Probing baryon asymmetry of the Universe at LHC and SHiP

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The origin of the baryon asymmetry of the Universe (BAU) is one of the major puzzles beyond the Standard Model. Detecting the particles responsible for the generation of the BAU would enormously boost our understanding of physics of the early Universe. Here we demonstrate that searches for displaced vertices at ATLAS, CMS and LHCb allow detecting heavy neutral leptons (HNL) with parameters that can simultaneously lead to the successful generation of the BAU and explain the masses and oscillations of active neutrinos. The combination of a dedicated LHC search program and a complementary Intensity Frontier experiment (such as SHiP) will allow exploring a sizeable part of the “minimal HNL baryogenesis” parameter space.

Introduction. Heavy Neutral Leptons (also known as HNLs, right-handed, Majorana or sterile neutrinos) can provide resolutions to several beyond-the-Standard-Model puzzles. They can explain neutrino masses and oscillations (via the so-called type I seesaw mechanism [1–6]); can generate the baryon asymmetry of the Universe via the process known as leptogenesis (see reviews [7–11] and references therein); and can provide a dark matter candidate (see e.g. [12] for review). Moreover, all three phenomena can be explained within one compact extension of the Standard Model, known as the Neutrino Minimal Standard Model or νMSM [13, 14], see [15] for review. In particular, the mass scale of the HNLs responsible for the generation of BAU can be as low as GeV [13, 14, 16], thus opening the possibility of probing a leptogenesis scenario in particle physics laboratories. Many subsequent works have investigated the leptogenesis with GeV-scale HNLs, see e.g. [17–42]. At the same time, searches for heavy neutral leptons have been performed and are included into the scientific plans of most of the currently running particle physics experiments [43–51]. Many search strategies have been proposed, some of them having potential to reach deep into the HNL’s parameter space using the high luminosity phase of the LHC [52–75]. A number of proposed experiments will further probe the HNL’s parameter space [76–85].

The question whether the HNLs, probed in particle physics experiments, can be responsible for the generation of BAU has been addressed before (see e.g. [64] for review). The current work is motivated by several recent theoretical and experimental developments:

(1) The recent work [42] has elaborated the region in the parameter space where successful baryogenesis is possible. In particular it has been demonstrated that HNLs with larger than previously estimated mixing angles can lead to successful baryogenesis. Ref. [42] has been limited to HNLs with masses $m_N \lesssim 10\text{ GeV}$. In this work we extend the results of [42] to higher masses.

(2) The HNL searches with displaced vertices (DV) at ATLAS and CMS experiments have been discussed in [72]. We revise this strategy and discuss another DV strategy for CMS.

(3) The estimates of the sensitivity of the LHCb experiment have concentrated on HNLs produced from the W bosons [66]. Searches [44] concentrated on a rare production channel $B \to \mu N$ followed by $N \to \mu \pi$. We update the sensitivity estimates by including the HNLs produced in the decays of the $B$ mesons and decaying to different final states.

(4) The sensitivity of the SHiP experiment for heavy neutral leptons has been revised [86], in particular for masses $m_N \sim 5\text{ GeV}$ and mixing angles $U^2 \gtrsim 10^{-8}$. We show that the synergy between the LHC and the intensity frontier searches can allow covering a sizeable part of the parameter space where successful baryogenesis can take place.

The paper is organized as follows. First we summarize recent baryogenesis results and extend them to higher masses. Then we give a brief overview of the DV search strategies at the LHC. Sec. I presents our estimates of the sensitivity in the DV searches at ATLAS, CMS and LHCb. In Sec. II we present our results.

Leptogenesis with GeV-scale HNLs. At least two HNLs, highly degenerate in mass are needed for the successful baryogenesis in the GeV-mass range [13, 14]. Ref. [42] has focused on the region of the parameter space $0.1\text{ GeV} \lesssim m_N \lesssim 10\text{ GeV}$, which is important for the intensity frontier experiments. Since the DV signature at the LHC allows probing heavier masses, we extent the analysis of [42] by computing the rates entering the kinetic equations describing the generation of baryon asymmetry for masses $10\text{ GeV} \lesssim m_N \lesssim 30\text{ GeV}$, and perform

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1 Flavor dependent mixing angles $U_{\alpha}^2, U_{\nu}^2, U_{\tau}^2$ specify by how much the interaction of HNLs with $W/Z$ bosons is weaker than that of the Standard Model neutrinos. The total mixing is defined as $U^2 = \sum_{\alpha} |U_{\alpha}|^2$. 

