PIONEER 実験:
パイオンの稀崩壊から探る
レプトン普遍性の破れと CKMユニタリティ

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他 PIONEER コラボレーション

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PIONEER Experiment:
A Precision Study of Rare Pion Decays to Explore Lepton Universality Violation & CKM Unitarity

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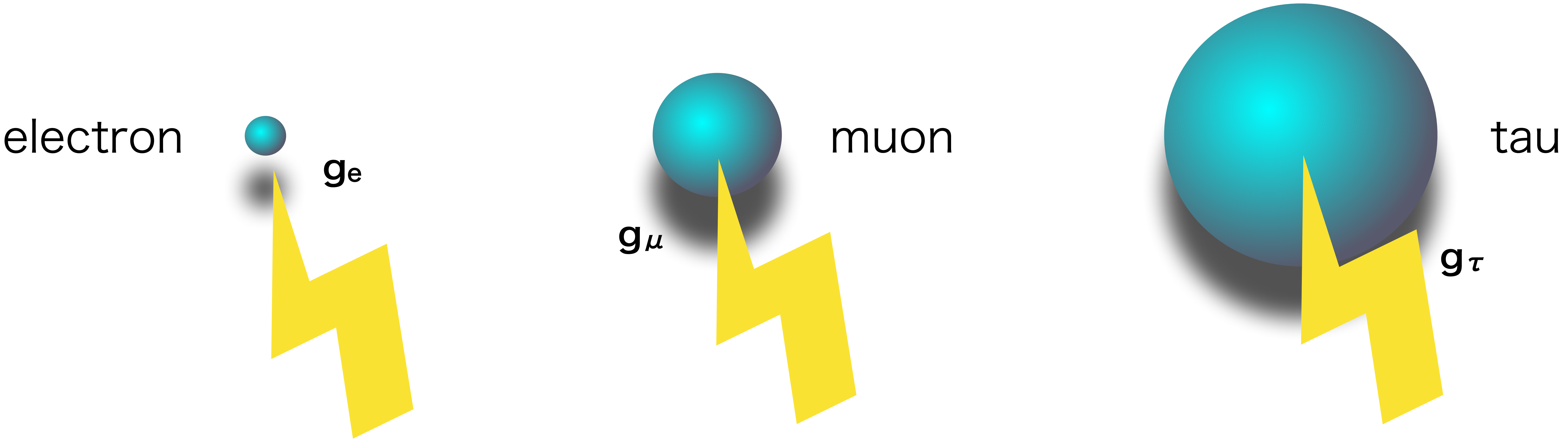
研究拠点形成事業
Core-to-Core Program

JPS 2023 Spring Meeting 24 March 2023 24pT1-2

Lepton Universality (LU)

- Gauge Symmetry dictates our Universe:
  - Gauge interactions operate universally on particles of all generations
  - Precisely tested & established with leptons — “Lepton Universality”

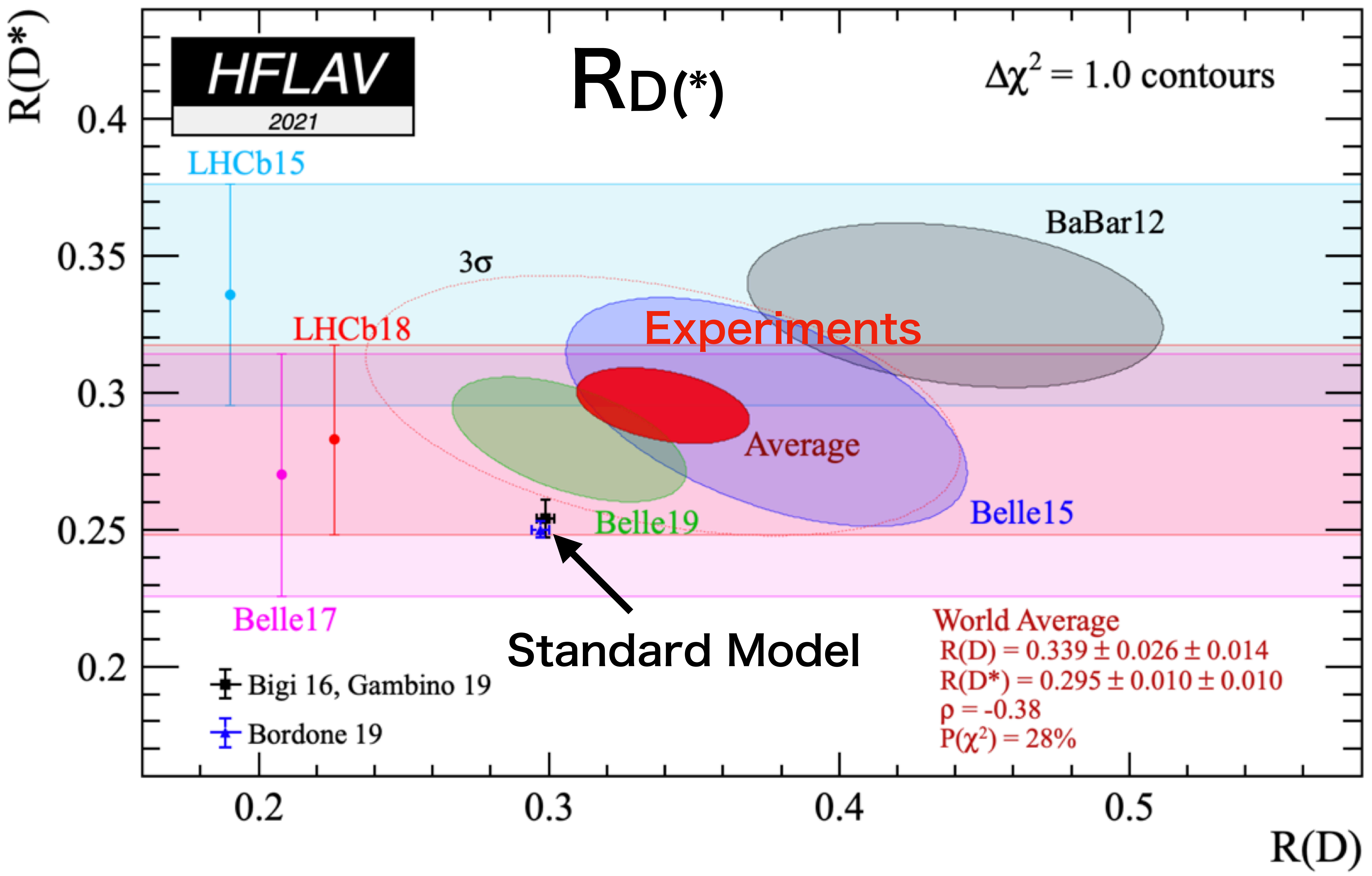


leptons of three generations $g_e = g_\mu = g_\tau$

Hints of LU Violation?

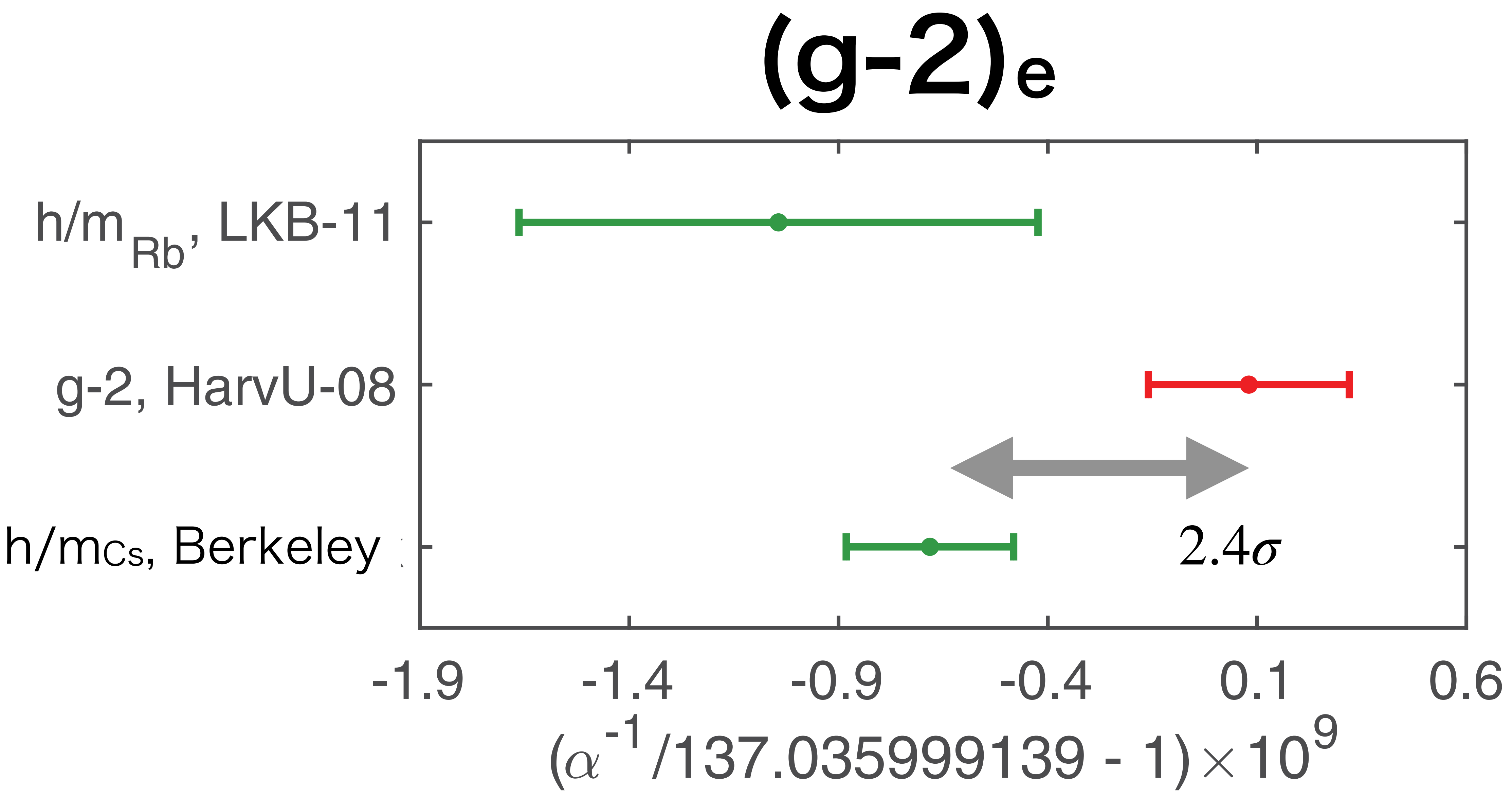
- Recently several experimental results seem to indicate that Lepton Universality is actually violated (LUV):
  - B decays (R_D, R_{D^*}, etc)

