Electroweak-scale Right-handed Neutrino Model, 126 GeV Higgs boson and BSM Scalars

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Collaborators Prof. P. Q. Hung and Vinh Hoang
(Nucl. Phys. B, **877** 190, and paper in preparation)

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Outline

- Motivation

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- Overview of the Electroweak-scale Right-handed Neutrino (EWν_R) model

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- Overview of the Electroweak-scale Right-handed Neutrino (EWν_R) model
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- BSM scalars in EWν_R model

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- Two of the most pressing problems in particle physics
  - Nature of spontaneous breaking of the electroweak symmetry
  - Nature of neutrino masses and mixings

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  - Nature of spontaneous breaking of the electroweak symmetry
  - Nature of neutrino masses and mixings
- Discovery of a new 126 GeV Higgs is significant step in unfolding the first mystery

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Dirac mass

Majorana mass

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possible with EWν_R model

[P. Q. Hung, PLB 649 (2007)]

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Majorana

$$\mathcal{L}_M = g_M \left(l_R^{M,T} \sigma_2 \right) \left(\qquad \right) l_R^M + h.c.$$

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$$\widetilde{\chi} \left(3, \frac{Y}{2} = 1 \right)$$

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Z width $\Rightarrow$ $M_R > M_Z$ / 2

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$$\mathcal{L}_S = g_{sl} \bar{l}_L \phi_S l_R^M + h.c.$$

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Dirac

$$\mathcal{L}_S = g_{sl} \bar{l}_L \phi_S l_R^M + h.c.$$

$$\phi_S \left(1, \frac{Y}{2} = 0\right)$$

$$m_\nu^D = g_{Sl} v_S \qquad \text{where} \qquad < \phi_S >= v_S$$

$$m_\nu \leq 1eV \quad \Rightarrow \quad v_S \sim 10^{5-6} eV \text{ with } g_{Sl} \sim \mathcal{O}(1)$$

$$\text{or} \quad v_S \sim \Lambda_{EW} \text{ with } g_{Sl} \sim \mathcal{O}(10^{-6})$$

$$\rho = \frac{M_W^2}{M_Z^2 cos\theta_W^2} = 1 \Rightarrow$$

Tree level

$$\rho = \frac{M_W^2}{M_Z^2 cos\theta_W^2} = 1 \Rightarrow \quad \text{add} \quad \xi\,(3,\ \frac{Y}{2} = 0);\ < \xi^0 >= v_M$$

Tree level

$$< \phi^0 > \equiv \frac{v_2}{\sqrt{2}}, \qquad < \chi^0 > \equiv v_M, \qquad < \xi^0 > \equiv v_M$$

$$v = \sqrt{v_2^2 + 8 v_M^2} \approx 246\text{GeV}$$

$$SU(2)_L \times SU(2)_R$$

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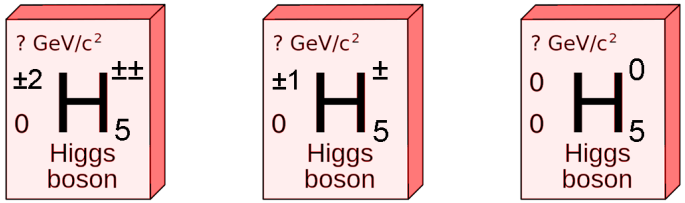

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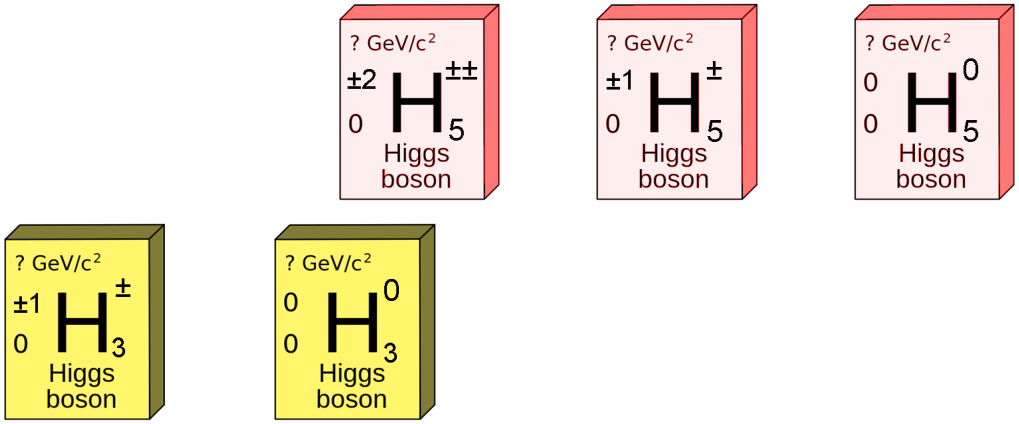

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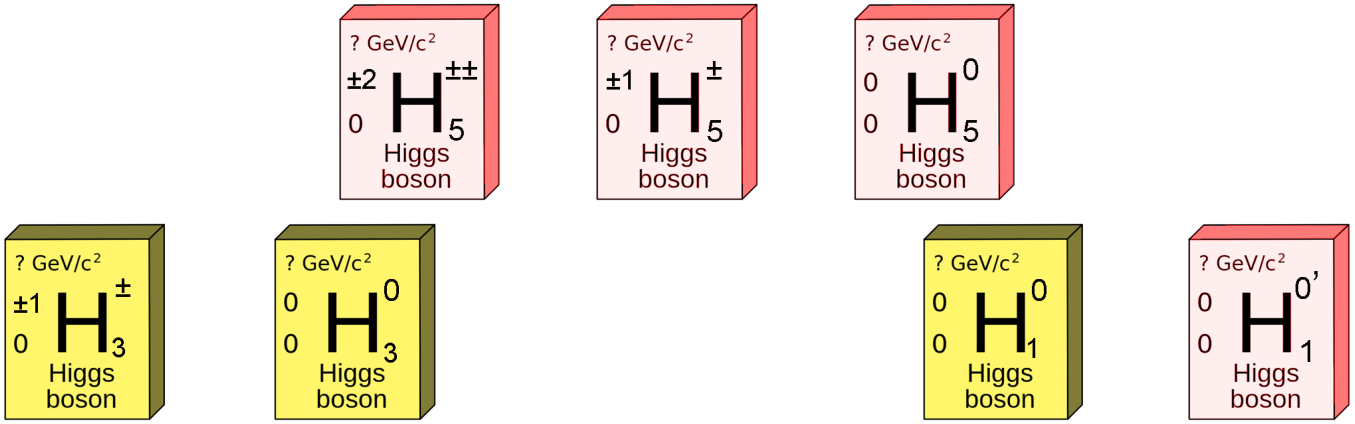

