Exploring Alternative Left-Right Model: Phenomenological and Cosmological Imprints

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 double beta $(0\nu\beta\beta)$ decay in ALRM
- Leptogenesis and Dark matter in ALRM
- Collider Signatures of ALRM
- Summary and conclusion

The Standard Model (SM) and beyond

- Theoretical predictions of the Standard Model match experimental searches with great accuracy.

- Gauge Structure : $\mathscr{G}_{\text{SM}} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$.

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- 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

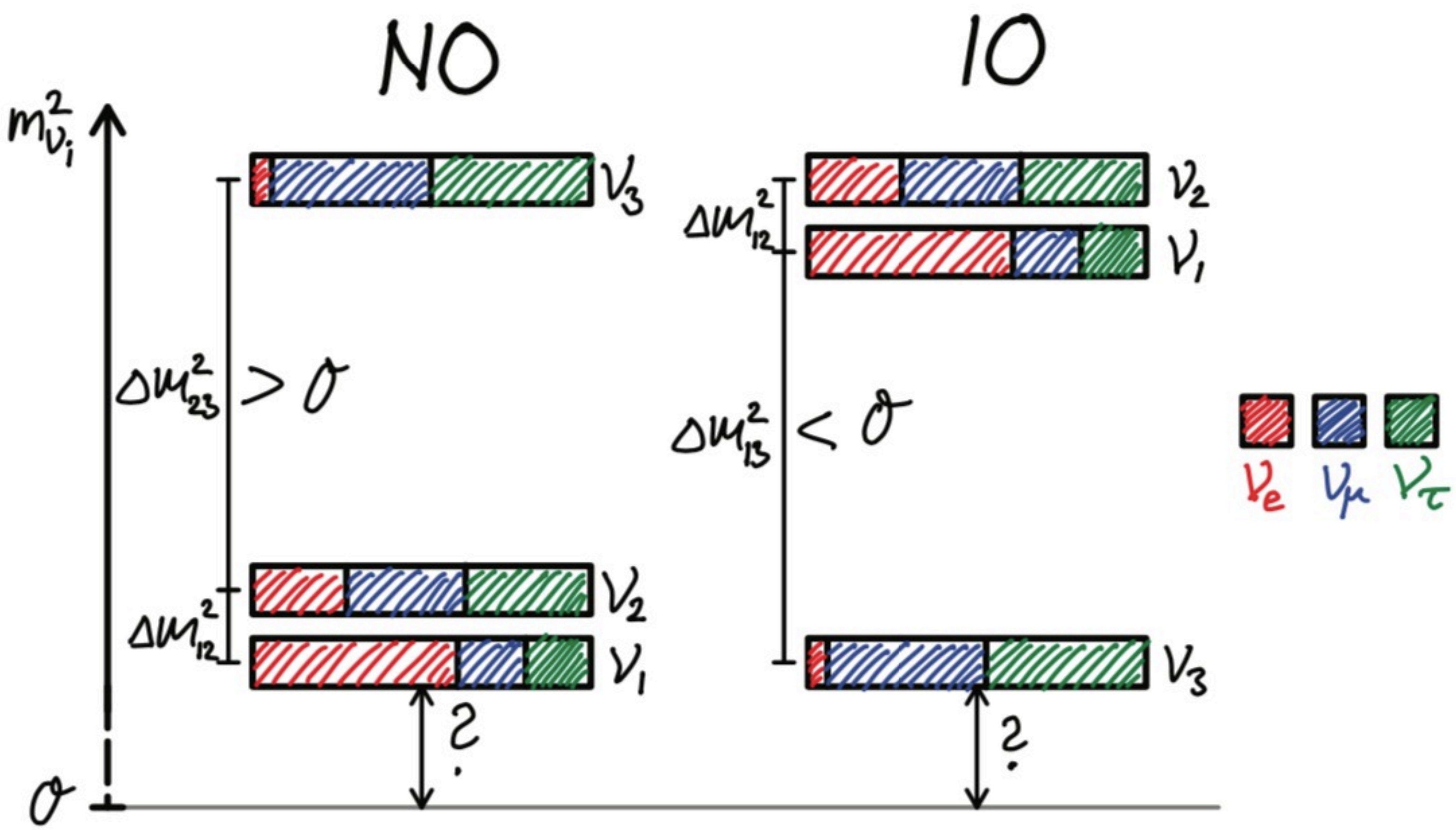
(c) Baryon asymmetry of the universe (BAU)

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

$\Downarrow$

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

Neutrinos



Courtesy : Frank F. Deppisch, A modern introduction to neutrino physics

Unknowns

⇓

A. Dirac or Majorana
B. “Correct” mass generation mechanism
C. Absolute mass scale
D. Mass Hierarchy (normal or inverted) …..

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

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.
- 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).

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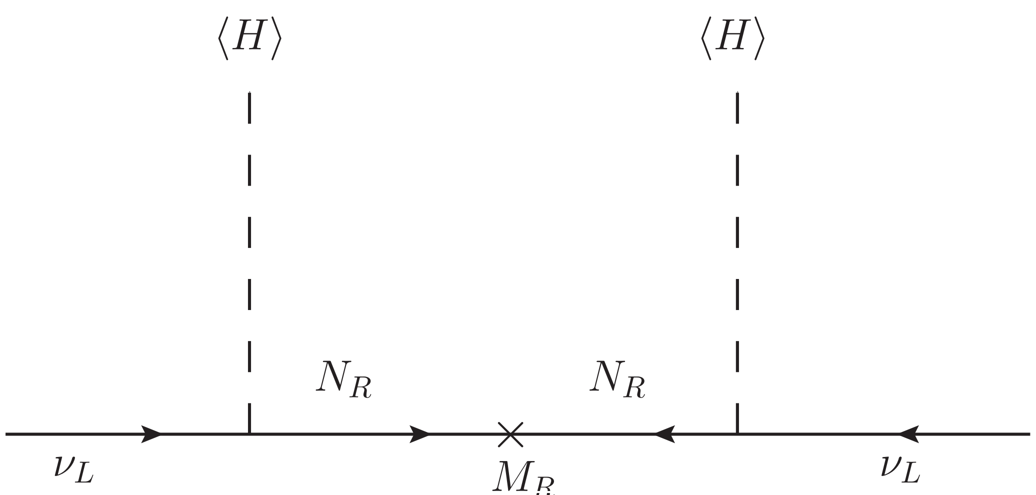


Type-I Seesaw : SM + fermion singlet

$$m_\nu = -M_D M_R^{-1} M_D^T \sim \frac{v^2}{M_R}$$

Other types of Seesaw : Type-II and III.