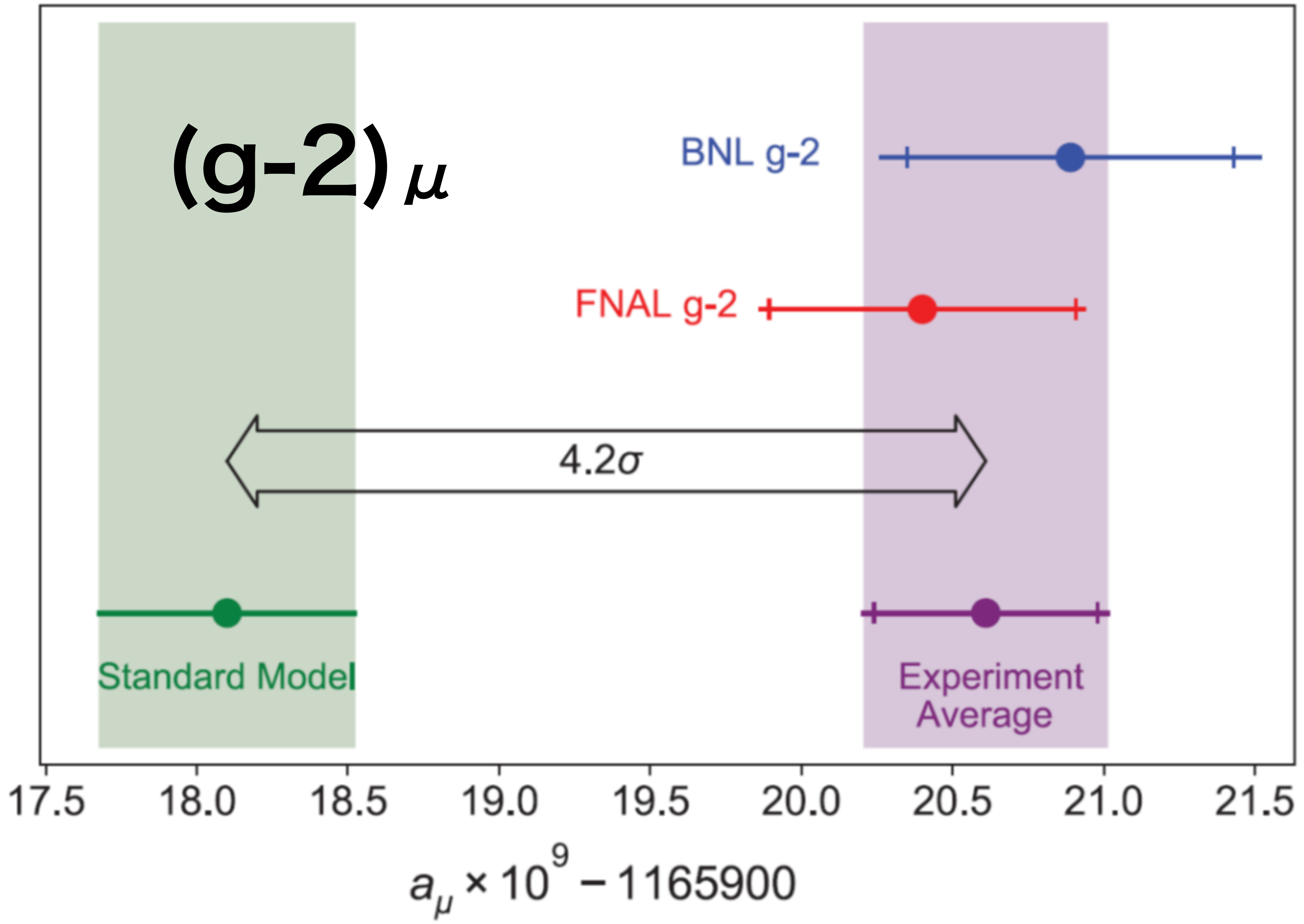
$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$



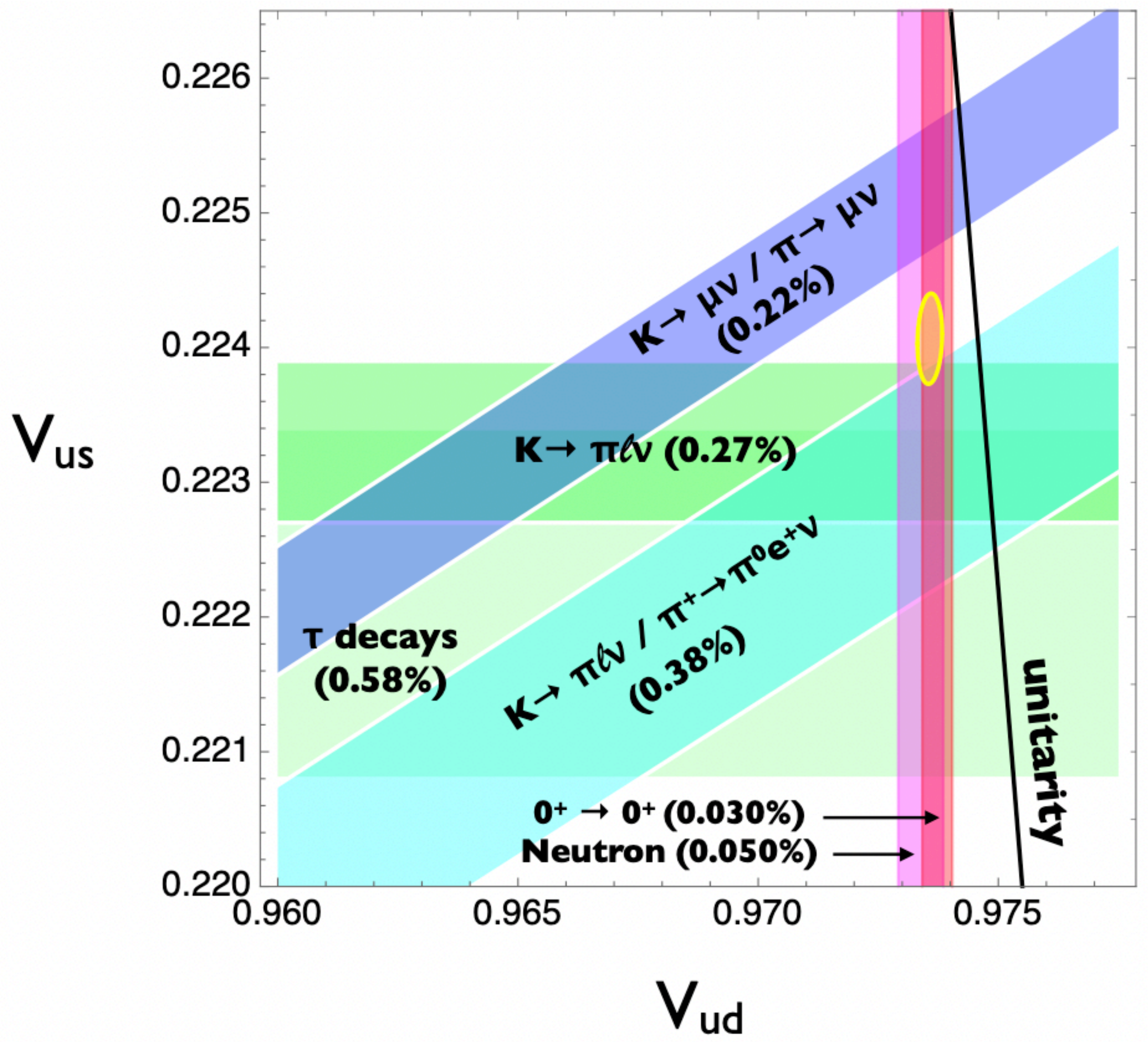
→ **new particle / new interaction?**

Anomalous magnetic moments of muon and electron





The origin of the long-standing deviation seems to be "Lepton Universality Violating"



Unitarity of 1st row of CKM matrix

Discrepancy between:

$K \to \mu\nu$, $K \to \pi\mu\nu$

and

$0^+ \to 0^+$ nuclear beta decays

Another hint of LUV?