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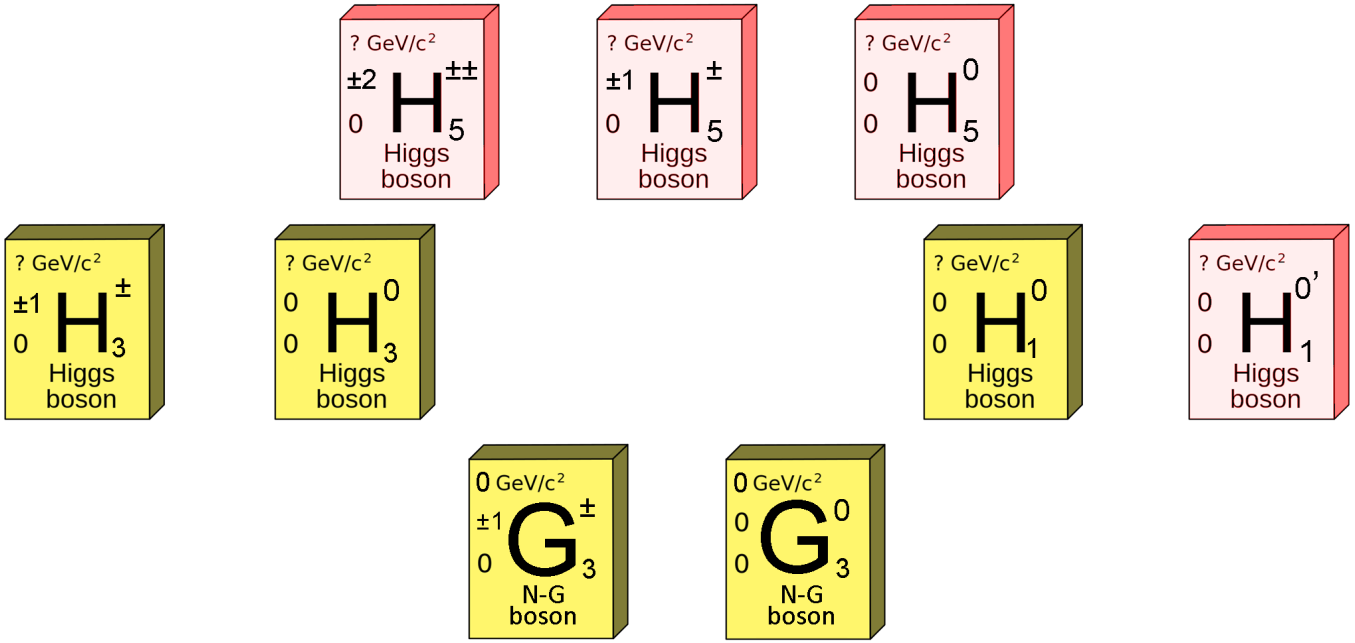

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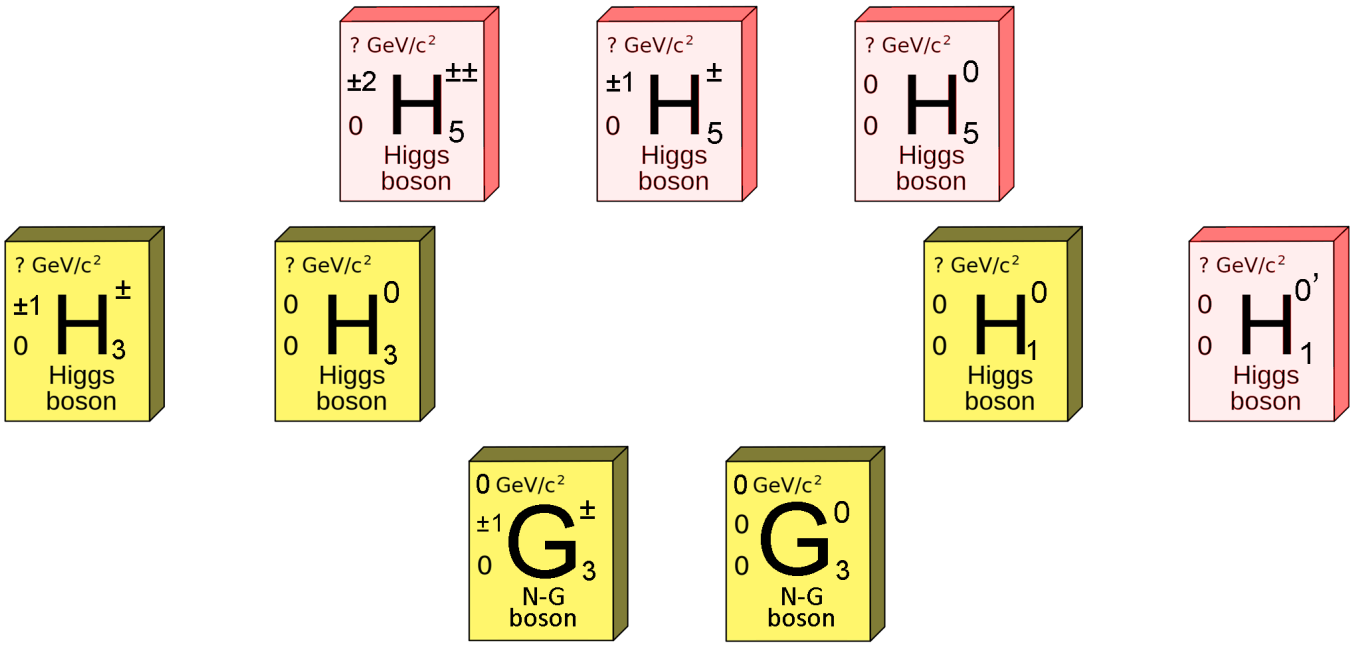

with $H_5^{--} = (H_5^{++})^\star$, $H_5^- = -(H_5^+)^\star, H_3^- = -(H_3^+)^\star$ and $H_3^0 = -(H_3^0)^\star$

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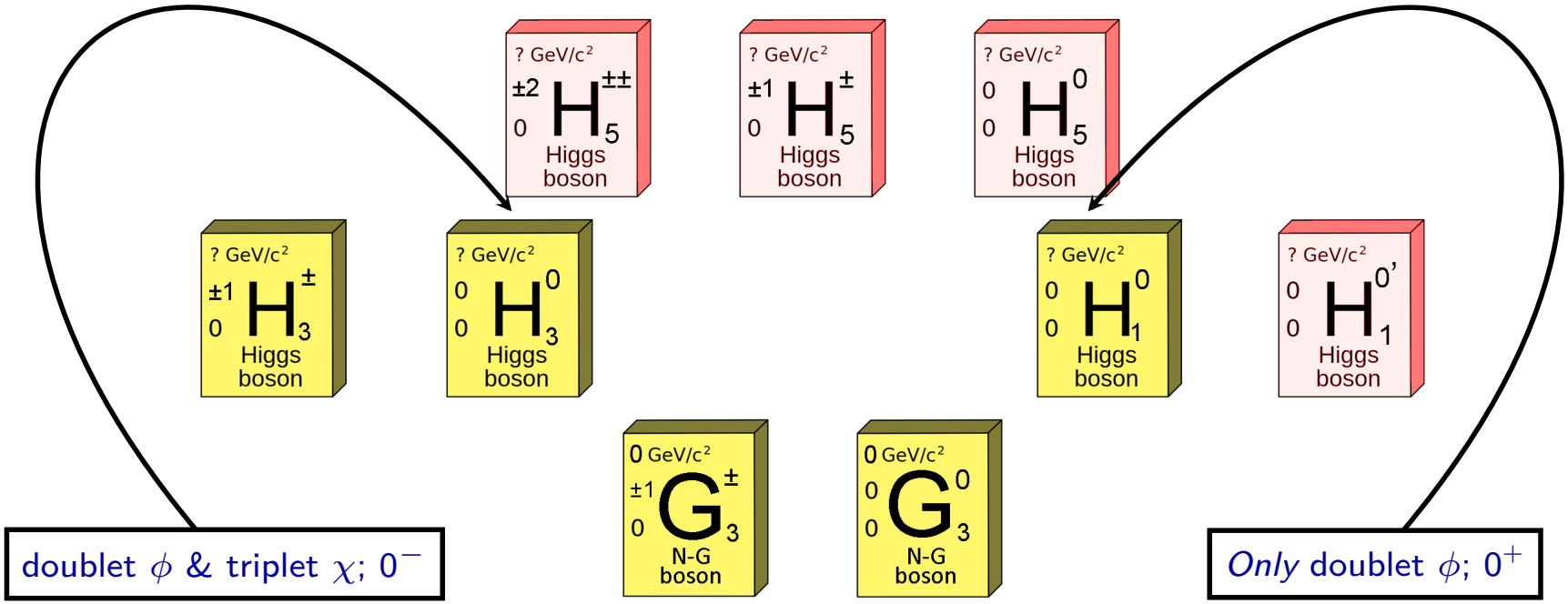

