Exploring new physics signatures in an Alternative Left-Right Model

New physics searches at the precision frontier
INT 23-1b,17th May, 2023

Based on : Phys.Rev.D 102, 075020 (2020), JHEP03(2022)065, JHEP12(2022)032

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Plan of the talk

- Motivation to Alternative Left-Right Model (ALRM)
- Neutrinoless doble beta decay in ALRM
- Leptogenesis in ALRM
- Vacuum Structure stability and Dark matter in ALRM
- Summary and conclusion

The Standard Model (SM) and beyond

- Theoretical predictions of the Standard Model match experimental searches with great accuracy.
- Gauge Structure : $\mathscr{G}_{\text{SM}} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$.
- There remains unresolved issues within the SM that cannot be adequately addressed :

(a) Origin of small neutrino masses

(b) Parity violation in low-energy weak interactions

(c) Baryon asymmetry of the universe (BAU)

(d) Dark matter and dark energy and so on…

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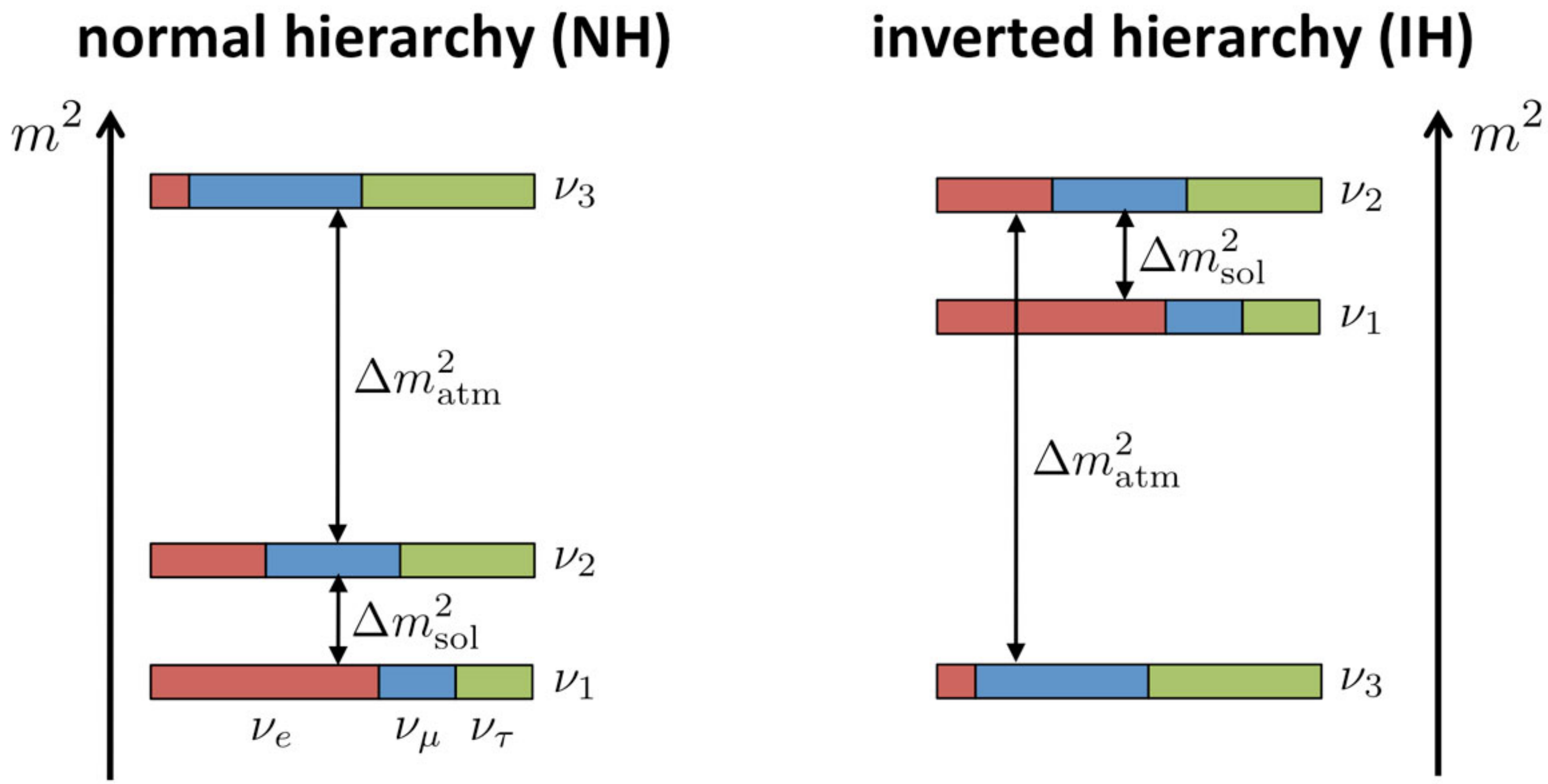
Indicate the existence of the Beyond SM (BSM) frameworks.

Neutrinos



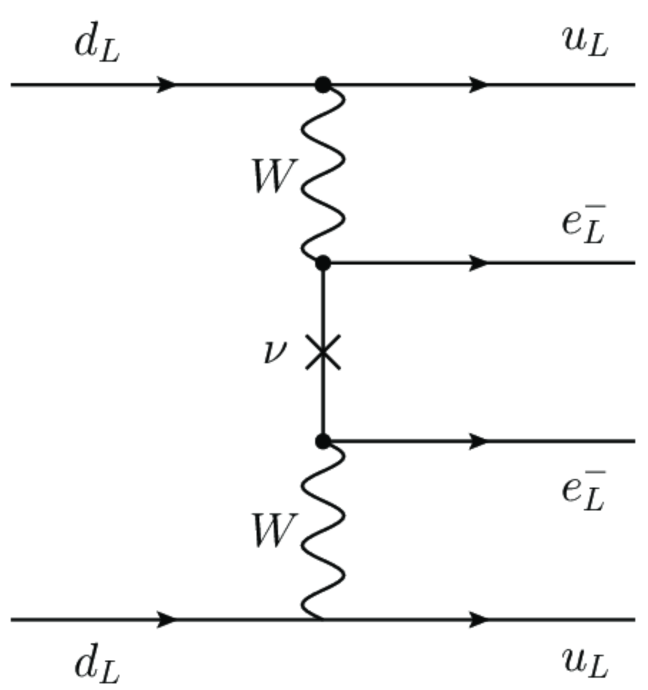
Unknowns in this sector :

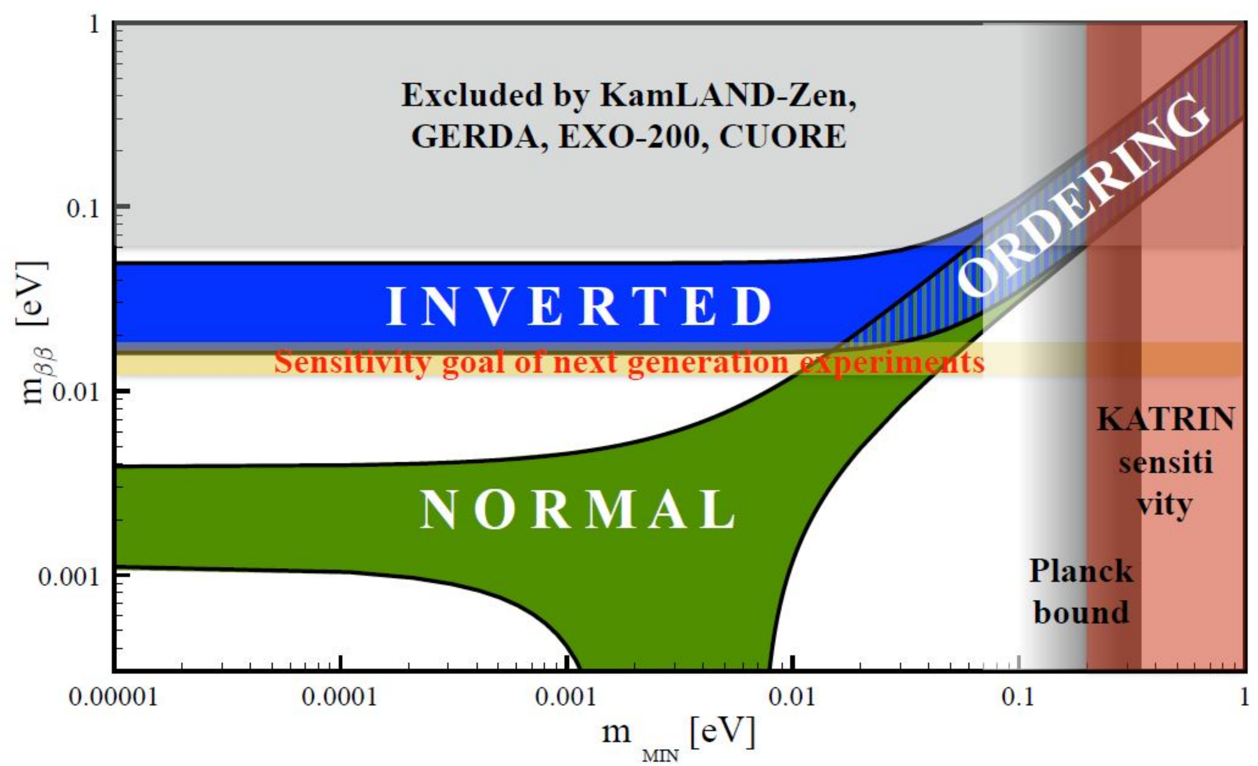
A. Dirac or Majorana?
B. "Correct" mass generation mechanism
C. Absolute mass scale
D. Mass Hierarchy (IH or NH?)

