パイオンの稀崩壊を精密測定するPIONEER実験にて迫るレプトン普遍性の破れ

岩本敏幸、潘晟，L. Gerritzen, 松下彩華^A^，三原智^B^，森俊則，大谷航，内山雄祐^B^,
他PIONEERコラボレーション
東京大学素粒子物理国際研究センター、東大理^A^，高エ研^B^

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北海道大学

東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo

東京大学
THE UNIVERSITY OF TOKYO

Lepton flavor universality

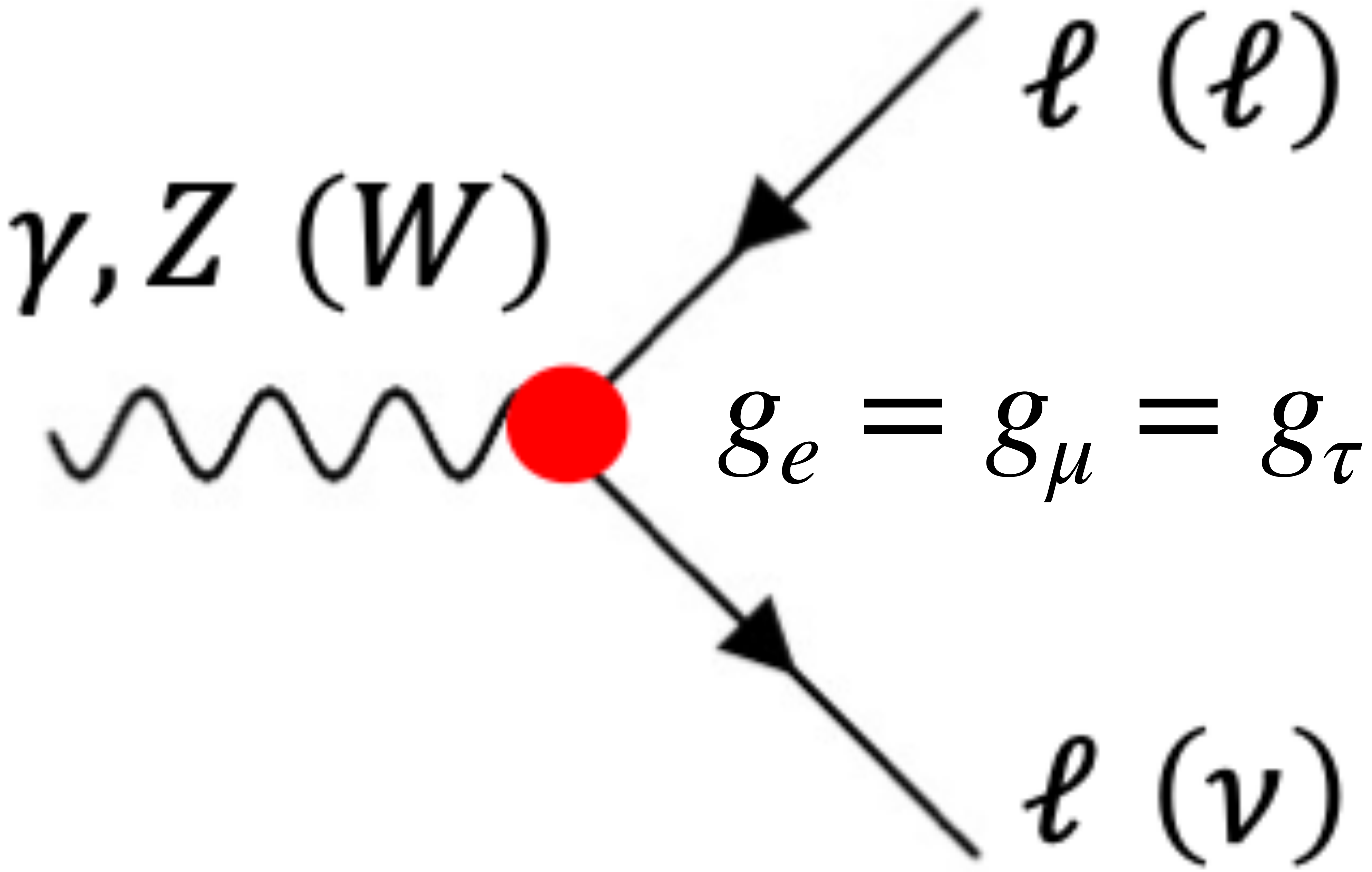
Lepton flavor universality is a fundamental principle in the standard model of particle physics

Gauge interactions of W and Z bosons are the same for all flavors

The only difference in flavors is their mass, $m_e \neq m_\mu \neq m_\tau$ (not universal in Yukawa sector)

Precise verification of lepton flavor universality in the gauge sector leads to verification of the standard model

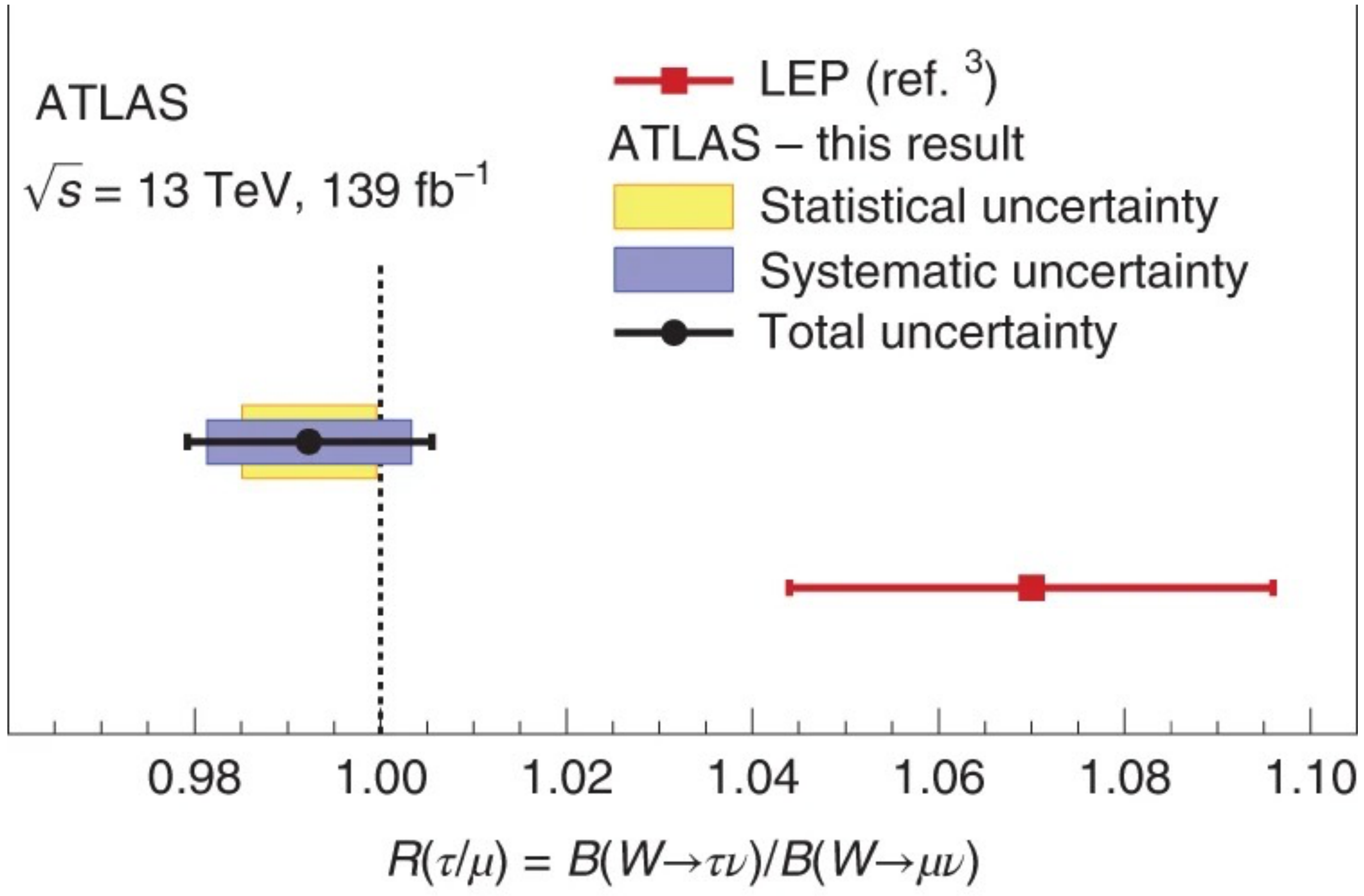
Any deviation from the universality requires new physics beyond the standard model



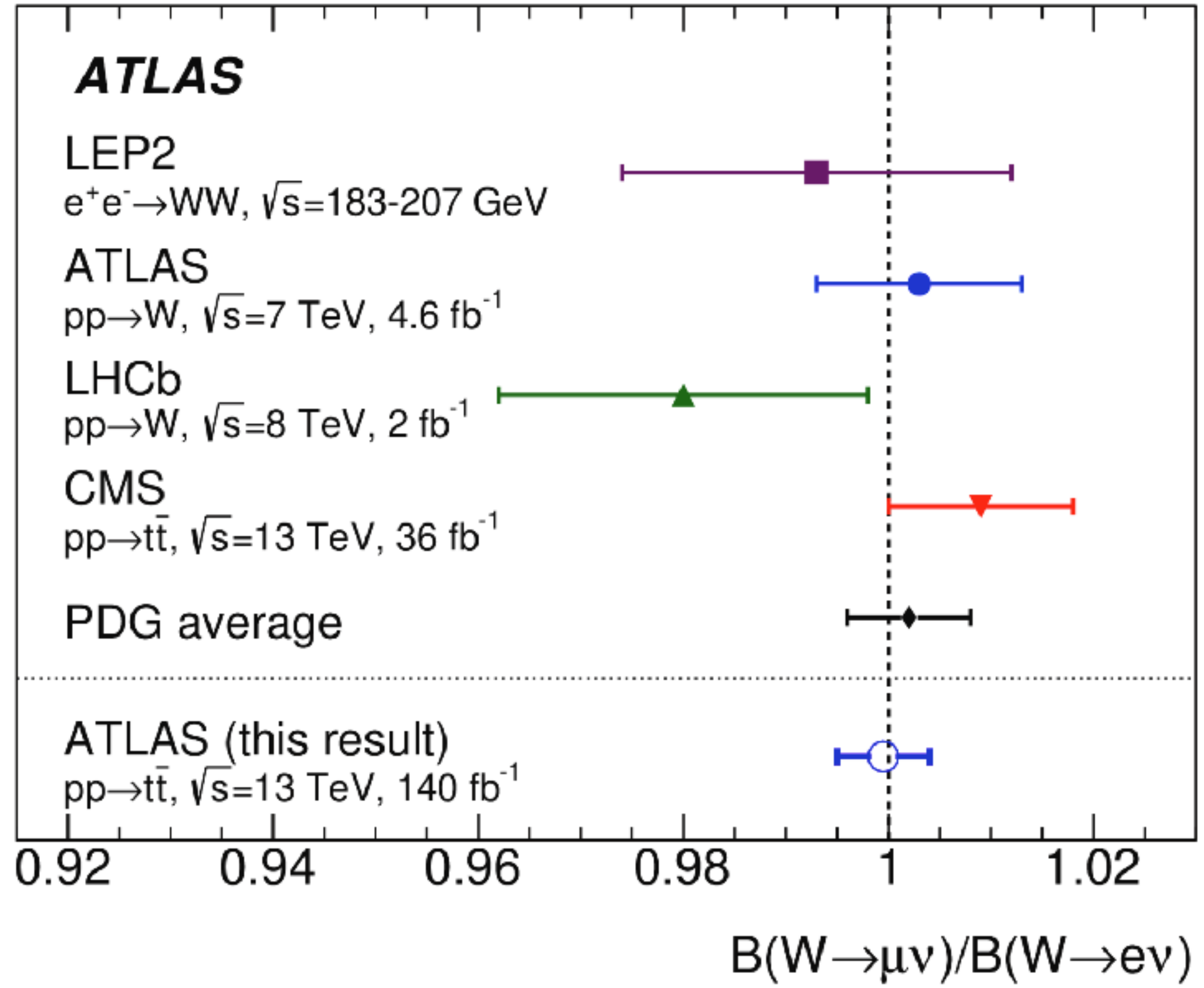
Verification of lepton flavor universality so far

- Precision measurements are performed with sub % level precision

$B(W \to \tau\nu)/B(W \to \mu\nu)$, $B(W \to \mu\nu)/B(W \to e\nu)$



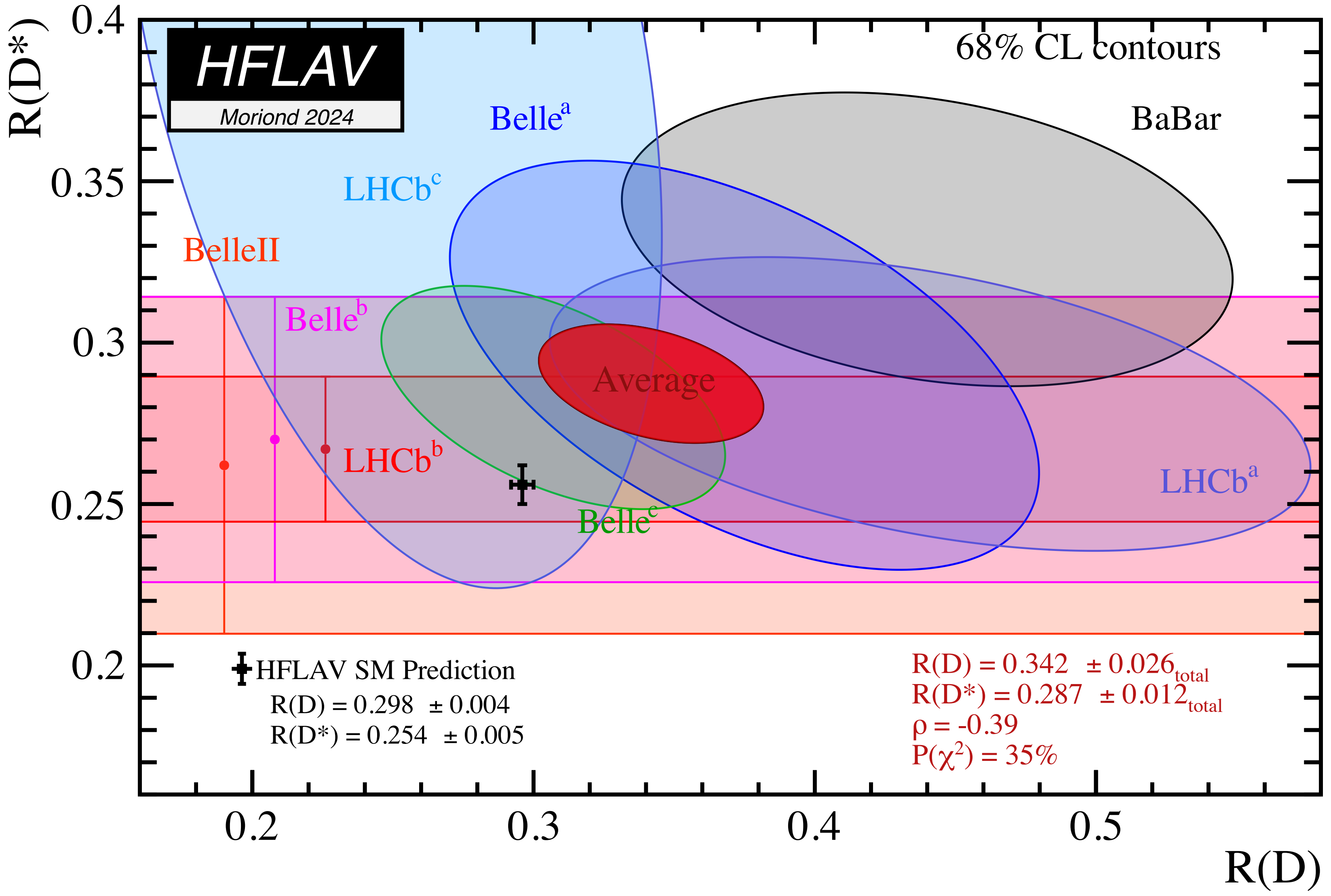
Nature Physics 17, 813-818 (2021)



ArXiv: 2403.02133

Hints of lepton flavor universality violation ?

