



# New benchmark models for heavy neutral lepton searches

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**Abstract** The sensitivity of direct searches for heavy neutral leptons (HNLs) in accelerator-based experiments depends strongly on the particles properties. Commonly used benchmark scenarios are important to ensure comparability and consistency between experimental searches, re-interpretations, and sensitivity studies for different facilities. In models where the HNLs are primarily produced and decay through the weak interaction, benchmarks are in particular defined by fixing the relative strengths of their mixing with SM neutrinos of different flavours, and the interpretation of experimental data is known to strongly depend on those ratios. The commonly used benchmarks in which a single HNL flavour exclusively interacts with one Standard Model generation do not reflect what is found in realistic neutrino mass models. We identify two additional benchmarks for accelerator-based direct HNL searches, which we primarily select based on the requirement to provide a better approximation for the phenomenology of realistic neutrino mass models in view of present and future neutrino oscillation data.

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## 1 Introduction and summary

Heavy Neutral Leptons (HNLs) that interact through the weak interaction via their mixing with ordinary neutrinos (“neutrino portal”) are a much studied extension of the Standard Model (SM) of particle physics. The physical motivation for HNLs is rich [1]; most notably they can be associated with the generation of light neutrino masses via the type-I seesaw mechanism [2–7], can explain the observed baryon asymmetry of the universe [8] via leptogenesis [9], and can serve as Dark Matter candidates [10]. Phenomenological studies are commonly based on the model

$$\mathcal{L} \supset -\frac{m_W}{v} \bar{N} \theta_\alpha^* \gamma^\mu e_{L\alpha} W_\mu^+ - \frac{m_Z}{\sqrt{2}v} \bar{N} \theta_\alpha^* \gamma^\mu \nu_{L\alpha} Z_\mu - \frac{M}{\sqrt{2}v} \theta_\alpha h \bar{\nu}_{L\alpha} N + \text{h.c.}, \quad (1)$$

where the spinor  $N$  represents a single flavour of HNLs of mass  $M$ , while  $\nu_{L\alpha}$  and  $e_{L\alpha}$  are SM neutrinos and charged leptons, respectively,  $h$  is the physical Higgs field and  $v \simeq 174$  GeV is its vacuum expectation value. The HNLs’ interaction strength is determined by the magnitudes  $U_\alpha^2 \equiv |\theta_\alpha|^2$  of their mixing angles  $\theta_\alpha$  with SM generation  $\alpha = e, \mu, \tau$ . Ignoring kinematical factors, the cross section for HNL production along with leptons of flavour  $\alpha$  and their decay into gauge bosons and leptons of flavour  $\alpha$  are both proportional to  $U_\alpha^2$ .<sup>1</sup>  $N$  can in principle be a Dirac or a Majorana spinor. In the latter case the ratio  $R_{\ell\ell}$  between lepton number violating (LNV) and lepton number conserving (LNC) HNL decays is  $R_{\ell\ell} = 1$ , while in the former case  $R_{\ell\ell} = 0$ .

<sup>1</sup> Many extensions of the SM predict HNLs with additional interactions, including new gauge interactions or an extended scalar sector. In such models HNL production and decay may be governed by different parameters. For the present purpose we focus on scenarios in which all HNL interactions at the experimentally relevant energies can effectively be parameterised by their mixing with SM neutrinos.

Realistic implementations of the type-I seesaw as the origin of neutrino masses necessarily require the existence of several HNL flavours; more precisely, the number  $n$  of HNL flavours must be equal or larger than the number of massive SM neutrino flavours, implying  $n \geq 2$  if the lightest neutrinos mass  $m_{\text{lightest}}$  vanishes and  $n \geq 3$  for  $m_{\text{lightest}} > 0$ . The simple Lagrangian (1) with  $n = 1$  does not represent a realistic model of neutrino masses, but can effectively capture many phenomenological aspects of seesaw-models with only five parameters  $(M, U_e^2, U_\mu^2, U_\tau^2, R_{\ell\ell})$ . Depending on the HNL mass spectrum, their lifetime, and the underlying symmetries, the ratios observed at accelerator experiments may effectively interpolate between the cases  $R_{\ell\ell} = 0$  and  $R_{\ell\ell} = 1$  [11, 12]. Moreover, specific neutrino mass models make predictions for the HNL flavour mixing pattern, i.e., the relative size of the ratios  $U_\alpha^2/U^2$  with  $U^2 = \sum_\alpha U_\alpha^2$ , often presented in the form  $U_e^2:U_\mu^2:U_\tau^2$ . The sensitivity of experiments can strongly depend on these ratios even for fixed total mixing  $U^2$  [13–15].

