Radiative Neutrino Mass in light of the 750 GeV Diphoton Excess

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SM Higgs Relatives:

1. Participating in EWSB
   Perturbative unitarity & Diphoton excess
   M. Fabbrichesi, A. Urbano/1601.02447

2. In Radiative Neutrino Models
   Without or with a loop/dark $Z_2$ Symmetry
   V. Brdar, IP, B. Radovčić, PLB 728 (2014) 198

3. In Scotogenic Neutrino Models
   Derived dark $Z_2$ Symmetry
   E. Ma, IP, B. Radovčić, PLB 726 (2013) 744
   Induced accidental $Z_2$ Symmetry
   P. Ćuljak, IP, K. Kumerički, PLB 744 (2015) 237
1.1 On July 4, 2012, we learned of the discovery of SM Higgs

- An excitation of a field that cooled with the rest of the universe underwent a condensation;
- Massive fields in SM acquire their masses from this condensate
These are relative masses not size – they have no measurable size.

For reference:

Proton
0.938 GeV

Originally thought to be massless but now not.
Pure Quantum- Discovery @ LHC: gluon fusion + rare decay
<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BR.</th>
<th>Notes (as of early 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb$</td>
<td>58%</td>
<td>Observed at about $2\sigma$ at CMS</td>
</tr>
<tr>
<td>$WW^*$</td>
<td>22%</td>
<td>Observed at $4\sigma$</td>
</tr>
<tr>
<td>$gg$</td>
<td>8.6%</td>
<td></td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>6.3%</td>
<td>Observed at 1–2 $\sigma$</td>
</tr>
<tr>
<td>$c\bar{c}$</td>
<td>2.9%</td>
<td></td>
</tr>
<tr>
<td>$ZZ^*$</td>
<td>2.6%</td>
<td>Discovery mode (in $ZZ^* \rightarrow 4\mu, 2\mu 2e, 4e$)</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.23%</td>
<td>Discovery mode</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>0.15%</td>
<td></td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>0.022%</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}$</td>
<td>4.1 MeV</td>
<td></td>
</tr>
</tbody>
</table>
BSM fields may give diphoton excess (important charged scalars)

\[ \Gamma(h \rightarrow \gamma \gamma) = \frac{\alpha^2 m_h^3}{256 \pi^3 v_H^2} \left[ A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t) + N_{c,s} Q_s^2 \frac{c_s}{2} \frac{v_H^2}{m_s^2} A_0(\tau_s) \right]^2 \]
No more Diboson Excess at 125 GeV in 2014

\[ m_H = 125.4 \pm 0.4 \text{ GeV} \]
1.2 Perturbative hints for the “BSM” discoveries in the past (dim 6 op’s leading to $E^2$ scatt. ampl.)

- NP beyond the Fermi theory
  \[ G_F E^2 \sim \frac{E^2}{v^2} < 16\pi^2 \implies m_W < 4\pi v \]

- The search for the top quark, because
  \[ g_W^2 E^2 / m_W^2 < 16\pi^2 \implies m_t < 4\pi v \]

New theory must show up at an energy scale below $4\pi / \sqrt{G_F} \approx 4\pi v$, having expressed $G_F = 1 / \sqrt{2} v^2$ in terms of the EWSB scale $v \approx 246$ GeV.
The expectation of the Higgs, because of the quadratic term in the scatt. ampl.

\[ + \ldots \sim g_W^2 E^2 / m_W^2 < 16\pi^2 \quad \rightarrow \quad m_H < 4\pi v \]

the critical threshold of \( 4\pi v \sim 3 \text{ TeV} \) is within the reach of the LHC collider.

Each time we replaced one \( d=6 \) operator with one new discovered state!

After discovering the Higgs we are left with genuinely \( g \)-inv ren-ble theory!

