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
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5th May, 2014
Outline

- Motivation

Motivation

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

Accommodating the 126 GeV Higgs boson

BSM scalars in EWν_R model
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- Accommodating the 126 GeV Higgs boson
- BSM scalars in EW$\nu_R$ model
Motivation

Two of the most pressing problems in particle physics

- Nature of spontaneous breaking of the electroweak symmetry
- Nature of neutrino masses and mixings
Motivation

- Two of the most pressing problems in particle physics
  - 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
Motivation

- Neutrino ($\nu$) masses $\rightarrow$ popular "Seesaw mechanism"
Motivation

- Neutrino ($\nu$) masses → popular "Seesaw mechanism"
  - In general Seesaw Mechanism:
    - $\nu_R \to SU(2)_L \times U(1)_Y$ singlet
    - Right-handed neutrino mass at GUT scale → NOT directly testable at LHC

$$m_\nu \sim \frac{(m_{\nu}^D)^2}{M_R} \leq 1\text{eV}$$

Dirac mass

Majorana mass
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possible with $EW\nu_R$ model

[P. Q. Hung, PLB 649 (2007)]
Motivation
EW$\nu_R$ Model
126 GeV Candidate
BSM scalars in EW$\nu_R$ model

What’s next option after a singlet $\nu_R$?

\[ I_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \ e_R \]
What’s next option after a singlet $\nu_R$?

\[
I_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad e_R \\
I_R^M = \begin{pmatrix} \nu_R \\ e^M_R \end{pmatrix}, \quad e^M_L
\]
To ensure anomaly cancellation

\[ q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R \]
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\[ q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R \quad q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}, u_L^M, d_L^M \]
Motivation
EWν\(_R\) Model
126 GeV Candidate
BSM scalars in EWν\(_R\) model

\[ l_L = \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right), \quad e_R \quad l_R^M = \left( \begin{array}{c} \nu_R^M \\ e_R^M \end{array} \right), \quad e_L^M \]
\[ I_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \ e_R \quad I_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}, \ e_L^M \]

**Majorana**

\[ \mathcal{L}_M = g_M (I^M_R, \sigma_2) (I^M_R) + h.c. \]
\[ l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}, \quad e_L^M \]

**Majorana**

\[ \mathcal{L}_M = g_M (l_R^M, T \sigma_2) (i \tau_2 \tilde{\chi}) l_R^M + h.c. \]

\[ \tilde{\chi} \left( 3, \frac{Y}{2} = 1 \right) \]
\[ I_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad I_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}, \quad e_L^M \]

**Majorana**

\[ \mathcal{L}_M = g_M (I_R^M)^T \sigma_2 (i \tau_2 \tilde{\chi}) I_R^M + \text{h.c.} \]

\[ \tilde{\chi} \ (3, \ \frac{Y}{2} = 1) \]

\[ M_R = g_M v_M; \quad \langle \chi^0 \rangle = v_M \sim \Lambda_{EW} \]

\[ \tilde{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}} \chi^+ \end{pmatrix} \]
$I_L = \left( \nu_L, e_L \right), e_R \quad I_R^M = \left( \nu_R^M, e_R^M \right), e_L^M$

**Majorana**

$$\mathcal{L}_M = g_M \left( I_R^M, T \sigma_2 \right) \left( i \tau_2 \tilde{\chi} \right) I_R^M + h.c.$$  

$$\tilde{\chi} (3, \frac{Y}{2} = 1)$$

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

$$\tilde{\chi} = \begin{pmatrix} 
\frac{1}{\sqrt{2}} \chi^+ & \chi^{++} \\
\chi^0 & -\frac{1}{\sqrt{2}} \chi^+ 
\end{pmatrix}$$

$Z$ width $\Rightarrow M_R > M_Z / 2$
\[ l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \ e_R \quad l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}, \ e_L^M \]
\[ I_L = \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right), e_R \quad I^M_R = \left( \begin{array}{c} \nu_R \\ e^M_R \end{array} \right), e_L^M \]

**Dirac**

\[ \mathcal{L}_S = g_{s} \bar{I}_L \phi_S I^M_R + h.c. \]
\[ I_L = \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right), \quad I_R^M = \left( \begin{array}{c} \nu_R \\ e_R^M \end{array} \right), \quad I_R^M = \left( \begin{array}{c} \nu_R \\ e_R^M \end{array} \right), \quad e_L^M \]

