Probing right-handed neutrinos dipole operators

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See-saw mechanism

- Neutrino masses require new physics beyond the Standard Model
- The see-saw mechanism is the simplest SM extension able to explain neutrino masses
- The mass of the needed right-handed neutrinos could lie along a huge range of values, from EW to grand unification scale
- Small active-sterile mixing angles imply long lifetime for RH neutrinos

m_N

$$m_\nu \simeq \frac{y_\nu^2 v^2}{m_N}$$

$$c\tau \sim 5\,\mathrm{m}\left(\frac{10^{-10}}{\theta^2}\right)\left(\frac{10\ \mathrm{GeV}}{m_N}\right)^5$$

νSMEFT theory

New physics scale Λ:

$\psi, \phi, \ldots$

Energy scale

- Here we consider RH neutrinos with masses at the EW scale
- The phenomenology of the see-saw model could be modified by new physics at higher scale
- The effects of new physics is included within an EFT framework

EW scale: $$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{N}\partial\!\!\!/ N - \bar{L}_L Y_\nu \tilde{H} N - \frac{1}{2}\bar{N}^c M_N N + \sum_{n>4}\frac{\mathcal{O}^n}{\Lambda^{n-4}} + h.c.$$

- There are only two operators at dimension $d = 5$

$$\mathcal{O}_{NH} = NNH^\dagger H$$
$$\mathcal{O}_{NB} = N\sigma^{\mu\nu}NB_{\mu\nu}$$

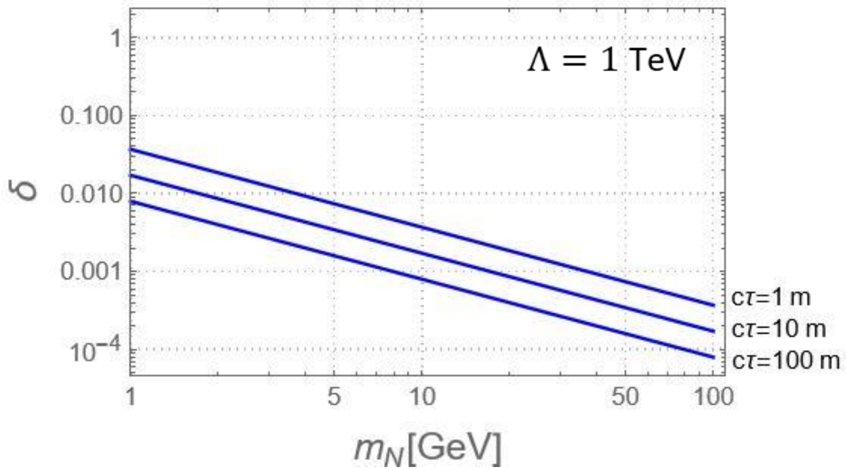
Our minimal scenario

- Here we consider two RH neutrinos with masses at GeV scale, assuming suppressed active-sterile mixing
- We are interested in the phenomenology due to the dipole operator

$$\mathcal{O}^5_{NB} = \frac{g_Y}{16\pi^2}\frac{e^{i\alpha}}{\Lambda}\bar{N}_1^c\sigma^{\mu\nu}N_2 B_{\mu\nu} + h.c.$$

- The Wilson coefficient is normalized assuming a weakly coupled UV theory
- The operator induces the following decay

$$N_{\rm heavy} \to N_{\rm light} + \gamma$$



$$c\tau \simeq 0.5\ {\rm m}\left(\frac{0.1}{\delta}\right)^3\left(\frac{\Lambda}{100\ {\rm GeV}}\right)^2\left(\frac{0.1\ {\rm GeV}}{m_{N_1}}\right)^3$$

$$\delta = \frac{m_{N_2} - m_{N_1}}{m_{N_1}}$$

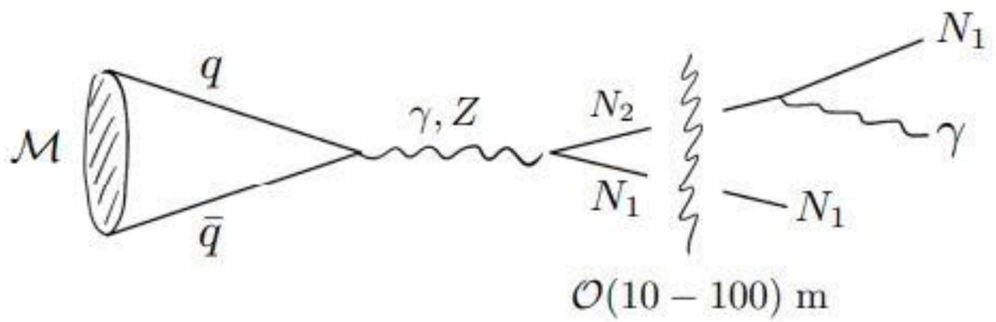
Testing our minimal scenario

- Many experiments are sensitive to decay length along 10-100 meters
- The main experimental signature of the our minimal scenario is a single photon
- The parameter space is spanned by the lighter neutrino mass, the mass splitting and the dipole Wilson coefficient

