Sensitivity of Lepton Number Violating Meson Decays in Different Experiments

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Abstract

In the framework of right handed (RH) neutrinos extended Standard Model (SM), three body lepton number violating (LNV) meson decays $M_1^- \to \ell_1^-\ell_2^- M_2^+$ resonantly enhanced, if the mass of N lies in the range (100 MeV - 6 GeV). We study the discovery prospects of these LNV meson decays in various experiments. Non-observation give bounds on light-heavy mixing angle $|V_{\ell N}|^2$. We show that, inclusion of parent meson momentum can account to a large difference for active-sterile mixing.

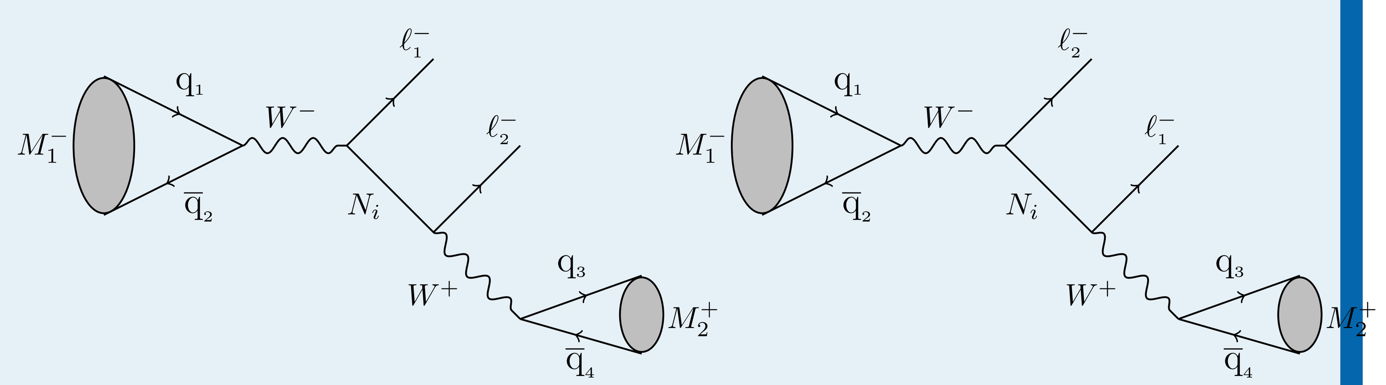
The Model

SM+RH neutrino extensions introduces mixing of N with the active neutrinos: $\nu_\ell = \sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N^c_{m'}$. Additional term in charged current interaction:

$$\mathcal{L}_\ell^{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{\ell=e}^{\tau} V^*_{\ell N} \overline{N^c_{m'}} \gamma^\mu P_L \ell\right) + h.c.$$

Assumption: one RH neutrino lies in the mass range $0.140\,\text{GeV} \le M_N \le 6\,\text{GeV}$ and contributes.