New physics is needed to explain Dark Matter, neutrino masses, Inflation and Baryogenesis.
1.3 Only one Higgs doublet?
Difficult to imagine given the

- Huge disparity among SM fermion masses
- Lightness of neutrinos
- Fine tuning in the Higgs potential:

\[ V = \text{const.} + m_H^2 |H|^2 + \lambda |H|^4 \]

- Cosmological constant problem
- Higgs naturalness problem
- Vacuum stability problem
Veltman parameter close to 1

\[ \rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \quad \rho_{\text{exp}} = 1.0004^{+0.0003}_{-0.0004} \]

In extended Higgs sectors

\[ \rho_{\text{tree}} = \frac{\sum_i [T_i(T_i + 1) - Y_i^2]v_i^2}{2\sum_i Y_i^2 v_i^2} \]

SM tree-value unchanged provided

\[ T_i(T_i + 1) - 3Y_i^2 = 0 \]

Three main possibilities:

- Isospin singlets with \( Y_i = 0 \),
- Doublets with \( Y_i = 1/2 \),
- Septets with \( Y_i = 2 \)

larger isospin representation fields

Isospin 26-plet with \( Y_i = 15/2 \)

cause violation of perturbative unitarity
Additional Complex Scalar Multiplet $X$

gauge-kinetic Lagrangian

$$\mathcal{L} \supset (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) + (\mathcal{D}_\mu X)^\dagger (\mathcal{D}^\mu X)$$

$$\mathcal{D}_\mu = \partial_\mu - ig' B_\mu Y - ig W^a_\mu T^a = \partial_\mu - ig' B_\mu Y - ig \left[ \frac{1}{2} (W^+_\mu T^+ + W^-_\mu T^-) + W^3_\mu T^3 \right]$$

- Masses for $W$ and $Z$ the terms proportional to $v^2_X$

$$(\mathcal{D}_\mu X)^\dagger (\mathcal{D}^\mu X) \supset X^\dagger \left[ \frac{g^2}{4} W^+_\mu W^-_\mu (T^+ T^- + T^- T^+) + g^2 W^3_\mu W^3_\mu (T^3)^2 

+ g'^2 B_\mu B^\mu (Y)^2 + 2gg' B_\mu W^3_\mu (YT^3) \right] X,$$

use $Q = T^3 + Y$ so that $T^3 = Q - Y = -Y$ for the neutral component of $X$ where the vev lives
For a scalar $X$ of isospin $T$

\[
T^+T^- + T^-T^+ = \sqrt{2}(T^1 + iT^2)\sqrt{2}(T^1 - iT^2) + \sqrt{2}(T^1 - iT^2)\sqrt{2}(T^1 + iT^2)
= 4 [(T^1)^2 + (T^2)^2]
= 4 [|\vec{T}|^2 - (T^3)^2]
= 4 [T(T + 1) - (T^3)^2],
\]

**Contributions – in convention** $Q=T+Y$

\[
(D_\mu X)^\dagger(D^\mu X) \supset X^\dagger \left\{ g^2 W^+_\mu W^-\mu \left[ T(T + 1) - Y^2 \right] + g^2 W^3_\mu W^{3\mu} (Y)^2 + g'^2 B_\mu B^\mu (Y)^2 - 2gg' B_\mu W^{3\mu} (Y)^2 \right\} X.
\]

◇ Doublet, $Y = 1/2$: $T(T + 1) - Y^2 = \frac{1}{2}$, $Y^2 = \frac{1}{4}$.
◇ Triplet, $Y = 0$: $T(T + 1) - Y^2 = 2$, $Y^2 = 0$.
◇ Triplet, $Y = 1$: $T(T + 1) - Y^2 = 1$, $Y^2 = 1$. 
2. The 2HD Benchmark Model and Beyond

Theoretical problems of the SM

- Strong CP: \( \bar{\theta} G^\mu{}\nu \tilde{G}_{\mu\nu} \quad (D = 4) \) \( \Rightarrow \bar{\theta} \lesssim 10^{-11} \)
- EW naturalness: \( \Lambda^2 H^\dagger H \quad (D = 2) \) \( \Rightarrow \Lambda \approx 100 \text{ GeV} \)
- Cosmological constant: \( \Lambda^4 \sqrt{g} \quad (D = 0) \) \( \Rightarrow \Lambda \approx 10^{-3} \text{ eV} \)
- Landau poles
- ...

