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

FLASY2019

C. S. Kim (Yonsei University)

w/ D. Sahoo & D. H. Lee

Contents

- Introduction
- Choosing appropriate production modes
- Constraints on $|U_{\mu N}|^2$ and $|U_{\tau N}|^2$
- Probing Dirac and Majorana nature of N
- Conclusion

Introduction

- Unresolved mysteries of (active) neutrinos:

  mass? why so light? (& PMNS parameters, CP)

  Dirac or Majorana particle?

  .....

- Possible the best solution:

  see-saw with heavy (Majorana) sterile neutrinos

  → light mass

  Majorana (active) nu

  (possible candidate of) dark matter

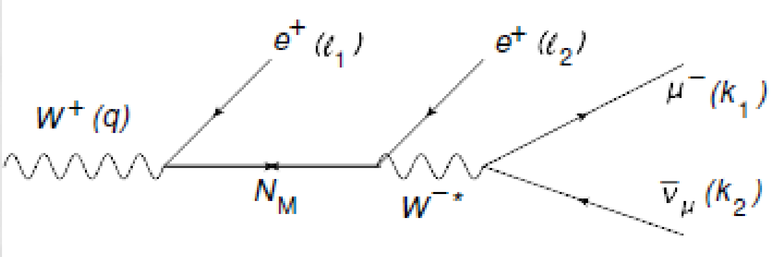
NEED to discover Sterile Neutrino(s)

Introduction

- Search of (sterile) neutrino

Lepton Number Violating (LNV) processes at LHC

especially (on-shell) W-decays, $W^+ \to e^+ e^+ \mu^- \overline{\nu}$



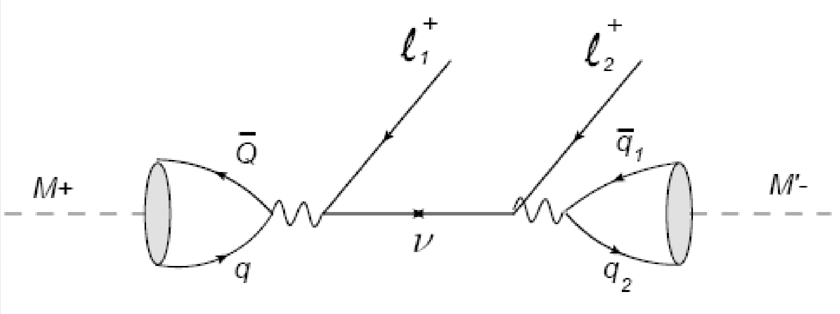
LNV tau decays

LNV rare meson decays

rare LNV decays of $K, D_{(s)}, B_{(c,s)}, ...$ mesons

eg. $B \to ll\pi$, $B \to Dll\pi$, ... at Belle-II, LHCb, BES, ...

(to give constraints on m_N and U_{Nl})



Introduction

- $B \to D^{(*)} l l \pi$ vs. $B \to D^{(*)} l N$

  $B \to D^{(*)} l l \pi = B \to D^{(*)} l N (\to l\pi)$

  ⟶ 1. life-time of N (> detector size L_D)
  2. possible helicity-flip depending on $N \to l^{\pm}\pi^{\mp}$

- (a) Up until now, no systematic analysis including suppression factors of 1 (and 2), step-by-step

  (b) $Br(B \to DlN) >> Br(B \to Dll\pi)$

  $B \to DlN$ can be useful only at Belle-II.

  (* Need full reconstruction of initial B)

Choosing appropriate production modes

- Sterile neutrino is

  (a) electrically neutral $B \to Dl\nu$ → $B \to DlN$

  $D \to KlN, K \to \pi lN, ...$ (OK) $B \to DlN \gg B \to lN$

  (b) spin ½ fermion

  $B \to D^{*}lN, D \to K^{*}lN, B \to KNN, ...$ (spin=3/2, so Not OK)

  (c) massive

  Non-zero fixed mass, so $B \to D\mu\nu_{\mu}\nu_{e}\bar{\nu}_{e}$ not background

  (d) long-living

  Need careful systematic analysis for τ_N and $L_{detector}$, ...

➔ Displaced vertex signatures can also be used to veto any background events

Choosing appropriate production modes

- Need fully reconstructed initial B for $B \to DlN$

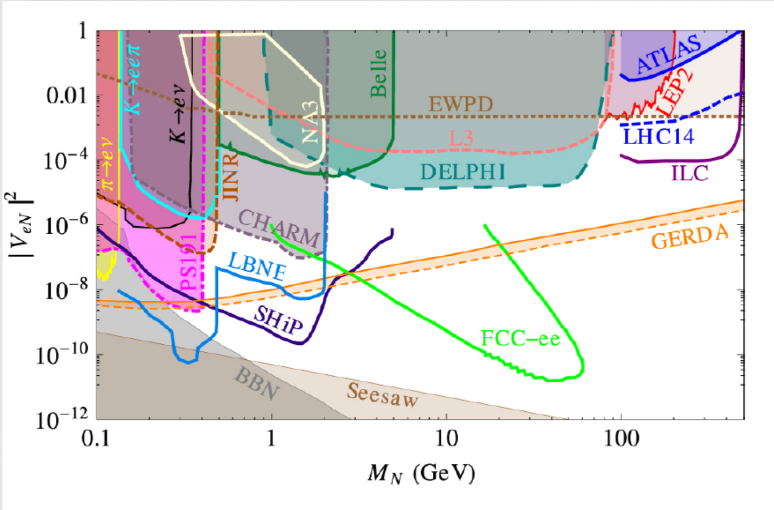
upgraded LHCb can do $B \to D\mu^{\pm}\mu^{\pm}\pi^{\mp}$ with $4.8\times10^{12}\,B$

