Precision measurements of charged pion decays with the PIONEER Experiment

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ICHEP2024 @ Prague
July 18 2024

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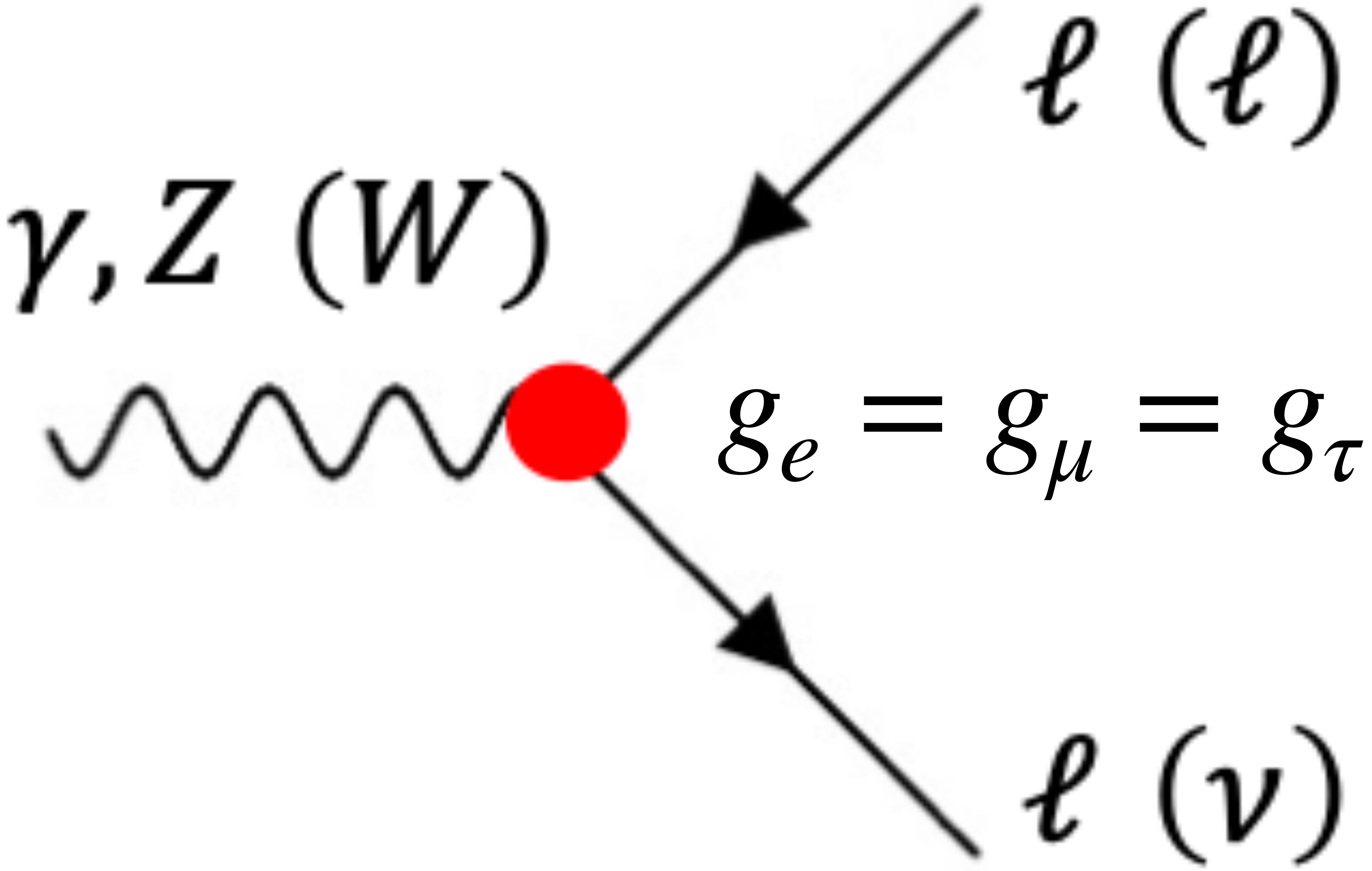
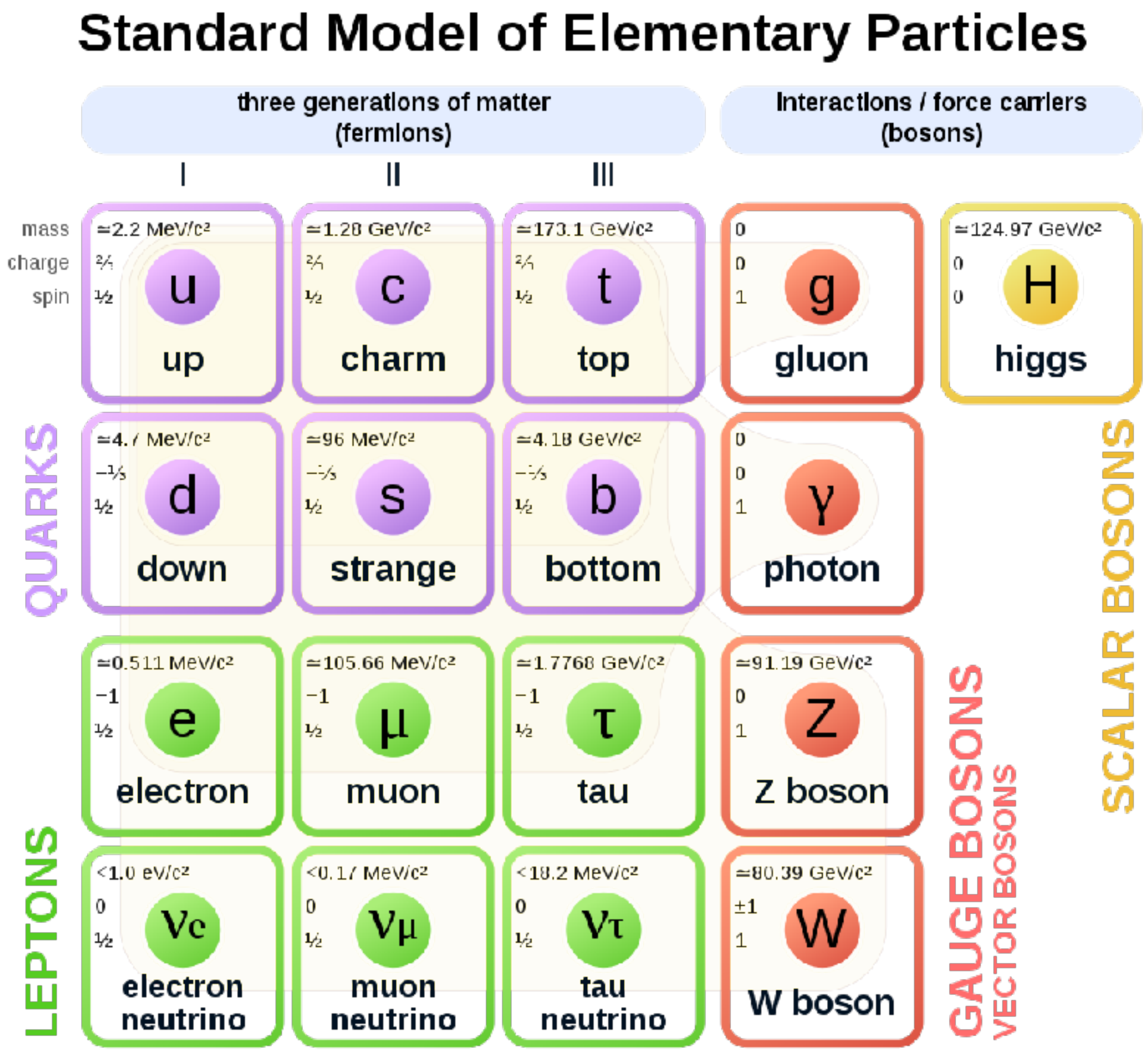
Introduction

Gauge interactions are lepton flavor universal in the standard model

- Precise evaluation of lepton flavor universality is important to look for new physics



Any deviation from the universality?



Hints of lepton flavor violation ?

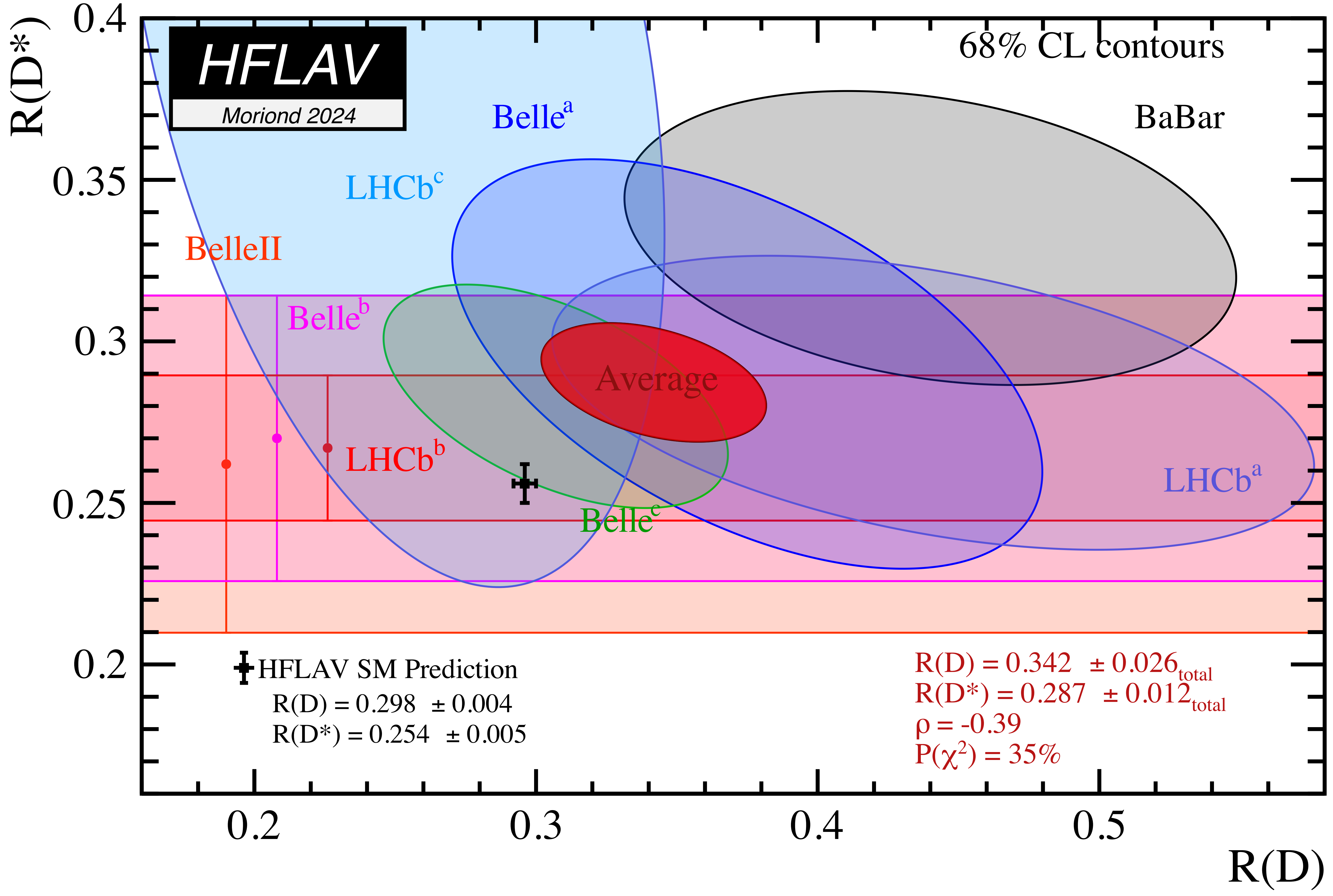
$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

R(D), R(D*) deviate from the SM expectation by more than 3σ

- Can be a hint of LFUV between τ and μ

$(g-2)_l$ $(l = e, \mu, \tau)$ of charged leptons are sensitive probes of LFUV

- longstanding $(g-2)_\mu$ deviation can be considered as another hint of LFUV when compared to $(g-2)_e$