All of this gives rise to a rich phenomenology [1, 11, 16–20]. Currently most searches assume that a single HNL flavour ( $n = 1$ ) couples exclusively to one SM generation (“single flavour mixing”), corresponding to the benchmarks BC6, BC7 and BC8 defined in [21],

$$U_e^2:U_\mu^2:U_\tau^2 = 1:0:0 \quad \text{BC6} \tag{2a}$$

$$U_e^2:U_\mu^2:U_\tau^2 = 0:1:0 \quad \text{BC7} \tag{2b}$$

$$U_e^2:U_\mu^2:U_\tau^2 = 0:0:1 \quad \text{BC8} \tag{2c}$$

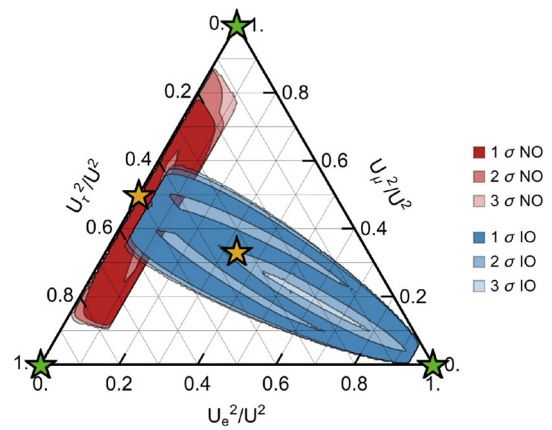
with either  $R_{\ell\ell} = 1$  or  $R_{\ell\ell} = 0$ . While these provide well-defined benchmarks for experimental searches and sensitivity studies, they are inconsistent with the observed light neutrino properties. We propose an extended set of benchmark scenarios that can effectively describe many phenomenological aspects of realistic neutrino mass models within the Lagrangian (1). Specifically, we propose the two new benchmarks for the flavour mixing patterns,

$$U_e^2:U_\mu^2:U_\tau^2 = 0:1:1 \tag{3a}$$

$$U_e^2:U_\mu^2:U_\tau^2 = 1:1:1 \tag{3b}$$

while keeping the choices  $R_{\ell\ell} = 1$  and  $R_{\ell\ell} = 0$ . The new and previous benchmarks (3) and (2), respectively, are compared in Fig. 1.

The physical motivation for choosing the new benchmarks is based on the requirement to capture the HNL properties typically predicted by realistic neutrino mass models (and not on the properties of specific experiments), they may be used in searches, reinterpretations and sensitivity projections for experiments. Additional motivation for an extended set of benchmarks is based on the observation that the sensitivity of both fixed target experiments [13, 14] and collider exper-



**Fig. 1** The new benchmarks (3) and old benchmarks (2) for  $U_e^2:U_\mu^2:U_\tau^2$  (here displayed in the form  $U_\alpha^2/U^2$ ) are represented by the yellow and green stars, respectively. They are compared to the range of  $U_\alpha^2/U^2$  consistent with light neutrino oscillation data [23] for normal (red) and inverted (blue) ordering of light neutrino masses in the large mixing limit (4) of the *minimal seesaw model A*. In this limit these ratios are completely fixed by the light neutrino oscillation parameters, and are in particular independent of  $M$  across the entire mass range targeted by direct searches at accelerators

iments [15, 22] can change by orders of magnitude when e.g. changing the flavour mixing pattern.

This article is organised as follows. In Sect. 2 we outline the criteria on which we base the benchmark selection. In Sect. 3.1 we apply these criteria to motivate the proposed benchmark in the minimal type-I seesaw model. In Sect. 3.2 we comment on the robustness of the motivation for the new benchmarks when going beyond that minimal model.

## 2 Criteria for the benchmark selection

For given HNL mass  $M$  a benchmark in the sense considered here is defined by fixing the ratios  $U_e^2:U_\mu^2:U_\tau^2$  as well as  $R_{\ell\ell}$ . For the sake of definiteness, we base the benchmark selection on the requirement to explain the known properties of the light neutrino mass and mixing matrices  $m_\nu$  and  $V_\nu$  in models that can effectively be described within the pure type-I seesaw Lagrangian, i.e., the extension of the SM by  $n$  flavours of right-handed neutrinos, and apply the following criteria.

- (1) **Consistency with neutrino oscillation data.** Our key requirement is to effectively reproduce the phenomenology of realistic neutrino mass models within the phenomenological model (1). In comparison to previous studies that took a similar approach [13, 14, 24] we use an updated global fit to light neutrino oscillation data to constrain the  $U_e^2:U_\mu^2:U_\tau^2$ , and we take into consideration how those global fits can evolve when the Dirac phase

$\delta$  is measured in future experiments. The latter ensures a maximal robustness of the selected benchmarks with respect to future neutrino oscillation data.

