

Non-standard spontaneous symmetry breaking in the scalar sector at eV and TeV scale

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Plan:

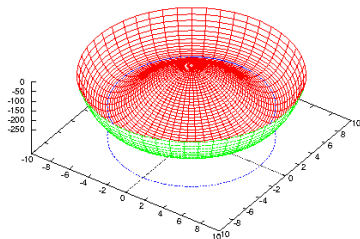
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Standard Model scalar potential

$$V = \mu^2 \phi^\dagger \phi + \frac{\lambda}{4} (\phi^\dagger \phi)^2$$

$$\phi_{\text{SM}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\phi + h_\phi + i z_\phi \end{pmatrix}$$

$$\langle \phi_{\text{SM}} \rangle = \sqrt{\frac{-2\mu^2}{\lambda}} = \frac{v}{\sqrt{2}}$$



$$v = 246 \text{ GeV}$$

Extensions of the SM

Extensions of the Standard Model

Two ways to extend the scalar sector:

Extensions of the Standard Model

Two ways to extend the scalar sector:

- Directly - introducing additional multiplets

Extensions of the Standard Model

Two ways to extend the scalar sector:

- Directly - introducing additional multiplets
- Indirectly - by extending the gauge group

Extensions of the Standard Model

- Left Right Symmetric Model (LRSM)

Extended gauge group: $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$.

In the most popular version for breaking the symmetry two additional triplets are introduced.

$$\Delta_{L,R} = \frac{1}{\sqrt{2}} \begin{pmatrix} w_{L,R}^+ & \sqrt{2}\delta_{L,R}^{++} \\ v_{L,R} + h_{L,R} + iz_{L,R} & -w_{L,R}^+ \end{pmatrix}$$

- Higgs Triplet Model (HTM)

One additional $SU(2)_L$ triplet

$$\Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} w_{\Delta}^+ & \sqrt{2}\delta^{++} \\ v_{\Delta} + h_{\Delta} + iz_{\Delta} & -w_{\Delta}^+ \end{pmatrix}$$

Extensions of the Standard Model

- Parameter ρ

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1.0008^{+0.0017}_{-0.0007}$$

$$\rho = \frac{\sum_i (T_i(T_i + 1) - T_{3i}^2) v_i}{2 \sum_i T_{3i}^2 v_i}$$

- For example for SM doublet $\phi : (T, T_3) = (\frac{1}{2}, \pm\frac{1}{2})$: $\rho = 1$
- For an additional $SU(2)_L$ triplet (Phys. Rev. D 21, 1404):

$$\rho = \frac{1 + \frac{2v_\Delta}{v_\phi}}{1 + \frac{4v_\Delta}{v_\phi}} \quad v_{\Delta\max} \sim \mathcal{O}(\text{GeV})$$

Extensions of the Standard Model

HTM	MLRSM
Type II See-Saw	Three heavy neutrinos
$SU(2) \times U(1)$	$SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ $W_1, W_2, Z_1, Z_2, \gamma$
$h, H, A, H^\pm, H^{\pm\pm}$	$h, H_1, H_2, H_3, A_1, A_2$ $H_1^\pm, H_2^\pm, H_1^{\pm\pm}, H_2^{\pm\pm}$
$v_\Delta \lesssim \text{GeV}$	$v_L = 0$ $v_R \gtrsim \text{TeV}$

eV, keV, GeV or TeV ???

Higgs Triplet Model (HTM)

HTM - Lagrangian

$$\begin{aligned} V = & -m_\phi^2 (\Phi^\dagger \Phi) + M^2 \text{Tr} (\Delta^\dagger \Delta) + \{ \mu (\Phi^T i \sigma_2 \Delta^\dagger \Phi) + \text{h.c.} \} \\ & + \frac{\lambda}{4} (\Phi^\dagger \Phi)^2 + \lambda_1 (\Phi^\dagger \Phi) \text{Tr} (\Delta^\dagger \Delta) + \lambda_2 \{ \text{Tr} (\Delta^\dagger \Delta) \}^2 \\ & + \lambda_3 \text{Tr} [(\Delta^\dagger \Delta)^2] + \lambda_4 (\Phi^\dagger \Delta \Delta^\dagger \Phi) \end{aligned}$$