- Experiments like T2K, NOvA, and DUNE are dedicated to study neutrino oscillations and the determination of the neutrino mass hierarchies.

Neutrinoless double beta $(0\nu\beta\beta)$ decay

- Double beta decay without neutrino emission : $(A, Z) \to (A, Z+2) + 2e^-$.





https://tinyurl.com/2796wj2c

Current Limits :

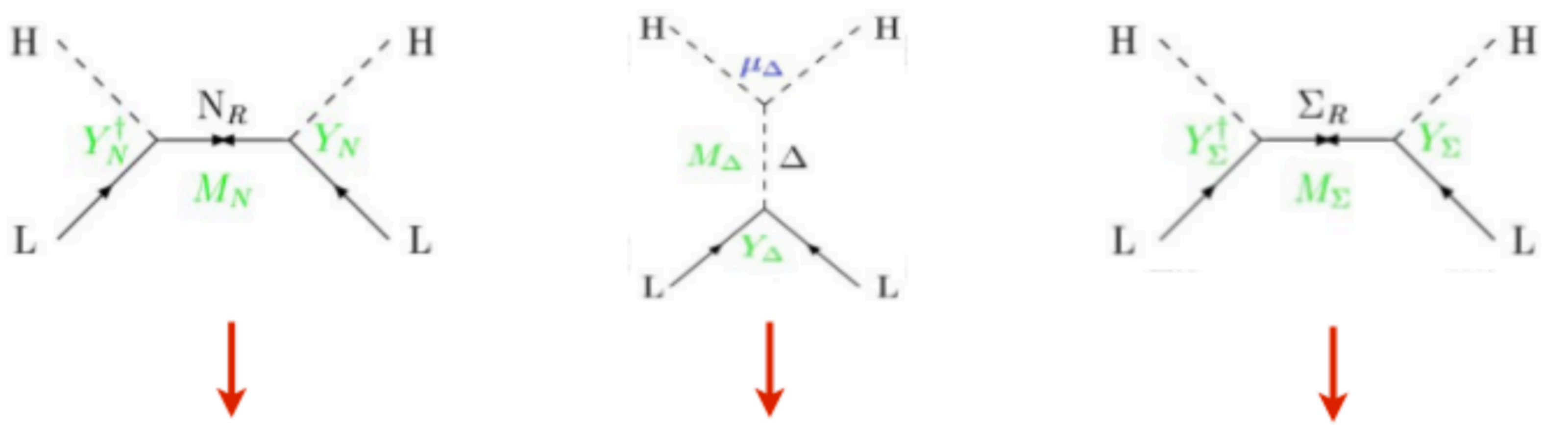
$T_{1/2}^{0\nu}(^{76}Ge) > 1.8 \times 10^{26}$ yrs at 90% C.L. : M. Agostini et al. (GERDA Collaboration), Phys. Rev. Lett. **125**, 252502

$T_{1/2}^{0\nu}(^{136}Xe) > 2.3 \times 10^{26}$ yrs : S. Abe et al. (KamLAND-Zen Collaboration), PhysRevLett.130.051801

Neutrino mass generation

- In SM, Dirac mass term for neutrinos i.e., $m_D \bar{\nu}_L N_R$ is not possible as there is no right-handed neutrinos (RHNs).
- Majorana mass terms i.e., $m_M \bar{\nu}_L^c \nu_L$ is not possible as it violates gauge symmetry.
- Only non-renormalizable dimension-5 operator in BSM paradigm (constructed out of SM fields) : Weinberg operator $\sim \frac{\kappa}{\Lambda} LLHH$ (S. Weinberg '79).

Right-handed singlet: (type-I seesaw) | Scalar triplet: (type-II seesaw) | Fermion triplet: (type-III seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2 \qquad m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2 \qquad m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Left-Right Symmetric Model (LRSM)

- Left-Right Symmetric Model (LRSM) is one of the promising approaches as BSM scenario.

- Gauge Group : $\mathscr{G}_{LR} \equiv SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

- Particle Content : $Q_L \equiv (3,2,1,1/3)$, $Q_R \equiv (3,1,2,1/3)$,

$$\ell_L \equiv (1,2,1,-1),\ \ell_R \equiv (1,1,2,-1),$$

$$\Phi \equiv (1,2,2,0),\ \Delta_L \equiv (1,3,1,2),\ \Delta_R \equiv (1,1,3,2).$$

- The right-handed neutrino is the natural new ingredient of LRSM (Pati et al.'74, Mohapatra et al.'75 and others).

- Left-right (LR) parity breaking scale is related to the generation of neutrino masses.

- The light neutrino masses can be generated via type-I+II seesaw formula.

$$\Downarrow$$

A very high right-handed breaking scale (>10^{14} GeV).

Motivation to ALRM

- LRSM, while quite successful as a BSM scenario, unfortunately suffers from unavoidable flavor-changing neutral current (FCNC) constraints.

- Unavoidable FCNCs in fermion-neutral Higgs couplings in conventional LRSMs (Ecker *et al.*'83, Y. Zhang *et al.*' 2008).

$$\lambda_{ijk}^{H\bar{U}U} = \frac{(v_u(Z_S)_{1k} - v_d(Z_S)_{2k})}{v_u^2 - v_d^2} M_{u_i}\delta_{ij} + \frac{(-v_d(Z_S)_{1k} + v_u(Z_S)_{2k})}{v_u^2 - v_d^2} \sum_{\ell=1}^{3} V_{i\ell}^{L} M_{d_\ell} V_{j\ell}^{R*}$$

- Possible remedy : High scale LR breaking ⇒ makes framework less interesting phenomenologically !!!

- Need some alternative approach : Low energy fermions belong to 27-representation of E_6 ⇒ fermion structure should be rearranged as compared to conventional LRSM ⇒ Alternative Left-Right Model (ALRM) proposed by Ernest Ma (1987).

- This model permits an accessible right-handed breaking scale of a few TeV.

- Gauge group : $\mathscr{G}_{ALRM} \equiv SU(3)_C \otimes SU(2)_L \otimes SU(2)_{R'} \otimes U(1)_{B-L} \otimes U(1)_S$.

- ALRM can be embedded in complex rank 6 Lie group E_6. It has two maximal subgroups :

  $SO(10) \otimes U(1)$ and $SU(3) \otimes SU(3) \otimes SU(3)$.

- Without invoking supersymmetry, model can provide two scenarios of DMs with generalised lepton number defined either by $L = S - T_{3R'}$ (Dark LR model : DLRM) (S. Khalil *et al.*'2009) or by $L = S + T_{3R'}$ (Dark LR model 2 : DLRM2) (S. Khalil *et al.*'2010).

Particle Content

- In this study we consider a doublet variant scalar sector of ALRM.

