Searches for Sterile Neutrino Effects with PIONEER

Robert Shrock

C. N. Yang Institute for Theoretical Physics and Dept. of Physics and Astronomy, Stony Brook University; email: robert.shrock@stonybrook.edu

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Outline

- Peak search experiments with $\pi^+_{\ell 2}$ decays

- Constraints from measurements of the ratio $\frac{BR(\pi^+ \to e^+ \nu_e)}{BR(\pi^+ \to \mu^+ \nu_\mu)}$

- Future prospects with PIONEER

- Other constraints

- Conclusions

Peak Search Method

Denote the charged weak current as $J_\lambda = \bar{\ell}_L \gamma_\lambda \nu_{\ell,L}$, where $\ell = e,\ \mu,\ \tau$, with

$$\nu_\ell = \sum_{i=1}^{3+n_s} U_{\ell i} \nu_i$$

where ν_i are neutrino mass eigenstates. Three of these, ν_i, $i = 1, 2, 3$, comprise the main components of the active neutrino interaction (flavor) eigenstates ν_e, ν_μ, and ν_τ, and there could be some number n_s of other ν_i, which would be the main mass eigenstates in electroweak-singlet (sterile) neutrino interaction eigenstates ν_{s_1}, ..., $\nu_{s_{n_s}}$.

Focus on the simplest case $n_s = 1$ here, so ν_4 is the possible heavy neutrino.

The ν_4 could occur as a decay product in particle decays (and nuclear decays). Suggestion to search for this and application to existing data to set limits in RS, Phys. Lett. B 96, 159 (1980); Phys. Rev. D 24, 1232 (1981); Phys. D24, 1275 (1981); some recent results in Bryman and RS, Phys. Rev. D 100, 053006, 073011 (2019).

A particularly sensitive test makes use of the 2-body leptonic decays of pseudoscalar mesons M^+, including π^+ and K^+, as well as heavy-quark mesons D^+, D_s^+, B^+.

For PIONEER, $M^+ = \pi^+$, but we will use general notation, so the decay is $M^+ \to \ell^+ \nu_\ell$ with $\ell = e,\ \mu$ (denoted as $M_{\ell 2}^+$).

Signal is a monochromatic peak in the energy spectrum of the final-state ℓ^+ recoiling opposite the massive neutrino ν_4, with energy (in M^+ rest frame)

$$E_\ell = \frac{m_M^2 + m_\ell^2 - m_{\nu_4}^2}{2m_M}$$

If m_{ν_4} is a substantial fraction of $m_M - m_\ell$, then E_ℓ is significantly reduced relative to its value for the emission of the dominantly coupled ν_i in ν_ℓ, with negligibly small masses m_{ν_i}, $i = 1, 2, 3$. This type of search is commonly called a "peak search" exp.

If such an additional peak in the $d\Gamma/dE_\ell$ spectrum from the decay is observed, one can immediately determine the value of m_{ν_4} from E_ℓ, independent of $|U_{\ell 4}|$.

From an experimental upper bound on $BR(M^+ \to \ell^+ \nu_4)$, one can obtain an upper bound on $|U_{\ell 4}|$ for a given m_{ν_4}.

This peak search test for heavy neutrino emission has been applied in experiments with $\pi^+ \to \ell^+ \nu_\ell$ from 1981 to the present, yielding increasingly stringent upper limits on $|U_{\ell 4}|^2$, $\ell = e,\ \mu$ (given at 90 % CL here and in graphs below):

TRIUMF peak search exps. (D. Bryman, spokesperson)

π^+_{e2}: D. Bryman et al., Phys. Rev. Lett. 50, 1546 (1983)

π^+_{e2}: G. Azuelos et al., Phys. Rev. Lett. 56, 2241 (1986)

π^+_{e2}: D. Britton et al., Phys. Rev. D 46, R885 (1992)

$\pi^+_{\mu 2}$: D. Bryman and T. Numao, Phys. Rev. D 53, 558 (1996)

π^+_{e2}: M. Aoki et al. (PIENU) Phys. Rev. D 84, 052002 (2011)

π^+_{e2}: A. Aguilar-Arevalo et al. (PIENU), Phys. Rev. D 97, 072012 (2018)
$\Longrightarrow$ $|U_{e4}|^2 \lesssim 10^{-8} - 10^{-7}$ for $60 \text{ MeV} < m_{\nu_4} < 135$ MeV

$\pi^+_{\mu 2}$: A. Aguilar-Arevalo et al. (PIENU), Phys. Lett. B 798, 134980 (2019)
$\Longrightarrow$ $|U_{\mu 4}|^2 < \text{few} \times 10^{-6} - 10^{-5}$ for $16 \text{ MeV} < m_{\nu_4} < 33.8$ MeV.

SIN/PSI peak search exps:

$\pi^+_{\mu 2}$: R. Abela et al. Phys. Lett. B 105, 263 (1981)

$\pi^+_{\mu 2}$: R. Minehart et al. (SIN+ UVa), Phys. Rev. Lett. 52, 804 (1984)

$\pi^+_{\mu 2}$: M. Daum et al. (SIN + UVa, Phys. Rev. D 36, 2624 (1987)

π^+_{e2}: De Leener-Rosier et al. Phys. Rev. D 43, 3611 (1991)

$\pi^+_{\mu 2}$: M. Daum et al., Phys. Lett. B 361, 179 (1995)

$\pi^+_{\mu 2}$: K. Assamagan et al., Phys. Lett. B 434, 158 (1995)

$\pi^+_{\mu 2}$: M. Daum et al., Phys. Rev. Lett. 85, 1815 (2000)

The peak search method has also been used to search for heavy neutrino emission in $K^+_{\ell 2}$ decay at KEK, BNL, Serpukhov, and CERN:

KEK (T. Yamazaki, spokesperson):

$K^+_{\mu 2}$: Y. Asano et al.,Phys. Lett. 104B, 84 (1981)

$K^+_{\mu 2}$: R. Hayano et al., Phys. Rev. Lett. 49, 1305 (1982)

K^+_{e2}: Yamazaki, Neutrino-84

BNL E949 $K^+_{\mu 2}$: (D. Bryman, S. Kettell, S. Sugimoto, spokespersons) A. Artamanov et al., Phys. Rev. D 91, 052001 (2015)

Serpukhov OKA exp. $K^+_{\mu 2}$: A. Sadovsky et al., Eur. Phys. J. C 78, 92 (2018).

CERN NA62 (C. Lazzeroni, spokesperson):

$K^+_{\mu 2}$: C. Lazzeroni et al. (NA62) , Phys. Lett. B 772, 712 (2017)

$K^+_{\mu 2}$, K^+_{e2}: E. Cortina Gill et al. (NA62), Phys. Lett. B 778, 137 (2018)

K^+_{e2}: E. Cortina Gill et al. (NA62), Phys. Lett. B 807, 135599 (2020);
$\Longrightarrow$ $|U_{e4}|^2 \lesssim 2 \times 10^{-9}$ for $150 \text{ MeV} < m_{\nu_4} < 400$ MeV

$K^+_{\mu 2}$: E. Cortina Gill et al. (NA62), Phys. Lett. B 816, 136259 (2021)
$\Longrightarrow$ $|U_{\mu 4}|^2 \lesssim 10^{-8}$ for $200 \text{ MeV} < m_{\nu_4} < 380$ MeV

Massive neutrino emission would also change the ratio

$$R^{(M)}_{e/\mu} = \frac{BR(M^+ \to e^+\nu_e)}{BR(M^+ \to \mu^+\nu_\mu)}$$

for meson $M^+ = \pi^+$, $M^+ = K^+$, etc. from the respective SM values.

So the agreement of the measured ratios $R^{(\pi)}_{e/\mu}$, $R^{(K)}_{e/\mu}$, and, e.g., $R^{(D_s)}_{\mu/\tau}$, with SM predictions provide further constraints.

Measurements of $R^{(\pi)}_{e/\mu}$ played a key role in testing the $V - A$ structure of the charged weak current in period 1958-1964. Post-1980 $R^{(\pi)}_{e/\mu}$ measurements include

TRIUMF: D. Bryman et al. PRL 50, 7 (1983)

D. Bryman et al. PRL 50, 7 (1986); PRD 33, 1211 (1986)

D. Britton et al. PRL 68, 3000 (1992); PRD 49, 28 (1994)

best current measurement: A. Aguilar-Arevalo et al. (PIENU at TRIUMF), PRL 115, 071801 (2015): $R^{(\pi)}_{e/\mu} = (1.2344 \pm 0.0023(\text{stat}) \pm 0.0019(\text{syst})) \times 10^{-4}$,

SIN/PSI: G. Czapek et al. PRL 70, 17 (1993);

PEN exp. (PSI) http://pen.phys.virginia.edu (D. Počanić)

In the Standard Model (SM)

$$\Gamma(M^+ \to \ell^+\nu_\ell)_{SM} = \frac{G_F^2|V_{ab}|^2 f_M^2 m_M m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_M^2}\right)^2$$

where $V_{ab} = V_{ud}$ for $M^+ = \pi^+$, $V_{ab} = V_{us}$ for $M^+ = K^+$, etc. and $f_\pi = 130$ MeV, $f_K = 160$ MeV.