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

theoretically clean, free of hadronic corrections

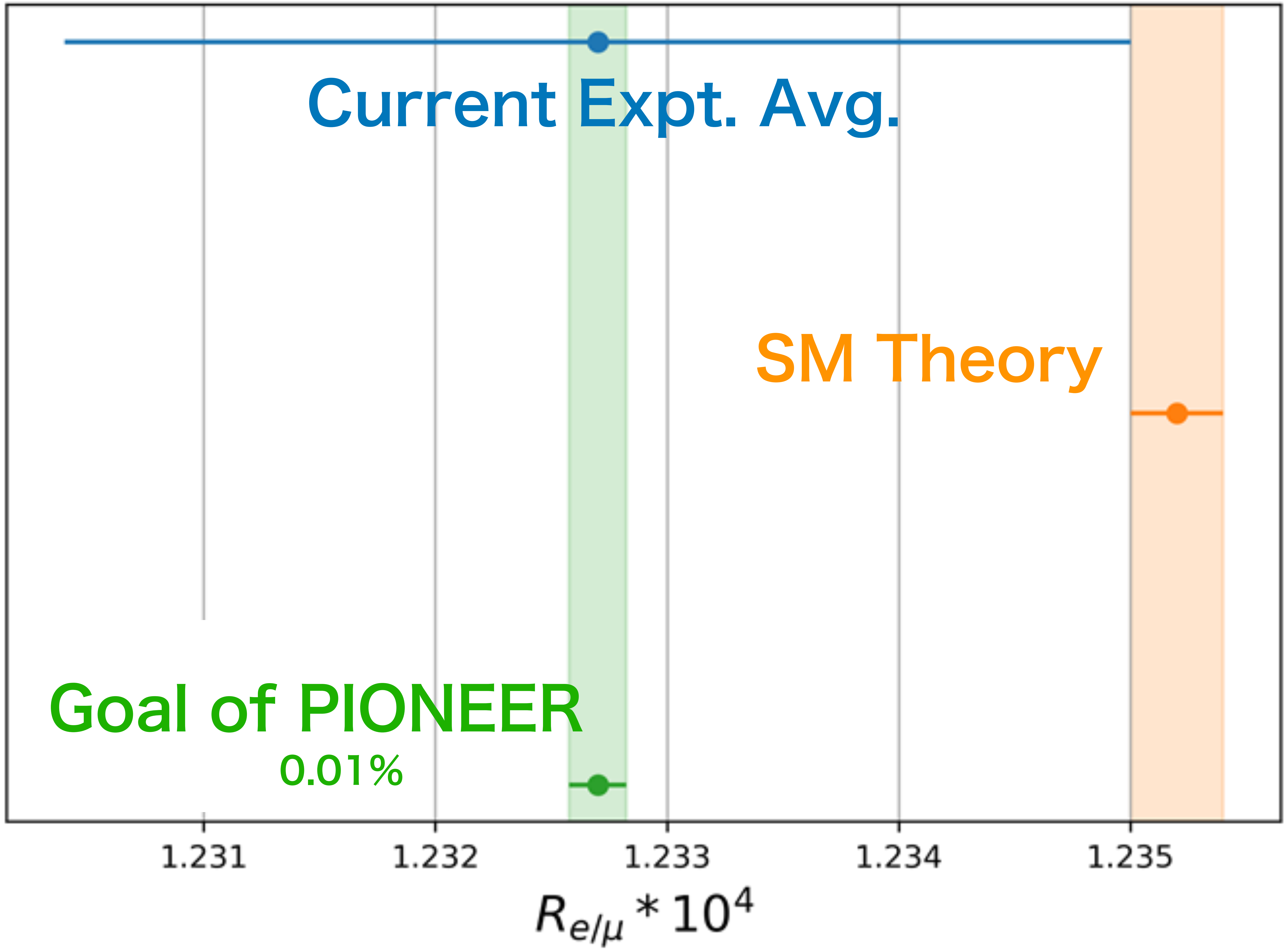
Goal of PIONEER

Most scrutinising test of Lepton Universality by measuring rare pion decays

~10^{-4}

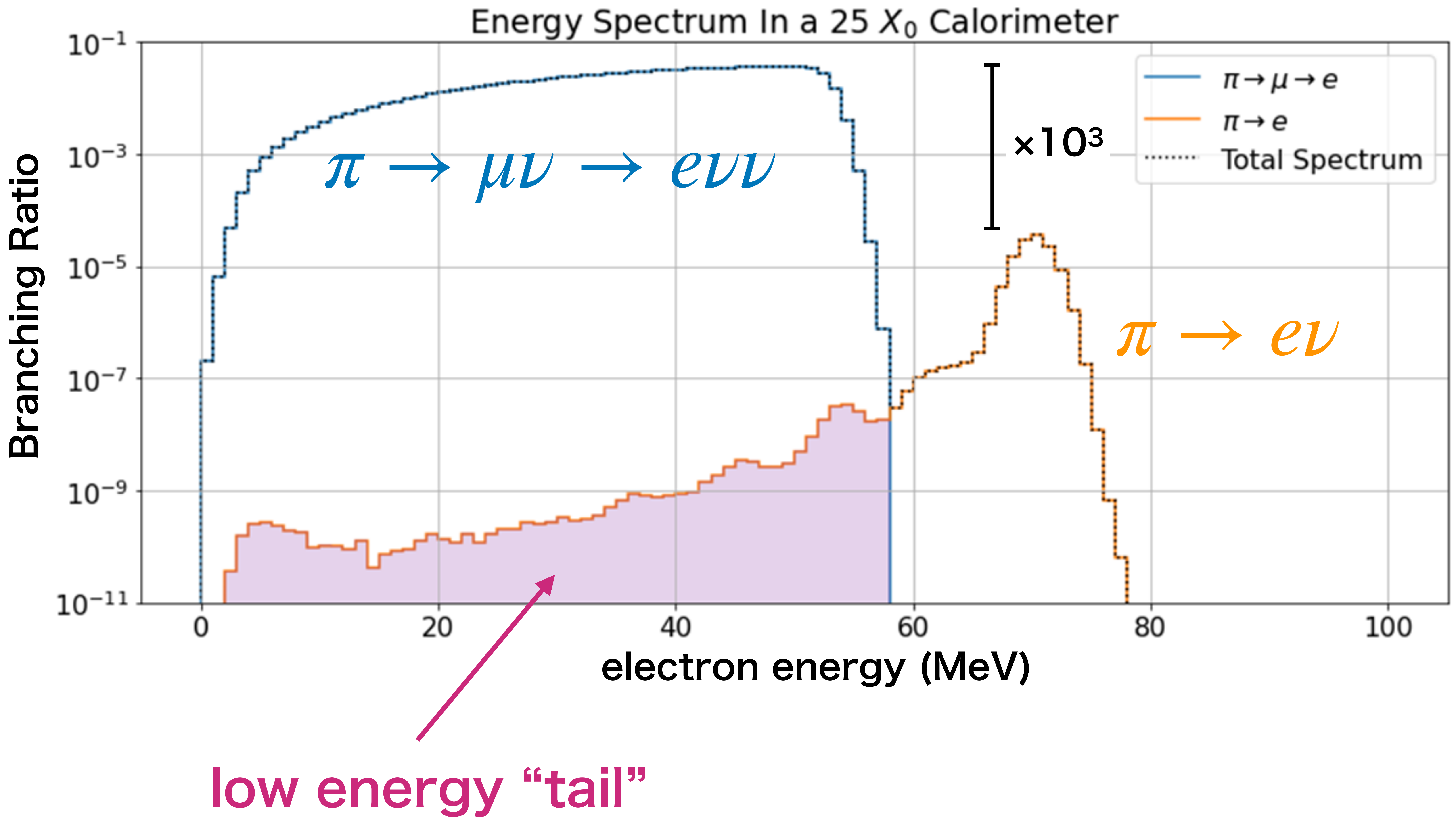
$$R_{e/\mu} = \frac{\pi \to e\nu}{\pi \to \mu\nu}$$

~100%



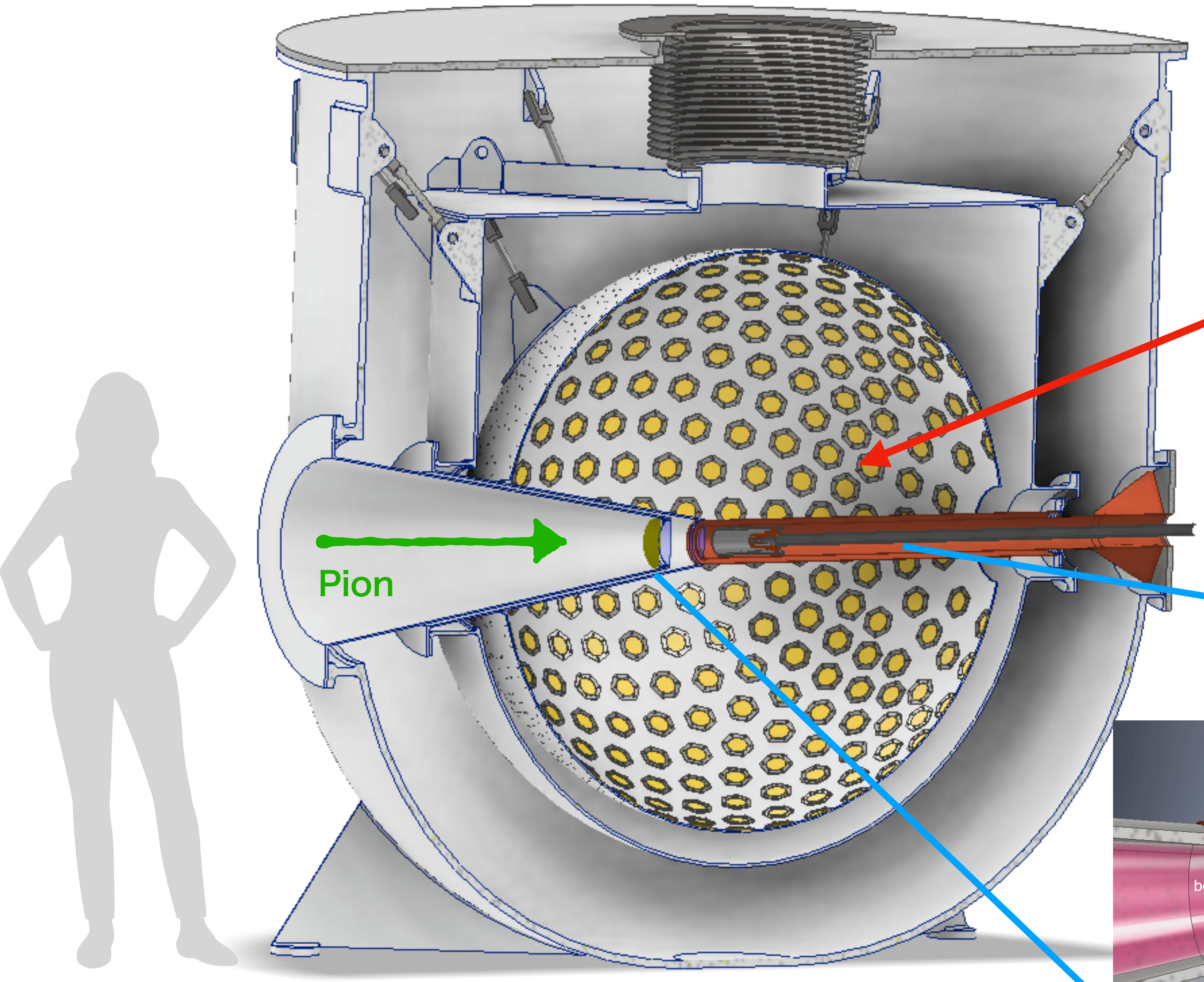
Second Phase: Pion beta decay $\pi^+ \to \pi^0 e^+ \nu$