Quark sector : $Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} : (3,2,1,1/6,0), \;\; Q_R \equiv \begin{pmatrix} u_R \\ d'_R \end{pmatrix} : (3,1,2,1/6,-1/2),$

$d'_L : (3,1,1,-1/3,-1), \;\; d_R : (3,1,1,-1/3,0).$

Lepton sector : $\ell_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} : (1,2,1,-1/2,0), \;\; \ell_R \equiv \begin{pmatrix} n_R \\ e_R \end{pmatrix} : (1,1,2,-1/2,1/2),$

$n_L : (1,1,1,0,1), \;\; \nu_R : (1,1,1,0,0).$

Scalar sector : $\Phi : (1,2,2,0,-1/2), \;\; \chi_L : (1,2,1,1/2,0), \;\; \chi_R : (1,1,2,1/2,1/2).$

- Two step symmetry breaking :

1. The vev acquired by the neutral component of χ_R breaks the $SU(2)_{R'} \otimes U(1)_{B-L}$ symmetry down to $U(1)_Y$,

2. $SU(2)_L \otimes U(1)_Y$ is further broken to the electromagnetic gauge symmetry by the vevs of the bidoublet and left-handed doublet fields.

$$\text{vevs}: \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ 0 & v_2 \end{pmatrix}, \quad \langle \chi_{L,R} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_{L,R} \end{pmatrix}.$$

- $\langle \phi_1^0 \rangle = 0 \Rightarrow$ 1. It avoids unwanted mixing between d, d' and ν_L, n_R.

  2.It forbids mixing between $W_L - W_R$ gauge bosons.

- Fermion masses :

$$\boxed{m_u = \frac{Y^q v_2}{\sqrt{2}}, \quad m_d = \frac{Y_L^q v_L}{\sqrt{2}}, \quad m_\ell = \frac{Y^\ell v_2}{\sqrt{2}}, \quad m_\nu = \frac{1}{m_N} \left(\frac{Y_L^\ell v_L}{\sqrt{2}} \right)^2}$$

$$\Downarrow$$

No liberty to take $v_L \to 0$.

$0\nu\beta\beta$ in ALRM

- W_R does not couple to usual ν_R, d_R rather connects with exotics $\Rightarrow$ No W_R mediation contribution present.
- Absence of $W_L - W_R$ mixing $\Rightarrow$ No mixed helicity η diagram.
- Heavier charged Higgs $H_1^\pm$ relevant for $0\nu\beta\beta$ decay as it connects with quarks and leptons.
- $H_2^\pm$ connects with exotics $\Rightarrow$ not relevant here.
- Half-life :

$$\frac{1}{T^{0\nu}_{1/2}} = G_{01}\,|\,\mathcal{M}^W_{\nu_L}\eta^W_{\nu_L}|^2 + G^R_{HH}\,|\,\mathcal{M}^H_{\nu_L}\eta^H_{\nu_L}|^2 + G^L_{HH}\,|\,\mathcal{M}^H_{\nu_R}\eta^H_{\nu_R}|^2 + G^{LL}_{WH}\,|\,\mathcal{M}^{WH}_{\lambda}\eta^{WH}_{\lambda}\,|^2 + G^{LR}_{WH}\,|\,\mathcal{M}^{WH}_{\nu_L}\eta^{WH}_{\nu_L}\,|^2$$

- Standard vector-vector mediation with $e_L - e_L$ emission.
- Scalar-Scalar $(H_1 - H_1)$ mediation with $e_R - e_R$ emission (Mohapatra'95, M. Doi *et al.*'85) .
- Scalar-Scalar $(H_1 - H_1)$ mediation with $e_L - e_L$ emission .
- Vector-Scalar $(W_L - H_1)$ mediation with $e_L - e_L$ emission (Mohapatra'95, K. Babu & Mohapatra'95) .
- Vector-Scalar $(W_L - H_1)$ mediation with $e_L - e_R$ emission.

Fig.1 :

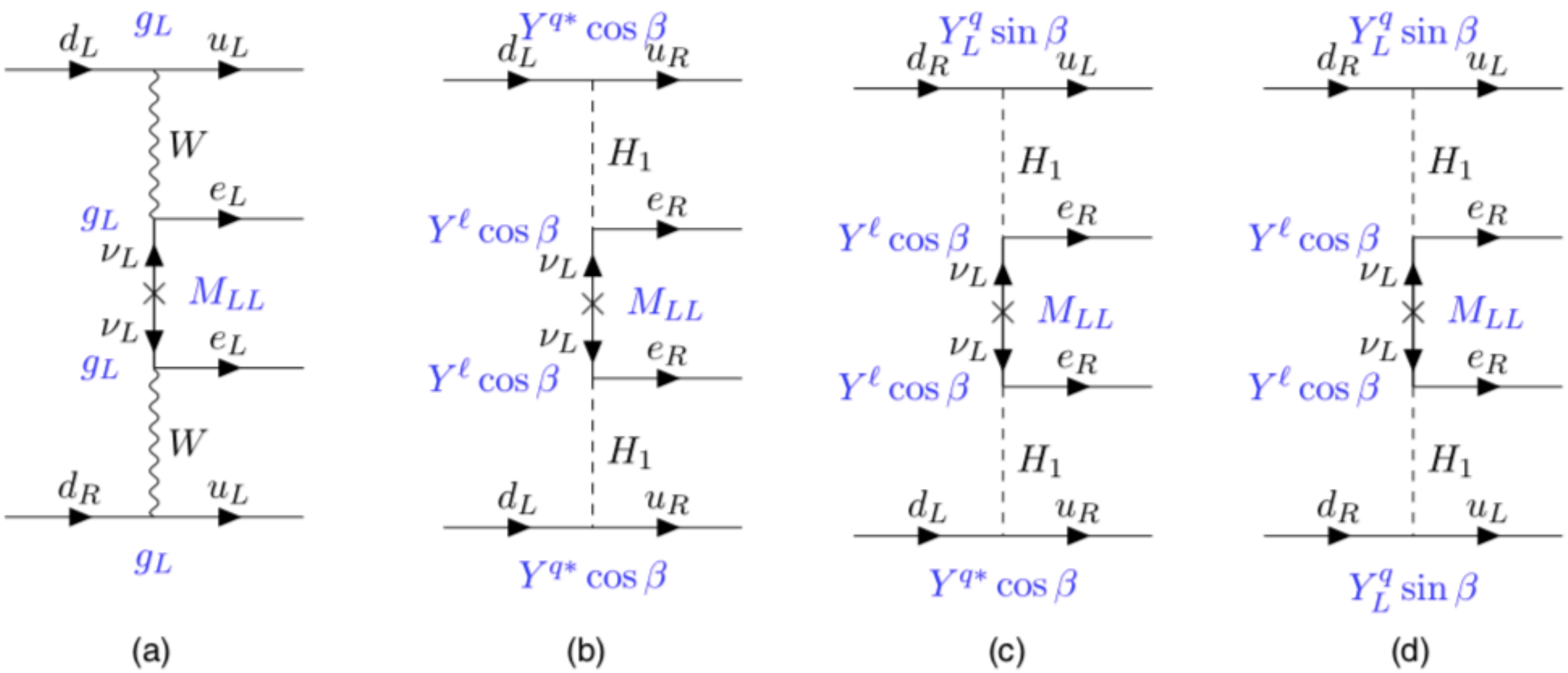


Fig.2 :

