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

Magdalena Kordiaczyńska

University of Silesia

in collaboration with
Tripurari Srivastava, Janusz Gluza

06.09.2019

Coimbra

National Science Centre
grant 2015/17/N/ST2/04067

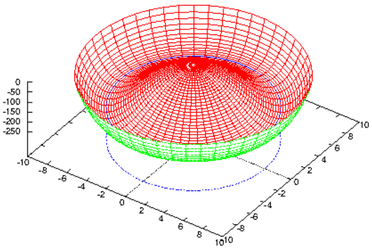
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Plan:

1. Introduction
2. Extensions of the Standard Model
3. Higgs Triplet Model
4. Left-Right Symmetric Model
5. Experimental constraints
6. Pair production in lepton and hadron colliders
7. Four lepton signal and hadron colliders
8. Summary

Introduction

Standard Model scalar potential...



$$\phi_{\text{SM}} := \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad , \qquad V = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

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

Extensons of the Standard Model

- Georgi-Machacek model
  An additional complex scalar triplet with $Y = 1$ and one real $SU(2)_L$ triplet with $Y = 0$.
- 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.
- Higgs Triplet Model (HTM)
  One additional triplet

Extensions of the Standard Model

- HTM - one additional triplet:

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

- LRSM - two additional triplets:

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

Extensions of the Standard Model

- Parameter ρ

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1.0008 \begin{array}{l} +0.0017 \\ \text{-}0.0007 \end{array}$$

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

- For example for an additional triplet:

$$\rho = \frac{1 + \frac{2v_\Delta}{v_\phi}}{1 + \frac{4v_\Delta}{v_\phi}}$$

Extensions of the Standard Model

HTM	MLRSM
Type II See-Saw	Three heavy neutrinos
$SU(2) \times U(1)$	$SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ $W_1,\ W_2,\ Z_1,\ Z_2,\ \gamma$
$h, H, A, H^{\pm}, H^{\pm\pm}$	$h, H_1, H_2, H_3, A_1, A_2$ $H_1^{\pm}, H_2^{\pm}, H_1^{\pm\pm}, H_2^{\pm\pm}$
$v_\Delta \lesssim 1$ GeV	$v_L = 0$ $v_R \gtrsim 3000$ GeV

HTM

HTM - Lagrangian

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

HTM - Lagrangian

$$
\begin{aligned}
M_A^2 &= \frac{\mu}{\sqrt{2}v_\Delta}(v_\Phi^2 + 4v_\Delta^2) \\
M_h^2 &= \lambda v_\Phi^2 \cos^2\alpha + \left(\frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} + 2v_\Delta^2(\lambda_2 + \lambda_3)\right)\sin^2\alpha \\
&\quad +2\left(v_\Phi v_\Delta(\lambda_1 + \lambda_4) - \sqrt{2}\mu v_\Phi\right)\cos\alpha\sin\alpha \\
M_H^2 &= \lambda v_\Phi^2 \sin^2\alpha + \left(\frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} + 2v_\Delta^2(\lambda_2 + \lambda_3)\right)\cos^2\alpha \\
&\quad -2\left(v_\Phi v_\Delta(\lambda_1 + \lambda_4) - \sqrt{2}\mu v_\Phi\right)\cos\alpha\sin\alpha \\
M_{H^\pm}^2 &= \frac{(2\sqrt{2}\mu - \lambda_4 v_\Delta)}{4v_\Delta}(v_\Phi^2 + 2v_\Delta^2) \\
M_{H^{\pm\pm}}^2 &= \frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} - \frac{\lambda_4}{2}v_\Phi^2 - \lambda_3 v_\Delta^2
\end{aligned}
$$

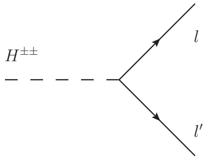
$$|M_{H^{\pm\pm}} - M_{H^\pm}| \leq 40\ \text{GeV}$$