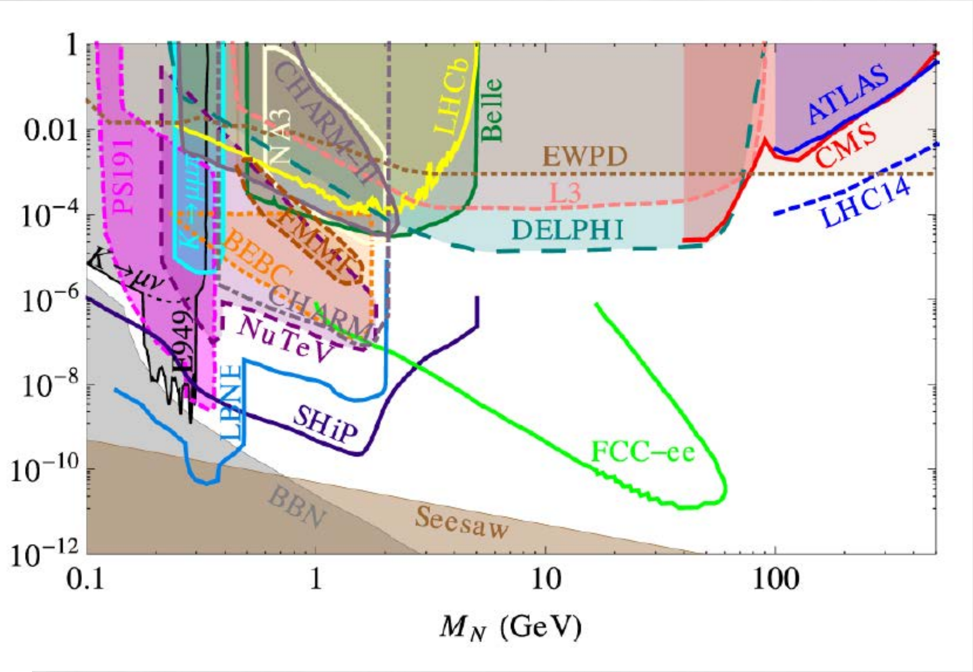
Belle-II can do $B \to DlN$ with fully reconstructed $4.8\times10^{8}\,B$

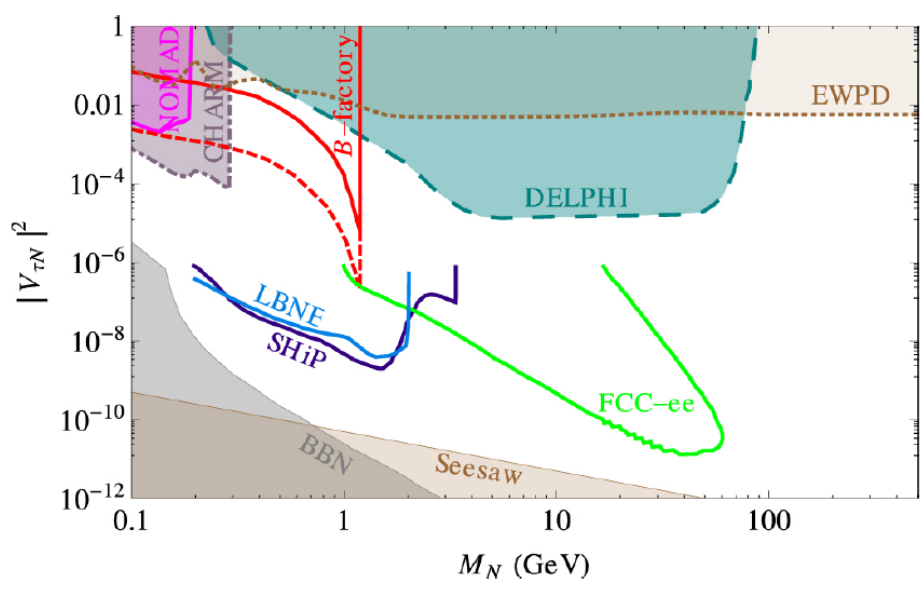
about 0.61% of charged B events and 0.34% of neutral B events can be fully reconstructed from hadronic tagging

for $B \to D\tau N$, assuming 0.1% chance of full reconstruction of tau from its decay (3-4 prongs) $4.8\times10^{5}\,B$

Constraints on $|U_{\mu N}|^2$ and $|U_{\tau N}|^2$.







Present Bounds

Ref: F. Deppish etal, New J. Phys. 17 (2015)

Constraints on $|U_{\mu N}|^2$ and $|U_{\tau N}|^2$.

