Potential signals of doubly charged Higgs scalars at future colliders

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ParticleFace Webinar https://indico.cern.ch/event/1071301/
30 August 2021

NATIONAL SCIENCE CENTRE
POLAND

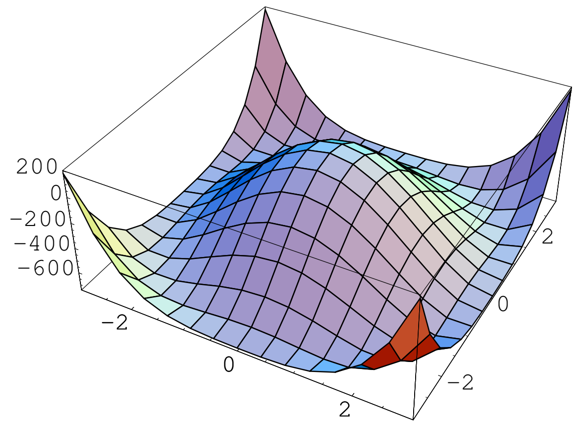
One fact and two important questions

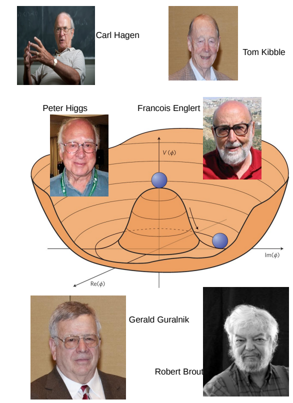
❖ **There is a scalar, fundamental particle!**

1. Do we need more of them?

Is Particle Physics scalar landscape so simple? Mount Mayon

(Renowned as the "perfect cone" because of its almost symmetric conical shape)





$$\Phi \equiv \Phi_{SM} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$V_{min} = v/\sqrt{2}, v = \sqrt{\mu^2/\lambda} \simeq 250 \text{ GeV}$$

One fact and two important questions

- **There is a scalar, fundamental particle!**

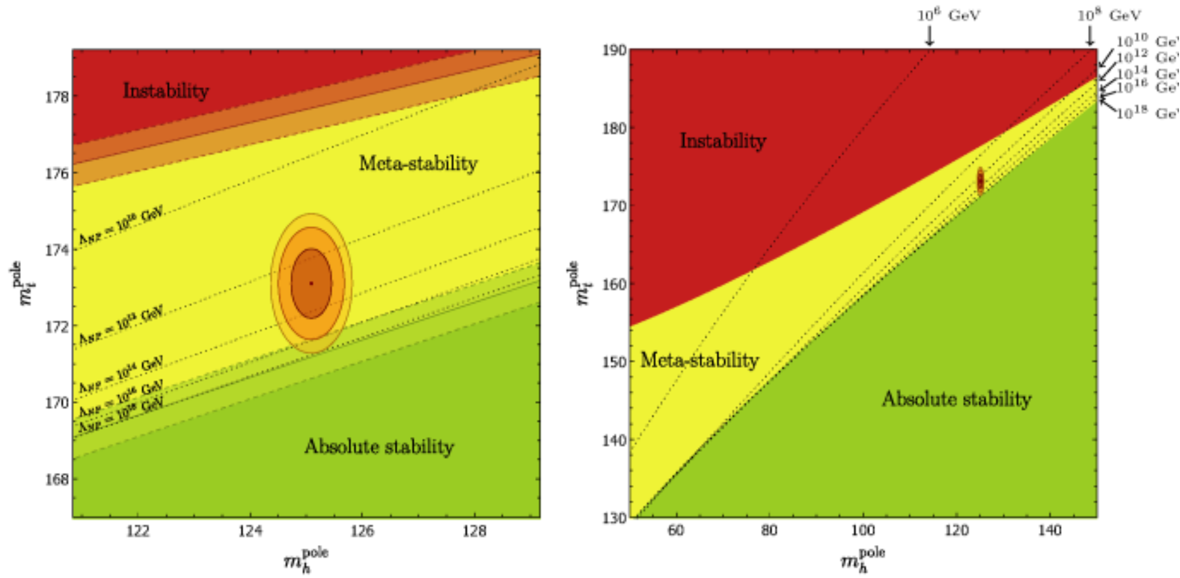
1. Do we need more of them?

2. What kind of?

I focus on non-supersymmetric theories.

Many fascinating problems connected with the scalar potential, see e.g.: D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio and A. Strumia, "Investigating the near-criticality of the Higgs boson", https://doi.org/10.1007/JHEP12(2013)089

The ‘universe’ stability fate phase diagram, https://arxiv.org/abs/1707.08124



Is BSM needed there? ‘The Standard Model of Particle Physics as a Conspiracy Theory and the Possible Role of the Higgs Boson in the Evolution of the Early Universe’, F. Jegerlehner, 2106.00862

Extensions of the Standard Model

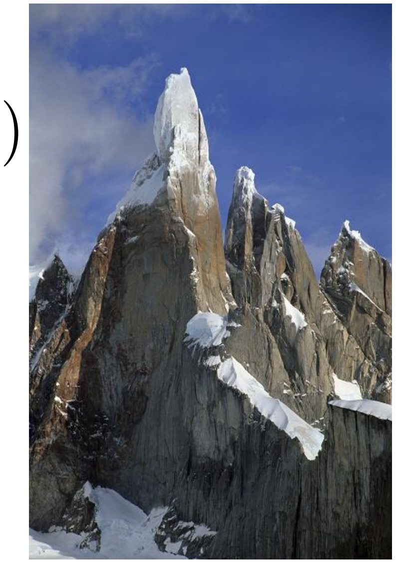
- **Left Right Symmetric Model (LRSM)**
  Extended gauge group: $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$.
  In the most popular version for breaking the symmetry two additional triplets are introduced.

$$\Delta_{L,R} = \frac{1}{\sqrt{2}} \begin{pmatrix} \delta^+_{L,R} & \sqrt{2}\delta^{++}_{L,R} \\ v_{L,R} + h_{L,R} + i z_{L,R} & -\delta^+_{L,R} \end{pmatrix}, \; \phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix}.$$

- **Higgs Triplet Model (HTM)**
  One additional $SU(2)_L$ triplet

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

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



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

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

$$
\begin{aligned}
V_{MLRSM} =& -\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}
$$

Our aim and strategy for tracing VEV scales: eV or TeV

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

HTM

$$\mu = 1.7 \times 10^{-7}, \quad \lambda = 0.519, \quad \lambda_1 = 0.519, \quad \lambda_2 = 0, \quad \lambda_3 = -1, \quad \lambda_4 = 0.$$

$M_h = 125.3$ GeV, $M_H = 700$ GeV, $M_{H^\pm} = 700$ GeV, $M_{H^{\pm\pm}}$ **= 700 GeV**.

MLRSM

$$\lambda_1 = 0.129,\ \rho_1 = 0.0037,\ \rho_2 = 0.0037,\ \rho_3 - 2\rho_1 = 0.015,\ \alpha_3 = 4.0816,\ 2\lambda_2 - \lambda_3 = 0.$$

$M_{H_0^0} = 125.3$ GeV, $M_{H_1^0} = 10$ TeV, $M_{H_2^0} = 600$ GeV, $M_{H_3^0} = 605.4$ GeV,

$M_{H_1^{\pm\pm}}$ **= 700 GeV**, $M_{H_2^{\pm\pm}}$ **= 700 GeV**, $M_{H_1^\pm} = 654.4$ GeV, $M_{H_2^\pm} = 10\,003.1$ GeV.

MLRSM, pluses

Start: 1973-1974,

Pati, Salam, Senjanovic, Mohapatra

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

(i) restores left-right symmetry to e-w interactions

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}, \qquad \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

(ii) hypercharge interpreted as a difference of baryon and lepton numbers

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$\begin{array}{ccc} W_L^{\pm}, W_L^0 & & W_1^{\pm}, W_2^{\pm} \\ W_R^{\pm}, W_R^0 & \rightarrow [SSB?] & Z_1, Z_2 \\ B^0 & & \gamma \end{array}$$

(iii)

$$M_\nu = \begin{pmatrix} M_L(v_L) & M_D(\kappa_{1,2}) \\ M_D^T & M_R(v_R) \end{pmatrix}, v_L \ll \kappa_{1,2} \ll v_R, M_R(m_N) = \sqrt{2} h_M v_R.$$

$$M = \begin{pmatrix} 2\epsilon^2\lambda_1 & 2\epsilon^2\lambda_4 & \alpha_1\epsilon \\ 2\epsilon^2\lambda_4 & \frac{1}{2}\left[4(2\lambda_2+\lambda_3)\epsilon^2+\alpha_3\right] & 2\alpha_2\epsilon \\ \alpha_1\epsilon & 2\alpha_2\epsilon & 2\rho_1 \end{pmatrix}.$$

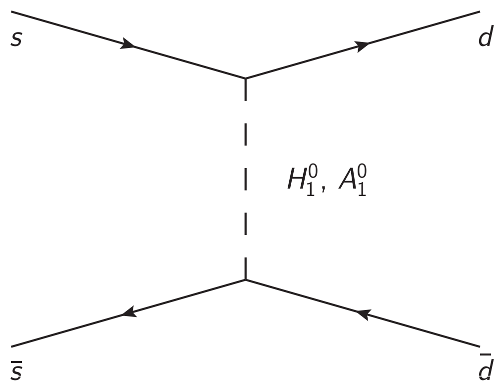
Expanding eigenvalues of this matrix in a small $\epsilon = \sqrt{\kappa_1^2+\kappa_2^2}/v_R$ parameter we get

$$M^2_{H^0_0} = 2\left(\lambda_1 - \frac{\alpha_1^2}{4\rho_1}\right)(\kappa_1^2+\kappa_2^2) \qquad \simeq (125\ \text{GeV})^2,$$

$$
\begin{aligned}
M^2_{H_1^0} &= \frac{1}{2}\alpha_3 v_R^2 && > (10\ \text{TeV})^2, \\
M^2_{H_2^0} &= 2\rho_1 v_R^2, && \\
M^2_{H_3^0} &= \frac{1}{2}(\rho_3 - 2\rho_1) v_R^2 && > (55.4\ \text{GeV})^2, \\
M^2_{A_1^0} &= \frac{1}{2}\alpha_3 v_R^2 - 2(\kappa_1^2 + \kappa_2^2)(2\lambda_2 - \lambda_3) && > (10\ \text{TeV})^2, \\
M^2_{A_2^0} &= \frac{1}{2}(\rho_3 - 2\rho_1) v_R^2 && \\
M^2_{H_1^\pm} &= \frac{1}{2}(\rho_3 - 2\rho_1) v_R^2 + \frac{1}{4}\alpha_3(\kappa_1^2 + \kappa_2^2), && \\
M^2_{H_2^\pm} &= \frac{1}{2}\alpha_3 v_R^2 + \frac{1}{4}\alpha_3(\kappa_1^2 + \kappa_2^2) && > (10\ \text{TeV})^2, \\
M^2_{H_1^{\pm\pm}} &= \frac{1}{2}(\rho_3 - 2\rho_1) v_R^2 + \frac{1}{2}\alpha_3(\kappa_1^2 + \kappa_2^2), && \\
M^2_{H_2^{\pm\pm}} &= 2\rho_2 v_R^2 + \frac{1}{2}\alpha_3(\kappa_1^2 + \kappa_2^2), &&
\end{aligned}
$$

FCNC

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



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

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

- $H_1^0, A_1^0 \sim 10$ TeV (M.E.Pospelov, [hep=ph/9611422])

Discriminating models with doubly charged Higgs scalars (Bartek's view)

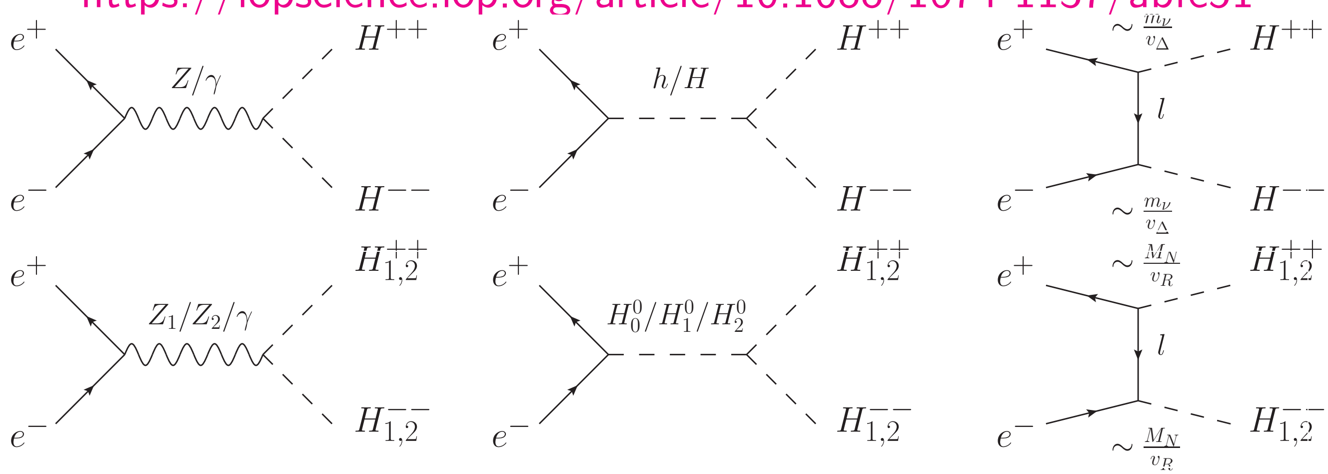
- Is it possible, and if so, how to distinguish between these models?
- The question is how to find to which non-standard model does the signal belong to?

