Phenomenological consequences for the seesaw type II mechanism in the left-right symmetric model

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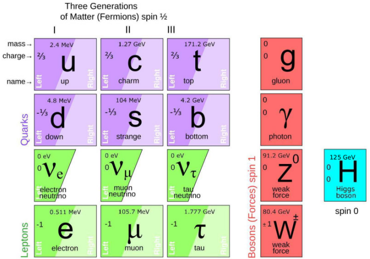
Introduction

SM can not solve

- the problem of neutrino masses
- the DM problem
- the problem of baryon asymmetry in the Universe (BAU)
- ...



M. Shaposhnikov, J. Phys. Conf. Ser. 408 (2013) 012015

Left-right simmetric models based on the group

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

can solve these problems

- the symmetry between right- and left-handed $SU(2)$ groups is restored
- the smallness of m_ν by seesaw mechanism and neutrino oscillations
- BAU ...

Minimal left-right-symmetric model

Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	New particles
$L_{iL} = \begin{pmatrix} \nu'_i \\ l'_i \end{pmatrix}_L$	1	2	1	-1	
$L_{iR} = \begin{pmatrix} \nu'_i \\ l'_i \end{pmatrix}_R$	1	1	2	-1	N_1, N_2, N_3
$Q_{iL[R]} = \begin{pmatrix} u'_i \\ d'_i \end{pmatrix}_{L[R]}$	3	2 [1]	1 [2]	1/3	
$W_L = \{W_L^+, W_L^-, W_L^3\}$	1	3	1	0	W_2
$W_R = \{W_R^+, W_R^-, W_R^3\}$	1	1	3	0	Z_2
B	1	1	1	0	
$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}$	1	2	2	0	H_{125} H_1^0, H_2^0, H_3^0
$\Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \delta_L^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$	1	3	1	2	A_1^0, A_2^0 $H_1^\pm, H_2^\pm$
$\Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \delta_R^0 & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix}$	1	1	3	2	$H_1^{\pm\pm}, H_2^{\pm\pm}$

Higgs potential

$$
\begin{aligned}
V(\phi, \Delta_L, \Delta_R) \quad = \quad & -\mu_1^2 \left(Tr[\phi^\dagger \phi] \right) - \mu_2^2 \left(Tr[\tilde{\phi} \phi^\dagger] + \left(Tr[\tilde{\phi}^\dagger \phi] \right) \right) - \mu_3^2 \left(Tr[\Delta_L \Delta_L^\dagger] + Tr[\Delta_R \Delta_R^\dagger] \right) \\
+ \quad & \lambda_1 \left(\left(Tr[\phi \phi^\dagger] \right)^2 \right) + \lambda_2 \left(\left(Tr[\tilde{\phi} \phi^\dagger] \right)^2 + \left(Tr[\tilde{\phi}^\dagger \phi] \right)^2 \right) + \lambda_3 \left(Tr[\tilde{\phi} \phi^\dagger] Tr[\tilde{\phi}^\dagger \phi] \right) \\
+ \quad & \lambda_4 \left(Tr[\phi \phi^\dagger] \left(Tr[\tilde{\phi} \phi^\dagger] + Tr[\tilde{\phi}^\dagger \phi] \right) \right) \\
+ \quad & \rho_1 \left(\left(Tr[\Delta_L \Delta_L^\dagger] \right)^2 + \left(Tr[\Delta_R \Delta_R^\dagger] \right)^2 \right) \\
+ \quad & \rho_2 \left(Tr[\Delta_L \Delta_L] Tr[\Delta_L^\dagger \Delta_L^\dagger] + Tr[\Delta_R \Delta_R] Tr[\Delta_R^\dagger \Delta_R^\dagger] \right) \\
+ \quad & \rho_3 \left(Tr[\Delta_L \Delta_L^\dagger] Tr[\Delta_R \Delta_R^\dagger] \right) \\
+ \quad & \rho_4 \left(Tr[\Delta_L \Delta_L] Tr[\Delta_R^\dagger \Delta_R^\dagger] + Tr[\Delta_L^\dagger \Delta_L^\dagger] Tr[\Delta_R \Delta_R] \right) \\
+ \quad & \alpha_1 \left(Tr[\phi \phi^\dagger] \left(Tr[\Delta_L \Delta_L^\dagger] + Tr[\Delta_R \Delta_R^\dagger] \right) \right) \\
+ \quad & \alpha_2 \left(Tr[\phi \tilde{\phi}^\dagger] Tr[\Delta_R \Delta_R^\dagger] + Tr[\phi^\dagger \tilde{\phi}] Tr[\Delta_L \Delta_L^\dagger] \right) \\
+ \quad & \alpha_2^* \left(Tr[\phi^\dagger \tilde{\phi}] Tr[\Delta_R \Delta_R^\dagger] + Tr[\tilde{\phi}^\dagger \phi] Tr[\Delta_L \Delta_L^\dagger] \right) \\
+ \quad & \alpha_3 \left(Tr[\phi \phi^\dagger \Delta_L \Delta_L^\dagger] + Tr[\phi^\dagger \phi \Delta_R \Delta_R^\dagger] \right) \\
+ \quad & \beta_1 \left(Tr[\phi \Delta_R \phi^\dagger \Delta_L^\dagger] + Tr[\phi^\dagger \Delta_L \phi \Delta_R^\dagger] \right) + \beta_2 \left(Tr[\tilde{\phi} \Delta_R \phi^\dagger \Delta_L^\dagger] + Tr[\tilde{\phi}^\dagger \Delta_L \phi \Delta_R^\dagger] \right) \\
+ \quad & \beta_3 \left(Tr[\phi \Delta_R \tilde{\phi}^\dagger \Delta_L^\dagger] + Tr[\phi^\dagger \Delta_L \tilde{\phi} \Delta_R^\dagger] \right), \qquad (1)
\end{aligned}
$$