$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

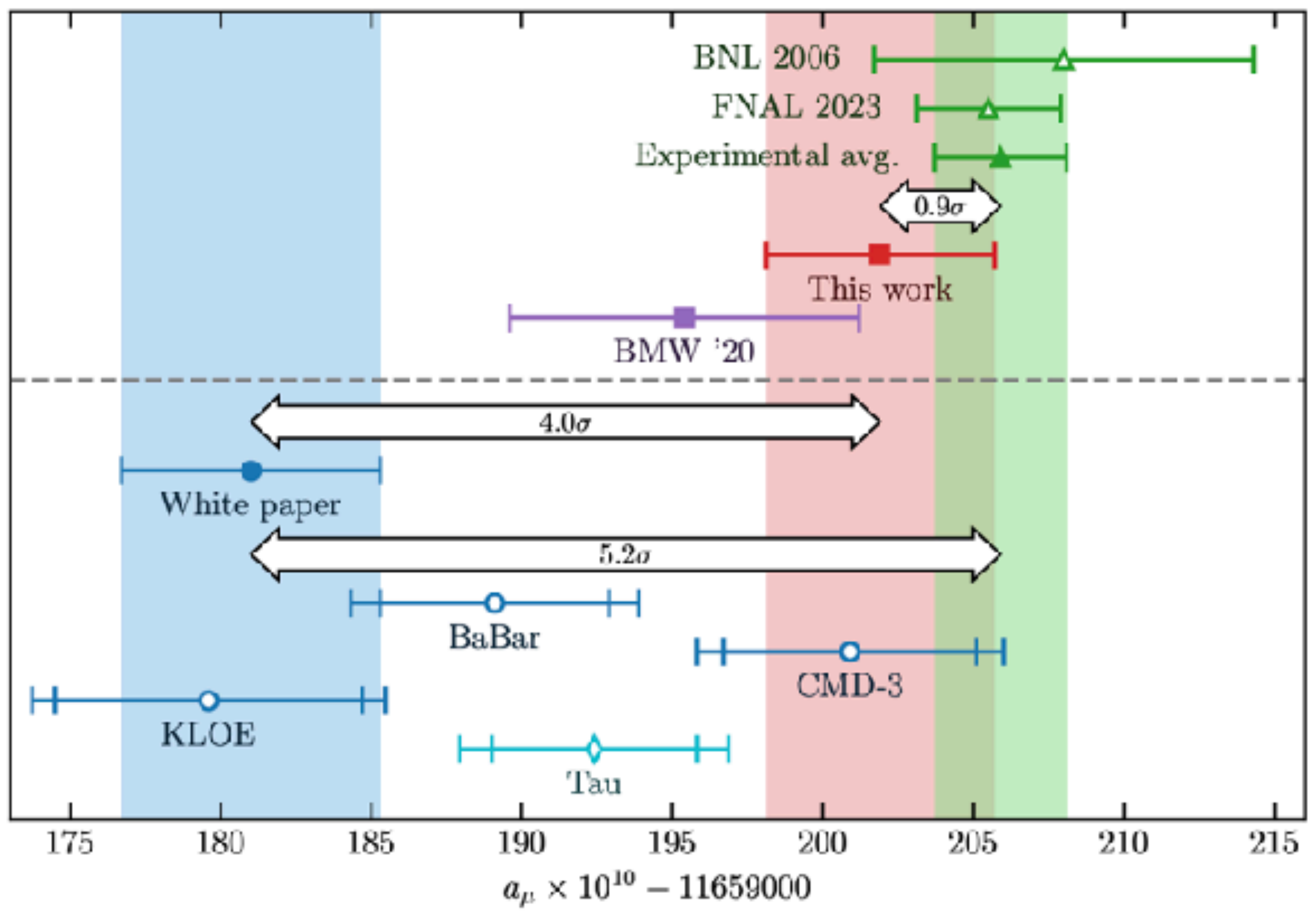


more than 3σ deviation

- Can be a hint of LFUV between τ and μ

R(K*) consistent with the SM (arXiv: 2212.09152)

Muon
anomalous magnetic moment



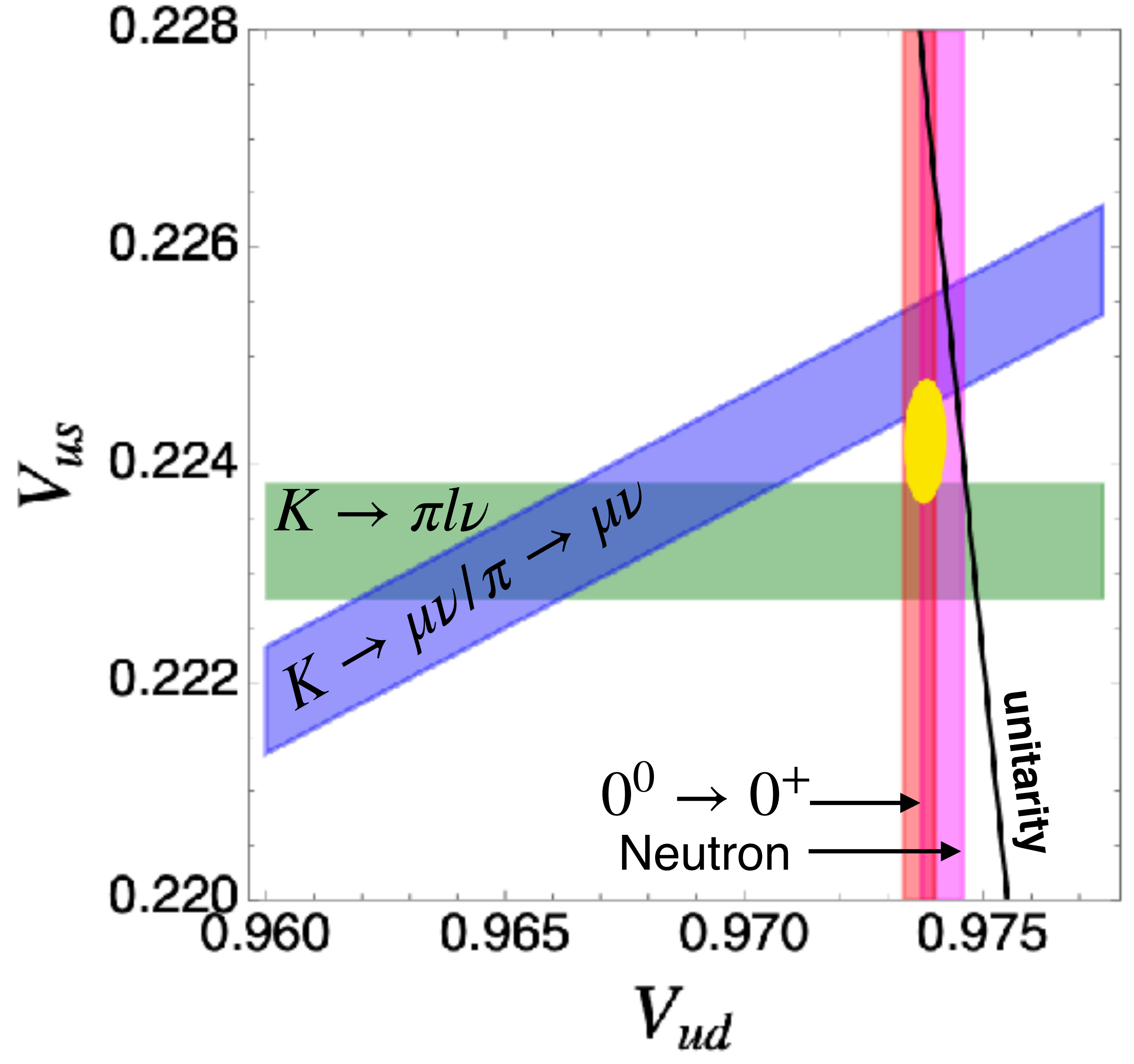
$(g-2)_l \ (l = e, \mu, \tau)$

- $\Delta a_\mu \sim (2.5 \pm 0.6) \times 10^{-9}$
- $\Delta a_e \sim (-8.8 \pm 3.6) \times 10^{-13}$
- Can be a hint of LFUV between μ and e

arXiv: 2407.10913

Unitarity of the CKM matrix

$$\Delta_{\mathrm{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$



~3σ deviation (Cabibbo Angle Anomaly)
This can also be interpreted as a LFUV

- V_{ud} from e, V_{us} from μ meas.

arXiv: 2208.11707

PIONEER goal

Phase I

- Measures $R^{\pi}_{e/\mu} = \Gamma(\pi \to e\bar{\nu}_e(\gamma))/\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))$ with 0.01% precision (15x better)
- Comparable with the theoretical uncertainty (0.01%)
- NP at the PeV scale can be probed

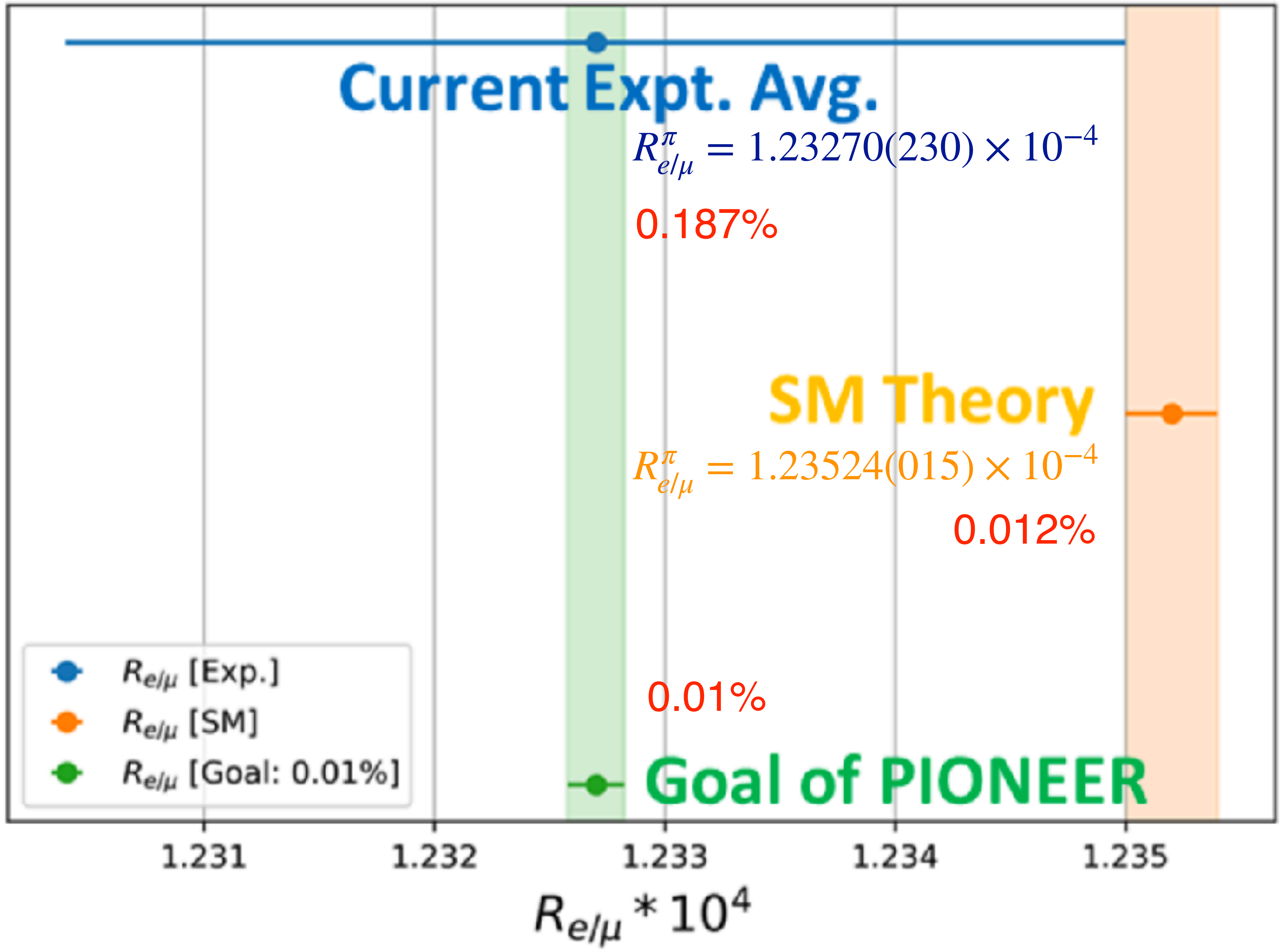
Phase II & III

- Current pion beta decay $\pi^+ \to \pi^0 e^+ \nu$ ~ 0.2% precision
- Improvement by a factor of 3 (Phase II) / 10(Phase III)
- CKM unitarity check by theoretically cleanest $|V_{ud}|$

Exotic searches

- Heavy neutral lepton

PIONEER experiment is approved by Paul Scherrer Institute in Switzerland in 2022



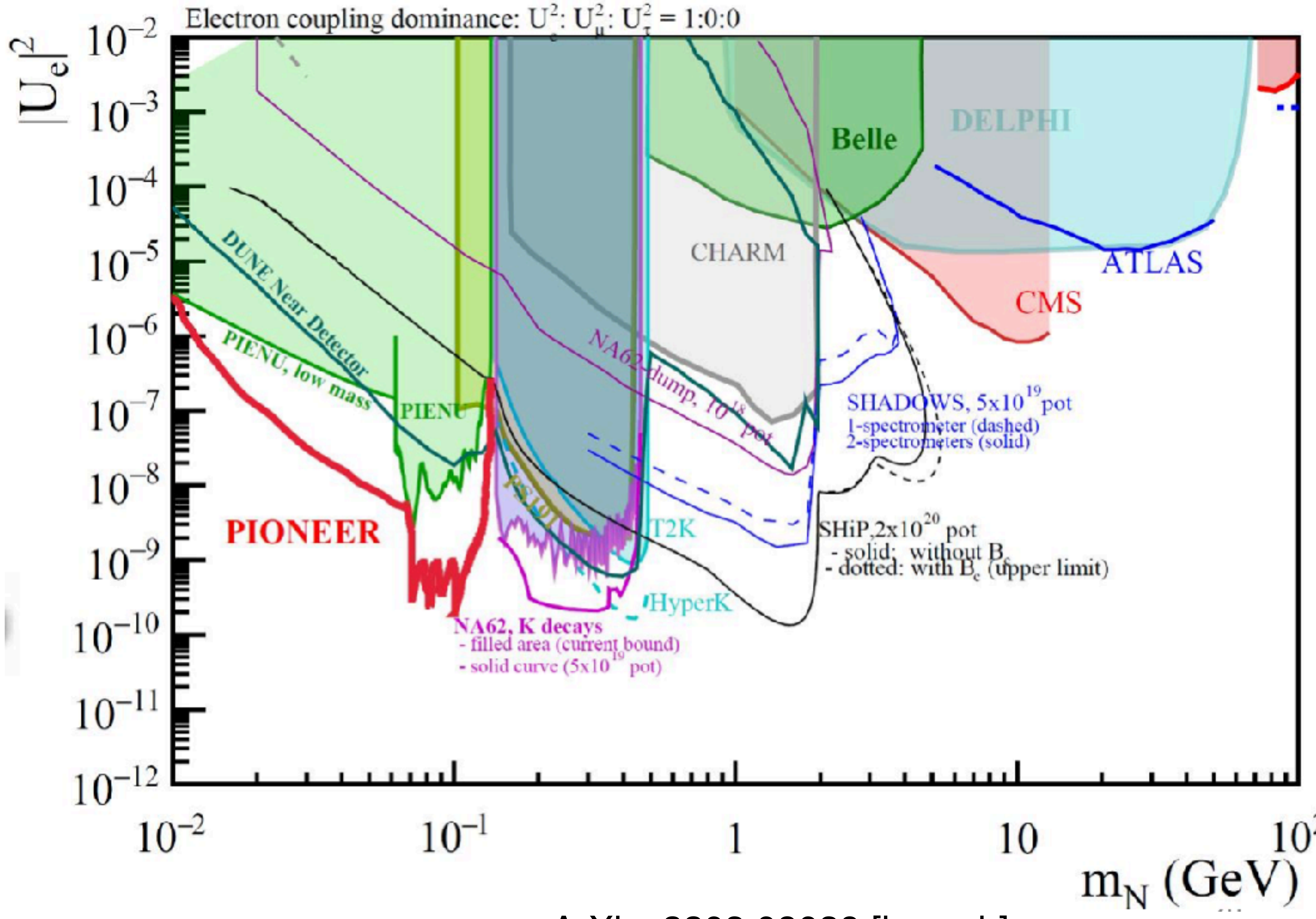
Exotic decay search

Search for exotic decays beyond previous limits

- Heavy neutrinos $\pi^+ \rightarrow l^+\nu_H$
- pion decays to various light dark sector particles
- lepton-flavor violating decays of the muon into light NP particles $\mu^+ \rightarrow e^+X_H$

About one order of magnitude for exotic decays in the low mass region 10-120MeV

Heavy Neutral Lepton search



ArXiv: 2203.08039 [hep-ph]

Basics of pion decays

PIONEER measures

$$R^{\pi}_{e/\mu} = \frac{\pi \rightarrow e\bar{\nu}_e(\gamma)}{\pi \rightarrow \mu\bar{\nu}_\mu(\gamma)}$$

<u>Measurements:</u>

What a pion decays to "normally" → $BR\left(\pi^+ \rightarrow \mu^+\nu_\mu(\gamma)\right) = 0.999877 = \pm 0.0000004$

The helicity suppressed "e" branch → $BR\left(\pi^+ \rightarrow e^+\nu_e(\gamma)\right) = 1.2327 \pm 0.0023) \times 10^{-4}$

