Electroweak scale neutrinos and Higgses

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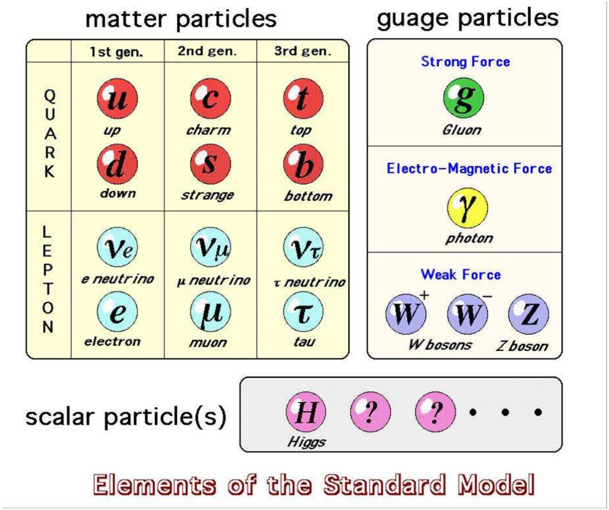
Outline

Particle Content



Gauge Structure.

interactions

1. $SU(3)_C \times SU(2)_W \times U(1)_Y$
2. 8 gluon fields for the Strong interaction.
3. 3 gauge fields for the Weak interaction.
4. 1 gauge field for the Electromagnetic interaction.

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$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$e_R \quad \mu_R \quad \tau_R \qquad u_R \quad d_R \quad c_R \quad s_R \quad t_R \quad b_R$$

Higgs - The missing ingredient.

Massive force carriers!

1. Principle of Gauge Symmetry $\rightarrow$ Massless Gauge bosons.
2. Massive Gauge bosons $\rightarrow$ inconsistent theory!
3. Solution: Spontaneous Symmetry Breaking - Higgs Mechanism

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SM predicts the existence of a new particle, the Higgs.

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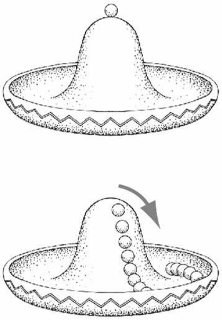

Why go beyond the Standard Model?

Experimental Evidence

1. Neutrinos are MASSIVE.
2. Baryon Asymmetry - A mystery.
3. Dark Matter
4. Dark Energy

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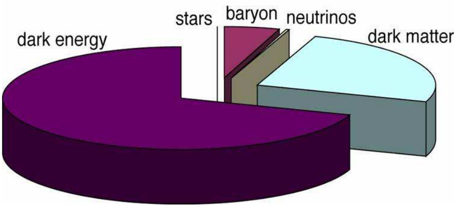

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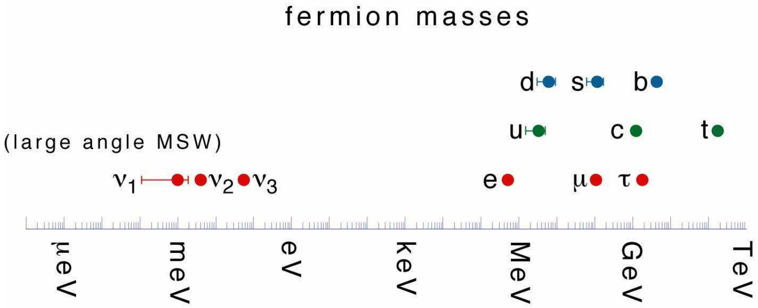

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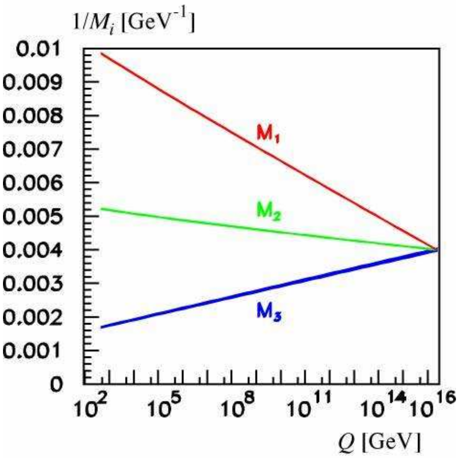

