Unravelling neutrino mass and dark matter in the radiative seesaw model with gauged $\mathrm{U}(1)_{B-L} \times \mathbb{Z}_2$ extension [arXiv:2410.22835]

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Introdution and Motivation

- ✓ Completion of the Standard model
- ▶ BSM phenomena: neutrino mass, dark matter, baryogeneis
- ▶ The radiative seesaw model with gauged $\mathrm{U}(1)_{B-L} \times \mathbb{Z}_2$ extension [1]

$$\Downarrow$$

Consistent predictions of neutrino masses and the abundance of dark matter

- ■ Revisiting this model with the latest constraints from dark matter searches, neutrino oscillations, flavor experiments and collider experiments.
- ■ Exploring the possibility of baryogeneis in this model.

Radiative seesaw model with gauged $\mathrm{U}(1)_{B-L} \times \mathbb{Z}_2$ extension

- ▶ **Lagrangian**

$$\mathcal{L}_N = \sum_{\alpha=1}^{3}\left(-\sum_{i=1}^{3} g_{i\alpha}\overline{L_i}\tilde{\eta}N_\alpha - \frac{y_\alpha^R}{2}\overline{N_\alpha^c}SN_\alpha + \mathrm{h.c.}\right),$$

$$V(\Phi,\eta,S) = \mu_1^2|\Phi|^2 + \mu_2^2|\eta|^2 + \mu_S^2|S|^2 + \frac{\lambda_1}{2}|\Phi|^4 + \frac{\lambda_2}{2}|\eta|^4 + \lambda_S|S|^4$$
$$+ \lambda_3|\Phi|^2|\eta|^2 + \lambda_4\left|\Phi^\dagger\eta\right|^2 + \frac{\lambda_5}{2}\left[(\Phi^\dagger\eta)^2 + \mathrm{h.c.}\right] + \tilde{\lambda}|\Phi|^2|S|^2 + \lambda|\eta|^2|S|^2,$$

- ▶ **Higgs mixing**

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \phi \\ \phi_S \end{pmatrix},$$

- ▶ **Mass spectrum**

$$m_{N_\alpha} = \frac{y_\alpha^R v_S}{\sqrt{2}},\ m_{Z'} = 2g_{B-L}v_S,$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{\lambda}{2}v_S^2 + \frac{\lambda_3}{2}v^2,$$
$$m_H^2 = \mu_2^2 + \frac{\lambda}{2}v_S^2 + \frac{\lambda_3+\lambda_4+\lambda_5}{2}v^2,$$
$$m_A^2 = \mu_2^2 + \frac{\lambda}{2}v_S^2 + \frac{\lambda_3+\lambda_4-\lambda_5}{2}v^2.$$

Neutrino masses

- ▶ Tiny neutrino masses are generated via the one-loop induced operator $S\overline{(L\Phi)^c}L\Phi/\Lambda^2$

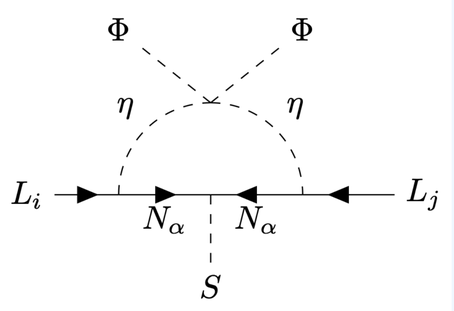

FIG. 1. The one-loop diagram which generates small neutrino masses.

Dark matter abundance

- ▶ N_1 can annihilate via $N_1N_1 \to h_1, h_2, Z' \to f\bar{f}, ZZ, W^+W^-, h_1(h_2)h_1(h_2)$ processes

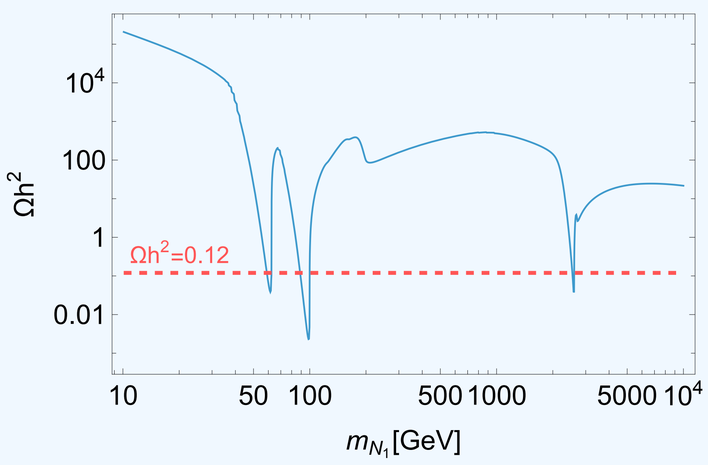

FIG. 2. Relic abundance of N_1 as a function of m_{N_1}. The red dashed line is the current bound of DM relic abundance from the Planck experiment.

- ▶ Annihilations of RH neutrinos to the SM particles are enhanced resonantly via s-channel exchange of h_1, h_2 and Z' [2].

Reference: [1] Kanemura, Seto, Shimomura, 2011. [2] Okada, Seto, 2010.
[3] Borah, et al, 2018. [4] Carena, et al, 2004. [5] Toma, Vicente, 2014.