HTM - Lagrangian

$$M_A^2 = \frac{\mu}{\sqrt{2}v_\Delta}(v_\Phi^2 + 4v_\Delta^2)$$

$$M_h^2 = \lambda v_\Phi^2 \cos^2 \alpha + \left(\frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} + 2v_\Delta^2(\lambda_2 + \lambda_3) \right) \sin^2 \alpha \\ + 2(v_\Phi v_\Delta(\lambda_1 + \lambda_4) - \sqrt{2}\mu v_\Phi) \cos \alpha \sin \alpha$$

$$M_H^2 = \lambda v_\Phi^2 \sin^2 \alpha + \left(\frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} + 2v_\Delta^2(\lambda_2 + \lambda_3) \right) \cos^2 \alpha \\ - 2(v_\Phi v_\Delta(\lambda_1 + \lambda_4) - \sqrt{2}\mu v_\Phi) \cos \alpha \sin \alpha$$

$$M_{H^\pm}^2 = \frac{(2\sqrt{2}\mu - \lambda_4 v_\Delta)}{4v_\Delta}(v_\Phi^2 + 2v_\Delta^2)$$

$$M_{H^{\pm\pm}}^2 = \frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} - \frac{\lambda_4}{2}v_\Phi^2 - \lambda_3 v_\Delta^2$$

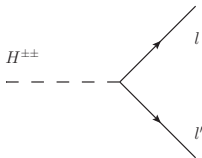
$$|M_{H^{\pm\pm}} - M_{H^\pm}| \leq 40 \text{ GeV}$$

1209.1303, 1206.0535

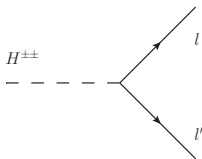
$H^{\pm\pm} - l - l'$ coupling

$$\mathcal{L}_Y = \frac{1}{2} f_{\ell\ell'} L_\ell^T C^{-1} i\sigma_2 \Delta L_{\ell'} + \text{h.c.}$$

$$\mathcal{L}_\nu = \frac{1}{2} \bar{\nu}_\ell \frac{v_\Delta}{\sqrt{2}} f_{\ell\ell'} \nu_{\ell'}$$



HTM - $H^{\pm\pm}$ - l - l' coupling



$$f = \frac{1}{\sqrt{2}v_\Delta} V_{PMNS}^* D_\nu V_{PMNS}^\dagger$$

$$D_\nu = \frac{1}{2} \text{diag}\{m_1, m_2, m_3\}$$

$$v_\Delta \iff f_{ll'} \iff \begin{array}{l} \text{Neutrino parameters} \\ \theta_{12}, \theta_{23}, \theta_{13}, \delta_{\text{CP}} \\ m_1, m_2, m_3 \end{array}$$

Left Right Symmetric Model (LRSM)

The Left-Right Symmetric Model

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

$$L_{iL} = \begin{pmatrix} \nu'_i \\ l'_i \end{pmatrix}_L, Q_{iL} = \begin{pmatrix} u'_i \\ d'_i \end{pmatrix}_L$$

$$L_{iR} = \begin{pmatrix} \nu_i \\ l_i \end{pmatrix}_R, Q_{iR} = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_R$$

Left Right Symmetric Model

- Two triplets under the $SU(2)_L$ and $SU(2)_R$ groups with hypercharge $Y = 2$:

$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$
$$\langle \Delta_{L,R} \rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R}/\sqrt{2} & 0 \end{pmatrix}$$

Left Right Symmetric Model

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- 7 gauge fields

$$\vec{W}_{L\mu}, \vec{W}_{R\mu}, B_\mu, \vec{W}_{1\mu}, W_2^\pm, Z_1, Z_2, \gamma$$

[SSB]

Left Right Symmetric Model

- Two triplets under the $SU(2)_L$ and $SU(2)_R$ groups with hypercharge $Y = 2$:

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$$\langle \Delta_{L,R} \rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R}/\sqrt{2} & 0 \end{pmatrix}$$

- 7 gauge fields

$$\vec{W}_{L\mu}, \vec{W}_{R\mu}, B_\mu, \overrightarrow{[SSB]} W_1^\pm, W_2^\pm, Z_1, Z_2, \gamma$$

$$M_{W_2} \simeq 0.47 v_R, \quad M_{Z_2} \simeq 0.78 v_R$$

LRSM - Lagrangian

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

LRSM - Lagrangian

$$L_Y^l = -\bar{L}_R^c i\sigma_2 \Delta_L h_M L_L - \bar{L}_R^c i\sigma_2 \Delta_R h_M L_L + h.c.$$



LRSM - Lagrangian

$$L_Y^l = -\bar{L}_R^c i\sigma_2 \Delta_L h_M L_L - \bar{L}_R^c i\sigma_2 \Delta_R h_M L_L + h.c.$$

