Minimal type-II seesaw model with alternative $U(1)_X$ and cosmology

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§ Introduction

Nonvanishing neutrino mass

- Neutrino oscillation

  tiny (< 0.1 eV) but massive neutrino

- **Seesaw mechanism** for Majorana neutrino

[Minkowski (1977), Yanagida, Gell-Mann et al (1979)]

$$\begin{pmatrix} 0 & yv \\ yv & M_N \end{pmatrix} \quad \rightarrow \quad \begin{pmatrix} -(yv)^2/M_N & 0 \\ 0 & M_N \end{pmatrix}$$

- Majorana M_N mass might come from the breaking of the gauged B-L symmetry. [Davidson (1979), Mohapatra and Marshak (1980), …]

Anomaly cancellation for gauged B-L

- Two choices of RH neutrino charges

Field	standard	alternative
$\nu_R^1, \nu_R^2, \nu_R^3$	-1,-1,-1	-4,-4,+5

- Once the charges are set to be anomaly free under $U(1)_Y$ and $U(1)_{B-L}$, it is so under a linear combination $X = x_H Y + (B - L)$ too.
  - Convenient parametrization
  - $x_H = 0, U(1)_{B-L}$
  - $x_H = -2, U(1)_R$ [Jung et al (2010)]

Anomaly cancellation for gauged B-L

- Two choices of RH neutrino charges

Field	standard	alternative
$\nu_R^1, \nu_R^2, \nu_R^3$	-1,-1,-1	-4,-4,+5

- The standard is standard.
- For the alternative, Type-I seesaw and Majorana mass is not easy [Ma and Srivastava, Sanchez-Vega and Schmitz (2015), …, Asai, Nakayama and Tseng (2021)]
- How about Type-II?
- Type-II by triplet Higgs [Schechter and Valle, Magg and Wetterich, Cheng and Li (1980)]

§ Model

- Alternative charge of $U(1)_X$
- Type-II

§§ Particle content

- The anomaly cancellation fixes fermions
- Triplet Δ for neutrino mass
- Φ_1 for the tadpole of Δ
  - ➢ No Yukawa
- Φ_X
  - ➢ $U(1)$ breaking
  - ➢ Mass of ν_R
  - ➢ Mass of NG (CP odd Higgs)
- $\nu_R^i \nu_R^3$: stable, dark matter

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{1}{6}x_H + \frac{1}{3}$
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{2}{3}x_H + \frac{1}{3}$
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$-\frac{1}{3}x_H + \frac{1}{3}$
l_L^i	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$-\frac{1}{2}x_H - 1$
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	$-x_H - 1$
ν_R^1	$\mathbf{1}$	$\mathbf{1}$	0	-4
ν_R^2	$\mathbf{1}$	$\mathbf{1}$	0	-4
ν_R^3	$\mathbf{1}$	$\mathbf{1}$	0	5
Φ_1	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\frac{1}{2}x_H + 1$
Φ_2	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\frac{1}{2}x_H$
Δ_3	$\mathbf{1}$	$\mathbf{3}$	1	$x_H + 2$
Φ_X	$\mathbf{1}$	$\mathbf{1}$	0	1

§ § Interactions and masses

- $\mathcal{L} \supset -\frac{1}{\sqrt{2}} Y_\Delta^{ij} \overline{l_L^{i\,C}} \cdot \Delta\, l_L^j - \sum_{i=1,2} Y_{\nu_R^i}\, \Phi_X^\dagger \overline{\nu_R^{3\,C}}\, \nu_R^i$
  $+\mathrm{H.c.}$
- LH Neutrino mass

$$(m_\nu)_{ij} = Y_\Delta^{ij} v_\Delta$$

§ § Interactions and masses

- RH Neutrino mass

$$\mathcal{L} \supset -\left(\nu_R^{1\dagger}, \nu_R^{2\dagger}, \nu_R^{3T}\right) \begin{pmatrix} 0 & 0 & Y_{\nu_R^1} \\ 0 & 0 & Y_{\nu_R^2} \\ Y_{\nu_R^1} & Y_{\nu_R^2} & 0 \end{pmatrix} \frac{v_X}{\sqrt{2}} \begin{pmatrix} \nu_R^1 \\ \nu_R^2 \\ \nu_R^{3*} \end{pmatrix}$$