GUT and/or SUSY: $\beta_i = 0$ or $\beta_i \simeq 0$

Symmetry breaking

1. The initial LR symmetry is spontaneously broken

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle \Delta_R \rangle} SU(2)_L \times U(1)_Y, \tag{2}$$

$$\langle \Delta_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad v_R \gtrsim \mathcal{O}(\text{TeV}) \tag{3}$$

2. The bidoublet and the left handed triplet acquire VEVs as a result of spontaneous symmetry breaking

$$SU(2)_L \times U(1)_Y \xrightarrow{\langle \phi \rangle, \langle \Delta_L \rangle} U(1)_Q, \tag{4}$$

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \qquad \langle \Delta_L \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix}, \tag{5}$$

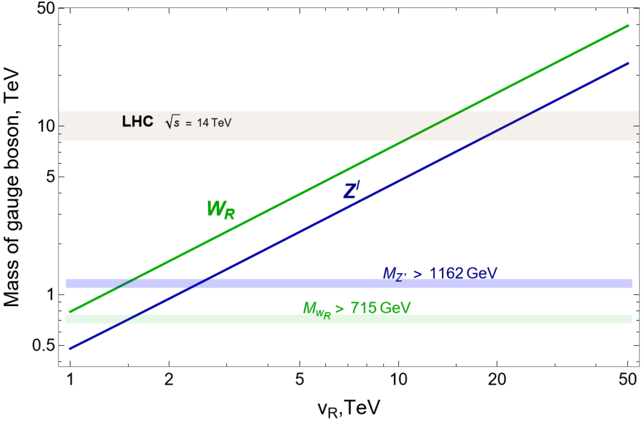
where $\sqrt{k_1^2 + k_2^2} = 246$ GeV,

$$v_L = \frac{1}{v_R} \frac{\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2}{(2\rho_1 - \rho_3)} \simeq 0 \qquad \text{VEV seesaw} \tag{6}$$