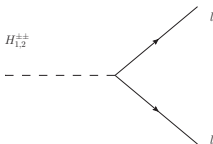


- See-saw mechanism: 3 light and 3 heavy neutrino states:

$$\nu_e, \nu_\mu, \nu_\tau, \\ N_1, N_2, N_3$$

LRSM - $H^{\pm\pm}$ - l - l' coupling

$$L_Y^l = -\bar{L}_R^c i\sigma_2 \Delta_L h_M L_L - \bar{L}_R^c i\sigma_2 \Delta_R h_M L_L + h.c.$$



$$f = \frac{2}{\sqrt{2}v_R} M_{Ni}$$

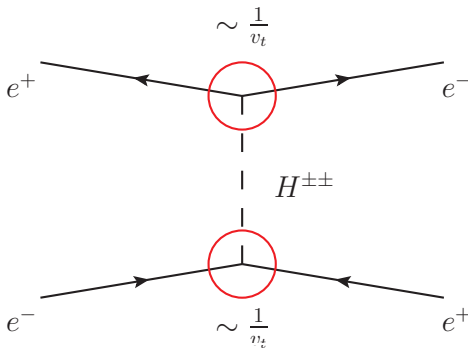
Experimental constraints on LFV vertices

Experimental constraints

- High energy:

- Bhabha scattering: $f_{ee}^2 \leq 6.0 \times 10^{-6} M_{H^{\pm\pm}}$

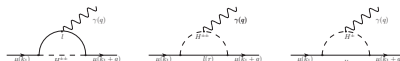
[Phys.Rev. D40 (1989) 1521] , [hep-ph/0304069]



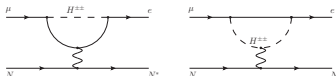
Experimental constraints

- Low energy:

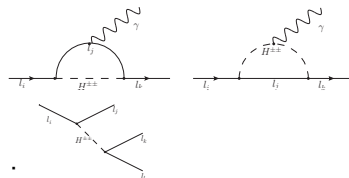
- $(g - 2)_\mu$ contribution:



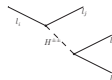
- μ to e conversion:



- Radiative LFV decays:



- LFV three body decays :



Experimental constraints

- $(g - 2)_\mu$

$$\Delta a_{(\mu g-2)} = (29.3 \pm 9.0) \times 10^{-10}$$

- μ to e (for Au)

$$\text{BR}(\mu N \rightarrow e N^*) < 7.0 \times 10^{-13}$$

- Radiative LFV decays

$$\text{BR}(\mu \rightarrow e \gamma) < 5.7 \times 10^{-13}$$

$$\text{BR}(\tau \rightarrow e \gamma) < 3.3 \times 10^{-8}$$

$$\text{BR}(\tau \rightarrow \mu \gamma) < 4.4 \times 10^{-8}$$

- LFV three body decays

$$\text{BR}(\tau \rightarrow \mu \gamma) < 4.4 \times 10^{-8}$$

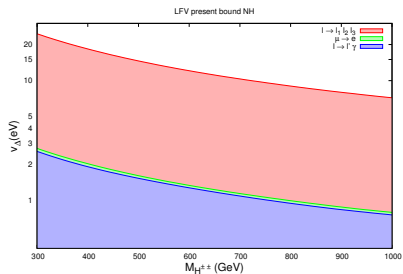
$$\text{BR}(\tau \rightarrow 3\mu) < 2.1 \times 10^{-8}$$

[arXiv:1512.03581] , $\text{BR}(\tau \rightarrow e \mu^+ \mu^-) < 2.7 \times 10^{-8}$

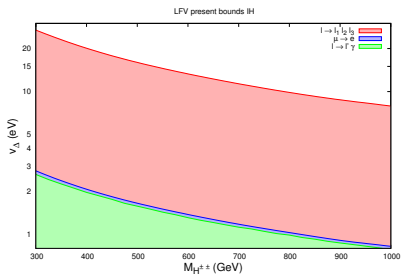
[Nucl. Phys. B299 (1988) 1-6] $\text{BR}(\mu \rightarrow 3e) < 1.0 \times 10^{-12}$

v_Δ vs $M_{H^{\pm\pm}}$

NH

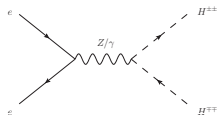


IH

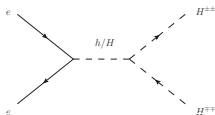


HTM vs LRSM

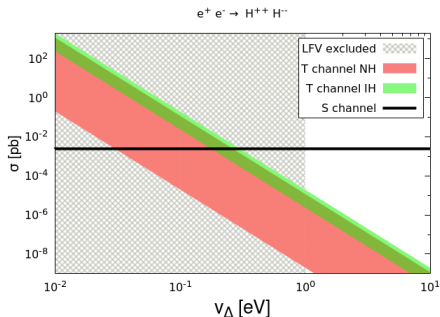
$H^{\pm\pm}$ pair production in e^+e^- colliders



