[arXiv:1908.00376]

Probing sterile neutrino in meson decays with and without sequential neutrino decay

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We present the most systematic approach to discover a sterile neutrino N or constrain $|U_{\ell N}|^2$, the mixing between active neutrino ν_ℓ (with $\ell = \mu, \tau$) and the sterile neutrino N, from $B \to D \ell N$ decays. Our constraint on $\left|U_{\mu N}\right|^2$ achievable from Belle II data is comparable with that from the much larger data set of upgraded LHCb, even much better for mass of sterile neutrino $m_N < 2$ GeV. We can also probe the Dirac and Majorana nature of N by observing the sequential decay of N, including suppression factors associated with observation of a displaced vertex and helicity flip, for Majorana N.

Keywords: sterile neutrino; Majorana neutrino; leptonic decays; semileptonic decays; displaced vertex

Properties of sterile neutrino

- Mixing with SM ν

  Mixing parameter : U_{lN} SM : $B \to D\mu\nu$ BSM : $B \to D\mu N$

- Spin ½

  $B \to D^{*}\mu N$ & $B \to KNN$: S_N=1/2 **or 3/2**

  $B \to D\mu N$: S_N=**1/2 only**.

- Massive

  $\boldsymbol{p_N^2}$**=**$\boldsymbol{m_N^2}$. This allow us to consider $B \to D\mu + missing$ with $p_{missing}^2$=m_N^2

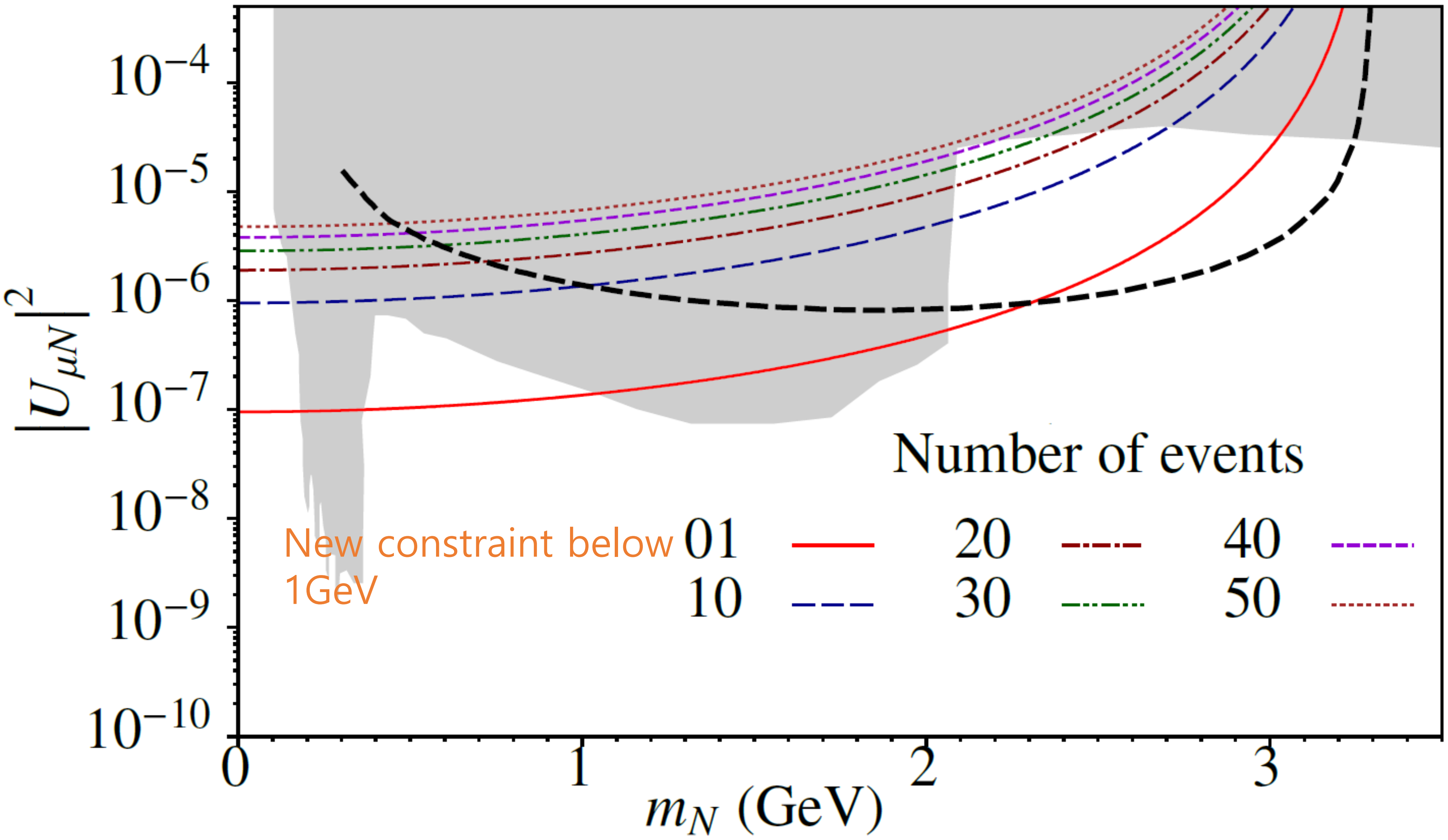
  (when all the other particle's momenta are known, **including** $\boldsymbol{p_B}$).

- Long-living

  $|U_{lN}|^2$ is already constraint to be very small that N will live long. It may or **may not** decay inside a detector.

- Majorana or Dirac

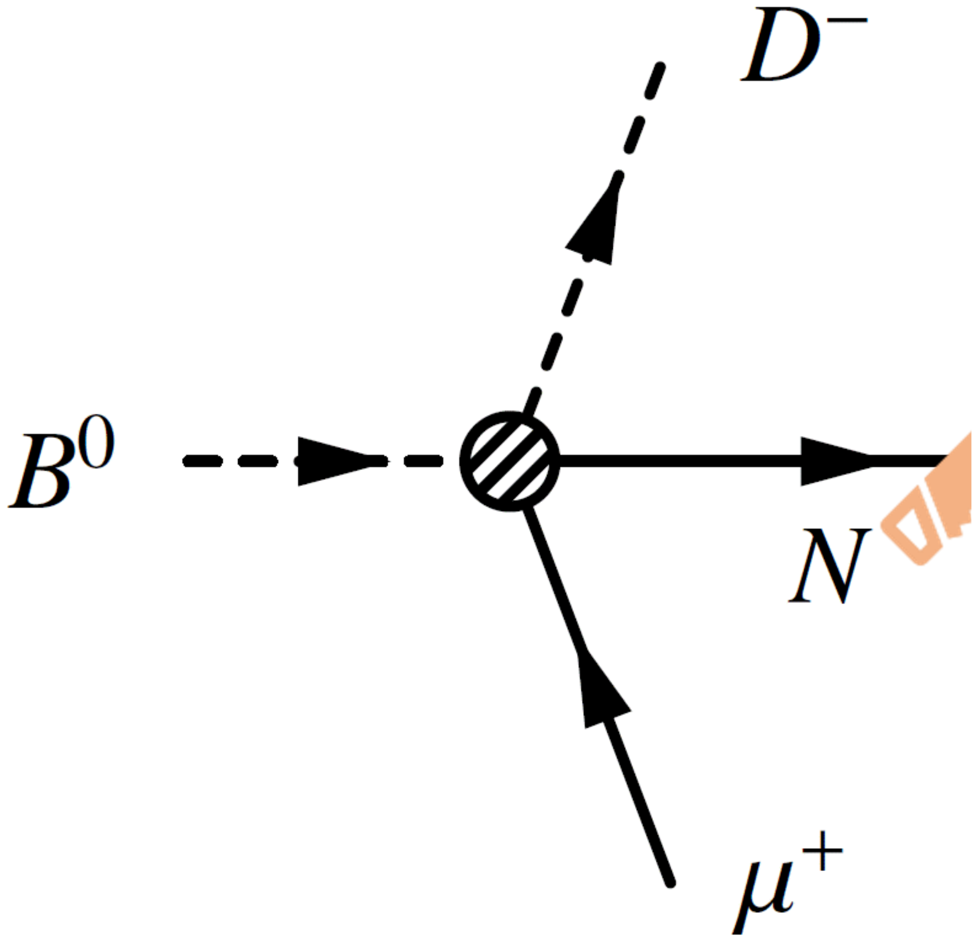
  N is Dirac or Majorana. We can distinguish it by observing LNV decay of N.



