Searches for right-handed neutrinos at accelerators

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Extensions to the SM featuring a low-scale seesaw can be used to to explain the observation of neutrino oscillations, baryogenesis and dark matter. I present the potential to search for right-handed neutrinos using current experiments. I compare the reach of the main detectors at the LHC when a displaced vertex signature in proton collisions is used. Additionally, I show the potential to improve on that using heavy ion collisions. Finally, I present the reach of the fixed target experiment NA62.

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1. Introduction

A well motivated minimal extension to the Standard Model (SM) consists of the addition of three right-handed neutrinos via [3]

$$\mathcal{L}_{\nu_R} = -y_{ai}\bar{\ell}_a \varepsilon \phi \nu_{Ri} - \frac{1}{2}\overline{\nu_{Ri}^c}M_{ij}\nu_{Rj} + \text{h.c.} \tag{1.1}$$

where M_{ij} is the Majorana mass. The SM on its own is invariant under a global $B - L$ symmetry, requiring M_{ij} to be small minimizes its breaking. After electroweak symmetry breaking the Yukawa coupling y_{ai} generates a Dirac mass $m_{ai} = vy_{ai}$. Subsequently, the seesaw mechanism $m_\nu = -m_{ai}M_{ij}^{-1}m_{bj}^T = -\theta_{ai}M_{ij}\theta_{bj}^T$, where $\theta_{ai} = m_{aj}M_{ij}^{-1}$ produces tiny masses for the left handed neutrinos and results in a small mixing into mass eigenstates $\nu \simeq U_\nu^\dagger(\nu_L - \theta\nu_R^c)$ and $N \simeq \nu_R + \theta^T\nu_L^c$. These heavy neutrinos N couple to the bosons of the SM via

$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta_a^* \gamma^\mu e_{La}W_\mu^+ - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta_a^* \gamma^\mu \nu_{La}Z_\mu - \frac{M}{v}\theta_a h\overline{\nu_{L\alpha}}N + \text{h.c.} \tag{1.2}$$

The resulting lifetime for light right-handed neutrinos is depicted in Figure 1, while the branching fractions for even lighter right-handed neutrinos into leptons and mesons is depicted in Figure 2. The νMSM realizes this low scale type I seesaw and is able to explain not only the neutrino masses, but also neutrino oscillation data, baryogenesis via leptogenesis and has a dark matter candidate [4]. In the following we use the abbreviation $U^2 = \sum_a U_a^2$, where $U_a^2 = \sum_i U_{ai}^2$ and $U_{ai}^2 = |\theta_{ai}|^2$. The ratio U_a^2/U_2 is independent of other heavy neutrino parameter and can be calculated from neutrino oscillation data. The resulting probability contours for two active flavours are given in Figure 3.
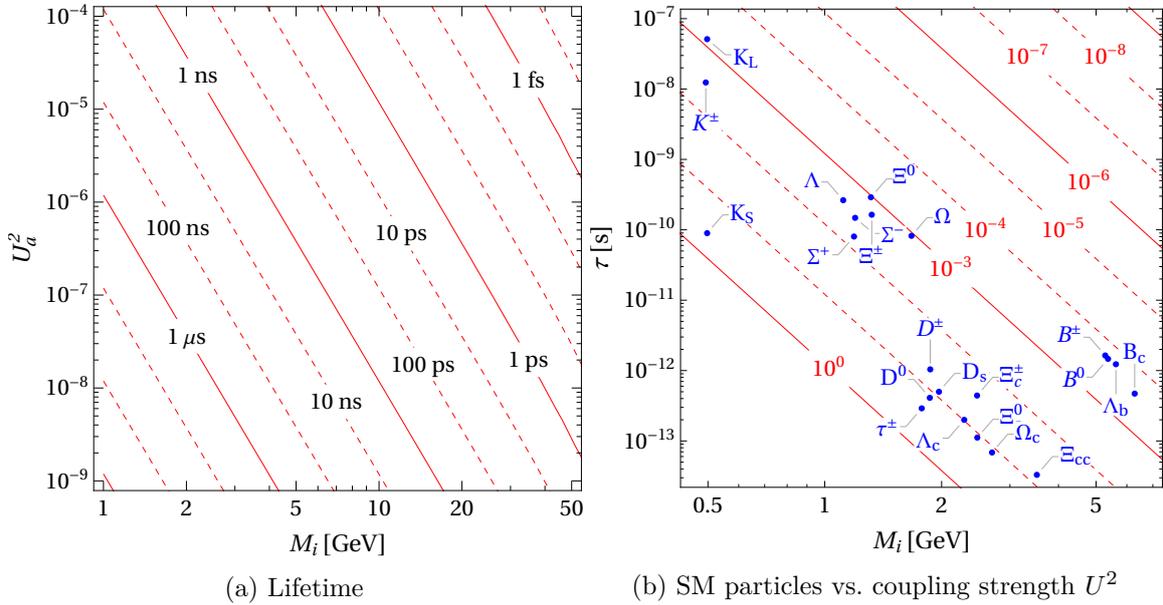