Equivalently $\Gamma(M^+ \to \ell^+\nu_\ell)_{SM} = \frac{G_F^2|V_{ab}|^2 f_M^2 m_M^3}{8\pi}\,\delta_\ell^{(M)}\left(1 - \delta_\ell^{(M)}\right)^2$

where $\delta_\ell^{(M)} = m_\ell^2/m_M^2$ is the well-known helicity suppression factor, which accounts for the very small values (PDG averages)

$BR(\pi^+ \to e^+\nu_e) = (1.2327 \pm 0.0023) \times 10^{-4}$ versus

$BR(\pi^+ \to \mu^+\nu_\mu) = 0.9998770 \pm 0.00004$ and

$BR(K^+ \to e^+\nu_e) = (1.582 \pm 0.007) \times 10^{-5}$ versus

$BR(K^+ \to \mu^+\nu_\mu) = 0.6356 \pm 0.0011$

With a heavy ν_4 and $|U_{\ell 4}| > 0$,

$$\Gamma(M^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 |V_{ab}|^2 f_M^2 m_M^3}{8\pi} \left[\sum_{i=1}^{3} |U_{\ell i}|^2 \, \delta_\ell^{(M)} \left(1 - \delta_\ell^{(M)}\right)^2 + \right.$$
$$\left. |U_{\ell 4}|^2 \, \rho(\delta_\ell^{(M)}, \delta_{\nu_4}^{(M)}) \theta(m_M - m_\ell - m_{\nu_4}) \right]$$

where $\delta_\ell^{(M)} = m_\ell^2 / m_M^2$ as above, $\delta_{\nu_4}^{(M)} = m_{\nu_4}^2 / m_M^2$,

$$\rho(x, y) = f_{\mathcal{M}}(x, y) [\lambda(1, x, y)]^{1/2}$$

and $\theta(x) = 1$ if $x > 0$, $\theta(x) = 0$ if $x \leq 0$.

The factor $f_{\mathcal{M}}(x, y)$ arises from the square of the matrix element,

$$f_{\mathcal{M}}(x, y) = x + y - (x - y)^2$$

and the factor $[\lambda(1, x, y)]^{1/2}$ arises from the 2-body final-state phase space:

$$\lambda(z, x, y) = x^2 + y^2 + z^2 - 2(xy + yz + zx)$$

For ν_i with negligibly small mass, $f_{\mathcal{M}}(x, 0) = x(1 - x)$ and $[\lambda(1, x, 0)]^{1/2} = 1 - x$, so $\rho(x, 0) = x(1 - x)^2$ with $x = \delta_\ell^{(M)}$. The $\sum_{i=1}^{3} |U_{\ell i}|^2 = 1 - |U_{\ell 4}|^2$, so the SM decay term is reduced by this factor.

$\pi^+ \longrightarrow \mu^+\nu_4$ decay allowed if $m_{\nu_4} < 33.91$ MeV
$\pi^+ \longrightarrow e^+\nu_4$ decay allowed if $m_{\nu_4} < 139.06$ MeV

The function $f_{\mathcal{M}}(\delta_\ell^{(M)}, \delta_{\nu_4}^{(M)})$ increases from a minimum at $\delta_{\nu_4}^{(M)} = 0$ to a maximum at $\delta_{\nu_4}^{(M)} = (1/2) + \delta_\ell^{(M)}$, where it has the value $f_{\mathcal{M},max} = 2\delta_\ell^{(M)} + (1/4)$. The maximum in $f_{\mathcal{M}}$ is in the physical region if $m_\ell < (m_M/4)$.

The ratio of the value of $f_{\mathcal{M},max}$ divided by $f_{\mathcal{M}}$ for emission of neutrinos of negligible mass is

$$\frac{f_{\mathcal{M},max}}{f_{\mathcal{M}}(\delta_\ell^{(M)}, 0)} = \frac{2\delta_\ell^{(M)} + \frac{1}{4}}{\delta_\ell^{(M)}(1 - \delta_\ell^{(M)})}$$

For decays in which $m_\ell \ll m_M$ and hence $\delta_\ell^{(M)} \ll 1$, this produces a large enhancement, since then

$$\frac{f_{\mathcal{M},max}}{f_{\mathcal{M}}(\delta_\ell^{(M)}, 0)} \simeq \frac{1}{4\delta_\ell^{(M)}} \gg 1$$

For example, for π^+_{e2} and K^+_{e2} decays this ratio has the very large values 1.87×10^4 and 2.33×10^5. Physically, these large enhancement factors are due to the removal of the helicity suppression of the decay of the M^+ into a light ℓ^+ and neutrinos ν_i with negligibly small masses.

It is convenient to define the ratio

$$\bar{\rho}(x,y) \equiv \frac{\rho(x,y)}{\rho(x,0)} = \frac{\rho(x,y)}{x(1-x)^2}$$

The 2-body phase space factor decreases quite slowly until m_{ν_4} reaches nearly its maximum value, $m_M - m_\ell$, so this behavior of $f_{\mathcal{M}}$ dominates the behavior of $\bar{\rho}$.

For the $M^+ \to e^+\nu_4$ decays, the ratio $\bar{\rho}(\delta_\ell^{(M)}, \delta_{\nu_4}^{(M)})$ increases very rapidly as $\delta_{\nu_4}^{(M)}$ increases from 0. In general,

$$\left.\frac{d\bar{\rho}(x,y)}{dy}\right|_{y=0} = \frac{1-3x^2}{x(1-x)^2}$$

So, with $\bar{\rho}(x,y) = \bar{\rho}(\delta_\ell^{(M)}, \delta_{\nu_4}^{(M)})$, since $\delta_e^{(M)} \ll 1$,

$$\left.\frac{d\bar{\rho}(\delta_e^{(M)}, \delta_{\nu_4}^{(M)})}{d\delta_{\nu_4}}\right|_{\delta_{\nu_4}^{(M)}=0} = \frac{1}{\delta_e^{(M)}}\left[1 + O(\delta_e^{(M)})\right] \gg 1$$

For a given x, the maximal value of $\bar{\rho}(x,y)$, as a function of y occurs where $d\rho(x,y)/dy = 0$, or equivalently, $d\bar{\rho}(x,y)/dy = 0$, with $d^2\rho(x,y)/dy^2 < 0$ in the physical region.

A particularly simple analytic result applies for $M^+ \longrightarrow e^+\nu_4$ decays, since $x = \delta_e^{(M)} \ll 1$, and the maximum in $\bar{\rho}(x, y)$ occurs at $y = \delta_{\nu_4}^{(M)} = 1/3$, i.e., $m_{\nu_4} = m_M/\sqrt{3}$.

Then (with $x \ll 1$), $[\bar{\rho}(x, y)]_{max} \simeq \bar{\rho}(x, 1/3) = \frac{4}{27x} \gg 1$.

Decay	$(m_{\nu_4})_{\bar{\rho}_{max}}$	$\bar{\rho}_{max}$
$\pi^+ \longrightarrow e^+\nu_4$	80.6	1.105×10^4
$K^+ \longrightarrow e^+\nu_4$	285	1.38×10^5
$D^+ \longrightarrow e^+\nu_4$	1.08×10^3	1.98×10^6
$D_s^+ \longrightarrow e^+\nu_4$	1.14×10^3	2.20×10^6
$B^+ \longrightarrow e^+\nu_4$	3.05×10^3	1.58×10^7
$\pi^+ \longrightarrow \mu^+\nu_4$	3.46	1.00
$K^+ \longrightarrow \mu^+\nu_4$	263	4.13
$D^+ \longrightarrow \mu^+\nu_4$	1.07×10^3	47.3
$D_s^+ \longrightarrow \mu^+\nu_4$	1.13×10^3	52.4
$B^+ \longrightarrow \mu^+\nu_4$	3.05×10^3	371

Now

$$\frac{\Gamma(M^+ \to \ell^+\nu_4)}{\Gamma(M^+ \to \ell^+\nu_\ell)_{SM}} = \frac{|U_{\ell 4}|^2\bar{\rho}(\delta_\ell^{(M)}, \delta_{\nu_4}^{(M)})}{1-|U_{\ell 4}|^2} \simeq |U_{\ell 4}|^2\bar{\rho}(\delta_\ell^{(M)}, \delta_{\nu_4}^{(M)})$$

since $|U_{\ell 4}|^2 \ll 1$.

Hence, denoting $\Gamma(M^+ \to \ell^+\nu_4)_{ul}$ as the upper limit on $\Gamma(M^+ \to \ell^+\nu_4)$ from experiment, one derives the resultant upper limit on $|U_{\ell 4}|^2$:

$$|U_{\ell 4}|^2 < \frac{\frac{\Gamma(M^+ \to \ell^+\nu_4)_{ul}}{\Gamma(M^+ \to \ell^+\nu_\ell)_{SM}}}{\bar{\rho}(\delta_\ell^{(M)}, \delta_{\nu_4}^{(M)})}$$

Summarizing: these 2-body leptonic decays give rise to very high sensitivity to emission of a massive neutrino:

(i) signal is monochromatic in E_ℓ (in the meson rest frame)

(ii) 2-body phase space factor is not suppressed until m_{ν_4} approaches close to its kinematic limit $m_{\nu_4} < m_M - m_\ell$

(iii) there is a very large enhancement in the kinematic rate factor for $M^+ \to e^+\nu_4$ relative to $M^+ \to e^+\nu_e$ because of the removal of the helicity suppression factor.