- (2) **Added value.** In view of the considerable effort that any experimental search requires, new benchmark scenarios can only be justified if they lead to phenomenological predictions for accelerator-based experiments that are clearly distinguishable from the existing benchmarks BC6-BC8. Past studies have shown that percent-level changes in the  $U_e^2:U_\mu^2:U_\tau^2$  only affect the experimental sensitivities near the single-flavour benchmarks BC6-BC8 in (2), in particular near the BC8 [14].
- (3) **Symmetry considerations.** We generally follow an agnostic approach that makes (1) and (2) the most important criteria. If these criteria do not conclusively prefer one amongst several possible choices of the  $U_e^2:U_\mu^2:U_\tau^2$ , we take into account which one of them can be motivated by model building considerations, in particular discrete symmetries of the fermion mixing matrices (cf. [25–27]). We further consider maximal CP-violation in the direction of the current experimental hints appealing.
- (4) **Simplicity.** Between benchmarks that are similarly strongly motivated by the criteria (1)–(3), we give preference to ratios  $U_e^2:U_\mu^2:U_\tau^2$  that are simple and can be easily communicated to the community.
- (5) **Leptogenesis.** A second motivation for the existence HNLs with sub-TeV masses (in addition to explaining the light neutrino masses) lies in the possibility to explain the observed baryon asymmetry of the universe through low scale leptogenesis [28–30]. Amongst those candidates for benchmark models that are similarly well-motivated by the criteria (1)–(4), scenarios that can accommodate leptogenesis in an experimentally accessible range of  $M$  and  $U^2$  are favoured.

### 3 Benchmark selection

We consider two types of scenarios, both based on the most general renormalisable extension of the SM by  $n$  flavours of right-handed neutrinos and no other new particles,

- (A) **Minimal seesaw model.** The minimal realisation of the type-I seesaw Lagrangian that is consistent with all light neutrino oscillation data includes two HNLs ( $n = 2$ ), which implies  $m_{\text{lightest}} = 0$  up to one-loop level [31].
- (B) **Next-to-minimal seesaw model.** The minimal realisation of the type-I seesaw Lagrangian that can give mass to all three SM neutrinos ( $m_{\text{lightest}} > 0$ ) includes three HNLs ( $n = 3$ ). This choice is also necessary for anomaly cancellation in any extension of the SM that includes a gauged  $U(1)_{B-L}$  symmetry, where  $B$  and  $L$  refer to the baryon and lepton number, respectively.

#### 3.1 The minimal model (A)

From the viewpoint of direct searches for HNLs at accelerator based experiments, the interesting scenarios are those with  $M$  below the TeV scale and mixing angles that are much larger than the naive seesaw expectation,

$$U^2 \gg \sqrt{\sum_i m_i^2}/M. \quad (4)$$

A consistent theoretical framework in which these conditions are fulfilled is represented by the class of neutrino mass models that can effectively be described within the minimal seesaw model (A) in the *symmetry protected scenario* in which the two right-handed neutrinos approximately respect a generalisation of the global  $U(1)_{B-L}$  symmetry known in the SM [32,33]. This implies that the two HNLs  $N_I$  (with  $I = 1, 2$ ) have quasi-degenerate masses, and their mixing angles  $\theta_{\alpha I}$  with individual SM flavours approximately fulfil the relation  $\theta_{\alpha 2} \simeq i\theta_{\alpha 1}$ . This has several advantages.

- The presence of a generalised  $B - L$  symmetry that suppresses the light neutrino masses  $m_i$  is a necessary condition to make mixing angles (4) that are large enough to detect the HNLs at in accelerator-based experiments consistent with the smallness of the  $m_i$  without fine-tuning [33,34]. It permits technically natural low scale seesaw models with  $M$  below the electroweak scale and coupling constants of order one, cf. section 5.1 in [35].
- This model effectively describes the phenomenology of popular extensions of the SM, including the Neutrino Minimal Standard Model ( $\nu$ MSSM) [30,36] and inverse [37–41] and linear [42–44] seesaws scenarios.
- Its minimality makes the model highly predictive [45,46]. In particular, in the phenomenologically relevant regime (4) the ratios  $U_e^2:U_\mu^2:U_\tau^2$  are in good approximation determined by the parameters in the light neutrino mixing matrix  $V_\nu$  alone.
- The model is self-consistent in the sense that it could in principle be a complete effective field theory up to the Planck scale [47].
- The model allows for low scale leptogenesis in the range of  $M$  and  $U_\alpha^2$  that is accessible to experiments, cf. [48–50] for updated parameter space scans.

Based on the criteria (1)–(5) we propose the two new benchmarks for the flavour mixing pattern given in (3). The new benchmarks (3) are compared to the existing ones (2) in Fig. 1. If relevant for the respective search, we further propose considering the choices  $R_{\ell\ell} = 1$  and  $R_{\ell\ell} = 0$  for each benchmark in (2) and (3).

*Dirac vs Majorana HNLs* The choices  $R_{\ell\ell} = 1$  and  $R_{\ell\ell} = 0$  correspond to assuming a pure Majorana or a pure Dirac HNL

