TRIUMF

PIONEER @ PSI Prospects for Rare Pion Decays

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Outline

Rare Pion Decays Program

PIONEER @ PSI

Searches for Weakly Interacting Particles

Summary & Outlook

Rare Pion Decays Program

A number of anomalies hint for a possible violation of the lepton flavour universality (e.g. arXiv:2204.12175).

Pion decays are a fertile ground for precision tests of the Standard Model, and searches for new physics:

$R_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+ \nu(\gamma)\right)}{\Gamma(\pi^+ \to \mu^+ \nu(\gamma))}$, e–μ coupling universality test, BSM physics.

$R_{\pi\beta} = \frac{\Gamma\left(\pi^+ \to \pi^0 e^+ \nu\right)}{\Gamma(\text{total})}$, clean extraction of $|V_{ud}|$, Cabibbo angle anomaly.

Search for weakly interacting neutral particles.

Rare Pion Decays – State of the Art

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

$R_{e/\mu}$	$1.2352(01) \times 10^{-4}$	(SM, $\epsilon = 0.01$ %!) PRL 99, 231801 (2007)
	$1.230(4) \times 10^{-4}$	(dominated by PIENU @ TRIUMF) PDG (2022)

Measurement consistent with the SM prediction $\to g_e/g_\mu = 1.0010(9)$.

Annu. Rev. Nucl. Part. Sci 72, 69 (2022)

$R_{\pi\beta} = 1.036(6) \times 10^{-8}$ (PIBETA @ PSI) PRL 93, 181803 (2004)

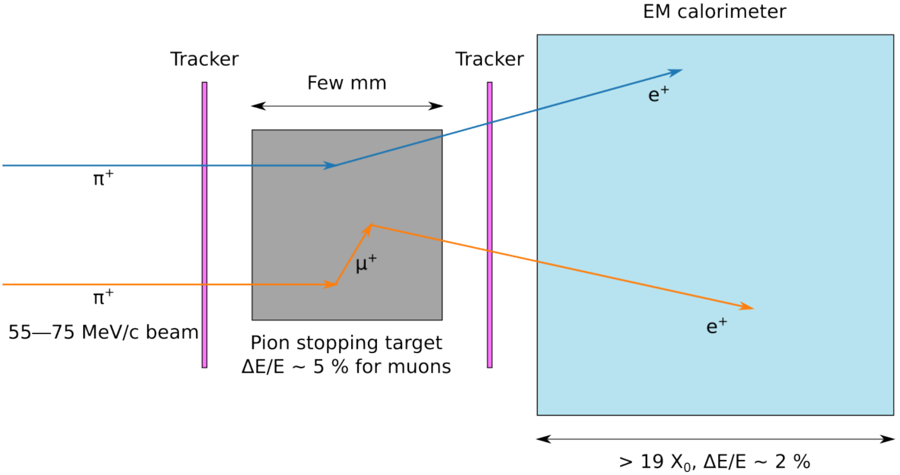
$\lvert V_{ud}\rvert$	$0.97373(31)$	(Superallowed β decays) PRC 102, 045501 (2020)
	$0.9739(28)_{\mathrm{exp}}(5)_{\mathrm{th}}$	($R_{\pi\beta}$) PRL 124, 192002 (2020)

$\lvert V_{ud}\rvert$ extraction not yet competitive with the superallowed β decays but theoretically clean.

Sterile neutrino mixing parameters $\lvert U_{e4}\rvert$ and $\lvert U_{\mu4}\rvert$; Searches for weakly interacting neutral boson $\to$ Today's focus.

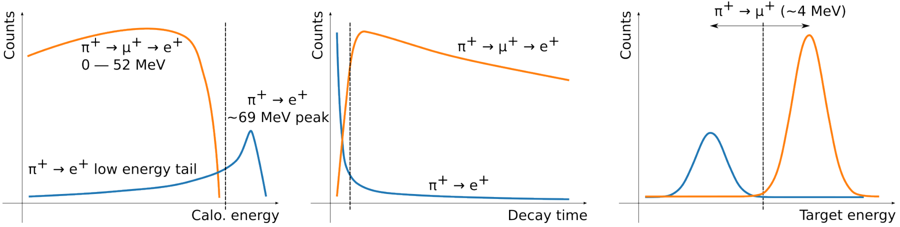
Pion Decays at Rest – Basic Principles

$R_{e/\mu}$: Positron is measured in both cases $\rightarrow$ Systematics cancel.

