Status of the PIONEER Experiment Testing Lepton Flavor Universality in Pion Decays

L. Gerritzen, S. Ban, T. Iwamoto, A. Matsushita, S. Mihara, T. Mori, W. Ootani, Y. Uchiyama on behalf of the PIONEER Collaboration

The Physical Society of Japan 2023 Annual Meeting

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

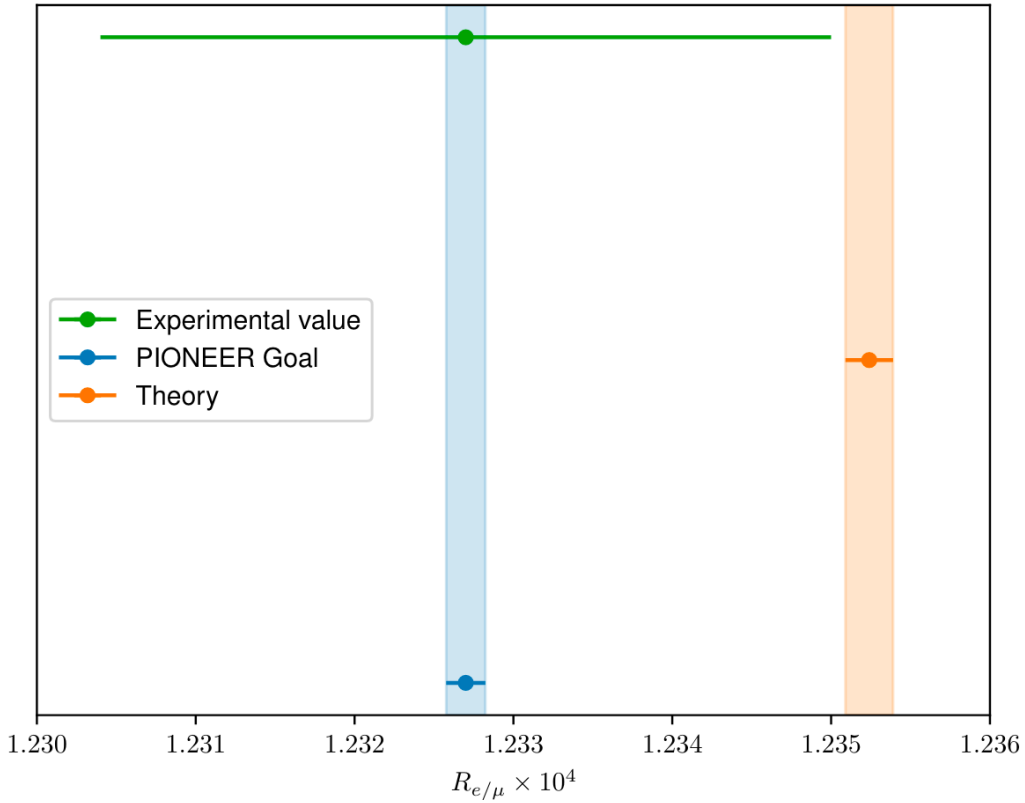
Physics Cases

- Phase I: Lepton Flavor Universality

$R_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+ \nu(\gamma)\right)}{\Gamma\left(\pi^+ \to \mu^+ \nu(\gamma)\right)}$ with 0.01% uncertainty

- Phase II: CKM Matrix Unitarity

$\frac{\Gamma\left(\pi^+ \to \pi^0 e^+ \nu\right)}{\Gamma_{tot}}$ with uncertainty < 0.2%



