

Heavy Neutrinos in displaced vertex searches at the LHC and HL-LHC

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Abstract

We study the sensitivity of displaced vertex searches for heavy neutrinos produced in W boson decays in the LHC detectors ATLAS, CMS and LHCb. We also propose a new search that uses the muon chambers to detect muons from vertices with very large displacement. The sensitivity estimates are based on benchmark models in which the heavy neutrinos mix exclusively with one of the three Standard Model generations. The displaced vertex searches can cover a significant part of the parameter region where heavy neutrinos can explain the baryon asymmetry of the universe via low scale leptogenesis.

1 Introduction

Heavy right handed neutrinos ν_R appear in many extensions of the Standard Model (SM) of particle physics and provide an elegant explanation for the masses of the SM neutrinos via the type-I *seesaw mechanism* [1–6]. Depending on their masses, they can potentially also explain several other open puzzles in cosmology and particle physics, *cf. e.g.* [7] for an overview. For instance, they may explain the matter-antimatter asymmetry in the early universe that is believed to be the origin of baryonic matter in the present day universe¹ via *leptogenesis* [9] (*cf. e.g.* [10] for a recent review), compose the Dark Matter (DM) [11] (*cf. e.g.* [12, 13] for recent reviews) or explain anomalies in some neutrino oscillation experiments (*cf. e.g.* [14]).

In order to explain the light neutrino masses, the right handed neutrino flavours ν_{Ri} must necessarily mix with the left handed SM neutrinos ν_{La} , with $a = e, \mu, \tau$. Through this mixing they can interact with the weak gauge bosons. More precisely, the mass eigenstates N_i after electroweak symmetry breaking couple to the weak interaction with amplitudes that are suppressed by small mixing angles θ_{ai} in the Lagrangian (1). This interaction is unavoidable in the framework of the seesaw mechanism. In general the heavy neutrinos can, in addition to this, have new gauge interactions that may lead to an interesting phenomenology [15]. In the present work we take the conservative approach and assume that the N_i can exclusively be produced and decay via their θ -suppressed weak interactions. Then the phenomenology of heavy neutrinos N_i in collider experiments can be entirely characterised by their mass M_i and the mixing angle θ_{ai} that suppresses their weak interaction with SM generation a : If kinematically

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¹A discussion of this hypothesis can *e.g.* be found in [8].

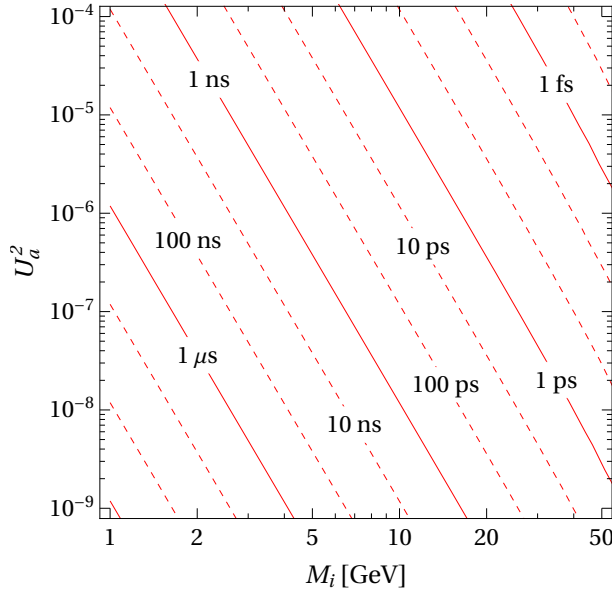


Figure 1: The heavy neutrino life time as a function of its mass and coupling calculated with **MadWidth** (*cf.* also relation (3)).

allowed, the N_i appear in any process that involve ordinary neutrinos of flavour a , but with a coupling constant that is suppressed by θ_{ai} and a phase space that is affected by their mass M_i [16, 17]. In particular, in the relativistic regime, their production cross section is simply given by $U_{ai}^2 \sigma_{\nu_a}$, where σ_{ν_a} is the ordinary neutrino production cross section per generation and we have defined $U_{ai}^2 = |\theta_{ai}|^2$. Their decay width parametrically scales as $\Gamma_{N_i} \propto M_i^5 U_i^2$ with $U_i^2 = \sum_a U_{ai}^2$ [18–21], where the precise prefactor depends on the mass range, for the masses under consideration here it is approximately given in relation (3).² For sufficiently small mixing angles, the heavy neutrinos are *long lived particles* that can travel macroscopic distances before they decay into SM particles, *cf.* Figure 1, giving rise to displaced vertex signatures.

In the present work we explore the sensitivity of the LHC main detectors to heavy neutrinos with masses between the B meson and W boson masses in the type-I seesaw model. From a theoretical viewpoint this mass range is interesting because the heavy neutrinos could simultaneously explain the light neutrino masses via the seesaw mechanism and the matter-antimatter asymmetry of the universe via low scale leptogenesis [24, 25], while avoiding the weak hierarchy problem [26] due to the smallness of their interactions.³ From an experimental viewpoint this mass range is particularly interesting because the heavy neutrinos can be produced in comparably large numbers at the Large Hadron Collider (LHC) in the decays of real gauge bosons, *cf.* Figure 2. For larger masses the production cross section is much smaller than the exchanged W boson is virtual, and the heavy neutrinos always decay promptly, *cf. e.g.* ref. [30] for a recent study. For smaller masses the heavy neutrinos tend to be too long lived to decay inside the main LHC detectors in sizeable numbers, though some improvement can be achieved by using parked data

²The strong dependence of the lifetime $1/\Gamma_{N_i}$ on M_i is the reason why heavy neutrinos with masses $M_i > 100$ MeV are not subject to any constraints from the Cosmic Microwave Background or primordial nucleosynthesis [22, 23].

³In fact, an extension of the SM by three right handed neutrinos known as *Neutrino Minimal Standard Model* (ν MSM) [25, 27] could in addition to this also explain the observed DM density [20, 28], and could in principle be a complete theory of nature up to the Planck scale [29].

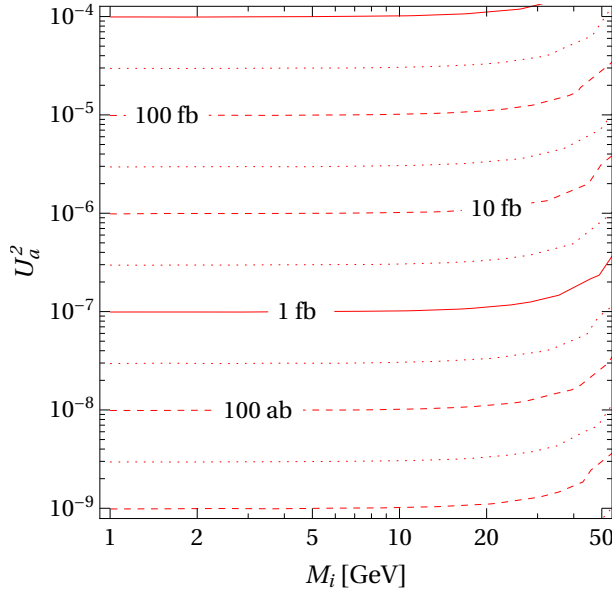


Figure 2: Cross section of the process $pp \rightarrow l_a^\pm N \rightarrow l_a^\pm l_a^\mp f f'$ at the 14 TeV LHC as a function of the heavy neutrino mass and its coupling (calculated using MadGraph).

or data from heavy ion runs [31]. A better sensitivity can be reached with the recently approved FASER experiment [32] and other proposed dedicated detectors [33–38], *cf.* [34, 36, 39]. For an overview of proposed dedicated long lived particle searches at the LHC see Reference [40]. Fixed target experiments like NA62 [41, 42], T2K [43], DUNE [44] and in the future at SHiP [45–47] are generally more sensitive than the LHC [48].

Currently the strongest collider constraints come from a recent CMS study [49, 50] and LEP data [51]. It has previously been pointed out in a number of theoretical papers that the sensitivity could be further improved by searching for displaced signatures [31, 52–62]. We extend these studies in several ways.

1. We compare the sensitivity of ATLAS, CMS and LHCb in a single study.
2. We estimate the sensitivity that can be achieved with the HL-LHC in all three experiments. Apart from an increased luminosity of 3000 fb^{-1} for ATLAS and CMS and 380 fb^{-1} for LHCb and collision energy of 14 TeV, this means that CMS will be able to detect particles with larger pseudorapidity $|\eta| < 4$ [63].
3. We study the sensitivity of each experiment for heavy neutrinos that mix with any of the SM generations in both, charged and neutral current interactions. Sensitivity estimates for heavy neutrinos that mix with $\nu_{L\tau}$ were previously made in [60, 62], but were restricted to decays via neutral current interactions.
4. We propose a new search based on the idea to use the muon chambers for long lived particle searches [64, 65], which was shown to be feasible in [66]. We should add that a similar proposal was made independently in [62], which appeared while we were in the final stage of our analysis.