Process



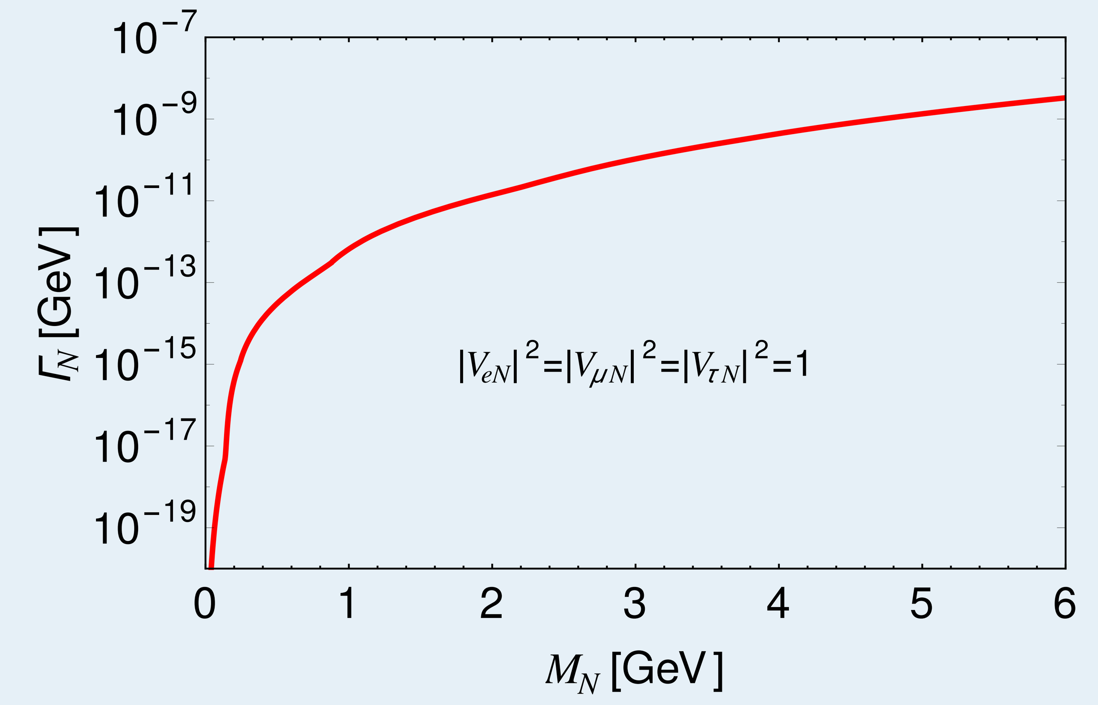
$$\mathcal{M} = G_F^2 V^{CKM}_{M_1} V^{CKM}_{M_2} f_{M_1} f_{M_2} (V_{\ell_1 N} V_{\ell_2 N}) \quad (1)$$

$$\bar{u}(k_1) \not{p} \not{k}_3 (1+\gamma_5) v(k_2) \frac{M_N}{(p-k_1)^2 - M_N^2 + i M_N \Gamma_N}$$

Inputs

- NA62: $N_{K^+} = 1.35\times 10^{13}$, $p_K = 75$ GeV, $L_D = 65$ m.
- LHCb: $N_{B^+} = 2.6\times 10^{13}$, $N_{D^+} = 2.5\times 10^{14}$, $N_{D_s^+} = 10^{14}$, $N_{B_c} = 10^{11}$, $p_{M_1} = 100$ GeV, $L_D = 20$ m.
- SHiP: $N_{D^+} = 1.02\times 10^{17}$, $N_{D_s^+} = 2.72\times 10^{16}$, $N_{B^+} = 10^{13}$, $N_{B_c} = 10^{11}$, $p_{M_1} = 58$ GeV, $L_D = 60$ m.
- MATHUSLA: $N_B = 5.7\times 10^{14}$, $N_D = 5.4\times 10^{13}$, $\gamma_B = 2.3$, $\gamma_D = 2.6$, $L_D = 38$ m.
- Belle-II: $N_B = 1.1\times 10^{11}$, $N_{D^+} = 3.4\times 10^{10}$, $N_{D_s^+} = 10^{10}$, $L_D = 2$ m.

TOTAL DECAY WIDTH OF N



$\frac{1}{(p_N^2-M_N^2)^2+M_N^2\Gamma_N^2} \approx \frac{\pi}{M_N\Gamma_N}\delta(p_N^2-M_N^2)$ and $\Gamma(M_1 \to \ell_1\ell_2 M_2) \approx \Gamma(M_1\to\ell_1 N)\mathrm{Br}(N\to\ell_2 M_2)$. As decay length is large, we need to take into account the probability of N to decay inside the detector when calculating the signal events.