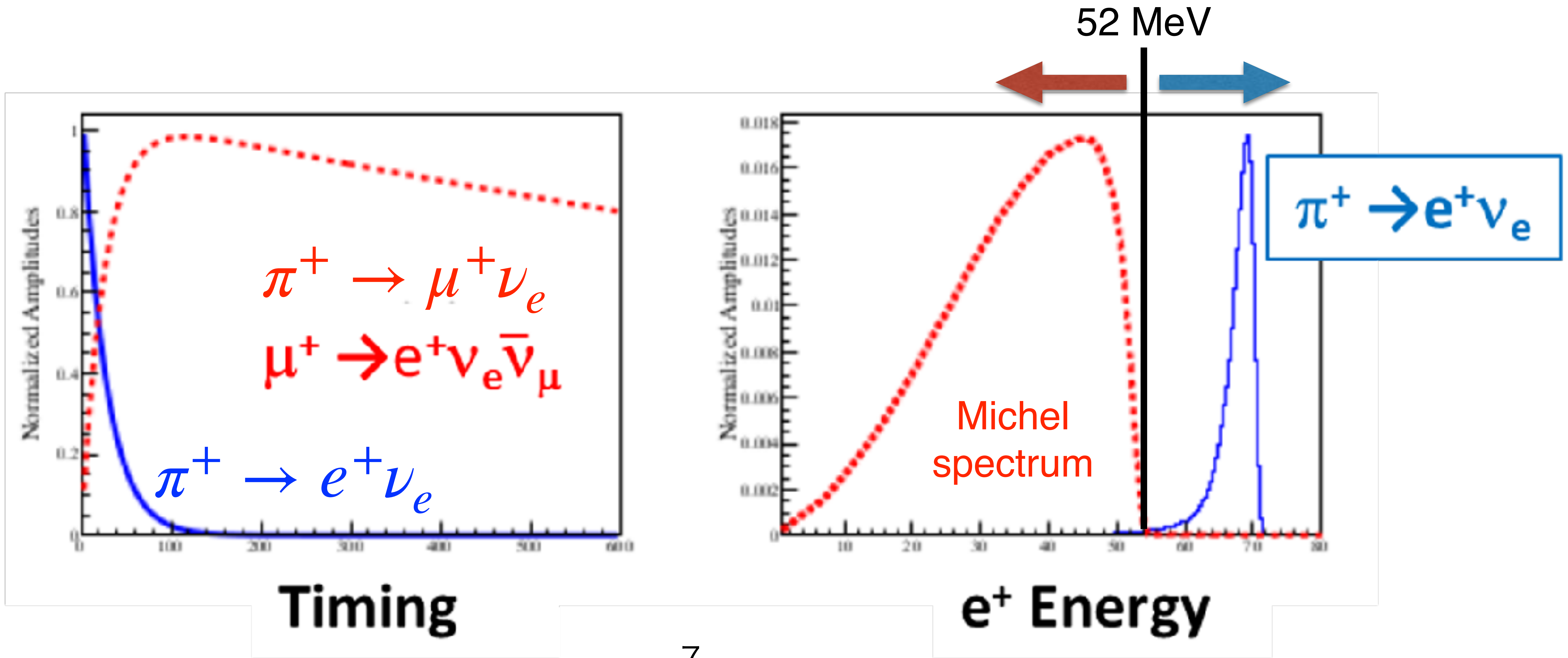
} → Phase I

The "beta decay" branch → $BR\left(\pi^+ \rightarrow e^+\nu_e\pi^0\right) = 1.036 \pm 0.006) \times 10^{-8}$ → Phase II

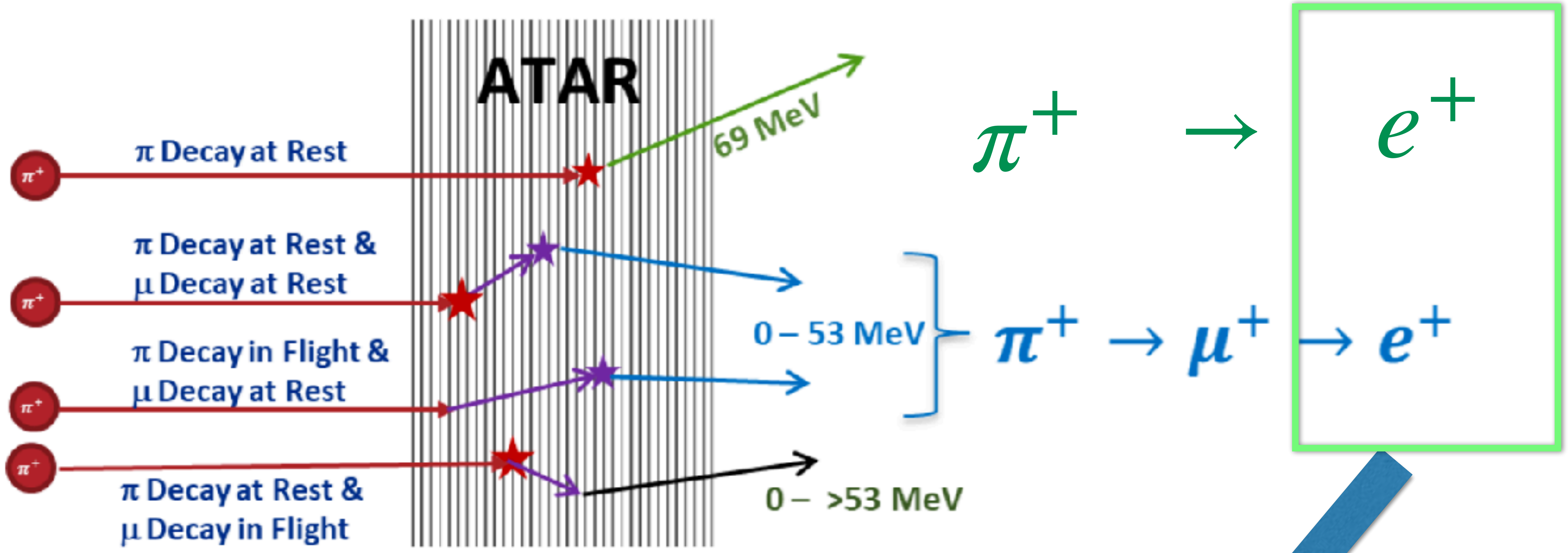
<u>Reminders:</u>

Pion lifetime: 26 ns
Muon lifetime: 2197 ns

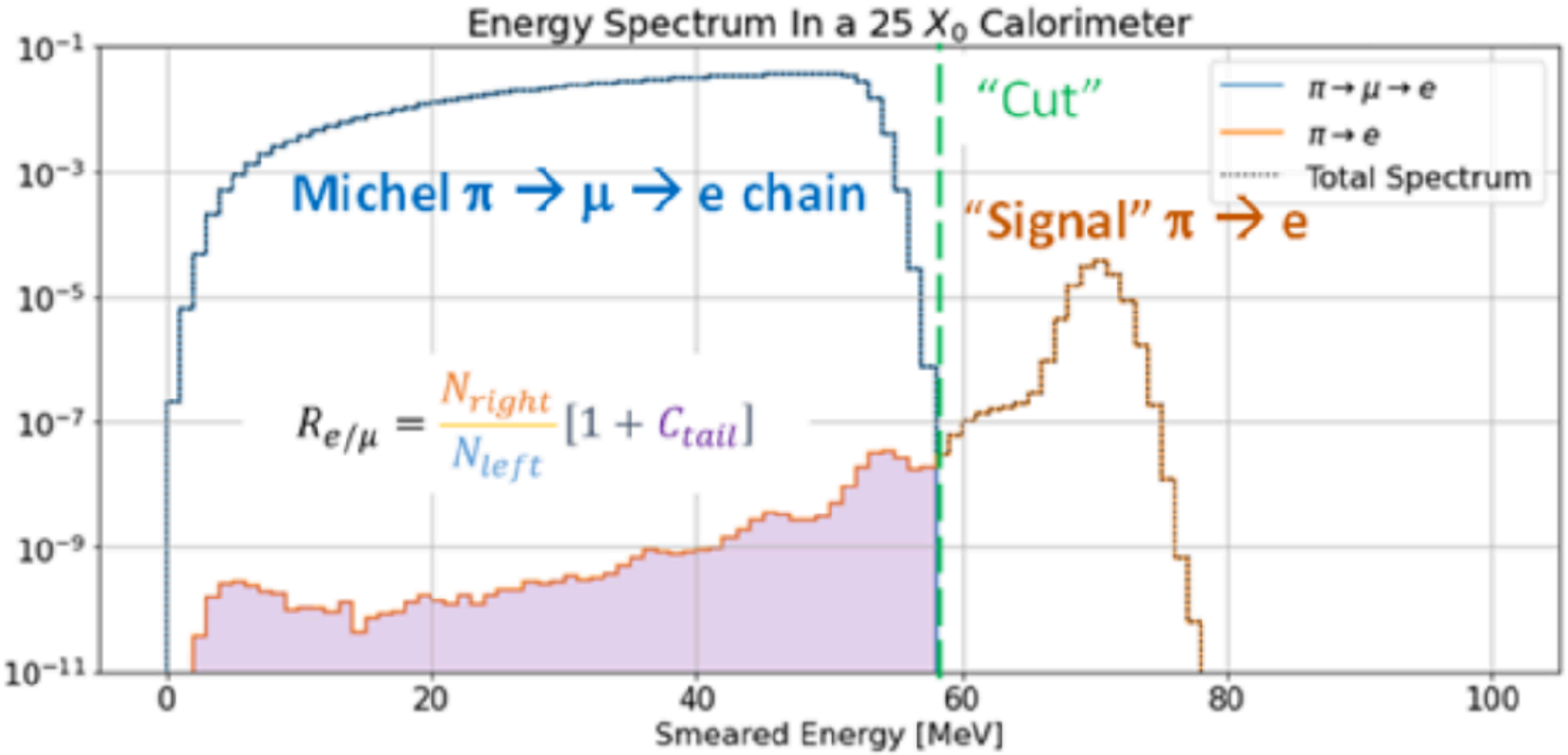
Pion mass: 139.6 MeV
Muon mass: 105.7 MeV



Measurement principle



ATAR Tracking



Calorimeter energy deposit

World most intense pion beam

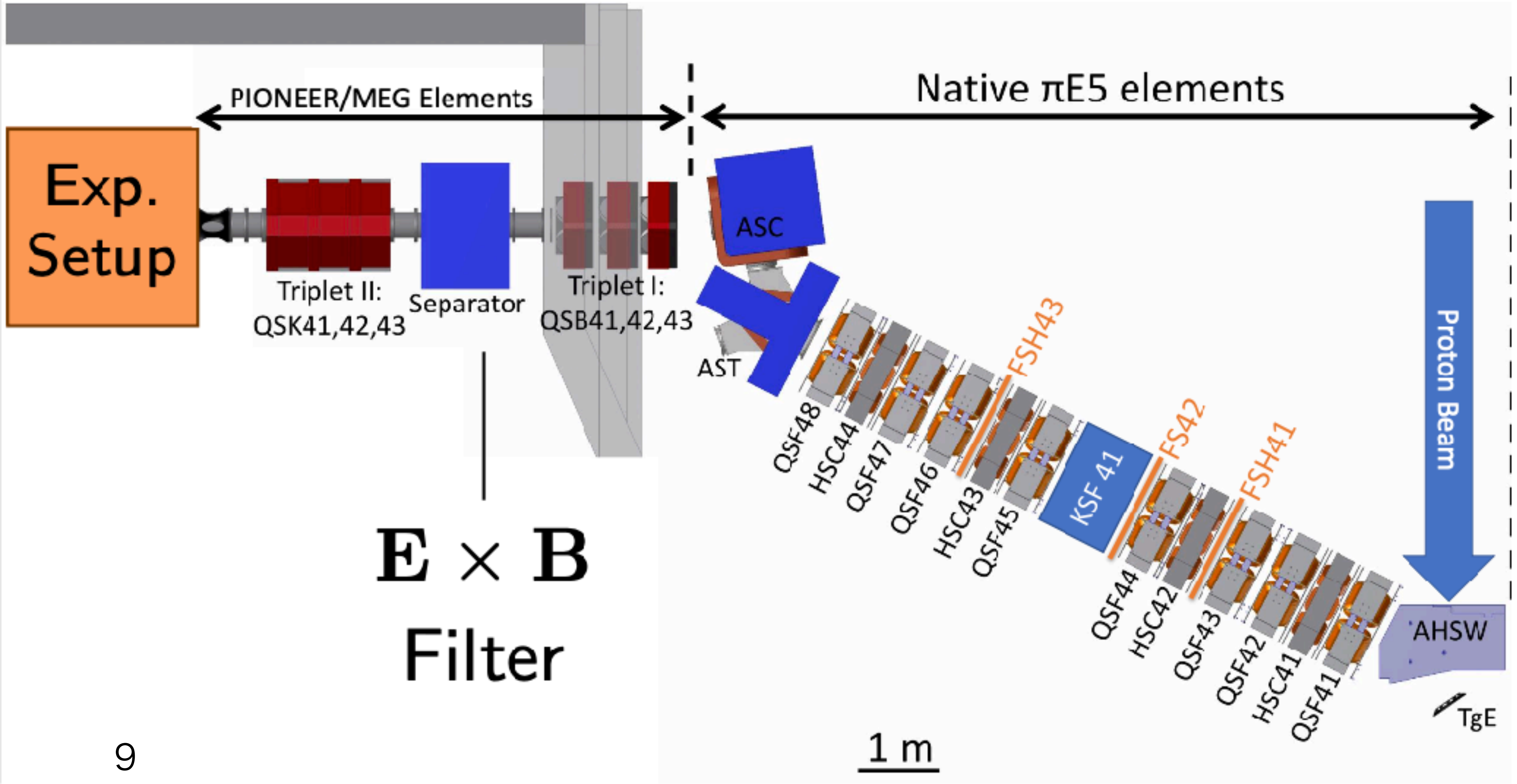
Requirements

- Momentum : 65 MeV/c
- Rate : $> 3 \times 10^5$ π^+/s
- Beam size : σ_x, $\sigma_y < 10$ mm
- Momentum bite : $dp/p < 2\%$
- Contamination : < 10% e, μ

1.4 MW 590 MeV proton accelerator in Paul Scherrer Institute in Switzerland

Paul Scherrer Institute

- PiE5 beam line would be the only candidate in terms of rate.



PIONEER detectors

Tracker

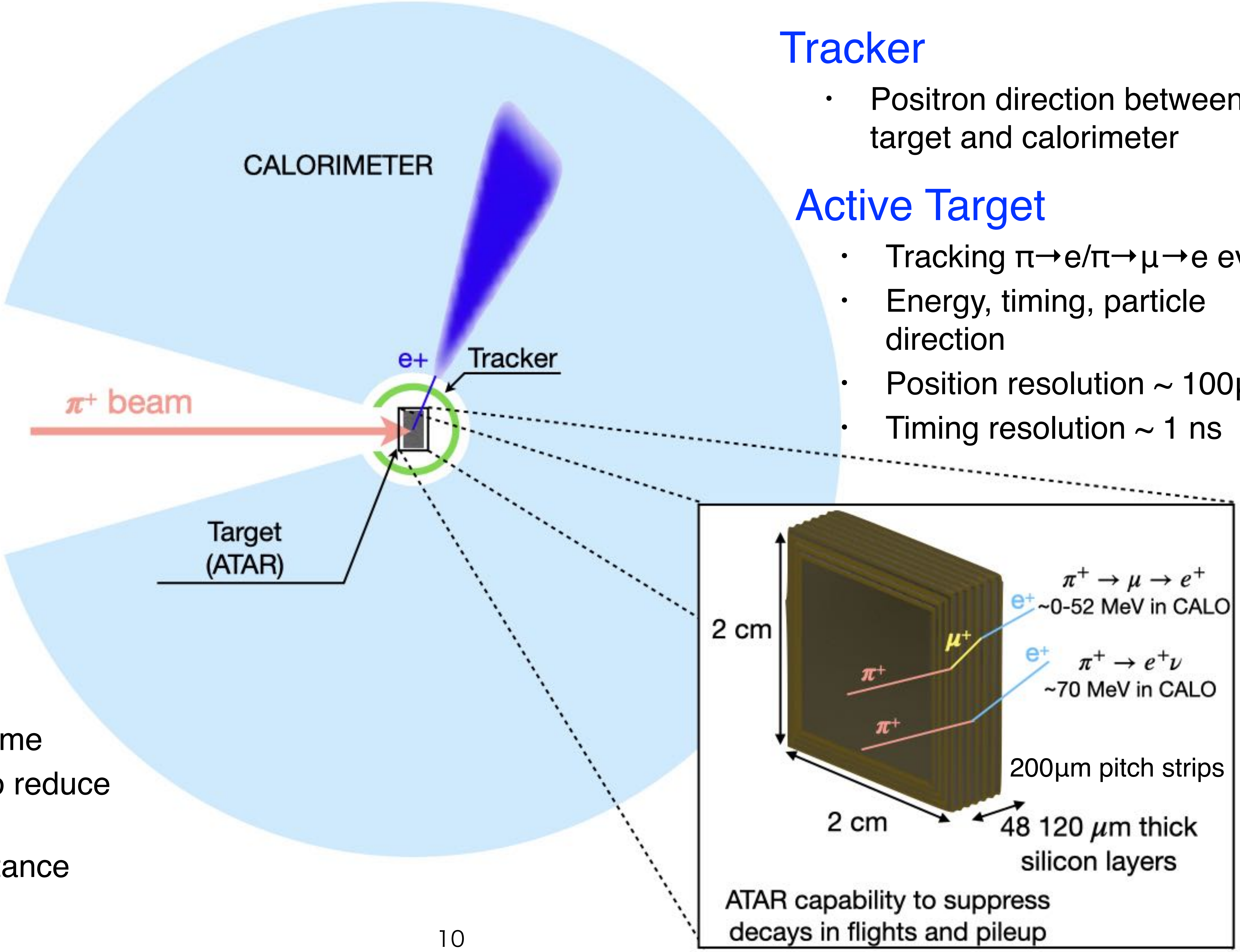
- Positron direction between target and calorimeter