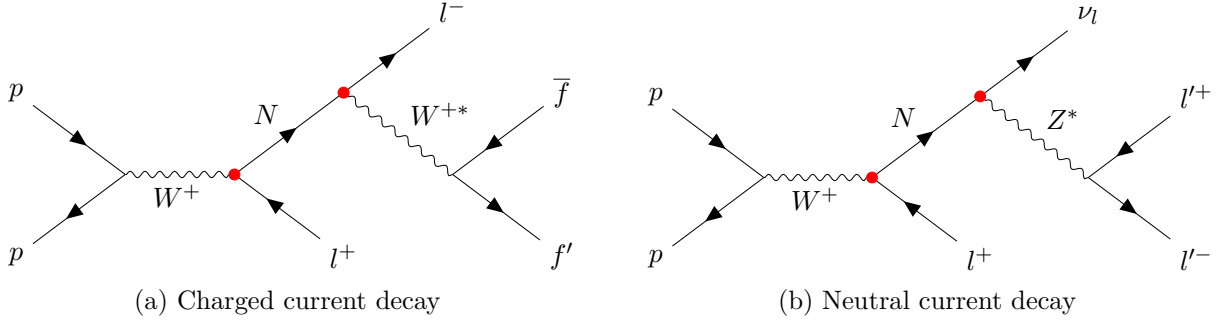


Figure 3: Feynman diagrams for the processes $pp \rightarrow l_a^\pm N \rightarrow l_a^\pm l_a^\mp f \bar{f}'$ for neutrino decay via charged and neutral current in Panel (a) and (b), respectively.

2 Signatures

We study the LHC sensitivity to heavy neutrinos from displaced vertex signatures in a simple model with effectively only one heavy neutrino N with mass M and mixing angles θ_a to the SM flavours. We further restrict ourselves to three scenarios in each of which the heavy neutrinos exclusively mix with one SM generation,

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

Here h the physical Higgs field and $v = 174 \text{ GeV}$ is its vacuum expectation value. These extreme cases can be used as benchmark scenarios, and the sensitivity for more realistic flavour mixing patterns can be estimated by interpolating between them.⁴

We search for displaced vertex signatures from the N decay inside one of the LHC main detectors. We consider only the dominant production through the decay of real W bosons, in which the N are produced along with a neutrino or charged lepton ℓ_a , *cf.* Figure 3. We do not take the production via Z decays into account because this channel does not produce a prompt charged lepton from the interaction point that one can trigger on. The authors of Reference [61] have included such processes, but we estimated that the much stronger cuts that are necessary to suppress backgrounds in this case make the gain in sensitivity marginal. For the same reason we neglect the production via Higgs decays. At the lower end of the mass spectrum under consideration here the N can also be produced in B hadron decays. We have estimated the reach of searches for displaced vertices from N that are produced in B decays for CMS in [31],⁵ here we do not include it because this would require a refinement in the computation of the production cross section from B decays that goes beyond the scope of this work. Moreover, for ATLAS and CMS the vast majority of events would fail to pass the cut on the transversal momentum p_T of the prompt lepton.

For the N decay we include processes mediated by both, virtual W^* and Z^* bosons. For decays mediated by the charged current, a charged lepton of flavour a is necessarily produced

⁴The simple model (1) is not realistic because the seesaw mechanism requires at least one flavour of right handed neutrinos to explain each non-zero light neutrino mass m_i , i.e., the number n of their flavours ν_{Ri} should be at least two ($n \geq 2$) if the lightest SM neutrino is massless and at least three ($n \geq 3$) if it is massive. Moreover, the heavy neutrinos must mix with all SM generations to explain the observed light neutrino mixing angles. Recent discussions of the constraints on the heavy neutrino flavour mixing pattern from light neutrino oscillation data can *e.g.* be found in [42, 67, 68]. A justification for our simple phenomenological model (1) is given in Appendix A.

⁵The sensitivity has been calculated more rigorously for LHCb in [62] and for MATHUSLA in [36].

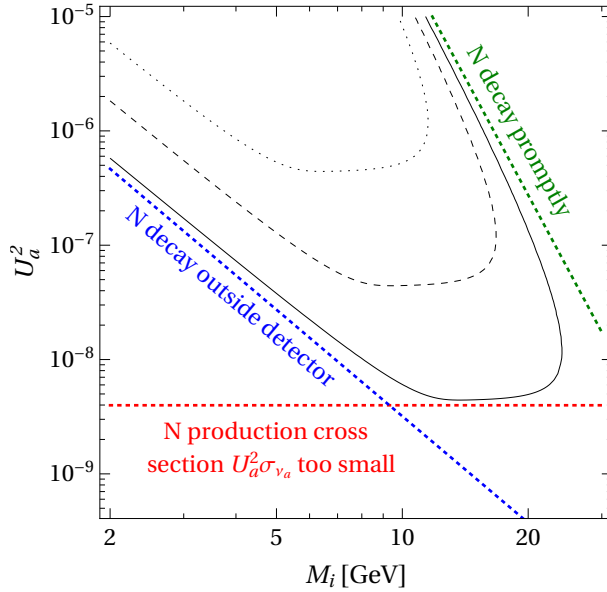


Figure 4: A simplified sensitivity estimate based on the analytic approximation (2) using $l_0 = 5$ mm and $l_1 = 3$ m illustrates the three main obstacles in improving the sensitivity (colored dotted lines). The three black sensitivity curves correspond to nine expected events for integrated luminosities of 3, 30, 300 fb^{-1} , and we have assumed that all efficiencies are 100 %.

along with the W^* bosons. The W^* can then decay into leptons and neutrinos or quarks that hadronise, so that the final states of the N decay can be leptonic or semileptonic. N decays mediated by the neutral current can also have purely hadronic detector-visible final states.

For $a = e, \mu$ the first lepton produced in W^* mediated decays is detector stable and can be used to reconstruct the displaced vertex. For $a = \tau$ the τ -lepton decays within the detector, mostly pions, leptons and neutrinos. It has been pointed out in Reference [60] that the finite lifetime of the τ -lepton implies that the published ATLAS efficiencies for displaced vertices [69] cannot be applied because they assume that all decay products appear promptly at the displaced vertex. To avoid this problem the authors only included N decays mediated by the neutral current. The same strategy was also adapted in Reference [62]. This drastically reduces the sensitivity in the scenario with $a = \tau$ when a cut on the displaced vertex invariant mass is applied because the unobservable ν_τ that unavoidably appears in decays mediated by Z^* carries away part of the energy and momentum. In the present work we include both, N decays mediated by neutral and charged currents, for all three scenarios $a = e, \mu, \tau$. For $a = \tau$ this can be justified with two arguments. First, for τ -leptons with energies ~ 10 GeV in the laboratory frame the opening angle between decay products is so small that it is hardly noticeable that they do not promptly originate from the displaced vertex. Second, the displaced vertex reconstruction algorithms can be improved in the future and therefore do not pose a fundamental restriction. Such studies are *e.g.* already under way in the CMS collaboration.

It is instructive to illustrate the dependence of the expected number of events on the model parameters within a simplified spherical detector of radius l_1 . Under the assumptions summarised in Section 2 the cross section of events in a scenario where the right handed neutrinos mix with

lepton flavour a can be estimated as⁶

$$\sigma(W \rightarrow \ell_a N \rightarrow \ell_a \ell_b f f) \sim \sigma_{\nu_a} U_a^2 \left(e^{-\gamma_N \Gamma_N l_0} - e^{-\gamma_N \Gamma_N l_1} \right), \quad (2)$$

where γ_N is the Lorentz factor and l_0 is the minimal displacement that is required by the trigger. An illustrative sensitivity estimate based on equation (2) is shown in Figure 4, it qualitatively reproduces the most important features of the results of our simulations. For $M \gg 5 \text{ GeV}$ the N decay width only depends on U_a^2 and M , it can be estimated as⁷

$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U_a^2 M^5, \quad (3)$$

see also Figure 1. We recall that we only study N that are produced in W boson decays, *i.e.*, σ_{ν_a} is the production cross section of neutrinos ν_{La} in W boson decays. We do not actually use the cross section (2) to obtain our results, but this estimate is nevertheless helpful to qualitatively understand their dependence on the model parameters.

3 Analysis

We calculate the Feynman rules of heavy neutrinos coupled to the SM with **FeynRules** 2.3 [71] using the implementation [72] based on the calculations in refs. [19, 73]. Subsequently, we generate events with **MadGraph5_aMC@NLO** 2.6.4 [74] (*cf.* Figure 3). Thereby, we calculate the total decay width of the heavy neutrinos with **MadWidth** [75] and simulate their decays with **MadSpin** [76, 77] (*cf.* Figure 1). Finally we hadronise and shower coloured particles with **Pythia** 8.2 [78]. We calculate the efficiencies of the three LHC main detector using our own code based on public information of the detector geometry.

- The ATLAS detector covers a pseudo-rapidity of $|\eta| < 2.5$. The tracking system extends to 1.1 and 3.4 m in the transversal and longitudinal direction, respectively, while the muon chamber covers 5–10 m and 7–21 m in the transversal and longitudinal direction, respectively.
- Up to Run 3 the CMS detector covers a pseudo-rapidity of $|\eta| < 2.5$, after the upgrade for the HL-LHC the pseudo-rapidity coverage will be extended to $|\eta| < 4$. The tracker extends to 1.1 and 2.8 m in the transversal and longitudinal direction, respectively. The muon chamber extends over 4–7 m and 7–11 m in the transversal and longitudinal direction, respectively.
- The LHCb detector is optimized for measurements along the beam and has a pseudo-rapidity coverage of $2 < \eta < 5$. It has three tracking systems, the vertex locator (VELO) spanning 50 and 40 cm in transversal and longitudinal direction and two Ring Imaging Cherenkov (RICH) detectors. The first RICH is located at a distance of 1 m from the interaction point and has a size of 60 and 100 cm in transversal and longitudinal direction, respectively. The second RICH is located at 9 m and has a size of 4 and 3 m in transversal and longitudinal direction. The muon chamber is located at 15 m and has a size of 5 m in both directions. This layered design allows to reconstruct secondary vertices with very large displacement as the inner tracker can provide a veto for appearing track candidates.