Challenges



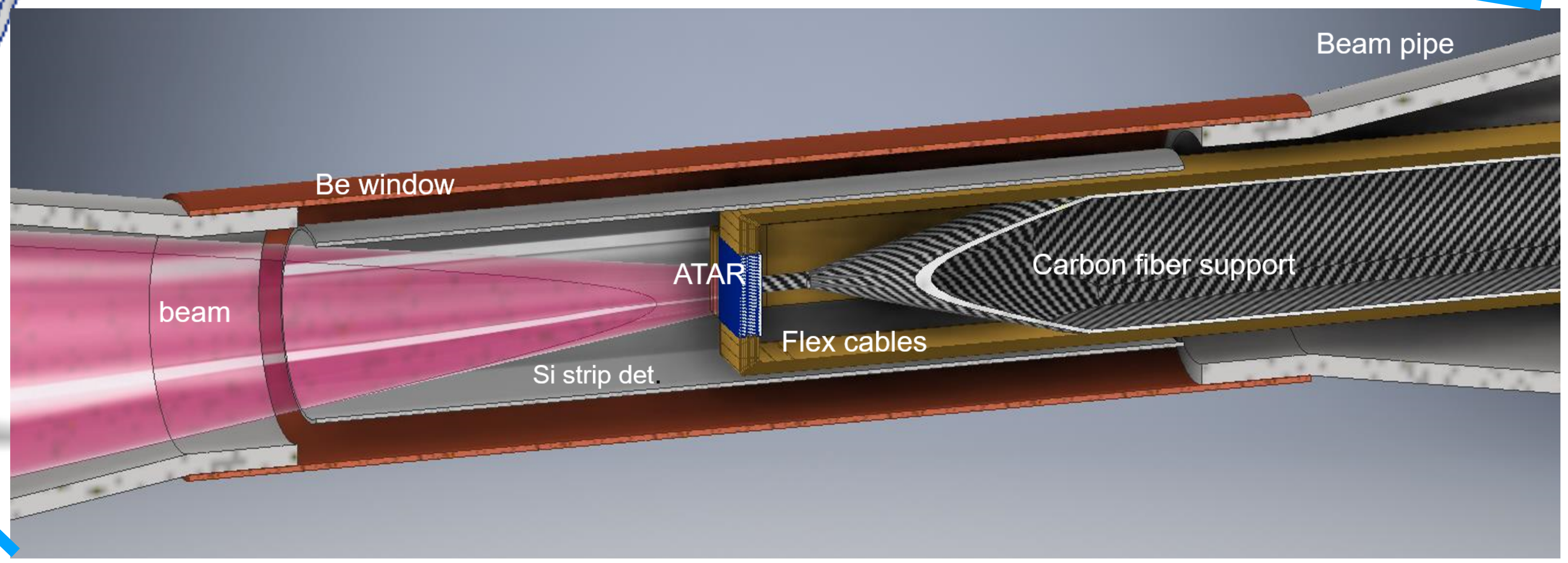
Energy Spectrum In a 25 X_0 Calorimeter
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
Branching Ratio
0
20
40
60
80
100
electron energy (MeV)
$\pi \rightarrow \mu \rightarrow e$
$\pi \rightarrow e$
Total Spectrum
$\times 10^3$
$\pi \rightarrow \mu\nu \rightarrow e\nu\nu$
$\pi \rightarrow e\nu$
low energy "tail"