Beta Decays and CKM Unitarity

Unitarity of the CKM matrix

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

$(|V_{ub}|^2 < 10^{-5})$

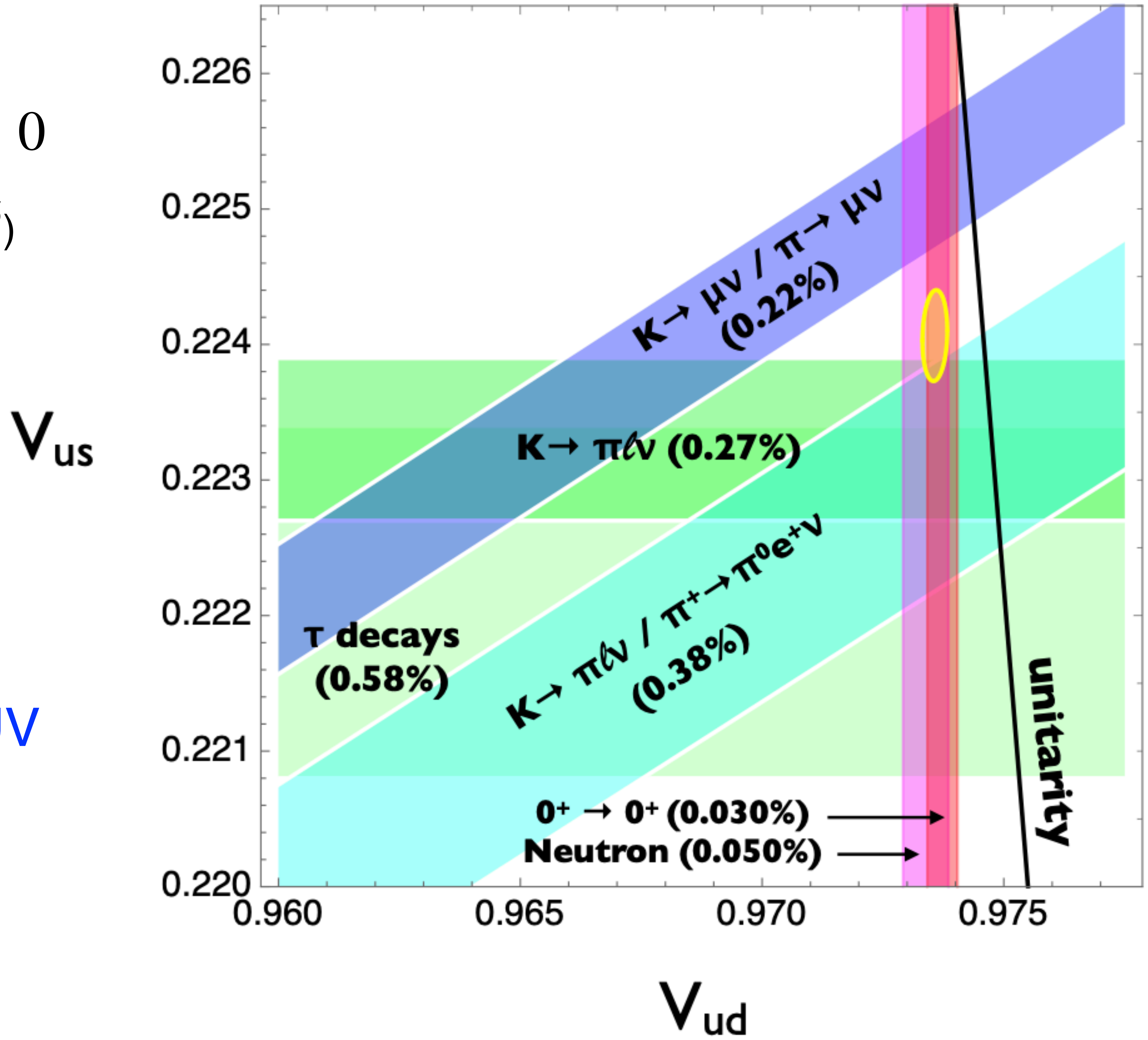
only V_{ud} and V_{us} are concerned

$$\Delta_{\rm CKM} = (-19.5 \pm 5.3) \times 10^{-4},$$

3.7σ effect (Cabbibo Angle Anomaly)

This can also be interpreted as a LFUV

- V_{ud} dominant from electron meas.
- V_{us} dominant from muon meas.



PIONEER goal

Phase I

- $R^{\pi}_{e/\mu} = \Gamma(\pi \to e\bar{\nu}_e(\gamma)/\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))$
  Improvement by a factor of 15
- Comparable with the theoretical uncertainty
- NP at the PeV scale can be probed

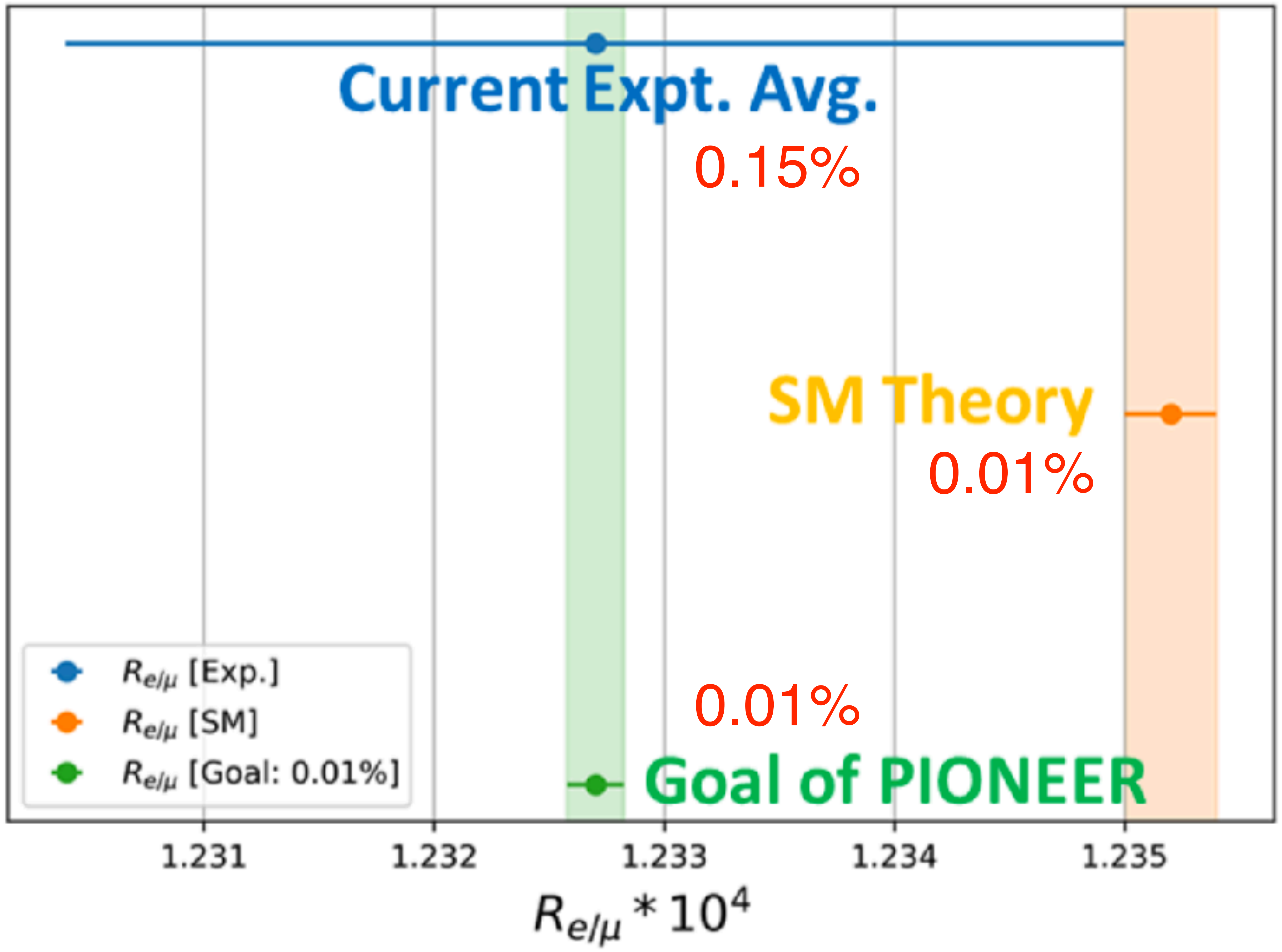
Phase II & III

- $\frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\text{Total})}$ with a precision < 0.2%
- 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



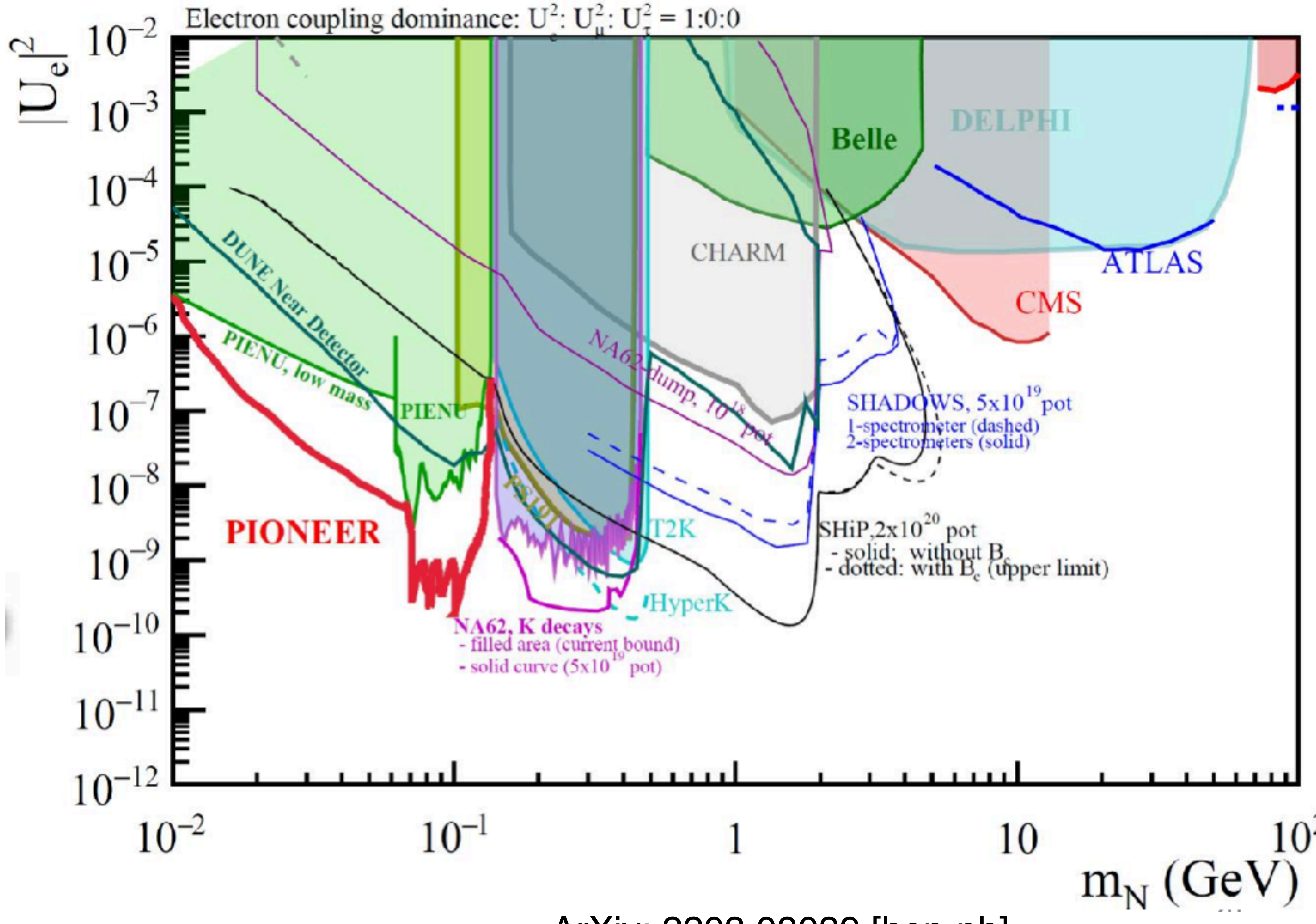
Exotic decay search

Search for exotic decays beyond previous limits

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

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

Measurements:

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

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

} → Phase I

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

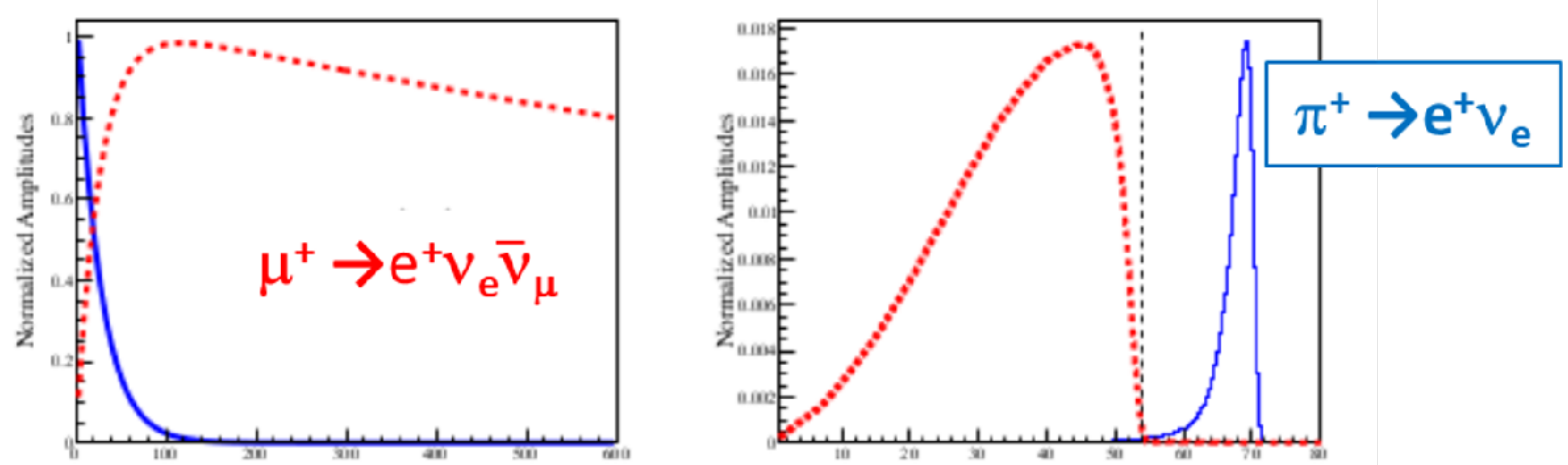
Reminders:

Pion lifetime: 26 ns

Muon lifetime: 2197 ns

Pion mass: 139.6 MeV

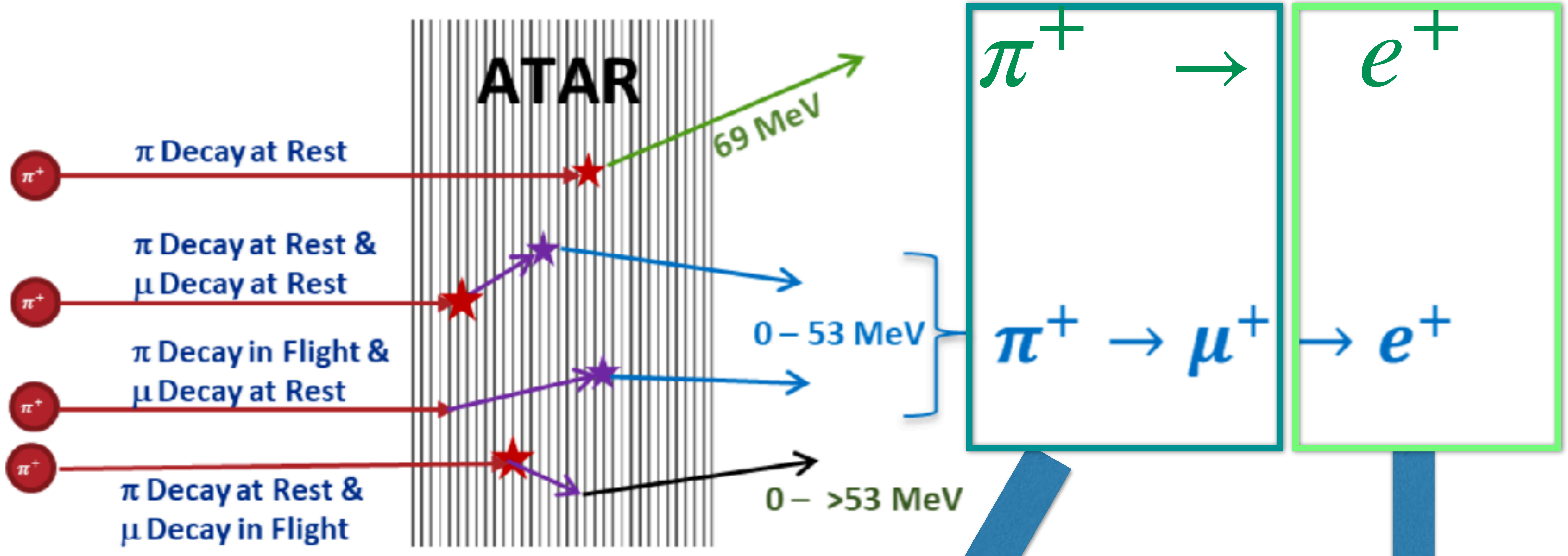
Muon mass: 105.7 MeV



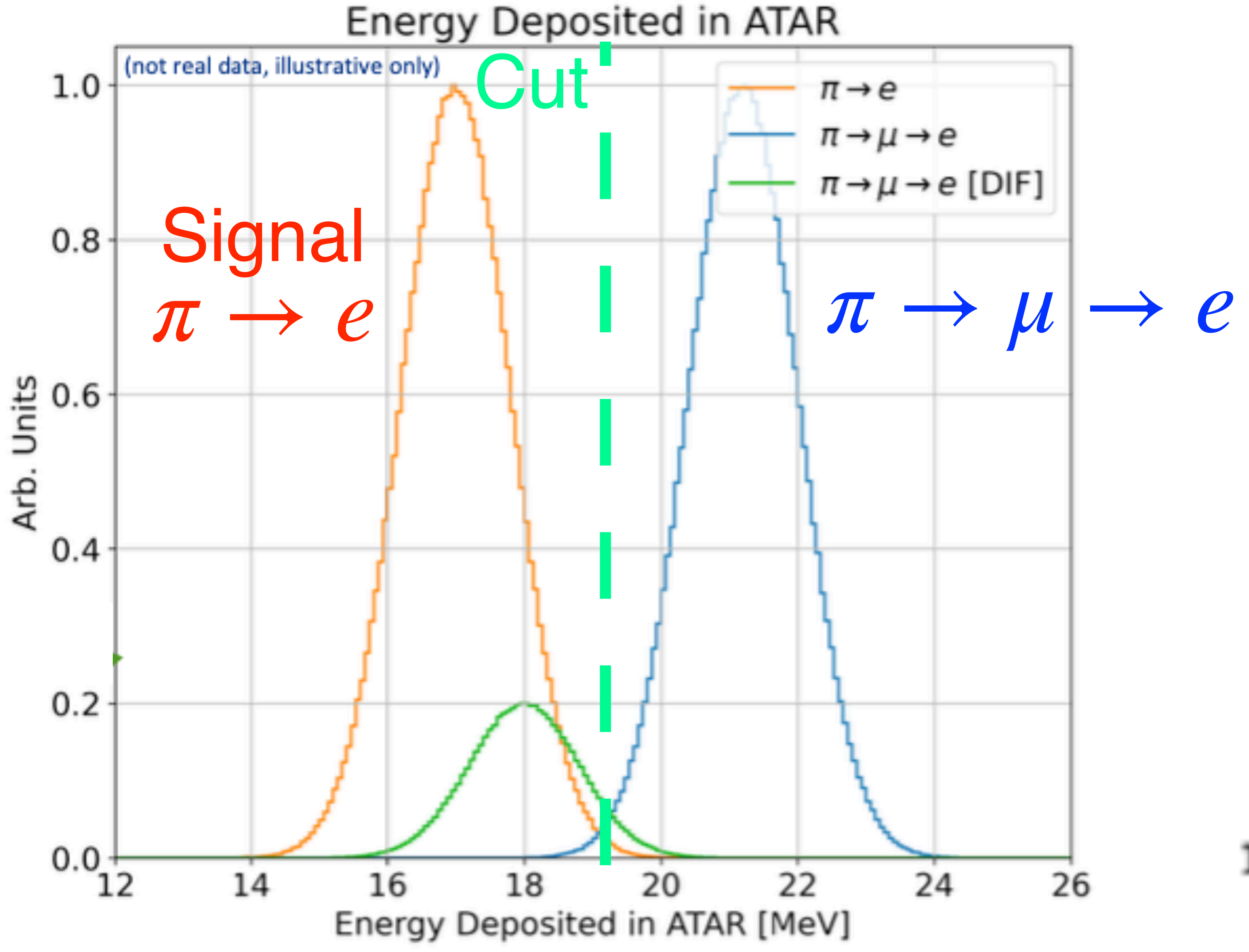
Timing

e^+ Energy

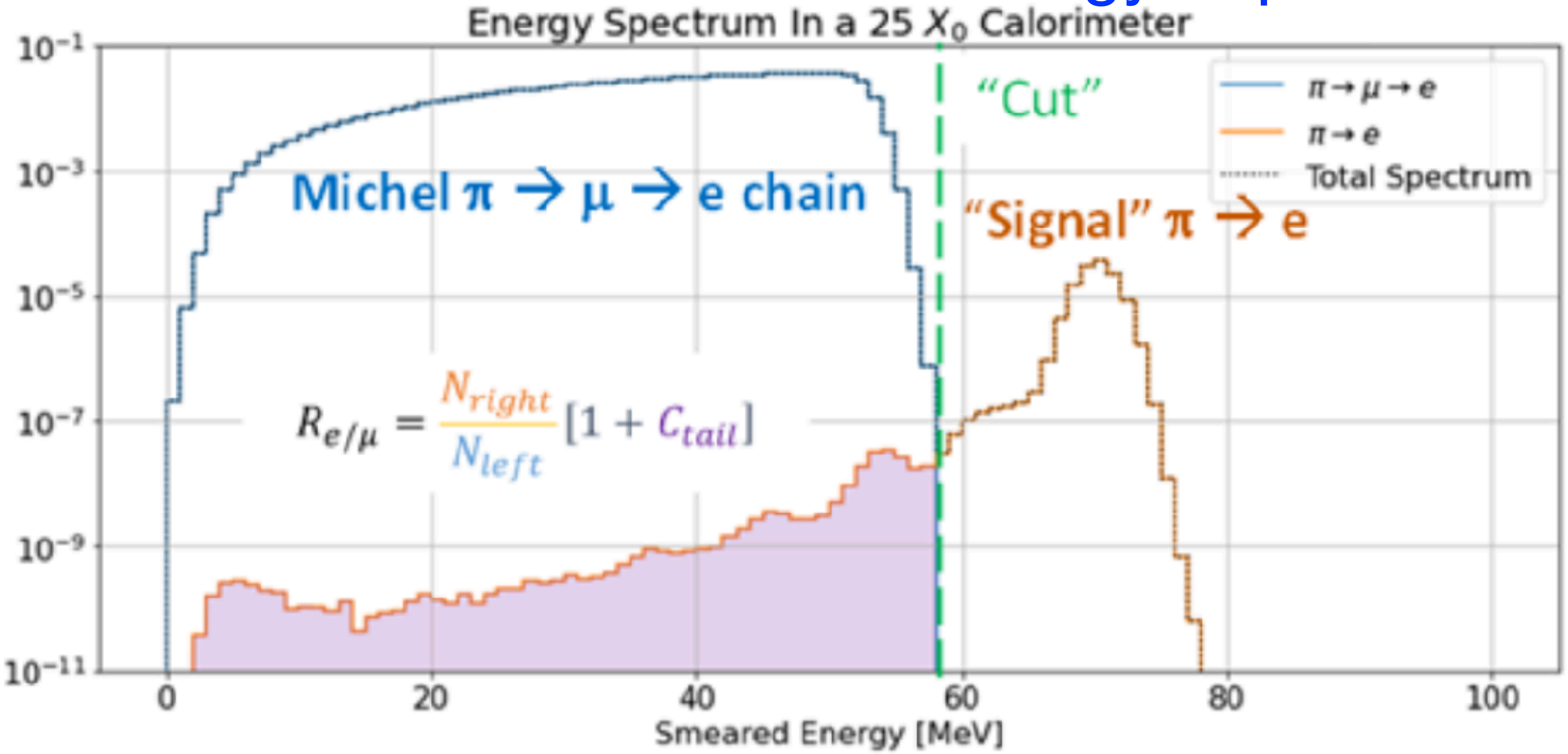
Measurement principle



ATAR energy deposit



Calorimeter energy deposit



World most intense pion beam

Requirements

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

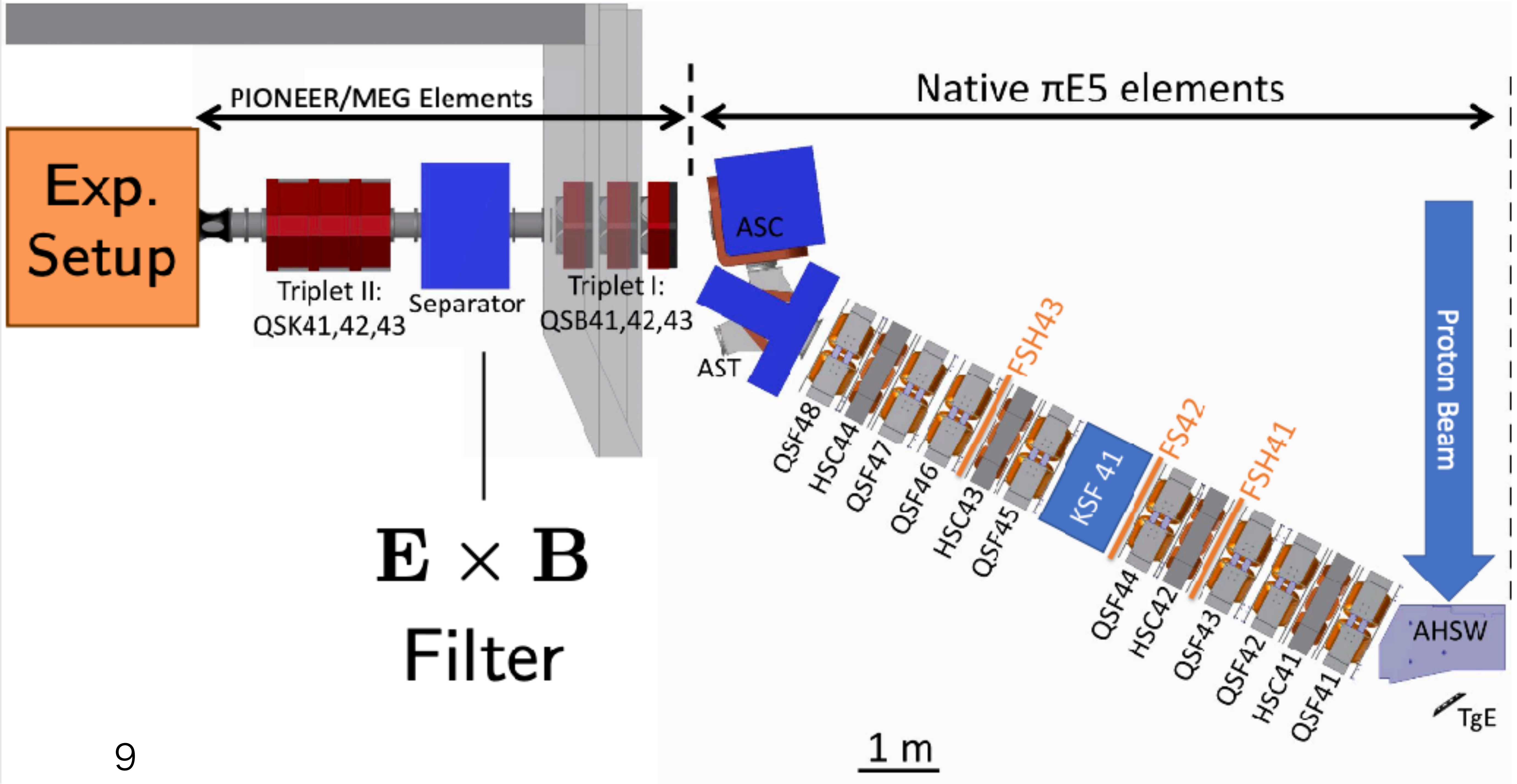
Paul Scherrer Institute

- PiE5 beam line would be the only candidate in terms of rate.
- The beam profile should be tested
- The possibility of other beamlines like PiE1 will be tested too
  - MEG, Mu3e will occupy the PiE5 at least until 2026

Status

- Beam quality test in PiE5 beam in 2022

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



PIONEER detectors

Intense π^+ beam

- $> 3\times10^5\ \pi^+/s$
- Available at PSI

Active Target

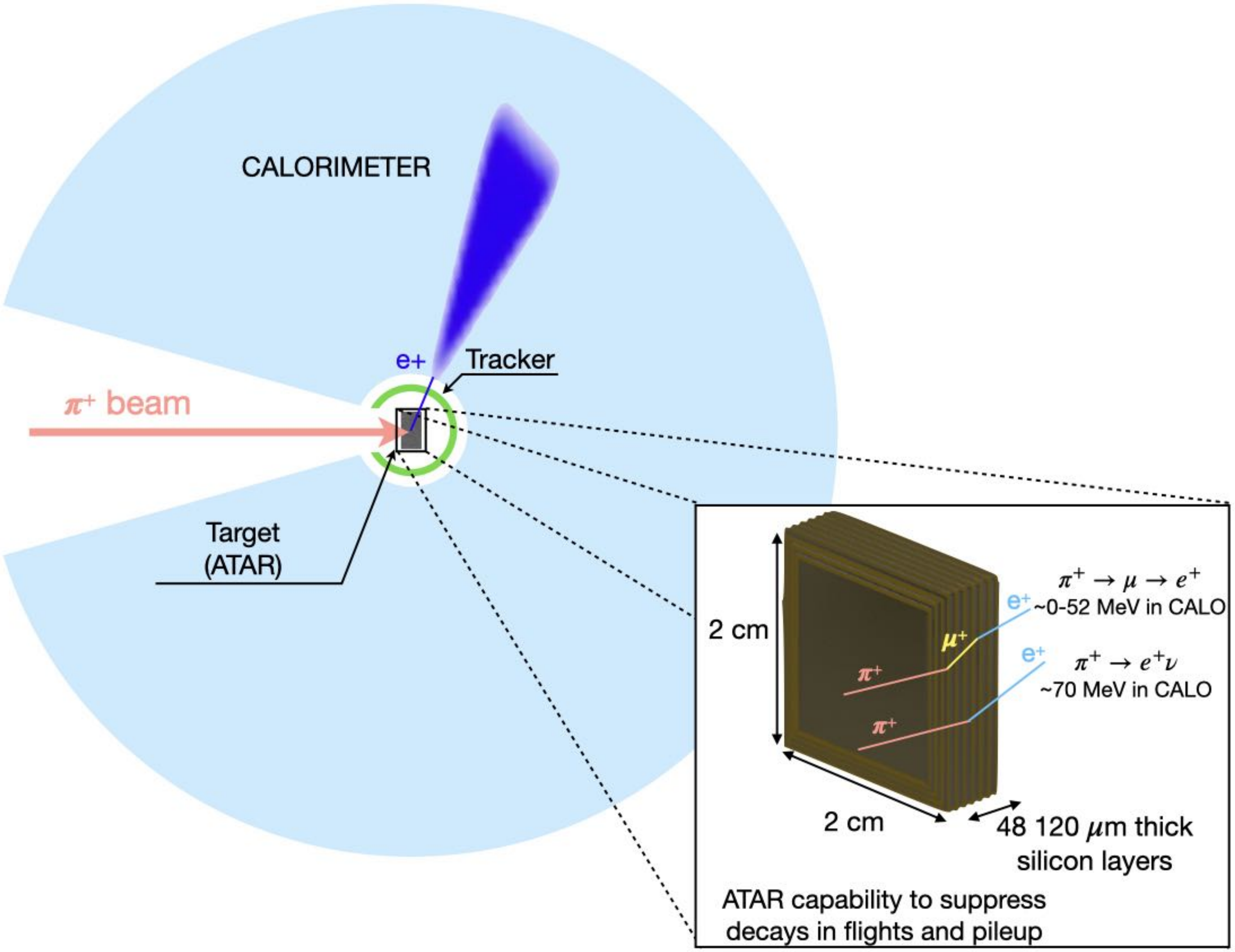
- Tracking $\pi\to e/\pi\to\mu\to e$ events
- Energy, timing, particle direction
- Position resolution ~ 100µm
- Timing resolution ~ 1 ns

Calorimeter

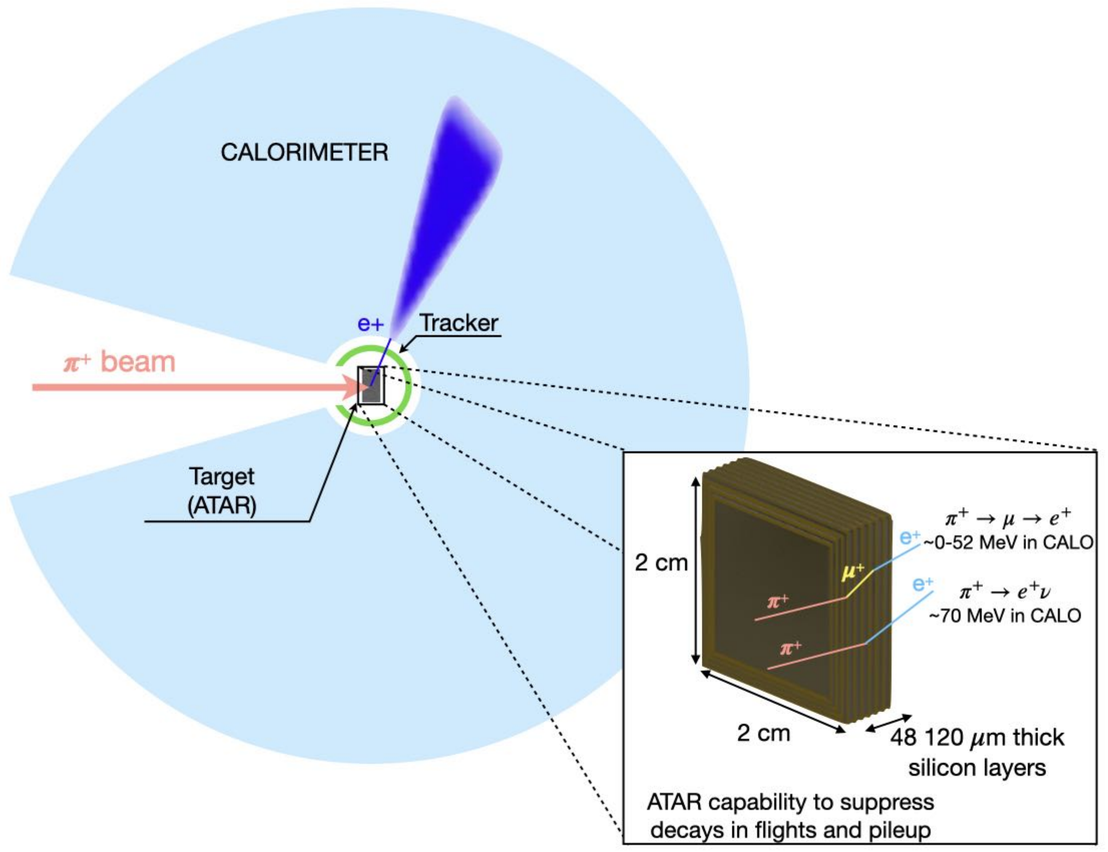
- Positron energy, time
- Depth of ~20 X_0 to reduce low energy events
- Large area acceptance

