Sterile Neutrinos at the LHC in Effective Field Theory

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arXiv: 2010.07305,

with J. de Vries, H. Dreiner, J. Günther, Z. Wang

Outline

- Sterile neutrinos and effective filed theory
- Displaced vertices search at the LHC
- Numerical results
- Conclusion

Sterile Neutrinos in Effective Field Theory

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

- Explain the neutrino oscillation, dark matter and the asymmetry between matter and antimatter.
- Model independent

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

Dimension-6 operators with one sterile neutrino

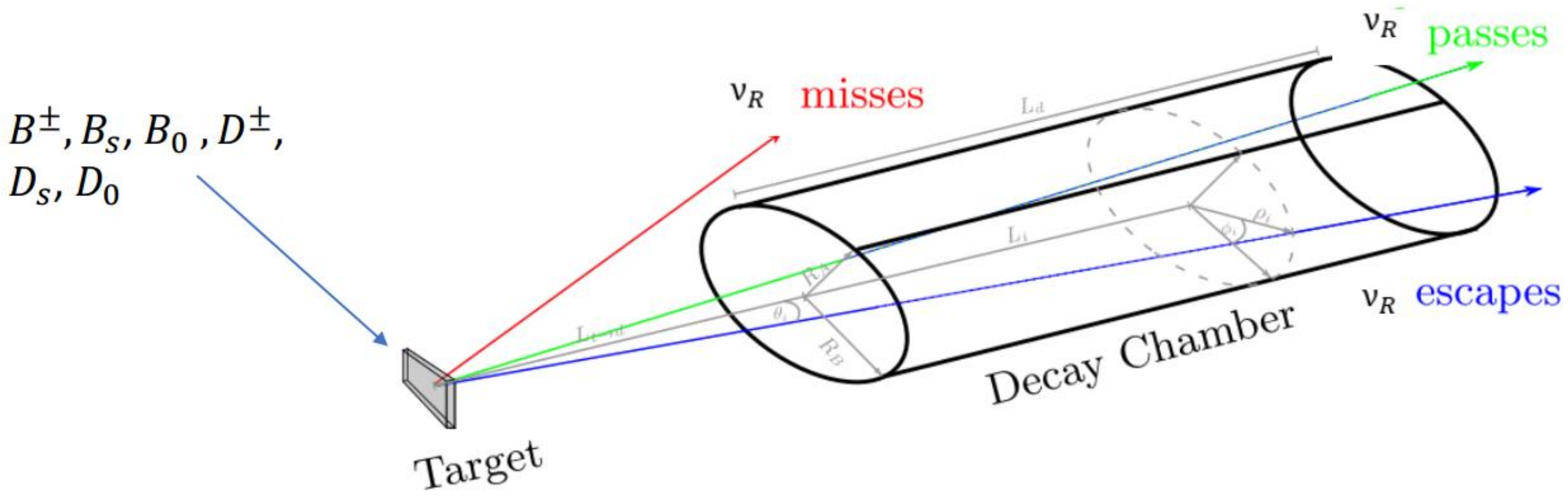
After EWSB and rotating to the neutrino mass basis,

$$\mathcal{L}_{\rm mass}^{(6,7)} = \frac{2G_F}{\sqrt{2}}\Bigg\{\bar{u}_L\gamma^\mu d_L\left[\bar{e}_L\gamma_\mu C_{\rm VLL}^{(6)}\,\nu + \bar{e}_R\gamma_\mu C_{\rm VLR}^{(6)}\,\nu\right] + \bar{u}_R\gamma^\mu d_R\,\bar{e}_R\,\gamma_\mu C_{\rm VRR}^{(6)}\,\nu$$

$$\bar{u}_L d_R\,\bar{e}_L\,C_{\rm SRR}^{(6)}\nu + \bar{u}_R d_L\,\bar{e}_L\,C_{\rm SLR}^{(6)}\nu + \bar{u}_L\sigma^{\mu\nu}d_R\,\bar{e}_L\sigma_{\mu\nu}C_{\rm TRR}^{(6)}\nu$$

$$+\frac{1}{v}\bar{u}_L\gamma^\mu d_L\,\bar{e}_L\,C_{\rm VLR}^{(7)}\,i\overleftrightarrow{D}_\mu\nu\Bigg\} + \text{h.c.}\,,$$