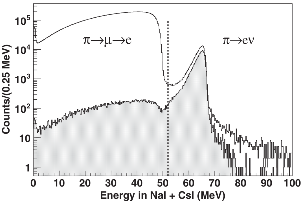


Trackers allow to tag π-decays-in-flight (πDIF) upstream of the target, detect pile-up, reconstruct π-decay vertices and define the e^+ acceptance.

Pion Decays at Rest – $\pi^+ \to e^+\nu(\gamma)$



Left Fig.: Typical PIENU $\pi^+ \to e^+\nu$ energy spectra (after background reduction in gray), $\pi^+ \to \mu^+ \to e^+$ dominates up to about 50 MeV.



Understanding the $\pi^+ \to e^+\nu$ low-energy tail is crucial for a successful measurement:

- Direct: shoot a positron beam in the EM calo,
- Indirect: suppress the $\pi^+ \to \mu^+ \to e^+$ background enough.

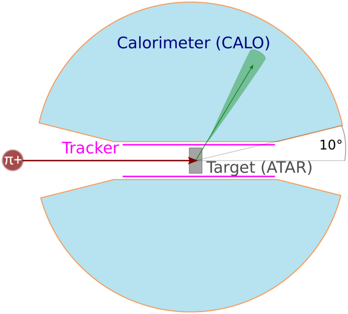
PIONEER @ PSI

Build upon the legacy of PIENU, PEN (PSI) and PIBETA, main objectives:

- Phase I: $R_{e/\mu}$ – Reach the theoretical precision (0.01 %)
  $\rightarrow$ Probe NP at the PeV scale. Annu. Rev. Nucl. Part. Sci 61, 331 (2011)
- Phase II: $R_{\pi\beta}$ – Three to 10-fold improvement in sensitivity
  $\rightarrow$ Competitive V_{ud} extraction.

Key Improvements:

- Segmented active target (ATAR)
  $\rightarrow$ 4D tracking, LGAD technology.
- 3π, 25 X_0 EM calorimeter (CALO)
  $\rightarrow$ Baseline option: LXe, $\Delta E/E < 2\%$.

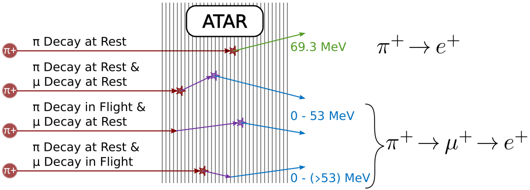


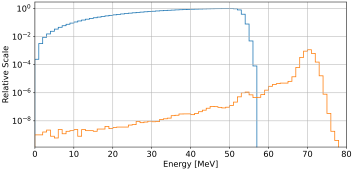
> Also substantially increases the reach of searches for weakly interacting neutral particles.

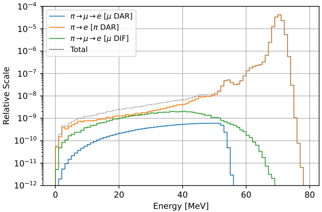
Proposal approved by PSI this year. arXiv:2203.01981, PSI website

PIONEER – Active Target (ATAR)

Baseline design: $\approx$ 50, 120 µm thick, alternating LGAD strips planes $\rightarrow 20 \times 20 \times 6\mathrm{mm}^3$ active area.







Requirements:

- Large dynamic range, (MIPs $\rightarrow \pi^+/\mu^+$ decays),
- Good time resolution, (pulse separation down to < 1.5 ns),
- Sufficient granularity.

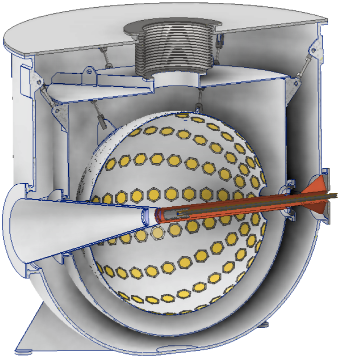
PIONEER – EM Calorimeter

Baseline design: 25 X_0 liquid Xenon calorimeter with (UV) light readout.

Aim at $\Delta E/E = 1.5$ %, draw from MEG and MEG II experience.