Constraints from $R^{(\pi)}_{e/\mu}$

In addition to producing an anomalous peak in $d\Gamma/dE_\ell$, the emission of a heavy neutrino in $M^+_{\ell 2}$ decays would cause a deviation from the SM prediction for the ratio of decay rates or branching ratios,

$$R^{(M)}_{\ell/\ell'} \equiv \frac{BR(M^+ \to \ell^+ \nu_\ell)}{BR(M^+ \to \ell'^+ \nu_{\ell'})}$$

where $m_\ell < m_{\ell'}$, e.g., $R^{(\pi)}_{e/\mu}$, $R^{(K)}_{e/\mu}$, $R^{(D_s)}_{\mu/\tau}$, $R^{(B)}_{\mu/\tau}$, etc.

Specialize to $M^+ = \pi^+$, $\ell = e$, $\ell' = \mu$. In the SM,

$$R^{\pi}_{e/\mu,SM} = \frac{\rho(\delta^\pi_e, 0)}{\rho(\delta^\pi_\mu, 0)}(1+\delta_{RC}) = \frac{m_e^2}{m_\mu^2}\left[\frac{1-\frac{m_e^2}{m_\pi^2}}{1-\frac{m_\mu^2}{m_\pi^2}}\right]^2(1+\delta_{RC})$$

where $m_\pi \equiv m_{\pi^+} = 139.570$ MeV and δ_{RC} is the radiative correction term. Define

$$\bar{R}^{(\pi)}_{e/\mu} = \frac{R^{(\pi)}_{e/\mu}}{R^{(\pi)}_{e/\mu,SM}}$$

With a heavy ν_4,

$$R^{\pi}_{e/\mu} = \left[\frac{(1-|U_{e4}|^2)\rho(\delta_e^{(\pi)},0) + |U_{e4}|^2\rho(\delta_e^{(\pi)},\delta_{\nu_4}^{(\pi)})}{(1-|U_{\mu 4}|^2)\rho(\delta_\mu^{(\pi)},0) + |U_{\mu 4}|^2\rho(\delta_\mu^{(\pi)},\delta_{\nu_4}^{(\pi)})}\right](1+\delta_{RC})$$

with the $\theta(m_\pi - m_\mu - m_{\nu_4})$ implicit (exp. cuts and resolution must also be included). Equivalently,

$$\bar{R}^{(\pi)}_{e/\mu} = \frac{1-|U_{e4}|^2 + |U_{e4}|^2\bar{\rho}(\delta_e^{(\pi)},\delta_{\nu_4}^{(\pi)})}{1-|U_{\mu 4}|^2 + |U_{\mu 4}|^2\bar{\rho}(\delta_\mu^{(\pi)},\delta_{\nu_4}^{(\pi)})}$$

There are three different intervals for m_{ν_4}

1. $I_1^{(\pi)}$: $m_{\nu_4} < m_\pi - m_\mu = 33.91$ MeV
2. $I_2^{(\pi)}$: $m_\pi - m_\mu < m_{\nu_4} < m_\pi - m_e$: $33.91\ \mathrm{MeV} < m_{\nu_4} < 139.06$ MeV
3. $I_3^{(\pi)}$: $m_{\nu_4} > m_\pi - m_e = 139.06$ MeV

1. if $m_{\nu_4} \in I_1^{(\pi)}$, then both the $\pi^+ \longrightarrow e^+\nu_4$ and $\pi^+ \longrightarrow \mu^+\nu_4$ decays can occur;
2. if $m_{\nu_4} \in I_2^{(\pi)}$, then the $\pi^+ \longrightarrow e^+\nu_4$ can occur, but the $\pi^+ \longrightarrow \mu^+\nu_4$ decay is kinematically forbidden;
3. if $m_{\nu_4} \in I_3^{(\pi)}$, then both of the decays $\pi^+ \longrightarrow e^+\nu_4$ and $\pi^+ \longrightarrow \mu + \nu_4$ are kinematically forbidden.

The consistency of $[\bar{R}^{(\pi)}_{e/\mu}]_{exp.}$ with the SM value $[\bar{R}^{(\pi)}_{e/\mu}]_{SM} = 1$ yields correlated constraints on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ as a function of m_{ν_4}.

For example, for $m_{\nu_4} \in I_2^{(\pi)}$, i.e., $33.91 \text{ MeV} < m_{\nu_4} < 139.06$ MeV,

$$\bar{R}^{(\pi)}_{e/\mu} = \frac{1 - |U_{e4}|^2 + |U_{e4}|^2 \bar{\rho}(\delta_e^{(\pi)}, \delta_{\nu_4}^{(\pi)})}{1 - |U_{\mu 4}|^2}$$

If for a given m_{ν_4}, one knows, e.g., from peak-search experiments, that $|U_{\mu 4}|^2$ is sufficiently small that the denominator can be approximated well by 1, then an upper bound on the deviation of $[\bar{R}^{(\pi)}_{e/\mu}]_{exp}$ from 1 yields an upper bound on $|U_{e4}|^2$:

$$|U_{e4}|^2 < \frac{\bar{R}^{(\pi)}_{e/\mu} - 1}{\bar{\rho}(\delta_e^{(\pi)}, \delta_{\nu_4}^{(\pi)}) - 1}.$$

One does know $|U_{\mu 4}|^2 \ll 1$ in this mass range from TRIUMF and SIN/PSI peak search experiments. Hence, as with the peak search method, this gives a very stringent upper limits on $|U_{e4}|^2$, because $\bar{\rho}(\delta_e^{(\pi}, \delta_{\nu_4}^{(\pi)}) \gg 1$ over much of the kinematic region in m_{ν_4} (graphs).

If ν_4 is too heavy to be emitted in either π^+_{e2} or $\pi^+_{\mu 2}$ decay, then

$$\bar{R}^{(\pi)}_{e/\mu} = \frac{1 - |U_{e4}|^2}{1 - |U_{\mu 4}|^2}$$

so $\bar{R}^{(\pi)}_{e/\mu}$ still generically deviates from 1. Other BSM physics can also produce $\bar{R}^{(\pi)}_{e/\mu} \neq 1$, a motivation for PIONEER.

Best current measurement of $R^{(\pi)}_{e/\mu}$ from PIENU exp. at TRIUMF (Aguilar-Arevalo et al., PRD 97, 072012 (2018)):

$$R^{(\pi)}_{e/\mu} = (1.2344 \pm 0.0023_{stat} \pm 0.0019_{syst}) \times 10^{-4}$$

PDG average: $R^{(\pi)}_{e/\mu} = (1.2327 \pm 0.0023) \times 10^{-4}$. In comparison with the SM prediction (including radiative corrections by Marciano and Sirlin, PRL 71, 3629 (1993); Cirigliano and Rosell, PRL 99, 231801 (2007))

$$R^{(\pi)}_{e/\mu,SM} = 1.23524(15) \times 10^{-4}$$

yields $\bar{R}^{(\pi)}_{e/\mu} = 0.9980 \pm 0.0019$, consistent with SM.

Since the current exp. measurement of $R^{(\pi)}_{e/\mu}$ is consistent with SM, LFU, this was used in Bryman and RS, PRD 100, 053006, 073011 (2019) to derive bounds on heavy neutrino emission (graphs below).

We also performed a corresponding analysis for $R^{(K)}_{e/\mu}$. The SM prediction with radiative corrections is

$$R^{(K)}_{e/\mu,SM} = (2.477 \pm 0.001) \times 10^{-5}$$

The current PDG value of $R^{(K)}_{e/\mu}$ is dominated by the measurement by NA62 exp. (C. Lazzeroni et al., Phys. Lett. B 719, 326 (2013)), $R^{(K)}_{e/\mu} = (2.488 \pm 0.010) \times 10^{-5}$ and is $R^{(K)}_{e/\mu} = (2.488 \pm 0.009) \times 10^{-5}$, yielding

$$\bar{R}^{(K)}_{e/\mu} = 1.0044 \pm 0.0037,$$

consistent with SM. This was also used in the Bryman-RS paper to derive bounds on heavy neutrino emission.