PIONEER



25X_0 Liquid Xenon Calo

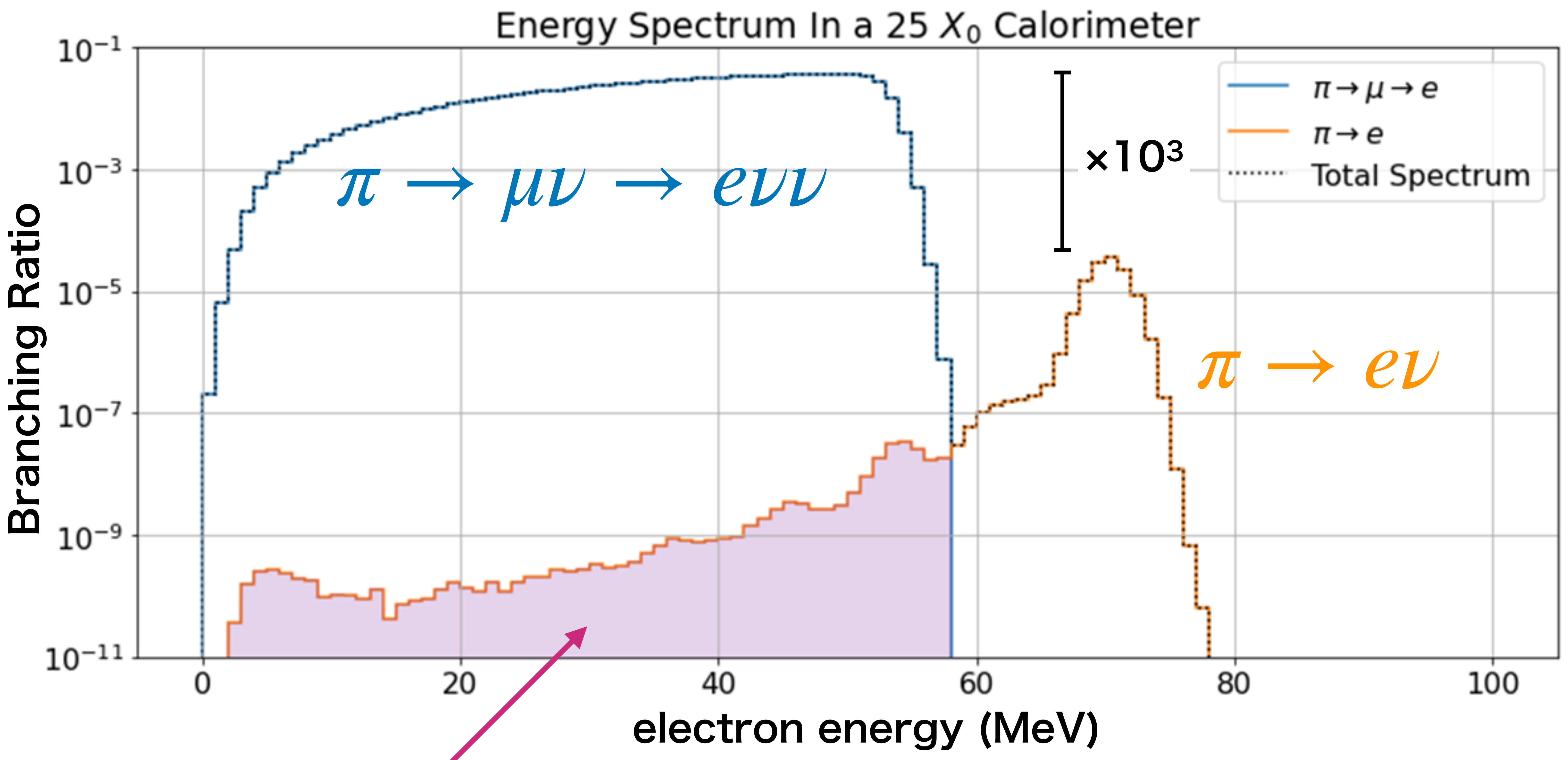
3π solid angle



“5D” Active Target (ATAR) & Tracker

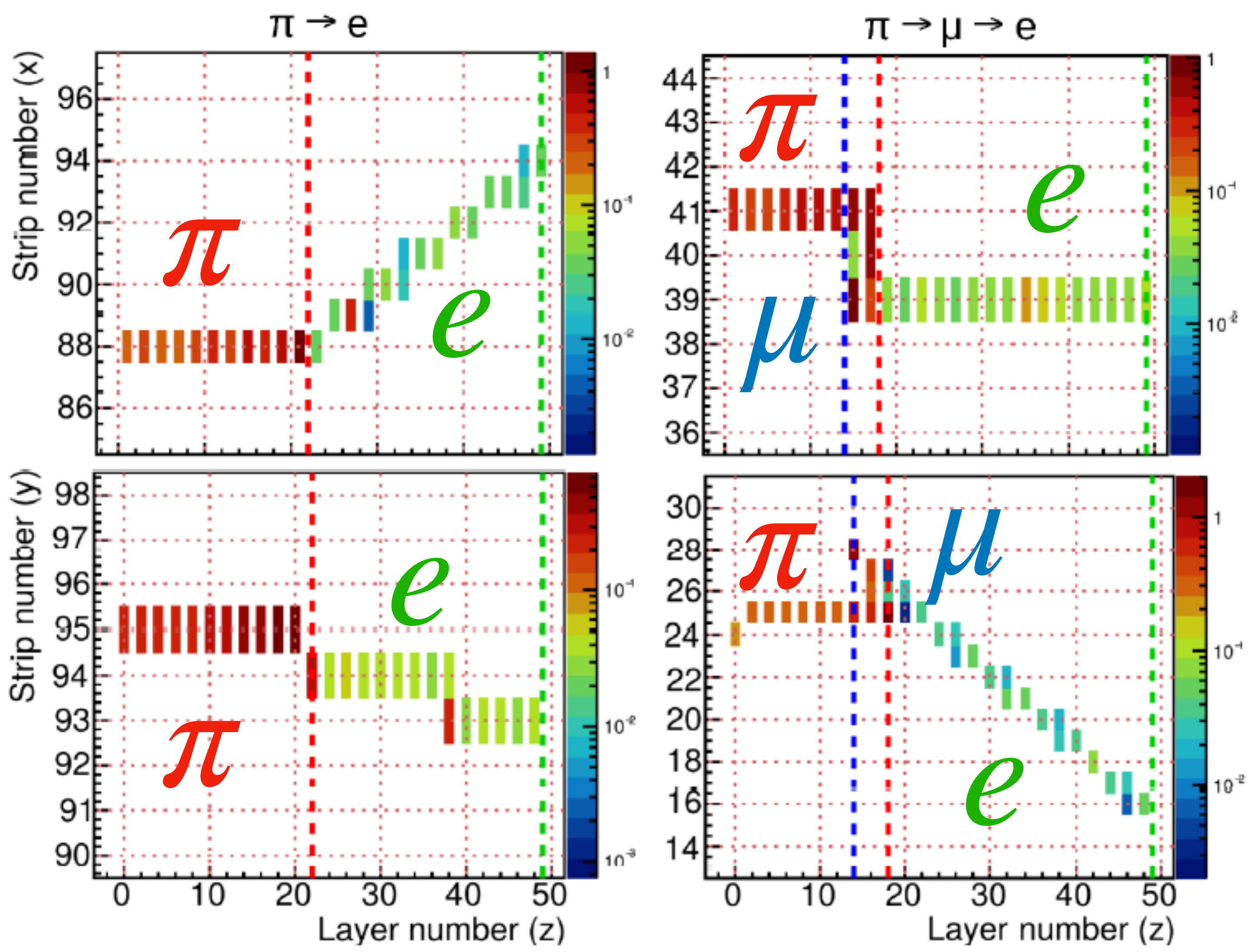
3D + time + energy

Fast, uniform LXe Calorimetry with excellent energy resolution <1.5%

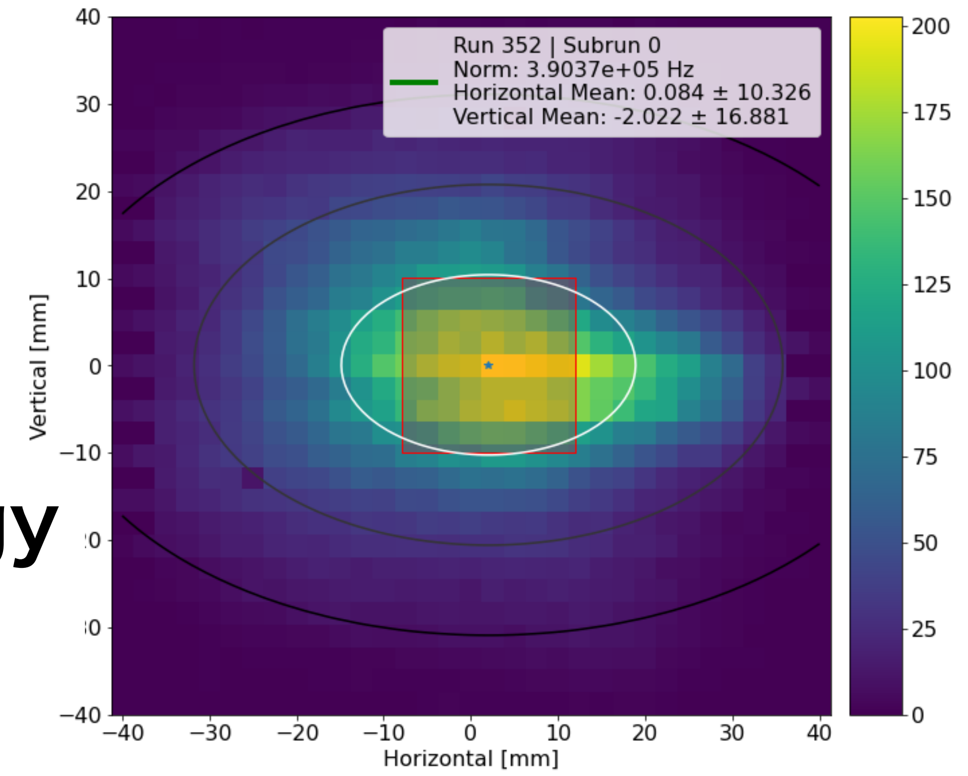


25X₀ Calorimeter reduces the tail: 3% —> 0.5%

5D event identification by ATAR (LGAD technology)



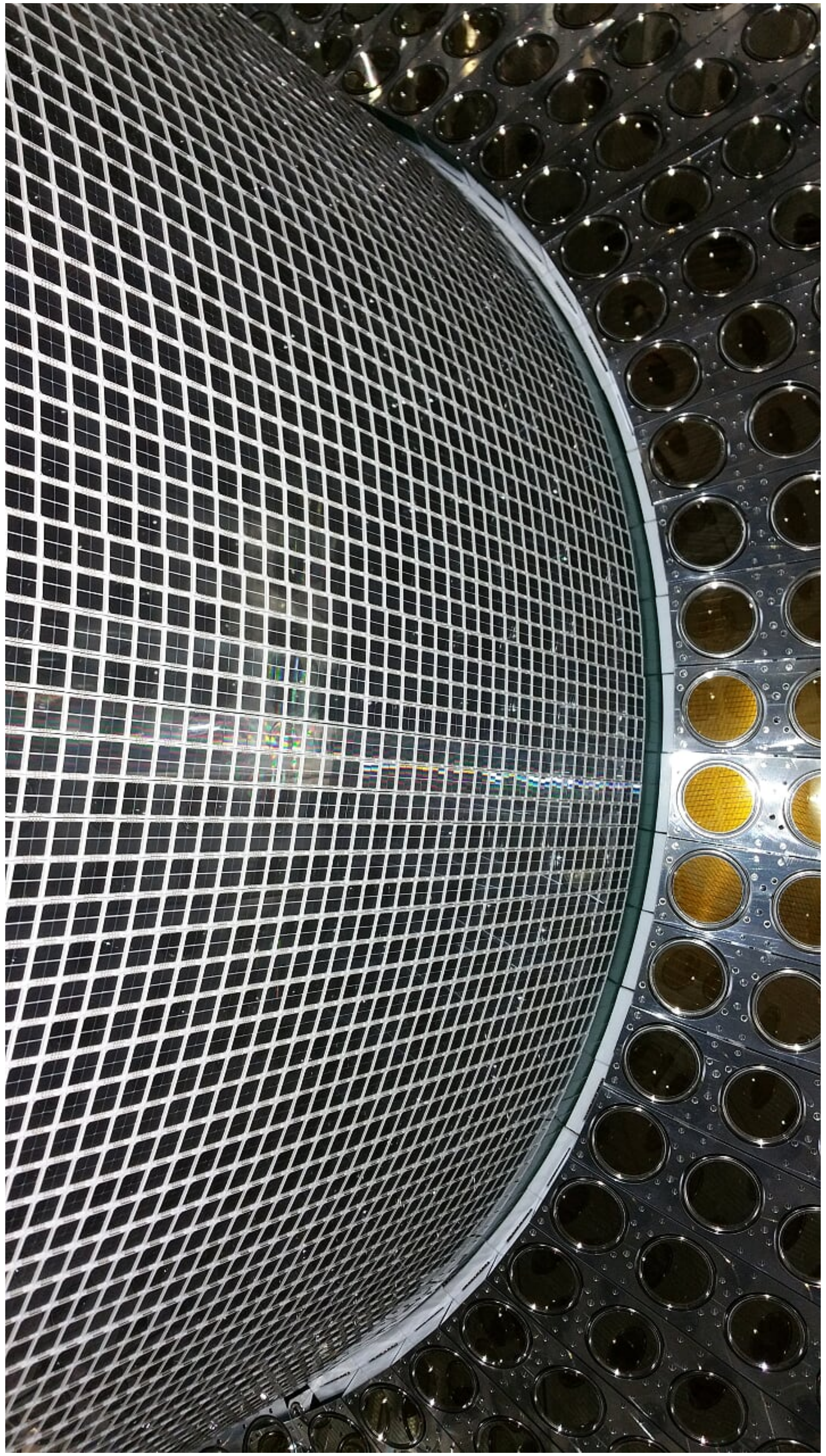
pion beam profile (beam test 2022)