$|U_{\mu N}|^2$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
1
2
3
m_N (GeV)
Number of events
01
10
20
30
40
50
New constraint below 1GeV

We will revisit this, but only after anlyzing

Gorazd Cvetic and C. S. Kim(2019) [arXiv:1904.12858]



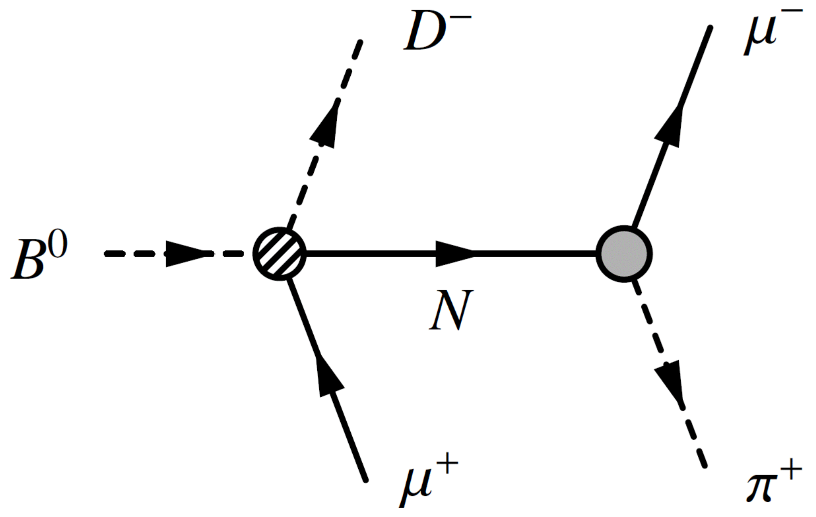
- Which has a better effective branching ratio (considering detector size).
- And wider kinematically allowed range for m_N

Assumptions

- One sterile neutrino m_N ~ GeV

  $\boldsymbol{m_\mu} + \boldsymbol{m_\pi} \leq m_N \leq m_B - m_D - m_\mu$
- N is on-shell

$\boldsymbol{B \to D\mu\mu\pi}$



Goal

- Find N or constrain $|U_{lN}|^2$
- And **Distinguish Majorana** nature of N
  LNV

Feature

- Displaced vertex due to small Γ_N.
  (eliminates background) But N **may or may not** decay inside a detector.

$$\frac{\overline{\Gamma}_{N\to\mu\pi}}{\overline{\Gamma}_N}\ [1 - exp(-\lambda t)]$$

Assumptions

- One sterile neutrino m_N ~ GeV

$$m_N \le m_B - m_D - m_\mu$$

- N is on-shell

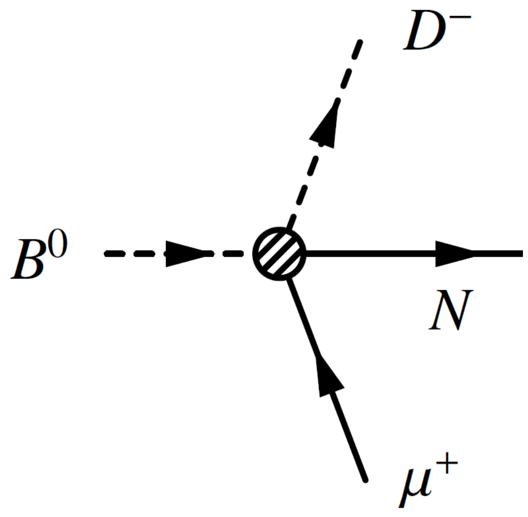
Goal

- Find N or constrain $|U_{lN}|^2$

Feature

- Fixed missing momentum squared $(p_B - p_D - p_\mu)^2 = m_N{}^2$ if N exists and has proper mixing values.

$B \to D\mu N$



Factoring $|U_{\mu N}|^2$ out of Γ(B→DμN) and Br(B→DμN)

- Define theoretically calculable quantities $\underline{Br}$, canonical branching ratio and $\underline{\Gamma}$, canonical decay width by factoring out unknown $|U_{\mu N}|^2$ from Br and Γ respectively.

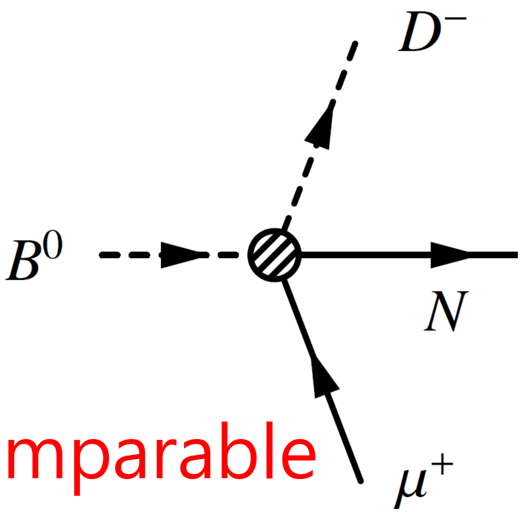
$$\Gamma(B \to D\mu N) = |U_{\mu N}|^2 \ \underline{\Gamma}(B \to D\mu N)$$

$$\mathrm{Br}(B \to D\mu N) = |U_{\mu N}|^2 \ \underline{\mathrm{Br}}(B \to D\mu N) = \frac{N_{B \to D\mu N}}{N_B}$$

- So we can find $|U_{\mu N}|^2$ (and $|U_{\tau N}|^2$) or constrain them with the formula