- Constraints from $$|U_{\ell N}|^2 = \frac{N_{B\to D\ell N}}{N_B \times \underline{\mathrm{Br}}\,(B \to D\ell N)}.$$

where	$N_{B\to DlN}$	the number of such decays observed in the detector
	N_B	the total number of fully reconstructed parent B
	$\underline{Br}(B \to D\ell N)$	the canonical branching ratio of a decay by factoring out $|U_{lN}|^2$ from theoretically calculable branching ratio

- → We can show $|U_{\mu N}|^2$ and $|U_{\tau N}|^2$ as function of m_N

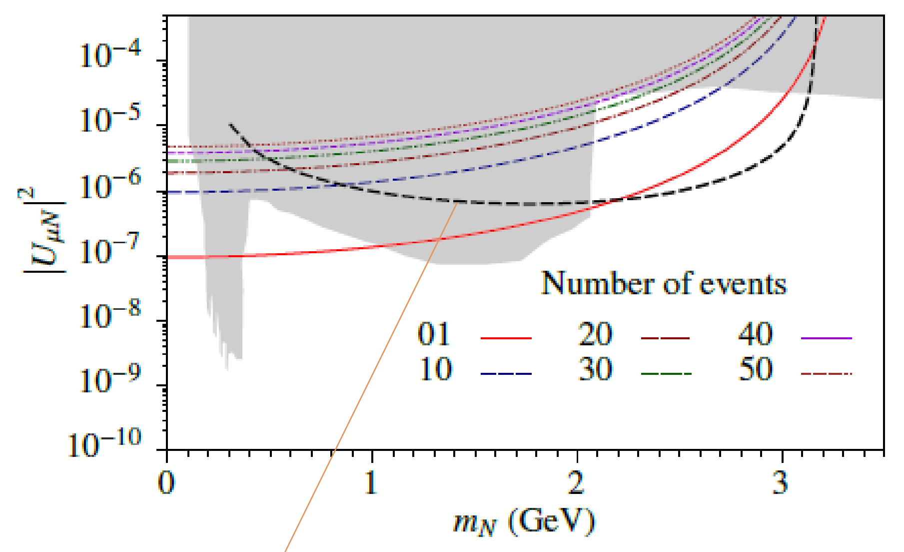
for $N_{B\to DlN}$ = 1, 10, 20, … and

$N_B = 4.8\times10^8 B$ and

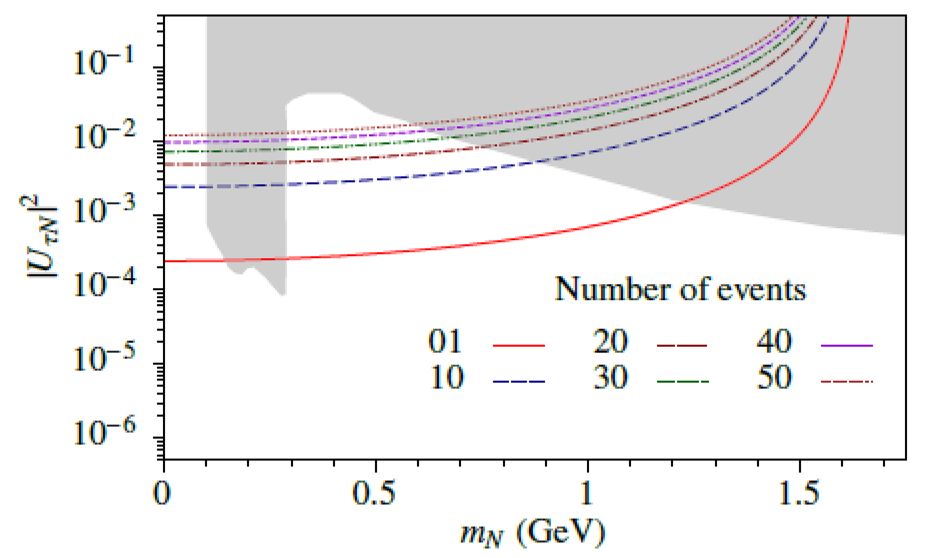
assuming 0.1% chance of full reconstruction of tau

$$N_B = 4.8\times10^5 B$$

Constraints on $|U_{\mu N}|^2$ and $|U_{\tau N}|^2$.



(a) From the decay $B \to D\mu N$.



