# Doubly charged scalars' signal and low energy constraints

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Coimbra

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# 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. Summary

# Introduction

# Introduction

| Fermions | | | Bozons | |
|---|---|---|---|---|
| u | c | t | $\gamma$ | Z |
| d | s | b | g | $W^{\pm}$ |
| e | $\mu$ | $\tau$ | | |
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | | |

# Introduction

| Fermiony | | | Bozony | |
|---|---|---|---|---|
| u<br>2,3 MeV | c<br>1,275 GeV | t<br>173,21 GeV | $\gamma$<br>$m < 10^{-18}$ eV | Z<br>91,1876 GeV |
| d<br>4,8 MeV | s<br>95 MeV | b<br>4,18 GeV | g | $W^{\pm}$<br>80,385 GeV |
| e<br>0,511 MeV | $\mu$<br>105,658 MeV | $\tau$<br>1776,86 MeV | | |
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | | |

*Particle Data Group http://pdg.lbl.gov/*

# Introduction

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| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | | |

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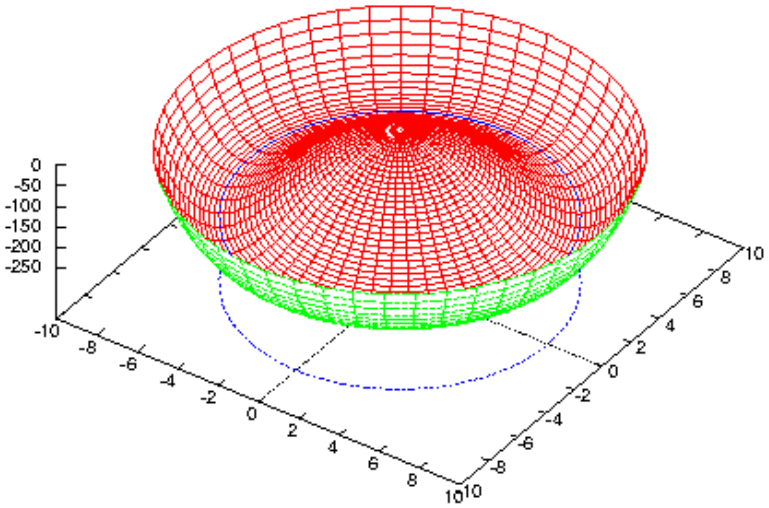
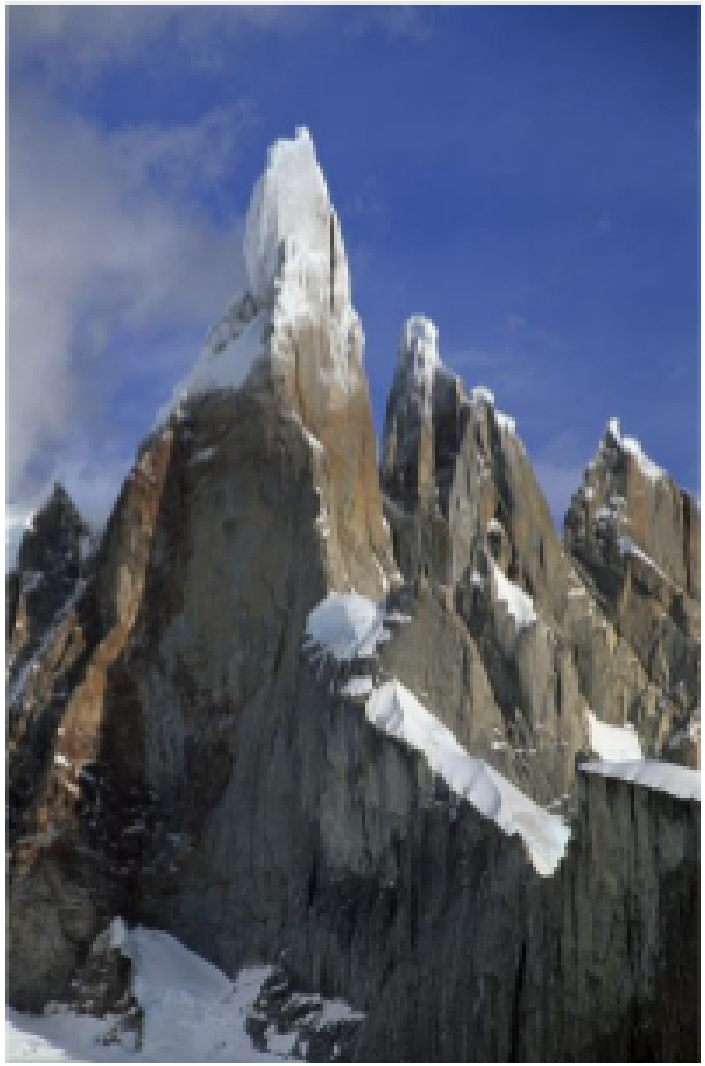
# Standard Model scalar potential...




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

# ... or maybe...



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

# Extensions of the SM

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Two ways to extend the scalar sector:

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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 $\rho$

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

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

- 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 |
| $SU(2) \times U(1)$ | $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$<br>$W_1,\ W_2,\ Z_1,\ Z_2,\ \gamma$ |
| $h, H, A, H^{\pm},\ H^{\pm\pm}$ | $h, H_1, H_2, H_3, A_1, A_2$<br>$H_1^{\pm}, H_2^{\pm},\ H_1^{\pm\pm}, H_2^{\pm\pm}$ |
| $v_\Delta \lesssim 1$ GeV | $v_L = 0$<br>$v_R \gtrsim 3000$ 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

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

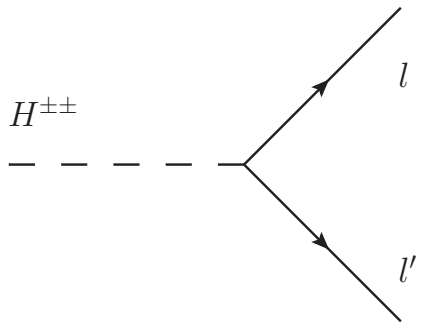
$$|M_{H^{\pm\pm}} - M_{N^\pm}| \leq 40 \text{ GeV}$$