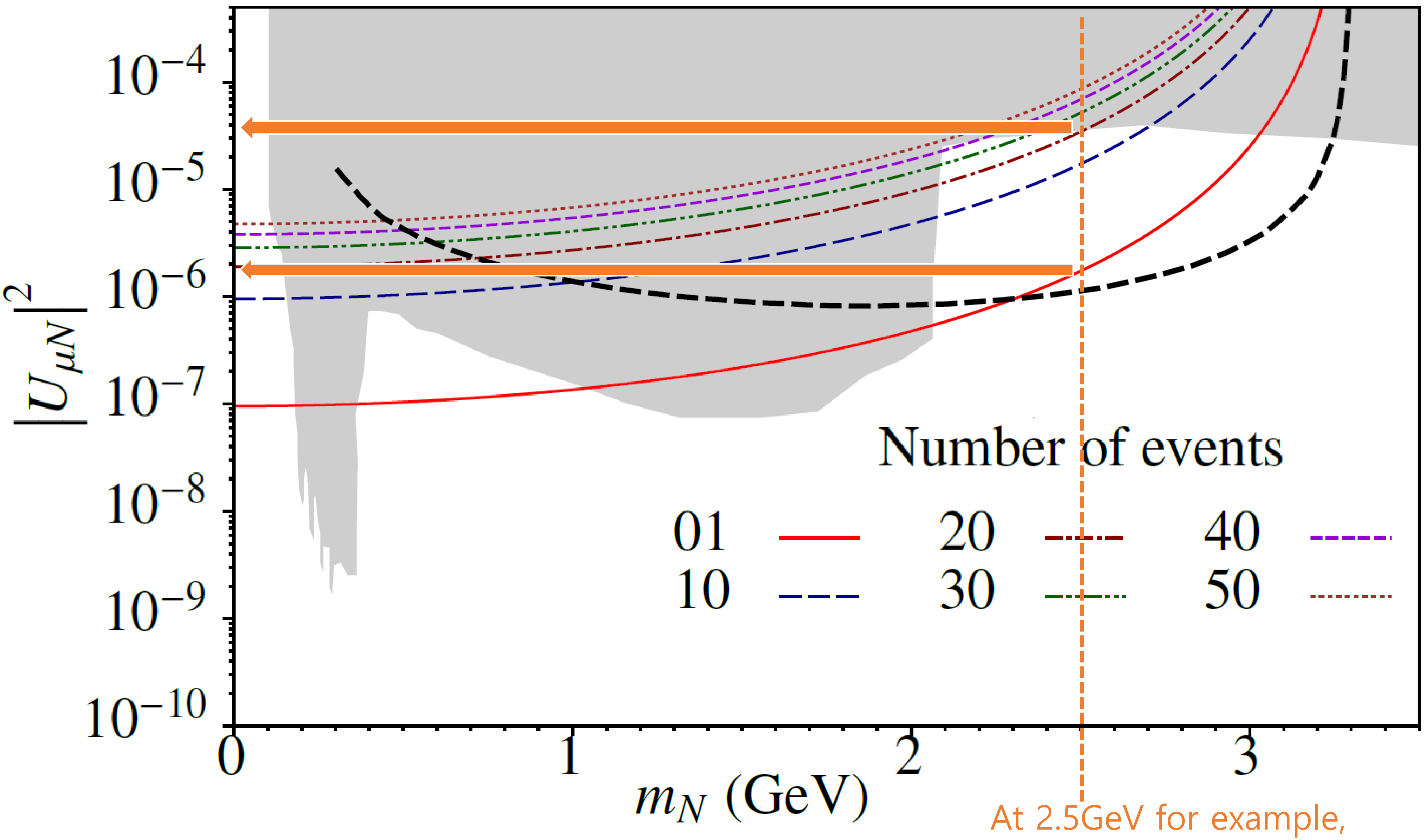
$$|U_{\mu N}|^2 = \frac{N_{B \to D\mu N}}{N_B \ \underline{\mathrm{Br}}(B \to D\mu N)}$$

$$|U_{\mu N}|^2 = \frac{N_{B\to D\mu N}}{N_B \ \underline{\mathrm{Br}}(B \to D\mu N)}$$



10000 times Less but the results are comparable

- $4.8 * 10^8$ fully reconstructed B mesons at Belle-II out of 10^{11}
- $4.8 * 10^{12}$ B mesons at LHCb
- But for first stage of our study (without considering decay of N), only Belle-II kind of experiment is available where all the momenta of Initial and final particle except N are measurable.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m_N (GeV)
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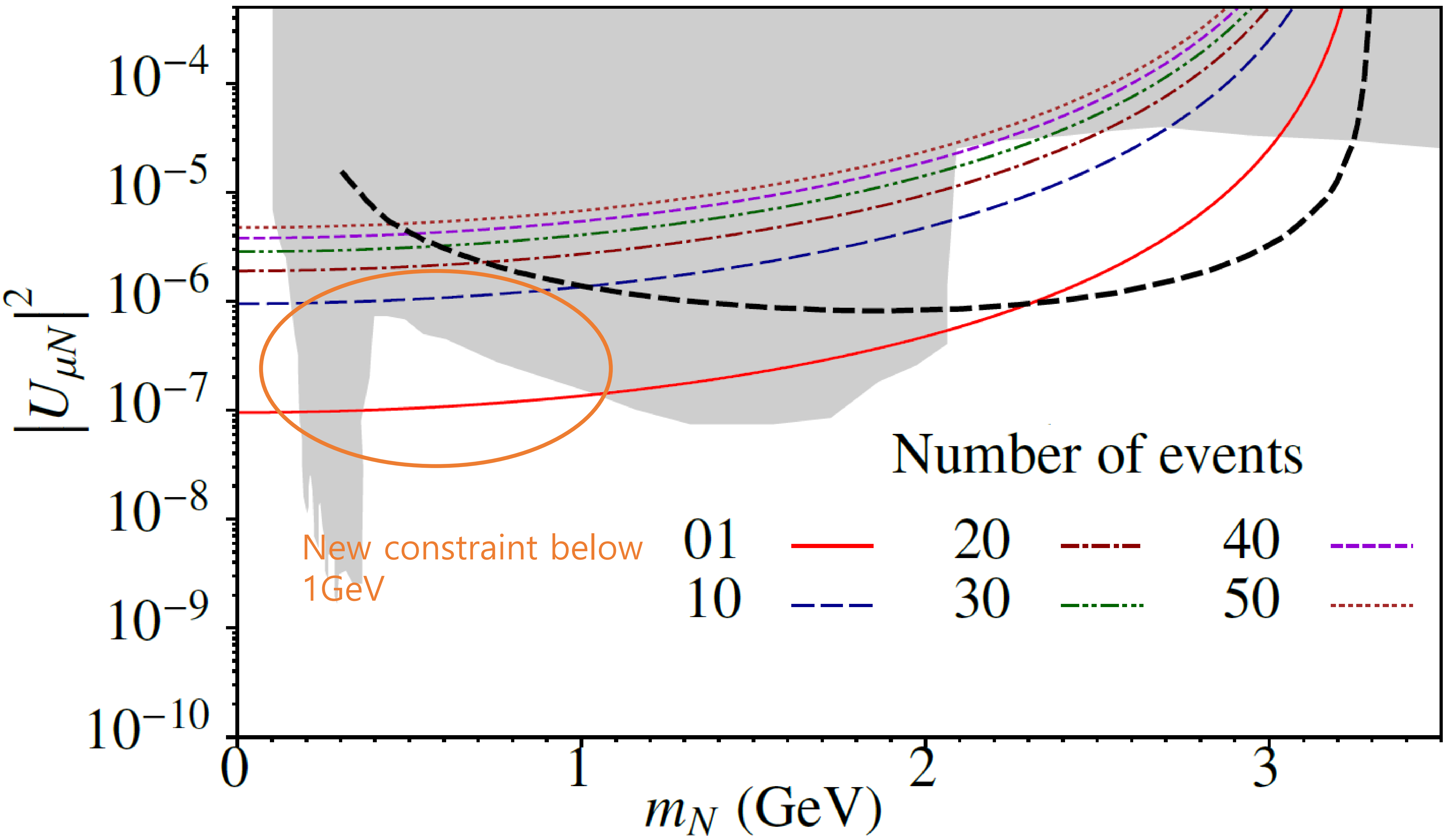
At 2.5GeV for example,