in the phenomenological model (1). In an effective description of technically natural realisations of the minimal realistic seesaw model (A),  $R_{\ell\ell}$  can take any value between 0 and 1 [51].<sup>2</sup> An experimental determination of  $R_{\ell\ell}$  is in principle possible through several observables (including direct observations of the ratio between lepton number violating and conserving decays [12,52,53], its dependence on position [54–56], the momentum distribution [57–62] and polarisation [62] of the decay products, the  $U_\alpha^2/U^2$  [63], and the lifetime [64]), and would be very interesting from the viewpoint of testing the underlying model [45,46,65]. However, performing analyses for a sizeable number of values for  $R_{\ell\ell}$  would be a considerable effort, and an additional difficulty is posed by the fact that current event generators cannot simulate the HNL oscillations that can occur for values that interpolate between  $R_{\ell\ell} = 0$  and  $R_{\ell\ell} = 1$  [54–56,66–69] in a straightforward way. Due to these technical and practical limitations, at this stage it seems reasonable to continue using the limiting cases  $R_{\ell\ell} = 0$  and  $R_{\ell\ell} = 1$  for which software tools are readily available (cf. e.g. [70–73]),<sup>3</sup> knowing that they only represent limiting cases of realistic neutrino mass models, the phenomenology of which can be much richer than the five parameter model (1) and potentially depends on a large number of parameters (e.g. the complex phases in the complex HNL mixing angles  $\theta_{\alpha I}$ ). A near-future goal is to identify ways to capture as many aspects of realistic models as possible within an effective description in terms of a small set of parameters and benchmarks.<sup>4</sup> Addressing these matters is important even prior to a discovery of HNLs because the (re)interpretation of experimental data in terms of exclusion bounds does depend on them, and deviations from the predictions based on simulations in the model (1) with  $n = 1$  may be mistaken for signs of new other particles or interactions.

*The flavour mixing pattern* We apply the criteria (1)–(5) to the minimal seesaw model (A) in order to motivate the new

<sup>2</sup> Within the reach of near-future experiments, the requirement to avoid tunings points towards values  $R_{\ell\ell} \sim 1$  for  $M \ll m_W$  and  $R_{\ell\ell} \ll 1$  for  $M \gg m_W$  in the model (A), with a sizeable regime in between in which any value  $0 \leq R_{\ell\ell} \leq 1$  can be realised.

<sup>3</sup> A FeynRules [74] model file and a patch for MadGraph [75] that permit to effectively simulate HNL oscillations in the detector have recently been developed in [69]. The availability of this tool may affect extended benchmark recommendations in the future.

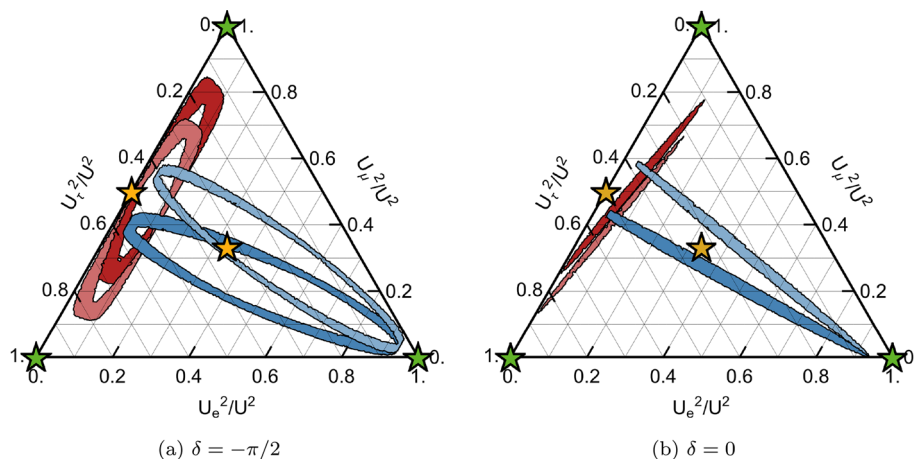
<sup>4</sup> In the context of long-lived HNLs, one possibility to go beyond the description in terms of  $(M, U_e^2, U_\mu^2, U_\tau^2, R_{\ell\ell})$  is to introduce a sixth parameter that characterises the ratio between the effective mixings that govern their production rate and lifetime (e.g.  $c_{\text{dec}}/c_{\text{prod}}$  in the notation of [76]). This ratio is also affected by the amount of LNV (Majorana HNLs can decay into twice as many final states as Dirac HNLs), but it is not uniquely fixed by specifying  $R_{\ell\ell}$  in models with mass-degenerate HNLs (cf. [68,69,76] and references therein). Another possibility would be to introduce a displacement-dependent  $R_{\ell\ell}$  to describe HNL oscillations in the detector [55,56,69].