Many, many works on $H^{\pm\pm}$

S. Kanemura, B. Dev, R. Mohapatra, R. Ruiz, A. Das, G. Senjanovic, M. Nemevsek, J. Chakrabortty, D. Das, M. Mitra, M. Spanowsky, M. Ramsey-Musolf, $+$ collaborators ... see references in our last CPC paper - next slide.

The case study: ‘Discriminating the HTM and MLRSM models in collider studies via doubly charged Higgs boson pair production and the subsequent leptonic decays’,
Chinese Physics C, JG, M.Kordiaczynska, T.Srivastava,
https://iopscience.iop.org/article/10.1088/1674-1137/abfe51

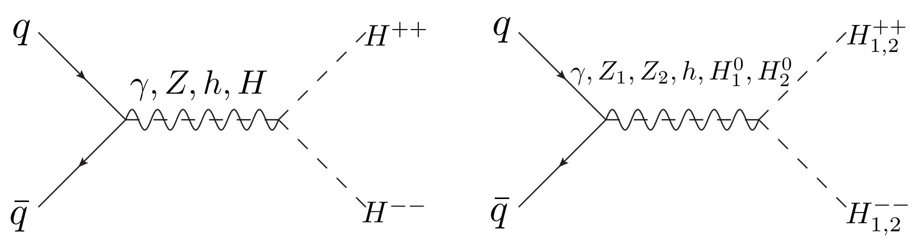
e^+e^-



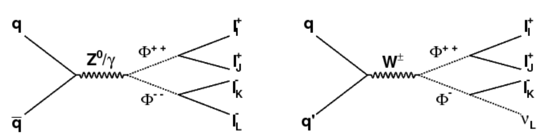
HTM

MLRSM

pp



HTM **MLRSM**



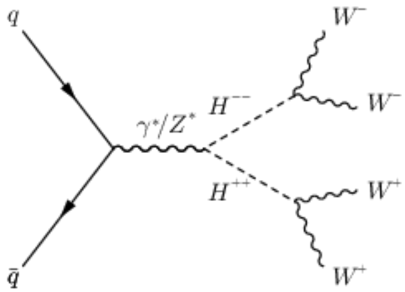
Present bounds on the doubly charged scalar masses

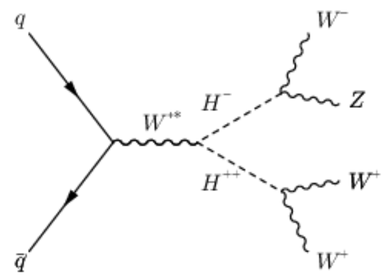
BR	ll	ee	$e\mu$	$\mu\mu$
0.01	216.3	249.2	216.3	309.7
0.02	279.4	310.9	300.0	335.7
0.03	308.5	323.7	316.6	367.5
0.04	316.8	333.9	329.5	418.2
0.05	324.3	342.5	339.5	434.1
0.1	473.7	478.5	473.7	480.7
0.2	493.5	613.7	573.1	557.9
0.3	518.1	638.9	648.0	683.4
0.4	645.4	658.4	671.7	714.6
0.5	662.7	691.5	690.0	734.0
0.6	679.6	752.6	749.3	754.4
0.7	695.6	755.8	776.5	808.3
0.8	753.3	758.3	805.8	839.4
0.9	756.8	761.9	829.4	857.8
1.0	763.8	768.3	846.2	874.7

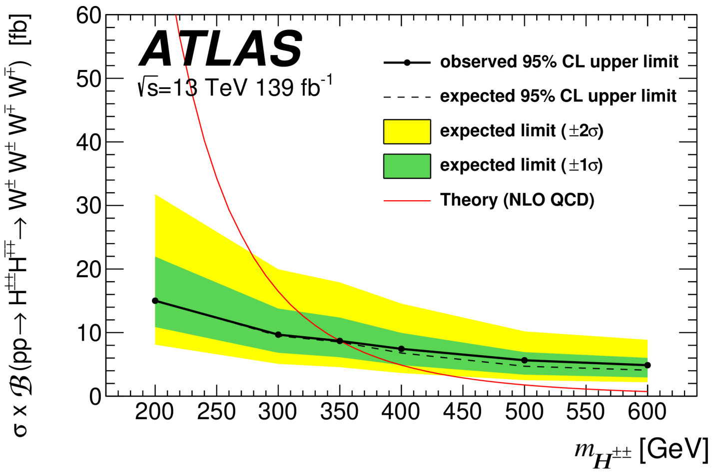
Lowest limits on a mass of the doubly charged scalar boson $M_{H_L^{\pm\pm}}$ for different branching ratios

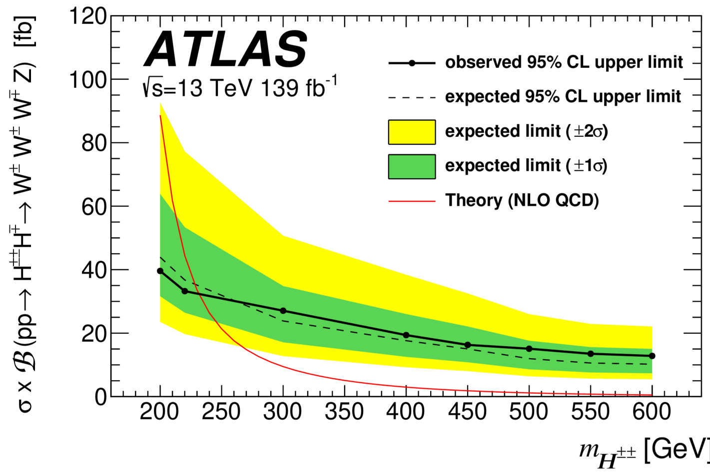
ATLAS Collaboration, 1710.09748.

LHC bounds on the doubly charged scalar masses









$H^{\pm\pm}$ bosons are excluded at 95% C.L. up to 350 GeV and 230 GeV for the pair and associated production modes, 2101.11961.

Low energy constraints on VEVs

Plenty of them, but of special importance is the ρ parameter

❖ Parameter ρ

$$\rho = \frac{J_{NC}}{J_{CC}} = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1.00037 \pm 0.00023$$

$\rho_{exp} = 1$, with a very good accuracy.
Can be expressed by VEVs and multiplet isospins

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

❖ It is automatically one for doublet Higgs fields, for example, for the SM doublet $\phi : (t, t_3) = (\frac{1}{2}, \pm\frac{1}{2})$: $\rho = 1$.

- For an additional $SU(2)_L$ triplet, T. Rizzo, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.21.1404:

$$\rho = \frac{1 + \frac{2v_\Delta}{v_\phi}}{1 + \frac{4v_\Delta}{v_\phi}} \qquad \longrightarrow v_{\Delta\text{max}} = 1.7 \text{ GeV (at } 2\sigma), v_L \sim 0.$$

As we can seen, $\rho_{exp} = 1$ with a very good accuracy, it is automatically one for doublet Higgs fields, $(t, t_3) = (1/2, \pm 1/2)$.

Curiosity: Can we obtain $\rho_{exp} = 1$ independently of v_i values?

Rizzo showed that it happens for values which satisfies the equation $3t_3^2 = t(t+1)$, so, e.g. $(1/2, \pm 1/2)$, next is $(3, \pm 2)$ - 7-plet (note, usual triplet models $(\Phi^0, \Phi^-, \Phi^{--})$ gives $\rho \neq 1$):

$$(\Phi^+, \Phi^0, \Phi^-, \Phi^{--}, ..., \Phi^{-----})$$

TABLE III. Values of t^H and t_3^H which yield $\kappa^2 = 1$ for $t_3^H \leqslant 28$ $(t=\frac{1}{2})$.

t^H	$\lvert t_3^H \rvert$
$\frac{1}{2}$	$\frac{1}{2}$
3	2
$\frac{25}{2}$	$\frac{15}{2}$
48	28

Why does $\rho \neq 1$ matters?

Important for specific models, link: hep-ph/9909242.
$\Delta\rho = \epsilon_1$ (Altarelli, ...), $\Delta\rho \simeq T$ (Peskin, Takeuchi).

Confronting electroweak precision measurements with New Physics models

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Received: 9 September 1999 / Published online: 25 February 2000 – © Springer-Verlag 2000

Abstract. Precision experiments, such as those performed at LEP and SLC, offer us an excellent opportunity to constrain extended gauge model parameters. To this end, it is often assumed that in order to obtain more reliable estimates, one should include the sizable one-loop standard model (SM) corrections, which modify the Z^0 couplings as well as other observables. This conviction is based on the belief that the higher order contributions from the "extension sector" will be numerically small. However, the structure of higher order corrections can be quite different when comparing the SM with its extension; thus one should avoid assumptions which do not take account of such facts. This is the case for all models with $\rho_{\rm tree} \equiv M_W^2/(M_Z^2 \cos^2 \Theta_{\rm W}) \neq 1$. As an example, both the manifest left–right symmetric model and the $SU(2)_{\rm L} \otimes U(1)_Y \otimes \tilde{U}(1)$ model, with an additional Z' boson, are discussed, and special attention to the top contribution to $\Delta\rho$ is given. We conclude that the only sensible way to confront a model with the experimental data is to renormalize it self-consistently. If this is not done, parameters which depend strongly on quantum effects should be left free in fits, though essential physics is lost in this way. We should note that the arguments given here allow us to state that at the level of loop corrections (indirect effects) there is nothing like a "model-independent global analysis" of the data.