- Evidence/hints for physics beyond the SM

  - Neutrino oscillations
  - Dark Matter
  - Baryon asymmetry
  - EW vacuum instability
  - Gravity

A simple scalar extension of the SM may account for all these issues.
i) **Real triplet**

\( T=1, \ Y=0 \) (VEV):

\[ \frac{1}{2} (\mathcal{D}_\mu \Xi) \dagger (\mathcal{D}^{\mu} \Xi) \supset g^2 v_\xi^2 W_\mu^+ W^{-\mu} \]

- \( Y=0 \), so no contribution to neutral boson masses

\[ \Xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix} \rightarrow \begin{pmatrix} \xi^+ \\ \xi^0 + v_\xi \\ \xi^- \end{pmatrix} \]

\[ \langle \Xi \rangle = \begin{pmatrix} 0 \\ v_\xi \\ 0 \end{pmatrix} \]

\[ M^2_\Xi = v_\xi^2 \begin{pmatrix} g^2 & 0 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 & 0 \\ 0 & 0 & g^2 & 0 & 0 \\ 0 & 0 & 0 & g^2 & 0 \\ 0 & 0 & 0 & 0 & g^2 \end{pmatrix} \]
ii) Complex triplet

\[ T=1, \ Y=1 \ \text{(VEV):} \]

\[
X = \begin{pmatrix}
\chi^{++} \\
\chi^+ \\
\chi^0 \\
\end{pmatrix} \rightarrow \begin{pmatrix}
\chi^{++} \\
v_\chi + (h_\chi + ia_\chi)/\sqrt{2} \\
\end{pmatrix}
\]

\[
(D_\mu X)^\dagger (D^\mu X) \supset g^2 v_\chi^2 W_\mu^+ W^{-\mu} + g^2 v_\chi^2 W_\mu^3 W^{3\mu} + g^2 v_\chi^2 B_\mu B^\mu - 2gg' v_\chi^2 B_\mu W^{3\mu}
\]

**Mass-square contributions for W i Z**

\[
M_X^2 = v_\chi^2 \begin{pmatrix}
g^2 & 0 & 0 & 0 & 0 \\
0 & g^2 & 0 & 0 & 0 \\
0 & 0 & 2g^2 & -2gg' & 2g'^2 \\
0 & 0 & -2gg' & 2g'^2 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

the lower 2 \times 2 block of this matrix is still diagonalized by the same weak mixing angle \( \theta_W \)

does not generate the same masses for the W and Z in the limit \( g' \rightarrow 0 \)
Custodial symm. restoration for both triplets, \( Y=0 \) & \( Y=1 \)

\[
M_W^2 = \frac{g^2}{4} (v_\phi^2 + 4v_\xi^2 + 4v_\chi^2)
\]

\[
M_Z^2 = \frac{g^2 + g'^2}{4} (v_\phi^2 + 8v_\chi^2) = \frac{g^2}{4c_W^2} (v_\phi^2 + 8v_\chi^2)
\]

\[
\rho \equiv \frac{M_W^2}{c_W^2 M_Z^2} = \frac{v_\phi^2 + 4v_\xi^2 + 4v_\chi^2}{v_\phi^2 + 8v_\chi^2}
\]

The rho parameter tuned to 1 for aligned

\[
v_\xi = v_\chi \equiv v_3
\]

\[
M_{X+\Xi}^2 = 2v_3^2 \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & -gg' \\ 0 & 0 & -gg' & g'^2 \end{pmatrix}
\]

