Prospects for PIONEER

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On behalf of the PIONEER collaboration 2203.01981

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Santiago de Compostela

PIONEER @ PSI

A next-generation rare PION dEcay ExpeRiment

- Physics goals
  - (Phase I) **Lepton flavor universality** at 10^{-4} in

$$R_{e/\mu} = \frac{\Gamma[\pi^+ \to e^+ \nu_e(\gamma)]}{\Gamma[\pi^+ \to \mu^+ \nu_\mu(\gamma)]}$$

  - (Phase II+III) **CKM unitarity** V_{ud} at 3×10^{-4}
  - Searches for **exotics** (heavy neutrinos, ...)
- Status
  - Approved to run at PSI 2203.01981
  - R&D ongoing, Phase I to start in 2029

Lepton flavor universality: precision goal

- **Standard model** prediction Cirigliano, Rosell 2007

$$R_{e/\mu}^{\rm SM} = 1.23524(15) \times 10^{-4}$$

$\hookrightarrow$ precision of 1.2×10^{-4} for hadronic observable!

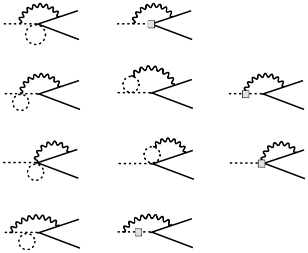
- **Experiment** dominated by PIENU 2015

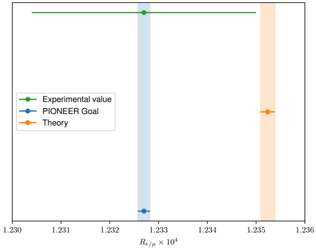
$$R_{e/\mu}^{\rm exp} = 1.2327(23) \times 10^{-4}$$

$\hookrightarrow$ order of magnitude away from theory!

- Expect $\simeq$ factor 3 from PEN PSI and PIENU TRIUMF

$\hookrightarrow$ experience informs PIONEER design





Lepton flavor universality: physics context

- $R_{e/\mu}$ **extremely sensitive probe of (pseudo-)scalar currents** due to chiral enhancement $\propto \frac{M_\pi^2}{m_e(m_u+m_d)}$

  $\hookrightarrow$ $R_{e/\mu}$ at 10^{-4} tests scales up to several 1000 TeV

- Best constraints on **modified W couplings**

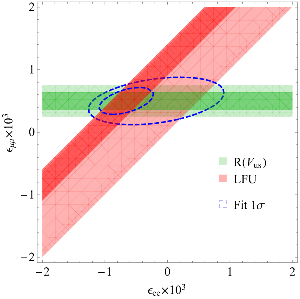
  $\mathcal{L} = -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L \nu_j W_\mu (\delta_{ij} + \varepsilon_{ij})$

$$\frac{R_{e/\mu}^{\text{SM}}}{R_{e/\mu}^{\text{exp}}} = 1 + \varepsilon_{\mu\mu} - \varepsilon_{ee} = 1.0010(9)$$

- Possible connection to other hints for LFUV

  $\hookrightarrow$ $R(D^{(*)})$, a_ℓ, $q\bar{q} \to \ell^+\ell^-$, **CKM unitarity**

- LFUV and CKM unitarity



Crivellin, MH, 2020

$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^{\beta}} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1-(V_{ud}^{\beta})^2 - |V_{ub}|^2}} = 1 - \left(\frac{V_{ud}}{V_{us}}\right)^2 \varepsilon_{\mu\mu} + \mathcal{O}(\varepsilon^2)$$

$\hookrightarrow$ LFUV effect enhanced by $(V_{ud}/V_{us})^2 \sim 20!$

CKM unitarity: physics context

- **Kaon decays**
  - V_{us} from $K_{\ell 3}$ decays talks by Gorchtein, Passeri
  - V_{ud}/V_{us} from $\pi_{\ell 2}/K_{\ell 2}$, new measurement of $K_{\mu 3}/K_{\mu 2}$ to resolve/corroborate kaon tension talk by Moulson
- **β decays**
  - Superallowed β decays talk by Gorchtein

$$V_{ud}^{0^+\to 0^+} = 0.97367(11)_{\text{exp}}(13)_{\Delta_V^R}(27)_{\text{NS}}[32]_{\text{total}}$$

  $\hookrightarrow$ nominally best precision, but nuclear uncertainties?