SM + scalar triplet

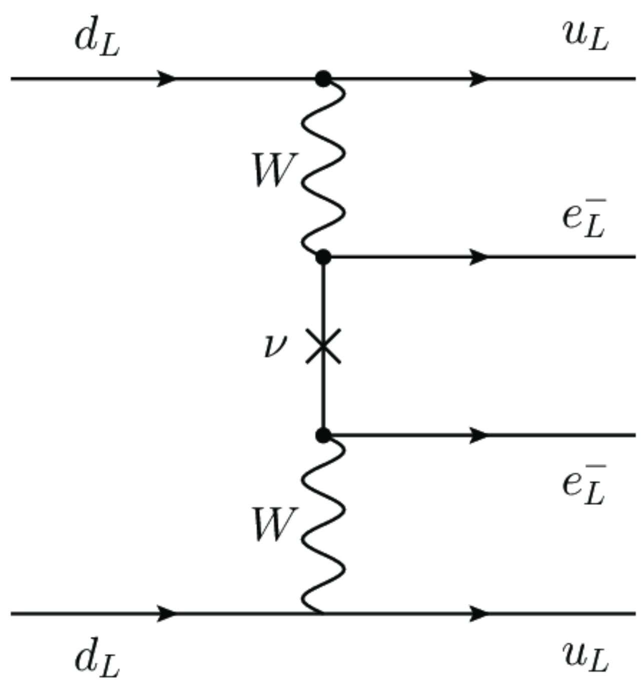
SM + fermion triplet

Naturally suppressed by large scale !!!

High Scale Seesaw !!!

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

- In order to probe Majorana nature of massive neutrinos and LNV signatures, we need to study $0\nu\beta\beta$ decay : $(A, Z) \to (A, Z+2) + 2e^-$.



Standard Mechanism

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \, |M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$$

$$\langle m_{\beta\beta} \rangle = \left| \sum U_{ei}^2 m_i \right|$$

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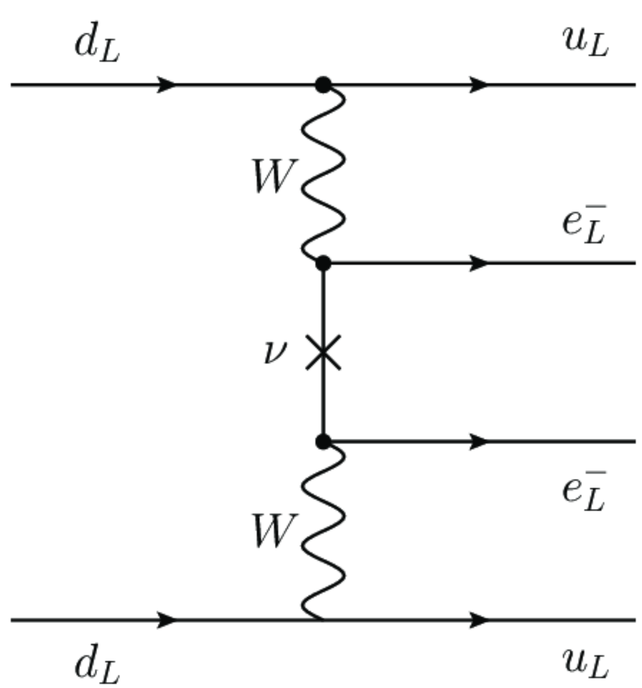

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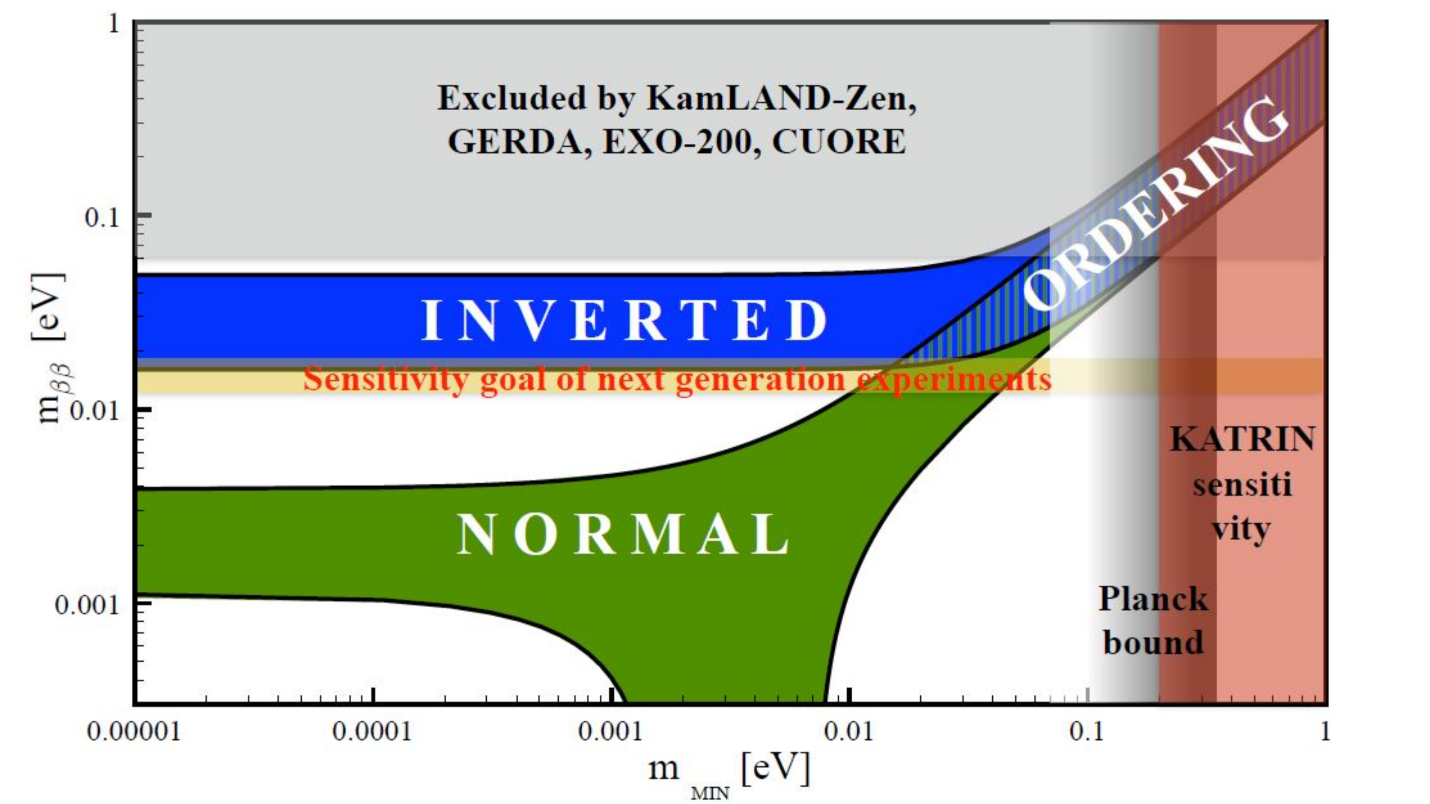

$T^{0\nu}_{1/2}(^{76}Ge) > 1.8 \times 10^{26}$ yrs at 90% C.L., Phys. Rev. Lett. **125**, 252502

$T^{0\nu}_{1/2}(^{136}Xe) > 2.3 \times 10^{26}$ yrs, Phys. Rev. Lett. **130,** 051801

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 & Salam'74, Mohapatra & Senjanovic'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).