Displaced search for sterile neutrino at the LHC



from 1511.07436, H. Dreiner, J. de Vries

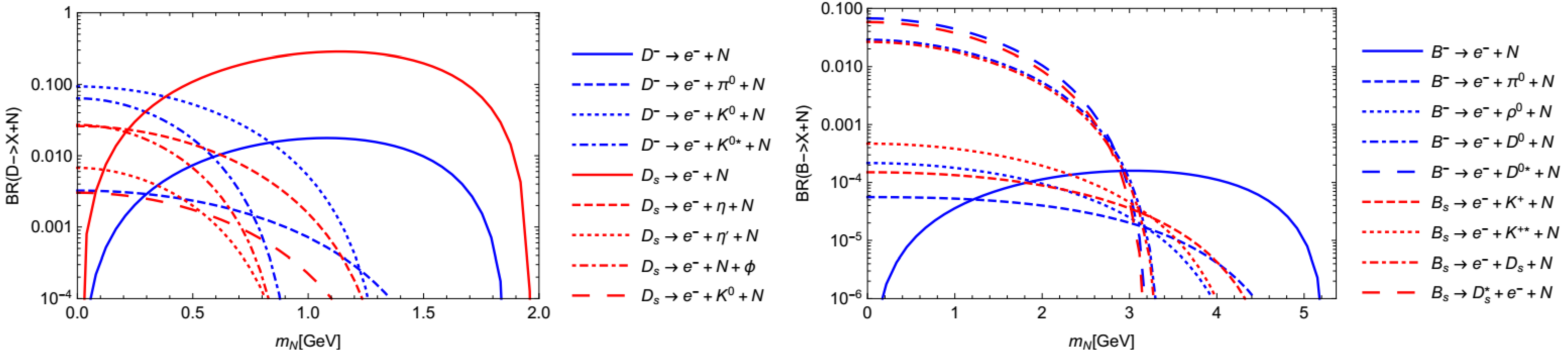
Production of the sterile neutrino:

(1). *D* and *B* pseudoscalar mesons decay, including leptonic and semi-leptonic decays.

(2). Direct production with parton collisions, sub-dominant when neutrino is lighter than B meson.

