Sensitivity of LNV meson decays in different experiments

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How to probe RH Neutrinos

In various seesaw models, the inclusions of SM singlet RH neutrinos (sterile neutrinos) to the SM particle content is one of the best motivated ways to account for the observed neutrino masses

These RH neutrinos mass scale can lie in a wide range depending upon the models

Search strategy varies depending on the mass scale.

For eV scale, neutrino oscillations and neutrino less double beta decay.

For KeV scale sterile neutrinos, peak searches in leptonic decays of pions and kaons.

For mass scale of few GeV, various three and four body LNV meson decays can be used as a probe: $M_1^- \to \ell_1^- \ell_2^- M_2^+$,

For mass range 100 GeV or more, accelerator and collider experiments such as $e^+e^-, e\gamma, pp, p\bar{p}$ *as well as in top quark and W-boson rare decays.*

Inclusion of RH neutrino modifies the charged and neutral current due to active-sterile mixing and this can provide novel signatures.

$$\nu_{\ell L} = \sum_{m=1}^{3} U_{\ell m}\nu_{mL} + \sum_{m'=4}^{3+n} V_{\ell m'} N^c_{m'L}, \text{ with } UU^\dagger + VV^\dagger = 1$$

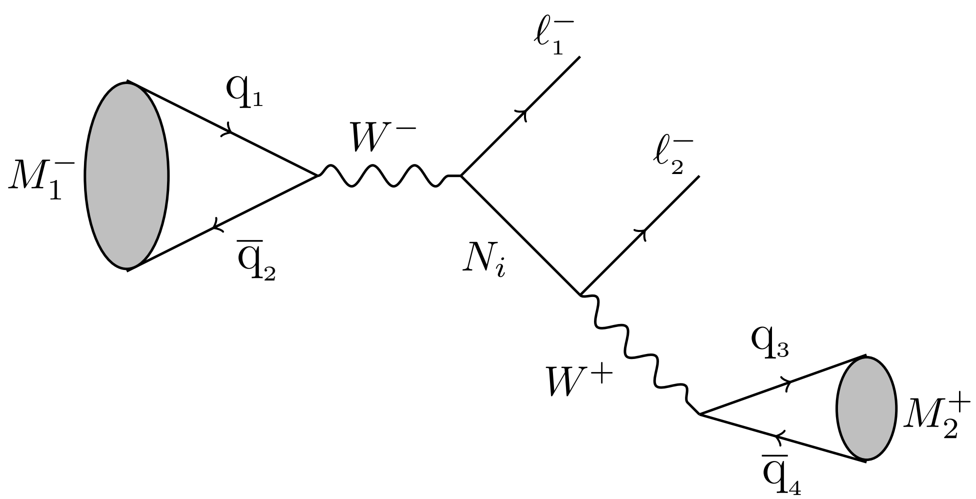
Active-sterile mixing

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W^-_\mu \bar{\ell}\gamma^\mu P_L V_{\ell j} N_j + \text{H.c.},$$

Additional term in CC interaction

If RHN are Majorana type and mass of few GeV then LNV meson decay $M_1^- \to \ell_1^- \ell_2^- M_2^+$

$$M_1^- \to \ell_1^- N, N \to \ell_2^- \pi^+$$

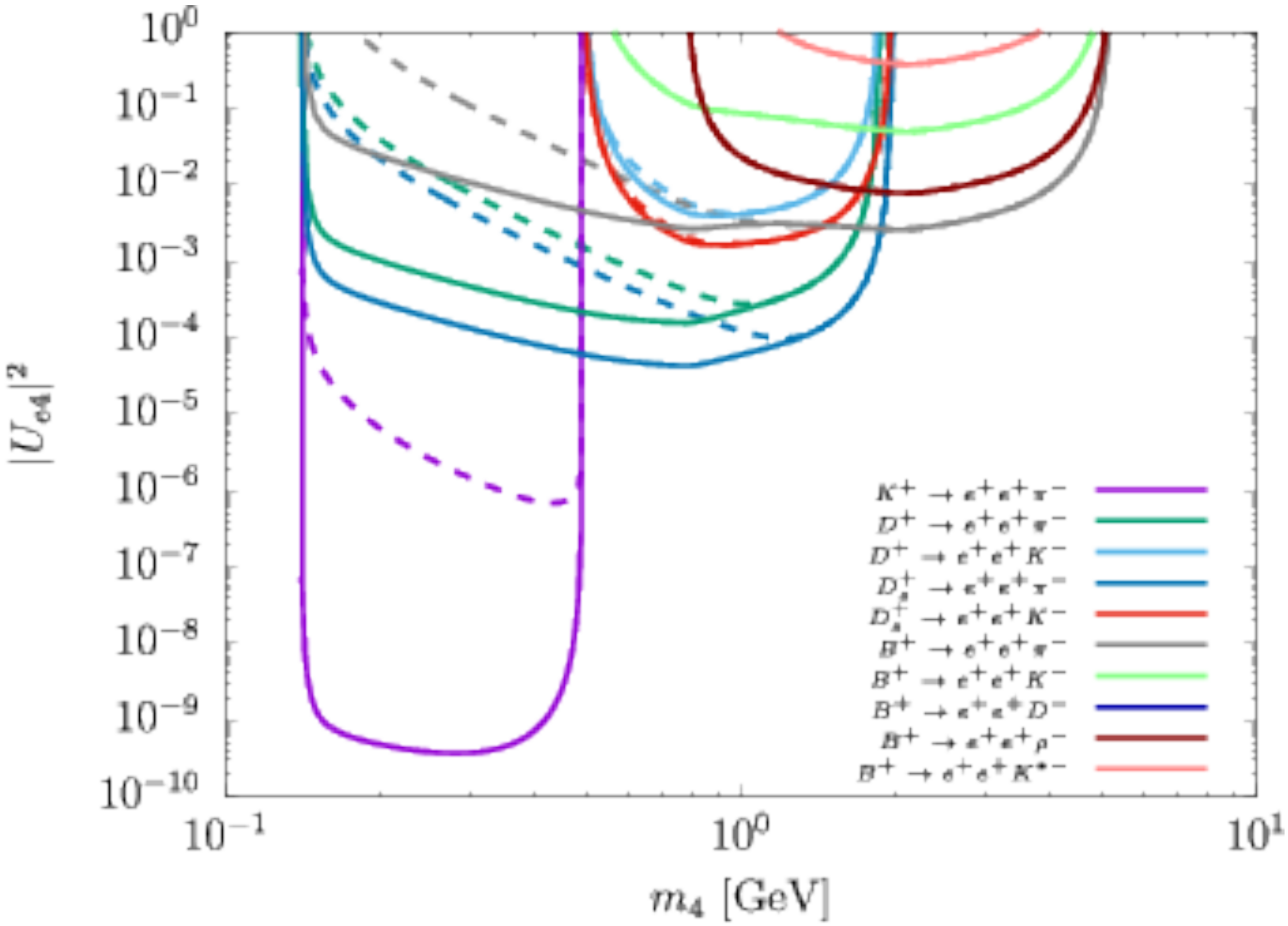


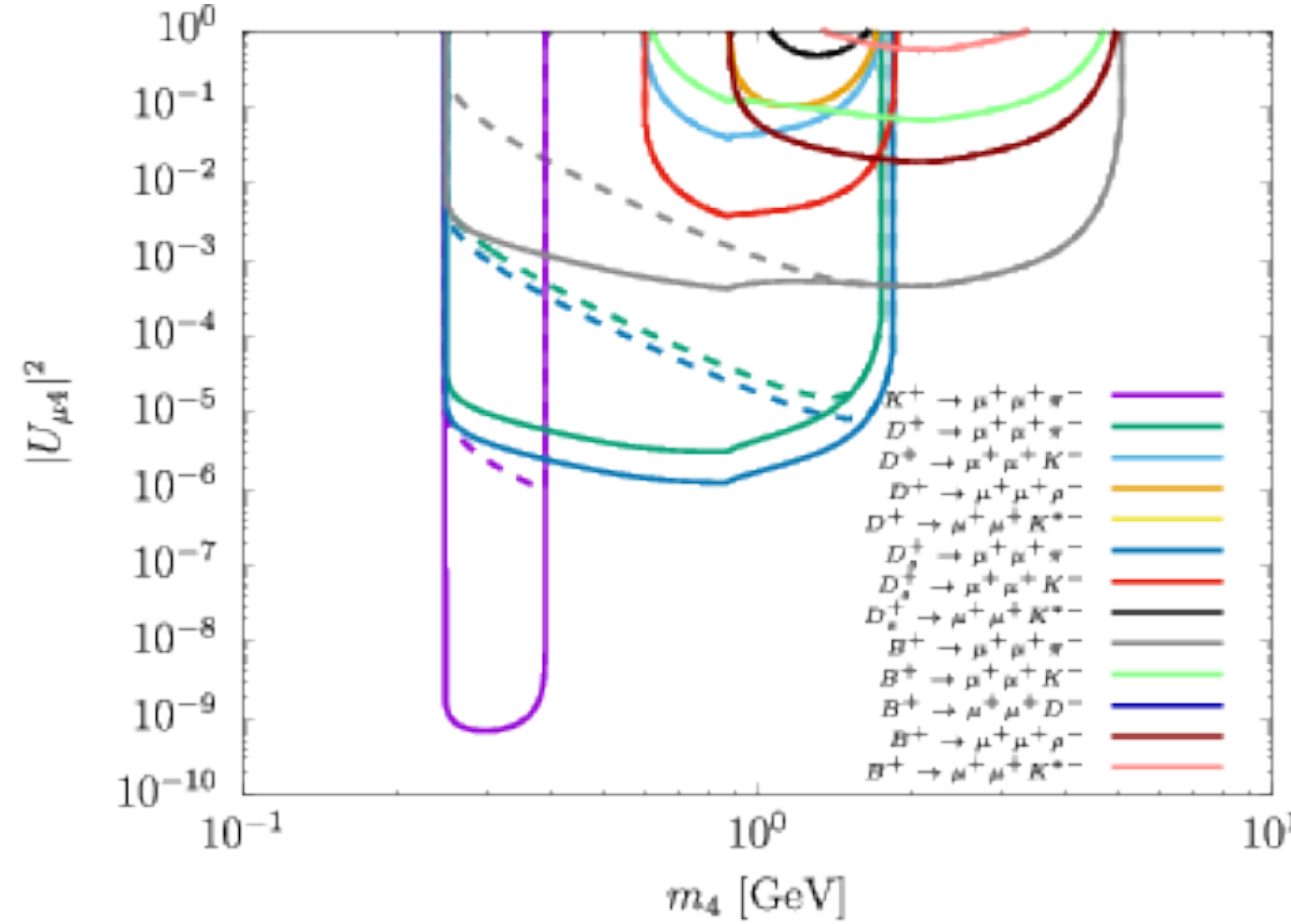
If the mass of N lies in the range ~(100 MeV - 5 GeV), N on shell

$$N_{\text{event}} = f(M_N, V_{\ell N}, p_{M_1}, L_D)$$

Assumption: Mass and mixing elements are free parameters, constrained only by experimental conservations.