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

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- 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).

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

Particle Content :

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), ν_R : (1,1,1,0,0).

Scalar sector : Φ : (1,2,2,0, − 1/2), χ_L : (1,2,1,1/2,0), χ_R : (1,1,2,1/2,1/2).

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- 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.

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

Advantages :

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

- 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).

- No FCNC in the Higgs sector $\Rightarrow$ the scalar masses can be light.

Stability of scalar potential

Scalar Potential :

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

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$$+2\rho_2\left(\chi_L^\dagger\chi_L\right)\left(\chi_R^\dagger\chi_R\right) + 2\alpha_1 \text{Tr}\left[\Phi^\dagger\Phi\right]\left(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R\right) + 2\alpha_2\left[\chi_L^\dagger\Phi\Phi^\dagger\chi_L + \chi_R^\dagger\Phi^\dagger\Phi\chi_R\right]$$
$$+2\alpha_3\left[\chi_L^\dagger\tilde{\Phi}\tilde{\Phi}^\dagger\chi_L + \chi_R^\dagger\tilde{\Phi}^\dagger\tilde{\Phi}\chi_R\right] + \mu_3\left[\chi_L^\dagger\Phi\chi_R + \chi_R^\dagger\Phi^\dagger\chi_L\right]$$

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

$\Downarrow$

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

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Masses for the scalars :

Charged Higgs bosons :

$$m^2_{H_1^\pm} = -\left[v_2 v_L\left(\alpha_2-\alpha_3\right)+\frac{\mu_3 v_R}{\sqrt{2}}\right]\frac{v^2}{v_2 v_L}$$

$$m^2_{H_2^\pm} = -\left[v_2 v_R\left(\alpha_2-\alpha_3\right)+\frac{\mu_3 v_L}{\sqrt{2}}\right]\frac{v'^2}{v_2 v_R}$$

CP-odd Higgs boson :

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

Pseudoscalar boson :

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

CP-even Higgs boson : $m^2_{H_1^0} = m^2_{A_1}$

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

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

Requirement of non-tachyonic Higgs boson masses : $\mu_3 < 0$ and $\alpha_2 = \alpha_3$.

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The minimisation of the potential ensures $\langle \phi_1^0 \rangle = 0$

$\Downarrow$

1. It avoids unwanted mixing between d, d' and ν_L, n_R.
2. It forbids mixing between $W_L - W_R$ gauge bosons.

Yukawa interactions :

$$-\mathscr{L}_Y = \overline{Q}_L Y^q \tilde{\Phi} Q_R + \overline{Q}_L Y_L^q \chi_L d_R + \overline{Q}_R Y_R^q \chi_R d_L' + \overline{L}_L Y^\ell \Phi L_R + \overline{L}_L Y_L^\ell \tilde{\chi}_L \nu_R + \overline{L}_R Y_R^\ell \tilde{\chi}_R \nu_L + h.c.$$

Fermion Masses :

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

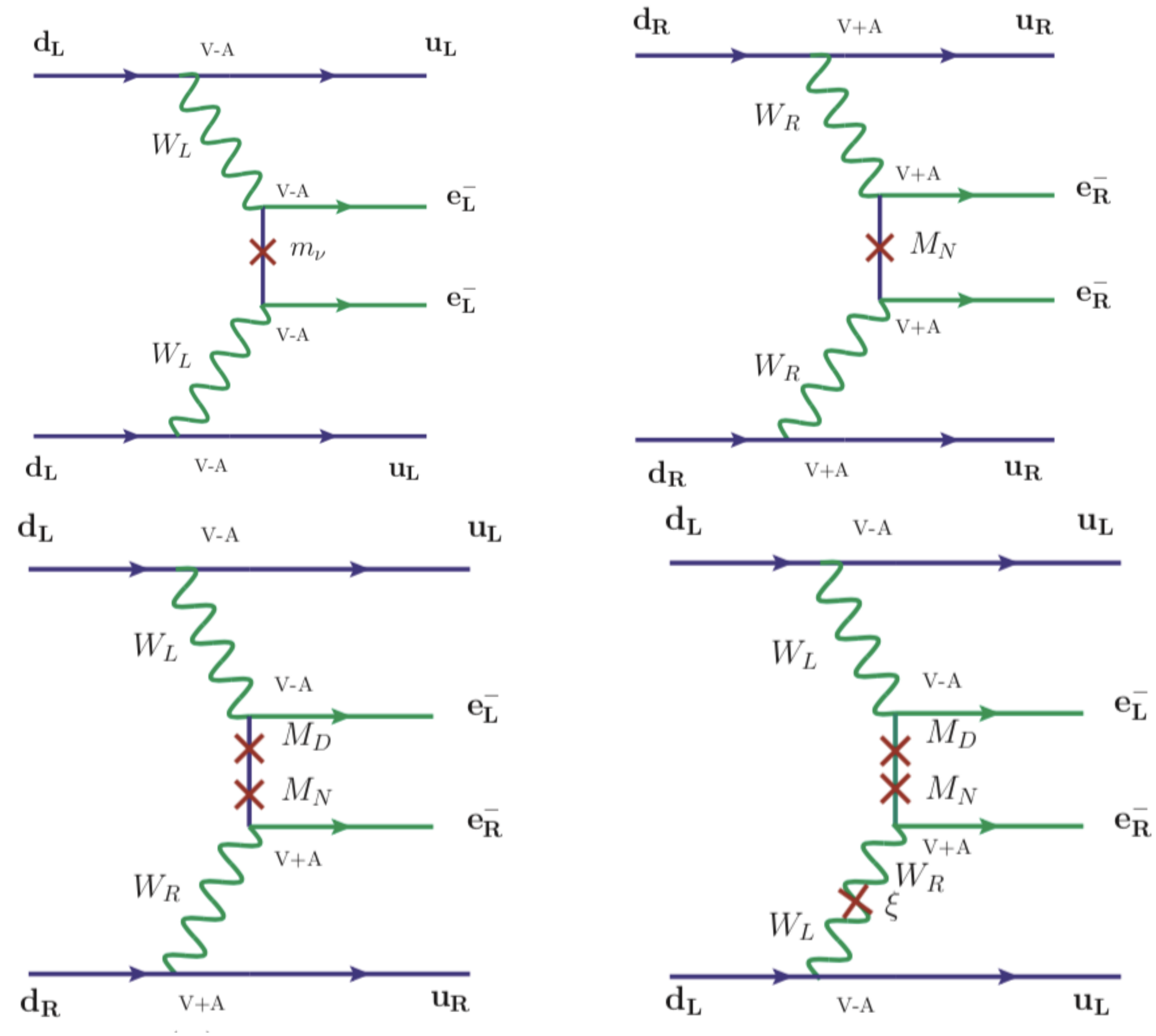
$\Downarrow$

No liberty to take $v_L \to 0$.

