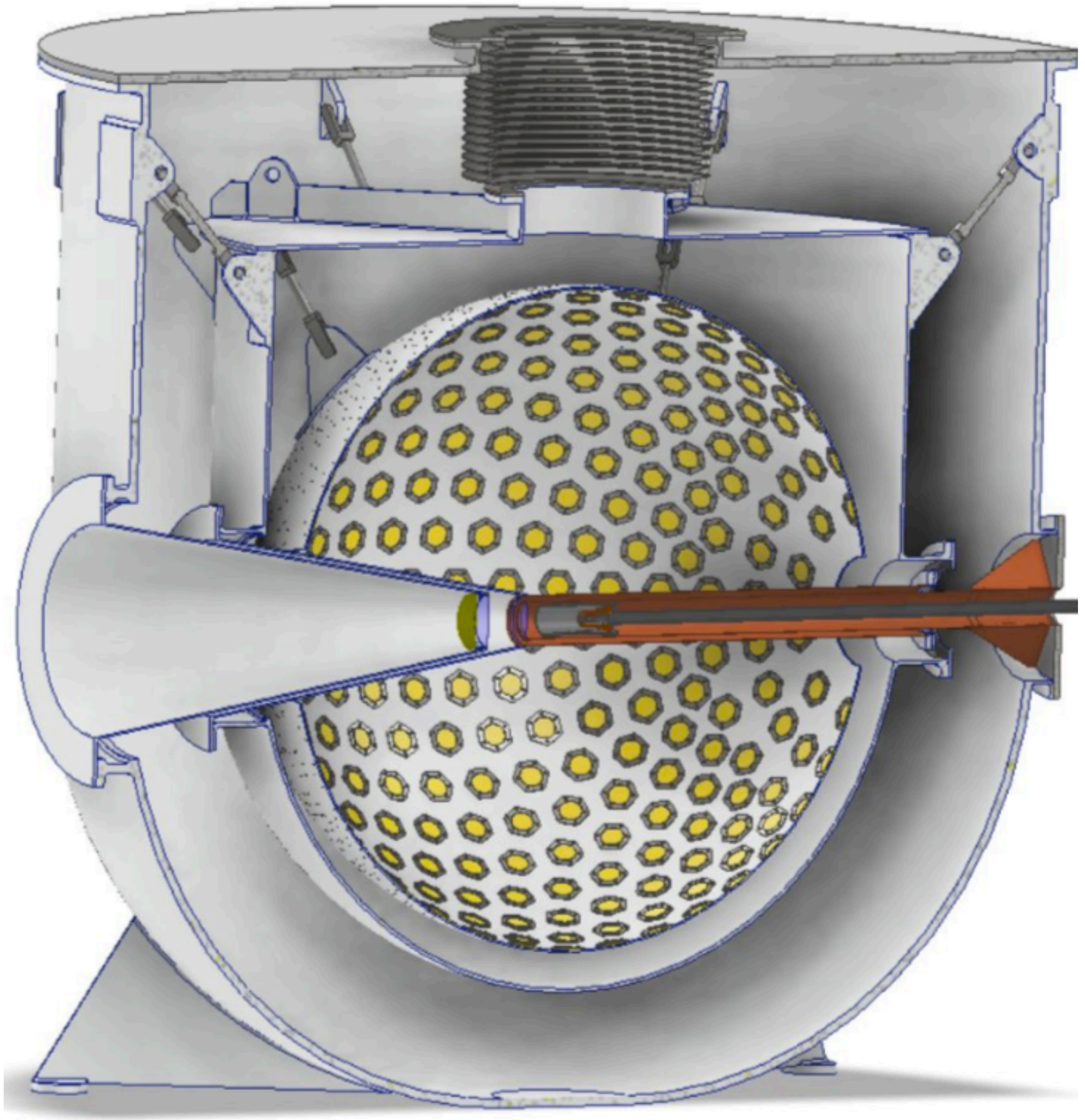
TRIUMF

A next generation pion decay experiment

PIONEER



Katherine Pachal

IPP AGM June 2023 - Fredericton

Discovery, accelerated

PIONEER COLLABORATION

- **International collaboration** across Asia, Europe & North America

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(*: co-spokespersons)

University of California Santa Cruz, University of Washington, University of Chicago, Mc Gill University, University of British Columbia, TRIUMF, Paul Scherrer Institute, Tsinghua University, Institute for Nucl. Theory, University of Washington, Argonne National Laboratory, University of Zurich, CERN, Tec de Monterrey, Brookhaven National Laboratory, University of Mainz, Fermilab, Cornell University, University of Virginia, ETH Zurich, University of Kentucky, University of Bern, KEK, University of Tokyo, Stony Brook University, University of Victoria, Inst. Div, BNL

- Participants from PIENU, PEN/PiBeta, and MEG/MEGII as well as international experts in rare kaon decays, low-energy stopped muon experiments, the muon g – 2 experimental campaign, high energy collider physics, neutrino physics etc

- The collaboration is still developing and **welcomes new members**

PHYSICS CASES

- **Phased approach**
  - Phase I : Improved measurement of $R^{\pi} = \dfrac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$ by an order of magnitude
  - Phase II : Improved measurement of $B(\pi^+ \to \pi^0 e^+ \nu)$ by a factor 3
  - Phase III: Improved measurement of $B(\pi^+ \to \pi^0 e^+ \nu)$ by an order of magnitude
- Proposal submitted to Paul Scherrer Institute (PSI) in Jan 2022 ➙ **Phase I accepted with high priority**

PHYSICS CASES

- Rare pion decays studies are **sensitive probes for new physics**

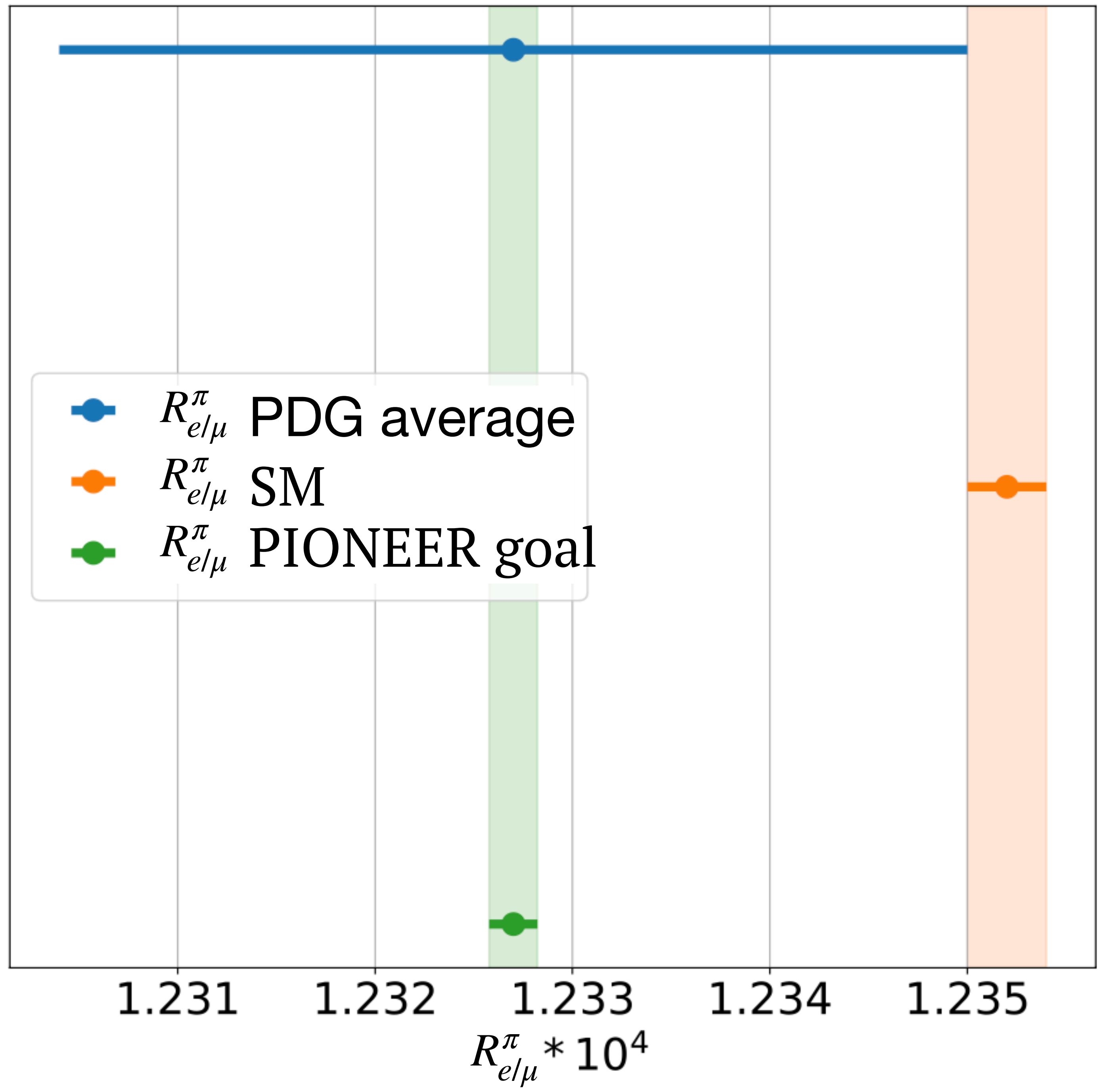
$$R^{\pi}_{SM} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)} = (1.23534 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%)$$