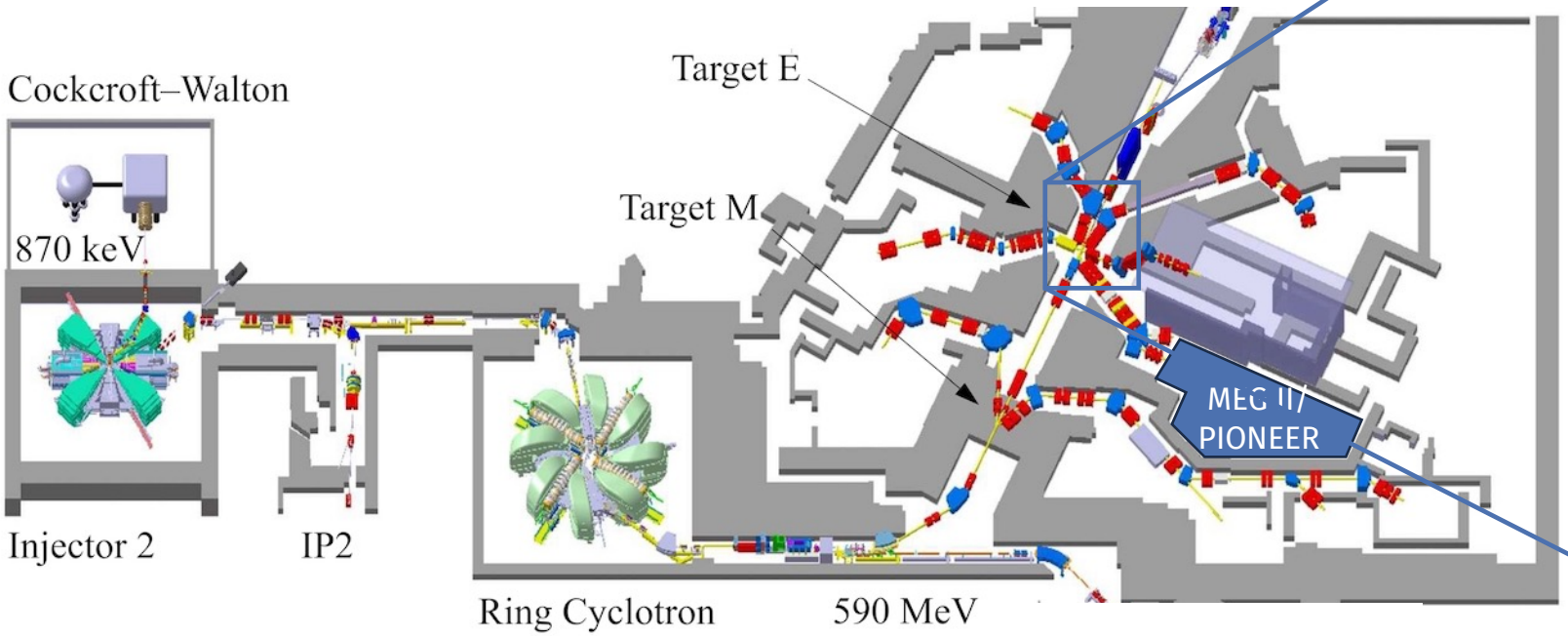
Paul Scherrer Institute

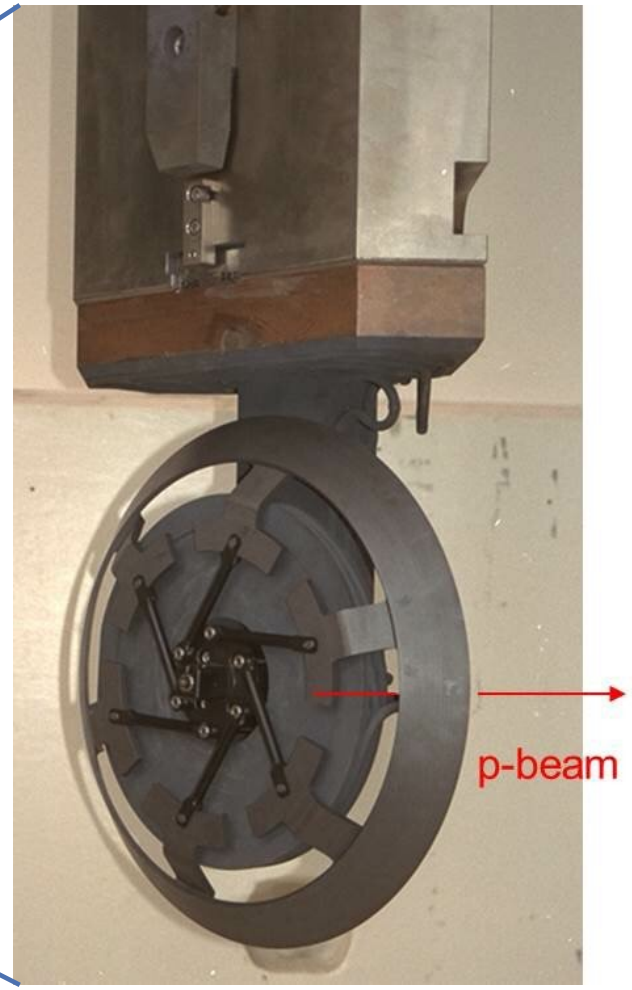
PAUL SCHERRER INSTITUT

- Swiss federal research institute
- Combines many fields

- Research with Neutrons and Muons (NUM)
- Photon Science (PSD)
- Energy and Environment (ENE)
- Nuclear Energy and Safety (NES)
- Biology and Chemistry (BIO)
- Scientific Computing, Theory and Data (SCD)

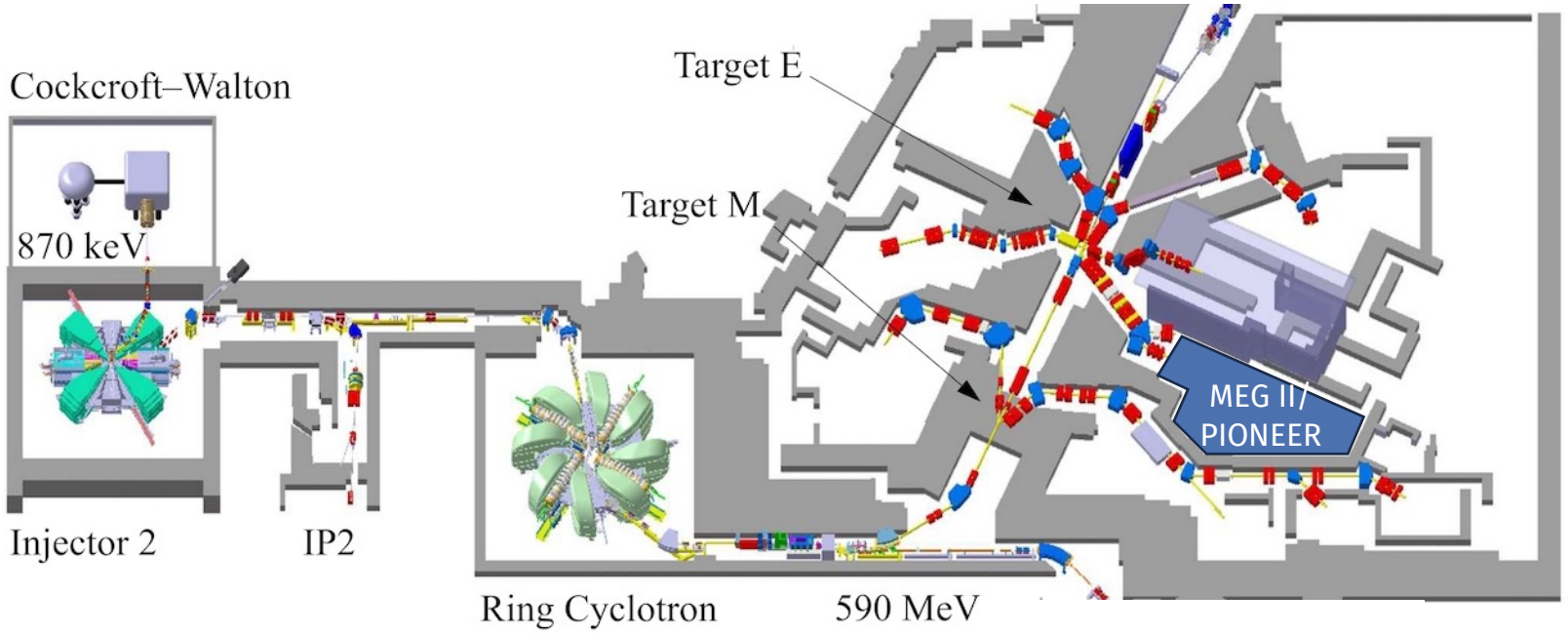
Accelerator Complex





$p + {}^{12}C \rightarrow \pi + X$

Accelerator Complex



High Intensity Proton Accelerator (HIPA)