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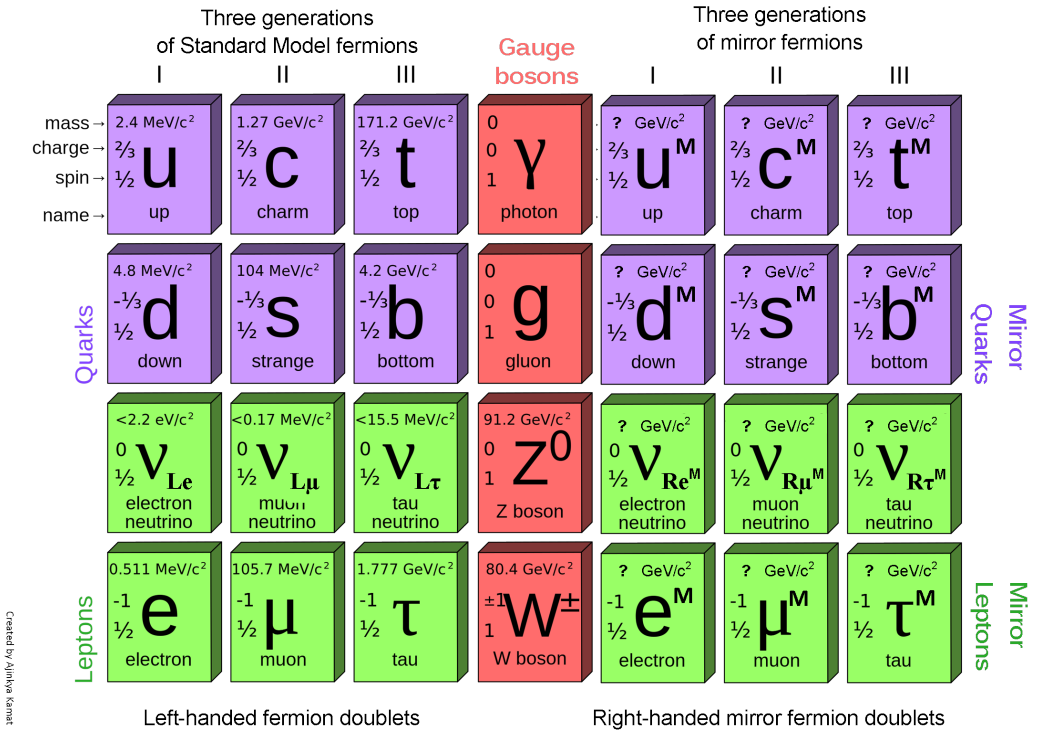
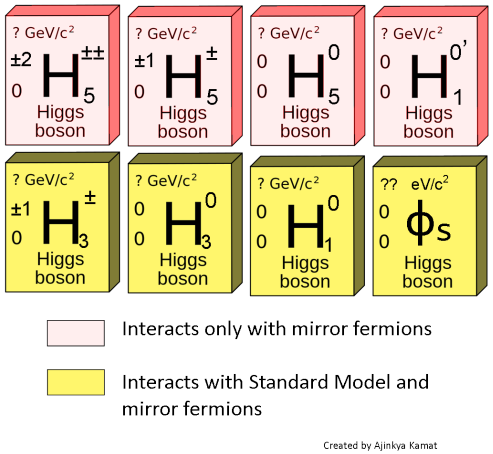
EWν_R Model Particle Content



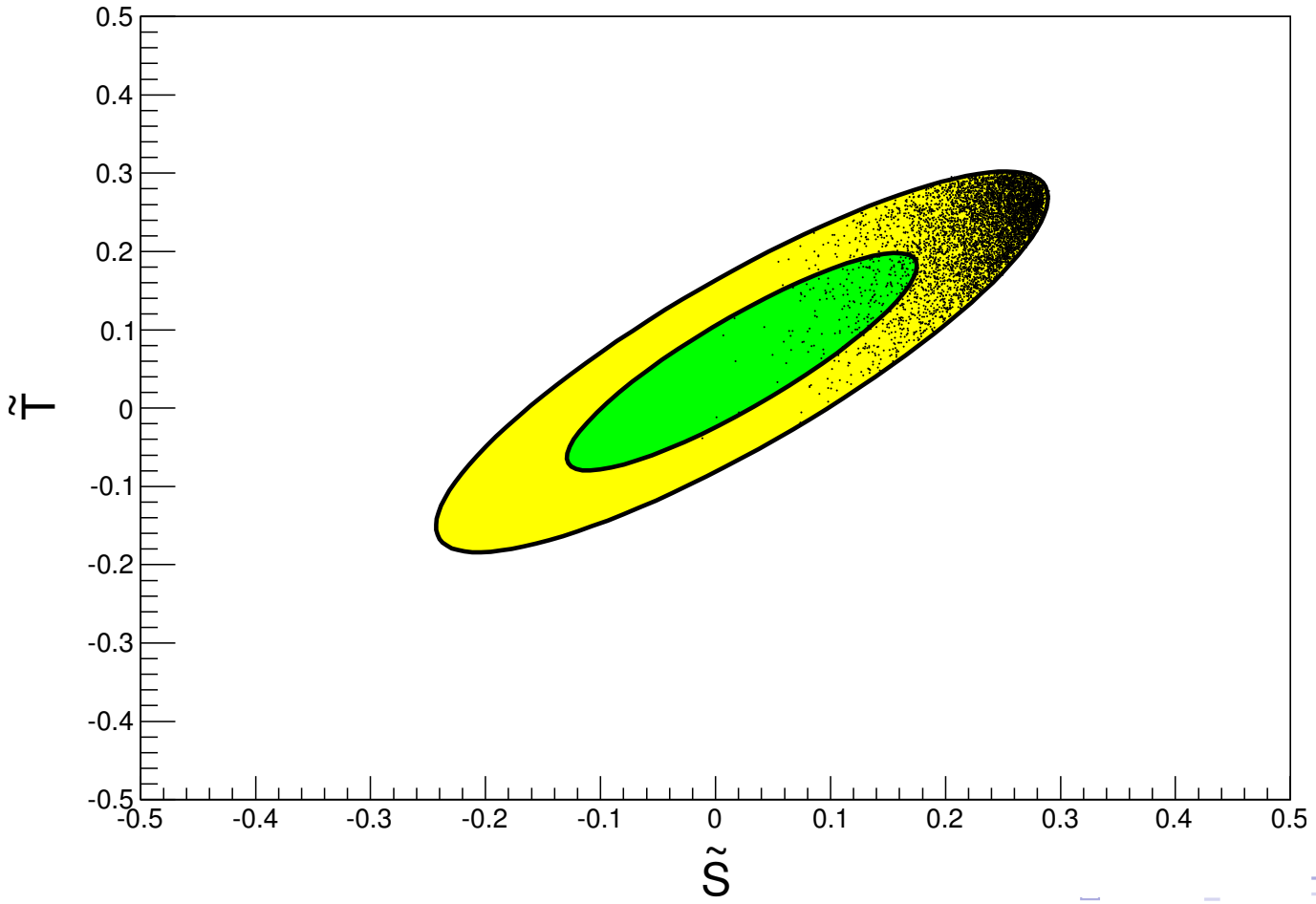


Does the EWν_R model agree with the experimental constraints on

the EW precision parameters- S, T?