Advantage compare to $0\nu\beta\beta$ *: lesser uncertainties in the meson decay constant compare to nuclear matrix elements.*





A. Atre, T. Han, S. Pascoli and B. Zhang, arXiv:0901.3589

Dashed lines are with detector probability

J.C. Hello et al, arXiv:1005.1607

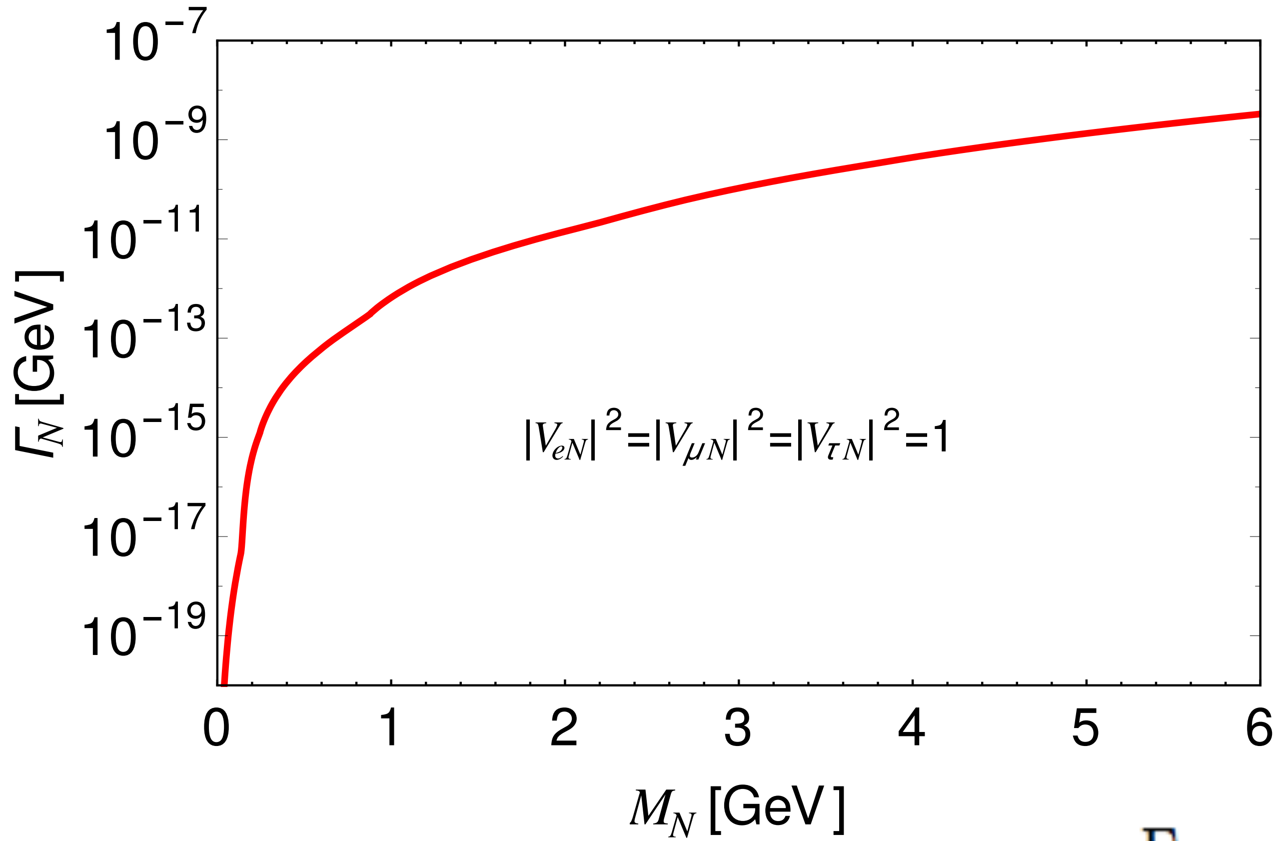
Asmaa Abada et al, JHEP 02 (2018) 169

Inclusion of parent meson momentum will change the bound on mixing angles

For the mass range 0.1-0.4 GeV, tightest bound comes from $K^+ \to e^+ e^+ \pi^-$

For the mass range 0.4-2 GeV, tightest bound comes from $D_s^+ \to e^+ e^+ \pi^-$

For the mass range 2-5 GeV, tightest bound comes from $B^+ \to e^+ e^+ \pi^-$



$$\Gamma_{N_i} = \sum_{\ell,P} 2\Gamma^{\ell^- P^+} + \sum_{\ell,P^0} \Gamma^{\nu_\ell P^0} + \sum_{\ell,V} 2\Gamma^{\ell^- V^+} + \sum_{\ell,V^0} \Gamma^{\nu_\ell V^0} + \sum_{\ell_1,\ell_2(\ell_1\neq\ell_2)} 2\Gamma^{\ell_1\ell_2\nu_{\ell_2}} + \sum_{\ell_1,\ell_2} \Gamma^{\nu_{\ell_1}\ell_2\ell_2} + \sum_{\nu_{\ell_1}} \Gamma^{\nu_{\ell_1}\nu\bar{\nu}}. \quad (2)$$

where, $\ell = e, \mu, \tau$, $P^+ = \pi^+, K^+, D^+, D_s^+$, $P^0 = \pi^0, \eta, \eta', \eta_c$, $V^+ = \rho^+, K^{*+}, D^{*+}, D_s^{*+}$, $V^0 = \rho^0, \omega, \phi, J/\psi$, $\ell_1, \ell_2 = e, \mu, \tau, \ell_1 \neq \ell_2$.

$$\Gamma_N = a_e(m_N) \mid V_{eN} \mid^2 + a_\mu(m_N) \mid V_{\mu N} \mid^2 + a_\tau(m_N) \mid V_{\tau N} \mid^2$$

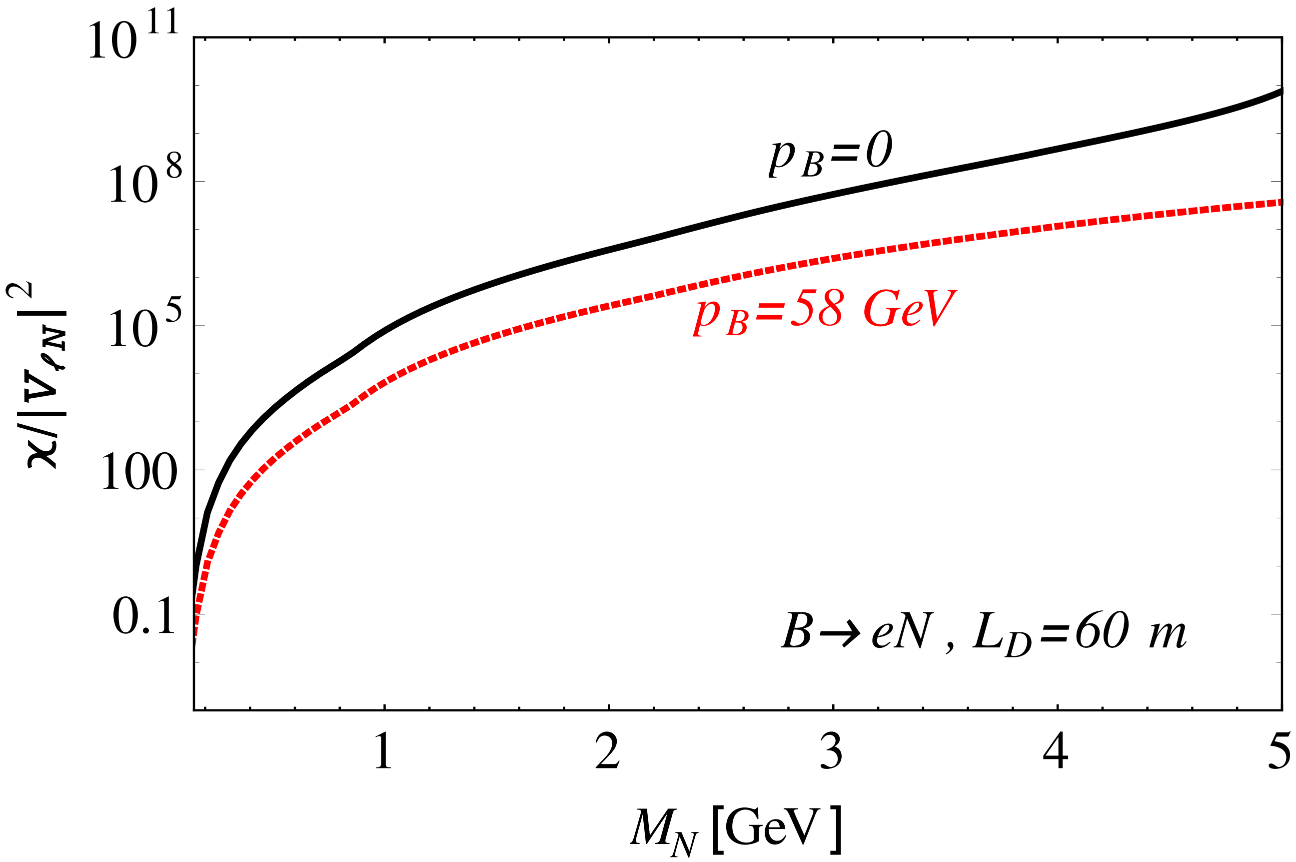
Narrow width approximation: $|M|^2 \propto \frac{1}{(p_N^2 - M_N^2)^2 + M_N^2\Gamma_N^2} \propto \frac{\pi}{M_N\Gamma_N}\delta(p_N^2 - M_N^2)$