**Dirac**

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

\[ \phi_S (1, \frac{Y}{2} = 0) \]

\[ m^D_\nu = g_{sl} \nu_S \quad \text{where} \quad < \phi_S > = \nu_S \]

\[ m_\nu \leq 1\text{eV} \quad \Rightarrow \quad \nu_S \sim 10^{5-6}\text{eV} \quad \text{with} \quad g_{sl} \sim \mathcal{O}(1) \]

or \[ \nu_S \sim \Lambda_{EW} \quad \text{with} \quad g_{sl} \sim \mathcal{O}(10^{-6}) \]
\[ \rho = \frac{M_W^2}{M_Z^2 \cos \theta_W^2} = 1 \quad \Rightarrow \]

Tree level
$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1 \Rightarrow \text{add } \xi (3, \frac{Y}{2} = 0); \langle \xi^0 \rangle = v_M$

Tree level
\[ \langle \phi^0 \rangle \equiv \frac{v_2}{\sqrt{2}} , \quad \langle \chi^0 \rangle \equiv v_M , \quad \langle \xi^0 \rangle \equiv v_M \]

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

\[ SU(2)_L \times SU(2)_R \]
\[ <\phi^0> \equiv \frac{v_2}{\sqrt{2}}, \quad <\chi^0> \equiv v_M, \quad <\xi^0> \equiv v_M \]

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\[ SU(2)_D \]
\[ < \phi^0 > \equiv \frac{v_2}{\sqrt{2}}, \quad < \chi^0 > \equiv v_M, \quad < \xi^0 > \equiv v_M \]

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\[ SU(2)_D \]
Motivation
EW\nu_R Model
126 GeV Candidate
BSM scalars in EW\nu_R model

\langle \phi^0 \rangle \equiv \frac{v_2}{\sqrt{2}}, \quad \langle \chi^0 \rangle \equiv v_M, \quad \langle \xi^0 \rangle \equiv v_M

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

SU(2)_D

\begin{align*}
\text{Higgs bosons:} & \quad H^{\pm}_{5}, H^{0}_{5}, H^{\pm}_{3}, H^{0}_{3} \\
\text{masses (GeV):} & \quad ? GeV/c^2, \quad ? GeV/c^2, \quad ? GeV/c^2, \quad ? GeV/c^2
\end{align*}
\[<\phi^0> \equiv \frac{\nu_2}{\sqrt{2}}, \quad <\chi^0> \equiv \nu_M, \quad <\xi^0> \equiv \nu_M\]
\[\nu = \sqrt{\nu_2^2 + 8\nu_M^2} \approx 246\text{GeV}\]

\[SU(2)_D\]
$\langle \phi^0 \rangle \equiv \frac{v_2}{\sqrt{2}}, \quad \langle \chi^0 \rangle \equiv v_M, \quad \langle \xi^0 \rangle \equiv v_M$

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

$SU(2)_D$
Motivation

$\langle \phi^0 \rangle \equiv \frac{\nu_2}{\sqrt{2}}$, \hspace{1cm} $\langle \chi^0 \rangle \equiv \nu_M$, \hspace{1cm} $\langle \xi^0 \rangle \equiv \nu_M$

$$\nu = \sqrt{\nu_2^2 + 8\nu_M^2} \approx 246\text{GeV}$$

$SU(2)_D$

with $H_5^{--} = (H_5^{++})^*$, $H_5^- = -(H_5^+)^*$, $H_3^- = -(H_3^+)^*$ and $H_3^0 = -(H_3^0)^*$
\[ <\phi^0> \equiv \frac{v_2}{\sqrt{2}}, \quad <\chi^0> \equiv v_M, \quad <\xi^0> \equiv v_M \]
\[ v = \sqrt{v_2^2 + 8v_M^2} \approx 246 \text{GeV} \]

\[ SU(2)_D \]

doublet \( \phi \) & triplet \( \chi; 0^- \)

with \( H_5^{--} = (H_5^{++})^*, \ H_5^- = -(H_5^+)^*, \ H_3^- = -(H_3^+)^* \) and \( H_3^0 = -(H_3^0)^* \)
**Motivation**

**EW$\nu_R$ Model**

126 GeV Candidate

BSM scalars in EW$\nu_R$ model

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**EW$\nu_R$ Model Particle Content**