Agreement with Precision Measurements

New Physics contributions, $\widetilde{S}$ and $\widetilde{T}$, due to EWν_R model are seen to, indeed, satisfy the constraints from precision measurements [V.Hoang, P.Q.Hung, A.S.Kamat, Nucl. Phys. B, **877** 190]



How EWν_R model accommodates Standard Model-like Higgs boson having 126 GeV mass

126 GeV candidate in minimal EWν_R

- Back of the envelope: if mirror quarks contribute as much as top quark

$$\sigma\left(gg \to H_1^0\right) \sim \mathbf{49} \times \frac{v^2}{v_2^2}\, \sigma_{SM}\left(gg \to H\right) \qquad !!$$

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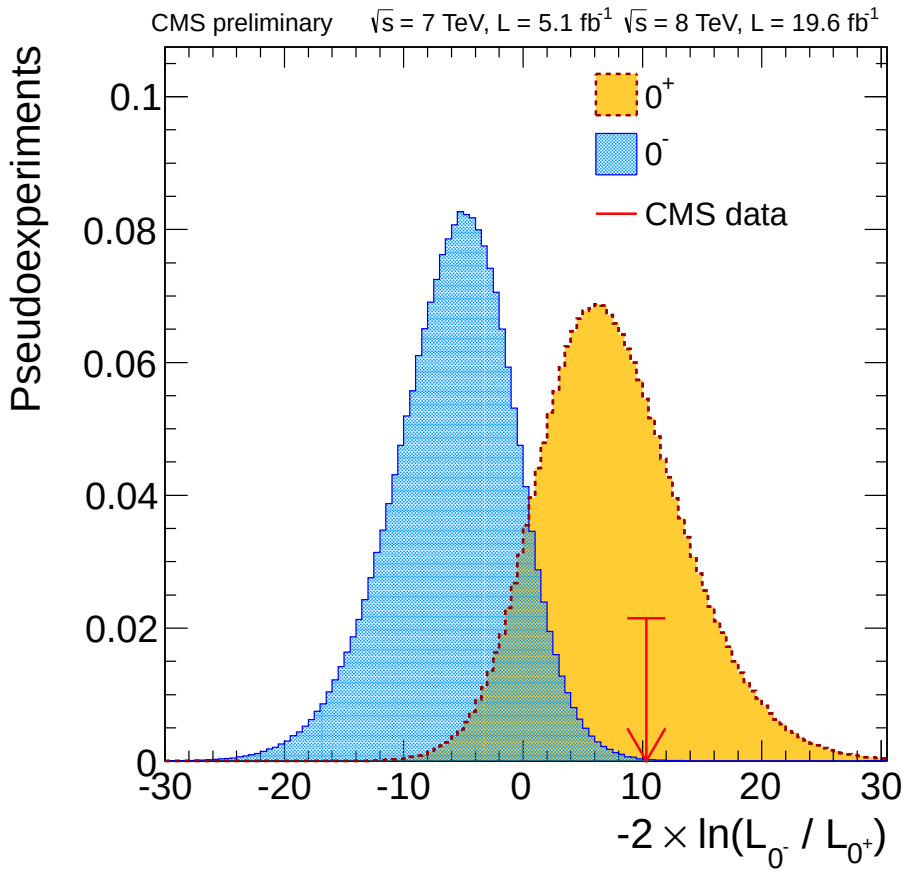
- Thus, for $v_M^2/v_2^2 \sim 1$, H_3^0 could reproduce $\sigma_{SM}\left(gg \to H\right)$

Spin-Parity Result from CMS

[CMS collaboration, CMS-PAS-HIG-13-002, March 2013]



Disfavored up to $> 3\sigma$ relative to 0^+

How EWν_R accommodates 126 GeV particle as CP-even (0^+) Higgs

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Not with the minimal EWν_R model just explained

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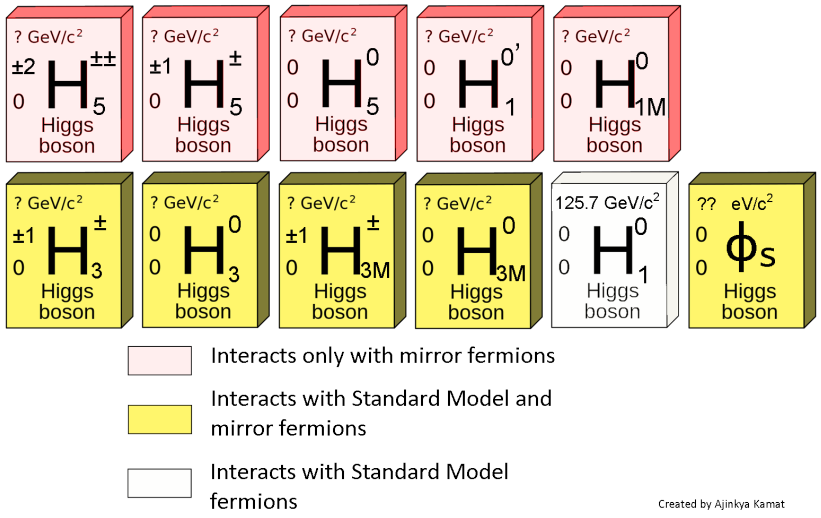

