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PIONEER: a next generation rare pion decay experiment

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PIONEER is a rapidly developing effort aimed to perform a pristine test of lepton flavour universality (LFU) and of the unitarity of the first row of the CKM matrix by significantly improving the measurements of rare decays of the charged pion. The experiment is approved at the Paul Scherrer Institute (PSI). In Phase I, PIONEER aims to measure the charged-pion branching ratio to electrons vs. muons $R_{e/\mu}$ to 1 part in 10^4, improving the current experimental result $R_{e/\mu}$ (exp) $= 1.2327(23) \times 10^{-4}$ by a factor of 15. This precision on $R_{e/\mu}$ will match the theoretical accuracy of the SM prediction allowing for a test of LFU at an unprecedented level, probing non-SM explanations of LFU violation through sensitivity to quantum effects of new particles up to the PeV mass scale.

Phase II and III will aim to improve the experimental precision of the branching ratio of pion beta decay, $\pi^+ \to \pi^0 e^+ \nu(\gamma)$, currently at $1.036(6) \times 10^{-8}$, by a factor
of three and six, respectively. The improved measurements will be used to extract V_{ud} in a theoretically pristine manner. The ultimate precision of V_{ud} is expected to reach the 0.05\,\% level, allowing for a stringent test of CKM unitarity.

The PIONEER experiment will also improve the experimental limits
by an order of magnitude or more on a host of exotic decays that probe the effects of heavy neutrinos and dark sector physics.

The conceptual design of PIONEER includes a 3π-sr 19 radiation length calorimeter, a segmented low-gain avalanche diode (LGAD) stopping target, a positron tracker, and ultra-fast electronics. Compared to the previous generation of rare pion decay experiments, the 5-D (position, time, and energy) tracking capability of the LGAD-based active target allows for excellent separation of $\pi \to e\nu$ signal from vast amount of $\pi \to \mu \to e$ background ($\pi \to \mu\nu$ followed by $\mu \to e\nu\overline{\nu}$).

The PIONEER collaboration consists of participants from both the nuclear and particle physics communities including PIENU, PEN/PiBeta, and MEG/MEGII collaborations, as well as experts in rare kaon decays,
low-energy stopped muon experiments, the Muon $g-2$ experimental campaign, high energy collider physics, neutrino physics, and other areas. The collaboration is engaged in R\&D in several critical areas including i) beam studies, ii) LGAD-based active target (sensor and readout electronics), iii) calorimetry (Noble gas and crystals), iv) DAQ, and v) trigger. A detailed simulation framework is used to estimate sensitivity and systematics. The collaboration is still developing and welcomes new members.

This input to the 2026 update of the European Strategy for Particle Physics Strategy describes the physics motivation and the conceptual design of the PIONEER experiment, and is prepared based on the PIONEER proposal submitted to and approved with high priority by the PSI program advisory committee (PAC). Using intense pion beams, and state-of-the-art instrumentation and computational resources, the PIONEER experiment is aiming to begin data taking by the end of this decade

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