Three generations of Standard Model fermions

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Gauge bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>Y photon</td>
</tr>
<tr>
<td>c charm</td>
<td></td>
</tr>
<tr>
<td>t top</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BSM scalars</th>
<th>Mirror quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs boson</td>
<td></td>
</tr>
</tbody>
</table>

Left-handed fermion doublets

<table>
<thead>
<tr>
<th>Leptons</th>
<th>126 GeV scalars</th>
</tr>
</thead>
<tbody>
<tr>
<td>e electron</td>
<td></td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td></td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td></td>
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Right-handed mirror fermion doublets

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<tr>
<th>Leptons</th>
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<td></td>
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</tbody>
</table>
Does the EW$\nu_R$ model agree with the experimental constraints on
the EW precision parameters- $S$, $T$?
Agreement with Precision Measurements

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

How EW$\nu_R$ model accommodates
Standard Model-like Higgs boson having
126 GeV mass
126 GeV candidate in minimal EW$_{\nu R}$

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

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

Cannot be compensated for in all the branching ratios
126 GeV candidate in minimal EW$\nu_R$

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

$$\sigma(gg \rightarrow H^0_1) \sim 49 \times \frac{v^2}{v_2^2} \sigma_{SM}(gg \rightarrow H)$$

Cannot be compensated for in all the branching ratios.

- $H^0_1$ in EW$\nu_R$ model cannot be the new 126 GeV particle.
126 GeV candidate in minimal EW$\nu_R$

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

\[ \sigma(gg \rightarrow H_1^0) \sim 49 \times \frac{v^2}{v'^2} \sigma_{SM}(gg \rightarrow H) \]

Cannot be compensated for in all the branching ratios

- $H_1^0$ in EW$\nu_R$ model cannot be the new 126 GeV particle

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

\[ \sigma(gg \rightarrow H_3^0) \sim \frac{v'^2}{v^2} \sigma_{SM}(gg \rightarrow H) \]

!!
126 GeV candidate in minimal EWνR

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

\[ \sigma(gg \rightarrow H^0_1) \sim 49 \times \frac{v^2}{v^2_2} \sigma_{SM}(gg \rightarrow H) \]

Cannot be compensated for in all the branching ratios

- \( H^0_1 \) in EWνR model cannot be the new 126 GeV particle

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

\[ \sigma(gg \rightarrow H^0_3) \sim \frac{v^2_M}{v^2_2} \sigma_{SM}(gg \rightarrow H) \]

Thus, for \( v^2_M/v^2_2 \sim 1 \), \( H^0_3 \) could reproduce \( \sigma_{SM}(gg \rightarrow H) \)
Spin-Parity Result from CMS

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

Disfavored up to $> 3\sigma$ relative to $0^+$
How $\text{EW}_\nu R$ accommodates 126 GeV particle as CP-even ($0^+$) Higgs
How \( EW\nu_R \) accommodates 126 GeV particle as CP-even \((0^+)\) Higgs

Not with the minimal \( EW\nu_R \) model just explained
An Extended EW$\nu_R$ (V. Hoang, P.Q.Hung, A.S.Kamat: paper in preparation)
Add another $SU(2)$ scalar doublet $\Phi_{2M}$ ($Y/2 = 1$)
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- Add another \(SU(2)\) scalar doublet \(\Phi_2 M\) (\(Y/2 = 1\))
- \(\Phi_2 \rightarrow\) couples \textit{only} to SM fermions; gives masses to left-handed fermion doublets
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- Physical scalar states of $SU(2)_D$ custodial symmetry:
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- Physical scalar states of \(SU(2)_D\) custodial symmetry:
The custodial singlets mix to give mass eigenstates

\[
\begin{pmatrix}
\tilde{H}_1^0 \\
\tilde{H}_1^{0,M} \\
\tilde{H}_1^{0,\prime}
\end{pmatrix}
= \begin{pmatrix}
a_1,1 & a_1,1M & a_1,1' \\
a_1M,1 & a_1M,1M & a_1M,1' \\
a_1',1 & a_1',1M & a_1',1'
\end{pmatrix}
\begin{pmatrix}
H_1^0 \\
H_1^{0,M} \\
H_1^{0,\prime}
\end{pmatrix}
\]
In Minimal EWνR Model

In a Simplest Extension

Motivation

EWνR Model

126 GeV Candidate

BSM scalars in EWνR model

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**Higgs boson**

- **H → bb**
  \[ \mu = 1.0 \pm 0.5 \]