⁶An similar estimate for a general flavour mixing pattern is given by equation (7).

⁷The numerical prefactor in the decay width (3) depends on the way how the hadronisation of quark final states is treated. The results given in the appendices of [18, 20] (*cf.* also [21, 70]) suggest a value of 11.9, while the value used in this analysis is derived using **MadWidth** which neglects hadronisation effects.

	Single Lepton			Lepton Pair					
	e	μ	τ	e, e	e, μ	e, τ	μ, μ	μ, τ	τ, τ
$p_T^{\min}$ [GeV]	27	27	170	18, 18	8, 25 18, 15	30, 18	15, 15 23, 9	30, 15	40, 30

Table 1: Minimal transverse momenta used for the ATLAS single lepton and lepton pair triggers [79].

We propose to search in event samples which have been triggered by a single lepton or a pair of leptons [79, 80]. The minimal lepton p_T used for the pair triggers can be considerable softer than for the single lepton triggers, most notable when a τ -lepton is involved. For the single lepton trigger at CMS and LHCb we use $p_T(e, \mu, \tau) = 30, 25, 140$ GeV and $p_T(e, \mu, \tau) = 10, 15, 50$ GeV, respectively. Exemplarily, we show the complete trigger values used for the ATLAS detector in Table 1. For the tracking and tagging efficiencies we use the values found in the DELPHES 3.4.1 [81] detector cards. In order to reduce the background stemming from long lived SM hadrons we require the secondary vertices to have a minimal displacement l_0 of 5 mm. During the reconstruction of the displaced vertices we require at least 2 tracks with an invariant mass of 5 GeV in order to suppress further backgrounds, originating in particular from “nuclear interactions” with the detector material. In the case of purely muonic displaced vertices we do not apply this invariant mass cut, as we assume that all hadronic backgrounds are removed by the calorimeter. The reconstruction is well established if the produced particles traverse almost the entire tracker. If a particle transverses only a part of the tracking system the efficiency must drop off. In order to be able to compare different experiments we require that the remaining tracks transverse at least half of the tracker⁸ and that the reconstruction efficiency drops off linearly before that. This functional form is consistent with efficiency dependence published by ATLAS [69], and we assume that the behaviour is similar for CMS and LHCb. In order to calculate the remaining path of the particle we use ray tracing [82, 83].

The muon chamber systems can record muons which are an order of magnitude further away from the primary interaction vertex than the inner tracking system. Therefore, it is compelling to search for long lived particles using also the muon chambers to identify displaced vertices as we have also proposed before in the context of displaced signatures in supersymmetric models [64, 65]. In the meantime it has been demonstrated that such a search is feasible [66]. In order to be conservative we require reconstructed particle to transverses the whole muon chamber.

For n observed events the significance is given by [84]

$$S(n|h) = \sqrt{-2 \ln \frac{P(n|h)}{P(n|n)}} \quad \text{where} \quad P(n|h) = \frac{h^n}{n!} e^{-h}, \quad (4)$$

is the Poisson probability and h is either the number of events predicted by the *background only hypothesis* b or by the *background with signal hypothesis* $b + s$. For the exclusion and discovery of a model we require $S(n|b + s) \geq 2$ and $S(n|b) \geq 5$, respectively. In order to project to future searches we estimate the observed number of events n with the prediction for the alternative hypothesis. Hence, we use $S(b|b + s) \geq 2$ and $S(b + s|b) \geq 5$, for exclusion and discovery, respectively. In doing so we neglect the systematic uncertainties of the signal and the background estimation.

⁸Thereby we assume that the largest observable displacement can be improved by a factor of two compared to current ATLAS estimates [69] by using improved algorithms in the future.

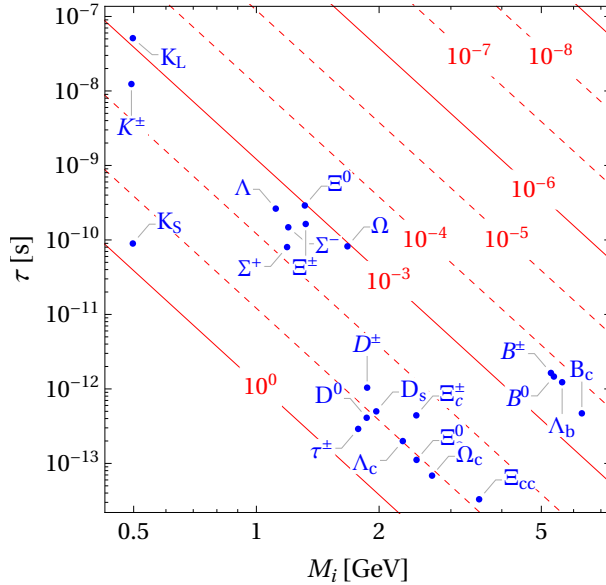


Figure 5: Heavy neutrino coupling as a function of its mass and life time (red lines) compared to potentially relevant SM backgrounds (blue dots), *cf.* also Figure 1.

The SM background can be efficiently excluded with the cuts on the invariant mass and the displacement, *cf.* Figure 5. It is not easy to quantify the remaining backgrounds without an extremely realistic simulation of the whole detector. In this analysis we ignore backgrounds originating from cosmic rays and beam-halo muons, based on the low rate in the LHC experimental caverns and the good capability of the experiments to recognize them as such [85]. We also ignore the scattering of ordinary neutrinos that come from the collision point, based on the low cross section of charged-current interaction in the detector material. We assume that the background number is smaller than one and calculate the efficiencies based on one background event. In this case the non-observation of four events and the observation of nine events suffices for exclusion and discovery, respectively.

4 Results

We present our results for each experiment (ATLAS, CMS and LHCb) and each benchmark scenario (exclusive mixing with e , μ or τ) in Figure 6. Due to their similar geometry ATLAS and CMS have comparable sensitivities. For pure electron or muon mixing they can exclude heavy neutrinos with couplings as small as $\sim 5 \times 10^{-8}$ and masses up to ~ 20 GeV with an integrated luminosity of 300 fb^{-1} . With 3000 fb^{-1} mixing angles of $\sim 5 \times 10^{-10}$ and masses up to ~ 40 GeV become accessible. LHCb can exclude down to 5×10^{-7} and 5×10^{-8} and masses up to 12 and 20 GeV for LHC and HL-LHC. ATLAS and CMS can exclude heavy neutrinos with pure tau couplings up to $\sim 10^{-6}$ and $\sim 10^{-8}$ with masses up to 15 and 25 GeV for integrated luminosities of 300 fb^{-1} and 3000 fb^{-1} , respectively.

For masses below the mass of optimal sensitivity the sensitivity is limited by the fact that the N are too long lived and do not decay inside the detector, *cf.* Figure 4. The reach in this region can be extended by using the muon chamber. This approach is especially fruitful for masses as small as a few GeV because we assume that for purely muonic vertices no invariant mass cut is necessary in order to remove the hadronic background. For ATLAS and CMS the