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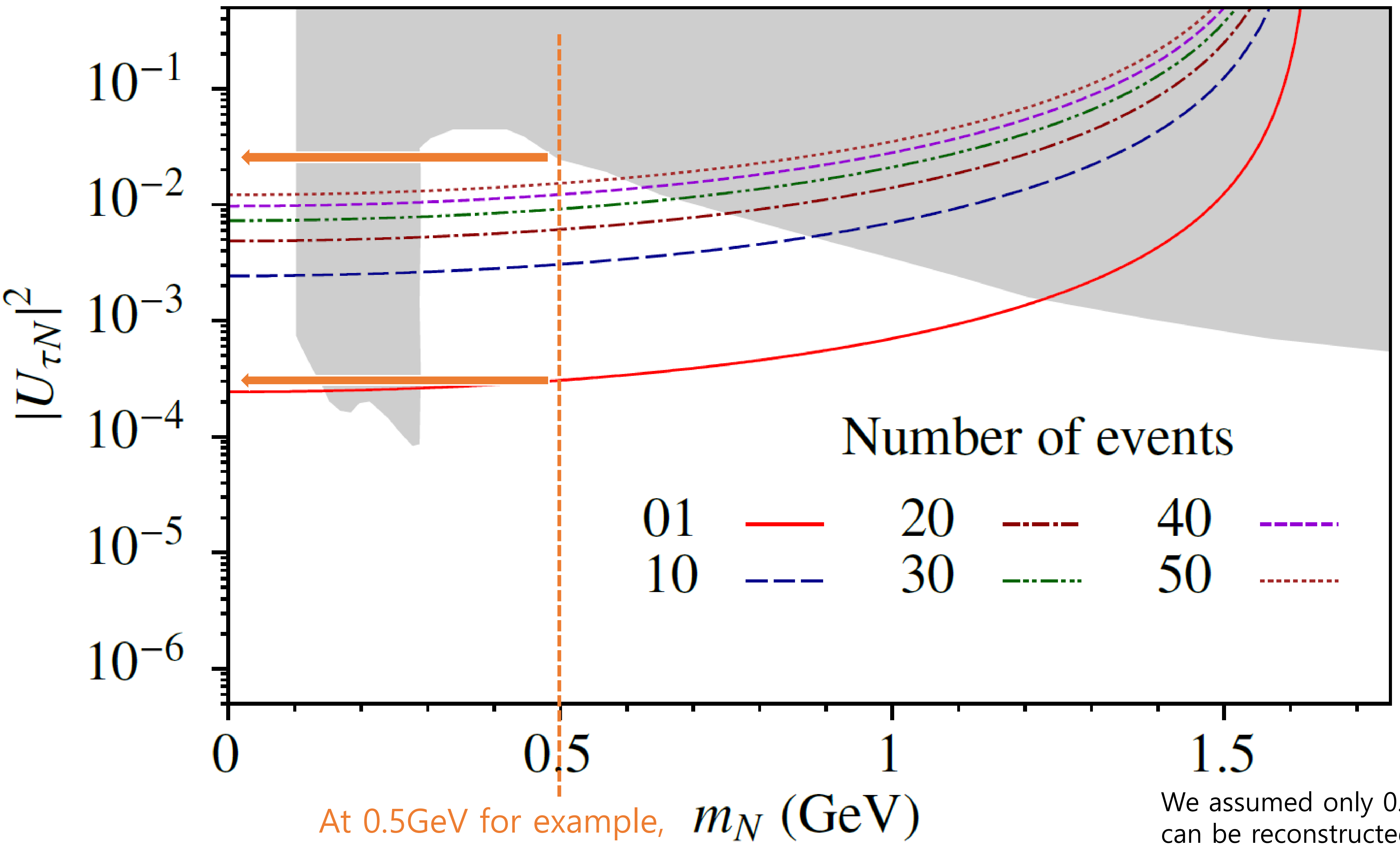
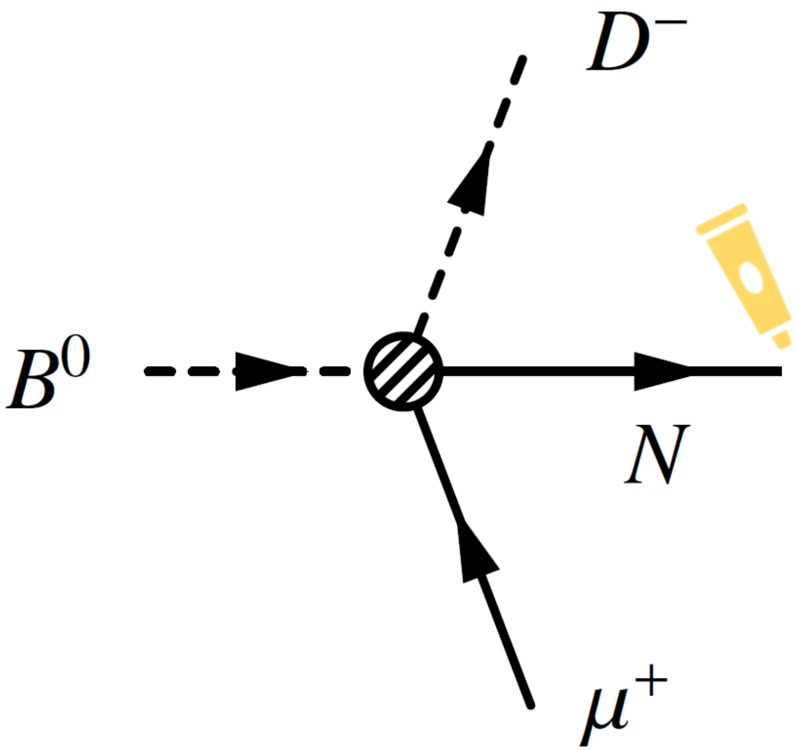