$$N_{\text{signal}} = N_{\text{prod}} \langle f_{\text{dec}} \, \epsilon_{\text{det}} \rangle$$

$$f_{\text{dec}} = e^{-L_{\text{entry}}/L_{N_2}} - e^{-L_{\text{exit}}/L_{N_2}}$$

For $m_N \lesssim 1$ GeV dominant production via meson decay



Colliders

- We recollected the constraints coming from collider experiments
- Different searches apply based on the range of N_2's lifetime

1) Prompt, smaller than 1 mm: LEP, BaBar
2) Displaced, between 1 mm and 1 m: ALEPH, ATLAS, CDFII, DELPHI
3) Stable, larger than 1 m: LEP limits on invisible Z width

- For all the cases, we obtain that the bounds on the NP scale lie beyond the validity of the EFT and hence no meaningful constraints can be set

Beam dump experiments

- We recollected the actual constraints coming from beam-dump experiment
- The main experiments were

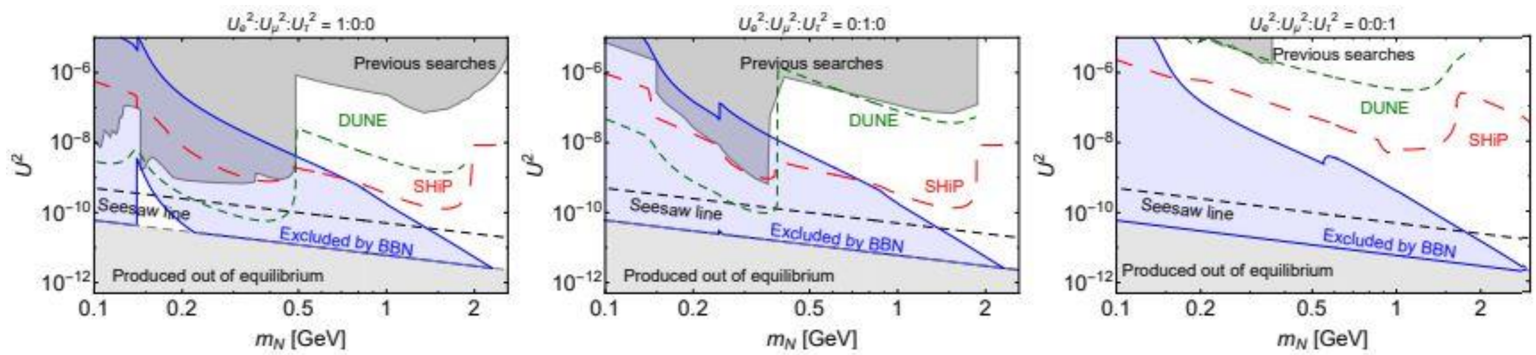
1) CHARM: 400 GeV proton beam dumped into a copper target
   F. Bergsma et al. Phys. Lett. B 157 (1985) 458–462
2) NuCal: 70 GeV proton beam dumbed into an iron target
   J. Blumlein and J. Brunner Phys. Lett. B 701 (2011) 155–159
3) NA64: 100 GeV electron beam dumbed on a lead target
   D. Banerjee et al. Phys. Rev. Lett. 125 (2020), no. 8 081801

- We find that the number of events produced at NA64 is too small to put any bound on the parameter space

Astrophysics and cosmology

- We also checked the actual constraints from astrophysics and cosmology
- The main constraint comes from BBN

Boyarsky, Ovchynnikov, Ruchayskiy and Syvolap arxiv:2008,00749



- A detailed analysis of bounds from supernovae was not performed but we expect these limits to affect only a quite region of the parameter space

