Pair production of doubly charged scalar particles in future colliders

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Plan:

1. Doubly charged scalar particles
   - Extensions of the Standard Model
2. Higgs Triplet Model
3. $H^{\pm\pm} - l - l'$ coupling
4. Experimental constraints
5. Pair production and collider signals
6. Summary

Extensions 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

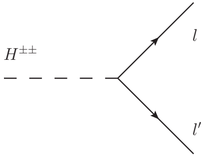
HTM	MLRSM
Type II See-Saw	Three heavy neutrinos
$SU(2) \times U(1)$	$SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ $W_1,\ W_2,\ Z_1,\ Z_2,\ \gamma$
$h, H, A, H^{\pm},\ H^{\pm\pm}$	$h, H_1, H_2, H_3, A_1, A_2$ $H_1^{\pm}, H_2^{\pm},\ H_1^{\pm\pm}, H_2^{\pm\pm}$

HTM - Lagrangian

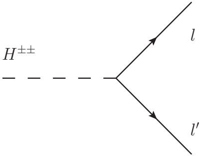
$$
\begin{aligned}
V = & -m_\Phi^2 \left(\Phi^\dagger \Phi\right) + M^2 \mathrm{Tr}\left(\Delta^\dagger \Delta\right) + \left\{\mu\left(\Phi^T i\sigma_2 \Delta^\dagger \Phi\right) + \text{h.c.}\right\} \\
& + \frac{\lambda}{4}\left(\Phi^\dagger \Phi\right)^2 + \lambda_1 \left(\Phi^\dagger \Phi\right)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

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

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



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



$$f = \frac{1}{\sqrt{2}v_t} \; V^{*}_{PMNS} \, D_\nu \; V^{\dagger}_{PMNS} \qquad\qquad D_\nu = \tfrac{1}{2}\,\mathrm{diag}\{m_1, m_2, m_3\}$$

$$v_t \iff f_{ll'} \iff$$

Neutrino parameters

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

m_1, m_2, m_3

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

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

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

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

Neutrino oscillation data

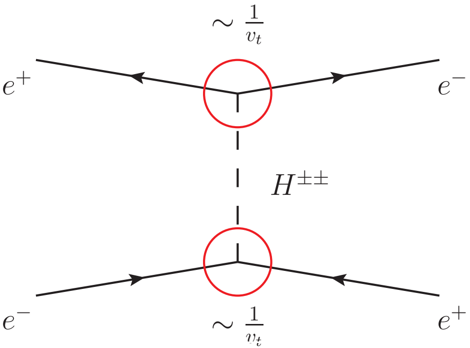
	Normal hierarchy			Inverted hierarchy		
	Best fit:	σ	bfp$\pm 2\sigma$	Best fit:	σ	bfp$\pm 2\sigma$
$\sin^2\theta_{12}$	0.306	$^{+0.012}_{-0.012}$	$0.282 \div 0.330$	0.306	$^{+0.012}_{-0.012}$	$0.282 \div 0.330$
$\sin^2\theta_{23}$	0.441	$^{+0.027}_{-0.021}$	$0.399 \div 0.495$	0.587	$^{+0.020}_{-0.024}$	$0.539 \div 0.627$
$\sin^2\theta_{13}$	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	$^{+40}_{-46}$	$185 \div 357$
$\frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2}$	7.50	$^{+0.19}_{-0.17}$	$7.16 \div 7.88$	7.50	$^{+0.19}_{-0.17}$	$7.16 \div 7.88$
$\frac{\Delta m^2_{3l}}{10^{-3}\mathrm{eV}^2}$	$+2.524$	$^{+0.039}_{-0.040}$	$2.445 \div 2.602$	-2.514	$^{+0.038}_{-0.041}$	$-2.596 \div -2.438$

[www.nu-fit.org , arXiv:1611.01514]

Experimental constraints

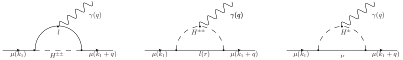
- High energy:
  - Bhabha scattering: $f_{ee}^2 \leq 6.0 \times 10^{-6} M_{H^{\pm\pm}}$

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

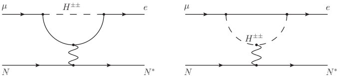


Experimental constraints

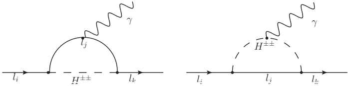
- Low energy:
  - $(g-2)_\mu$ contribution:



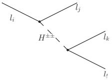
  - μ to e conversion:



  - 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

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

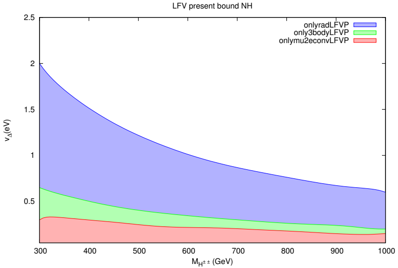
[arXiv:1512.03581] , $\mathrm{BR}(\tau \to e\mu^+\mu^-) < 2.7 \times 10^{-8}$