The custodial SU(2) symmetry is restored:

\[
W^1 \leftrightarrow W^2 \leftrightarrow W^3
\]

in the limit \( g' \to 0 \), the \( W \) and \( Z \) masses again become equal
Georgi-Machacek model with bidoublet-like 3x3 object - containing both triplets $Y=1$ & $Y=0$

to engineer the relationship $\nu_\xi = \nu_\chi$

$$\langle \tilde{X} \rangle = \begin{pmatrix} \nu_\chi & 0 & 0 \\ 0 & \nu_\chi & 0 \\ 0 & 0 & \nu_\chi \end{pmatrix}$$

$$\tilde{X} = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}$$

where $\chi^- = -\chi^{++}$ and $\xi^- = -\xi^{++}$

transforms as a triplet under both the global $SU(2)_L$ and $SU(2)_R$

by allowing an alignment among VEVs, we can keep $\rho_{\text{tree}} = 1$

If this is symmetry of the scalar potential

the resulting model is called the Georgi-Machacek model

“Doubly Charged Higgs Bosons,”

2.2 Two Higgs Doublet - 2HDM

the most explored benchmark model

\[ \Phi_1 = \left( \frac{\phi_1^+}{(h_1 + v_1 + i a_1)/\sqrt{2}} \right), \quad \Phi_2 = \left( \frac{\phi_2^+}{(h_2 + v_2 + i a_2)/\sqrt{2}} \right) \]

- Both fields participate in EWSB
- Real VEVs avoid CPV in scalar sector
- Can provide a custodial singlet with the couplings to g. b. fixed by g-inverse, to cancel the unitarity growth
Most general non-SuSy 2HDM with CP conserving potential

\[ \Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} (G^+ \cos \beta - H^+ \sin \beta) \\ v_1 - h \sin \alpha + H \cos \alpha + i (G \cos \beta - A \sin \beta) \end{pmatrix} \]

\[ \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} (G^+ \sin \beta + H^+ \cos \beta) \\ v_2 + h \cos \alpha + H \sin \alpha + i (G \sin \beta + A \cos \beta) \end{pmatrix} \]

\[ \mathcal{V}_{2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.] \]

\[ + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \]

\[ + \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + h.c. \right\} . \]

- To avoid FCNC (with “natural flavor cons”)

  impose a $Z_2$ symmetry so that each type of fermion only couples to one of the doublets

  (forcing $\lambda_6 = \lambda_7 = 0$)
**Natural Flavor Conservation NFC**

- **Type I:** \( u_R, d_R, e_R \rightarrow -u_R, -d_R, -e_R \)
- **Type II:** \( u_R \rightarrow -u_R \) and \( d_R, e_R \rightarrow d_R, e_R \)
- **Type X** (lepton specific): \( u_R, d_R \rightarrow -u_R, -d_R \) and \( e_R \rightarrow e_R \)
- **Type Y** (flipped): \( u_R, e_R \rightarrow -u_R, -e_R \) and \( d_R \rightarrow d_R \)

**TABLE I.** Four types of the charge assignment of the \( Z_2 \) symmetry.

<table>
<thead>
<tr>
<th></th>
<th>( \Phi_1 )</th>
<th>( \Phi_2 )</th>
<th>( u_R )</th>
<th>( d_R )</th>
<th>( \ell_R )</th>
<th>( Q_L, L_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-I</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Type-II</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Type-X</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Type-Y</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>
2.3 Custodial Triplet (GMM) contains a singlet resonance that can take part in EWSB and still belong to a perturbative regime

\[ \Phi_{(2,2)} \equiv \begin{pmatrix} \phi^0 & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \quad \Delta_{(3,3)} \equiv \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix} \]

whose VEVs are

\[ \langle \Phi \rangle = \frac{v_\phi}{\sqrt{2}} \hat{I}_{2 \times 2} \quad \text{and} \quad \langle \Delta \rangle = \frac{v_\Delta}{\sqrt{2}} \hat{I}_{3 \times 3} \]

with \( v_\phi^2 + 8v_\Delta^2 = v^2 = 1/\sqrt{2}G_F \approx (246 \text{ GeV})^2 \)
C-W Chiang, A-L Kuo/1601.06394 fit the 750 diphoton resonance with the Singlet of Custodial Triplet Model