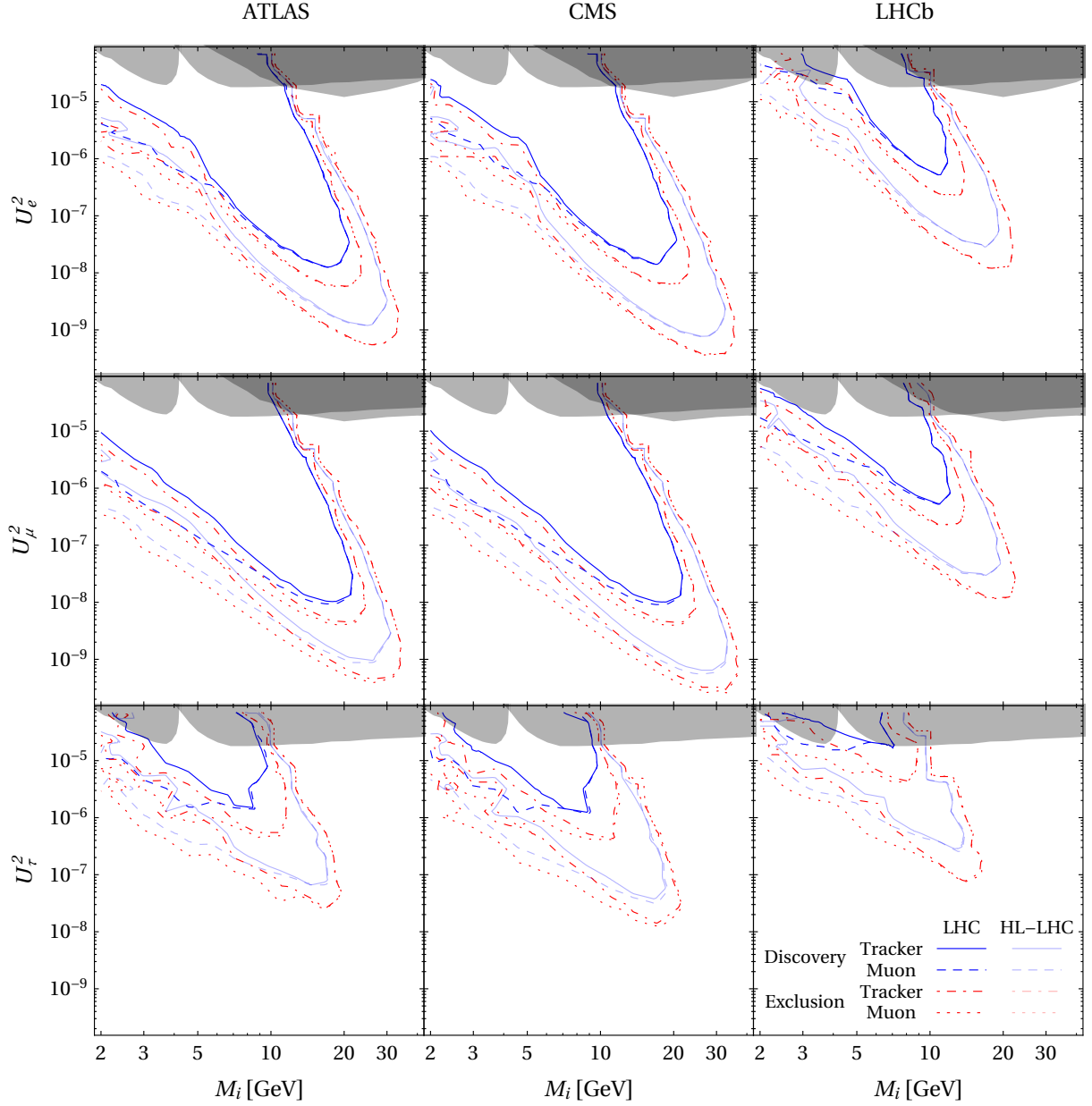


Figure 6: Sensitivity reach of the 13 and 14 TeV LHC. The three columns show the results for ATLAS, CMS and LHCb. The luminosities assumed for CMS and ATLAS are 0.3 and 3 ab^{-1} and for LHCb are 30 and 380 fb^{-1} . The three rows constitute the three extreme cases of pure electron, muon and tau coupling, respectively. The blue (red) curves show the discovery (exclusion) potential, both of which are shown for searches using only the tracker and using the tracker together with the muon chamber. For the simulation of LHCb we require decays to happen before or within the first RICH (*cf.* also Figure 8). The gray bands represent the exclusion bound from DELPHI [51] and CMS [49].

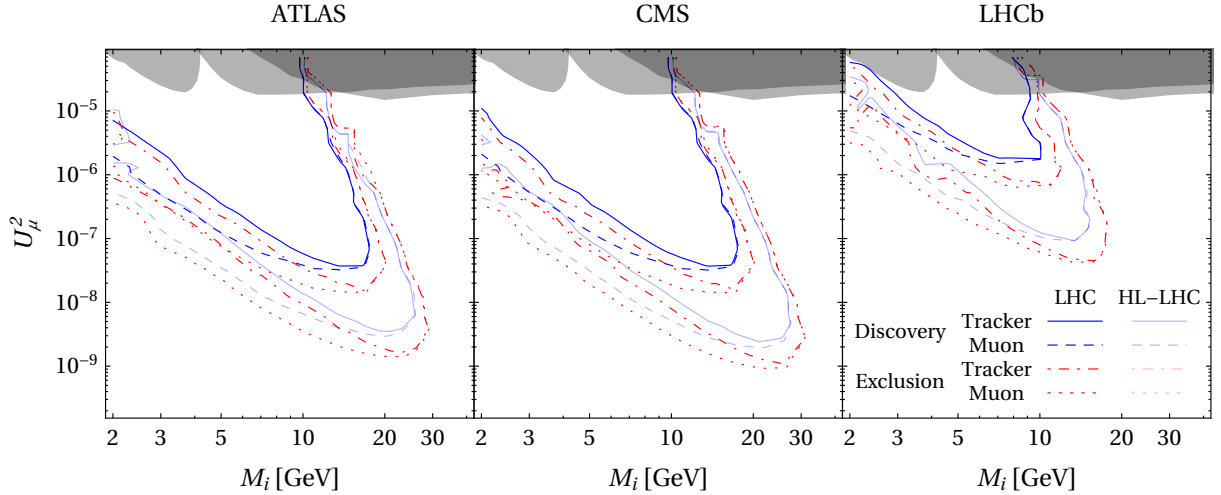


Figure 7: Sensitivity reach of a purely leptonic search.

improvement amounts only to a factor of order one in the scenario with pure muon mixing and less than that in the other scenarios. This can be understood as a result of the scaling $\sigma(W \rightarrow \ell_a N \rightarrow \ell_a \ell_b f f) \propto U_a^4 M^5$ in this regime, which can be obtained by expanding the exponential functions in relation (2) to linear order in $\Gamma_N l_0$ and $\Gamma_N l_1$ and using the estimate (3).

Additionally, we show the sensitivity reach of a purely leptonic search in the case of pure muon mixing in Figure 7. The reach in U_μ^2 is one order of magnitude weaker than the inclusive reach shown in Figure 6. Finally, we show the reach of the LHCb detector under the assumptions that the secondary vertex must either lie within the VELO or is allowed to lie before or within one of the two RICHs, in Figure 8.

In Figure 9 we summarise our most optimistic estimates for the reach of each experiment in each of the benchmark scenarios. For this plot we have additionally relaxed the lower bound on the displaced vertex invariant mass to 2 GeV. Qualitatively all of the presented results are in good agreement with the analytic estimate (2) plotted in Figure 4, which can explain the overall shape of the sensitivity regions.

5 Discussion and conclusions

We have compared the sensitivity of the LHC detectors ATLAS, CMS and LHCb to heavy neutrinos from W boson decays in displaced vertex searches in three benchmark models, in each of which the heavy neutrinos mix exclusively with one SM generation. Moreover, we propose a new search strategy that includes the muon chambers to detect tracks from the displaced vertex. We summarise our main results in Figure 9. In Figure 6 we present more detailed estimates for each of the different scenarios we investigated when both, leptonic and hadronic final states are included. Figure 7 shows the sensitivity for purely leptonic decays, and Figure 8 illustrates how the LHCb sensitivity depends on the part of the tracker that is used for the displaced vertex search.

We find that the sensitivity that can be reached at ATLAS or CMS with 300 fb^{-1} exceeds existing bounds by three orders of magnitude for mixing with the first and second generation and by one order of magnitude for mixing with the third generation. The reach of LHCb is a bit more than an order of magnitude worse than ATLAS and CMS. It is noteworthy that the

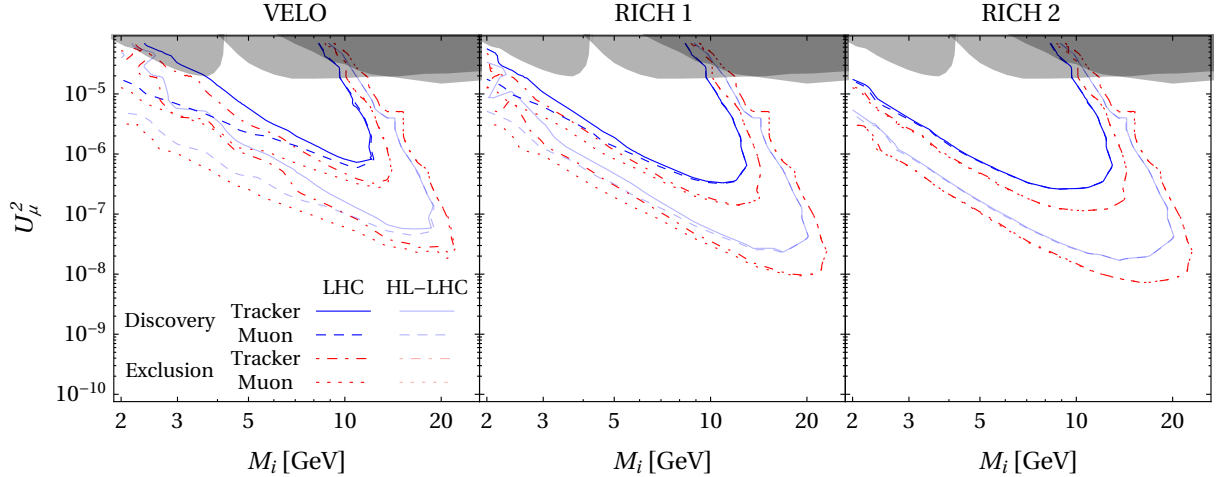


Figure 8: Comparison of the sensitivity reach of LHCb at 13 and 14 TeV with 30 and 380 fb⁻¹ for pure muon mixing, under the assumptions that the neutrino has to decay within the VELO and before or within the first or second RICH, respectively.

sensitivity in terms of the squared mixing angle U_a^2 scales linearly with the integrated luminosity, which can be illustrated with the simple estimate (2). The reason is that the LHC is practically used as an intensity frontier machine. This has the important implication that the HL-LHC can further improve the sensitivity by an additional order of magnitude, as shown in Figure 6. Our results qualitatively agree with other recent studies, but are more general in the sense that we for the first time compare all three detectors in all three scenarios for both, the LHC and HL-LHC.

The considerable improvement in sensitivity compared to the existing bounds is particularly interesting from a cosmological viewpoint because it implies that the LHC can probe a considerable part of the parameter region where low scale leptogenesis can generate the observed matter-antimatter asymmetry of the universe. In the minimal model with two heavy neutrinos ($n = 2$) and in the ν MSM this parameter region is inaccessible to conventional LHC searches, *cf.* [62, 86–88] for updated parameters scans. In this model, independent measurements of all U_{ai}^2 and the heavy neutrino mass spectrum at colliders would, together with a measurement of leptonic CP violation in neutrino oscillation experiments, in principle allow to constrain all parameters in the Lagrangian (5), making this a fully testable model of neutrino masses and baryogenesis [67]. In practice it is unlikely that data from the LHC will be accurate enough to pin down all parameters, but measurements of the flavour mixing pattern at the LHC would nevertheless provide an important test of the hypothesis that heavy neutrinos are responsible for the light neutrino masses and baryogenesis and motivate further studies at future colliders [87]. If three heavy neutrinos contribute to leptogenesis and the seesaw mechanism ($n = 3$) then the viable parameter space for leptogenesis is much larger [89], and the LHC could possibly observe tens of thousands of events.