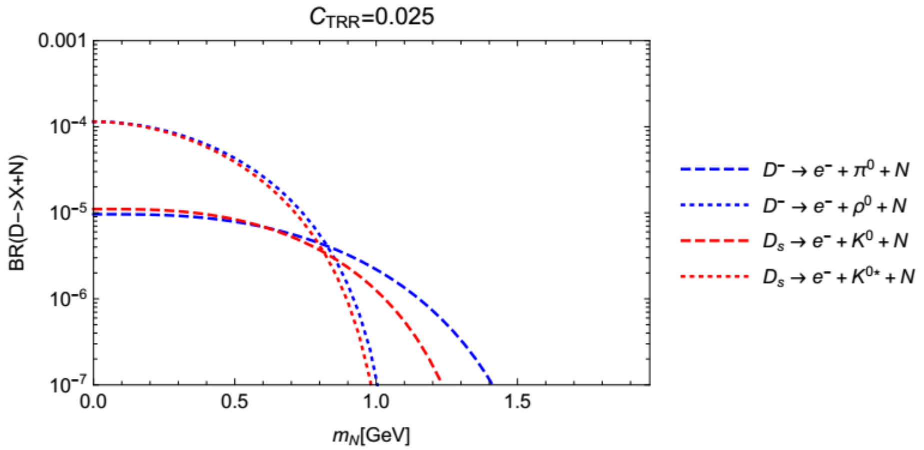
Production in the minimal model

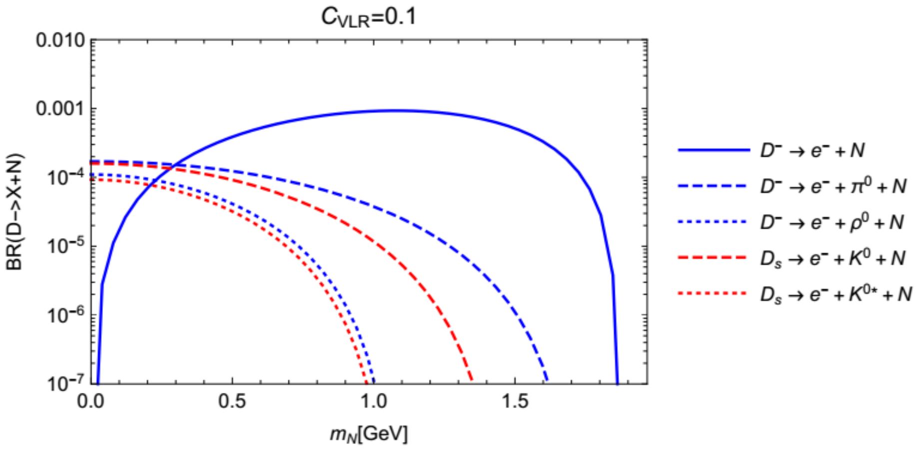
- Only one sterile neutrino
- interact with SM fields via the mixing
- The mixing angle is set to be $U_{e4} = 1$



Production from dimension-6 operators only

{ijkl}=21e4





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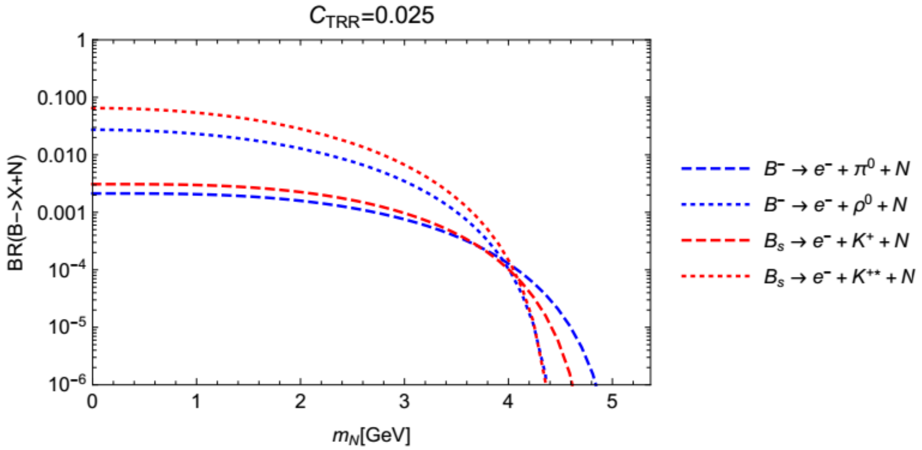
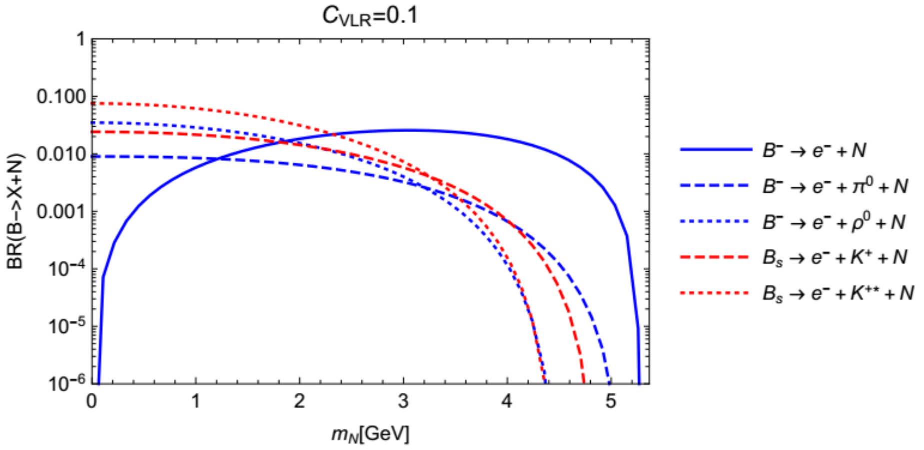