The value of the Δ_R-VEV, v_R

$$M^2_{W_{1,2}} = \frac{g^2}{4}\left[k_+^2 + v_R^2 \mp \sqrt{v_R^4 + 4\,k_1^2\,k_2^2}\,\right],$$

$$M^2_{Z_{1,2}} = \frac{1}{4}\left[\left[g^2 k_+^2 + 2v_R^2(g^2+g'^2)\right] \mp \sqrt{\left[g^2k_+^2 + 2v_R^2(g^2+g'^2)\right]^2 - 4g^2(g^2+2g'^2)\,k_+^2 v_R^2}\right]$$



Seesaw type II mechanism in neutrino sector

$$\mathcal{L} \supset (\overline{\nu_L} \ \ \overline{\nu_R^c}) M_\nu \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}, \quad \text{where} \quad M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \tag{7}$$

$$M_D = \frac{h_L k_1 + \tilde{h}_L k_2}{\sqrt{2}}, \qquad M_L = \sqrt{2} h_M v_L, \qquad M_R = \sqrt{2} h_M v_R, \tag{8}$$

$$\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = P_L \mathcal{U} \begin{pmatrix} \nu \\ N \end{pmatrix}, \qquad \begin{aligned} \nu_L &= U_{\text{PMNS}} P_L \nu + \Theta P_L N, \\ \nu_R &= -\theta^T U_\nu^* P_R \nu + U_N P_R N, \end{aligned} \tag{9}$$

where

$$\mathcal{U} = W \cdot \begin{pmatrix} U_\nu & 0 \\ 0 & U_N^* \end{pmatrix}, \quad W \simeq \begin{pmatrix} 1 - \frac{1}{2}\theta\theta^\dagger & \theta \\ -\theta^\dagger & 1 - \frac{1}{2}\theta^\dagger\theta \end{pmatrix}, \quad \theta \ll I, \qquad \begin{aligned} U_{\text{PMNS}} &\simeq (1 - 1/2\theta\theta^\dagger) U_\nu, \\ \Theta &\simeq \theta U_N^* \end{aligned}$$

$$m_\nu \simeq M_L - M_D M_R^{-1} M_D^T \qquad \text{seesaw II} \tag{10}$$

An active-sterile mixing matrix Θ can be parametrized as $(\Omega\Omega^T = I)$

$$\Theta = i U_{\text{PMNS}} \sqrt{\tilde{m}}\, \Omega \sqrt{\hat{M}}\, U_N^\dagger, \tag{11}$$

$$\text{where} \quad \tilde{m} = \hat{m} - U_{\text{PMNS}}^\dagger M_L U_{\text{PMNS}}^*, \qquad \text{or}^* \quad \tilde{m} = \hat{m} - \frac{v_L}{v_R} U_{\text{PMNS}}^\dagger \hat{M} U_{\text{PMNS}}^* \tag{12}$$

* in the approximation $\mathcal{O}(\theta^2) \ll 1$, $\hat{m} \ll \hat{M}$, $U_N = I$ Dubinin, Fedotova, Kazarkin, 2506.04035 [hep-ph]

Currents in lepton sector

$$L_{lep} = \bar{L}_I \gamma^\mu \left(i\partial_\mu + g_I \frac{\vec{\sigma}}{2} \cdot \vec{W}_{L\mu} + g' \frac{Y}{2} B_\mu \right) L_I, \qquad I = L, R \tag{13}$$

$$\mathcal{L}^{\nu}_{NC} = \frac{1}{2} \sum_{X=Z_1,Z_2} \overline{\nu} \gamma^\mu X_\mu \left[(U^\dagger U) a^L_X P_L + (U^T \Theta^*)(\Theta^T U^*) a^R_X P_R \right] \nu,$$

$$\mathcal{L}^{\nu}_{CC} = \frac{g}{\sqrt{2}} \sum_{X=W_1,W_2} \bar{l} \gamma^\mu X^-_\mu \left[U\, a^L_X P_L + (\Theta^T U^*) a^R_X P_R \right] \nu + \text{h.c.},$$

$$\mathcal{L}^{N}_{NC} = \frac{1}{2} \sum_{X=Z_1,Z_2} \overline{N} \gamma^\mu X_\mu \left[(\Theta^\dagger \Theta) a^L_X P_L + a^R_X P_R \right] N$$