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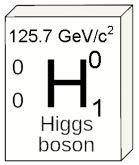
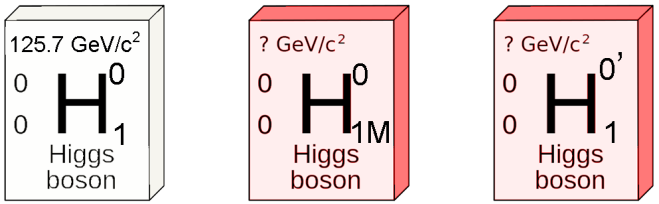
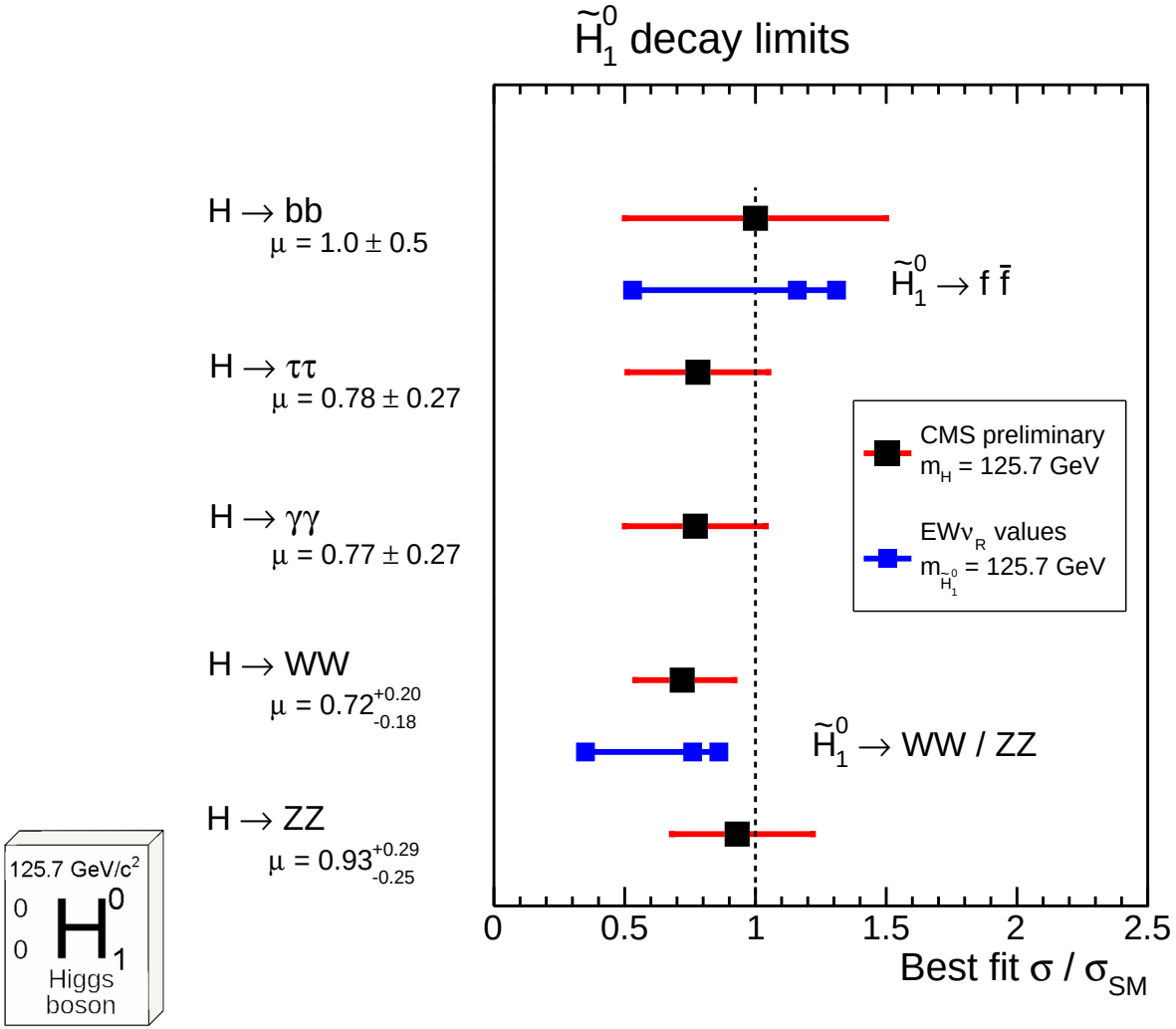
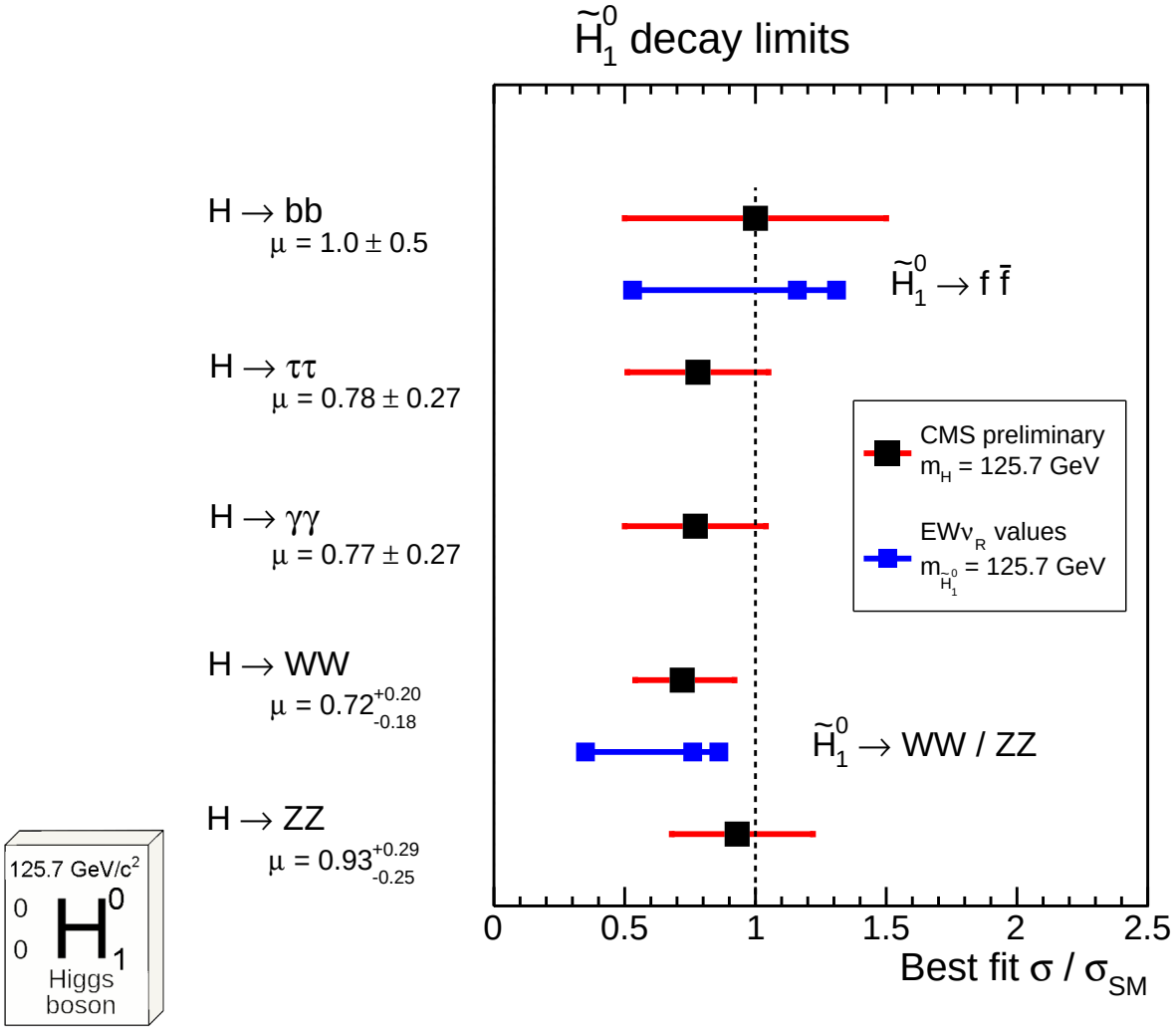