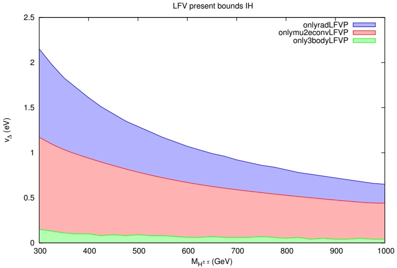
[Nucl. Phys. B299 (1988) 1-6] $\mathrm{BR}(\mu \to 3e) < 1.0 \times 10^{-12}$

v_t vs $M_{H^{\pm\pm}}$

NH

IH

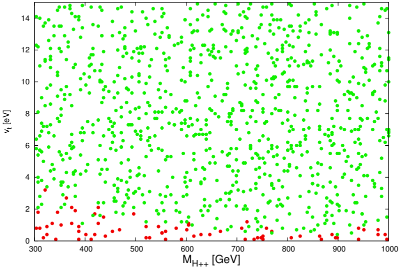




Oscillation parameter in the 2σ range, $\sum m_i \leq 0.58$ eV

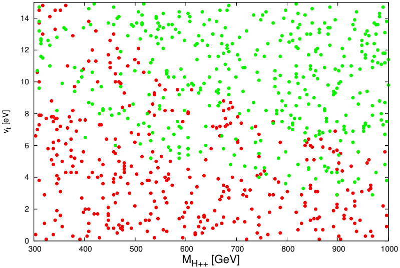
v_t vs $M_{H^{\pm\pm}}$: $\mu \to 3e$

NH



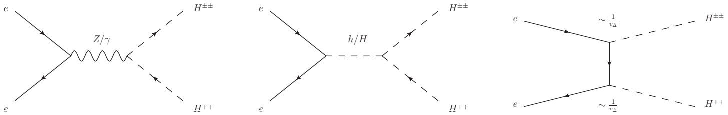
$v_{t_{min}}(M_{H^{\pm\pm}} = 500\text{GeV}) = 0.6$ eV

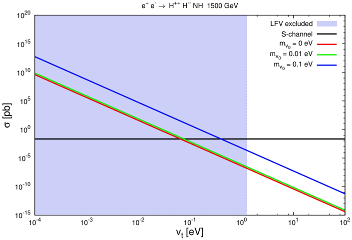
IH

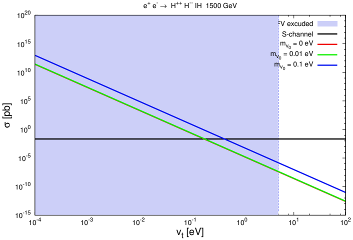


$v_{t_{min}}(M_{H^{\pm\pm}} = 500\text{GeV}) = 5$ eV

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

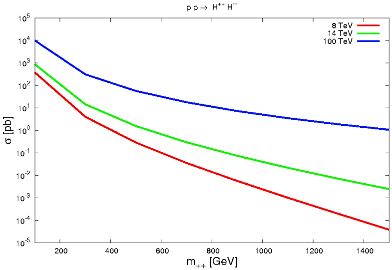






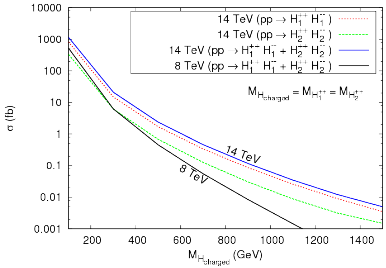
$H^{\pm\pm}$ pair production in hadron colliders

HTM



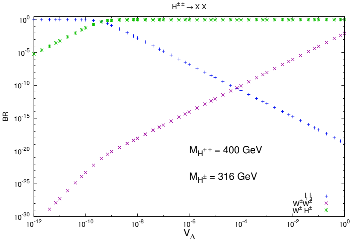
MLRSM

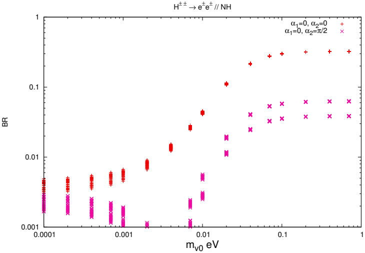
[arXiv:1311.4144]

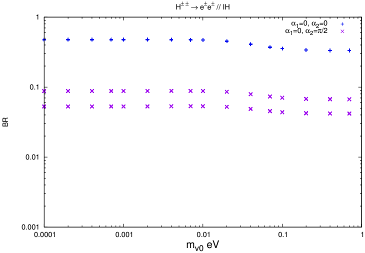


$H^{\pm\pm}$ decay

$$H^{\pm\pm} \rightarrow l_j \; l_j$$
$$H^{\pm\pm} \rightarrow W^{\pm} \; W^{\pm}$$
$$H^{\pm\pm} \rightarrow H^{\pm} \; H^{\pm}$$