(a) Lifetime   (b) SM particles vs. coupling strength U^2

Figure 1: Lifetime of right-handed neutrinos calculated with MadGraph5_aMC@NLO. For $M \gg 5\,\text{GeV}$ the decay width can be estimated by $\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3}U_a^2 M^5$. Figure taken from [1].
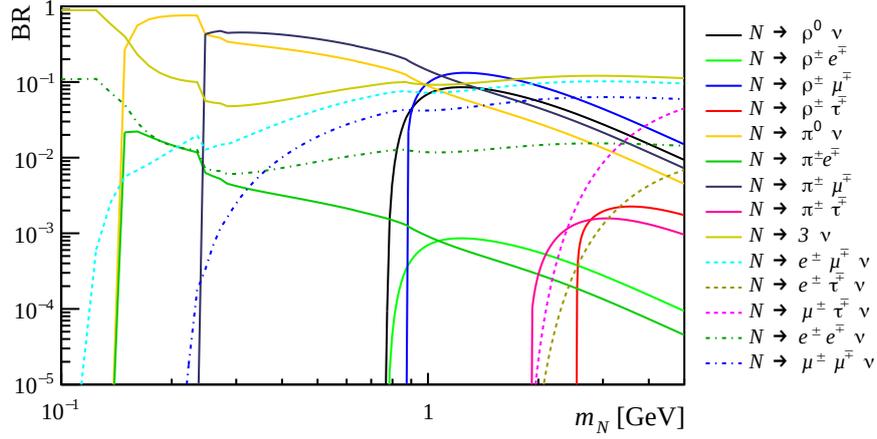
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Figure 2: Branching Fractions for light right-handed neutrinos with $U_{ie}^2 : U_{i\mu}^2 : U_{i\tau}^2 = 1 : 160 : 27.8$. Figure taken from [2].

2. NA62

NA62 is a fixed target experiment in the North Area of CERN using the SPS with the goal to measure the very rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ and extract a 10% measurement of the CKM parameter $|V_{td}|$. NA62 can also be used to search for hidden new physics such as a heavy neutrinos as depicted in Figure 4. In its target mode only K^+ induced processes are relevant and in its dump mode D- and B-meson induced processes become important. Using a toy Monte Carlo we have simulated heavy neutrino production in 10^{18} proton on
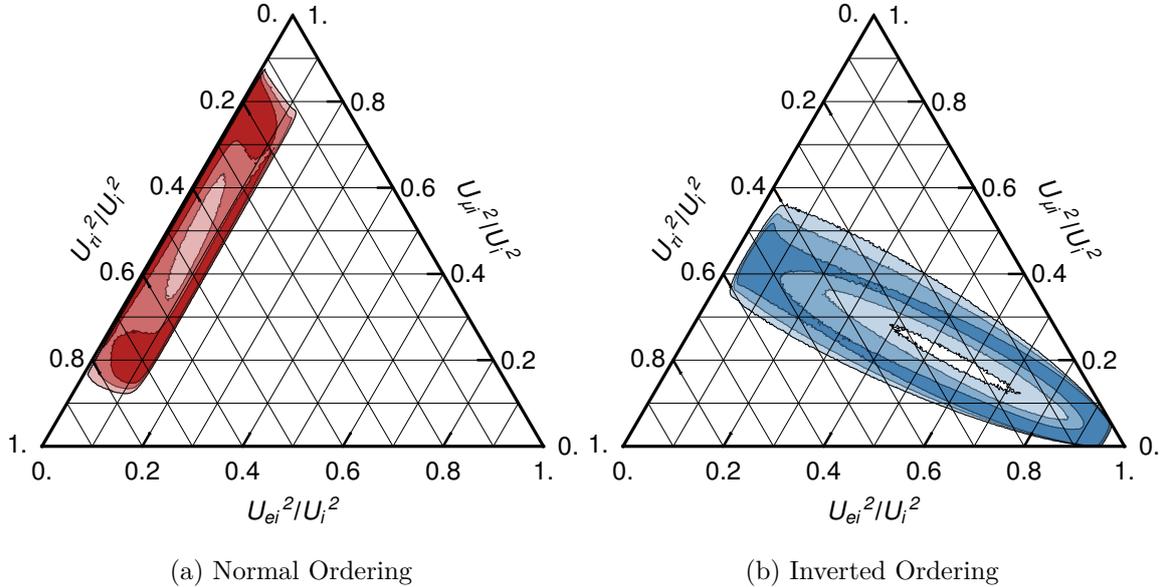