Tracker

- Positron direction between target and calorimeter



Active target



Requirements

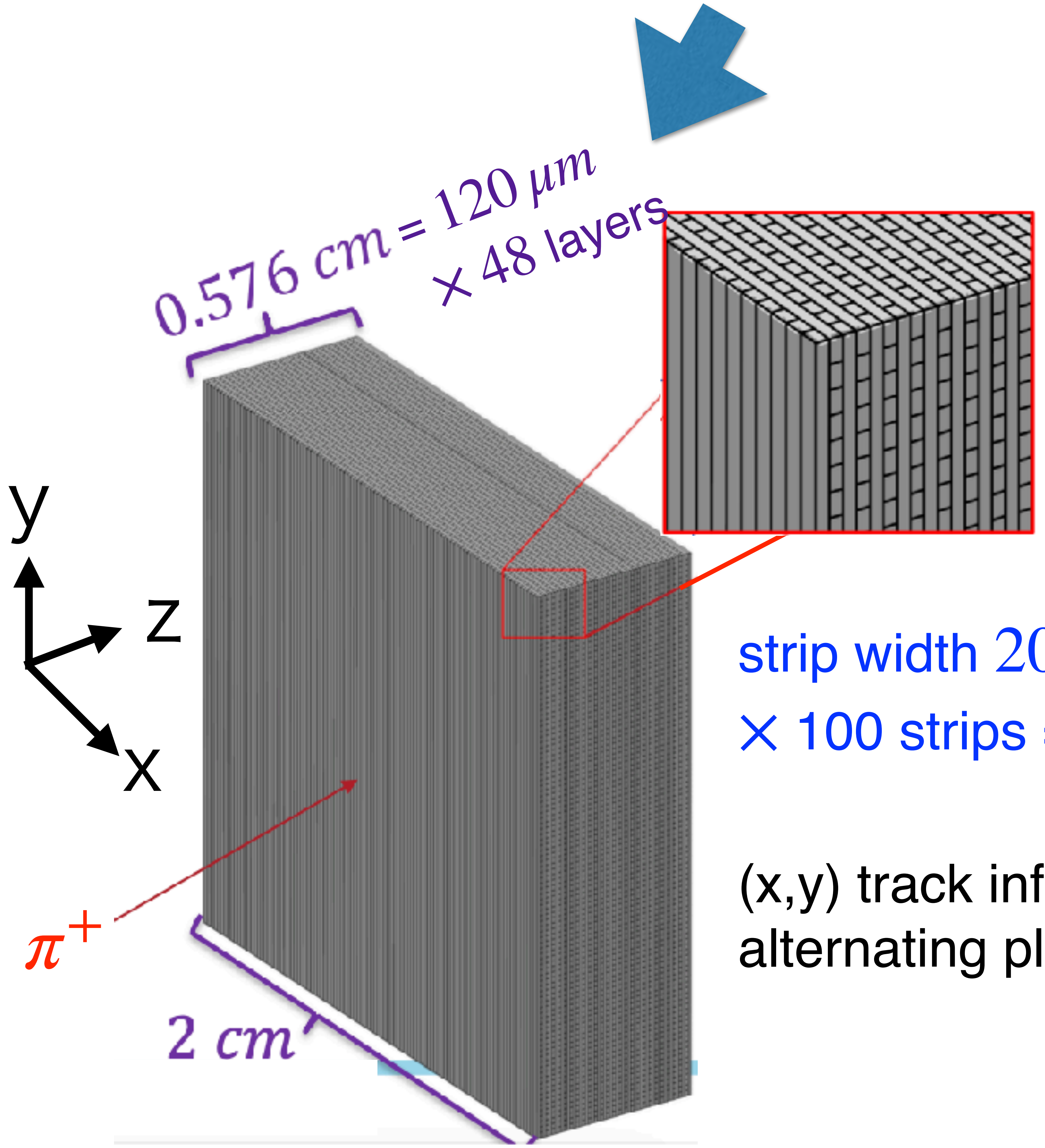
- Energy response
  - 30 keV MIP ~ 4 MeV μ+ Bragg peak
  - High resolution, large dynamic range
- Tracking (π/μ/e)
  - High granularity in (X,Y,Z)
  - 4 MeV μ+ travels 0.8mm in Si
- Timing
  - π/μ hit separation by 1.5ns for 300kHz

Baseline technology

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

Status

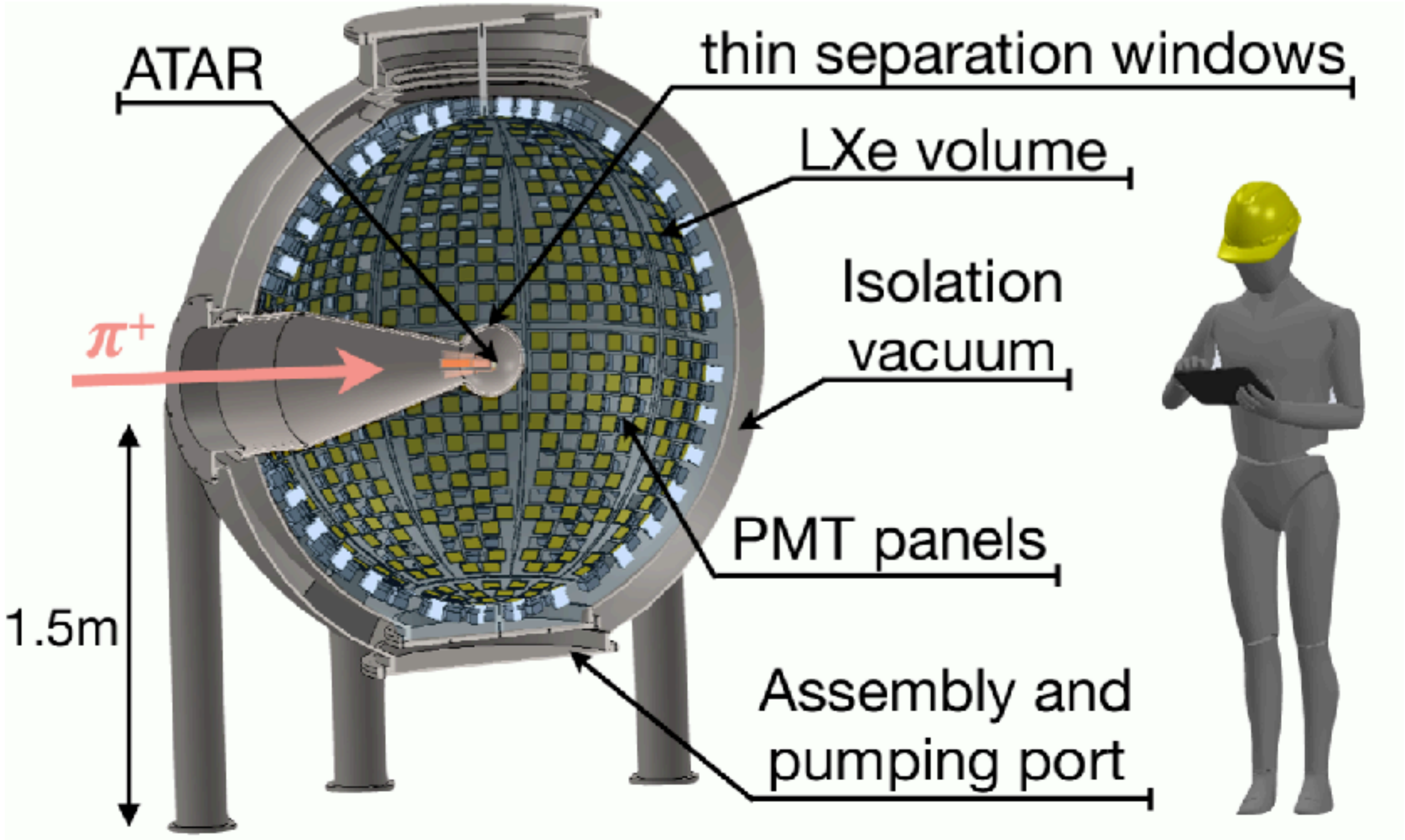
- R&D of the technology on AC-LGAD, TI-LGAD etc.
- Minimal cross talk, small gain saturation, large dynamic range



strip width 200 μm
× 100 strips = 2 cm

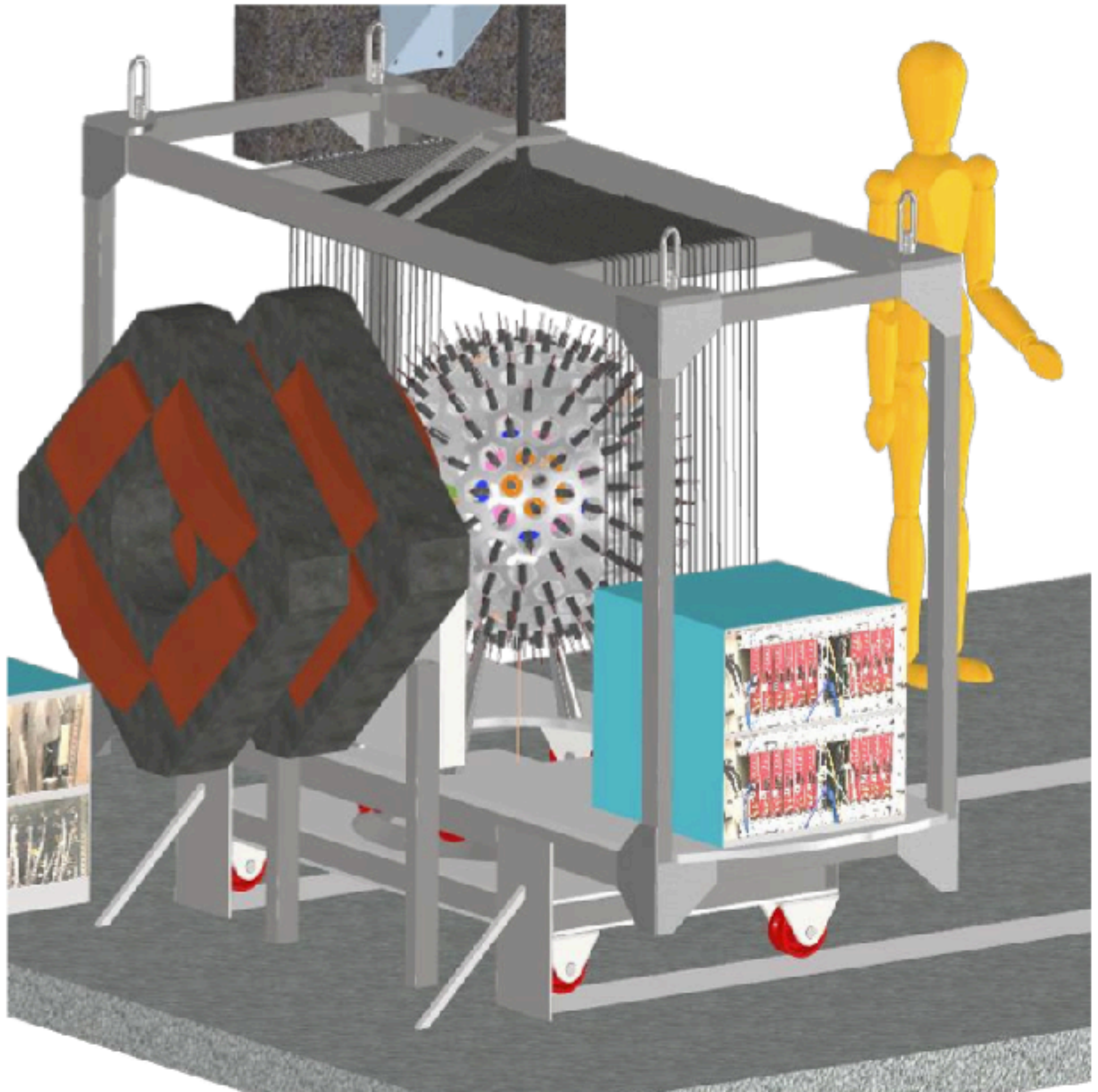
(x,y) track info. from alternating planes