benchmarks (3). Our primary selection criterion is (1), i.e., the consistency with current and future neutrino oscillation data. Due to its minimality, the model (A) can make testable predictions for the ratios  $U_\alpha^2/U^2$ , cf. Fig. 1. The flavoured mixing ratios  $U_e^2:U_\mu^2:U_\tau^2$  are determined by the parameters in the light neutrino mass and mixing matrices  $m_\nu$  and  $V_\nu$  alone [45,46], with the main uncertainties currently coming from the lack of knowledge about the CP phase  $\delta$  and the Majorana phase  $\alpha$ .<sup>5</sup> This can be nicely displayed in the form of ternary diagrams [77], cf. Fig. 1. As we are mapping the seven neutrino oscillation parameters (three angles, two mass splittings and two phases) onto a two-dimensional space of flavour ratios, each choice of ratios  $U_\alpha^2/U^2$  corresponds to a continuum of neutrino oscillation parameters. Using the Casas–Ibarra parameterisation [78], we vary the neutrino oscillation parameters within the  $3\sigma$  allowed range from NuFIT 5.1 [23], and we keep the Majorana phase as a free parameter  $\in [0, 4\pi]$  [79]. For each choice of parameters one can estimate the  $\chi^2$  by combining the 1-d projections for  $\Delta m_{ij}^2$ ,  $s_{12}$  and  $s_{13}$  with the 2-d  $\chi^2$  projection for the parameters  $s_{23}$  and  $\delta$ , which have the largest deviation from Gaussianity. We follow the procedure from [80] and collect the points generated this way into  $U_e^2:U_\mu^2:U_\tau^2$  bins and take the minimal value of  $\chi^2$ .<sup>6</sup> The results are shown in Fig. 1. There is a significant degeneracy among the allowed mixing angles, as the ratios  $U_\alpha^2/U^2$  have a strong dependence on the unknown Majorana phase. Besides this 1-dimensional degeneracy, the strongest dependence remains on the CP phase  $\delta$ , and the value of  $s_{23}$  as the remaining parameters are already measured at a much higher precision. In practice it is therefore sufficient to only vary the Majorana phase, and  $s_{23}^2$  and  $\delta$  in the allowed  $3\sigma$  regions, and fix the remaining parameters to their best fit values.

An interesting observation is that the centres of the allowed regions are already slightly disfavoured by current neutrino oscillation data, meaning that the naive approach of placing a benchmark somewhere in the middle of these region is not the best way to ensure robustness with respect to future neutrino oscillation data. This is a result of the current information about  $\delta$ . Once  $\delta$  is measured, the allowed region will further reduce, and a measurement of the  $U_\alpha^2/U^2$  would allow to measure the Majorana phase [45,46,85], provided that  $\delta$  is measured independently at DUNE [81] or HyperK [83]. This would in turn permit to predict the rate of neutrinoless double  $\beta$ -decay in the model (A), cf. Fig. 3. We show in the left panel of Fig. 2 how the allowed range of  $U_\alpha^2/U^2$  is expected to change with future neutrino oscillation experiments, considering the future DUNE sensitivity from [82] for the true values  $(\delta, s_{23}^2) = (-\pi/2, 0.58)$ ,  $(\delta, s_{23}^2) = (-\pi/2, 0.42)$ ,

<sup>5</sup> Note that there is only one physical Majorana phase in  $V_\nu$  for  $n = 2$ .

<sup>6</sup> Alternatively, one can instead assign a posterior probability to the flavour ratios as was done in [14].



**Fig. 2** Projected 90% CL for the allowed range of  $U_\alpha^2/U^2$  after 15 years of data taking at DUNE [81] in case of normal ordering (red) and inverted ordering (blue). The contours are generated by assuming For this forecast we vary the CP phase  $\delta$  and  $s_{23}$  within the expected 90% CI regions from [82] corresponding to two true values of  $\delta = (-\pi/2, 0)$ , and two benchmark values of the light neutrino mixing

$(\delta, s_{23}^2) = (0, 0.58)$  and  $(\delta, s_{23}^2) = (0, 0.42)$ .<sup>7</sup> Note that the sensitivities to  $\delta$  and  $\theta_{23}$  of HyperK [83] and DUNE [82] are quite similar and, therefore, very similar results are expected using HyperK. The combination of DUNE and HyperK data would lead to a more precise determination of both parameters [84], further reducing the future allowed regions in Fig. 2.

A comparison between the allowed regions for the two chosen values of  $s_{23}^2$  in that figure suggests that benchmarks with

$$U_e^2 \ll U_\mu^2 \simeq U_\tau^2 \tag{5}$$

are the ones that are most safe from being ruled out in the case of normal ordering (the allowed region roughly moves up and down parallel to the  $U_e^2 = 0$  line in Fig. 2 when changing  $s_{23}^2$ ), while scenarios with

$$U_e^2 \gg U_\mu^2 \simeq U_\tau^2 \tag{6}$$

are most the most safe ones in case of inverted ordering (the allowed region roughly rotates around the benchmark point (2b) in the  $U_\mu^2$ -corner when changing  $s_{23}^2$ ). However, points

of the type (6) are disfavoured by criterion (2): They would provide little added value, as they are relatively close to the existing benchmark (2a). At the same time inverted ordering clearly allows for points in which all three mixings are of comparable size,

angle  $s_{23}^2 \equiv \sin^2 \theta_{23} = 0.58$  (darker region) and  $s_{23}^2 = 0.42$  (lighter region) that were used in the DUNE TDR [82]. Comparable sensitivity can be expected at Hyper-K [83,84]. The remaining parameters are fixed to their current best fit values. Note that the projected regions are independent of  $M$