HTM



LRSM

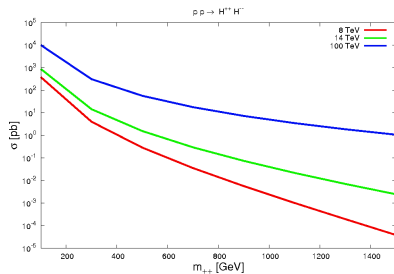


$$S = 1.57 \times 10^{-3} \text{ pb}$$

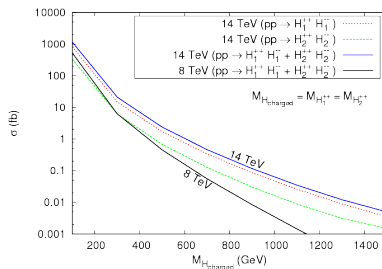
$$T = 1.01 \times 10^{-8} \text{ pb}$$

$H^{\pm\pm}$ pair production in hadron colliders

HTM



LRSM

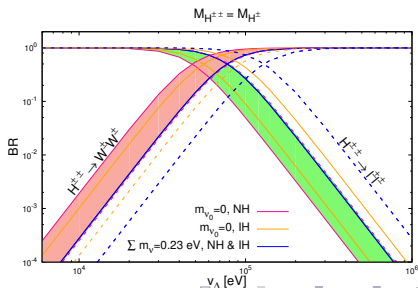
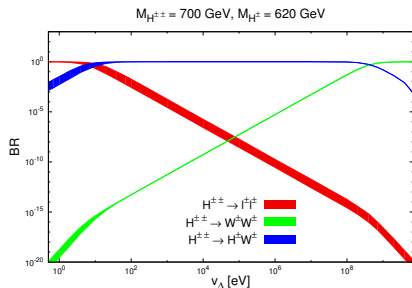


arXiv:1311.4144

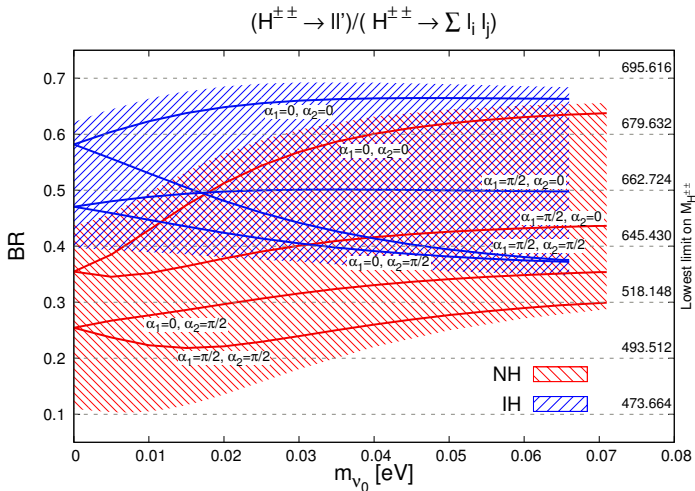
$H^{\pm\pm}$ decays

$H^{\pm\pm}$ decay

- $H^{\pm\pm} \rightarrow l_i l_j$
- $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$
- $H^{\pm\pm} \rightarrow H^{\pm} W^{\pm}$
- $H^{\pm\pm} \rightarrow H^{\pm} H^{\pm}$



$H^{\pm\pm}$ decay - HTM



$H_{1,2}^{\pm\pm}$ decay - LRSM

$H_1^{\pm\pm} \rightarrow H_1^\pm + W_1^\pm$	$H_2^{\pm\pm} \rightarrow W_2^\pm + W_2^\pm$ $H_2^{\pm\pm} \rightarrow H_2^\pm + W_2^\pm$ $H_2^{\pm\pm} \rightarrow H_2^\pm + H_2^\pm$
$H_{1,2}^{\pm\pm} \rightarrow l_i + l_i$	

4l signal

4-leptons signal in e^+e^- colliders

Luminosity 1500 fb^{-1} , $\sqrt{s} = 1500 \text{ TeV}$,
 $M_{H^{\pm\pm}} = 700 \text{ GeV}$

signal	SM	HTM		LRSM
		NH	IH	
$eeee$	235.0	28.2	87.1	130.5
$\mu\mu\mu\mu$	6.9	160.9	106.9	197.4

Summary

- $H^{\pm\pm}$ pair production in colliders gives possibility for clean BSM 4l signals
- For $\theta_{13} \neq 0$ the strongest limit on v_t comes from the $\mu \rightarrow 3e$ LFV process
- T channel contribution to the $H^{\pm\pm}$ pair production in lepton colliders is negligible due to the low energy constraints
- Heavy gauge bosons (RH currents) do not influence the pair $H^{\pm\pm}$ production
- 4-lepton signal in lepton and hadron colliders might distinguish between HTM and LRSM