1209.1303, 1206.0535

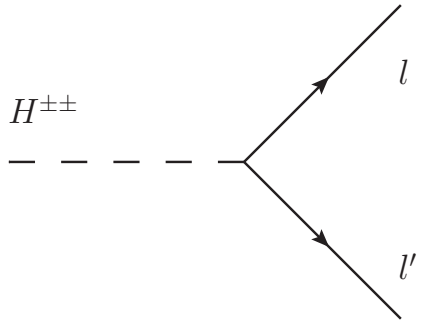
# HTM - $H^{\pm\pm} - l - l'$ coupling

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

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



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




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

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

# 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

- 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

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

# 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}
$$

# LRSM - Lagrangian

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

$$\Longrightarrow$$

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

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

# See-saw mechanism

- Mass matrix for neutrinos:

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

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

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

# 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

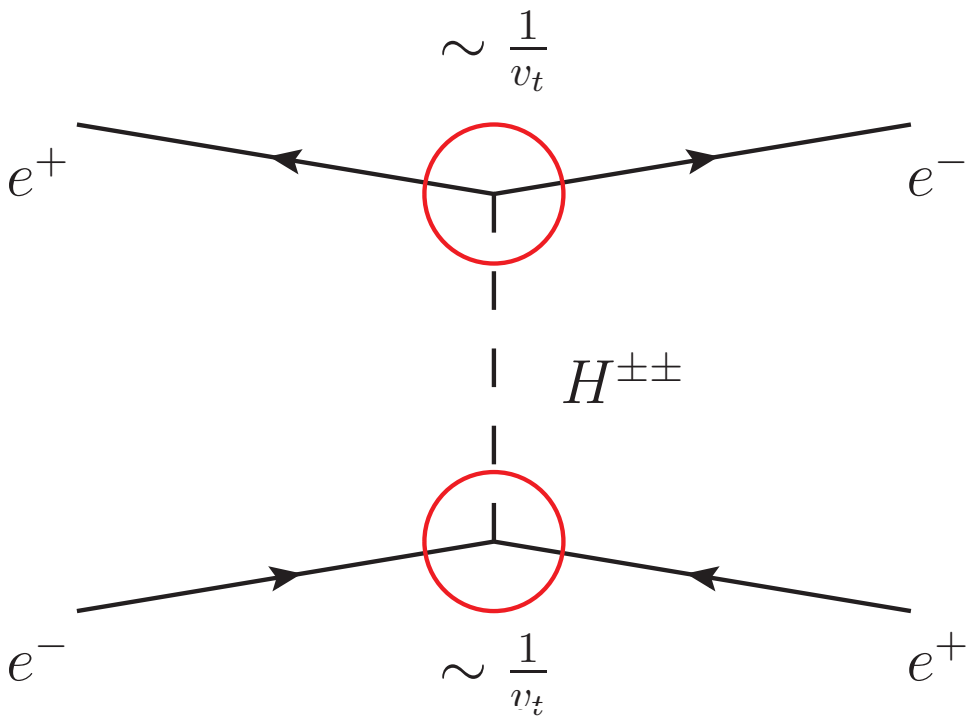
# $f_{ll'}$ coupling and parameter's constraints

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

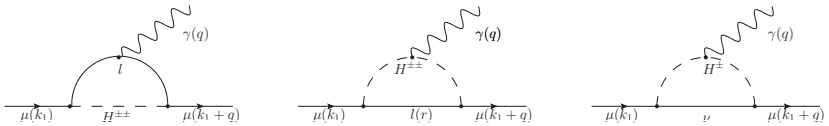
# Experimental constraints

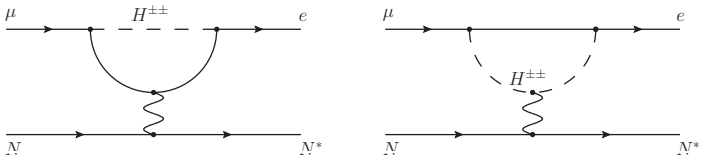
- High energy:
  - Bhabha scattering: $f_{ee}^2 \leq 6.0 \times 10^{-6} M_{H^{\pm\pm}}$

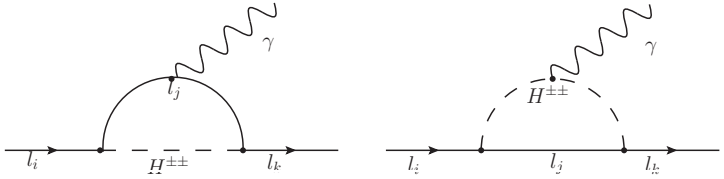
[Phys.Rev. D40 (1989) 1521] , [hep-ph/0304069]

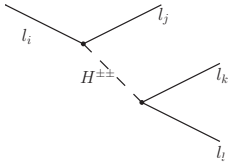


# Experimental constraints

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

  - $\mu$ to $e$ conversion: 

  - Radiative LFV decays: 

  - LFV three body decays : 

# Experimental constraints

- $(g-2)_\mu$

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

- $\mu$ 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] $\mathrm{BR}(\mu \to 3e) < 1.0 \times 10^{-12}$

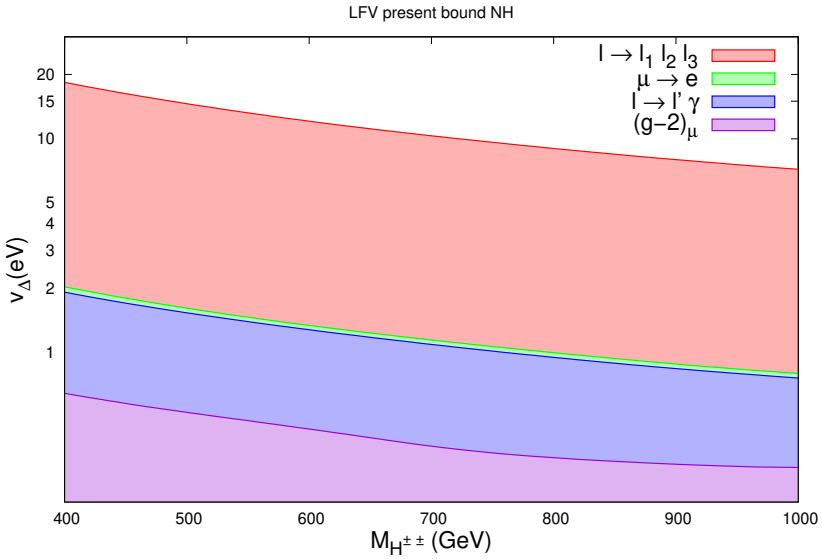
# Neutrino oscillation data

| | Normal hierarchy | | | Inverted hierarchy | | |
|---|---|---|---|---|---|---|
| | Best fit: | $\sigma$ | bfp$\pm 2\sigma$ | Best fit: | $\sigma$ | 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]