$$+ \frac{1}{2} \left(\sum_{X=Z_1,Z_2} \overline{\nu} \gamma^\mu X_\mu \left[(U^\dagger \Theta) a^L_X P_L - (U^T \Theta^*) a^R_X P_R \right] N + \text{h.c.} \right),$$

$$\mathcal{L}^{N}_{CC} = \frac{g}{\sqrt{2}} \sum_{X=W_1,W_2} \bar{l} \gamma^\mu X^-_\mu (\Theta a^L_X P_L - a^R_X P_R) N + \text{h.c.},$$

where $U = U_{\text{PMNS}}$, $a^L_{W_1} = -a^R_{W_2} = \cos\xi$, $a^L_{W_2} = a^R_{W_1} = \sin\xi$, and

$$a^L_{Z_1} = e\left[t^{-1}_W c_\phi + t_W (c_\phi - c^{-1/2}_{2W} s_\phi) \right], \qquad a^R_{Z_1} = -e s_\phi \left[2c^{1/2}_{2W} s^{-1}_{2W} + t_W c^{-1/2}_{2W} \right],$$

$$a^L_{Z_2} = e\left[t^{-1}_W s_\phi + t_W (s_\phi + c^{-1/2}_{2W} c_\phi) \right], \qquad a^R_{Z_2} = e c_\phi \left[2c^{1/2}_{2W} s^{-1}_{2W} + t_W c^{-1/2}_{2W} \right],$$

$c_\phi = \cos\phi$, $s_{2W} = \sin 2\theta_W$, $t_W = \tan\theta_W$, $g = e/s_W$, θ_W is the Weinberg angle, ϕ, ξ are mixing angles in the gauge sector, $V^l_{L,R} = I$, $U_N = I$, $g_L = g_R = g$ Dubinin, Fedotova, Kazarkin, 2506.04035 [hep-ph]

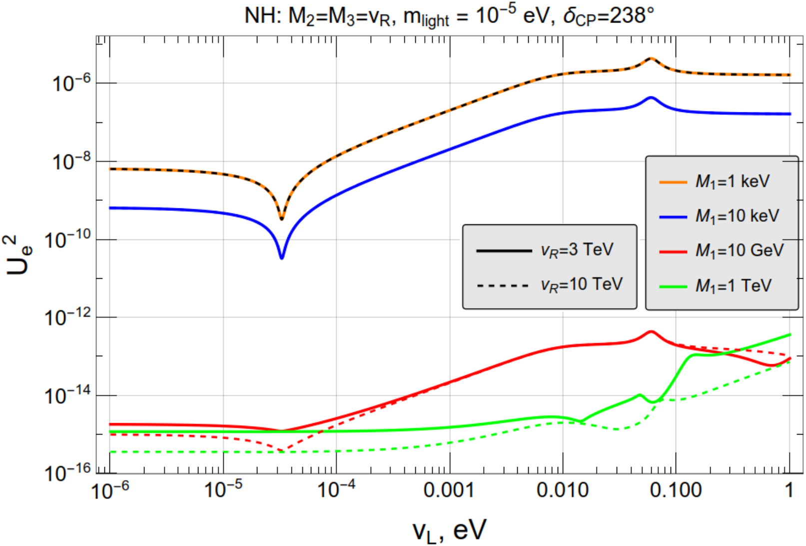
HNL phenomenology at low energy

Θ : $$\tilde{m} = \hat{m} - \frac{v_L}{v_R} U^{\dagger}_{\text{PMNS}} \hat{M} U^{*}_{\text{PMNS}},$$ $$\hat{m} = \text{diag}(m_1, m_2, m_3),$$ $$\hat{M} = \text{diag}(M_1, M_2, M_3)$$

	Case 1	Case 2		Case 3
If	$M_I \ll v_R$ and/or v_L=0	$M_I \sim v_R$, $v_L \ll m_i$	$v_L \sim m_i$	$M_1 \ll v_R$, $M_{2,3} \sim v_R$, $v_L \sim m_i$
then Θ_{MLRM}	$\tilde{m} \simeq \hat{m}$ $\Theta_{\nu\text{MSM}}$		strong sensitivity to v_L, eq. (11)	
Eff.theory at low $\sqrt{s}$	νMSM	SM		SM+N_1