- **H → ττ**
  \[ \mu = 0.78 \pm 0.27 \]

- **H → γγ**
  \[ \mu = 0.77 \pm 0.27 \]

- **H → WW**
  \[ \mu = 0.72^{+0.20}_{-0.18} \]

- **H → ZZ**
  \[ \mu = 0.93^{+0.29}_{-0.25} \]

---

**H~^0 decay limits**

- \[ \sim H_1^0 \rightarrow f \bar{f} \]
  \[ CMS \text{ preliminary} \]
  \[ m_{H_1} = 125.7 \text{ GeV} \]

- \[ \sim H_1^0 \rightarrow WW / ZZ \]
  \[ EWνR \text{ values} \]
  \[ m_{H_1^0} = 125.7 \text{ GeV} \]

---
Motivation

EW$\nu_R$ Model
126 GeV Candidate
BSM scalars in EW$\nu_R$ model

In Minimal EW$\nu_R$ Model
In a Simplest Extension

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

$\tilde{H}_1^0 \rightarrow f \bar{f}$

$H \rightarrow \mu = 1.0 \pm 0.5$

$H \rightarrow \tau \tau$
$\mu = 0.78 \pm 0.27$

$H \rightarrow \gamma \gamma$
$\mu = 0.77 \pm 0.27$

$H \rightarrow WW$
$\mu = 0.72^{+0.20}_{-0.18}$

$H \rightarrow ZZ$
$\mu = 0.93^{+0.29}_{-0.25}$

Best fit $\sigma / \sigma_{SM}$

$\tilde{H}_1^0 \rightarrow WW / ZZ$
\[ \mu(H_1^0 \rightarrow \gamma \gamma) = \frac{\sigma(gg \rightarrow \tilde{H}_1^0 \rightarrow \gamma \gamma)}{\sigma(gg \rightarrow H_{SM} \rightarrow \gamma \gamma)} \]

\[ m_{H_1^0} = 400 \text{ GeV} \]

\[ m_{H_1^0} (\text{GeV}) \]

\[ m_{H_1^0} = 200 \]

\[ m_{H_1^0} = 400 \]

\[ m_{H_1^0} = 600 \]

\[ \mu(H_1^0 \rightarrow \gamma \gamma) \] spans from \( \sim 0 \) to \( \sim 2.5 \) even in this ‘example’ plot
BSM scalars in EW$\nu_R$ model - preliminary
Motivation

EW\nu_R Model

126 GeV Candidate

BSM scalars in EW\nu_R model

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

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[SM Higgs search plot: with courtesy of CMS]
Motivation
EW$\nu_R$ Model
126 GeV Candidate
BSM scalars in EW$\nu_R$ model

\[
\mu(H_3^0 \rightarrow \gamma\gamma)
\]

Data not yet sensitive to mass range of $H_3^0$ (and hence $H_{3M}^0$) for which $\mu(H_3^0 \rightarrow \gamma\gamma) \lesssim 1$
Motivation
EW\(\nu_R\) Model
126 GeV Candidate
BSM scalars in EW\(\nu_R\) model

Summary

A model with Electroweak-scale Right-handed Neutrino (EW\(\nu_R\))
with Majorana mass

Does not violate constraints from EW precision measurements

Properties of 126 GeV candidate in a simply extended EW\(\nu_R\) model

agree with the data

More data at LHC will be sensitive to the BSM scalars
Summary

- A model with Electroweak-scale Right-handed Neutrino ($\text{EW}_{\nu_R}$) with Majorana mass
Summary

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Notes

Motivation
EWνR Model
126 GeV Candidate
BSM scalars in EWνR model

Notes

- Makes Seesaw mechanism testable at LHC and near future colliders through signals such as like-sign dilepton events (H−−5 → e−e−).
- These signals of the EWνR model have not yet been ruled out by the searches for charged Higgs bosons at the LHC.

- A unified model of DM asymmetry ⇒ Leptogenesis ⇒ Baryogenesis contains Mirror Fermions: Paul Frampton and P. Q. Hung (refer talk "Luminogenesis RG flow" by Kevin Ludwick in Cosmology section this afternoon).

Ajinkya S. Kamat (U. Virginia)
Notes

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  \((H_5^{--} \rightarrow e^M - e^M -)\)

- These signals of the EW\(\nu_R\) model have not yet been ruled out by the searches for charged Higgs bosons at the LHC.