$$(\Delta\rho)_{SM} \simeq \frac{m_t^2}{M_W^2};$$

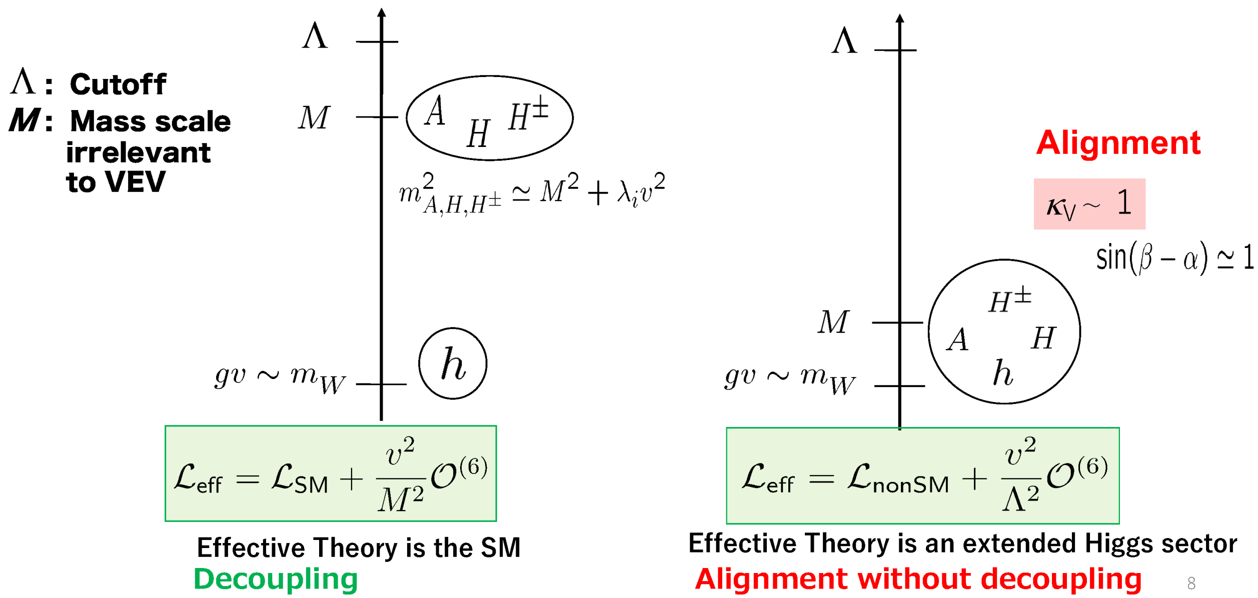
$$(\Delta\rho)_{LRM} \simeq \frac{m_t^2}{\mathbf{M^2_{W_2}} - M_{W_1}^2};$$

$$(\Delta\rho)_{HTM} \simeq \ln \frac{m_t^2}{M_W^2};$$

$$G_\mu(\text{fixed}) \sim \frac{g^2}{M_W^2},\ M_W \to \infty \Longrightarrow g \to \infty$$

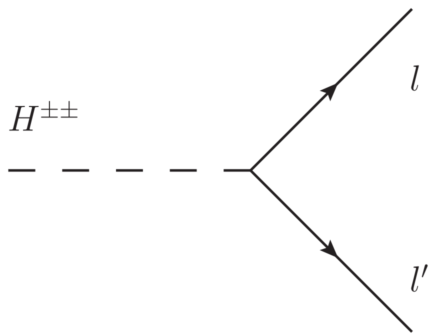
BSM and new scales, S. Kanemura, FCC November Week 2020
https://indico.cern.ch/event/923801

Two Possibilities satisfying current data



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

$$\mathcal{L}_Y = \frac{1}{2} f_{\ell\ell'} L_\ell^T C^{-1} i\sigma_2 \Delta L_{\ell'} + \text{h.c.} \longrightarrow \mathcal{L}_\nu = \frac{1}{2}\, \bar{\nu}_\ell \, \frac{v_\Delta}{\sqrt{2}}\, f_{\ell\ell'}\, \nu_{\ell'}$$



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

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

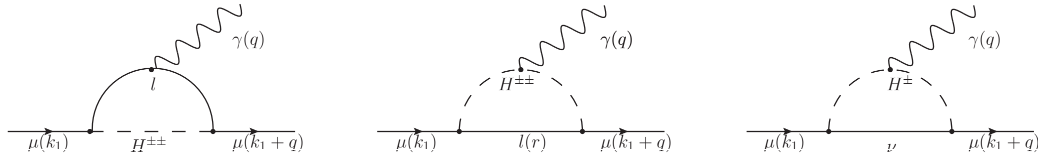
$$V_{\text{PMNS}} = \begin{bmatrix} c_{12}c_{13}e^{i\alpha_1} & s_{12}c_{13}e^{i\alpha_2} & s_{13}e^{-i\delta_{CP}} \\ (-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_1} & (c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_2} & s_{23}c_{13} \\ (s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_1}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

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

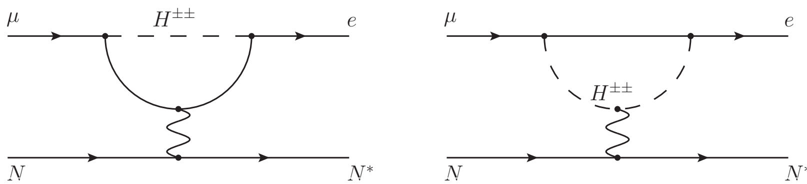
Neutrino parameters

θ_{12}, θ_{23}, θ_{13}, δ_{CP}, $\alpha_{1,2}$, m_1, m_2, m_3

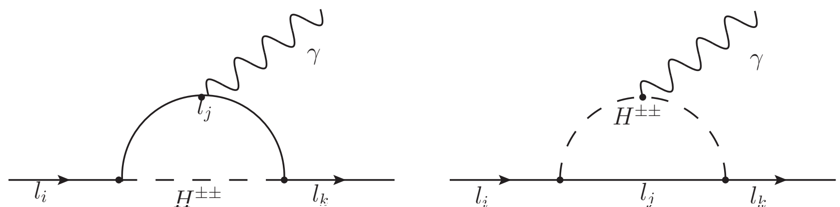
- $(g-2)_\mu$ contribution:



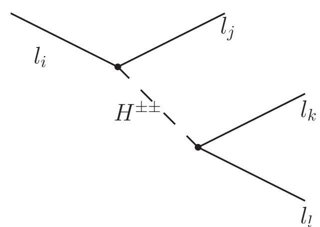
- μ to e conversion:



- Radiative LFV decays:



- LFV three body decays :



Low energy constraints: Neutrinos

- Gauge singlet right-handed neutrino: minuscule Yukawa Dirac couplings - no other effects than explaining neutrino oscillations
- additional heavy particles - see-saw mechanism, Majorana terms - lepton number violation, $0\nu\beta\beta$

Heavy neutrinos: see-saw type-I

Seesaw I: right handed singlets

$$\mathcal{L}_{\mathsf{Y}} = -Y_{ij}\,\overline{L'_{iL}}N'_{jR}\,\tilde{\phi} + \text{H.c.}$$

$$\mathcal{L}_{\mathsf{M}} = -\frac{1}{2}M_{ij}\overline{N'_{iL}}N'_{jR} + \mathrm{H.c.}\,,$$

$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\begin{pmatrix}\bar{\nu}'_L & \bar{N}'_L\end{pmatrix}\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}Y \\ \frac{v}{\sqrt{2}}Y^T & M \end{pmatrix}\begin{pmatrix}\nu'^c_L \\ N'_R\end{pmatrix} + \mathrm{H.c.}\,.$$

The neutrino mass matrix

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

with $M_D \ll M_R$.

$$m_N \sim M_R$$

$$m_{\rm light} \sim M_D^2/M_R$$

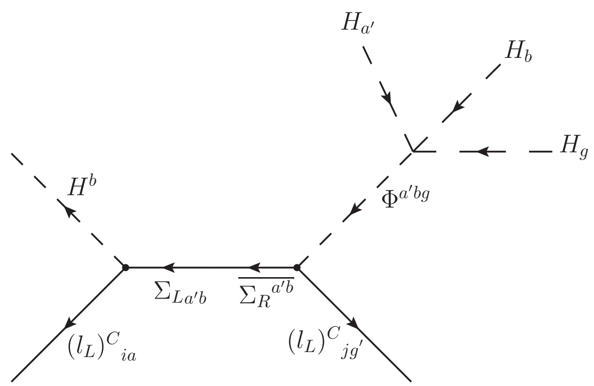
$M_D \sim \mathcal{O}(1)\ \mathrm{GeV} \rightarrow \mathrm{M_R} \sim 10^{15}\ \mathrm{GeV}$, if light neutrino masses of the order of 0.1 eV.

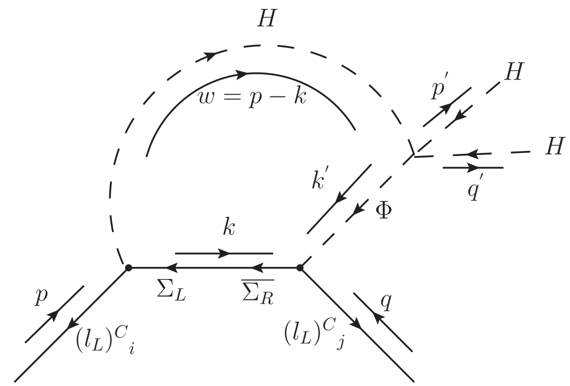
Effective operators - Weinberg,...

This is a typical situation for effective dimension-5 operators generated by $\kappa LLHH$ terms, for $M_R \sim 1$ TeV $M_D \sim 10^{-6}$. Consequently, Yukawa couplings Y are small, no effects in colliders

To lower see-saw scale to TeV, higher dimension operators can be used, e.g. dimension-7

Examples (1305.2795) - 7-dimensional and 5-dimensional induced loop operators





Σs here are triplet fermions

Seesaw II (scalar triplets)

$$\mathcal{L}_{\mathsf{Y}} = \frac{1}{\sqrt{2}} Y_{ij}\, \overline{\tilde{L}_{iL}}\, (\vec{\tau}\cdot\vec{\Delta})\, L_{jL} + \mathrm{H.c.}\,,$$

$$\Delta^{++} = \frac{1}{\sqrt{2}}(\Delta^1 - i\Delta^2)\,, \quad \Delta^+ = \Delta^3\,, \quad \Delta^0 = \frac{1}{\sqrt{2}}(\Delta^1 + i\Delta^2)$$

can be left and right handed triplets

possible messengers at LHC

$$q\bar{q} \to Z^* \,/\, \gamma^* \to \Delta^{++}\Delta^{--}\,,$$
$$q\bar{q}' \to W^* \to \Delta^{\pm\pm}\Delta^{\mp}\,,$$
$$q\bar{q} \to Z^* \,/\, \gamma^* \to \Delta^{+}\Delta^{-}\,.$$

Seesaw III (3 leptonic triplets)

$$
\begin{aligned}
\mathcal{L}_{\mathsf{Y}} &= -Y_{ij}\,\bar{L}'_{iL}(\vec{\Sigma}_j\cdot\vec{\tau})\,\tilde{\phi} + \text{H.c.}\,,\\
\mathcal{L}_{\mathsf{M}} &= -\frac{1}{2}\,M_{ij}\,\overline{\vec{\Sigma}_i^c}\cdot\vec{\Sigma}_j + \text{H.c.}\,,\\
\Sigma_j^+ &= \frac{1}{\sqrt{2}}(\Sigma_j^1 - i\Sigma_j^2)\,,\quad \Sigma_j^0 = \Sigma_j^3\,,\quad \Sigma_j^- = \frac{1}{\sqrt{2}}(\Sigma_j^1 + i\Sigma_j^2)\\
\mathcal{L}_{\nu,\text{mass}} &= -\frac{1}{2}\,(\bar{\nu}'_L\ \bar{N}'_L)\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}Y \\ \frac{v}{\sqrt{2}}Y^T & M \end{pmatrix}\begin{pmatrix} \nu'_R \\ N'_R \end{pmatrix} + \text{H.c.}
\end{aligned}
$$

possible messengers at LHC

$$
\begin{aligned}
q\bar{q} &\to Z^*\,/\,\gamma^* \to E^+E^-\,,\\
q\bar{q}' &\to W^* \to E^{\pm}N\,.
\end{aligned}
\tag{1}
$$

Example

	Seesaw I $m_N = 100$ GeV	Seesaw II $m_\Delta = 300$ GeV	Seesaw III $m_\Sigma = 300$ GeV
Six leptons	–	–	$\times$
Five leptons	–	–	28 fb^{-1}
$\ell^\pm \ell^\pm \ell^\pm \ell^\mp$	–	–	15 fb^{-1} m_E rec
$\ell^+ \ell^+ \ell^- \ell^-$	–	19 / 2.8 fb^{-1} $m_{\Delta^{++}}$ rec	7 fb^{-1} m_E rec
$\ell^\pm \ell^\pm \ell^\pm$	–	–	30 fb^{-1}
$\ell^\pm \ell^\pm \ell^\mp$	< 180 fb^{-1}	3.6 / 0.9 fb^{-1} $m_{\Delta^{++}}$ rec	2.5 fb^{-1} m_N rec
$\ell^\pm \ell^\pm$	< 180 fb^{-1} m_N rec	17.4 / 4.4 fb^{-1} $m_{\Delta^{++}}$ rec	1.7 fb^{-1} m_Σ rec
$\ell^+ \ell^-$	$\times$	15 / 27 fb^{-1} m_Δ rec	80 fb^{-1} m_Σ rec
$\ell^\pm$	$\times$	$\times$	$\times$

Aguilar-Saavedra et al, NPB

Another way out, observable TeV scale see-saw I and II models

$$M_D = \begin{pmatrix} m_1 & \delta_1 & \epsilon_1 \\ m_2 & \delta_2 & \epsilon_2 \\ m_3 & \delta_3 & \epsilon_3 \end{pmatrix} \text{ and } M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & \delta M & 0 \\ 0 & 0 & M_2 \end{pmatrix}$$

with $\epsilon_i, \delta_i \ll m_i$ and $\delta M \ll M_i$.