The custodial singlets mix to give mass eigenstates



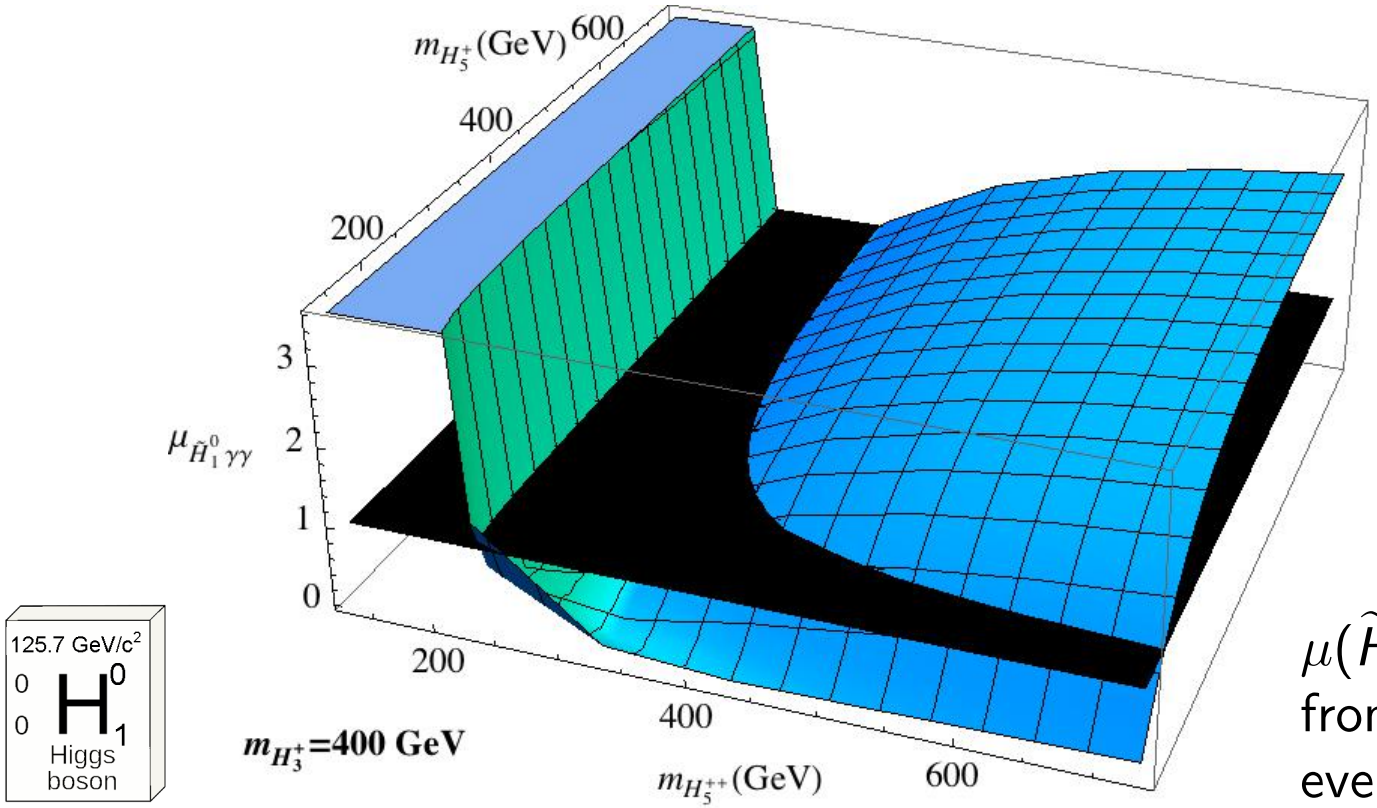
$$\begin{pmatrix} \widetilde{H}_1^0 \\ \widetilde{H}_{1M}^0 \\ \widetilde{H}_1^{0\prime} \end{pmatrix} = \begin{pmatrix} a_{1,1} & a_{1,1M} & a_{1,1'} \\ a_{1M,1} & a_{1M,1M} & a_{1M,1'} \\ a_{1',1} & a_{1',1M} & a_{1',1'} \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_{1M}^0 \\ H_1^{0\prime} \end{pmatrix}$$


$\tilde{H}_1^0$ decay limits
H → bb
μ = 1.0 ± 0.5
H → ττ
μ = 0.78 ± 0.27
H → γγ
μ = 0.77 ± 0.27
H → WW
μ = 0.72 +0.20 -0.18
H → ZZ
μ = 0.93 +0.29 -0.25
$\tilde{H}_1^0 \to f\,\bar{f}$
$\tilde{H}_1^0 \to$ WW / ZZ
CMS preliminary
m_H = 125.7 GeV
EWν$_R$ values
$m_{\tilde{H}_1^0}$ = 125.7 GeV
0
0.5
1
1.5
2
2.5
Best fit σ / σ$_{SM}$
125.7 GeV/c^2
0
0
H^0_1
Higgs boson



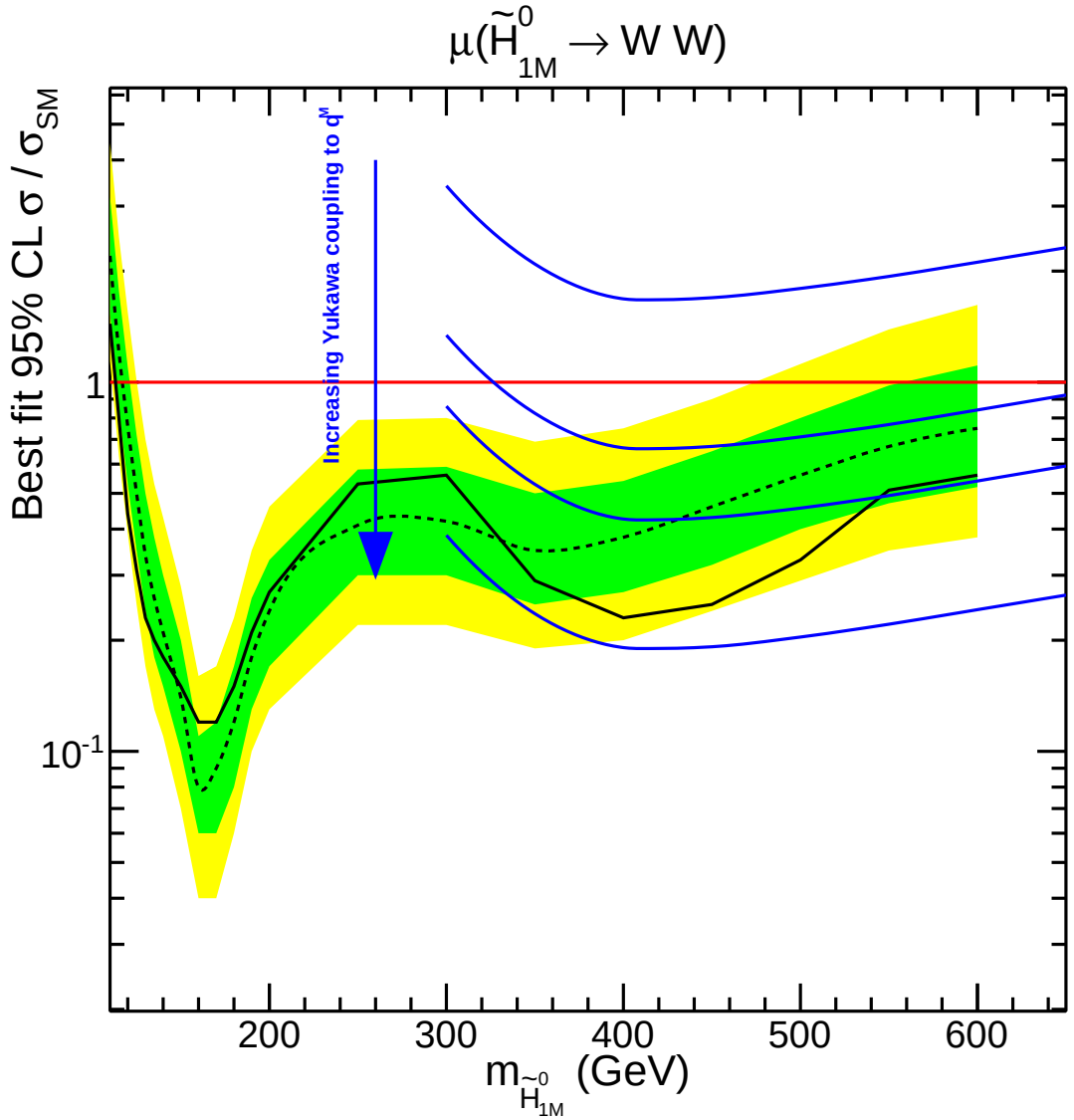
$\tilde{H}_1^0 \to \gamma\gamma$ not displayed, because its predicted value in EWν_R model spans a wide range...

