Long-lived Sterile Neutrinos at the LHC in Effective Field Theory

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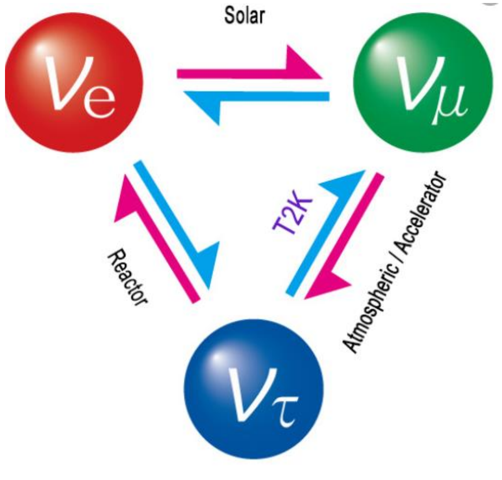
Nov. 2020

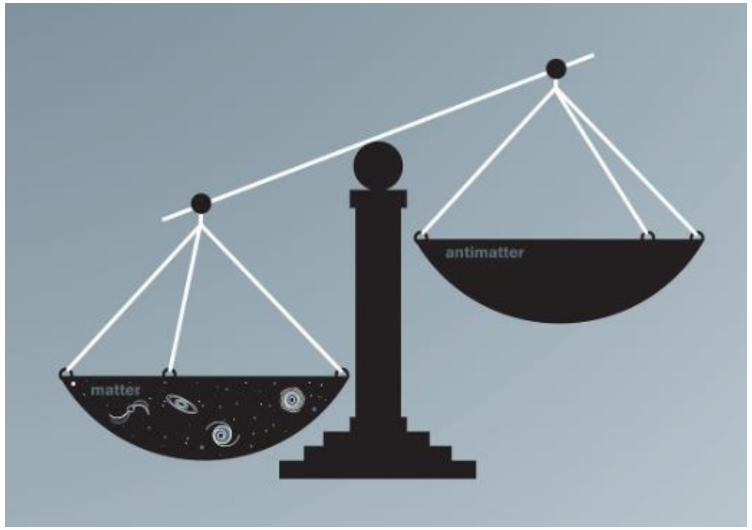
Based on: 2010.07305, with Jordy de Vries,
Herbert K.Dreiner, Julian Y. Günther
, Zeren Simon Wang

Background

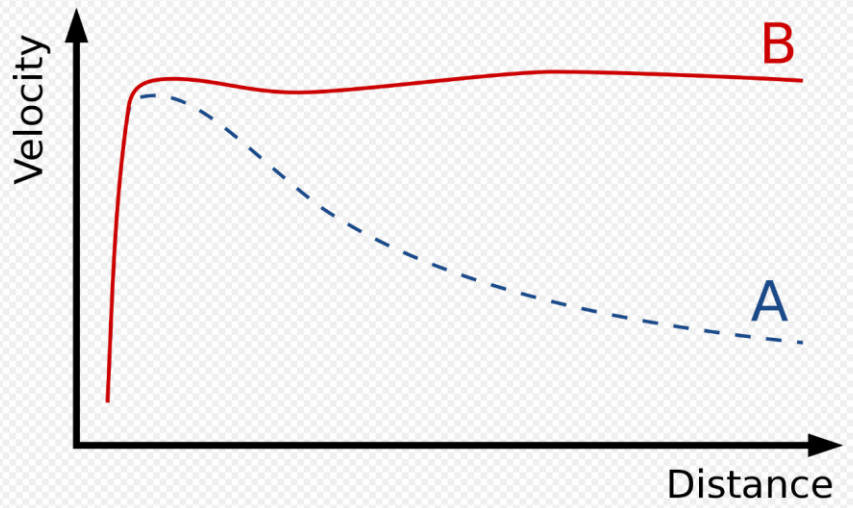
The standard model works well in a wide range of experiments, however, there are some phenomena it fails to explain:



Neutrino oscillation between three generations



Rotation curve of a typical spiral galaxy



All these problems could be solved if we introduce right-handed gauge-singlet neutrinos, the sterile neutrinos!