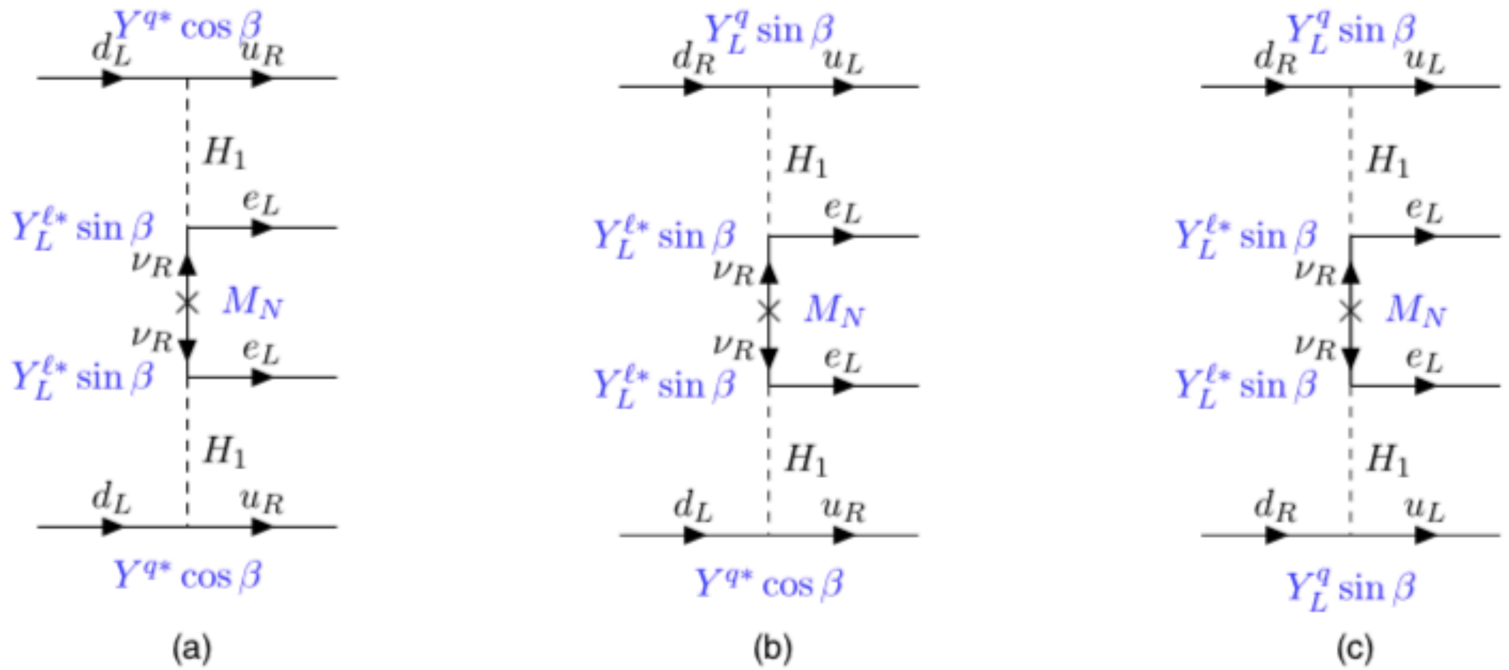
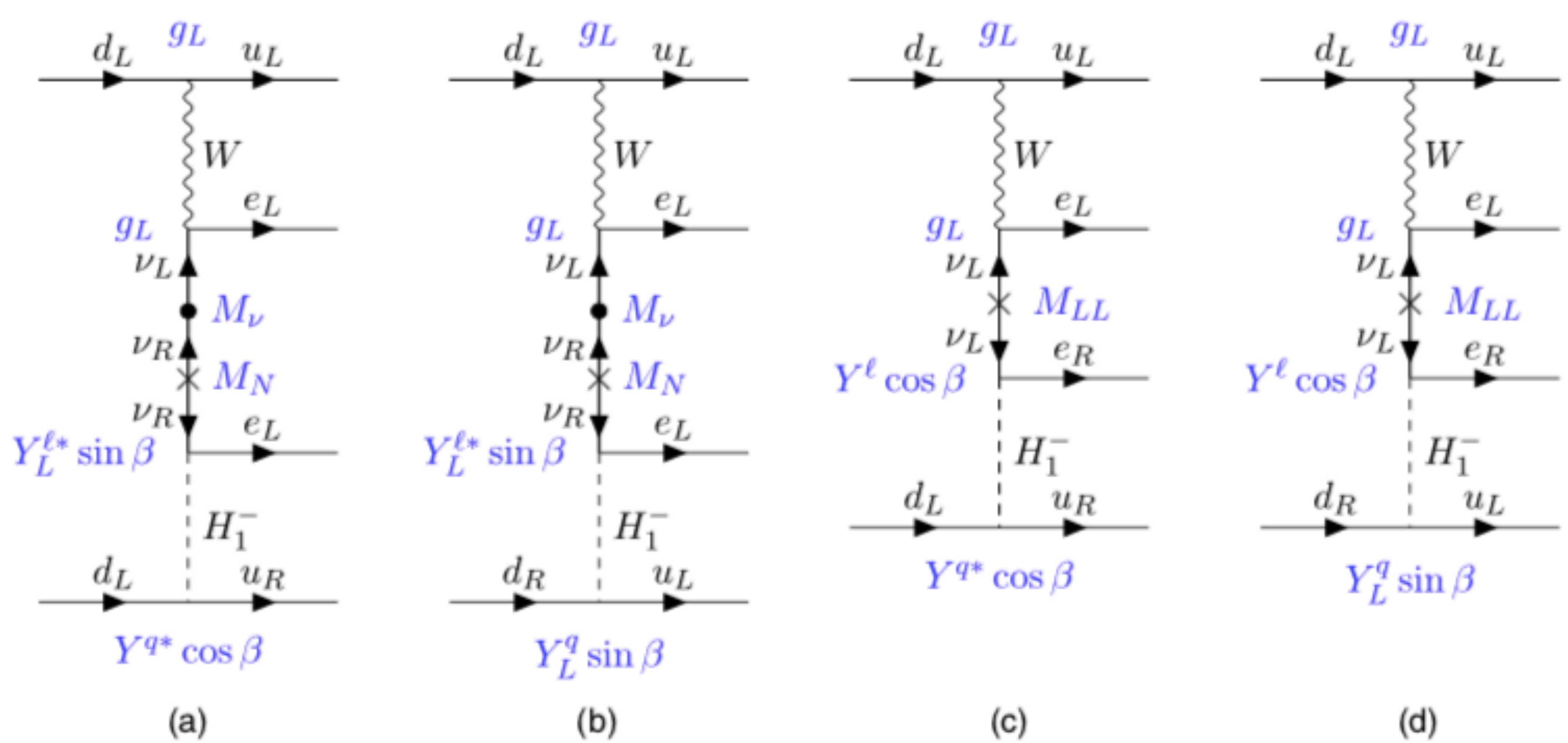


Fig.3 :



- Standard vector-vector mediation with $e_L - e_L$ emission.

- Scalar-Scalar ($H_1 - H_1$) mediation with $e_R - e_R$ emission (Mohapatra'95, M. Doi *et al.*'85) :

$$\mathscr{A}^{H_1H_1}_{\sigma\sigma',\nu_L} \sim \frac{G_F^2}{g_L^4}\frac{M^4_{W_L}}{M^4_{W_R}}\kappa^2_{ud}(Y^{\ell})^2 cos^2\beta \sum_i \left(\frac{\mathscr{V}^{\nu\nu 2}_{\alpha i} m_{\nu_i}}{p^2} - \frac{\mathscr{V}^{\nu N 2}_{\alpha i}}{m_{N_i}}\right).$$

- Scalar-Scalar ($H_1 - H_1$) mediation with $e_L - e_L$ emission :

$$\mathscr{A}^{H_1H_1}_{\sigma\sigma',\nu_R} \sim \frac{G_F^2}{g_L^4}\frac{M^4_{W_L}}{M^4_{W_R}}\kappa^2_{ud}(Y^{\ell *}_L)^2 sin^2\beta \sum_i \left(\frac{\mathscr{V}^{N\nu 2}_{\alpha i} m_{\nu_i}}{p^2} - \frac{\mathscr{V}^{NN 2}_{\alpha i}}{m_{N_i}}\right).$$

- Vector-Scalar ($W_L - H_1$) mediation with $e_L - e_L$ emission (Mohapatra'95, K. Babu & Mohapatra'95):

$$\mathscr{A}^{W_LH_1}_{\sigma\sigma',\lambda} \sim \frac{G_F^2}{g_L^2}\frac{M^2_{W_L}}{M^2_{H_1}}\kappa_{ud}Y^{\ell *}_L sin\beta \sum_i \left(\frac{\mathscr{V}^{\nu\nu}_{\alpha i}\mathscr{V}^{N\nu *}_{\alpha i}}{\gamma\cdot p} - \frac{\mathscr{V}^{\nu N}_{\alpha i}\mathscr{V}^{NN *}_{\alpha i}}{m_{N_i}}\right).$$

- Vector-Scalar ($W_L - H_1$) mediation with $e_L - e_R$ emission :

$$\mathscr{A}^{W_LH_1}_{\sigma\sigma',\nu_L} \sim \frac{G_F^2}{g_L^2}\frac{M^2_{W_L}}{M^2_{H_1}}\kappa_{ud}Y^{\ell} cos\beta \sum_i \left(\frac{\mathscr{V}^{\nu\nu 2}_{\alpha i}}{\gamma\cdot p} - \mathscr{V}^{\nu N 2}_{\alpha i}\frac{\gamma\cdot p}{m^2_{N_i}}\right).$$

