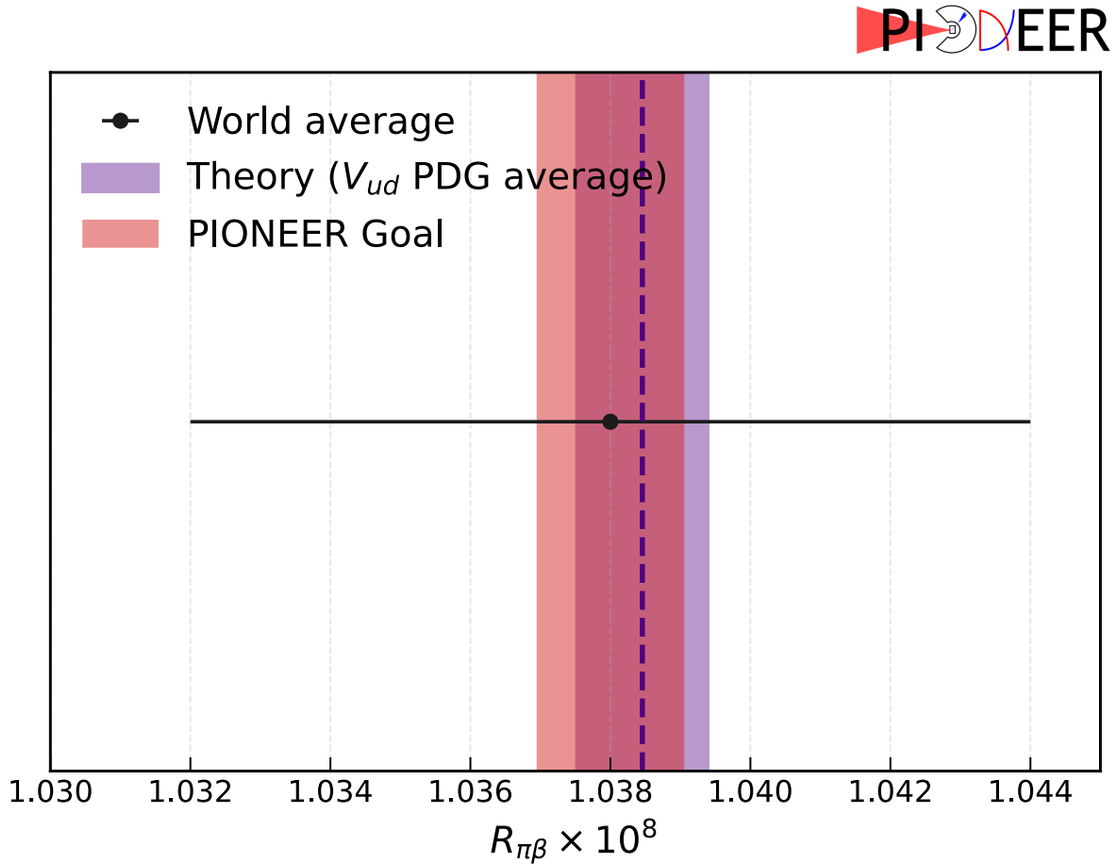



**Testing lepton flavor universality to 0.01%…**

**…requires a 15-fold improvement in the measurement!**

# Goals of the PIONEER Experiment

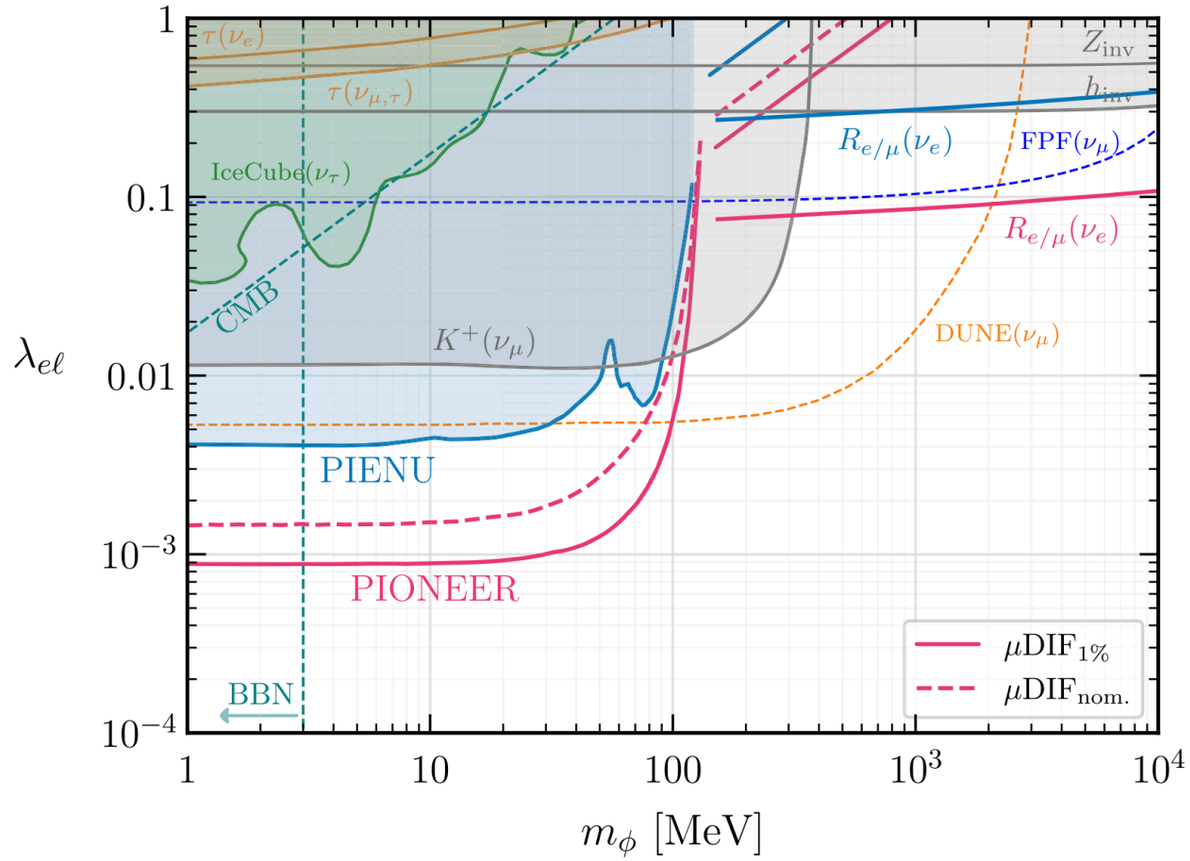
- **Physics case II**: test CKM matrix unitarity.
- **Physics case III**: search for weakly coupled new physics.




Pion beta decay: $\pi^+ \to \pi^0 e^+ \nu_e$

PIBETA, PRL 93, 181803 (2004)

Cirigliano *et al.*, PRL 137, 051902 (2026)

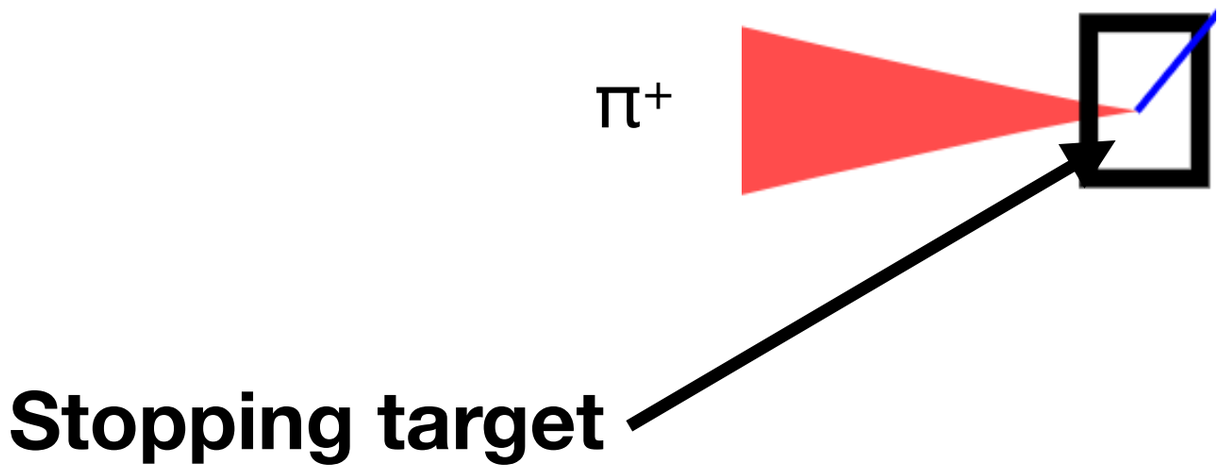



de Lima et al., PRD 113, 095016 (2026)

# The Measurement Principle

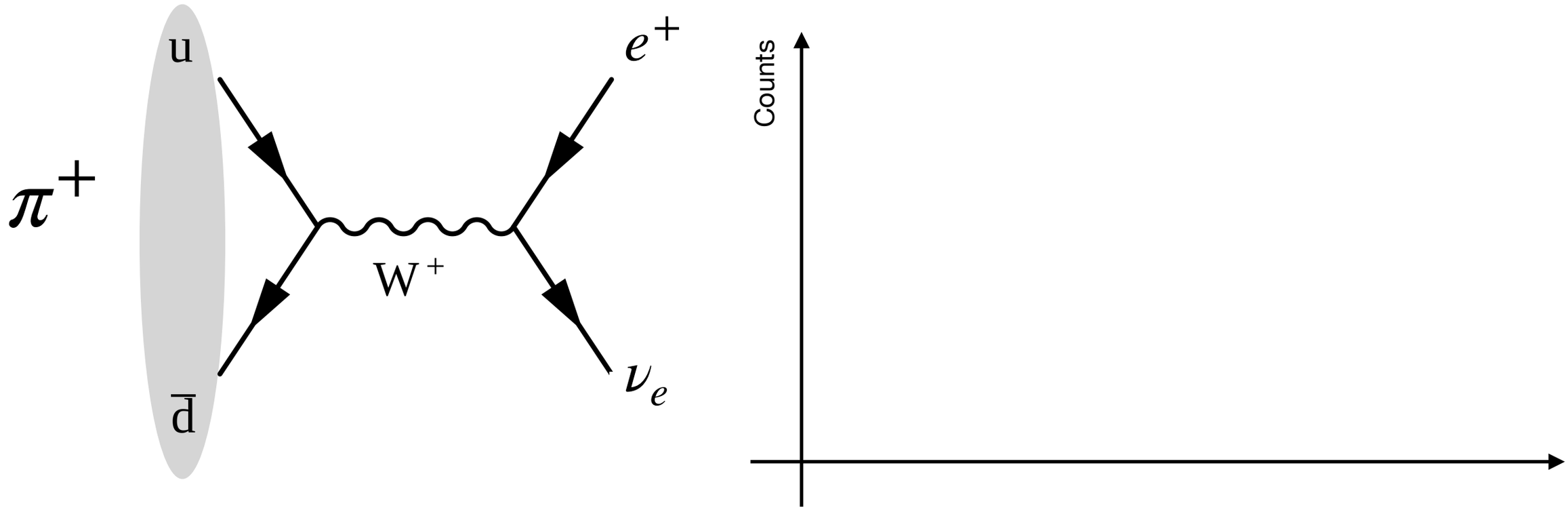
# **Basic requirements:** a target

- We need a **source** of pions.
- We need a **target** to stop the incoming pions.



# Measurement strategy

- $R_{e/\mu}$ measurement strategy

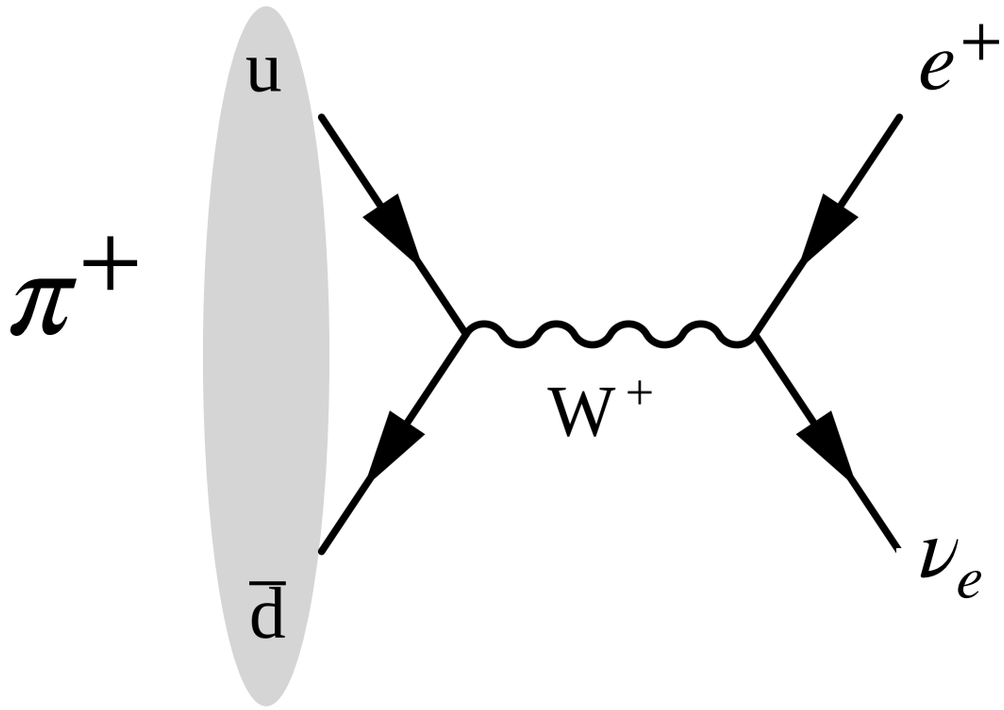



$$m_{\pi^+} = 139.6\,\text{MeV}$$
$$\tau_{\pi^+} \approx 26\,\text{ns}$$

The pion stops in the target and decays.

# Measurement strategy

- $R_{e/\mu}$ measurement strategy





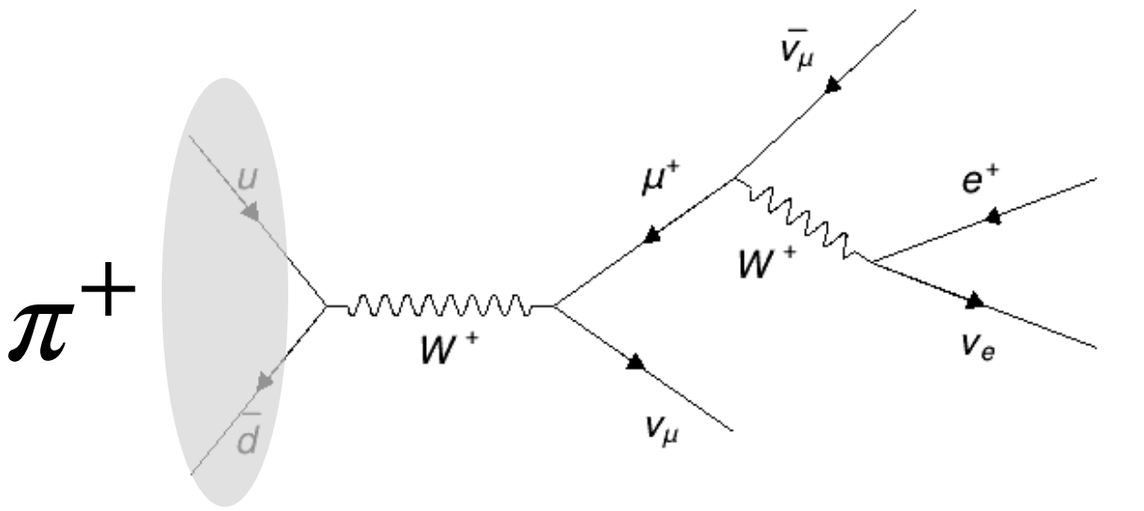


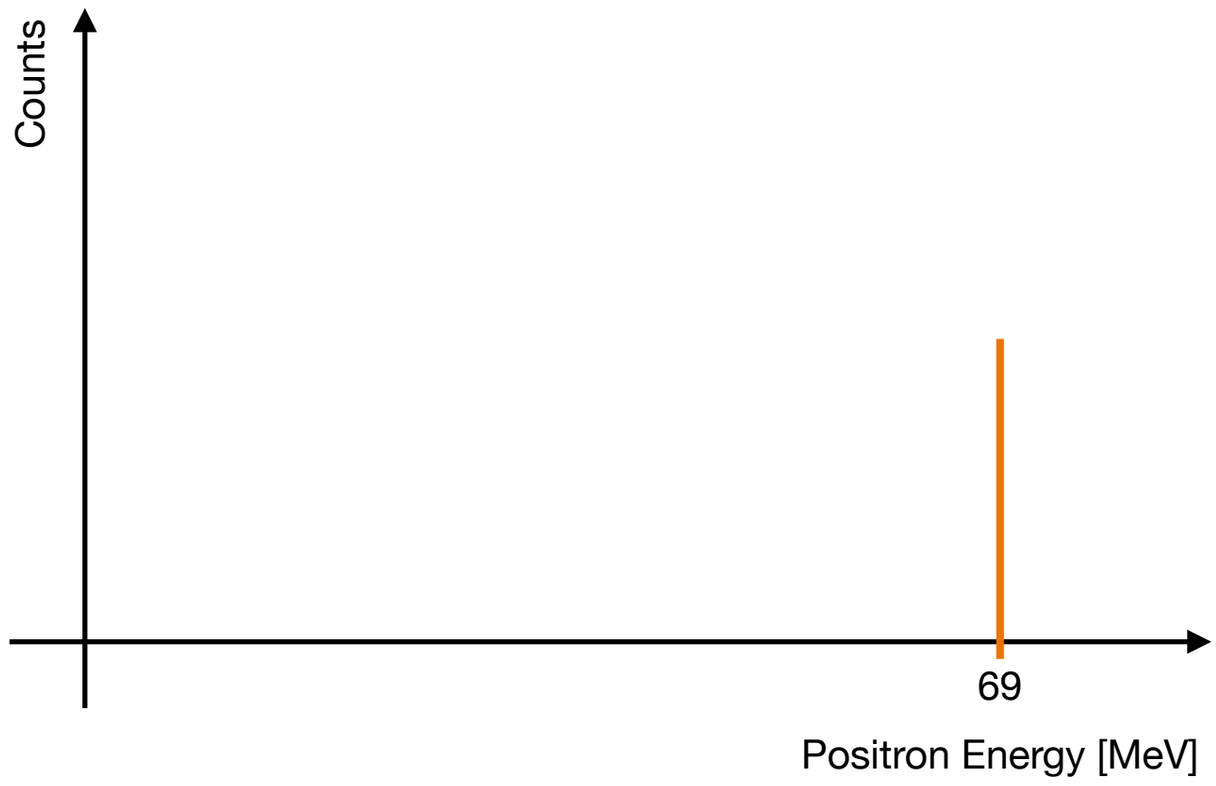
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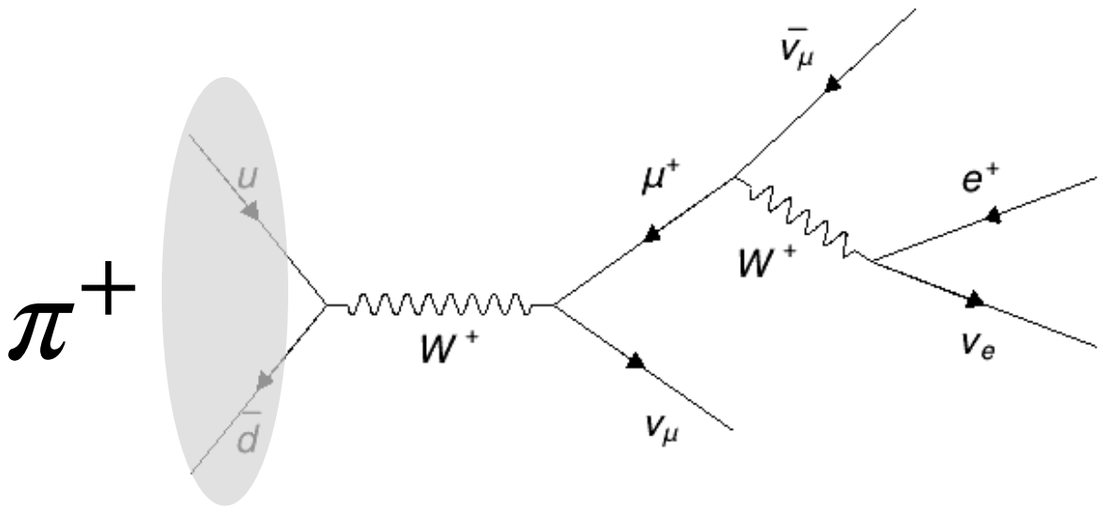

$$m_{\pi^+} = 139.6\,\text{MeV}$$
$$m_{\mu^+} = 105.7\,\text{MeV}$$
$$\tau_{\mu^+} \approx 2.2\,\mu\text{s}$$

The pion stops in the target and decays.