Our results provide a strong motivation to improve the displaced vertex reconstruction efficiencies in LHC experiments. Moreover, a better understanding of the backgrounds would also be highly desirable. If one could, for instance, lower the cut on the displaced vertex mass, this would make it possible to search for heavy neutrinos with smaller masses. Those could be produced in considerable numbers in the decay of B hadrons, which are much more numerous in LHC collisions than the W bosons considered here. In this regime the sensitivity can further be improved by using the muon chambers to detect tracks from displaced vertices that lie outside

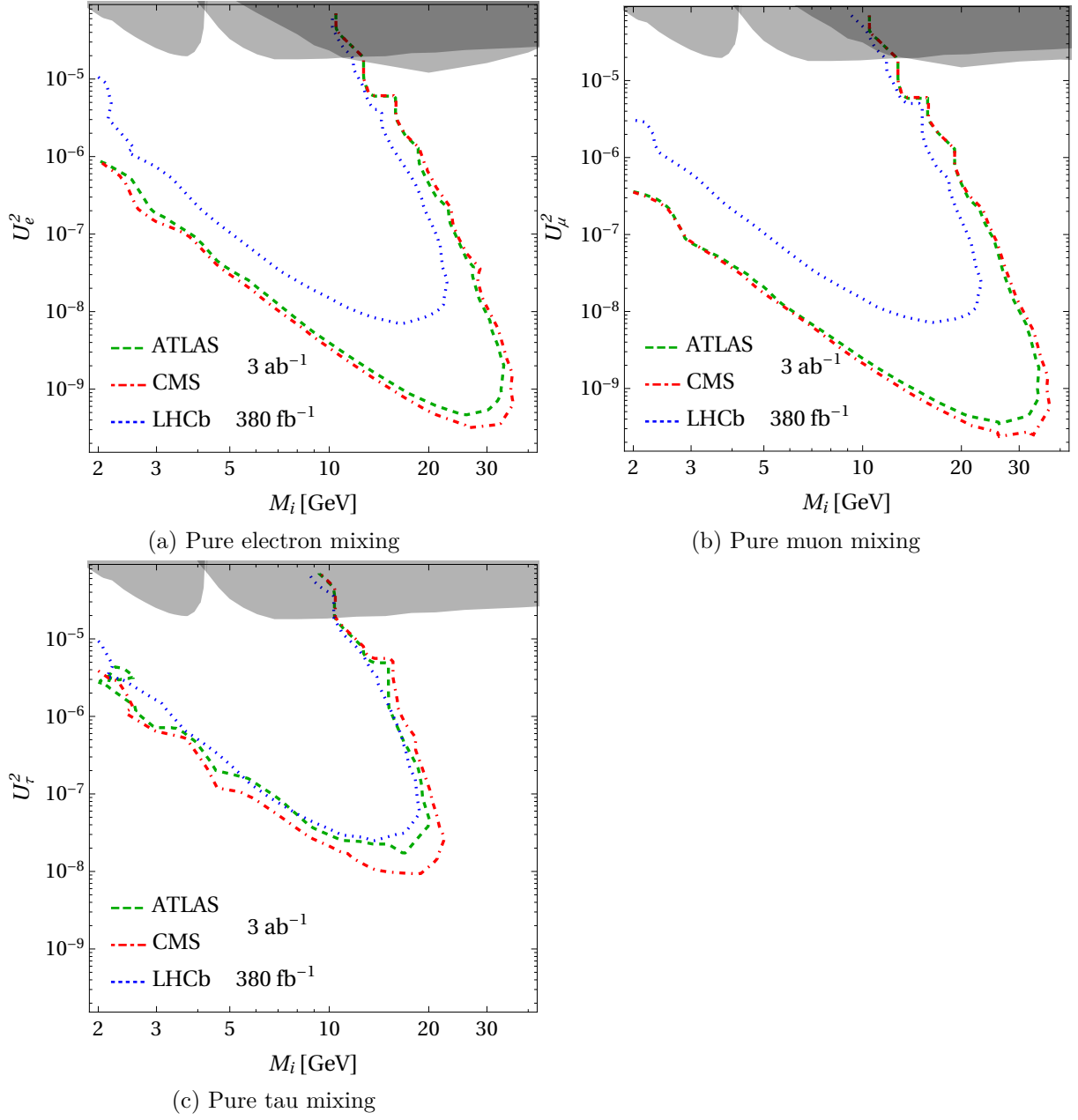


Figure 9: Exclusion reach of ATLAS, CMS with 3 ab^{-1} and LHCb with 380 fb^{-1} for the HL-LHC for pure electron, muon and tau mixing in Panel (a), (b) and (c), respectively.

the main tracker.

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A Type I seesaw model

The type-I seesaw model is given by the most general renormalisable extension of the SM Lagrangian $\mathcal{L}_{\text{SM}}$ that only contains n sterile neutrinos ν_{Ri} as new fields,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i \overline{\nu_{Ri}} \not{\partial} \nu_{Ri} - \frac{1}{2} \left(\overline{\nu_{Ri}^c} M_i \nu_R + \overline{\nu_{Ri}} M_i \nu_{Ri}^c \right) - F_{ai} \bar{\ell}_a \varepsilon \phi^* \nu_{Ri} - F_{ai}^* \overline{\nu_{Ri}} \phi^T \varepsilon^\dagger \ell_a . \quad (5)$$

Here ℓ_a are the SM lepton doublets and ϕ the SM Higgs doublet. The F_{ai} are Yukawa coupling constants, and we have chosen a flavour basis where the Majorana mass matrix M_M of the ν_{Ri} is diagonal. After the spontaneous breaking of the electroweak symmetry by the Higgs vacuum expectation value $v = 174 \text{ GeV}$ there are $3 + n$ mass eigenstates: three light neutrinos ν_i with masses m_i^2 given by the eigenvalues of the matrix $m_\nu^\dagger m_\nu$ with $m_\nu = -\theta M_M \theta^T$ and n heavy mass eigenstates N_i with masses M_i^2 approximately given by the eigenvalues of $M_M^\dagger M_M$,

$$\nu = U_\nu^\dagger (\nu_L - \theta \nu_R^c) + \text{c.c.} , \quad N \simeq U_N^\dagger (\nu_R + \theta^T \nu_L^c) + \text{c.c.} . \quad (6)$$

Here c.c. refers to the charge conjugation, which acts as $\nu_R^c = C \overline{\nu_R}^T$ with $C = i \gamma_2 \gamma_0$. U_ν is the standard light neutrino mixing matrix and U_N its equivalent amongst the heavy neutrinos. We use the tree level relation and expand to leading order in the mixing between left and right handed neutrinos, which is quantified by the matrix $\theta = v F M_M^{-1}$.

Naively one would expect the magnitude of the mixing angles θ_{ai} to be comparable to the ratio between light and heavy neutrino masses, $\theta^2 \sim m_i/M_i$. However, if the M_i and F_{ai} approximately respect a generalised $B - L$ symmetry [90], then the mixings $U_{ai}^2 = |\theta_{ai}|^2$ can be large enough to be within reach of the LHC [91].⁹ While the symmetry naturally explains the smallness of the light neutrino masses for below the electroweak scale and Yukawa couplings that are larger than that of the electron, it also parametrically suppresses the rate of lepton number violating processes [91]. This includes as the decay of W bosons into same sign dileptons, which are considered to be a “golden channel” for heavy neutrino searches, *cf. e.g.* [93, 94] for recent updates. A precise quantification of this suppression difficult because it depends on the splitting between the heavy neutrino masses. If all mass splittings are bigger than the experimental resolution, then cross section (2) can simply be generalised to the case with several heavy neutrino flavours; the cross section of events with lepton flavour a from the first vertex (N production) and b from the second vertex (N decay) that can be seen in a detector can be estimated as

$$\sigma(W \rightarrow \ell_a N_i \rightarrow \ell_a \ell_b f f) \sim \sigma_{\nu_a} U_{ai}^2 \frac{U_{bi}^2}{U_i^2} \left(e^{-\gamma_{N_i} \Gamma_{N_i} l_0} - e^{-\gamma_{N_i} \Gamma_{N_i} l_1} \right) . \quad (7)$$

Parametrically this estimate applies to both, decays that violate the SM lepton number L and those that conserve it. If the mass splittings are too small to be experimentally resolved, but still

⁹For $n = 3$ the approximate $B - L$ symmetry implies $F_{a2} \simeq -i F_{a3}$, $|F_{a1}| \ll |F_{a2}| \simeq |F_{a3}|$ and $M_2 \simeq M_3$, *cf. e.g.* [89] for a detailed discussion. In the νMSM this could explain the feeble coupling of the DM candidate as well as the mass degeneracy $|M_3 - M_2| \ll M_2, M_3$ that is required to generate the matter-antimatter asymmetry [90]. Similar arguments can be made for $n > 3$ [92].

much larger than the Γ_{N_i} , then one has to simply add the event rates from the decays of the mass-degenerate states for both, L conserving and L violating decays. In the context of realistic seesaw models, we can identify $U_a^2 = |\theta_a|^2$ in the estimate (2) based on the phenomenological model (1) with U_{a2}^2 or U_{a3}^2 in (2). If the mass splitting is smaller than Γ_{N_i} , then the destructive interference between contributions from different N_i to the diagram in Figure 3 leads to a suppression of processes that violate L [91]. In the intermediate regime where $|M_i - M_j| \sim \Gamma_{N_i}, \Gamma_{N_j}$ there can be non-trivial effects due to coherent oscillations amongst the heavy neutrinos [56, 58, 87, 95, 96]. Hence, a precise prediction of the number of events depends on parameters that may not be directly observable if the mass splitting is smaller than the kinematic resolution of the detector. However, our present analysis does not require lepton number violation because we use the displacement of the vertex in with the N_i decay to suppress the SM backgrounds. Whether or not lepton number violating processes contribute therefore at most amounts to a factor two in the heavy neutrino decay rate Γ_{N_i} . This rate in principle enters the cross section (7) exponentially. However, in most of the testable region in the mass-mixing plane the exponentials can be approximated linearly. In the double-logarithmic sensitivity plots in the mass-mixing plane the main difference is a shift of the sensitivity region in the direction of comparable large masses and large couplings, where it is cut off due to the fact that the N_i decay before they travel a distance l_0 . Therefore we can perform the analysis in the effective model (1).