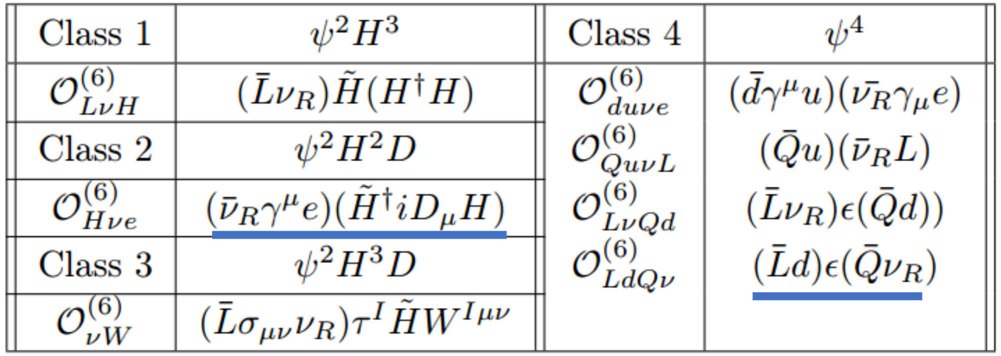
Neutrino extended Standard Model Effective Field Theory

Why SMEFT?

- Heavy particles exist in many BSM theories
- A model independent way

$$\begin{aligned}\mathcal{L} \;&=\; \mathcal{L}_{SM} - \frac{1}{2}\bar{\nu}_R^c\,\bar{M}_R\nu_R - \left(\bar{L}\tilde{H}Y_\nu\nu_R + \text{h.c.}\right)\\ &\quad + \mathcal{L}_{\nu_L}^{(\bar{5})} + \mathcal{L}_{\nu_R}^{(\bar{5})} + \mathcal{L}_{\nu_L}^{(\bar{6})} + \mathcal{L}_{\nu_R}^{(\bar{6})} + \mathcal{L}_{\nu_L}^{(\bar{7})} + \mathcal{L}_{\nu_R}^{(\bar{7})}\,,\end{aligned}$$

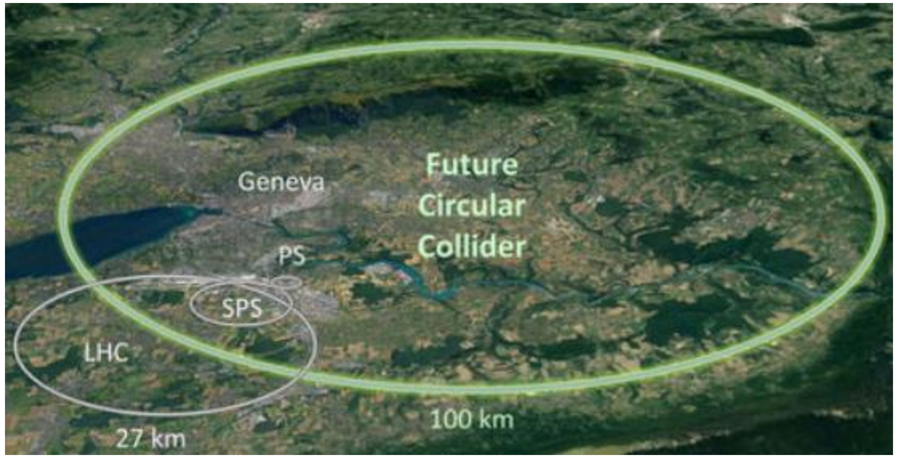
Dimension-6 operators with one sterile neutrino