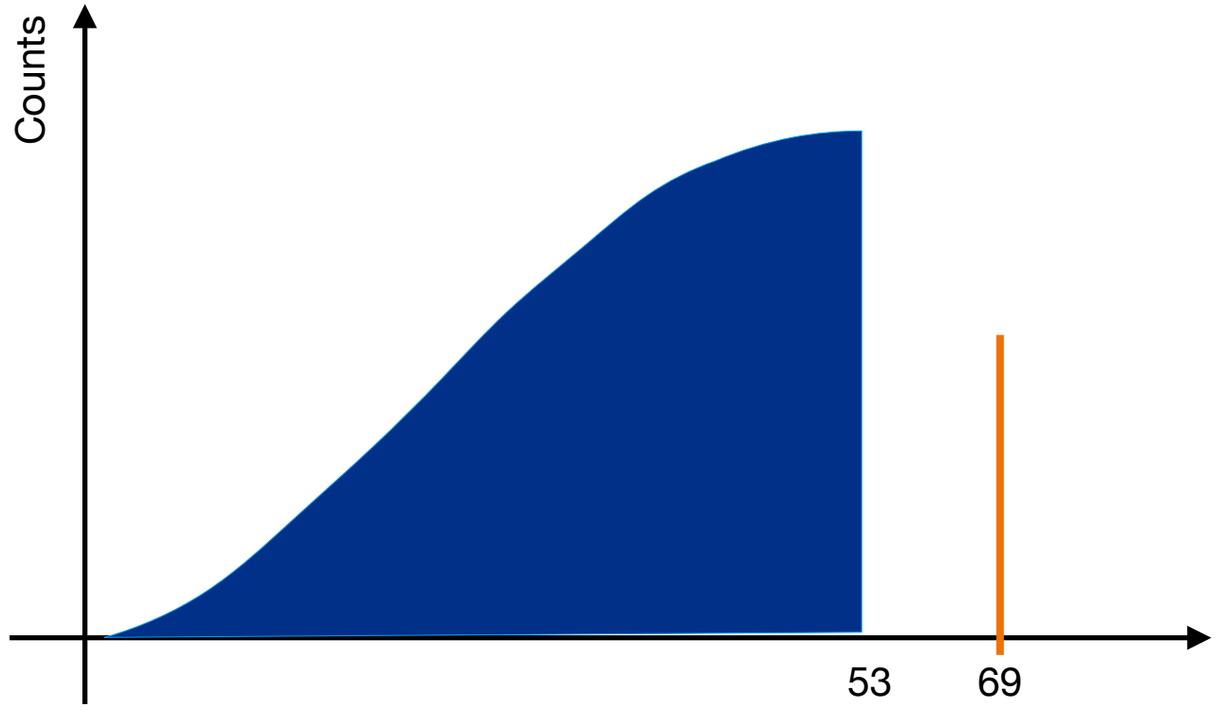
Then the muon stops in the target and decays.

# Measurement strategy

- $R_{e/\mu}$ measurement strategy




$$m_{\pi^+} = 139.6\,\text{MeV}$$
$$m_{\mu^+} = 105.7\,\text{MeV}$$
$$\tau_{\mu^+} \approx 2.2\,\mu\text{s}$$

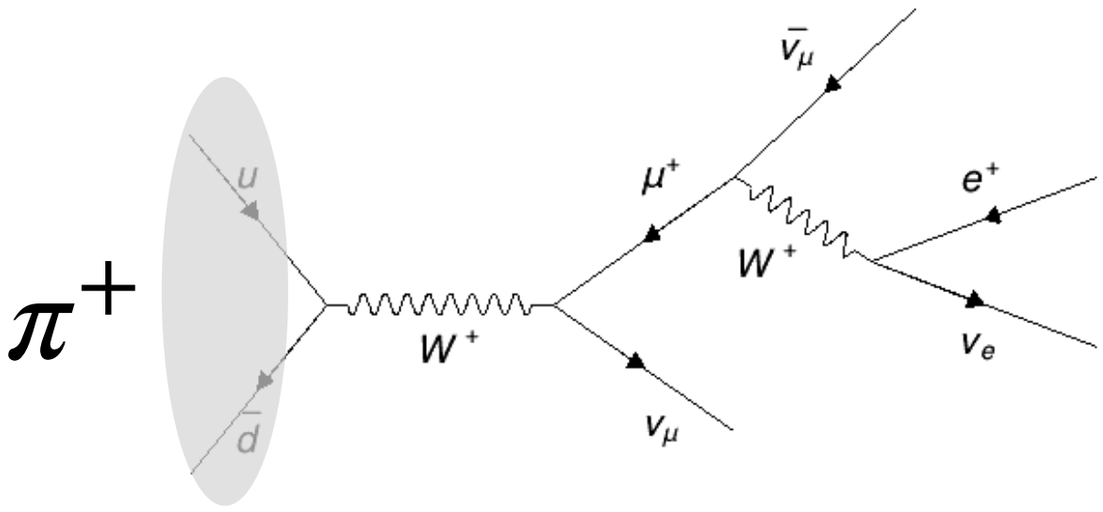



The pion stops in the target and decays.

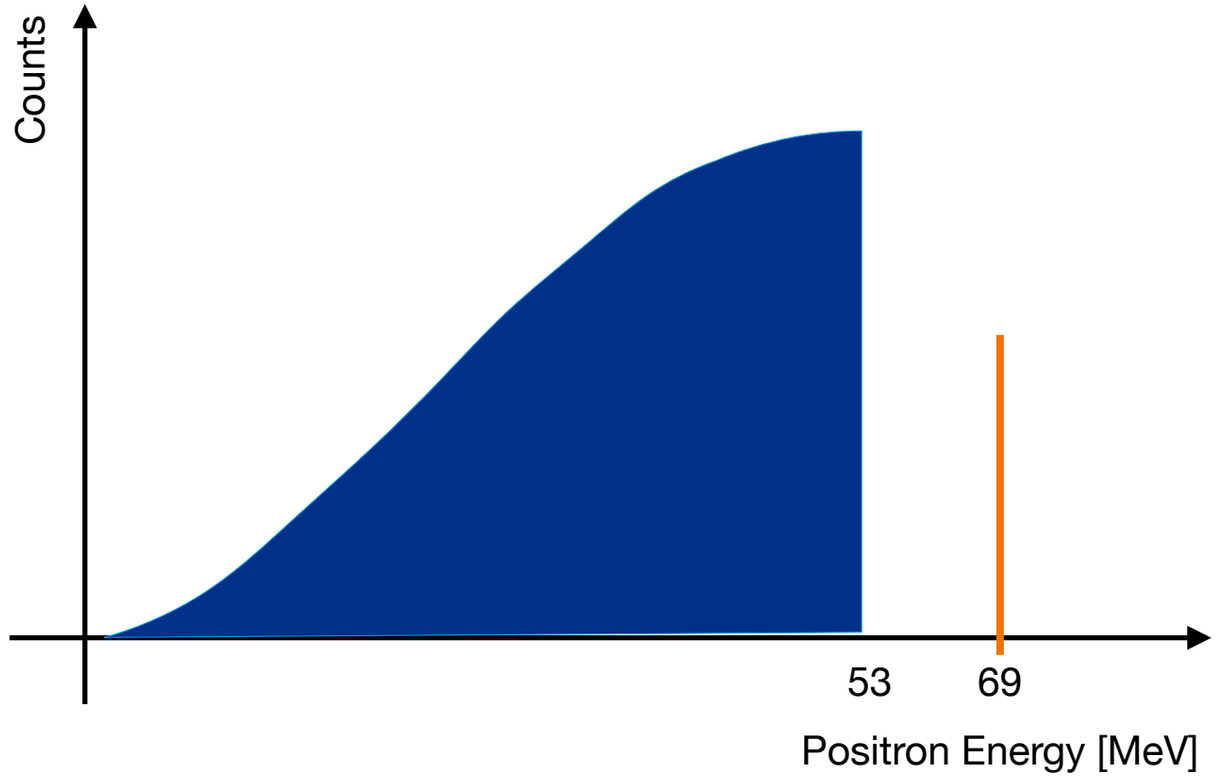
Then the muon stops in the target and decays.

# Measurement strategy

- $R_{e/\mu}$ measurement strategy




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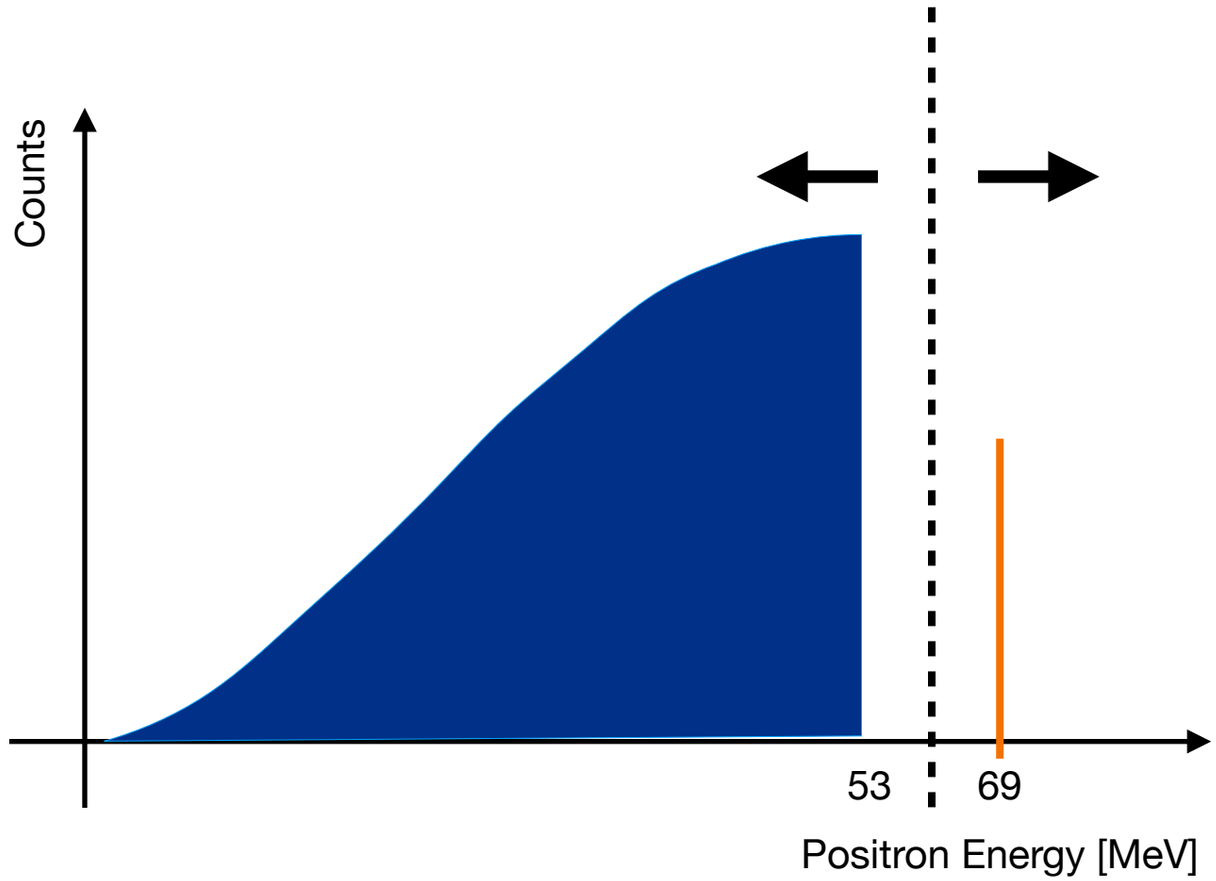



Not to scale!

The pion stops in the target and decays.

Then the muon stops in the target and decays.

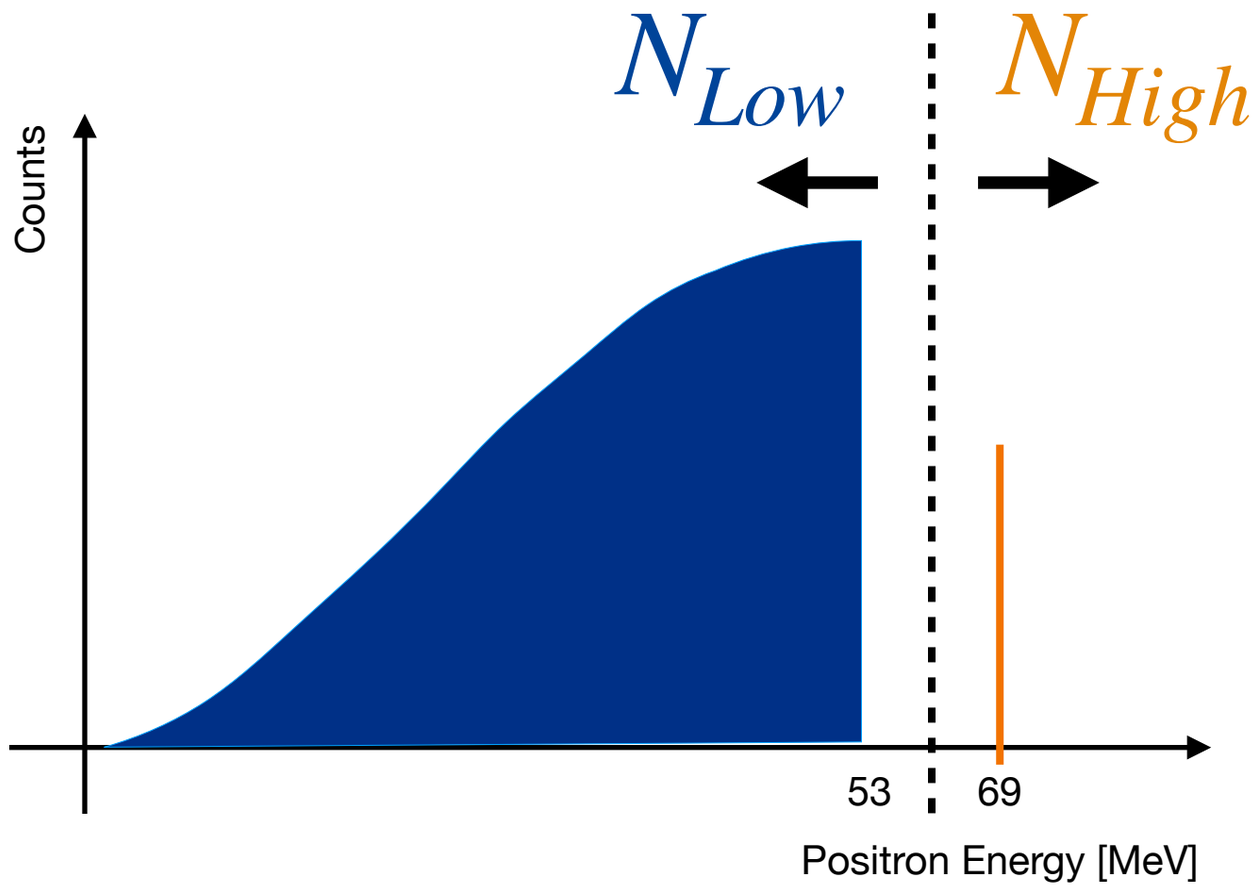
# A counting experiment




Not to scale!

Count events above and below an energy threshold.