- In the limit of $\epsilon_i, \delta_i, \delta M \to 0$, the neutrino masses vanish, although the heavy-light mixing parameters given by $\xi_{ij} \sim m_i / M_j$ can be quite large.
- The neutrino masses given by the seesaw formula are dependent upon small parameters ϵ_i and δ_i.
- If by some symmetry one can guarantee the smallness of δ_i and ϵ_i, then we have a TeV-scale seesaw model with enhanced heavy-light mixing.
- Model can be embedded into LR models (plus global $D \equiv Z_4 \times Z_4 \times Z_4$ symmetry)

Natural TeV-Scale Left-Right Seesaw for Neutrinos and Experimental Tests P. S. Bhupal Dev, Chang-Hun Lee, R.N. Mohapatra, arXiv:1309.0774

$\mu \to 3e$ conversion

The sensitivities for various nuclei are expected to be improved by several orders of magnitude,

$$R^{Ti}_{\mu \to e} \lesssim 10^{-18} \quad ,$$

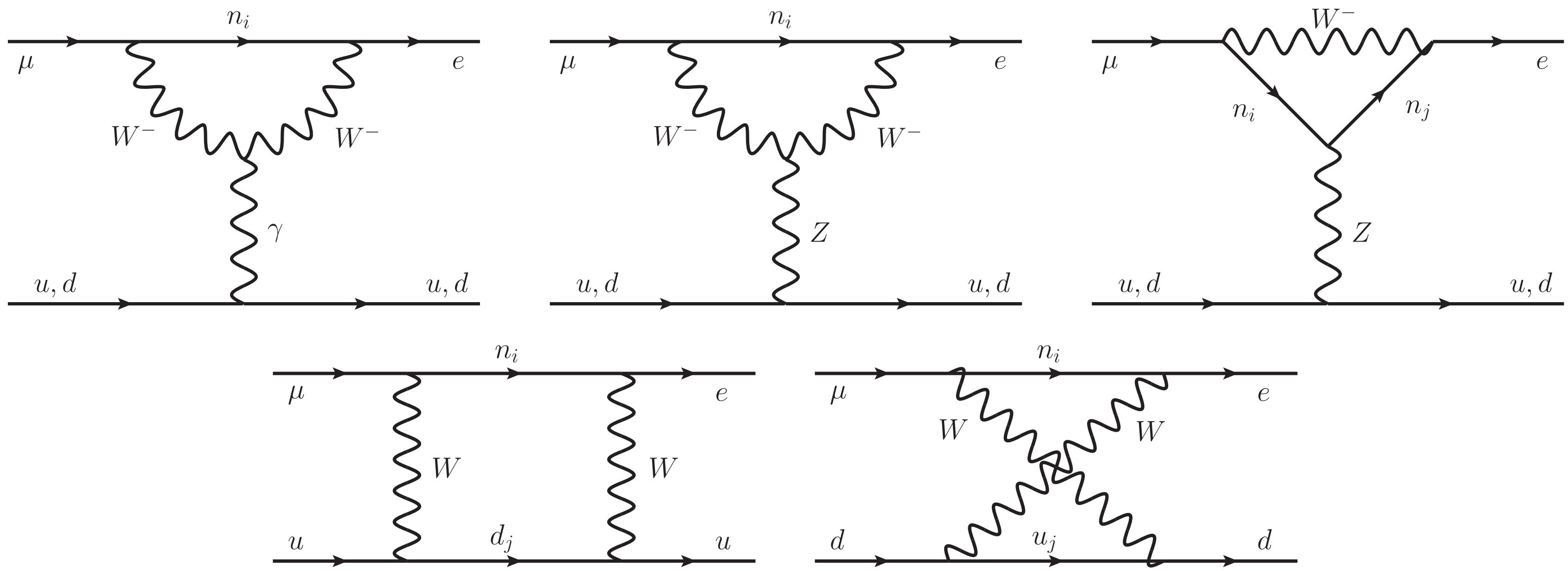
$$R^{Al}_{\mu \to e} \lesssim 10^{-16} \quad ,$$

as compared to the present sensitivities

$$R^{Ti}_{\mu \to e} < 4.3 \times 10^{-12} ,$$

$$R^{Au}_{\mu \to e} < 7 \times 10^{-13},$$

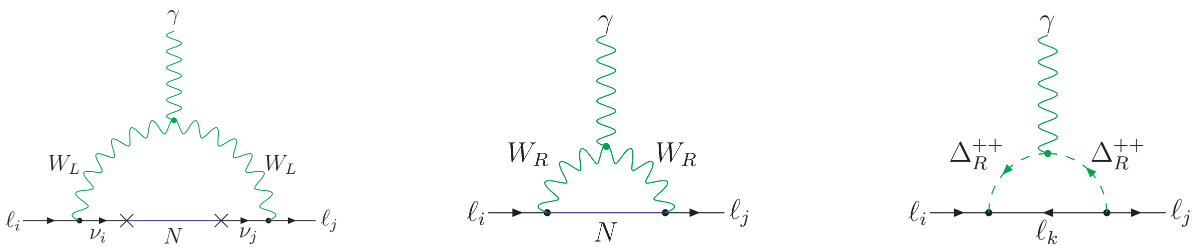
$$R^{Pb}_{\mu \to e} < 4.6 \times 10^{-11} .$$



arXiv:1209.2679, Muon conversion to electron in nuclei in type-I seesaw models, Rodrigo Alonso, Mikael Dhen, Belen Gavela, Thomas Hambye

$$\mathrm{BR}(\mu \to 3e) \simeq \frac{1}{2}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \left(\frac{M_{N,12}M_{N,11}}{M^2_{\Delta_R^{++}}}\right)^2, \quad M_{W_R} = 3\ TeV$$

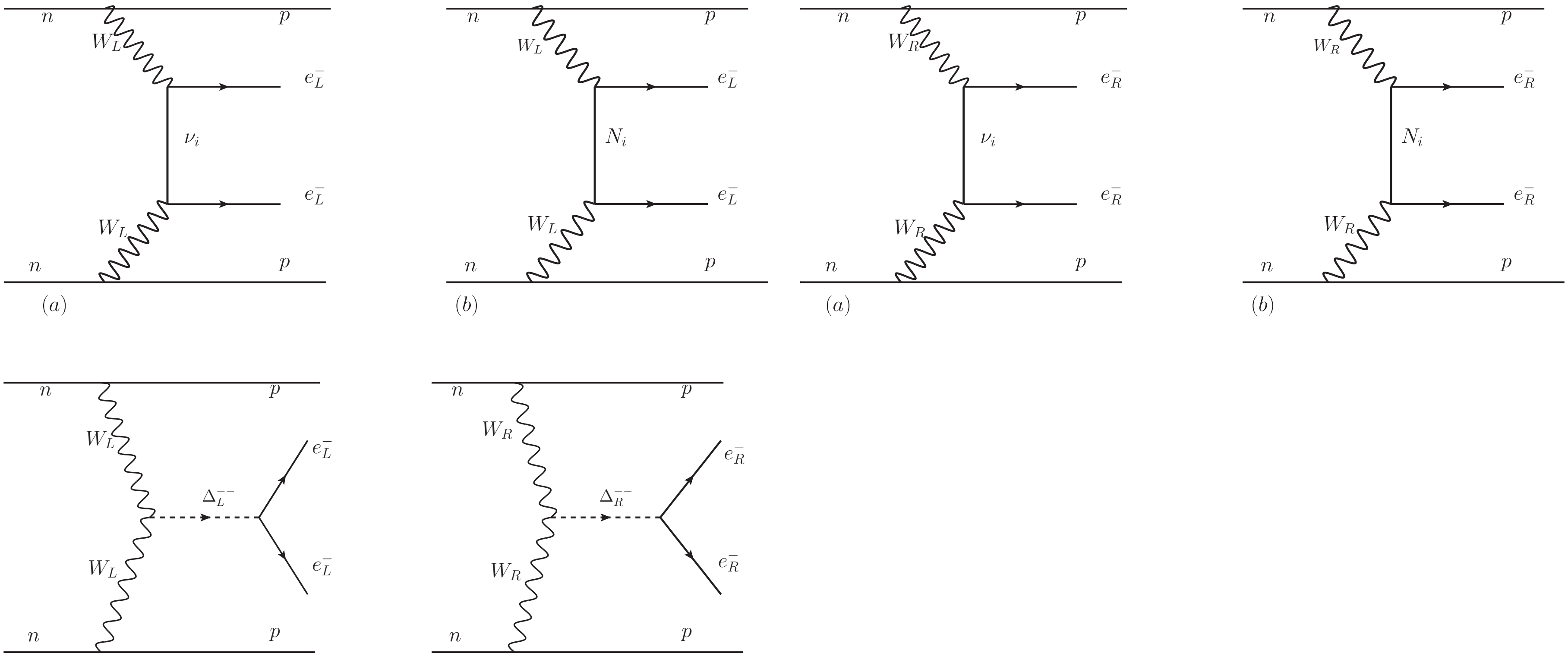
$\mu \to e\gamma$



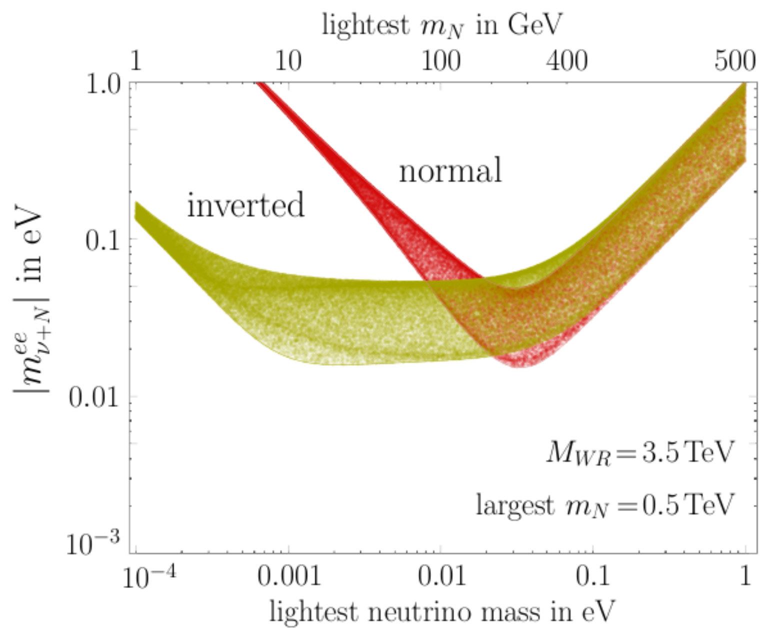
$$\mathrm{BR}(\mu \to e\gamma)_{\Delta_R^{++}} \simeq \frac{2\alpha_W M_{W_L}^4}{3\pi g^4}\left[\frac{(ff^\dagger)_{12}}{M^2_{\Delta_R^{++}}}\right]^2$$