Signal Events

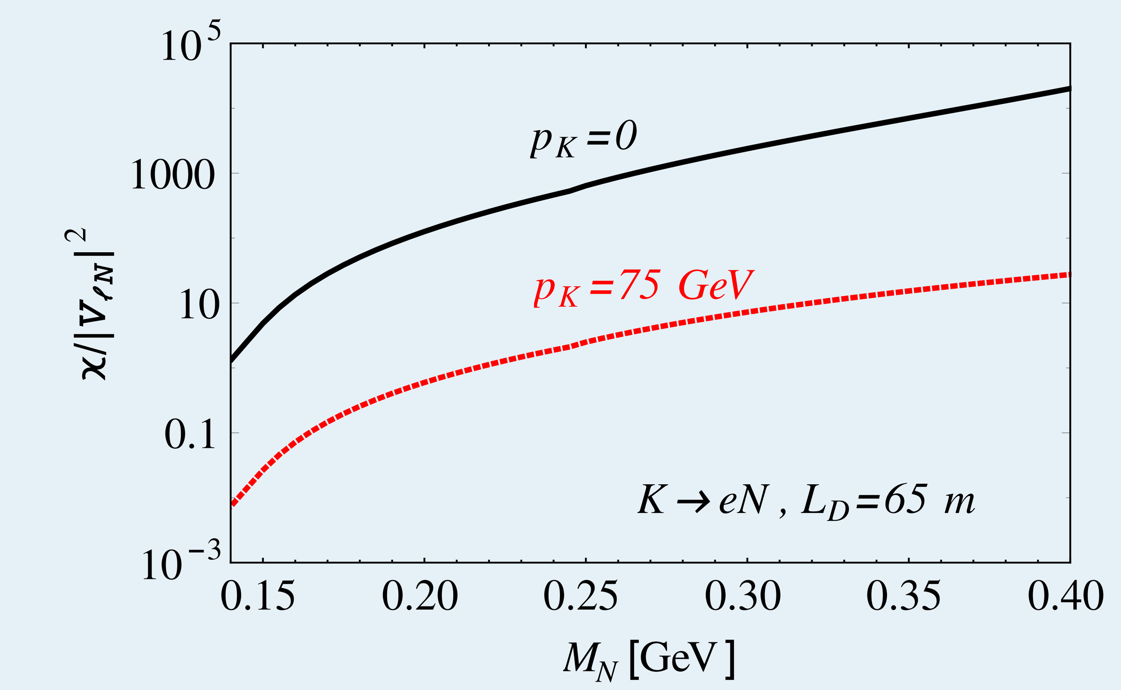
Assuming the parent meson M_1 decays at rest:

$$N_{\text{event}} = 2N_{M_1^-}\mathrm{Br}\left(M_1^- \to \ell_1^- N\right)\frac{\Gamma(N\to\ell_2^- M_2^+)}{\Gamma_N}\mathcal{P}_N$$

For the case of meson decay in flight:

$$N_{\text{event}} = 2N_{M_1^-}\int_{E_N^-}^{E_N^+} dE_N \mathrm{Br}\left(M_1^- \to \ell_1^- N\right)\frac{m_{M_1}}{2p_N^*|\vec{p}_{M_1}|}\frac{\Gamma(N\to\ell_2^- M_2^+)}{\Gamma_N}\mathcal{P}'_N$$

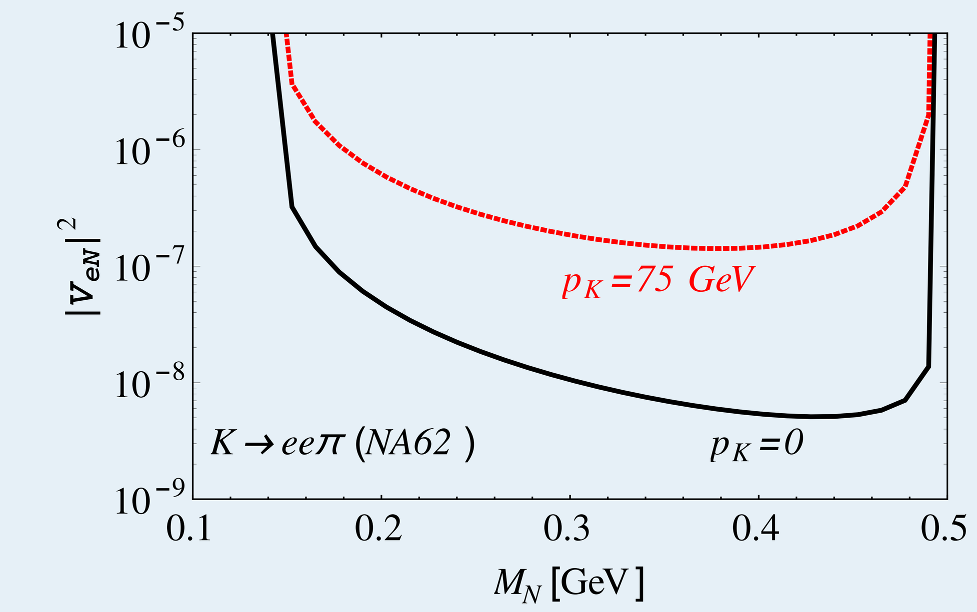
Effect of meson momentum on $\mathcal{P}_N$



$$\mathcal{P}_N = 1 - \exp\left(-L_D\Gamma_N\frac{M_N}{p_N}\right) = 1 - \exp(-x);$$