We assumed only 0.1% of τ can be reconstructed

After rewriting the Γ, we revisit



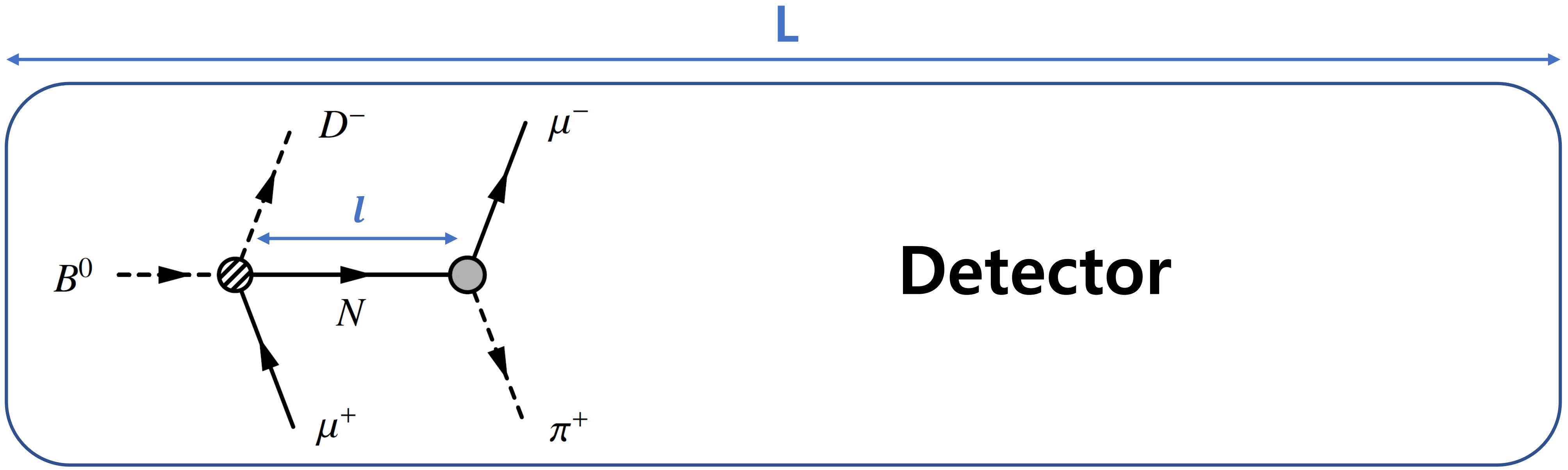
$$N_{\text{singal}} = N_B\, |U_{\mu N}|^2 \Gamma_{B\to D\mu N}\, \frac{1}{\Gamma_B}$$

$$N_{\text{singal}} = N_B\, |U_{\mu N}|^2 \int dE_N\, \frac{d\Gamma_{B\to D\mu N}}{dE_N}\, \frac{1}{\Gamma_B}$$

$$\frac{\Gamma_{N\to\mu\pi}}{\Gamma_N}\left[1 - exp\left(-\frac{L}{\beta_N}\frac{\Gamma_N}{\gamma_N}\right)\right] \Leftarrow \frac{\overline{\Gamma}_{N\to\mu\pi}}{\overline{\Gamma}_N}\left[1 - exp\left(-\lambda t\right)\right]$$

- What proportion of N will decay to $\mu\pi$
- within the length L

*Only those event with $l \leq$ **L** can be observed



Upper bound on $|U_{\mu N}|^2$

$$N_{\text{signal observed}} = N_B \, |U_{\mu N}|^2 \int dE_N \, \frac{d\overline{\Gamma}_{B\to D\mu N}}{dE_N} \, \frac{1}{\Gamma_B} \, \frac{\overline{\Gamma}_{N\to\mu\pi}}{\overline{\Gamma}_N} \, \left[1 - exp\left(-\frac{L}{\beta_N}\frac{\Gamma_N}{\gamma_N}\right)\right]$$

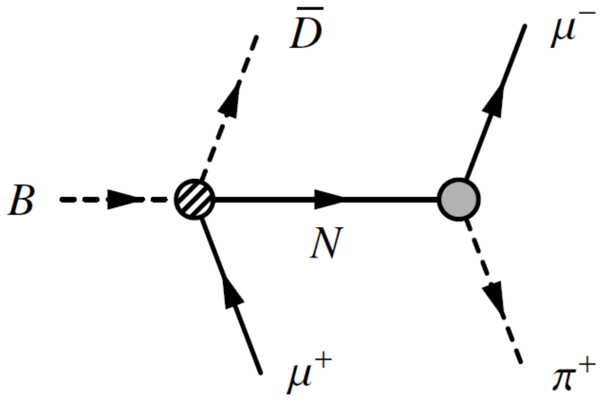
- So once the experiment is done, with an observed value of m_N, solving the above equation in terms of $|U_{\mu N}|^2$ will give the value of $|U_{\mu N}|^2$.
- Or if such a signal is not observed at all, we can give an upper bound on $|U_{\mu N}|^2$ by solving follow

$$1 > N_{\text{signal observed}} = N_B \, |U_{\mu N}|^2 \int dE_N \, \frac{d\overline{\Gamma}_{B\to D\mu N}}{dE_N} \, \frac{1}{\Gamma_B} \, \frac{\overline{\Gamma}_{N\to\mu\pi}}{\overline{\Gamma}_N} \, \left[1 - exp\left(-\frac{L}{\beta_N}\frac{\Gamma_N}{\gamma_N}\right)\right]$$

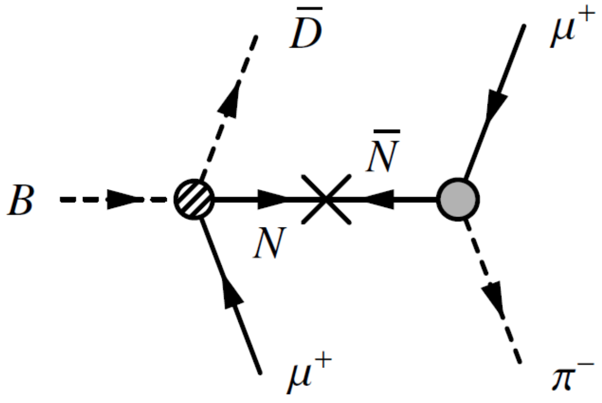
Majorana N

- Both LNC and **LNV** modes.
- additional LNV contributions on Γ_N.
- **Helicity flip** of N
- Expected N_{signal}, and the upper bound on $|U_{\mu N}|^2$ can be similarly calculated as before.