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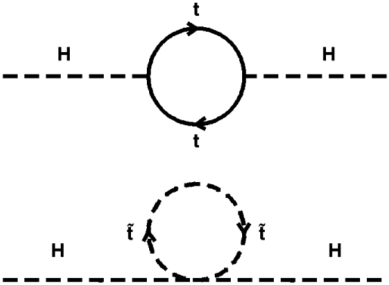

Why go beyond the Standard Model?

Theoretical Evidence

1. GRAVITY.

How do we go beyond the Standard Model?

Approaches

1. Grand Unified Theories.
2. Supersymmetry.
3. Extra dimensions.
4. $\bigcirc \; \Diamond \; \odot$

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Paradigm: Something is happening at high (very high) energy scales.

Minimalistic additions

Proposal

1. Any addition to the Standard Model should NOT introduce higher energy scales [a].

2. Effects of additions should be testable at future accelerators: LHC/ILC

[a] A.A, Omar Blanno and J. Lorenzo Díaz-Cruz, Physics Letters B 660, 62-66 (2008)

Right-handed neutrinos at the Electroweak scale

The model

- SM particle content and gauge interactions.
- Existence of 3 RH neutrinos with a mass scale of EW size.
- Global $U(1)_L$ spontaneously (and/or explicitly) broken at the EW scale by a single complex scalar field.
- Higgs sector: $SU(2)_L$ doublet Higgs field Φ and a SM singlet complex scalar field η.

Neutrino and scalar sector

The Lagrangian

$$\mathcal{L}_{\nu H} = \mathcal{L}_{\nu y} - V \ ,$$

with

$$\mathcal{L}_{\nu y} = -y_{\alpha i}\bar{L}_\alpha N_{Ri}\Phi - \frac{1}{2}Z_{ij}\eta\bar{N}^c_{Ri}N_{Rj} + h.c. \ ,$$

$$\begin{aligned} V &= \mu_D^2\Phi^\dagger\Phi + \frac{\lambda}{2}\left(\Phi^\dagger\Phi\right)^2 + \mu_S^2\eta^*\eta + \lambda'\left(\eta^*\eta\right)^2 \\ &+ \kappa\left(\eta\Phi^\dagger\Phi + h.c.\right) + \lambda_m\left(\Phi^\dagger\Phi\right)\left(\eta^*\eta\right) . \end{aligned}$$

Breaking the symmetry

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi^0 + v}{\sqrt{2}} \end{pmatrix} \quad \text{and} \quad \eta = \frac{\rho + u + i\sigma}{\sqrt{2}} \; , \tag{1}$$

Breaking the symmetry

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi^0 + v}{\sqrt{2}} \end{pmatrix} \text{ and } \eta = \frac{\rho + u + i\sigma}{\sqrt{2}} , \quad (1)$$

Scalar masses

$$M_S^2 = \begin{pmatrix} \lambda v^2 & vu(\lambda_m - \sqrt{2}r) \\ vu(\lambda_m - \sqrt{2}r) & 2\lambda' u^2 + \frac{1}{\sqrt{2}} r v^2 \end{pmatrix} \quad (2)$$

$$M_\sigma^2 = \frac{rv^2}{\sqrt{2}} \quad (3)$$

Physical states

$$\mathcal{H} = \begin{pmatrix} \phi^0 \\ \rho \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix} \tag{4}$$

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Lagrangian

$$\begin{aligned} \mathcal{L}_{\nu y} \supset & \left(-\frac{y_{\alpha i}}{\sqrt{2}} \bar{\nu}_{L\alpha} N_{Ri} (c_\alpha h - s_\alpha H) + h.c. \right) \\ - & \left(\frac{i}{2\sqrt{2}} Z_{ij} \bar{N}^c_{Ri} N_{Rj} \sigma + h.c. \right) \\ - & \left(\frac{1}{2\sqrt{2}} Z_{ij} \bar{N}^c_{Ri} N_{Rj} (s_\alpha h + c_\alpha H) + h.c \right) . \end{aligned} \quad (5)$$

