Heavy Neutral Leptons

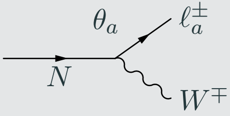
Juraj Klarić

Bethe Forum on Long-Lived Particles
November 14th 2023

What do we look for when we look for HNLs?

Direct probes of the HNL parameter space

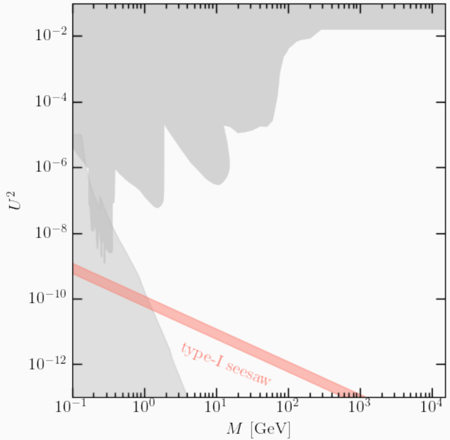
HNL mixing



$$U_a^2 = |\theta_a|^2$$

$$U^2 = \sum_a U_a^2$$

$$U^2 \gtrsim m_\nu / M$$



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

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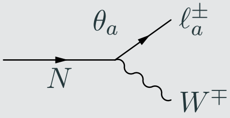

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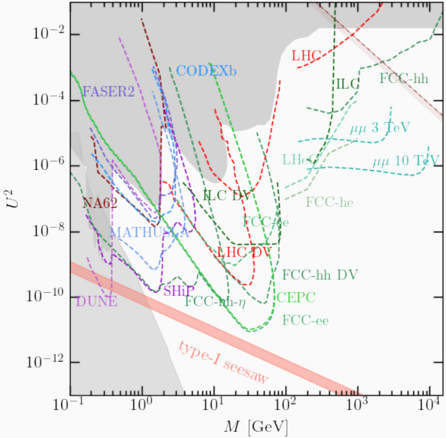

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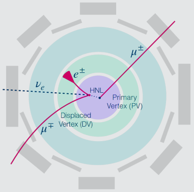
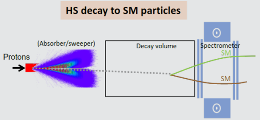
Direct probes of the HNL parameter space

Displaced Vertices



[graphic by D. Trischuk]

LLP experiments



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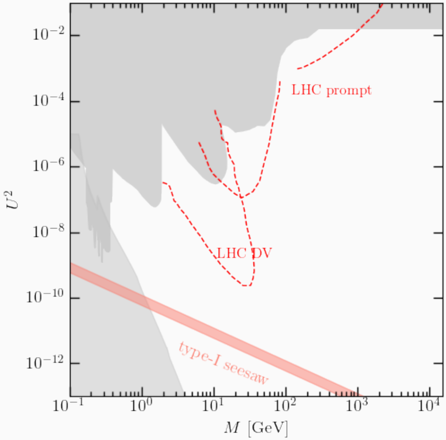

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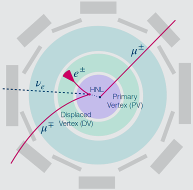

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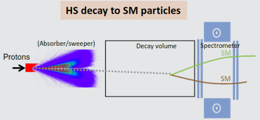

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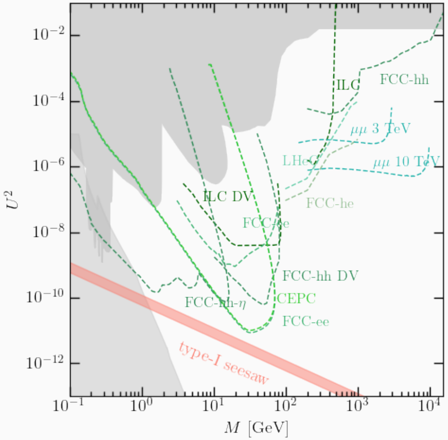

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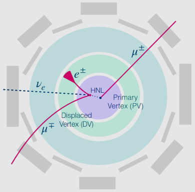

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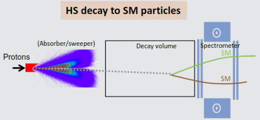

