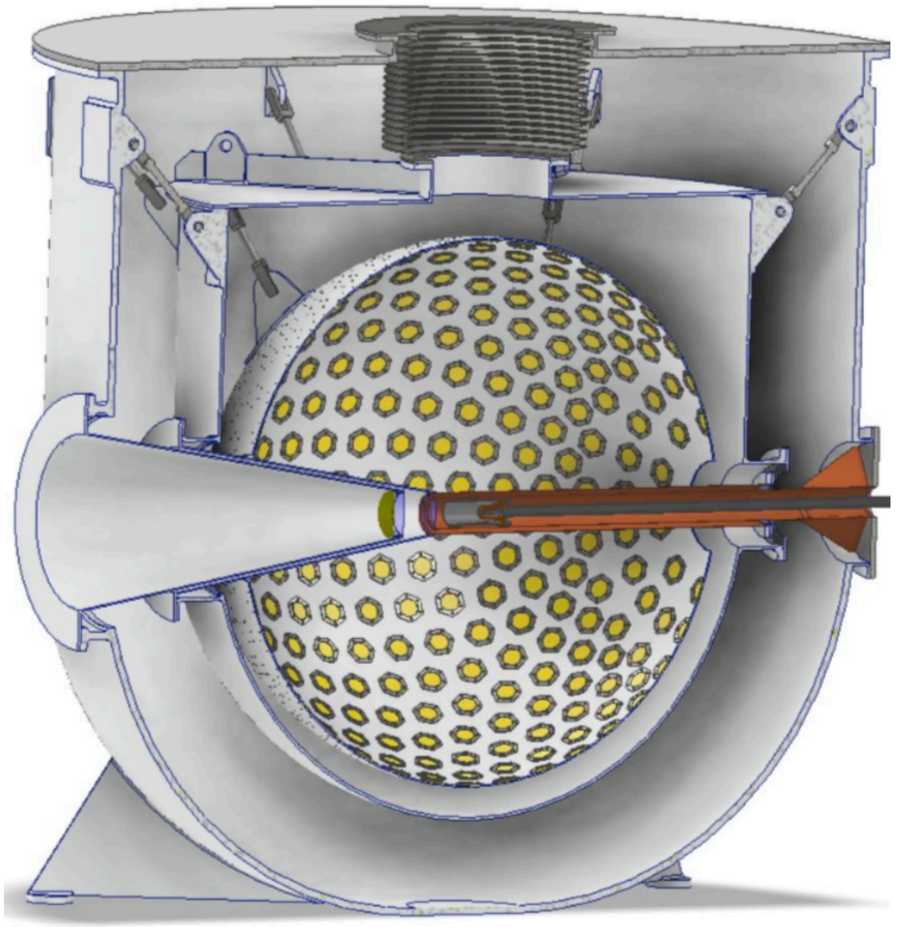
A next generation pion decay experiment

PIONEER



Chloé Malbrunot
on behalf of the PIONEER group at TRIUMF
Particle physics department

5YP Planning within Particle Physics for 2025-2030
29/03/2022

PIONEER COLLABORATION

- International collaboration across Asia, Europe & North America

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spokespersons

- 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

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PHYSICS CASE

- 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?

PIENU @ TRIUMF

PDG 2018

±0.19 %

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.2327±0.0023 OUR AVERAGE						
1.2344±0.0023±0.0019	400k	AGUILAR-AR...	15	CNTR	+	Stopping π^+
1.2346±0.0035±0.0036	120k	CZAPEK	93	CALO		Stopping π^+
1.2265±0.0034±0.0044	190k	BRITTON	92	CNTR		Stopping π^+
1.218 ±0.014	32k	BRYMAN	86	CNTR		Stopping π^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.273 ±0.028	11k	[1] DICAPUA	64	CNTR		
1.21 ±0.07		ANDERSON	60	SPEC		

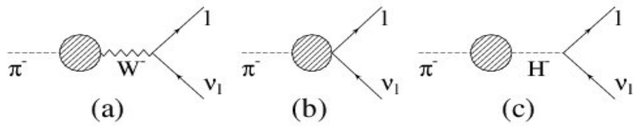
[1] DICAPUA 64 has been updated using the current mean life.

- However charged Lepton Flavor Universality tested at $\mathcal{O}(10^{-3})$ level in π, τ, K decays (PDG value, mostly constrained by PIENU results : $\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$)
- Further improved measurements of leptons flavour universality might provide additional clues on these tensions

PHYSICS CASE (Cont.)

- Pion branching ratio is sensitive to new physics at high mass scales: “power” of high precision low energy exp.

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

- Sensitive to many other new physics scenarios
  - Leptoquarks
  - Induced scalar currents
  - Excited gauge bosons
  - Compositeness
  - SU(2)xSU(2)xSU(2)xU(1)
  - Hidden sector ....