The decay of sterile neutrino

1. N $\rightarrow$ leptons (minimal scenario only)
2. N$\rightarrow$ P/V +e,

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

3. N$\rightarrow$ 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

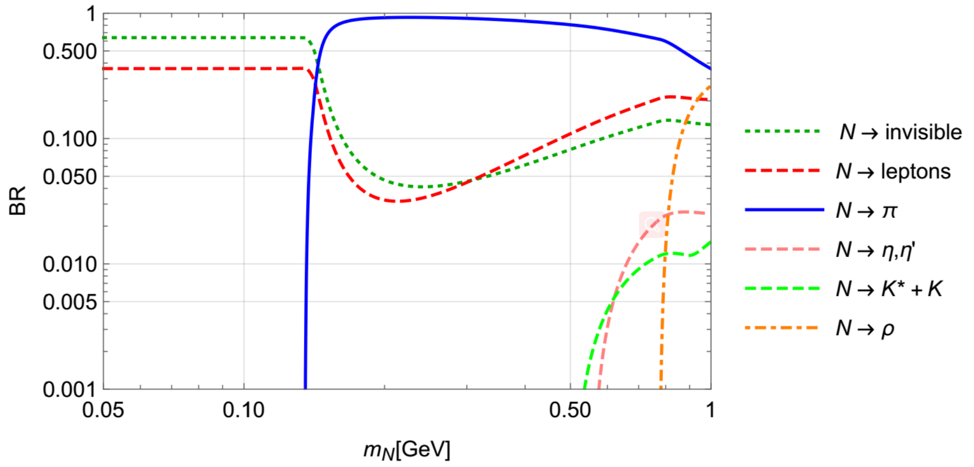
4. N$\rightarrow$ 2 and more mesons

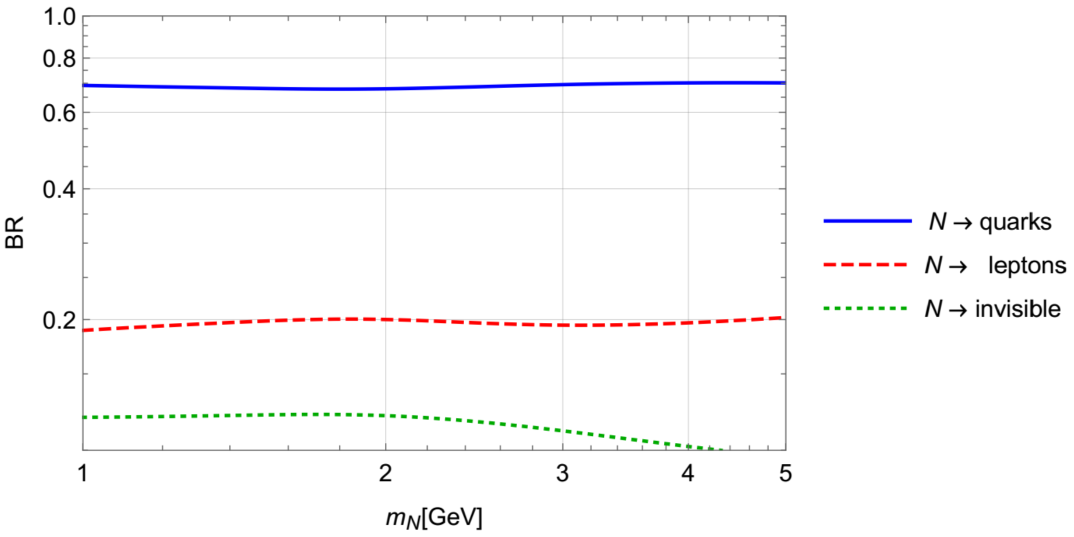
mixing : N to quarks,   EFT: only N to one meson