# A counting experiment



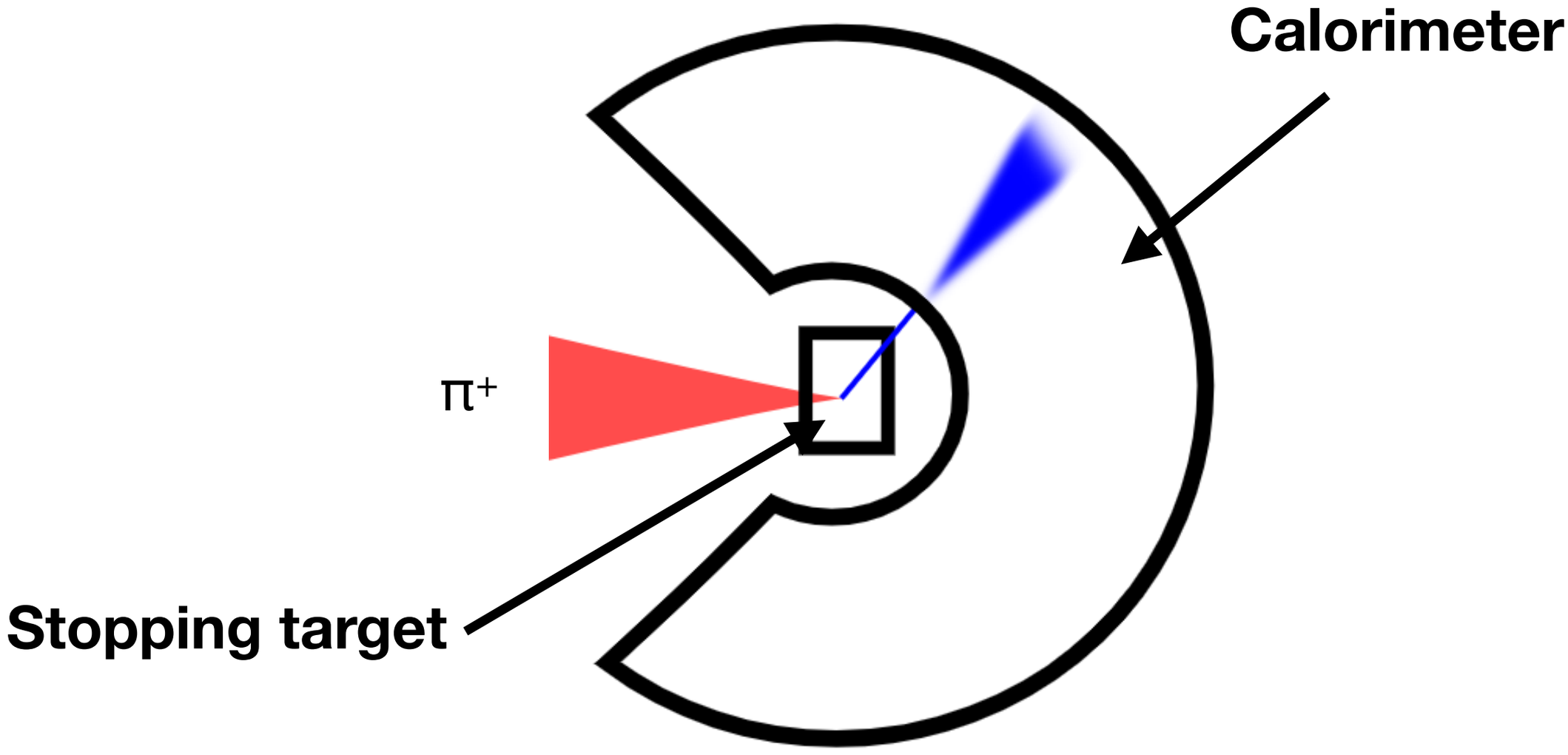

Not to scale!

Count events above and below an energy threshold.

$$R_{e/\mu} = \frac{N_{High}}{N_{Low}}$$

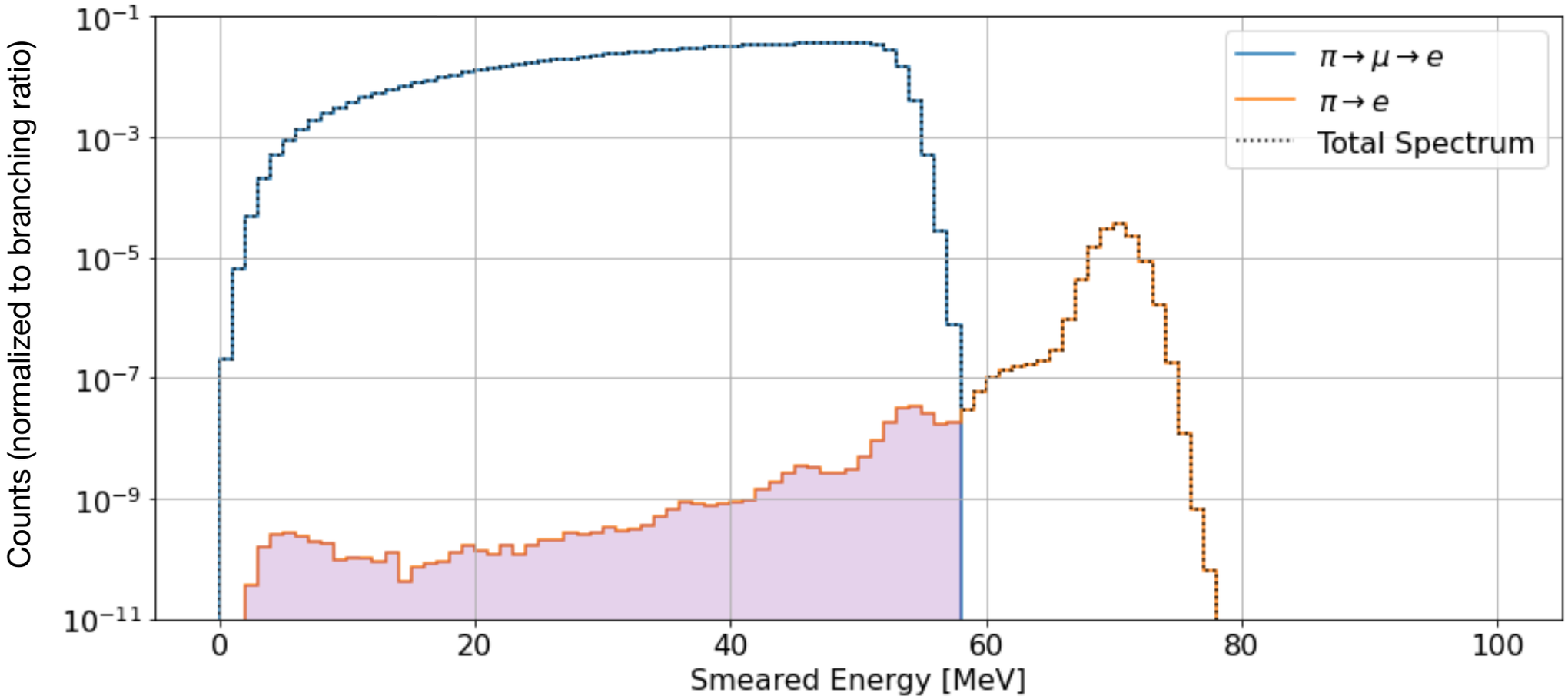
# **Basic requirements:** a calorimeter

- A calorimeter surrounds the stopping target to intercept decay positron and measure its energy.

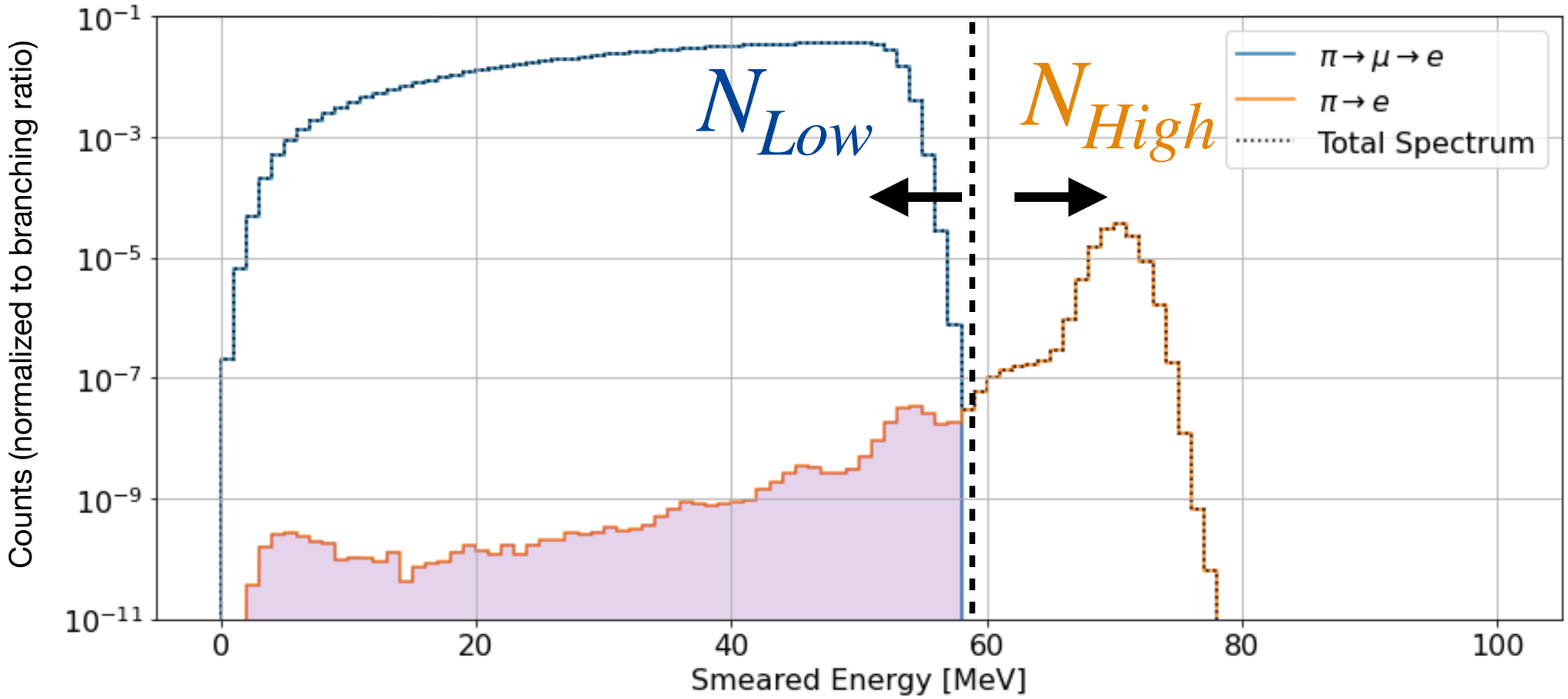


# Reality complicates the picture

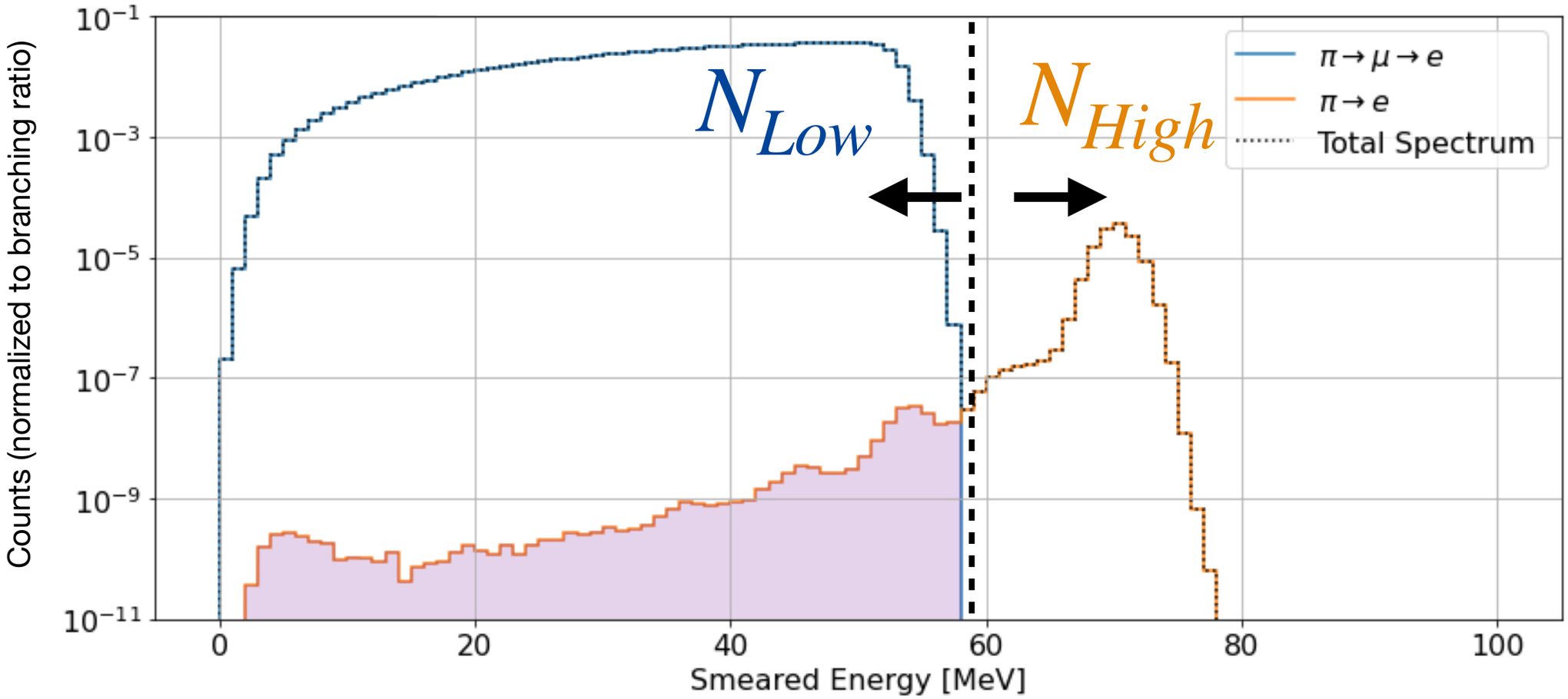
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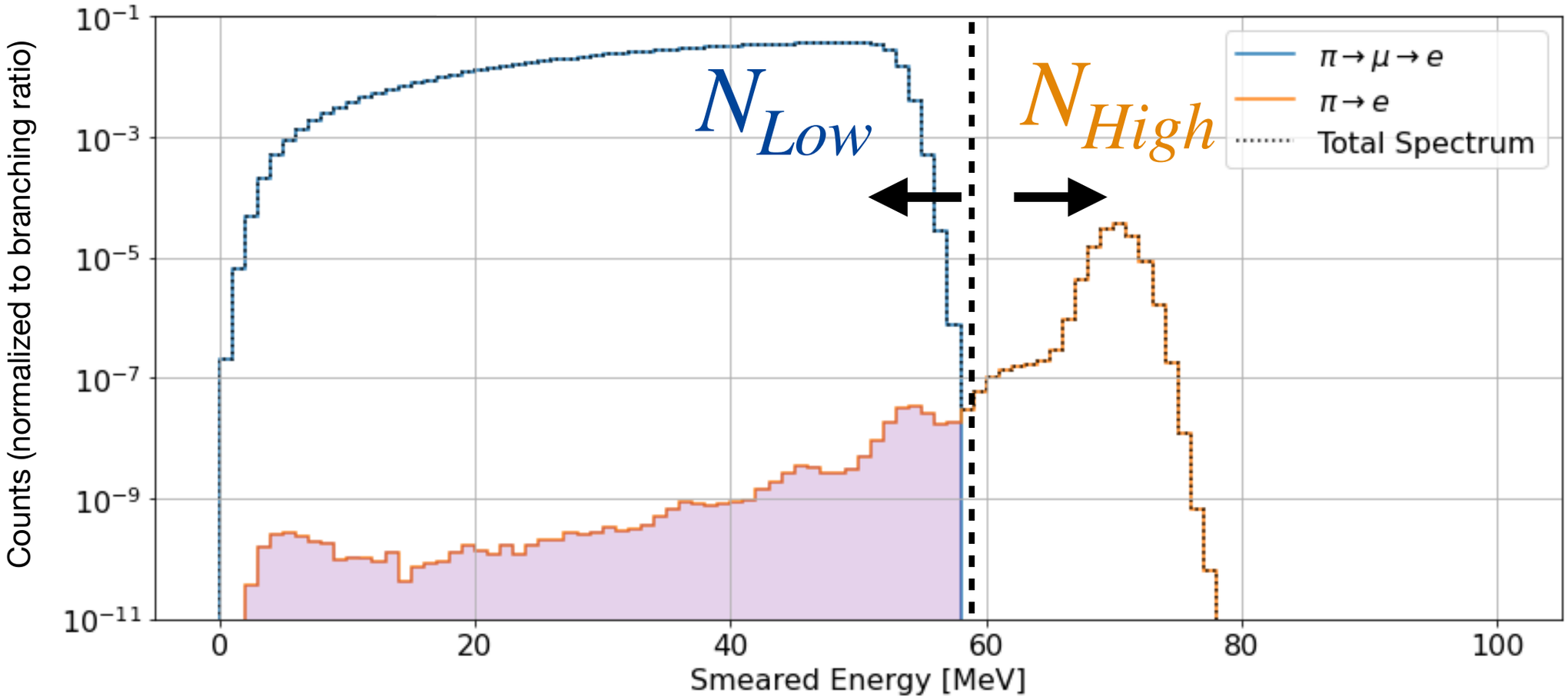


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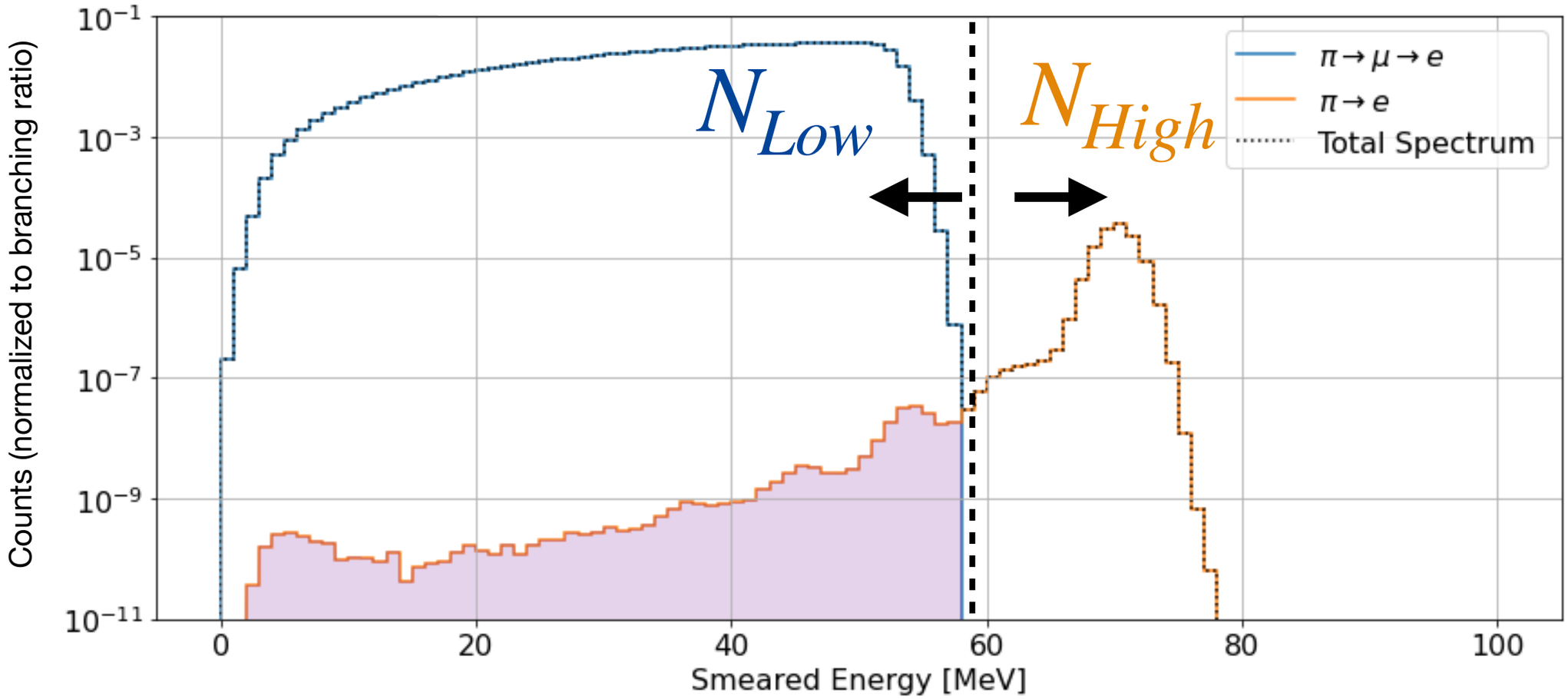

$$R_{e/\mu} = \frac{N_{high}}{N_{low}}$$

# Reality complicates the picture




$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right]$$

# Reality complicates the picture




$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

Acceptance

# Achieving a 0.01% measurement

$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

# Achieving a 0.01% measurement

- Goal: $\Delta R_{e/\mu} = 0.01\,\%$

$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

# Achieving a 0.01% measurement

- Goal: $\Delta R_{e/\mu} = 0.01\,\%$

$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

$$\Delta N = \frac{1}{\sqrt{N}}$$

- Need $N_{high} \sim 2 \times 10^8$
- Need $N_{low} \sim 2 \times 10^8$

# Achieving a 0.01% measurement

- Goal: $\Delta R_{e/\mu} = 0.01\,\%$

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$$\Delta N = \frac{1}{\sqrt{N}}$$

- Need $N_{high} \sim 2 \times 10^8$
- Need $N_{low} \sim 2 \times 10^8$

- $\Delta C_{tail} \approx 0.01\,\%$
- If $C_{tail} = 1\,\%$ then $\frac{\Delta C_{tail}}{C_{tail}} \approx 1\,\%$

# Achieving a 0.01% measurement

- Goal: $\Delta R_{e/\mu} = 0.01\,\%$

- $R_\epsilon$ = acceptance ratio
- Need $\dfrac{\Delta R_\epsilon}{R_\epsilon} \approx 0.01\,\%$

$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_\epsilon$$

$$\Delta N = \frac{1}{\sqrt{N}}$$

- Need $N_{high} \sim 2 \times 10^8$
- Need $N_{low} \sim 2 \times 10^8$

- $\Delta C_{tail} \approx 0.01\,\%$
- If $C_{tail} = 1\,\%$ then $\dfrac{\Delta C_{tail}}{C_{tail}} \approx 1\,\%$

# Guiding principles for designing the experiment

$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

# Guiding principles for designing the experiment

1. Collect a large dataset of rare $\pi^+ \to e^+\nu_e$ decays.

$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

# Guiding principles for designing the experiment

1. Collect a large dataset of rare $\pi^+ \to e^+\nu_e$ decays.
2. Keep size of the tail at less than 1% of the signal.

$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

# Guiding principles for designing the experiment

1. Collect a large dataset of rare $\pi^+ \to e^+\nu_e$ decays.
2. Keep size of the tail at less than 1% of the signal.
3. Measure tail to a precision of 1%.