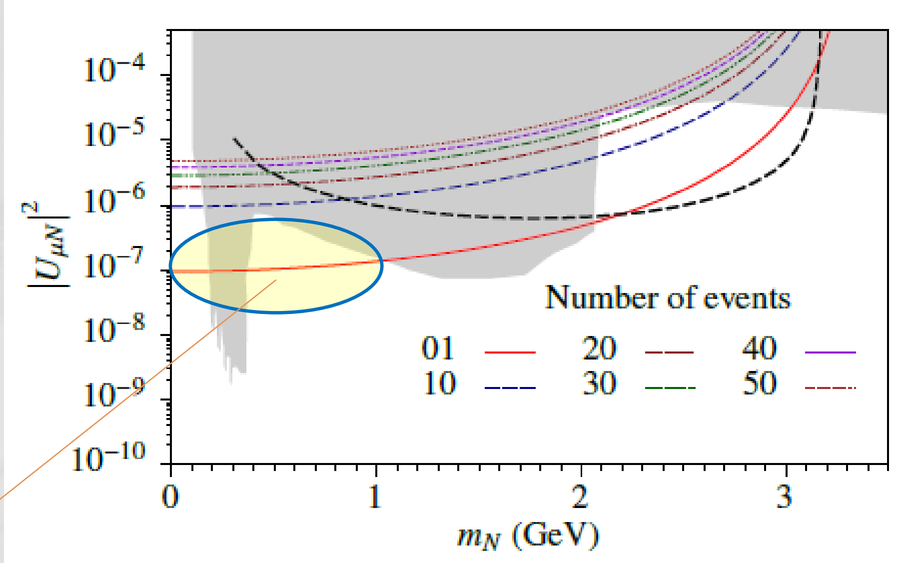
(b) From the decay $B \to D\tau N$.

---------- : 95% CL (ie 3 events) from $B \to D^* \mu^\pm \mu^\pm \pi^\mp$

with $4.8\times 10^{12} B$ at upgraded LHCb

G Cvetic, CSK PRD100 (2019) 015014

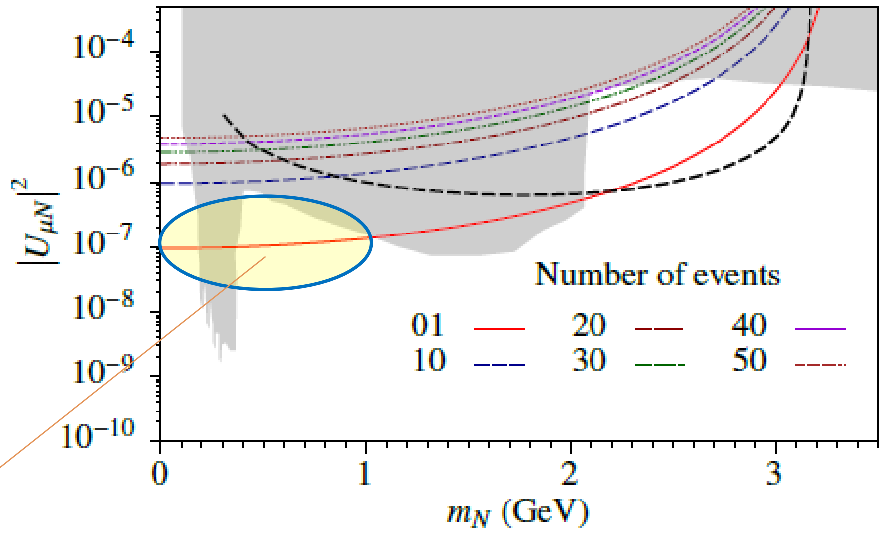
Constraints on $|U_{\mu N}|^2$ and $|U_{\tau N}|^2$.



(a) From the decay $B \to D\mu N$.

Very important region for very light sterile neutrino

Constraints on $|U_{\mu N}|^2$ and $|U_{\tau N}|^2$.



(a) From the decay $B \to D\mu N$.

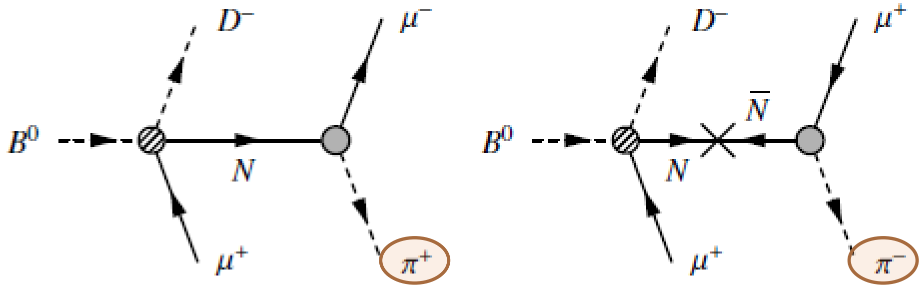
Very important region for very light sterile neutrino

- **One drawback:** the Dirac and Majorana nature of the sterile neutrino can be probed only when its sequential decay inside detector is considered.

Probing Dirac and Majorana nature of N

Need to consider the sequential decay of N,

e.g. $$B^0 \to D^- \mu^+ \mu^\mp \pi^\pm \equiv (B^0 \to D^- \mu^+ N) \otimes (N \to \mu^\mp \pi^\pm)$$



(a) Both Dirac and Majorana type of N

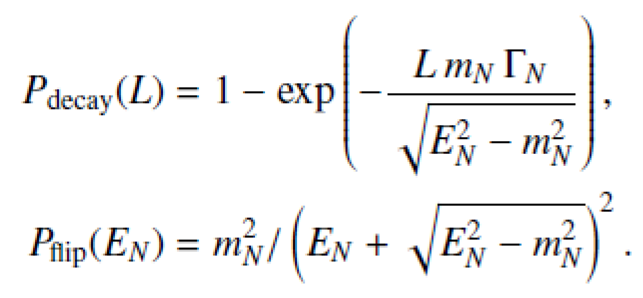
(b) Only Majorana type of N

- sterile neutrino is produced at the first vertex and decays at the second vertex → vertex displacement
- X : the helicity flip, involved in the decay

