PROCEEDINGS OF SCIENCE

Probing right-handed neutrinos dipole operators

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We consider the minimal see-saw extension of the Standard Model with two right-handed singlet fermions $N_{1,2}$ with mass at the GeV scale, augmented by an effective dipole operator between the sterile states. We review current bounds on this effective interaction from fixed-target as well as from cosmological observations. We then highlight the prospects for testing the decay $N_2 \to N_1 \gamma$ induced by the dipole at the future facilities targeting long-lived particles FASER 2 and SHiP.

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1. Introduction

The see-saw mechanism is arguably the simplest extension of the Standard Model (SM) that is able to explain the observed pattern of neutrino masses and oscillations. In its simplest incarnation, it consists in adding to the SM particle content a right-handed (RH) neutrino, that is a spin 1/2 fermion, singlet under the SM gauge group, which has a Yukawa interaction with SM leptons, as well as a Majorana mass term. One of the active neutrinos acquires thus a non-vanishing mass and a mixing with the new sterile state. While the see-saw model is a full-fledged ultraviolet (UV) complete theory, at least in the same way as the SM is, in the case of EW scale RH neutrinos it is interesting to consider it as a low energy effective field theory (EFT) extended with higher dimensional operators built from the SM and the RH neutrino fields. The resulting theory is called νSMEFT. Interestingly, already at $d = 5$ two genuine νSMEFT operators appear[1]. The first is an operator coupling the RH neutrinos with the Higgs boson, $O^5_{NH} = \bar{N}^c N H^\dagger H$, while the second is a dipole with the hypercharge gauge boson that we parametrize as:

$$O^5_{NB} = \frac{g_Y}{16\pi^2}\frac{e^{i\alpha}}{\Lambda}\bar{N}^c_1 \sigma^{\mu\nu} N_2 B_{\mu\nu} + h.c.\ . \tag{1}$$

Here N_2 and N_1 are two RH neutrinos (a straightforward generalization applies for more RH neutrino flavours) and N_1 denotes the lightest one. Λ parametrizes the Wilson coefficient of the operator, while g_Y and $B_{\mu\nu}$ are the $U(1)_Y$ coupling and field strength tensor respectively. The loop suppression factor is explicitly introduced since this operator only arises at loop level in any weakly coupled UV completion, while the hypercharge coupling is added because of the presence of $B_{\mu\nu}$. Since the Wilson coefficient can be complex, we show explicitly its phase α.

Among other effects, the operator above generates the decay

$$N_2 \to N_1 + \gamma. \tag{2}$$

This interaction is the subject of our study. Our focus will be on light RH neutrinos with masses up to a few GeV. Such light states can be produced not only at high-energy colliders via parton interactions but also at fixed-target experiments, typically via meson decay. More specifically, we compute the predicted sensitivity of the proposed experiments FASER 2 [1] and SHiP [2]. In addition we analyze current bounds from accelerator experiments and from cosmology and astrophysics. We defer to [3] for more details.

2. Results

For large enough Λ, N_2 is a long-lived state with a macroscopic decay length. The decay in eq.(2) leads to mono-photon signals at accelerator experiments. We present the prospects for their detection at SHiP and FASER 2. FASER is a detector at the Large Hadron Collider (LHC) recently constructed and placed along the beam axis, near the ATLAS experiment. This detector is dedicated to the study of long-lived particles. To fully exploit the potential of the High Luminosity LHC phase, an extension, called FASER 2, has been proposed. Another proposed experiment with high

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[1] The other $d = 5$ operator is clearly the Weinberg operator $O^5_W = (\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L)$.

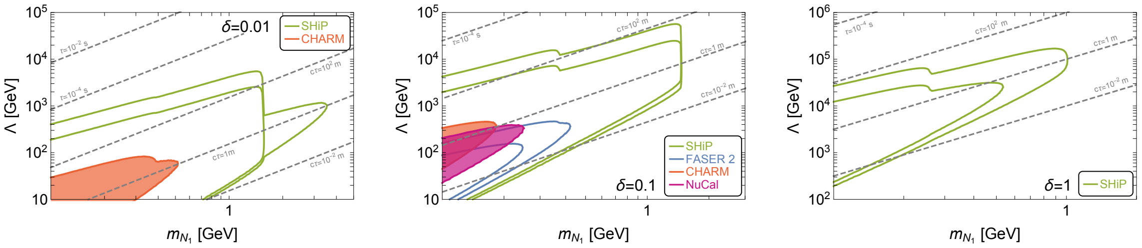

Figure 1: Green and blue lines are the sensitivity reach of the SHiP and FASER 2 experiments. For SHiP we show isocontours of $N_{\text{signal}} = 3$ and $N_{\text{signal}} = 63.8$. For FASER 2 we show isocontours of $N_{\text{signal}} = 3$ and $N_{\text{signal}} = 63.8$. The orange and magenta shaded regions are excluded by the CHARM and NuCal experiments. The dashed lines are contour of constant N_2 lifetime or proper decay length. We fix $\alpha = \pi/2$.

sensitivity to long-lived particle decays is SHiP. This fixed-target experiment aims at accumulating $N_{\text{POT}} = 2 \times 10^{20}$ protons on a target composed of Molybdenum and Tungsten in 5 years of operation.