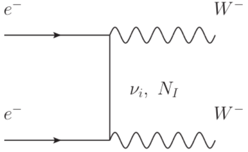
Mixing sensitivity to the Δ_L-VEV, v_L

$$U_{\alpha I}^2 = |\Theta_{\alpha I}|^2, \qquad U_\alpha^2 = \sum_I U_{\alpha I}^2$$

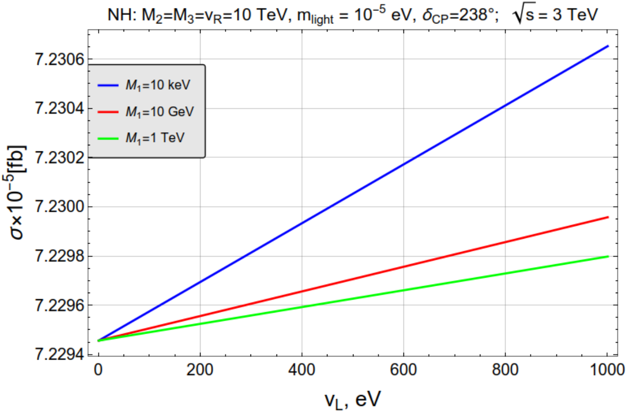


Inverse neutrinoless double beta decay, $i0\nu\beta\beta$

$$e^- e^- \to W^- W^-$$



The calculations are based on analytical formulas in Asaka, Tsuyuk, 1508.04937 [hep-ph]



Prospects and conclusions

We considered the minimal $SU(2)_R \times SU(2)_L \times U(1)$ model with a nonzero v_L

- We discussed three model regimes that correspond to such effective theories at low energies as νMSM, SM+HNL or SM. The phenomenological consequences are well studied in the literature.

- We found out that the mixing parameter strongly depends on v_L in the following cases

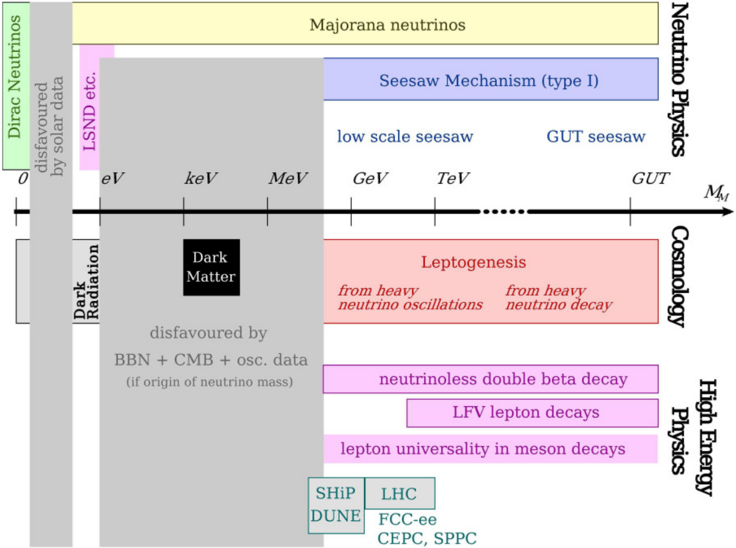
$$v_L \sim m_i \quad \text{and} \quad \text{(i) } M_{2,3} \sim v_R \qquad \text{or} \qquad \text{(ii) } M_{1,2,3} \sim v_R$$

- However, the dependence of $\sigma(e^- e^- \to W^- W^-)$ on v_L is extremely small. It seems that it is hardly possible to determine the value of v_L experimentally.
    - The calculation of $\sigma(e^- e^- \to W^- W^-)$ must be performed using a different method.
    - New processes need to be found and analyzed.