$$P_{\text{flip}}(E_N) = m_N^2 / \left(E_N + \sqrt{E_N^2 - m_N^2}\right)^2$$



(a) Both Dirac and Majorana type of N

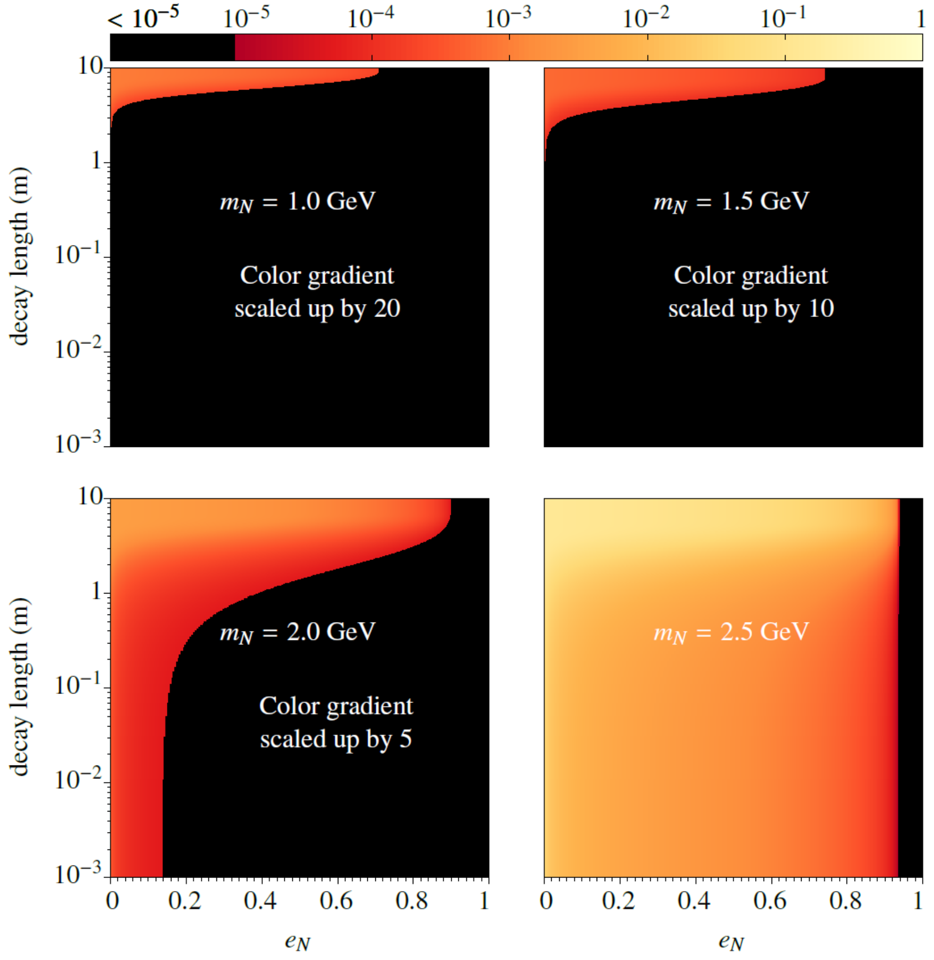


(b) Only Majorana type of N

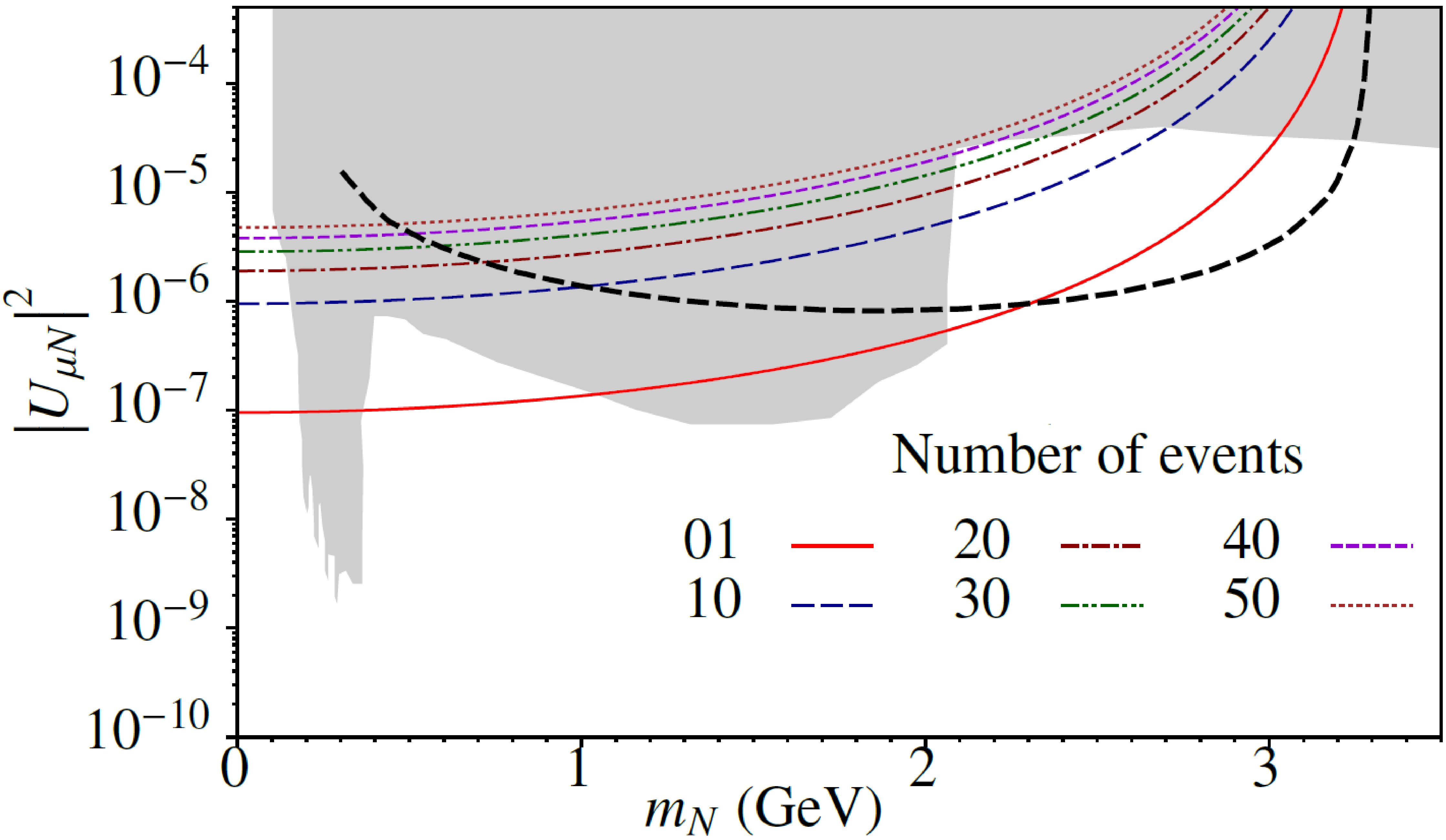
$$Feasibility = \frac{1}{\Gamma_{B\to D\mu N}} \frac{d\Gamma_{B\to D\mu N}}{dE_N} \times \frac{\Gamma_{N\to\mu\pi}}{\Gamma_N} \left[1 - exp\left(-\frac{L}{\beta_N}\frac{\Gamma_N}{\gamma_N}\right)\right]$$

- Among decayed N
- some portion will have energy around E_N, how many such N will be there,
- which decay to $\mu\pi$
- within the detector size L

$$e_N = \left(E_N - E_N^{\min}\right) / \left(E_N^{\max} - E_N^{\min}\right)$$



Current bound on $|U_{lN}|^2$ are assumed.