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Thank You!
Backup Slides
Table: $\mu = \sigma / \sigma_{SM}$ for decay channels as measured at CMS and as calculated in EW$\nu_R$ model in $gg \rightarrow \tilde{H}^0_1$ production channel for given values of the parameters.

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Observed $\mu$ at CMS</th>
<th>Calculated $\mu$ ($\sim$ 5% accuracy) for $b1 = -0.001$ to $0.0001$ ($-0.0477$ to $-0.0489$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW$</td>
<td>$0.72^{+0.20}_{-0.18}$ (ggH, VBF, VH channels) [CMS Dec 2013]</td>
<td>$0.68 - 0.76$ ($0.68 - 0.74$)</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.93^{+0.26}<em>{-0.23}$ (stat) $^{+0.13}</em>{-0.09}$ (syst) (ggH, VBF, t\bar{t}H, VH channels) [CMS Dec 2013]</td>
<td>$0.68 - 0.76$ ($0.68 - 0.74$)</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>$0.78 \pm 0.29$ (non-VH channels) [CMS Jan 2014]</td>
<td>$1.03 - 1.16$ ($1.06 - 1.16$)</td>
</tr>
<tr>
<td>$bb$</td>
<td>$1.0 \pm 0.5$ (VH channels) [CMS Oct 2013]</td>
<td>$1.03 - 1.16$ ($1.06 - 1.16$)</td>
</tr>
<tr>
<td>$bb$ and $\tau\tau$ combined</td>
<td>$0.83 \pm 0.24$ [CMS Jan 2014]</td>
<td>$1.03 - 1.16$ ($1.06 - 1.16$)</td>
</tr>
</tbody>
</table>
Table: Allowed ranges of VEVs. All VEVs are given in GeV.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>69</td>
<td>$\lesssim v_2$</td>
<td>$\lesssim 234$</td>
</tr>
<tr>
<td>27</td>
<td>$\lesssim v_{2M}$</td>
<td>$\lesssim 234$</td>
</tr>
<tr>
<td>13</td>
<td>$\lesssim v_M$</td>
<td>$\lesssim 80$</td>
</tr>
</tbody>
</table>
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 $\nu$’s from getting large Majorana mass (terms like $g_L l_L^T \sigma_2 \tau_2 \tilde{\chi} l_L$ and $l_L^T \sigma_2 \tau_2 \tilde{\chi} l_R^M$)

$U(1)_M$ symmetry,

$$(l_R^M, e_L^M) \rightarrow e^{i\theta_M}(l_R^M, e_L^M),$$

$$\tilde{\chi} \rightarrow e^{-2i\theta_M}\tilde{\chi},$$

$$\phi_S \rightarrow e^{-i\theta_M}\phi_S$$
To forbid left-handed $\nu$’s from getting large Majorana mass (terms like $g_L l_L^T \sigma_2 \tau_2 \tilde{\chi} l_L$ and $l_L^T \sigma_2 \tau_2 \tilde{\chi} l_R^M$)

$U(1)_M$ symmetry,

$$(l_R^M, e_L^M) \rightarrow e^{i\theta_M}(l_R^M, e_L^M),$$

$$\tilde{\chi} \rightarrow e^{-2i\theta_M}\tilde{\chi},$$

$$\phi_s \rightarrow e^{-i\theta_M}\phi_s$$

Terms like $\bar{q}_L q_R^M, \bar{u}_R u_R^M, \bar{d}_R d_R^M$ also don’t occur
### EW$\nu_R$ model Yukawa couplings