Projected sensitivity on SHiP and FASER 2

- SHiP is a fixed-target experiment, based on a high intensity 400 GeV proton beam dumped on a heavy target

$$N_{\text{prod}} = \sum_M N_{\text{POT}}\, N_M\, \text{BR}(M \to N_1 N_2)$$

ρ, ω, J/ψ and Υ production simulated with **Pythia 8.3**

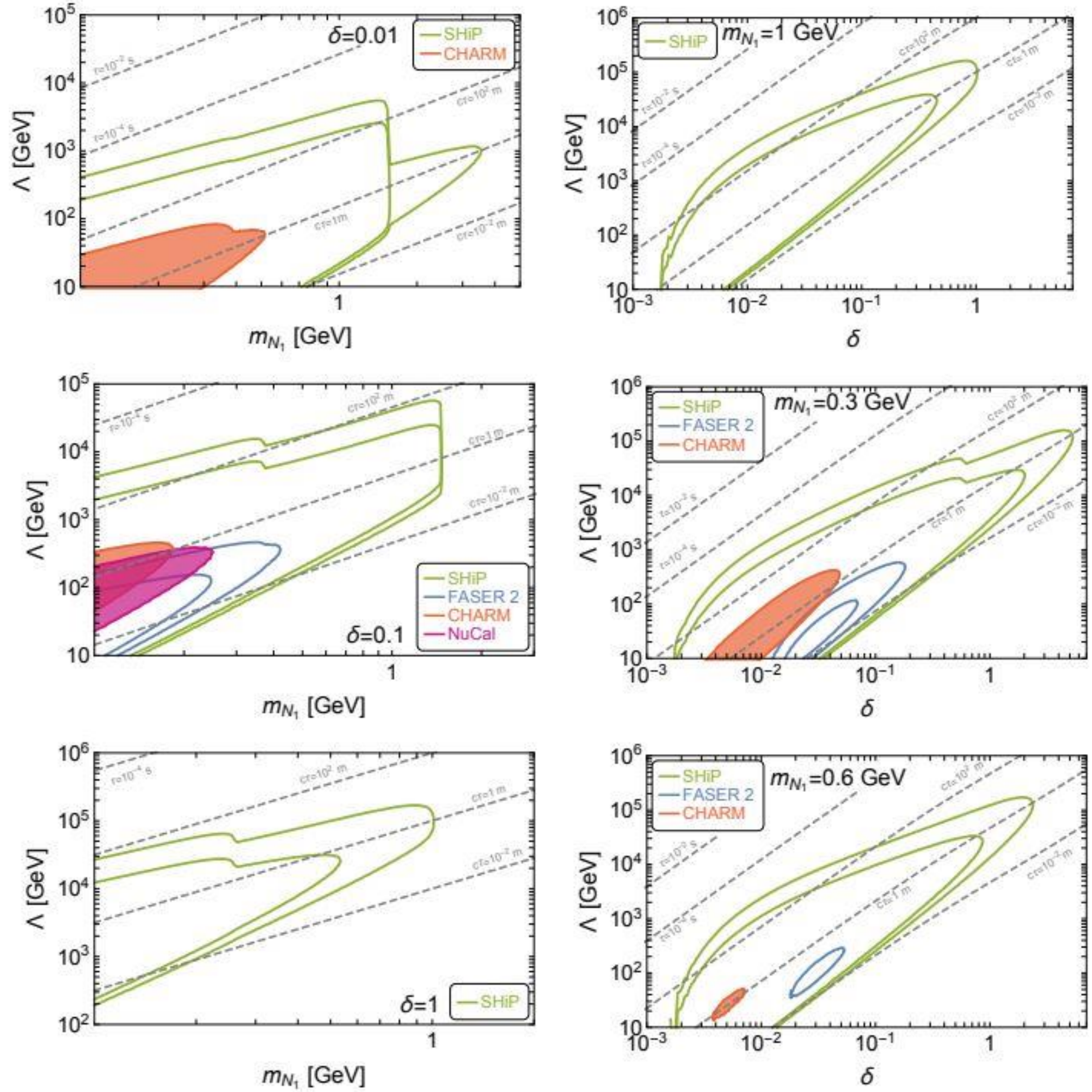
- FASER 2 is an LHC experiment, which aims at exploiting the proton collisions occurring at $\sqrt{s} = 14$ TeV during the High-Luminosity LHC program

$$N_{\text{prod}}^{\text{LHC}} = \sum_M \sigma_{\text{ine}}\, \mathcal{L}\, N_M\, \text{BR}(M \to N_1 N_2)$$

ρ and ω production simulated with **EPOS-LHC**,
J/ψ and Υ production simulated with **PYTHIA 8.3**