$$U_e^2 \simeq U_\mu^2 \simeq U_\tau^2, \tag{7}$$

a scenario that is not reflected in the current benchmarks (2). The criterion (2) implies that we should add a benchmark of the kind (7) to capture the qualitatively different phenomenology that one can expect from this compared to the benchmarks (2). Neither current neutrino oscillation data in Fig. 1 nor the projections in Fig. 2 single out a particular point amongst all combinations of the type (7) (keeping in mind that any value between the two chosen examples for  $s_{23}^2$  is possible). Since all combinations of the type (7) are expected to lead to similar phenomenology at accelerator experiments, the simplicity criterion 4) can be used to argue for the equipartition benchmark (3b) to represent them. The benchmark (3b) can in addition be motivated by criterion (3): As illustrated in Fig. 4, the statistically favoured region is roughly centred around the value  $\delta = -\pi/2$ . Finally, benchmark (3b) can be used when connecting accelerator-based experiments to neutrinoless double  $\beta$ -decay. In the large mixing limit (4) and neglecting the HNL contribution to  $m_{\beta\beta}$  (which is justified for sufficiently mass-degenerate HNLs and  $M \gg 160$  MeV [86]),<sup>8</sup> knowledge of  $U_e^2/U^2$  determines  $m_{\beta\beta}$  in the symmetry protected limit (4) of model (A):

<sup>7</sup> We have checked that for  $\delta = \pi/2$  and the same true values for  $s_{23}$  [82], the allowed projections shown in Fig. 2 do not change significantly.

<sup>8</sup> Note that the contribution from HNLs can in principle be sizeable [87,88] and play a crucial role for the testability of the model (A) and leptogenesis [45,89,90].

$$|m_{\beta\beta}|^2 = \begin{cases} U_e^2/U^2(m_2 + m_3)[m_2(2s_{12}^2c_{13}^2 - U_e^2/U^2) + m_3(2s_{13}^2 - U_e^2/U^2)] & \text{for NO, and,} \\ U_e^2/U^2(m_1 + m_2)[m_1(2c_{12}^2c_{13}^2 - U_e^2/U^2) - m_2(2s_{12}^2s_{13}^2 + U_e^2/U^2)] & \text{for IO,} \end{cases} \quad (8)$$

as shown in Fig. 3. The benchmark (3b) lies in the region where  $m_{\beta\beta}$  is close to its maximal value for inverted ordering. Finally, it is worthwhile mentioning that leptogenesis in the model (A) is feasible in the vicinity of this benchmark [45, 46, 50, 65].

Turning to the case of normal ordering, we notice that literally all allowed points exhibit the hierarchy  $U_e^2 \ll U_\mu^2, U_\tau^2$ . Amongst these, the criteria (1) and (2) both prefer points of the kind (5): Those are the most robust against varying  $s_{23}$  in Fig. 2, and they are the furthest away from the existing benchmarks (2), potentially giving rise to qualitatively different phenomenology in direct searches for HNLs. If we fix  $U_\mu^2 \approx U_\tau^2$  (consistent with proposed  $\mu - \tau$  flavour symmetries, cf. [25]), the points with  $U_e^2/U^2 \sim 0.005$  and  $U_e^2/U^2 \sim 0.12$  are favoured from the viewpoint of Fig. 2. Between them the smaller one, which leads to the combination

$$U_e^2:U_\mu^2:U_\tau^2 = 2:199:199 \quad (9)$$

is favourable with respect to criterion (2), as it is further away from (3b). Further, by obeying a  $\mu - \tau$  flavour symmetry and being consistent with values  $\delta = -\pi/2$  (cf. Fig. 4), it obeys criterion (3). The combination (9) has the disadvantage that it involves fractions, which is in tension with criterion (4). These shortcomings can be overcome by using (3a) instead of (9), which comes at the price that (3a) strictly speaking cannot reproduce the observed light neutrino oscillation data in the symmetry protected model (A) (as it would lead to  $\nu_{Le}$  not mixing with other flavours). However, for all observables that do not crucially rely on a non-zero  $U_e^2$ , the phenomenology of the combinations (9) and (3a) is likely to be very similar. This applies to most direct searches at experiments involving proton beams. At  $e^+e^-$ -colliders (3a) is preferred from the viewpoint of the added value criterion (2) because it suppresses charged current HNL production at tree level, hence comparing (3a) to (3b) as well as (2) permits to map out the most optimistic and most pessimistic scenarios.<sup>9</sup> Finally, the

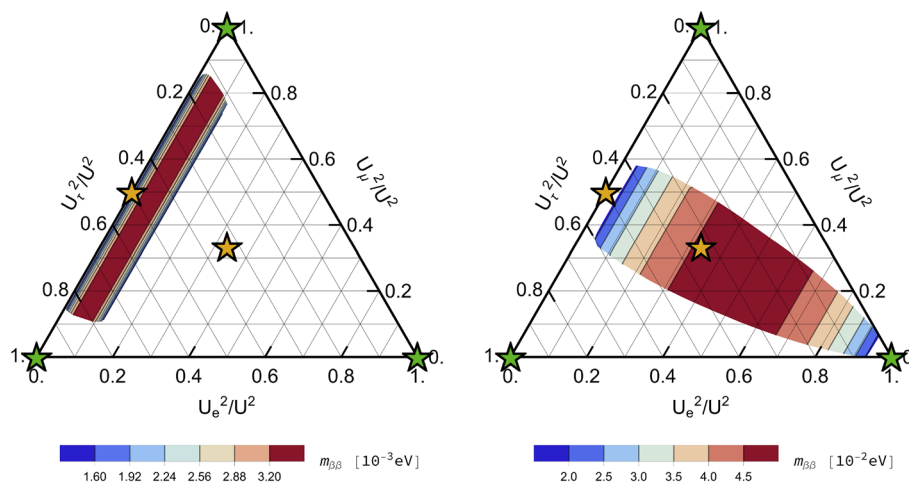
benchmark (3a) is well-motivated from the viewpoint of criterion (5), as leptogenesis for the largest  $U^2$  in the model (A) requires a strong hierarchy between the  $U_\alpha^2/U^2$ . In particular, for normal ordering configurations of the kind (5) allow for the largest  $U^2$  consistent with leptogenesis [46, 50, 65], and hence the largest production cross section in particle collisions.