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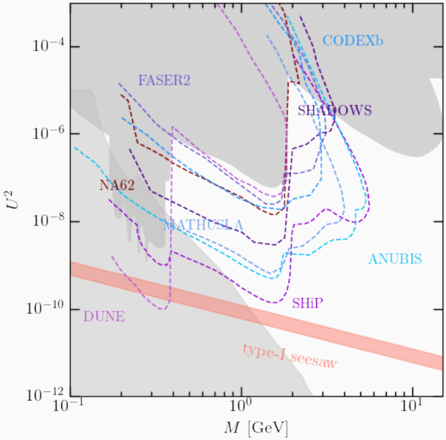

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The phenomenological HNL model

Most phenomenological studies are based on the Lagrangian:

Phenomenological Lagrangian

$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta_a^*\gamma^\mu e_{La}W_\mu^+ - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta_a^*\gamma^\mu \nu_{L\alpha}Z_\mu - \frac{M}{v}\theta_a h\overline{\nu_{L}}_a N + \text{h.c.}$$

where $U_a^2 = |\theta_a|^2$, and the field N can be either a Dirac or a Majorana field.

With only 4 free parameters!

Realistic models of neutrino masses

In a realistic model we instead have more fields N_I (where $I = 1, 2 \ldots$) and parameters:

Realistic parameters

$$\theta_a \to \theta_{aI}\,, \quad \text{and} \quad M \to M_I$$

But also more constraints!

Seesaw relation

$$(m_\nu)_{ab} = -\theta_{aI} M_I (\theta)_{bI}$$

HNL mixing angles in realistic neutrino mass models

$$\theta = iU_\nu\sqrt{m_\nu^{\text{diag}}}\mathcal{R}\sqrt{M_M^{-1}}$$

[Casas, Ibarra 2001]

2 Heavy Neutrinos

+ 2 RHN masses

2 parameters

3 Heavy Neutrinos

+ 3 RHN masses

3 parameters

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HNL mixing angles in realistic neutrino mass models

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2 Heavy Neutrinos

- 2 RHN masses
- 1 *complex* $(\times 2)$ angle
- **2 light neutrino masses**
- **3 PMNS angles**
- 1 CP phase δ
- 1 Majorana phase α

11 (6 free) parameters

3 Heavy Neutrinos

- 3 RHN masses
- 3 *complex* $(\times 2)$ angles
- **$2 + 1$ light neutrino masses**
- **3 PMNS angles**
- 1 CP phase δ
- 2 Majorana phases $\alpha_{1,2}$

18 (13 free) parameters

How to map realistic models onto the phenomenological Lagrangian

Mass and mixing angle

We assume close to mass degenerate HNLs:

$$M_1 \approx M_2$$

Only consider the *total* mixng angle:

$$U_a^2 = \sum_I U_{aI}^2 \,, \quad \text{and} \quad U^2 = \sum_a U_a^2$$

Back to 4 parameters and a discrete assumption about the a Dirac or Majorana nature of the HNL.

Still too many parameters for efficient experimental exploration?
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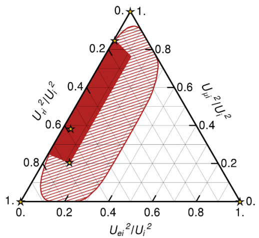
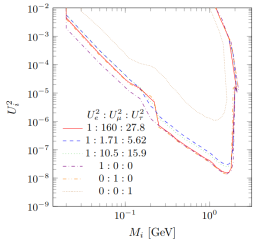
Sensitivity of experiments highly depends on mixing ratios

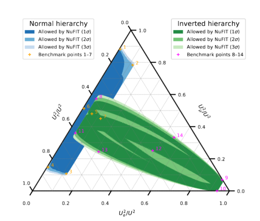
NA62 in beam dump

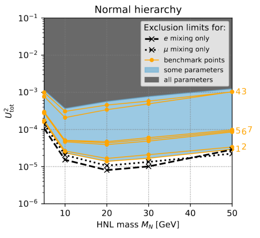




[Drewes/Hajer/JK/Lanfranchi 1801.04207]