Thank you for your attention

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4 lepton - cuts

- Parton Distribution Factor (PDF): CTEQ6L1
- Lepton identification: $p_T \geq 10 \text{ GeV}$, $|\eta| < 2.5$
- Detector efficiency for electron (muon): 70% (90%)
- Lepton-lepton separation: $\Delta R_{ll} \geq 0.2$
- Lepton-photon separation $\Delta R_{l\gamma} \geq 0.2$ with $p_{T_\gamma} > 10 \text{ GeV}$
- Lepton-jet separation $\Delta R_{lj} \geq 0.4$
- Hadronic activity cut: $\sum p_{T_{hadron}} \geq 0.2 \times p_{T_l}$
- Z-veto: $|m_{l_1 l_2} - M_{Z_1}| \geq 6 \Gamma_{Z_1}$

$$V_{PMNS} = \begin{bmatrix} c_{12}c_{13}e^{i\alpha_1} & s_{12}c_{13}e^{i\alpha_2} & s_{13}e^{-i\delta_{CP}} \\ (-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_1} & (c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_2} & s_{23}c_{13} \\ (s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_1} & (-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_2} & c_{23}c_{13} \end{bmatrix} \quad (1)$$

ρ and T parameters

$$\Delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

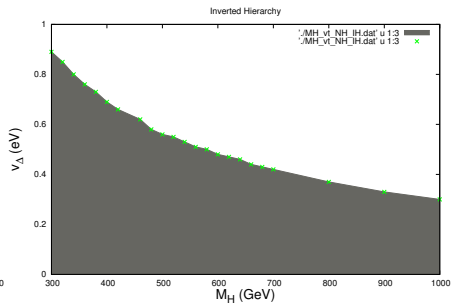
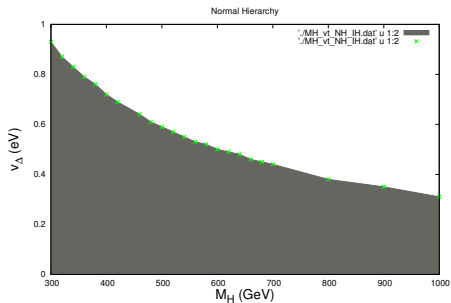
$$T = \frac{1}{\alpha} \left(\frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} \right) = \frac{\rho - 1}{\alpha} = 0.05 \pm 0.12$$

$$\Delta T = \frac{1}{4\pi \sin^2 \theta_W M_W^2} (F(M_{H^\pm}^2, M_A^2) + F(M_{H^{\pm\pm}}^2, M_{H^\pm}^2))$$

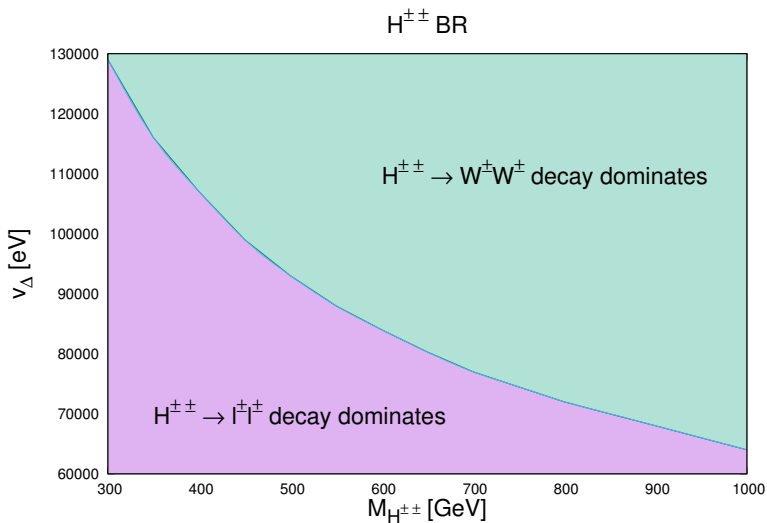
$$\Delta T < 0.2$$

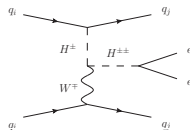
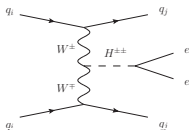
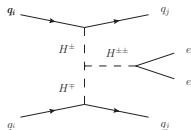
$$F(x, y) = \frac{x + y}{2} - \frac{xy}{x - y} \ln \left(\frac{x}{y} \right)$$