Calorimeter



Requirements

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



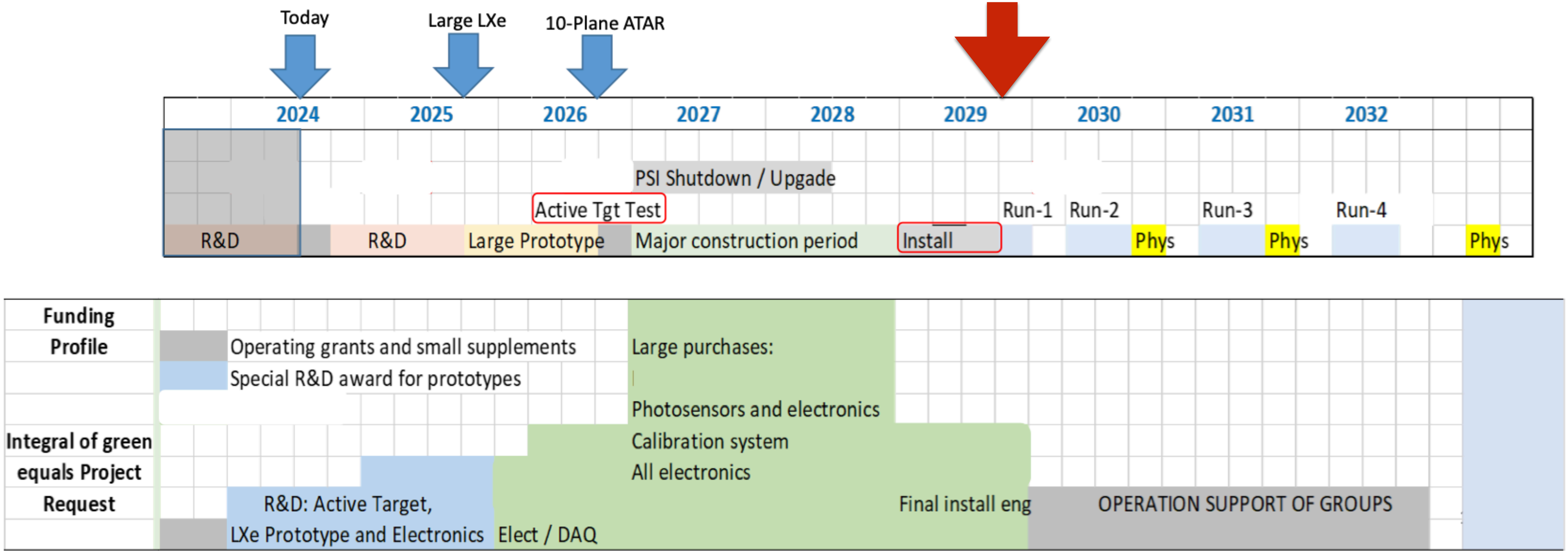
Two options

- 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

Status

- Prototype tests are ongoing with beam test

PIONEER timelines

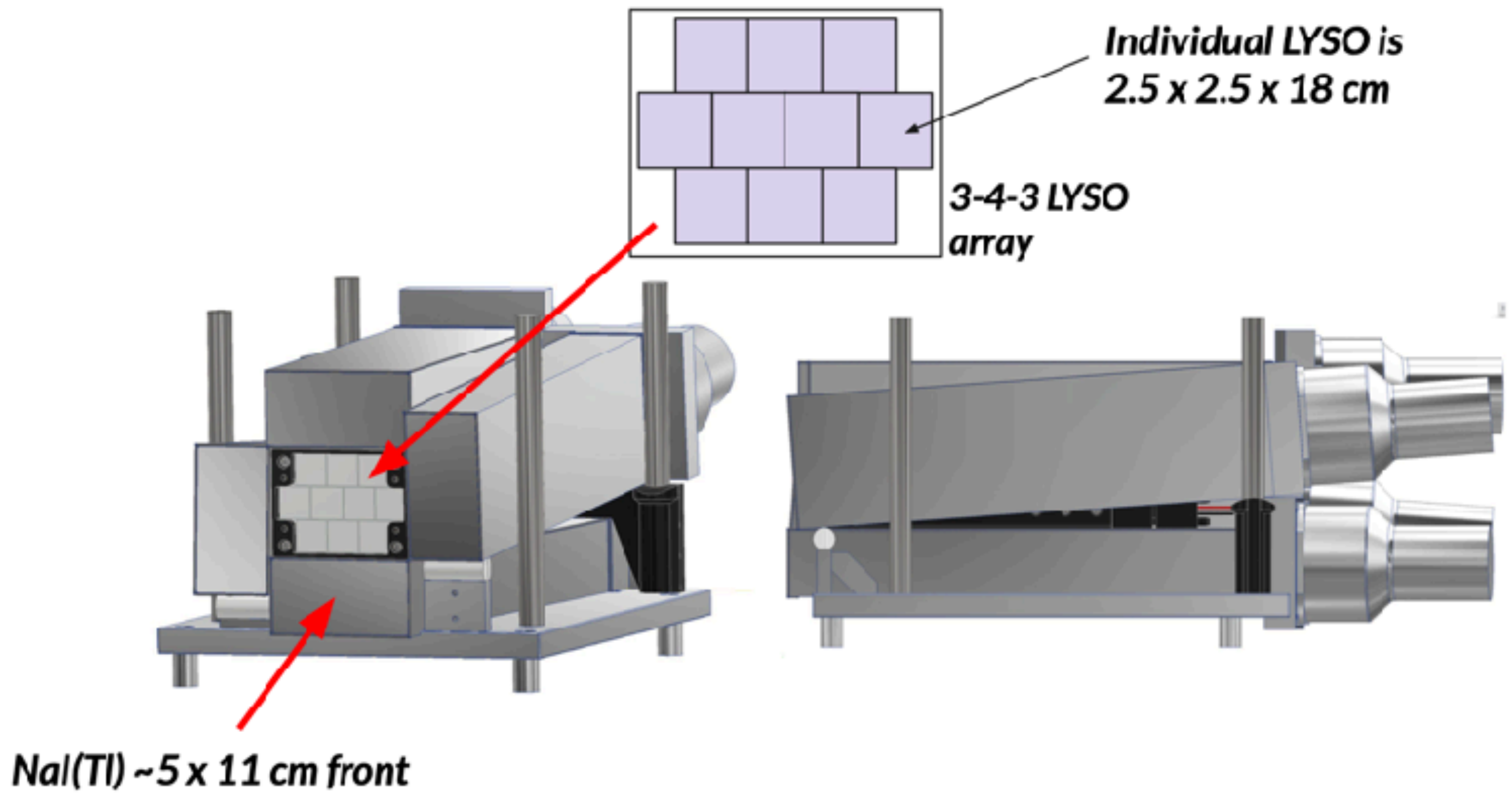


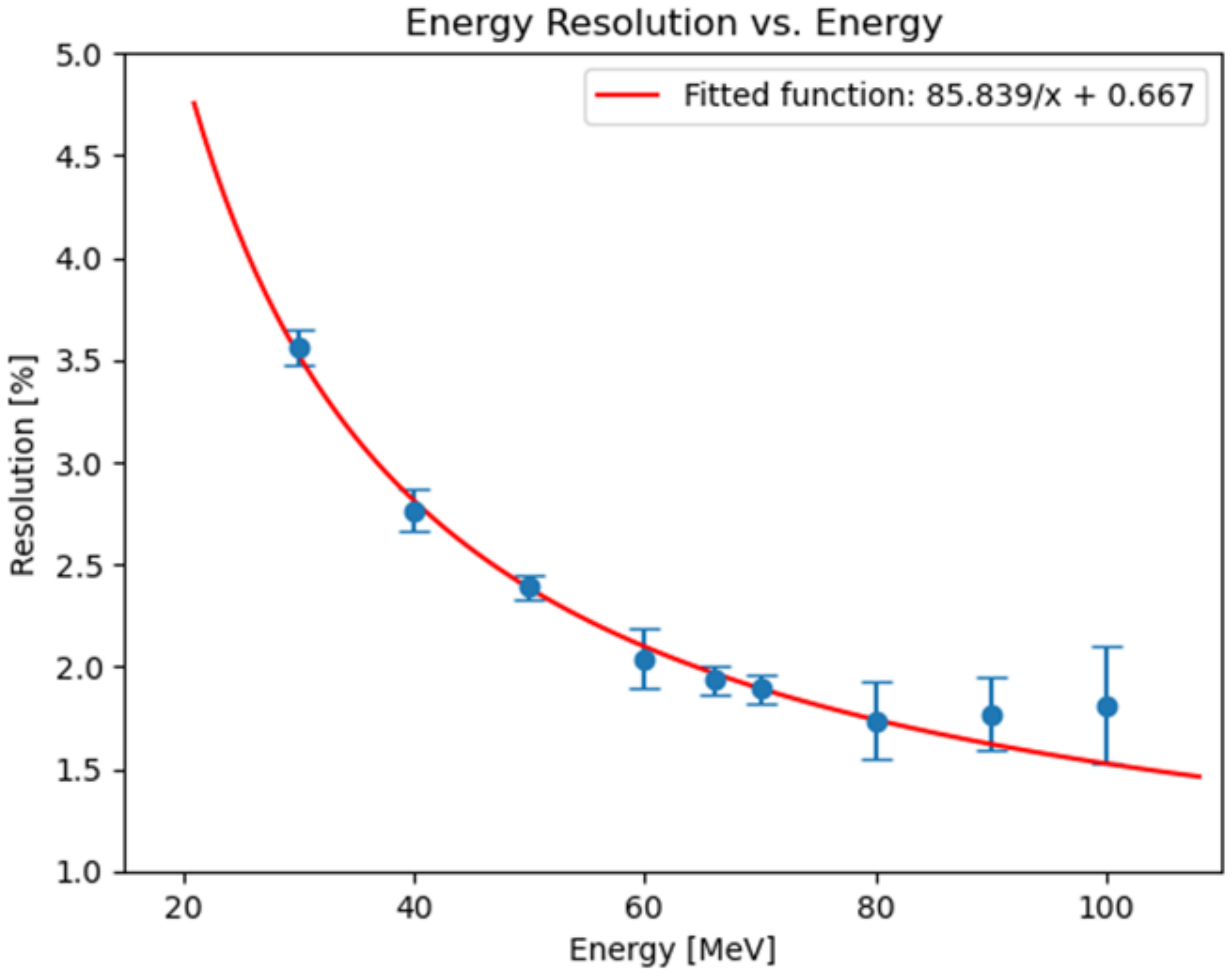
- PSI has a long shutdown between 2027 and 2028
- The PIONEER experiment will aim at the detector construction during that, and start the run from 2029