Most intense, high quality, low-energy pion beam at PSI, Switzerland

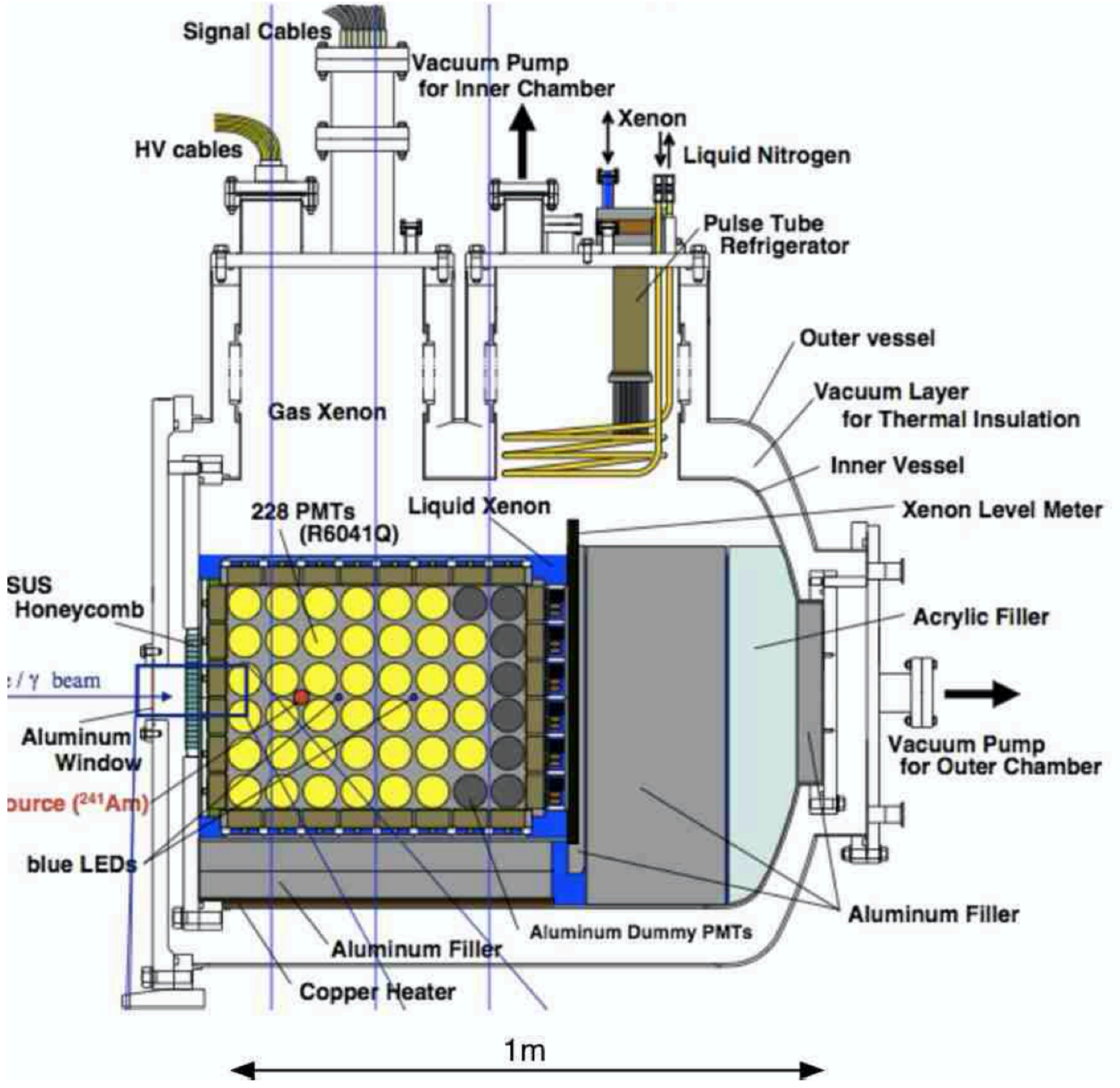
Matured LXe Technology

Developed for MEG



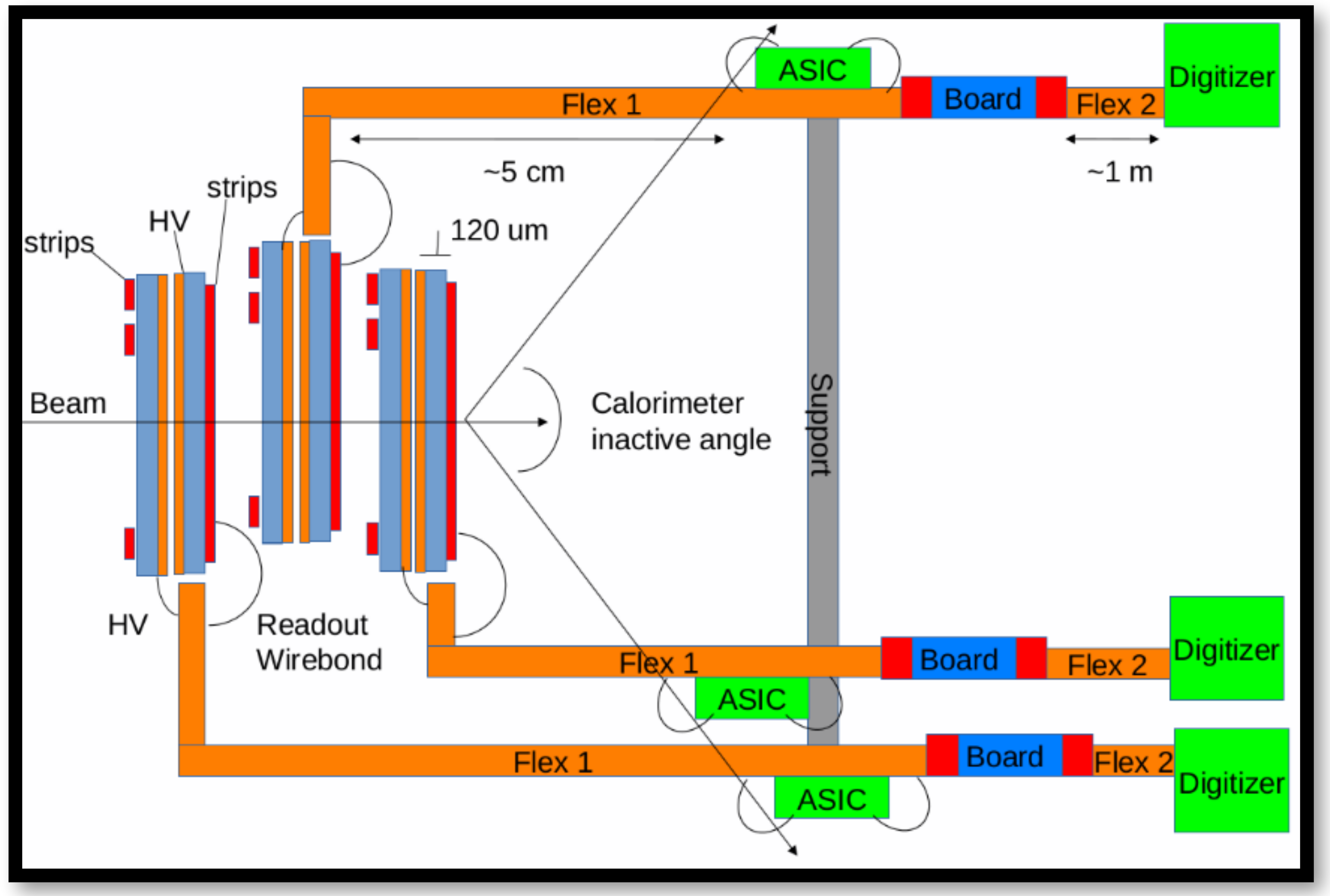
◀Inside the 2.7ton MEG II LXe detector
(VUV SiPMs & PMTs are seen)
The necessary performance established

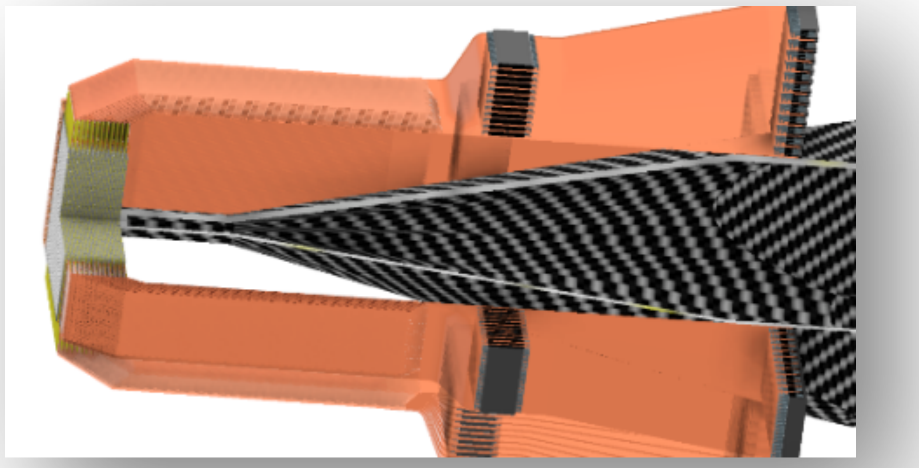
▼ Prototype Detector to be used for R&D for PIONEER