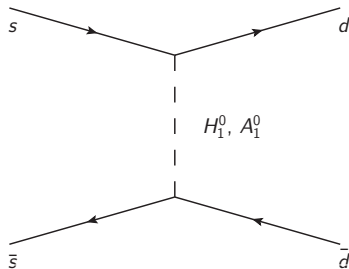
$$(g - 2)_\mu$$



$H^{\pm\pm}$ decay







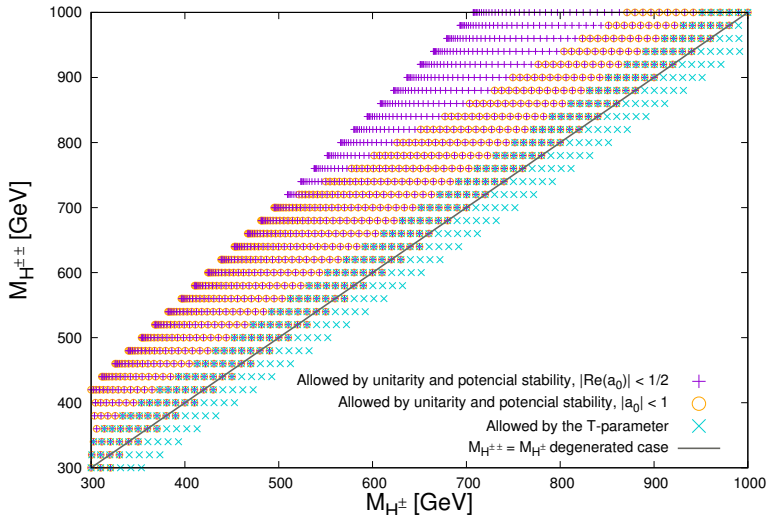
Potential stability

$$\begin{aligned}
 & \lambda > 0 \\
 & \lambda_2 + \lambda_3 \geq 0 \\
 & \lambda_2 + \frac{\lambda_3}{2} \geq 0 \\
 & \lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \\
 & \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \\
 & \left[\begin{array}{l} |\lambda_4| \sqrt{\lambda_2 + \lambda_3} - \lambda_3 \sqrt{\lambda} \geq 0 \\ \text{or } 2\lambda_1 + \lambda_4 + \sqrt{(2\lambda\lambda_3 - \lambda_4^2) \left(\frac{2\lambda_2}{\lambda_3} + 1 \right)} \geq 0 \end{array} \right]
 \end{aligned}$$

Unitarity

$$\begin{aligned} \left| (\lambda + 4\lambda_2 + 8\lambda_3) \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2} \right| &\leq 64\pi \\ \left| (3\lambda + 16\lambda_2 + 12\lambda_3) \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2} \right| &\leq 64\pi \\ |\lambda| &\leq 32\pi \\ |2\lambda_1 + 3\lambda_4| &\leq 32\pi \\ |2\lambda_1 - \lambda_4| &\leq 32\pi \\ |\lambda_1| &\leq 16\pi \\ |\lambda_1 + \lambda_4| &\leq 16\pi \\ |2\lambda_2 - \lambda_3| &\leq 16\pi \\ |\lambda_2| &\leq 8\pi \\ |\lambda_2 + \lambda_3| &\leq 8\pi \end{aligned}$$

Unitarity, stability

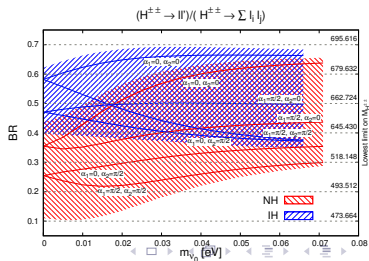
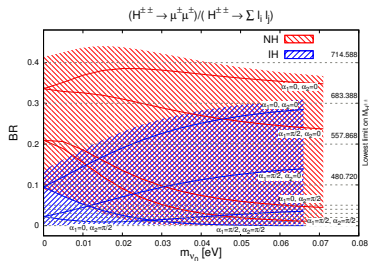
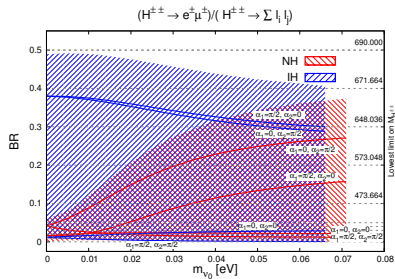
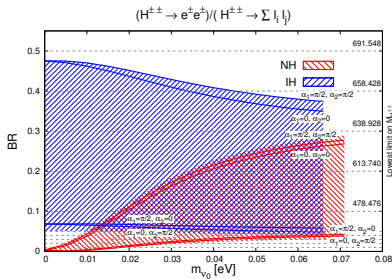