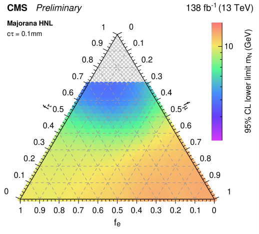
ATLAS

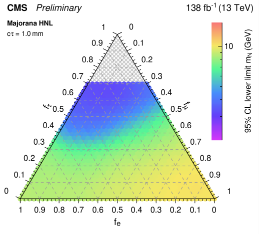




[Tastet/Ruchayskiy/Timiryasov 2107.12980]

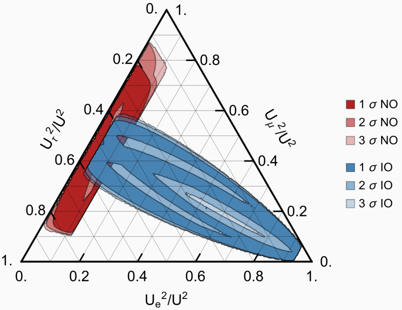
CMS





[CMS-PAS-EXO-21-013]

Constraints from the seesaw mechanism



[Drewes/JK/Lopez-Pavon 2207.02742]

[using nuFIT 5.1 2007.14792]

- in the minimal seesaw model the flavour ratios are completely determined by U_{PMNS}
- uncertainty dominated by Majorana phase η, Dirac phase δ and θ_{23}
- allowed ratios become smaller as we pin down the PMNS parameters
- How to choose future-proof benchmarks?

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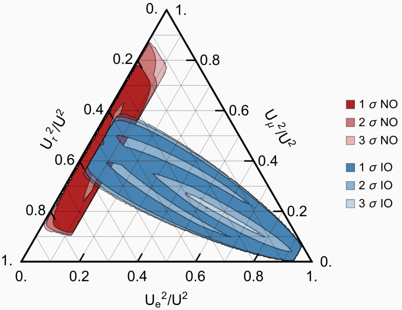

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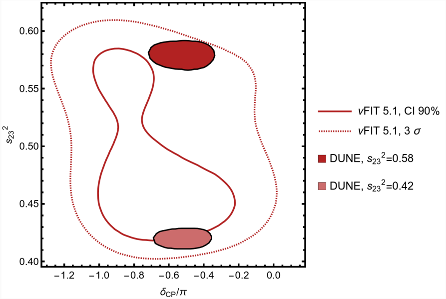
Future sensitivity?

- significant improvement expected with DUNE and HyperK
- we can use the sensitivity estimates to estimate how the allowed flavor ratios change



[nuFIT 5.1 2007.14792]

[DUNE TDR 2002.03005]

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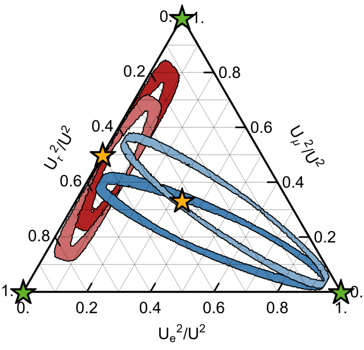

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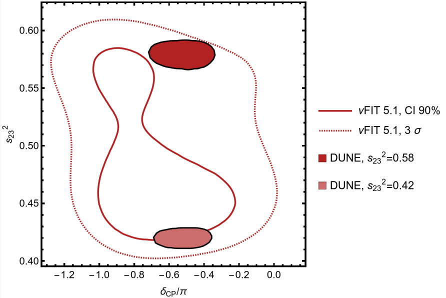

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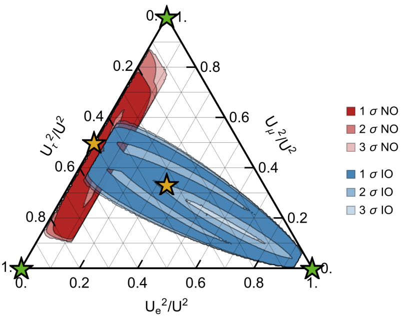

[Figure from 2207.02742]