Results

- Isocontours of $N_{signal} = 3$ and $N_{signal} = 63{,}8$ for SHiP and FASER 2 sensitivity
- Only a small portion of the parameter space is actually excluded by CHARM and NuCal experiments



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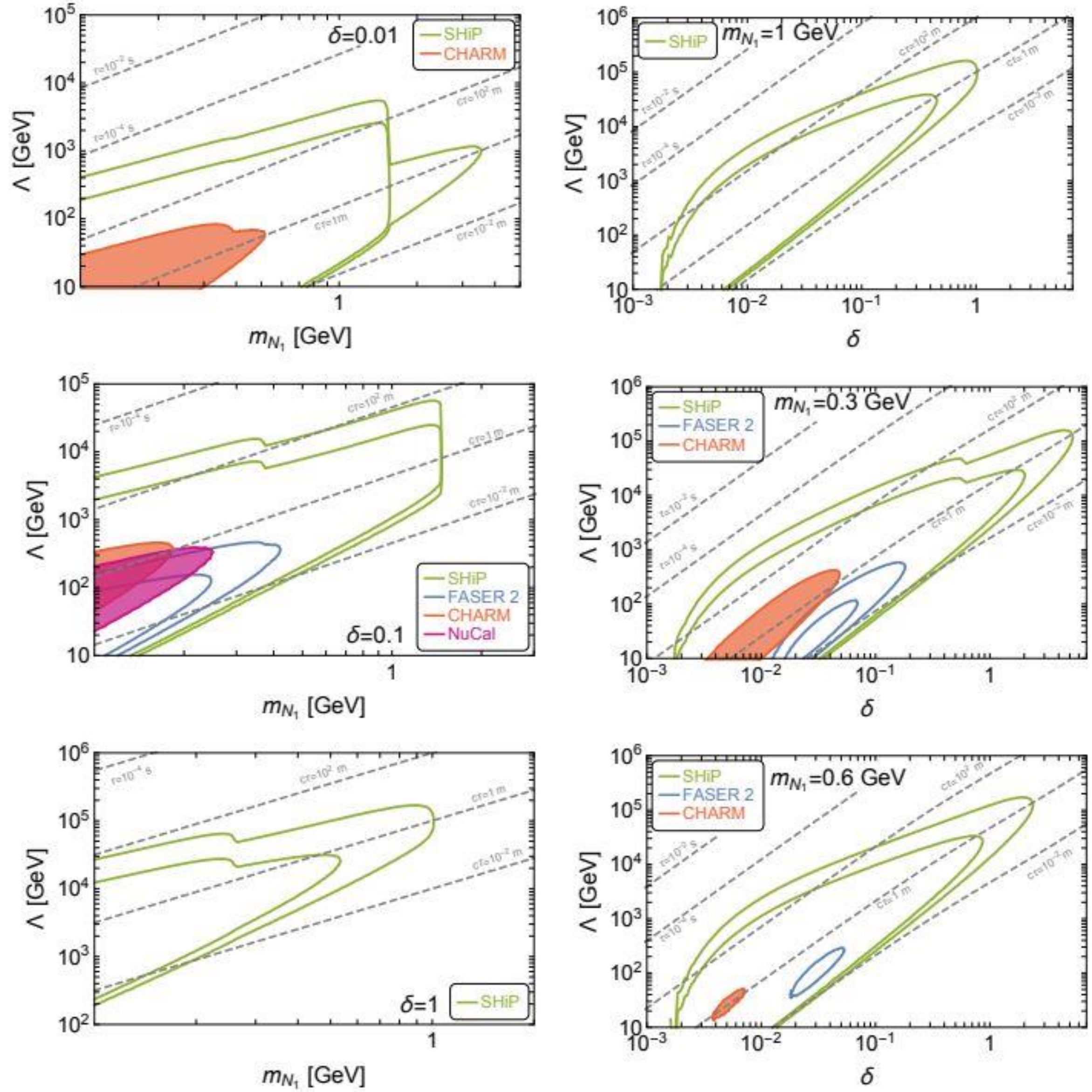
Results

- SHiP will be able to probe ample regions of the parameter space not yet excluded by current data, testing the Wilson coefficient up to $\Lambda \sim 10^5$ GeV, while the sensitivity of FASER 2 is more limited



Conclusion

- We provide a first realistic estimate on 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
- We conclude that SHiP and FASER 2 will be able to probe large part of the parameter space
- We are still considering possible follow up of this line of work

Thanks for the attention!