Class 1	$\psi^2 H^3$	Class 4	ψ^4
$\mathcal{O}^{(6)}_{L\nu H}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}^{(6)}_{du\nu e}$	$(\bar{d}\gamma^\mu u)(\bar{\nu_R}\gamma_\mu e)$
Class 2	$\psi^2 H^2 D$	$\mathcal{O}^{(6)}_{Qu\nu L}$	$(\bar{Q}u)(\bar{\nu}_R L)$
$\mathcal{O}^{(6)}_{H\nu e}$	$\underline{(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger i D_\mu H)}$	$\mathcal{O}^{(6)}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d))$
Class 3	$\psi^2 H^3 D$	$\mathcal{O}^{(6)}_{LdQ\nu}$	$\underline{(\bar{L}d)\epsilon(\bar{Q}\nu_R)}$
$\mathcal{O}^{(6)}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$		

Search for Sterile neutrinos at the LHC

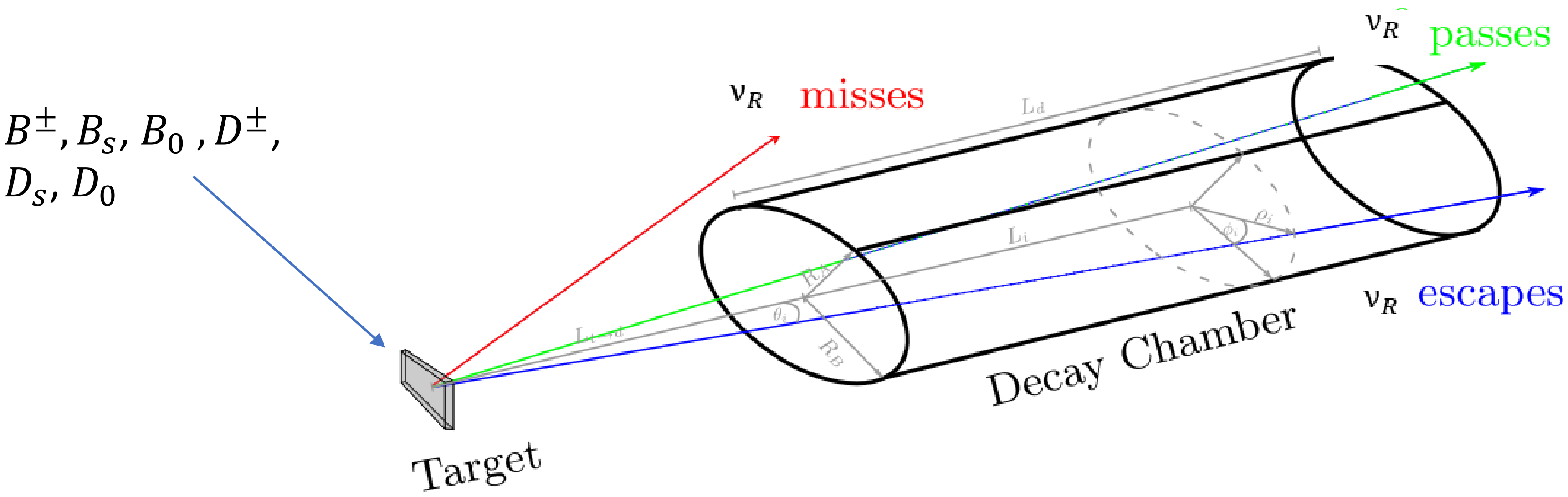
The high luminosity LHC is going to deliver up to 3/ab of data, we can use the dedicated experiments at the LHC to probe the parameter space of various models containing sterile neutrinos.



Experimental setup

Consider the SHiP as an example,

400 GeV proton beam from the CERN SPS incident on a fixed target.



$B^{\pm}, B_s, B_0, D^{\pm},$
D_s, D_0

from [1511.07436](https://arxiv.org/abs/1511.07436), H. Dreiner, J. de Vries

Ingredients to analyze the experiment sensitivity

- The number of neutrinos produced:

$$N_N^{\mathrm{prod}} = N_{M_{jk}^{\pm}} \cdot \mathrm{Br}(M_{jk}^{\pm} \to N \ )$$

Large production cross sections

- The number of neutrinos detected:

$$\begin{aligned} N_N^{\mathrm{dec}} &= N_N^{\mathrm{prod}} \cdot \langle P[N \text{ in f.v.}] \rangle \cdot \mathrm{Br}(N \to \text{signal}), \\ \langle P[N \text{ in f.v.}] \rangle &= \frac{1}{N_N^{\mathrm{MC}}} \sum_{i=1}^{N_N^{\mathrm{MC}}} P[N_i \text{ in f.v.}], \end{aligned}$$

To get these two numbers, of course, we need the half-life time of heavy mesons (known) and sterile neutrinos (unknown).