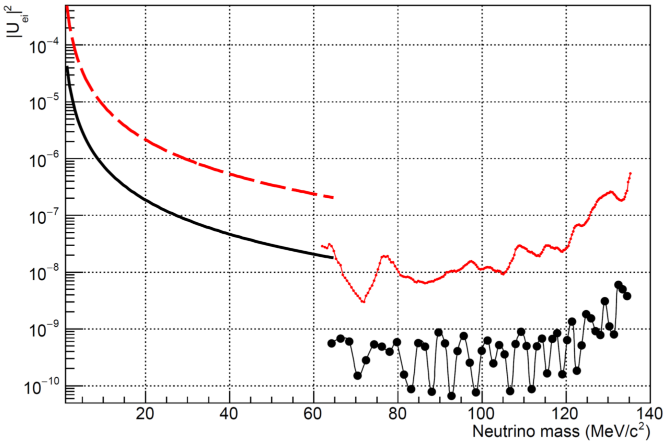
LXe strong points:

- Good time resolution,
  $\tau_d \approx 45$ ns for relativistic electrons,
- High light yield, about 80 % of NaI(Tl),
  $\lambda = 171$ nm,
- Uniform response and high density,
  (2.95 g cm^{-3}, $X_0 = 2.77$ cm).



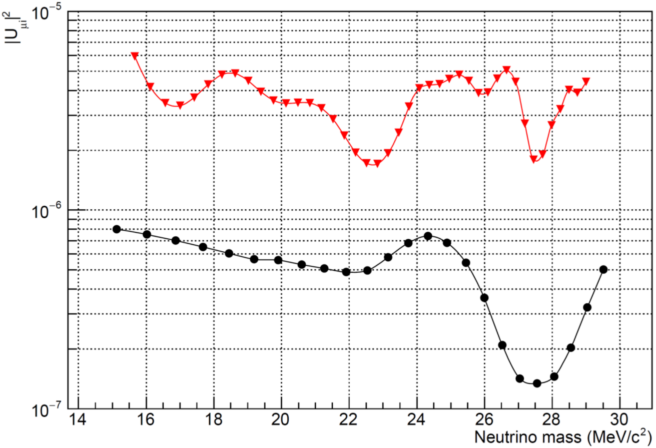
A LYSO crystal calorimeter is also being investigated as an alternative to LXe.

Limit on the Mixing Matrix Element $|U_{e4}|^2$ – $\pi^+ \to e^+\nu_H$



Solid red: PIENU limit, peak search in the background-suppressed positron energy spectrum; Dashed red: PIENU limit extracted from $R_{e/\mu}$; Black: PIONEER projections. Phys. Rev. D 97, 072012 (2018), Phys. Rev. D 100, 053006 (2019).

Limit on the Mixing Matrix Element $|U_{\mu 4}|^2$ – $\pi^+ \to \mu^+ \nu_H$

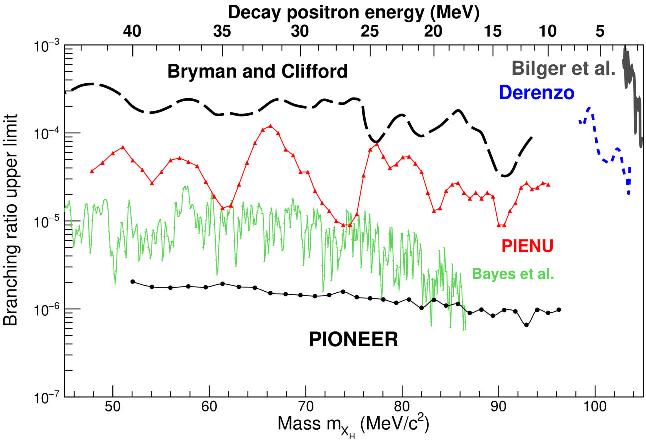


Solid red: PIENU limit, peak search in the μ^+ kinematic energy spectrum (target). Black: PIONEER projections.

Search for $\mu^+ \rightarrow e^+ X_H$

Charged lepton flavor violating decay where X_H is a massive boson.