- new benchmarks prepared for the HNL WG of the FIPs physics centre
- selection criteria:
    1. consistency with ν-osc. data
    2. added value
    3. symmetry considerations
    4. simplicity
    5. leptogenesis
- in addition to the single flavor benchmarks, we propose the new points:
    - $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 1$
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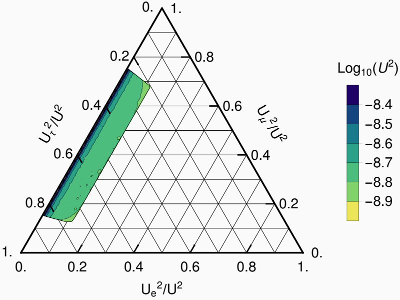
- Common benchmarks can used to compare the reach of different searches

New Benckmark Points

NO, $M = 30$ GeV



[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

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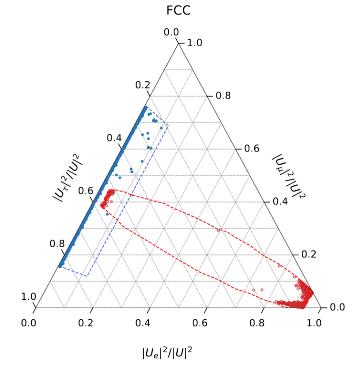

$$\Delta M/M = 10^{-2}$$

[Hernandez/Lopez-Pavon/Rius/Sandner 2207.01651]

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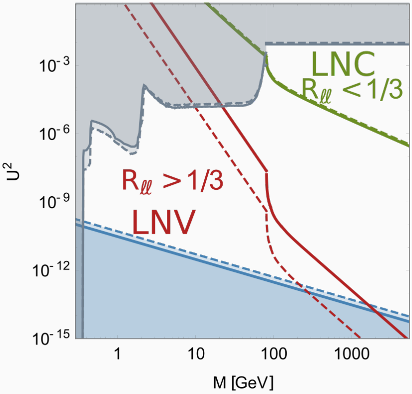

[Drewes/Klose/JK 1907.13034]

LNV / LNC ratio

$$R_{\ell\ell} = \frac{\Delta M_N^2}{2\Gamma_N^2 + \Delta M_N^2}$$

[Anamiati/Hirsch/Nardi 1607.05641]

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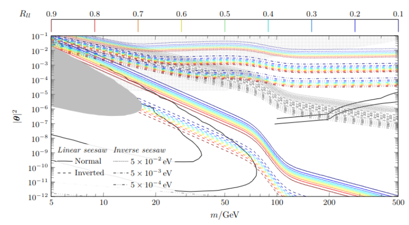

[Antusch/Hajer/Rosskopp 2307.06208]

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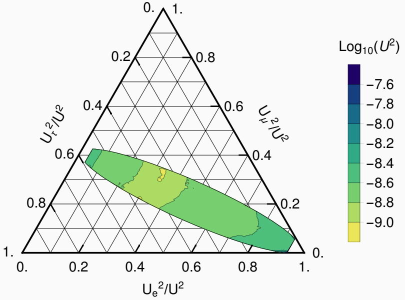
- ratio can be modified by decoherence effects

From discovery to tests

Measuring flavor ratios at experiments

- the HNL branching ratios are constrained for a fixed U^2
- large number of HNLs possible at FCC-ee allow for measurement of U_e^2/U^2
- similar sensitivity @ SHiP
- strong constraints on flavour for large ΔM
- even more predictive when combined with discrete flavour and CP symmetries (in the case with 3 RHN)

IO, $M = 30$ GeV



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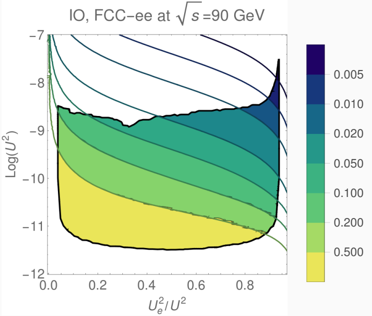

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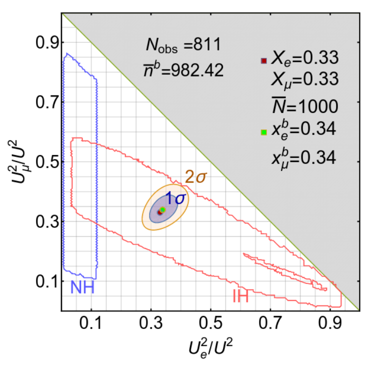
$M_N = 1$ GeV @ SHiP