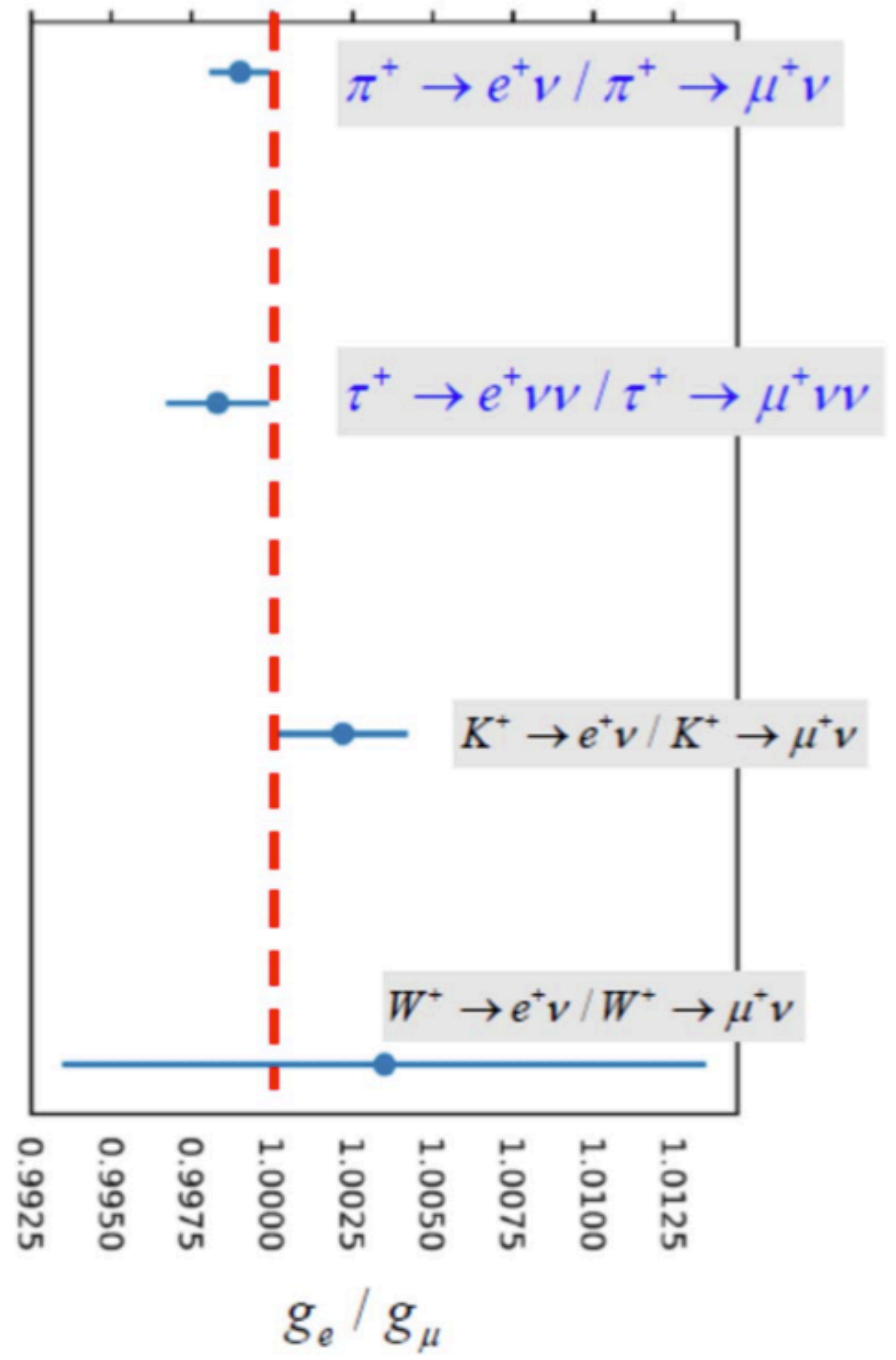
- Possibly the most accurately calculated decay process involving hadrons

- Experiments are **an order of magnitude less precise** than theory
  → window for new physics

- Addressing **existing tensions in flavour physics**
  - Muon g-2
    Deviation (4.2 σ) from theory - new physics?
  - B decays O(10%) deviations from universality.
    Both heavy quarks and leptons involved!
  - CKM unitarity tests from β and K decays (2 - 3 σ)
    Maybe related to LFUV?

- **Charged Lepton Flavor Universality** tested at $\mathcal{O}(10^{-3})$ level in π, τ, K decays
  (PDG value, mostly constrained by PIENU @ TRIUMF results :
  $$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$$)