Even though the above discussion regarding the selection of the new benchmarks partially relies on the assumption of maximal CP violation, as by current global fits [23], we would like to remark that the proposed benchmarks lie inside or close to the future allowed regions even if the less appealing possibility of CP conservation is assumed, as shown in the right panel of Fig. 2.

### 3.2 The model (B) with three HNLs

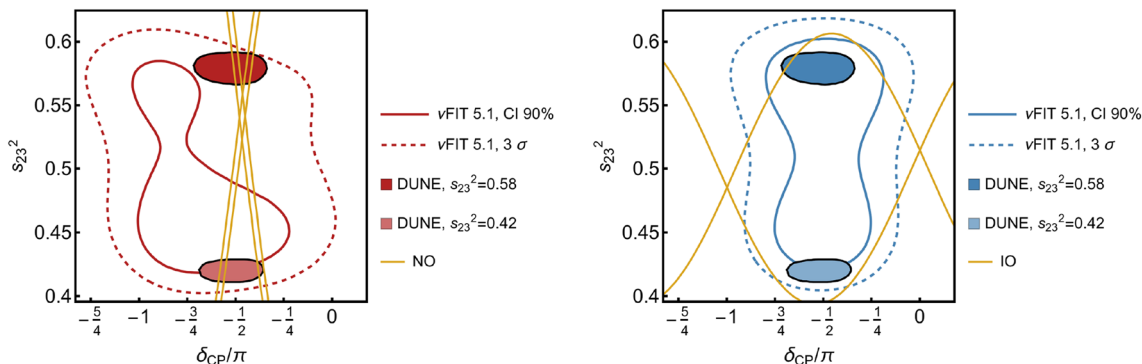
The type-I seesaw model with three HNLs can give masses to all three SM neutrinos. This comes at the price of a considerably larger parameter space comprising 18 instead of the 11 new parameters in the model (A) with two HNLs. As a result, the model is far less predictive, making it more difficult to single out well-motivated benchmarks. The  $U_\alpha^2/U^2$  are not determined by light neutrino parameters in  $m_\nu$  and  $V_\nu$  alone any more, but also depend on phases in the HNL sector. As a result, knowledge of the  $U_\alpha^2/U^2$  and light neutrino parameters is not sufficient any more to compute  $m_{\beta\beta}$ . The ranges of values for the  $U_\alpha^2/U^2$  that are consistent with neutrino oscillation data increases with  $m_{\text{lightest}}$ . For values  $m_{\text{lightest}} < 10^{-5}$  eV they roughly agree with Fig. 1, but already for  $m_{\text{lightest}} \sim 10^{-2}$  eV they cover almost the entire triangle for both light neutrino mass orderings [91]. Hence, neither laboratory measurements nor cosmology will impose a sufficiently strong upper bound on  $m_{\text{lightest}}$  in the near future to substantially restrict the range of  $U_\alpha^2/U^2$ . The maximal  $U^2$  consistent with leptogenesis is several orders of magnitude larger than in the minimal model (A) with two HNLs, but there is no clear preference for hierarchical  $U_\alpha^2/U^2$  because the large  $U^2$  can be achieved through other dynamical effects [92, 93]. As a result the range of  $U_\alpha^2/U^2$  can be treated as unconstrained for all practical purposes. Within specific models that exhibit additional symmetries (such as discrete flavour symmetries) this range can be restricted, but such restrictions are strongly model dependent. If any data in the future points to a particular class of models, or if a consensus in the scientific community is reached to identify a particular set of symmetries as reference models, this would permit to define additional benchmarks for the  $U_e^2:U_\mu^2:U_\tau^2$ . Within the

<sup>9</sup> These considerations are tailored to direct searches for HNLs. In some important indirect probes (such as neutrinoless double  $\beta$ -decay,  $\mu \rightarrow e\gamma$  decays, and  $\mu$  conversion in nuclei) the small but non-zero  $U_e^2$  required by neutrino oscillation data is crucial, and a benchmark as (9) can be useful. The same caveat holds for direct searches involving triggers or vetoes that rely on charged lepton flavour violating processes including electrons. This e.g. explains the surprisingly large difference observed between benchmarks 5 and 6 defined in [15] (which closely resemble our new benchmarks) for the case of Dirac HNLs ( $R_{\ell\ell} = 0$ ), which is caused by the opposite-sign same-flavour veto.