$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

# Guiding principles for designing the experiment

1. Collect a large dataset of rare $\pi^+ \to e^+\nu_e$ decays.
2. Keep size of the tail at less than 1% of the signal.
3. Measure tail to a precision of 1%.
4. Understand acceptance effects to a precision of 0.01%.

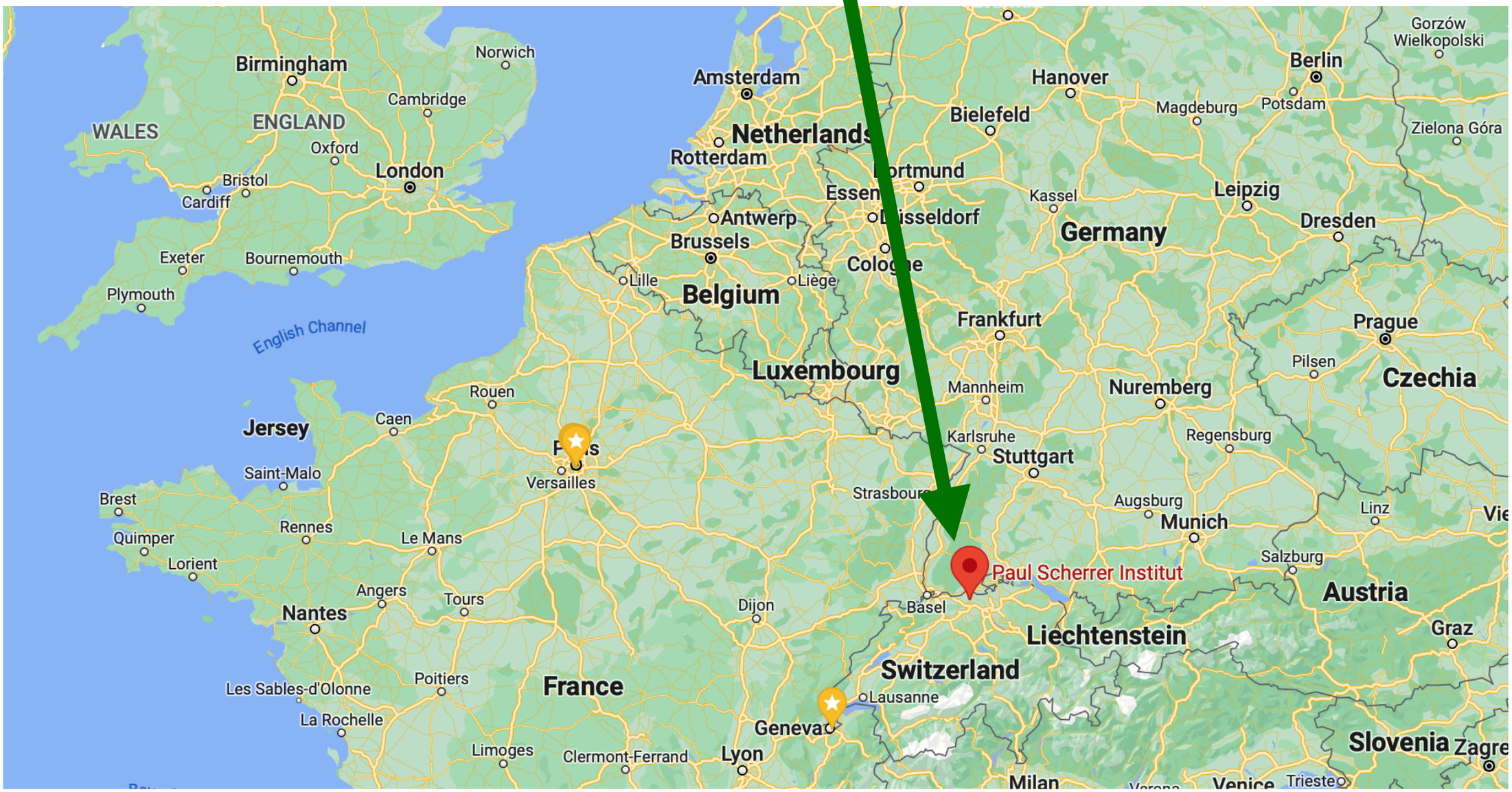
$$R_{e/\mu} = \frac{N_{high}}{N_{low}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

# The PIONEER Experiment

# 1. Collect a large dataset of rare $\pi^+ \to e^+\nu_e$ decays

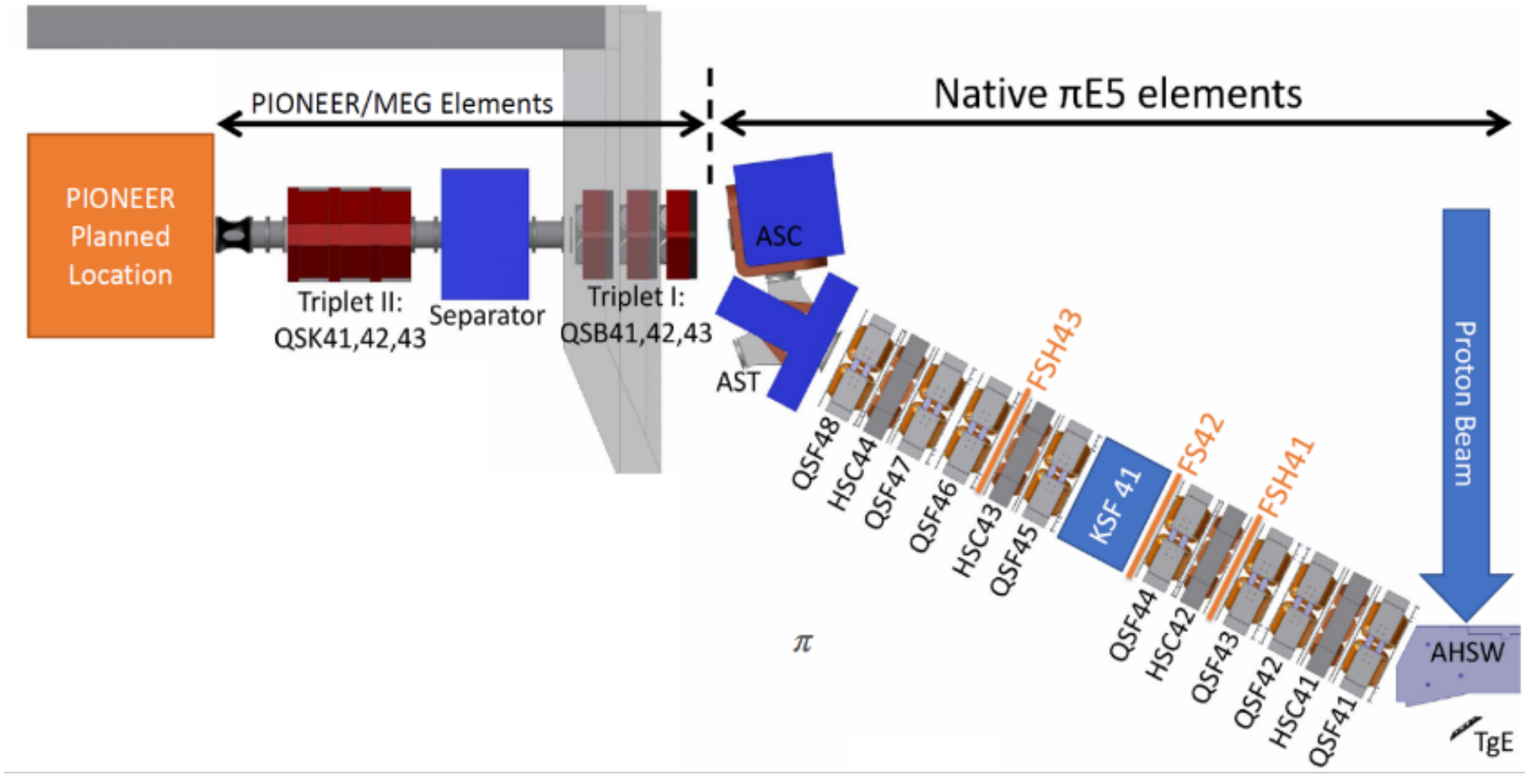
**PSI**

Paul Scherrer Institute
Located near Zurich, Switzerland
World's most intense source of low-energy pions



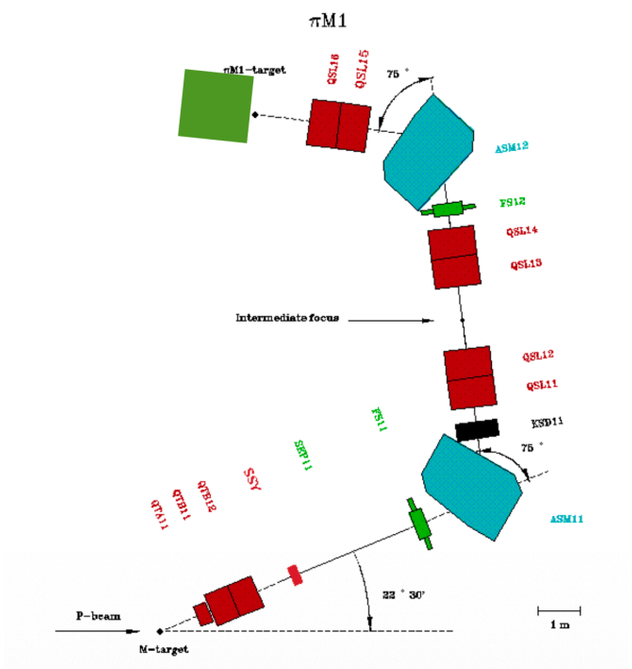
# Pion beam

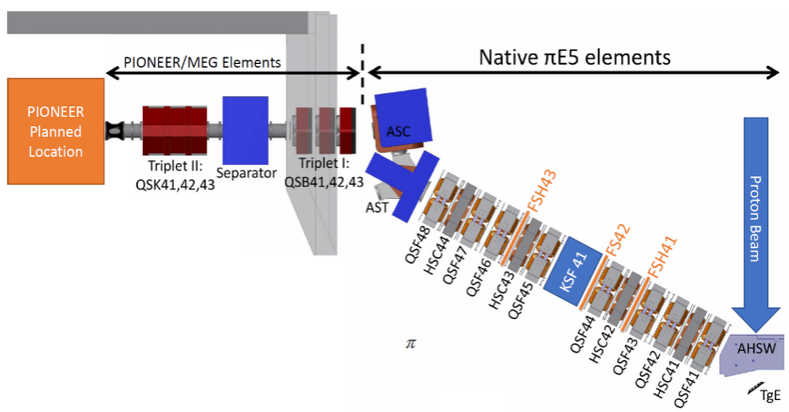
- We will use the $\pi$E5 beam line at PSI.
- Provides 65 MeV/c DC beam @300 kHz, directed on target.
  - 1 pion every 3.3 μs



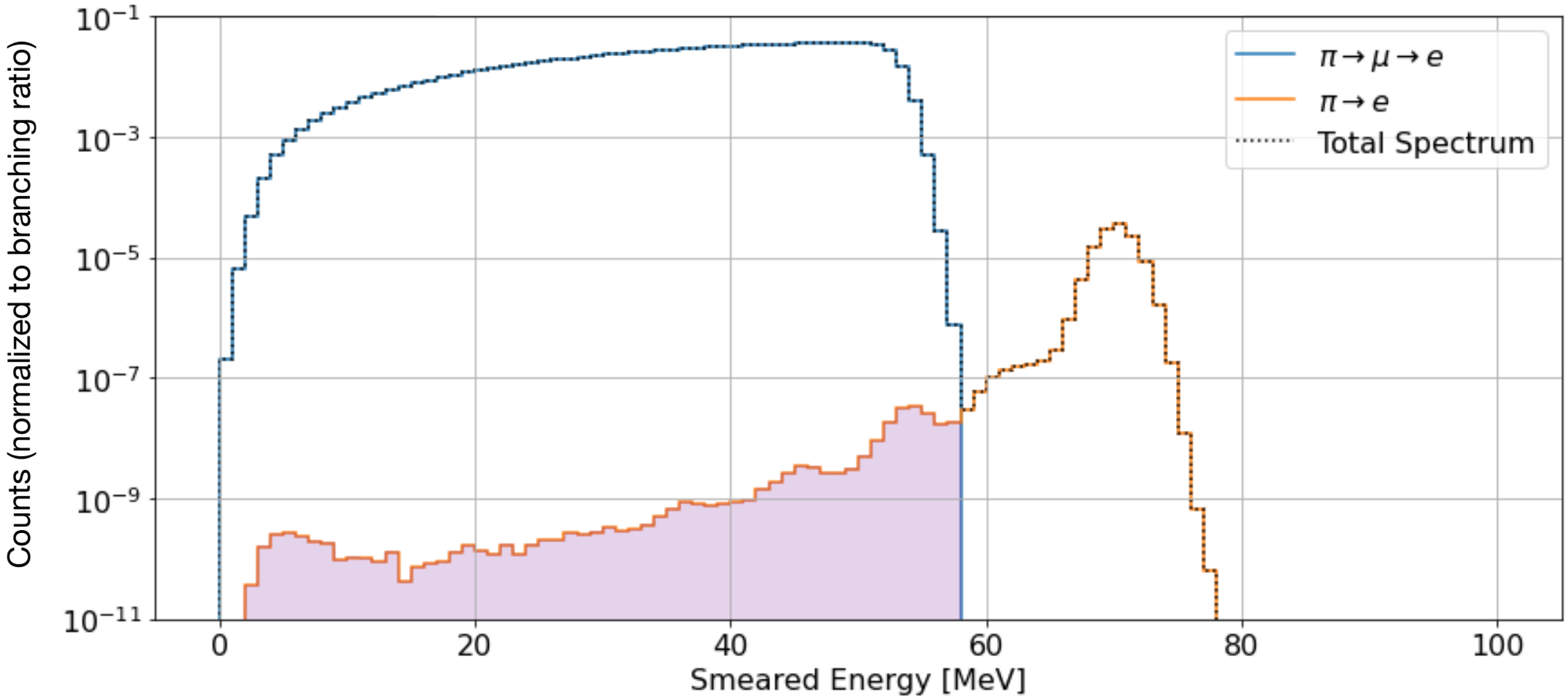
# Phase space measurements this year!

- Two beam times at PSI this year: $\pi$M1 (Sept. 21-27, 2026) and $\pi$E5 (Oct. 5-11, 2026).
- Goal: understand the beam's phase space
  - Knowledge will aid experiment beam line design for **particle separation** and **beam focusing**.
- Analysis ongoing.



# 2. Keep size of the tail at less than 1% of the signal




- Calorimeter requirements:
  - **Energy resolution**: at least 2% for 70 MeV positrons.
  - **Shower containment**: at least 19 radiations lengths.