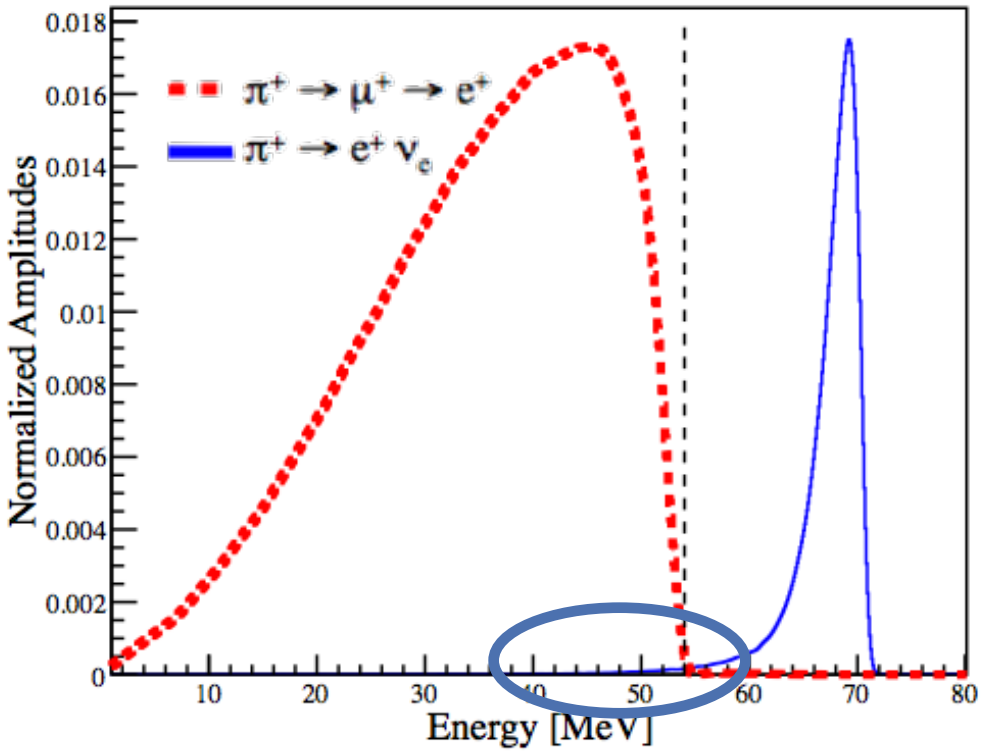
- 590 MeV proton beam
- 2.4 mA nominal current
- Two carbon targets

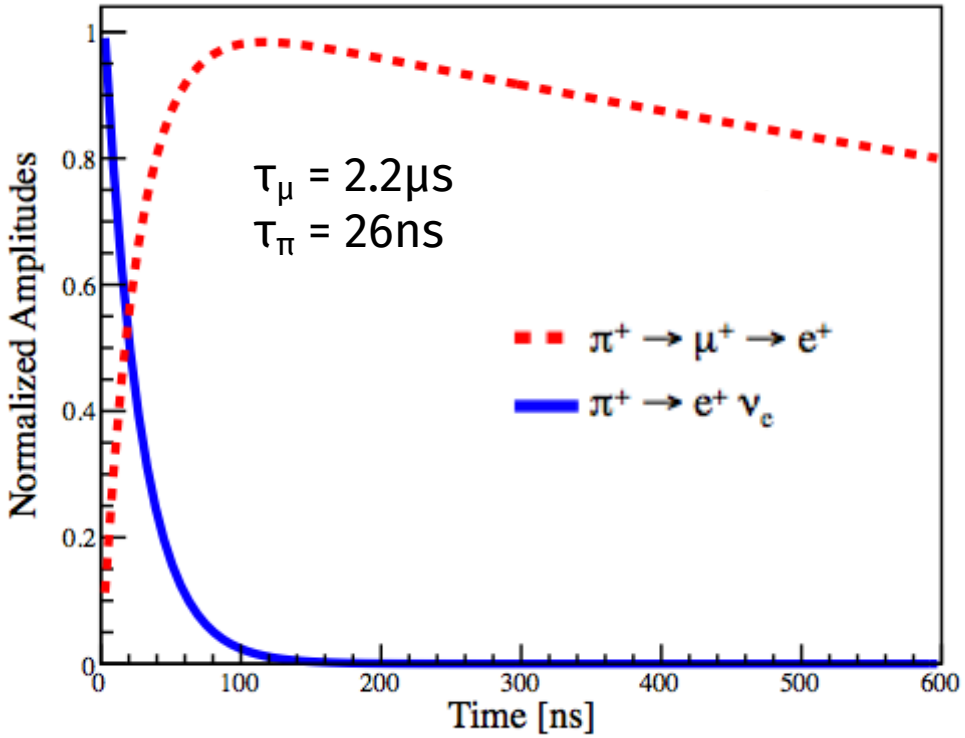
Secondary Beamlines (SBL)

- Production of $\mu^{\pm}$, $\pi^{\pm}$, $e^{\pm}$
- World's highest-intensity beamlines
- Extremely reliable schedule
- Currently hosting MEG II

Pion Decays

$B(\pi^+ \to \mu^+\nu) \approx 100\%$
$B(\pi^+ \to e^+\nu) \approx 10^{-4}$
$B(\pi^+ \to \pi^0 e^+\nu) \approx 10^{-8}$