Probing Dirac and Majorana nature of N

2 suppression factors

- (1) $P_{decay}(L)$, the probability of decay of N within $L < L_D$
- (2) $P_{flip}(E_N)$, the probability of helicity flip required for LNV



$$P_{\rm decay}(L) = 1 - \exp\left(-\frac{L\, m_N\, \Gamma_N}{\sqrt{E_N^2 - m_N^2}}\right),$$

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

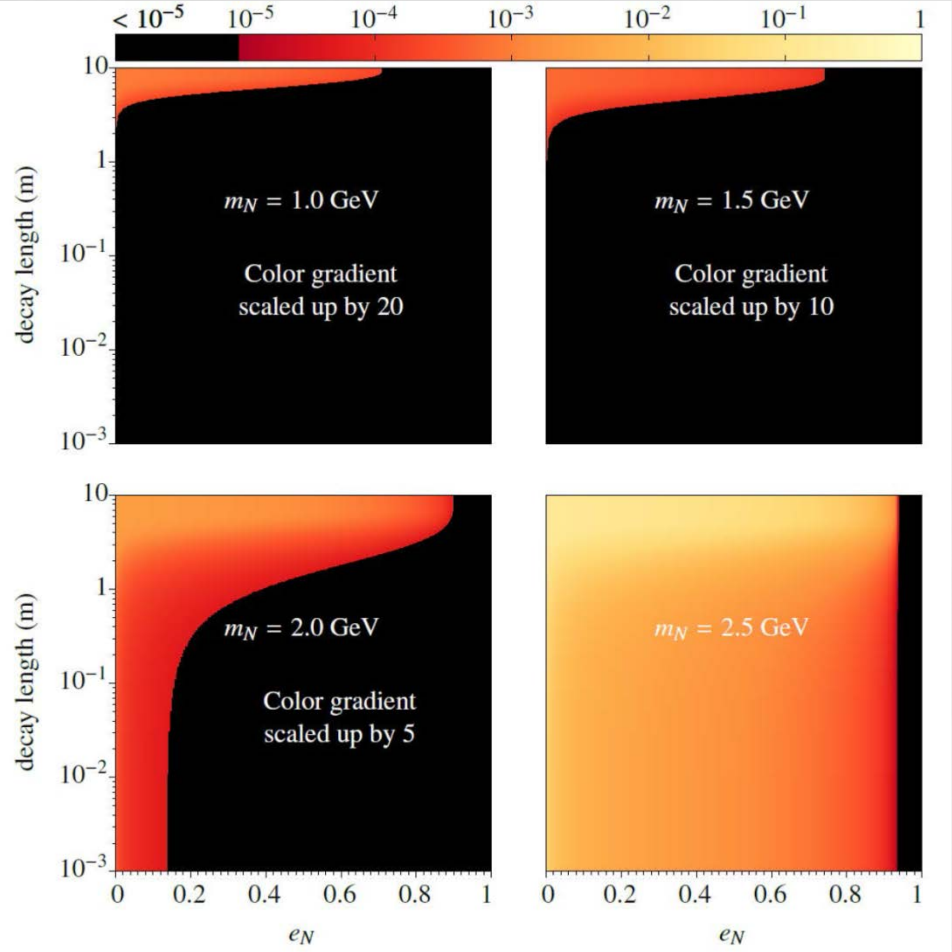
L : decay length

L_D : detector size = 1 m (Belle-II)

= 0.751 m (LHCb)