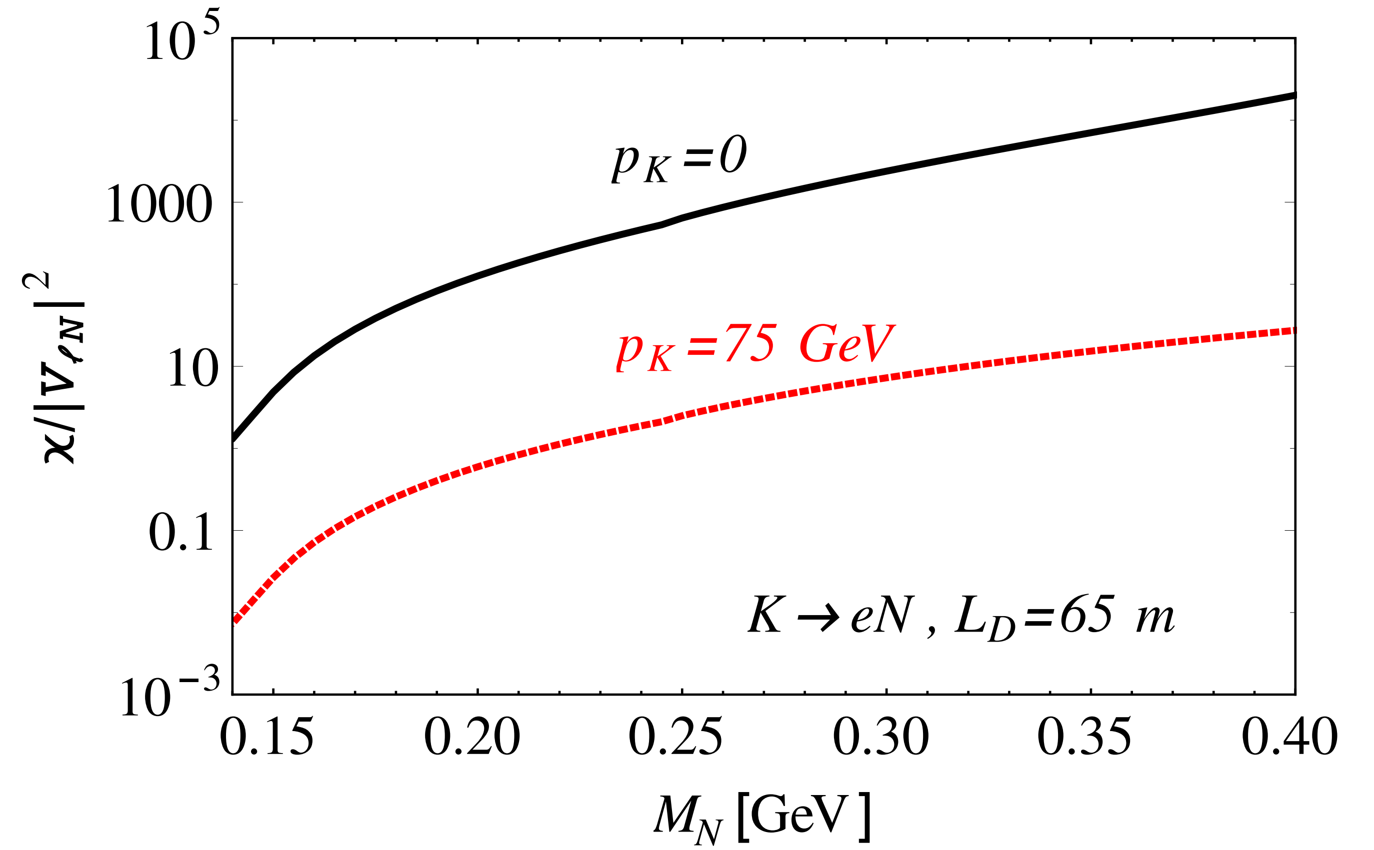
Detector probability: $\mathcal{P}_N = 1 - \exp\left(-L_D\Gamma_N\frac{M_N}{p_N}\right) = 1 - \exp\left(-\frac{L_D}{L_N}\right) = 1 - \exp(-x)$

For x>>1 (for large detector length and small decay length): $\mathcal{P}_N \approx 1$

Probability factor depends on three momentum p_N *which in turn depends on the velocity of decaying meson*

In decaying meson rest frame: $p_N = p_N^* = \frac{m_{M_1}}{2}\lambda^{\frac{1}{2}}\left(1, \frac{m_\ell^2}{m_{M_1}^2}, \frac{M_N^2}{m_{M_1}^2}\right)$





x decreases for fixed mixing angle in the case of meson decay in flight compared to meson decay at rest

For small x, $\mathcal{P}_N$ is also small

Hence the probability of RH neutrino to decay inside the detector is smaller in the case of meson decay in flight compared to meson decay at rest

As a result, compared to meson decay at rest, in the case of meson decay in flight we get lesser number of events => a rather loose bound on mixing angle

Assuming the parent meson decays at rest, the expected number of events:

$$N_{event} = 2N_{M_1^+}\mathrm{Br}\left(M_1^+ \to \ell^+\ell^+M_2^-\right)\mathcal{P}_N; \\ \approx 2N_{M_1^+}\mathrm{Br}\left(M_1^+ \to \ell^+N_i\right)\frac{\Gamma(N_i \to \ell^+M_2^-)}{\Gamma_{N_i}}\mathcal{P}_N;$$

$$\mathcal{P}_N = \left[1 - exp\left(-\frac{M_{N_i}\Gamma_{N_i}L_D}{p^*_{N_i}}\right)\right].$$

L_D *is the detector length*

For the case of meson decay in flight:

The energy E_{N_i} *of the* N_i *in the boosted* M_1 *frame lies in the range,*

$$E_{N_i} = \left[\left(\gamma E^*_{N_i} - p^*_{N_i}\sqrt{\gamma^2-1}\right), \left(\gamma E^*_{N_i} + p^*_{N_i}\sqrt{\gamma^2-1}\right)\right]$$

Hence, the energy distribution of N can be written as,

$$\frac{1}{\Gamma\left(M_1^+ \to \ell^+N_i\right)}\frac{d\Gamma\left(M_1^+ \to \ell^+N_i\right)}{dE_{N_i}} = \frac{1}{2p^*_{N_i}\sqrt{\gamma^2-1}}$$

The signal events for this case is:

$$N_{event} \approx 2N_{M_1^+}\int_{E^-_{N_i}}^{E^+_{N_i}} dE_{N_i}\mathrm{Br}\left(M_1^+ \to \ell^+N_i\right) \frac{m_{M_1}}{2p^*_{N_i}\left|\vec{p}_{M_1}\right|}\frac{\Gamma(N_i \to \ell^+M_2^-)}{\Gamma_{N_i}}\mathcal{P}'_N$$

Inputs for different experiments

NA62

$$N_K = 1.35 \times 10^{13},\ L_D = 100\,m,\ \beta_K = 75\,\mathrm{GeV}$$

Belle II

$$N_D = 3.4 \times 10^{10},\ N_{D_s} = 10^{10},\ N_B = 5.5 \times 10^{10}$$
$$L_D = 1.5\,\mathrm{m},\ \beta_{D,D_s,B} \approx 0$$

LHCb

$$N_D = 5 \times 10^{12},\ N_{D_s} = 2.3 \times 10^{12},\ N_B = 7.7 \times 10^{11}$$
$$L_D = 20\,\mathrm{m},\ \beta_{D,B} = 100\,\mathrm{GeV}$$