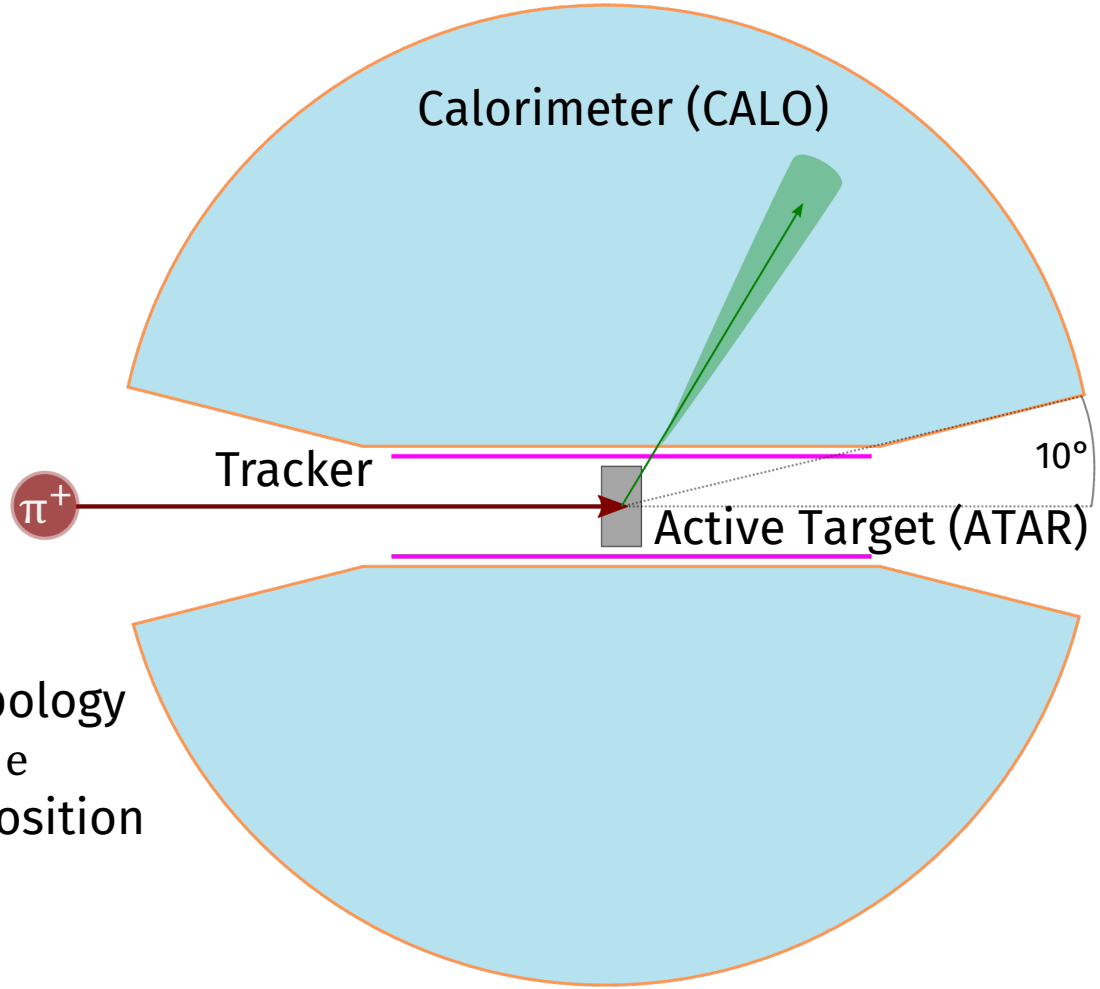


~1% of $\pi \to e\nu$ events
are expected < 55 MeV

Analysis in **energy** and **time**

PIONEER Detector Concept

Pion Beam
- > 3×10^5 s^{-1}
- Provided by PSI



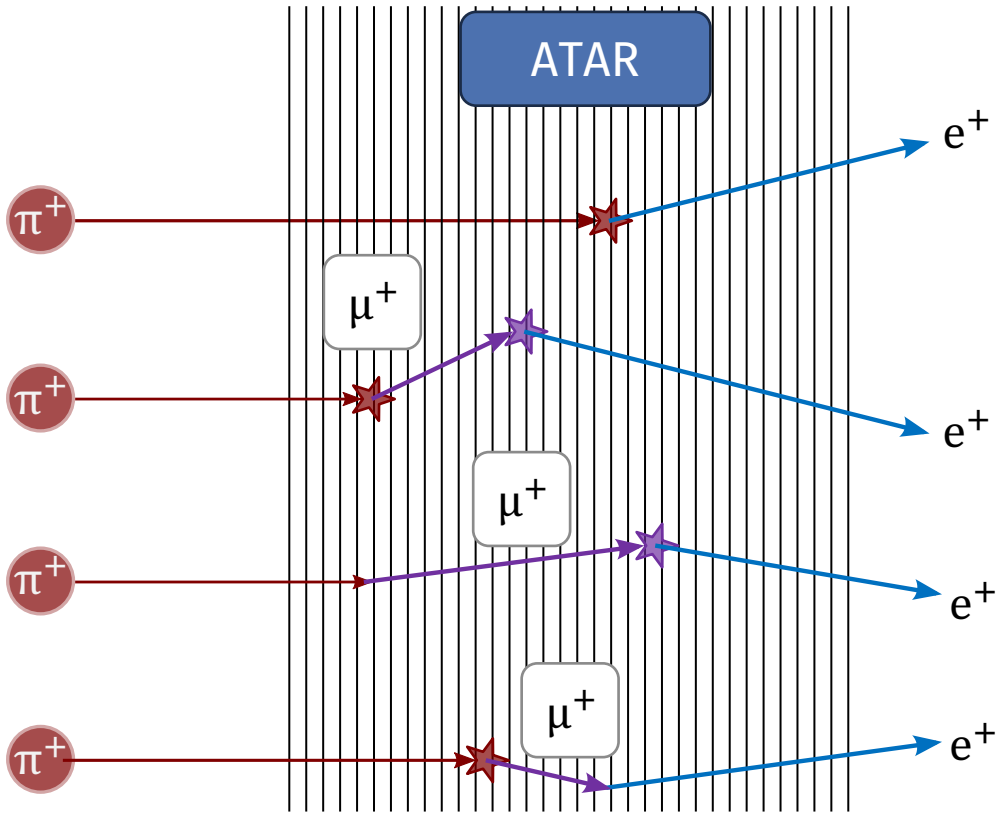
Calorimeter
- 25 X_0 depth
- 3π angular coverage
- $\frac{\delta E}{E} \leq 1.5\%$
- Good timing

Active Target
- Tracking decay topology
- Identifies $\pi \rightarrow \mu \rightarrow e$
- Detect energy deposition
- Good timing