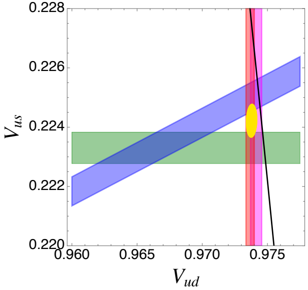
  - Neutron decay talks by Dekens, Märkisch, Schmidt

$$V_{ud}^{\text{n, PDG}} = 0.97441(3)_f(13)_{\Delta_R}(82)_\lambda(28)_{\tau_n}[88]_{\text{total}}$$
$$V_{ud}^{\text{n, best}} = 0.97413(3)_f(13)_{\Delta_R}(35)_\lambda(20)_{\tau_n}[43]_{\text{total}}$$

  $\hookrightarrow$ need precise experiments for λ and τ_n

  - **Pion β decay** PIONEER Phase II+III

  $\hookrightarrow$ theoretically cleanest channel



Crivellin, Cirigliano, MH, Moulson 2023

CKM unitarity: pion β decay

- Master formula Cirigliano, Knecht, Neufeld, Pichl 2003, Czarnecki, Marciano, Sirlin 2020, Feng et al. 2020

$$\Gamma(\pi^+ \to \pi^0 e^+ \nu_e(\gamma)) = \frac{G_F^2 |V_{ud}|^2 M_{\pi^\pm}^5 |f_+^\pi(0)|^2}{64\pi^3}(1 + \Delta_{RC}^{\pi\ell}) I_{\pi\ell}$$

- (Theory) inputs
  - Phase space $I_{\pi\ell} = 7.3766(43) \times 10^{-8}$, uncertainty from $\Delta_\pi = M_{\pi^+} - M_{\pi^0}$
  - Form factor $f_+^\pi(0) = 1 - 7 \times 10^{-6}$

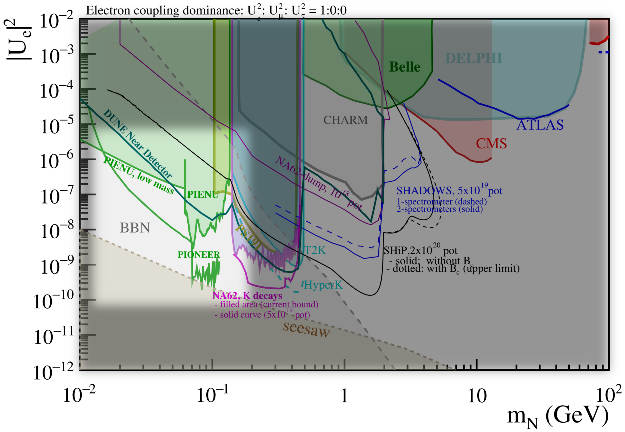
    $\hookrightarrow$ protected by $SU(2)$ Ademollo–Gatto theorem (Behrends–Sirlin)
  - Radiative corrections $\Delta_{RC}^{\pi\ell} = 0.0334(10)$ ChPT, $\Delta_{RC}^{\pi\ell} = 0.0332(3)$ lattice QCD
- Resulting V_{ud} extracted from PIBETA 2004

$$V_{ud}^\pi = 0.97386(281)_{BR}(9)_{\tau_\pi}(14)_{\Delta_{RC}^{\pi\ell}}(28)_{I_{\pi\ell}}[283]_{total}$$