FCC

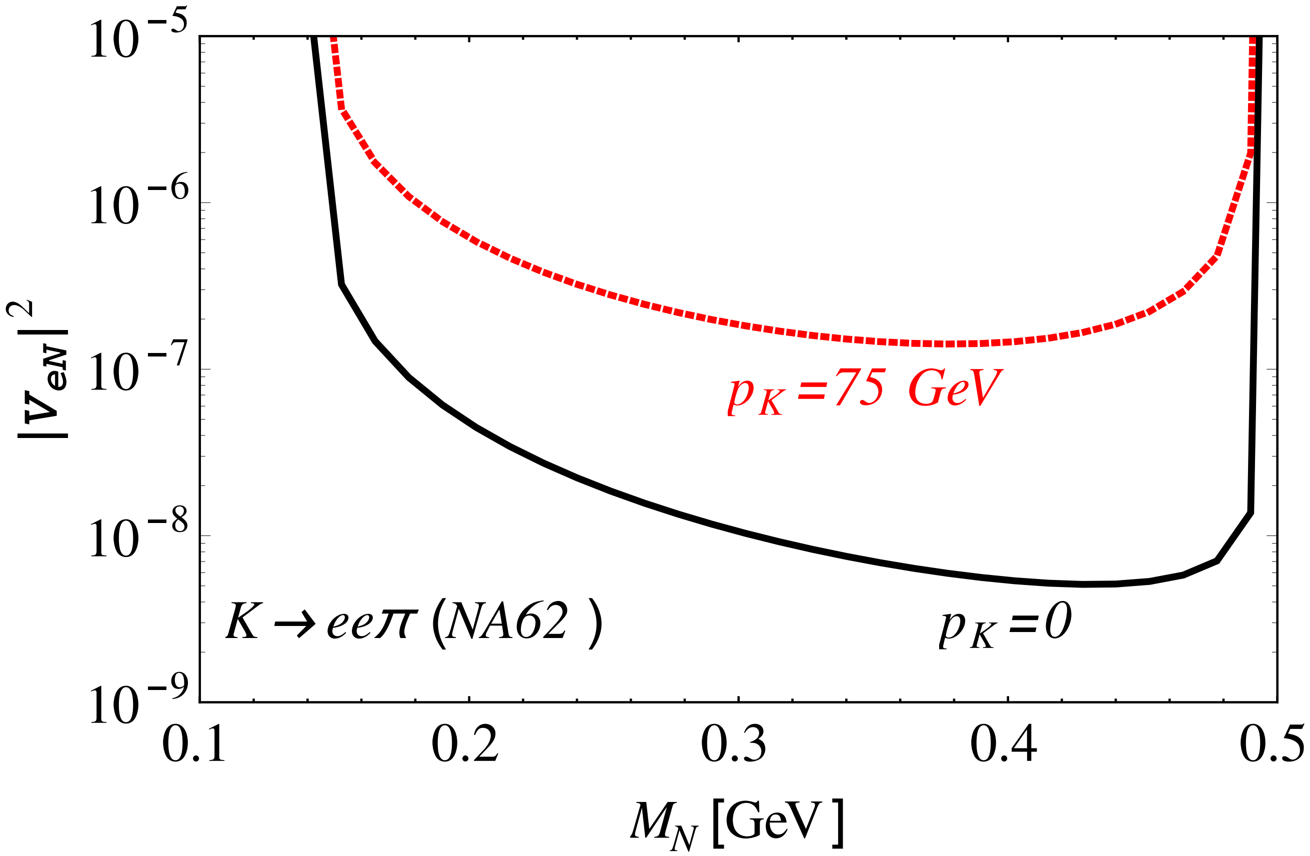
$$N_B = 6 \times 10^{11},\ L_D = 2\,\mathrm{m},\ \beta_B = \frac{M_Z}{2}$$

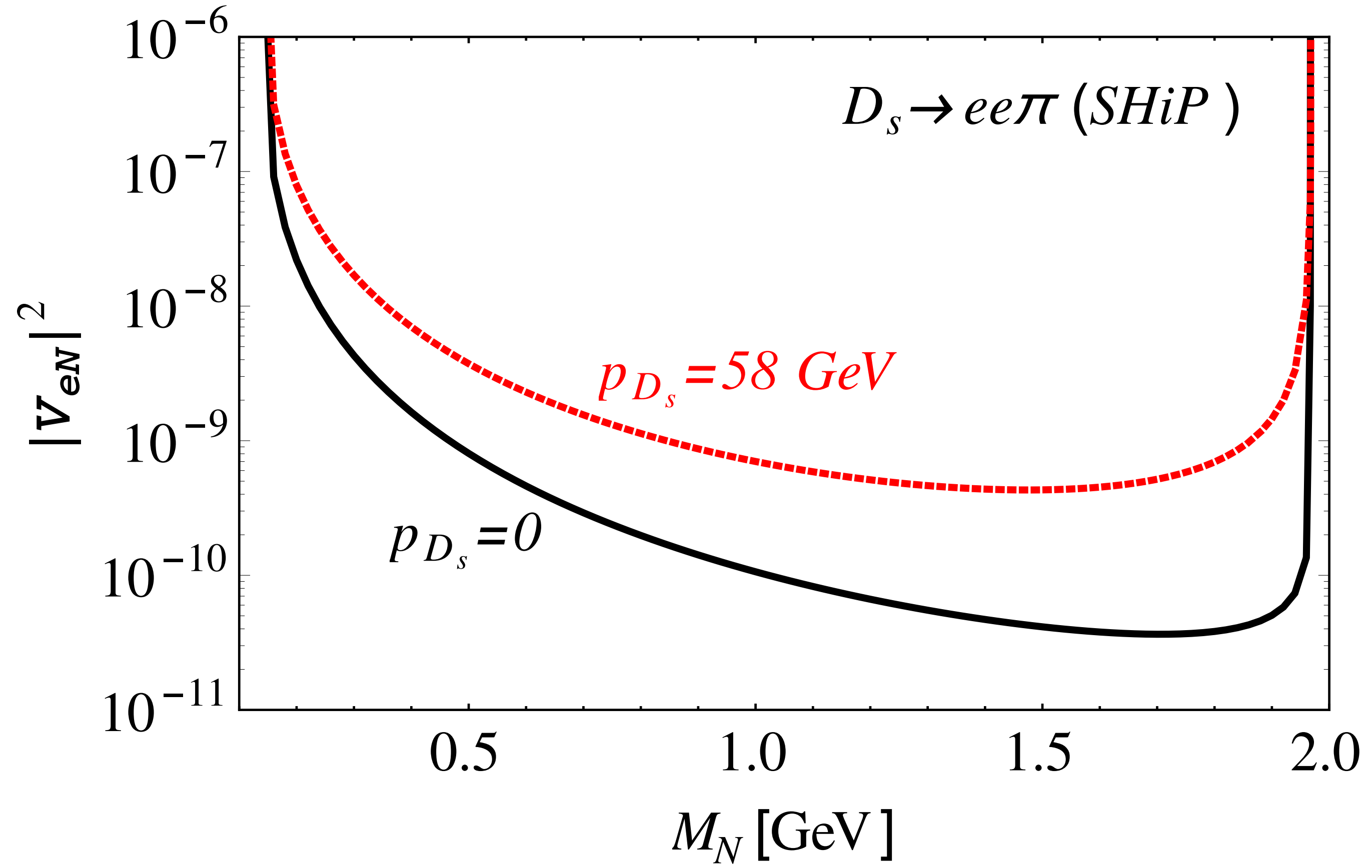
SHiP

$$N_D = 1.02 \times 10^{17},\ N_{D_s} = 2.72 \times 10^{16},\ L_D = 60\,\mathrm{m},$$
$$\beta_{D,D_s} = 58\,\mathrm{GeV}$$

MATHUSLA

$$N_B = 5.7 \times 10^{14},\ N_D = 5.4 \times 10^{13},\ \langle\gamma_B\rangle = 2.3,\ \langle\gamma_D\rangle = 2.6,\ L_D = 38\,\mathrm{m}.$$





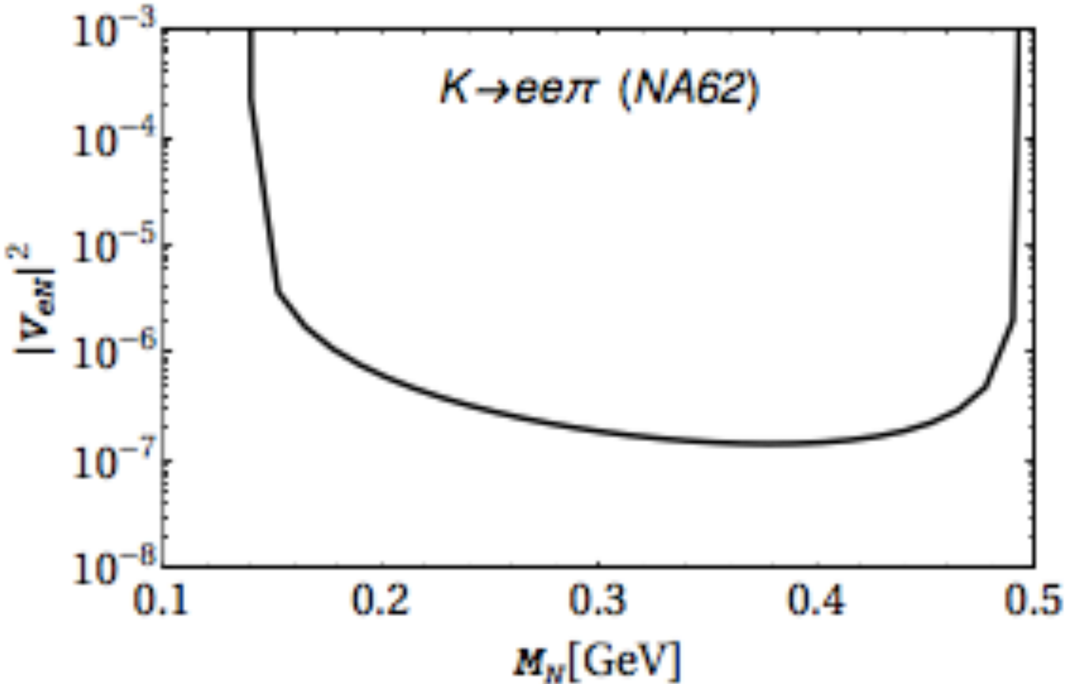
Obtained mixing angles are loose in case of meson decay at flight compared to meson decay at rest.