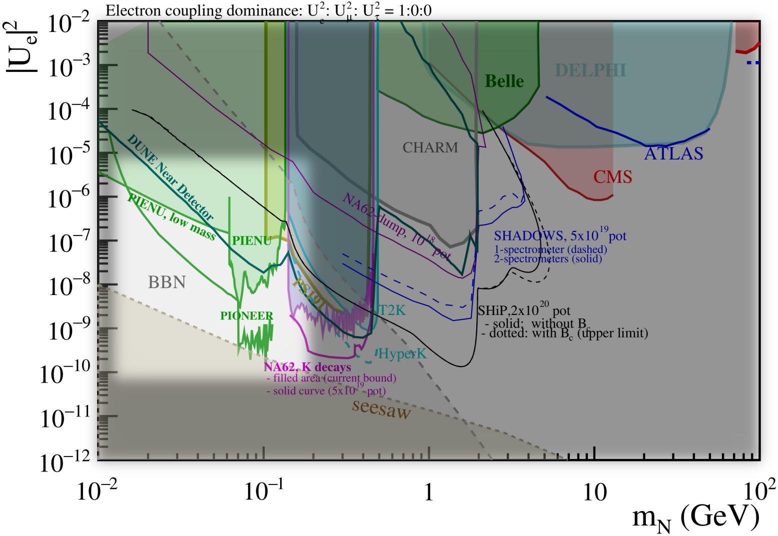
Phys. Rev. Lett. 49, 1549 (1986)



Assumes $\tau_X > 10^{-9}$ s, peak search in the background-suppressed positron energy spectrum.

Summary & Future Prospects – PIONEER

PIONEER is uniquely positioned to search for pion decays to light NP states.



arXiv:2203.08039

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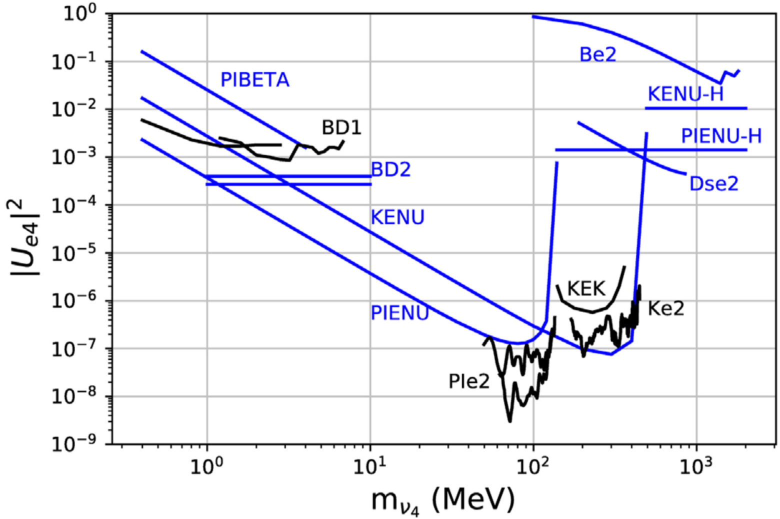
Backup Slides

Constrains on Sterile Neutrinos – $R_{e/\mu}$



Phys. Rev. D 100, 053006 (2019)

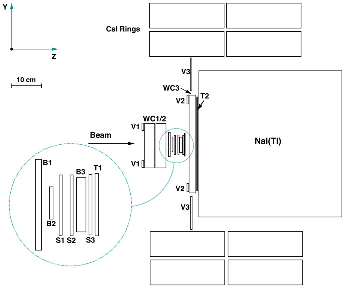
PIENU @ TRIUMF

Installed on the M13 beamline at TRIUMF, 60 kHz pions at 75 MeV/c.

Geometrical acceptance was about 20 %.

Main elements:

- Target: Plastic scintillator counters (B3),
- Beam π^+ and e^+ tracking: Multiwire proportional chambers (WC) and silicon strip detectors (S),
- EM Calo: Monolithic NaI(Tl) crystal (19 X_0, $\Delta E = 2.2\%$) surrounded by CsI crystals,
- B1 and T1 give the pion time and positron time, respectively.

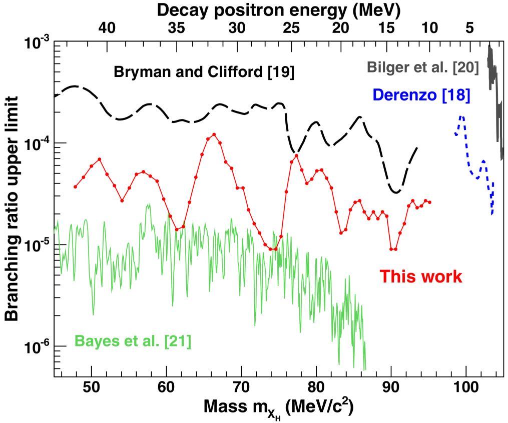


NIMA 791, 38 (2015)

Search for $\mu^+ \to e^+ X_H$ – PIENU

Charged lepton flavour violating decay, X_H is a massive neutral boson.