1209.1303, 1206.0535

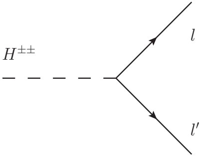
HTM - $H^{\pm\pm} - l - l'$ coupling

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

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



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



$$f = \frac{1}{\sqrt{2} v_\Delta} V^*_{PMNS} D_\nu V^\dagger_{PMNS} \qquad D_\nu = \frac{1}{2} \mathrm{diag}\{m_1, m_2, m_3\}$$

$$v_\Delta \iff f_{ll'} \iff$$

Neutrino parameters

$\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}$

m_1, m_2, m_3

LRSM

LRSM - The Higgs potential

$$
\begin{aligned}
V =& -\mu_1^2 \left(Tr[\phi^\dagger\phi]\right) - \mu_2^2 \left(Tr[\tilde{\phi}\phi^\dagger] + Tr[\tilde{\phi}^\dagger\phi]\right) - \mu_3^2 \left(Tr[\Delta_L\Delta_L^\dagger] + Tr[\Delta_R\Delta_R^\dagger]\right) \\
&+\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) \\
&+\lambda_4 \left(Tr[\phi\phi^\dagger] \left(Tr[\tilde{\phi}\phi^\dagger] + Tr[\tilde{\phi}^\dagger\phi]\right)\right) + \rho_1 \left(\left(Tr[\Delta_L\Delta_L^\dagger]\right)^2 + \left(Tr[\Delta_R\Delta_R^\dagger]\right)^2\right) \\
&+\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) + \rho_3\, Tr[\Delta_L\Delta_L^\dagger]\, Tr[\Delta_R\Delta_R^\dagger] \\
&+\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) \\
&+\alpha_1 \left(Tr[\phi\phi^\dagger] \left(Tr[\Delta_L\Delta_L^\dagger] + Tr[\Delta_R\Delta_R^\dagger]\right)\right) \\
&+\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) \\
&+\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) \\
&+\alpha_3 \left(Tr[\phi\phi^\dagger\Delta_L\Delta_L^\dagger] + Tr[\phi^\dagger\phi\Delta_R\Delta_R^\dagger]\right) \\
&+\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) \\
&+\beta_3 \left(Tr[\phi\Delta_R\tilde{\phi}^\dagger\Delta_L^\dagger] + Tr[\phi^\dagger\Delta_L\tilde{\phi}\Delta_R^\dagger]\right)
\end{aligned}
$$

The $H^{\pm\pm} - l - l'$ vertex

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

$$\Longrightarrow$$

$$f_{ll} = \frac{2i}{\sqrt{2}v_R} M_{N_l}$$

Experimental constraints

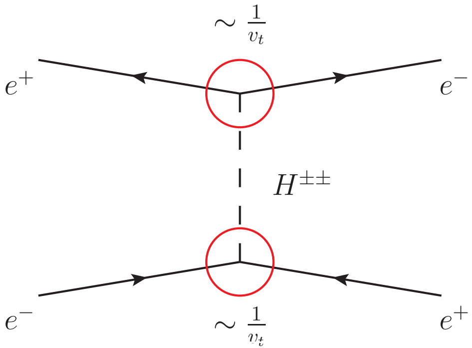
$f_{ll'}$ coupling and parameter's constraints

- $10^{-7} \leq f_{ll'} \leq \sqrt{4\pi}$ [hep-ex/0309076]
- Limits on the triplets' VEVs v_Δ, $v_{L,R}$
- Neutrino parameters $\sum m_i \leq 0.23$ eV - astrophysics
- Low energy processes
- Scattering limits

Experimental constraints

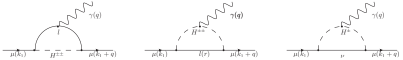
- High energy:
  - Bhabha scattering: $f_{ee}^2 \leq 6.0 \times 10^{-6} M_{H^{\pm\pm}}$

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

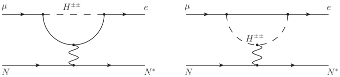


Experimental constraints

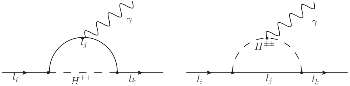
- Low energy:
  - $(g-2)_\mu$ contribution:



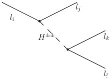
  - μ to e conversion:



  - Radiative LFV decays:



  - LFV three body decays :



Experimental constraints

- $(g-2)_\mu$

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

- μ to e (for Au)

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

- Radiative LFV decays

$$\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$$
$$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$
$$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

- LFV three body decays

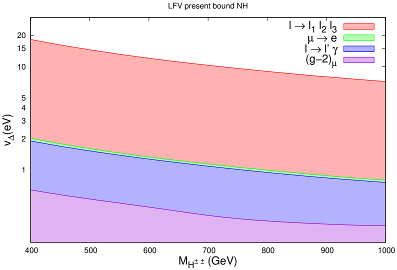
$$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$
$$\mathrm{BR}(\tau \to 3\mu) < 2.1 \times 10^{-8}$$