The decay of sterile neutrino

1. **N → leptons (minimal scenario only)**
2. **N→ P/V +e,**

   P: π, K, D and D_s. **V: ρ, D^*, D_s^*, K^***

3. **N→ P^0/V^0 +ν_e (minimal scenario only)**

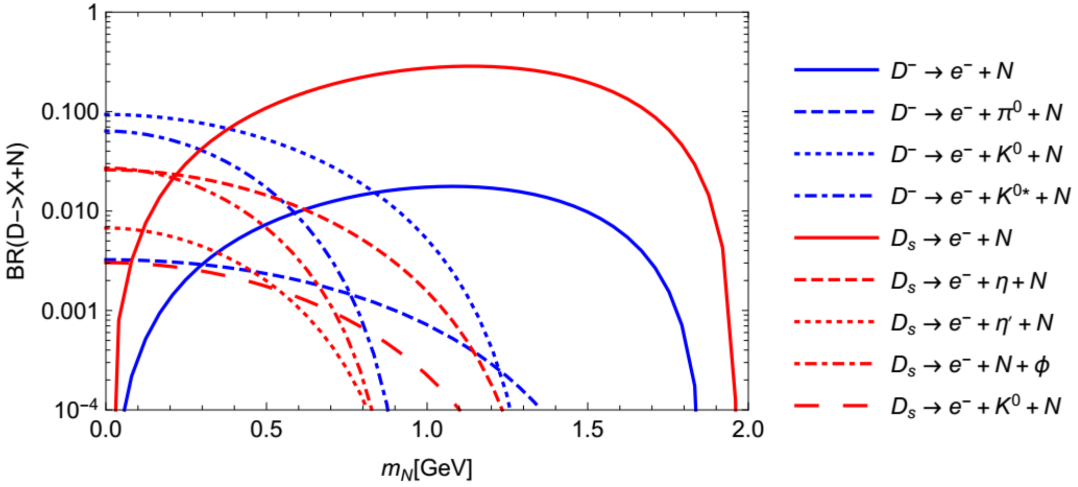
   P^0: π^0, η, η’, η^c. **V^0 : ρ^0, ω, ϕ, J/ψ**