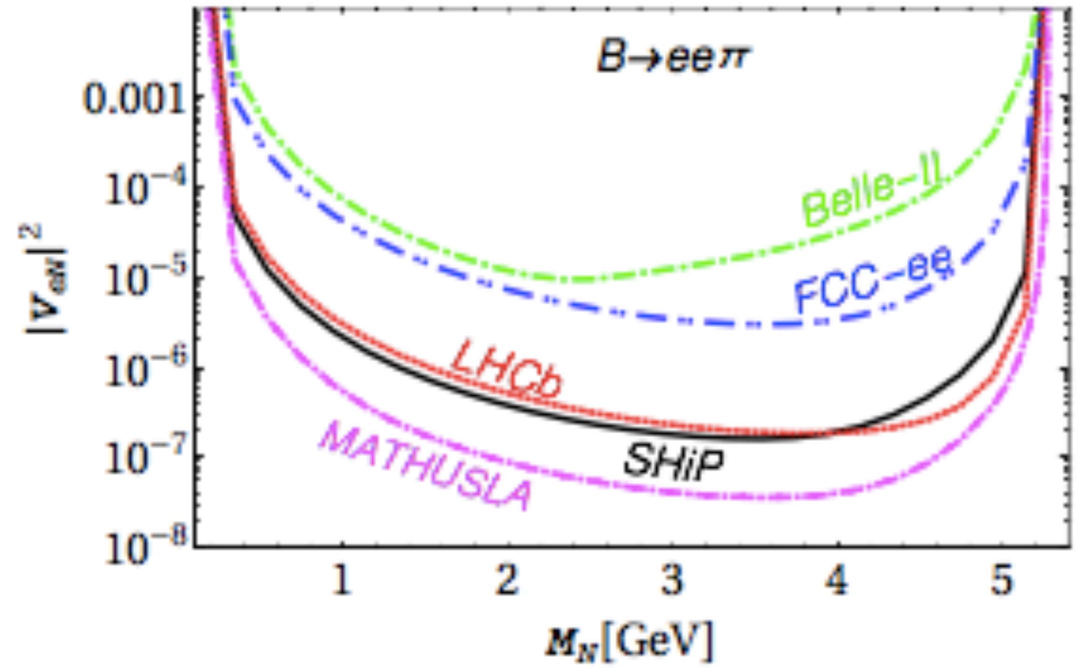
For K meson decay at NA62 and Ds meson decay at SHiP, there are order of 2 and 1 difference in the obtained mixing angle.

This shows that inclusion of parent meson momentum is indeed very important when calculating the bounds on mixing angles.

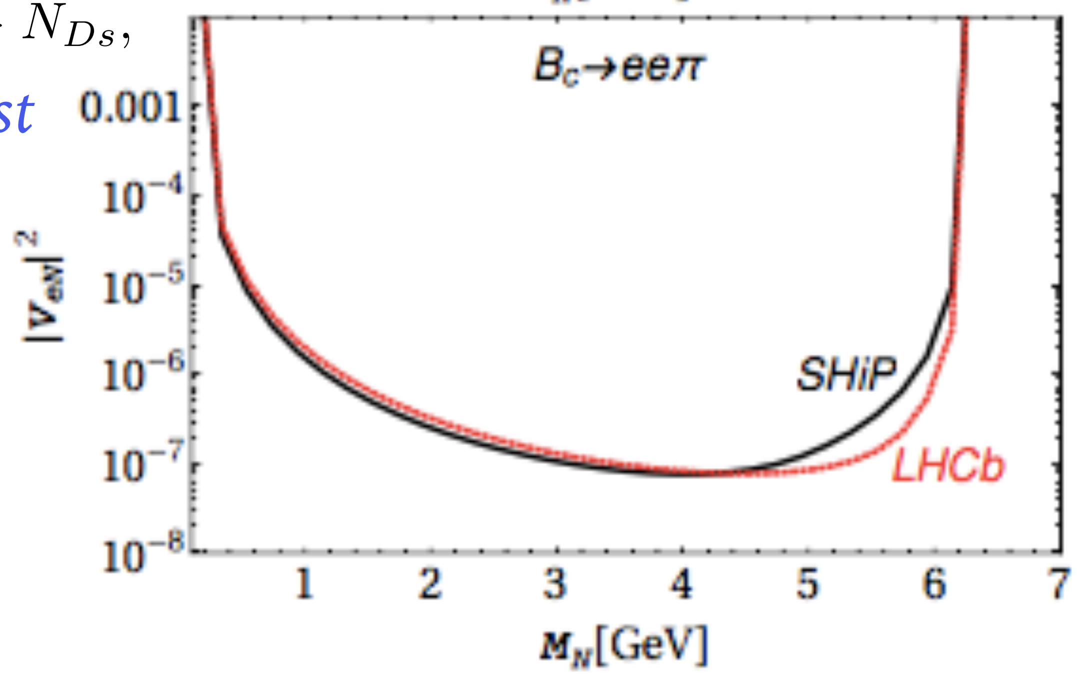
We find that including parent meson momentum, tightest bound in $0.14\,\mathrm{GeV} \leq M_N \leq 0.49\,\mathrm{GeV}$ *comes from Ds meson decay at SHiP instead of K meson decay*

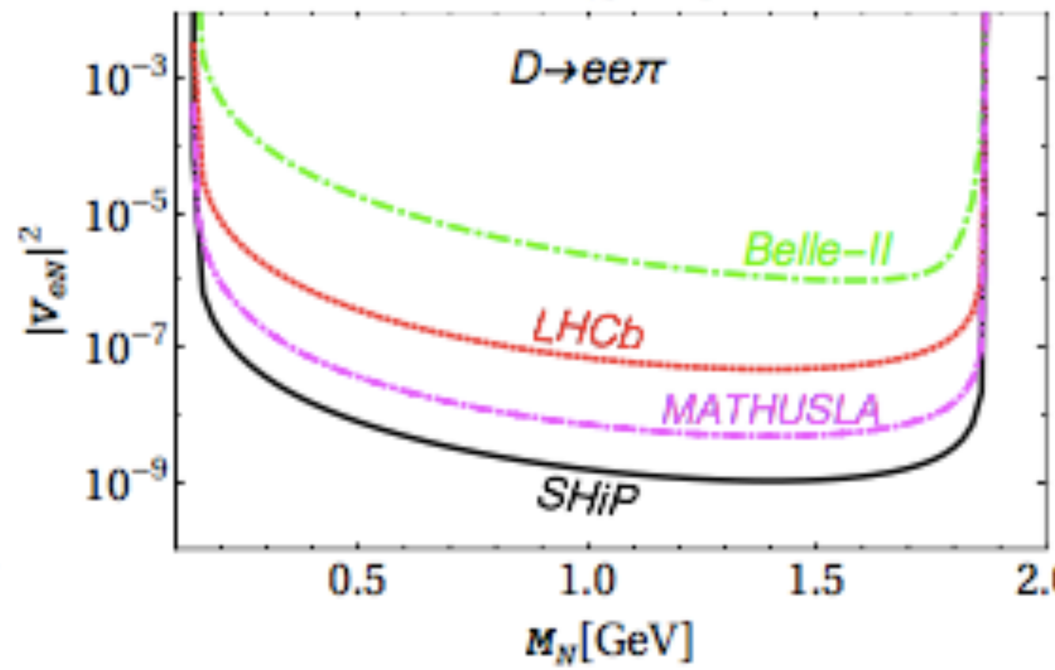
Similar results for $\mu\mu, e\mu$ **final states**





Though at SHiP $N_D > N_{Ds}$, *as* $V_{cs} > V_{cd}$, *tightest bound comes from Ds meson decay.*