$pp \to H^{++}H^{--}$ 4-leptons signal

Luminosity $25fb^{-1}$, $\sqrt{s} = 14$ TeV

$M_{H^{\pm\pm}}$	SM	MLRSM	HTM			
			NH		IH	
			$\alpha_1 = 0,\ \alpha_2 = 0$	$\alpha_1 = 0,\ \alpha_2 = \frac{\pi}{2}$	$\alpha_1 = 0,\ \alpha_2 = 0$	$\alpha_1 = 0,\ \alpha_2 = \frac{\pi}{2}$
400	2.9	30	7.3	2.6	33	20
600		4.4	1.0	0.4	4.9	2.9

Summary

- For $\theta_{13} \neq 0$ the strongest limit on v_t comes from the $\mu \to 3e$ 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 total number of event for the 4-lepton signal in hadron colliders
- $H^{\pm\pm}$ pair production in colliders gives possibility for clean BSM 4l signals

Thank you for your attention

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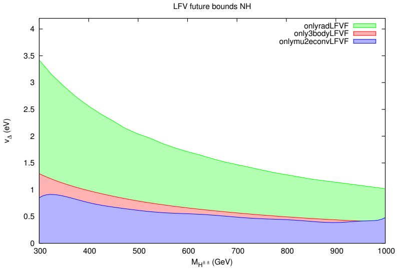
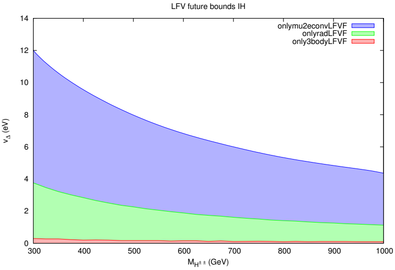
Future limits

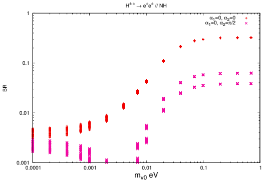
NH

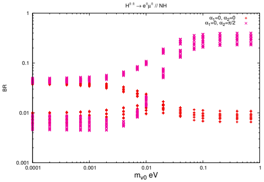


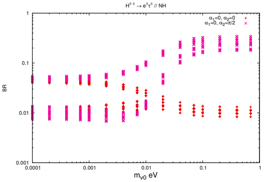
IH

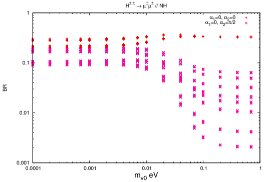


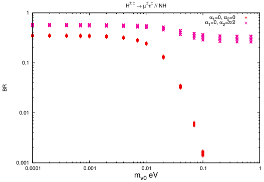
Branching Ratio's NH

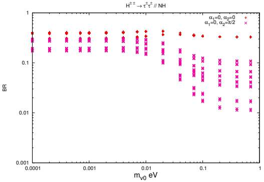




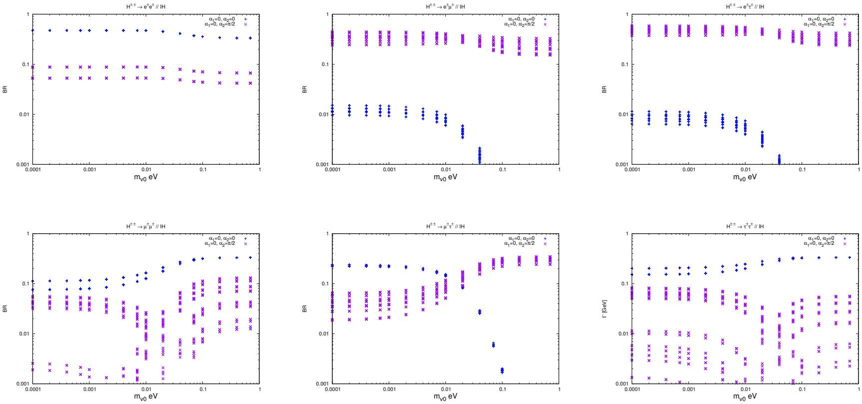




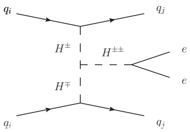




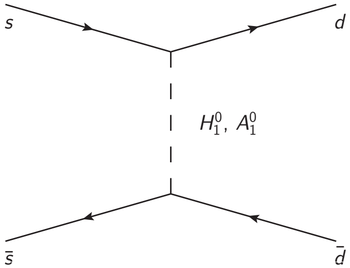
Branching Ratio's IH



$0\nu\beta\beta$



FCNC



U_{PMNS}

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