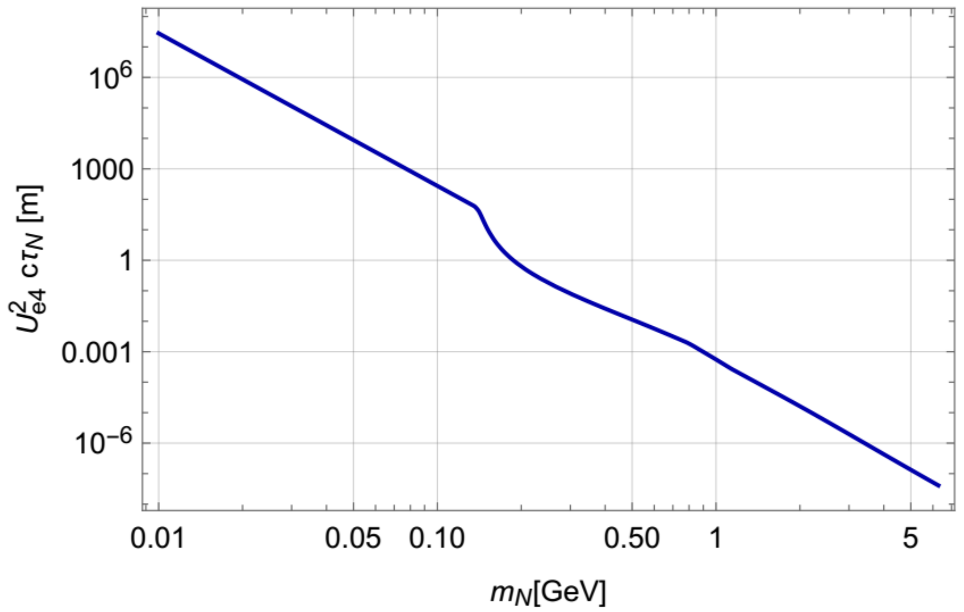
$$1+\Delta_{QCD}(m_N) \equiv \frac{\Gamma(N\to e^-/\nu_e+\text{hadrons})}{\Gamma_{\text{tree}}(N\to e^-/\nu_e+\bar{q}q)}, \qquad \Delta_{QCD}=\frac{\alpha_s}{\pi}+5.2\frac{\alpha_s^2}{\pi^2}+\dots,$$

Decay in the minimal model

- Sterile neutrinos decay only through the mixing with ν_e.