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Back Up slides

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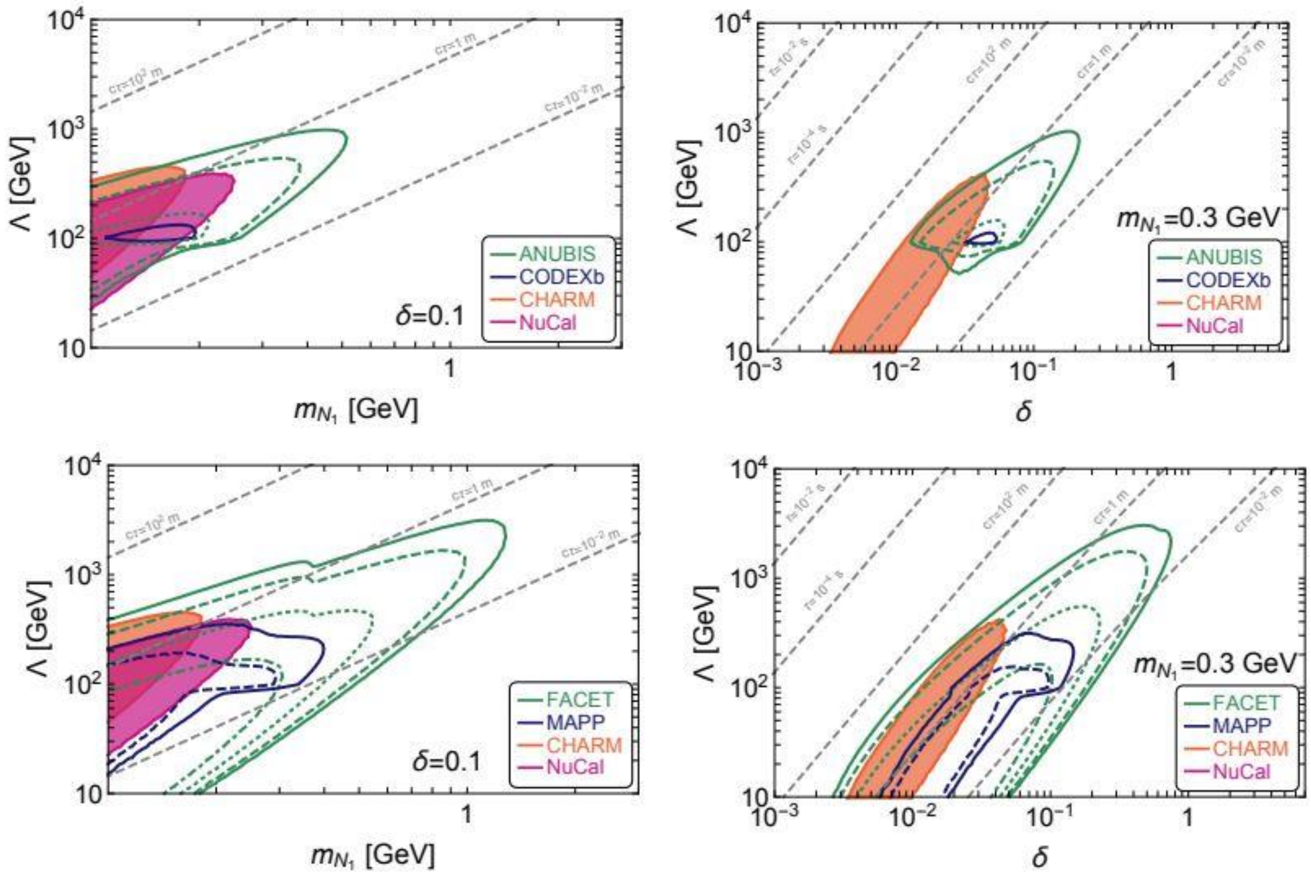
Other future LHC experiments

- Solid, dashed, dotted and dot-dashed lines correspond to $N_{signal} = 3$, $N_{signal} = 10$, $N_{signal} = 100$. and $N_{signal} = 1000$



Electron recoil searches

- The dipole operator induces the inelastic scattering processes of RH neutrino with electrons

$$N_1 e^- \to N_2 e^- \qquad\qquad N_2\, e^- \to N_1\, e^-$$

- We consider the impact of such processes in the e-recoil searches of experiments like SHiP, CHARMII and DUNE
- We find the number of recoil events to be negligible for values of Λ above 1 GeV, independently of the values of lighter neutrino mass and mass splitting
- We then conclude that searches through electron recoils do not impose relevant constraint on the parameter space