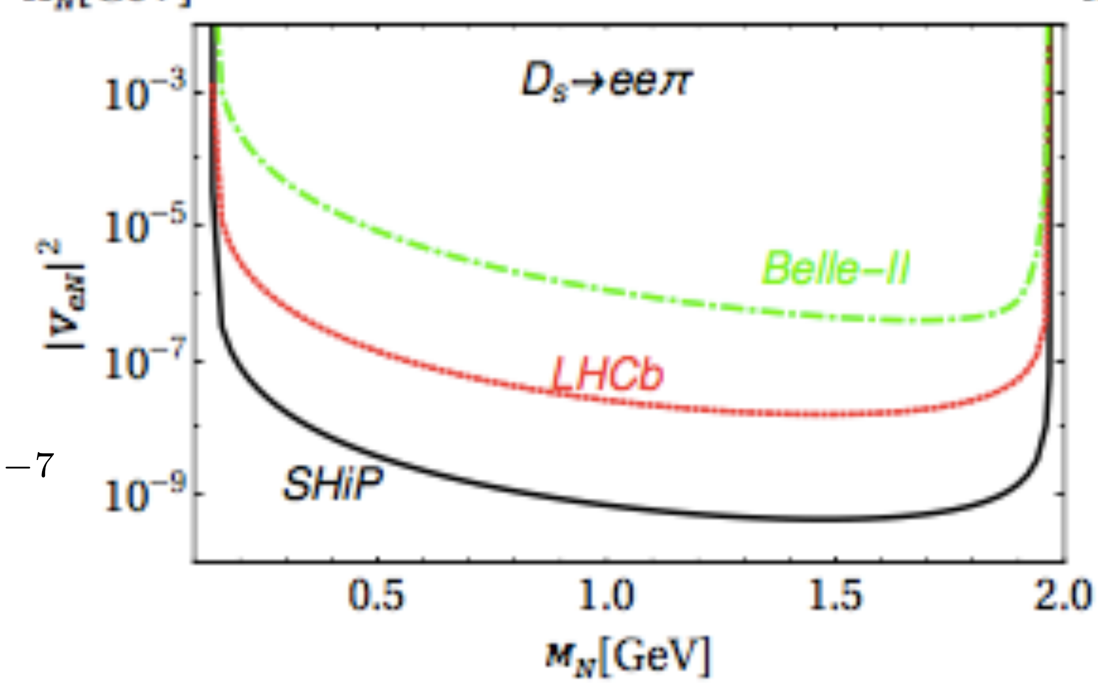


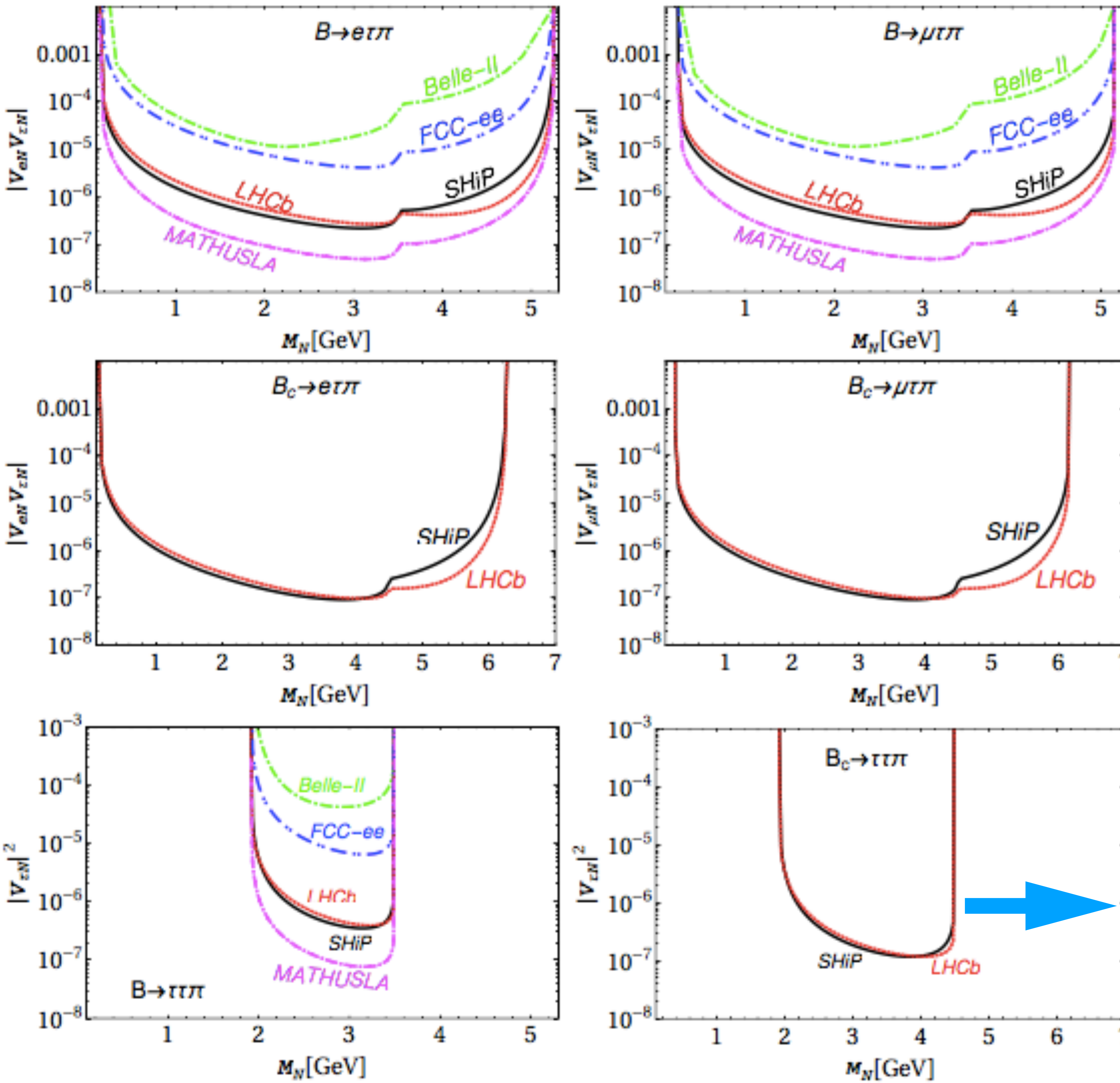
In mass range $0.14\,\text{GeV} \leq M_N \leq 1.9\,\text{GeV}$,

$|V_{eN}|^2, |V_{\mu N}|^2, |V_{eN} V_{\mu N}| \sim 10^{-9}$ **(SHiP)**

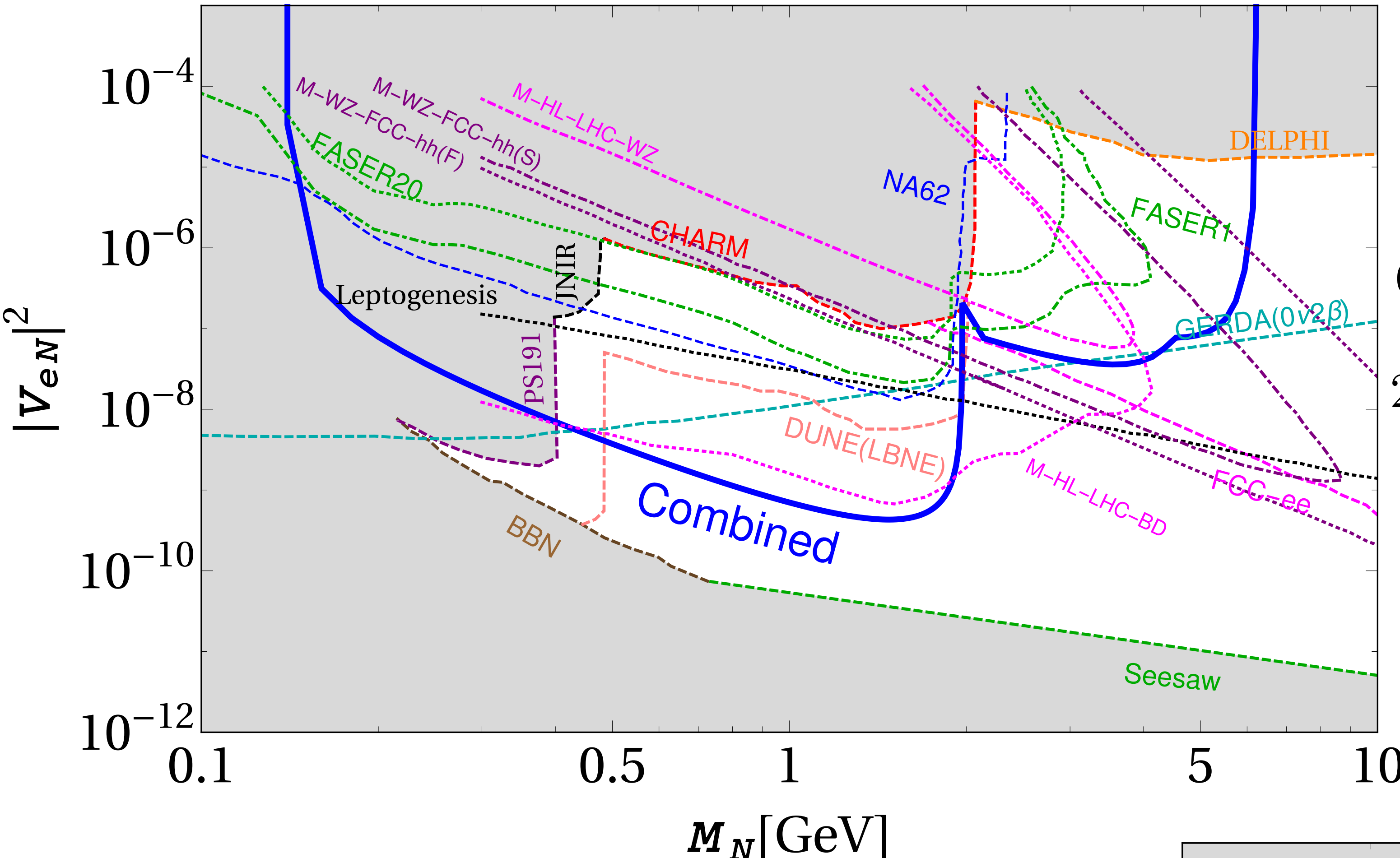
For $2\,\text{GeV} \leq M_N \leq 6\,\text{GeV}$,