$\hookrightarrow$ factor 10 possible before other errors creep in (same as for $R_{e/\mu}$)

- Feasibility of new measurement of τ_π under study at TRIUMF (improve Δ_π?)
- PIONEER Phase II competitive measurement of V_{ud}/V_{us} from $\pi_{\ell 3}/K_{\ell 3}$
- PIONEER Phase III theoretically pristine value of V_{ud} at 3×10^{-4}

Searches for exotics



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- Search for **heavy neutrinos** and other dark sector physics

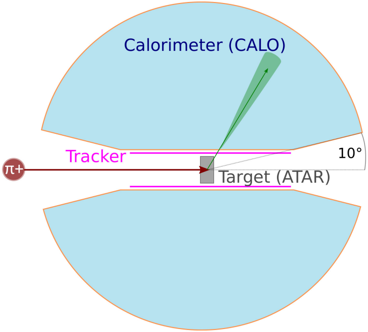
  $\hookrightarrow$ e.g., peak searches in the positron energy spectrum $\pi^+ \to e^+\nu_h$

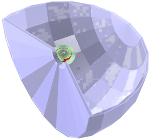
- PIENU also searched for $\pi^+ \to \mu^+\nu_h$, $\mu^+ \to e^+X$, $\pi^+ \to \ell^+\nu X$, ...

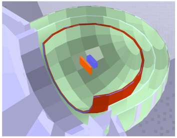
  $\hookrightarrow$ expect improvement by an order of magnitude

PIONEER @ PSI

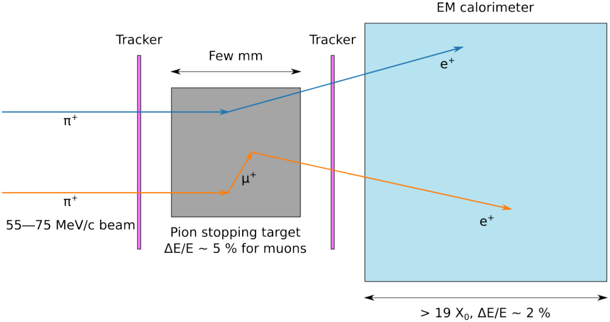
- See PSI proposal 2203.01981, following slides adapted from Bob Velghe, CLFV 2023 https://indico.desy.de/event/37920/contributions/139574/
- Build upon the legacy of PIENU, PEN, and PIBETA
- Key improvements:
  - Segmented active target (ATAR) $\hookrightarrow$ 5D tracking (energy, time, $3\times$space), silicon-strip, low-gain avalanche detectors (LGADs)
  - 3π, 25 X_0 EM calorimeter (CALO) $\hookrightarrow$ Baseline option: LXe, $\delta E/E \leq 1.5\%$ (LYSO crystal calorimeter being investigated as alternative)
- Proposal approved by PSI in 2022







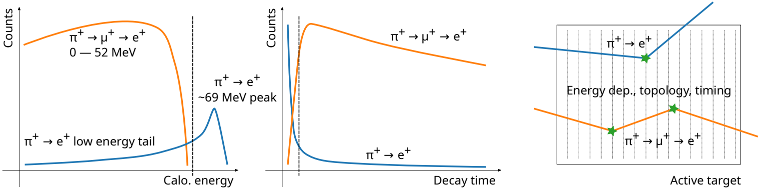
PIONEER Phase I: basic principle



- Focus on **positrons**, $\pi^+ \to e^+\nu_e$ and $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\nu_\mu\bar{\nu}_\mu$
- "Count and sort" the positrons emitted by the stopped pions

  $\hookrightarrow$ many systematics cancel in the ratio $R_{e/\mu}$

PIONEER Phase I: basic principle



- Understanding the $\pi^+ \to e^+\nu_e$ low-energy tail is key

$\hookrightarrow$ more radiation lengths and better energy resolution, ATAR information critical