$0\nu\beta\beta$ decay in LRSM

In usual LRSM with doublet Higgs, contributing channels :

1. Standard $W_L - W_L$ mediation,
2. Purely $W_R - W_R$ mediation,
3. Mixed helicity λ and η diagrams.



Half-life :

$$(T^{0\nu}_{1/2})^{-1} = G_{01}\left(|\mathcal{M}_\nu \eta^L_\nu + \mathcal{M}'_N \eta^L_N|^2 + |\mathcal{M}'_N \eta^R_N + \mathcal{M}_\nu \eta^R_\nu|^2 + |\mathcal{M}'_\lambda(\eta^\nu_\lambda + \eta^N_\lambda) + \mathcal{M}'_\eta(\eta^\nu_\eta + \eta^N_\eta)|^2\right)$$

$0\nu\beta\beta$ 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.

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Contributions :

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

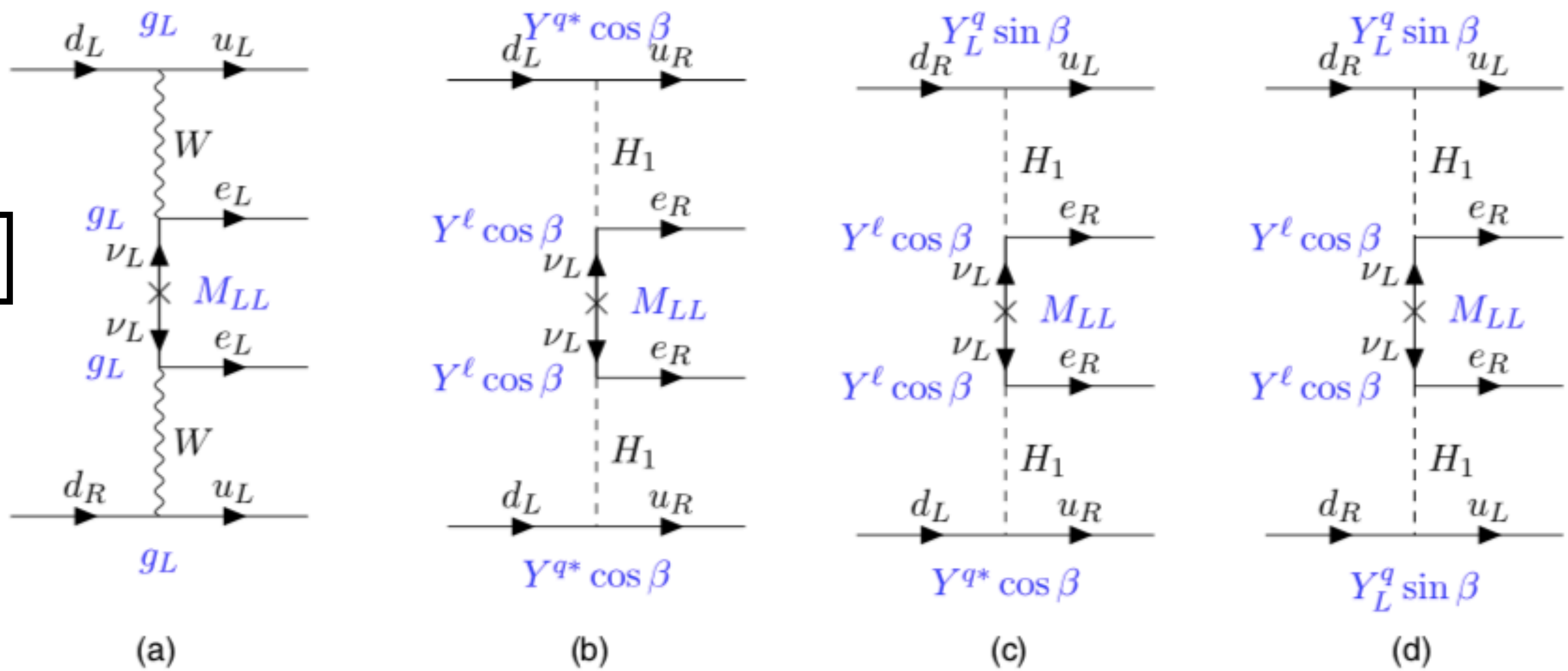
Half-life :

$$(T_{1/2}^{0\nu})^{-1} = G_{01} |\mathcal{M}_{\nu_L}^W \eta_{\nu_L}^W|^2 + G_{HH}^R |\mathcal{M}_{\nu_L}^H \eta_{\nu_L}^H|^2 + G_{HH}^L |\mathcal{M}_{\nu_R}^H \eta_{\nu_R}^H|^2 + G_{WH}^{LL} |\mathcal{M}_\lambda^{WH} \eta_\lambda^{WH}|^2 + G_{WH}^{LR} |\mathcal{M}_{\nu_L}^{WH} \eta_{\nu_L}^{WH}|^2$$

Standard Contribution

$(H_1 - H_1)$ mediation with $e_R - e_R$ emission

Fig.1 :



