Electroweak-scale Right-handed Neutrino Model

Ajinkya Shrish Kamat

University of Virginia

ajinkya@virginia.edu
http://people.virginia.edu/∼ask4db/

With Prof. P. Q. Hung and Vinh Van Hoang

[arXiv:1303.0428, submitted to PRD; and more]

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Motivation

- Two 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 particle could be significant step in unfolding the first mystery

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[Hung, PLB 649 (2007)]

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

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$$M_R = g_M v_M;\ < \chi^0 >= v_M \sim \Lambda_{EW}$$

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$$Z \text{ width} \Rightarrow\ M_R > M_Z \,/\, 2$$

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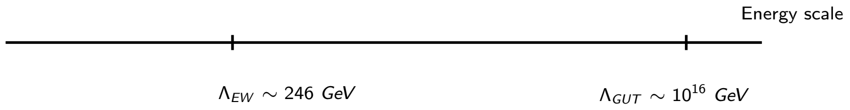
$$\mathcal{L}_S = g_{sl} \bar{l}_L \phi_S l_R^M + h.c.$$

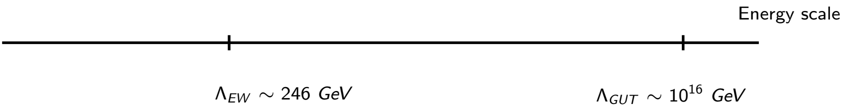
$$\phi_S \left(1, \frac{Y}{2} = 0\right)$$

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

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

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


Energy scale
$\Lambda_{EW} \sim 246\ GeV$
$\Lambda_{GUT} \sim 10^{16}\ GeV$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v_S
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Energy scale

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

$$\rho = \frac{M_W^2}{M_Z^2 cos\theta_W^2} = \frac{\sum_{T,Y}[4T(T+1) - Y^2]|V_{T,Y}|^2 c_{T,Y}}{\sum_{T,Y} 2Y^2 |V_{T,Y}|^2}$$

Tree level; $c_{T,Y} = 1,\ (1/2)$ for (T,Y) complex (real) rep.

[*The Higgs Hunter's Guide*, Gunion et.al.]

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

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

Proper vacuum alignment for custodial symmetry

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

Proper vacuum alignment for custodial symmetry

$SU(2)_D$

Proper vacuum alignment for custodial symmetry

$SU(2)_D$

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}, \quad \Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}.$$

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Proper vacuum alignment so that $SU(2)_L \times U(1)_Y \to U(1)_{em}$ and global $SU(2)_D$ custodial is preserved

$$\langle\chi\rangle = \begin{pmatrix} v_M & 0 & 0 \\ 0 & v_M & 0 \\ 0 & 0 & v_M \end{pmatrix}, \text{ and } \langle\Phi\rangle = \begin{pmatrix} v_2/\sqrt{2} & 0 \\ 0 & v_2/\sqrt{2} \end{pmatrix}.$$

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

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

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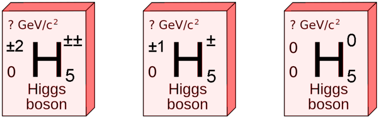

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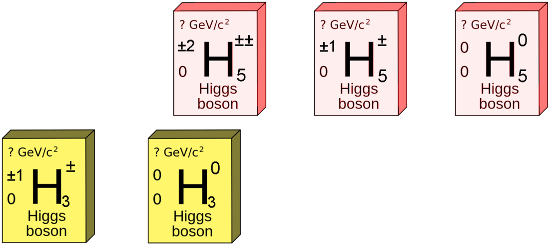

$$< \phi^0 >\equiv \frac{v_2}{\sqrt{2}}, \qquad < \chi^0 >\equiv v_M, \qquad < \xi^0 >= v_M$$

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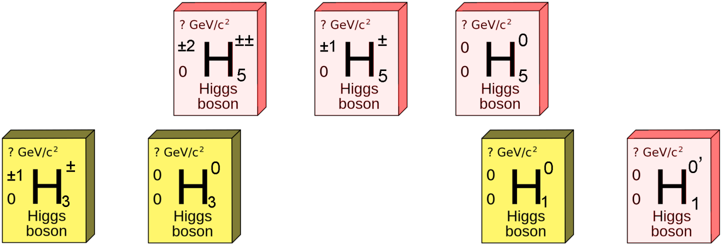