The sensitivities of these experiments are presented in Fig. 1. For the sake of definiteness, we fix the phase to $\alpha = \pi/2$, but the results remain qualitatively the same for other choices. We present the results for three choices of the mass splitting $\delta \equiv (m_{N_2} - m_{N_1})/m_{N_1}$, namely $\delta = 0.01, 0.1, 1$. The sensitivities of SHiP and FASER 2 are computed for two numbers of signal events (N_{signal}), corresponding to different choices of the background rate at these experiments. In one case, we assume that the backgrounds can be reduced at a negligible level, as expected also for other searches in these experiments. A 95% CL upper limit is obtained for a number of signal events $N_{\text{signal}} = 3$. Then, we also consider a more conservative approach for the background rare, see [3]. We also present the region of parameter space excluded by the past fixed-target experiments CHARM and NuCal. When the line associated to a specific experiment is missing in our plots, this means that the corresponding experiment has not enough sensitivity to probe the parameter space. As evident in Fig. 1, for a mass splitting $\delta = 0.1$, both SHiP and FASER 2 will be able to extend the current limits from CHARM and NuCal, and probe an uncharted region of the parameter space. In particular the sensitivity of SHiP reaches N_1 masses around the kinematical threshold for production from the decay of the J/Ψ meson, *i.e.* $m_{N_1} \sim 1.5$ GeV. A more modest sensitivity is obtained for FASER 2. It is worth recalling that despite small values of Λ are formally not excluded in the EFT of Eq. (1), weakly coupled UV completions with $\Lambda \lesssim 100$ GeV are likely already ruled out from direct searches of additional EW-charged states. The cosmological constraints from Big Bang Nucleosynthesis on N_2 decays are of the order $\tau_{N_2} = O(10^{-2} - 1)$ s. Looking at the isocontour of τ_{N_2} in Fig. 1, one can notice that these bounds are not overlapping with the sensitivities of SHiP and FASER 2.

For the calculation above, we have considered that only photons above a threshold of $E_{\text{cut}} = 100$ GeV (FASER 2) and $E_{\text{cut}} = 10$ (SHiP) can be reconstructed. In the case of a small mass splitting, the choice of this ingredient plays an important role. Small values of δ reduce the energy of the photon produced in the N_2 decay. This implies that for $\delta = 0.01$ at FASER 2 most of the events do not satisfy the cut above, and therefore no sensitivity is obtained. To highlight the role of the energy threshold, in Fig. 2 we show the isocontours of $N_{\text{signal}} = 3$ for different values of E_{cut}, namely $E_{\text{cut}} = 0.1, 0.5, 1, 2, 10$ GeV for SHiP and $E_{\text{cut}} = 10, 50, 100, 200$ GeV for FASER 2. While for $\delta = 1$ the sensitivities are almost unchanged, for smaller δ the energy threshold has a significant impact. In particular, for $E_{\text{cut}} \sim 10$ GeV and provided that background can be kept negligible, FASER 2

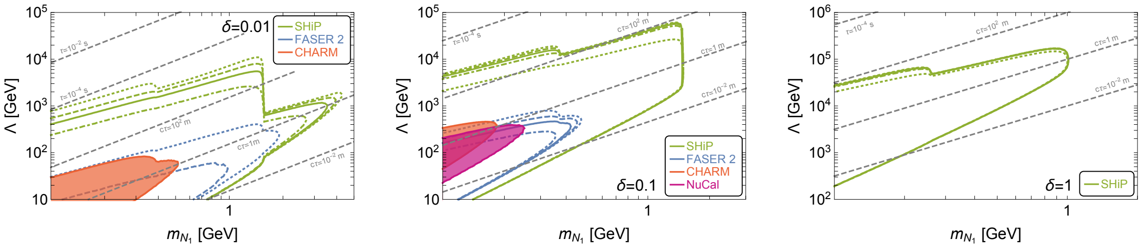

Figure 2: Isocontours of $N_{\text{signal}} = 3$ for SHiP (green lines) and FASER 2 (blue lines). For SHiP dotted, dashed, solid, dot-dashed and dotted lines are for $E_{\text{cut}} = 0.1, 0.5, 1, 2, 10$ GeV respectively while for FASER 2 dotted, dashed, solid and dot-dashed lines are for $E_{\text{cut}} = 10, 50, 100, 200$ GeV respectively. The CHARM and NuCal regions and the gray lines are as in Fig. 1. We fix $\alpha = \pi/2$.

will be able to test up to $\Lambda \sim 400$ GeV for $\delta = 0.01$, to be compared with a zero sensitivity scenario with $E_{\text{cut}} \sim 100$ GeV, shown in Fig. 1.

3. Conclusions

In this work we have studied the phenomenological consequences of a dipole operator between RH neutrino fields. This is described by the νSMEFT $d = 5$ operator $\bar{N}_2 \sigma^{\mu\nu} N_1 B_{\mu\nu}$ and triggers the decay $N_2 \to N_1 \gamma$, which is the subject of our study. Motivated by the current experimental and theoretical interest, we have focused on RH neutrino masses in the GeV range and considered the regime in which N_2 is long-lived, with a proper decay length of $O(10^{-2} - 10^3\ \text{m})$, while N_1 is considered to be stable on these length scales. We have subsequently investigated the sensitivity of the future proposed experiments FASER 2 and SHiP. We have shown that SHiP will be able to probe ample regions of the parameter space not yet excluded by current data, testing Wilson coefficients up to $\Lambda \sim 10^5$ GeV, while the sensitivity of FASER 2 is more limited. Given the early design stage of these experiments and the preliminary nature of the background estimates for the scenario under consideration, we have then studied how different cuts on the photon energy enforced at the analysis level affect the sensitivity reach. In conclusion, our work provides a first realistic estimate of the reach of experiments targeting long-lived particles on the lowest dimensional effective dipole operator that appears in the minimal see-saw extension of the Standard Model.

References

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