e.g. $M_{\Delta_R^{++}} \geq 1.7$ TeV for RH charged current mixing ~ 0.01

$0\nu\beta\beta$

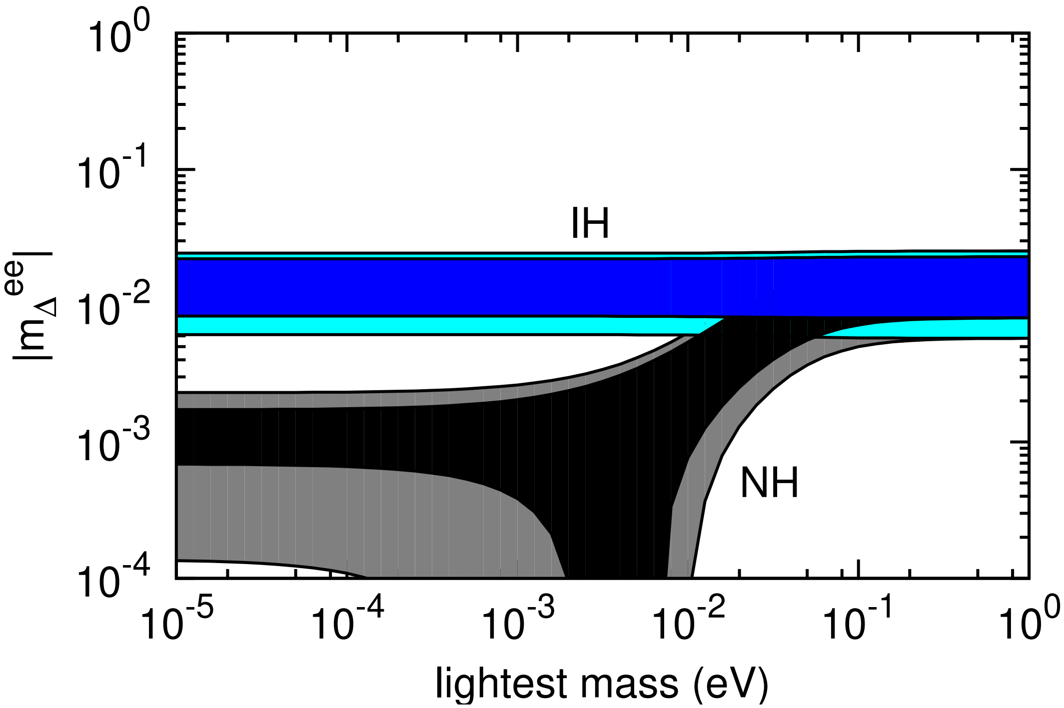


$$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G \cdot \left|\frac{\mathcal{M}_\nu}{m_e}\right|^2 \left(|m_\nu^{ee}|^2 + \left| p^2 \frac{M_W^4}{M_{W_R}^4} \frac{V_{Rej}^2}{m_{N_j}} \right|^2 \right)$$



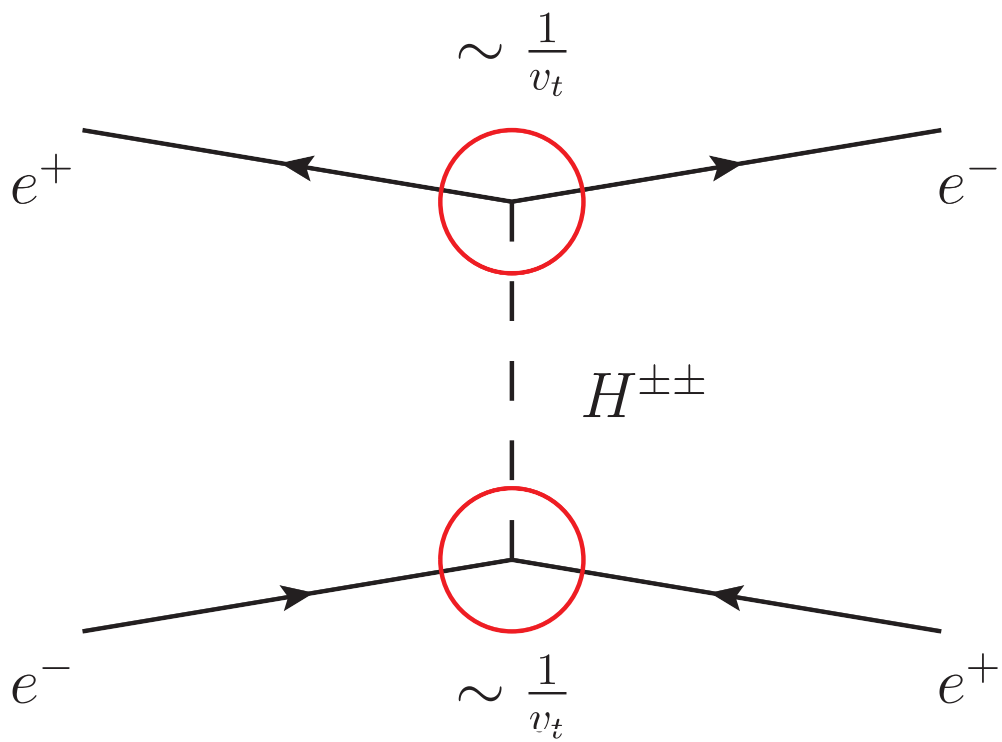
Left-Right Symmetry: from LHC to Neutrinoless Double Beta Decay, arXiv:1011.3522, Tello et al

$$|m_\Delta^{ee}| = \left| p^2 \, \frac{M_{W_L}^4}{M_{W_R}^4} \, \frac{2\, M_N}{M_{\Delta_R}^2} \right|$$



- 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]



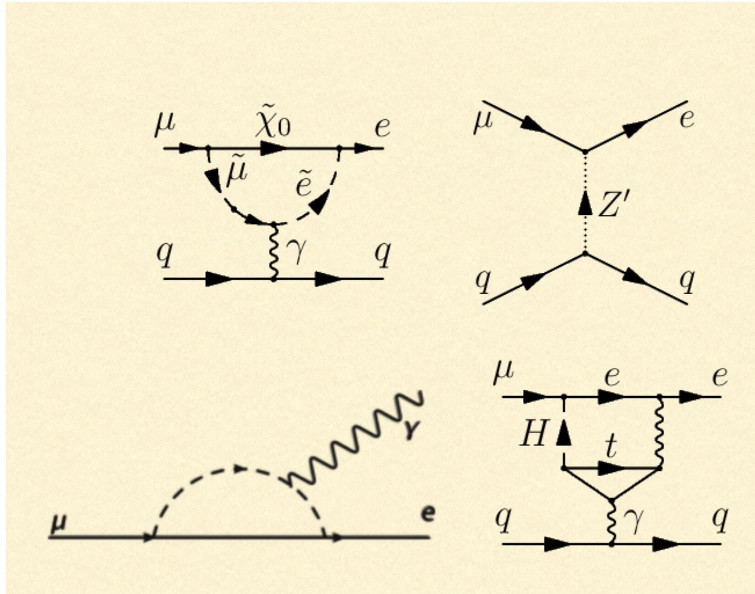
Lower bounds on the triplet vacuum expectation value v_Δ (in eV) for different values of Majorana phases and doubly charged scalar mass $M_{H^{\pm\pm}} = 700$ GeV.

Lower bounds on the triplet vacuum expectation value v_Δ (in eV) for various values of Majorana phases and doubly charged scalar mass $M_{H^{\pm\pm}} = 700$ GeV. The most strict limit is coming from the LFV processes named with the numerical value. The triplet VEV v_Δ is primarily bounded by experimental limits on $\mu \to eee$ and $\mu \to e\gamma$ dacays. The first four rows present results for the best fit of neutrino oscillation data. The last row shows the range of the lowest possible v_Δ for oscillation parameters within the $\pm 2\sigma$ range and Majorana phases within the entire 2π angle. All values in the table are in eV.

α_1	α_2	NH			IH		
		$m_{\nu_0} = 0$	$m_{\nu_0} = 0.01$	$m_{\nu_0} = 0.071$	$m_{\nu_0} = 0$	$m_{\nu_0} = 0.01$	$m_{\nu_0} = 0.066$
0	0	1.04 $\mu \to e\gamma$	1.60 $\mu \to eee$	6.45 $\mu \to eee$	3.36 $\mu \to eee$	3.74 $\mu \to eee$	7.47 $\mu \to eee$
0	$\frac{\pi}{2}$	1.04 $\mu \to e\gamma$	1.15 $\mu \to eee$	7.48 $\mu \to eee$	4.92 $\mu \to eee$	4.99 $\mu \to eee$	8.09 $\mu \to eee$
$\frac{\pi}{2}$	0	1.04 $\mu \to e\gamma$	1.04 $\mu \to e\gamma$	6.68 $\mu \to eee$	4.92 $\mu \to eee$	5.06 $\mu \to eee$	8.56 $\mu \to eee$
$\frac{\pi}{2}$	$\frac{\pi}{2}$	1.04 $\mu \to e\gamma$	1.71 $\mu \to eee$	5.61 $\mu \to eee$	3.36 $\mu \to eee$	3.09 $\mu \to eee$	3.15 $\mu \to eee$
Oscillations $\pm 2\sigma$			0.93÷10.31			1.07 ÷ 11.38	

HTM: $v_\Delta \sim eV$, not more than ~ 1.7 GeV.

Low energy intensity frontiers: Competition (and complementarity to HEP



$m_\mu \sim 200\ m_e$

$R^{\mu\to e} < 7 \cdot 10^{-13}$, expected 4 orders of magnitude improvement,

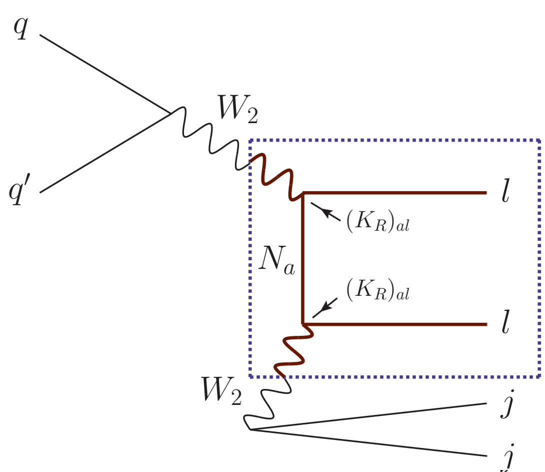
Sensitivity to NP $\sim$ 10 000 TeV!