Active Target

- Tracking π→e/π→μ→e events
- Energy, timing, particle direction
- Position resolution ~ 100μm
- Timing resolution ~ 1 ns

Intense π^+ beam

- > 3×10^5 π^+/s
- Available at PSI



Calorimeter

- Positron energy, time
- Depth of ~20 X_0 to reduce low energy events
- Large area acceptance

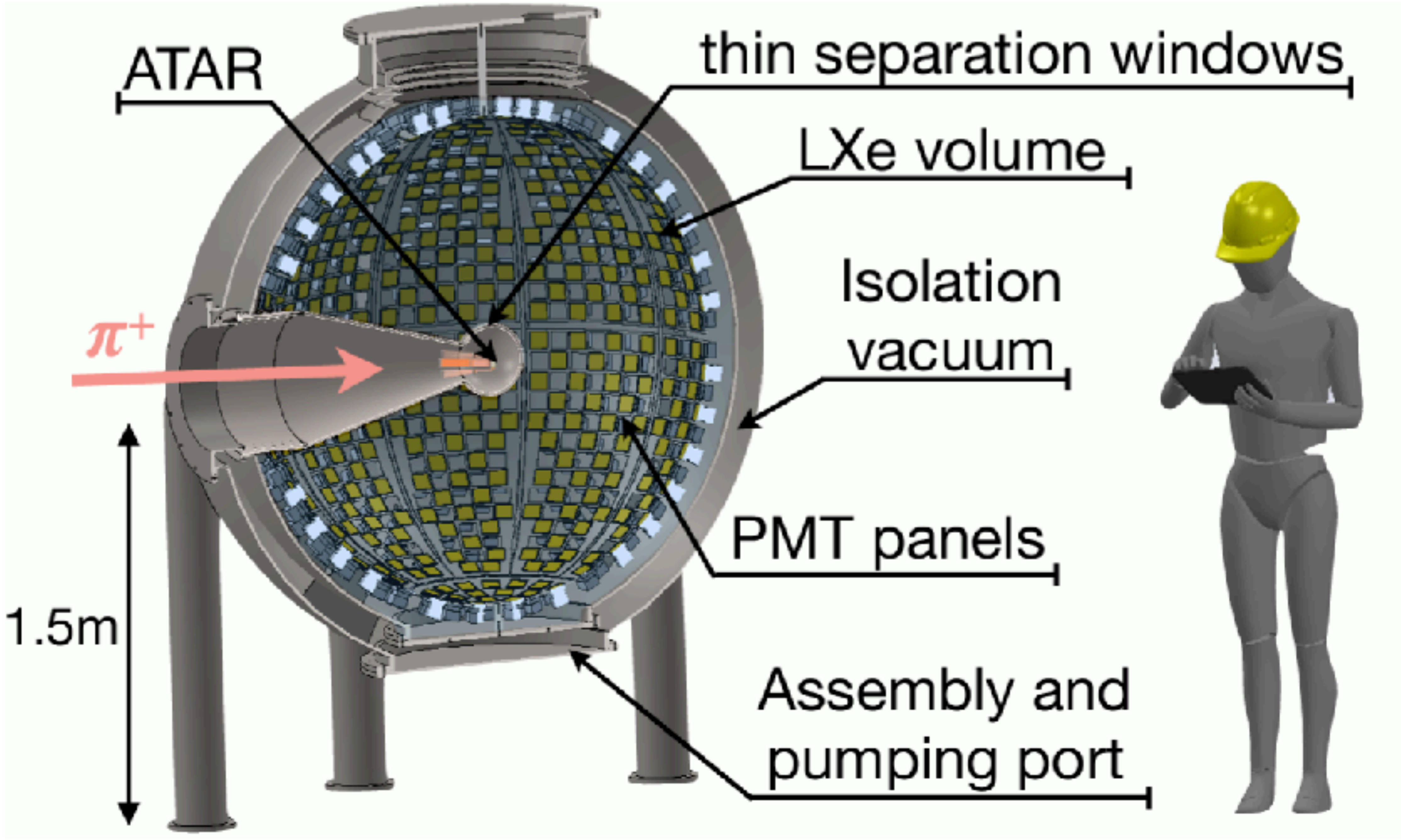
Calorimeter

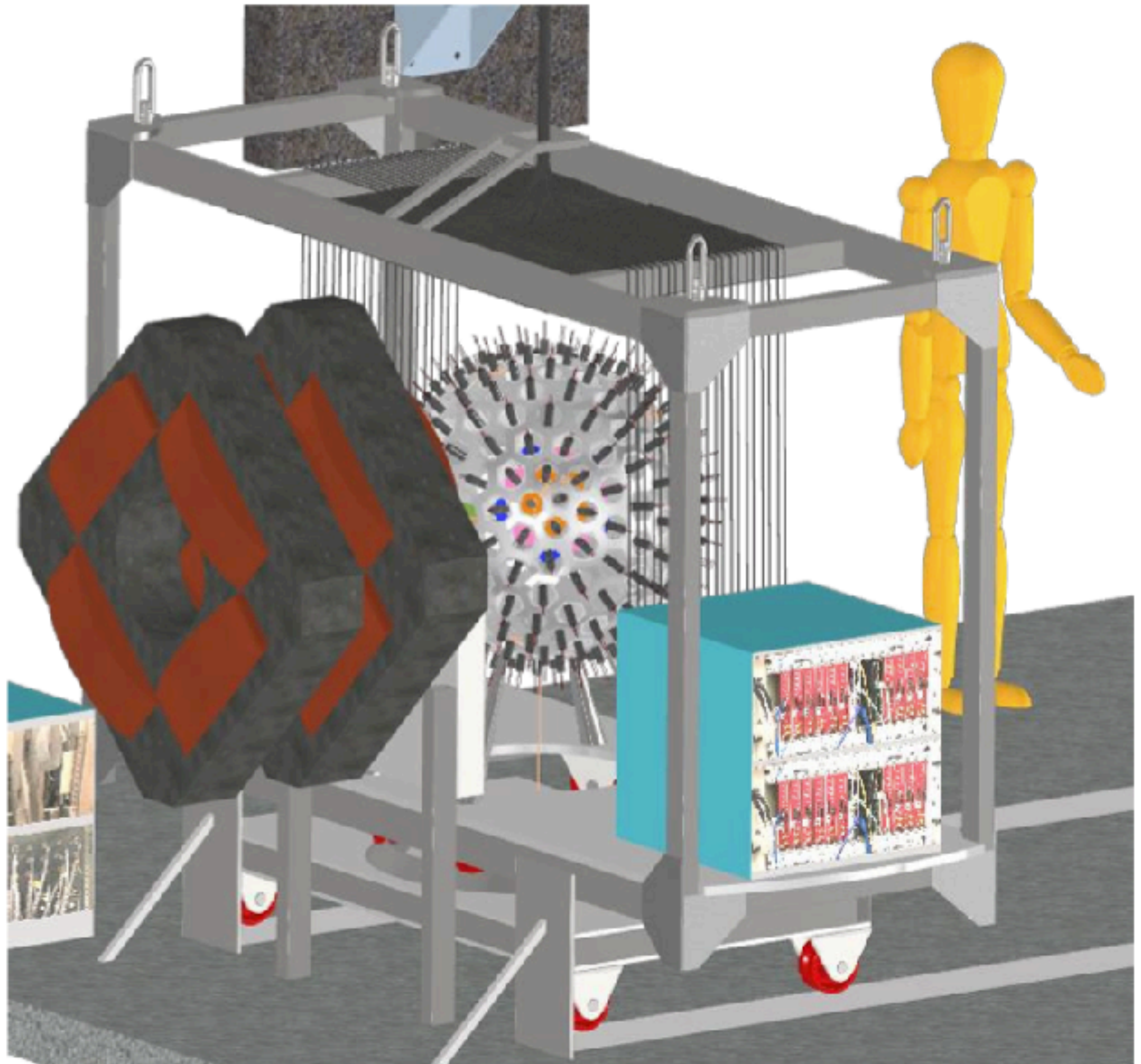
Requirements

- High uniformity, large coverage (3π)
- Sub-ns timing, energy resolution 1.5-2%
- Tail suppression (~20X_0)
- High rate tolerance, pileup separation

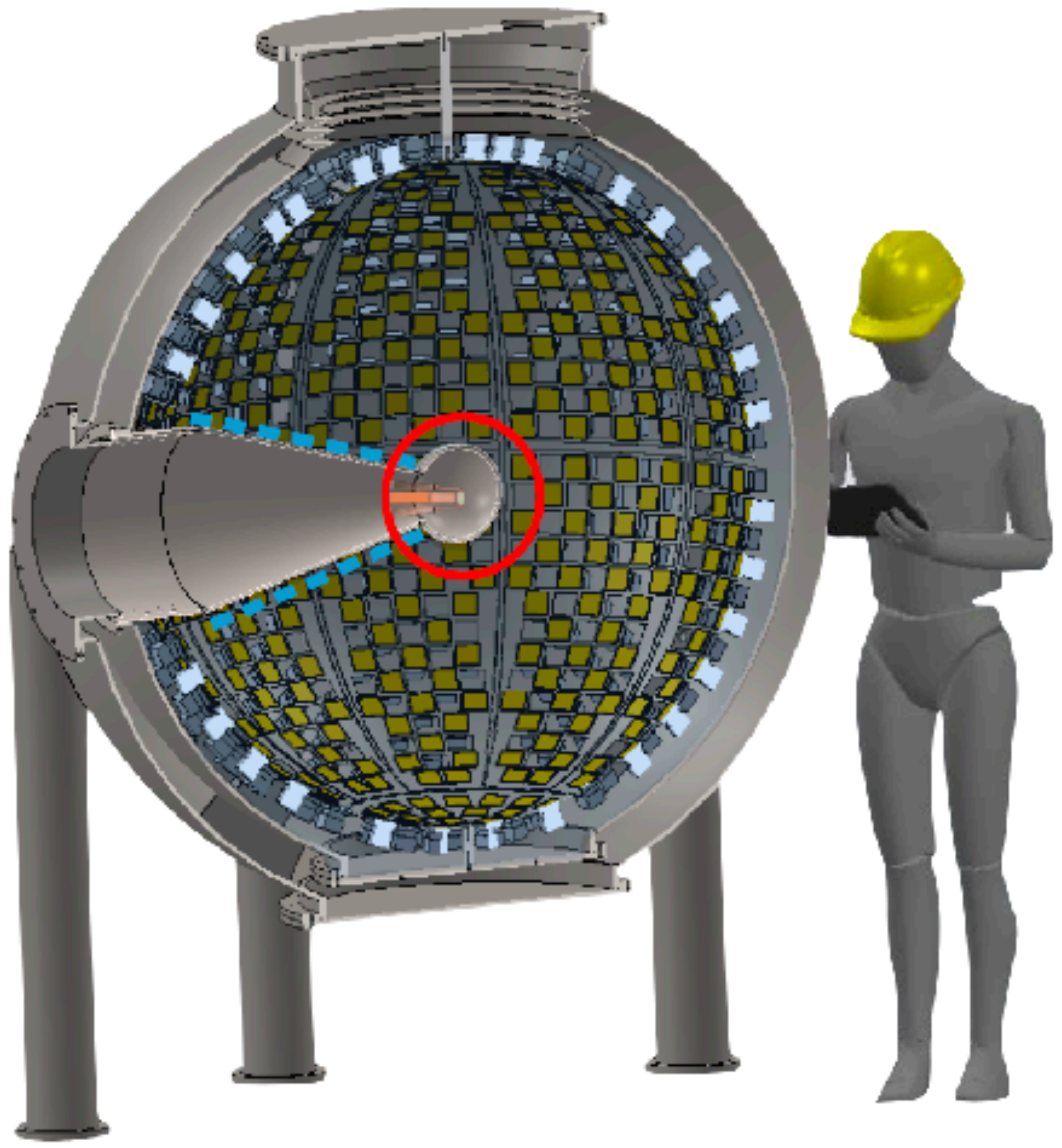
Two options

- LXe ~4 t (19X_0)
  - PMT coverage 25% (500)
    - R12699-406-M4 (VUV flat panel PMT)
- LYSO
  - 236 (or 330) blue PMTs viewing individual crystals

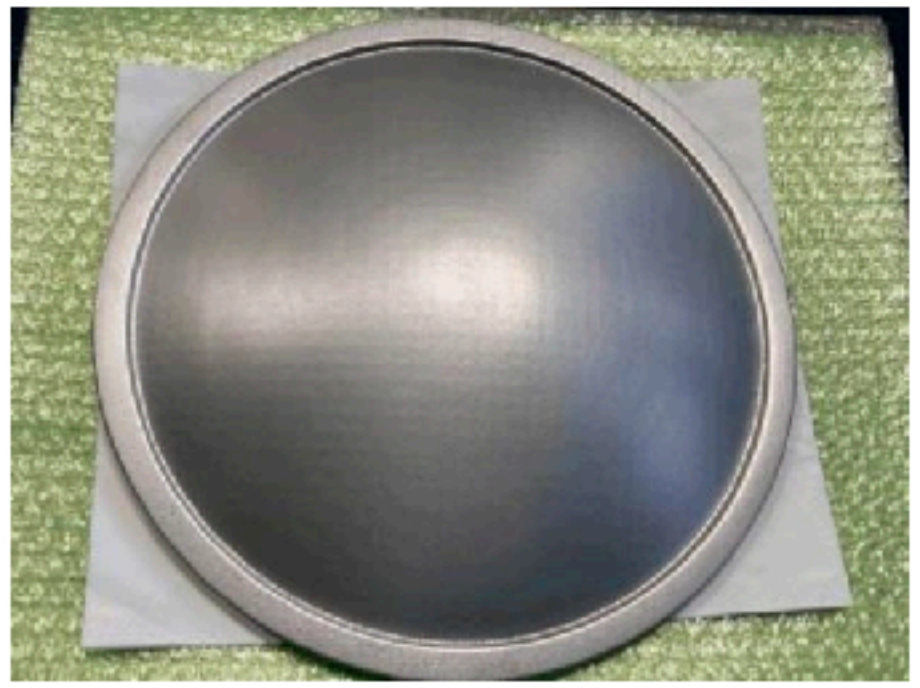




Calorimeter Development

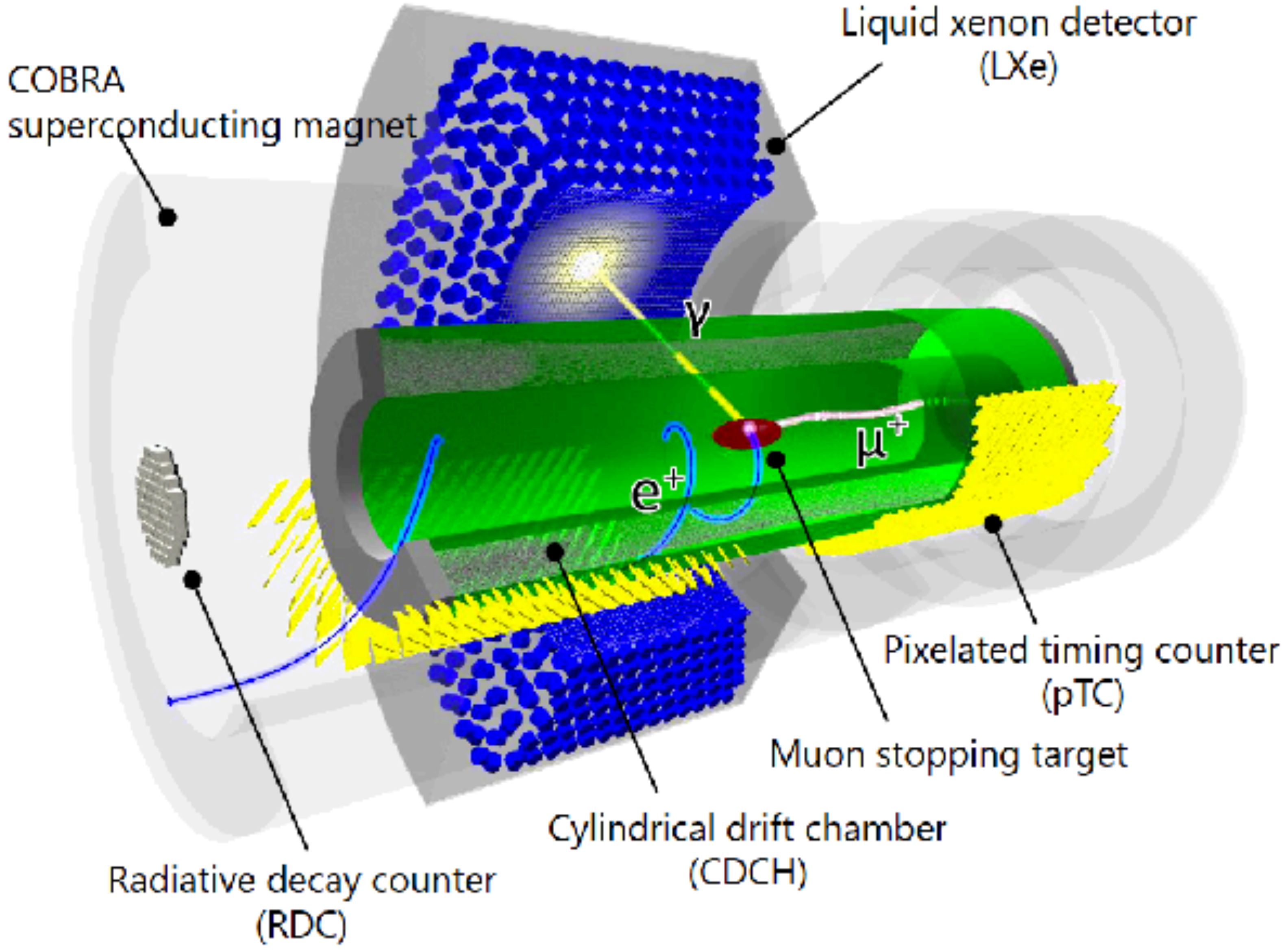


- Large volume liquid xenon detector
  - Experience from the MEG/MEG II LXe detector
  - 52.8MeV γ → 69.3MeV e^+ measurement
- Thin window development
  - 64Ti and Al
- Reconstruction
  - Sensors in outer sphere
- Inner sphere photo sensors
  - Thin VUV-MPPCs