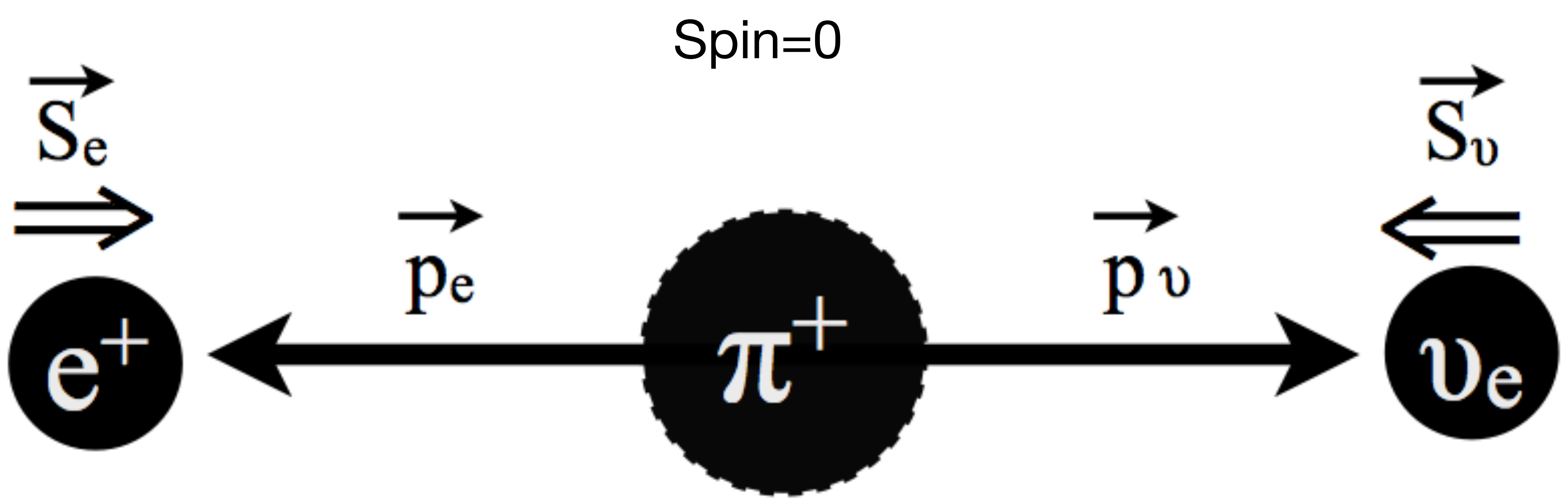


PHYSICS CASES

- **Sensitivity to new couplings at very high mass scales**

$$R^{\pi}_{SM} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)} = (1.23534 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%)$$

- Helicity- suppressed decay
- $\Rightarrow R^{\pi}$ is extremely sensitive to presence of new pseudoscalar or scalar couplings

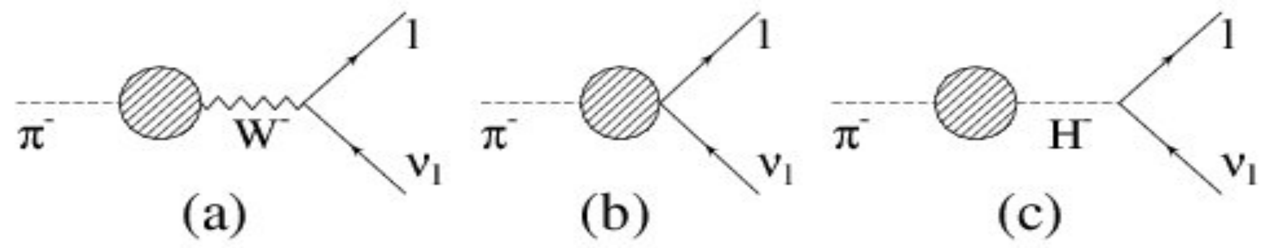


Weak Interaction

Neutrinos: left-handed helicity
= directions of spin and motion are opposite

Positron is forced into the wrong helicity

Pseudoscalar interactions



Charged Higgs (non-SM coupling)

$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m^2_\pi}{m_e(m_d + m_u)} \sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3$$

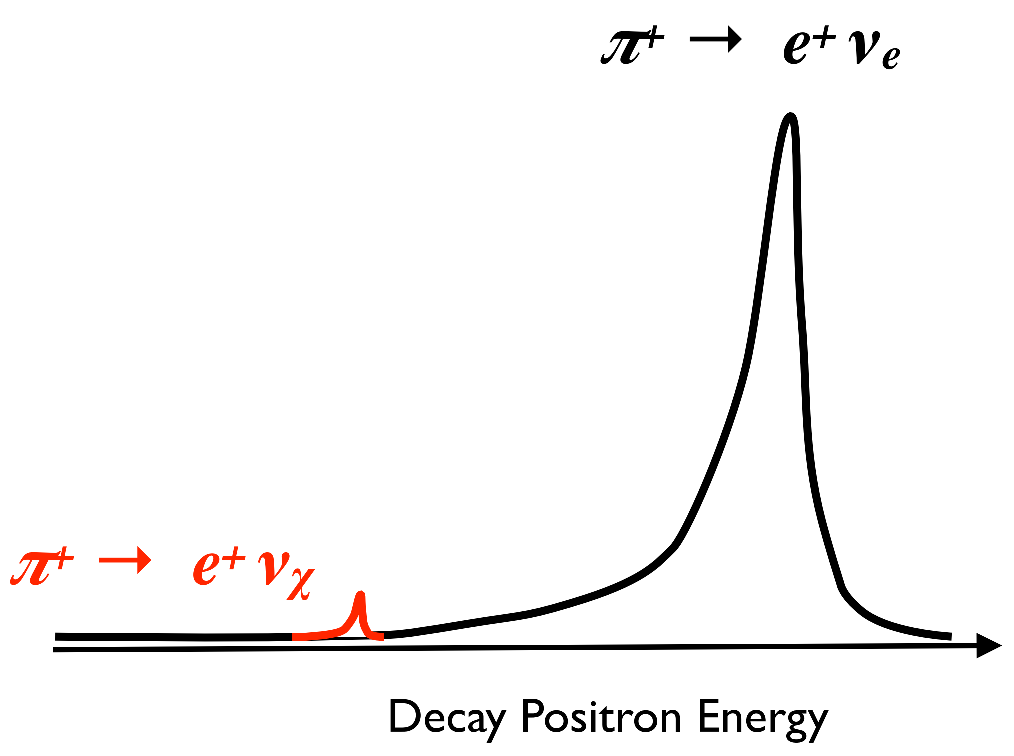
Marciano…

PIONEER PHASE I goal:

0.01 % measurement ➞ $\Lambda_{eP} \sim 3000$ TeV

PHYSICS CASES

- **Sensitivity to sterile heavy neutrinos**
- Peak search in the 2-body energy spectrum



R.E Shrock Phys.Rev.D 24, 1232 (1981), Phys. Lett. B 96, 159 (1980)