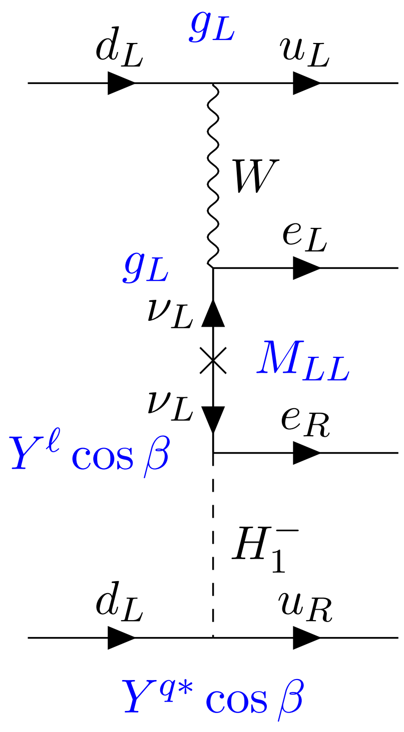
κ^2_{ud}

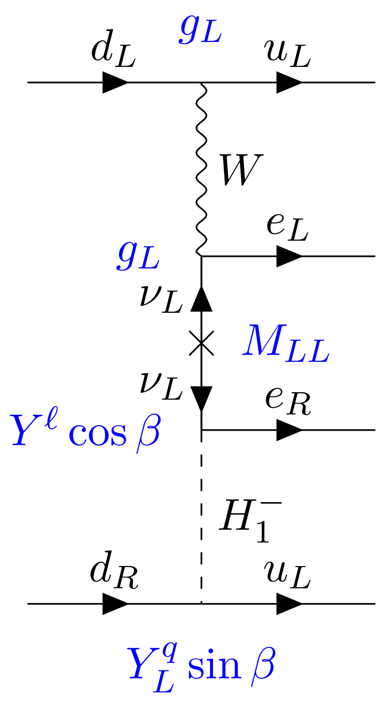
1. Both the u quarks are right-handed : $\kappa^2_{ud} = (Y^{q*})^2 \cos^2\beta$
2. Both the u quarks are left-handed : $\kappa^2_{ud} = (Y^q_L)^2 \sin^2\beta$
3. Mixed case : $\kappa^2_{ud} = Y^{q*} Y^q_L \cos\beta \sin\beta$

$$\tan\beta = \frac{v_2}{v_L}$$

$W_L W_L$ or $H_1 H_1$ mediated with ν_L		
Fig. 1(a)	$\lvert\eta^{\nu_i, W_L W_L}_{LL,\nu_L}\rvert$	2×10^{-8}
Fig. 1(b)	$\lvert\eta^{\nu_i, H_1 H_1}_{RR,\nu_L}\rvert$	1.3×10^{-36}
Fig. 1(c)	$\lvert\eta^{\nu_i, H_1 H_1}_{LR,\nu_L}\rvert$	6.6×10^{-33}
Fig. 1(d)	$\lvert\eta^{\nu_i, H_1 H_1}_{LL,\nu_L}\rvert$	3.5×10^{-29}
$H_1 H_1$ mediated with ν_R		
Fig. 2(a)	$\lvert\eta^{N_i, H_1 H_1}_{RR,\nu_R}\rvert$	1.4×10^{-26}
Fig. 2(b)	$\lvert\eta^{N_i, H_1 H_1}_{LR,\nu_L}\rvert$	7.4×10^{-23}
Fig. 2(c)	$\lvert\eta^{N_i, H_1 H_1}_{LL,\nu_R}\rvert$	3.8×10^{-19}
$W_L H_1$ mediated		
Fig. 3(a)	$\lvert\eta^{\nu_i, W_L H_1}_{LR,\lambda}\rvert$	1.2×10^{-25}
Fig. 3(b)	$\lvert\eta^{\nu_i, W_L H_1}_{LL,\lambda}\rvert$	6.4×10^{-22}
Fig. 3(c)	$\lvert\eta^{\nu_i, W_L H_1}_{LR,\nu_L}\rvert$	3.2×10^{-12}
Fig. 3(d)	$\lvert\eta^{\nu_i, W_L H_1}_{LL,\nu_L}\rvert$	1.7×10^{-8}

- Significant contributions : Vector-scalar mediated diagrams with $e_L - e_R$ emission.





$$T^{0\nu}_{\frac{1}{2},\,WH}(^{76}\mathrm{Ge}) = 3.6 \times 10^{26} \left(\frac{200\ \mathrm{MeV}}{\gamma\cdot p}\right)^2 \left(\frac{M_{H_1}}{200\ \mathrm{GeV}}\right)^4 \ \mathrm{yrs},$$

$$T^{0\nu}_{\frac{1}{2},\,WH}(^{136}\mathrm{Xe}) = 3.0 \times 10^{26} \left(\frac{200\ \mathrm{MeV}}{\gamma\cdot p}\right)^2 \left(\frac{M_{H_1}}{200\ \mathrm{GeV}}\right)^4 \ \mathrm{yrs}\,.$$

MF, CM, PP, **SS**, UAY; PRD 102 (2020) 7, 075020

Baryon asymmetry of universe (BAU)

- Big Bang Nucleosynthesis (BBN) Deuterium abundance + WMAP data on Cosmic Microwave Background (CMB) anisotropies (Aghanim *et al.*'2020) :

$$\Delta B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

- Dynamical generation of baryon asymmetry : conditions proposed by A. Sakharov (1967) →

(i) Baryon number violation.

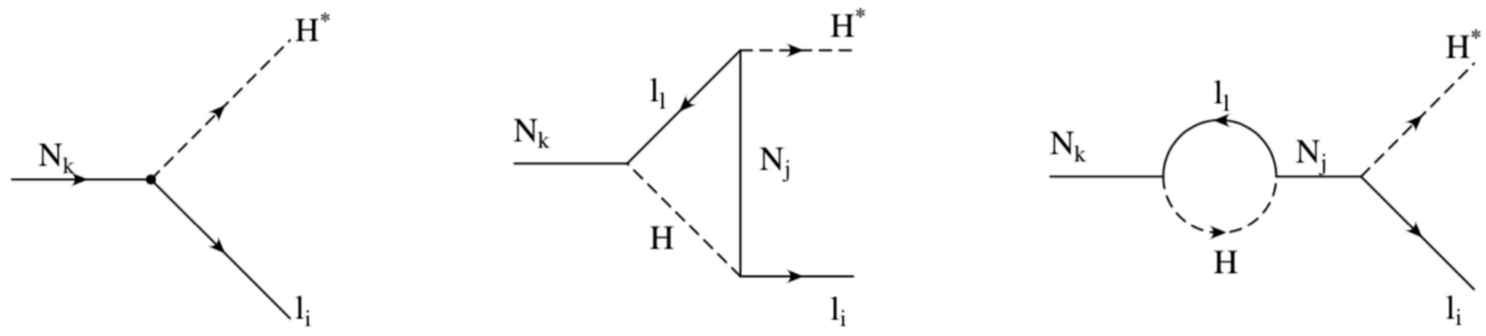
(ii) C and CP violation.

(iii) Departure from thermal equilibrium.

- Leptogenesis : Connecting BAU with neutrino mass generation.

Leptogenesis in ALRM

- Lepton number violation in this framework : $N_{iR} \to \ell_{iL}(H_1^{\pm})^{\dagger}, \quad N_{iR} \to \bar{\ell}_{iL}(H_1^{\pm})$.
- CP-asymmetry is provided by complex Yukawa couplings through interference between tree and one-loop diagrams.



- Strongly hierarchical scenario i.e., $m_{N_1} \ll m_{N_{2,3}} \Rightarrow \epsilon_v \sim \epsilon_s$.
- From the required out-of-equilibrium condition, the lower bound on the right-handed neutrino mass is $M_{N_1} > 10^8$ GeV $\Rightarrow$ Not our scenario !!!