Neutrino masses

Seesaw

$$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix} \quad (6)$$

- $(m_D)_{\alpha i} = y_{\alpha i} v / \sqrt{2}$
- Consider the third family (2×2 matrix)
- Assume $m_D << M_M \to m_1 = -m_D^2/M_M$ and $m_2 = M_M$
- Requiring $m_1 \sim$ O(eV) and $m_2 \sim (10 - 100)$ GeV leads to $y_{\tau i} \leq 10^{-6}$ (comparable to Yukawa coupling of the electron).

Neutrino eigenstates

$$\begin{aligned}\nu_\tau &= \cos\theta\, \nu_{L1} + \sin\theta\, \nu_{R2} \\ N &= -\sin\theta\, \nu_{L1} + \cos\theta\, \nu_{R2}\end{aligned}$$

with $\theta = \sqrt{m_D/m_2} \approx 10^{-(5-6)}$.

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Relevant terms

$$\begin{aligned} \mathcal{L} \supset\ & h\left[\bar{\nu}^c_{L1}\nu_{L1}\left(-\frac{Z}{2\sqrt{2}}s^2_\theta s_\alpha\right) + \bar{\nu}^c_{R2}\nu_{R2}\left(-\frac{Z}{2\sqrt{2}}c^2_\theta s_\alpha\right) + h.c.\right] \\ & + \bar{\nu}_{L1}\nu_{R2}\left(\frac{y_\nu}{\sqrt{2}}(s^2_\theta - c^2_\theta)c_\alpha\right) + \bar{\nu}_{R2}\nu_{L1}\left(\frac{y_\nu}{\sqrt{2}}(s^2_\theta - c^2_\theta)c_\alpha\right) \end{aligned}$$

where $y^*_\nu = y_\nu$ and $Z \equiv Z_{11}$

Higgs decays

$$\Gamma(h \to \bar{\nu}_1 \nu_1) = \frac{m_h}{64\pi} |Z|^2 s_\theta^4 s_\alpha^2$$

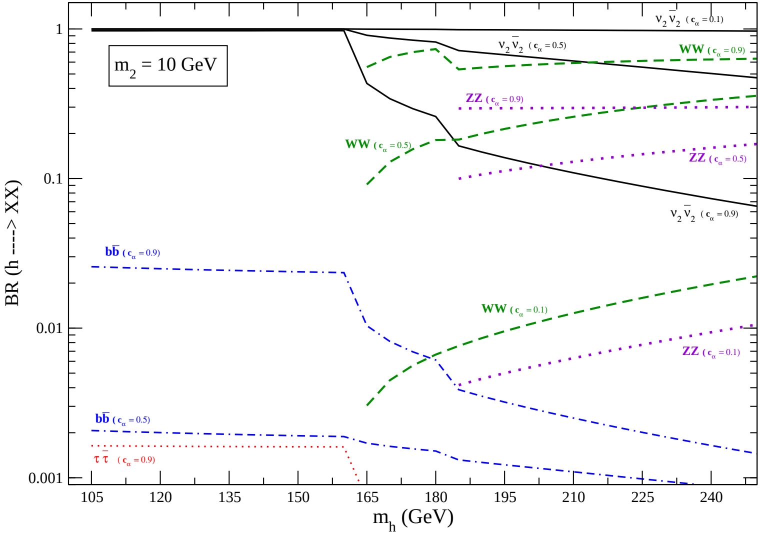
$$\Gamma(h \to \bar{\nu}_2 \nu_2) = \frac{m_h}{64\pi} |Z|^2 c_\theta^4 s_\alpha^2 \left(1 - \frac{4m_2^2}{m_h^2}\right)^{3/2}$$

$$\Gamma(h \to \bar{\nu}_1 \nu_2) = \frac{m_h}{16\pi} y_\nu^2 (s_\theta^2 - c_\theta^2)^2 c_\alpha^2 \left(1 - \frac{m_2^2}{m_h^2}\right)^2$$