Heavy υ

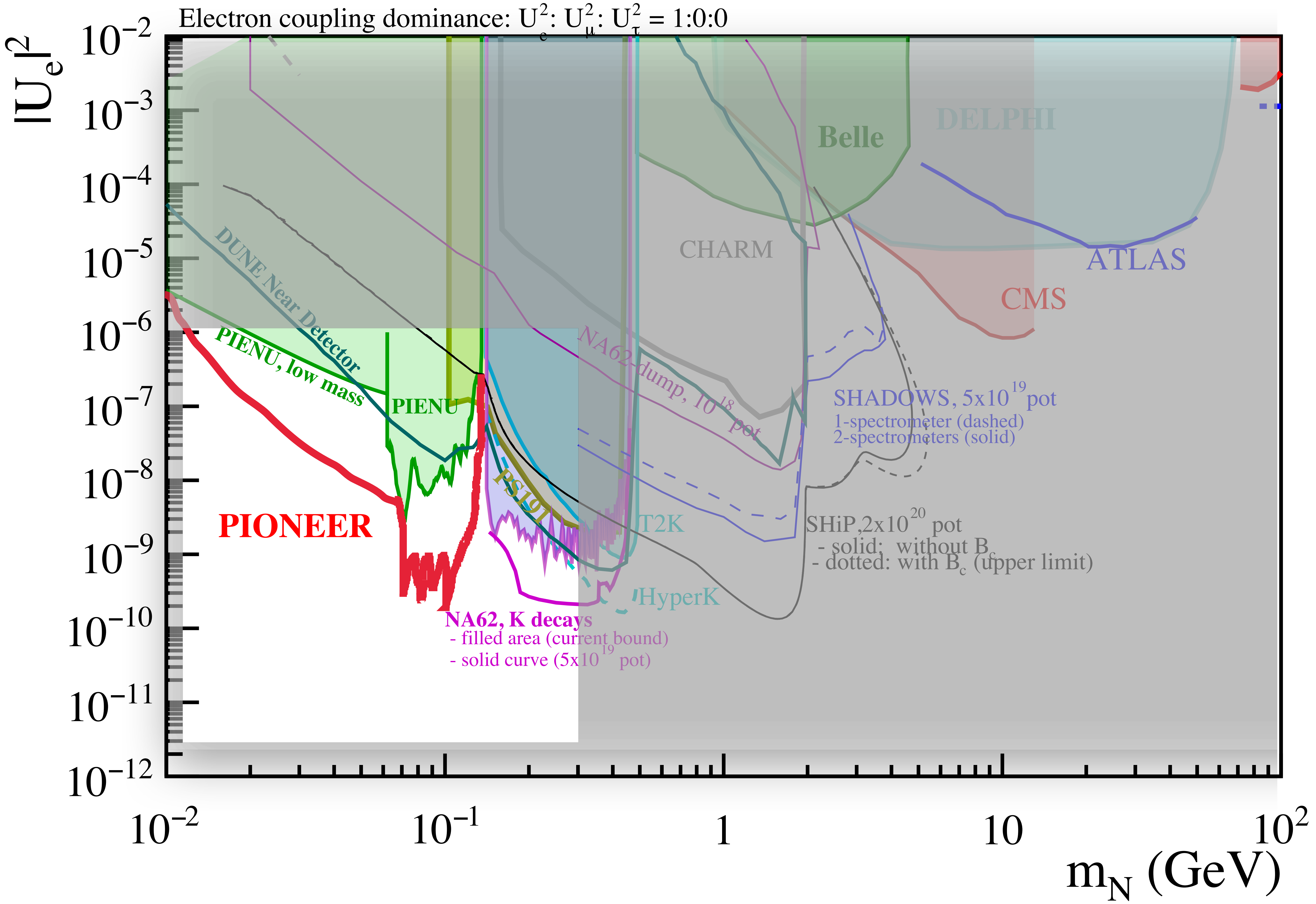
Kinematic factor

$$R_{ei} = \frac{\Gamma(\pi \to e\nu_i)}{\Gamma(\pi \to e\nu_l)} = |U_{ei}|^2 \rho_{ei}$$

Conventional υ

$$\nu_\ell = \Sigma_{i=1}^{3+k} U_{\ell i} \nu_i$$

$$\ell = e, \mu, \tau, \chi_1, \chi_2 ... \chi_k$$



Asli M. Abdullahi et al. “The Present and Future Status of Heavy Neutral Leptons”. *2022 Snowmass Summer Study*. Mar. 2022. arXiv: 2203.08039 [hep-ph]

PHYSICS CASES

- **testing CKM Unitarity**

- $\dfrac{B(K \to \pi l \nu)}{B(\pi^+ \to \pi^0 e^+ \nu)}$:Theoretically clean method to obtain $\dfrac{V_{us}}{V_{ud}}$

- **PIONEER Phase II goal:**

  Improve $B(\pi^+ \to \pi^0 e^+ \nu)$ precision by >3 $\dfrac{V_{us}}{V_{ud}} < \pm 0.2\,\%$

  Offers a new complementary constraint in the V_{us}/V_{ud} plane

- **PIONEER Phase III goal:**

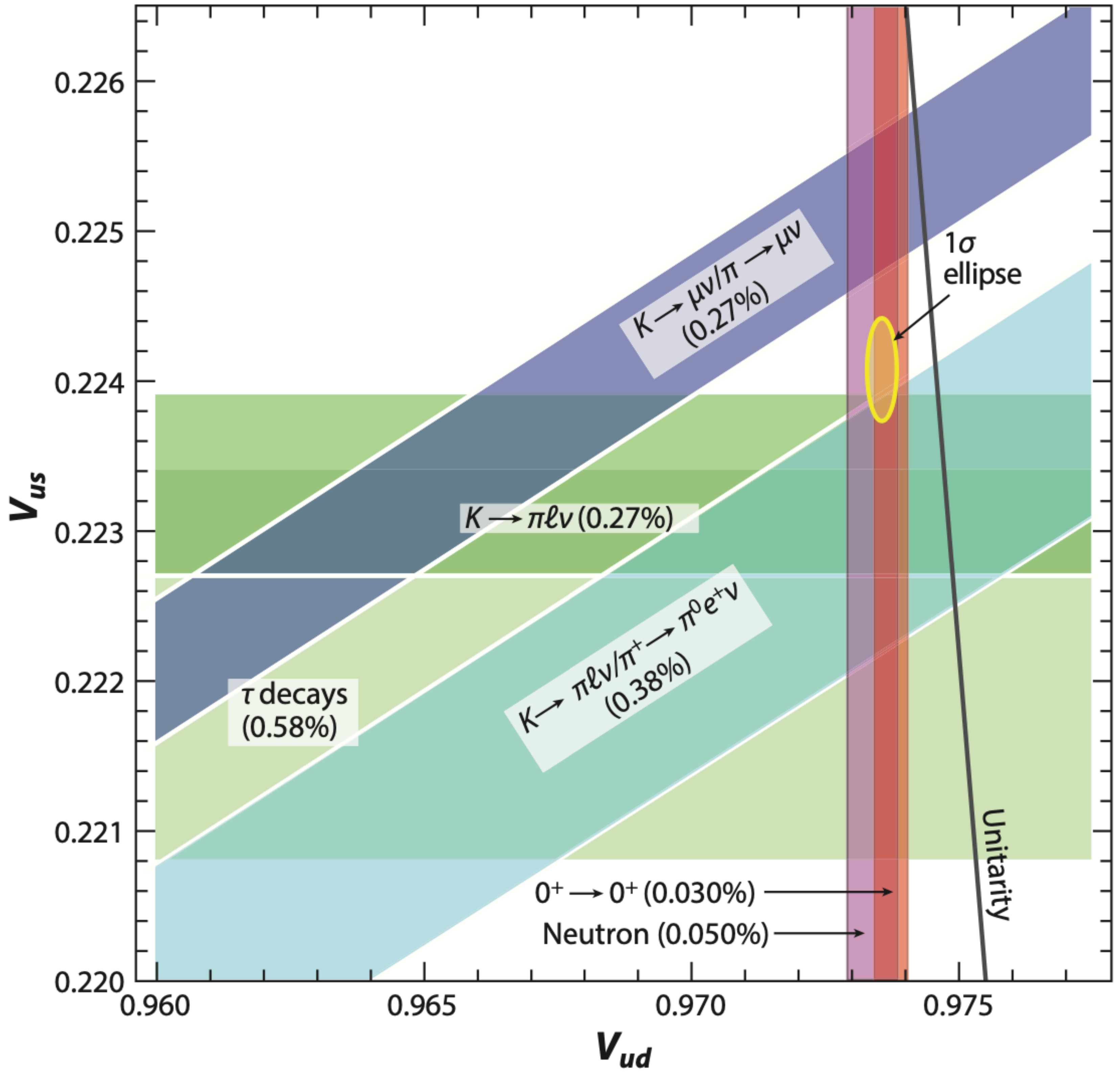
  Improve $B(\pi^+ \to \pi^0 e^+ \nu)$ precision by an order of magnitude