[Snowmass HNL WP 2203.08039]

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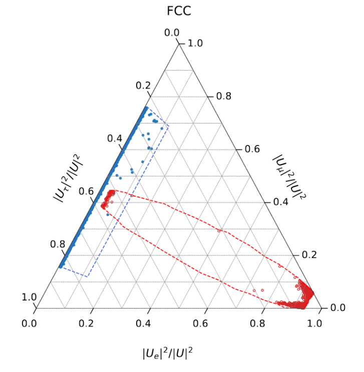

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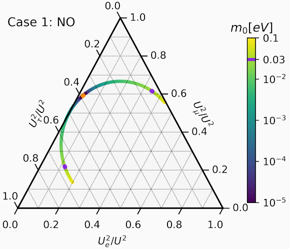
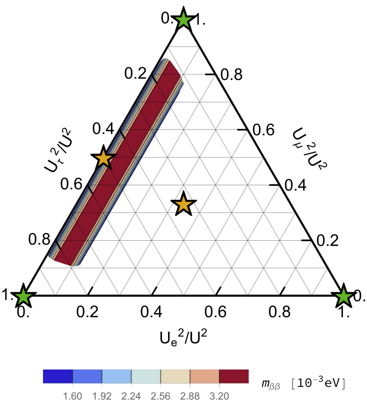


[Drewes/Georis/HagedornKlaric 2203.08538]

[Drewes/Georis/HagedornKlaric 230a.bcde]

Complementarity with neutrinoless double beta decay



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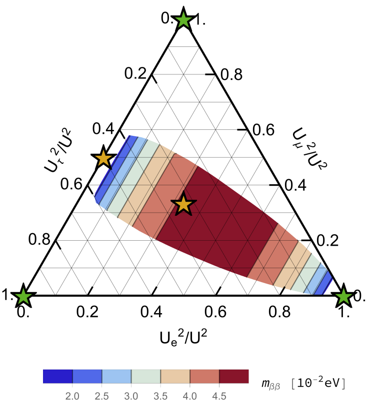

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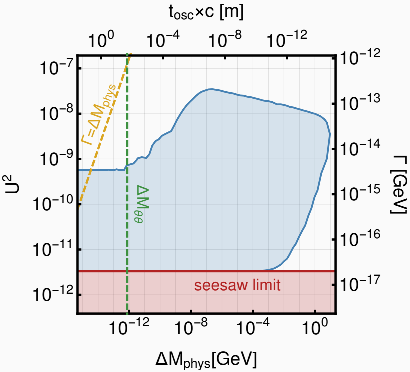
Measuring the mass splitting in model with 2 HNLs

Normal Ordering:



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[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK

1710.03744]

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- energy resolution of planned experiments - $\Delta M/M \sim \mathcal{O}$(few%)
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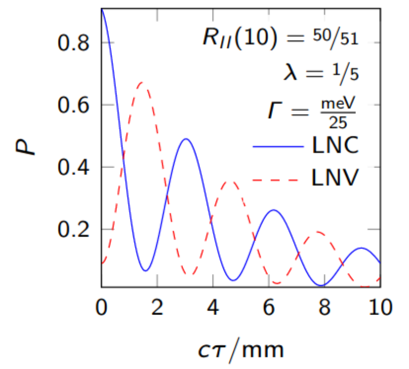

[Antusch/Hajer/Rosskopp 2210.10738]

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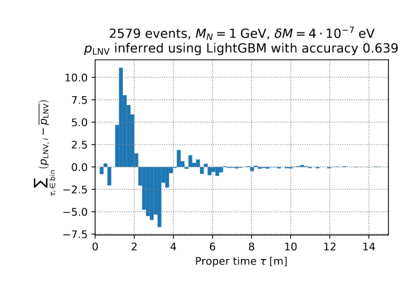

[Tastet/Timiryasov 1912.05520]