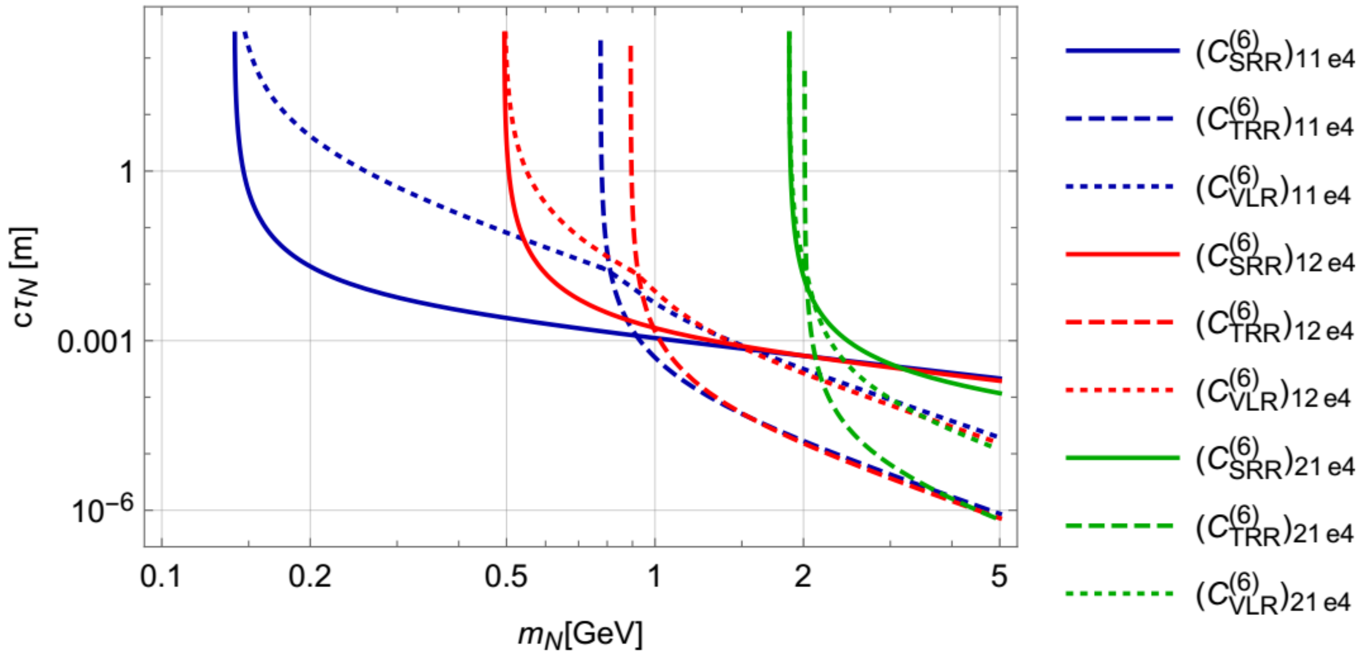






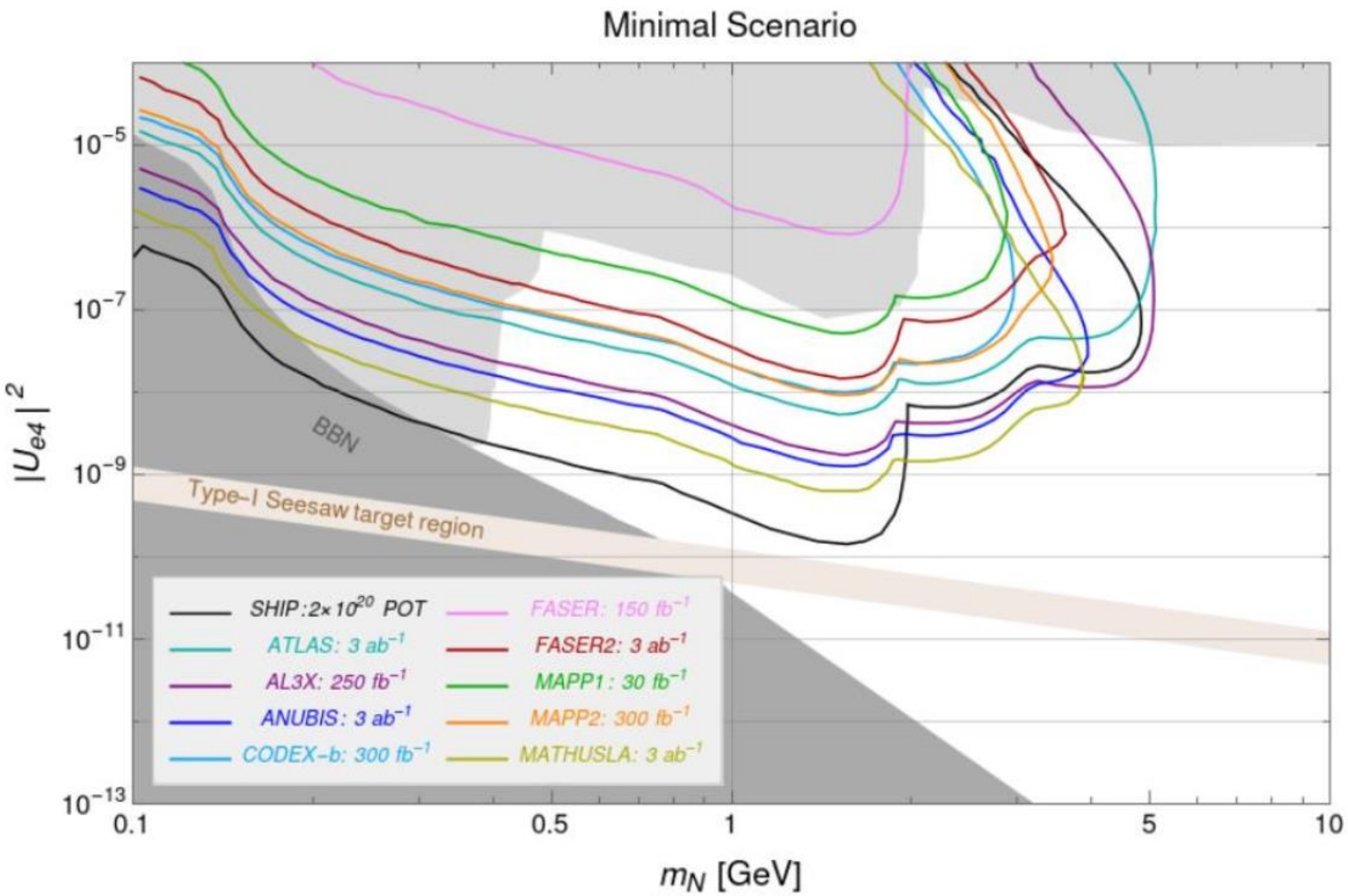
Decay from dimension-6 operators only

- Turn off the weak interaction
- Turn on only one unit WC at a time
- Each operator can only induce one