  $\pi^+ \to \pi^0 e^+ \nu$ is the theoretically cleanest method to obtain V_{ud}

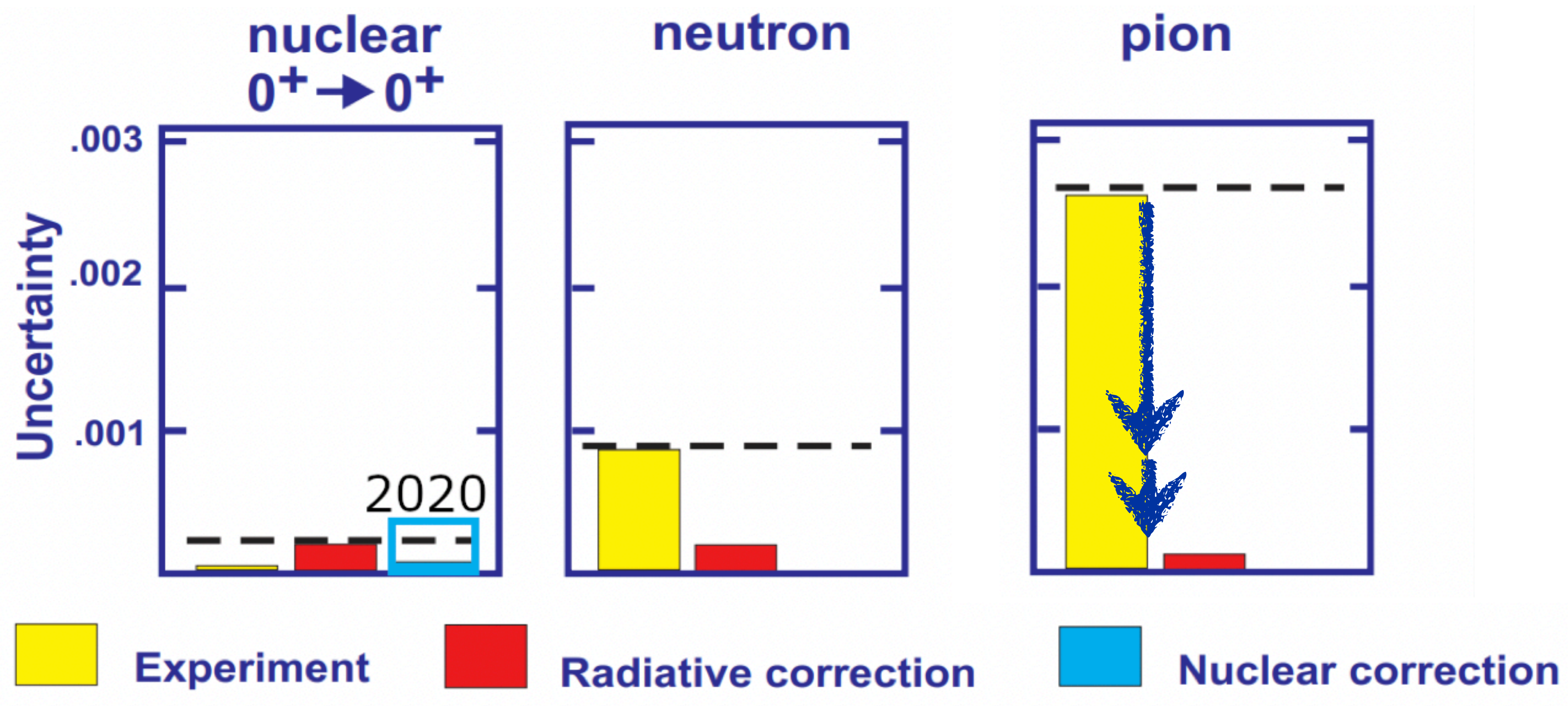
  PIBETA exp. ($\pm 0.6\%$)

  $B(\pi^+ \to \pi^0 e^+ \nu) = (1.038 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.002_{\pi e2}) \times 10^{-8}$

  Presently not competitive precision for but would be with an order of magnitude improvement (same precision as β decays)

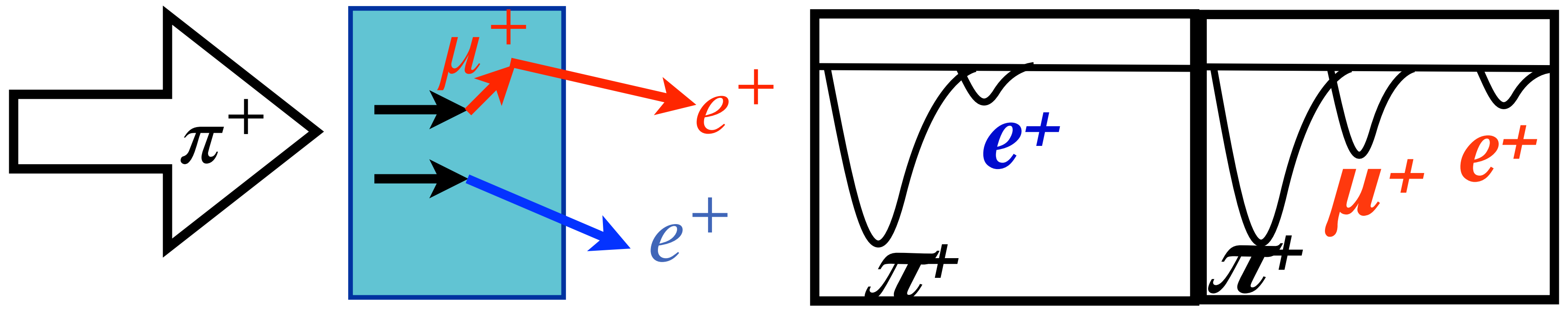


D. Bryman et al. Annu. Rev. Nucl. Part. Sci. 2022. 72:69–91



PHASE I MEASUREMENT CONCEPT

- **Measure precisely e^+ energy spectrum** and $t_{e^+} - t_{\pi^+}$ $\Longrightarrow$ different time and energy spectra - discrimination between the two decays



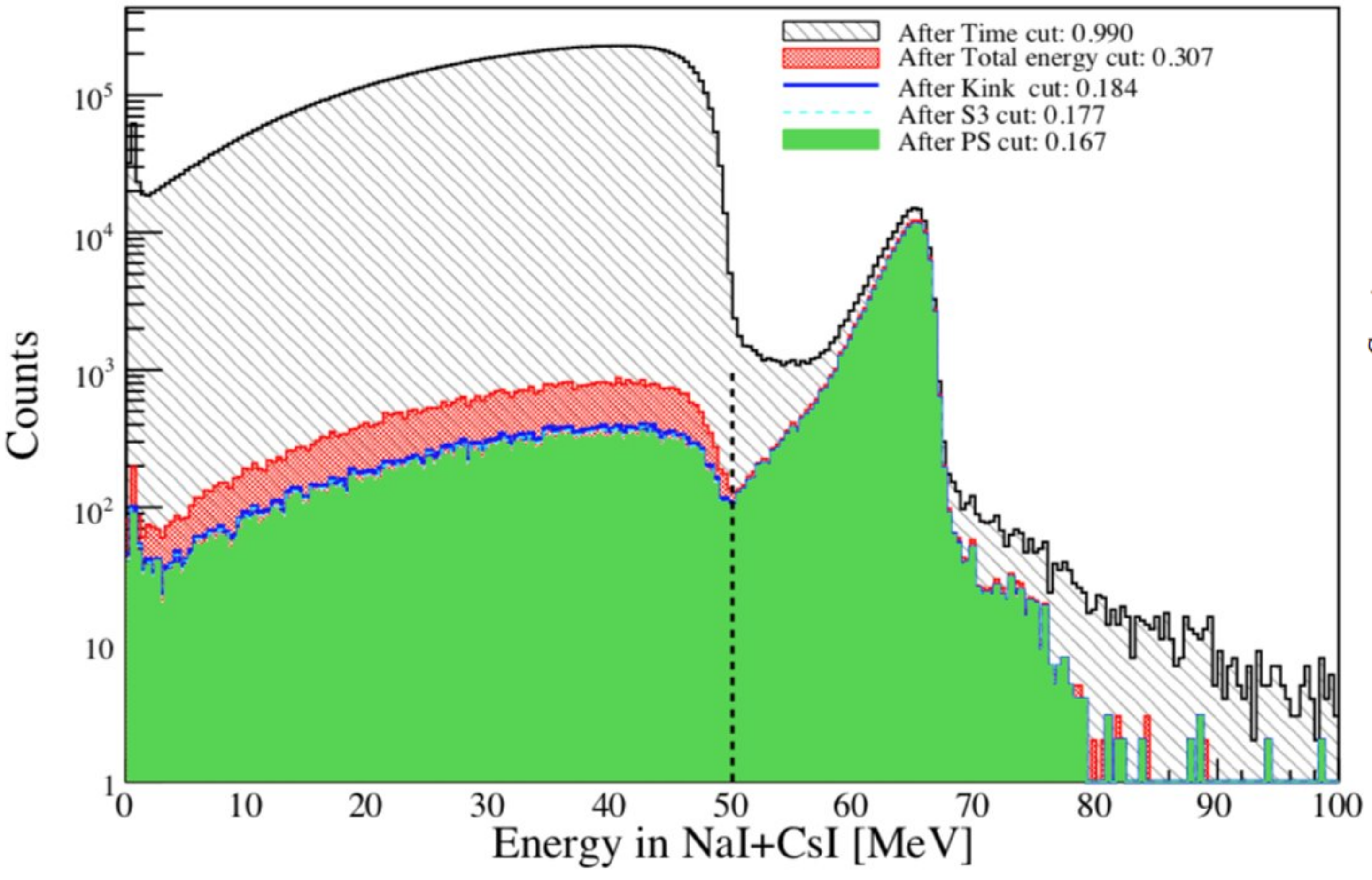
- Main systematic : **low energy tail** buried under Michel spectrum (energy resolution, photo nuclear interactions, shower leakage, geometrical acceptance, radiative decays etc)