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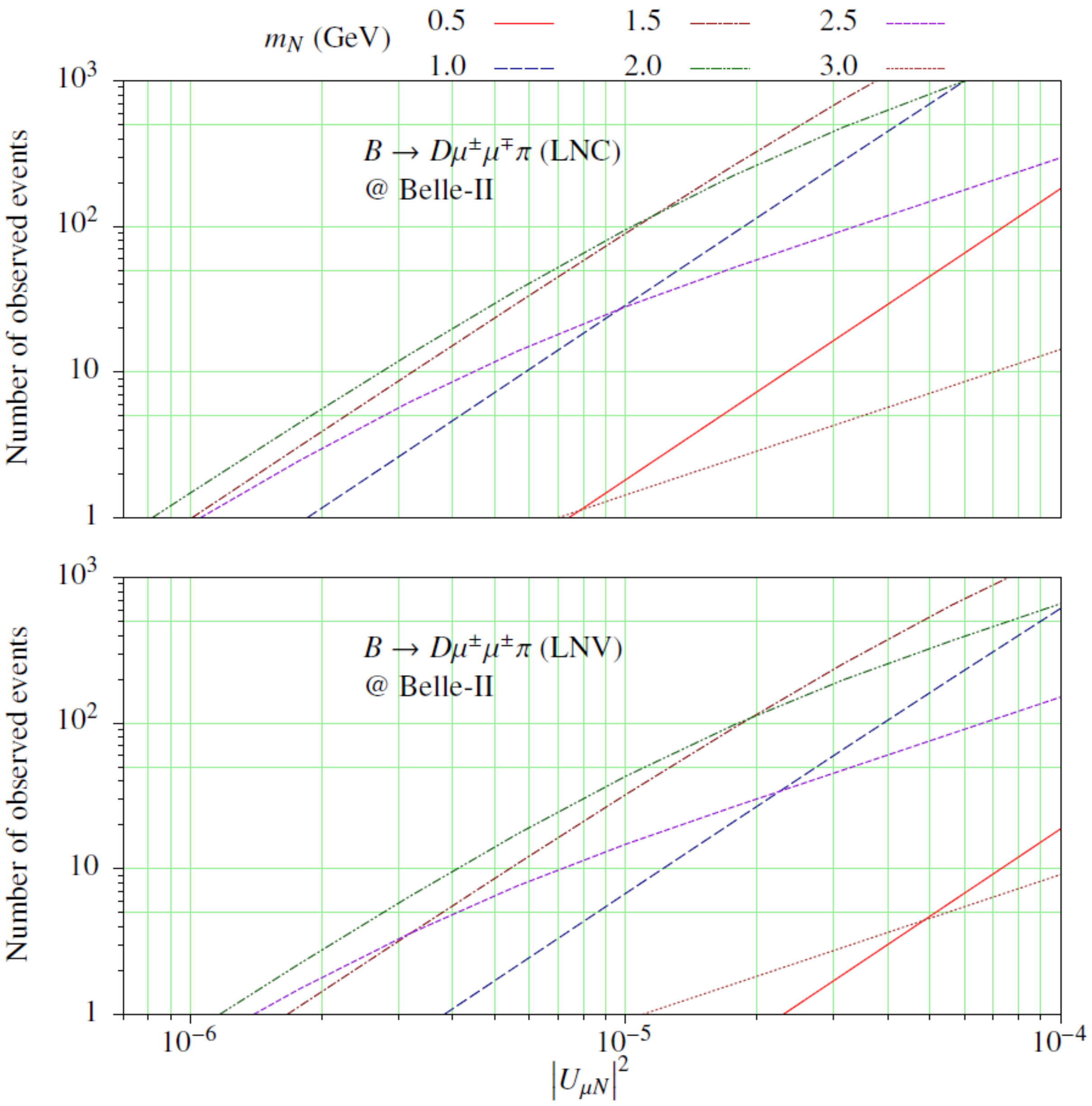
Observable number of events in terms of m_N and $|U_{\mu N}|^2$ at Belle-II.

- Above : LNC signals for Dirac N
- Below : LNV signals for Majorana N



Conclusion

- Strong constraints on $|U_{lN}|^2$, especially for $m_N < 1GeV$, can be imposed with the decay $B \to D\mu N$ at ongoing experiment Belle-II.
- When N is relatively light, missing momentum search with Belle type detector excels, if N is heavier whole decay search with LHCb type experiment is adequate.

Thank you

$$\Gamma_N = \widetilde{\mathcal{K}}\, \overline{\Gamma}_N(M_N)$$

$$\overline{\Gamma}_N(M_N) \equiv \frac{G_F^2 M_N^5}{96\pi^3}$$

$$\widetilde{\mathcal{K}}(M_N) \equiv \widetilde{\mathcal{K}} = \mathcal{N}_{eN}\, |U_{eN}|^2 + \mathcal{N}_{\mu N}\, |U_{\mu N}|^2 + \mathcal{N}_{\tau N}\, |U_{\tau N}|^2$$