# $v_\Delta$ vs $M_{H^{\pm\pm}}$

NH

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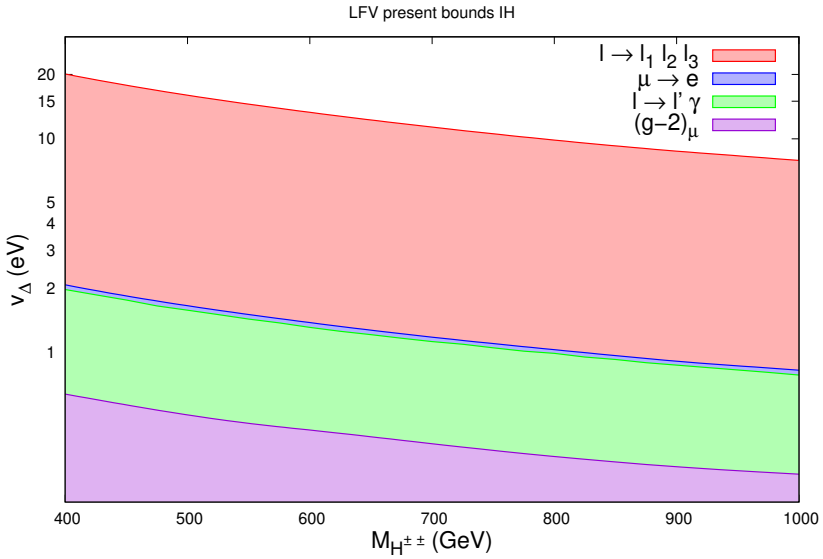

# $H^{\pm\pm}$ decay - HTM

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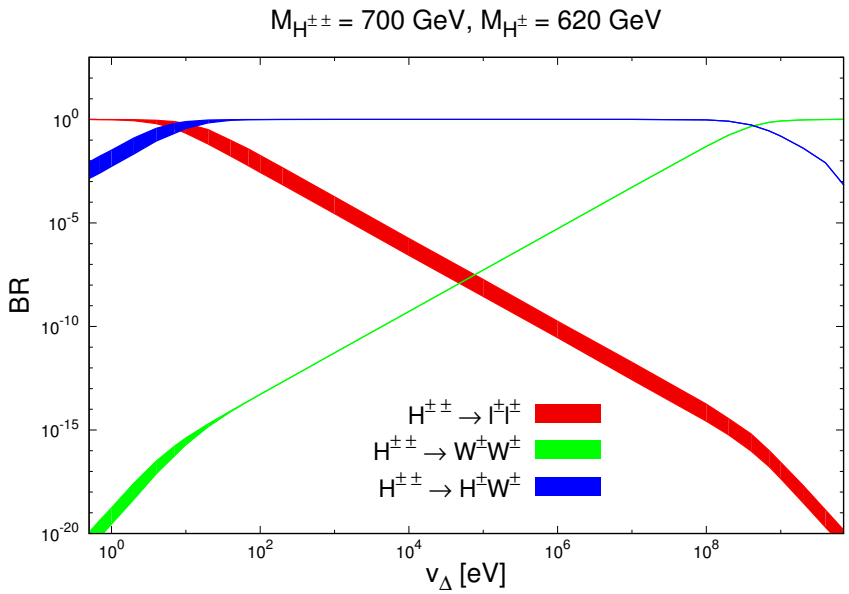
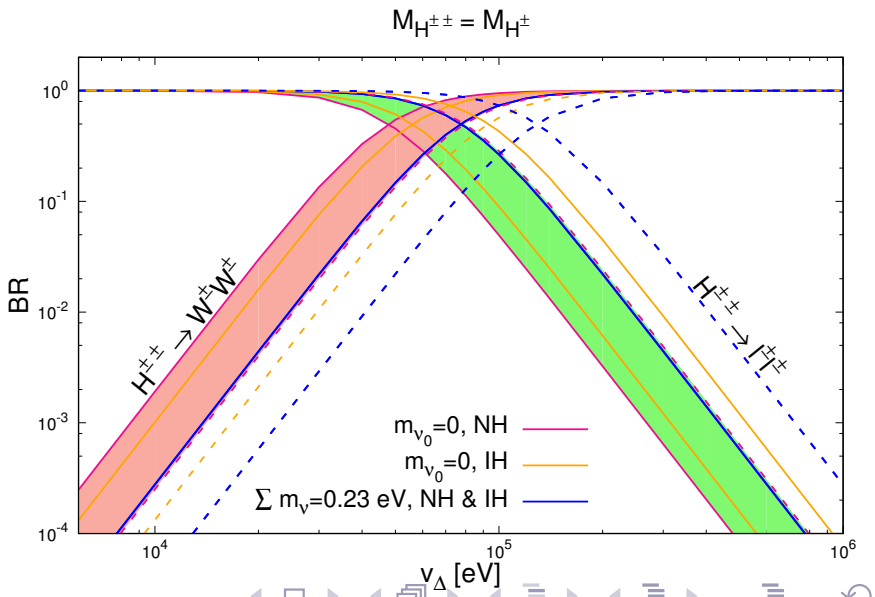
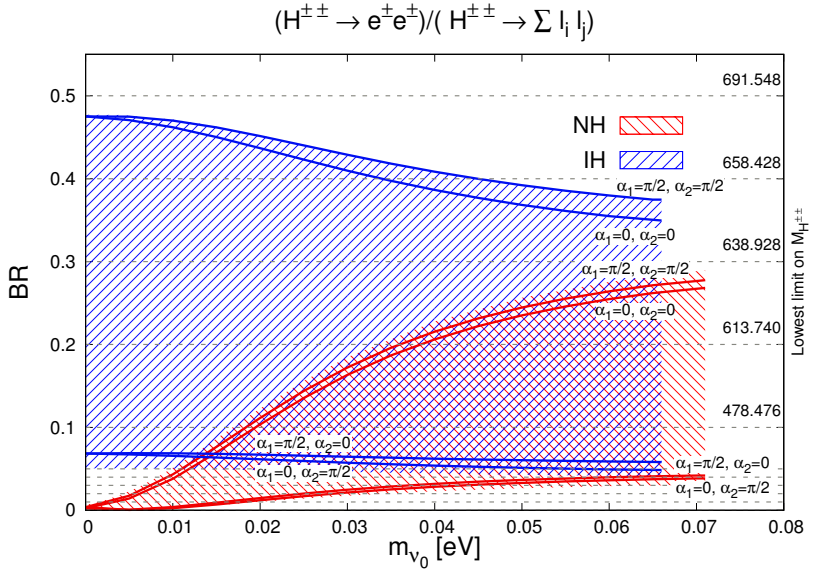
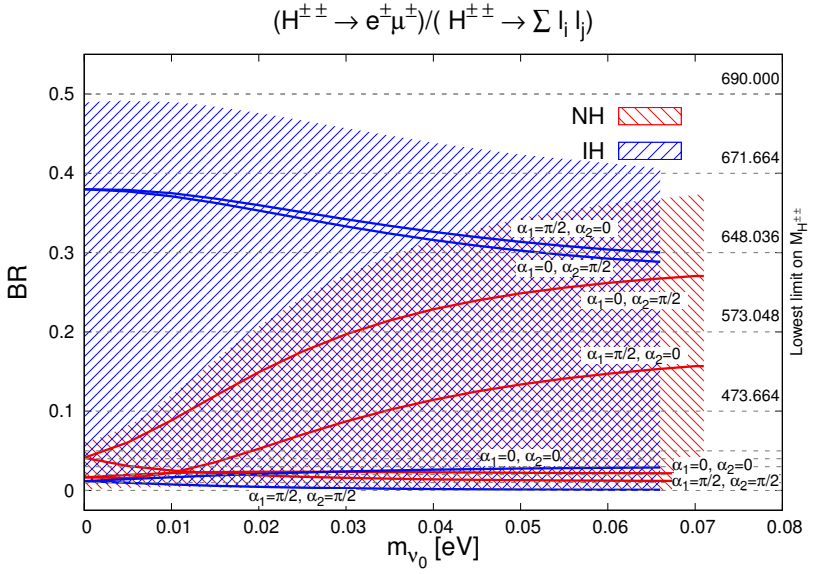
- $H^{\pm\pm} \to H^{\pm} H^{\pm}$