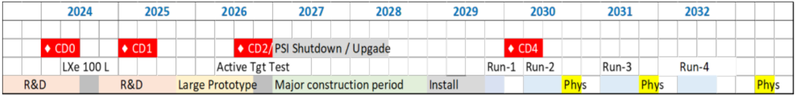
	PIENU 1505.02737	PEN hep-ex/0312017	PIONEER
π^+ stopping rate (Hz)	5×10^4	2×10^4	3×10^5
CALO radiation length (X_0)	19	12	25
CALO resolution σ, $\delta E/E$ (%)	0.9	12.8	1.5

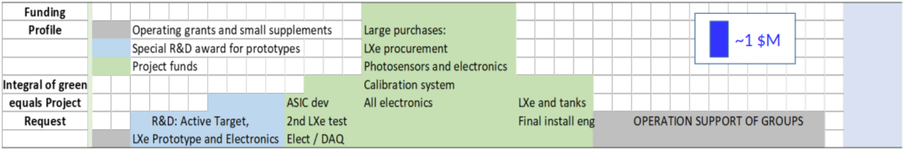
PIONEER Phase I: error budget

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 decay-in-flight	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**

- Table based on 2×10^8 $\pi^+ \to e^+\nu_e$ events ($3\times$ 5-month runs)
- PIENU reference point 1505.02737

Timeline and budget





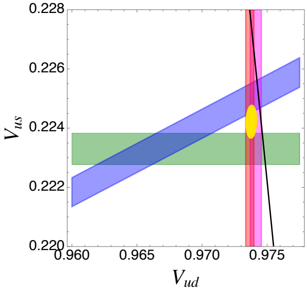
P5 presentation by D. Hertzog

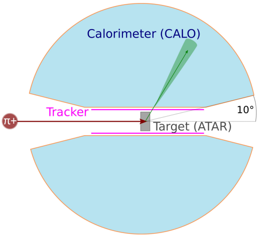
Conclusions

- **PIONEER ambitious next-generation experiment** to measure rare pion decays
  - (Phase I) $R_{e/\mu}$ at 10^{-4}
  - (Phase II+III) Pion β decay
  - Search for exotics

$\hookrightarrow$ improvement by factor 10, matching theory precision

- Approved to run at PSI
- State-of-the-art technologies
  - Active target (LGADs)
  - Fast and high resolution calorimetry
  - Low mass tracker
- Large and diverse group, collaborators from PIENU, PEN, NA62, MEG, $g-2$, HEP colliders, theory $\rightarrow$ **join us!**





- Generalize master formula to include **effective operators** not present in SM

$$\Gamma(\pi^+ \to \pi^0 e^+ \nu_e(\gamma)) = \frac{G_F^2 |V_{ud}|^2}{192\pi^3 M_\pi^3}(1+\Delta_{\text{RC}}^{\pi\ell}) \int_{m_e^2}^{(M_\pi - M_{\pi^0})^2} ds\, \lambda^{3/2}(s)\left(1+\frac{m_e^2}{2s}\right)\left(1-\frac{m_e^2}{s}\right)^2$$
$$\times \left[|V(s)|^2 + |A(s)|^2 + \frac{4(s-m_e^2)^2}{9sm_e^2}|T(s)|^2 + \frac{3m_e^2(M_\pi^2 - M_{\pi^0}^2)^2}{(2s+m_e^2)\lambda(s)}\left(|S(s)|^2 + |P(s)|^2\right)\right]$$

with $V(s)$, $A(s)$, ... depending on Wilson coefficients c_V, c_A, ...

- **Tensor**: $T(s) = \frac{3s}{2s+m_e^2}\frac{m_e}{M_\pi} c_T B_T^\pi(s)$

  $\hookrightarrow$ suppressed by electron mass and tensor form factor

- **Scalar**: potentially competitive with other β decays Falkowski, Gonzáles-Alonso, Naviliat-Cuncic 2020