References

- [1] P. Minkowski. “ $\mu \rightarrow e\gamma$ at a Rate of One Out of 10^9 Muon Decays?” *Phys. Lett.* 67B (1977), pp. 421–428. DOI: 10.1016/0370-2693(77)90435-X. №: PRINT-77-0182 (BERN).
- [2] M. Gell-Mann, P. Ramond, and R. Slansky. “Complex Spinors and Unified Theories”. *Conf. Proc.* C790927 (1979), pp. 315–321. arXiv: 1306.4669 [hep-th]. №: PRINT-80-0576.
- [3] R. N. Mohapatra and G. Senjanovic. “Neutrino Mass and Spontaneous Parity Nonconservation”. *Phys. Rev. Lett.* 44 (1980). [231 (1979)], p. 912. DOI: 10.1103/PhysRevLett.44.912. №: MDDP-TR-80-060, MDDP-PP-80-105, CCNY-HEP-79-10.
- [4] T. Yanagida. “Horizontal Symmetry and Masses of Neutrinos”. *Prog. Theor. Phys.* 64 (1980), p. 1103. DOI: 10.1143/PTP.64.1103. №: TU-80-208.
- [5] J. Schechter and J. W. F. Valle. “Neutrino Masses in $SU(2) \times U(1)$ Theories”. *Phys. Rev.* D22 (1980), p. 2227. DOI: 10.1103/PhysRevD.22.2227. №: SU-4217-167, COO-3533-167.
- [6] J. Schechter and J. W. F. Valle. “Neutrino Decay and Spontaneous Violation of Lepton Number”. *Phys. Rev.* D25 (1982), p. 774. DOI: 10.1103/PhysRevD.25.774. №: SU-4217-203, COO-3533-203.
- [7] M. Drewes. “The Phenomenology of Right Handed Neutrinos”. *Int. J. Mod. Phys.* E22 (2013), p. 1330019. DOI: 10.1142/S0218301313300191. arXiv: 1303.6912 [hep-ph]. №: TUM-HEP-881-13.
- [8] L. Canetti, M. Drewes, and M. Shaposhnikov. “Matter and Antimatter in the Universe”. *New J. Phys.* 14 (2012), p. 095012. DOI: 10.1088/1367-2630/14/9/095012. arXiv: 1204.4186 [hep-ph]. №: TTK-12-04.
- [9] M. Fukugita and T. Yanagida. “Baryogenesis Without Grand Unification”. *Phys. Lett.* B174 (1986), pp. 45–47. DOI: 10.1016/0370-2693(86)91126-3. №: RIFP-641.

- [10] E. J. Chun et al. “Probing Leptogenesis”. *Int. J. Mod. Phys. A* 33.05n06 (2018), p. 1842005. DOI: 10.1142/S0217751X18420058. arXiv: 1711.02865 [hep-ph].
- [11] S. Dodelson and L. M. Widrow. “Sterile-neutrinos as dark matter”. *Phys. Rev. Lett.* 72 (1994), pp. 17–20. DOI: 10.1103/PhysRevLett.72.17. arXiv: hep-ph/9303287 [hep-ph]. №: FERMILAB-PUB-93-057-A.
- [12] M. Drewes et al. “A White Paper on keV Sterile Neutrino Dark Matter”. *JCAP* 1701.01 (2017), p. 025. DOI: 10.1088/1475-7516/2017/01/025. arXiv: 1602.04816 [hep-ph]. №: FERMILAB-PUB-16-068-T.
- [13] A. Boyarsky et al. “Sterile Neutrino Dark Matter”. *Prog. Part. Nucl. Phys.* 104 (2019), pp. 1–45. DOI: 10.1016/j.ppnp.2018.07.004. arXiv: 1807.07938 [hep-ph].
- [14] K. N. Abazajian et al. “Light Sterile Neutrinos: A White Paper” (2012). arXiv: 1204.5379 [hep-ph]. №: FERMILAB-PUB-12-881-PPD.
- [15] Y. Cai et al. “Lepton Number Violation: Seesaw Models and Their Collider Tests”. *Front.in Phys.* 6 (2018), p. 40. DOI: 10.3389/fphy.2018.00040. arXiv: 1711.02180 [hep-ph]. №: PITT-PACC-1712, IPPP-17-74, COEPP-MN-17-17.
- [16] R. E. Shrock. “General Theory of Weak Leptonic and Semileptonic Decays. 1. Leptonic Pseudoscalar Meson Decays, with Associated Tests For, and Bounds on, Neutrino Masses and Lepton Mixing”. *Phys. Rev. D* 24 (1981), p. 1232. DOI: 10.1103/PhysRevD.24.1232. №: ITP-SB-80-56.
- [17] R. E. Shrock. “General Theory of Weak Processes Involving Neutrinos. 2. Pure Leptonic Decays”. *Phys. Rev. D* 24 (1981), p. 1275. DOI: 10.1103/PhysRevD.24.1275. №: ITP-SB-81-3.
- [18] D. Gorbunov and M. Shaposhnikov. “How to find neutral leptons of the ν MSM?” *JHEP* 10 (2007). [Erratum: *JHEP*11, 101 (2013)], p. 015. DOI: 10.1007/JHEP11(2013)101, 10.1088/1126-6708/2007/10/015. arXiv: 0705.1729 [hep-ph].
- [19] A. Atre et al. “The Search for Heavy Majorana Neutrinos”. *JHEP* 05 (2009), p. 030. DOI: 10.1088/1126-6708/2009/05/030. arXiv: 0901.3589 [hep-ph]. №: FERMILAB-PUB-08-086-T, NSF-KITP-08-54, MADPH-06-1466, DCPT-07-198, IPPP-07-99.
- [20] L. Canetti et al. “Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos”. *Phys. Rev. D* 87 (2013), p. 093006. DOI: 10.1103/PhysRevD.87.093006. arXiv: 1208.4607 [hep-ph]. №: TTK-12-05, TUM-HEP-852-12, CAS-KITPC-ITP-368.
- [21] K. Bondarenko et al. “Phenomenology of GeV-scale Heavy Neutral Leptons”. *JHEP* 11 (2018), p. 032. DOI: 10.1007/JHEP11(2018)032. arXiv: 1805.08567 [hep-ph].
- [22] O. Ruchayskiy and A. Ivashko. “Restrictions on the lifetime of sterile neutrinos from primordial nucleosynthesis”. *JCAP* 1210 (2012), p. 014. DOI: 10.1088/1475-7516/2012/10/014. arXiv: 1202.2841 [hep-ph]. №: CERN-PH-TH-2012-042.
- [23] P. Hernandez, M. Kekic, and J. Lopez-Pavon. “ N_{eff} in low-scale seesaw models versus the lightest neutrino mass”. *Phys. Rev. D* 90.6 (2014), p. 065033. DOI: 10.1103/PhysRevD.90.065033. arXiv: 1406.2961 [hep-ph]. №: IFIC-14-25, SISSA-19-2014-FISI.
- [24] E. K. Akhmedov, V. A. Rubakov, and A. Y. Smirnov. “Baryogenesis via neutrino oscillations”. *Phys. Rev. Lett.* 81 (1998), pp. 1359–1362. DOI: 10.1103/PhysRevLett.81.1359. arXiv: hep-ph/9803255 [hep-ph]. №: IC-98-22, INR-98-14-T.