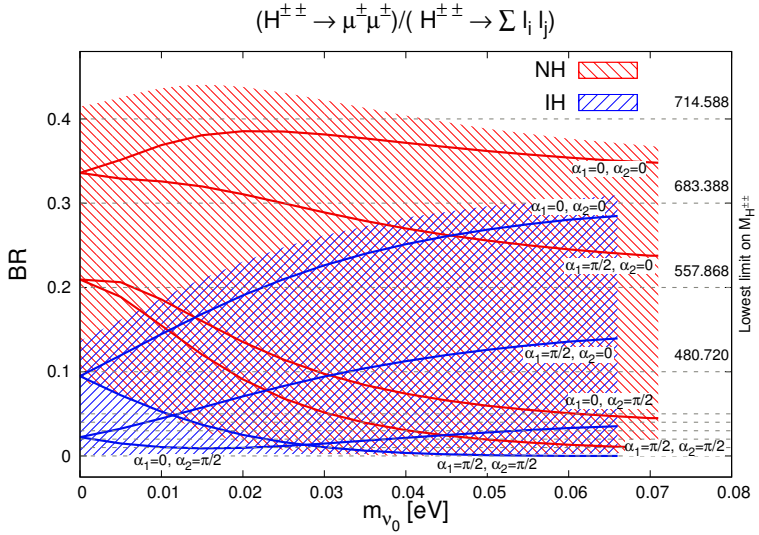


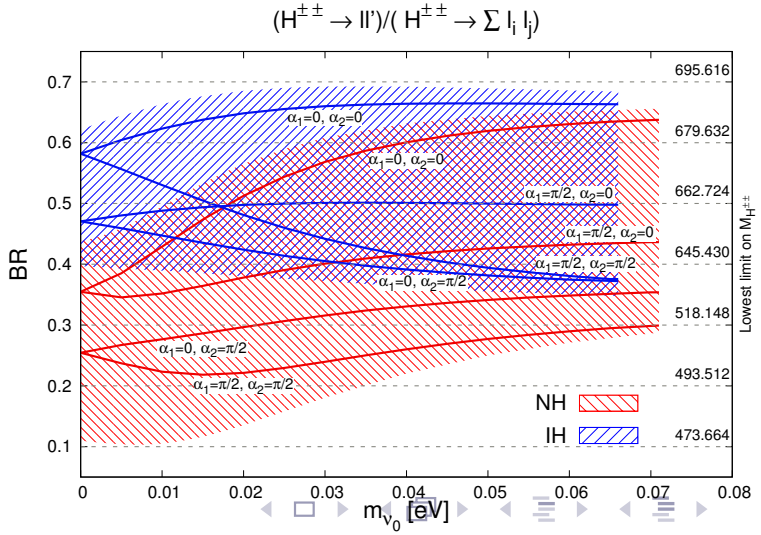



# $H^{\pm\pm}$ decay - HTM

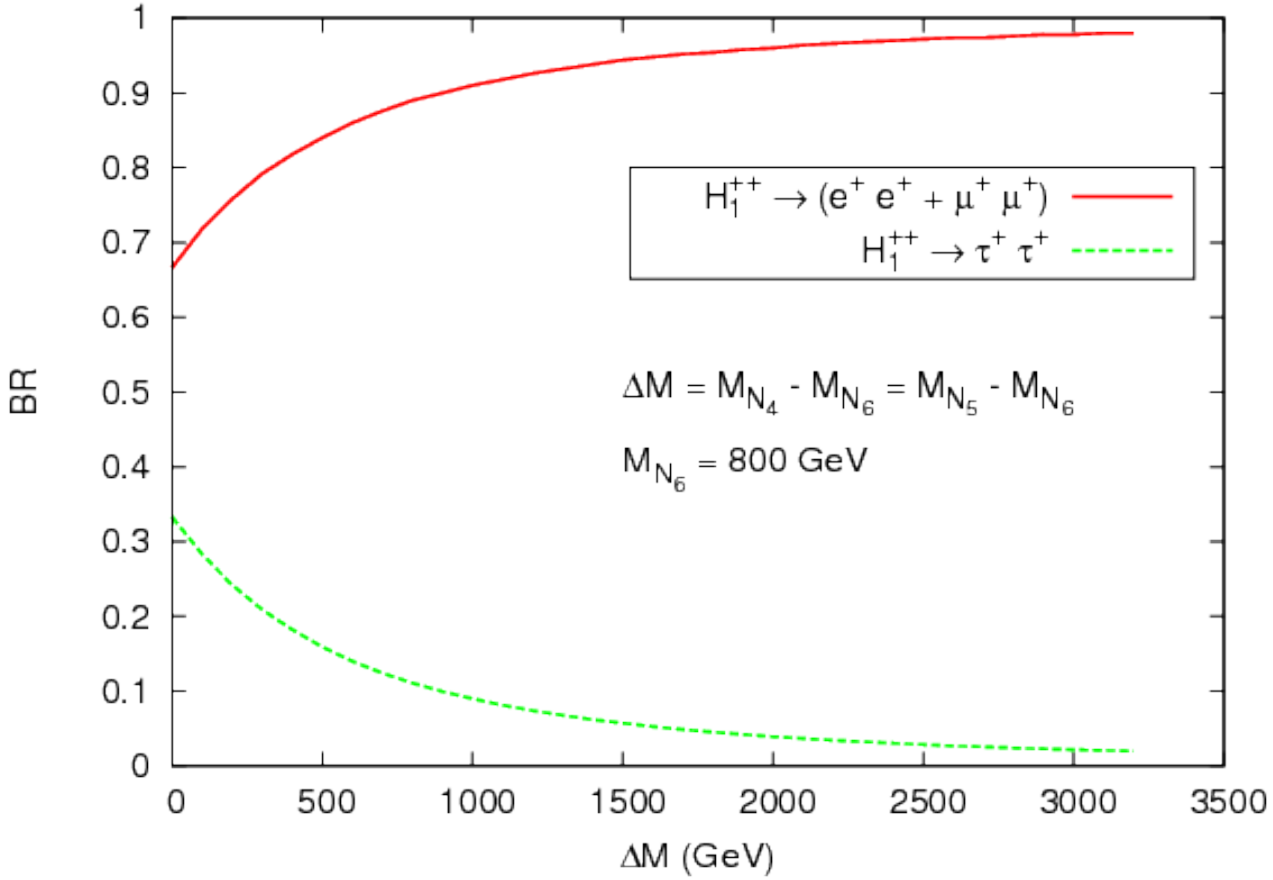


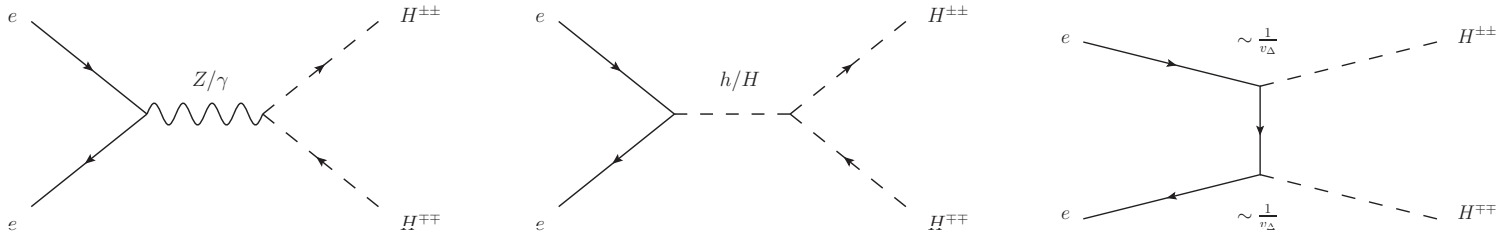