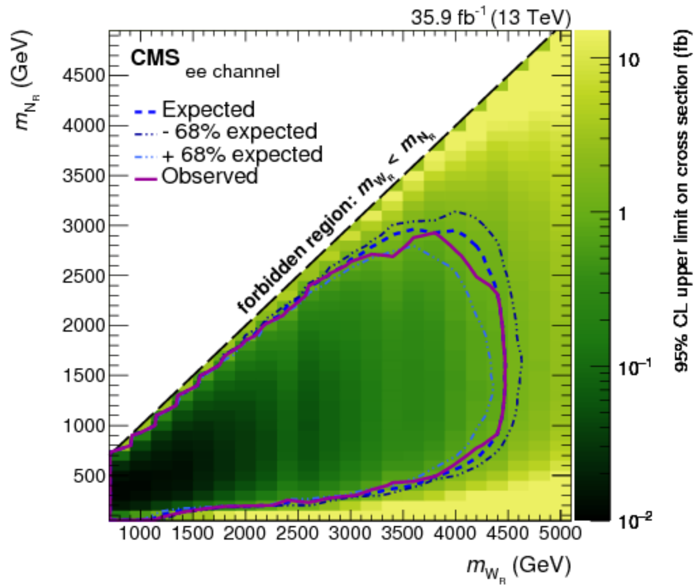
Primary production	Secondary production	Signal
I. $H_1^+ H_1^-$	$\ell^+ \ell^- \nu_L \nu_L$	$\ell^+ \ell^- \oplus MET$
–	$\ell^+ \ell^- \nu_R \nu_R$	depends on ν_R decay modes
–	$\ell^+ \ell^- \nu_L \nu_R$	depends on ν_R decay modes
II. $H_2^+ H_2^-$	$\ell^+ \ell^- \nu_L \nu_L$	$\ell^+ \ell^- \oplus MET$
–	$\ell^+ \ell^- \nu_R \nu_R$	depends on ν_R decay modes
–	$\ell^+ \ell^- \nu_L \nu_R$	depends on ν_R decay modes
III. $H_1^{++} H_1^{--}$	–	$\ell^+ \ell^+ \ell^- \ell^-$
–	$H_1^+ H_1^+ H_1^- H_1^-$	See I
–	$H_1^\pm H_1^\pm H_2^\mp H_2^\mp$	See I & II
–	$H_2^+ H_2^+ H_2^- H_2^-$	See II
–	$W_i^+ W_i^+ W_j^- W_j^-$	depends on W's decay modes
IV. $H_2^{++} H_2^{--}$	–	$\ell^+ \ell^+ \ell^- \ell^-$
–	$H_2^+ H_2^+ H_2^- H_2^-$	See II
–	$H_1^\pm H_1^\pm H_2^\mp H_2^\mp$	See I & II
–	$H_1^+ H_1^+ H_1^- H_1^-$	See I
–	$W_i^+ W_i^+ W_j^- W_j^-$	depends on W's decay modes
V. $H_1^{\pm\pm} H_1^\mp$	–	$l^\pm l^\pm l^\mp \nu_L$
VI. $H_2^{\pm\pm} H_2^\mp$	–	$l^\pm l^\pm l^\mp \nu_L$
VII. $H_1^\pm Z_i, H_1^\pm W_i$	–	See I & Z_i, W_i decay modes
VIII. $H_2^\pm Z_i, H_1^\pm W_i$	–	See II & Z_i, W_i decay modes
IX. $H_1^\pm A$	–	See I
X. $H_2^\pm A$	–	See II

'Production of the Doubly Charged Higgs Boson in Association with the SM Gauge Bosons and/or Other HTM Scalars at Hadron Colliders'
B. Dziewit, M. Kordiaczyńska, T. Srivastava, https://doi.org/10.1088/1674-1137/abfe51

	Process	Cross section [pb]		Process	Cross section [pb]
$I)$	$pp \to H^{\pm\pm}W^{\mp}$	$\sim 10^{-22}$ $(\sim 10^{-20})$	$II)$	$pp \to H^{\pm\pm}H^{\mp}$	8.13×10^{-5} (8.78×10^{-3})
$III)$	$pp \to H^{\pm\pm}ZW^{\mp}$	$\sim 10^{-12}$ (2.7×10^{-9})	$IV)$	$pp \to H^{\pm\pm}ZH^{\mp}$	6.29×10^{-7} (1.56×10^{-4})
$V)$	$pp \to H^{\pm\pm}W^{\mp}W^{\mp}$	$\sim 10^{-10}$ (1.87×10^{-9})	$VI)$	$pp \to H^{\pm\pm}W^{\mp}h$	$\sim 10^{-12}$ (3.47×10^{-8})
$VII)$	$pp \to H^{\pm\pm}W^{\mp}H$	1.35×10^{-6} (2.44×10^{-4})	$VIII)$	$pp \to H^{\pm\pm}W^{\mp}H^{\mp}$	2.88×10^{-6} (6.81×10^{-4})
$IX)$	$pp \to H^{\pm\pm}hH^{\mp}$	1.07×10^{-7}) $(1.63 \times 10^{-6}$	$X)$	$pp \to H^{\pm\pm}HH^{\mp}$	$\sim 10^{-29}$ $(\sim 10^{-26})$
$XI)$	$pp \to H^{\pm\pm}H^{\mp}H^{\mp}$	$\sim 10^{-31}$ $(\sim 10^{-28})$			

Cross section for a production of a single $H^{\pm\pm}$ boson with associated SM gauge bosons and other HTM scalars at the pp colliders in $2 \to 2$ and $2 \to 3$ processes. Cross sections are calculated for $\sqrt{s} = 14$ TeV (100 TeV). Charged scalar masses are degenerated, $M_{H^{\pm\pm}} = M_{H^{\pm}} = 1000$ GeV.





Upper limits on the 'golden' $pp \to eejj$ cross section (Senjanovic-Keung, 1983).

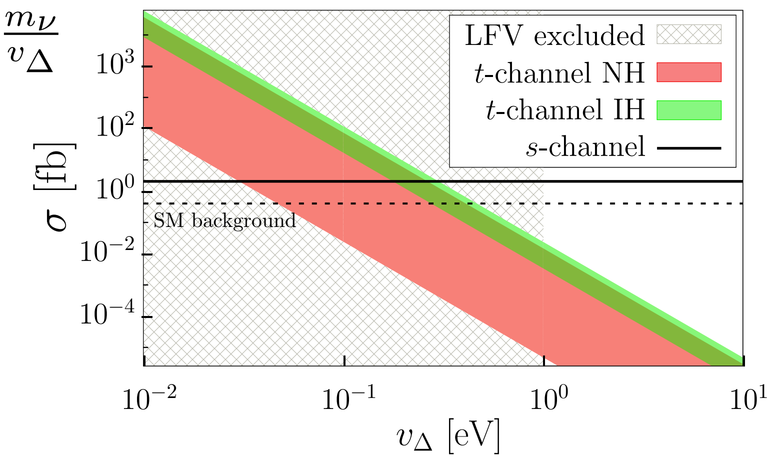
CMS, ATLAS simplify analysis by neglecting heavy neutrino mixings and the CP phases (destructive interferences release the constraints, https://doi.org/10.1016/j.physletb.2015.06.077).

We use the CMS (strict) bounds to constrains the $H^{++}H^{--}$ production processes.

$e^+e^- \to H^{++}H^{--}$ with low energy and LHC bounds, $m_{H^{\pm\pm}} = 700$ GeV, $\sqrt{s} = 1.5$ TeV

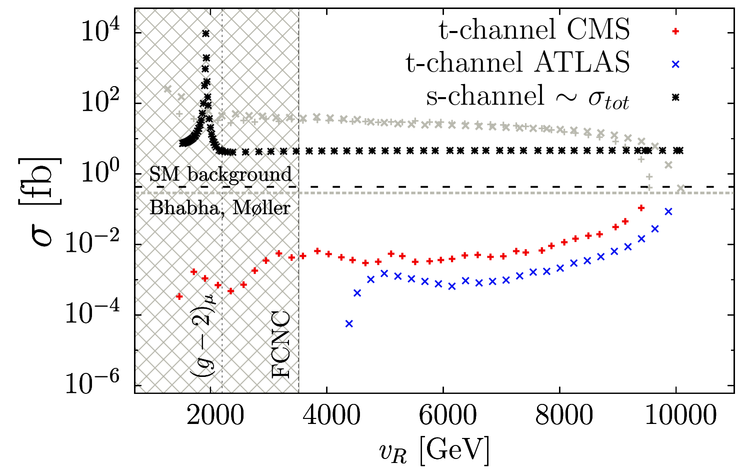
HTM

$f \sim \frac{m_\nu}{v_\Delta}$



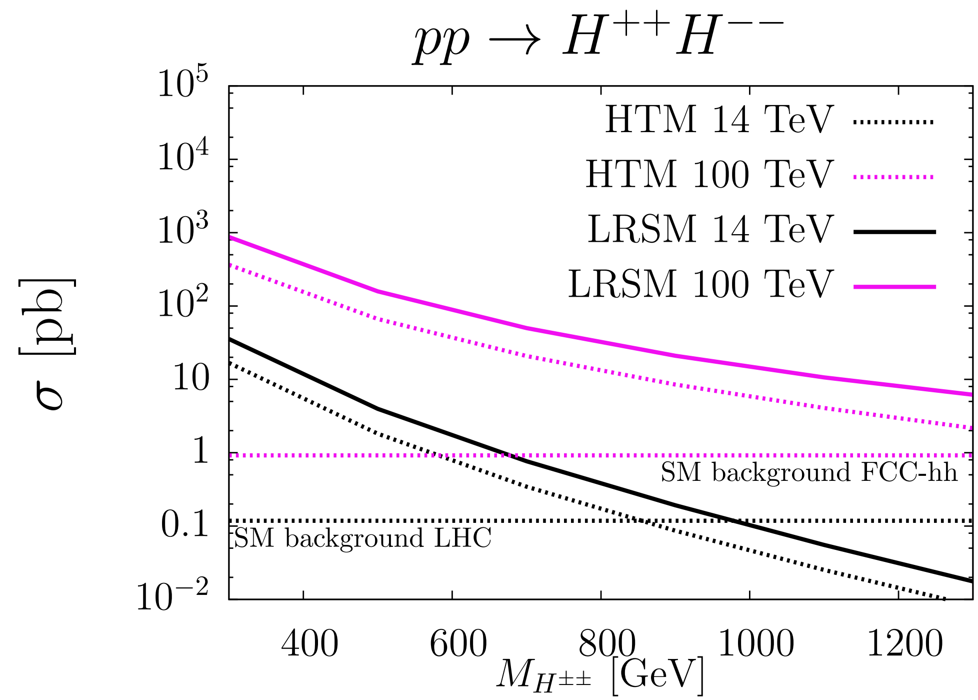
MLRSM

$h_M \sim \frac{m_N}{v_R}$



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

Four lepton background diagrams: $e^+e^- \to e^+e^-$ with FSR e^+e^- pair emission (a) and (b); with Z/γ^* production (c) and with multiperipheral processes (d).



Process	Energy	$t\bar{t}(Z/\gamma^*)$	$(Z/\gamma^*)(Z/\gamma^*)$	TOTAL
$\sigma(pp \to 4l)$ [fb]	14 TeV	0.060	0.054	0.114
	100 TeV	0.58	0.20	0.78

SM background. For the inclusive $t\bar{t}$ process the QCD NLO k-factor is 2.2, accordingly, for $t\bar{t}(Z/\gamma^*)$ it is $k = 1.6$, for $(Z/\gamma^*)(Z/\gamma^*)$ it is $k = 1.5$.

Individual channel contributions, HL-LHC, FCC-hh

		14 TeV				100 TeV			
Model	Process $pp \to$	γ	Z_1	Z_2	scalars	γ	Z_1	Z_2	scalars
MLRSM	$H_1^{++}H_1^{--}$	63%	36%	$< 1\%$	$\ll 1\%$	43%	27%%	30%	$\ll 1\%$
	$H_2^{++}H_2^{--}$	74%	25%	$\sim 1\%$	$\ll 1\%$	68%	9%	23%	$\ll 1\%$
HTM	$H^{++}H^{--}$	65%	35%	—	$\ll 1\%$	62%	38%	—	$\ll 1\%$

SM background: $e^+e^- \to 4l$	
$4e$	No cuts: $\sigma = 2.1$ fb After cuts: $\sigma = 0.13$ fb, N = **200**
4μ	No cuts: $\sigma = 0.07$ fb After cuts: $\sigma = 0.005$ fb, N = **8**

BSM signal: $e^+e^- \to H^{++}H^{--} \to 4l$		HTM		MLRSM	
		NH	IH	v_R = 6 TeV	v_R = 15 TeV
$4e$	No cuts:	0.19 fb	0.53 fb	0.06 fb	0.924 fb
	After cuts:	0.02 fb N=**30**	0.06 fb N=**90**	0.007 fb N=**10**	0.113 fb N=**169**
4μ	No cuts:	0.22 fb	0.19 fb	0.06 fb	0.33 fb
	After cuts:	0.08 fb N=**120**	0.08 fb N=**120**	0.03 fb N=**38**	0.137 fb N=**205**

$e^+e^- \to H^{++}H^{--} \to 4l$ for $M_{H^{\pm\pm}} = 700$ GeV and $\sqrt{s} = 1.5$ TeV. "N" estimates a number of final events with the assumed luminosity $L = 1500\ fb^{-1}$.