PHYSICAL REVIEW D **97,** 072012 (2018)

Editors' Suggestion

Improved search for heavy neutrinos in the decay $\pi \to e\nu$

PHYSICAL REVIEW D **102,** 012001 (2020)

PHYSICAL REVIEW D **101,** 052014 (2020)

Search for the rare decays $\pi^+ \to \mu^+\nu_\mu\nu\bar{\nu}$ and $\pi^+ \to e^+\nu_e\nu\bar{\nu}$

Improved search for two body muon decay $\mu^+ \to e^+X_H$

PHYSICAL REVIEW D **103,** 052006 (2021)

Search for three body pion decays $\pi^+ \to l^+\nu X$

Search for heavy neutrinos in $\pi \to \mu\nu$ decay

- Many exotic searches performed by the PIENU collaboration : e.g. sterile neutrinos which have implications for leptogenesis

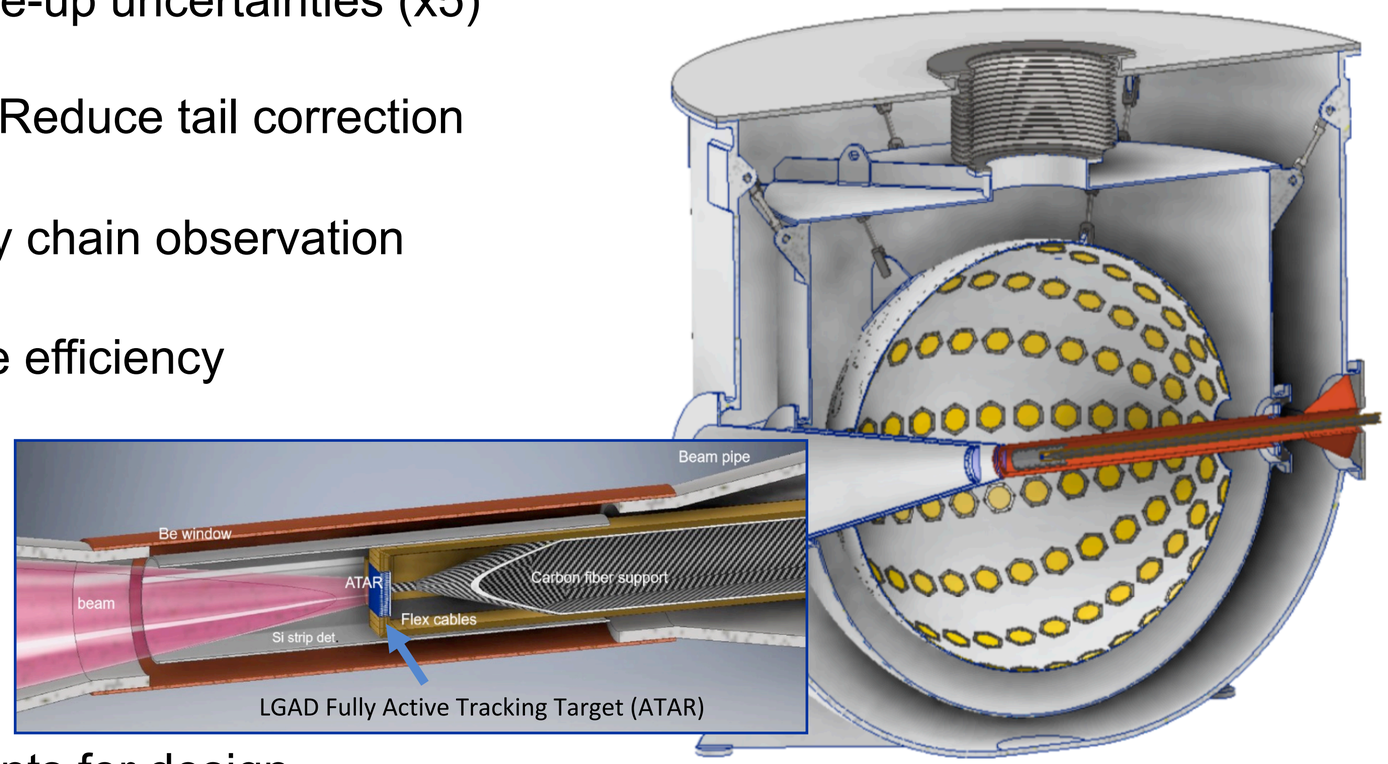
PIONEER DETECTOR CONCEPT

- 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 $\pi \rightarrow \mu \rightarrow e$ decay chain observation

  - Fast electronics and pipeline DAQ ➙ Improve efficiency



- Take into account PHASE 2 detector requirements for design

  ➙ PHASE 2 of PIONEER: improved pion β decay exp. ($R^{\pi\beta} = \dfrac{\Gamma(\pi^+ \rightarrow \pi^0 e^+ \nu)}{\Gamma(\pi^+ \rightarrow \text{all})} : \mathcal{O}(\pm 0.2\,\% \rightarrow \pm\, 0.05\%)$)