The research was carried out within the framework of the scientific program of the National Center for Physics and Mathematics, project “Particle Physics and Cosmology”

Thank you for your attention

N_1 as DM



Drewes, Garbrecht, 1502.00477 [hep-ph]

$$\nu\text{MSM}: \quad \Theta = iU_{\text{PMNS}}\sqrt{\hat{m}}\Omega\sqrt{\hat{M}}U_N^\dagger, \qquad \text{seesaw I} \tag{14}$$

Casas J., Ibarra A., Nucl.Phys.B 618 (2001) 171

$$\text{LRSM}: \quad \Theta = iU_{\text{PMNS}}\sqrt{\tilde{m}}\Omega\sqrt{\hat{M}}U_N^\dagger, \qquad \text{seesaw II} \tag{15}$$

Dubinin, Fedotova, Kazarkin, 2506.04035 [hep-ph]

where $\Omega\Omega^T = I$,

$$\hat{m} = \text{diag}(m_1, m_2, m_3), \qquad \hat{M} = \text{diag}(M_1, M_2, M_3)$$

$$g = \frac{e}{\sin\theta_W}, \qquad g' = \frac{e}{\sqrt{\cos 2\theta_W}}, \tag{16}$$

$$\tan 2\xi = -\frac{2k_1k_2}{v_R^2}, \qquad \sin 2\phi = -\frac{g^2k_+^2\sqrt{\cos 2\theta_W}}{2\cos^2\theta_W(M_{Z_2}^2 - M_{Z_1}^2)} \simeq -\frac{k_+^2(\cos 2\theta_W)^{3/2}}{2v_R^2\cos^4\theta_W} \tag{17}$$

Duka, Gluza, Zralek, hep-ph/9910279

$$\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix}$$

$$\begin{pmatrix} W_L^3 \\ W_R^3 \\ B \end{pmatrix} = \begin{pmatrix} c_W c_\phi & c_W s_\phi & s_W \\ -s_W s_M c_\phi - c_M s_\phi & -s_W s_M s_\phi + c_M c_\phi & c_W s_M \\ -s_W c_M c_\phi + s_M s_\phi & -s_W c_M s_\phi - s_M c_\phi & c_W c_M \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \\ A \end{pmatrix}$$

Duka, Gluza, Zralek, hep-ph/9910279

$$M^2_{H_0^0} \approx 2\,k_+^2\,\left(\lambda_1 + \frac{4k_1^2k_2^2}{k_+^4}(2\lambda_1+\lambda_3) + 2\lambda_4\frac{2k_1k_2}{k_+^2}\right),$$

$$M^2_{H_1^0} \approx \frac{1}{2}\,\alpha_3\,v_R^2\,\frac{k_+^2}{k_-^2}, \quad M^2_{H_2^0} \approx 2\,\rho_1\,v_R^2, \quad M^2_{H_3^0} = \frac{1}{2}v_R^2\,(\rho_3 - 2\rho_1),$$

$$M^2_{A_1^0} = \frac{\alpha_3\,v_R^2}{2}\,\frac{k_+^2}{k_-^2} - 2k_+^2(2\lambda_2 - \lambda_3), \quad M^2_{A_2^0} = \frac{1}{2}v_R^2(\rho_3 - 2\rho_1),$$

$$M^2_{H_1^\pm} = \frac{1}{4}(\alpha_3\,(k_-^2)) + \frac{1}{2}v_R^2(\rho_3 - 2\rho_1), \quad M^2_{H_2^\pm} = \frac{1}{4}\alpha_3\left(k_-^2 + 2\frac{k_+^2}{k_-^2}\,v_R^2\right),$$

$$M^2_{\delta_L^{\pm\pm}} = \frac{1}{2}\left(\alpha_3\,(k_-^2) + v_R^2(\rho_3 - 2\rho_1)\right), \quad M^2_{\delta_R^{\pm\pm}} = \frac{1}{2}\left(\alpha_3\,(k_-^2) + 4v_R^2\rho_2\right),$$

where $k_\pm^2 = k_1^2 \pm k_2^2$ $(k_+ = 246$ GeV$)$ Roitgrund, Eilam, Bar-Shalom, 1401.3345 [hep-ph]