$$\mu(\widetilde{H}_1^0 \to \gamma\gamma) = \frac{\sigma(gg \to \widetilde{H}_1^0 \to \gamma\gamma)}{\sigma(gg \to H_{SM} \to \gamma\gamma)}$$

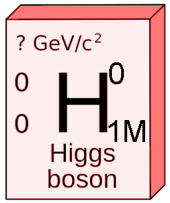


$\mu(\widetilde{H}_1^0 \to \gamma\gamma)$ spans from ~ 0 to ~ 2.5 even in this 'example' plot

BSM scalars in EWν_R model - preliminary

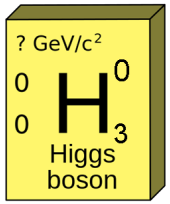


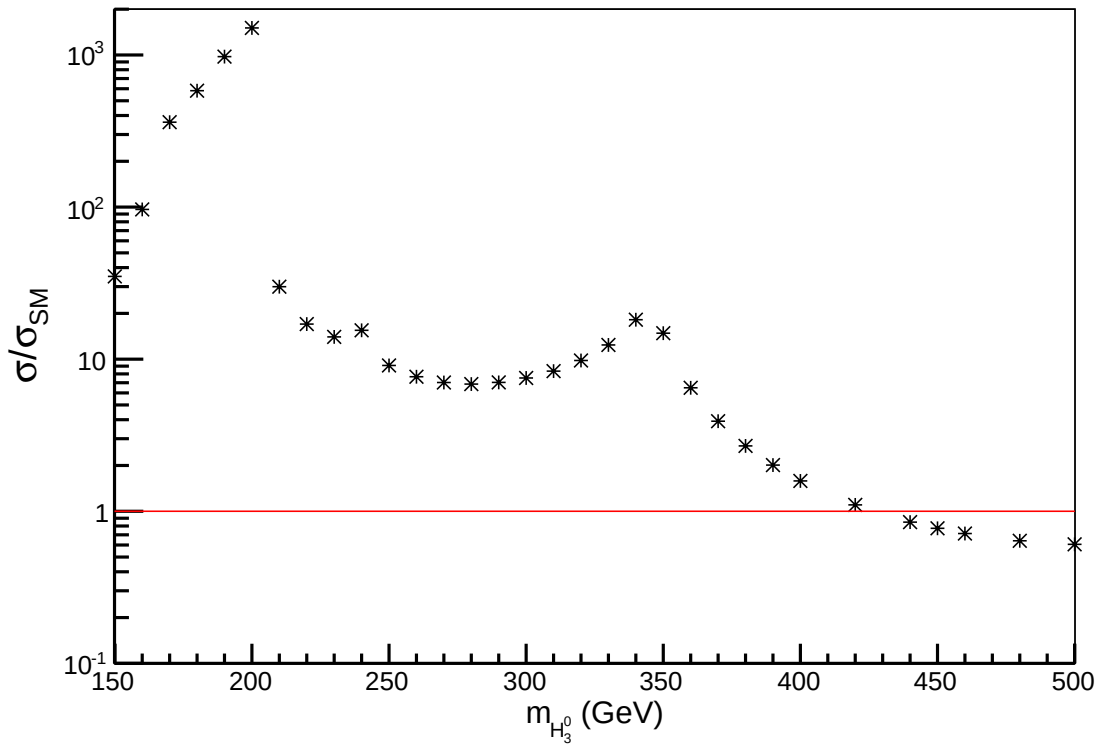
Data not yet sensitive to blue curves on or below the background bands



[SM Higgs search plot: with courtesy of CMS]

$$\mu(H_3^0 \to \gamma\gamma)$$





Data not yet sensitive to mass range of H_3^0 (and hence H_{3M}^0) for which $\mu(H_3^0 \to \gamma\gamma) \lesssim 1$

Summary

Summary

- A model with Electroweak-scale Right-handed Neutrino (EWν_R) with Majorana mass

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- Does not violate constraints from EW precision measurements
- Properties of 126 GeV candidate in a simply extended EWν_R model agree with the data
- More data at LHC will be sensitive to the BSM scalars

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- Makes Seesaw mechanism testable at LHC and near future colliders through signals such as like-sign dilepton events ($H_5^{--} \to e^{M\,-} e^{M\,-}$)
- These signals of the EWν_R model have not yet been ruled out by the searches for charged Higgs bosons at the LHC.
- A unified model of DM asymmetry $\Rightarrow$ Leptogenesis $\Rightarrow$ Baryogenesis contains Mirror Fermions: Paul Frampton and P. Q. Hung (refer talk "Luminogenesis RG flow" by Kevin Ludwick in Cosmology section this afternoon).

Thank You!

Backup Slides

Table: $\mu = \sigma/\sigma_{SM}$ for decay channels as measured at CMS and as calculated in EWν_R model in $gg \to \widetilde{H}_1^0$ production channel for given values of the parameters.

Decay Channel	Observed μ at CMS	Calculated μ ($\sim$ 5% accuracy) for b1 = -0.001 to 0.0001 (-0.0477 to -0.0489)
WW	$0.72^{+0.20}_{-0.18}$ (ggH, VBF, VH channels) [CMS Dec 2013]	0.68 - 0.76 (0.68 - 0.74)
ZZ	$0.93^{+0.26}_{-0.23}(\text{stat})^{+0.13}_{-0.09}(\text{syst})$ (ggH, VBF, t$\bar{\text{t}}$H, VH channels) [CMS Dec 2013]	0.68 - 0.76 (0.68 - 0.74)
$\tau\tau$	0.78 ± 0.29 (non-VH channels) [CMS Jan 2014]	1.03 - 1.16 (1.06 - 1.16)
bb	1.0 ± 0.5 (VH channels) [CMS Oct 2013]	1.03 - 1.16 (1.06 - 1.16)
bb and $\tau\tau$ combined	0.83 ± 0.24 [CMS Jan 2014]	1.03 - 1.16 (1.06 - 1.16)

Table: Allowed ranges of VEVs. All VEVs are given in GeV.

$69 \lesssim v_2 \lesssim 234$	$0.28 \lesssim s_2 \lesssim 0.95$
$27 \lesssim v_{2M} \lesssim 234$	$0.11 \lesssim s_{2M} \lesssim 0.95$
$13 \lesssim v_M \lesssim 80$	$0.15 \lesssim s_M \lesssim 0.91$

$$\begin{pmatrix} \widetilde{H}_1^0 \\ \widetilde{H}_{1M}^0 \\ \widetilde{H}_1^{0\prime} \end{pmatrix} = \begin{pmatrix} a_{1,1} & a_{1,1M} & a_{1,1'} \\ a_{1M,1} & a_{1M,1M} & a_{1M,1'} \\ a_{1',1} & a_{1',1M} & a_{1',1'} \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_{1M}^0 \\ H_1^{0\prime} \end{pmatrix}$$

Theoretically predicts

- Mirror Fermion sector with opposite chirality to SM Fermions
- BSM Higgs sector with doubly charged Higgs
- BSM contributions to the oblique parameters

- To forbid left-handed ν's from getting large Majorana mass (terms like $g_L l_L^T \sigma_2 \tau_2 \widetilde{\chi} l_L$) and $l_L^T \sigma_2 \tau_2 \widetilde{\chi} l_R^M$)
  $U(1)_M$ symmetry,

$$
\begin{aligned}
(l_R^M,\ e_L^M) &\rightarrow e^{i\theta_M}(l_R^M,\ e_L^M), \\
\widetilde{\chi} &\rightarrow e^{-2i\theta_M}\widetilde{\chi}, \\
\phi_S &\rightarrow e^{-i\theta_M}\phi_S
\end{aligned}
$$