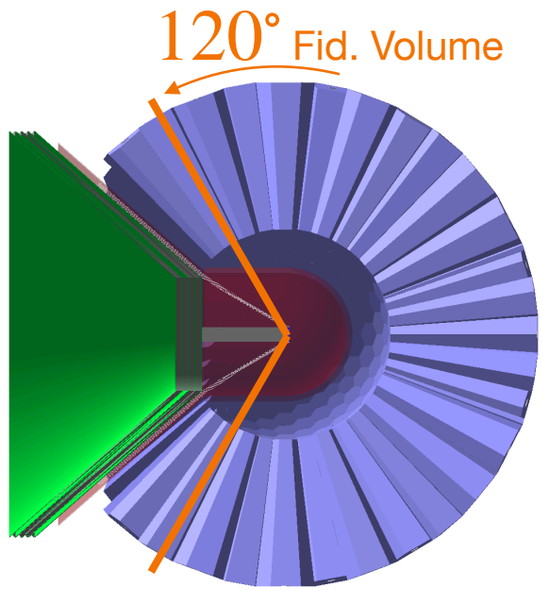
# Calorimeter — baseline

- LYSO-based calorimeter

  LYSO Crystals

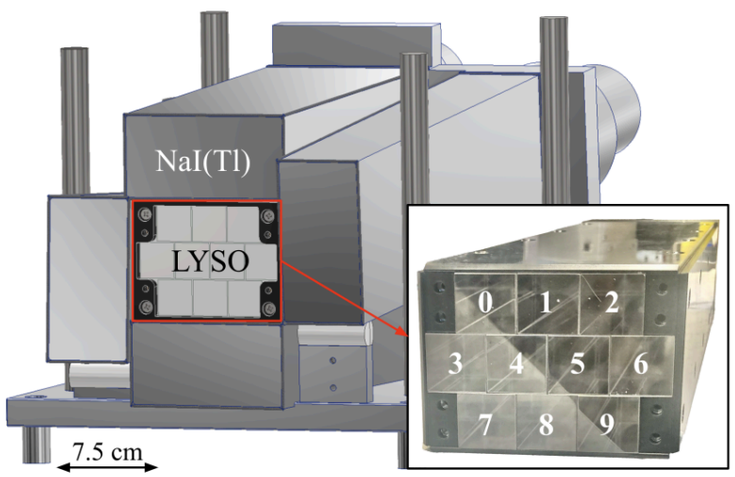
  Lutetium-yttrium oxyorthosilicate, $Lu_{2(1-x)}Y_{2x}SiO_5$

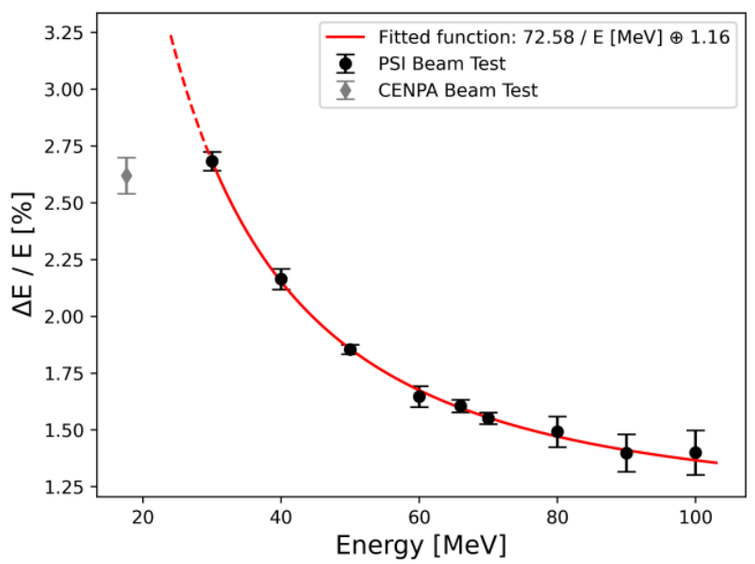
- Properties
  - High light yield ~30,000 photons/MeV
  - Short 40 ns decay time
  - Segmentation
  - Dense/high Z: 7.1 g/cm3, Z ~ 65
  - Radiation hard and limited temperature sensitivity
  - Intrinsic radioactivity

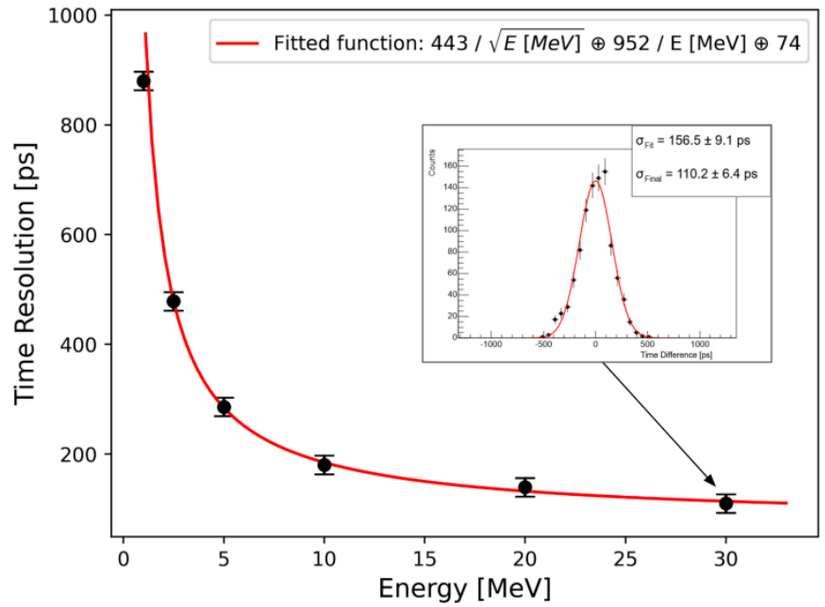



15 cm inner radius
42 cm total radius

# LYSO calorimeter test



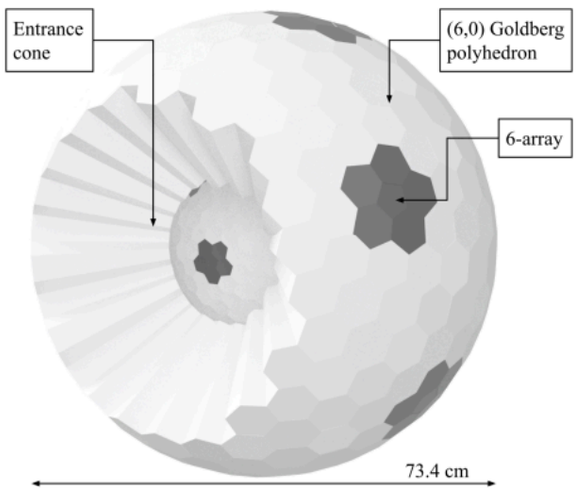



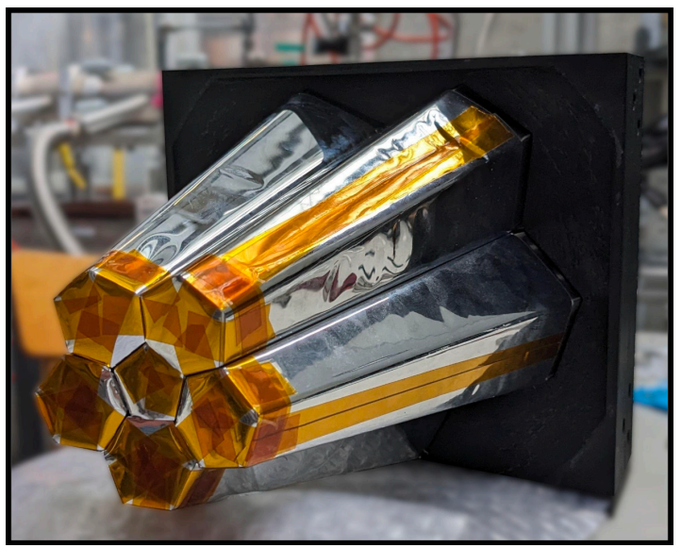



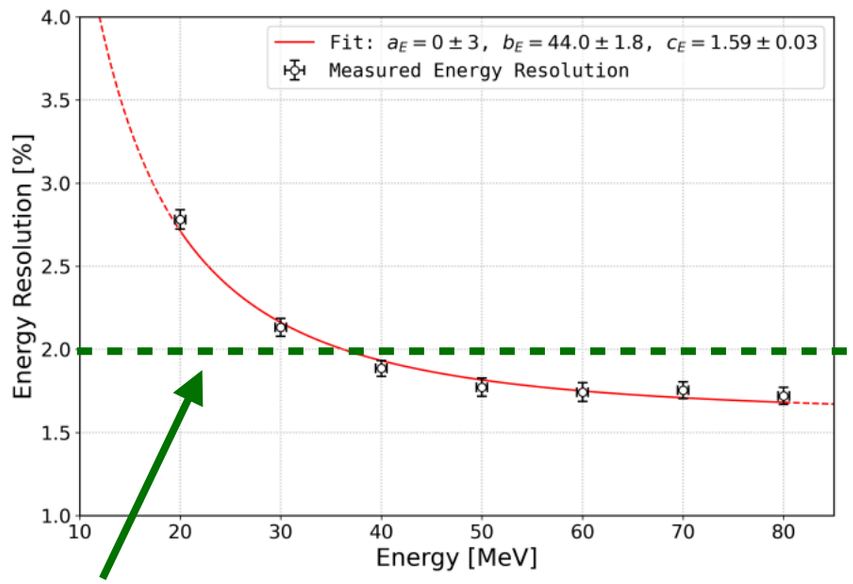

Beesley et al., NIM A 1075, 170320 (2025)

- In 2023, rectilinear array of 10 LYSO crystals tested at $\pi$M1 beam line at PSI, using a range of positron energies.
- Demonstrated:
  - Energy resolution of **1.52%** for **70 MeV.**
  - Time resolution of **~100 ps** at **30 MeV**.
  - Meets PIONEER requirements, but not the correct geometry.

# Testing tapered LYSO crystals

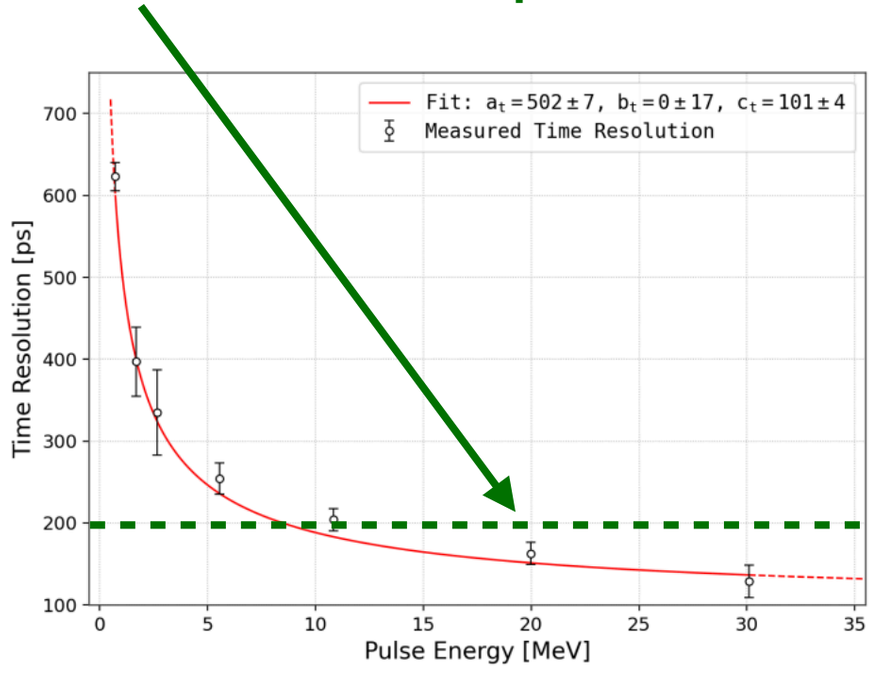





PIONEER requirement

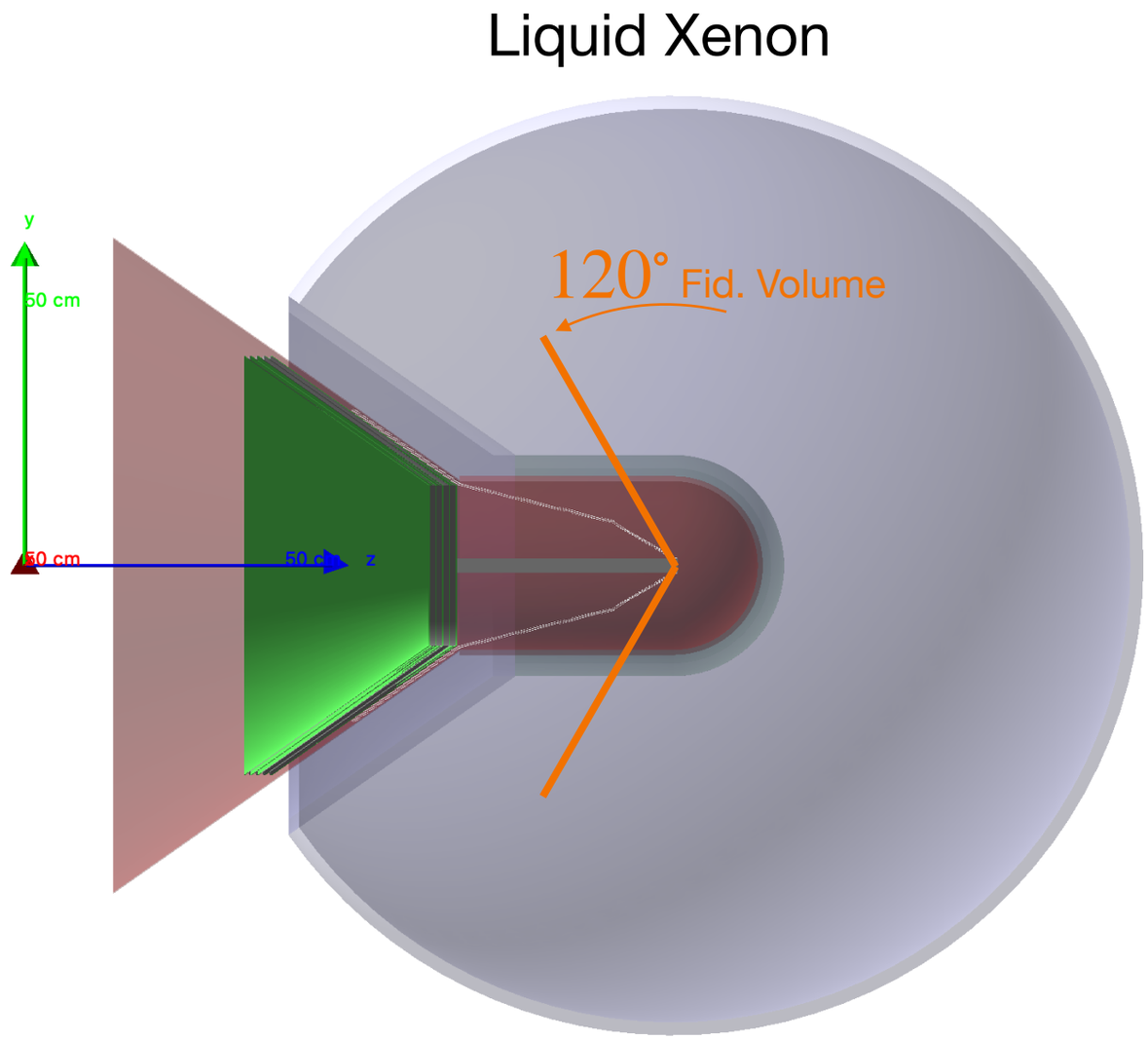
- In 2025, array of tapered LYSO crystals tested at $\pi$M1 beam line at PSI.
- Demonstrated:
  - Energy resolution better than **2%** above **35 MeV**.
  - Time resolution of **~135 ps** at **30 MeV**.
  - Meets PIONEER requirements, with correct geometry!




Beesley *et al.*, arXiv:2607.09226 (2026)

# Calorimeter — alternate

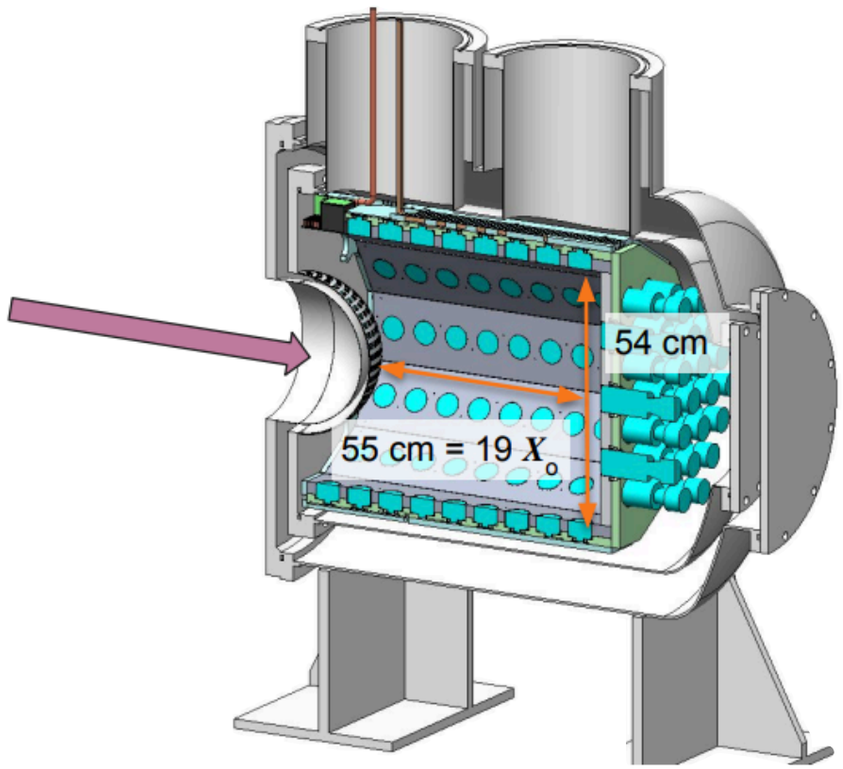
- LXe-based calorimeter




15 cm inner radius
77 cm total radius

# LXe calorimeter development

- **Development of a prototype**
  - Goals: test new hardware, compare measurements to MC, study shower leakage, photo-nuclear effects and pileup suppression.

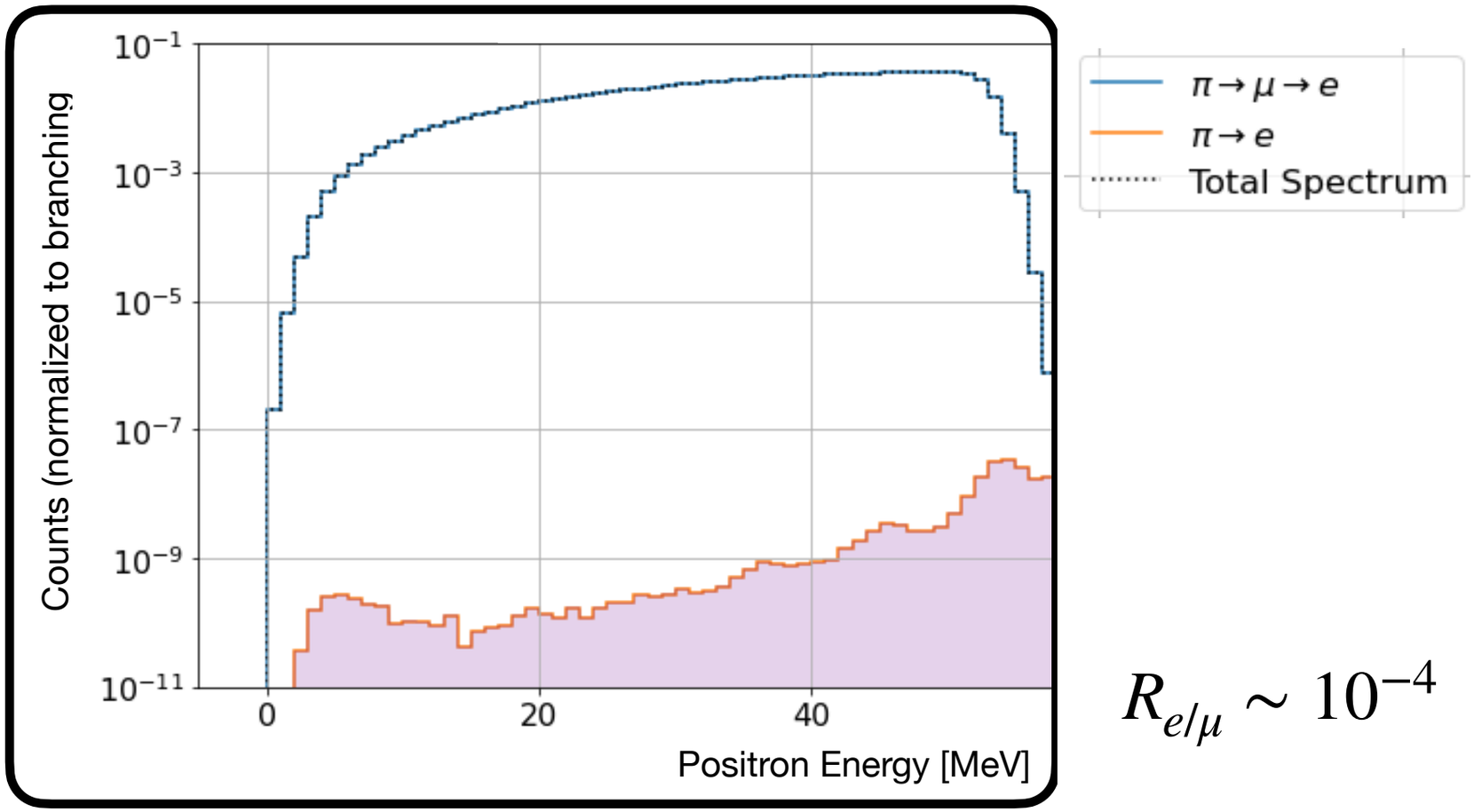



E. Klemets 2025 CIPANP talk

- **SiPM tests at PSI next week (!) and in November**
  - Goal is to investigate degradation of photo detection efficiency for different SiPMs.
  - SiPMs will be irradiated with a positron beam, as well as the LXe scintillation light.