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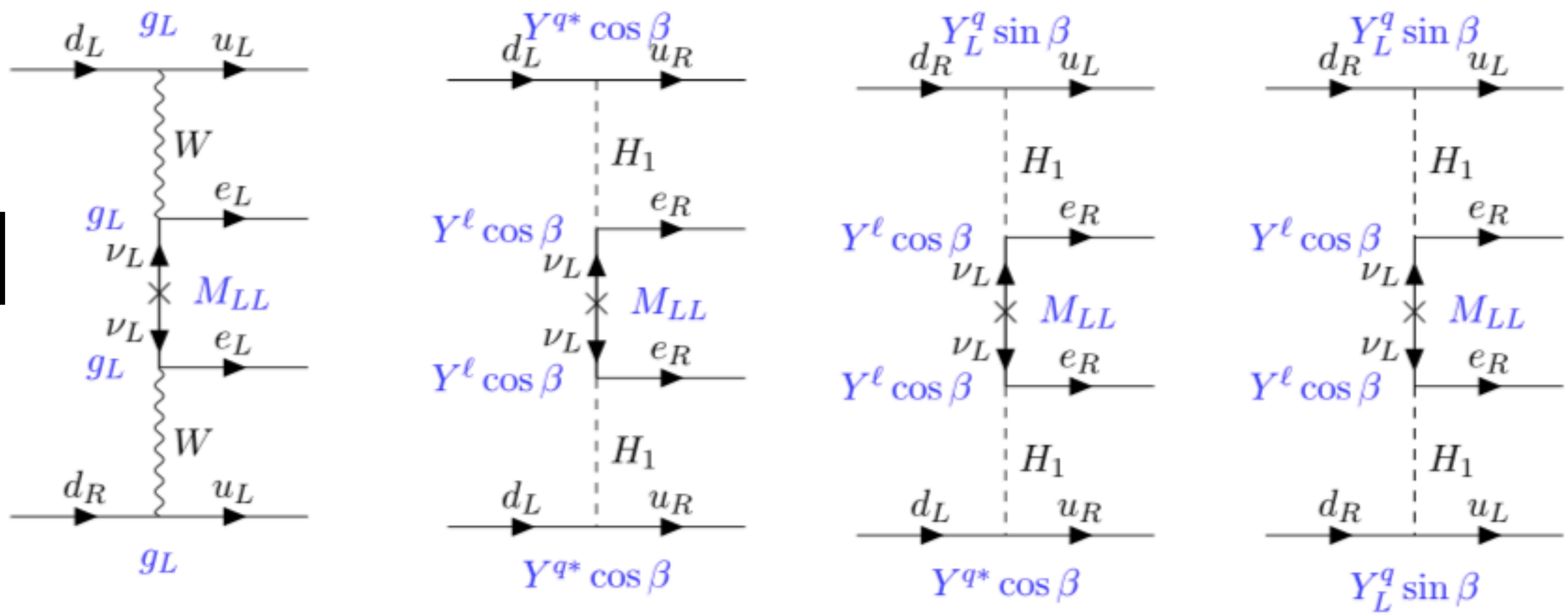


(a) (b) (c) (d)

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

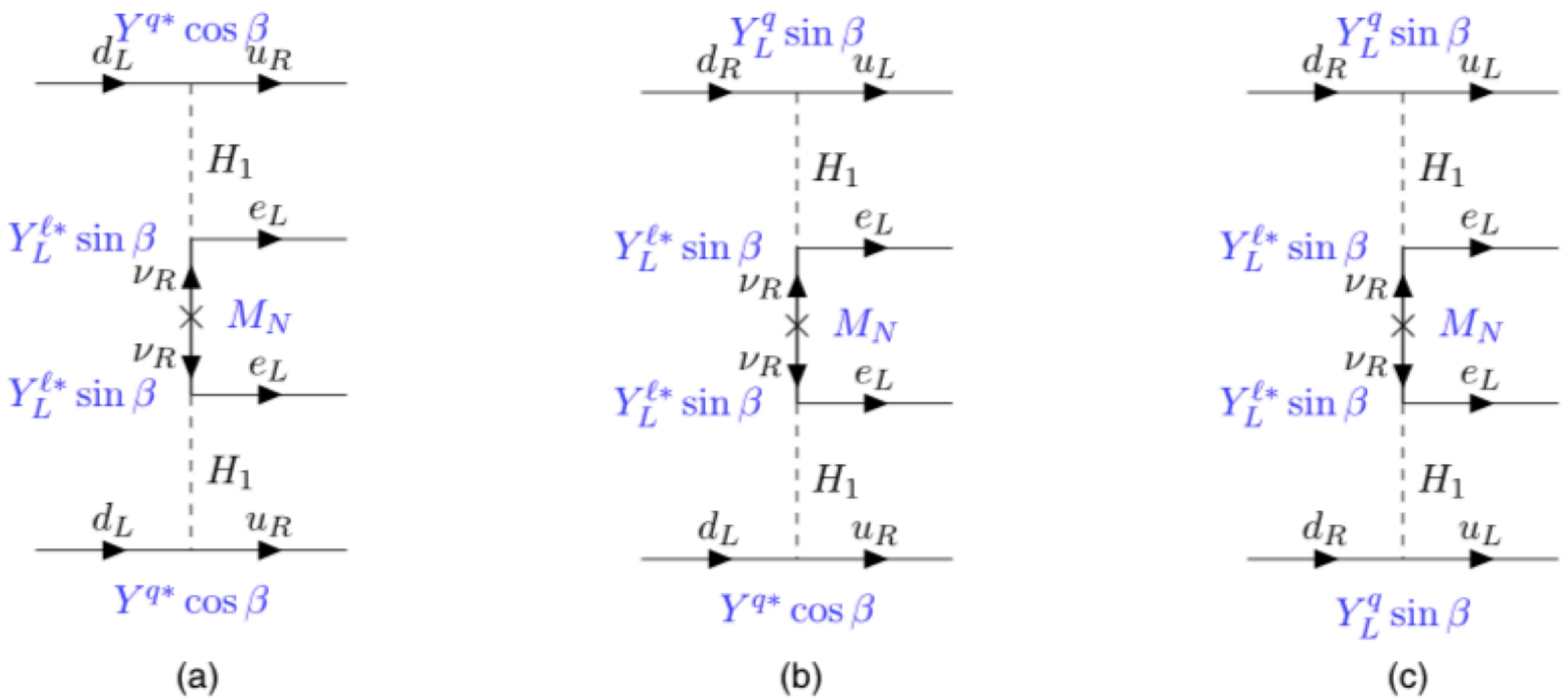
$$\mathscr{A}^{W_L W_L}_{LL,\nu_L} \sim G_F^2 \sum_i \left(\frac{\mathscr{V}^{\nu\nu^2}_{\alpha i} m_{\nu_i}}{p^2} - \frac{\mathscr{V}^{\nu N^2}_{\alpha i}}{m_{N_i}} \right)$$

$$\mathscr{A}^{H_1 H_1}_{\sigma\sigma',\nu_L} \sim \frac{G_F^2}{g_L^4} \frac{M^4_{W_L}}{M^4_{H_1}} \kappa^2_{ud} (Y^{\ell})^2 cos^2\beta \sum_i \left(\frac{\mathscr{V}^{\nu\nu 2}_{\alpha i} m_{\nu_i}}{p^2} - \frac{\mathscr{V}^{\nu N 2}_{\alpha i}}{m_{N_i}} \right)$$

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 : $\kappa^2_{ud} = Y^{q*} Y^q_L \cos\beta \sin\beta$