or two decay channels, N to one meson plus an electron



Results in the minimal scenario

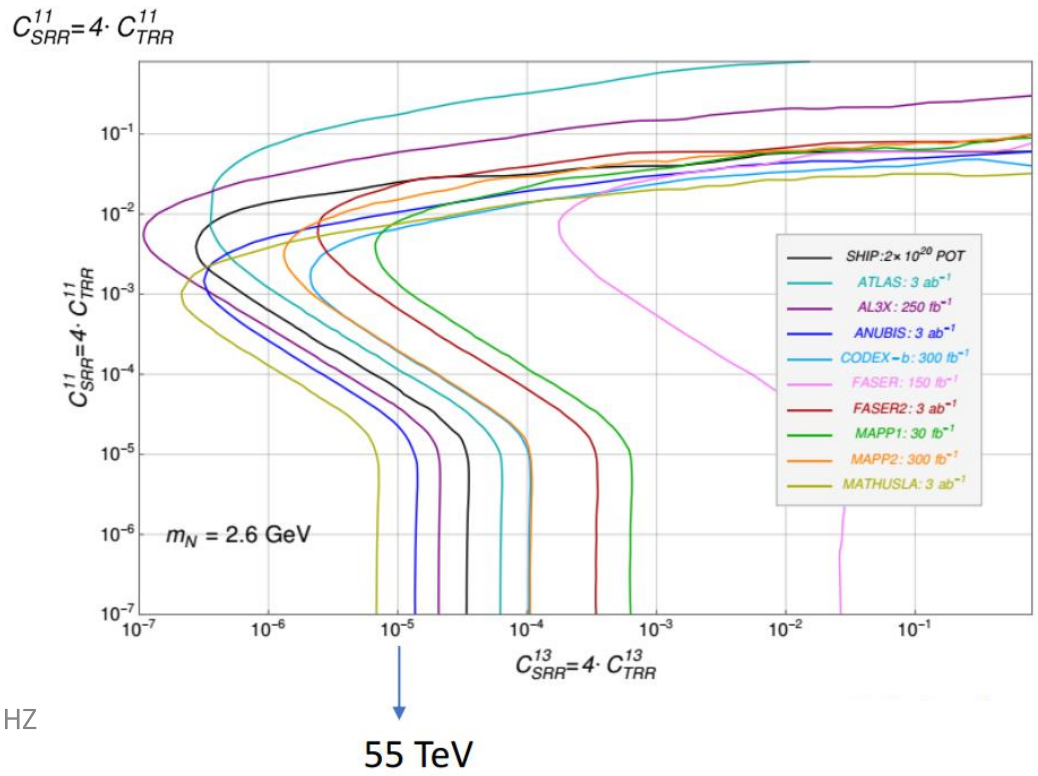
- Switch off higher-dimensional operators
- Consider only one sterile neutrino mixed with ν_e only