- [25] T. Asaka and M. Shaposhnikov. “The nuMSM, dark matter and baryon asymmetry of the universe”. *Phys. Lett.* B620 (2005), pp. 17–26. DOI: 10.1016/j.physletb.2005.06.020. arXiv: hep-ph/0505013 [hep-ph].
- [26] F. Vissani. “Do experiments suggest a hierarchy problem?” *Phys. Rev.* D57 (1998), pp. 7027–7030. DOI: 10.1103/PhysRevD.57.7027. arXiv: hep-ph/9709409 [hep-ph]. №: IC-97-148.
- [27] T. Asaka, S. Blanchet, and M. Shaposhnikov. “The nuMSM, dark matter and neutrino masses”. *Phys. Lett.* B631 (2005), pp. 151–156. DOI: 10.1016/j.physletb.2005.09.070. arXiv: hep-ph/0503065 [hep-ph].
- [28] L. Canetti, M. Drewes, and M. Shaposhnikov. “Sterile Neutrinos as the Origin of Dark and Baryonic Matter”. *Phys. Rev. Lett.* 110.6 (2013), p. 061801. DOI: 10.1103/PhysRevLett.110.061801. arXiv: 1204.3902 [hep-ph]. №: TTK-12-08, CAS-KITPC-ITP-315.
- [29] M. Shaposhnikov and C. Wetterich. “Asymptotic safety of gravity and the Higgs boson mass”. *Phys. Lett.* B683 (2010), pp. 196–200. DOI: 10.1016/j.physletb.2009.12.022. arXiv: 0912.0208 [hep-th].
- [30] S. Pascoli, R. Ruiz, and C. Weiland. “Heavy Neutrinos with Dynamic Jet Vetoes: Multi-lepton Searches at $\sqrt{s} = 14, 27$, and 100 TeV” (2018). arXiv: 1812.08750 [hep-ph]. №: CP3-18-77, IPPP/18/111, PITT-PACC-1821.
- [31] M. Drewes et al. “A Heavy Metal Path to New Physics” (2018). arXiv: 1810.09400 [hep-ph]. №: CP3-18-60.
- [32] J. L. Feng et al. “ForwArd Search ExpeRiment at the LHC”. *Phys. Rev.* D97.3 (2018), p. 035001. DOI: 10.1103/PhysRevD.97.035001. arXiv: 1708.09389 [hep-ph]. №: UCI-TR-2017-08.
- [33] J. P. Chou, D. Curtin, and H. J. Lubatti. “New Detectors to Explore the Lifetime Frontier”. *Phys. Lett.* B767 (2017), pp. 29–36. DOI: 10.1016/j.physletb.2017.01.043. arXiv: 1606.06298 [hep-ph].
- [34] F. Kling and S. Trojanowski. “Heavy Neutral Leptons at FASER”. *Phys. Rev.* D97.9 (2018), p. 095016. DOI: 10.1103/PhysRevD.97.095016. arXiv: 1801.08947 [hep-ph]. №: UCI-TR-2017-18.
- [35] V. V. Gligorov et al. “Searching for Long-lived Particles: A Compact Detector for Exotics at LHCb”. *Phys. Rev.* D97.1 (2018), p. 015023. DOI: 10.1103/PhysRevD.97.015023. arXiv: 1708.09395 [hep-ph].
- [36] D. Curtin et al. “Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case” (2018). arXiv: 1806.07396 [hep-ph]. №: FERMILAB-PUB-18-264-T.
- [37] D. Dercks et al. “Long-Lived Fermions at AL3X” (2018). arXiv: 1811.01995 [hep-ph]. №: BONN-TH-2018-14, DESY 18-197, IFIC/18-39, DESY-18-197.
- [38] **MATHUSLA**. “A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS.” (2018). arXiv: 1811.00927 [physics.ins-det]. №: CERN-LHCC-2018-025, LHCC-I-031.
- [39] J. C. Helo, M. Hirsch, and Z. S. Wang. “Heavy neutral fermions at the high-luminosity LHC”. *JHEP* 07 (2018), p. 056. DOI: 10.1007/JHEP07(2018)056. arXiv: 1803.02212 [hep-ph]. №: BONN-TH-2018-01, IFIC/18-08, IFIC-18-08.
- [40] J. Alimena et al. “Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider” (2019). arXiv: 1903.04497 [hep-ex].

- [41] **NA62**. “Search for heavy neutral lepton production in K^+ decays”. *Phys. Lett. B* 778 (2018), pp. 137–145. DOI: 10.1016/j.physletb.2018.01.031. arXiv: 1712.00297 [hep-ex]. №: CERN-EP-2017-311.
- [42] M. Drewes et al. “NA62 sensitivity to heavy neutral leptons in the low scale seesaw model”. *JHEP* 07 (2018), p. 105. DOI: 10.1007/JHEP07(2018)105. arXiv: 1801.04207 [hep-ph].
- [43] **T2K**. “Search for heavy neutrinos with the T2K near detector ND280” (2019). arXiv: 1902.07598 [hep-ex].
- [44] I. Krasnov. “On DUNE prospects in the search for sterile neutrinos” (2019). arXiv: 1902.06099 [hep-ph].
- [45] S. Alekhin et al. “A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case”. *Rept. Prog. Phys.* 79.12 (2016), p. 124201. DOI: 10.1088/0034-4885/79/12/124201. arXiv: 1504.04855 [hep-ph]. №: CERN-SPSC-2015-017, SPSC-P-350-ADD-1.
- [46] **SHiP**. “A facility to Search for Hidden Particles (SHiP) at the CERN SPS” (2015). arXiv: 1504.04956 [physics.ins-det]. №: CERN-SPSC-2015-016, SPSC-P-350.
- [47] **SHiP**. “Sensitivity of the SHiP experiment to Heavy Neutral Leptons” (2018). arXiv: 1811.00930 [hep-ph].
- [48] J. Beacham et al. “Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report” (2019). arXiv: 1901.09966 [hep-ex]. №: CERN-PBC-REPORT-2018-007.
- [49] **CMS**. “Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *Phys. Rev. Lett.* 120.22 (2018), p. 221801. DOI: 10.1103/PhysRevLett.120.221801. arXiv: 1802.02965 [hep-ex]. №: CMS-EXO-17-012, CERN-EP-2018-006.
- [50] **CMS**. “Search for heavy Majorana neutrinos in the same-sign dilepton channel in proton-proton collisions at $\sqrt{s} = 13$ TeV” (2018). №: CMS-PAS-EXO-17-028.
- [51] **DELPHI**. “Search for neutral heavy leptons produced in Z decays”. *Z. Phys.* C74 (1997). [Erratum: *Z. Phys.* C75, 580 (1997)], pp. 57–71. DOI: 10.1007/s002880050370. №: CERN-PPE-96-195.
- [52] J. C. Helo, M. Hirsch, and S. Kovalenko. “Heavy neutrino searches at the LHC with displaced vertices”. *Phys. Rev. D* 89 (2014). [Erratum: *Phys. Rev. D* 93, no. 9, 099902(2016)], p. 073005. DOI: 10.1103/PhysRevD.89.073005, 10.1103/PhysRevD.93.099902. arXiv: 1312.2900 [hep-ph].
- [53] E. Izaguirre and B. Shuve. “Multilepton and Lepton Jet Probes of Sub-Weak-Scale Right-Handed Neutrinos”. *Phys. Rev. D* 91.9 (2015), p. 093010. DOI: 10.1103/PhysRevD.91.093010. arXiv: 1504.02470 [hep-ph].
- [54] A. M. Gago et al. “Probing the Type I Seesaw Mechanism with Displaced Vertices at the LHC”. *Eur. Phys. J. C* 75.10 (2015), p. 470. DOI: 10.1140/epjc/s10052-015-3693-1. arXiv: 1505.05880 [hep-ph].
- [55] C. O. Dib and C. S. Kim. “Discovering sterile Neutrinos lighter than M_W at the LHC”. *Phys. Rev. D* 92.9 (2015), p. 093009. DOI: 10.1103/PhysRevD.92.093009. arXiv: 1509.05981 [hep-ph].
- [56] C. O. Dib et al. “Distinguishing Dirac/Majorana Sterile Neutrinos at the LHC”. *Phys. Rev. D* 94.1 (2016), p. 013005. DOI: 10.1103/PhysRevD.94.013005. arXiv: 1605.01123 [hep-ph]. №: DESY-16-077.

- [57] S. Antusch, E. Cazzato, and O. Fischer. “Sterile neutrino searches via displaced vertices at LHCb”. *Phys. Lett. B* 774 (2017), pp. 114–118. DOI: 10.1016/j.physletb.2017.09.057. arXiv: 1706.05990 [hep-ph].
- [58] G. Cvetič, A. Das, and J. Zamora-Saá. “Probing heavy neutrino oscillations in rare W boson decays” (2018). arXiv: 1805.00070 [hep-ph].
- [59] G. Cottin, J. C. Helo, and M. Hirsch. “Searches for light sterile neutrinos with multitrack displaced vertices”. *Phys. Rev. D* 97.5 (2018), p. 055025. DOI: 10.1103/PhysRevD.97.055025. arXiv: 1801.02734 [hep-ph].
- [60] G. Cottin, J. C. Helo, and M. Hirsch. “Displaced vertices as probes of sterile neutrino mixing at the LHC”. *Phys. Rev. D* 98.3 (2018), p. 035012. DOI: 10.1103/PhysRevD.98.035012. arXiv: 1806.05191 [hep-ph]. №: IFIC/18-25, IFIC-18-25.
- [61] A. Abada et al. “Inclusive Displaced Vertex Searches for Heavy Neutral Leptons at the LHC”. *JHEP* 01 (2019), p. 093. DOI: 10.1007/JHEP01(2019)093. arXiv: 1807.10024 [hep-ph]. №: LPT-ORSAY-18-79, PI/UAN-2018-631FT.
- [62] I. Boiarska et al. “Probing baryon asymmetry of the Universe at LHC and SHiP” (2019). arXiv: 1902.04535 [hep-ph].
- [63] D. Contardo et al. “Technical Proposal for the Phase-II Upgrade of the CMS Detector” (2015). №: CERN-LHCC-2015-010, LHCC-P-008, CMS-TDR-15-02.
- [64] S. Bobrovskiy et al. “Quasi-stable neutralinos at the LHC”. *JHEP* 09 (2011), p. 119. DOI: 10.1007/JHEP09(2011)119. arXiv: 1107.0926 [hep-ph]. №: DESY-11-077.
- [65] S. Bobrovskiy, J. Hajer, and S. Rydbeck. “Long-lived higgsinos as probes of gravitino dark matter at the LHC”. *JHEP* 02 (2013), p. 133. DOI: 10.1007/JHEP02(2013)133. arXiv: 1211.5584 [hep-ph]. №: DESY-12-175.
- [66] **CMS**. “Search for long-lived particles that decay into final states containing two muons, reconstructed using only the CMS muon chambers” (2015). №: CMS-PAS-EXO-14-012.
- [67] M. Drewes et al. “Testing the low scale seesaw and leptogenesis”. *JHEP* 08 (2017), p. 018. DOI: 10.1007/JHEP08(2017)018. arXiv: 1609.09069 [hep-ph]. №: TUM-HEP-1062-16.
- [68] P. Hernández et al. “Leptogenesis in GeV scale seesaw models”. *JHEP* 10 (2015), p. 067. DOI: 10.1007/JHEP10(2015)067. arXiv: 1508.03676 [hep-ph]. №: IFIC-15-44, SISSA-35-2015-FISI.
- [69] **ATLAS**. “Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”. *Phys. Rev. D* 97.5 (2018), p. 052012. DOI: 10.1103/PhysRevD.97.052012. arXiv: 1710.04901 [hep-ex]. №: CERN-EP-2017-202.
- [70] B. Shuve and M. E. Peskin. “Revision of the LHCb Limit on Majorana Neutrinos”. *Phys. Rev. D* 94.11 (2016), p. 113007. DOI: 10.1103/PhysRevD.94.113007. arXiv: 1607.04258 [hep-ph]. №: SLAC-PUB-16768, SLAC-PUB-16768.
- [71] A. Alloul et al. “FeynRules 2.0 - A complete toolbox for tree-level phenomenology”. *Comput. Phys. Commun.* 185 (2014), pp. 2250–2300. DOI: 10.1016/j.cpc.2014.04.012. arXiv: 1310.1921 [hep-ph]. №: CERN-PH-TH-2013-239, MCNET-13-14, IPPP-13-71, DCPT-13-142, PITT-PACC-1308.