**Fig. 3** The neutrinoless double  $\beta$ -decay parameter  $m_{\beta\beta}$  in model (A) as a function of the flavour mixing ratios  $U_\alpha^2/U^2$  in the case of normal ordering (left) and inverted ordering (right) in the limit (4) and neglecting the contribution from HNL exchange. Due to the significant uncertainties in the nuclear matrix elements, the value of  $m_{\beta\beta}$  cannot be

measured precisely enough to determine the Majorana phase. Nonetheless, it can still impose constraints on the allowed values of  $U_\alpha^2/U^2$ . Finally, we note that the benchmark point (3b) lies exactly in the region where  $m_{\beta\beta}$  is close to its maximal value for inverted ordering



**Fig. 4** The areas inside the lines represent the regions in the  $s_{23}^2$  and  $\delta$  plane preferred by the global fit NuFit 5.1 to light neutrino oscillation data for normal ordering (red, left panel) and inverted ordering (blue, right panel). The dotted line corresponds to  $3\sigma$  CL, the full one to 90%

CL. The filled regions are projections for DUNE data, using the values and colour coding as in Fig. 2. The yellow lines indicate combinations of  $s_{23}^2$  and  $\delta$  that correspond to the combinations (9) (left panel) and (3b) (right panel), i.e., along the lines the ratios  $U_\alpha^2/U^2$  are constant

agnostic approach we take, and in view of the present data, there appears to be no strong motivation to add any further benchmarks to (2) and (3).

### 4 Conclusions

The interpretation and re-interpretation of experimental searches for HNLs are greatly facilitated when different experiments perform their analyses for a commonly used set of benchmark scenarios. Using the same set of benchmarks also allows to make fair comparisons of the sensitivity of proposed future experiments, aiding institutions and funding agencies in their decisions between different proposals.

In the context of HNLs that exclusively interact through the SM weak interaction in (1) at the energies relevant for a given experiment, a benchmark comprises a selection of ratios  $U_e^2:U_\mu^2:U_\tau^2$  (with  $U_\alpha^2 = |\theta_\alpha|^2$ ), along with a specification of the ratio  $R_{\ell\ell}$  between LNV and LNC HNL decays. In [21] three benchmarks (2) were identified, which have been used by both PBC and collider experiments. While these single-flavour benchmarks provide well-defined reference points, a shortcoming is that they do not describe the properties of HNLs predicted by realistic neutrino mass models well. In the present article we propose two additional benchmarks (3) to alleviate this shortcoming. They are selected based on the criteria (1)–(5) defined in Sect. 2, with the main goal to provide a better approximation for the phenomenology of realistic neu-

**Table 1** The complete list of the benchmark points recommended in this document. For each of the five flavour ratios, when possible, one should also consider the limiting cases where  $R_{ll} = 0$  (Dirac-like) and  $R_{ll} = 1$  (Majorana-like). These ratios are independent of  $M$  and, thus, our proposal applies to the entire mass range targeted by direct searches at accelerators

	$U_e^2/U^2$	$U_\mu^2/U^2$	$U_\tau^2/U^2$	$R_{ll}$
(2a)	1	0	0	0 1
(2b)	0	1	0	0 1
(2c)	0	0	1	0 1
(new) (3a)	0	1/2	1/2	0 1
(new) (3b)	1/3	1/3	1/3	0 1

trino mass models within the framework of the phenomenological Lagrangian (1). The old and new benchmarks are shown in Fig. 1 and summarized in Table 1. In combination they provide an extended coverage of the range of possible HNL properties, and in particular effectively approximate the phenomenology of neutrino mass models within the type-I seesaw framework in accelerator-based direct HNL searches.

The combined sets (2) and (3) clearly cannot capture all phenomenological aspects of complete neutrino mass models, not only because they approximate the continuous ratios  $U_e^2:U_\mu^2:U_\tau^2$  by a discrete set, but also because there are phenomena that can qualitatively not be described within the single HNL Lagrangian (1), such as HNL oscillations in the detector and related effects, including CP-violation and non-integer values of  $R_{\ell\ell}$  that can depend on the HNL boost and displacement. In case any HNLs are discovered experimentally, all these phenomena will provide important keys to understand their properties, what role they may play for the mechanism of neutrino mass generation, baryogenesis, dark matter, and how they are embedded in a more fundamental theory of nature. However, most searches for HNLs that aim for discovery do not rely on such subtle effects, though the (re)interpretation of experimental data in terms of exclusion bounds can be sensitive to them. Hence, while more accurate modelling is clearly needed for precision studies, the combined sets of benchmarks in Table 1 can describe a wide range of signatures commonly used in searches for HNLs that interact with SM gauge bosons through their mixing with ordinary neutrinos. It would be highly desirable to define a similar set of benchmarks for models with an extended field content, but this remains challenging due to the wealth of possible extensions of the SM and their vastly different phenomenologies.

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