(a) Normal Ordering

(b) Inverted Ordering

Figure 3: Probability contours for U_a^2/U_2 in the case of two active flavours. The coloured areas are consistent with neutrino oscillation data at 1, 2, and $3\,\sigma$ and the unknown Majorana phase correspond to the circular structure. Figure taken from [2].
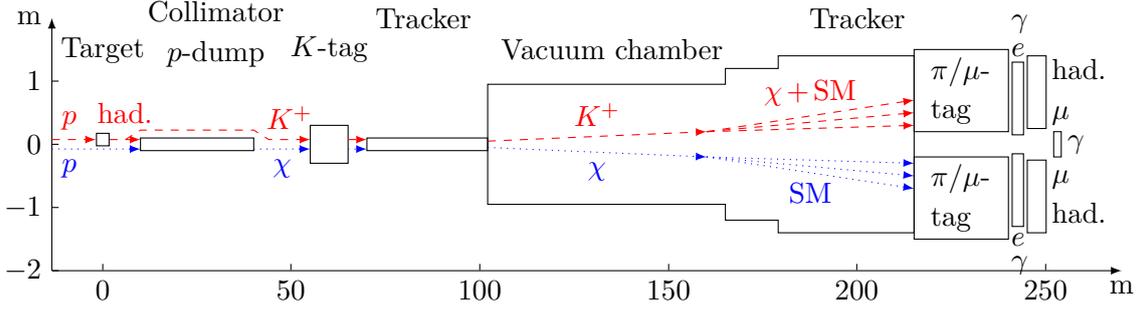
Figure 4: The NA62 experiment. The target mode is depicted in dashed red, the dump mode is shown in dotted blue, and χ indicates hidden new physics.

target (POT) in the dump mode which corresponds to 80 days of data taking planned for Run 3 (2021–2023). The heavy neutrinos are produced via 2×10^{15} D- and 10^{11} B-mesons

$$n_N \simeq 2N_{\text{POT}} \left(\chi_c f_D \, \text{BR} \left(D \to XN \right) + \chi_b f_B \, \text{BR} \left(B \to XN \right) \right) , \tag{2.1}$$

where χ is the production cross section and f is the production fractions of mesons. The number of reconstructed events is

$$N_{\text{obs}} = n_N \sum_{f, f'=e, \mu, \tau, \pi, K} \text{BR} \left(N_i \to f^+ f'^- X \right) \mathcal{A}_i \left(f^+ f'^- X, M_i, U^2_{e, \mu, \tau} \right) \varepsilon \left(f^+ f'^- X, M_i \right) , \tag{2.2}$$

where $\mathcal{A}_I$ is the geometrical acceptance and ε are the trigger, reconstruction, and selection efficiencies which are assumed to be $100\,\%$. Additionally we assume that all backgrounds can be neglected. The dominant decay modes are (cf. Figure 2) $N_i \to 3\nu, \pi^0\nu, \pi^\pm\ell^\mp, \rho^0\nu, \rho^\pm l, \ell^+\ell^-\nu, \dots$ and we assume that the detector is able to reconstruct all final states with two charged tracks. The results are presented in Figure 5.