  - One massless ν_R : Dark radiation
  - Two compose one Dirac χ : Dark matter candidate

$$m_\chi = \sqrt{\frac{Y_{\nu_R^1}^2 + Y_{\nu_R^2}^2}{2}}\, v_X$$

§ § Interactions and masses

- One singlet, two doublet, one triplet

$$\Phi_1^\dagger \Phi_2, \left(\Phi_1^\dagger \Phi_2\right)^2 \notin V$$

- $V \supset \lambda_{12} \Phi_X \left(\Phi_1^\dagger \Phi_2\right) - \frac{\Lambda_6}{\sqrt{2}} \left(\Phi_1^T \cdot \Delta_3 \Phi_1\right) + \mathrm{H.c.}$

pseudo-scalar mass

$$v_\Delta \cong \frac{v_1^2 \Lambda_6}{2\mu_3^2} \propto v_1^2$$

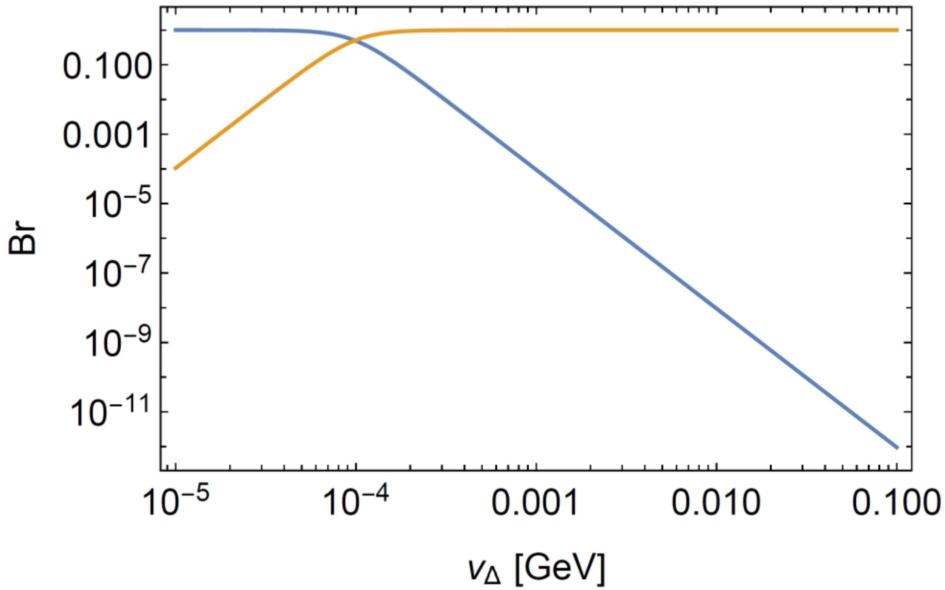
Small neutrino mass due to the small Higgs VEV

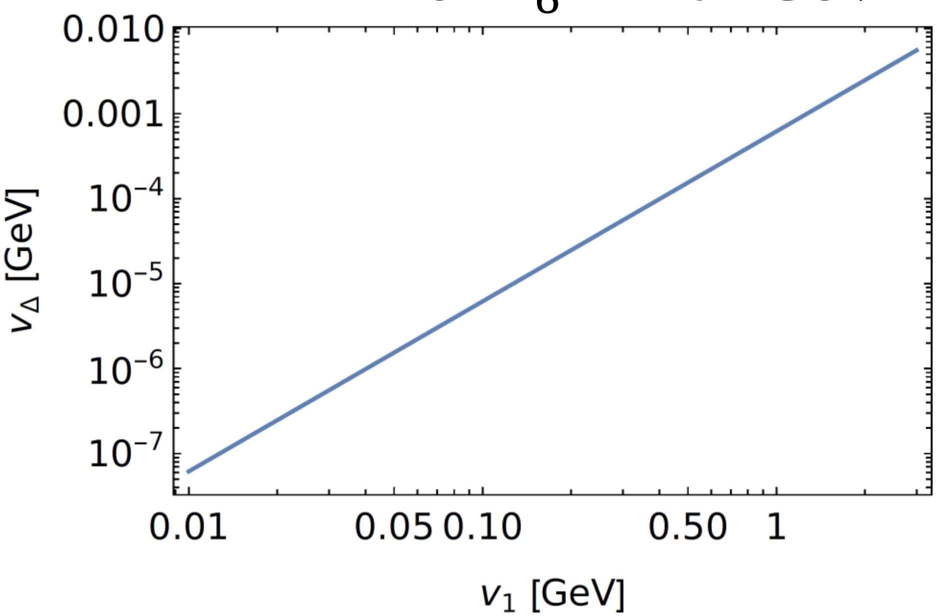
Philosophy of neutrinophilic Higgs model