Tracker
- Match positrons and pion stops
- Low mass

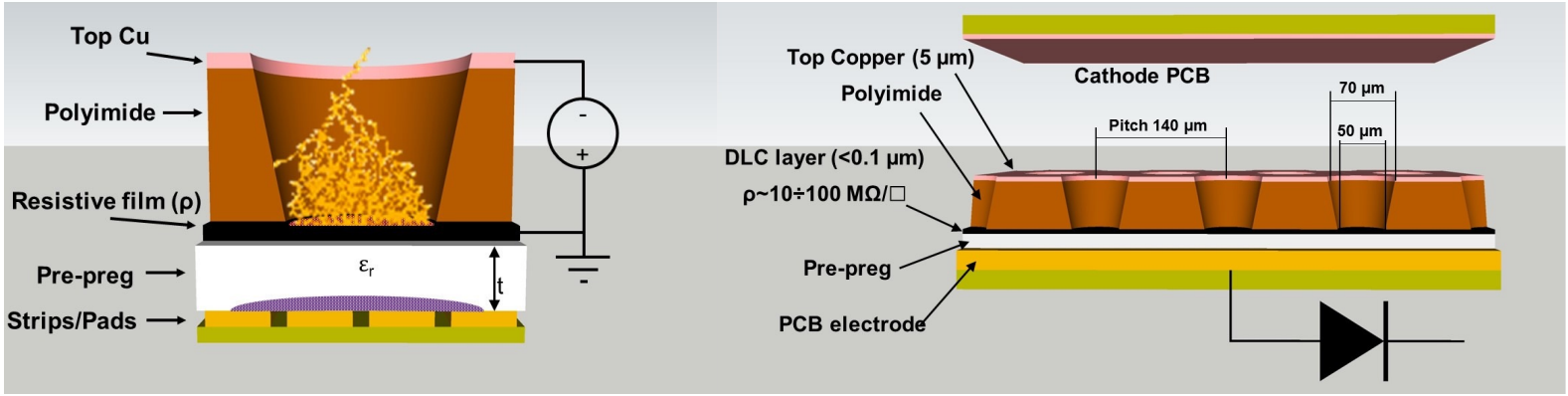
Active Target (ATAR)

- Baseline design: Low-gain avalanche detectors (LGAD) strips
- Allows the distinction of $\pi^+ \rightarrow e^+$ and $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
- Detect decay in flight of π^+ and μ^+



Tracker

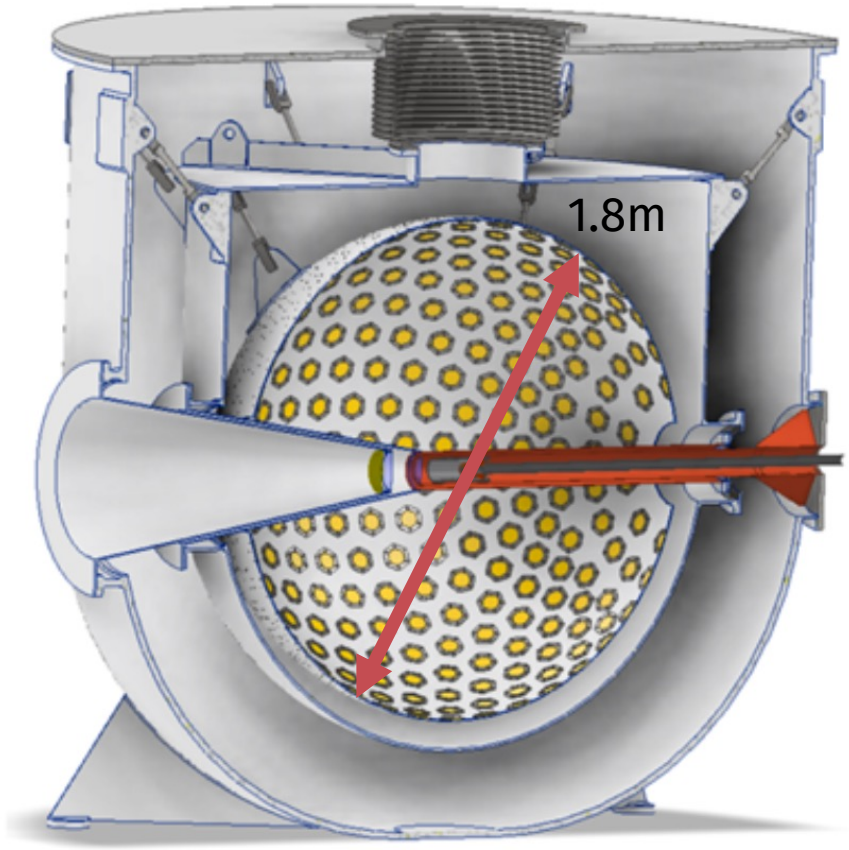
- Several low-mass technologies are considered
  - µ-RWELL (gas detector)
  - HV-MAPS (silicon pixels)
  - Silicon strips
- Time resolution O(few ns) needed



µ-RWELL

Calorimeter

- Baseline design: Liquid Xenon
- Experience from the MEG II calorimeter (UTokyo, KEK)
- High cost (several tons of Xe)
- Alternatives are being investigated (LYSO)



Recent and Current Activities

- Recent beam test for ATAR development in the US
- Optimization of calorimeter geometry
- Study of photonuclear reactions in MEG II LXe calorimeter

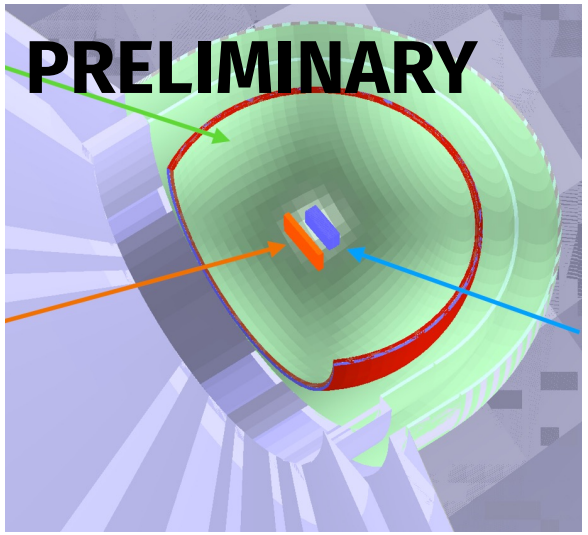


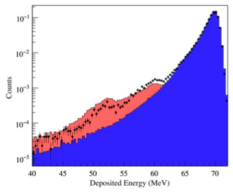
Photo-nuclear reaction

Photonuclear reactions in NaI detector

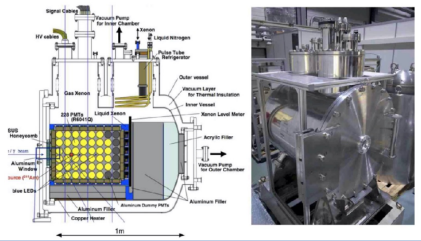
- ^{127}I captures γ(electromagnetic shower)
  → n(94%), p(4%), α(2%) emission
  → 1n, or 2n escape from NaI
  → peaks in low energy region
- This energy region is buried in π→μ→e decays, and Geant4 simulation should be tuned by data