Plots of Bounds

Figures from D. Bryman and RS, Phys. Rev. D 100, 053006, 073011 (2019) showing upper bounds on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ from peak searches in $\pi^+_{\ell 2}$ (TRIUMF PIENU, PSI) and $K^+_{\ell 2}$ decays (KEK, BNL E949, CERN NA62) and the $R^{(\pi)}_{e/\mu}$ and $R^{(K)}_{e/\mu}$ constraints, as well as other decays. Labelling:

- Bounds in MeV region are from analysis of $\pi^+ \longrightarrow \pi^0 e^+ \nu_e$ (PIBETA) and nuclear beta decay (BD1, BD2)
- Bounds from $R^{(\pi)}_{e/\mu}$ for lower-mass m_{ν_4} labelled PIENU (blue)
- Bounds from $R^{(\pi)}_{e/\mu}$ for high (H)-mass $m_{\nu_4} \in I_3^{(\pi)}$ labelled PIENU-H (blue)
- Bounds from PIENU π^+_{e2} peak search exp., labelled PIENU (black)
- Bounds from $R^{(K)}_{e/\mu}$ lower-mass m_{ν_4} labelled KENU (blue)
- Bounds from $R^{(K)}_{e/\mu}$ for high-mass m_{ν_4} labelled KENU-H (blue)
- Bounds from K^+_{e2} peak searches labelled KEK and NA62, NA62* (black)
- Other bounds from $(D_s)^+_{e2}$ and B^+_{e2} decays (blue)
- Similarly with bounds on $|U_{\mu 4}|^2$

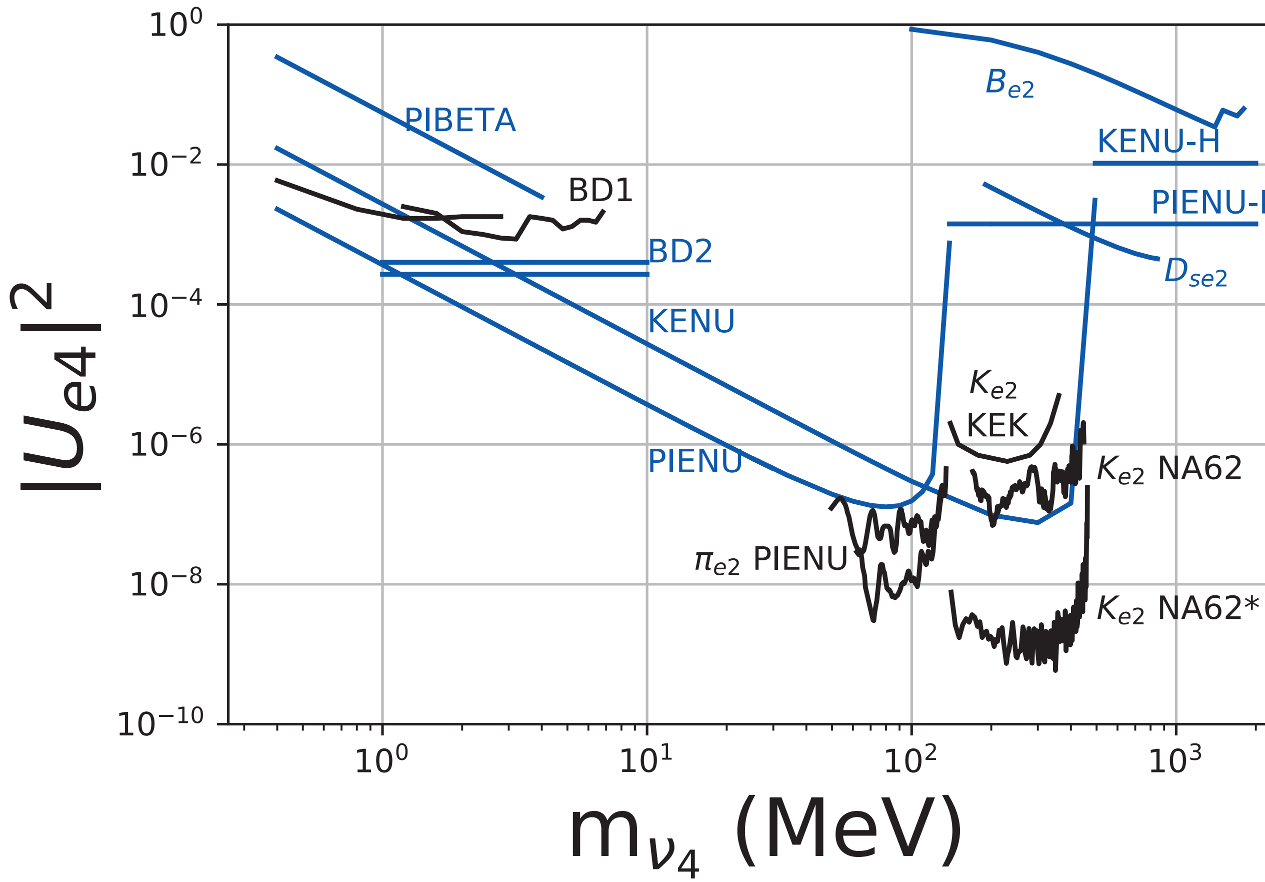

Figure 1: from D. Bryman and RS, PRD 100, 073011 (2019)

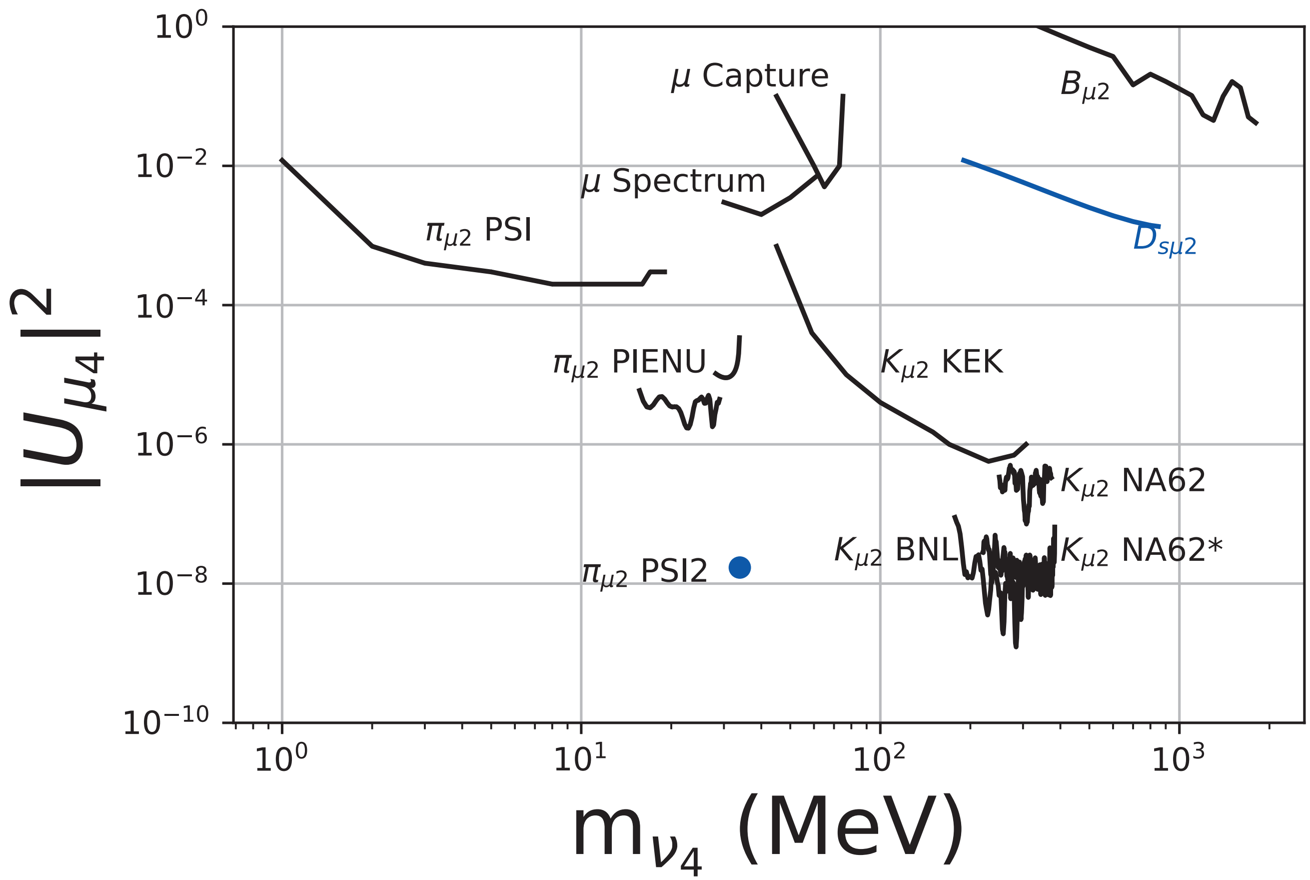

Figure 2: from D. Bryman and RS, PRD 100, 073011 (2019)

Future Prospects with PIONEER

The uncertainty in PIENU measurement $R_{e/\mu}^{(\pi)}$ is $\simeq 2 \times 10^{-3}$, while the estimated uncertainty in the theoretical calculation of $R_{e/\mu}^{(\pi)}$ is 1.2×10^{-4}.

Hence, motivation for the PIONEER exp. at PSI, to measure $BR(\pi^+ \to e^+\nu_e)$ to uncertainty of $\sim 10^{-4}$, matching accuracy of theoretical calculation, test $e-\mu$ universality and hints of violation of lepton flavor universality (LFU) from LHCb; PIONEER white papers: arXiv:2203.01981, arXiv:2203.05505; also Bryman, Cirigliano, Crivellin, Inguglia, arXiv:2111.05338).

In later stage of PIONEER, improve measurement of $BR(\pi^+ \to \pi^0 e^+\nu_e)$, test 1st-row CKM unitarity. (exp. and thy. talks on LFU violation, CKM unitarity by Bryman, Hertzog, Marciano, Pich, Gori, Crivellin, Hoferichter, Počanić... here).