Possible signatures

Higgs decay	$\nu_2 \to \nu_1 Z^*$	$\nu_2 \to l W^*$	$\nu_2 \to \nu_1 \gamma$
$h \to \nu_1 \nu_2$	$l^+ l^- + X$ $q\bar{q} + X$	$l + l' + X$ $l + q\bar{q}' + X$	$\gamma + X$
$h \to \nu_2 \nu_2$	$l^+ l^- + l^+ l^- + X$ $l^+ l^- + q\bar{q} + X$ $q\bar{q} + q\bar{q} + X$	$l + l' + l'' + l''' + X$ $l + l' + l'' + q\bar{q} + X$ $l + l' + q\bar{q} + q\bar{q} + X$	$\gamma + \gamma + X$
$h \to \nu_1 \nu_1$	-	-	-

Higgs Branching ratios



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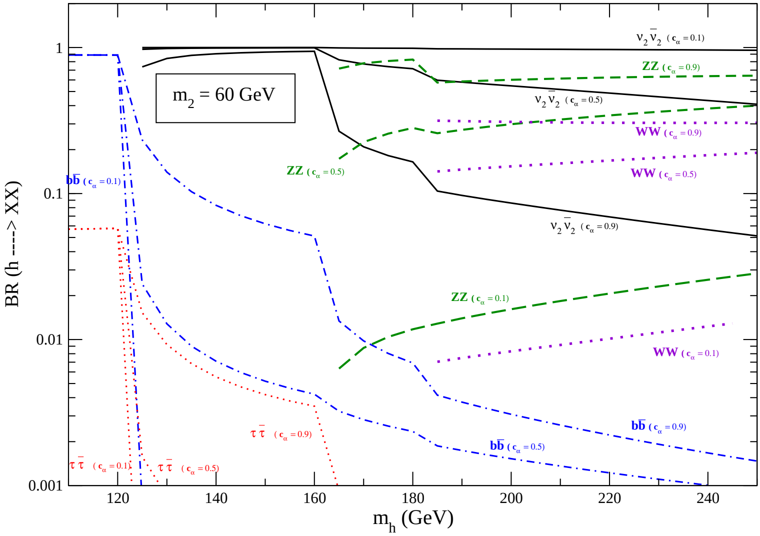

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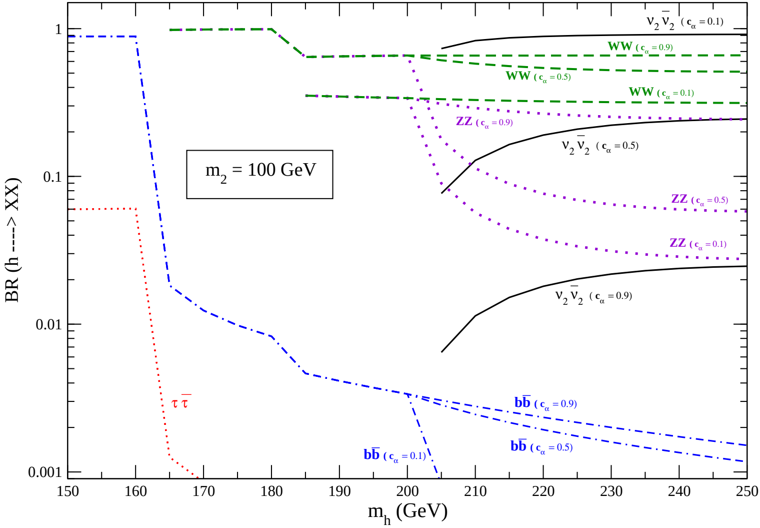
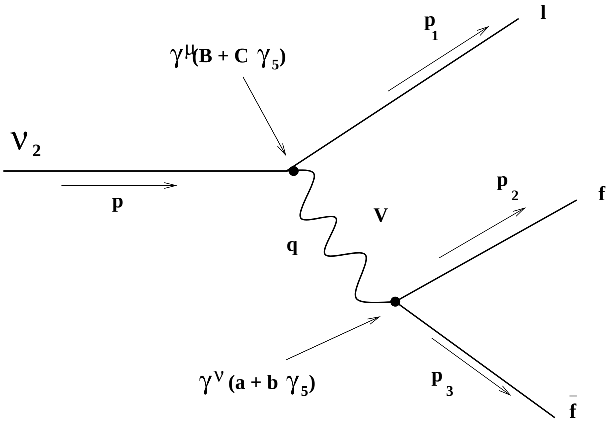