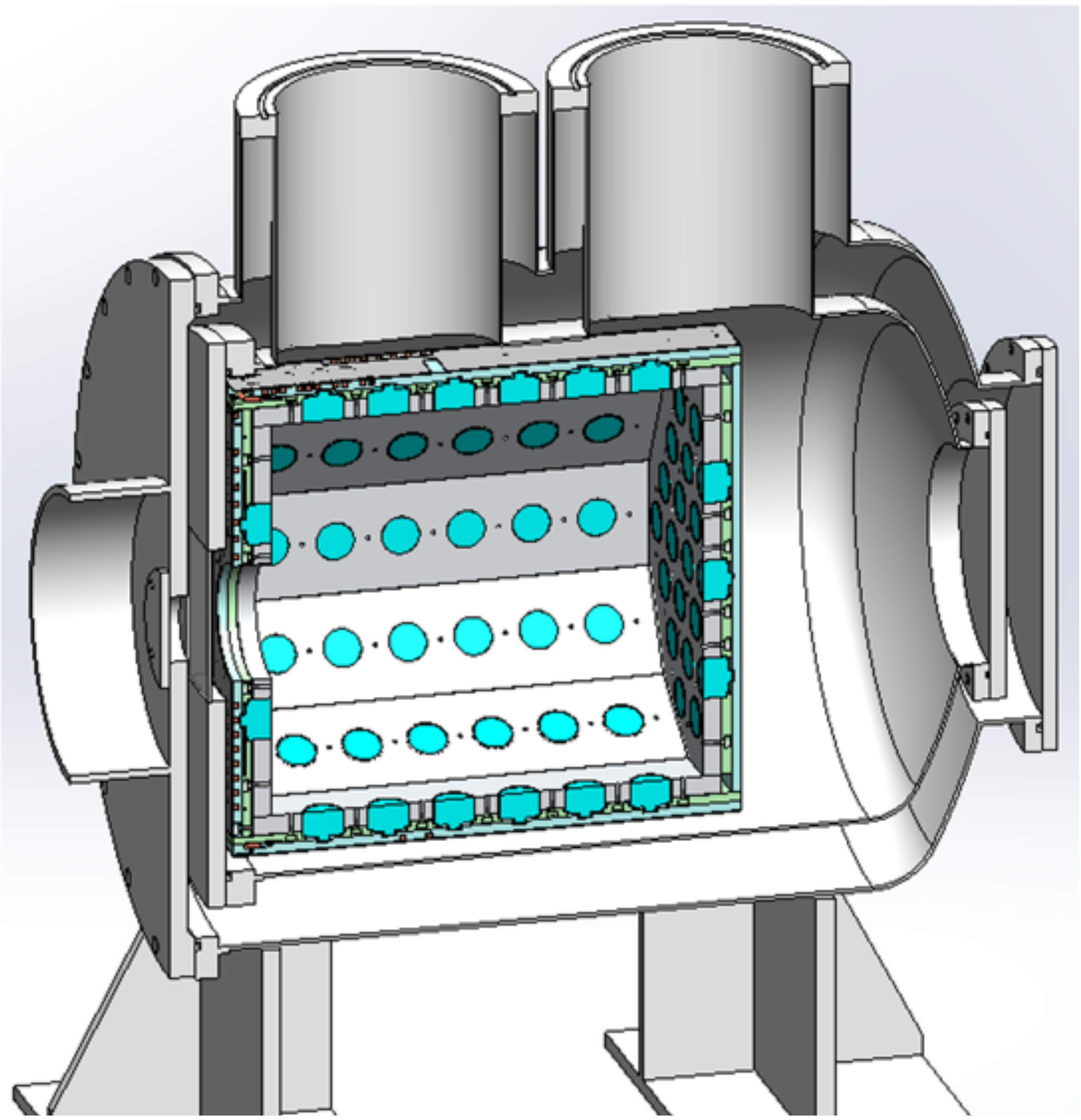
Summary

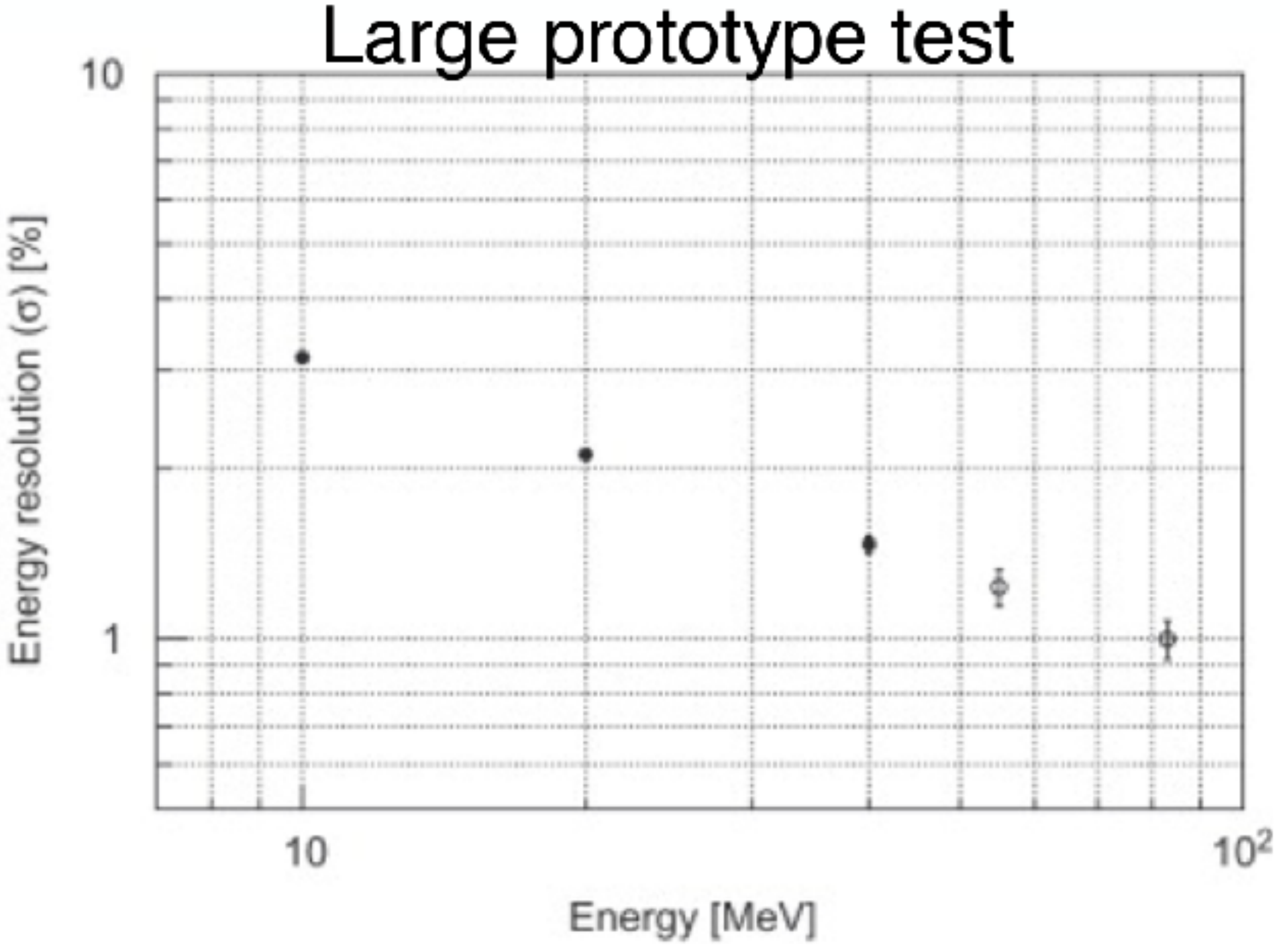
- The PIONEER experiment will explore the lepton flavor universality violation
  - The experiment was approved with high priority by PSI review committee in 2022
- Experimental challenges requires state-of-the-art technology including ATAR, high resolution, deep and fast EM calorimeter, advanced trigger, and detailed simulation
- The PIONEER collaboration grows internationally, and new ideas, expertise, and new collaborators are welcome