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a scan over the parameter space. Even heavier HNLs require yet another dedicated study. Indeed, as suggested in [90], the decays $N \rightarrow W\ell$—when kinematically allowed—lead to efficient washout of the generated asymmetry. Therefore, one can expect that the allowed region is bounded by $m_N \lesssim M_W$. This effect is not included in our kinetic equations and deserves a dedicated study.

Note that in the rVMSM the masses of the HNLs must be nearly degenerate since their oscillations play the crucial role in generating of the BAU. Therefore, two Majorana HNLs could be effectively described by a single Dirac particle [91] with the corrections of order $\Delta M/M$, where $\Delta M$ is the mass splitting. This means that the amplitudes of the lepton number violating processes (including same-sign lepton signatures) are suppressed.

**Displaced vertices at the LHC.** Current experimental bounds (summarized e.g. in [77]) put the mixing of HNLs at the level $U^2 \sim 10^{-5}$ for masses $m_N \gtrsim 2\text{GeV}$. HNLs with such parameters would travel distances of the order of meters for $\gamma$ factor $\sim 1$ [92].

Owing to a sufficiently long lifetime of HNLs one can search for their decays at macroscopic distance from the interaction point – displaced vertex (DV) signature. Such a search strategy drastically reduces possible backgrounds [55, 57, 66, 71, 72, 93], making this possibility particularly interesting at colliders. Usually the DV searches are performed using the inner trackers of ATLAS or CMS. In [94] it was proposed to utilize CMS muon tracker to reconstruct the HNLs that decay into pairs of muons. We call the latter strategy “Long DV” as this schema allows probing longer displacements. Correspondingly the other strategy will be called “short DV”.

**I. SENSITIVITY ESTIMATES**

The number of detected events is given by

$$N_{\text{events}} = N_{\text{parent}} \cdot \text{Br} \cdot P_{\text{dec}} \cdot \epsilon,$$

where $N_{\text{parent}}$ is the number of parent particles ($W$ bosons and/or $B$ mesons)\(^2\) shown in Table I; $\text{Br}$ is the branching fraction for $W^\pm \rightarrow N + l^\pm$ or (semi-)leptonic decays of $B$ mesons, see Fig. 1: $P_{\text{dec}}$ is the decay probability

$$P_{\text{dec}} = e^{-l_{\text{min}}/\epsilon\tau(\gamma_N)} - e^{-l_{\text{max}}/\epsilon\tau(\gamma_N)}$$

with $l_{\text{min}}$ and $l_{\text{max}}$ determined by the geometry of a tracker, and $\langle \gamma_N \rangle$ being the average $\gamma$ factor of the HNL.\(^3\) Finally, the parameter $\epsilon$ is the efficiency—the fraction of all HNL decays that occurred inside the decay volume (between $l_{\text{min}}$ and $l_{\text{max}}$) that have passed the selection criteria and were successfully reconstructed.

The sensitivity curve is determined by the condition $N_{\text{events}} \approx 3$ (95% confidence limit). The lower boundary of such a curve is determined by the regime $l_{\text{min}} \ll

\(^2\) Production from $Z$ and/or Higgs bosons, as well as direct production via Drell-Yan processes and quark/gluon fusion, is subdominant [57, 63, 65, 71, 97] and will be neglected in what follows.

\(^3\) For the HNLs produced from $B$ mesons we define $\langle \gamma_N \rangle = \sqrt{(\gamma_X)^2(\gamma_{N_{\text{rest}}})^2} - 1$, where $\gamma_X$ is the $\gamma$ factor of a parent meson that moves in the direction of the decay volume, and $\gamma_{N_{\text{rest}}}$ is the $\gamma$ factor of the HNL in the rest frame of the meson. For the HNLs from $W$ bosons we ran MadGraph5 [88] simulation to find the average $\gamma$ factor.

| Parent/Experiment | $l_{\text{min}}, l_{\text{max}}$ | Cross-section | Number | $(E)$ |
|-------------------|-----------------|----------------|---------|------|
| $W \oplus$ ATLAS/CMS, Short DV | $0.4\text{ cm}, 30\text{ cm}$ [72] | $\sigma_W \simeq 193\text{ nb}$ [87] | $5 \times 10^{11}$ | – |
| $W \oplus$ CMS, Long DV | $2\text{ cm}, 300\text{ cm}$ | $\sigma_W \simeq 193\text{ nb}$ [87] | $5 \times 10^{11}$ | – |
| $B \oplus$ LHCb | $2\text{ cm}, 60\text{ cm}$ [66] | $\sigma_{B\ell} \simeq 1.3 \times 10^8\text{ pb}$ [88] | $4.9 \cdot 10^{13}$ | $84\text{ GeV}$ [89] |