<table>
<thead>
<tr>
<th></th>
<th>SM Quarks</th>
<th>Mirror Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{H^0_{11} qq}$</td>
<td>$-i \frac{m_q g}{2 M_W s_2}$ .... ($q = t, b$)</td>
<td>$-i \frac{m_q g}{2 M_W s_2}$ .... ($q = t, b$)</td>
</tr>
<tr>
<td>$g_{H^0_{11} tt}$</td>
<td>$i \frac{m_t g s_M}{2 M_W c_M} \gamma_5$</td>
<td>$\frac{m_M g s_M}{2 M_W c_M} \gamma_5$</td>
</tr>
<tr>
<td>$g_{H^0_{11} bb}$</td>
<td>$-i \frac{m_b g s_M}{2 M_W c_M} \gamma_5$</td>
<td>$\frac{m_M g s_M}{2 M_W c_M} \gamma_5$</td>
</tr>
<tr>
<td>$g_{H^0_{11} t b}$</td>
<td>$\frac{g s_M}{2 \sqrt{2} M_W c_M}$</td>
<td>$\frac{g s_M}{2 \sqrt{2} M_W c_M}$</td>
</tr>
<tr>
<td></td>
<td>$\times \left[ m_t(1 + \gamma_5) - m_b(1 - \gamma_5) \right]$</td>
<td>$\times \left[ m_u M(1 - \gamma_5) - m_d M(1 + \gamma_5) \right]$</td>
</tr>
<tr>
<td>$g_{H^0_{33} tt}$</td>
<td>$-i \frac{m_t g s_{2 M}}{2 M_W s_2} \gamma_5$</td>
<td>$\frac{m_M g s_{2 M}}{2 M_W s_2} \gamma_5$</td>
</tr>
<tr>
<td>$g_{H^0_{33} bb}$</td>
<td>$i \frac{m_b g s_{2 M}}{2 M_W s_2} \gamma_5$</td>
<td>$i \frac{m_M g s_{2 M}}{2 M_W s_2} \gamma_5$</td>
</tr>
<tr>
<td>$g_{H^0_{33} t b}$</td>
<td>$i \frac{g s_{2 M}}{2 \sqrt{2} M_W s_2 c_M}$</td>
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<td>$\times \left[ m_t(1 + \gamma_5) - m_b(1 - \gamma_5) \right]$</td>
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</tr>
</tbody>
</table>
### EWνR model Yukawa couplings (contd..)

<table>
<thead>
<tr>
<th>SM Quarks</th>
<th>Mirror Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{H_1^0 i j}$</td>
<td>$-i \frac{m_l g}{2 M_W s_2}$ $\ldots (l = \tau, \mu, e)$ $g_{H_1^0 M_i i}$</td>
</tr>
<tr>
<td>$g_{H_3^0 i j}$</td>
<td>$-i \frac{m_l g s_M}{2 M_W c_M} \gamma_5$ $g_{H_3^0 M_i i}$</td>
</tr>
<tr>
<td>$g_{H_3^- \nu L i}$</td>
<td>$-i \frac{g m_l s_M}{2 \sqrt{2} M_W c_M} (1 - \gamma_5)$ $g_{H_3^- \nu R i}$</td>
</tr>
<tr>
<td>$g_{H_3^0 3M i i}$</td>
<td>$i \frac{m_l g s_{2M}}{2 M_W s_2} \gamma_5$ $g_{H_3^0 3M i i}$</td>
</tr>
<tr>
<td>$g_{H_3^- 3M \nu L i}$</td>
<td>$-i \frac{g m_l s_{2M}}{2 \sqrt{2} M_W s_2 c_M} (1 - \gamma_5)$ $g_{H_3^- 3M \nu R i}$</td>
</tr>
</tbody>
</table>
SM Fermions Yukawa couplings:

\[ \mathcal{L} = -h_{ij} \overline{\psi}_L \Phi \psi_R + h.c. \]

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

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

Similar couplings for SM leptons and mirror quarks.
Mirror Fermions’ kinetic Lagrangian

$$(L_{FM})_{int}$$

$$= \frac{g}{\sqrt{2}} \left[ (\bar{u}^M_R \gamma^\mu d^M_{Ri} + \bar{\nu}^i_R \gamma^\mu e^M_{Ri}) W^+_\mu + (\bar{d}^M_R \gamma^\mu u^M_{Ri} + \bar{e}^M_i \gamma^\mu \nu^M_{Ri}) W^-_\mu \right]$$

$$+ \frac{g}{c_W} \left[ \sum_{f^M = u^M, d^M, \nu^M, e^M} \left( T^M_3 - s^2_W Q_{f^M} \right) \bar{f}^M_i \gamma^\mu f^M_i \right]$$

$$+ \sum_{f^M = u^M, d^M, e^M} s^2_W Q_{f^M} \bar{f}^M_L \gamma^\mu f^M_L \right] Z_\mu$$

$$+ e \sum_{f^M = u^M, d^M, e^M} Q_{f^M} \left( \bar{f}^M_R \gamma^\mu f^M_R - \bar{f}^M_L \gamma^\mu f^M_L \right) A_\mu$$