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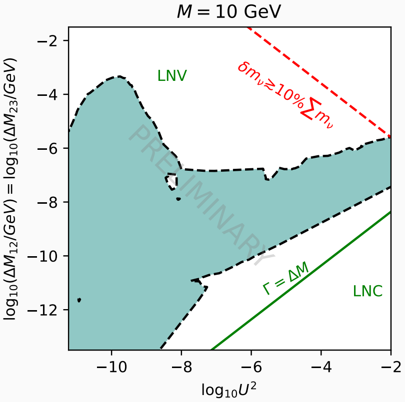
Mass splittings with 3 HNLs



- benchmark with fixed $U^2_{\alpha I}/U^2$
- upper bound on U^2 arises through a combination of baryogenesis + fine tuning constraints
- leptogenesis consistent with both LNV and LNC RHN decays
- nontrivial LNV/LNC ratios can further constrain the RHN parameters

[Drewes/Georis/JK 231x.xxxx]

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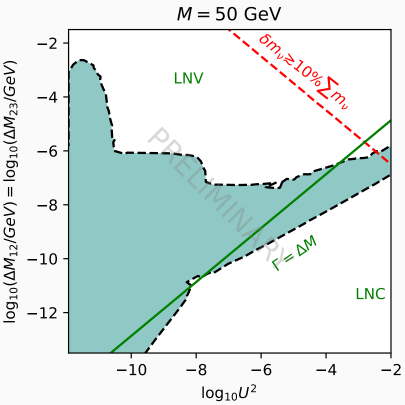

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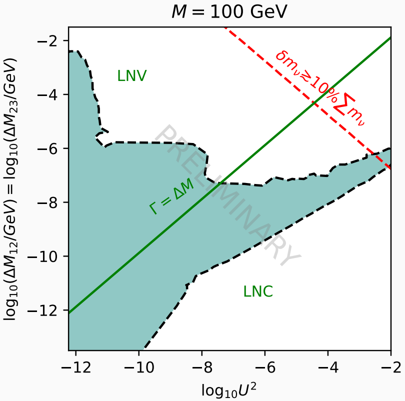

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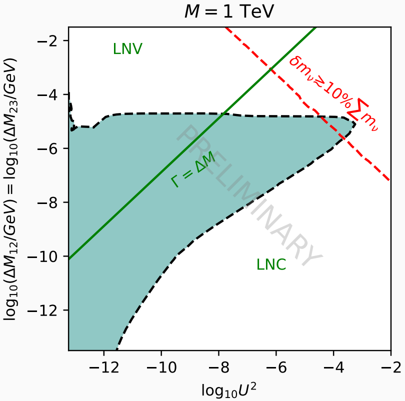

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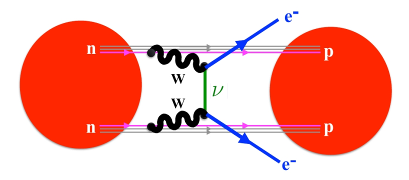
[Drewes/Georis/JK 231x.xxxx]

Indirect probes of HNLs

Probing HNLs in neutrinoless double β decay



[figure from 1910.04688]

HNL contribution to $0\nu\beta\beta$

$$m_{\beta\beta} \simeq \Big| [1 - f_A(\bar{M})] m^{\nu}_{\beta\beta} + 2 f_A^2(\bar{M}) \frac{\bar{M}^2}{\Lambda^2} \Delta M (\Theta_{e1}^2 - \Theta_{e2}^2) \Big|$$

- HNLs can contribute to $m_{\beta\beta}$ when $M \sim 100$ MeV
- the HNL contribution suppressed when $\Delta M \ll M$

  approximate lepton number conservation
- leptogenesis imposes bounds on the size of ΔM and Θ_{ei}^2
- parts of the leptogenesis parameter space can already be excluded in existing experiments
- much large parameter space with 3 HNLs
  - $m_{lightest} \neq 0$
  - larger rates due to wider range of ΔM_{ij}
  - large HNL contribution implies $M \lesssim 1$ GeV

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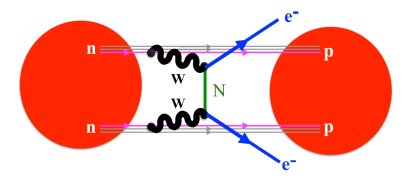