Recall techniques in $R_{e/\mu}^{(\pi)}$ measurement and peak searches: for SM decay, $E_e = 69.8$ MeV ($T_e = 69.3$ MeV); background from $\pi^+ \to \mu^+ \to e^+$ decay chain and from beam-related μ^+ and e^+. Use timing, energy, and tracking information to discriminate e^+s from π_{e2}^+ vs. $\pi^+ \to \mu^+ \to e^+$ decay chain; $\tau_{\pi^+} = 26$ nsec, vs. $\tau_\mu = 2.2$ μsec. In PIENU, set timing window $4 \text{ nsec} < t < 35$ nsec for event window.

In SM $\pi^+ \to \mu^+\nu_\mu$ decay, $E_\mu = 109.8$ MeV ($T_\mu = 4.1$ MeV); then $(E_e)_{max} = 52.8$ MeV ($(T_e)_{max} = 52.3$ MeV) from μ^+ decay, so for $R^{(\pi)}_{e/\mu}$ measurement, good energy separation between positrons from π^+_{e2} and $\pi^+ \to \mu^+ \to e^+$.

Improvements in PIONEER with respect to PIENU include

- active target (ATAR) to discriminate $\pi^+ \to e^+$ from $\pi^+ \to \mu^+ \to e^+$ for stopping π^+ (DAR) and backgrounds from π^+ and μ^+ decays in flight (DIF)
- improved calorimater (CALO) with increased solid angle coverage (3π str) and with excellent energy resolution and depth ($25 X_e$ radiation lengths in LXe)
- excellent time resolution and complete event reconstruction
- improved treatment of the low-energy tail of e^+ from π^+_{e2} decay extending below the upper endpoint of the Michel e^+ at $T_e = 52.3$ MeV; correcting for this was a major uncertainty in PIENU.
- greater statistics: PIENU exp. used approx. 10^7 π^+_{e2} events. PIONEER plans to obtain $\sim 2 \times 10^8$ π^+_{e2} events (and more in the later stage for π^+ β decay)
- Hence, considerably greater sensitivity to new physics (BSM), including possible heavy neutrino effects

With a measurement of $R_{e/\mu}^{(\pi)}$ to 1 part in 10^4 precision, if $\bar{R}_{e/\mu}^{(\pi)}$ is consistent with 1, this will yield an improved limit on heavy neutrinos.

The improvements, especially in understanding the low-energy tail of e^+ events from regular π_{e2}^+ decay, will increase the sensitivity of the peak search for emission of a heavy ν_4, since the signal is a peak at lower E_e.

With the increased statistics and detector advances, PIONEER should also achieve increased sensitivity in a peak search in $\pi_{\mu 2}^+$ decay. Here, the main background is from μ^+ with reduced energy due to regular $\pi^+ \to \mu^+\nu_\mu\gamma$ decays with $BR(\pi^+ \to \mu^+\nu_\mu\gamma) = (2.00 \pm 0.25) \times 10^{-4}$.

For the PIONEER white papers: arXiv:2203.01981 and 2203.05505, preliminary Monte Carlo (MC) simulations were carried out with 10^8 π_{e2}^+ events and 1 % tail fraction with $E_e < 52$ MeV. Similar MC study carried out for $\pi_{\mu 2}^+$ decay, assuming 10^9 $\pi_{\mu 2}^+$ events. The results indicate that PIONEER should achieve a factor ~ 10 reduction in the upper bounds on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ from a combination of $R_{e/\mu}^{(\pi)}$ and peak searches, if the results are consistent with the SM.

Further refinements of these MC simulations, and decisions on detector (e.g., LXe vs. LYSO) will yield more definite expectations for improved sensitivity in these searches.

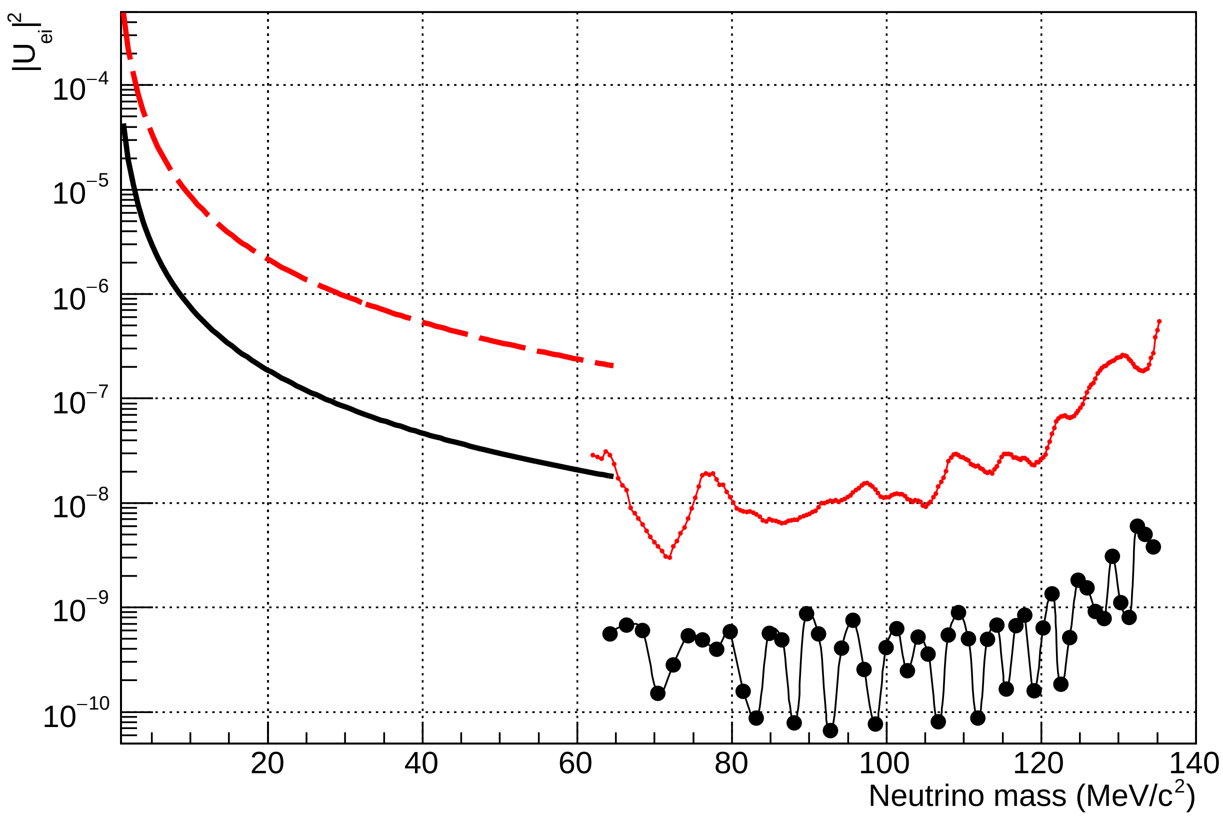

Figure 3: from PIONEER papers arXiv:2203.01981 and 2203.05505: dashed red curve: bound from $\boldsymbol{R}^{(\pi)}_{e/\mu}$ (Bryman-RS PRD 100, 073011 (2019)); solid red curve: bound from PIENU peak search, PRD 97, 072012 (2018); black curves and simulated data: projected PIONEER bounds. Notation: $|\boldsymbol{U}_{ei}|^2 \equiv |\boldsymbol{U}_{e4}|^2$ here.