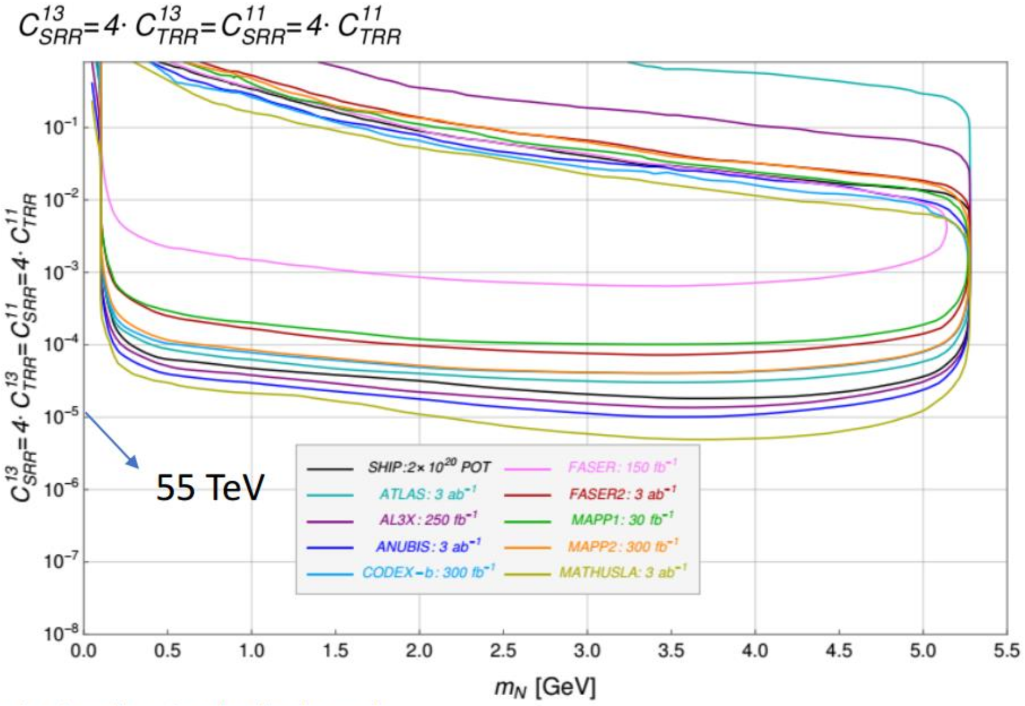


See also: 2001.04750
Hirsch, Wang

Results in the leptoquark scenario

- It induces two d-6 operators with $C_{SRR} = 4C_{TRR}$
- Minimal scenario is also included
- The mass of electron 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 can probe scales around 80 TeV, ANUBIS: 55 TeV, FASER2: 25 TeV.
- Our results are competitive with and complementary to the existing limits

Appendix

$$\langle 0|\bar{q}_i\gamma^\mu\gamma^5 q_j|M(q)\rangle \equiv iq^\mu f_M \,,$$

$$\langle M'_P(p')|\bar{q}_1\gamma^\mu q_2|M_P(p)\rangle = f_+(q^2)\left[(p+p')^\mu - \frac{M^2-m^2}{q^2}q^\mu\right] + f_0(q^2)\frac{M^2-m^2}{q^2}q^\mu \,,$$

$$\langle M'_P(p')|\bar{q}_1 q_2|M_P(p)\rangle = f_S(q^2)\,,$$

$$\langle M'_P(p')|\bar{q}_1\sigma^{\mu\nu} q_2|M_P(p)\rangle = \frac{2i}{M+m}[p^\mu p'^\nu - p^\nu p'^\mu]f_T(q^2)\,,$$