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

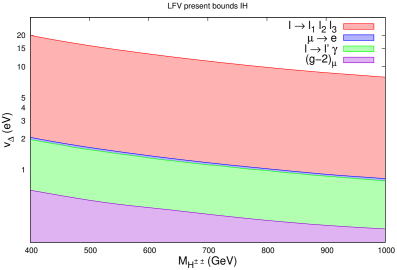
[Nucl. Phys. B299 (1988) 1-6] $$\mathrm{BR}(\mu \to 3e) < 1.0 \times 10^{-12}$$

v_Δ vs $M_{H^{\pm\pm}}$ - HTM

NH

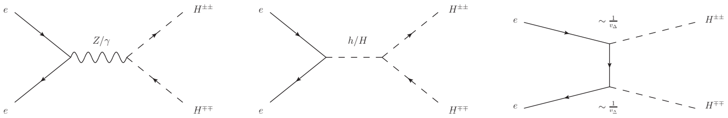


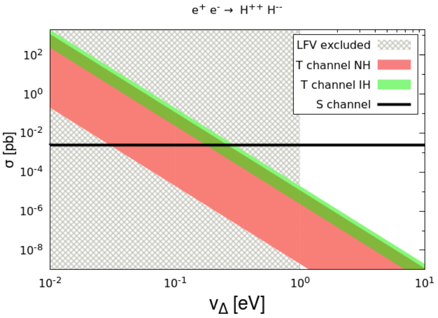
IH



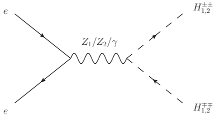
Pair production in lepton and hadron colliders

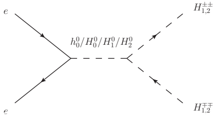
Pair production in e^+e^- colliders - HTM

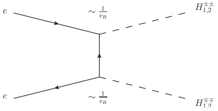


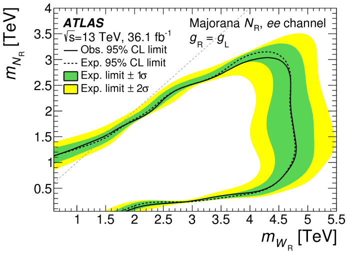


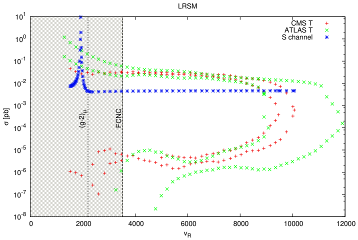
Pair production in e^+e^- colliders - LRSM