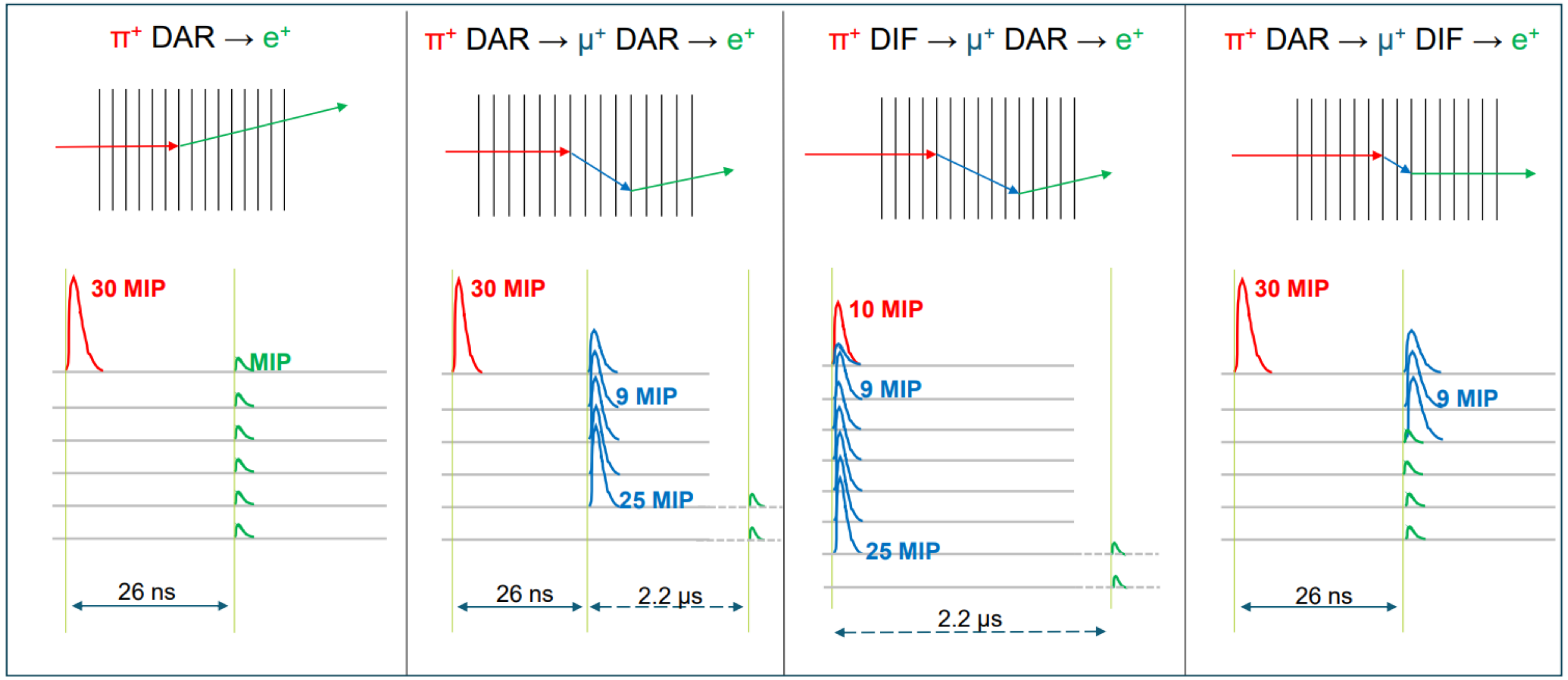


Active Target (ATAR)

key new technology to develop

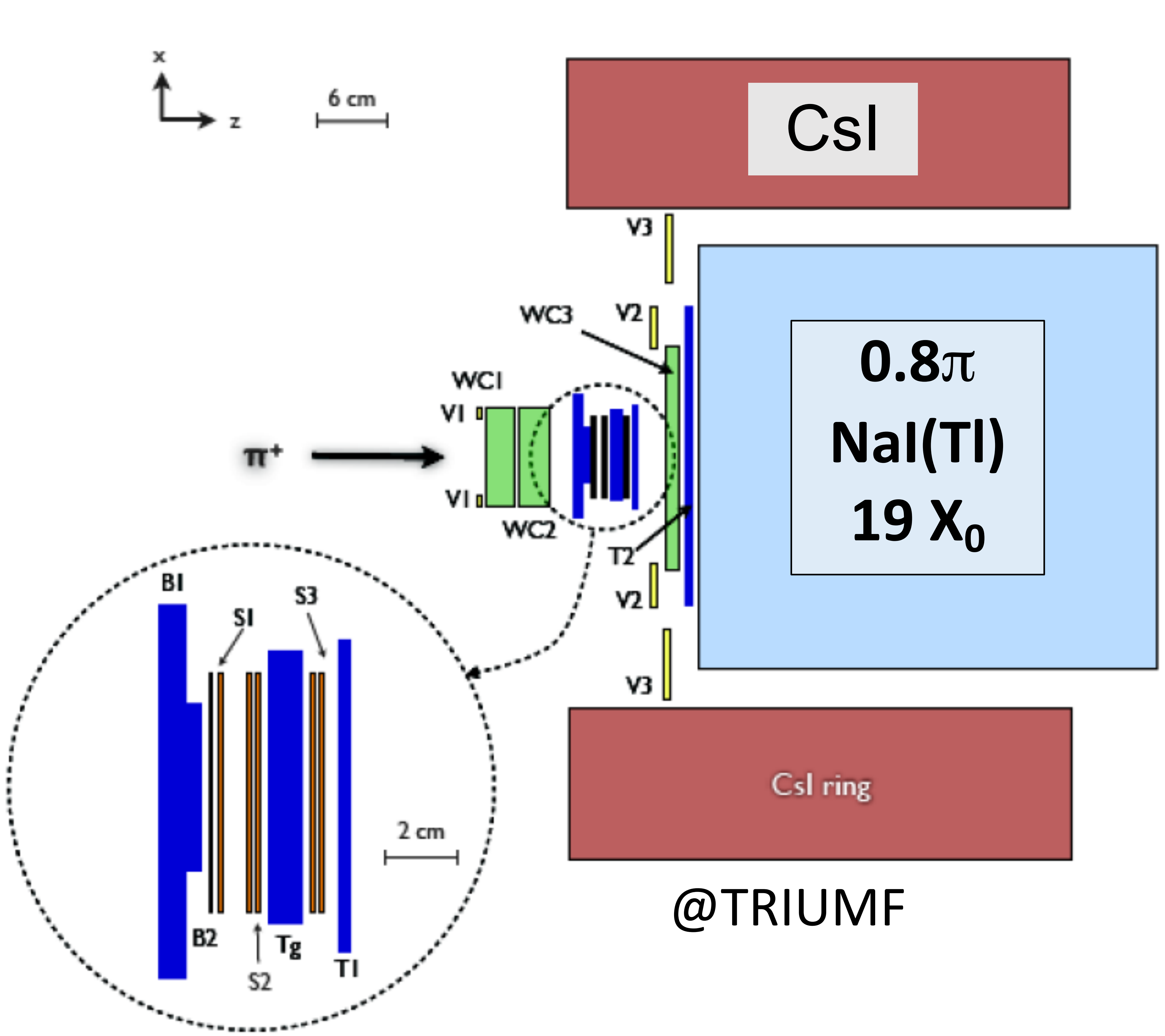




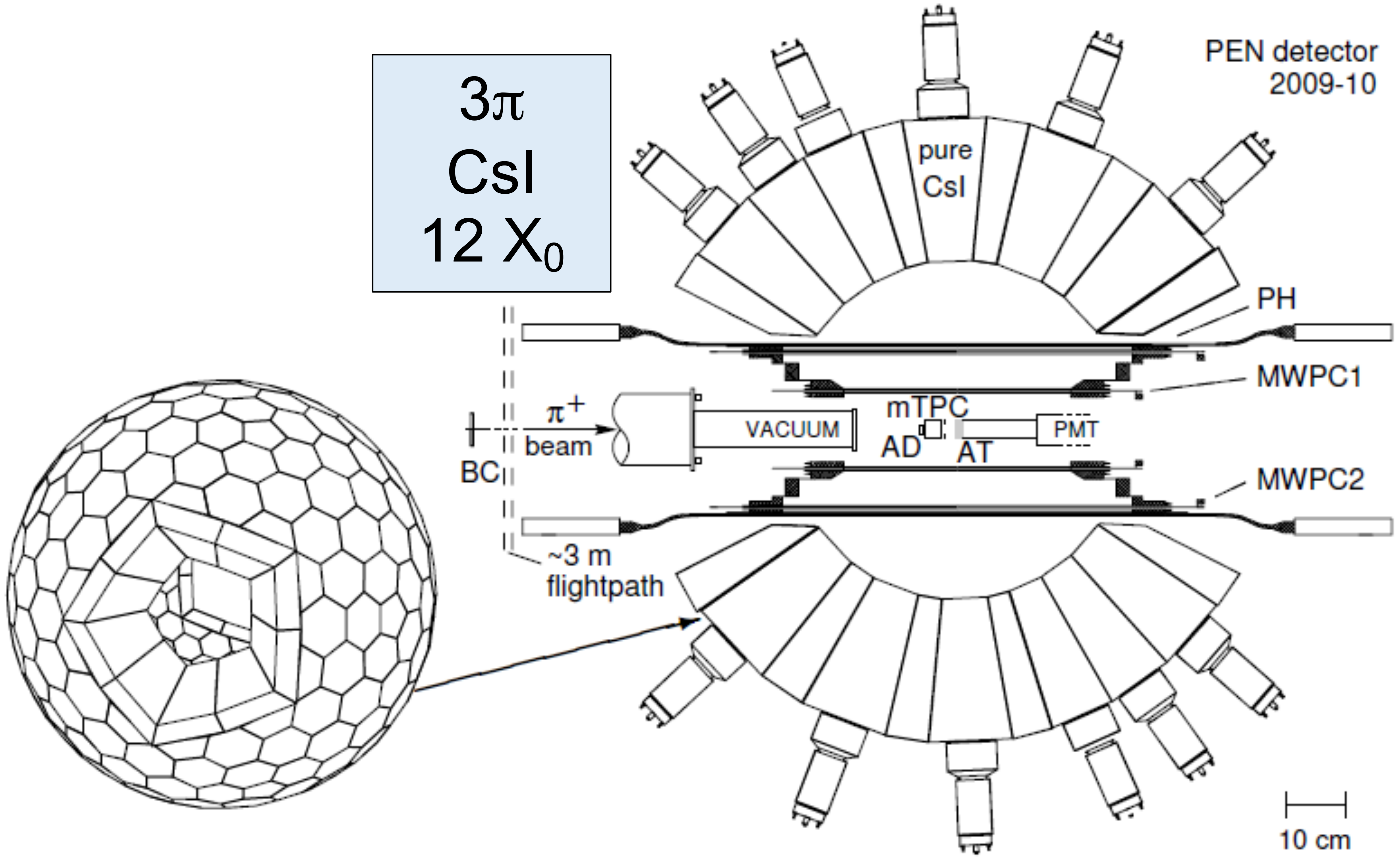


Past Pion Decay Experiments: PIENU and PEN/PIBETA

Both took data a long ago but have (known) challenges to overcome before final results



