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# Bounds on right handed neutrinos from observable leptogenesis

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I discuss the testability prospects of the minimal GeV-scale type-I seesaw model and the associated leptogenesis mechanism within future experiments as SHiP and FCC-ee. In particular, I show how to derive accurate analytical approximations to the solution of the kinetic equations, which expose the non-trivial parameter dependencies in the form of first principles CP invariants. On the one hand, this allows to derive robust mass-dependent upper and lower bounds on the HNL mixing. On the other hand, it also reveals the correlation of baryogenesis with other observables, as e.g. the flavour structure or neutrinoless double-beta decay.

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## 1. Introduction

Leptogenesis addresses the problem of the observed baryon asymmetry of our Universe (BAU) within a framework which can simultaneously provide masses to the active neutrinos. The minimal type-I seesaw model in accordance with neutrino oscillations data extends the Standard Model (SM) with two Majorana singlet fermions (HNLs) that couple to the SM via the fermion portal, is also able to explain the BAU for heavy state masses ranging from sub-GeV to $\sim 10^{15}$ GeV. An interesting scenario is that the Majorana masses are in the range of $(0.1 - 100)$ GeV, such that the HNLs can be produced at colliders. In this case, the relevant process to generate the BAU is via HNL oscillations during its freeze-in [1, 2]. Although this model has been extensively studied in the past (see [3] for a review), an accurate analytical understanding of the parameter space that leads to successful baryogenesis was first derived in [4]. In particular, the use of parametrization-independent CP flavour invariants allows to express the analytical solutions in terms of other flavour observables. This allows to either analytically predict the constraints on the BAU arising from putative future measurements of HNLs, CP violation in neutrino oscillations and neutrinoless double-beta decay or, alternatively, to set bounds on HNL parameters from the BAU. In the following I review the method we derived in [4] to analytically solve the complete linearized set of quantum Boltzmann equations. The solutions take into account mass effects in the interaction rates and cover all washout regimes. In section 3 I show some of the resulting constraints from the BAU.

## 2. The model and analytical approximation

The model considered is the type-I seesaw, which adds to the SM $n$ fermion singlets $N^i$. The Lagrangian therefore reads

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{\alpha,i} \bar{L}^\alpha Y^{\alpha i} \tilde{\Phi} N^i - \sum_{i,j=1}^{n} \frac{1}{2} \bar{N}^{ic} M_{Rij} N^j + h.c.,$$

where $Y$ is a $3 \times n$ complex Yukawa matrix and $M_R$ is a $n \times n$ complex symmetric matrix. $L$ is the fermion doublet and $\tilde{\Phi} = i\sigma_2 \Phi^*$ is the Higgs doublet. We consider the minimal model with $n = 2$. An approximate lepton number (LN) symmetry [5, 6] leads to testable mixings between the HNLs and the SM sector which exceed the naive seesaw scaling. Assigning the LN $L(N_1) = -L(N_2) = 1$, the textures of $Y$ and $M_R$ are given by

$$Y = \begin{pmatrix} y_e e^{i\beta_e} & y'_e e^{i\beta'_e} \\ y_\mu e^{i\beta_\mu} & y'_\mu e^{i\beta'_\mu} \\ y_\tau e^{i\beta_\tau} & y'_\tau e^{i\beta'_\tau} \end{pmatrix}, \quad M_R = \begin{pmatrix} \mu_1 & \Lambda \\ \Lambda & \mu_2 \end{pmatrix}. \tag{1}$$