# 3. Measure tail to a precision of 1%

- Challenging signal/background problem.

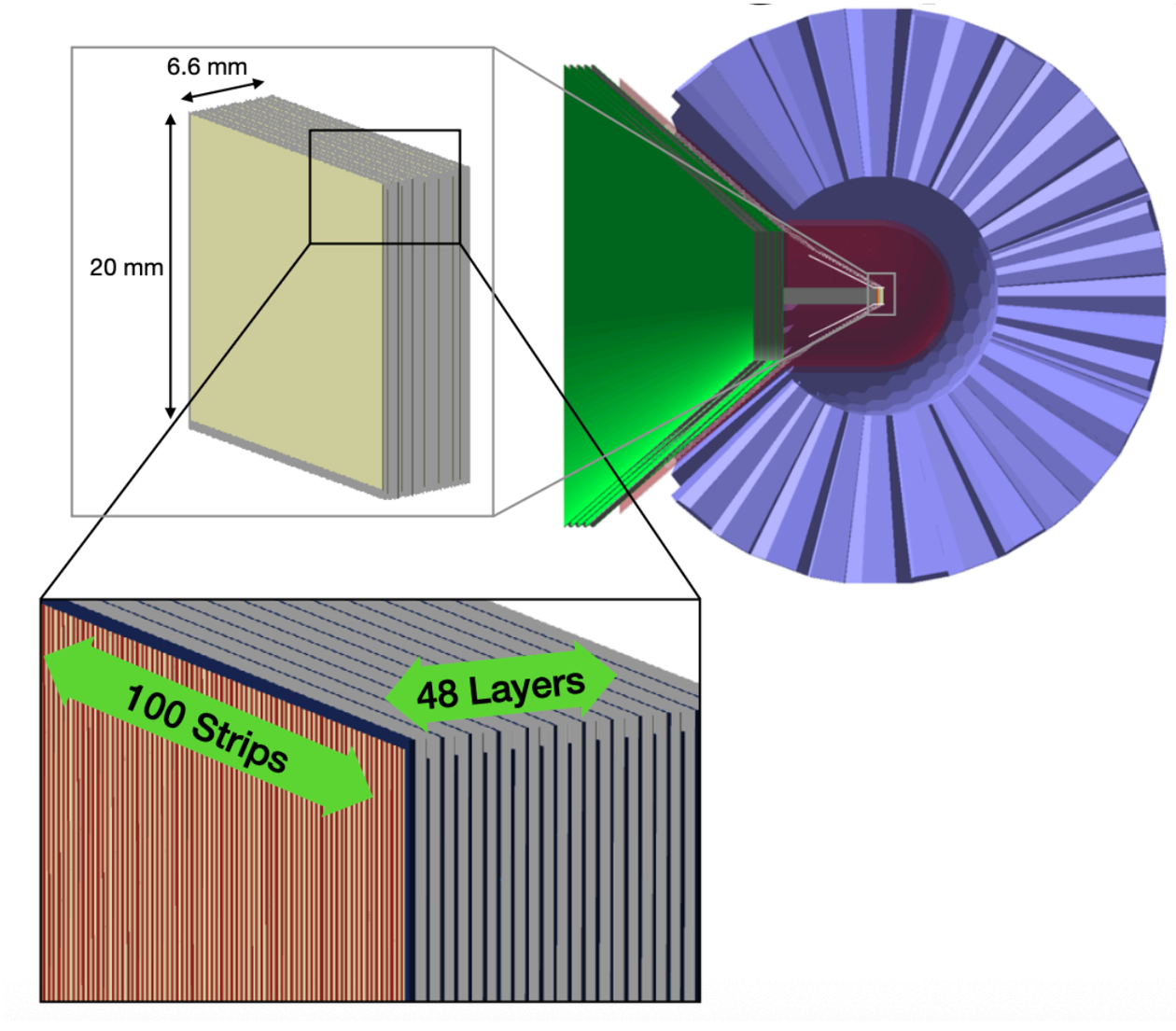


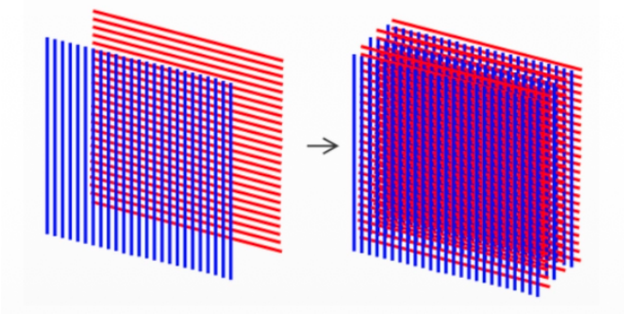

$$R_{e/\mu} \sim 10^{-4}$$

- If tail fraction is 1%, background is **$10^6$ larger** than signal.
- Requirements to achieve $\Delta C_{tail}/C_{tail} \approx 1\,\%$:
  - **Signal efficiency** of at least 1%
  - **Background reduction** by a factor of $10^7$

# Active TARget (ATAR) — the heart of PIONEER

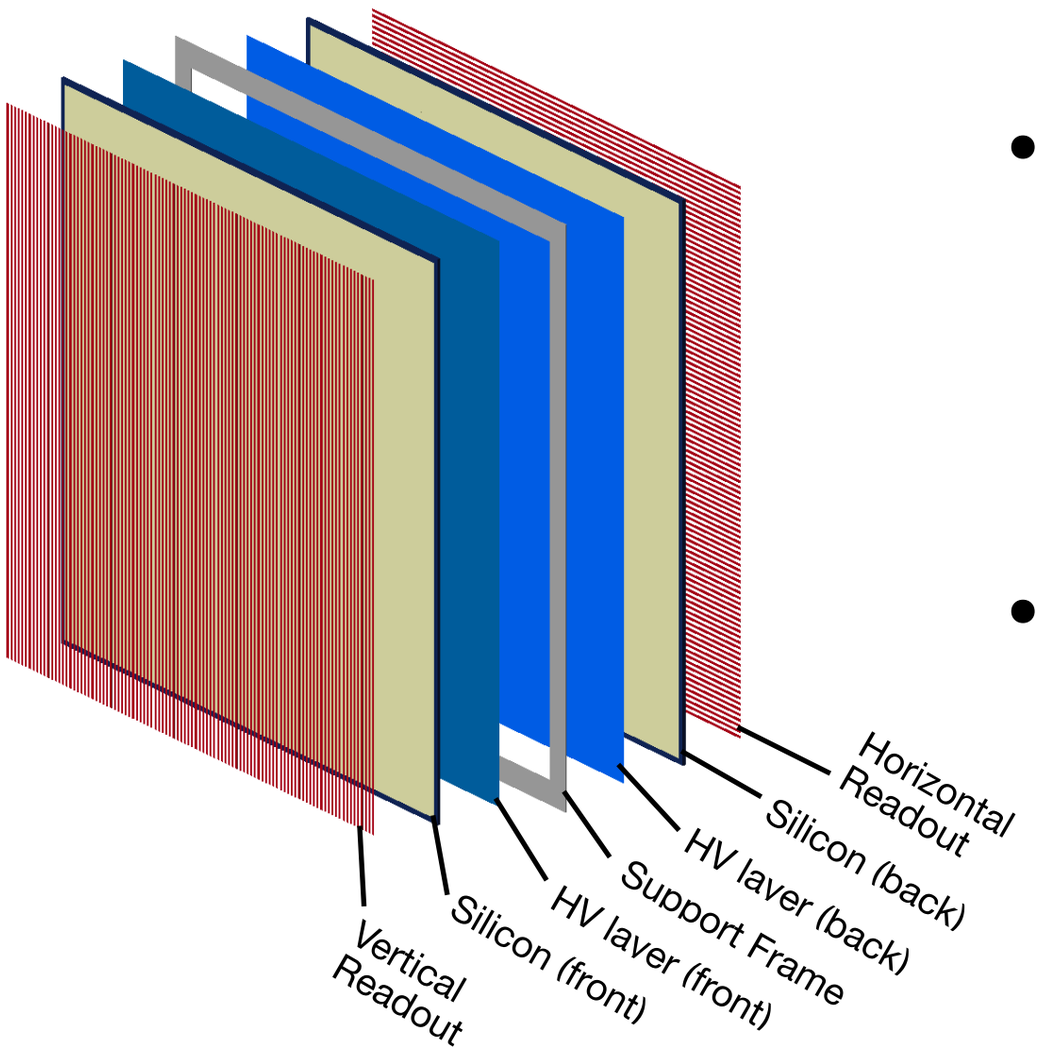
- The ATAR is a silicon detector.
  - 48 120μm layers (6mm total thickness)
  - 100 strips per layer (2x2 $cm^2$), alternating x/y orientation
- Silicon strips are TI-LGADs
  - Low-gain avalanche diodes
- Provides **5D track information**: energy deposition, time, and position (x,y,z).



# Low-gain avalanche diode (LGADs)

A single layer

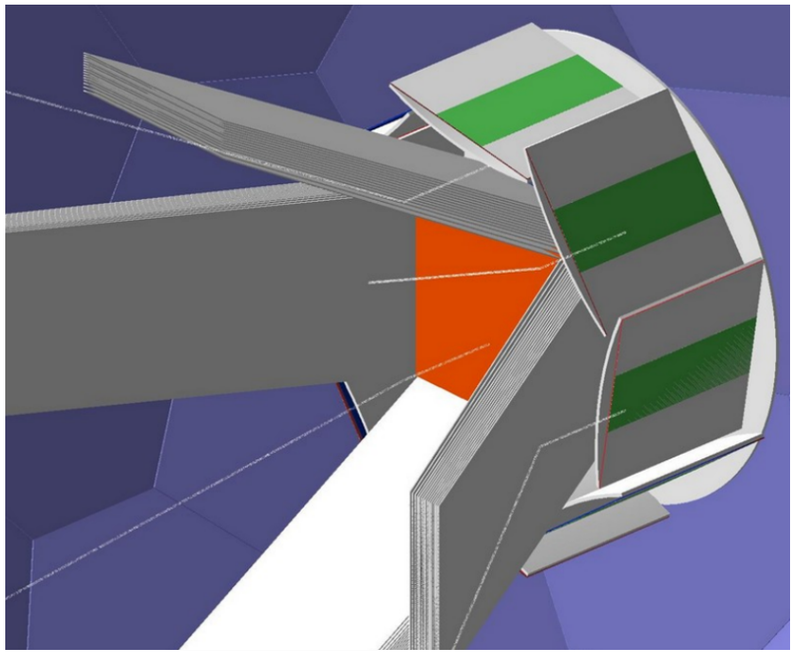



- Silicon detector with a thin gain layer.
- Benefits:
  - Excellent time resolution
  - Large dynamic range for each particle type
- Main challenge:
  - **Gain suppression** at larger energy depositions 1) degrades energy resolution and 2) introduces angular dependence.

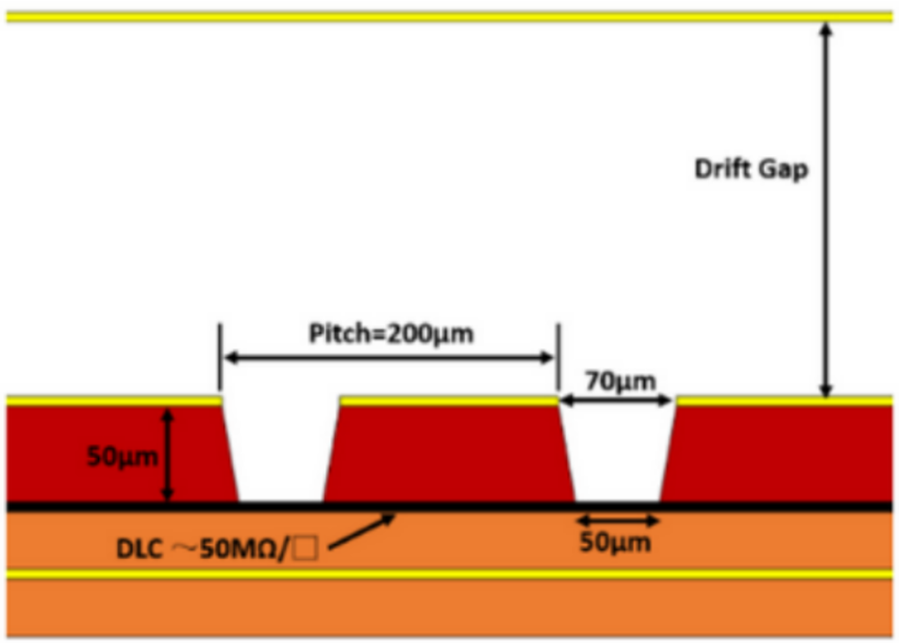
# Tracker

- Thin, fast tracking detector between ATAR and calorimeter under development.
- Team at Stony Brook working on tracker design.

DMAPS

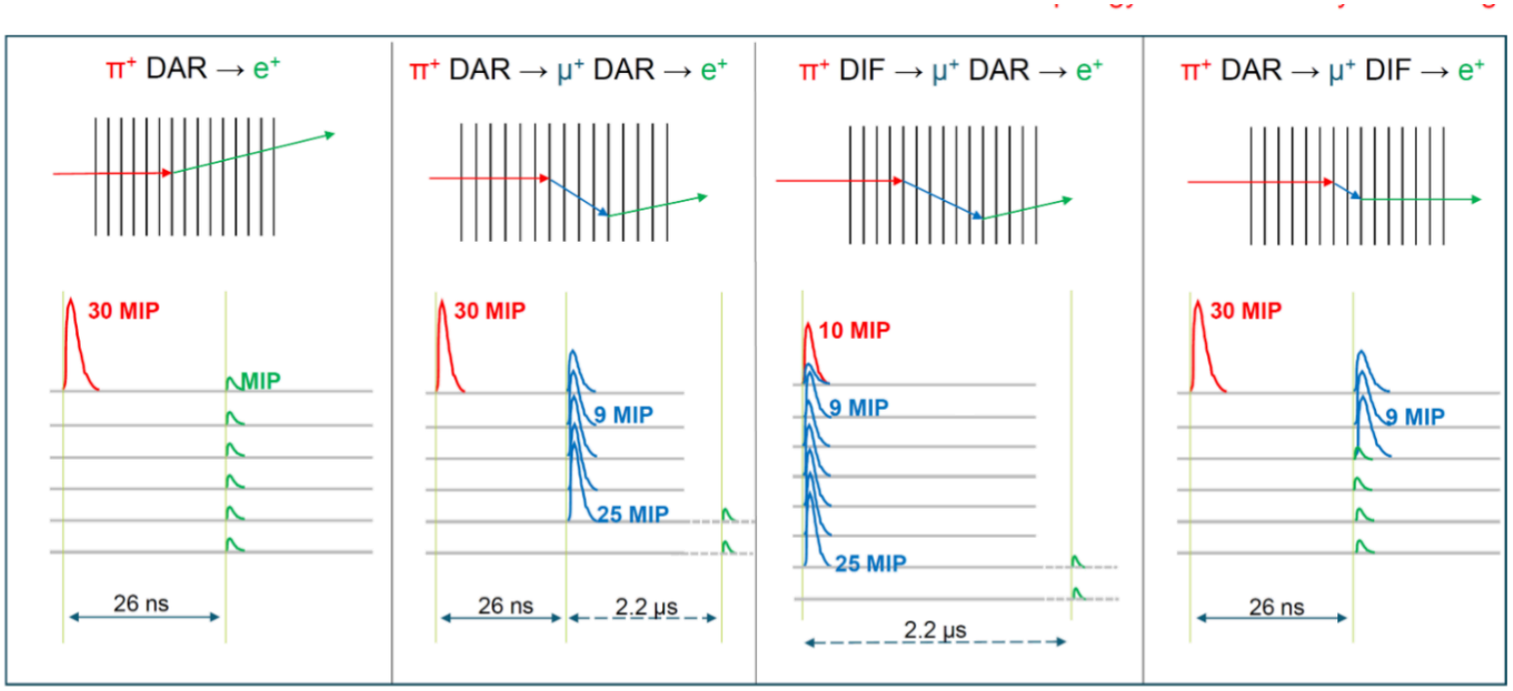


μRGroove



# Backgrounds

- Processes that contribute the background (events in the low bin that are *not* tail events).