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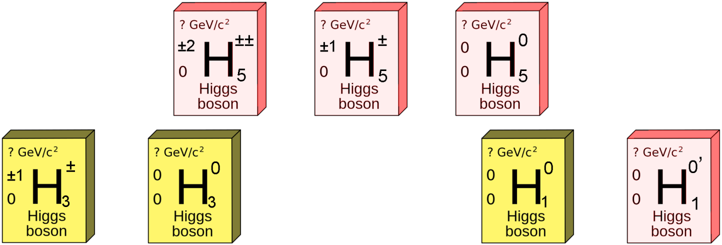

$G_3^{\pm}$ $\qquad$ G_3^{0}

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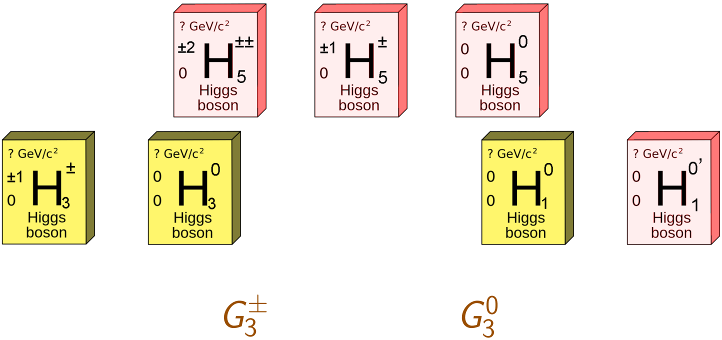

with $H_5^{--} = (H_5^{++})^\star$, $H_5^- = -(H_5^+)^\star, H_3^- = -(H_3^+)^\star$ and $H_3^0 = -(H_3^0)^\star$

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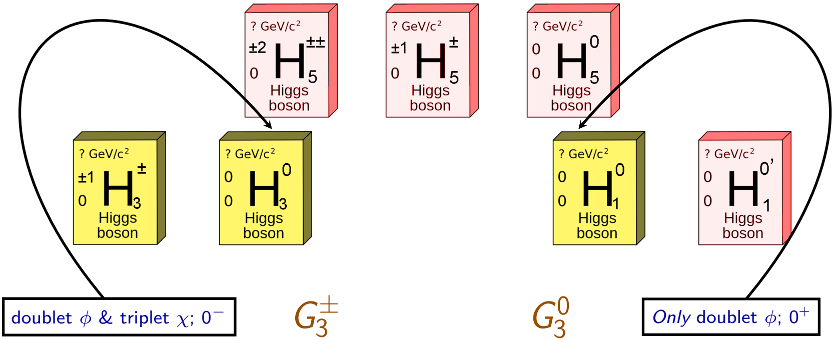

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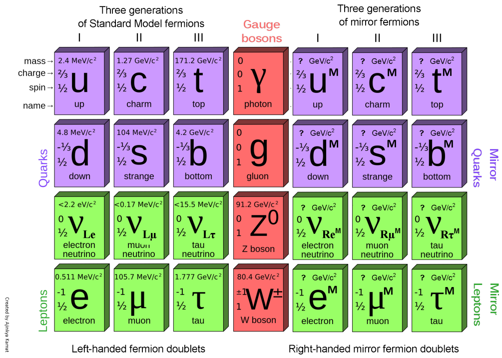
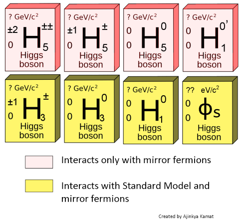
EWν_R Model Particle Content





Does the $EW\nu_R$ model agree with the experimental constraints on

the EW precision parameters- S, T?