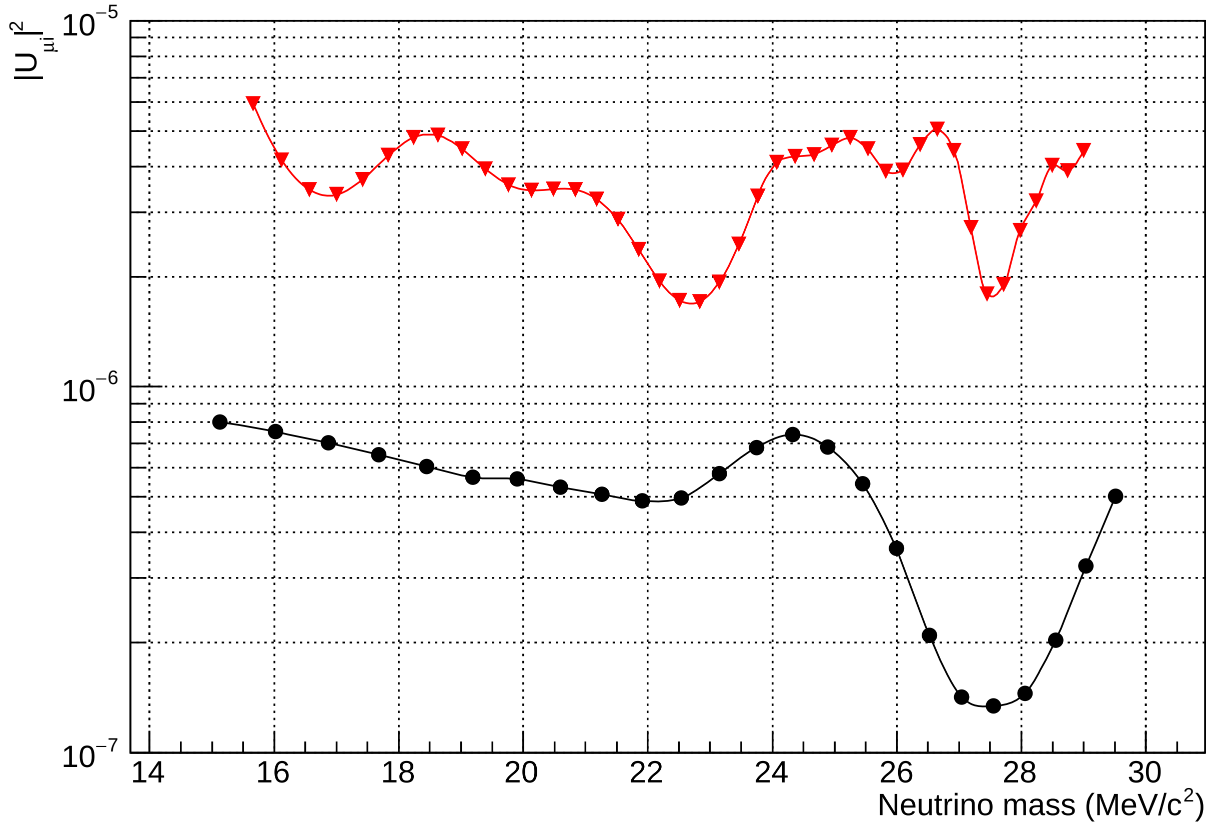

Figure 4: from PIONEER papers arXiv:2203.01981 and 2203.05505: red curve: bound from PIENU peak search with $\boldsymbol{T_\mu > 1.2}$ MeV, PLB 798, 134980 (2019); black curve: projected PIONEER bound. Notation: $|\boldsymbol{U_{\mu i}}|^2 \equiv |\boldsymbol{U_{\mu 4}}|^2$.

For a heavy neutrino ν_4 with a mass such that it could be emitted in $\pi^+ \to e^+\nu_4$ ($m_{\nu_4} < 33.9$ MeV) or $\pi^+ \to \mu^+\nu_4$ ($m_{\nu_4} < 139$ MeV), with the values of $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ being probed, ν_4 decays in the detector are unlikely.

For example, in $\pi^+ \to e^+\nu_4$ decay with $m_{\nu_4} = 100$ MeV, $\gamma_{\nu_4} = 1.06$, $\beta_{\nu_4} = 0.32$, so mean decay length

$$\ell_{\nu_4} = \gamma_{\nu_4}\beta_{\nu_4}c\tau_{\nu_4} = 10.2 \text{ km}\left(\frac{\tau_{\nu_4}}{10^{-4}\text{ sec}}\right)$$

However, other experiments have obtained limits on lepton mixings by searching for production and decay of heavy neutrinos, including fixed-target experiments (CHARM, NOMAD, PS191, NuTeV, T2K, MicroBooNE,...). Future searches of this type will be conductted with the DUNE near detector at Fermilab and are proposed at SHiP (Search for Hidden Particles) and SHADOWS (Search for Hidden and Dark Objects With SPS) at CERN,

At still heavier HNL masses, searches using the collider experiments ATLAS and CMS at the LHC.

Other Constraints

If neutrinos are Dirac fermions, they give no contribution to neutrinoless double beta ($0\nu 2\beta$) decay. If they are Majorana fermions, then a ν_4 in the mass range relevant for $\pi^+_{\ell 2}$ decays could give a significant contribution to neutrinoless double beta decay. For $m_{\nu_i} \lesssim p_F$ (Fermi momenta $p_F \sim 200$) MeV in nuclei), the effective mass combination constrained by $0\nu 2\beta$ decay is $m_{\beta\beta} = |\sum_i U^2_{ei}\, m_{\nu_i}|$.

Current exp. limits from KamLAND-Zen, EXO-200, GERDA, Majorana Demonstrator (dependent on nuclear matrix elements) are $m_{\beta\beta} \lesssim 0.1$ eV.

Assuming that the $U^2_{e4} m_{\nu_4}$ term dominates the sum in $m_{\beta\beta}$, this yields the rough upper limit $|U_{e4}|^2 \lesssim (0.1 \text{ eV})/m_{\nu_4}$, and thus

$$|U_{e4}|^2 \lesssim (0.2 \times 10^{-8}) \left(\frac{60 \text{ MeV}}{m_{\nu_4}} \right)$$

PIONEER will be able to reach this sensitivity, and its upper limit on $|U_{e4}|^2$ will have the advantage of being independent of whether ν_4 is Dirac or Majorana.

As a side note on theory, in the seesaw mechanism, the neutrino masses split into a light set given by eigenvalues of the matrix $M = M_D M_R^{-1} M_D^T$, where M_D and M_R are the $3 \times n_s$ Dirac mass matrix and M_R is the $n_s \times n_s$ right-handed Majorana mass matrices, and a heavy set of mostly sterile mass determined largely by M_R. These are generically Majorana neutrinos, since the Lagrangian contains $|\Delta L| = 2$ neutrino bilinears.

The light-neutrino mass eigenvalues $m_\nu \sim m_D^2/m_R$, providing an appealing explanation for the smallness of masses, since the EW-singlet neutrino bilinears can have entries in $M_R \gg$ Dirac (EW-sym-breaking) scale M_D.

In the original seesaw in grand unified theories (GUTs), $M_R \sim 10^{15}$ GeV, near the GUT scale. But the seesaw relation $M = M_D M_R^{-1} M_D^T$ is invariant under rescaling

$$M_D \to \epsilon M_D \ , \qquad M_R \to \epsilon^2 M_R$$

For $\epsilon \ll 1$, the n_s, mostly sterile mass eigenstates can occur, e.g., in the O(100) MeV mass region amenable to searches in $\pi^+_{\ell 2}$ (and $K^+_{\ell 2}$ decays). Many theoretical models yield this low-scale seesaw, e.g., Appelquist and RS, PLB 548, 204 (2002); PRL 90, 201801 (2003); Asaka and Shaposhnikov, PLB 620, 17 (2005), etc.

The LNV Majorana neutrino bilinears that drive the seesaw may be forbidden by additional symmetries, and neutrinos may be Dirac fermions, in which case, they do not contribute to LNV processes. The question of whether neutrinos are Dirac or Majorana fermions still remains open.

Other constraints on neutrino masses and mixing arise from cosmology. The general cosmological bound on the sum of stable neutrino masses $\sum_i m_{\nu_i} \lesssim 0.15$ eV is not relevant here because this assumes that the ν_i are stable over cosmological times, and this is not the case with a heavy neutrino with a mass in the range probed by $R_{e/\mu}^{(\pi)}$ and peak searches.

A restrictive but model-dependent bound from cosmology arises from the requirement that a heavy neutrino ν_4 should not upset the successful predictions of light element abundances by primordial nucleosynthesis (BBN), which starts at $t \sim 1$ sec in the early universe. The upper bound on τ_{ν_4} is estimated to be $\tau_{\nu_4} \lesssim 0.02 - 0.1$ sec. This BBN upper bound on τ_{ν_4} gives a lower bound on the ν_4 decay rate and hence, for a given m_{ν_4}, a lower bound on combinations of $|U_{\ell 4}|^2$.

Relevant neutrino decays include both charged-current (CC) and neutral-current (NC) contributions. The condition for the neutral weak leptonic current to be diagonal in mass eigenstates is that all leptons of a given charge and chirality must have the same weak T and T_3 (B. W. Lee and RS, PRD 16, 1444 (1977)).

The presence of EW-singlet neutrinos violates this condition, so in the presence of $\{\nu_s\}$, the neutral weak leptonic current contains terms nondiagonal in mass eigenstates.

Hence, a ν_4 in the relevant mass range for π^+ decays has, among its dominant decays, tree-level decays in which ν_4 makes a NC transition to ν_e, ν_μ, ν_τ and a virtual Z, which then materializes to $f\bar{f}$, where $f\bar{f} = \nu_\ell \bar{\nu}_\ell$, $e\bar{e}$.

These include the invisible NC decays $\nu_4 \longrightarrow \nu_\ell \bar{\nu}_{\ell'} \nu_{\ell'}$, and other NC leptonic decays such as $\nu_4 \longrightarrow \nu_\ell e^+ e^-$. There are also CC decays such as $\nu_4 \longrightarrow e^- e^+ \nu_e$.

Recent analyses of BBN constraints include Drewes and Garbrecht, Nucl. Phys. B 921, 250 (2017); Bondarenko, Boyarsky, et al., JHEP 07 (2021) 193, arXiv:2101.09255; see graph indicating allowed heavy neutrino mass region between 120 and 139 MeV allowed by BBN constraints in π^+_{e2} decay.

More generally, BBN bounds are model-dependent; new physics beyond the Standard Model modifies them. So it is still worthwhile to have direct laboratory limits.