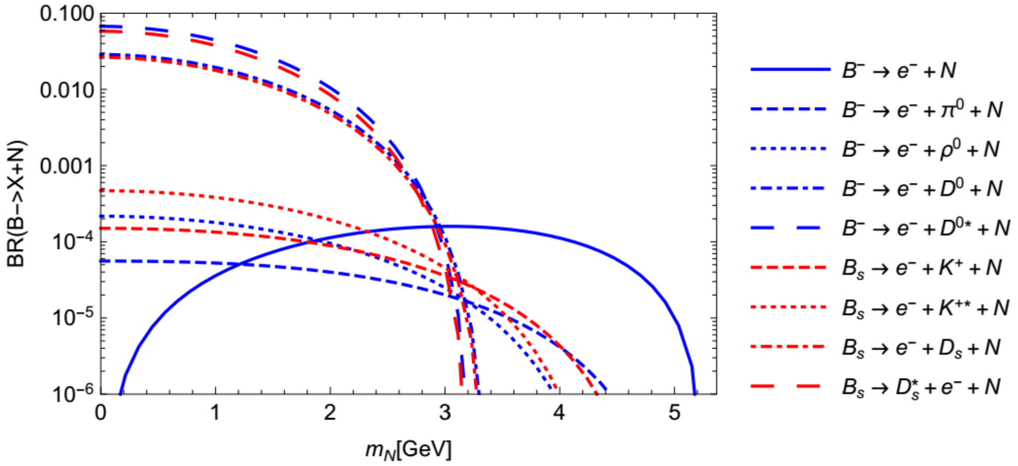
4. **N→ 2 and more mesons**

mixing : N to quarks, **EFT: only N to one meson**

$$1+\Delta_{QCD}(m_N)\equiv\frac{\Gamma(N\to e^-/\nu_e+\text{hadrons})}{\Gamma_{\text{tree}}(N\to e^-/\nu_e+\bar{q}q)}\,,\qquad \Delta_{QCD}=\frac{\alpha_s}{\pi}+5.2\frac{\alpha_s^2}{\pi^2}+\dots\,,$$

The branching ratios for the production of sterile neutrino in the minimal scenario



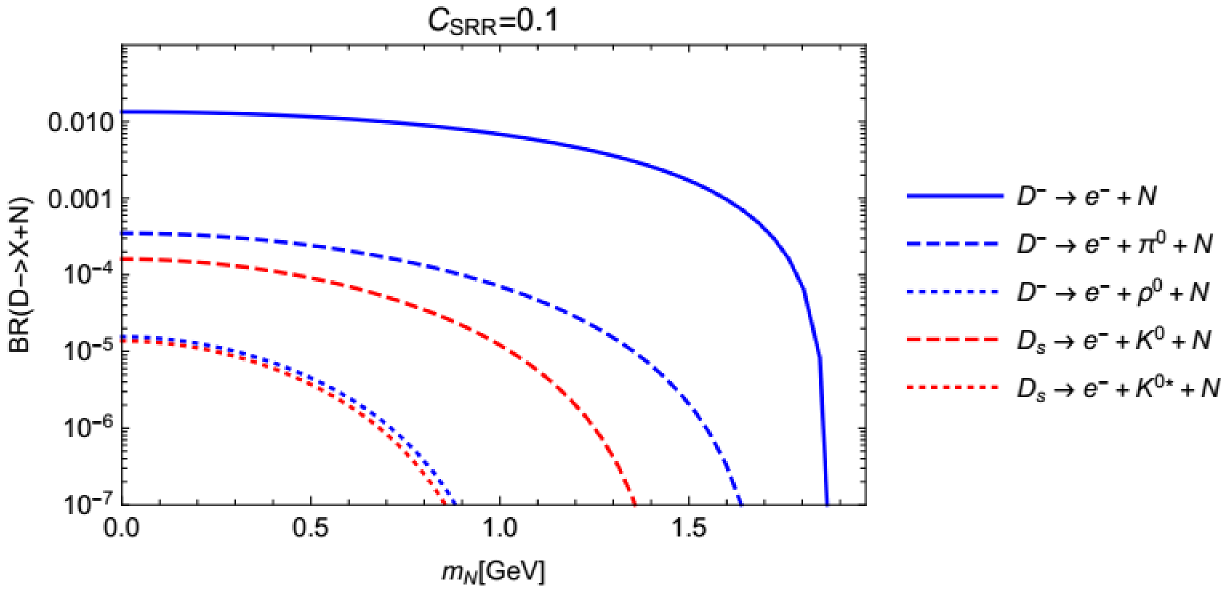


3-body decay plays an important role!