SHiP
MATHUSLA $|V_{eN}|^2, |V_{\mu N}|^2, |V_{eN} V_{\mu N}| \sim 10^{-7}$





This was so far been unconstrained by any of the tau or other meson decays



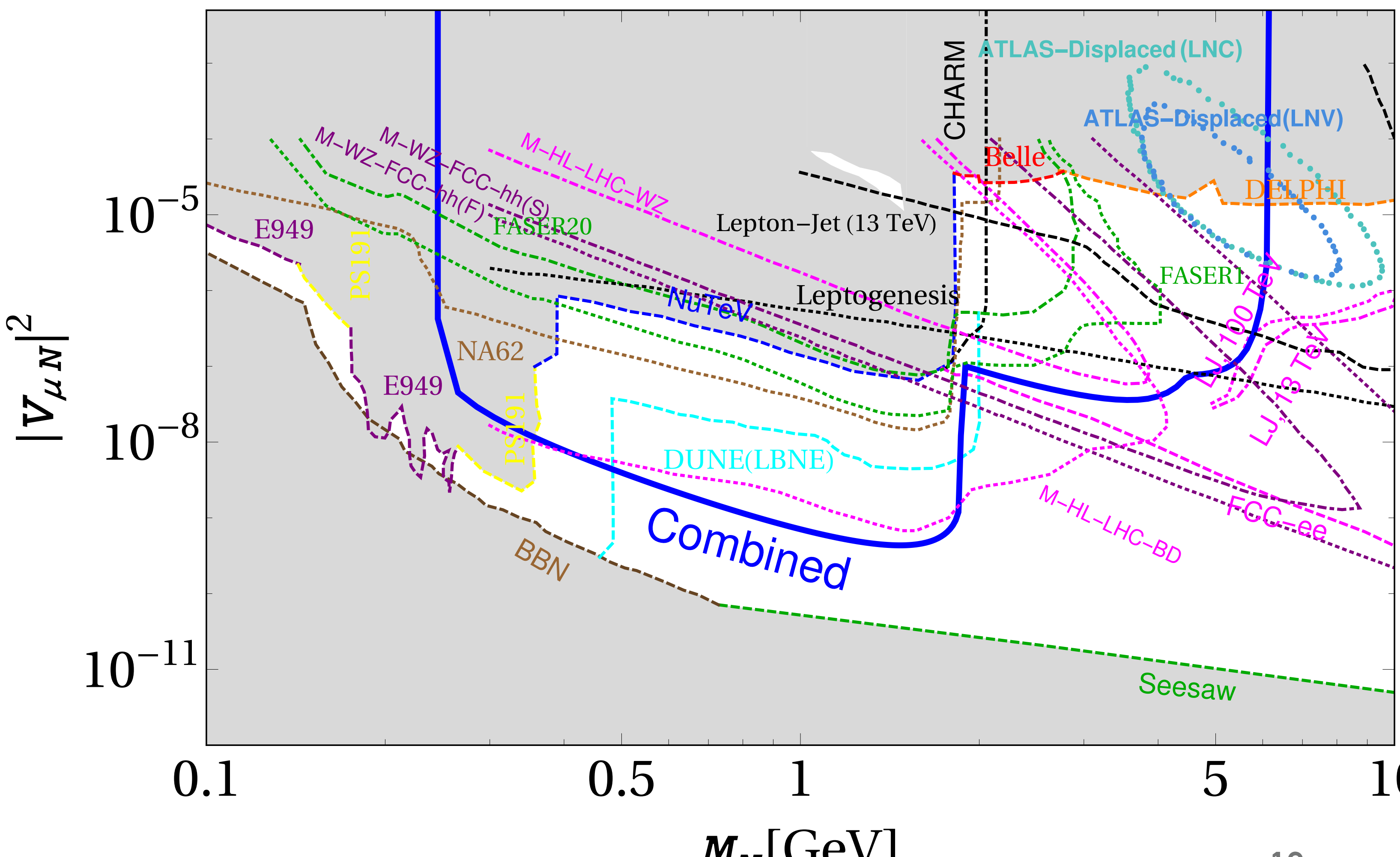
Combined tightest limit from ee channel.

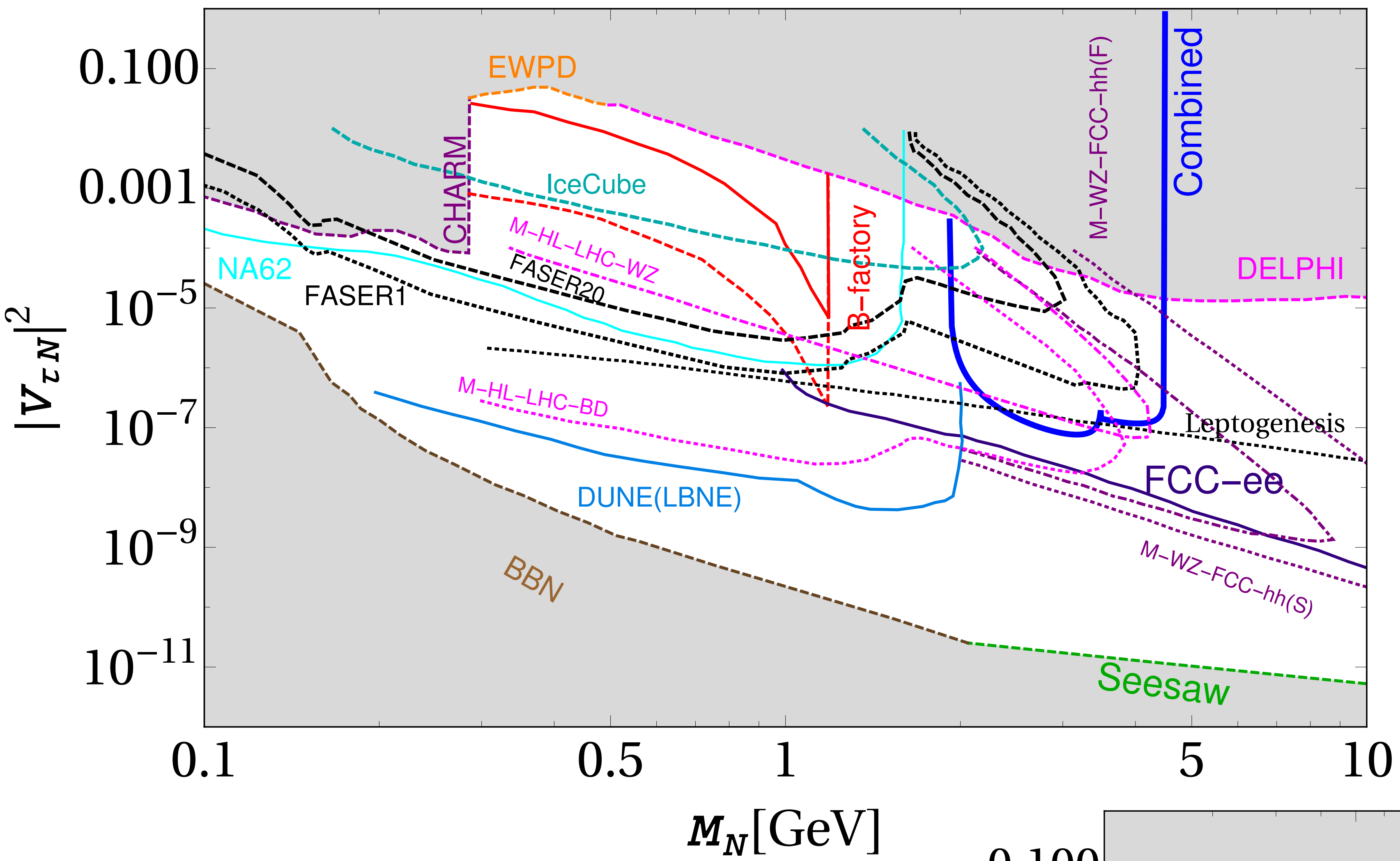
$0.14\,\text{GeV} \le M_N \le 1.9\,\text{GeV}$ → **Ds (SHiP)**