0.5mm 64Ti beam window

0.15mm Al rapture disk



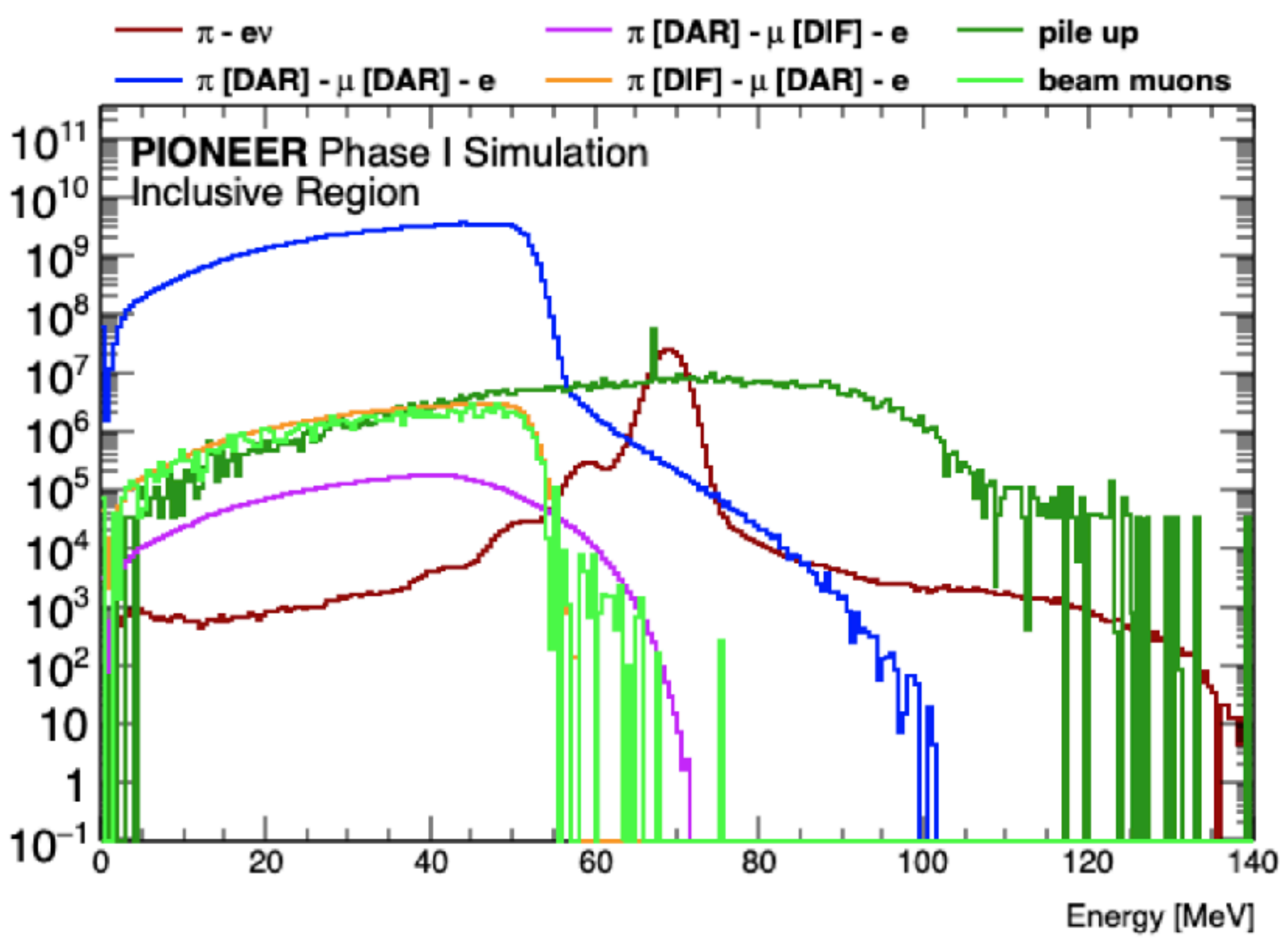
VUV-PMT (R12699-406-M4)

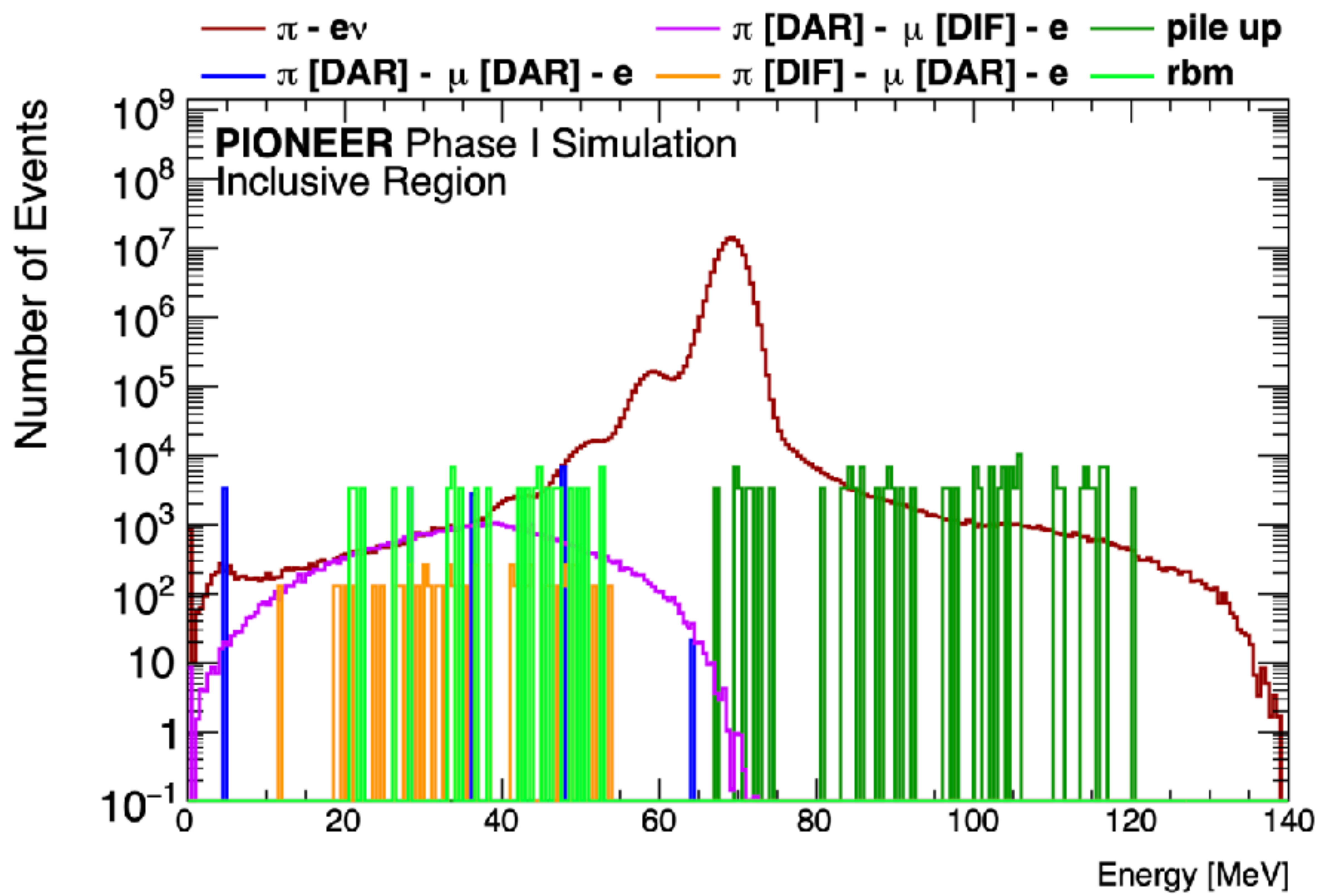
VUV-MPPC chip on film (CoF) package

https://indico.phys.ethz.ch/event/45/contributions/658/attachments/372/901/
Hamamatsu Introduction (Symposium) 20231017.pdf

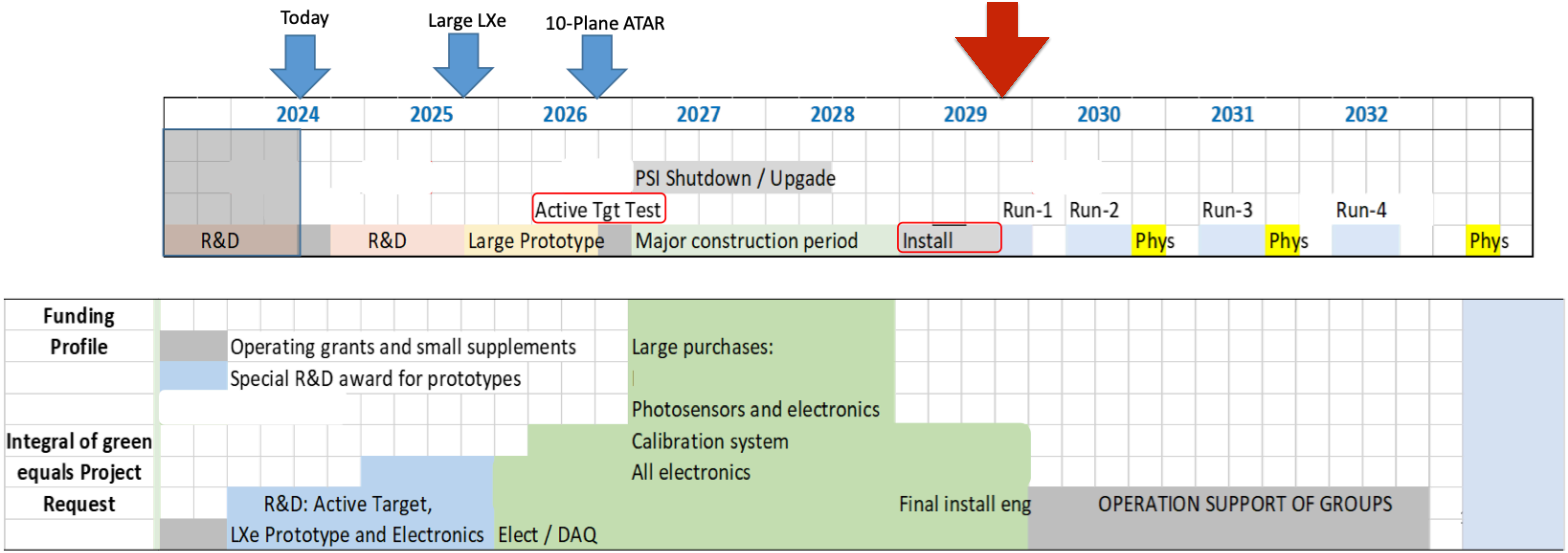
Simulation study

- Latest simulation result w/o any cuts(left) / timing and w/ ATAR information (right)
  - Calorimeter [5,500] ns window, energy deposit in ATAR
- Successful identification of $\pi \to \mu \to e$ events, pileup events
- Precise sensitivity estimate ongoing





PIONEER timelines



- PSI has a long shutdown between 2027 and 2028
- The PIONEER experiment will aim at the detector construction during that, and start the run from 2029

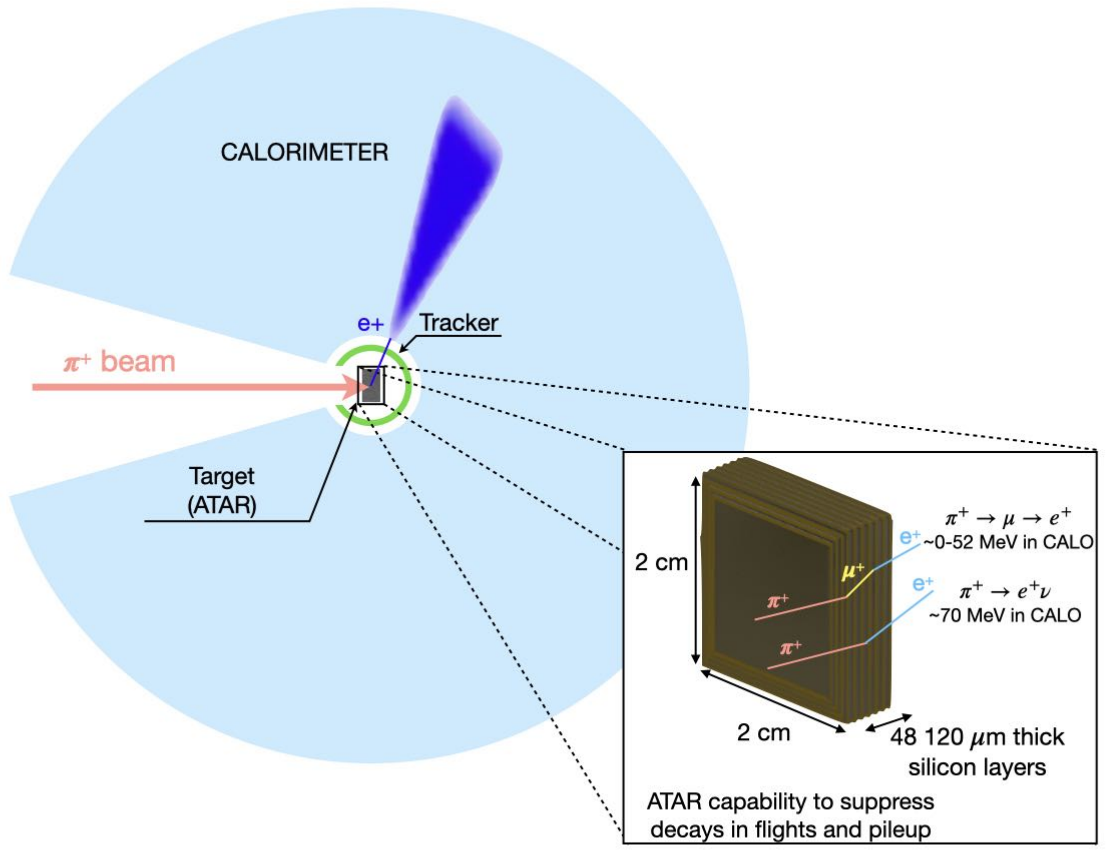
Summary

- The PIONEER experiment will explore the lepton flavor universality violation with 0.01% precision in the ratio measurement $R^{\pi}_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$
  - The experiment was approved with high priority by PSI review committee in 2022

- Experimental challenges requires state-of-the-art technology including ATAR, high resolution, deep and fast EM calorimeter, advanced trigger, and detailed simulation

- The PIONEER collaboration grows internationally, and new ideas, expertise, and new collaborators are welcome