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\end{aligned}
$$

- Terms like $\overline{q}_L q_R^M$, $\overline{u}_R u_R^M$, $\overline{d}_R d_R^M$ also don't occur

EWν_R model Yukawa couplings

SM Quarks		Mirror Quarks	
$g_{H_1^0 q\bar{q}}$	$-i\,\frac{m_q\ g}{2\ M_W\ s_2}\ \ldots.(q=t,\,b)$	$g_{H_{1M}^0 q^M \bar{q}^M}$	$-i\,\frac{m_q^M\ g}{2\ M_W\ s_{2M}}$
$g_{H_3^0 t\bar{t}}$	$i\,\frac{m_t\ g\ s_M}{2\ M_W\ c_M}\gamma_5$	$g_{H_3^0 u_i^M \bar{u}_i^M}$	$-i\,\frac{m_{u_i^M}\ g\ s_M}{2\ M_W\ c_M}\gamma_5$
$g_{H_3^0 b\bar{b}}$	$-i\,\frac{m_b\ g\ s_M}{2\ M_W\ c_M}\gamma_5$	$g_{H_3^0 d_i^M \bar{d}_i^M}$	$i\,\frac{m_{d_i^M}\ g\ s_M}{2\ M_W\ c_M}\gamma_5$
$g_{H_3^- t\bar{b}}$	$i\,\frac{g\ s_M}{2\sqrt{2}\ M_W\ c_M}$	$g_{H_3^- u_i^M \bar{b}_i^M}$	$i\,\frac{g\ s_M}{2\sqrt{2}\ M_W\ c_M}$
	$\times\left[m_t(1+\gamma_5)-m_b(1-\gamma_5)\right]$		$\times\left[m_{u_i^M}(1-\gamma_5)-m_{d_i^M}(1+\gamma_5)\right]$
$g_{H_{3M}^0 t\bar{t}}$	$-i\,\frac{m_t\ g\ s_{2M}}{2\ M_W\ s_2}\gamma_5$	$g_{H_{3M}^0 u_i^M \bar{u}_i^M}$	$-i\,\frac{m_{u_i^M}\ g\ s_2}{2\ M_W\ s_{2M}}\gamma_5$
$g_{H_{3M}^0 b\bar{b}}$	$i\,\frac{m_b\ g\ s_{2M}}{2\ M_W\ s_2}\gamma_5$	$g_{H_{3M}^0 d_i^M \bar{d}_i^M}$	$i\,\frac{m_{d_i^M}\ g\ s_2}{2\ M_W\ s_{2M}}\gamma_5$
$g_{H_{3M}^- t\bar{b}}$	$i\,\frac{g\ s_{2M}}{2\sqrt{2}\ M_W\ s_2\ c_M}$	$g_{H_{3M}^- u_i^M \bar{d}_i^M}$	$i\,\frac{g\ s_2}{2\sqrt{2}\ M_W\ s_{2M}\ c_M}$
	$\times\left[m_t(1+\gamma_5)-m_b(1-\gamma_5)\right]$		$\times\left[m_{u_i^M}(1-\gamma_5)-m_{d_i^M}(1+\gamma_5)\right]$

EWν_R model Yukawa couplings (contd..)

SM Quarks		Mirror Quarks	
${}^{g}_{H^0_1 l\bar{l}}$	$-i\,\frac{m_l\ g}{2\ M_W\ s_2}\ \ldots.(l=\tau,\ \mu,\ e)$	${}^{g}_{H^0_{1M} l^M \bar{l}^M}$	$-i\,\frac{m_l^M\ g}{2\ M_W\ s_{2M}}$
${}^{g}_{H^0_3 l\bar{l}}$	$-i\,\frac{m_l\ g\ s_M}{2\ M_W\ c_M}\gamma_5$	${}^{g}_{H^0_3 l_i^M \bar{l}_i^M}$	$i\,\frac{m_{l_i^M}\ g\ s_M}{2\ M_W\ c_M}\gamma_5$
${}^{g}_{H^-_3 \nu_L \bar{l}}$	$-i\,\frac{g\ m_l\ s_M}{2\sqrt{2}\ M_W\ c_M}(1-\gamma_5)$	${}^{g}_{H^-_3 \nu_{Ri} \bar{l}_i^M}$	$-i\,\frac{g\ m_{l_i^M}\ s_M}{2\sqrt{2}\ M_W\ c_M}(1+\gamma_5)$
${}^{g}_{H^0_{3M} l\bar{l}}$	$i\,\frac{m_l\ g\ s_{2M}}{2\ M_W\ s_2}\gamma_5$	${}^{g}_{H^0_{3M} l_i^M \bar{l}_i^M}$	$i\,\frac{m_{l_i^M}\ g\ s_2}{2\ M_W\ s_{2M}}\gamma_5$
${}^{g}_{H^-_{3M} \nu_L \bar{l}}$	$-i\,\frac{g\ m_l\ s_{2M}}{2\sqrt{2}\ M_W\ s_2\ c_M}(1-\gamma_5)$	${}^{g}_{H^-_{3M} \nu_{Ri} \bar{l}_i^M}$	$-i\,\frac{g\ m_{l_i^M}\ s_2}{2\sqrt{2}\ M_W\ s_{2M}\ c_M}(1+\gamma_5)$

SM Fermions Yukawa couplings:

$$\mathcal{L} = -h_{ij}\overline{\Psi}_{Li}\Phi\Psi_{Rj} + h.c.$$

Feynman Rules [PQ, Aranda, Hernández-Sánchez, JHEP11, 2008]

- $$g_{H_1^0 q\bar{q}} = -i\frac{m_q g}{2M_W c_H} \;....(q = t, b)$$
- $$g_{H_3^0 t\bar{t}} = i\frac{m_t g s_H}{2M_W c_H}$$
- $$g_{H_3^0 b\bar{b}} = -i\frac{m_b g s_H}{2M_W c_H}$$
- $$g_{H_3^0 - t\bar{b}} = i\frac{g s_H}{2M_W c_H}(m_t(1+\gamma_5) - m_b(1+\gamma_5))$$

Similar couplings for SM leptons and mirror quarks.

Mirror Fermions' kinetic Lagrangian

$$
\begin{aligned}
&(\mathcal{L}_{F^M})_{int} \\
&= \frac{g}{\sqrt{2}} \left[\left(\overline{u}_R^{Mi} \, \gamma^\mu d_{Ri}^M + \overline{\nu}_R^i \, \gamma^\mu e_{Ri}^M \right) W_\mu^+ + \left(\overline{d}_R^{M\,i} \, \gamma^\mu u_{R\,i}^M + \overline{e}_R^{M\,i} \, \gamma^\mu \nu_{R\,i}^M \right) W_\mu^- \right] \\
&+ \frac{g}{c_W} \left[\sum_{f^M = u^M, d^M, \nu^M, e^M} \left(T_3^{f^M} - s_W^2 Q_{f^M} \right) \overline{f}_R^{M\,i} \, \gamma^\mu f_{R\,i}^M \right. \\
&\left. + \sum_{f^M = u^M, d^M, e^M} s_W^2 Q_{f^M} \, \overline{f}_L^{M\,i} \, \gamma^\mu f_{L\,i}^M \right] Z_\mu \\
&+ e \sum_{f^M = u^M, d^M, e^M} Q_{f^M} \left(\overline{f}_R^{M\,i} \, \gamma^\mu f_{R\,i}^M - \overline{f}_L^{M\,i} \, \gamma^\mu f_{L\,i}^M \right) A_\mu
\end{aligned}
$$