Here, with $y^2 \equiv \sum_\alpha y_\alpha^2$ we have $y'_\alpha/y \ll 1$ and $\mu_i/\Lambda \ll 1$, because $y'_\alpha$ and $\mu_i$ break the LN symmetry. In particular, this guarantees the light neutrino masses to be under perturbative control $m_\nu = f(y'/y, \mu_i/\Lambda)$, while leading to unsuppressed HNL mixings $U^2 \simeq (yv/M)^2$, with $v =$ 246 GeV the Higgs vev and $M$ being the average of the physical HNL masses $\Lambda = (M_1+M_2)/2 \equiv M$. We will use eq. (1) to analytically solve for the baryon asymmetry $Y_B$ by perturbing around the symmetric limit. To do so, we make the following approximations. We first linearize the system, assume the interaction rates to evolve only linearly with the temperature at leading order and that the lepton chemical potentials do not receive flavour cross contributions from the $B/3 - L_\alpha$ chemical potentials. To find a closed form solution, we further need to employ an adiabatic approximation for cases in which there is a large hierarchy between the vacuum oscillation rate and thermalization rate of the right handed neutrinos, i.e. $\epsilon = \Gamma_{\rm osc}/\Gamma \ll 1$ or $\epsilon^{-1} \ll 1$. If however $\epsilon \ll 1$ only until some temperature $T_0 > T_{\rm EW}$ but then $\epsilon^{-1} \ll 1$ from $T_0$ down to $T_{\rm EW}$, a solution can be found via the projection of the solution found at $T_0$ onto the subsystem of the weak washout modes. This method allows to cover the *intermediate* regime which has not been considered in the literature before. Comparing the analytical result to the full numerical solution we find an agreement within at most a factor of two. Further imposing that the model resembles neutrino oscillations data, the parameter space gets tightly constrained and correlated. It is described by only 6 free parameters which are one Yukawa scale, two HNL masses and 3 phases encoding CP violation, i.e. the Dirac and Majorana PMNS phases and a high scale phase, see [4] for the parametrization. Our analytical approximations for the baryon asymmetry depends on CP flavour invariants, which can be used to derive robust connections between the generation of the baryon asymmetry and other observables, which I will discuss in the next section, but more details can be found in [4].

## 3. Constraints from the baryon asymmetry

By employing the perturbative methods discussed in the previous section, we can derive the constraints imposed by successful baryogenesis on the masses and mixings of the HNLs as well as the CP violating phases. Here I consider two particular examples, but see [4] for further details. On the one hand, I show how to derive an absolute upper bound on the mixing of the HNLs with the active neutrinos for which leptogenesis is possible. On the other hand, I show correlations in the flavour ratios $|U_\alpha^2|/U^2$ and implications on the amplitude of neutrinoless double-beta decay driven by $m_{\beta\beta}$.

**Analytical upper bound.** The largest mixings of the HNLs compatible with the BAU can be achieved if one weak mode ensures the out-of-equilibrium condition at the electroweak phase transition. The following physical scenario guarantees exactly this. As long as the LN symmetry of eq. (1) is approximately exact, the two HNLs are nearly degenerate, i.e. $\Delta M = 2\mu_2 \ll 1$. Furthermore, in the same basis it is evident that $N_2$ interacts with the thermal plasma only via the perturbatively small coupling $y' \ll y$. Imposing the constraints arising from neutrino oscillations it can be shown that in fact $y' \propto y^{-1}$ [4]. This means that the larger the HNL mixing the farther $N_2$ is kept out of thermal equilibrium. Such a scenario is known as the *overdamped* regime, in which the vacuum oscillation length of $N_1 \to N_2$, dictated by $\Delta M$, is larger than its plasma free streaming length. On the other hand, the analytical solution of the quantum kinetic equations reveals that the baryon asymmetry behaves as $Y_B \sim C_1 y'/y^3 + C_2 y'/y$ if helicity conserving interactions are weak or as $Y_B \sim C_3 y'/y$ if they are strong. This means that there is a non-trivial interplay between the generation of the light neutrino masses and the baryon asymmetry, which leads to an upper bound on the HNL mixing. Figure 1 shows the upper bound analytically derived in ref. [4] for both, normal and inverted, hierarchies. It is compared to the full numerical solution of a parameter space scan within the sensitivity reach of the future colliders `SHiP` and `FCC`. We can appreciate an excellent agreement.