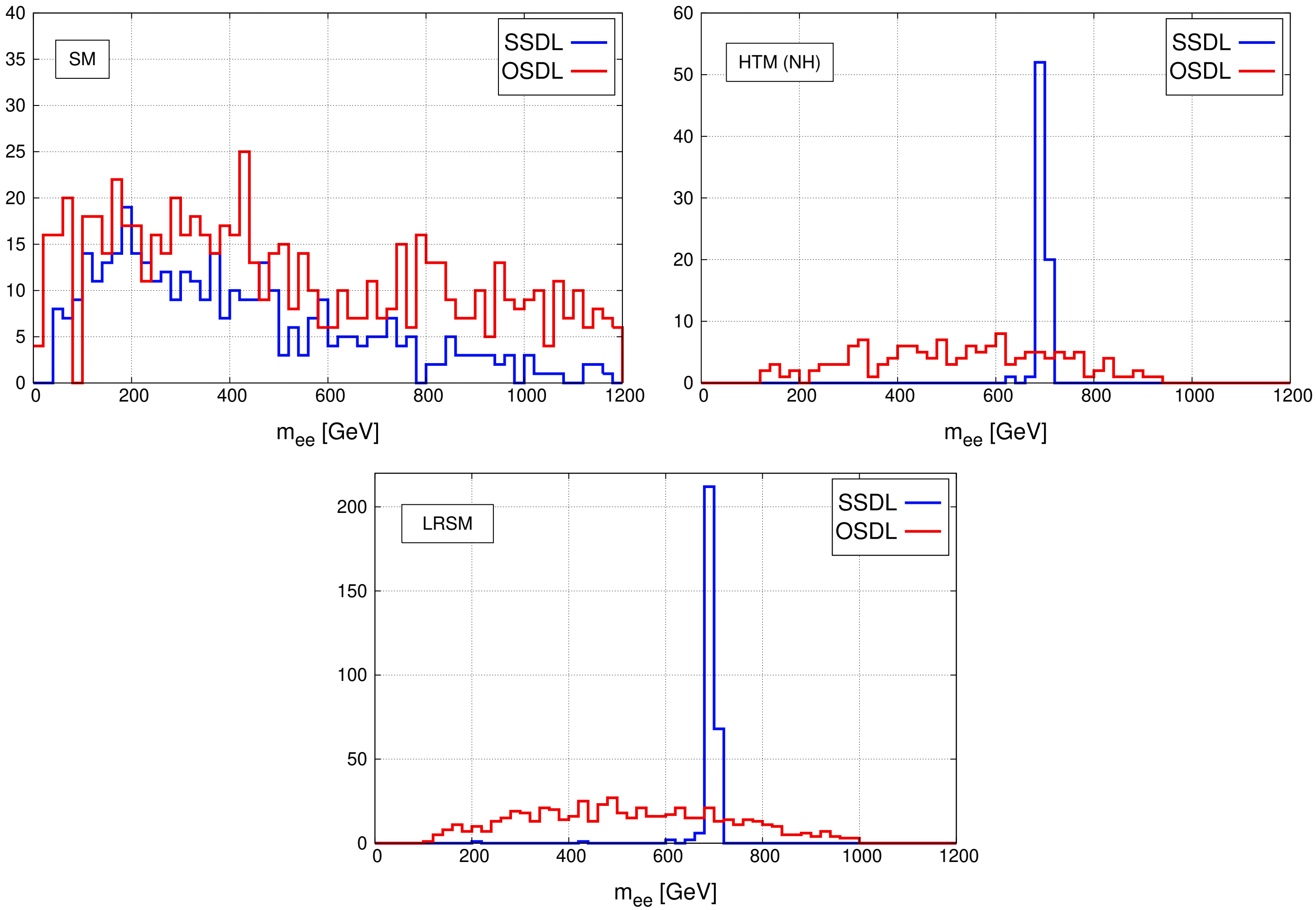
Kinematic cuts

- The Parton Distribution Function (PDF) CTEQ6L1
- Initially to select a lepton, CALCHEP, PYTHIA, $|\eta| < 2.5$ and $p_T >$ 10 GeV
- Detector efficiency cut for leptons is as follows:
  - ◇ For electron (either e^- or e^+) detector efficiency i s 0.7 (70%);
  - ◇ For muon (either μ^- or μ^+) detector efficiency i s 0.9 (90%).
- Smearing of electron energy and muon p_T are done
- Lepton-lepton separation. $\Delta R_{ll} \geq 0.2$
- Lepton-photon separation cut is also applied: $\Delta R_{l\gamma} \geq 0.2$ with all the photons having $p_{T\gamma} > 10$ GeV;
- Lepton-jet separation: The separation of a lepton with all the jets should be $R_{lj} \geq 0.4$, otherwise that lepton is not counted as lepton. Jets are constructed from hadrons using PYCELL within the PYTHIA.
- Hadronic activity cut. This cut is applied to take only pure kind of leptons that have very less hadronic activity around them. Each lepton should have hadronic activity, $\frac{\sum p_{T_{hadron}}}{p_{T_l}} \leq 0.2$ within the cone of radius 0.2 around the lepton.
- Hard p_T cuts: $p_{Tl_1} > 30$ GeV, $p_{Tl_2} > 30$ GeV, $p_{Tl_3} > 20$ GeV, $p_{Tl_4} > 20$ GeV.
- Missing p_T cut. Since 4-lepton final state is without missing p_T, missing p_T cut is not applied while for 3-lepton final state there is a missing neutrino, so missing p_T cut $(p_T > 30$ GeV) is applied.
- Z-veto is also applied to suppress the SM background. This has larger impact while reducing the background for four-lepton without missing energy.

SM background: $pp \to 4l$	
$4e$	No cuts: $\sigma = 9.1$ [102.6] fb After cuts: $\sigma = 0.0071$ [0.153] fb, N = **28 [3825]**
4μ	No cuts: $\sigma = 9.1$ [100.6] fb After cuts: $\sigma = 0.022$ [0.62] fb, N = **88 [15 167]**

BSM signal: $pp \to H^{++}H^{--} \to 4l$		HTM		LRSM	
		NH	IH	v_R = 6 TeV	v_R = 15 TeV
$4e$	No cuts:	0.0038 fb [0.39 fb]	0.0109 fb [1.11 fb]	0.0029 fb [0.87 fb]	0.136 fb [19.6 fb]
	After cuts:	0.00032 fb N=**1.3** [0.020 fb] [N=**484**]	0.00092 fb N=**3.7** [0.059 fb] [N=**1459**]	0.00026 fb N=**1.1** [0.0407 fb] [N=**1032**]	0.0116 fb N=**45** [0.98 fb] N=**[24 492]**
4μ	No cuts:	0.0092 [1.086 fb]	0.0039 fb [0.48 fb]	0.0029 fb [0.87 fb]	0.136 fb [19.6 fb]
	After cuts:	0.0031 N=**11.5** [0.202 fb] [N=**5057**]	0.00132 fb N=**5.3** [0.090 fb] [N=**2262**]	0.001 fb N=**4** [0.181 fb] [N=**4509**]	0.048 fb N=**180** [3.9 fb] N=[**97 199**]

Signals over background can be better seen with distributions

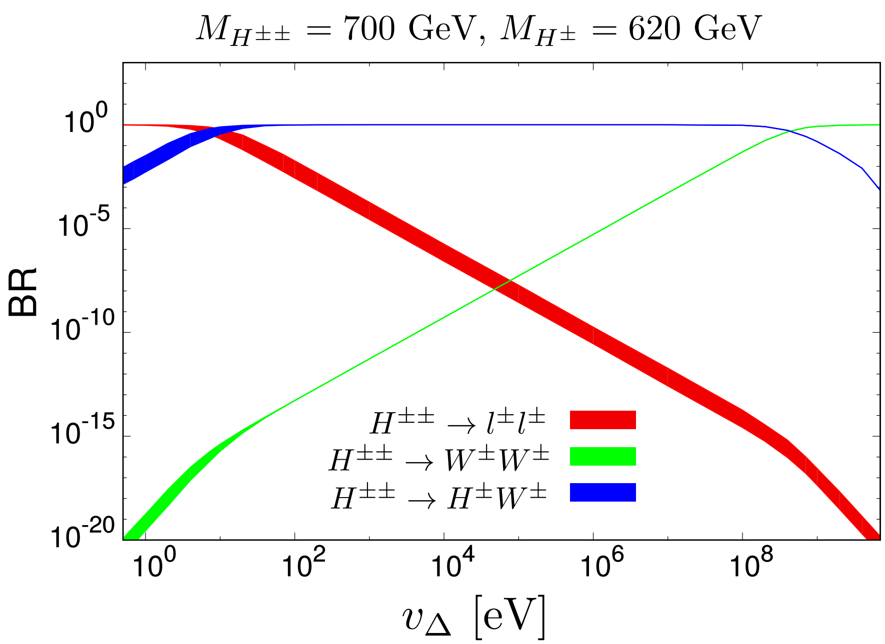


$+\Delta R_{ee}$ ...

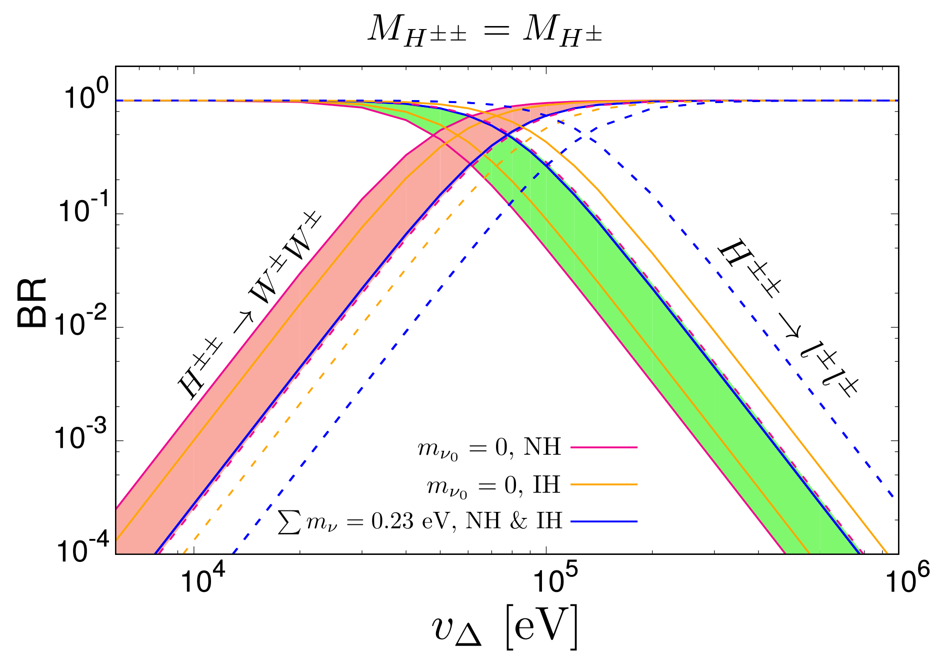
Summary

- $H^{\pm\pm}$ physics is a very interesting option for investigating BSM signals, we focused on the one process, $e^+e^-/pp \to H^{\pm\pm}H^{\mp\mp} \to 4l$.
- HL-LHC and FCC-hh can test different $H^{\pm\pm}$ scenarios, CP-violating effects (in scalar and lepton sectors) and low-energy constraints are important and can be discuss in details further.
- Elaborating actual models can help to extract observables and connections with effective models.

Backup slides



(a)



(b)

Used BRs for $M_{H_{1,2}^{\pm\pm}}$= 700 GeV

	ee	$\mu\mu$	$ee + \mu\mu$
$\mathrm{BR}_{H_1^{\pm\pm}}$	0.5	0.3	0.7
$\mathrm{BR}_{H_2^{\pm\pm}}$	1.0	0.8	1.0

Maximum branching ratios for $H_{1,2}^{\pm\pm} \to XX$ and $M_{H_{1,2}^{\pm\pm}}$= 700 GeV. Results for $H_1^{\pm\pm}$ coincides with slide 10. Branching ratios for $H_2^{\pm\pm}$ are due to right-handed leptonic couplings as analysed by ATLAS, EPJC'2018.