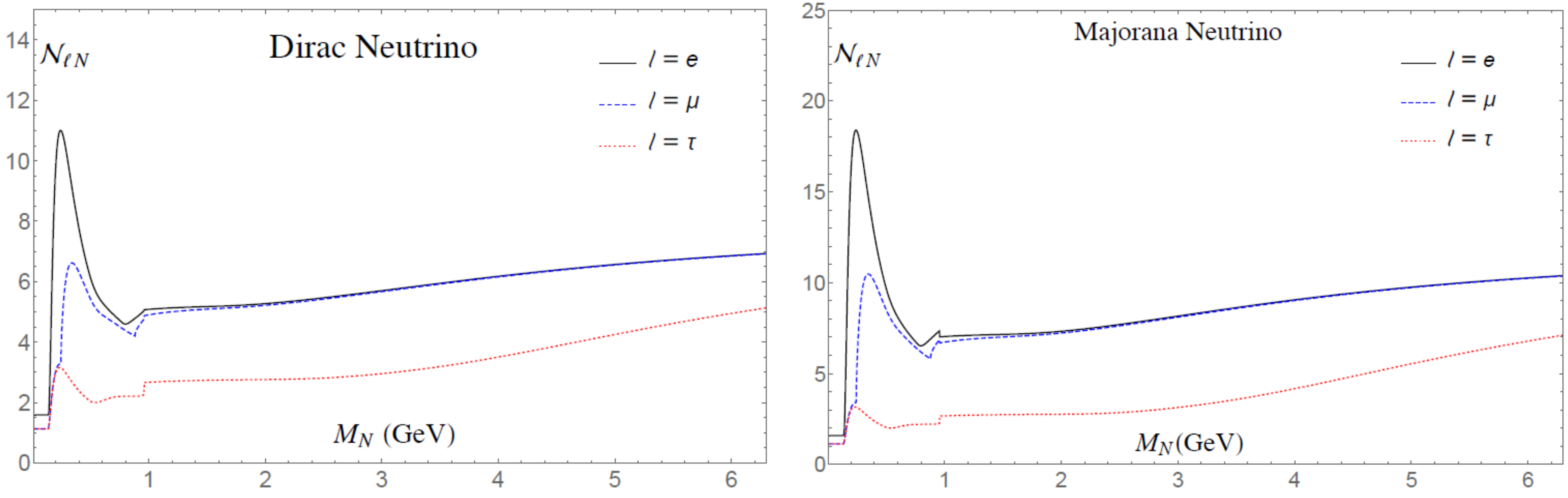
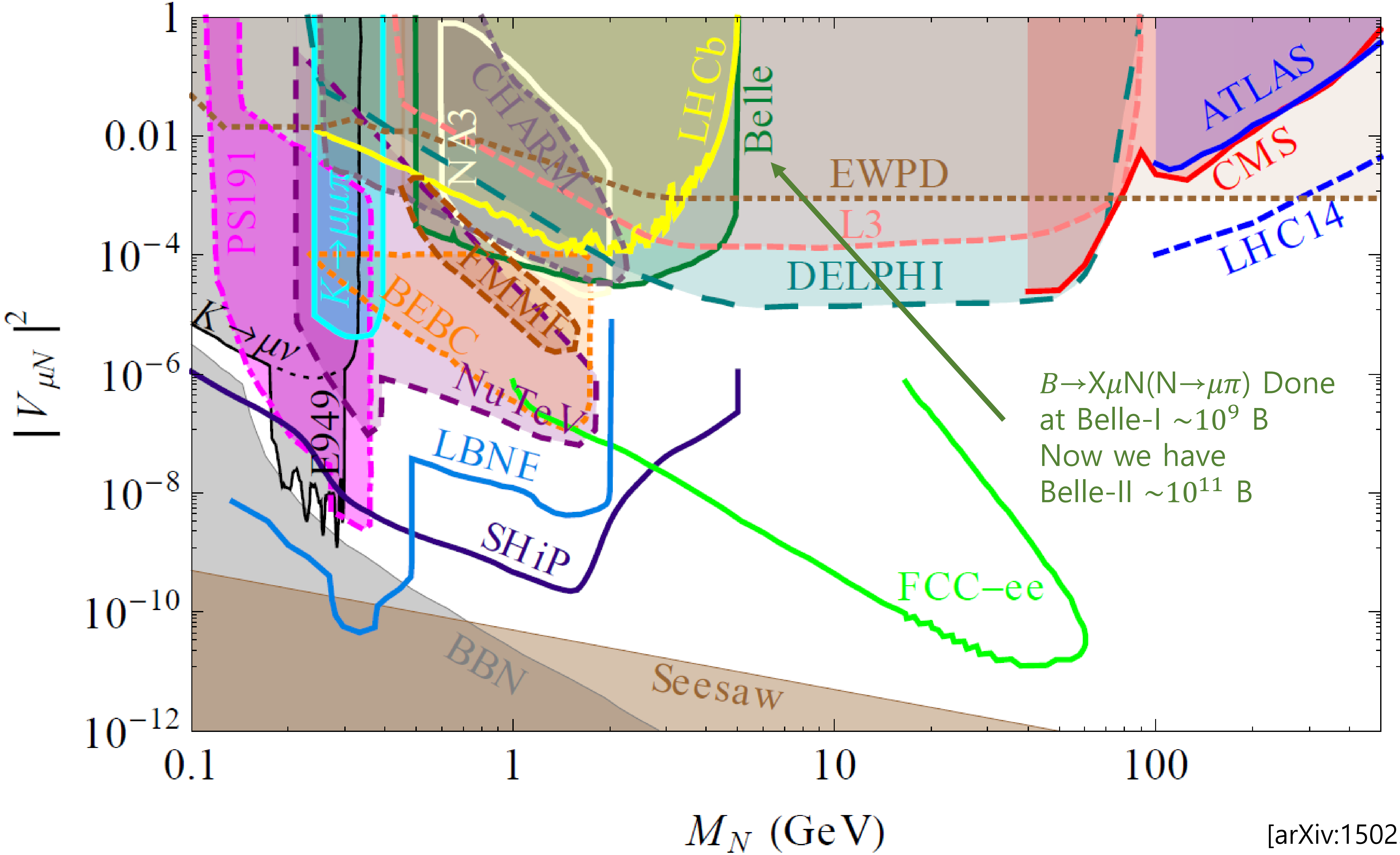
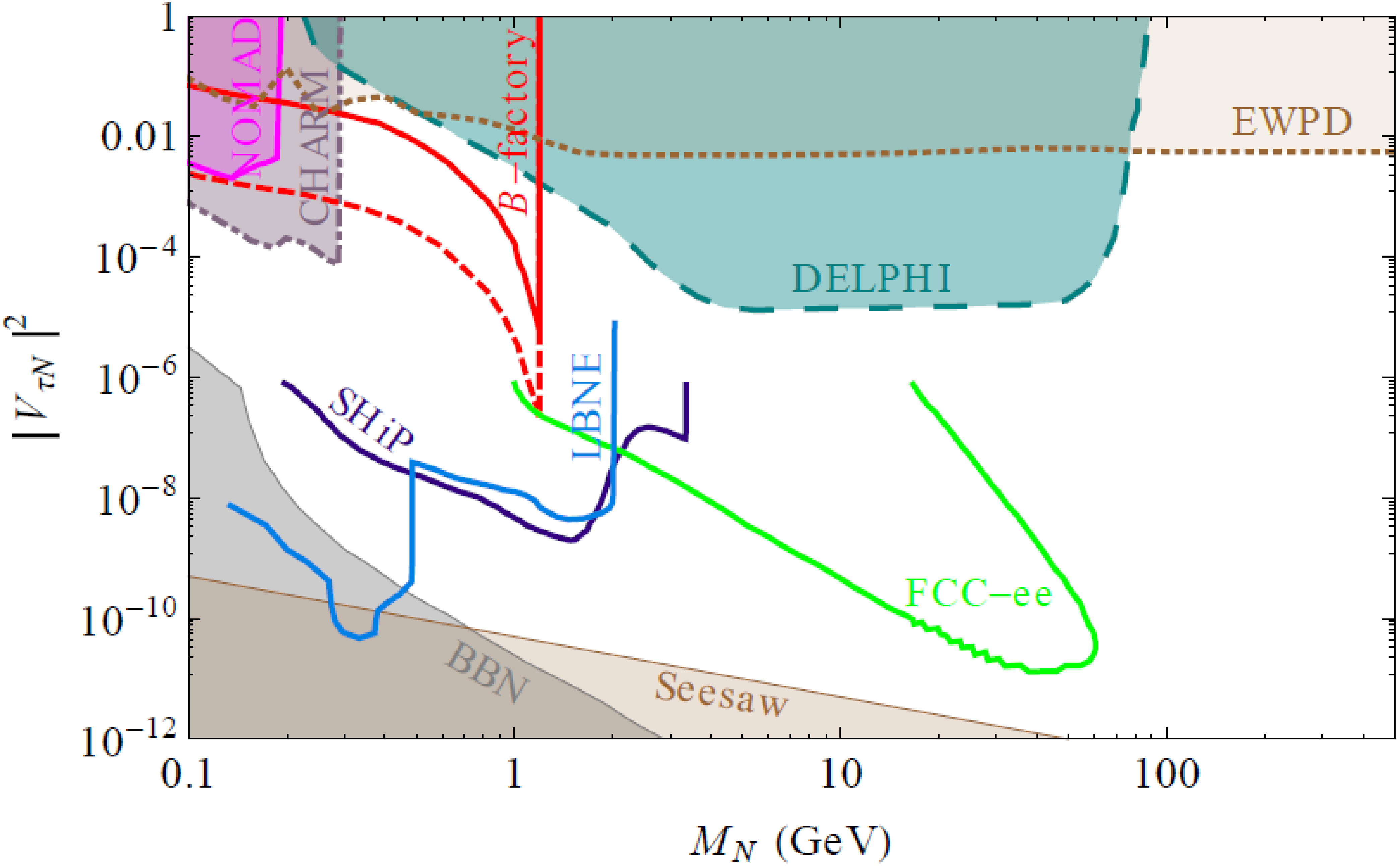


FIG. 8: The coefficients $\mathcal{N}_{\ell N}$ ($\ell = e, \mu, \tau$) appearing in Equations (30)–(32), as a function of the mass of the sterile neutrino N. The left-hand figure is for Dirac neutrino, and the right-hand figure for Majorana neutrino.

[arXiv:1705.09403]



[arXiv:1502.06541]



NOMAD
CHARM
B-factory
DELPHI
EWPD
SHiP
LBNE
FCC-ee
BBN
Seesaw
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0.1
1
10
100
$|V_{\tau N}|^2$
M_N (GeV)