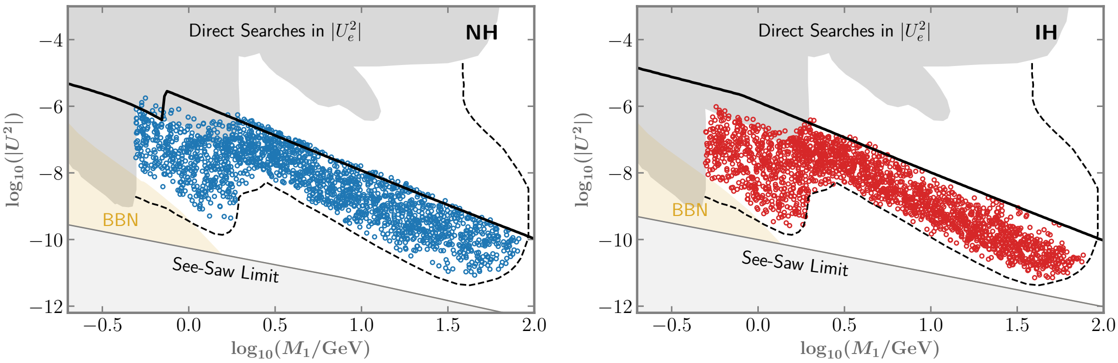


**Figure 1:** Numerical result of the Bayesian analysis (blue (red) points for NH (IH)) together with the analytical derived upper bound on the HNL mixing (black line). The grey shaded regions is excluded by direct searches or neutrino masses (seesaw limit), while the yellow one is excluded by big bang nucleosynthesis constraints.

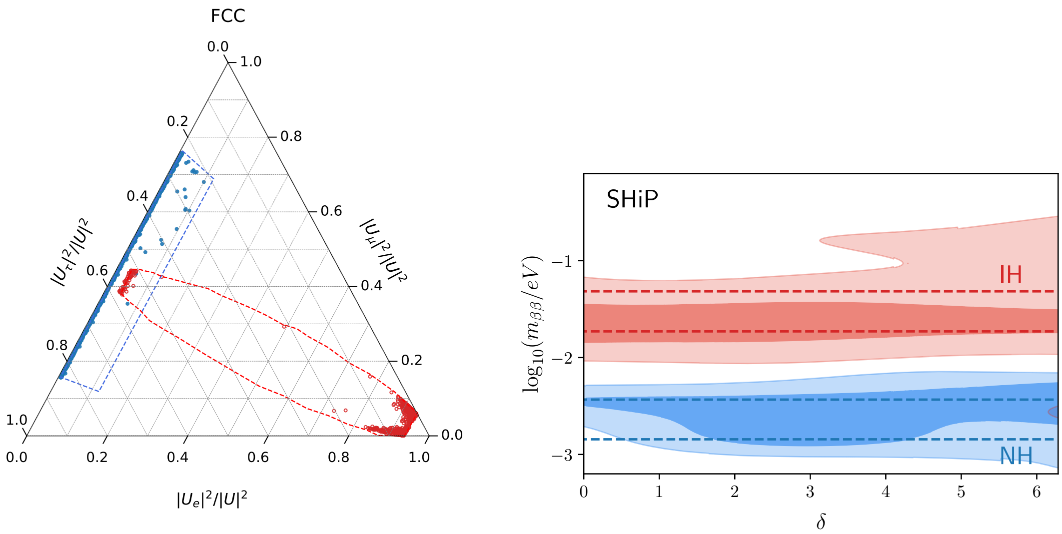


**Figure 2:** Solutions of a numerical scan with fixed $\Delta M/M = 10^{-2}$ for which the BAU can be explained. NH (IH) is shown in blue (red). Left: Flavour ratio of points testable at `FCC`. The dashed lines correspond to the region compatible with neutrino oscillation data. Right: 1 and $2\sigma$ region of points testable at `SHiP` on the plane $(\delta, m_{\beta\beta})$. The standard light neutrino contribution is contained within the dashed bands.

**Correlations of the BAU to other observables.** For concreteness we will focus on the scenario in which $\epsilon^{-1} \ll 1$ at the time of the first oscillation $T_{\rm osc}$. This is known as the *fast oscillations* regime. It requieres flavour hierarchical interactions, $\Gamma_\alpha(T_{\rm EW}) < H(T_{\rm EW})$ for some flavour $\alpha$, to achieve HNL mixings inside the sensitivity reach of `SHiP` and `FCC`. Such hierarchies are controlled by $\epsilon_\alpha = y_\alpha^2/y^2$, which is naturally expected to be $O(1)$. The farther suppressed $\epsilon_\alpha$ is compared to $O(1)$ the more pronounced is the flavour selection in $|U_\alpha|^2/U^2$. This can be seen in the left panel of fig. 2 for an exemplary and potentially measurable relative mass splitting of $\Delta M/M = 10^{-2}$. The right panel of figure 2 shows both the active neutrino and HNL contribution to $m_{\beta\beta}$ for HNLs with mixings to the active neutrinos which are testable at `SHiP`. Remarkably, the presently preferred range of $\delta \geq \pi$ [7, 8] corresponds to the region where HNLs effects lead to an enhancement of $m_{\beta\beta}$.

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