Beam test was performed with NaI in the previous experiment

Beam test with LXe prototype (~100l LXe) will be performed for that



Nucl. Instrum.Meth.A621(2010)188-191

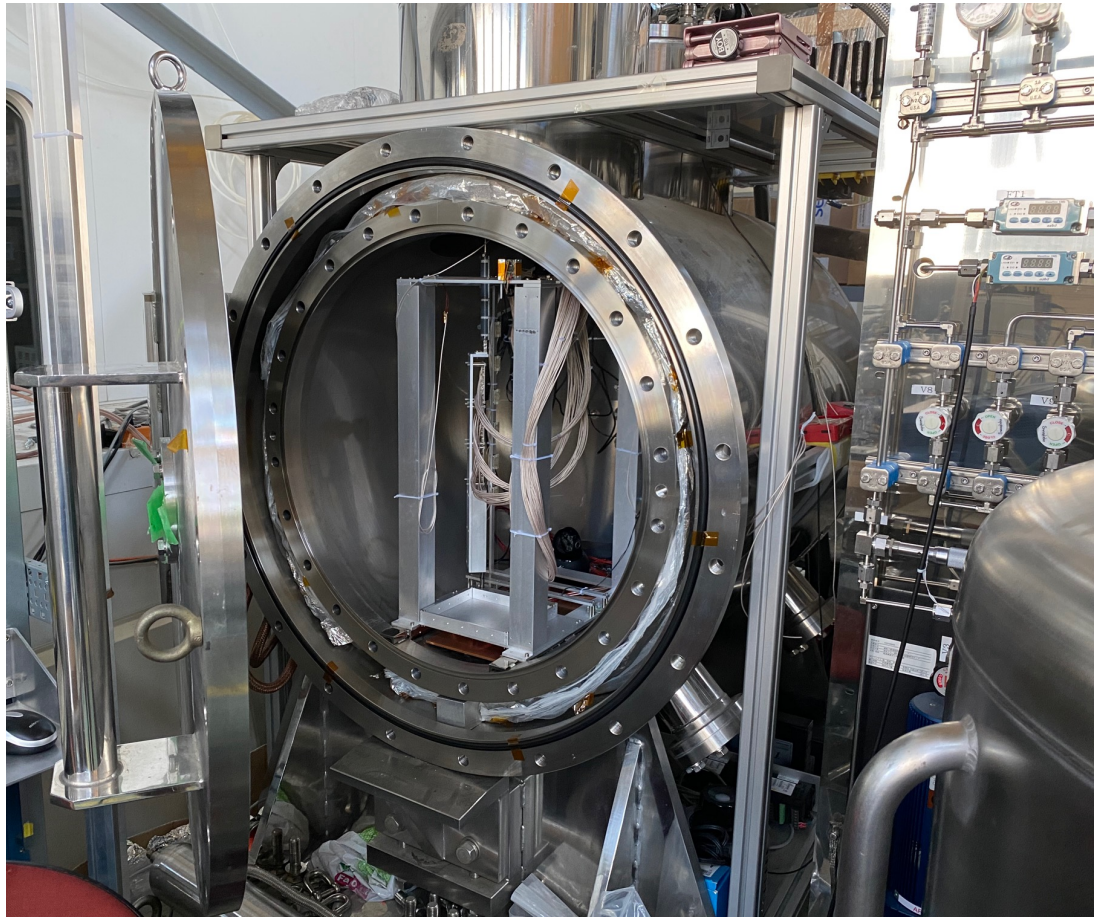


19

岩本敏幸
日本物理学会2023年春季大会
3月22~25日

Future Plans

- 2 weeks of beam time at PSI end of November (LYSO)
- Liquid xenon calorimeter beam test planned for next year using MEG “large prototype”