\[ \Phi = \begin{pmatrix} \phi^0 & \phi^+ \\ -\phi^- & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^- & \xi^0 & \chi^+ \\ \chi^{-} & -\xi^- & \chi^0 \end{pmatrix} \]

\[ V = \frac{1}{2} m_1^2 \text{tr}[\Phi^\dagger \Phi] + \frac{1}{2} m_2^2 \text{tr}[\Delta^\dagger \Delta] + \lambda_1 (\text{tr}[\Phi^\dagger \Phi])^2 + \lambda_2 (\text{tr}[\Delta^\dagger \Delta])^2 + \lambda_3 \text{tr}\left[(\Delta^\dagger \Delta)^2\right] + \lambda_4 \text{tr}[\Phi^\dagger \Phi] \text{tr}[\Delta^\dagger \Delta] + \lambda_5 \text{tr}\left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2}\right] \text{tr}[\Delta^\dagger T^a \Delta T^b] + \mu_1 \text{tr}\left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2}\right] (P^\dagger \Delta P)_{ab} + \mu_2 \text{tr}[\Delta^\dagger T^a \Delta T^b] (P^\dagger \Delta P)_{ab}, \]

\[ P = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 & i & 0 \\ 0 & 0 & \sqrt{2} \\ 1 & i & 0 \end{pmatrix} \]

diagonalizes the adjoint rep of SU(2)
10 phys. states among 13 rep's under SU(2)-custodial

\[(2, 2) \sim 1 \oplus 3, \text{ and } (3, 3) \sim 1 \oplus 3 \oplus 5\]

\(SU(2)_C\) singlets \(H_1^0, H_1^{0'}\) (the Higgs and the additional resonance)

one \(SU(2)_C\) triplet \((H_3^+, H_3^0, H_3^-)\)

one \(SU(2)_C\) quintuplet \((H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})\)

- Fabbrichesi-Urbano/1601.02447 fit the 750 diphoton resonance with the physical “additional resonance”

\[H = s_\alpha H_1^0 + c_\alpha H_1^{0'}\]
3. The Resonance at 750 GeV that Stole Christmas

the title of N. Craig et al./1512.04928

The ATLAS announcement [1] of a $3.6\sigma$ local excess in diphotons with invariant masses near $m_{\gamma\gamma} \sim 750$ GeV

\[
\sigma(pp \rightarrow \phi \rightarrow \gamma\gamma) = (6.2^{+2.4}_{-2.0}) \text{ fb (ATLAS)}
\]
\[
= (5.6 \pm 2.4) \text{ fb (CMS)}
\]
\[
\Gamma_{\text{tot}}(\phi) \sim 45\text{GeV (ATLAS)}
\]

3.1 Fitting the 750 GeV state

M.R. Buckley/1601.04751

as a follow-up to the work of Refs. [4–6], which have largely set the parameters which later papers have adopted

The most statistically significant deviation from the SM at the LHC made public since the discovery of the Higgs boson at 125 GeV

A hint of a second scalar boson like in Radiative Neutrino Models

- 2HDMs cannot accommodate without additional massive particles


- A need to go beyond purely scalar explanations

3.2 Radiative Neutrino Models

Integrating out BSM particles produces an effective Dim 5 neutrino-mass operator

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\lambda}{M} L \bar{H} H^T L^c + O\left(\frac{1}{M^2}\right) \]

- \(L_L\) — lepton doublet
- \(H\) — Higgs boson doublet
- \(M\) — heavy mass

\[ \langle H \rangle_0 = \nu \quad \rightarrow \quad m_\nu \sim \lambda \nu \left(\frac{\nu}{M}\right) \]
Dim 5 op. in scalar extensions: weak triplet w.r.t. 2nd doublet + charged scalars @ loop level

\[(\ell\ell HH)/\Lambda\quad (\ell\ell e e H)/\Lambda^3\quad (\ell\ell e e e e)/\Lambda^5\]

\[<H^0> + <H^0> \quad \times <H_u^0> \quad \times <H_d^0>\]

\[\nu_L \quad e_L \quad e_R \quad \nu_L \quad \nu_L \quad e_R \quad e_R \quad e_L \quad \nu_L\]