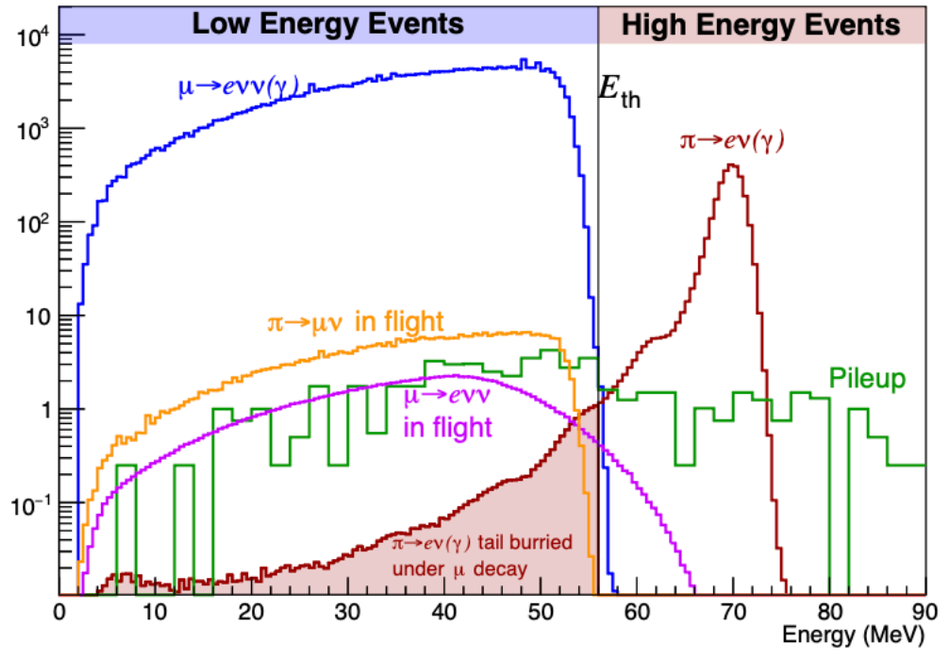



Signal

Pion decay at rest

Pion decay in flight

Muon decay in flight

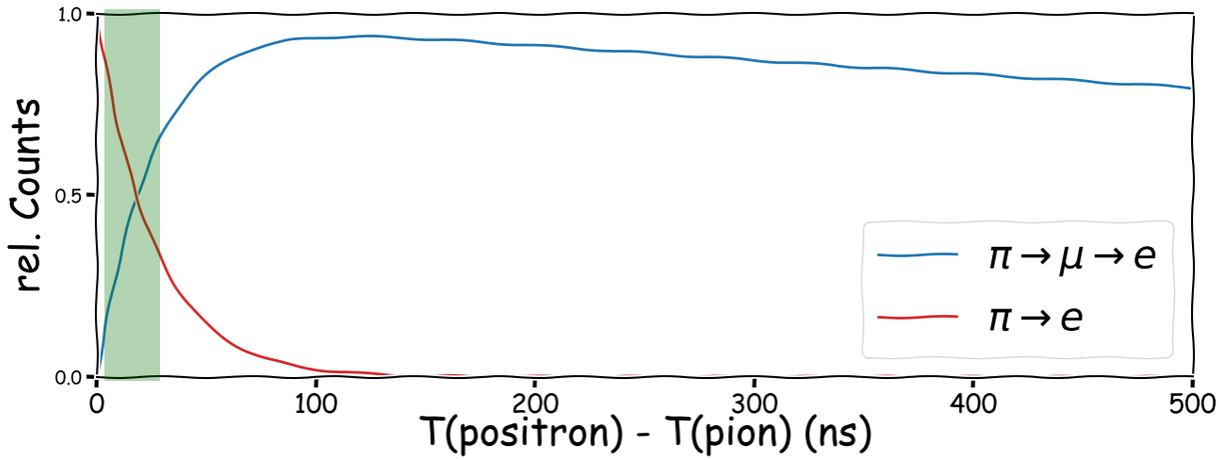


# ATAR reveals the tail

- Requirements
  - Selection efficiency: 1%
  - Rejection rate: $10^7$

# ATAR reveals the tail

- Requirements
  - Signal efficiency: 1%
  - Rejection rate: $10^7$
- Timing
  - Signal efficiency: 60%
  - Rejection rate: ~150

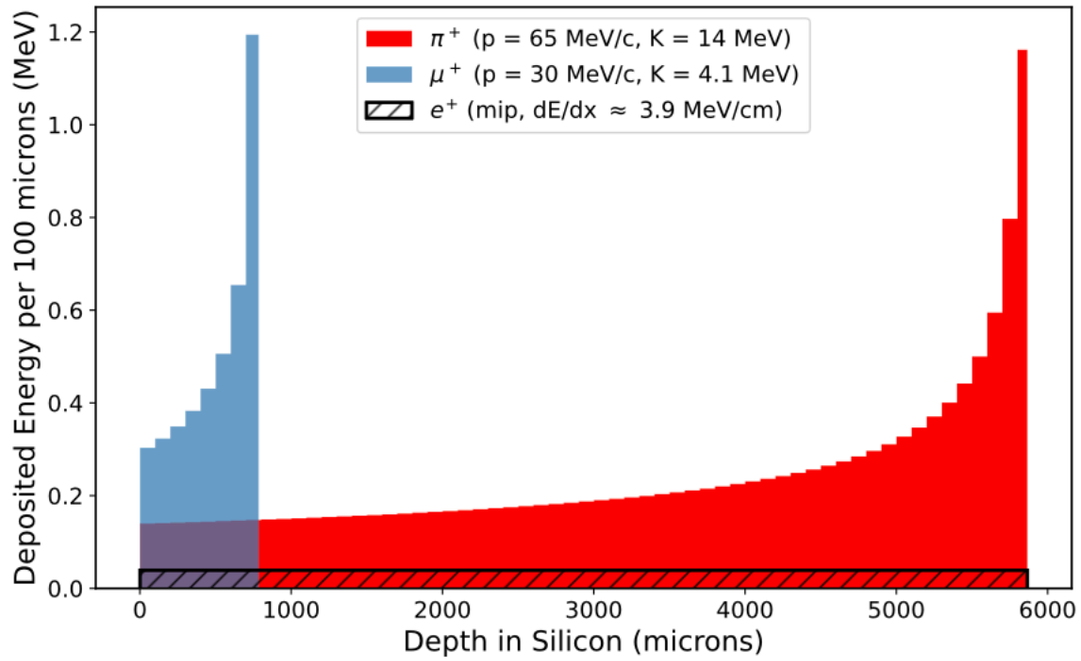



$\pi \to e$ events are prompt compared to $\pi \to \mu \to e$ events.

Restrict tail reveal analysis to **early times**.

# ATAR reveals the tail

- Requirements
  - Signal efficiency: 1%
  - Rejection rate: $10^7$
- Timing
  - Signal efficiency: 60%
  - Rejection rate: ~150
- Energy
  - Signal efficiency: ~85%
  - Rejection rate: ~$10^3$



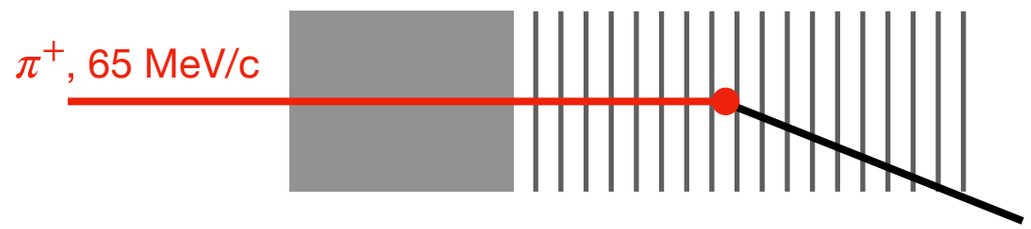

Pion, muon, and positron leave **characteristic signatures** in the ATAR:

- Positrons are MIPs: ~50 KeV per 120 μm thick silicon strip.
- Bragg peak for both pions and muons.
- Integrated energy deposited ~14 MeV for pions, 4.1 MeV for muons.

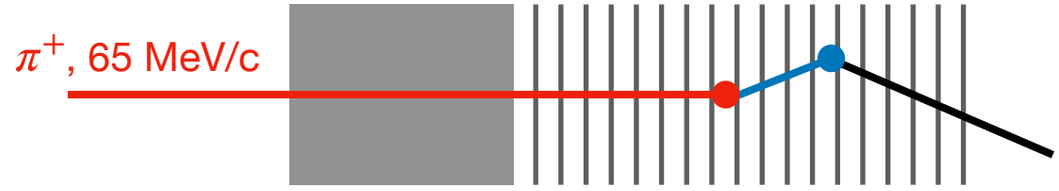
# ATAR reveals the tail

- Requirements
  - Signal efficiency: 1%
  - Rejection rate: $10^7$
- Timing
  - Signal efficiency: 60%
  - Rejection rate: ~150
- Energy
  - Signal efficiency: ~85%
  - Rejection rate: ~$10^3$
- Topology
  - Signal efficiency: 50%
  - Rejection rate: ~500

$\pi \rightarrow e$ topology



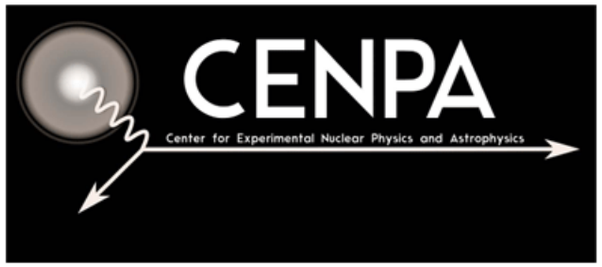

$\pi \rightarrow \mu \rightarrow e$ topology

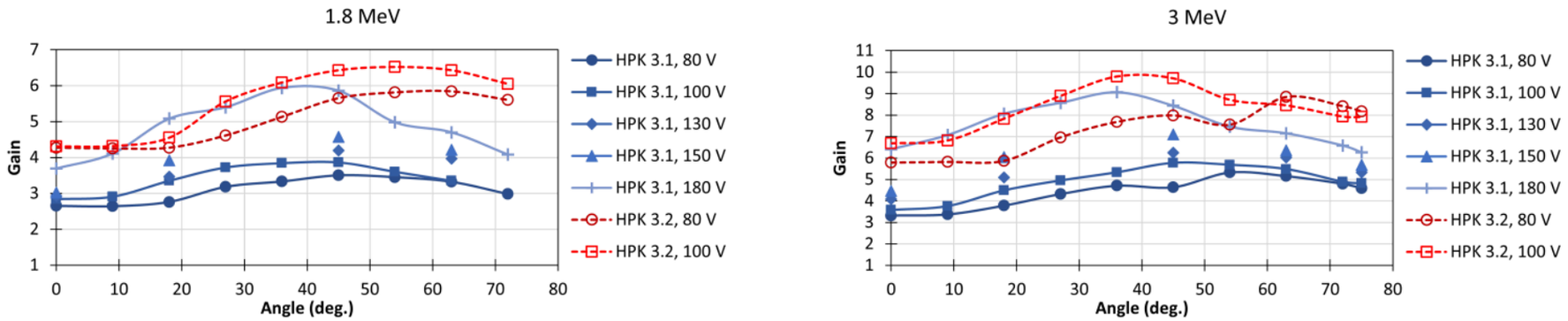



Trajectory of particles in a **segmented** ATAR let's you see the different topologies.

# LGAD gain suppression studies

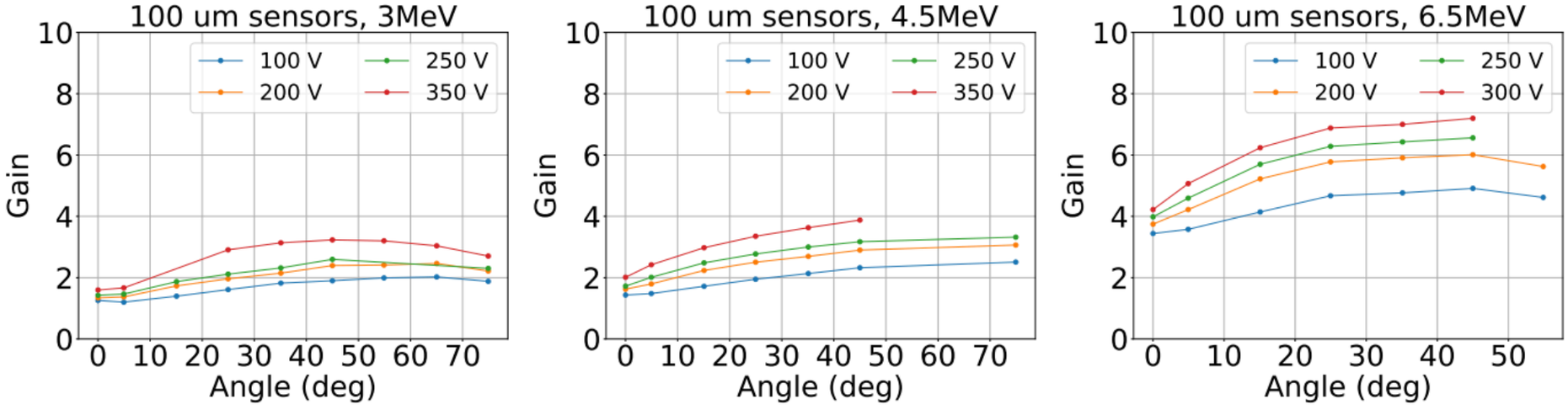
- LGADs from HBK and FBK have been characterized.
  - Gain suppression studies vs. positron energy, bias voltage, and angle of incidence.




Braun et al., arXiv:2405.02550 (2024)

Tandem Van der Graaff accelerator at CENPA supplies ~MeV protons.



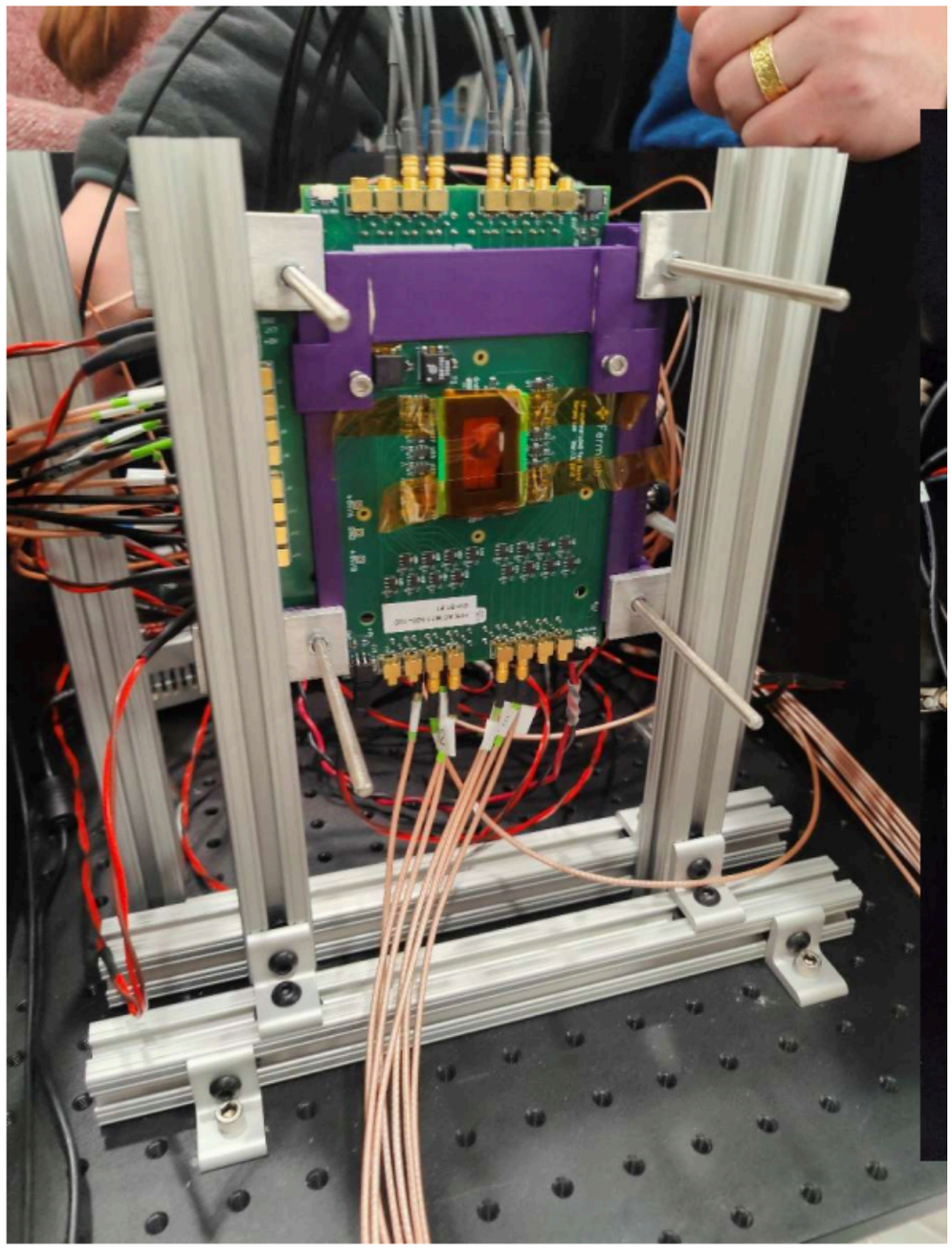

Yang et al., arXiv:2502.02244 (2025)

# Proto-ATAR studies

- December 2025 and January 2026 test at TRIUMF
  - Tested a telescope of 4-5 planes of thinned LGADs.
    - HPK AC-LGADs 5x5mm with 500um pitch
    - FBK TI-LGADs 3x3mm with 200um pitch
  - Testing two digitizers systems: HD-SOC and SAMPIC.

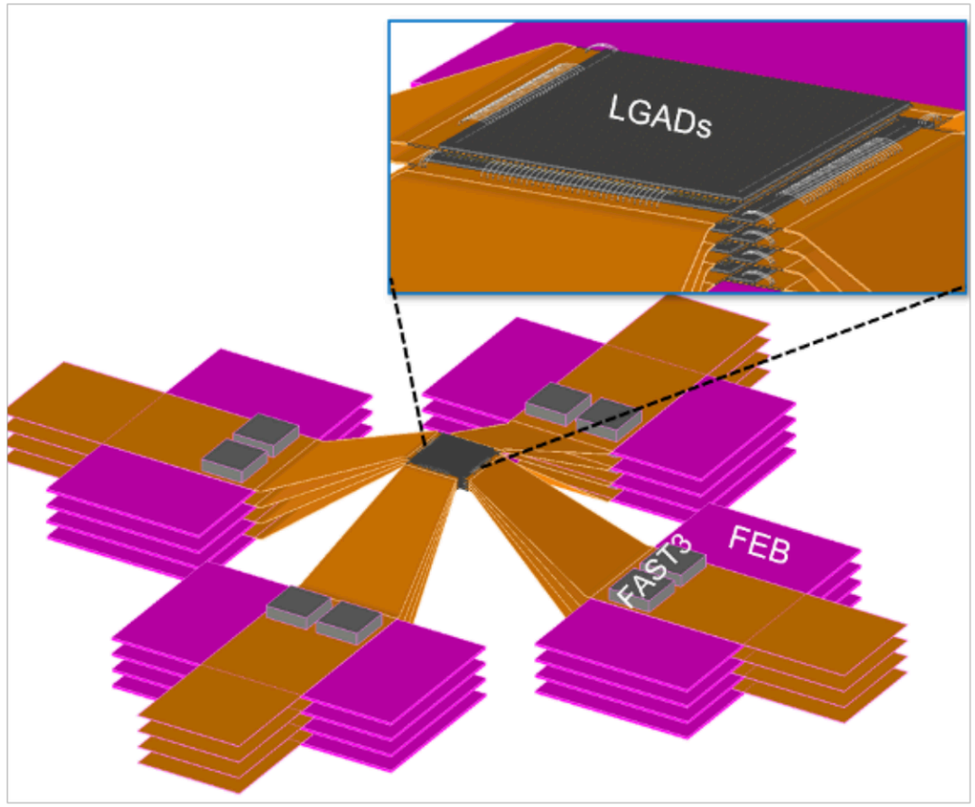
- Goals
  - Observe muon stops + decay positron in LGADs.
  - Characterize gain suppression.
  - Demonstrate tracking capabilities.