Resonant Leptogenesis

- Two lightest RHNs have almost degenerate masses ⇒ mass limits on RHNs can be significantly relaxed (A. Pilaftsis & T.E.Underwood'2004).
- Self-energy diagram will be the dominating one ⇒ $\epsilon_s \gg \epsilon_v$.
- Condition to achieve required BAU in ALRM :

$$\frac{Im\left[\sum_\alpha \left(h^*_{\alpha i} h_{\alpha j}\right) \sum_\beta \left(h^*_{\beta i} h_{\beta j}\right)\right]}{\left(\sum_\alpha |h_{\alpha i}|^2\right)\left(\sum_\beta |h_{\beta j}|^2\right)} \simeq 10^{-7} \text{ with } h^*_{\alpha i} = (Y_L^{\ell \alpha *}) sin\beta \mathscr{V}^{NN*}_{\alpha i} .$$

- Unlike LRSM, right handed neutrino masses are not related to W_R masses here ⇒ W_R mediation does not contribute to wash-out efficiency.

Restriction on Dirac CP-phase in RHN sector

- For $C_{ij}, S_{ij} \sim \mathcal{O}(0.1) \Rightarrow sin\delta_N \simeq 10^{-5}$.

- If neutrino mixing matrix is mostly diagonal i.e., $C_{ij} \sim \mathcal{O}(1) \gg S_{kl} \sim \mathcal{O}(0.01) \Rightarrow sin\delta_N \simeq 10^{-6}$.

- If neutrino mixing matrix is highly off-diagonal i.e., $S_{ij} \sim \mathcal{O}(1) \gg C_{kl} \sim \mathcal{O}(0.01) \Rightarrow sin\delta_N \simeq 10^{-6}$.

- If $m_{N_3} \gg m_{N_{1,2}}$ and N_3 decouples from the theory i.e., $S_{13} \sim S_{23} \sim \mathcal{O}(0.01)$ and first two RHNs mix maximally i.e., $C_{12} \sim S_{12} \sim \dfrac{1}{\sqrt{2}} \Rightarrow sin\delta_N \simeq 6 \times 10^{-12}$.

- Results are quite promising as for minuscule Dirac CP phase in RHN sector can generate sufficient leptogenesis to satisfy BAU constraint.

Stability of scalar potential

Scalar Potential :

$$\mathscr{V}_H = -\mu_1^2 \text{Tr}\left[\Phi^\dagger\Phi\right] - \mu_2^2\left(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R\right) + \lambda_1\left(\text{Tr}\left[\Phi^\dagger\Phi\right]\right)^2 + \lambda_2 \text{Tr}\left[\tilde{\Phi}^\dagger\Phi\right]\text{Tr}\left[\Phi^\dagger\tilde{\Phi}\right] + \rho_1\left[\left(\chi_L^\dagger\chi_L\right)^2 + \left(\chi_R^\dagger\chi_R\right)^2\right]$$
$$+2\rho_2\left(\chi_L^\dagger\chi_L\right)\left(\chi_R^\dagger\chi_R\right) + 2\alpha_1 \text{Tr}\left[\Phi^\dagger\Phi\right]\left(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R\right) + 2\alpha_2\left[\chi_L^\dagger\Phi\Phi^\dagger\chi_L + \chi_R^\dagger\Phi^\dagger\Phi\chi_R\right]$$
$$+2\alpha_3\left[\chi_L^\dagger\tilde{\Phi}\tilde{\Phi}^\dagger\chi_L + \chi_R^\dagger\tilde{\Phi}^\dagger\tilde{\Phi}\chi_R\right] + \mu_3\left[\chi_L^\dagger\Phi\chi_R + \chi_R^\dagger\Phi^\dagger\chi_L\right]$$

- With multiple scalar fields present, the parameter space needs to be analysed carefully to establish the viable ranges that can provide a stable vacuum.

Conditions for stability of scalar potential :

λ sector

$\Downarrow$

$$\lambda_1 > 0,\ \lambda_1 + \lambda_2 > 0$$

ρ sector

$\Downarrow$

$$\rho_1 > 0,\ \rho_1 + \rho_2 > 0$$

α sector

$\Downarrow$

$$\alpha_1 + \alpha_2 + \sqrt{\lambda_1\left(\frac{\rho_1+\rho_2}{2}\right)} > 0$$
$$\alpha_1 + \alpha_3 + \sqrt{\lambda_1\left(\frac{\rho_1+\rho_2}{2}\right)} > 0$$
$$\alpha_1 + \alpha_2 + \sqrt{\lambda_1\rho_1} > 0$$
$$\alpha_1 + \alpha_3 + \sqrt{\lambda_1\rho_1} > 0$$
$$(\alpha_2 - \alpha_3) \geq 0$$

MF, CM, PP, **SS**, UAY; JHEP03(2022)065

Masses for the Higges

Charged Higgs bosons :

$$m^2_{h_1^\pm} = -\left[v_2 v_L \left(\alpha_2 - \alpha_3\right) + \frac{\mu_3 v_R}{\sqrt{2}}\right] \frac{v^2}{v_2 v_L}$$

$$m^2_{h_2^\pm} = -\left[v_2 v_R \left(\alpha_2 - \alpha_3\right) + \frac{\mu_3 v_L}{\sqrt{2}}\right] \frac{v'^2}{v_2 v_R}$$

Pseudoscalar boson :

$$m^2_{A_2} = -\frac{\mu_3 v_L v_R}{\sqrt{2} v_2}\left[1 + v_2^2\left(\frac{1}{v_L^2} + \frac{1}{v_R^2}\right)\right]$$

Here $v^2 = v_2^2 + v_L^2, v'^2 = v_2^2 + v_R^2$.

CP-odd (and R-parity odd) Higgs boson :

$$m^2_{A_1} = 2v_2^2\lambda_2 - \left(\alpha_2 - \alpha_3\right)\left(v_L^2 + v_R^2\right) - \frac{\mu_3 v_L v_R}{\sqrt{2} v_2}$$

CP-even and R-parity odd Higgs boson : $m^2_{h_1^0} = m^2_{A_1}$

CP-even and R-parity even neutral Higgs bosons :

$$m^2_{h^0_{2,3}} = \frac{1}{2}\left[\mathfrak{a} - m_h^2 \mp \sqrt{\left(\mathfrak{a} - m_h^2\right)^2 + 4\left(\mathfrak{b} + m_h^2\left(\mathfrak{a} - m_h^2\right)\right)}\right]$$

- The scalar potential parameters should ensure the requirement of non-tachyonic Higgs boson masses.

- Non-tachyonic mass of the CP-odd physical scalar $A_2 \Rightarrow \mu_3$ should be negative while all the other parameters are positive.

- Two Different considerations :

(i) $\left(\alpha_2 - \alpha_3\right) \geq 0 \Rightarrow m^2_{h_1^\pm} > 0$ but $m^2_{h_2^\pm} < 0$

(ii) $\left(\alpha_2 - \alpha_3\right) \leq 0 \Rightarrow m^2_{h_1^\pm, h_2^\pm} > 0$

$\Downarrow$

only the allowed parameter space is the one where $\alpha_2 = \alpha_3$.

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- No FCNC in the Higgs sector ⇒ the scalar masses can be light.

- The lower limit on $m_{h_2^\pm}$ is restricted to be around 40 GeV (very low mass) for $\alpha_2 = \alpha_3$.

- The lower limit on $m_{h_1^\pm}$ are unrestricted and increase with decreasing v_L :

$$m_{h_1^\pm} > 14 \text{ TeV for } v_L = 5.95 \text{ GeV},$$

$$m_{h_1^\pm} > 50 \text{ TeV for } v_L = 1.68 \text{ GeV}.$$

- These masses are insensitive to variations in the vevs v_R and v_2.

Dark Matter (DM) in ALRM

- The ALRM augmented by the extra $U(1)_S$ symmetry allows the introduction of the generalised lepton number $L = S + T_{3R}$.

- Similarly, one can introduce a generalised R-parity, similar to the one existing in the supersymmetry, defined in a similar way as $(-1)^{3B+L+2S}$.

- The odd R-parity particles are as follows:

  Scalar sector : $\chi_R^{\pm}, \phi_1^{\pm}, \Re(\phi_1^0), \Im(\phi_1^0)$

  Fermion sector : the scotinos n_L, n_R, and the exotic quarks, d'_L, d'_R

  Gauge sector : W_R

- The existence of a dark matter sector arising from R-parity odd particles is another attractive feature of this model, and an advantage over the usual LRSM.

- The possible DM candidate is either the R-parity odd Higgs boson (scalar or pseudoscalar), or the scotino(s), or both .