$$P_{flip} \sim (m_N / E_N)^2$$

Probing Dirac and Majorana nature of N



$$e_N = \frac{E_N - E_N^{\min}}{E_N^{\max} - E_N^{\min}}$$

Detector size for vertex displacement

L_D = 1 m Belle-II

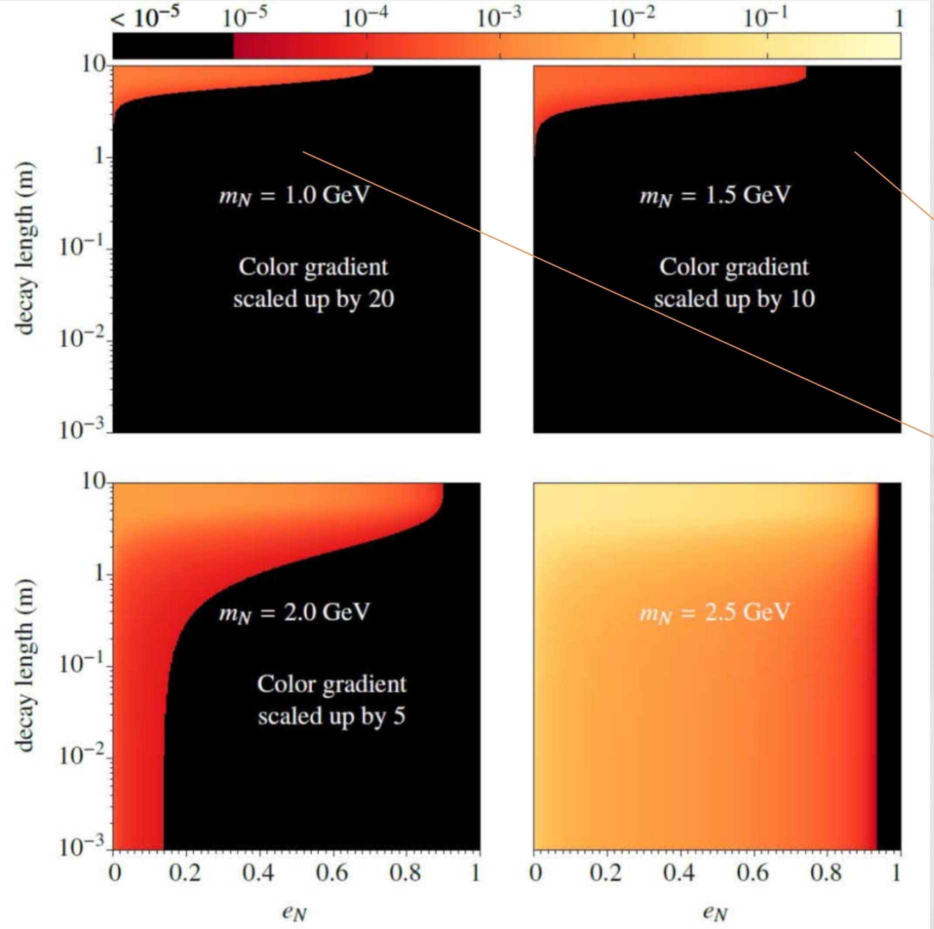
L_D = 0.751 m LHCb

LNC case shown here.

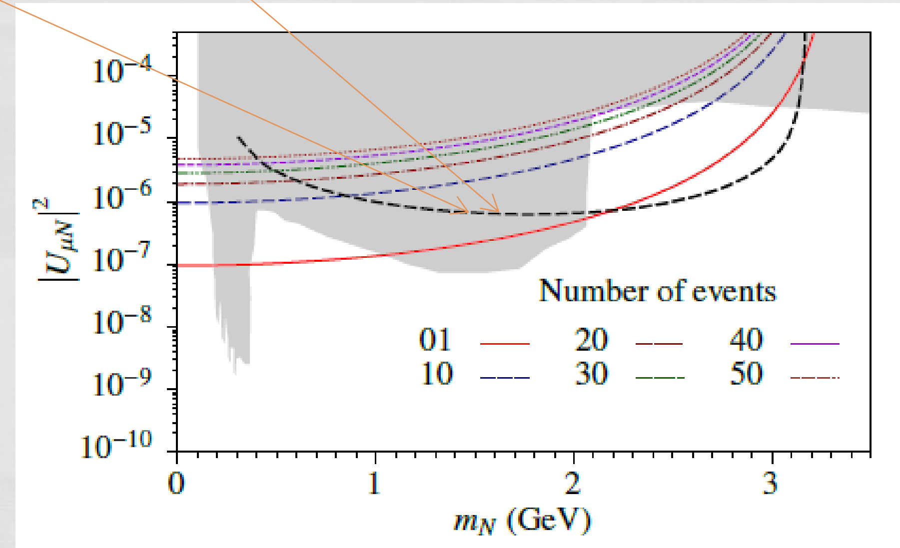
LNV case slightly more suppressed due to