Neutrino oscillation data

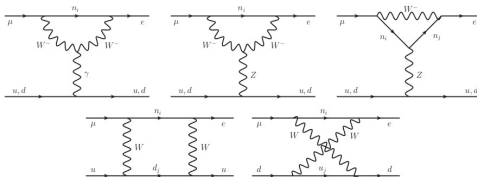
	Normal hierarchy			Inverted hierarchy		
	Best fit:	σ	bfp $\pm 2\sigma$	Best fit:	σ	bfp $\pm 2\sigma$
$\sin^2 \theta_{12}$	0.306	$+0.012$ -0.012	$0.282 \div 0.330$	0.306	$+0.012$ -0.012	$0.282 \div 0.330$
$\sin^2 \theta_{23}$	0.441	$+0.027$ -0.021	$0.399 \div 0.495$	0.587	$+0.020$ -0.024	$0.539 \div 0.627$
$\sin^2 \theta_{13}$	0.02166	$+0.00075$ -0.00075	$0.02016 \div 0.02316$	0.02179	$+0.00076$ -0.00076	$0.02027 \div 0.02331$
$\delta_{CP} [^\circ]$	261	$+51$ -59	$143 \div 363$	277	$+40$ -46	$185 \div 357$
$\frac{\Delta m_{21}^2}{10^{-5} \text{eV}^2}$	7.50	$+0.19$ -0.17	$7.16 \div 7.88$	7.50	$+0.19$ -0.17	$7.16 \div 7.88$
$\frac{\Delta m_{3l}^2}{10^{-3} \text{eV}^2}$	+2.524	$+0.039$ -0.040	$2.445 \div 2.602$	-2.514	$+0.038$ -0.041	$-2.596 \div -2.438$

[www.nu-fit.org , [arXiv:1611.01514](https://arxiv.org/abs/1611.01514)]

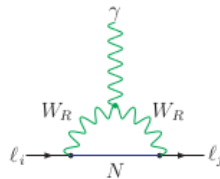
$H^{\pm\pm}$ decay



LFV - LRSM



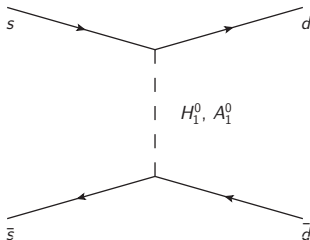
arXiv:1209.2679



arXiv:1309.0774

Flavour Changing Neutral Currents

$$\mathcal{L}_Y = Y_u \bar{Q}_{iL} \phi Q_{iR} + Y_d \bar{Q}_{iRL} \tilde{\phi} Q_{iR} + h.c$$



Left Right Symmetric Model

- Mixing angle:

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

$$\tan 2\xi = -\frac{2\kappa_1\kappa_2}{v_R^2}$$

- Gauge boson masses:

$$M_{W_1}^2 \simeq \frac{g^2}{4} \kappa_+^2 \left(1 - \frac{(\kappa_1\kappa_2)^2}{\kappa_+^2 v_R^2} \right) \sim \kappa_+^2$$

$$M_{W_2}^2 \simeq \frac{g^2 v_R^2}{2} \sim v_R^2$$

$$M_{Z_1}^2 \simeq \frac{g^2 \kappa_+^2}{4 \cos^2 \Theta_W} \left(1 - \frac{\cos^2 2\Theta_W \kappa_+^2}{2 \cos^4 \Theta_W v_R^2} \right)$$

$$M_{Z_2}^2 \simeq \frac{v_R^2 g^2 \cos^2 \Theta_W}{\cos 2\Theta_W}$$

$$\kappa_+ = \sqrt{\kappa_1^2 + \kappa_2^2}$$

$f_{\prime\prime}$ coupling and parameter's constraints

- $10^{-7} \leq f_{\prime\prime} \leq \sqrt{4\pi}$ [hep-ex/0309076]
- $v_{\Delta} \sim 1 \text{ GeV}$ [Phys.Rev. D21 (Mar, 1980) 1404-1409], [arXiv:0712.4053]

$$\rho = \frac{M_W^2}{M_Z^2 \cos \theta_W} = \frac{1 + 2 \frac{v_{\Delta}^2}{v_{\phi}^2}}{1 + 4 \frac{v_{\Delta}^2}{v_{\phi}^2}} = 1.00040 \pm 0.00024$$

- $\sum m_i \leq 2 \text{ eV}$ - Tritium decay [PDG]
 $\sum m_i \leq 0.23 \text{ eV}$ - astrophysics [arXiv:1303.5076]

The Left-Right Symmetric Model

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

$$L_{iL} = \begin{pmatrix} \nu'_i \\ l'_i \end{pmatrix}_L, Q_{iL} = \begin{pmatrix} u'_i \\ d'_i \end{pmatrix}_L$$

$$L_{iR} = \begin{pmatrix} \nu_i \\ l_i \end{pmatrix}_R, Q_{iR} = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_R$$