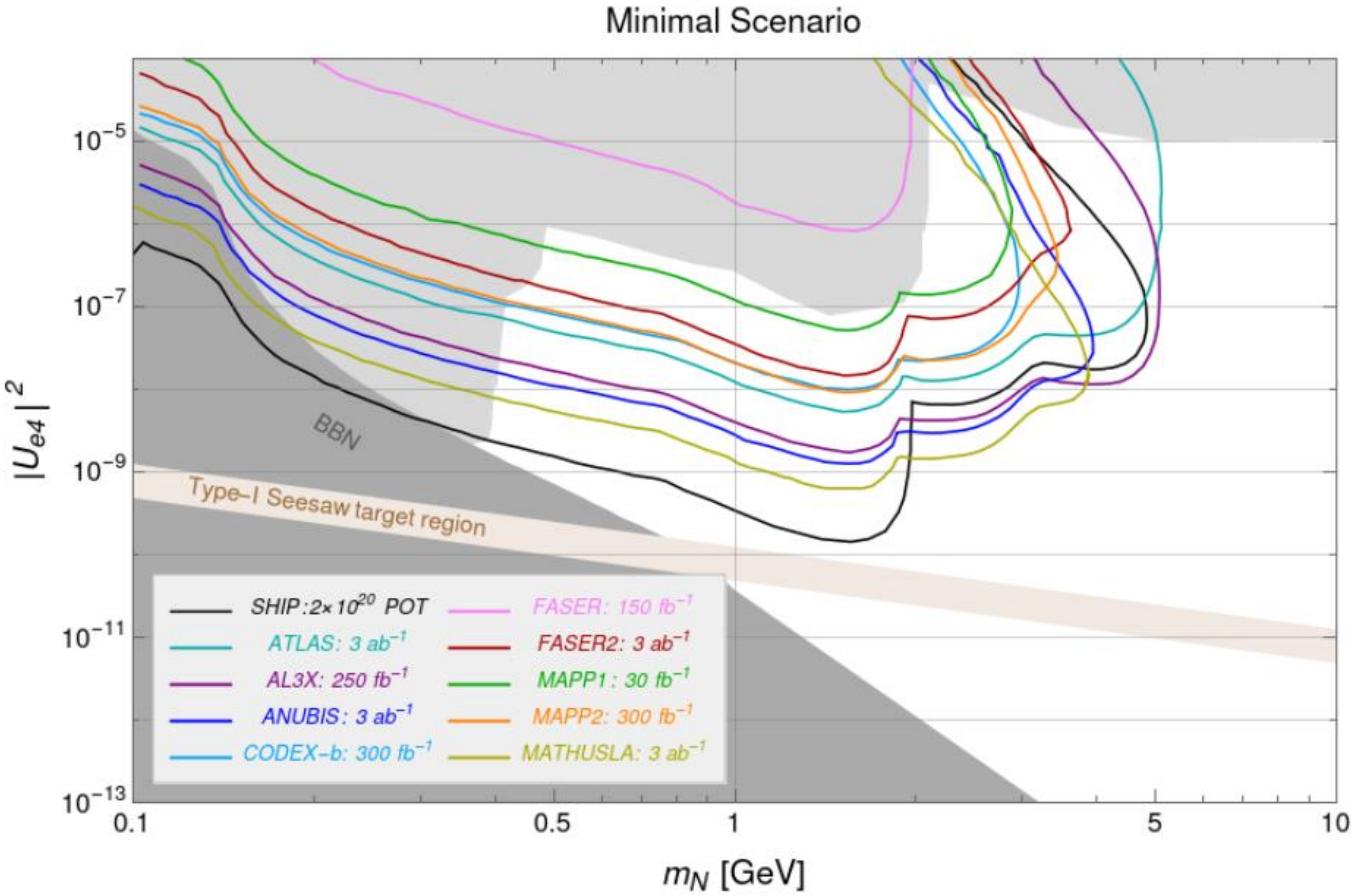
We consider only one sterile neutrino which mixes only with electron neutrino, $U_{e4} = 1$