HISTORY

- PIENU stopped data taking 10 years ago at TRIUMF
- PIONEER (PIENUX) LOI : Proposal to TRIUMF-EEC in March 2021 ➙ endorsed with high priority. Reviewed by PPAC in June 2021. Gate0 not granted: new beamline construction required for PIONEER not in line with TRIUMF long-term beamline refurbishment plans
- October 2021: submission of NSERC 1 year DG funding proposal to support initial PIONEER R&D on calorimeter (simulations & SiPM tests) : outcome should be known soon
- Full experimental proposal to PSI in January 2022 (https://arxiv.org/pdf/2203.01981.pdf) ➙ accepted with high priority
- SNOMASS White paper: https://arxiv.org/abs/2203.05505
- First beamtime scheduled in May 2022 at PSI (beam characterization)

5-YEARS PERSPECTIVE

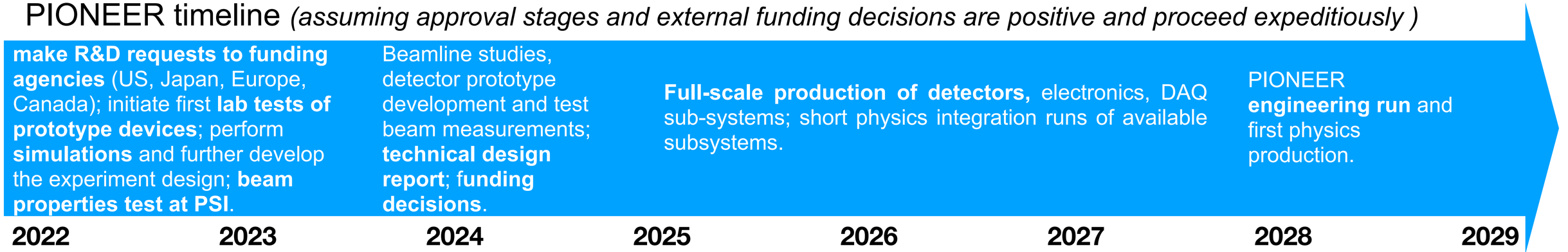
- Canadian group strongly involved in PIONEER - continuity and complementarity with current and past TRIUMF Rare Decay group activities

    - D. Bryman PIONEER co-spokerson, C. Malbrunot on publication & talk committee (PIONEER organizational chart & boards etc in development)
      on-going and planned simulation efforts (ML, GPUs) by TRIUMF postdocs and staff

- Prospect: With experiment taking place at PSI, the Canadian group should provide leadership on detectors
  Proposal : Canadian group takes on the “calorimeter” thread (with participation of Japanese colleagues from MEG?)
  LXe favoured contender (synergies with other activities at TRIUMF, see slide 9) but several question marks and open questions requiring large simulation effort, R&D and prototyping

- PIONEER cost estimate (~26 M$. Largest share taken by the calorimeter - 20M$)

PIONEER timeline *(assuming approval stages and external funding decisions are positive and proceed expeditiously)*



INFRASTRUCTURE & WORKFORCE NEEDS AT TRIUMF

- Taking on the calorimeter thread:
  - Build a strong Canadian group (so far TRIUMF-centred) with international collaborators from PIONEER in view of next round of CFI grant request
  - 2022: apply for 3-years NSERC Project grant to develop R&D and simulations: request for several postdocs and grad-students [embedded in the rare decay group at TRIUMF to have access to physics data while PIONEER in the R&D phase]
  - Require technical support from TRIUMF in cryogenics, machine shop etc
  - Development of (or use of MEG's) small LXe prototype to be hosted in existing lab space (MOB #149?)
  - Further identify and use synergies with existing TRIUMF efforts
- Use of TRIUMF accelerator facility : detector tests and commissioning, measurements of pion lifetime

SYNERGIES

- Sciences goals fit into current activities of the rare decay group at TRIUMF (NA62, PIENU)
- Large technological overlap with nEXO developments - LXe technology, VUV photon readout
  Envision use of common existing facilities (e.g, LoLX, Vera), development of new ones…
- Synergies with Silicon detector developments for NA62, ATLAS etc (LGADs, SiPM, strips)
- Geant4 simulations:
  - optical tracking (GPU-based): synergies with DarkLight, nEXO efforts
  - Analysis (of sim data) based on Machine learning algorithms: synergies with other efforts at TRIUMF
- International collaboration - strong network - including with “nearby ” CENPA (cf DND workshop series: Developing New Directions in Fundamental Physics)

SUMMARY

- major new experiment addressing emerging SM anomalies in flavor physics: augmenting the TRIUMF science program
- time-scale: 10-15 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. The group includes new TRIUMF BAEs, experts from previous PIENU and PEN experiments as well as a wide range of international collaborators from NA62, MEG, muon g-2, ATLAS, PSI scientists and leading theorists
- Canadian group aims at leading calorimeter design & construction
- strong detector synergy with other TRIUMF experimental efforts (including nEXO)

Thank you
Merci