$$P_{flip} \sim (m_N / E_N)^2$$

Probing Dirac and Majorana nature of N

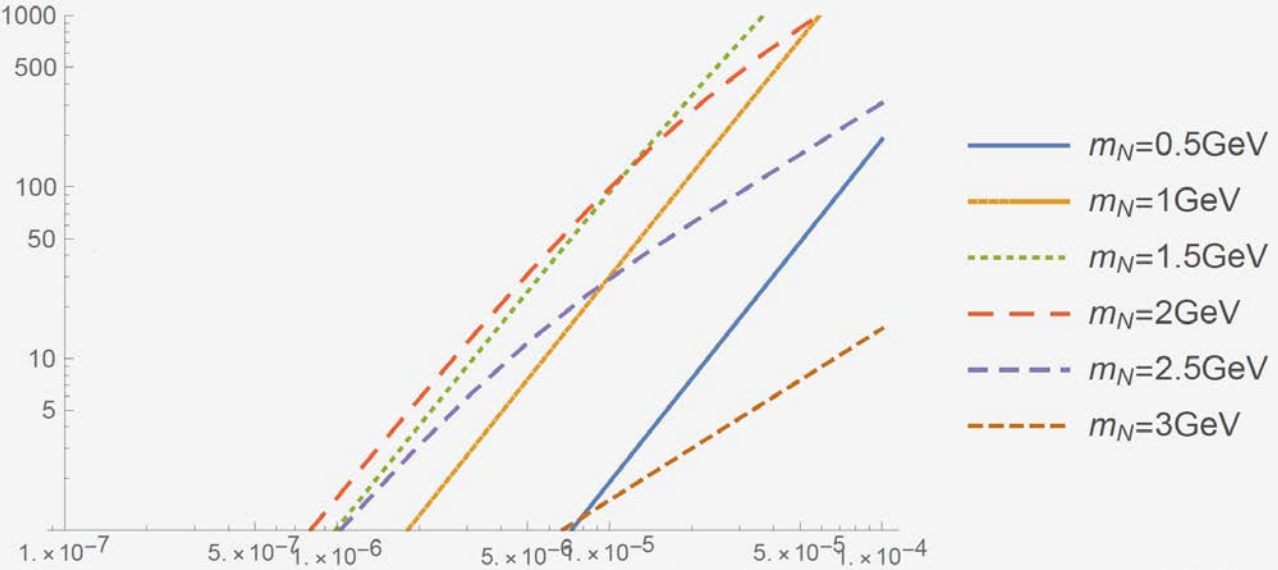


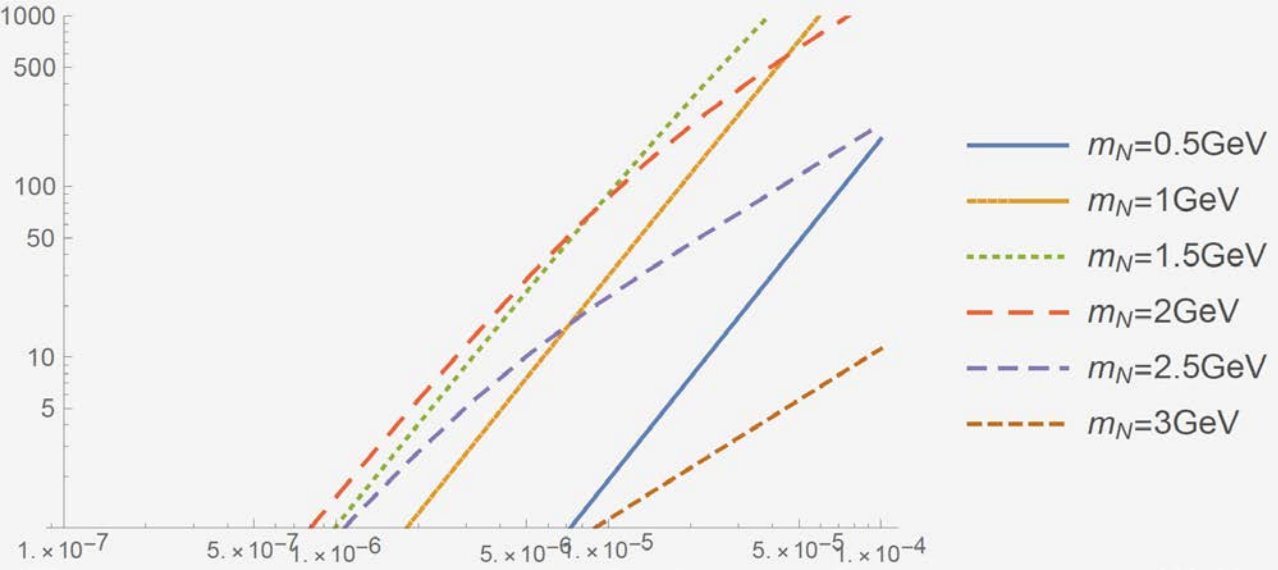
Strong suppression for $m_N < 2$ GeV



(a) From the decay $B \to D\mu N$.