- More in talk by Simone Mazza at ULTIMA 2026.



# ATAR-8 Demonstrator

- Test beam in December of this year for ATAR demonstrator with 8 planes.
  - In $\pi$M1 at PSI
- Goals of the test beam:
  - **Assemble and operate ATAR-8.**
    - Validate scalability of the project, ensure quality control, and define assembly process.
  - **Learn about ATAR detector response at both sensor and system levels.**
    - Sensor level: testing its dynamic range
    - System level: ability to do reconstruction tasks (tracking, vertexing).
  - **Assess analysis strategy for $R_{e/\mu}$ measurement.**



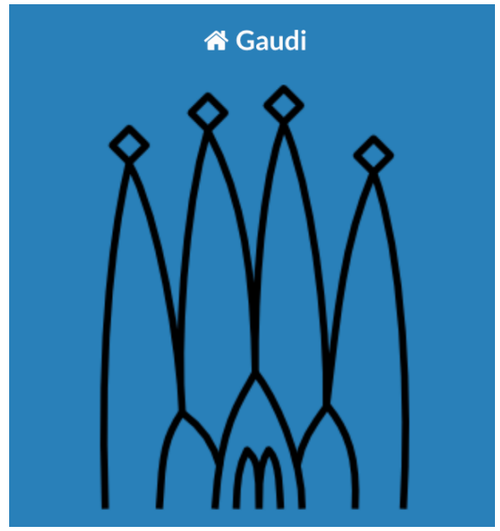
# Reconstruction and analysis

- Geant4-based Monte Carlo

- Detector response and reconstruction orchestrated with Gaudi

- Two reconstruction paths:
  - Rule-based
  - AI/ML-based

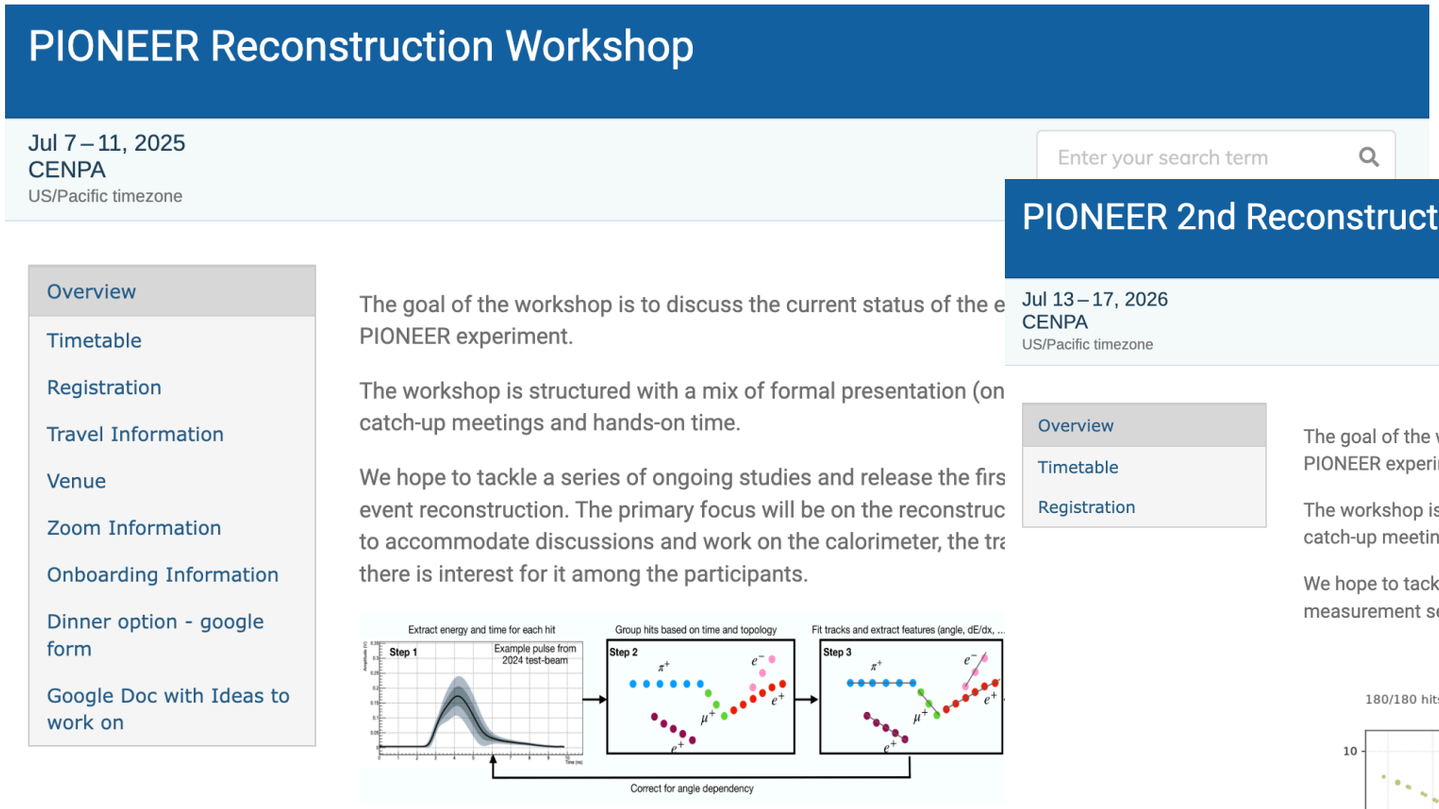
- Simulation campaign to demonstrate viability of the experiment

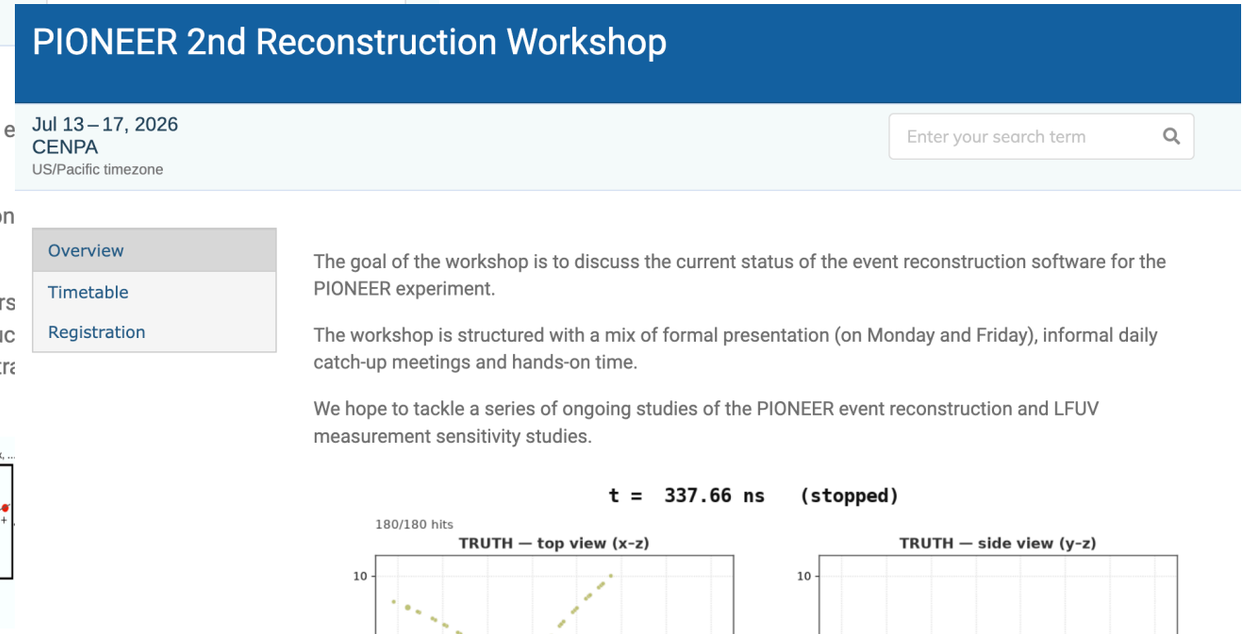



Gaudi event processing framework developed by LHC experiments

# Reconstruction workshops

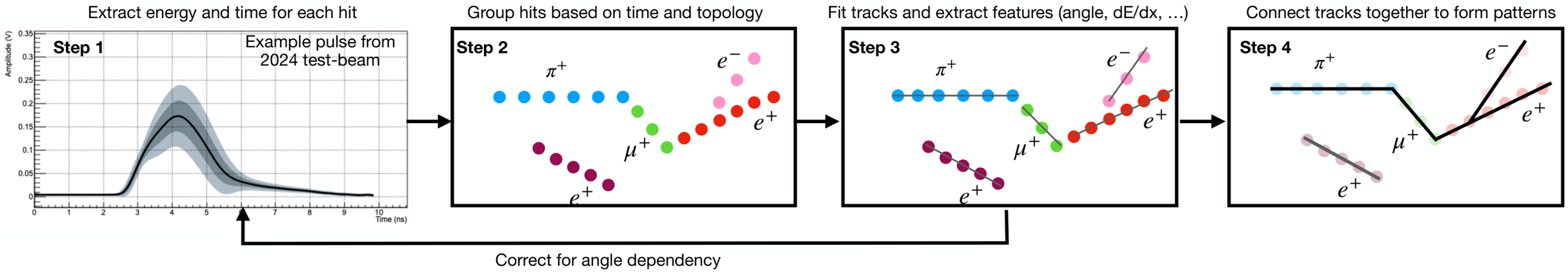
- Reconstruction workshops held in 2025 and 2026 at CENPA at the University of Washington.
  - Goal: discuss current status of the event reconstruction and tackle ongoing studies.



# Reconstruction approaches

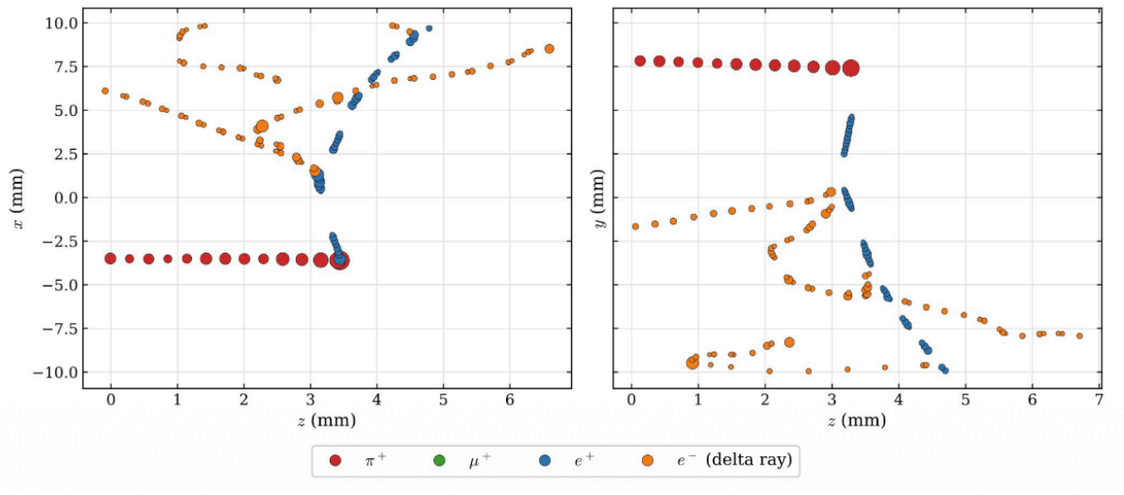
- Rule-based reconstruction
  - Conventional approach with well-defined steps taking detector hits and converting them intro reconstructed objects.




- AI/ML-based reconstruction
  - Transformer-based model that leverages data from all detector systems.

Goal is to handle **complex events**, like this one

Rare, but important for a 0.01% measurement!






O. Beesley PhD Thesis (2026)

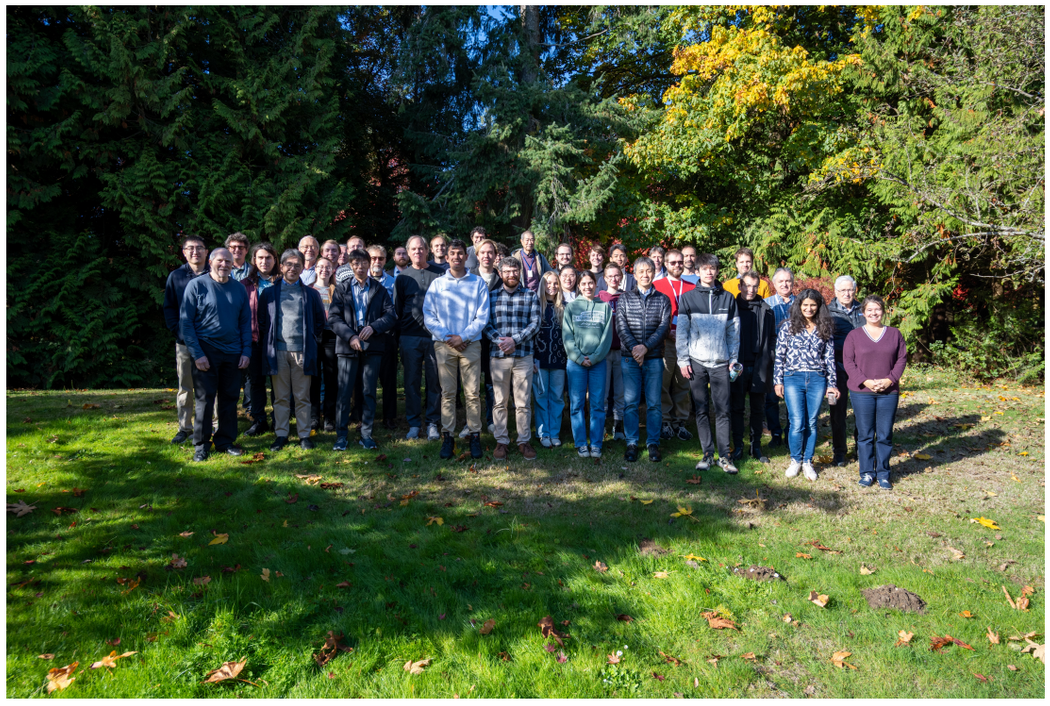
# Summary and Conclusions

# Timeline

- ATAR-8 demonstrator at PSI end of this year!
- ATAR-16 demonstrator end of 2027.
- PSI shutdown/upgrade end of 2027 - Sept. 2029.
  - Construction and installation.
- Begin commissioning full experiment ~2030.
  - First physics run following successful commissioning.

# Summary and Conclusions

- PIONEER is a next-generation rare pion decay experiment.
- Our phase I goal is to perform a **0.01% precision test of lepton flavor universality** using pion decay.
- Detector testing for the calorimeter and ATAR over the past few years, with plans for a demonstrator this year.
- Reconstruction and analysis development through simulation.



Collaboration meeting Oct. 2025 @ TRIUMF in Vancouver

# Backup

# Acknowledgments

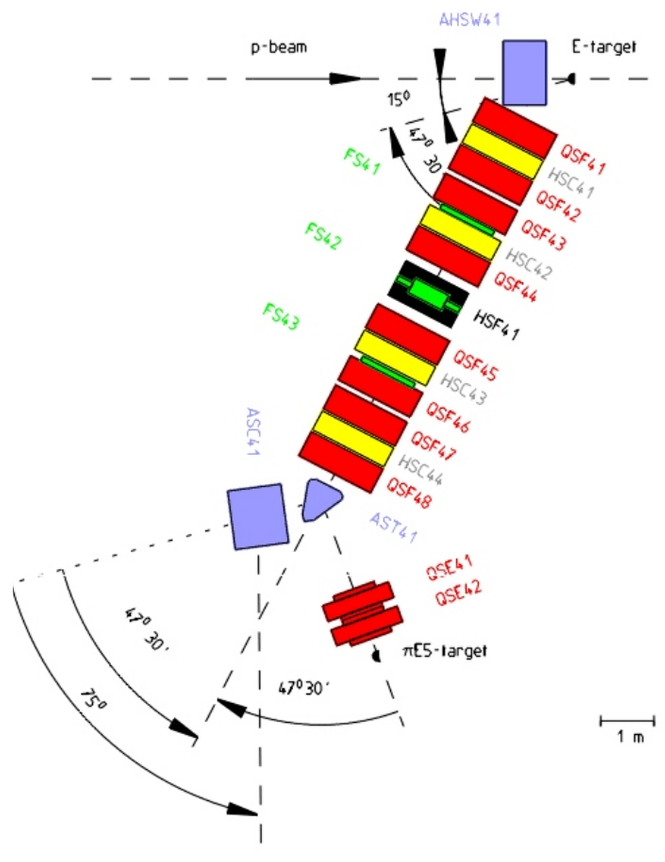

- Thanks to the many PIONEERs that supplied figures/ slides for this talk! A non-exhaustive list includes Quentin Buat, Josh LaBounty, Omar Beesley, Simone Mazza, Jessie Yang, Emma Klemets, Simone Mazza, and others!

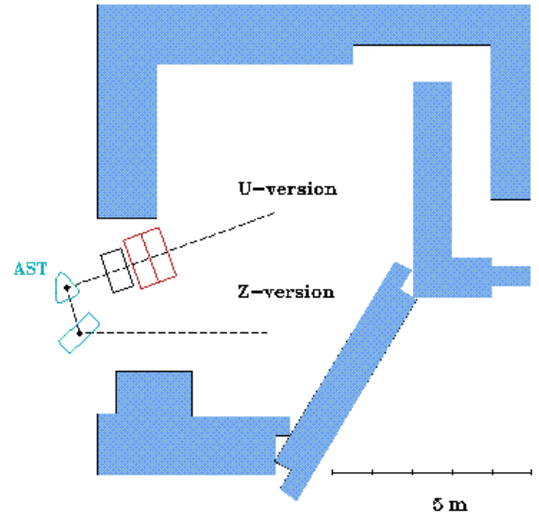
# $\pi$E5 beam line

## πE5 Beam Line

The πE5 beam line is a low energy (10-120 MeV/c) pion and muon beam line, viewing the thick target at 165° with respect to the primary proton beam. The main properties of the beam line are given in the following table. The beam line and a layout of the experimental area are shown in Fig 1 and Fig 2 respectively.

| | |
|---|---|
| Length | 10.4 m |
| Solide angle | 150 msr |
| Momentum acceptance (FWHM) | 10 % |
| Momentum resolution (FWHM) | 2 % |
| Spot size (FWHM) | 15 mm horizontal |
| | 20 mm vertical |
| Angular divergence (FWHM) | 450 mrad horizontal |
| | 120 mrad vertical |



# 3. Measure tail to a precision of 1%

- Selection efficiency
  - To achieve $10^8$ $\pi \to e$ events, we need $10^{12}$ $\pi \to \mu \to e$ events.
  - Tail fraction of 1% implies $10^6$ tail events.
  - Signal efficiency of 1% leaves $10^4$ events → 1% statistical uncertainty.

- Background reduction of $10^7$
  - Assumes a 10% background, measured to precision of 10%.

- Selection cuts must leave tail fraction unbiased!
  - Control of systematics will be very important.