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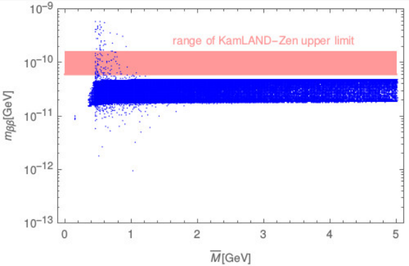

[Eijima/Drewes 1606.06221,

Hernández/Kekic/López-Pavón/Salvado 1606.06719]

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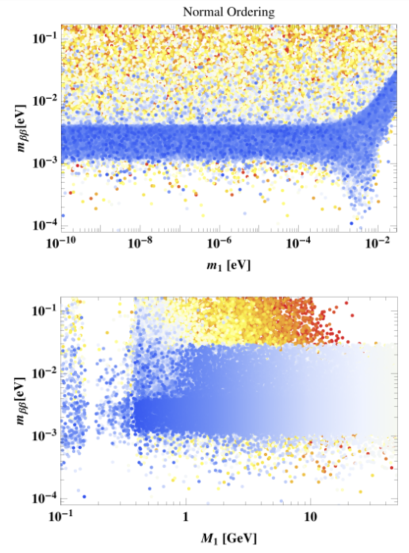

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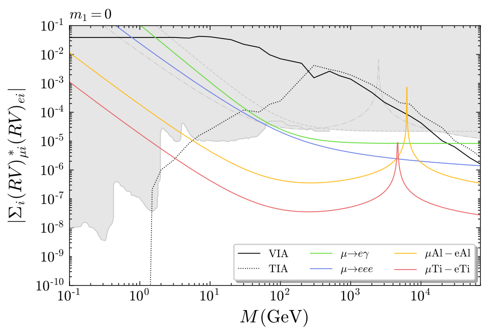
[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

Indirect probes: Charged LFV with 3 HNLs



[Granelli/JK/Petcov 2206.04342]

- parameters space in the TeV region already severly constrained by cLFV observables
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- simultaneous LFV possible in several channels

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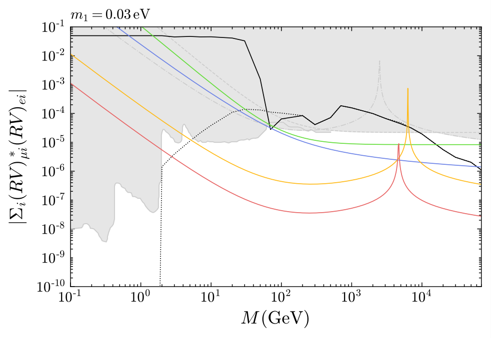

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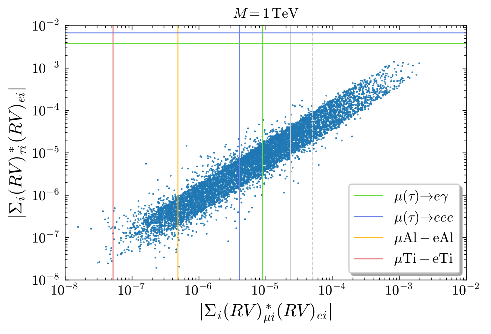

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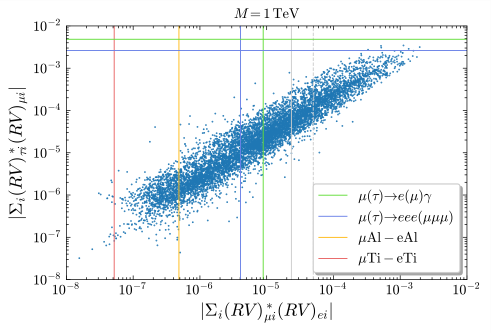

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Conclusions

- right-handed neutrinos can offer a minimal solution to the origins of neutrino masses and the baryon asymmetry of the Universe
- theoretical considerations can motivate benchmark models for experimental searches
- the existence right-handed neutrinos can be tested at existing and near-future experiments
    - excellent synergy between direct and indirect probes!
- HNLs can have a very rich phenomenology

  displaced vertices, LFV ($\mu \to e\gamma$), LNV ($0\nu\beta\beta$), HNL oscillations...

Thank you!