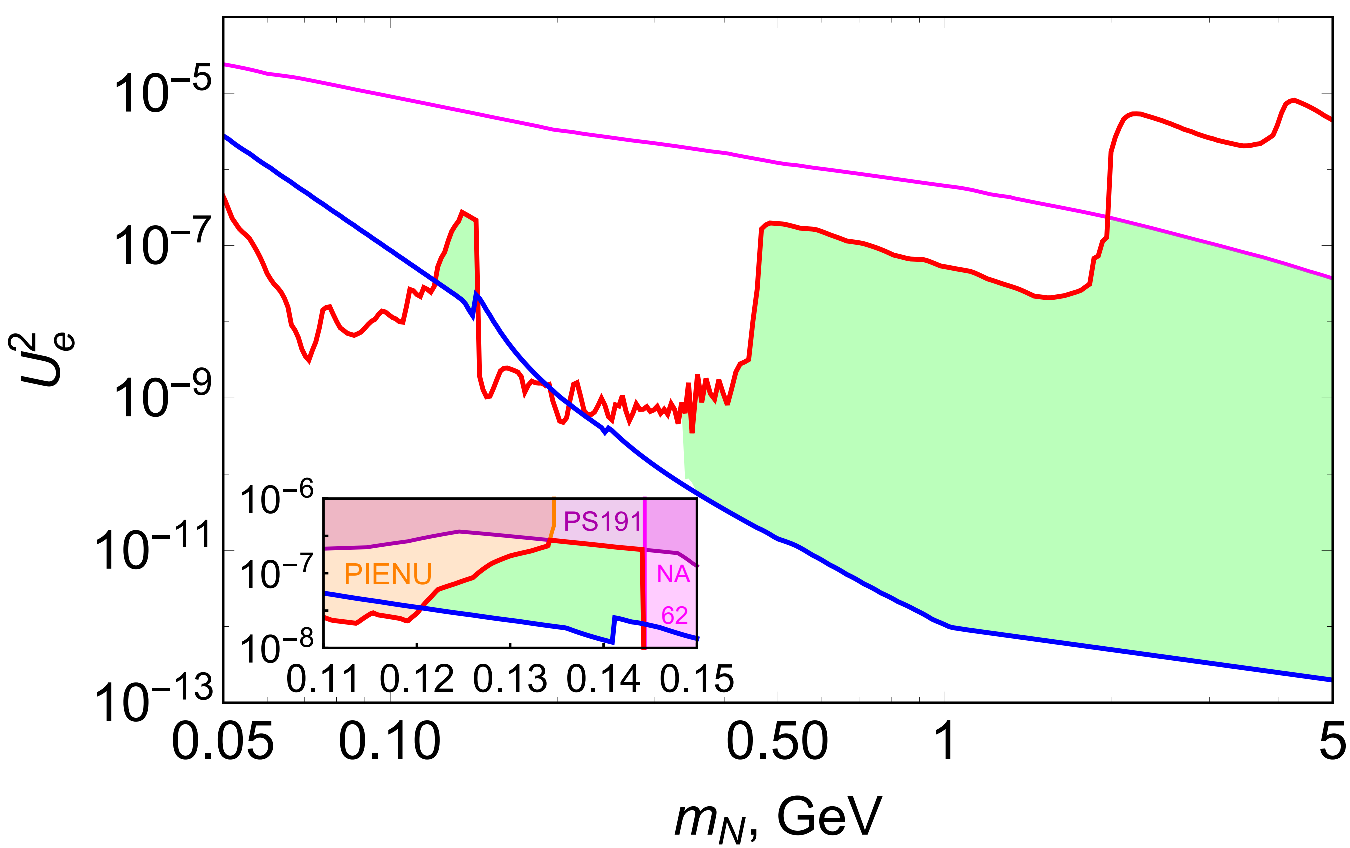

Figure 5: from Bondarenko, Boyarsky, et al., JHEP 07 (2021) 193, arXiv:2101.09255. Blue curve is BBN lower bound; red curves are exp. upper bounds. The green region is allowed. Notation: $\boldsymbol{U_e^2 \equiv |U_{e4}|^2}$. See paper for details.

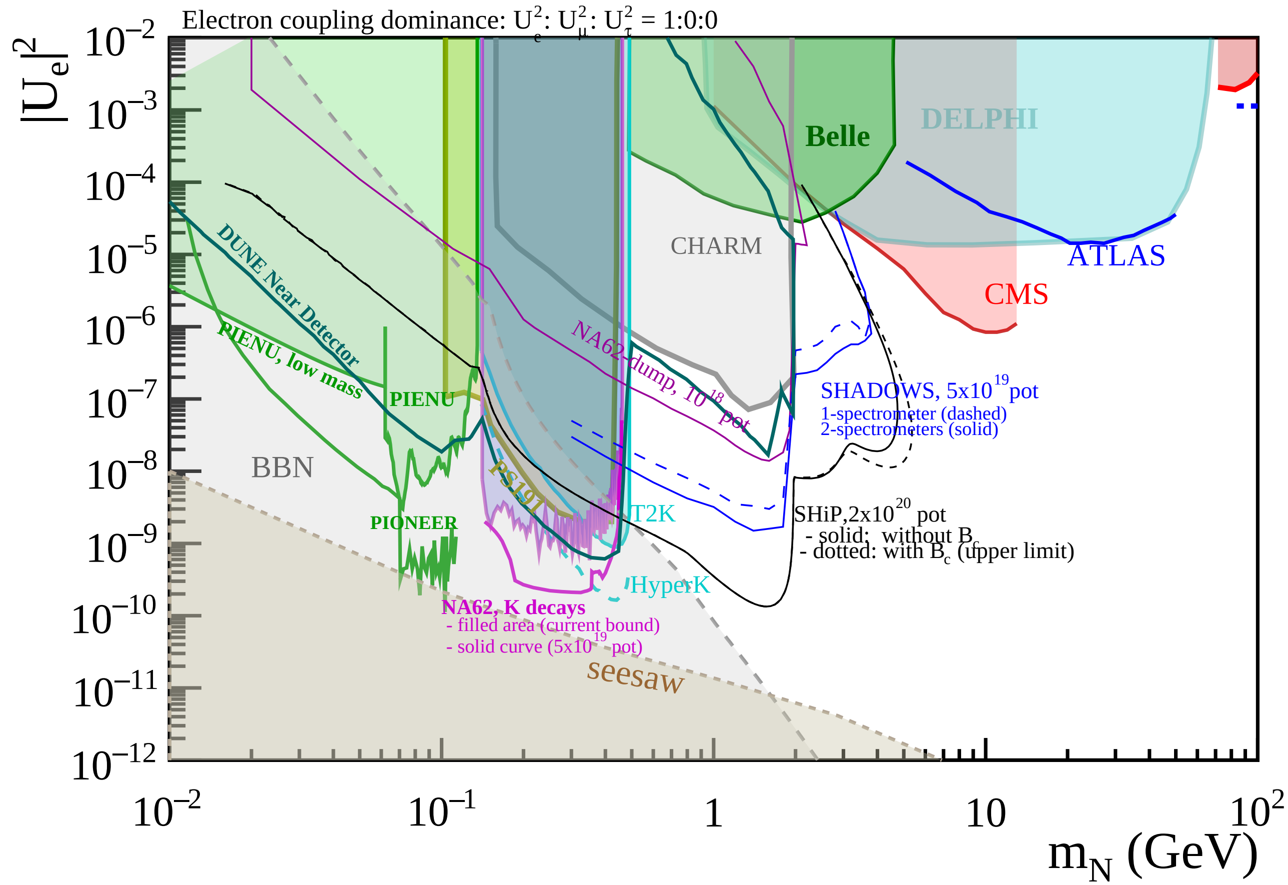

Figure 6: from Snowmass white paper on Heavy Neutral Leptons, arXiv:2203.08039. Notation: $|U_e|^2 \equiv |U_{e4}|^2$; assumes $U_{\mu 4} = 0$ and $U_{\tau 4} = 0$. See also Goudzovski et al., arXiv:2201.07805; Arguelles et al., PRD 105, 095006 (2022).