3. LHC

We propose to search for right-handed neutrinos using displaced vertices in the LHC [1, 5]. Using the processes shown in Figure 6 one can trigger on the first lepton and search for a secondary vertex. As the muon chamber reaches farther than the tracker it can be advantageous to search for long lived particles using only the muon chambers [1, 6–8]. For the displaced vertex reconstruction we require at least two tracks with an invariant mass of $5\,\text{GeV}$ in order to suppress nuclear interactions backgrounds. The particles must transverse at least half of the tracker or the complete muon chamber. The results of our study are presented in Figure 7, they can be described using a simplified model $N_d \sim L_{\text{int}}\sigma_\nu U^2 \left(e^{-l_0/\lambda_N} - e^{-l_1/\lambda_N} \right) f_{\text{cut}}$, where l_0 is the minimal displacement, l_1 is the detector length, $\lambda_N = \frac{\beta\gamma}{\Gamma_N}$ is the decay length, and f_{cut} are all efficiencies.

4. Heavy Ion Collisions

Finally we also propose to search for long lived particles such as light right-handed neutrinos in heavy ion collisions [9–11]. The advantages of using heavy ion collisions are
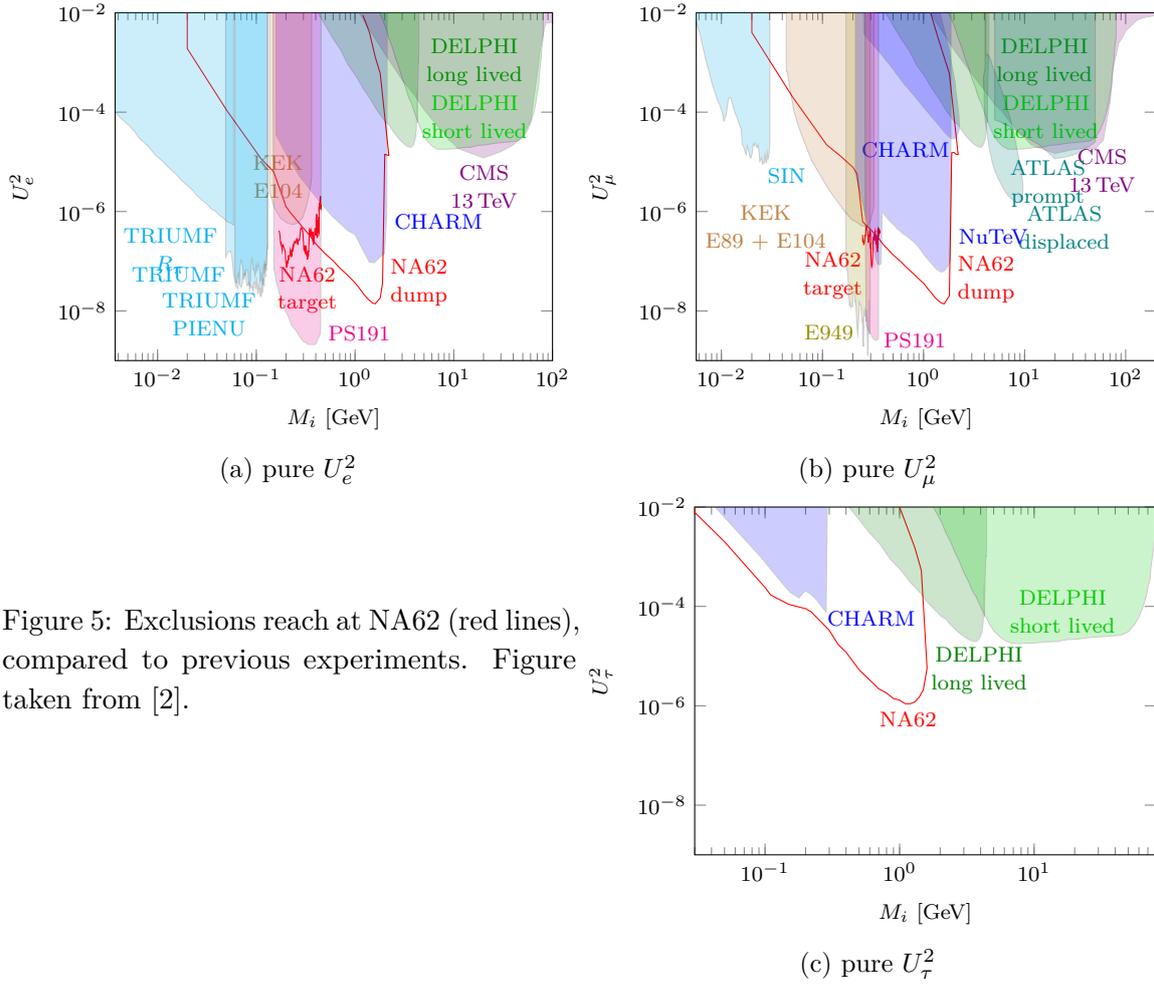
Figure 5: Exclusions reach at NA62 (red lines), compared to previous experiments. Figure taken from [2].