Used HTM benchmarks

$M_{H^{\pm\pm}}$	$H^{\pm\pm} \to XX$	HTM			
		NH		IH	
700 GeV ()	eemax $BR < 0.5$	BR=0.283	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = \frac{\pi}{2}$ $m_{\nu_0} = 0.071$ eV	BR=0.475	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = \frac{\pi}{2}$ $m_{\nu_0} = 0$
	$\mu\mu$max $BR < 0.3$	BR=0.3	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = 0$ $m_{\nu_0} = 0.025$ eV	BR=0.3	$\alpha_1 = 0$ $\alpha_2 = 0$ $m_{\nu_0} = 0.066$ eV
1000 GeV (•)	eemax	BR=0.283	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = \frac{\pi}{2}$ $m_{\nu_0} = 0.071$ eV	BR=0.475	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = \frac{\pi}{2}$ $m_{\nu_0} = 0$
	$\mu\mu$max	BR=0.438	$\alpha_1 = 0$ $\alpha_2 = 0$ $m_{\nu_0} = 0.015$ eV	BR=0.3	$\alpha_1 = 0$ $\alpha_2 = 0$ $m_{\nu_0} = 0.066$ eV

Chosen parameter set for maximum branching ratios BR$(H^{\pm\pm} \to ee)$ and BR$(H^{\pm\pm} \to \mu\mu)$ and for the best fit neutrino parameters.

Used MLRSM benchmarks

$M_{H^{\pm\pm}_{1,2}}$	MLRSM				$H^{\pm\pm}_{1,2} \to$
	$v_R = 6$ TeV		$v_R = 15$ TeV		
700 GeV	$\text{BR}^{ee,\mu\mu}_{H^{\pm\pm}_{1,2}} = 0.123$	$M_{N_1} = 250$ $M_{N_2} = 250$ $M_{N_3} = 620$	$\text{BR}^{ee}_{H^{\pm\pm}_{1,2}} = 0.5$ $\text{BR}^{\mu\mu}_{H^{\pm\pm}_{1,2}} = 0.25$	$M_{N_1} = 1300$ $M_{N_{2,3}} = 918$	$4e$
			$\text{BR}^{\mu\mu}_{H^{\pm\pm}_{1,2}} = 0.3$ $\text{BR}^{ee}_{H^{\pm\pm}_{1,2}} = 0.4$	$M_{N_1} = 1300$ $M_{N_{2,3}} = 1130$	4μ
1000 GeV	$\text{BR}^{ee,\mu\mu}_{H^{\pm\pm}_{1,2}} = 0.123$	$M_{N_1} = 250$ $M_{N_2} = 250$ $M_{N_3} = 620$	$\text{BR}^{ee}_{H^{\pm\pm}_{1,2}} \sim 1$	$M_{N_1} = 2867$ $M_{N_{2,3}} = 300$	$4e$
			$\text{BR}^{\mu\mu}_{H^{\pm\pm}_{1,2}} \sim 1$	$M_{N_2} = 5000$ $M_{N_{1,3}} = 300$	4μ

MLRSM parameters which maximize separately the branching ratios $\text{BR}(H^{\pm\pm} \to ee)$ and $\text{BR}(H^{\pm\pm} \to \mu\mu)$ for $v_R = 6$ TeV and $v_R = 15$ TeV. A scenario with $v_R = 6$ TeV has been covered already by the LHC analysis. The heavy neutrino masses for $v_R = 6$ TeV fulfill the low energy constraints. M_{N_1} is mostly restricted by the Møller scattering, while M_{N_2} is bounded by $(g-2)_\mu$.

$M_{H_{1,2}^{\pm\pm}}$ [GeV]	$v_R = 6$ TeV	$v_R = 15$ TeV
700	$M_{N_1} < 803$ GeV	$M_{N_1} < 2007$ GeV
1000	$M_{N_1} < 1147$ GeV	$M_{N_1} < 2867$ GeV

Upper limits on the heavy neutrino masses for different sets of doubly charged Higgs boson and the triplet VEV v_R, taking into account low energy LFV constraints and SM processes (Bhabha, Møller).

MLRSM and GUTs

breaking chains $G \to G^{(1)} \to G^{(2)} \ldots \to G^{(n)} \to G_{SM}$

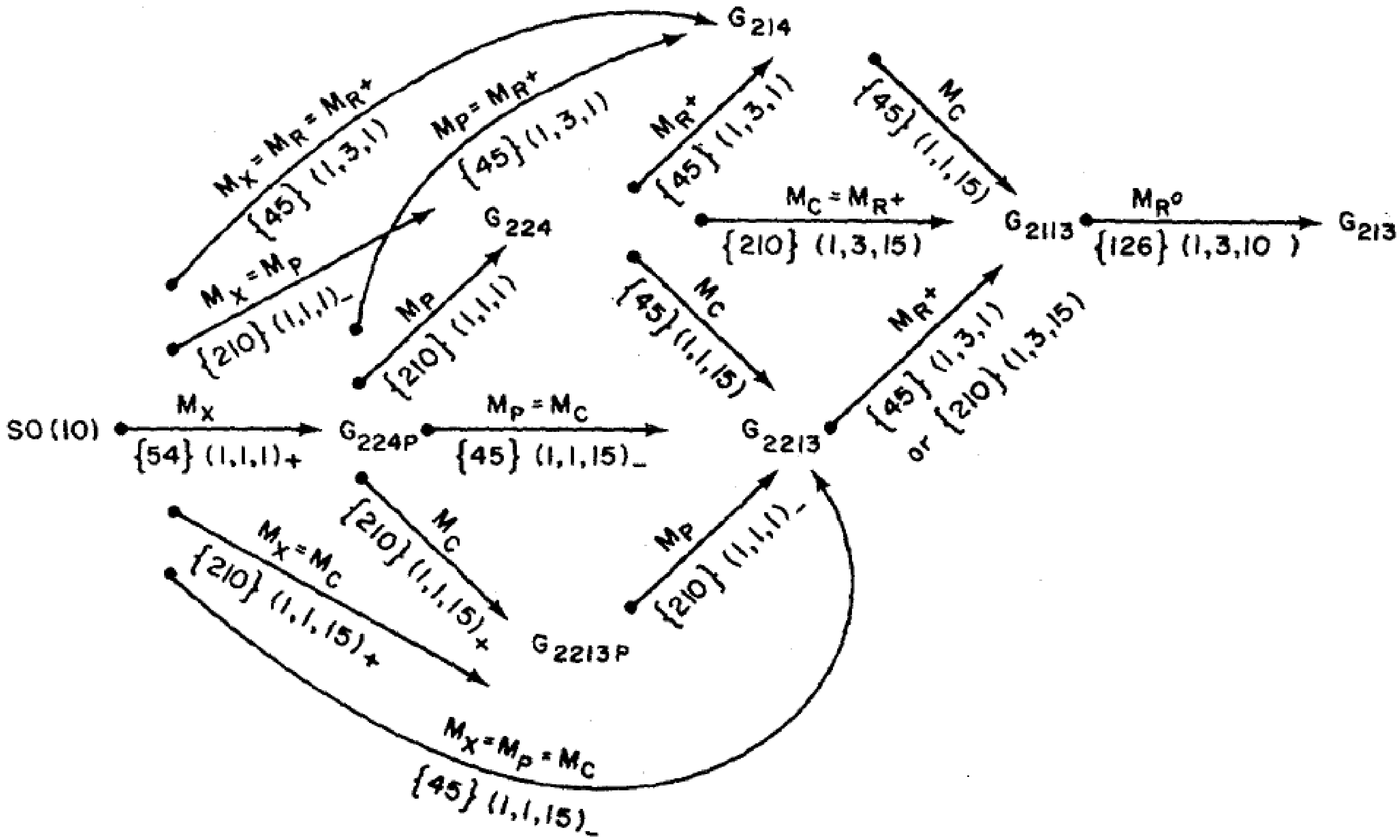
TABLE I. – *E_6 and its subgroups which contain G_{SM}. Here we use the inclusion relation $SO(7) \supset SU(4) \supset SU(3) \times U(1)$.*

E_6	F_4 $SO(10) \times U(1)$ $SU(2) \times SU(6)$ $SU(3) \times SU(3) \times SU(3)$
F_4	$SO(9)$ $SU(3) \times SU(3)$
$SO(9)$	$SU(2) \times SU(4)$
$SO(10)$	$SU(5) \times U(1)$ $SU(2) \times SU(2) \times SU(4)$ $SU(2) \times SO(7)$
$SU(6)$	$SU(5) \times U(1)$ $SU(2) \times U(1) \times SU(4)$ $SU(3) \times SU(3) \times U(1)$
$SU(5)$	$SU(3) \times SU(2) \times U(1)$

Extra gauge bosons

TABLE II. – *Group hierarchies which allow unification. Here the dots indicate that the hierarchy chains break directly into* G_{SM} *and* $G_{\mathrm{LR}} = SU(3) \times SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)$ *indicates the left-right–symmetric gauge group.*

E_6	G_{LR}	$\to \dots$	$\to \dots$	
	$SU(2) \times SU(2) \times SU(4)$	$\to \dots$	$\to \dots$	
		G_{LR}	$\to \dots$	
	$SO(10) \times U(1)$	$SU(2) \times SU(2) \times SU(4) \times U(1)$	$\to \dots$	G_{SM}
			G_{LR}	
		G_{LR}	$\to \dots$	
	$SU(2) \times SU(6)$	$SU(2) \times SU(3) \times SU(3) \times U(1)$	G_{LR}	
		$SU(2) \times SU(2) \times SU(4) \times U(1)$	$\to \dots$	
			G_{LR}	
		G_{LR}	$\to \dots$	
	$SU(3) \times SU(3) \times SU(3)$	G_{LR}	$\to \dots$	
$SO(10)$	$SU(2) \times SU(2) \times SU(4)$	$\to \dots$	$\to \dots$	
		G_{LR}	$\to \dots$	
	G_{LR}	$\to \dots$	$\to \dots$	

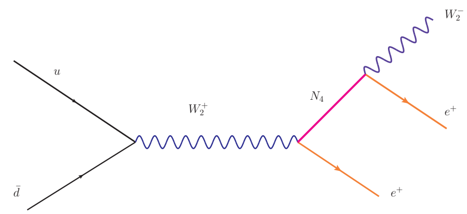


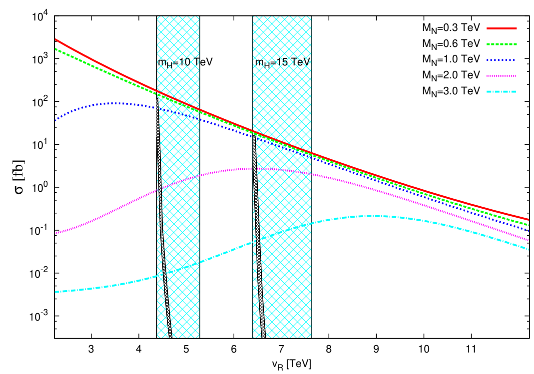
Diagrammatic sketch of 18 symmetry-breaking chains in SO(10).

Chang et al, PRD31, 1718 (1985)

Models consistency, beyound the tree level

"Left-Right Symmetry at LHC and Precise 1-Loop Low Energy Data", J. Chakrabortty et al, JHEP 1207 (2012) 038





Muon decay constrain parameter space of a model $\frac{G_F}{\sqrt{2}} = \frac{e^2}{8(1-M_W^2/M_Z^2)M_W^2}(1+\Delta r).$

M. Czakon, J. Gluza,M. Zrałek, Nucl. Phys. **B573** (2000) 57 and
M. Czakon, J. Gluza, J. Hejczyk, Nucl. Phys. **B642** (2002) 157-172.