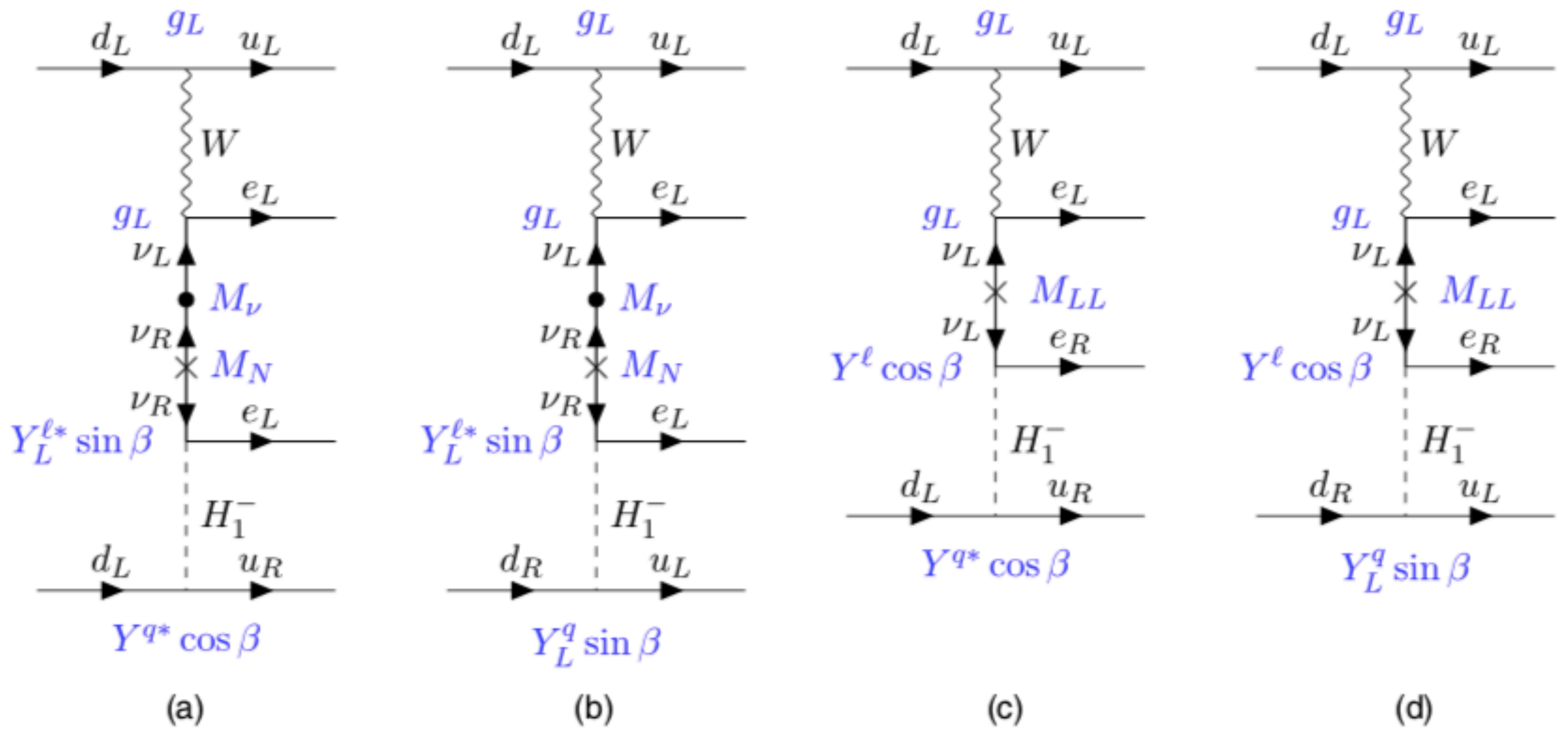
$(H_1 - H_1)$ mediation with $e_L - e_L$ emission

Fig.2 :



$(W_L - H_1)$ mediation with $e_L - e_L$ emission $\quad$ $(W_L - H_1)$ mediation with $e_L - e_R$ emission

Fig.3 :



- Significant contributions : Vector-scalar mediated diagrams.

$$T_{1/2}^{0\nu}(^{76}Ge) = 3.6 \times 10^{26} \left(\frac{M_{H_1}}{200 \text{ GeV}} \right)^4 \text{yrs},$$

$$T_{1/2}^{0\nu}(^{76}Xe) = 3.0 \times 10^{26} \left(\frac{M_{H_1}}{200 \text{ GeV}} \right)^4 \text{yrs}.$$

$\Downarrow$

Well within the sensitivity expected by experiments.

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.

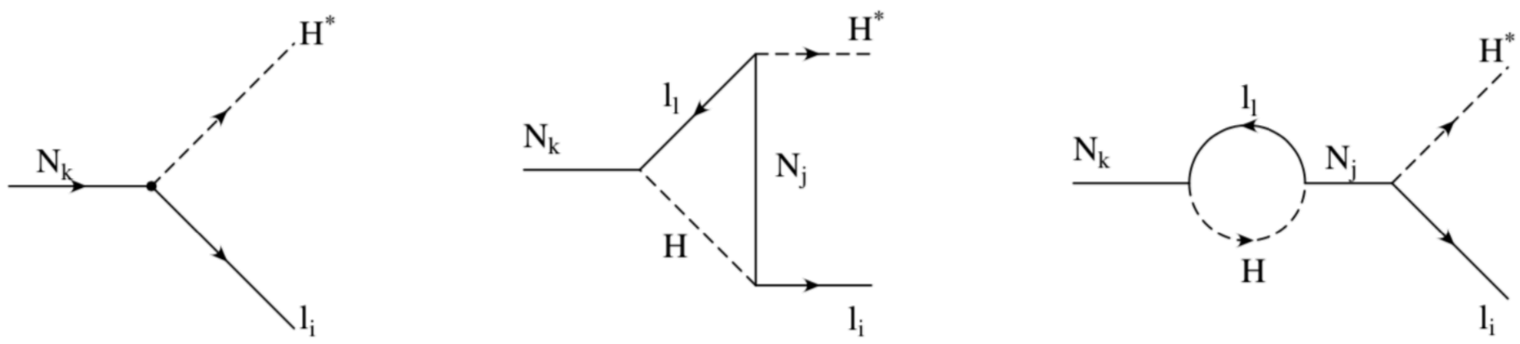
(ii) C and CP violation.

(iii) Departure from thermal equilibrium.

- Leptogenesis : Connecting BAU with neutrino mass generation.