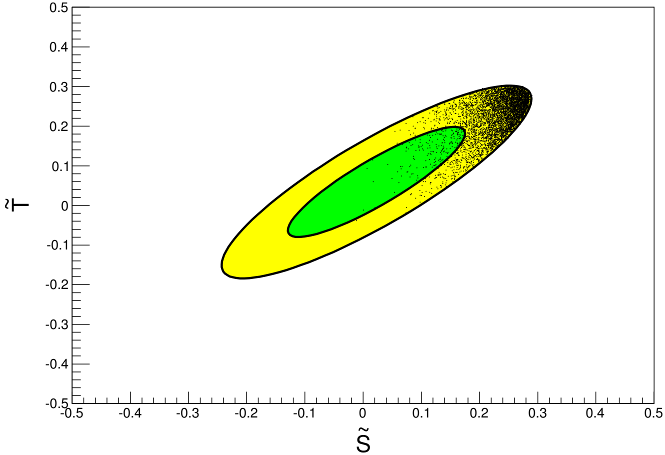
Oblique Parameters

$S \rightarrow$ **Difference between** Z **self-energy at** $q^2 = M_Z^2$ **and at** $q^2 = 0$

$T \rightarrow\sim \left(1 - \rho\right)$; **Difference between isospin currents** Π_{11} **and** Π_{33} **at** $q^2 = 0$

Agreement with Precision EW Measurements

New Physics contributions, $\widetilde{S}$ and $\widetilde{T}$, to S, T due to EWν_R model are seen to, indeed, satisfy the constraints from precision measurements



Standard Model-like Higgs boson having 126 GeV mass

How EWν_R model accommodates this

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$$\sigma_{\text{production}} \times \text{Branching Ratio(decay channel)}$$

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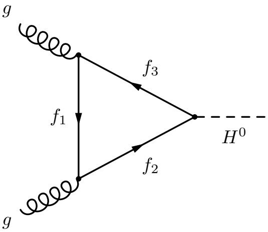

CP-even Physical Scalar in $EW\nu_R$

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

$$\sigma\left(gg \to H_1^0\right) \sim \mathbf{49} \times \frac{1}{\cos^2\theta_H}\,\sigma_{SM}\left(gg \to H\right) \qquad !!$$

Cannot be compensated for in all the branching ratios

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- H_1^0 **in EWν_R model cannot** be the new 126 GeV particle

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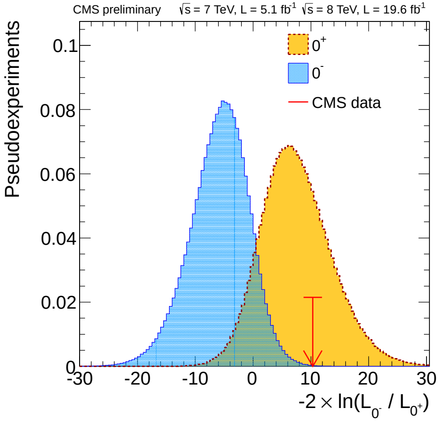
[CMS collaboration, CMS-PAS-HIG-13-002, March 2013]



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

How $EW\nu_R$ model accommodates 126 GeV particle as

CP-even (0^+) Higgs

How EWν_R model accommodates 126 GeV particle as

CP-even (0^+) Higgs

Not with the minimal EWν_R model just explained

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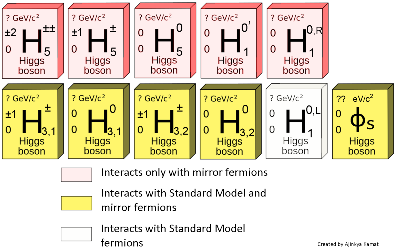

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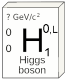

- $g_{H_1^{0,L} t\bar{t}} = -i \dfrac{m_t \; g}{2 \; M_W \; (v_1^L / v)}$

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$$\sigma\left(gg \to H_{1,1}^0\right) \sim |a_1|^2 \left(\frac{v}{v_1^L}\right)^2 \times \sigma_{SM}\left(gg \to H\right) ,$$

with singlet mixing parameter $a_1^2 \sim 1$ and $v_1^L \sim v$.