§ § Implication

- $H^{\pm\pm}$ decay
  - $H^{\pm\pm} \to W^{\pm}W^{\pm}$
  - $H^{\pm\pm} \to l^{\pm}l^{\pm}$
- Very small v_Δ from slightly small v_1

For $\Lambda_6 = 10^3$ GeV



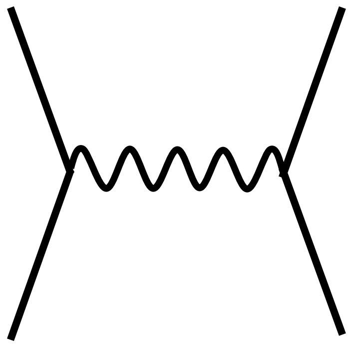


For $m_{H^{\pm\pm}} = 900$ GeV

§ § Cosmology

- Dark radiation
  - One massless
  - Interaction $f\bar{f} \leftrightarrow \nu_R \nu_R$ through $U(1)_X$

    [Heeck (2014), Fileviez Perez, Murgui and Plascencia (2019)]
- Dark matter
  - Stable due to charge mismatch, not a parity
  - $U(1)_X$ interacting Dirac fermion
  - Abundance : Z' resonance annihilation
  - Direct search bounds : SI from the vector interaction via Z'



§ § Experimental constraints

- ρ parameter
- The Z boson decay width [Kanemura et al (2013)]
- LFV [Chun et al, Kakizaki et al (2003), Akeroyd et al (2009)]
- $H^{\pm\pm}$ search at the LHC [ATLAS (2018, 2021)]
- X boson search at the LHC
  - $pp \to X \to l\bar{l}$, $pp \to X \to jj$
  - The most severe bound from dilepton $l\bar{l}$ $(l = e, \mu)$
- DM abundance and direct search bound
- DR abundance ($N_{\rm eff}$)