Active target



Requirements

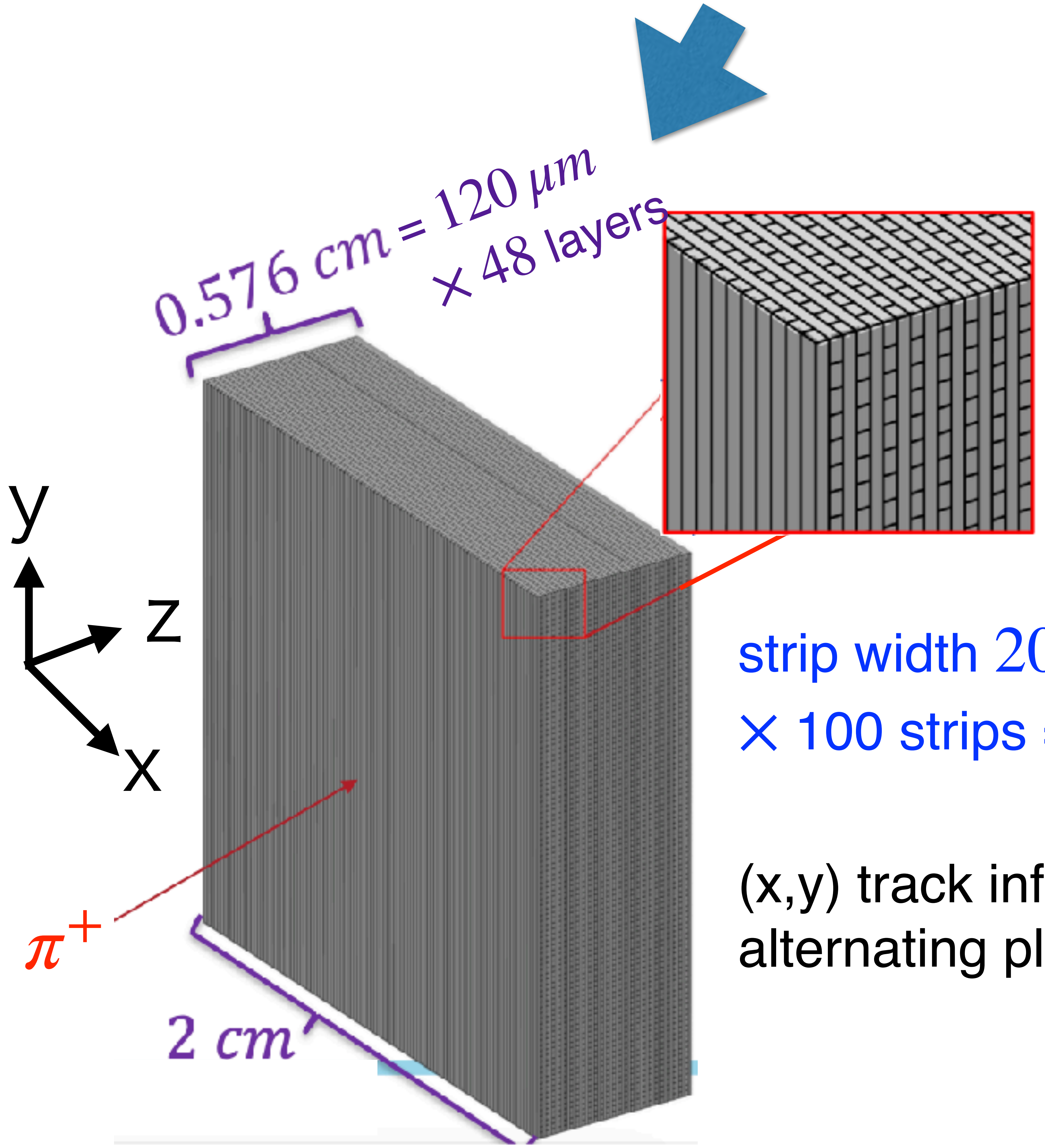
- Energy response
  - 30 keV MIP ~ 4 MeV μ+ Bragg peak
  - High resolution, large dynamic range
- Tracking (π/μ/e)
  - High granularity in (X,Y,Z)
  - 4 MeV μ+ travels 0.8mm in Si
- Timing
  - π/μ hit separation by 1.5ns for 300kHz

Baseline technology

- High granularity Low Gain Avalanche Diode (LGAD)
- High S/N, full fast collection time, great time resolution

Status

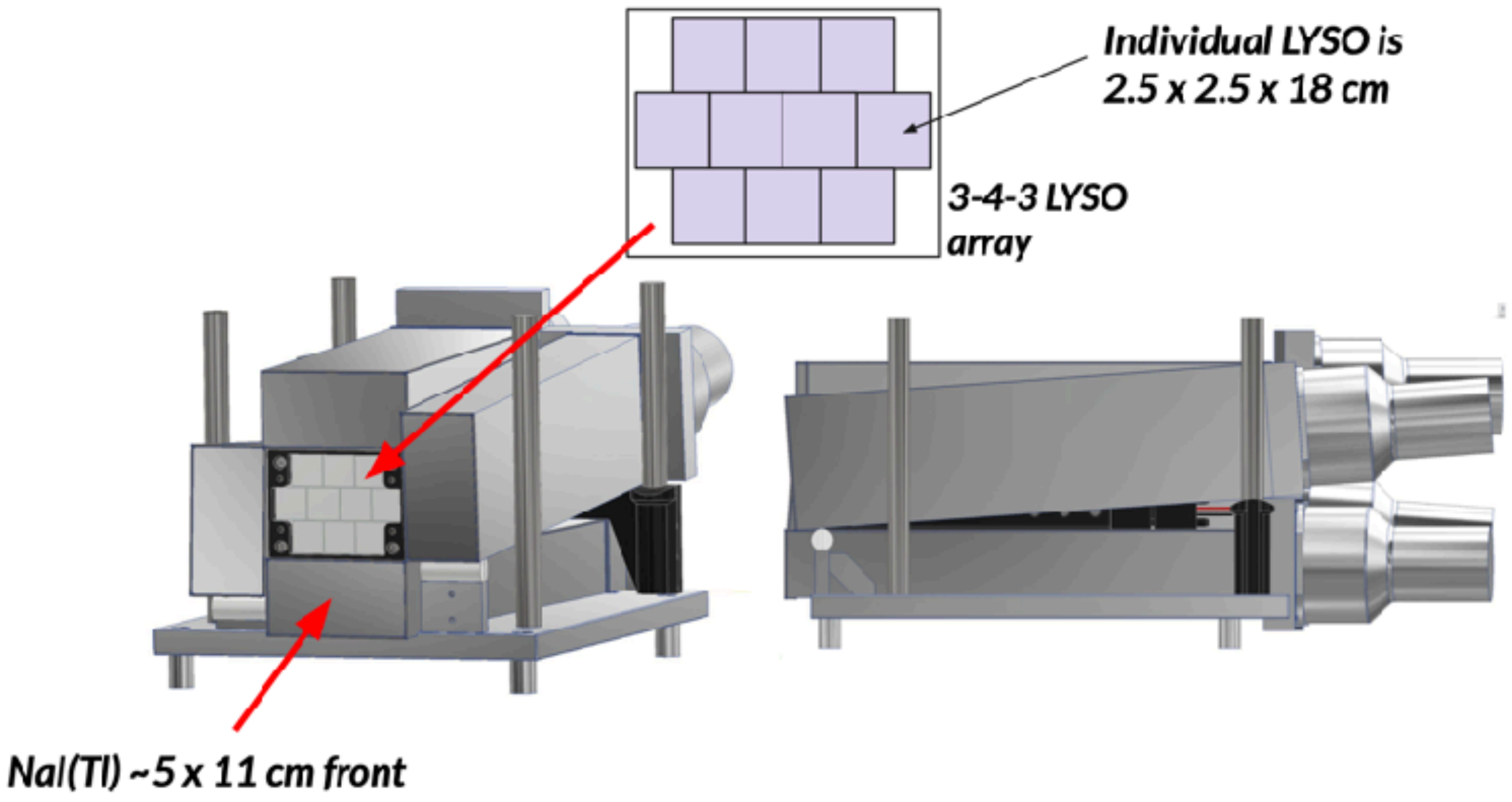
- R&D of the technology on AC-LGAD, TI-LGAD etc.
- Minimal cross talk, small gain saturation, large dynamic range