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- Makes Seesaw mechanism testable at LHC and near future colliders through signals such as like-sign dilepton events $(H_5^{--} \rightarrow e^{M\,-} e^{M\,-})$
- These signals of the EWν_R model have not yet been ruled out by the searches for charged Higgs bosons at the LHC.

Thank You!


HEY, LOOKS LIKE THIS ONE CAN ACCOMMODATE YOU TOO!
EW ν_R MODEL
THEN LET'S DRIVE TOGETHER
EW ν_R
126 GeV
PARITY
A.S.Kamat 02/26/13

Backup Slides

- 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,

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

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

$$
\begin{aligned}
H^0_{1,1} &= a_1\ H_1^{0\ L} + b_1\ H_1^{0\ R} + c_1\ H_1^{0\prime} \\
H^0_{1,2} &= a_2\ H_1^{0\ L} + b_2\ H_1^{0\ R} + c_2\ H_1^{0\prime} \\
H^0_{1,3} &= a_3\ H_1^{0\ L} + b_3\ H_1^{0\ R} + c_3\ H_1^{0\prime}
\end{aligned}
$$

Theoretically predicts

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

Simplest extension to $EW\nu_R$ model

- Add another $SU(2)$ scalar doublet ($Y/2 = 1$)
- With a global $U(1)_{SM} \times U(1)_{MF}$ symmetry such that

$$U(1)_{SM} \quad : \quad \begin{aligned} \Phi^L &\to e^{i\alpha_{SM}}\, \Phi^L \\ l_L^{SM} &\to e^{i\alpha_{SM}}\, l_L^{SM}\,, \end{aligned}$$

and

$$U(1)_{MF} \quad : \quad \begin{aligned} \Phi^R &\to e^{i\alpha_{MF}}\, \Phi^R \\ l_R^{M} &\to e^{i\alpha_{MF}}\, l_R^{M}\,. \end{aligned}$$

Also under $U(1)_{\mathrm{SM}} \times U(1)_{\mathrm{MF}}$

$$\phi_S \to e^{-i(\alpha_{MF} - \alpha_{SM})}\, \phi_S\,,$$

and other fields are singlets under this symmetry.

Oblique Parameters

[Peskin, Takeuchi, PRD 46, 1992]

- $\alpha S \equiv 4e^2[\Pi'_{33}(0) - \Pi'_{3Q}(0)]$
- $\alpha T \equiv \frac{e^2}{s_W^2 c_W^2 M_Z^2}[\Pi_{11}(0) - \Pi_{33}(0)]$
- $\alpha U \equiv 4e^2[\Pi'_{11}(0) - \Pi'_{33}(0)]$.

EWν_R Yukawa couplings

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

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

$$(\mathcal{L}_{F^M})_{int}$$

$$= \frac{g}{\sqrt{2}} \left[\left(\bar{u}_R^{Mi} \, \gamma^\mu d_{Ri}^M + \bar{\nu}_R^i \, \gamma^\mu e_{Ri}^M \right) W_\mu^+ + \left(\bar{d}_R^{M\,i} \, \gamma^\mu u_{R\,i}^M + \bar{e}_R^{M\,i} \, \gamma^\mu \nu_{R\,i}^M \right) W_\mu^- \right]$$

$$+ \frac{g}{c_W} \left[\sum_{f^M = u^M, d^M, \nu^M, e^M} \left(T_3^{f^M} - s_W^2 Q_{f^M} \right) \bar{f}_R^{M\,i} \, \gamma^\mu f_{R\,i}^M \right.$$

$$\left. + \sum_{f^M = u^M, d^M, e^M} s_W^2 Q_{f^M} \, \bar{f}_L^{M\,i} \, \gamma^\mu f_{L\,i}^M \right] Z_\mu$$

$$+ e \sum_{f^M = u^M, d^M, e^M} Q_{f^M} \left(\bar{f}_R^{M\,i} \, \gamma^\mu f_{R\,i}^M - \bar{f}_L^{M\,i} \, \gamma^\mu f_{L\,i}^M \right) A_\mu$$