the absence of pile-up, which leads to a single primary vertex, as well as the large nucleon multiplicity e.g. $A(\text{Pb}) = 208$, $Z(\text{Pb}) = 82$, which leads to a large number of parton level interactions per collision as it scales with A e.g. $\frac{\sigma_{\text{PbPb}}}{\sigma_{pp}} \propto A^2 = 43 \times 10^3$. The main drawbacks are the huge number of tracks near the interaction point, which makes the search for prompt new physics extremely challenging and the small collision energy per nucleon e.g. $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ for Pb, which is mostly problematic for heavy new physics. Additionally, the LHC has allocated much less time to heavy ions runs than to protons runs. But
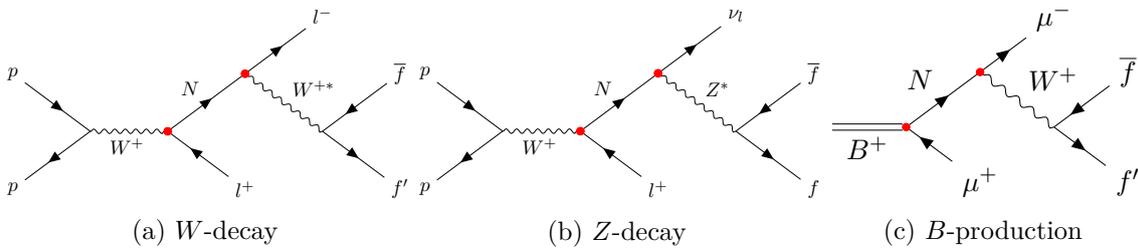

Figure 6: Displaced signatures at the LHC.

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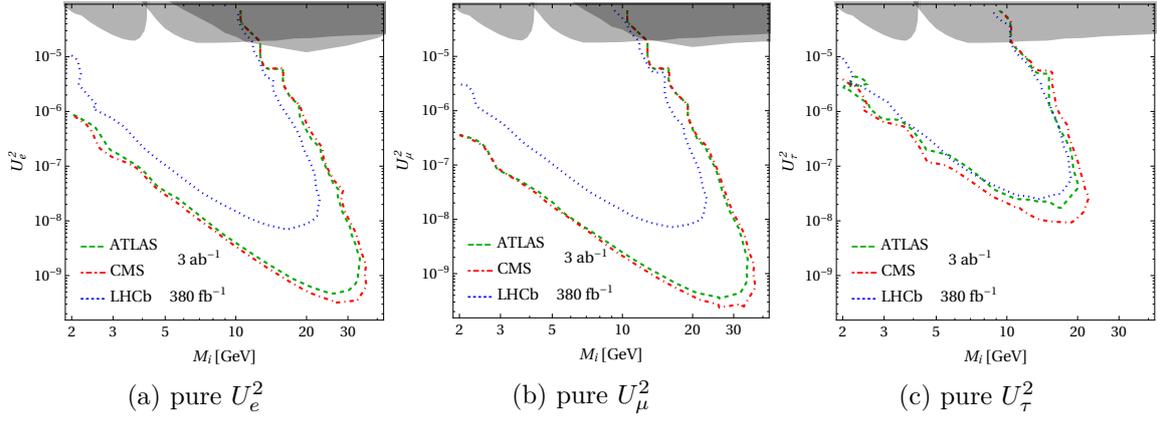(a) pure U_e^2 (b) pure U_μ^2 (c) pure U_τ^2