§ § Results

- LHC
- N_{eff}
  - 3.5 solid

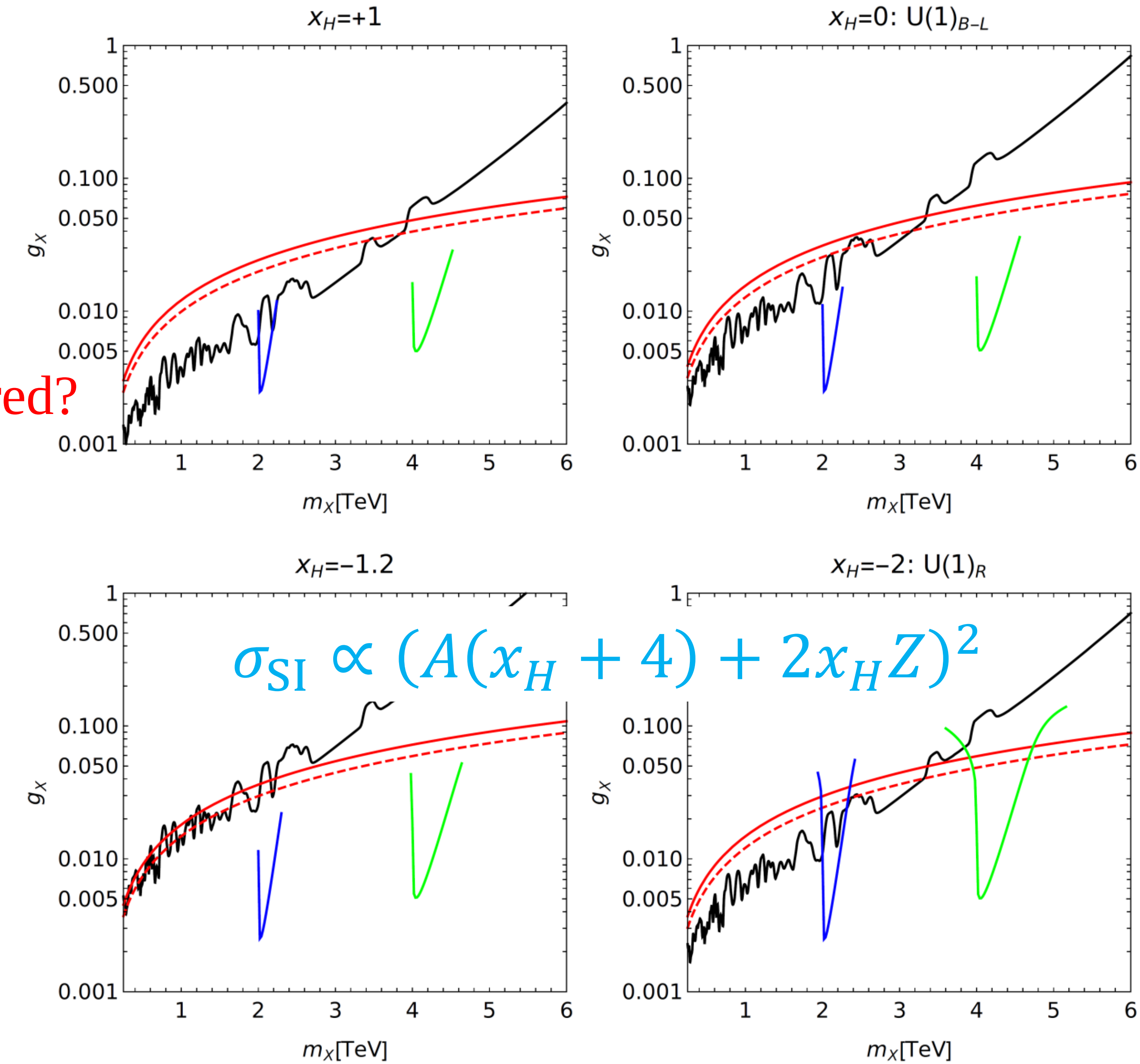
Hubble tension favoured?

  - 3.1 dashed

- DM($\Omega_\chi h^2$, XENON1T)

$m_\chi = 1$ TeV

$m_\chi = 2$ TeV



$\sigma_{\text{SI}} \propto (A(x_H + 4) + 2x_H Z)^2$

§ Summary

- Alternative B-L charge: possibility
  - Compatible with Type-II seesaw
  - Minimal Higgs sector
    - "Neutrinophilic"
    - Same sign di-lepton is likely
    - Anomaly cancellation requires DR and Dirac DM
    - WIMP DM without a parity by hand
- Constraints are derived for LHC, DR and DM

§ § Experimental constraints

- ρ parameter
  - $v_\Delta \lesssim 1$ GeV
- The Z boson decay width [Kanemura et al (2013)]
- $H^{\pm\pm}$ search at the LHC
  - $\gtrsim 880$ GeV for ll [ATLAS (2018)]
  - $\gtrsim 350$ GeV for WW [ATLAS (2021)]
- LFV [Chun et al, Kakizaki et al (2003), Akeroyd et al (2009)]
  - SINDRUM for $\mu \to eee$
  - MEG for $\mu \to e\gamma$
  - $v_\Delta \gtrsim 1$ eV

§ § Experimental constraints

- X boson search at the LHC
  - $pp \to X \to l\bar{l}$, $pp \to X \to jj$
  - The most severe bound from dilepton $l\bar{l}$ $(l = e, \mu)$
- Under the narrow width approximation, we calculate
  - $\sigma(pp \to X)\mathrm{Br}(X \to l\bar{l})$
  - $\mathrm{Br}\left(X \to l\bar{l}\right) = \frac{8+12x_H+5x_H^2}{F(x_H)}$
  - $F(x_H) = 13 + 16x_H + 10x_H^2$