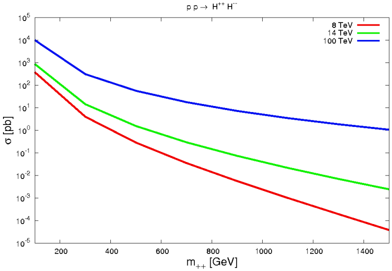




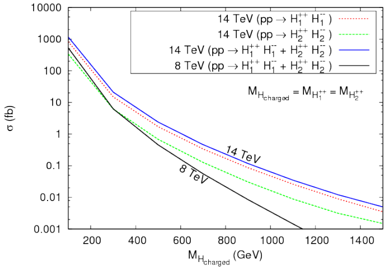


$H^{\pm\pm}$ pair production in hadron colliders

HTM



LRSM

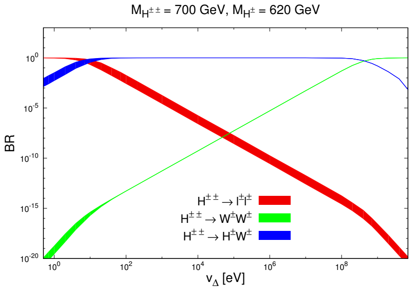


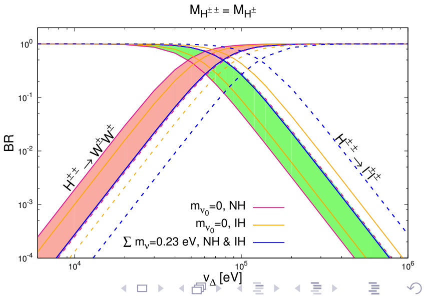
arXiv:1311.4144

Four lepton signal and hadron colliders

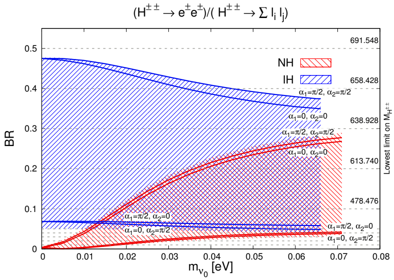
$H^{\pm\pm}$ decay - HTM

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

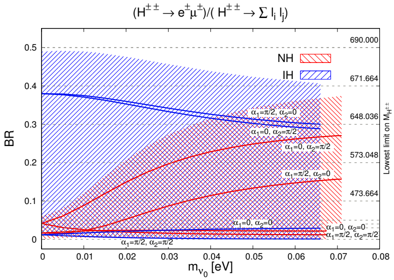




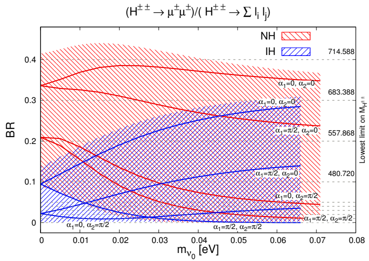
$H^{\pm\pm}$ decay



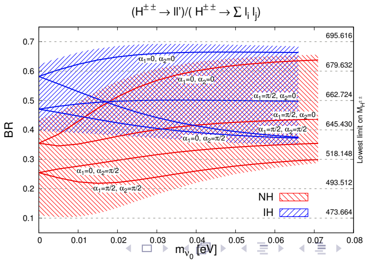
(H±± → e±e±)/(H±± → Σ li lj)
BR
NH
IH
691.548
658.428
638.928
613.740
478.476
α1=π/2, α2=π/2
α1=0, α2=0
α1=π/2, α2=π/2
α1=0, α2=0
α1=π/2, α2=0
α1=0, α2=π/2
α1=π/2, α2=0
α1=0, α2=π/2
Lowest limit on MH±±
mν0 [eV]



(H±± → e±μ±)/(H±± → Σ li lj)
BR
NH
IH
690.000
671.664
648.036
573.048
473.664
α1=π/2, α2=0
α1=0, α2=π/2
α1=0, α2=π/2
α1=π/2, α2=0
α1=0, α2=0
α1=0, α2=0
α1=π/2, α2=π/2
α1=π/2, α2=π/2
Lowest limit on MH±±
mν0 [eV]



(H±± → μ±μ±)/(H±± → Σ li lj)
BR
NH
IH
714.588
683.388
557.868
480.720
α1=0, α2=0
α1=0, α2=0
α1=π/2, α2=0
α1=π/2, α2=0
α1=0, α2=π/2
α1=π/2, α2=π/2
α1=0, α2=π/2
α1=π/2, α2=π/2
Lowest limit on MH±±
mν0 [eV]



(H±± → ll')/(H±± → Σ li lj)
BR
NH
IH
695.616
679.632
662.724
645.430
518.148
493.512
473.664
α1=0, α2=0
α1=0, α2=0
α1=π/2, α2=0
α1=π/2, α2=0
α1=π/2, α2=π/2
α1=0, α2=π/2
α1=0, α2=π/2
α1=π/2, α2=π/2
Lowest limit on MH±±
mν0 [eV]