Figure 7: Maximal exclusion reach at the HL-LHC. Figure taken from [1].

most importantly the instantaneous luminosity is lower for heavier ions. This is caused by additional electromagnetic contributions to the cross-section

Bound-Free Pair Production (BFPP): $^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^+$

Electromagnetic Dissociation (EMD): $^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n$

This results in faster beam decay and the production of secondary beams consisting of ions with different charge/mass ratio, which can accidentally quench the magnets [12]. This can be compensated by lowering the triggers which is allowed by the low luminosity and by using lighter ions which allows to increase luminosity again. Our results are presented in Figure 8.

(a) Full simulation of W production   (b) Simplified simulation of B production
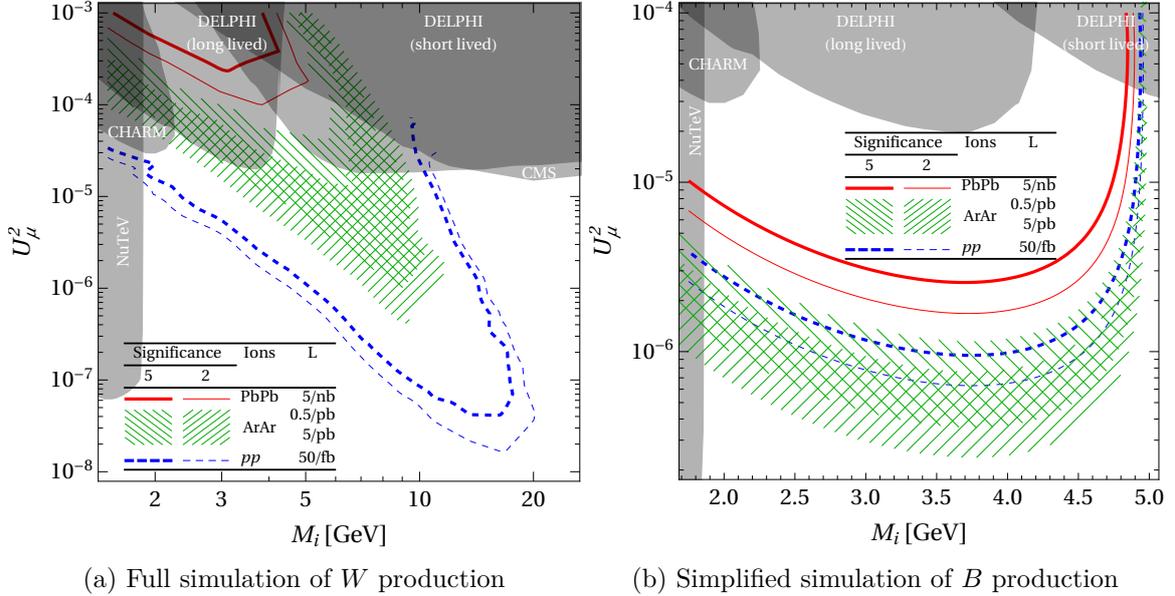
Figure 8: Exclusion reach in heavy ion collisions empowered by a low trigger threshold of $p_T > 3\,\text{GeV}$ for heavy ion collisions. Figure taken from [9].

5. Conclusion

A minimal extension to the SM featuring long lived particles is given by right-handed neutrinos. NA62 is, at the moment, the leading experiment capable of searching for right-handed neutrinos with masses between the K- and D-meson mass. Additionally, displaced vertices are a promising signature to detect right-handed neutrinos at the LHC and, finally, heavy ion collisions can also be exploited to search for right-handed neutrinos.

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