[Zee (1980), Wolfenstein (1980), Babu, Julio (2014)]

[Zee (1986), Babu (1988)]
Radiative mass with real ($Y=0$) Triplet Scalar  

$$\Delta = \frac{1}{\sqrt{2}} \sum_j \sigma_j \Delta_j = \begin{pmatrix} \frac{1}{\sqrt{2}} \Delta^0 \\ \Delta^- \end{pmatrix} - \frac{1}{\sqrt{2}} \Delta^0 \sim (3, 0)$$

- Additional charged scalar singlet $h^+ \sim (1, 2)$
- Additional vectorlike lepton doublet

$$\Sigma_R \equiv (\Sigma_R^0, \Sigma_R^-)^T \sim (2, -1) , \quad \Sigma_L \equiv (\Sigma_L^0, \Sigma_L^-)^T \sim (2, -1)$$
**Gauge invariant scalar potential**

\[
V(H, \Delta, h^+) = -\mu_H^2 H^\dagger H + \lambda_1 (H^\dagger H)^2 + \mu_h h^- h^+ + \lambda_2 (h^- h^+)^2 + \mu_\Delta \text{Tr}[\Delta^2] + \lambda_3 (\text{Tr}[\Delta^2])^2 + \lambda_4 H^\dagger H h^- h^+ + \lambda_5 H^\dagger H \text{Tr}[\Delta^2] + \lambda_6 h^- h^+ \text{Tr}[\Delta^2] + (\lambda_7 H^\dagger \Delta \tilde{H} h^+ + \text{H.c.}) + \mu H^\dagger \Delta H.
\]

**The neutrino mass matrix**

\[
M_{ij} = \sum_{k=1}^{3} \left[ \frac{(g_1)_{ik} (g_2)_{jk} + (g_2)_{ik} (g_1)_{jk}}{8\pi^2} \right] \lambda_7 \nu_H^2 M_{\Sigma_k} \\
M_{\Sigma_k}^2 m_{h+} \ln \frac{M_{\Sigma_k}^2}{m_{h+}^2} + M_{\Sigma_k}^2 m_{\Delta+} \ln \frac{m_{\Delta+}^2}{M_{\Sigma_k}^2} + m_{h+} m_{\Delta+} \ln \frac{m_{h+}^2}{m_{\Delta+}^2} \frac{(m_{h+}^2 - m_{\Delta+}^2)(M_{\Sigma_k}^2 - m_{h+}^2)(M_{\Sigma_k}^2 - m_{\Delta+}^2)}{(m_{h+}^2 - m_{\Delta+}^2)(M_{\Sigma_k}^2 - m_{h+}^2)(M_{\Sigma_k}^2 - m_{\Delta+}^2)}
\]
3.3 Inert-Scotogenic variants - as a link to DM problem

- Scotogenic model with $\mathbb{Z}_2$ symmetry
  V.Brdar, IP, B.Radovčič, PLB 728 (2014) 198

\[
\begin{pmatrix}
  h^- & \Delta^-
\end{pmatrix}
\begin{pmatrix}
  \mu_h^2 + \lambda_4 v_H^2 & \lambda_7 v_H^2 \\
  \lambda_7 v_H^2 & \mu_\Delta^2 + 2\lambda_5 v_H^2
\end{pmatrix}
\begin{pmatrix}
  h^+ \\
  \Delta^+
\end{pmatrix}
\]

relation to the mass eigenstates is given by

\[
\begin{pmatrix}
  h^+ \\
  \Delta^+
\end{pmatrix} = 
\begin{pmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
  S_1^+ \\
  S_2^+
\end{pmatrix}.
\]

- Scotogenic model with $\mathbb{U}(1)_D$ gauge symm.
  E.Ma, IP, B.Radovčič, PLB 726 (2013) 744

\[
\Delta V(H, \Delta) = \lambda_8 (\Delta^\dagger \tau^{(3)}_a \Delta)^2 + \lambda_9 (H^\dagger \tau^{(2)}_a H)(\Delta^\dagger \tau^{(3)}_a \Delta)
\]
Radiative mass with $Y=2$ Inert Triplet Scalar