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

$H_1^{\pm\pm}$	$\rightarrow$	$W_1 + W_1$	$H_2^{\pm\pm}$	$\rightarrow$	$W_1 + W_1$
$H_1^{\pm\pm}$	$\rightarrow$	$W_1 + W_2$	$H_2^{\pm\pm}$	$\rightarrow$	$W_1 + W_2$
$H_1^{\pm\pm}$	$\rightarrow$	$W_2 + W_2$	$\mathbf{H_2^{\pm\pm}}$	$\boldsymbol{\rightarrow}$	$\mathbf{W_2 + W_2}$
$\mathbf{H_1^{\pm\pm}}$	$\boldsymbol{\rightarrow}$	$\mathbf{H_1^{\pm} + W_1}$	$H_2^{\pm\pm}$	$\rightarrow$	$H_2^{\pm} + W_1$
$H_1^{\pm\pm}$	$\rightarrow$	$H_1^{\pm} + W_2$	$H_2^{\pm\pm}$	$\rightarrow$	$H_2^{\pm} + W_2$
$H_1^{\pm\pm}$	$\rightarrow$	$H_1^{\pm} + H_1^{\pm}$	$H_2^{\pm\pm}$	$\rightarrow$	$H_1^{\pm} + H_1^{\pm}$
$H_1^{\pm\pm}$	$\rightarrow$	$H_2^{\pm} + H_2^{\pm}$	$H_2^{\pm\pm}$	$\rightarrow$	$H_2^{\pm} + H_2^{\pm}$
$H_1^{\pm\pm}$	$\rightarrow$	$H_1^{\pm} + H_2^{\pm}$	$H_{1,2}^{\pm\pm}$	$\rightarrow$	$H_{2,1}^{\pm\pm} + H_0^0$
$H_{1,2}^{\pm\pm}$	$\rightarrow$	$H_{2,1}^{\pm\pm} + H_1^0$	$H_{1,2}^{\pm\pm}$	$\rightarrow$	$H_{2,1}^{\pm\pm} + H_2^0$
$H_{1,2}^{\pm\pm}$	$\rightarrow$	$H_{2,1}^{\pm\pm} + H_3^0$	$H_{1,2}^{\pm\pm}$	$\rightarrow$	$H_{2,1}^{\pm\pm} + A_2^0$

$$\mathbf{H_{1,2}^{\pm\pm} \rightarrow ll}$$

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

- Parton Distribution Factor (PDF): CTEQ6L1
- Lepton identification criteria: transverse momentum $p_T \geq 10$ GeV, pseudorapidity $|\eta| < 2.5$
- 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 $p_{T_\gamma} > 10$ GeV
- Lepton-jet separation $\Delta R_{lj} \geq 0.4$
- Hadronic activity cut - within the cone of radius 0.2 around the lepton the hardonic activity should fulfill the unequality: $\sum p_{T_{hadron}} \geq 0.2 \times p_{T_l}$
- Z-veto - $|m_{l_1 l_2} - M_{Z_1}| \geq 6\,\Gamma_{Z_1}$

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

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

signal	SM	HTM		LRSM
		NH	IH	
$eeee$	235.0	28.2	87.1	130.5
$\mu\mu\mu\mu$	65.9	160.9	106.9	197.4

4-leptons signal in pp colliders

Luminosity 3000 fb^{-1}, $\sqrt{s} = 14000$ TeV,
$M_{H^{\pm\pm}} = 700$ GeV

signal	SM	HTM		LRSM
		NH	IH	
$eeee$	12.8	6.4	14.9	116.1
$\mu\mu\mu\mu$	40.5	35.1	25.0	57.6

Summary

Summary

- $H^{\pm\pm}$ pair production in colliders gives possibility for clean BSM 4l signals. Large difference between LRSM and HTM, hierarchies might be distinguished.
- The strongest limit on v_t comes from the $\mu \to 3e$ and $\mu \to e\gamma$ LFV processes
- T channel contribution to the $H^{\pm\pm}$ pair production within the HTM in lepton colliders is negligible due to the low energy constraints
- Heavy gauge bosons (RH currents) do not influence the total number of event for the 4-lepton signal in hadron colliders

Thank you for your attention

mkordiaczynska@us.edu.pl

U_{PMNS}

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

ρ and T parameters

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

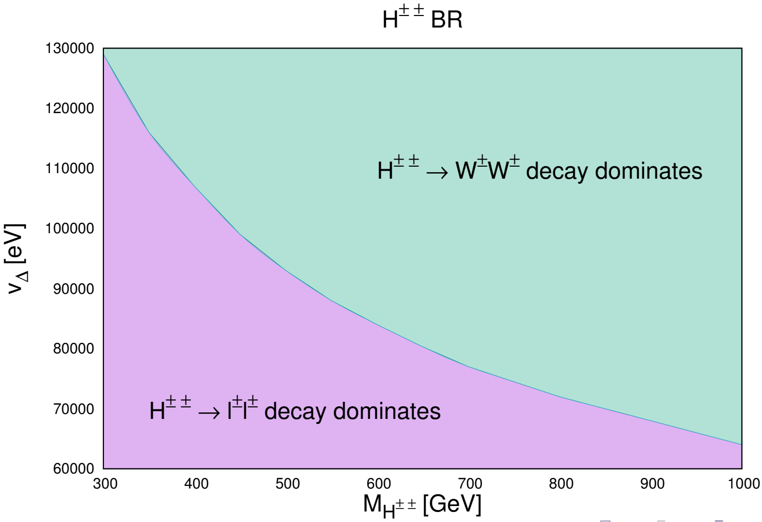
$$T = \frac{1}{\alpha}\left(\frac{\prod_{WW}(0)}{M_W^2} - \frac{\prod_{ZZ}(0)}{M_Z^2}\right) = \frac{\rho - 1}{\alpha} = 0.05 \pm 0.12$$