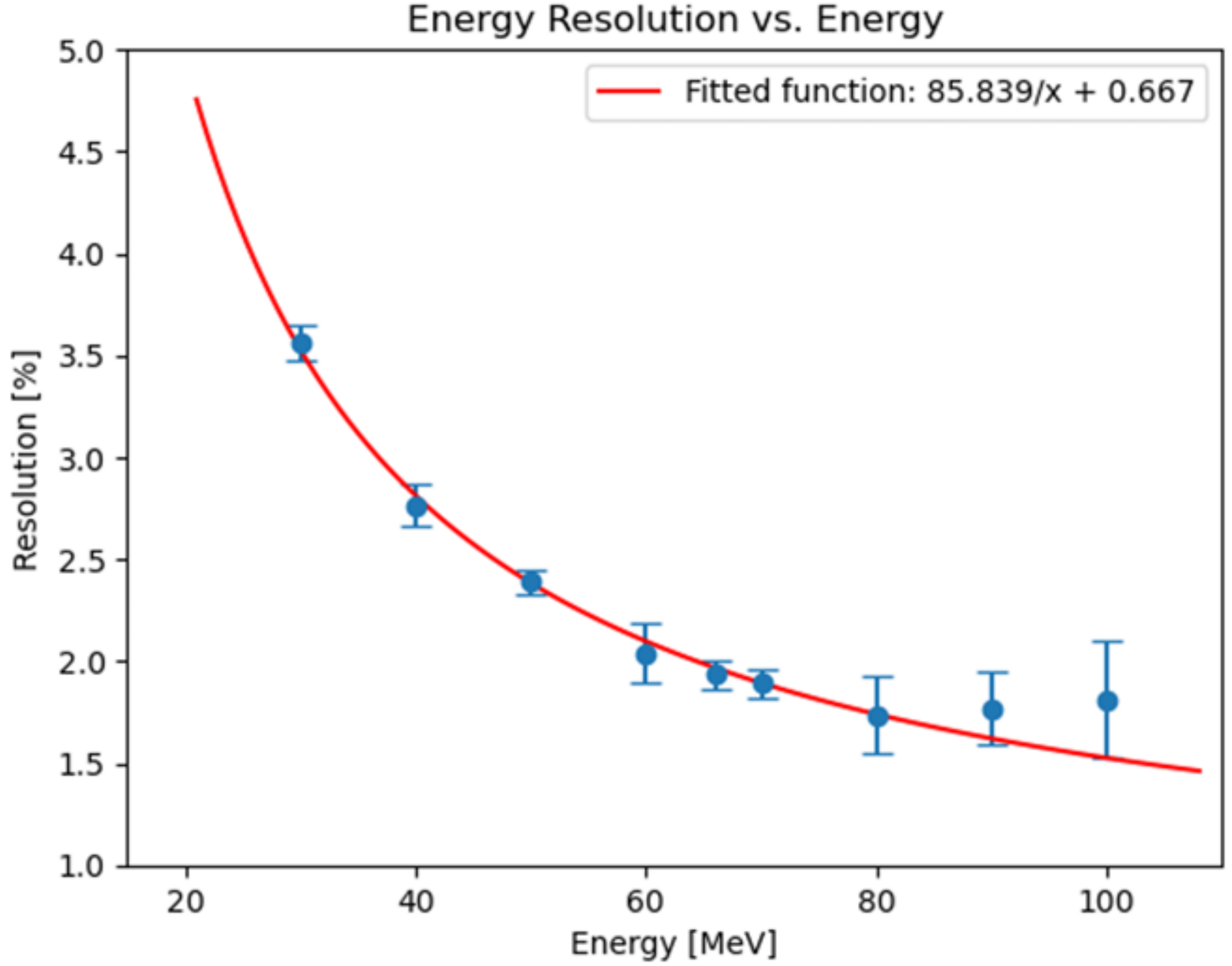


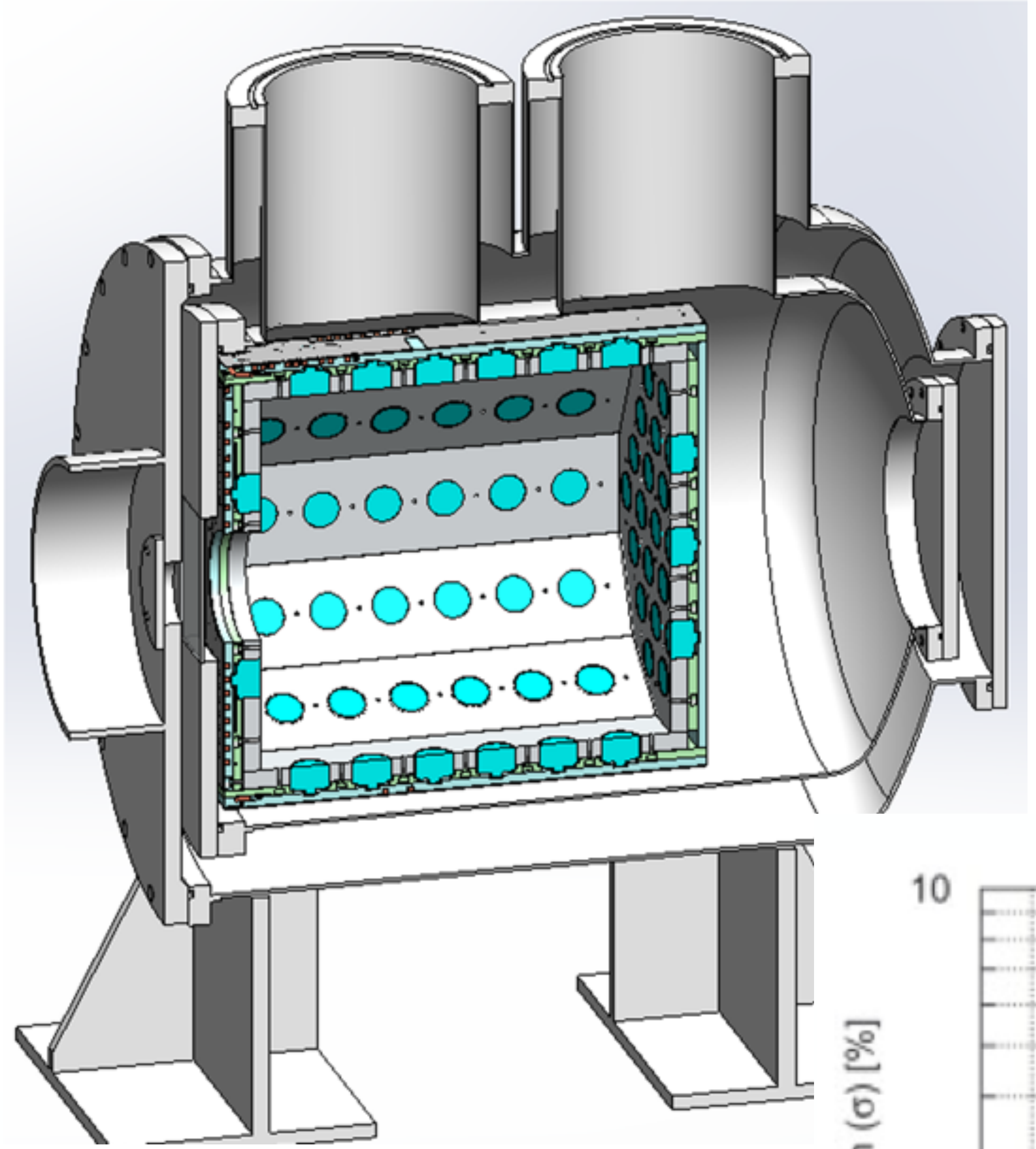
strip width 200 μm
× 100 strips = 2 cm

(x,y) track info. from alternating planes

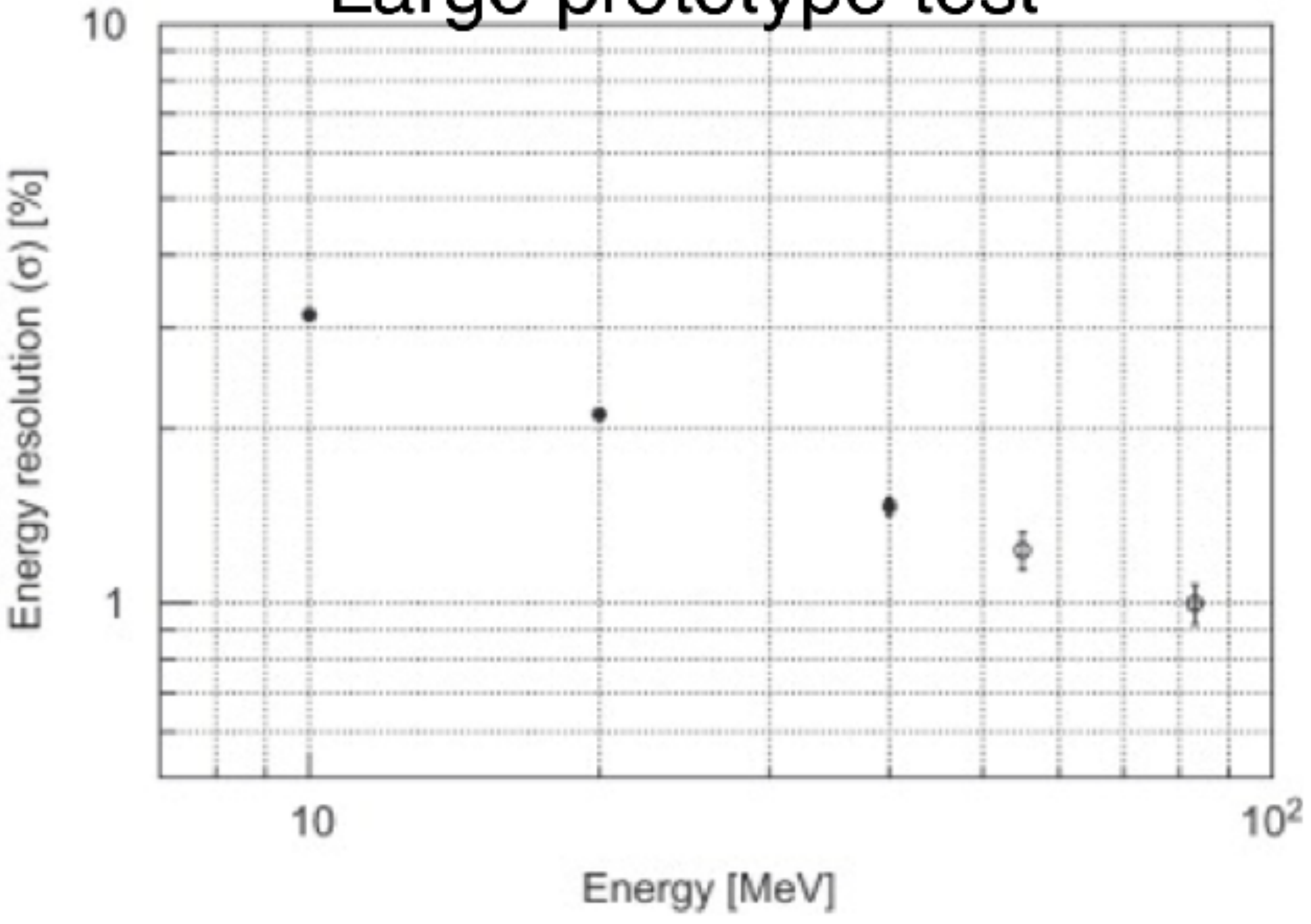
Calorimeter R&D







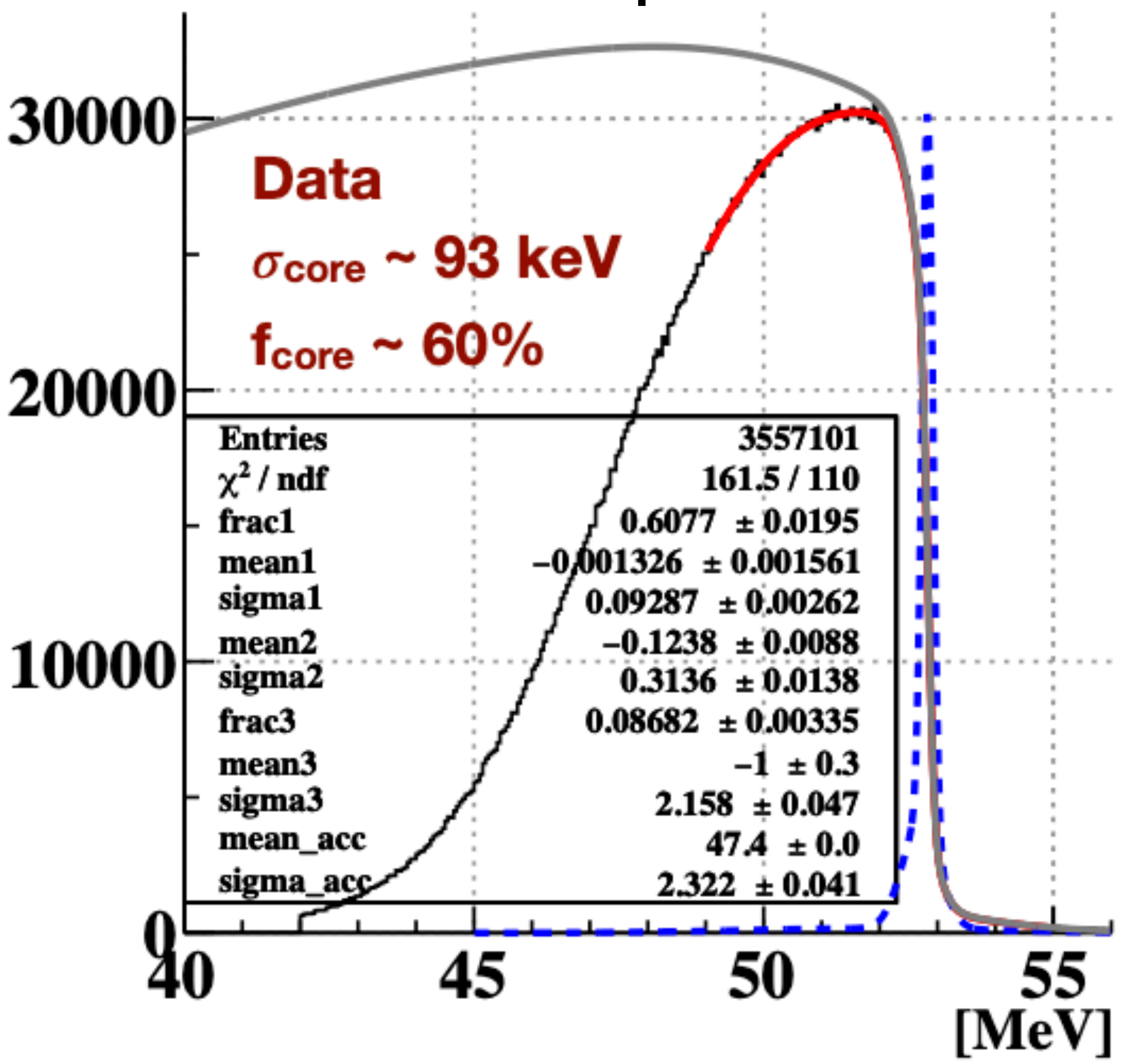
Large prototype test

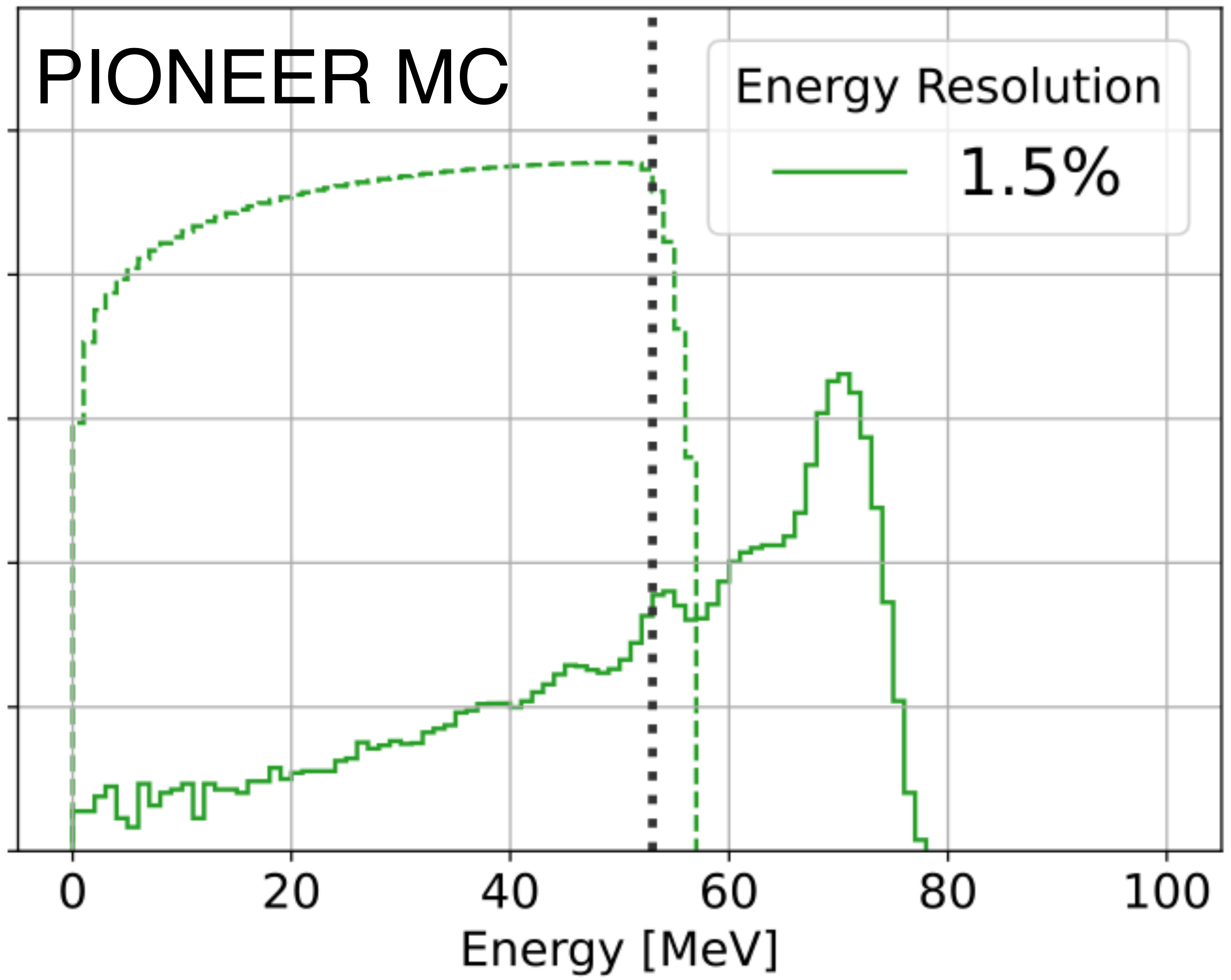


R. Sawada, NIMA581(2007)522

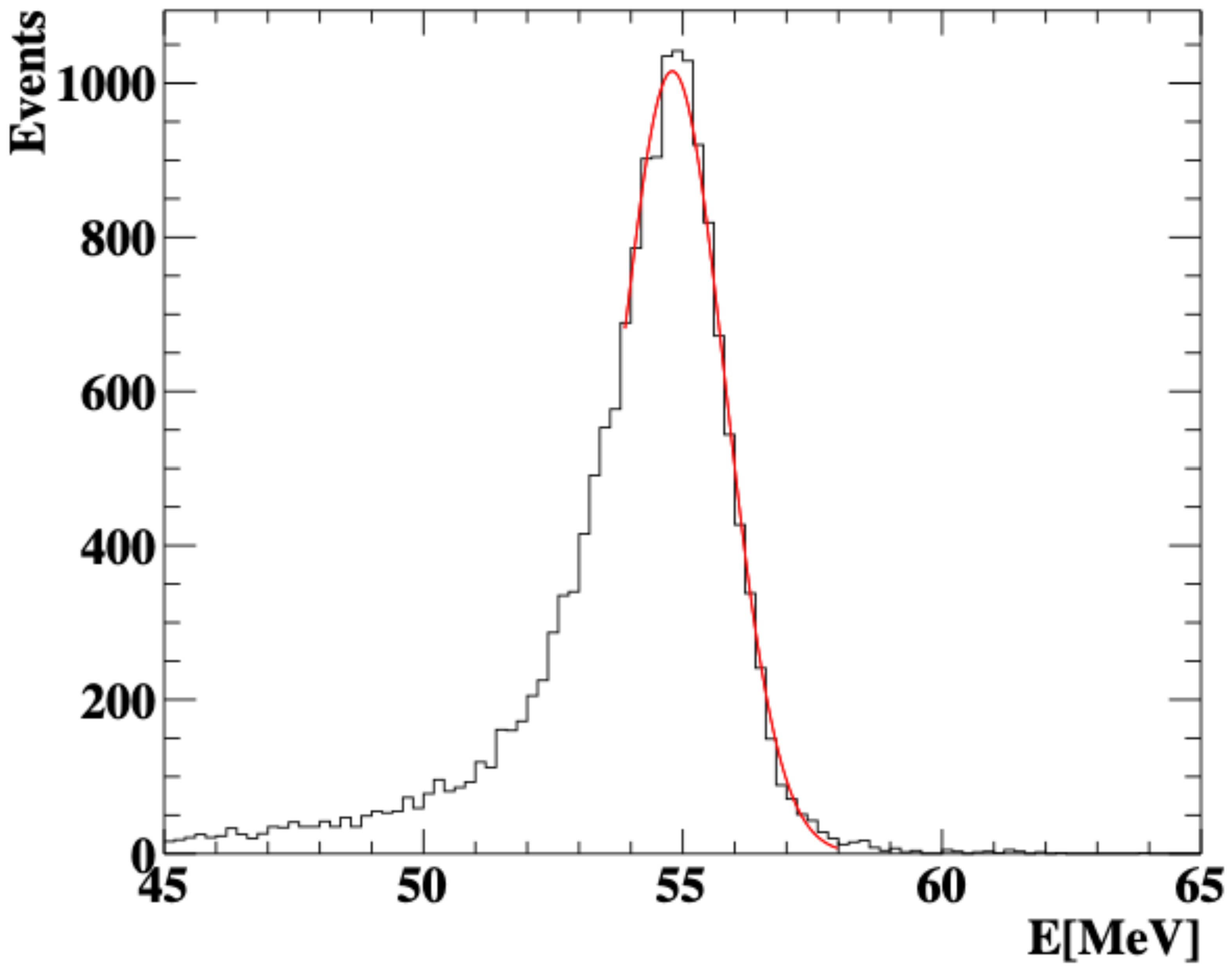
PIONEER case

MEG e^+ spectrum





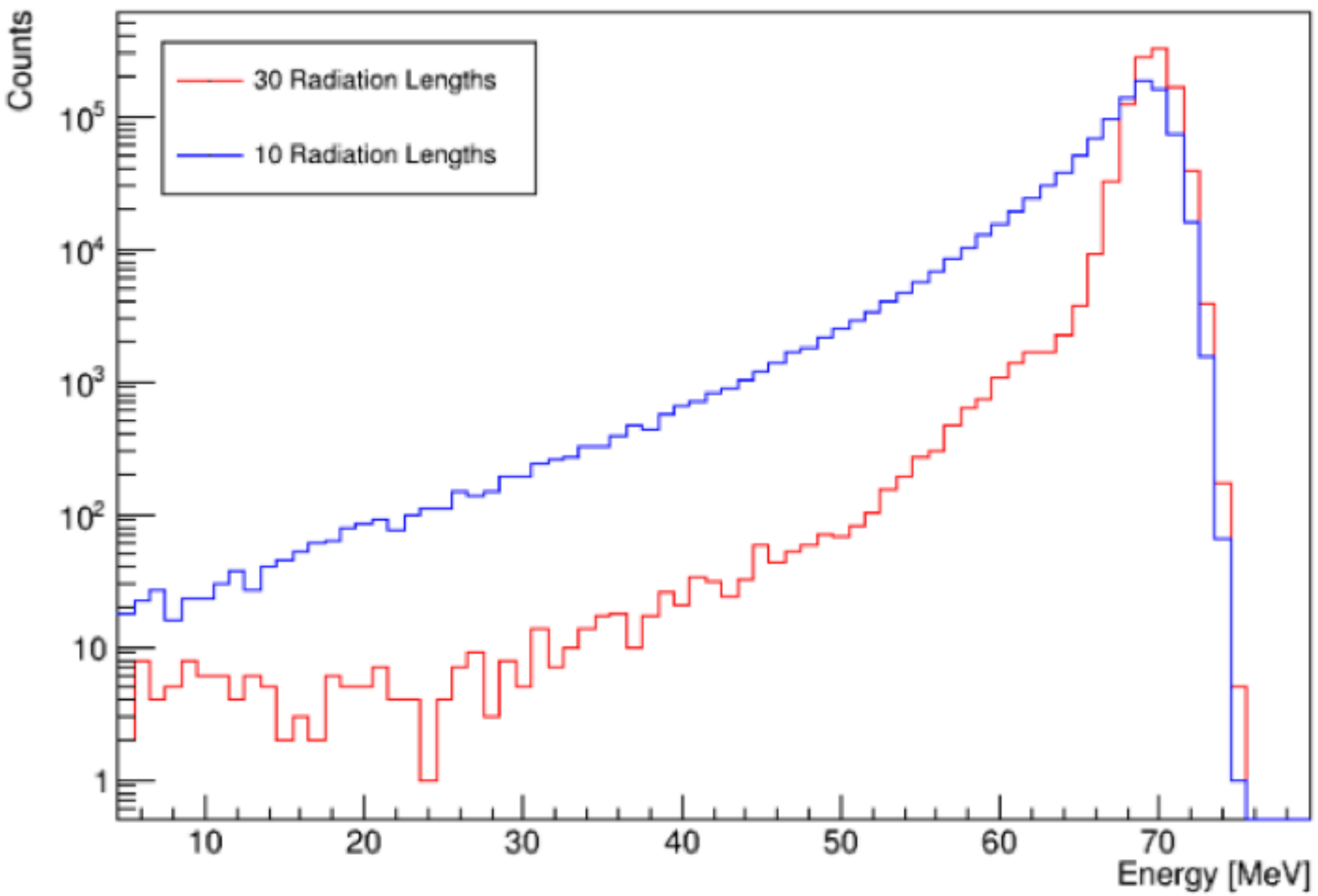
MEG γ spectrum



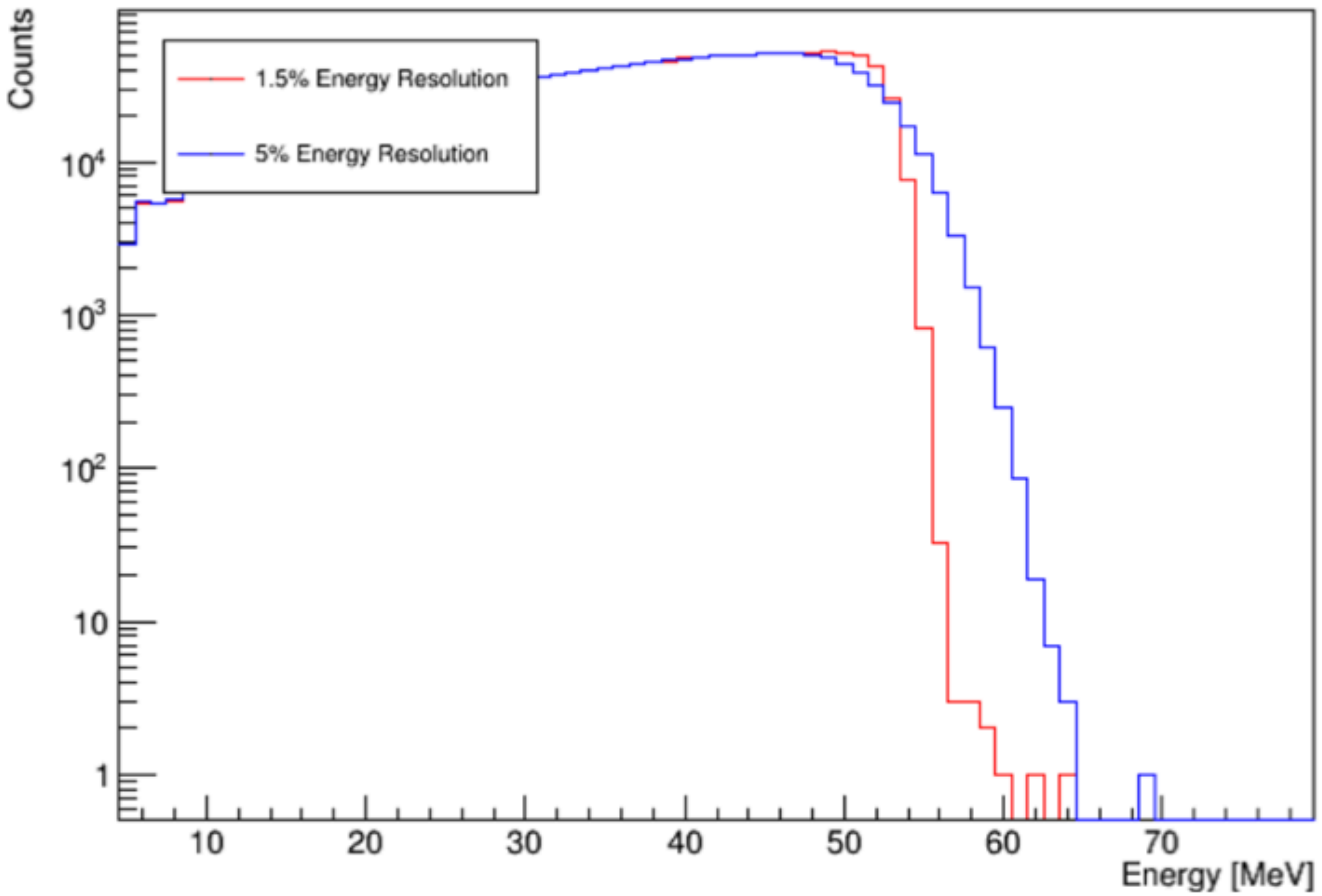
- Energy scale, resolution can be directly extracted from 70 MeV peak and from 53MeV Michel edge in PIONEER (robust calibration possible)
- Sensor calibration, LXe light yield monitoring by LED, α crucial
- Other γ calibration sources (AmBe 4.4MeV, Ni 9MeV, Li 17.6MeV, π^0 55MeV, Cosmics) are optional
- Positron incident position can be measured by trackers
- Each photo sensor time offset might be available from the LGAD time as a reference