Proposal: arXiv:2203.01981
Witepaper: arXiv:2203.05505

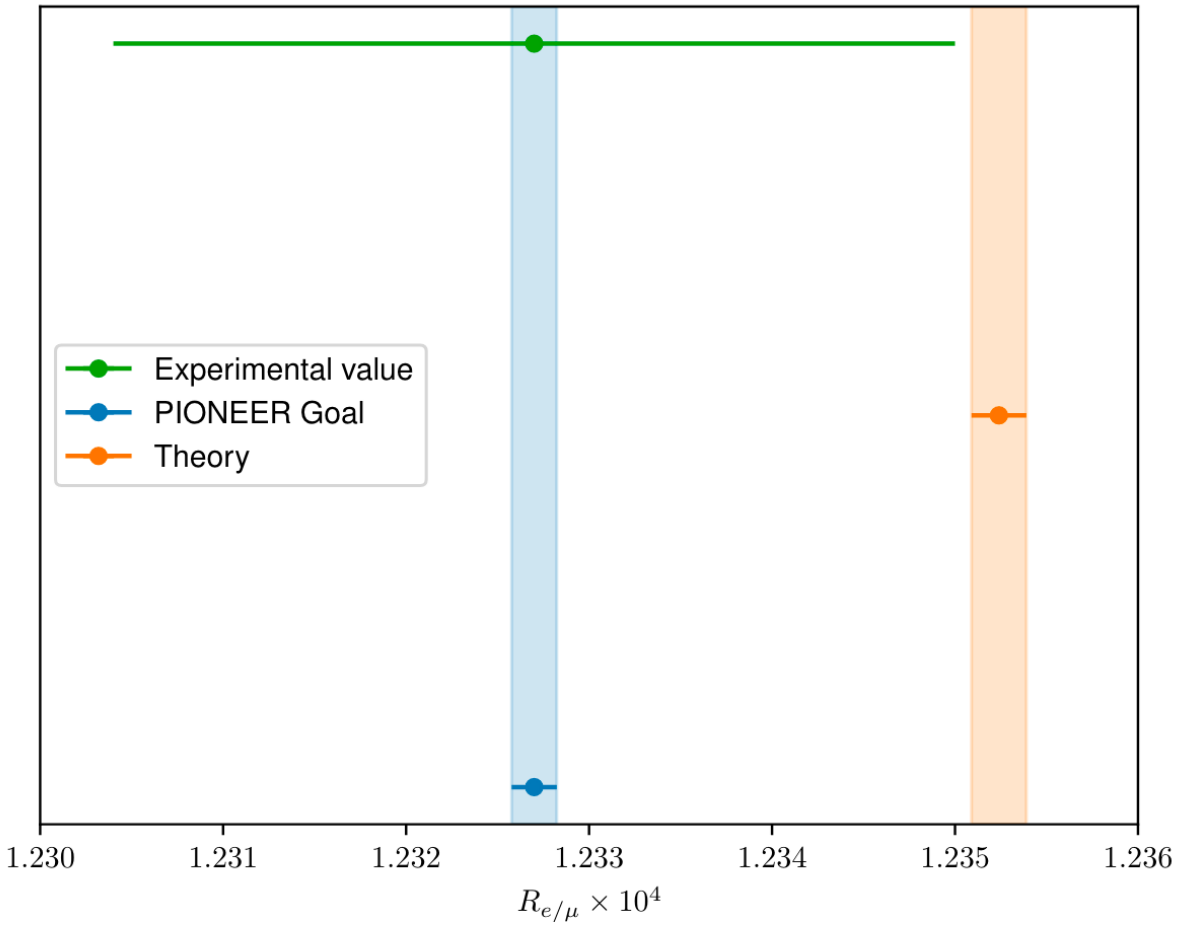
Current Status and Summary

- Strong support and official approval by PSI (R-22-01.1)
- Lots of detector R&D
- Young and active collaboration with experts from MEG II, PIENU and g-2
- If you want to join us, please contact Prof. Mori or me:
  - mori@icepp.s.u-tokyo.ac.jp
  - gerritzen@icepp.s.u-tokyo.ac.jp

Backup

Lepton Flavor Universality

- Anomalies in the recent years:
  - ~~R_K and R_{K^*} (LHCb)~~
  - R_D and R_{D^*} (BABAR, Belle, LHCb)
  - g – 2 (very recent new results)
  - ~~CKM first row unitarity~~ (see next slide)

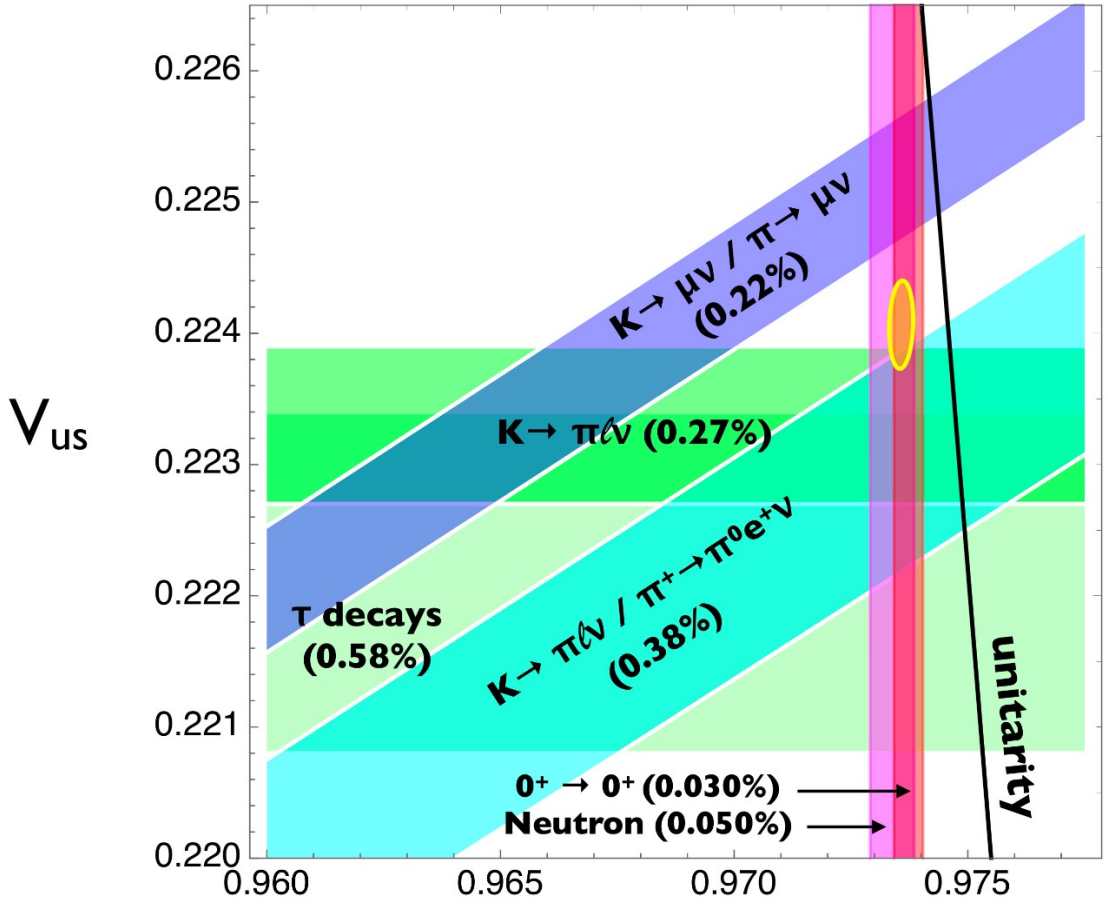


CKM First Row Unitarity

- Unitarity would require $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- Previously 3.7σ tension
- PDG increased the uncertainty of $|V_{ud}|$ by more than factor 2