$2\,\text{GeV} \le M_N \le 5\,\text{GeV}$ → **B (MATHUSLA)**

$5\,\text{GeV} \le M_N \le 6\,\text{GeV}$ → **Bc (LHCb)**

Combined tightest limit from $\mu\mu$ *channel.*





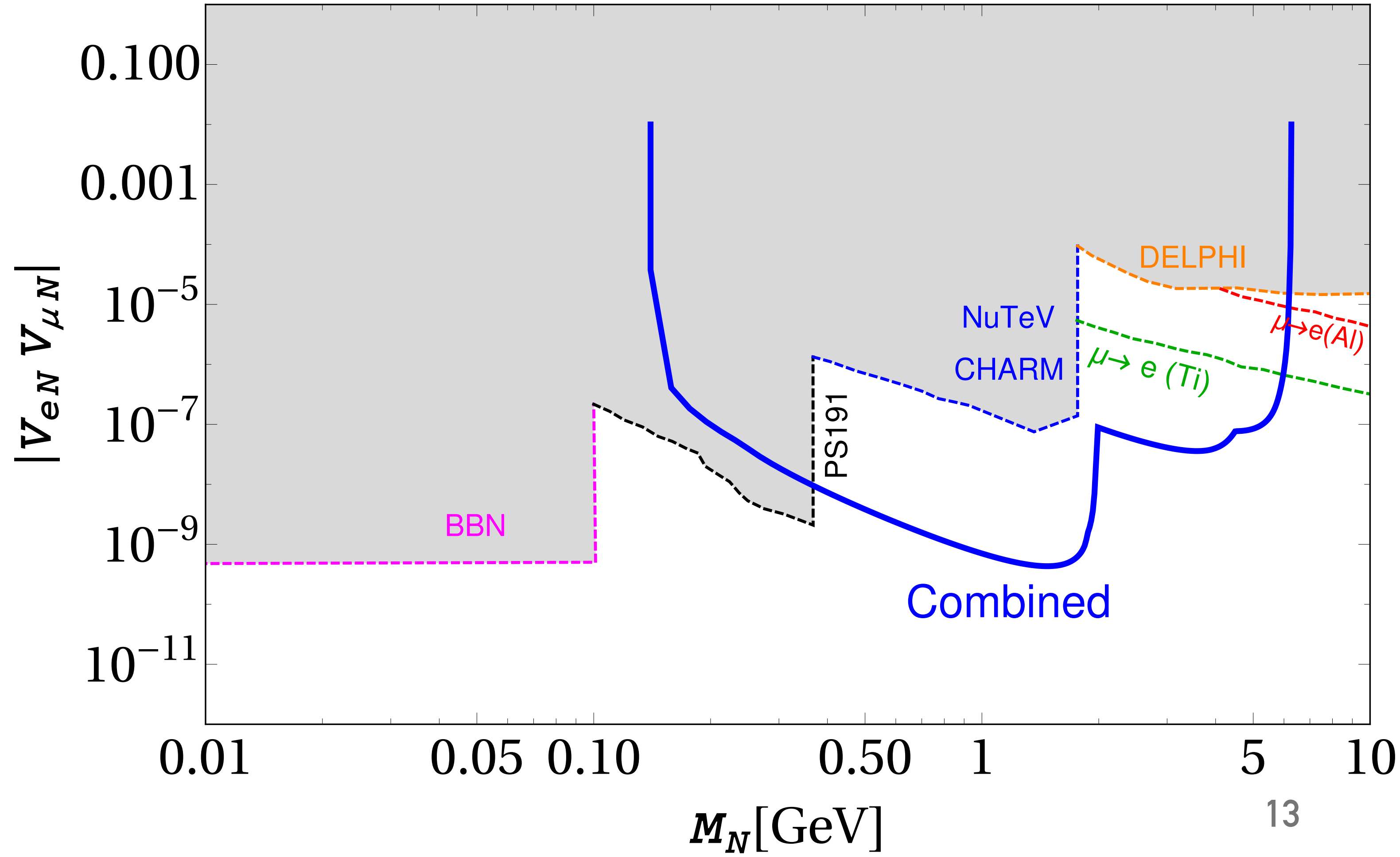
Combined tightest limit from

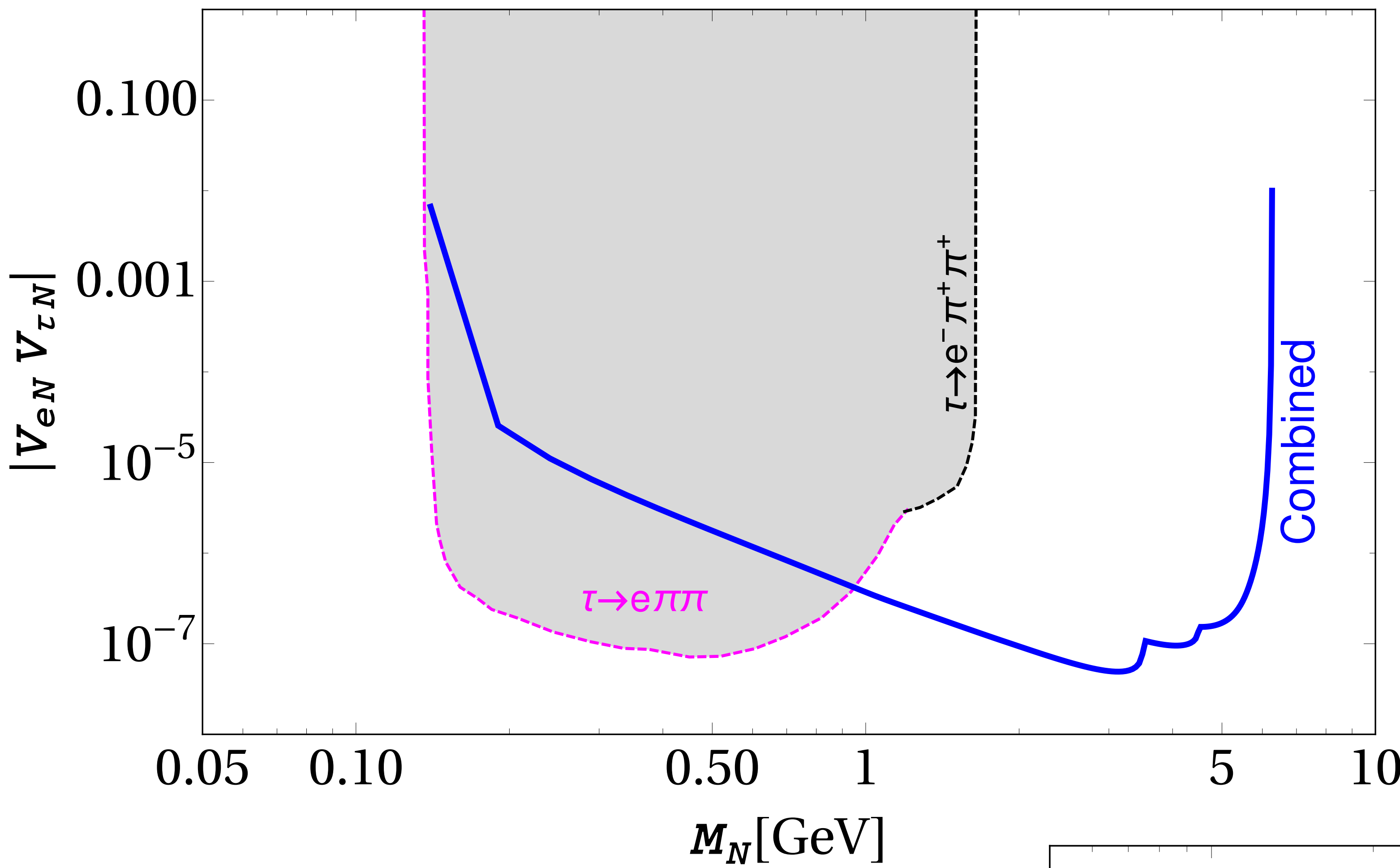
$\tau\tau$ *channel*

Comes from $B \to \tau\tau\pi$ **at MATHUSLA.**

Combined tightest limit from

$e\mu$ *channel*



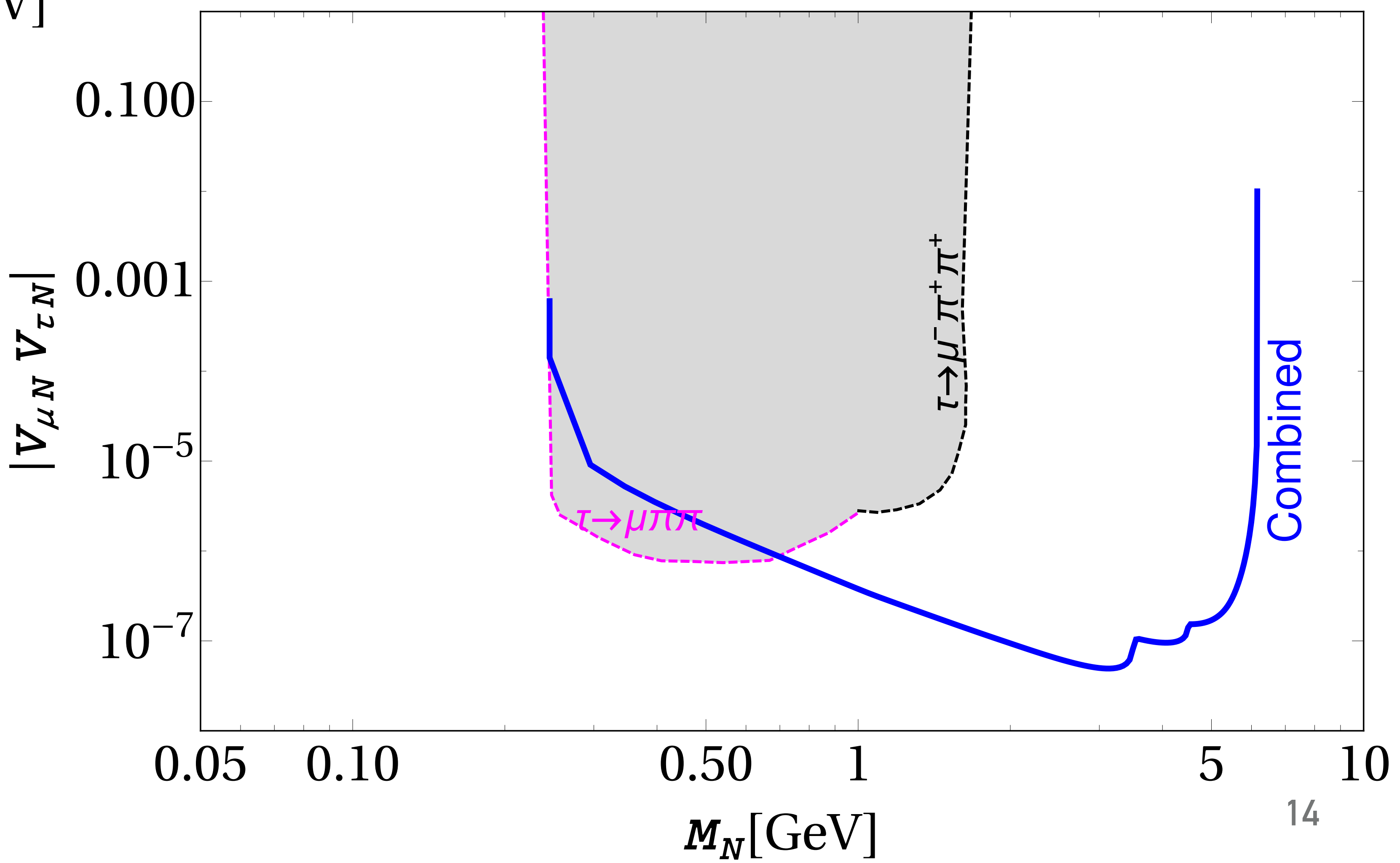


Combined tightest limit from

$e\tau$ *channel*

Combined tightest limit from

$\mu\tau$ *channel*



Conclusions

The meson decays are sensitive for low mass right handed neutrinos, (in few 100 MeV to few GeV range) in providing tight constraints on the light-sterile mixing angle.

These bounds are complementary to LHC, which is sensitive to few hundred GeV to TeV mass neutrinos.

We explore the effect of parent meson momentum on the sensitivity reach of the mixing in various experiments.

We find that inclusion of parent meson momentum can give one or two orders of magnitude shift in the mixing.

Searches for RH neutrinos, particularly Majorana sterile neutrinos need to be performed at all possible scale, as their discovery may provide hints of any new physics responsible for neutrino mass generation