# $H^{\pm\pm}$ decay - LRSM

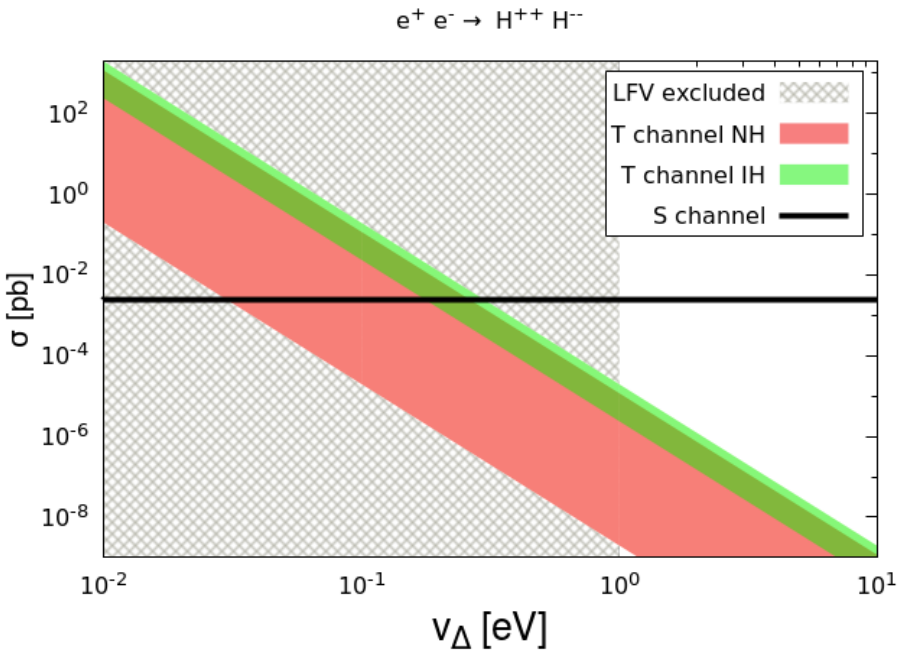



arXiv:1311.4144

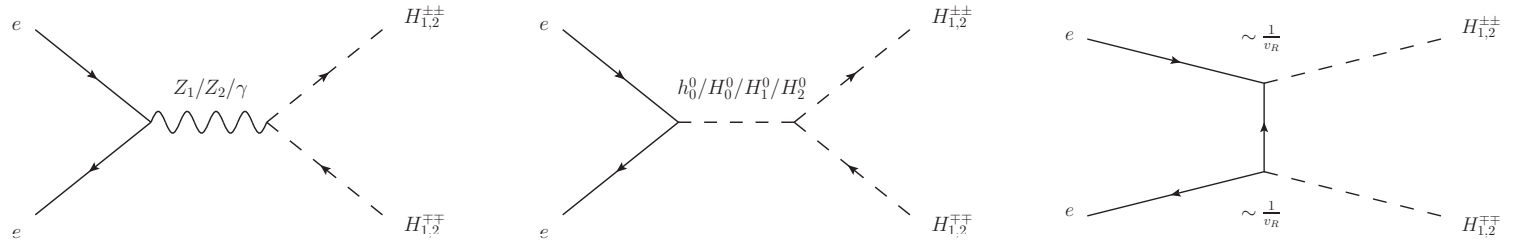
# Pair production in lepton and hadron colliders