Left Right Symmetric Model

- One bidoublet two triplets:

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}$$
$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

- VEV for neutral scalar fields:

$$\langle \varphi \rangle = \begin{pmatrix} \kappa_1/\sqrt{2} & 0 \\ 0 & \kappa_2/\sqrt{2} \end{pmatrix}$$
$$\langle \Delta_{L,R} \rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R}/\sqrt{2} & 0 \end{pmatrix}$$

Left Right Symmetric Model

- Gauge transformation:

$$\psi_L \rightarrow \left[e^{-ig' \frac{Y}{2} \Theta(x) - i g_L \frac{\vec{\sigma}}{2} \vec{\Theta}(x)} \right] \psi_L$$

$$\psi_R \rightarrow \left[e^{-ig' \frac{Y}{2} \Theta(x) - i g_R \frac{\vec{\sigma}}{2} \vec{\Theta}(x)} \right] \psi_R$$

- Covariant derivative:

$$D_\mu \psi_L = \left(\partial_\mu - ig' \frac{Y}{2} B_\mu - ig_L \frac{\vec{\sigma}}{2} \vec{W}_{L\mu} \right) \psi_L,$$

$$D_\mu \psi_R = \left(\partial_\mu - ig' \frac{Y}{2} B_\mu - ig_R \frac{\vec{\sigma}}{2} \vec{W}_{R\mu} \right) \psi_R,$$

- 7 gauge fields

$$\vec{W}_{L\mu}, \vec{W}_{R\mu}, B_\mu, \overrightarrow{[SSB]} W_1^\pm, W_2^\pm, Z_1, Z_2, \gamma$$

Left Right Symmetric Model

- Mixing angle:

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

$$\tan 2\xi = -\frac{2\kappa_1\kappa_2}{v_R^2}$$

- Gauge boson masses:

$$M_{W_1}^2 \simeq \frac{g^2}{4} \kappa_+^2 \left(1 - \frac{(\kappa_1\kappa_2)^2}{\kappa_+^2 v_R^2} \right) \sim \kappa_+^2$$

$$M_{W_2}^2 \simeq \frac{g^2 v_R^2}{2} \sim v_R^2$$

$$M_{Z_1}^2 \simeq \frac{g^2 \kappa_+^2}{4 \cos^2 \Theta_W} \left(1 - \frac{\cos^2 2\Theta_W \kappa_+^2}{2 \cos^4 \Theta_W v_R^2} \right)$$

$$M_{Z_2}^2 \simeq \frac{v_R^2 g^2 \cos^2 \Theta_W}{\cos 2\Theta_W}$$

$$\kappa_+ = \sqrt{\kappa_1^2 + \kappa_2^2}$$

LRSM - Lagrangian

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

LRSM - Lagrangian

$$L_Y^I = -\bar{L}_R^c i\sigma_2 \Delta_L h_M L_L - \bar{L}_R^c i\sigma_2 \Delta_R h_M L_L + h.c.$$



$$L_{\text{mass}}^\nu = -\frac{1}{2} (\bar{n}_L'^c M_\nu n_{R'} + \bar{n}_R'^c M_\nu n_L')$$

$$n_{R'} = \begin{pmatrix} \nu_{R'}'^c \\ \nu_{R'}' \end{pmatrix} \quad n_L' = \begin{pmatrix} \nu_L'^c \\ \nu_L' \end{pmatrix}$$

See-saw mechanism

- Mass matrix for neutrinos:

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R(v_R) \end{pmatrix}$$

- $M_D = \frac{1}{\sqrt{2}}(h_I \kappa_1 + \tilde{h}_I \kappa_2)$
 $M_R = \sqrt{2} h_M v_R, h_M^T = h_M$
- $M_D \ll M_R$

$$\begin{aligned} m_N &\sim M_R \\ m_\nu &\sim M_D^2 / M_R \end{aligned}$$

Experimental limits for models parameters

- $M_{W_2} \geq 2.8 \text{ TeV}$ (CMS Collaboration [arXiv:1212.6175], ATLAS Collaboration [arXiv:1209.2535])
 $M_{W_2} \simeq 0.47 v_R, \quad M_{Z_2} \simeq 0.78 v_R$
- $M_{H_0^3} \geq 55.4 \text{ GeV}$ (Anindya Datta, Amitava Raychaudhuri [hep-ph/9905421])
- $H_1^0, A_1^0 \sim 10 \text{ TeV}$ (M.E.Pospelov, [hep-ph/9611422])
- $M_{H^{\pm\pm}} \geq 870 \text{ GeV}$