Leptogenesis in ALRM

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



Leptogenesis in ALRM

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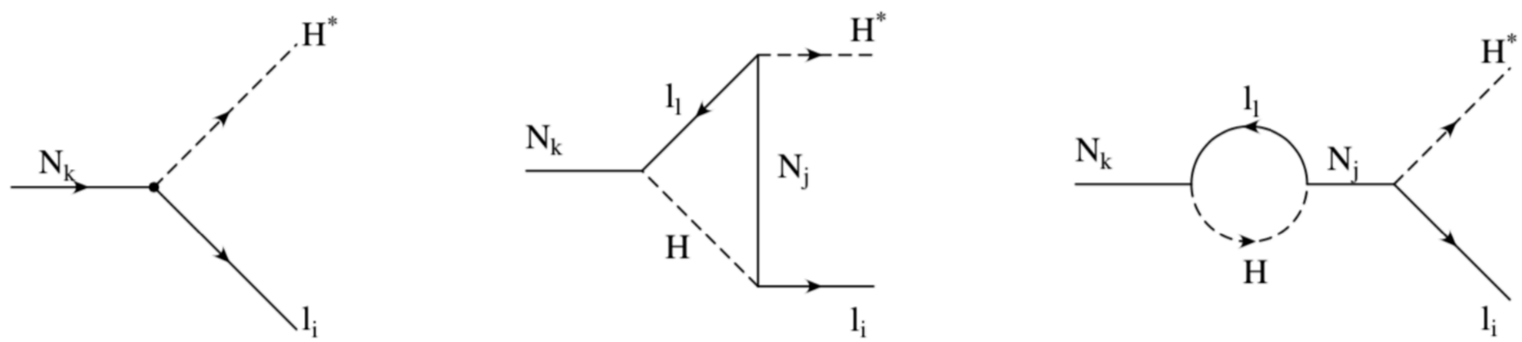
- CP-asymmetry is provided by complex Yukawa couplings through interference between tree and one-loop diagrams.



- Strongly hierarchical scenario i.e., $m_{N_1} \ll m_{N_{2,3}} \Rightarrow \epsilon_\nu \sim \epsilon_s$.
- 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 because we have considered $m_{N_1} = 10^4$ GeV !!!

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.

- We assume two right-handed neutrinos N_1 and N_2, which are quasi-degenerate, only contributing maximally to leptogenesis.
- Lepton Asymmetry : $\epsilon_s^{\nu N_1} \simeq \frac{S_{13}^2 C_{23}\left(S_{12}^2 S_{13} + C_{12}^2 S_{23}\right)\left[C_{23}\left(S_{12}^2 S_{13} - C_{12}^2 S_{23}\right) + S_{12} C_{12}\left(S_{23} - C_{23}^2 S_{12}\right)\right]}{\left(S_{12} S_{13} - C_{12} C_{23} S_{13}\right)^2 \left(C_{12} S_{23} + S_{12} C_{23} S_{13}\right)^2} \sin\delta_N.$
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Different Cases :

(a) $C_{ij} \sim \mathcal{O}(1) \gg S_{kl} \sim \mathcal{O}(0.01) \Rightarrow sin\delta_N \simeq 10^{-6}$, (b) $S_{ij} \sim \mathcal{O}(1) \gg C_{kl} \sim \mathcal{O}(0.01) \Rightarrow sin\delta_N \simeq 10^{-6}$,

(c) $C_{ij}, S_{ij} \sim \mathcal{O}(0.1) \Rightarrow sin\delta_N \simeq 10^{-5}$, (d) $S_{13} \sim S_{23} \sim \mathcal{O}(0.01), C_{12} \sim S_{12} \sim \frac{1}{\sqrt{2}} \Rightarrow sin\delta_N \simeq 6 \times 10^{-12}$.

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Minuscule Dirac CP phase in RHN sector can generate required leptogenesis to satisfy BAU constraint.

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

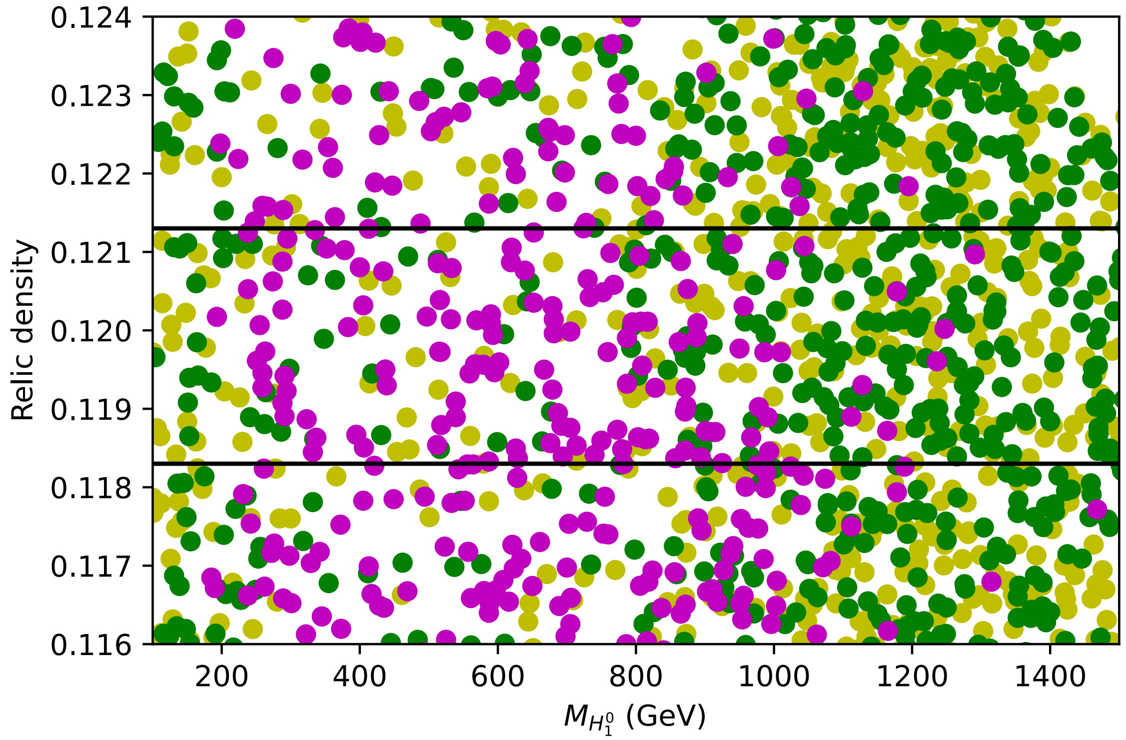
  Fermion sector : the scotinos n_L, n_R, and the exotic quarks, d'_L, d'_R