What π decay to "normally": $B(\pi^+ \to \mu^+\nu(\gamma)) = 0.999877 \pm 0.0000004$

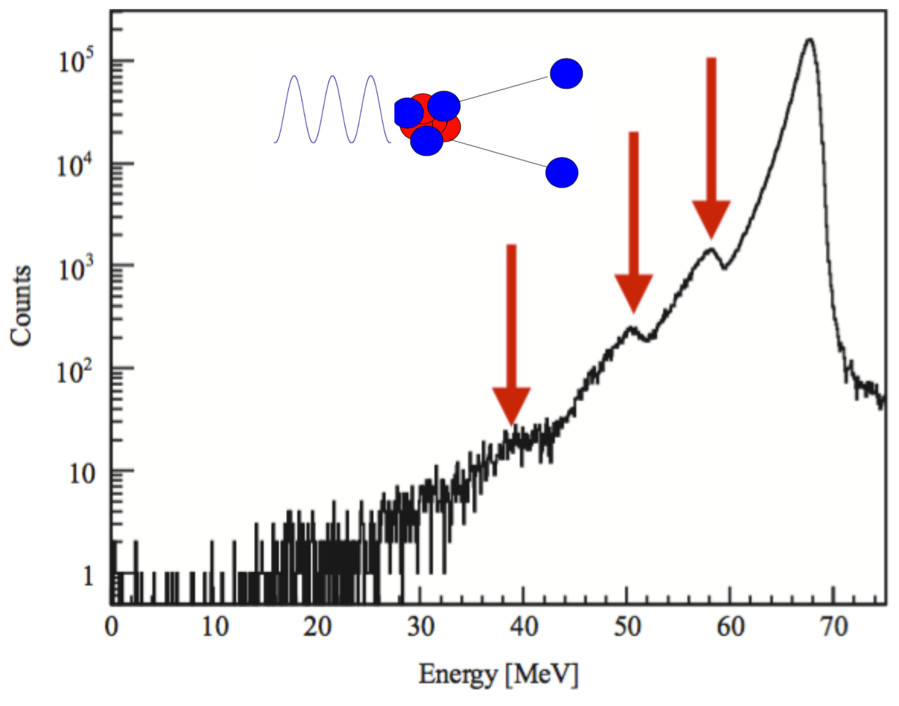
Helicity suppressed decay:

$B(\pi^+ \to e^+\nu_e(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}$

Pion β decay: $B(\pi^+ \to e^+\nu_e\pi^0) = (1.036 \pm 0.006) \times 10^{-8}$

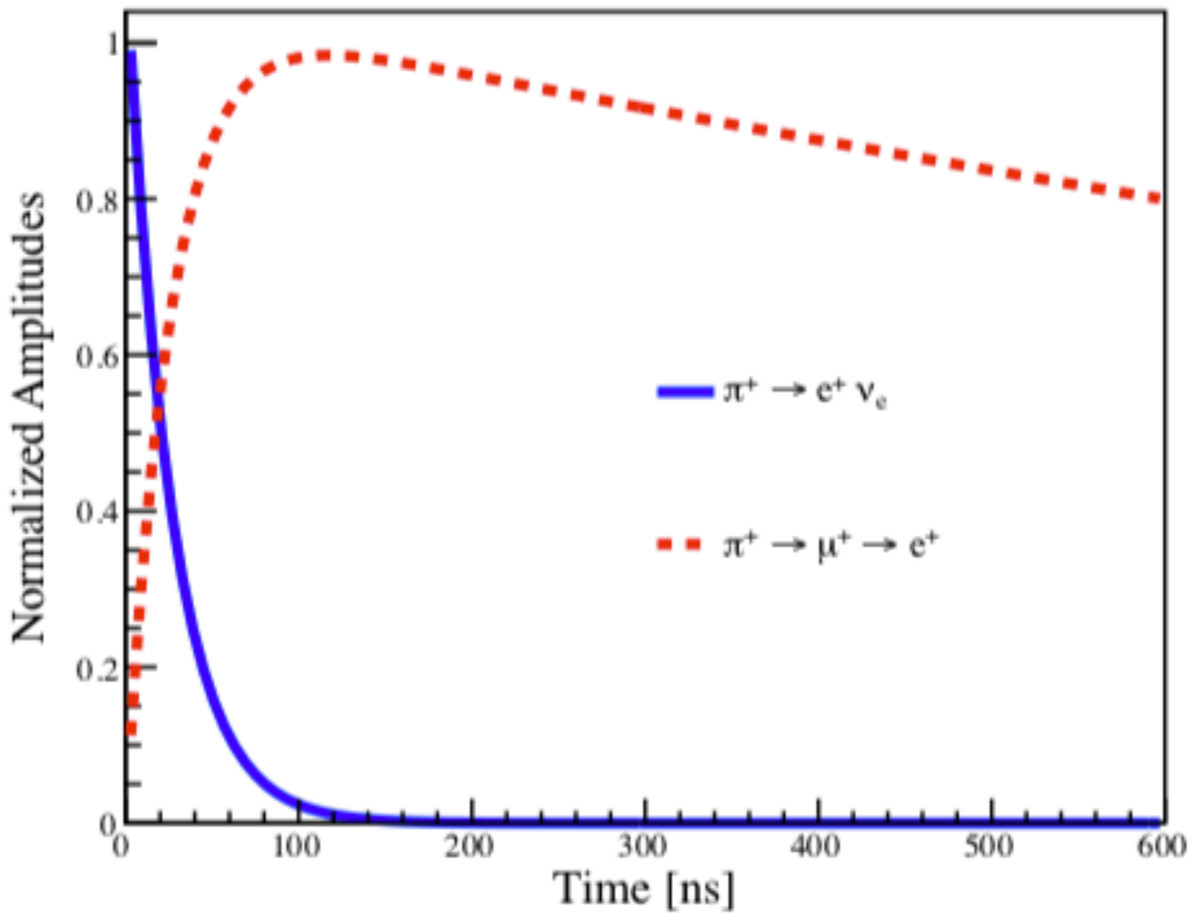


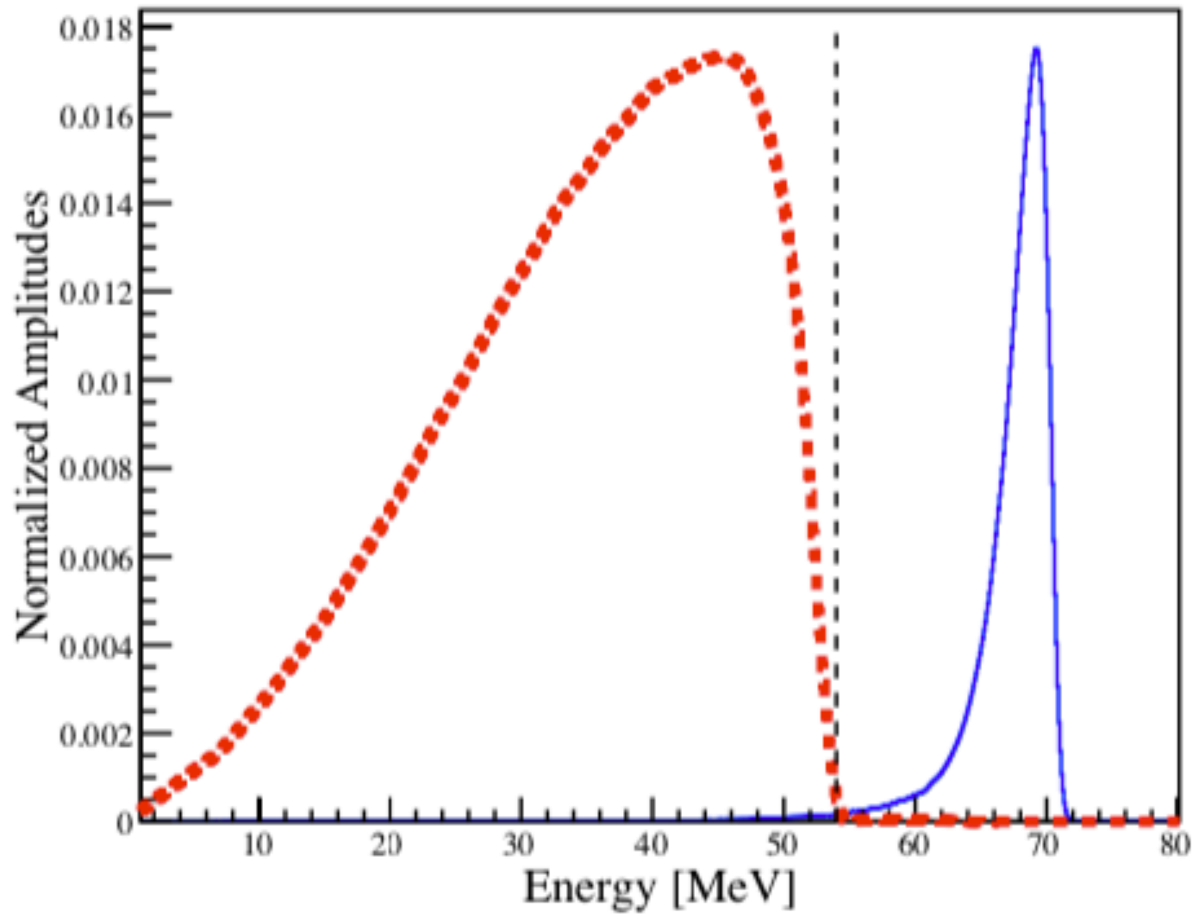
PIENU *suppressed* spectrum



A. Aguilar-Arevalo et al., Nuclear Instruments and Methods in Physics Research A 621 (2010) 188–191

PIENU lineshape measurement with e+ beam





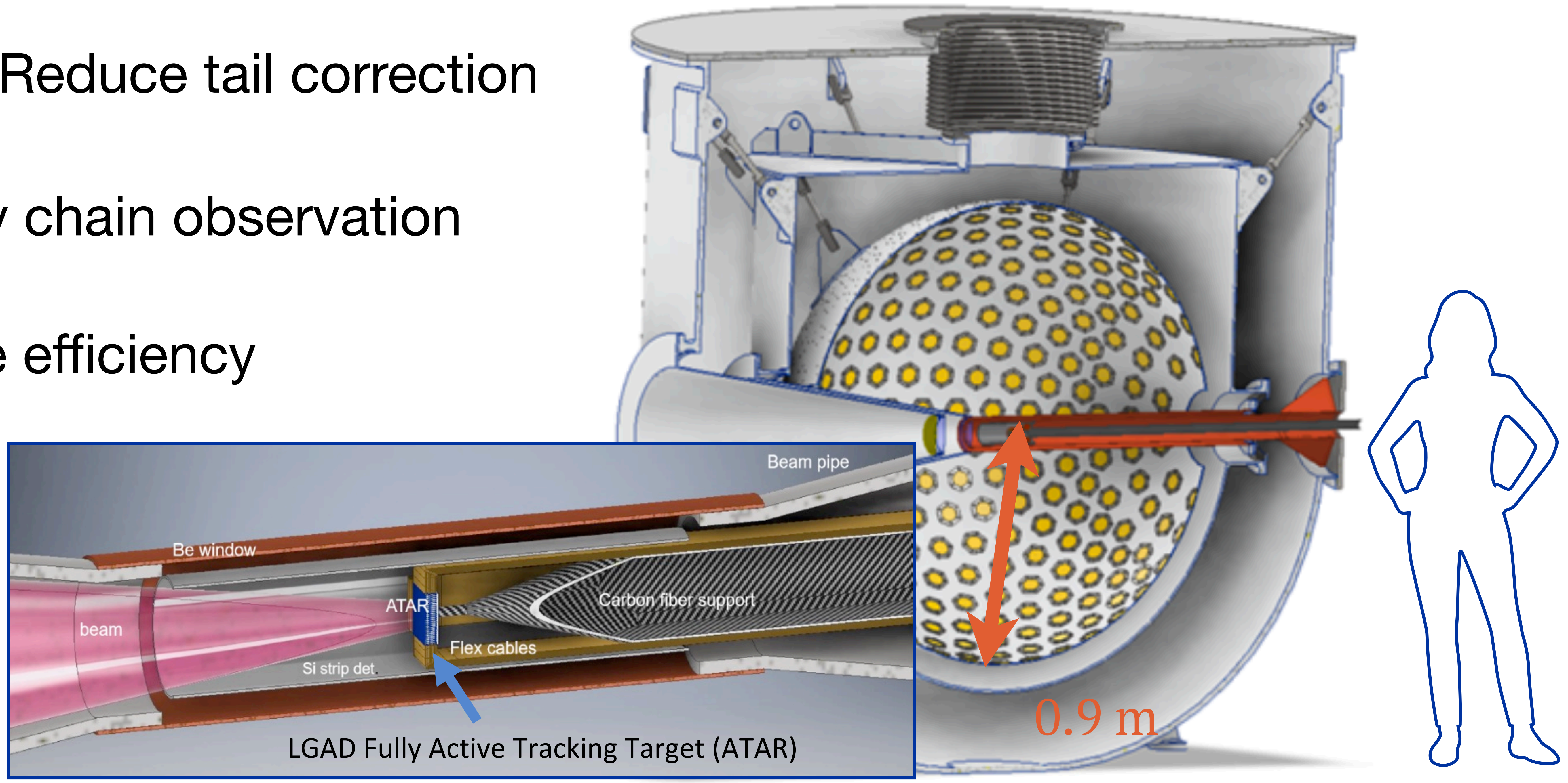
PIONEER DETECTOR CONCEPT

- Building on previous experiences (PIENU and PEN/PIBETA) : use of emerging technologies (LXe, LGADs)

  - 25 X_0, 3π sr calorimeter ➝ Reduce tail corrections (x5) ➝ Improve uniformity (x5)
    Fast scintillator response (LXe) ➝ Reduce pile-up uncertainties (x5)