R&D





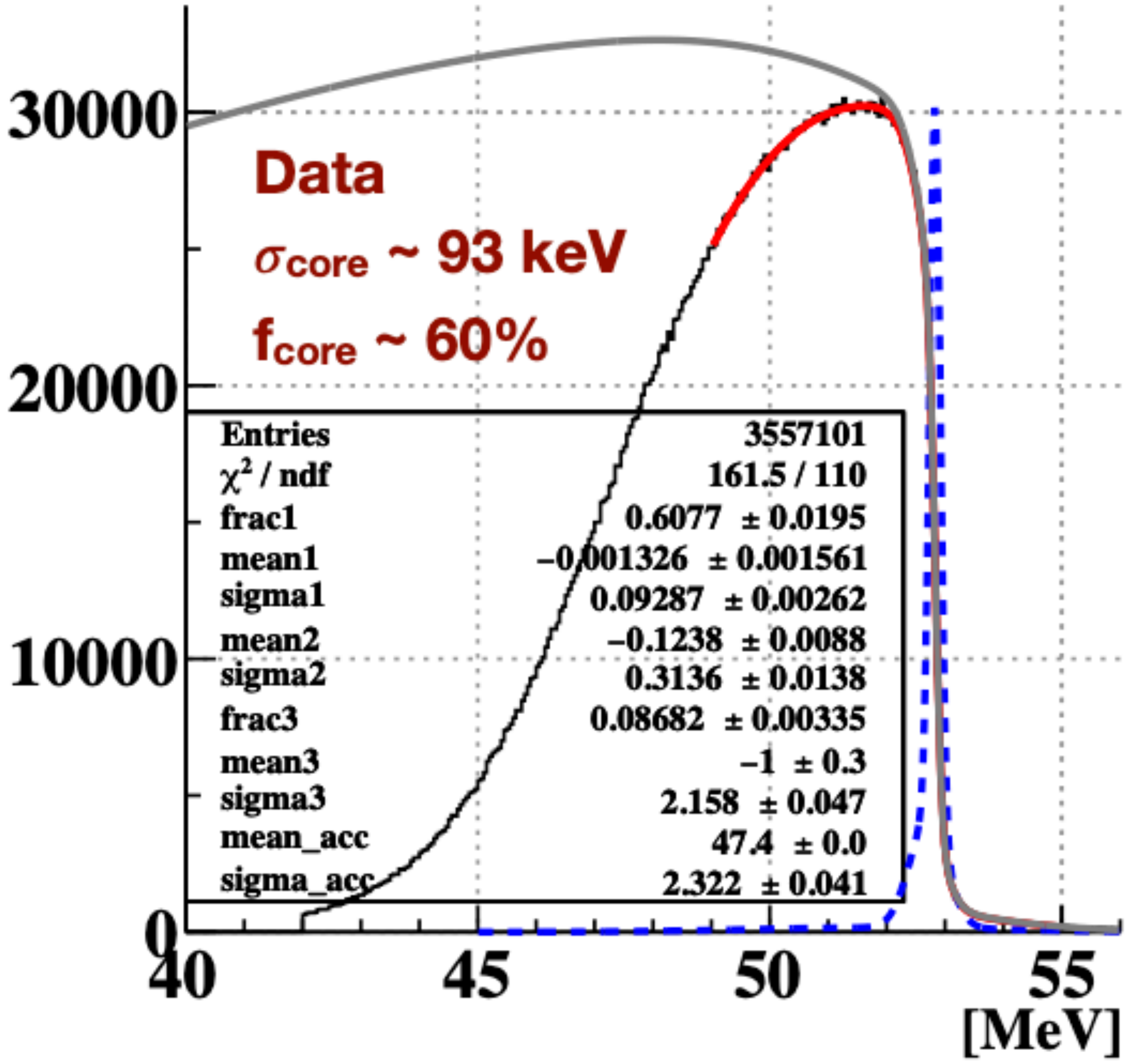


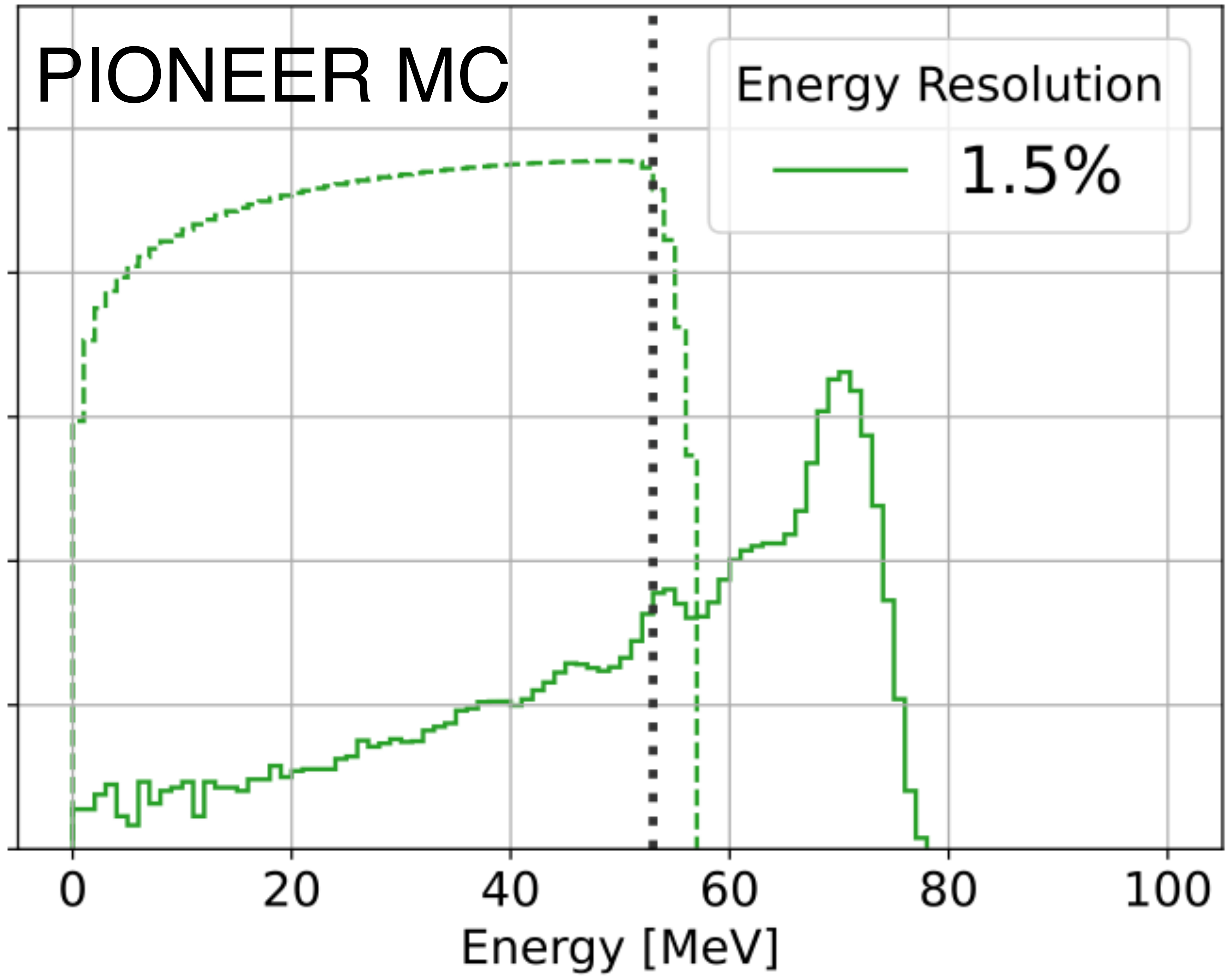


R. Sawada, NIMA581(2007)522

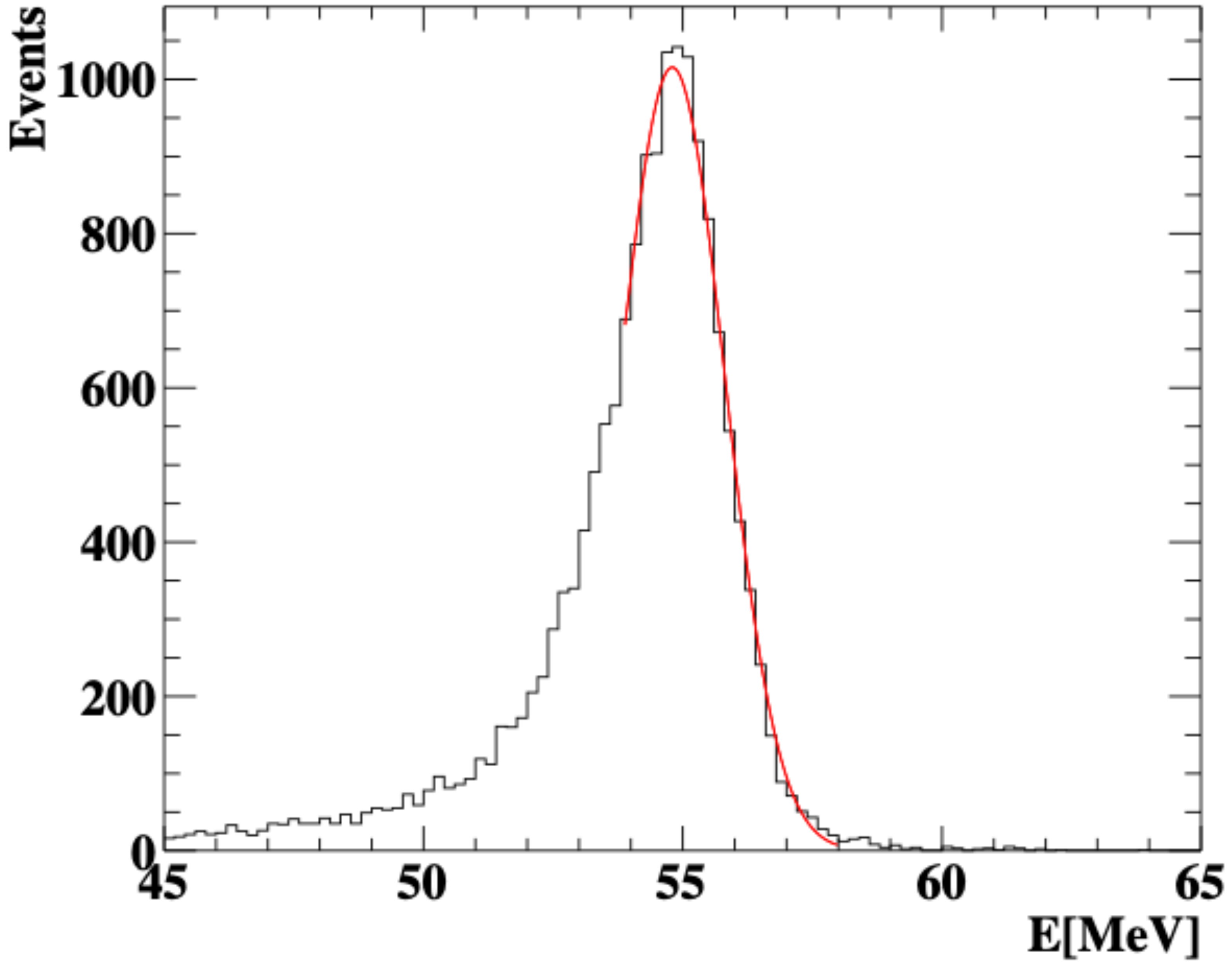
PIONEER case

MEG e^+ spectrum





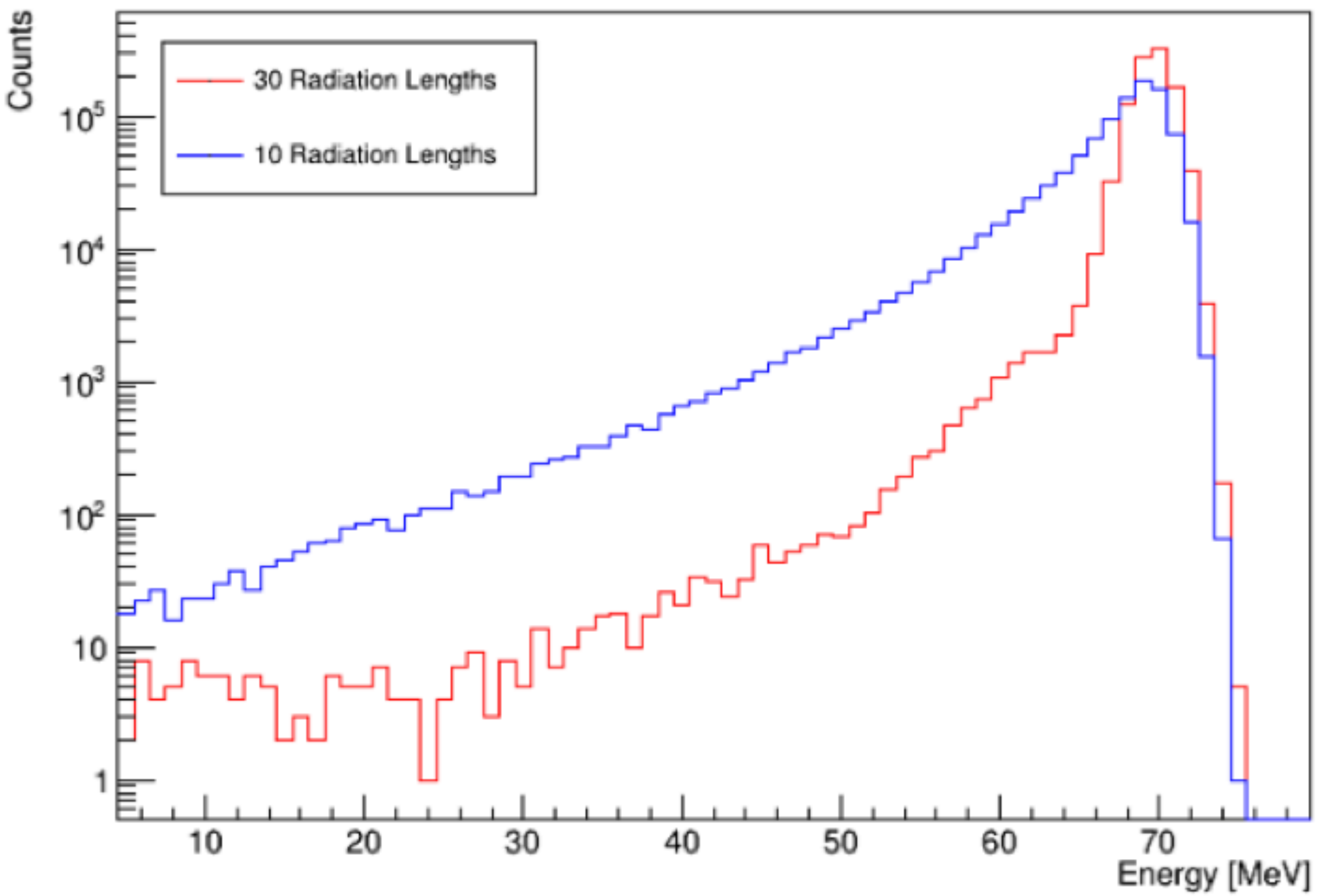
MEG γ spectrum



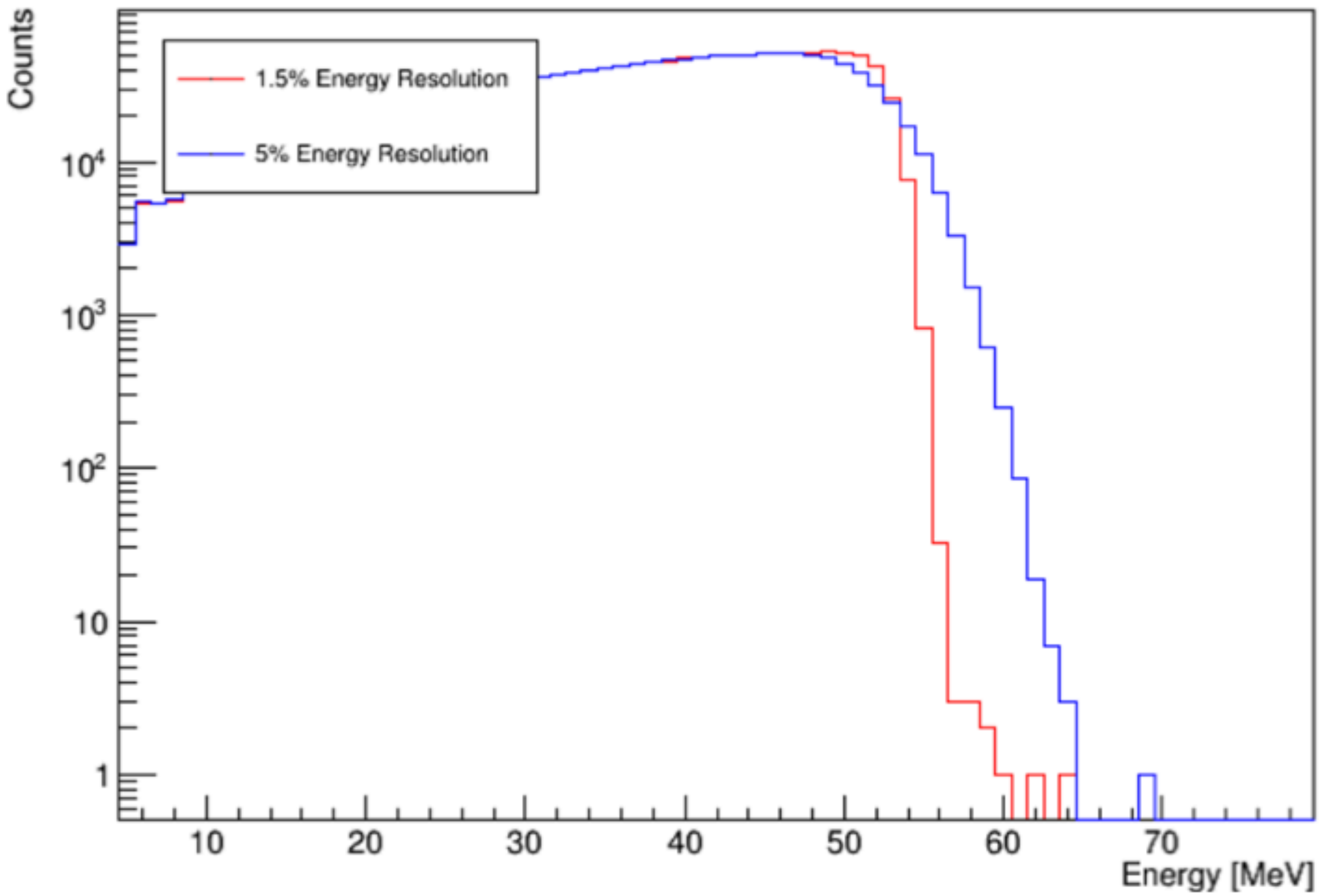
- Energy scale, resolution can be directly extracted from 70 MeV peak and from 53MeV Michel edge in PIONEER (robust calibration possible)
- Sensor calibration, LXe light yield monitoring by LED, α crucial
- Other γ calibration sources (AmBe 4.4MeV, Ni 9MeV, Li 17.6MeV, π^0 55MeV, Cosmics) are optional
- 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