Table I. Number of parent particles ($W$ bosons or $B$ mesons), their average energy $\langle E \rangle$ and corresponding parameters of the DV search schemes used for the estimates. All numbers are given for the high luminosity phase of the LHC ($L = 3000\text{ fb}^{-1}$ for CMS/ATLAS and $L = 380\text{ fb}^{-1}$ for the LHCb) and can be proportionally rescaled for other luminosities. To obtain the average energy of $B$ mesons we use their spectrum at $\sqrt{s} = 13\text{ TeV}$ in the pseudorapidity range of LHCb as provided by FONLL simulations [89].
\( cT_N \langle \gamma_N \rangle \) where the number of events scales approximately as \( N_{\text{events}} \propto U^4 \) which allows to find the \( U^2 \) value for the lower boundary from Eqs. (1)–(2). The upper boundary is found in the regime \( l_{\text{min}} > cT_N \langle \gamma_N \rangle \) so that \( P_{\text{dec}} \approx \exp \left[ -l_{\text{min}}/(cT_N \langle \gamma_N \rangle) \right] \) and \( N_{\text{events}} \) is exponentially sensitive to \( \gamma_N \). Therefore the HNL momentum distribution becomes important with the most energetic HNLs determining the exact shape of the boundary. By assuming that all of the HNLs are produced with the average \( \gamma \) factor, we underestimate the position of the upper boundary and, as a result, the maximal mass probed, which is defined as the intersection of the lower and the upper bounds of the sensitivity.

**Short DV at ATLAS and CMS.** The analysis of this case has been performed in [72] using Monte Carlo (MC) simulations. Below we compare their result with our analytic estimates.

The efficiency of the HNL detection is determined by the cuts imposed in order to reduce background and efficiently reconstruct displaced vertex in the ATLAS inner detector [99]:

- One prompt lepton (\( e \) or \( \mu \)) with \( p_T > 25 \) GeV that serves for tagging of the process \( W \to \ell + N \). In case of mixing with \( \tau \), the reconstruction of prompt \( \tau \) leads to the reduced efficiency.
- The distance between the interaction point and the decay position must be between \( l_{\text{min}} \) and \( l_{\text{max}} \).
- There should be at least four charged decay products with \( p_T > 1 \) GeV and transverse impact parameter \( |d_0| > 2 \) mm.
- The invariant mass of the DV reconstructed by the selected decay products must be larger than 5 GeV.

The last two criteria reduce the search to the background free region (see a discussion in [72]).

In our estimates we use efficiencies \( \epsilon \) provided by the authors of [72].\(^4\) To obtain the average energy of the HNLs \( \langle E_N \rangle \) and the geometric acceptance \( \epsilon_{\text{geom}} \)\(^5\) we simulated the process \( pp \to W + X \) to leading order in MadGraph 5 [98]. Using the resulting spectrum of the \( W \) bosons, we calculated the energy distribution of the HNLs in the pseudorapidity range \( \eta_N < 2.5 \) (see Appendix A for details). In the mass range \( m_N \lesssim 30 \) GeV we obtained \( \langle E_N \rangle \approx 80 \) GeV and \( \epsilon_{\text{geom}} \approx 0.5 \).

Our resulting estimates of the sensitivity for ATLAS/CMS short DV searches, together with the sensitivity estimates from the simulations in [72], are shown in Fig. 2. We limit our analysis to HNLs with \( m_N > 5 \) GeV. For lower masses production from \( B \) mesons starts to contribute/dominates the production of HNL. For completeness, we show in Fig. 3 the value of the efficiencies

\[^4\] We are grateful to the authors of [72] for sharing with us the results of their MC simulations.

\[^5\] We define the geometrical acceptance as the amount of the HNLs that fly in the direction of ATLAS experiment.

**Figure 2.** The sensitivity of DV searches with the ATLAS inner tracker (short DV, DV\textsubscript{S}). The green solid line shows our estimate, while the green dashed line shows the sensitivity based on the MC simulations from [72].

**Figure 3.** The efficiency for the “short DV” search schemes for mixing with \( \nu_\mu \) (blue curve) and \( \nu_\tau \) (green curve).

for mixing with \( \nu_\mu \) and \( \nu_\tau \) close to the lower boundary of the sensitivity region.

We expect that the DV searches with the CMS inner tracker will provide similar sensitivity.