The branching ratios in the presence of higher dimensional operators

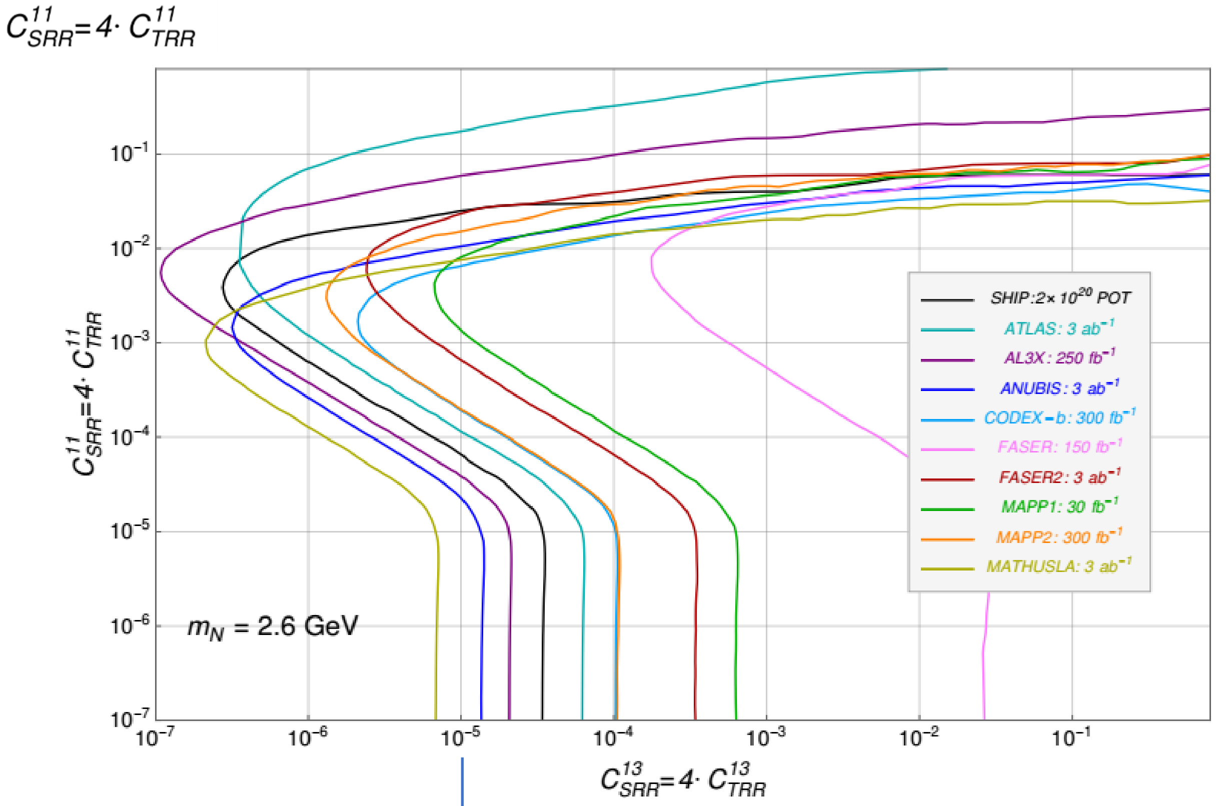
- Let us consider $(C^{(6)}_{SRR})_{21} = 0.1$