@TRIUMF



@PSI

- Single large NaI - excellent resolution but slow
- Small solid angle, $19X_0$ - large shower leakage and tail

- Large solid angle
- Calorimeter depth of $12X_0$ - large tail under muon spectrum

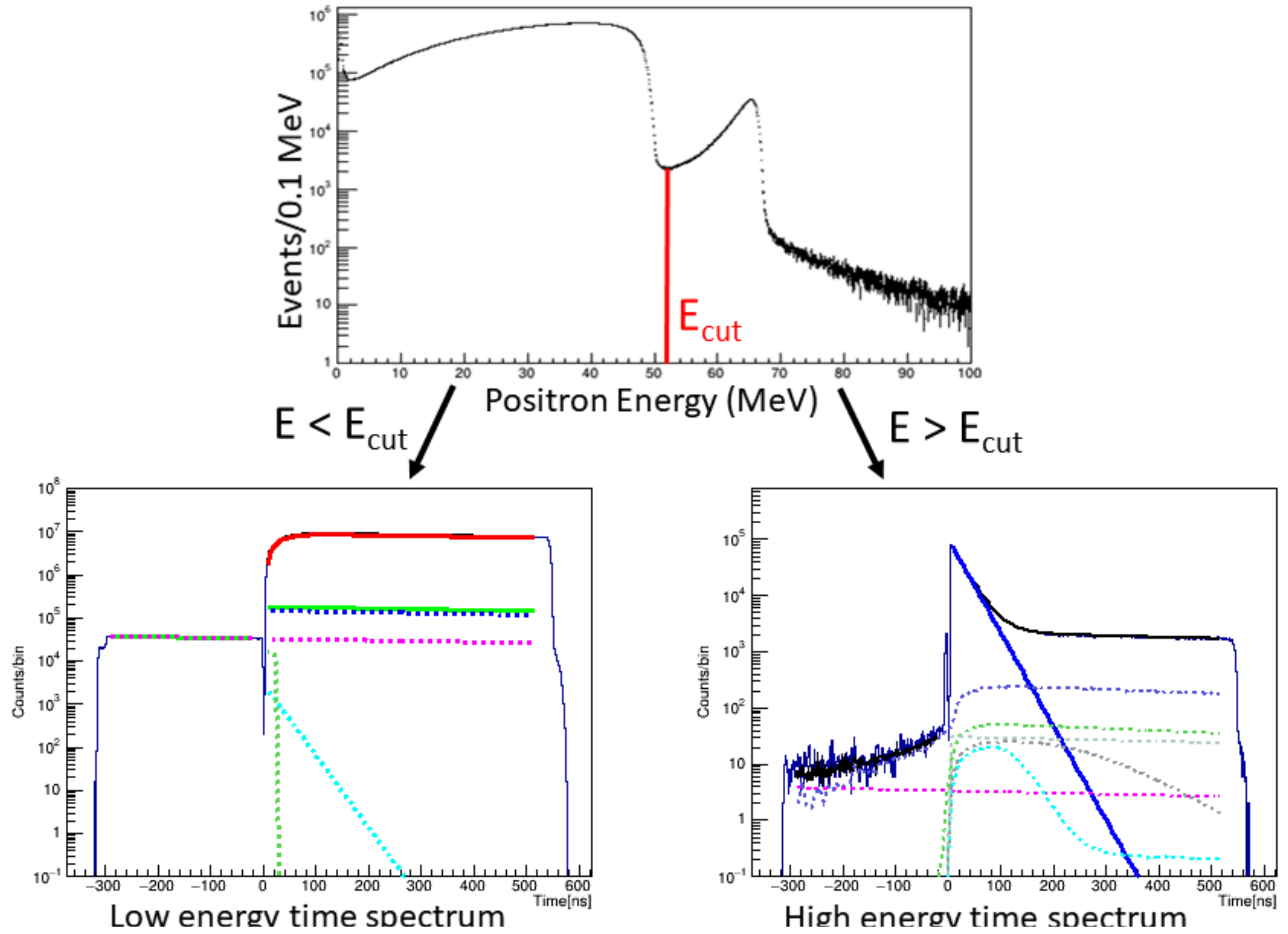
Strategy for 10^{-4} precision experiment

$\boxed{\sigma_{stat} = \sigma_{sys} = 0.7 \times 10^{-4}}$

- Statistics
  - 2 x 10^8 $\pi \rightarrow e\nu$ events
    in 2-3 years with 3×10^5 π/sec beam

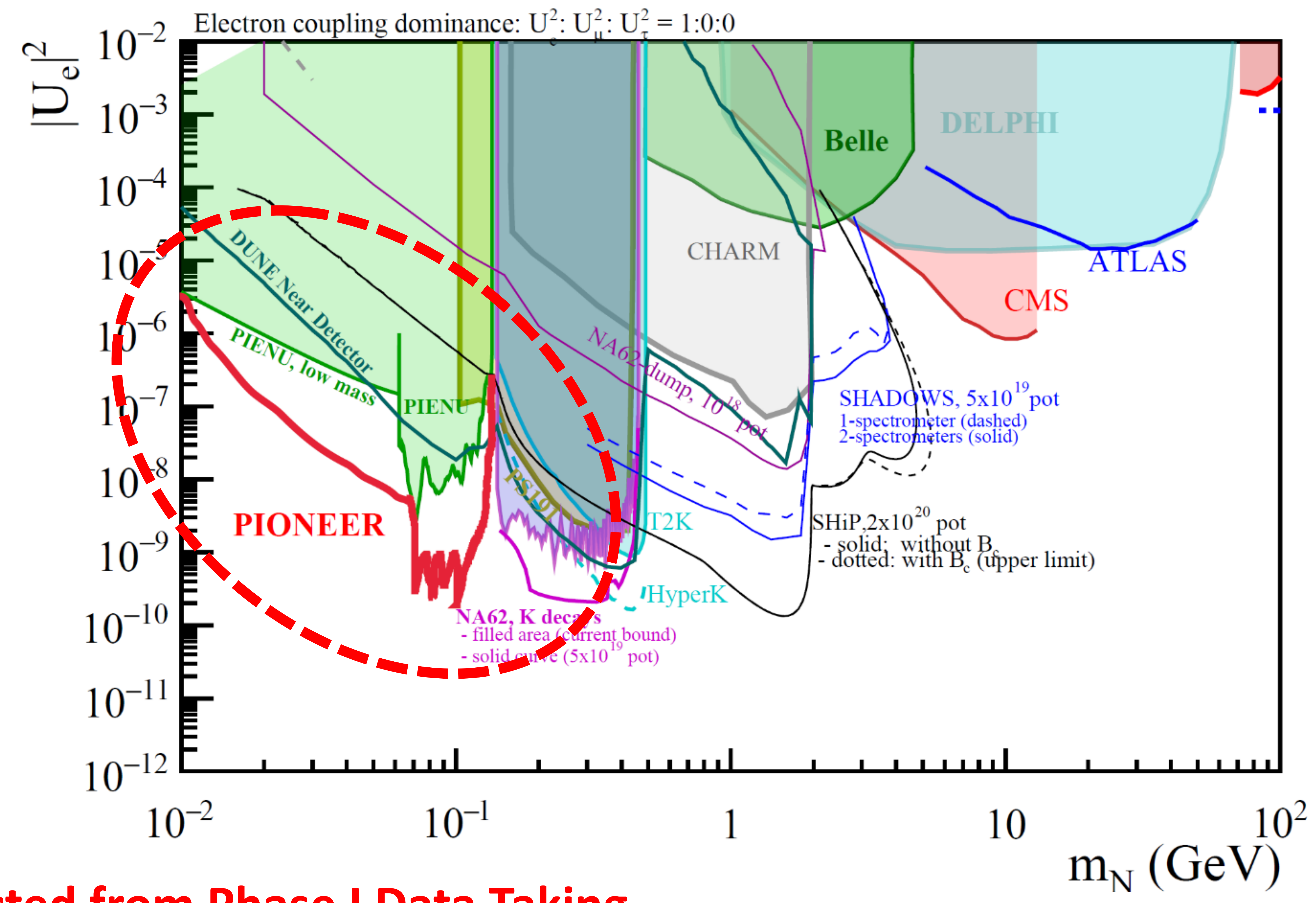
- Analysis
  - fit high/low energy e^+ time distributions with various components:
    - $\pi - e$
    - $\pi - \mu - e$
    - background, pileup, etc

- Systematic improvements
  - intense, high quality π^+ beam
  - ATAR with 5D capability to identify events
  - LXe calorimeter: 3π, $25X_0$, high res., fast



Error Source	PIENU 2015 %	PIONEER Estimate %
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**

Sterile neutrinos and exotic decays



Expected from Phase I Data Taking

Unique sensitivity in the low mass region 1-120 MeV

Snowmass paper: The Present and Future Status of Heavy Neutral Leptons; Abdullahi et al
https://arxiv.org/pdf/2203.08039.pdf

Heavy sterile neutrino and hidden sector searches improved by factor of 10

$$\pi \to e\nu_H$$

$$\pi \to \mu\nu_H$$

$$\pi \to e\nu X$$

Example papers published by PIENU

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

PIONEER approved at PSI addressing 3 Physics Questions

10 x Improvements in precision

- **Lepton Flavor Universality**
- **Cabibbo Angle Anomaly**
- **Sterile neutrinos and exotic decays**

Jan. 2022 ***Approved with high priority @ PSI***

https://arxiv.org/abs/2203.01981

PSI Ring Cyclotron Proposal R-22-01.1

PIONEER: Studies of Rare Pion Decays

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Snowmass 2022 White Paper

Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment

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arXiv:2203.05505v1 [hep-ex] 10 Mar 2022

Notional Timeline

PIONEER

Join us!

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