Probing Dirac and Majorana nature of N





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

- Above : LNC signals for Dirac N

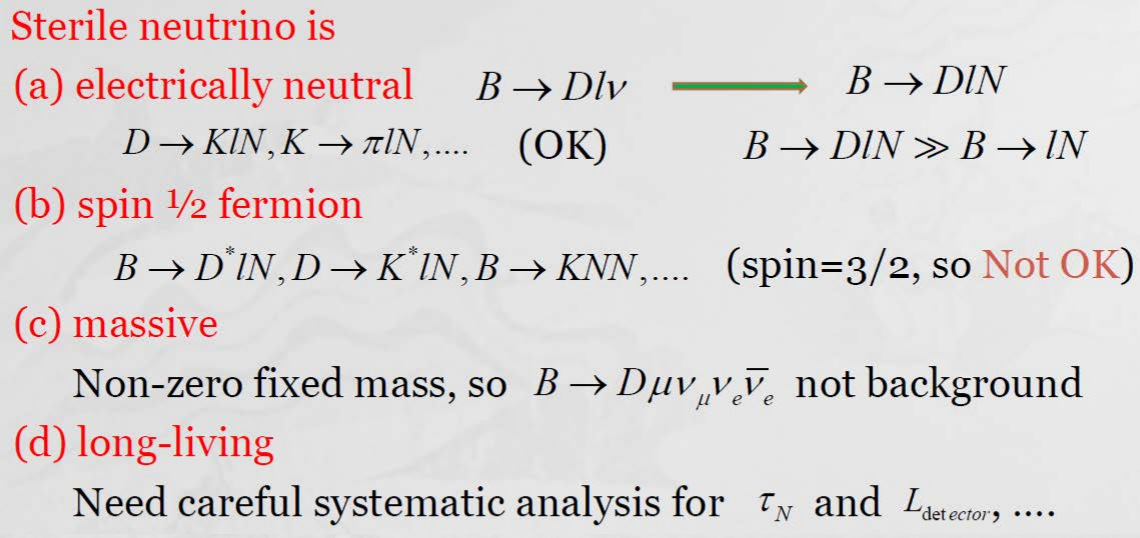
$$B^0 \to D^- \mu^+ \mu^- \pi^+$$

- Below : LNV signals for Majorana N

$$B^0 \to D^- \mu^+ \mu^+ \pi^-$$

Conclusion

- We have provided the simple, most systematic and efficient strategy to use the semi-leptonic decays $B \to DlN$ with $l = \mu, \tau$ to put much stringent constraint on the active-sterile mixing parameters $|U_{Nl}|^2$



Sterile neutrino is

(a) electrically neutral $B \to Dl\nu \longrightarrow B \to DlN$

$D \to KlN, K \to \pi lN, \ldots$ (OK) $B \to DlN \gg B \to lN$

(b) spin ½ fermion

$B \to D^* lN, D \to K^* lN, B \to KNN, \ldots$ (spin=3/2, so Not OK)

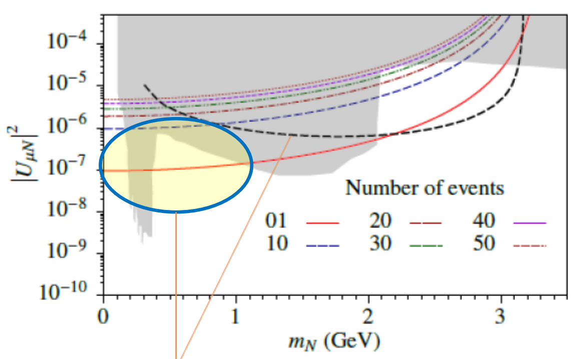
(c) massive

Non-zero fixed mass, so $B \to D\mu\nu_\mu\nu_e\bar{\nu}_e$ not background

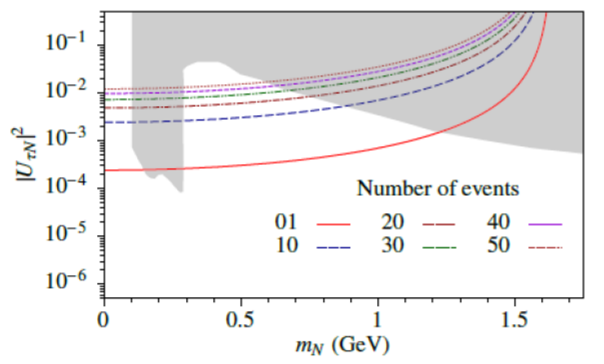
(d) long-living

Need careful systematic analysis for τ_N and $L_{\det ector}$, ...

Conclusion



(a) From the decay $B \to D\mu N$.

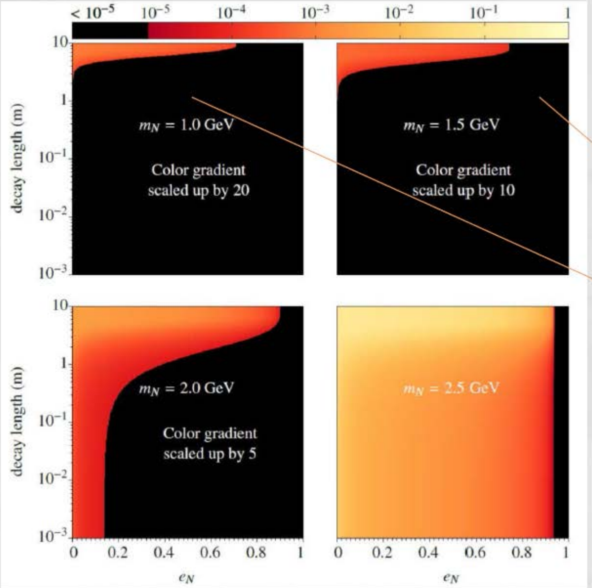


(b) From the decay $B \to D\tau N$.

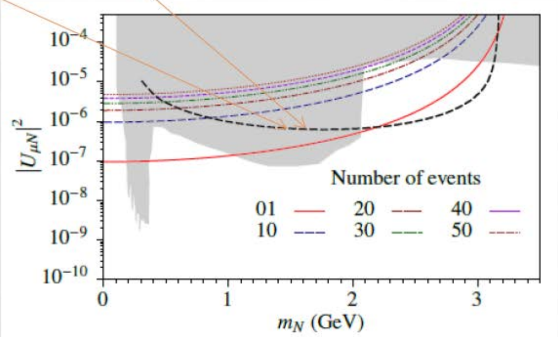
– – – – – – – – – – : 95% CL (ie 3 events) from $B \to D^* \mu^\pm \mu^\pm \pi^\mp$

with $4.8 \times 10^{12}\, B$ at upg

Very important region for very light sterile neutrino



Strong suppression for $m_N < 2$ GeV



(a) From the decay $B \to D\mu N$.