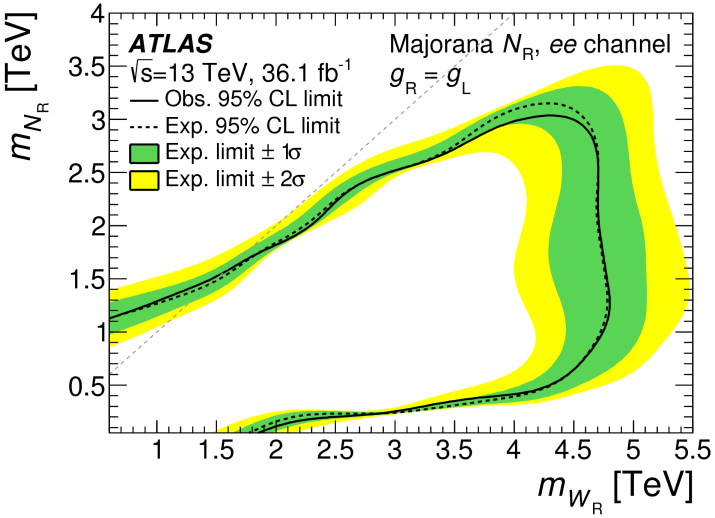
# Pair production in $e^+e^-$ colliders - HTM

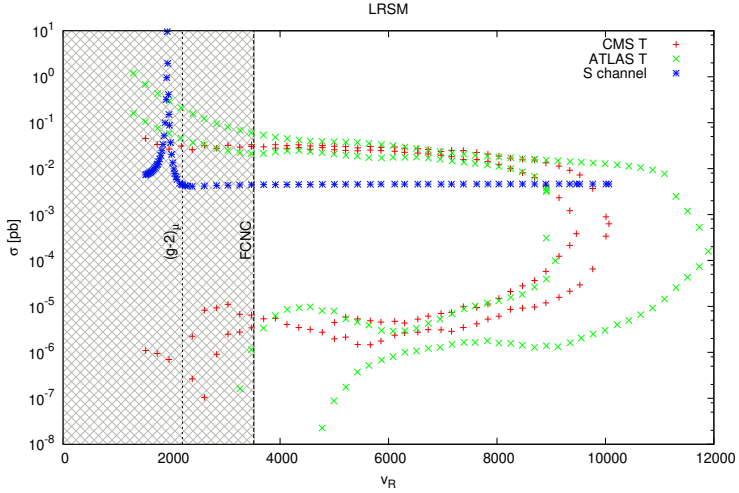


# Pair production in $e^+e^-$ colliders - LRSM

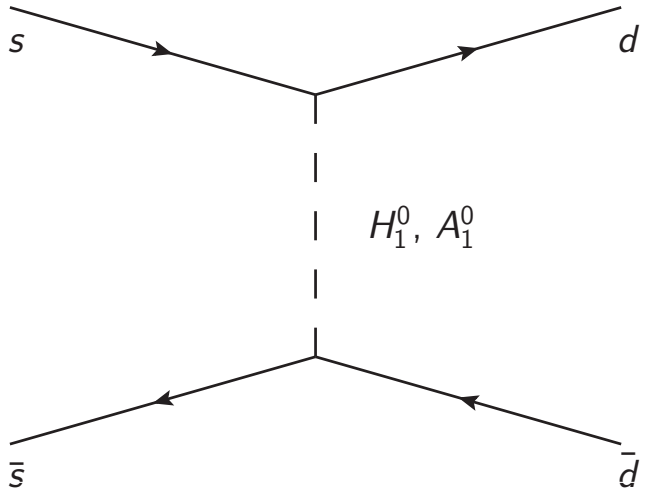


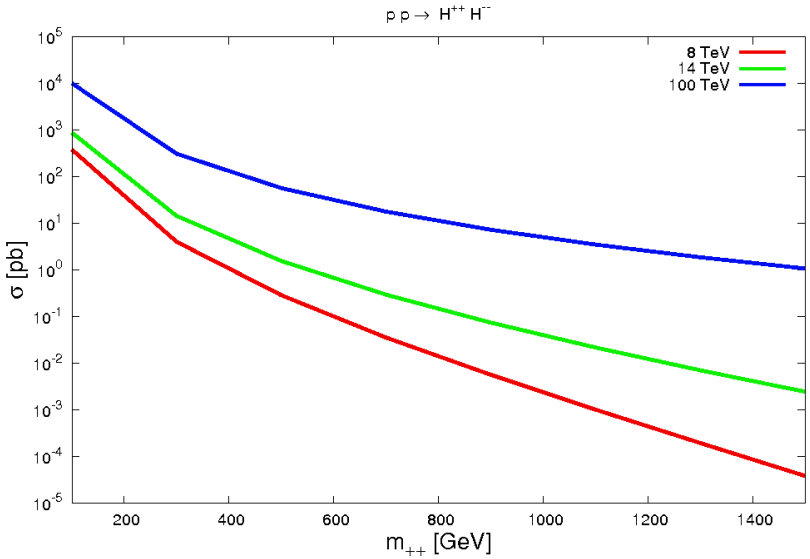
# Flavour Changing Neutral Currents

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

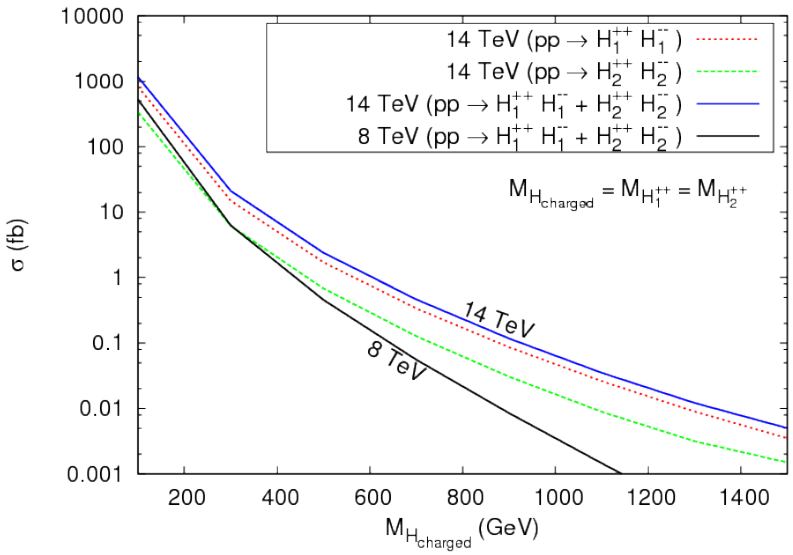


# $H^{\pm\pm}$ pair production in hadron colliders

HTM




LRSM




arXiv:1311.4144

# Summary

# 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 $\mu \to 3e$ LFV process
- 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