Particle content
H. Okada, Y. Orikasa:
1512.06687
Baroque Scotogenic Model

Three-loop $\nu$MDM model

Yukawa interaction

$$\mathcal{L}_Y = -y e_i \bar{L}_{iL} H_1 e_{iR} - Y_{i\alpha} (e_{iR})^c \Phi^* \Sigma_{\alpha R} + \text{h.c.}$$

$\tilde{Z}_2$-symmetric mixing quartic term

$$V_m(H_1, H_2, \Phi, \chi) = \kappa H_1 H_2 \Phi \chi + \text{h.c.}$$
Exotic multiplets on top of 2HD

$$\Sigma_\alpha \sim (5, 0) \quad \Phi \sim (5, -2) \quad \chi \sim (7, 0)$$

$$\Sigma_{1111} = \Sigma_R^{++}$$
$$\Sigma_{1112} = \frac{1}{\sqrt{4}} \Sigma_R^+$$
$$\Sigma_{1122} = \frac{1}{\sqrt{6}} \Sigma_R^0$$
$$\Sigma_{1222} = \frac{1}{\sqrt{4}} (\Sigma_L^+)^c$$
$$\Sigma_{2222} = (\Sigma_L^{++})^c$$

$$\Phi_{1111} = \phi^+$$
$$\Phi_{1112} = \frac{1}{\sqrt{4}} \phi^0$$
$$\Phi_{1122} = \frac{1}{\sqrt{6}} \phi^-$$
$$\Phi_{1222} = \frac{1}{\sqrt{4}} \phi^{--}$$
$$\Phi_{2222} = \phi^{---}$$

$$\chi_{111111} = \chi^{+++}$$
$$\chi_{211111} = \frac{1}{\sqrt{6}} \chi^{++}$$
$$\chi_{221111} = \frac{1}{\sqrt{15}} \chi^+$$
$$\chi_{222111} = \frac{1}{2\sqrt{5}} \chi^0$$
$$\chi_{222211} = \frac{1}{\sqrt{15}} \chi^-$$
$$\chi_{222221} = \frac{1}{\sqrt{6}} \chi^{--}$$
$$\chi_{222222} = \chi^{----}$$
Accidental DM protecting symmetry

dimension-three $Z_2$-noninvariant operator

$$\mu \Phi \Phi^* \chi$$

is forbidden by the $\tilde{Z}_2$ symmetry enforced on the 2HD sector

$$(H_1, H_2) \rightarrow (H_1, -H_2)$$

In the “lepton-specific” (Type X or Type IV) model $H_2$ couples to all quarks whereas $H_1$ couples to all leptons

<table>
<thead>
<tr>
<th></th>
<th>$Q_i$</th>
<th>$u_{iR}$</th>
<th>$d_{iR}$</th>
<th>$L_{iL}$</th>
<th>$e_{iR}$</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>$\Phi$</th>
<th>$\chi$</th>
<th>$\Sigma_\alpha$</th>
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<tbody>
<tr>
<td>$Z_2$ accidental</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{Z}_2$ exact, imposed</td>
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<td>-</td>
<td>-</td>
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<td>+</td>
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</tbody>
</table>
Conclusions:

- Diphoton excess (if confirmed) is in favour of a setup which is appropriate for Radiative Neutrino Models (minimal or baroque):
  - Triplet $Y=0$ scalar which mixes with SM Higgs
  - Triplets ($Y=0$ and/or 2) which are constrained by imposing loop- or DM protecting $Z_2$ symmetry
  - Conceivable scenarios with authomatic dark $Z_2$ symmetry - an example of fermion quintuplet Majorana DM candidate with mass < 450 GeV discoverable using monojet searches @HL-LHC

- Diphoton and other measured signals may help to discriminate between different scenarios