- [72] C. Degrande et al. “Fully-Automated Precision Predictions for Heavy Neutrino Production Mechanisms at Hadron Colliders”. *Phys. Rev. D* 94.5 (2016), p. 053002. DOI: 10.1103/PhysRevD.94.053002. arXiv: 1602.06957 [hep-ph]. №: IPPP-16-13, MCNET-16-05.
- [73] D. Alva, T. Han, and R. Ruiz. “Heavy Majorana neutrinos from $W\gamma$ fusion at hadron colliders”. *JHEP* 02 (2015), p. 072. DOI: 10.1007/JHEP02(2015)072. arXiv: 1411.7305 [hep-ph]. №: PITT-PACC-1407.
- [74] J. Alwall et al. “MadGraph 5 : Going Beyond”. *JHEP* 06 (2011), p. 128. DOI: 10.1007/JHEP06(2011)128. arXiv: 1106.0522 [hep-ph]. №: FERMILAB-PUB-11-448-T.
- [75] J. Alwall et al. “Computing decay rates for new physics theories with FeynRules and MadGraph5_aMC@NLO”. *Comput. Phys. Commun.* 197 (2015), pp. 312–323. DOI: 10.1016/j.cpc.2015.08.031. arXiv: 1402.1178 [hep-ph]. №: CERN-PH-TH-2014-020, MCNET-14-03, IPPP-14-10, DCPT-14-20, CP3-14-11, CALT-68-2877, ZU-TH-02-14.
- [76] S. Frixione et al. “Angular correlations of lepton pairs from vector boson and top quark decays in Monte Carlo simulations”. *JHEP* 04 (2007), p. 081. DOI: 10.1088/1126-6708/2007/04/081. arXiv: hep-ph/0702198 [HEP-PH]. №: CAVENDISH-HEP-07-01, GEF-TH-09-2007, ITP-UU-07-10, NIKHEF-2007-004.
- [77] P. Artoisenet et al. “Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations”. *JHEP* 03 (2013), p. 015. DOI: 10.1007/JHEP03(2013)015. arXiv: 1212.3460 [hep-ph]. №: NIKHEF-2012-021, CERN-PH-TH-2012-329.
- [78] T. Sjöstrand et al. “An Introduction to PYTHIA 8.2”. *Comput. Phys. Commun.* 191 (2015), pp. 159–177. DOI: 10.1016/j.cpc.2015.01.024. arXiv: 1410.3012 [hep-ph]. №: LU-TP-14-36, MCNET-14-22, CERN-PH-TH-2014-190, FERMILAB-PUB-14-316-CD, DESY-14-178, SLAC-PUB-16122.
- [79] **ATLAS**. *Trigger Menu in 2016*. Tech. rep. ATL-DAQ-PUB-2017-001. Geneva: CERN, Jan. 2017. URL: <https://cds.cern.ch/record/2242069>.
- [80] **LHCb**. “Search for Dark Photons Produced in 13 TeV pp Collisions”. *Phys. Rev. Lett.* 120.6 (2018), p. 061801. DOI: 10.1103/PhysRevLett.120.061801. arXiv: 1710.02867 [hep-ex]. №: LHCB-PAPER-2017-038, CERN-EP-2017-248.
- [81] **DELPHES 3**. “DELPHES 3, A modular framework for fast simulation of a generic collider experiment”. *JHEP* 02 (2014), p. 057. DOI: 10.1007/JHEP02(2014)057. arXiv: 1307.6346 [hep-ex].
- [82] B. Smits. “Efficiency Issues for Ray Tracing”. *J. Graph. Tools* 3.2 (1998), pp. 1–14. DOI: 10.1080/10867651.1998.10487488.
- [83] A. Williams et al. “An Efficient and Robust Ray-Box Intersection Algorithm”. *J. Graph. Tools* 10.1 (2005), pp. 49–54. DOI: 10.1080/2151237X.2005.10129188.
- [84] G. Cowan et al. “Asymptotic formulae for likelihood-based tests of new physics”. *Eur. Phys. J. C* 71 (2011). [Erratum: *Eur. Phys. J. C* 73, 2501 (2013)], p. 1554. DOI: 10.1140/epjc/s10052-011-1554-0, 10.1140/epjc/s10052-013-2501-z. arXiv: 1007.1727 [physics.data-an].
- [85] C. Liu and N. Neumeister. “Reconstruction of cosmic and beam-halo muons”. *Eur. Phys. J. C* 56 (2008), pp. 449–460. DOI: 10.1140/epjc/s10052-008-0674-7. №: CERN-CMS-NOTE-2008-001.

- [86] P. Hernández et al. “Testable Baryogenesis in Seesaw Models”. *JHEP* 08 (2016), p. 157. DOI: 10.1007/JHEP08(2016)157. arXiv: 1606.06719 [hep-ph].
- [87] S. Antusch et al. “Probing Leptogenesis at Future Colliders”. *JHEP* 09 (2018), p. 124. DOI: 10.1007/JHEP09(2018)124. arXiv: 1710.03744 [hep-ph]. №: TUM-1160/18, CP3-17-48.
- [88] S. Eijima, M. Shaposhnikov, and I. Timiryasov. “Parameter space of baryogenesis in the ν MSM” (2018). arXiv: 1808.10833 [hep-ph].
- [89] A. Abada et al. “Low-scale leptogenesis with three heavy neutrinos”. *JHEP* 01 (2019). [JHEP19,164(2020)], p. 164. DOI: 10.1007/JHEP01(2019)164. arXiv: 1810.12463 [hep-ph]. №: CP3-18-59, DESY 18-174, DESY-18-174, LPT-ORSAY-18-85.
- [90] M. Shaposhnikov. “A Possible symmetry of the nuMSM”. *Nucl. Phys.* B763 (2007), pp. 49–59. DOI: 10.1016/j.nuclphysb.2006.11.003. arXiv: hep-ph/0605047 [hep-ph]. №: CERN-PH-TH-2006-079.
- [91] J. Kersten and A. Y. Smirnov. “Right-Handed Neutrinos at CERN LHC and the Mechanism of Neutrino Mass Generation”. *Phys. Rev.* D76 (2007), p. 073005. DOI: 10.1103/PhysRevD.76.073005. arXiv: 0705.3221 [hep-ph].
- [92] K. Moffat, S. Pascoli, and C. Weiland. “Equivalence between massless neutrinos and lepton number conservation in fermionic singlet extensions of the Standard Model” (2017). arXiv: 1712.07611 [hep-ph].
- [93] **CMS**. “Search for heavy Majorana neutrinos in same-sign dilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *JHEP* 01 (2019), p. 122. DOI: 10.1007/JHEP01(2019)122. arXiv: 1806.10905 [hep-ex]. №: CMS-EXO-17-028, CERN-EP-2018-159.
- [94] **ATLAS**. “Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with two charged leptons and two jets at $\sqrt{s} = 13$ TeV with the ATLAS detector”. *JHEP* 01 (2019), p. 016. DOI: 10.1007/JHEP01(2019)016. arXiv: 1809.11105 [hep-ex]. №: CERN-EP-2018-199.
- [95] G. Anamiati, M. Hirsch, and E. Nardi. “Quasi-Dirac neutrinos at the LHC”. *JHEP* 10 (2016), p. 010. DOI: 10.1007/JHEP10(2016)010. arXiv: 1607.05641 [hep-ph]. №: IFIC-16-48.
- [96] S. Antusch, E. Cazzato, and O. Fischer. “Heavy neutrino-antineutrino oscillations at colliders” (2017). arXiv: 1709.03797 [hep-ph].