⇒ Tension reduced to 2.2σ

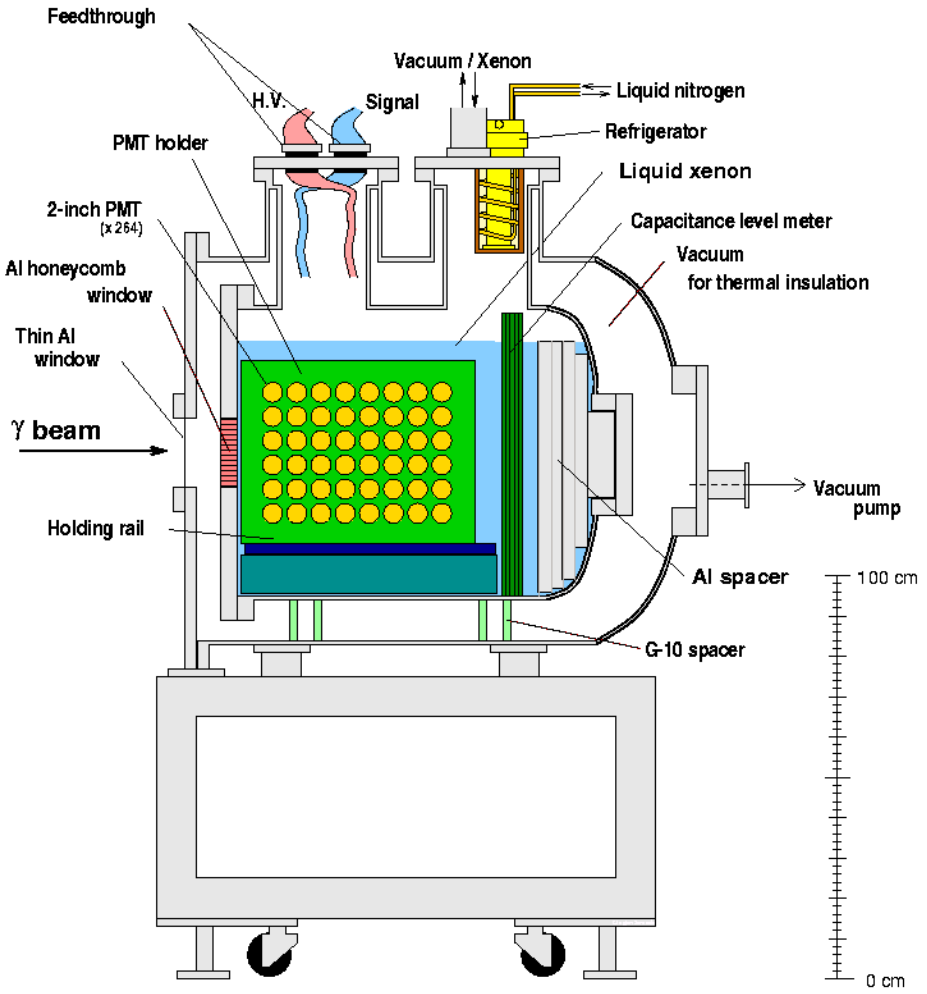
- Measurement of $\Gamma(\pi^+ \to \pi^0 e^+ \nu)$ is sensitive to $|V_{ud}|$
- $K \to \pi \ell \nu / \pi^+ \to \pi^0 e^+ \nu$ is sensitive to $|V_{us}|/|V_{ud}|$



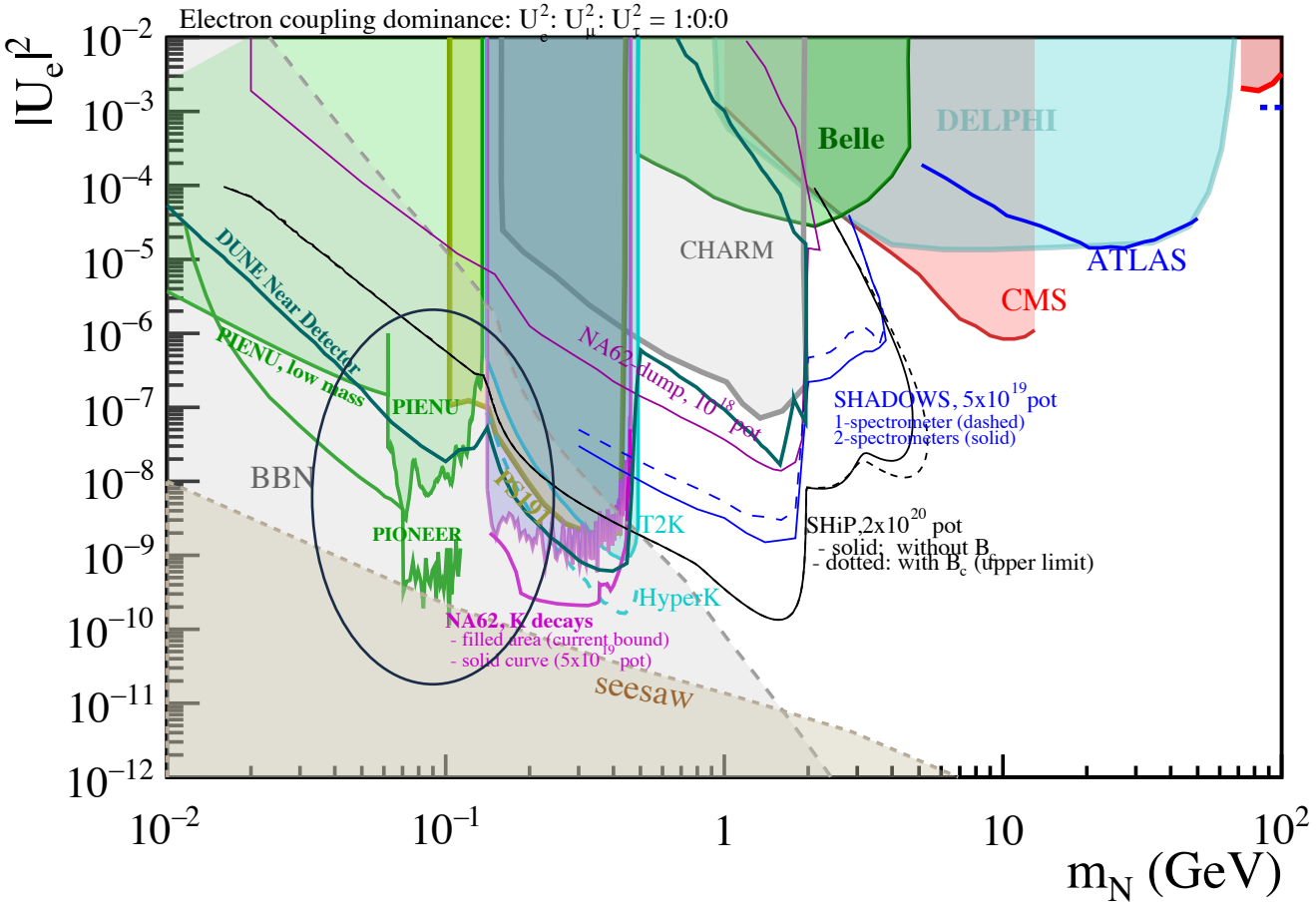
[arXiv:2111.05338]

~100l LXe Prototype

- Built for the MEG experiment
- PIONEER tests are planned



Heavy Neutral Lepton Search



[arXiv:2203.08039]

Decay in Flight