Calorimeter concept

$\pi \to e\nu$ signal



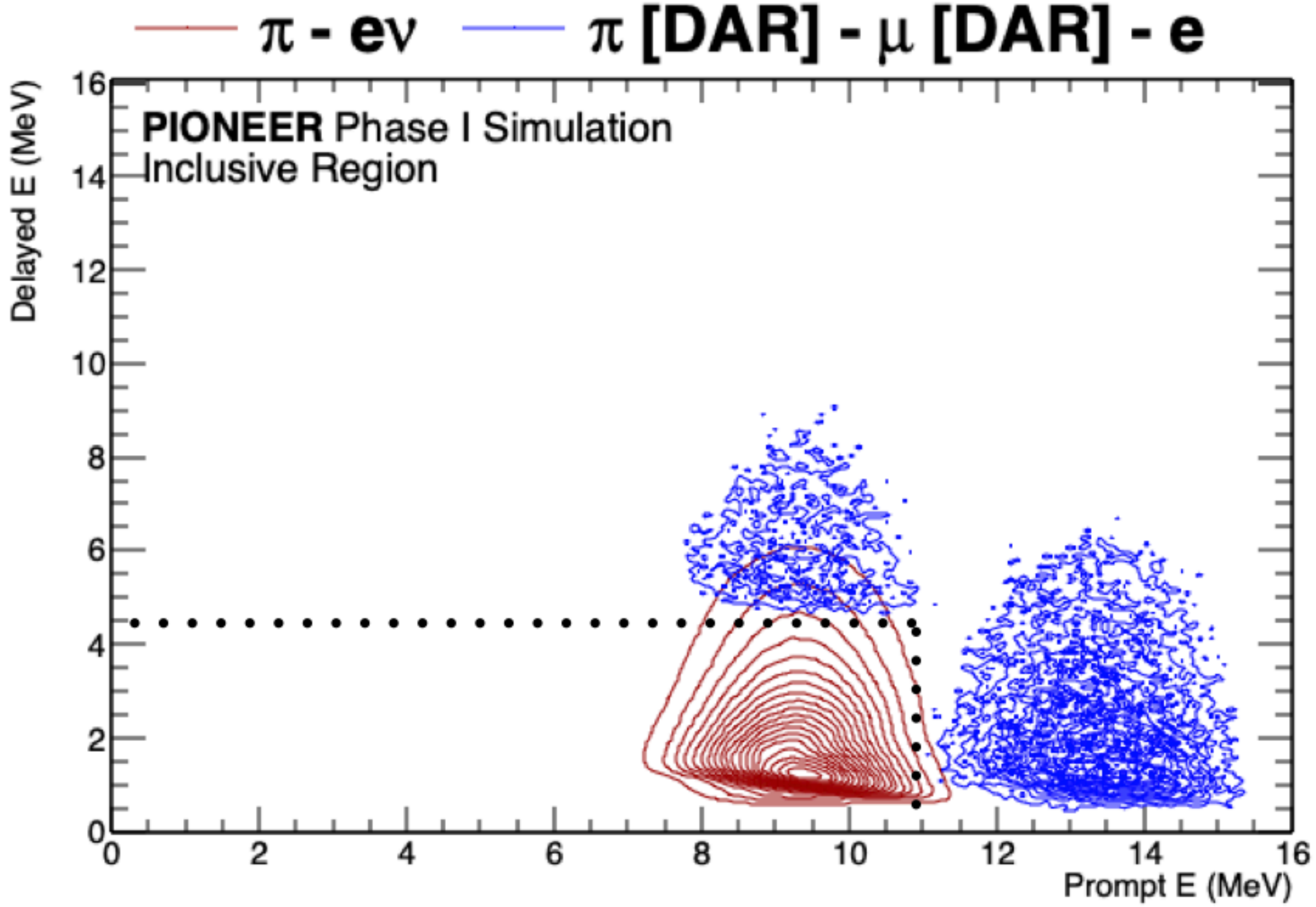
$\pi - \mu - e$ background



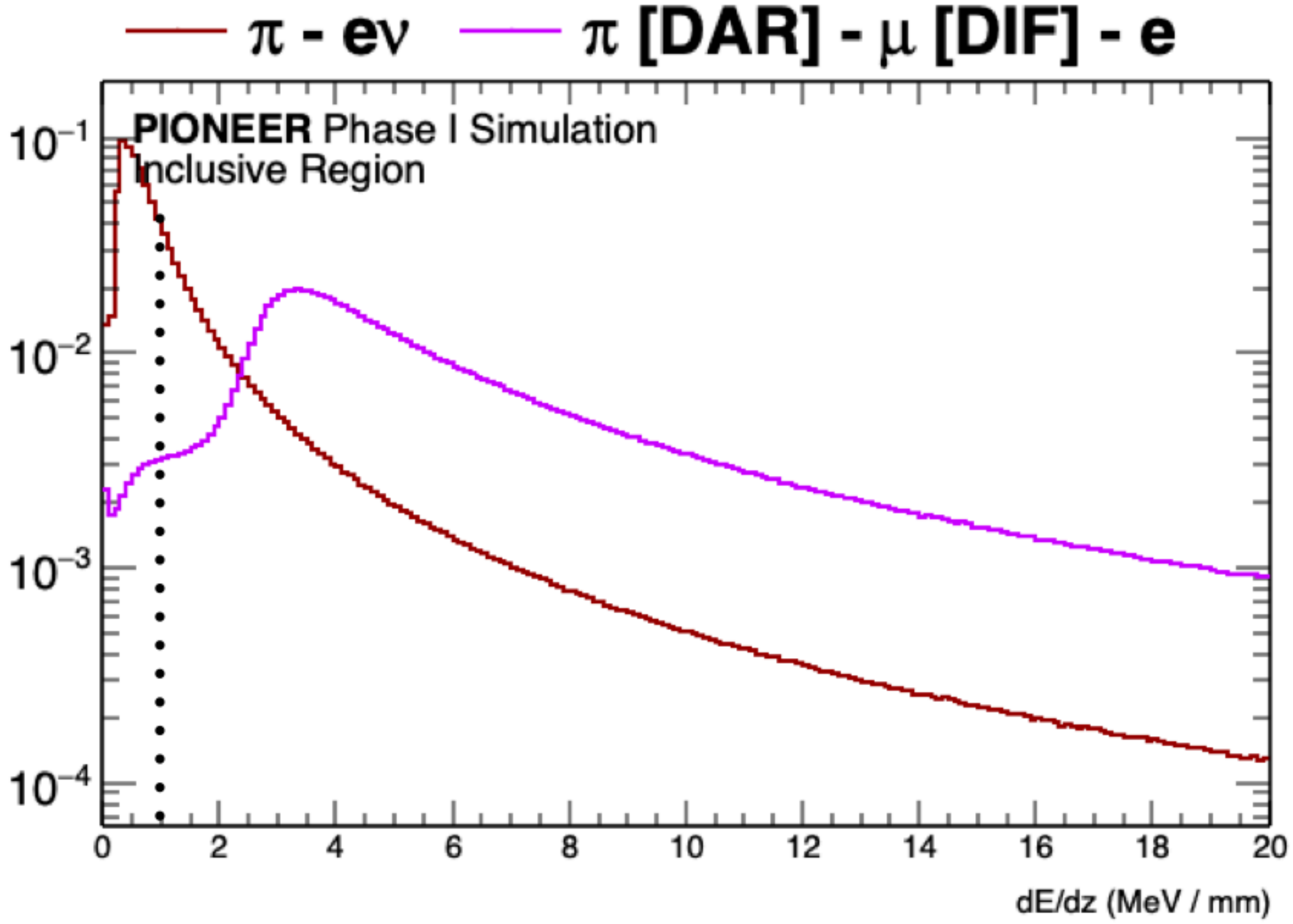
Target: ~25 X_0, 2% energy resolution at 70 MeV

What is measured in ATAR

Simulation study for background suppression



Energy cuts to suppress Michel events



dE/dx cut along the z-direction to suppress muon decay in flight

Statistics & Systematic improvements

Intense, high quality π^+ beam

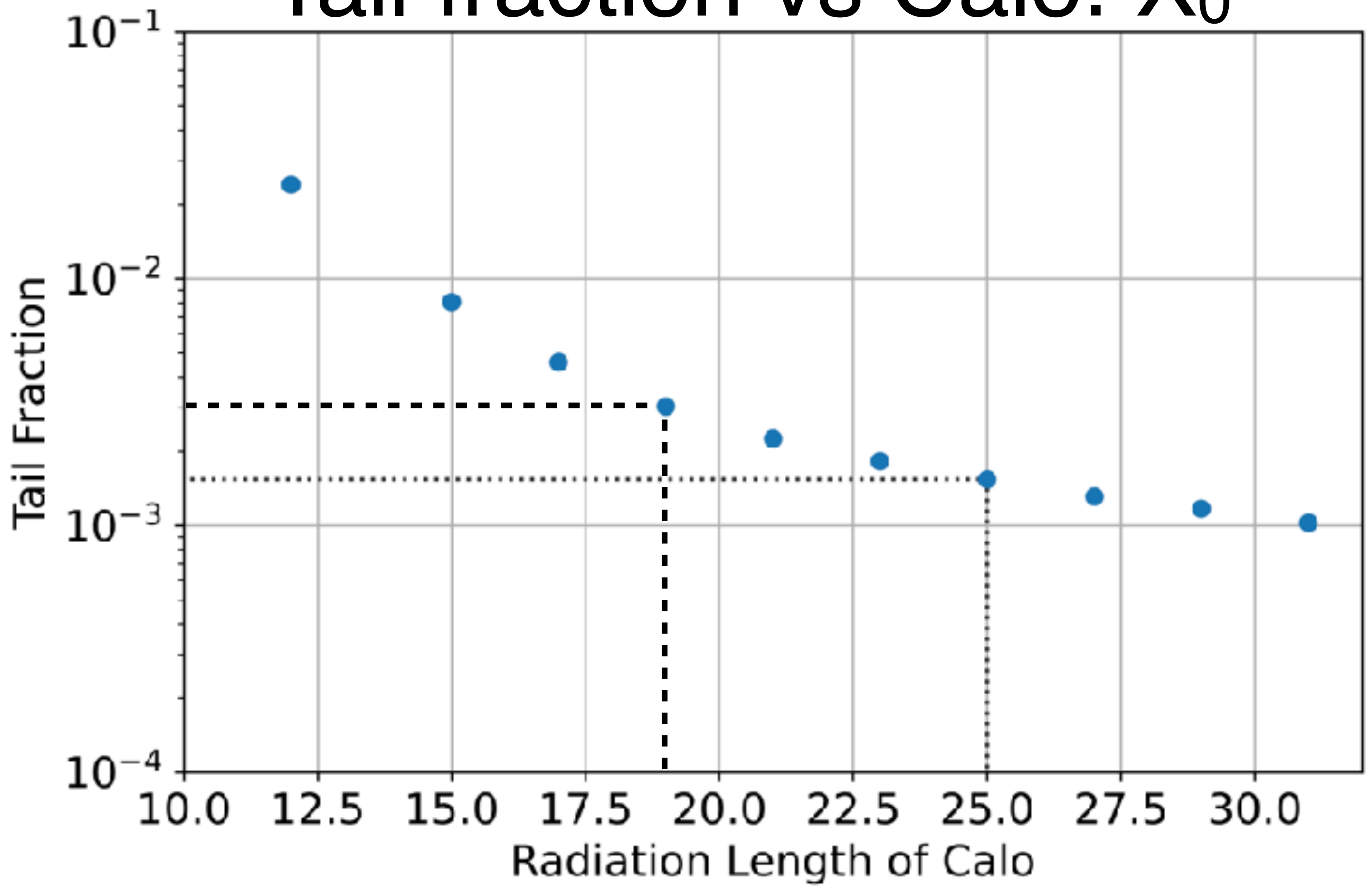
2×10^8 $\pi \to e\nu$ events in 2–3 years
with 3×10^5 π^+/s beam

Active target with new new technology

Calorimeter 3π, 19X_0, high res., fast
Dominant systematics from tail correction

	PIENU 2015	PIONEER Estimate
Error Source	%	%
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	**$\leq$ 0.01**

Tail fraction vs Calo. X_0



- Detector R&D with prototypes to demonstrate the above uncertainties in a few years (TDR will be prepared)
- Construction for 2-3 years, and starting the run in ~2029