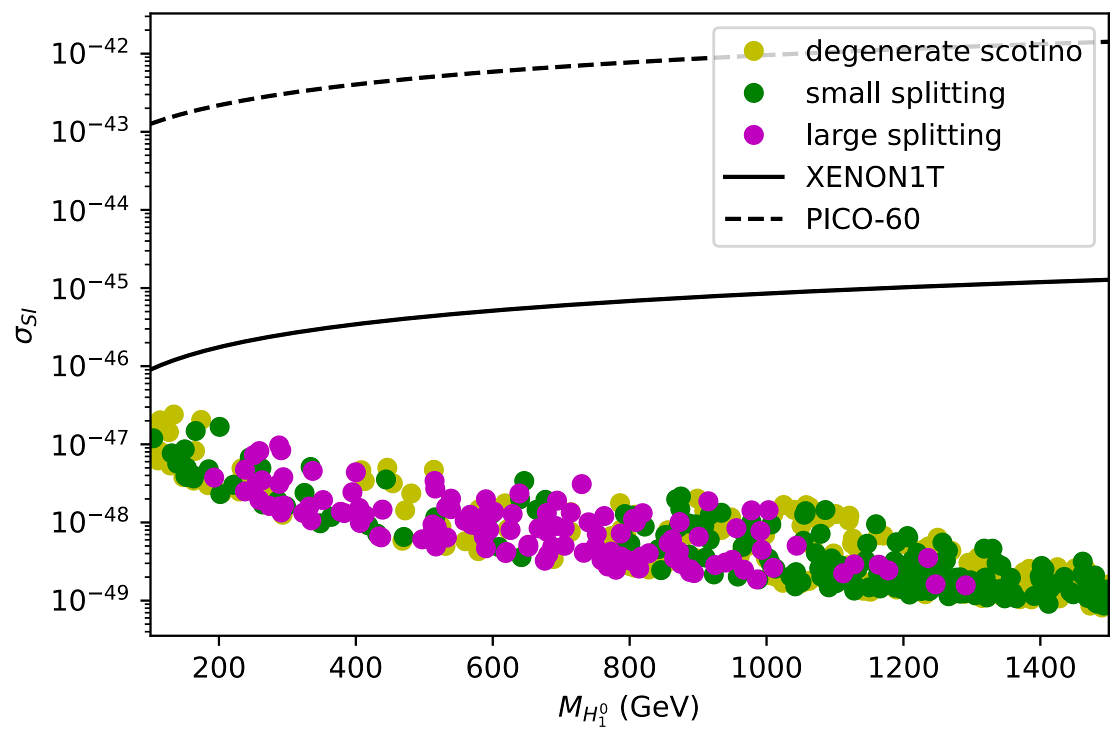
  Gauge sector : W_R

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

Scalar Dark Matter

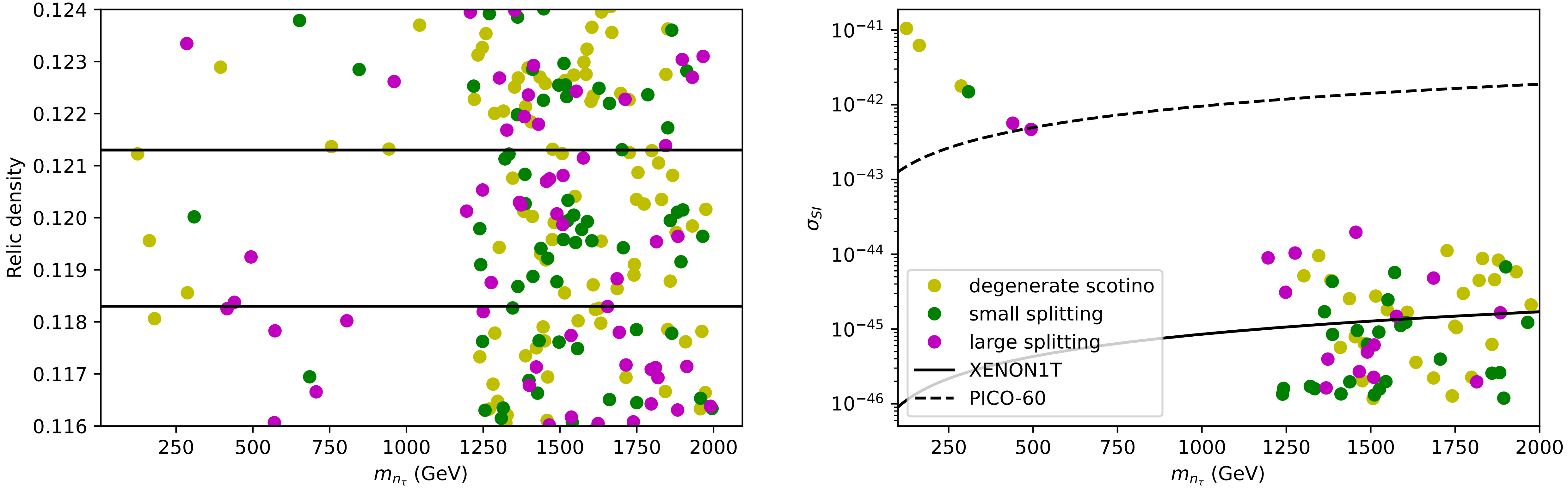
m_{n_e} and m_{n_μ}	
Case (i) (degenerate)	$m_{n_e} = m_{n_\mu} = m_{n_\tau}$
Case (ii) (small splitting)	$(m_{n_e} = m_{n_\mu}) - m_{n_\tau}$ = Range (10 keV–20 MeV)
Case (iii) (large splitting)	$(m_{n_e} = m_{n_\mu}) - m_{n_\tau}$ = Range (100 MeV–10 GeV)





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

Fermion Dark Matter



- We have light as well as heavy scalar DM or heavy fermion DM in ALRM depending on the mass hierarchy of the particles.

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

Collider Signatures

- The scalar dark matter, H_1^0/A_1, could be probed by the production through two exotic quarks $pp \to d'\overline{d'}$, followed by the decays into bH_1^0/A_1.

- Even considering that the background can be much larger, this signal can be probed at LHC with 300 fb^{-1}, and would be indicative of exotic d' quarks with masses in the TeV range.

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- The fermion dark matter, n_τ, could be produced through $pp \to H_2^+ H_2^- \to n_\tau n_\tau \tau^+ \tau^-$.

- Signals from the fermionic candidates imply the existence of charged Higgs bosons, all with masses in the TeV region. This signal can be probed at LHC with 300 fb^{-1} as well as 3000 fb^{-1} depends on the parameter choice of the models.

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

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Processes :

A. $pp \to W_R W_R \to 4j + \tau^+\tau^- + \text{MET}$

B. $pp \to W_R H_2^{\pm} \to 2j + \tau^+\tau^- + \text{MET}$

C. $pp \to W_R W_R + W_R H_2^{\pm} + H_2^+ H_2^- \to e^+ e^- + \text{MET}$

D. $pp \to W_R W_R + W_R H_2^{\pm} + H_2^+ H_2^- \to \tau^+\tau^- + \text{MET}$

E. $pp \to W_R W_R + W_R H_2^{\pm} + H_2^+ H_2^- \to 2j + e^- + \text{MET}$

Work in Progress !!!

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.
- 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.
- Model allows distinct and interesting detectable signatures in colliders.

Thank you for your attention!

Comments, Questions, Suggestions!!!

Backup Slide 1 :

$M_{H_1^0}$ (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
$M_{H_1^0} = M_{A_1}$	(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
$\lvert\mu_3\rvert$	(100 – 2000) GeV

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)

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