**Possible alternatives to the short DV strategy.** One of the selection criterion that strongly affects the efficiency is the requirement of at least four charged tracks needed to suppress hadronic background. An alternative way to suppress it is to search for DVs events with three
leptons – one prompt lepton originating from the decay \( W \to N + l \) and two other from the decay \( N \to l + l' + X \). Let us estimate the sensitivities of this “three lepton scheme” for the HNLs mixing with \( \nu_\mu \) when all 3 leptons are muons. For the efficiency of the three leptons scheme we have

\[
\epsilon_{3\mu} = \epsilon_{\text{track DV}} \cdot \epsilon_{\mu\mu} \cdot \epsilon_{\text{prompt}} \cdot \text{Br}_{N \to \mu\mu N} \approx 3 \cdot 10^{-3},
\]

where \( \epsilon_{\text{track DV}} \approx 0.1 \) is the efficiency of the reconstruction of the two-track DV, \( \epsilon_{\mu\mu} \approx 0.6 \) is the efficiency of the reconstruction of two muons from the DV, and \( \epsilon_{\text{prompt}} \approx 0.9 \) is the efficiency of the reconstruction of the prompt muon originating from \( W^{\pm} \to \mu^{\pm} + N \). The branching fraction \( \text{Br}_{N \to \mu\mu N} \approx 6 \cdot 10^{-2} \). We see that \( \epsilon_{3\mu} \) is always smaller than the efficiency of the scheme from [72, 99] at the lower boundary of the sensitivity region, see Fig. 3. Therefore we conclude that the scheme with two leptons is less efficient for the detection of the HNLs.

\[\footnote{We are grateful to Philippe Mermod for providing us with these efficiencies.}\]

**Long DV at CMS.** An alternative way to search for DV is to use the CMS muon tracker and to reconstruct the displaced vertex from two muons (see [94] for more details). This opens a possibility reconstructing a decay point at distances as far as \( l_{\text{max}} \approx 3 \text{ m} \) [100], that is why we call this method “long DV” scheme. The selection criteria are:

- Two displaced muon tracks, each with \( p_T > 5 \text{ GeV} \);
- The position of the DV must be within \( l_{\text{min}} = 2 \text{ cm} \) and \( l_{\text{max}} = 3 \text{ m} \).

Both cuts are essential to make the long DV searches background free. The comparison of the sensitivities of the “short DV” and “long DV” schemes is shown in Fig. 4.

**DV at LHCb.** We identify an HNL decay event at LHCb as a DV event if it passes the following selection criteria adapted from [44]:

- Decay products must be produced in pseudorapidity range \( 2 < \eta < 5 \).
- The single muon must have \( p_T > 1.64 \text{ GeV} \) to pass the trigger.
- Hadrons must have \( p > 2 \text{ GeV} \) and \( p_T > 1.1 \text{ GeV} \) to be tracked.
Lepton products of HNL decay should have $p > 3$ GeV and $p_T > 0.75$ GeV.

Following [44], we estimate the corresponding efficiency as $\epsilon \sim 10^{-2}$ for all visible decay channels.

The main parameters for the LHCb experiment are given in Table I. We notice that at the energies of the LHC for large masses of the HNL ($m_N \simeq 3$ GeV in the case of the mixing with $\nu_e/\mu$ and $m_N \simeq 2$ GeV in the case of the mixing with $\nu_\tau$) the main production channel is the 2-body leptonic decays of the $B_\tau$ mesons (see, e.g., [86, 92]). This makes possible to probe HNL masses up to $m_{B_\tau} \approx 6.3$ GeV. The mixing angle $U^2$ at the lower bound of the sensitivity is given by

$$U^2_{\bar{b}b} = 2.6 \cdot 10^{-6} \sqrt{\frac{300}{\mathcal{L}[fb^{-1}]}} \frac{10^{-2} c\tau_N}{\epsilon} \frac{(\gamma_N)}{m \sum_B f_{B \to B} B_{B \rightarrow N + X}},$$

(4)
The relevant parameters for masses of 2 and 4 GeV are summarized in Table II.

| Mixing | $m_N$, GeV | $f_{b \to B} \text{Br}_{B \to N + X}$ | $c \tau_N$, m | $(\gamma_N)$ |
|--------|------------|-----------------|----------------|-------------|
| $\mu$  | 2          | $9.7 \cdot 10^{-3}$ | $1.7 \cdot 10^{-6}$ | 22.5 |
| $\mu$  | 4          | $1.8 \cdot 10^{-4}$ | $4.5 \cdot 10^{-7}$ | 14.3 |
| $\tau$ | 2          | $2.4 \cdot 10^{-4}$ | $4.5 \cdot 10^{-7}$ | 22.5 |
| $\tau$ | 4          | $1.3 \cdot 10^{-4}$ | $9.6 \cdot 10^{-7}$ | 14.3 |

Table II. The values of the parameters from the estimate (4) of the lower bound of the LHCb experiment for particular masses. We use the value of the momentum of the $B$ meson from Sec. I, the HNL production branching from the Fig. 1 and the discussion above (4) for the details.