Neutrino decay



2 - body

$$\Gamma = \frac{(B^2 + C^2)(m_2^2 - M_V^2)^2(1 + 2\frac{M_V^2}{m_2^2})}{8\pi M_V^2 m_2^2} \; .$$

3 - body

$$\Gamma = \frac{m_2^5}{384\pi^3 M_V^4}\left[(B^2 + C^2)(a_f^2 + b_f^2)\right] \; ,$$

A model with Higgs triplets

Additional fields [a]	$SU(2)_W$	$U(1)_Y$
$L_R^M = \begin{pmatrix} \nu_R & e_R^M \end{pmatrix}$	**2**	0
$\tilde{\chi} = \begin{pmatrix} \chi^0 & \chi^+ & \chi^{++} \end{pmatrix}^T$	**3**	-2
$\xi = \begin{pmatrix} \xi^+ & \xi^0 & \xi^+ \end{pmatrix}^T$	**3**	0
e_L^M	**1**	0
ϕ_S	**1**	0

An additional $U(1)_M$ under which

$$L_R^M,\ e_L^M \rightarrow e^{i\theta_M} L_R^M,\ e_L^M;\quad \tilde{\chi} \rightarrow e^{-2i\theta_M}\tilde{\chi},\quad \phi_S \rightarrow e^{-i\theta_M}\phi_S$$

[a] AA, J. Hernández-Sánchez and P.Q Hung; arXiv:0809.2791

Virtues

- Since ν_R is not an SU(2)$_L$ singlet, it does not couple to $\bar{L}_L \tilde{\Phi}$
- The Dirac mass for neutrinos comes from the term $\mathcal{L}_S = -g_{sl} \bar{L}_L \phi_S L_R^M + h.c.$ which leads to $M_\nu^D = g_{sl} v_s$.
- The Dirac mass for neutrinos is *independent* of the EW scale
- The U(1)$_M$ symmetry forbids the terms $g_L L_L^T \sigma_2 \tau_2 \tilde{\chi} L_L$ and $L_L^T \sigma_2 \tau_2 \tilde{\chi} L_R^M$ at tree level.
- The Dirac mass for the neutrinos comes from v_s and M_L arises at the one-loop level and can be much smaller than M_R.

Neutrino masses

- Majorana mass matrix:

$$\mathcal{M} = \begin{pmatrix} M_L & m_\nu^D \\ m_\nu^D & M_R \end{pmatrix}$$

- where $M_L \sim \epsilon (m_\nu^D)^2/M_R < 10^{-2}(m_\nu^D)^2/M_R$.
- If $g_{sl} \sim \mathrm{O}(g_M)$ and $v_M >> v_S \rightarrow -(g_{sl}^2/g_M)(v_S/v_m)v_S(1-\epsilon)$ and M_R, where $\epsilon < 10^{-2}$
- Since $v_M \sim \Lambda_{EW}$, and $m_\nu \leq 1$ eV

$$v_S \approx \sqrt{(1\mathrm{eV}) \times v_M} \sim \mathrm{O}(10^{5-6}\mathrm{eV})$$

Scalar phenomenology

χ^{++}

Doubly charged Higgs $\rightarrow$ interesting phenomenology.
Different from that of the general two triplets model due to the following observations:

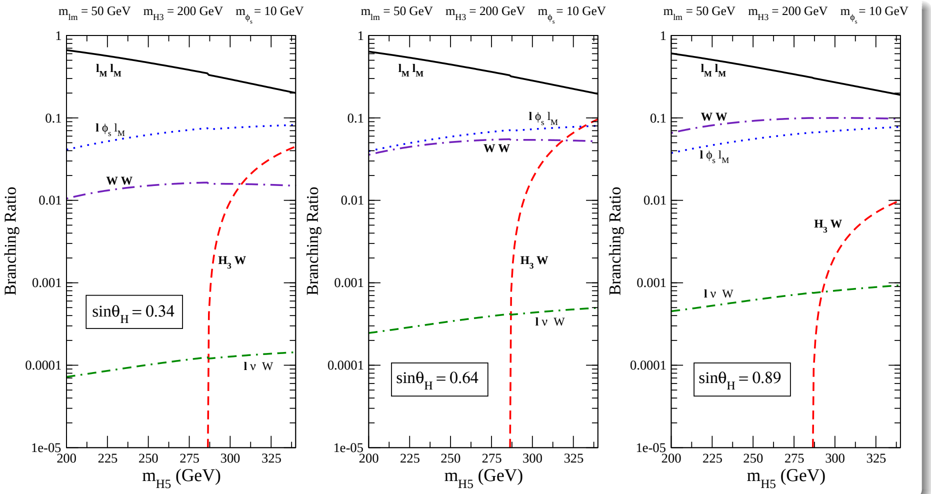
- Due to the U(1)$_M$ symmetry of the model the decay $\Gamma(\chi^{++} \rightarrow l^+ l^+)$ is not present.
- Specific modes of the model: $\Gamma(\chi^{++} \rightarrow l_i^M \; l_j^M)$ and $\Gamma(\chi^{++} \rightarrow l \; \phi_S \; l_M)$ or even $\Gamma(\chi^{++} \rightarrow l l \phi_S \phi_S)$.

χ^{++} decays

Relevant decays

- $B(\chi^{++} \to l_M^+ l_M^+)$
- $B(\chi^{++} \to W^+ W^+)$
- $B(\chi^{++} \to H_3^+ W^+)$
- $B(\chi^{++} \to l^+ \nu W^+)$
- $B(\chi^{++} \to l^+ \phi_S l_M^+)$

χ^{++} branching ratios



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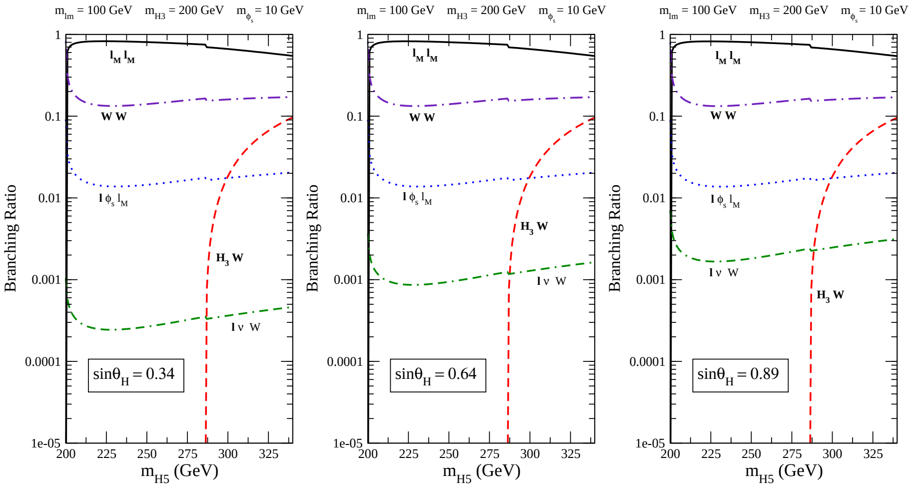

Final remarks

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2. Addition of EW scale RH neutrinos and a complex scalar
3. Role of the MAJORON - underway

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1. Triplet Higgses and RH neutrinos might be related
2. Seesaw testable at colliders!
3. Rich and testable phenomenology