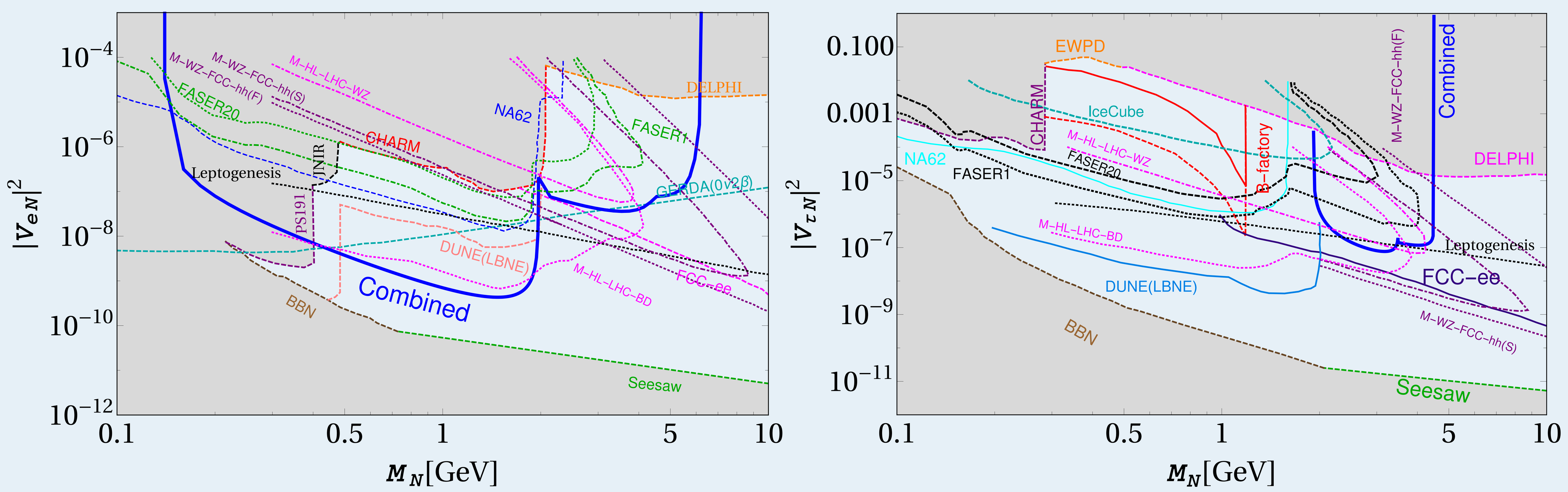
$$x = \frac{L_D}{L_N};\ \mathcal{P}_N \approx 1 \text{ for } L_D\to\infty \text{ or } L_N \to 0.$$