Peak search in the background-suppressed positron energy spectrum:



Limit on the $\mathcal{BR}$ in neutral boson mass region 47.8 – 95.1 MeV/c^2.

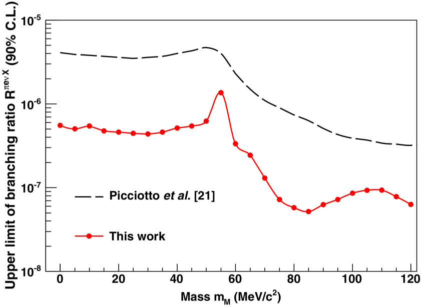
Phys. Rev. D 101, 052014 (2020)

Searches for $\pi^+ \to l^+ \nu X$ – PIENU

Search for 3 body π decays where X is a weakly interacting neutral particle.

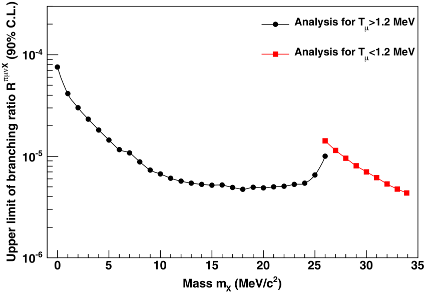
$\pi^+ \to e^+ \nu X$

Fit the background-suppressed positron energy spectrum:



$\pi^+ \to \mu^+ \nu X$

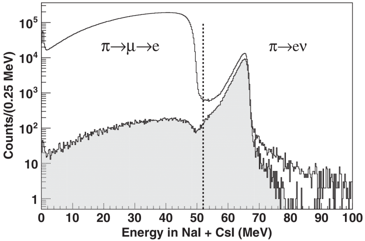
Two regimes, depending on the muon kinematic energy deposited in the target:

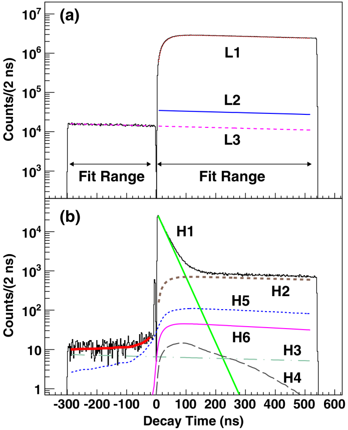


Phys. Rev. D 103, 052006 (2021)

$R_{e/\mu}$ Extraction – PIENU

Fit two time spectra, one for $E_e^+ < 52$ MeV (L) and one for $E_e^+ > 52$ MeV (H):





PIENU – main contributions:

- L1: $\pi^+ \to \mu^+ \to e^+$,
- L2: πDIF, followed by $\mu^+ \to e^+\nu\overline{\nu}$,
- H1: $\pi^+ \to e^+\nu$,
- H2: Energy resolution ($\pi^+ \to \mu^+ \to e^+$), radiative μ decays & pile-up.

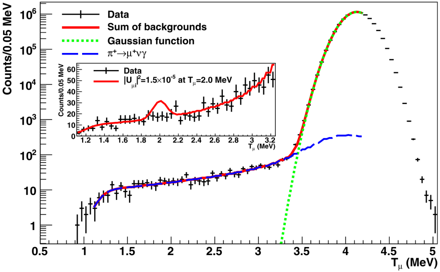
$\to$ See PRL 115, 071801 (2015) for more details.

Limit on $|U_{\mu}4|^2$ – $\pi^+ \to \mu^+\nu_H$ – PIENU

Two regimes, depending on the muon kinematic energy deposited in the target:

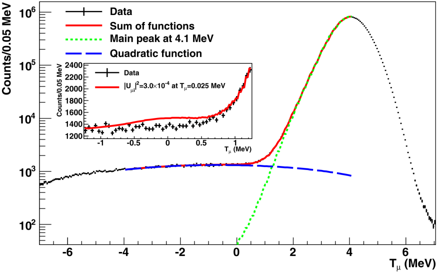
$T_\mu > 1.2$ MeV

Identify a second pulse in the target due to the μ^+ kinematic energy.



$T_\mu < 1.2$ MeV

Integrate the energy in the target to capture the whole $\pi^+ \to \mu^+ \to e^+$. Subtract the pion and positron kinematic energy.



Phys. Lett. B 798, 134980 (2019)