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

$$\Delta T < 0.2$$

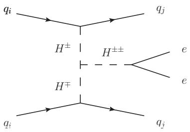
$$F(x,y) = \frac{x+y}{2} - \frac{xy}{x-y}\ln\left(\frac{x}{y}\right)$$

$H^{\pm\pm}$ decay

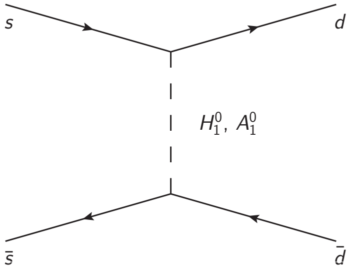


H±± BR
130000
120000
110000
100000
90000
80000
70000
60000
300
400
500
600
700
800
900
1000
v_Δ [eV]
M_H±± [GeV]
H±± → W±W± decay dominates
H±± → l±l± decay dominates

$0\nu\beta\beta$



FCNC



Potential stability

$$
\begin{aligned}
\lambda &> 0 \\
\lambda_2 + \lambda_3 &\geq 0 \\
\lambda_2 + \frac{\lambda_3}{2} &\geq 0 \\
\lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} &\geq 0 \\
\lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} &\geq 0
\end{aligned}
$$

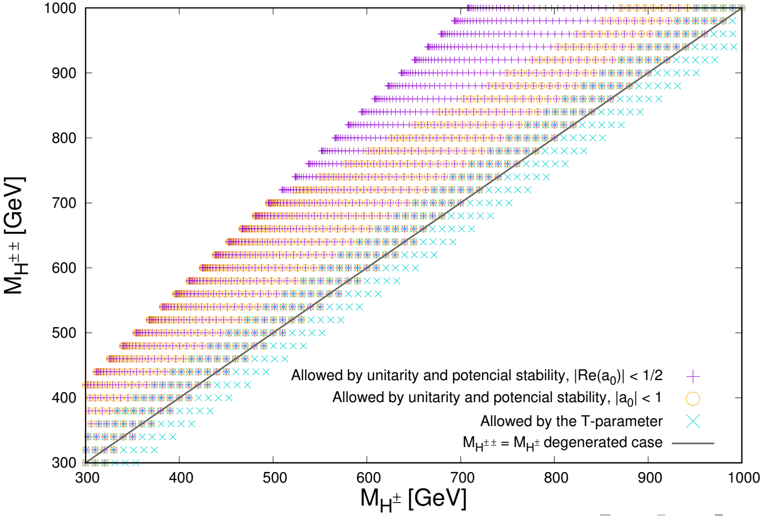
$$
\Bigg[\quad |\lambda_4|\sqrt{\lambda_2 + \lambda_3} - \lambda_3\sqrt{\lambda} \geq 0
$$

$$
\text{or} \quad 2\lambda_1 + \lambda_4 + \sqrt{(2\lambda\lambda_3 - \lambda_4^2)\left(\frac{2\lambda_2}{\lambda_3} + 1\right)} \geq 0 \quad \Bigg]
$$

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 - HTM



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:

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

$$M_{W_2}^2 \simeq \frac{g^2 v_R^3}{2} \sim v_R^2$$

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

$$M_{Z_2}^2 \simeq \frac{v_R^2 g^2 \cos^2\Theta_W}{cos2\Theta_W}$$

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

Masses of the scalar bosons

$$
\begin{aligned}
M^2_{H^0_0} &\simeq 2\kappa_+^2\lambda_1 \\
M^2_{H^0_1} &\simeq \tfrac{1}{2}\alpha_3 v_R^2 \\
M^2_{H^0_2} &\simeq 2\rho_1 v_R^2 \\
M^2_{H^0_3} &\simeq \tfrac{1}{2}v_R^2(\rho_3 - 2\rho_1) \\
M^2_{A^0_1} &\simeq \tfrac{1}{2}\alpha_3 v_R^2 - 2\kappa_+^2(2\lambda_2 - \lambda_3) \\
M^2_{A^0_2} &\simeq \tfrac{1}{2}v_R^2(\rho_3 - 2\rho_1) \\
M^2_{H^\pm_1} &\simeq \tfrac{1}{2}v_R^2(\rho_3 - 2\rho_1) + \tfrac{1}{4}\alpha_3\kappa_+^2 \\
M^2_{H^\pm_2} &\simeq \tfrac{1}{2}\alpha_3\left[v_R^2 + \tfrac{1}{2}\kappa_+^2\right] \\
M^2_{H^{\pm\pm}_1} &\simeq \tfrac{1}{2}\left[v_R^2(\rho_3 - 2\rho_1) + \alpha_3\kappa_+^2\right] \\
M^2_{H^{\pm\pm}_2} &\simeq 2\rho_2 v_R^2 + \tfrac{1}{2}\alpha_3\kappa_+^2
\end{aligned}
$$

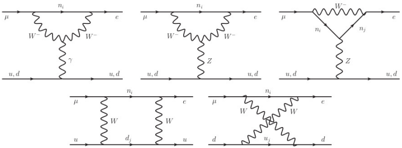
Experimental limits for models parameters - LRSM

- $M_{W_2} \geq 2.8$ TeV (CMS Collaboration [arXiv:1212.6175], ATLAS Collaboration [arXiv:1209.2535])

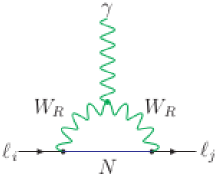
$$M_{W_2} \simeq 0.47 v_R, \quad M_{Z_2} \simeq 0.78 v_R$$

- $M_{H_0^3} \geq 55.4$ GeV (Anindya Datta, Amitava Raychaudhuri [hep-ph/9905421])
- $H_1^0, A_1^0 \sim 10$ TeV (M.E.Pospelov, [hep=ph/9611422])
- $M_{H^{\pm\pm}} \geq 870$ GeV

LFV - LRSM



arXiv:1209.2679



arXiv:1309.0774

LRSM - Lagrangian

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

$$\Longrightarrow$$

$$L_{\text{mass}}^{\nu} = -\frac{1}{2}\left(\bar{n}_L{}^{\text{`}c} M_\nu n_R{}^{\text{`}} + \bar{n}_R{}^{\text{`}c} M_\nu n_L{}^{\text{`}}\right)$$

$$n_R{}^{\text{`}} = \begin{pmatrix} \nu_R{}^{\text{`}c} \\ \nu_R{}^{\text{`}} \end{pmatrix} \quad n_L{}^{\text{`}} = \begin{pmatrix} \nu_L{}^{\text{`}c} \\ \nu_L{}^{\text{`}c} \end{pmatrix}$$

See-saw mechanism

- Mass matrix for neutrinos:

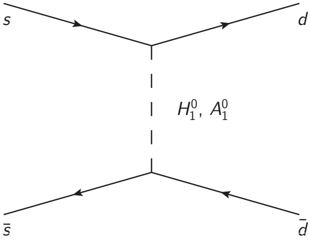
$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R(v_R) \end{pmatrix}$$

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

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

Flavour Changing Neutral Currents

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



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 bidublet 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:

$$< \varphi >= \begin{pmatrix} \kappa_1/\sqrt{2} & 0 \\ 0 & \kappa_2/\sqrt{2} \end{pmatrix}$$

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

Left Right Symmetric Model

- Gauge transformation:

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

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

- Covariant derivative:

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

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

- 7 gauge fiels

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

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	$^{+0.00076}_{-0.00076}$	$0.02027 \div 0.02331$
$\delta_{CP}[^o]$	261	$^{+51}_{-59}$	$143 \div 363$	277	$^{+40}_{-46}$	$185 \div 357$
$\frac{\Delta m^2_{21}}{10^{-5}\text{eV}^2}$	7.50	$^{+0.19}_{-0.17}$	$7.16 \div 7.88$	7.50	$^{+0.19}_{-0.17}$	$7.16 \div 7.88$
$\frac{\Delta m^2_{3l}}{10^{-3}\text{eV}^2}$	+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]