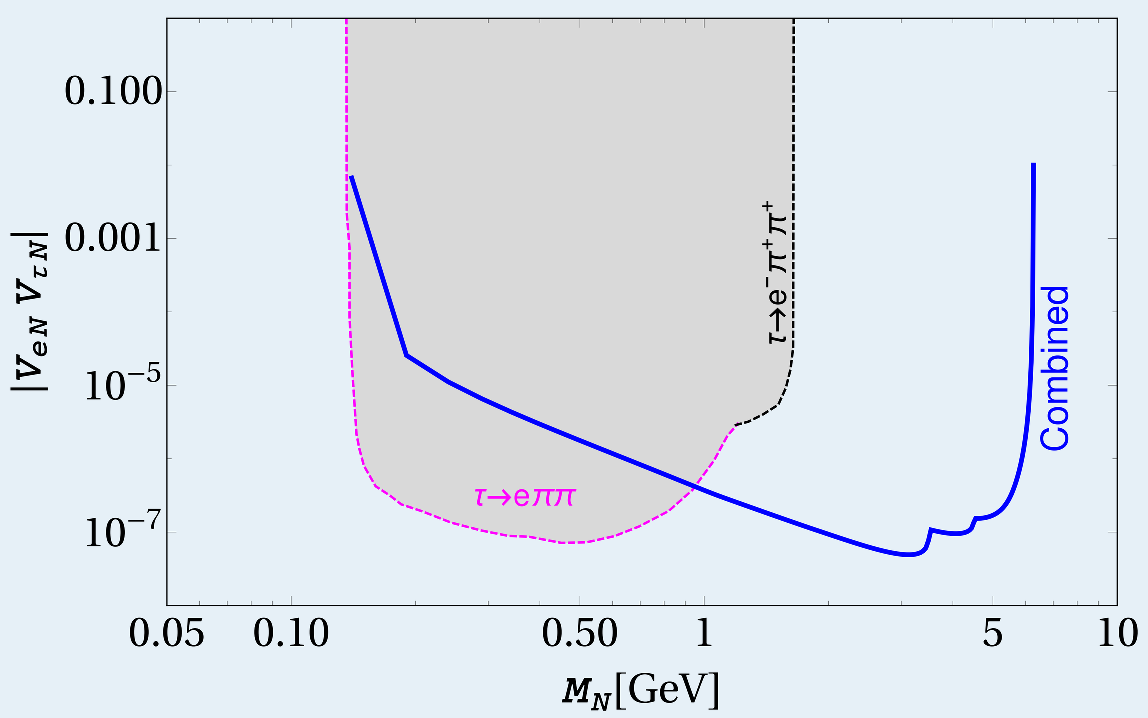
Effect of meson momentum on obtained mixing angles



$\mathcal{P}_N = f(M_N, L_D, p_N)$. Hence, probability is smaller in the case of meson decay in flight comapare to meson decayat rest, which implies rather loose bound on mixing angle from the expected signal events. We show how the momentum of the parent mesons affect the sensitivity reach of the mixing angles. For K meson decays, obtained mixing differs by two order of magnitudes.

Results





These are the combined tightest bounds on mixing angles from various meson decays in different experiments. Similar bound can be obtained for $|V_{\mu N}|^2$, $|V_{eN}V_{\mu N}|$ and $|V_{\mu N}V_{\tau N}|$. Sensitivity reach: $|V_{eN}|^2$, $|V_{\mu N}|^2$ and $|V_{eN}V_{\mu N}| \sim 10^{-9}$ $[0.14-2]$ GeV $\sim 10^{-7}$ $[2-5]$ GeV. $|V_{\tau N}|^2$, $|V_{eN}V_{\tau N}|$ and $|V_{\mu N}V_{\tau N}| \sim 10^{-7}$. Note that we have assumed $|V_{eN}|^2 = |V_{\mu N}|^2 = |V_{\tau N}|^2$ in Γ_N when deriving these bounds.

$|V_{eN}|^2$, $|V_{\mu N}|^2$ and $|V_{eN}V_{\mu N}|$: D_s at SHiP (0.14-2 GeV) + B at MATHUSLA (2-5 GeV). $|V_{eN}V_{\tau N}|$, $|V_{\mu N}V_{\tau N}|$ and $|V_{\tau N}|^2$: B at MATHUSLA and B_c at LHCb.

Conclusion

We analyse discovery prospect of a heavy Majorana neutrino via lepton number violating meson decays $M_1^- \to \ell_1^-\ell_2^-\pi^+$ at various ongoing and future experiments, such as, NA62, LHCb, FCC-ee, Belle-II, SHiP and MATHUSLA. Obtained mixing angles are loose in case of meson decay at flight compared to meson decay at rest. Hence we need to take account the parent meson momentum when considering specific experiments. The LNV meson decays can probe the product of the mixings $|V_{\mu N}V_{\tau N}|$, $|V_{eN}V_{\tau N}|$ in higher mass ranges $M_N \sim 5$ GeV, that are so far unconstrained.