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# $U_{PMNS}$

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

# $\rho$ and T parameters

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

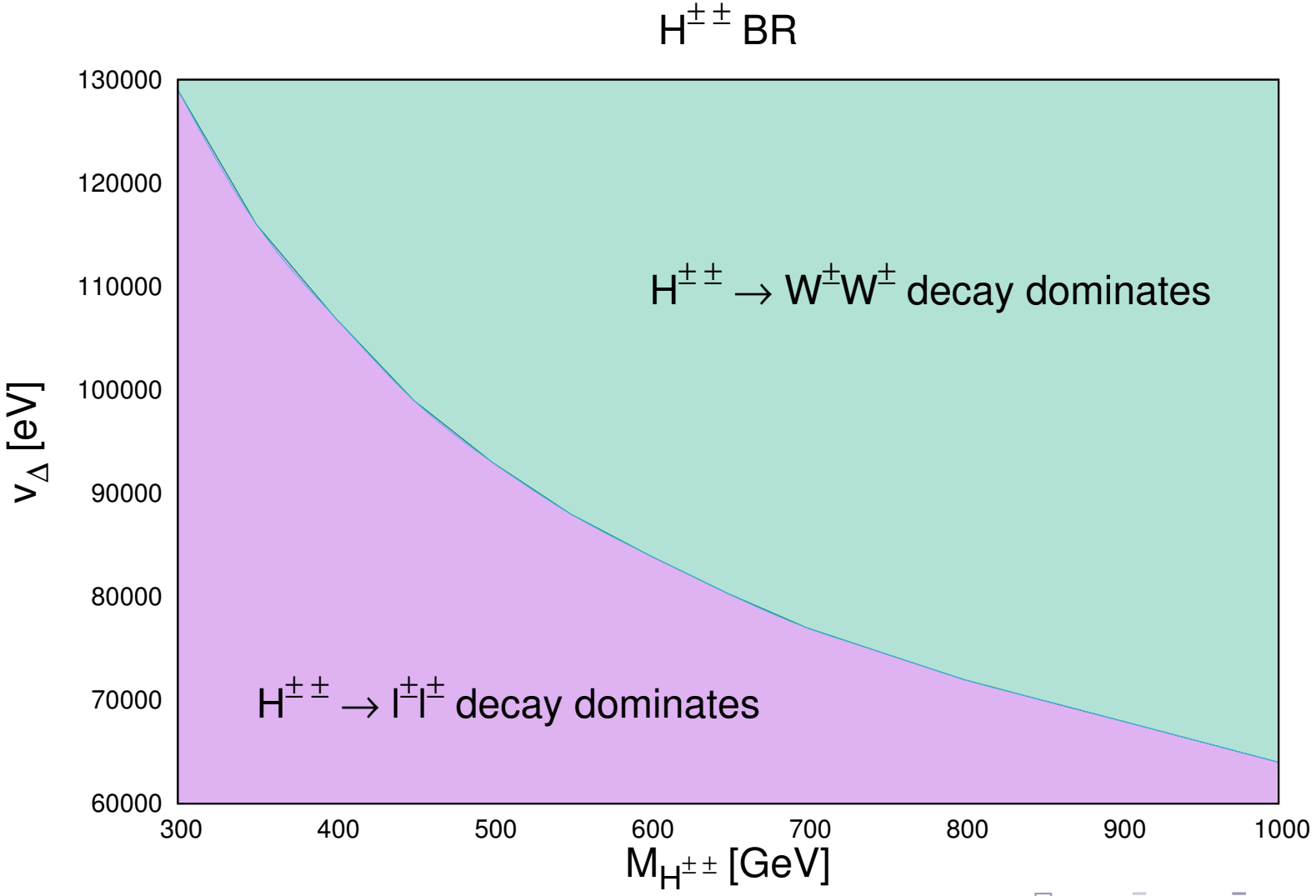
$$T = \frac{1}{\alpha}\left(\frac{\prod_{WW}(0)}{M_W^2} - \frac{\prod_{ZZ}(0)}{M_Z^2}\right) = \frac{\rho - 1}{\alpha} = 0.05 \pm 0.12$$