  - active target based on LGADs technology ➝ Reduce tail correction uncertainty (x10)
    Fast pulse shape ➝ allow $\pi \to \mu \to e$ decay chain observation

  - Fast electronics and pipeline DAQ ➝ Improve efficiency

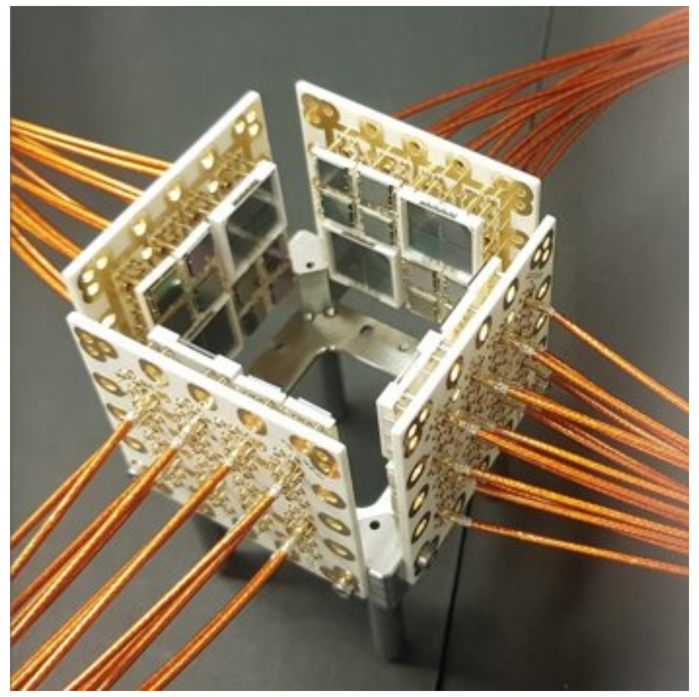


- Take into account PHASE II/III detector requirements for design

WHERE DO WE STAND?

- NSERC funding 2023-2025 : Canadian team involved in all aspects of the experiment but strong focus on the LXe Calorimeter

- **R&D and Prototyping phase** : inform PIONEER on the technology choice

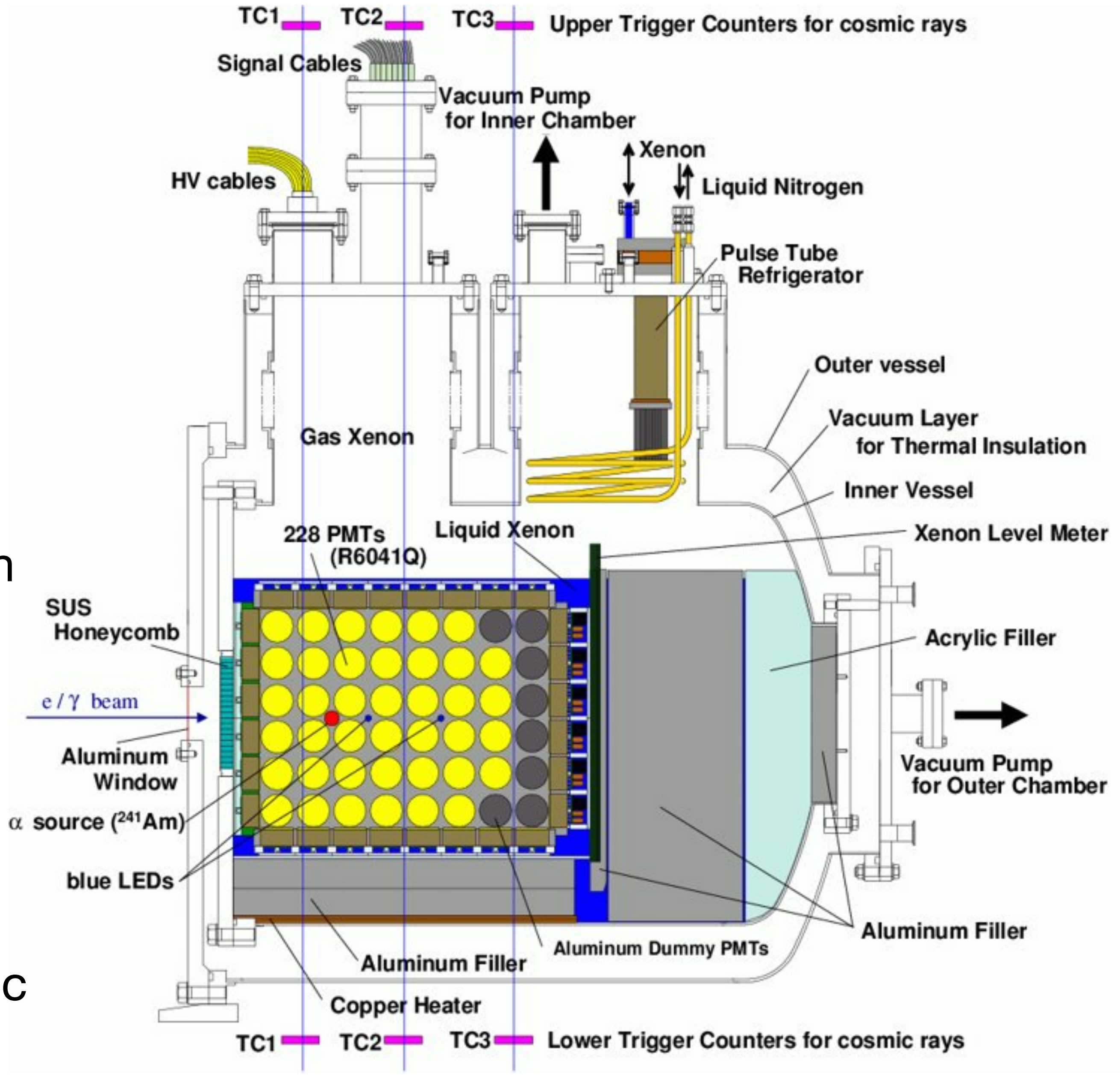


2L LXe cryostat at McGill University

- characterization/choice of photosensors
- effect of purity on light emission
- benchmark simulations on a simple system
- study optical properties of material in LXe

~100 L LXe former MEG large prototype

- Axial length ~ 25 X_0 = baseline radius for the PIONEER LXe “ball” effect of purity on light emission
- Measure energy resolution / benchmark simulations at high energy (~70 MeV)
- Measure contribution of photonuclear reactions
- R&D: Test of photosensors, optical segmentation etc



- LXe favoured contender (synergies with other Noble Liquid activities in Canada)

- several question marks and open questions requiring large simulation effort, R&D and prototyping

- Canadian group aims at leading calorimeter design & construction

SCHEDULE

- PHASE I
  Approved by PSI
  Low momentum pion beam at 55 MeV/c (±2% Δp/p) @ 300 kHz
  $2 \times 10^8 \;\; \pi^+ \rightarrow e^+\nu_e$ required to achieve 0.01% precision of $R_{e/\mu}$
  Expected in 3 year of running (5 months / year)

- PHASE II & PHASE III : 3 years each of data taking with pion flux > 10 MHz
  $7 \times 10^5 \;\; (7 \times 10^6) \;\; \pi^+ \rightarrow \pi^0 e^+ \nu_e$ events needed

- CFI funding request foreseen
- DOE process initiated
- Total budget ~$40 M

SUMMARY

- major new experiment addressing emerging SM anomalies in flavor physics
- time-scale: >15 years
- unique new information on Lepton Flavor Universality and CKM unitary with unprecedented precision
- 2-body spectra very sensitive to a wide range of exotics
- supported by a large, experienced international collaboration. Canadian group aims at leading calorimeter design & construction
- Canadian group playing major role in particular on developments toward a LXe calorimeter
- strong detector synergy with other experimental efforts (including nEXO)