The plot of the sensitivity is shown on Fig. 5.

II. RESULTS

Our main results are given in Fig. 6. We show the sensitivities for two different luminosities: $L_c$, which corresponds to the current accelerator statistics, and high luminosity $L_h$, which corresponds to LHC run 4. For LHCb they are $L_c = 6.7$ fb$^{-1}$ and $L_h = 300$ fb$^{-1}$, while for ATLAS/CMS they are $L_c \approx 160$ fb$^{-1}$ and $L_h = 3000$ fb$^{-1}$.

Our conclusions are the following:

- Intensity frontier experiments can probe the baryogenesis in the range $m_N \lesssim m_B$. For $m_N \lesssim m_d$ they are able to probe mixing angles almost all the way down to the lower boundary, determined by the requirement of the successful neutrino oscillations and BAU;

- DV search schemes at ATLAS and CMS have a potential to probe the baryogenesis parameter space in the mass range $m_N \gtrsim m_B$ and are complementary to the intensity frontier experiments;

- In the mass region $m_N \lesssim m_B$ there is a region that cannot be probed by any of the above searches. We argued that the LHCb DV search for HNLs produced in $B$ mesons decays and perhaps CMS long DV search have an ability to cover this domain.

In conclusion the combination of displaced vertex searches at the ATLAS, CMS and LHCb together with intensity frontier experiments can enter the cosmologically interesting part of the HNL parameter space and has the potential to discover particles responsible for both neutrino oscillations and baryon asymmetry of the Universe.

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Appendix A: Production of the HNLs from $W$-bosons

We estimate the number of the HNLs flying in the direction of the ATLAS and CMS experiments in the following way:

$$N_{\text{prod}} = \sigma_W \times \mathcal{L} \times \epsilon_{\text{geom}}, \quad (A1)$$

where $\sigma_W$ is the total production cross-section of the $W$ bosons at the LHC (we use $\sigma_W \approx 193$ nb from the experimental paper [87]) and $\epsilon_{\text{geom}}$ is the geometric acceptance (i.e. the amount of the HNLs that are produced in the direction of the pseudorapidity range of ATLAS $|\eta| < 2.5$).

The total value of the branching ratio of the $W$ boson decay to HNLs is shown in Fig. 1.

We estimate the momentum spectrum of the $W$ bosons $dN_W/dp_W$ by performing the leading order simulation of the process $p + p \rightarrow W + X$ in MadGraph 5. Using it, we obtained $\epsilon_{\text{geom}}$ and the average HNL energy $\langle E_N \rangle$ by calculating the distribution of the HNLs in the energy and the angle $\theta_N$ between the direction of motion of the HNL and the $W$ bosons (whose momenta are found to be collinear to the proton beam direction in the simulations):

$$\frac{d^2N_N}{dE_N d\theta_N} = \int dp_W \frac{dN_W}{dp_W} \times \frac{d^2\text{Br}_{W \to N + l}}{d\theta_N dE_N} \times P(\theta_N) \quad (A2)$$

Here

$$\frac{d^2\text{Br}_{W \to N + l}}{d\theta_N dE_N} = \frac{1}{\Gamma_W} \frac{|M_{W \to l + N}|^2}{8\pi} \times \delta(m_N^2 + m_W^2 - 2E_N E_W + 2p_{Nl} \cos(\theta_N)) \quad (A3)$$

is the differential production branching ratio, and $P(\theta_N)$ is a projector which takes the unit value if $\theta_N$ lies inside the range $|\eta| < 2.5$ and zero otherwise.

The resulting angular and energy distributions of the HNLs at ATLAS are shown in Fig. 7. For the mass range $m_N \lesssim 30$ GeV we obtained $\langle E_N \rangle \approx 80$ GeV and $\epsilon_{\text{geom}} \approx 0.5$ with the accuracy $\sim 20\%$. 


The contribution of the $W$ boson mass.

The nuMSM, dark matter and neutrino masses,

Figure 7. Left panel: the angular distribution of the HNLs produced in the decays of the $W$ bosons. The red dashed lines indicate the values of the angle corresponding to $\eta = \pm 2.5$. Right panel: the energy distribution of the HNLs flying in the direction of the ATLAS inner tracker. An HNL mass $m_N = 20$ GeV is used. The peak around $E_N \approx M_W/2$ is caused by the contribution of the $W$ bosons produced with very low $p_T$, so that all of the HNLs have the same energy equal to the half of the $W$ boson mass.

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