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

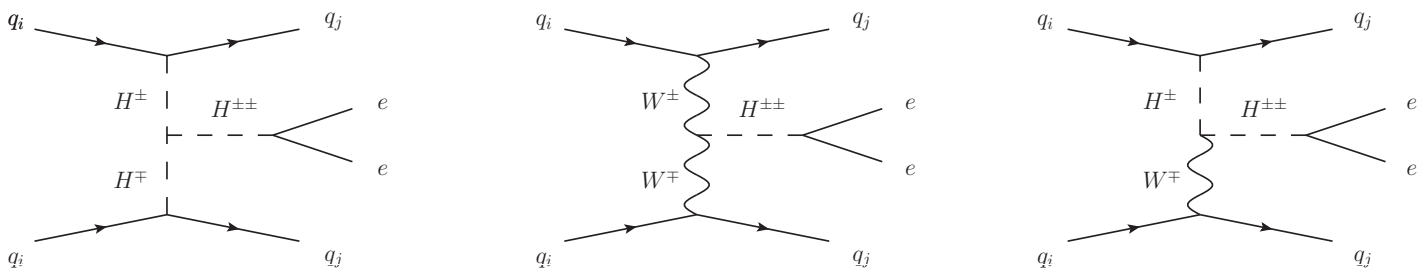
$$\Delta T < 0.2$$

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

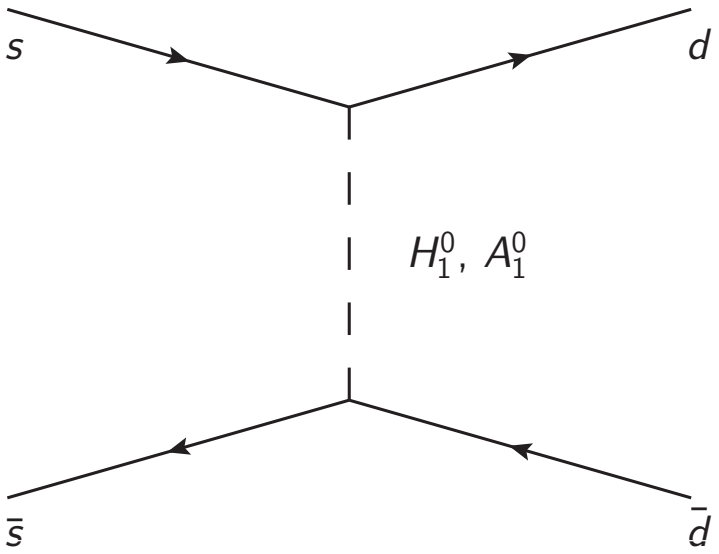
# $H^{\pm\pm}$ decay


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

# $0\nu\beta\beta$



# FCNC



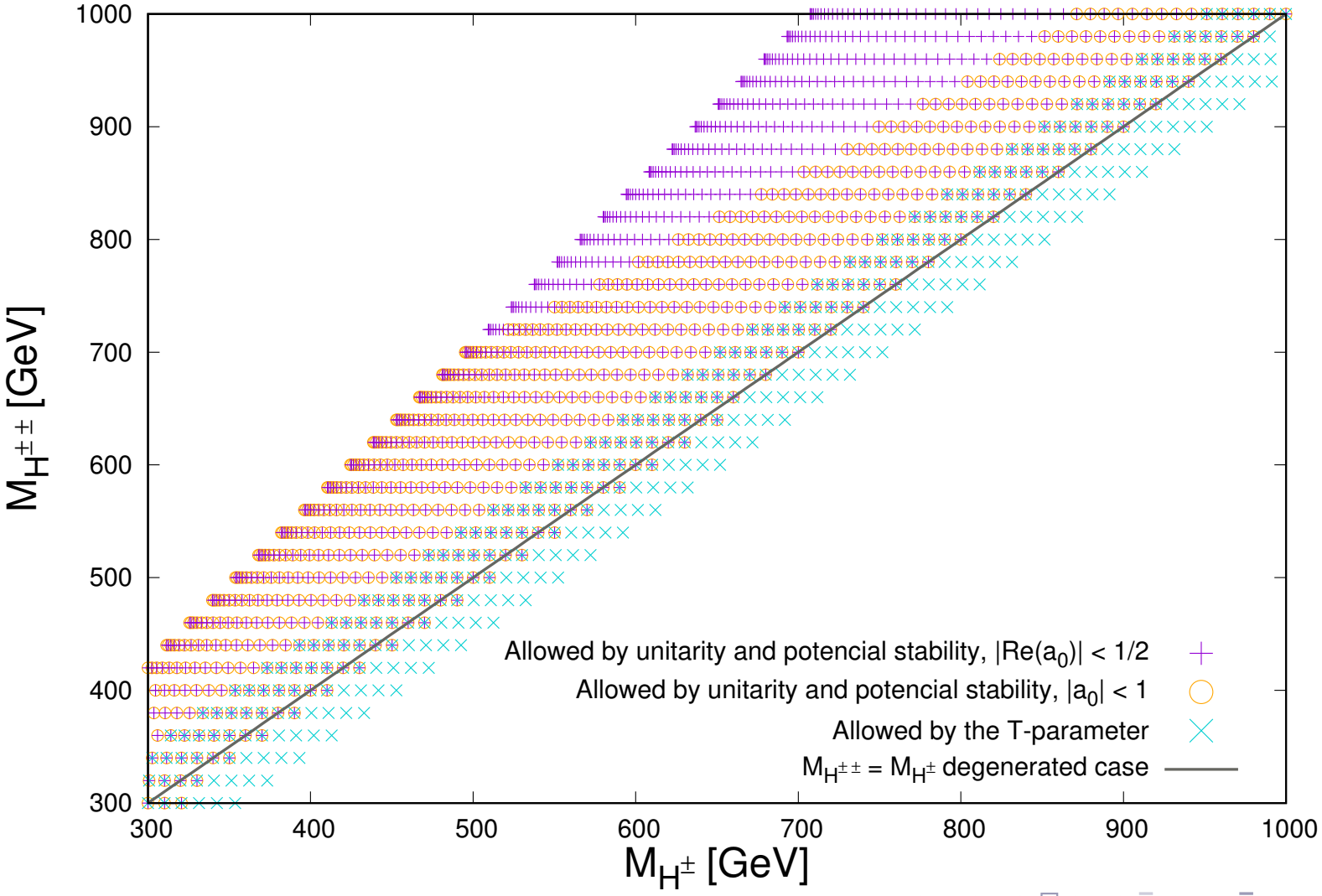
# Potential stability

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

# 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 - 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:

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

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

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

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

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

# Masses of the scalar bosons

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

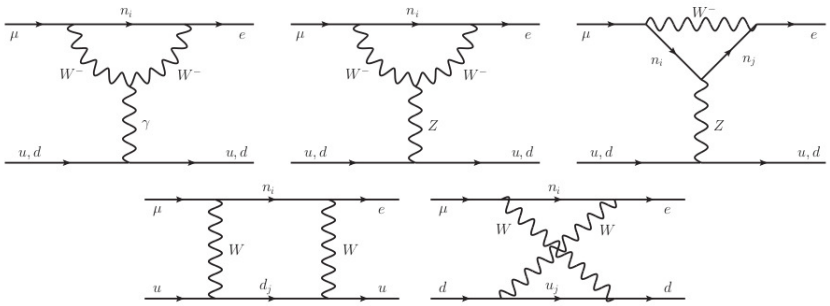
# Experimental limits for models parameters - LRSM

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

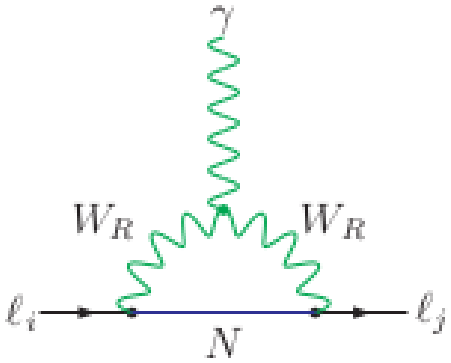
$$M_{W_2} \simeq 0.47 v_R, \quad M_{Z_2} \simeq 0.78 v_R$$

- $M_{H_0^3} \geq 55.4$ 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