Scalar Dark Matter

- The components of the ϕ_1^0 field $(\Re(\phi_1^0), \Im(\phi_1^0))$ do not mix with other states, as they are both R-parity odd. They yield the physical H_1^0 and A_1 eigenstates, which are degenerate in mass eigenstates.

- H_1^0 and A_1 are the scalar DM candidates if these are lightest R-parity odd particles.

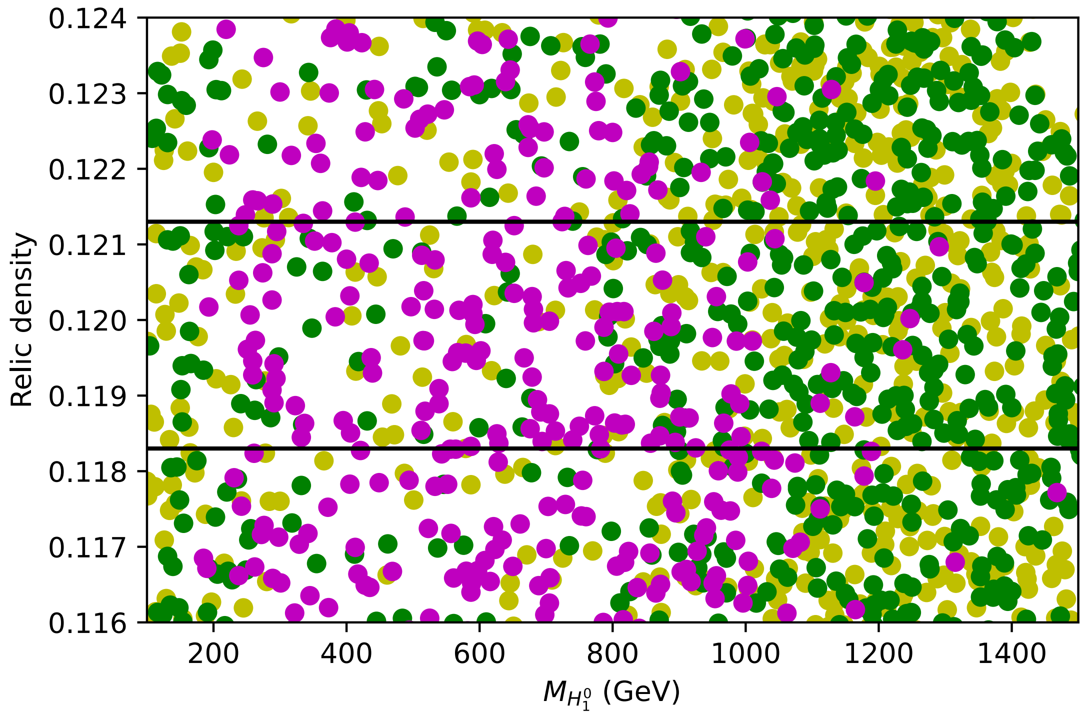
- Ensure that the chosen particles satisfy experiments searching for dark matter, and their interactions with ordinary matter.

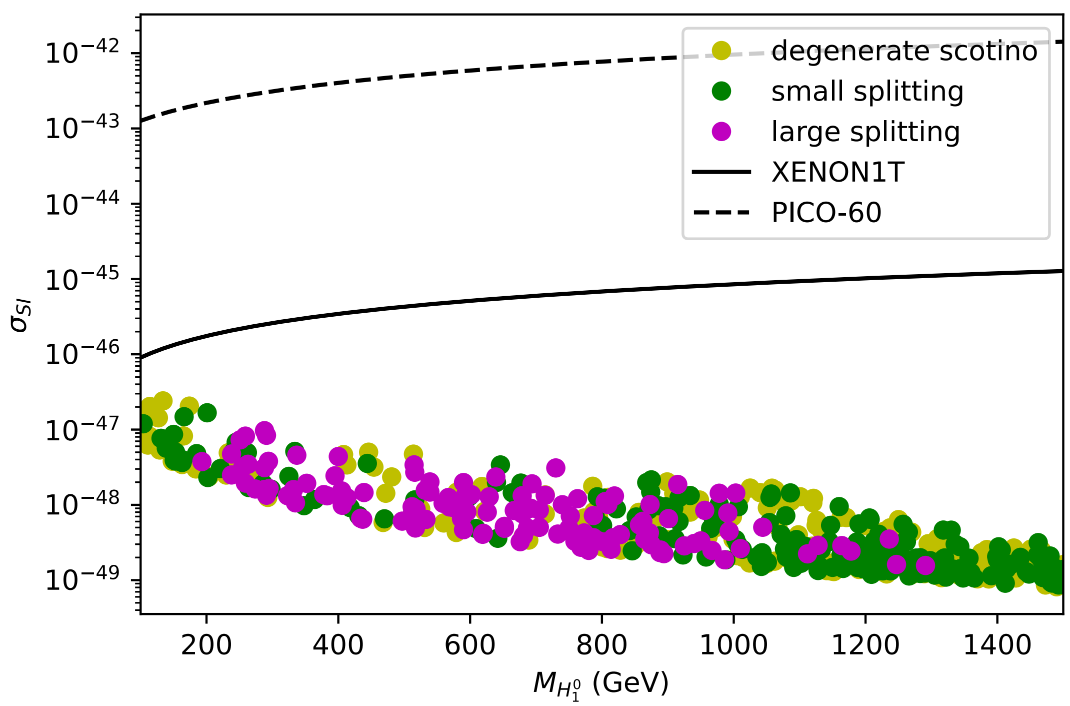
- We first investigate the amount of thermal relic abundance of DM, aiming to restrict the parameter space based on agreement with the measured cosmological DM density.

- The total DM relic density obtained from the anisotropy in the cosmic microwave background radiation (CMBR) measured by the Planck experiment is, $\Omega_{DM}h^2 = 0.120 \pm 0.001$.

- We take n_τ as the lightest scotino, as in the collider study τ-channel has the advantage of having larger Yukawa coupling.

m_{n_e} and m_{n_μ}	
Case (i) (degenerate)	$m_{n_e} = m_{n_\mu} = m_{n_\tau}$
Case (ii) (small splitting)	$(m_{n_e} = m_{n_\mu}) - m_{n_\tau}$ = Range (10 keV–20 MeV)
Case (iii) (large splitting)	$(m_{n_e} = m_{n_\mu}) - m_{n_\tau}$ = Range (100 MeV–10 GeV)