Allowed parameter space

- ▶ Benchmark parameters for h_2 resonance scenario

$$m_{N_1} = \frac{m_{h_2}}{2} - 0.1\ \mathrm{GeV},\ \lambda = 10^{-6},\ \lambda_3 = 0.1,\ \lambda_5 = -10^{-5},$$
$$m_{N_2} = 2500\ \mathrm{GeV},\ m_{N_3} = 3000\ \mathrm{GeV},\ m_{Z'} = 5.2\ \mathrm{TeV},\ m_{h_2} = 200\ \mathrm{GeV},$$
$$m_H = 300\ \mathrm{GeV},\ m_{H^\pm} = m_A,\ m_{H^\pm} = \sqrt{m_H^2 - \lambda_5 v^2}.$$

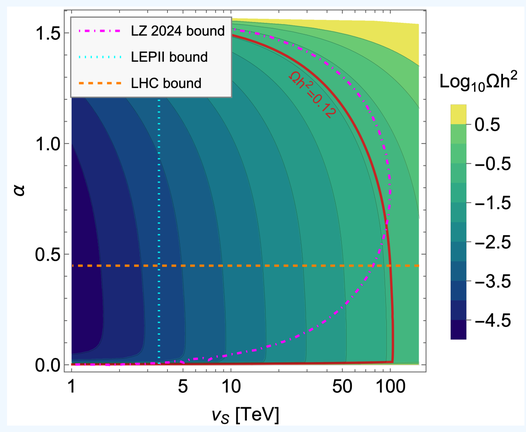

FIG. 3. Parameter space with constraints from LEPII, ATLAS, CMS and LZ 2024 experiments. The red line is the bound from the Planck experiment.

- ▶ There is still allowed region for this model under the latest experimental constraints.
- ■ For Z' resonance, the relic abundance is almost a constant due to the only dependence on $m_{Z'}$.

Parameter scan

- ▶ Exploring the allowed mass region of N_1 with h_2 resonance scenario

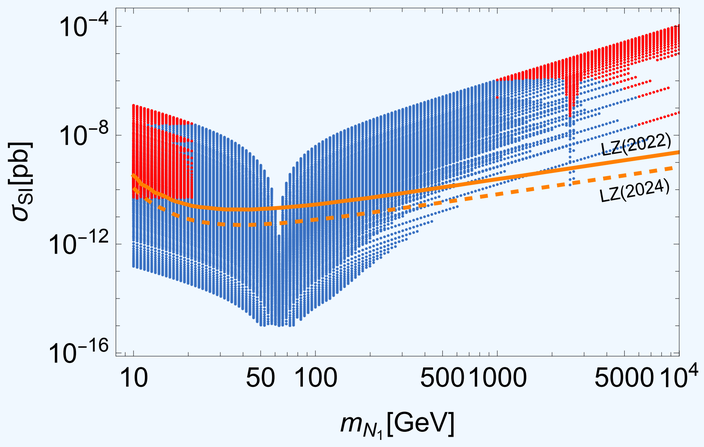

FIG. 4. Possible SI cross section of N_1 as a function of m_{N_1} in our parameter space. Red points are excluded by theoretical constraints. The orange line is the upper bound from the LZ 2022 results. The dashed orange line is the upper bound from the LZ 2024 results.

- ▶ In the mass region near $m_{N_1} \simeq m_{h_1}/2$, the SI cross section greatly reduces due to the destructive interference of the two Higgs states.
- ▶ Direct detection experiments give the most stringent constraints, providing the upper bounds on the mass of N_1.

Resonant leptogenesis(Work in progress)

- ■ $g_{i1} = 0 \Rightarrow$ No washout effects from N_1.
- ▶ Decays of N_2 and N_3 exhibit CP asymmetries $\Rightarrow$ Lepton number asymmetry

Benchmark parameters:

$$m_{N_2} = 3\ \mathrm{TeV}, m_{N_3} = 3 + 7\times10^{-6}\ \mathrm{TeV}, \lambda_3 = 0.1, \lambda = 10^{-6},$$
$$v_S = 30\ \mathrm{TeV},\ m_H = 300\ \mathrm{GeV}, m_A = 323\ \mathrm{GeV}, m_{H^\pm} = 323\ \mathrm{GeV}$$

The baryon asymmetry is

$$\eta_B = 6.20\times10^{-10}.$$

It is possible for this model to realize leptogenesis, and explain neutrino mass and dark matter simultaneously.

Discussions

- ▶ $pp \to H^+H^- \to N_1N_1l^+l^-$ processes are important signals in hadron colliders. LHC can produce $\mathcal{O}(10^3)$ signals, and HL-HLC can produce $\mathcal{O}(10^4)$ signals [3].
- ▶ Search for Z' boson: The branching ratios of $Z' \to q\bar{q}, l^+l^-, \nu_L\bar{\nu}_L, N_1N_1, h_1h_1, h_1h_2$ and h_2h_2 for our benchmark parameters are given by 0.20, 0.29, 0.15, 0.15, 6.9×10^{-4}, 0.044, 0.17 [4].
- ▶ LFV constraints: LFV processes can provide a lower bound on m_{N_1} depending on the chosen benchmark scenario [5].