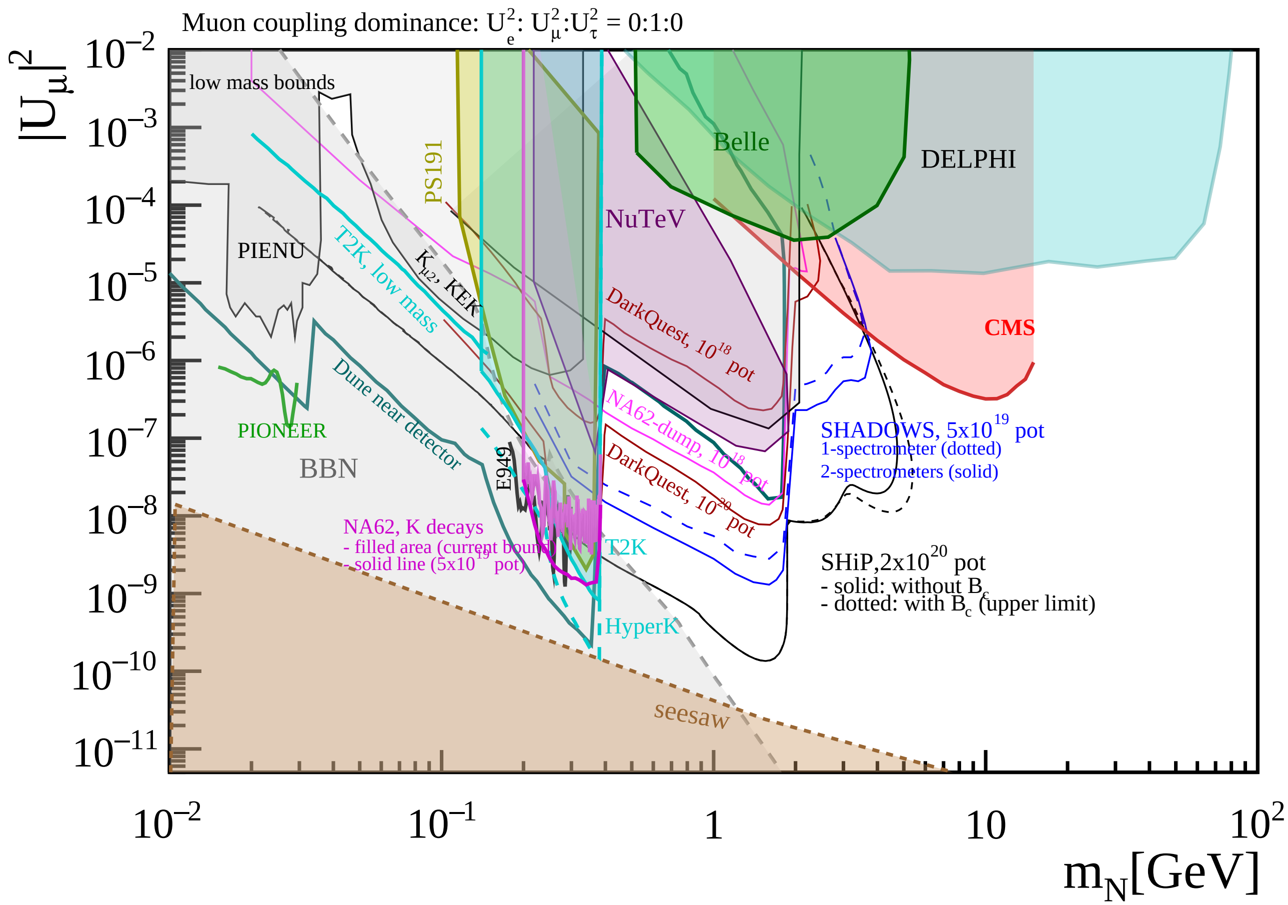

Figure 7: from Snowmass white paper on Heavy Neutral Leptons, arXiv:2203.08039. Notation: $|U_\mu|^2 \equiv |U_{\mu 4}|^2$; assumes $U_{e4} = 0$ and $U_{\tau 4} = 0$.

Conclusions

- Searches for heavy neutrino emission in π^+_{e2} and $\pi^+_{\mu2}$ (as well as K^+_{e2}, $K^+_{\mu2}$, etc.) are very powerful methods to obtain bounds, owing to the monochromatic nature of the signal and the removal of helicity suppression for $\pi^+ \to e^+\nu_4$ (and $K^+ \to e^+\nu_4$) for heavy m_{ν_4}.
- Dedicated experiments searching for peaks in $\pi^+_{\ell2}$ since 1981 have yielded very stringent upper limits on $|U_{e4}|^2$ and $|U_{\mu4}|^2$ for a heavy ν_4. Increasingly precise measurement of $BR(\pi^+ \to e^+\nu_e)$ also yielded very good upper limits on $|U_{e4}|^2$.
- Best current measurement of $R^{(\pi)}_{e/\mu}$ and best current limits from peak searches are from PIENU experiment at TRIUMF.
- PIONEER experiment plans to increase the accuracy of the $R^{(\pi)}_{e/\mu}$ by a factor of ~ 10, achieving an uncertainty of 10^{-4}; it should also increase the sensitivity in peak searches in both π^+_{e2} and $\pi^+_{\mu2}$ decay modes by a similar factor of ~ 10. These will further improve the upper limits on $|U_{e4}|^2$ and $|U_{\mu4}|^2$.

Thank you

backup slides

Some further references:

For some recent BSM models with Dirac neutrinos, see, e.g., Y. Grossman and D. J. Robinson, JHEP 01 (2011) 132; P. Langacker, Ann. Rev. Nuc. Part. Sci. $\mathbf{62}$, 215 (2012); S. Chulia, E. Ma, R. Srivastava, J. W. F. Valle, PLB 767, 209 (2017); E. Ma and O. Popov, Phys. Lett. B $\mathbf{764}$, 142 (2017); Z. Chacko, P. Bhupal Dev, R. N. Mohapatra, A. Thapa, PRD 102, 035020 (2020).

Early study of BBN constraints: Dolgov et al., NPB 590, 562 (2000); recent works on BBN constraints include Drewes and Garbrecht, NPB 921, 250 (2017); Gelmini et al., JCAP 09 (2020) 051; Sabti et al., JCAP 11 (2020) 056; Mastrototaro et al., PRD 104, 016026 (2021); Boyarsky et al., PRD 104, 023517 (2021); Bondarenko, Boyarsky et al., JHEP 07 (2021) 193.

Another plot from Snowmass white paper 2203.08039:

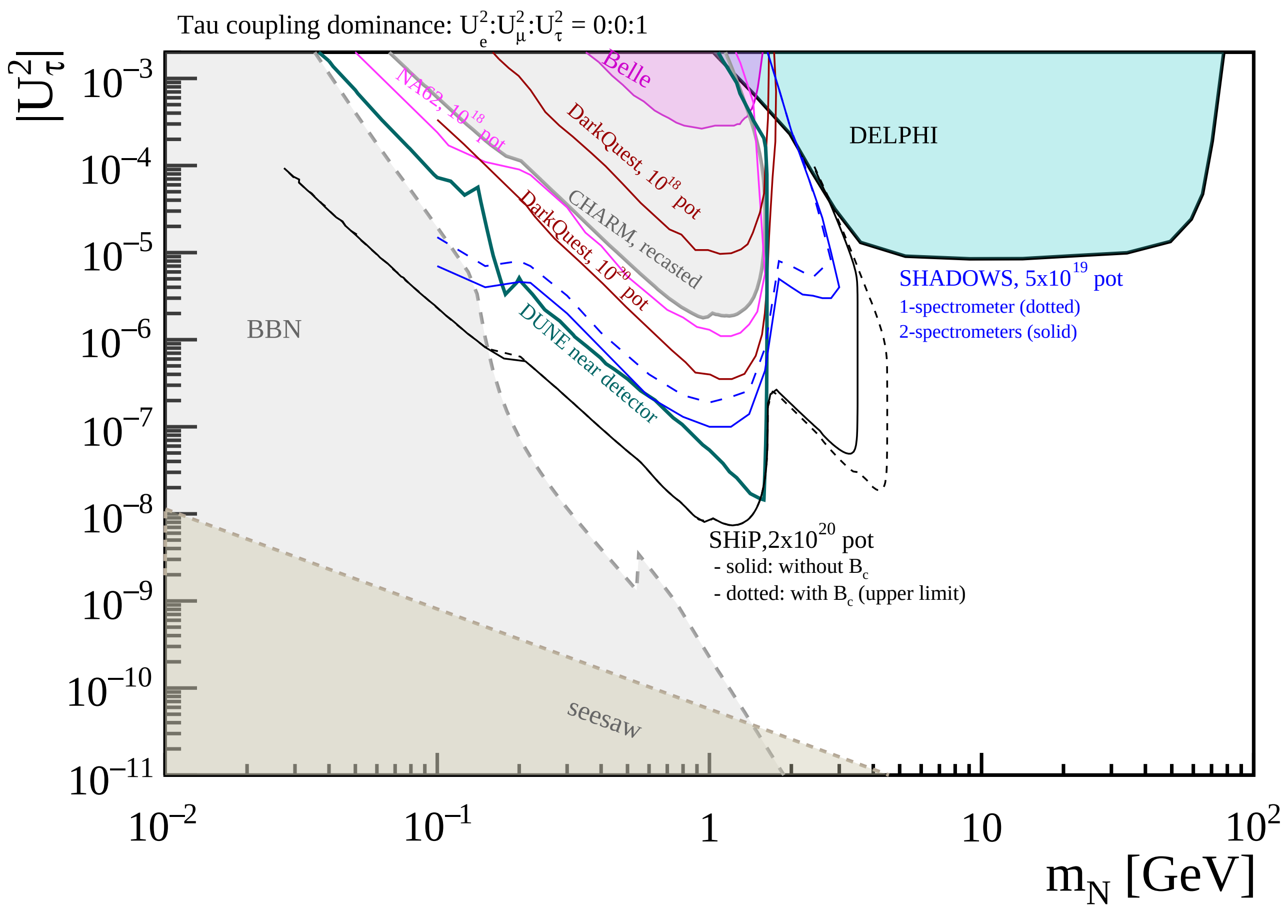

Figure 8: from Snowmass white paper on Heavy Neutral Leptons, arXiv:2203.08039. Notation: $|U_\tau|^2 \equiv |U_{\tau 4}|^2$; assumes $U_{e4} = 0$ and $U_{\mu 4} = 0$.