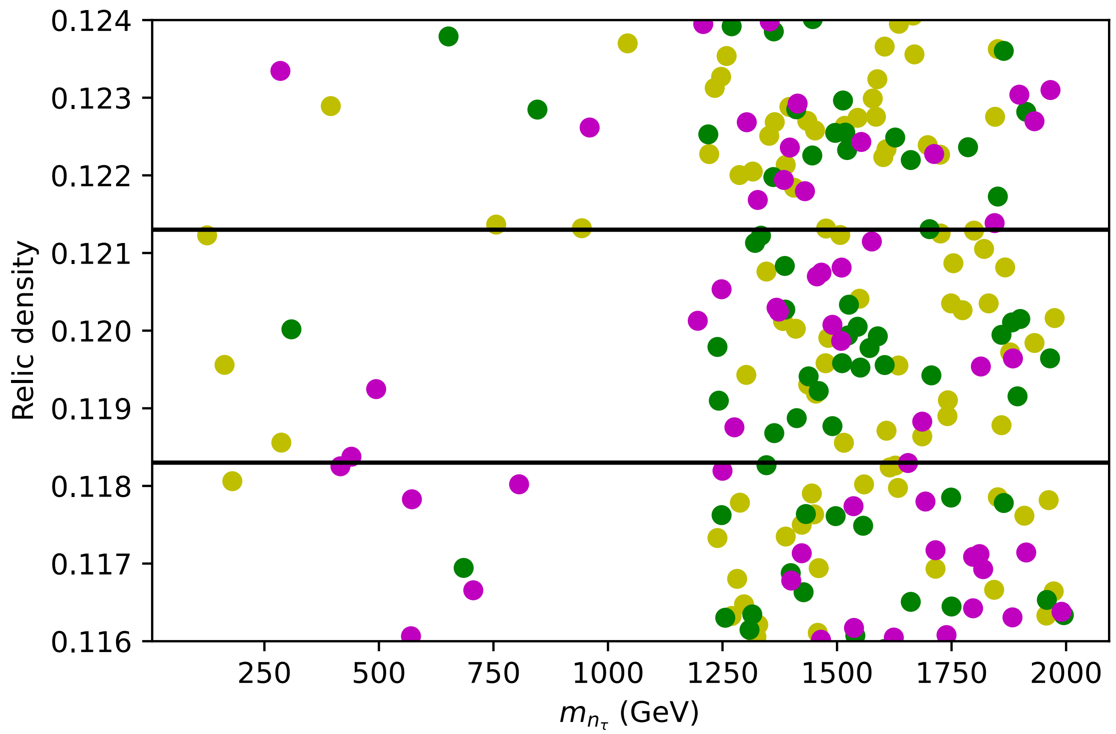


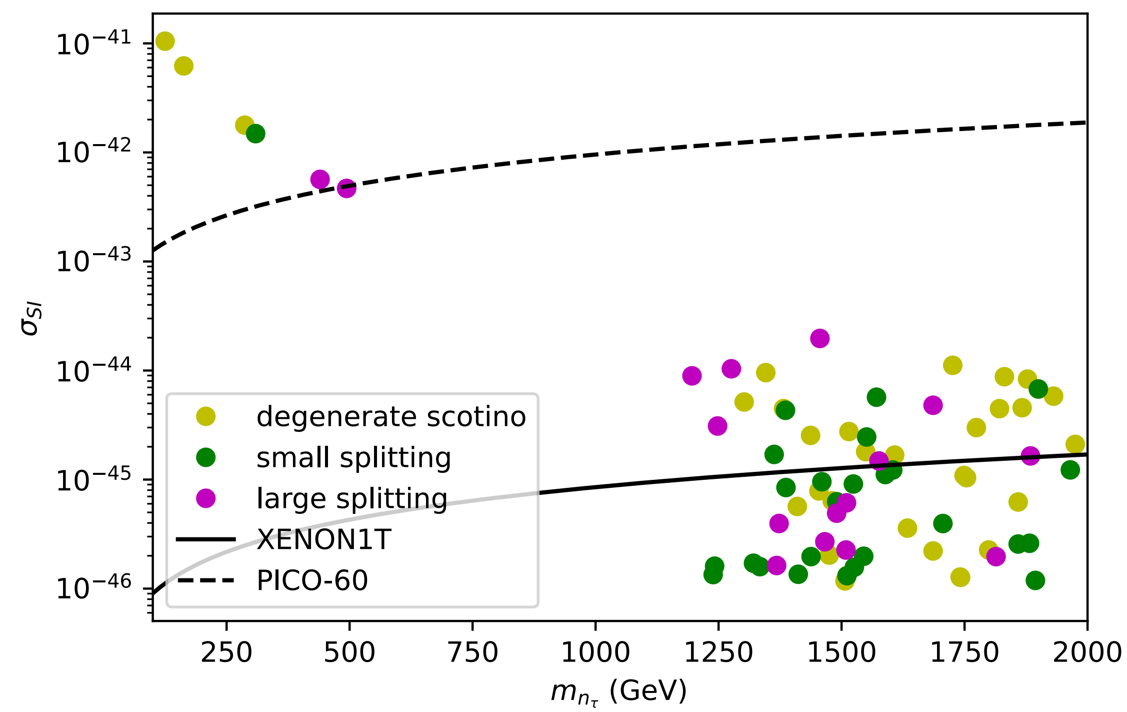


- In this case, the relic is sensitive to variations in $\tan\beta = v_2/v_L$.

MF, CM, PP, **SS**, UAY; JHEP12(2022)032

Fermion Dark Matter





MF, CM, PP, **SS**, UAY; JHEP12(2022)032

- The relic is sensitive to $v' = \sqrt{v_2^2 + v_R^2}$, as $Y_{n_\tau} = m_{n_\tau}/v_R$, so we have varied both v' and m_{n_τ}.

- For a fixed scotino DM mass, if the v' increases within the above-mentioned range $\Rightarrow$ the Yukawa couplings decrease $\Rightarrow$ the cross-section mediated by corresponding Higgs bosons would decrease and relic density increases.

- For fixed v', if we increase scotino DM mass $\Rightarrow$ the relic density for these associated channels decreases.

Summary

- The ALRM is a BSM framework with similar gauge structure of the conventional LRSM, but free from the unavoidable FCNC constraints.
- ALRM can be embedded in E_6 gauge group and allows the light scalar masses.
- This model can generate significant contributions to the $0\nu\beta\beta$ decay through vector-scalar (WH) mediation.
- Invoking the resonant leptogenesis, the required CP violation can be easily obtained, even for a small Dirac phase in the right-handed neutrino mass mixing matrix.
- We obtain constraints on the parameters of the model from collider data on the masses of the Higgs scalars.
- Depending on the mass hierarchy, the model allows either a scalar dark matter (neutral R-parity odd scalar and pseudoscalar) or a fermion (scotino) dark matter.

Thank you!

Comments, questions, Suggestions!!!

Backup Slide 1 :

- The lepton asymmetry in terms of the matrix elements

$$\epsilon_s^{\nu N1} \simeq \frac{S_{13}^2 C_{23}\left(S_{12}^2 S_{13} + C_{12}^2 S_{23}\right)\left[C_{23}\left(S_{12}^2 S_{13} - C_{12}^2 S_{23}\right) + S_{12} C_{12}\left(S_{23} - C_{23}^2 S_{12}\right)\right]}{\left(S_{12} S_{13} - C_{12} C_{23} S_{13}\right)^2 \left(C_{12} S_{23} + S_{12} C_{23} S_{13}\right)^2} \sin\delta_N\,.$$

$M_{H_1^0}$ (GeV)	Annihilation Channels
$M_{H_1^0} < M_h$	$H_1^0 H_1^0 \to WW,\ ZZ,\ GG,\ \gamma\gamma,\ b\bar{b}$
$M_h < M_{H_1^0} < m_t$	$H_1^0 H_1^0 \to WW,\ ZZ,\ GG,\ \gamma\gamma, b\bar{b},\ hh$
$m_t < M_{H_1^0} < M_{H_1^\pm}$	$H_1^0 H_1^0 \to WW, ZZ, GG, \gamma\gamma,\ b\bar{b},\ hh,\ t\bar{t}$
$(M_{H_1^\pm} + M_W) < 2M_{H_1^0}$	$H_1^0 H_1^0 \to WW, ZZ, GG, \gamma\gamma,\ b\bar{b},\ hh,\ t\bar{t},\ W^\pm H_1^\mp$

Parameter	Range (GeV)
m_{n_τ}	$(100 - 2000)$
$m_{q'} - m_{n_\tau}$	$(200 - 500)$
$M_{H_2^\pm} - M_{H_1^0}$	$(10 - 70)$
v'	$(1900 - 35000)$

Parameter	Range
$M_{H_1^0} = M_{A_1}$	$(100 - 2000)$ GeV
$M_{H_2^\pm} - M_{H_1^0}$	$(10 - 60)$ GeV
$m_{q'} - M_{H_1^0}$	$(200 - 500)$ GeV
$m_{n_\tau} - M_{H_1^0}$	$(0.001 - 1)$ GeV
λ_3	$(1.0 - 2.0)$
v'	$(1.9 - 35)$ TeV
$\|\mu_3\|$	$(100 - 2000)$ GeV

n_τ Annihilation Channels
$n_\tau \bar{n}_\tau \to \ell\bar{\ell},\ \nu\bar{\nu},\ q\bar{q},\ WW,\ ZZ,\ Zh,\ ZH_1^0,\ ZA_1^0,\ hh$

Backup Slide 2 :

- In usual LRSM with doublet Higgs, contributing channels :

  (i) Standard $W_L - W_L$ mediation,

  (ii) Purely $W_R - W_R$ mediation,

  (iii) Mixed helicity λ and η diagrams

- Half-life :

$$(T_{1/2}^{0\nu})^{-1} = G_{01}\left(|\mathcal{M}_\nu \eta_\nu^L + \mathcal{M}'_N \eta_N^L|^2 + |\mathcal{M}'_N \eta_N^R + \mathcal{M}_\nu \eta_\nu^R|^2 + |\mathcal{M}'_\lambda(\eta_\lambda^\nu + \eta_\lambda^N) + \mathcal{M}'_\eta(\eta_\eta^\nu + \eta_\eta^N)|^2 \right)$$