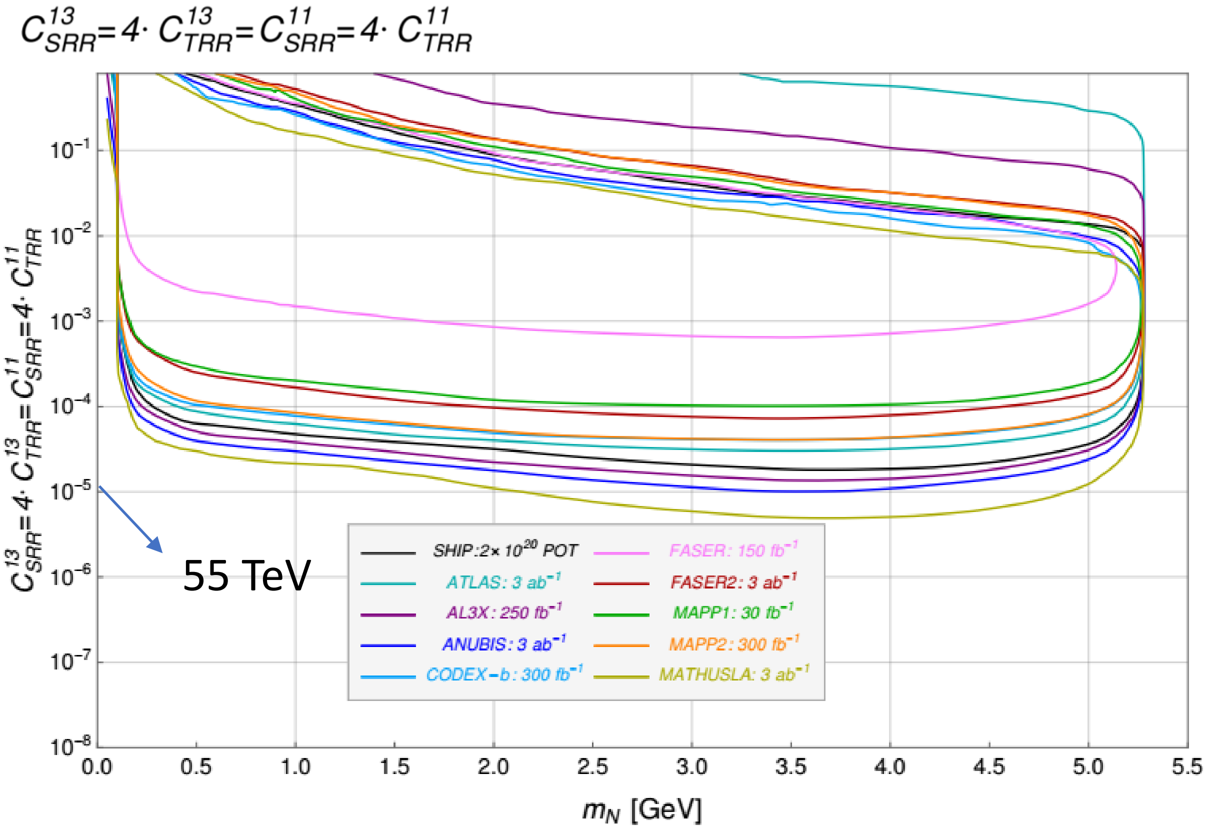
Results in the minimal scenario



Results in the leptoquark scenario



55 TeV



55 TeV

Minimal scenario is also included and
the mass of active neutrino is 0.05 eV

Conclusion

- We evaluate the sensitivity reach of ATLAS, AL3X, ANUBIS, CODEX-b, FASER, MATHUSLA, MoEDAL-MAPP, and SHiP
- Searches for displaced vertices of long-lived sterile neutrinos are a good probe of νSMEFT
- SHiP and MATHUSLA could probe scales around 80 TeV

THANK YOU!

Appendix

$$
\begin{aligned}
\mathcal{L}_{\text{mass}}^{(6,7)} \;=\; & \frac{2G_F}{\sqrt{2}}\Bigg\{\bar{u}_L\gamma^{\mu}d_L\left[\bar{e}_L\gamma_{\mu}C_{\text{VLL}}^{(6)}\,\nu+\bar{e}_R\gamma_{\mu}C_{\text{VLR}}^{(6)}\,\nu\right]+\bar{u}_R\gamma^{\mu}d_R\,\bar{e}_R\,\gamma_{\mu}C_{\text{VRR}}^{(6)}\,\nu \\
& \bar{u}_Ld_R\,\bar{e}_L\,C_{\text{SRR}}^{(6)}\nu+\bar{u}_Rd_L\,\bar{e}_L\,C_{\text{SLR}}^{(6)}\nu+\bar{u}_L\sigma^{\mu\nu}d_R\,\bar{e}_L\sigma_{\mu\nu}C_{\text{TRR}}^{(6)}\nu \\
& +\frac{1}{v}\bar{u}_L\gamma^{\mu}d_L\,\bar{e}_L\,C_{\text{VLR}}^{(7)}\,i\overleftrightarrow{D}_{\mu}\nu\Bigg\}+\text{h.c.}
\end{aligned}
$$