Radiative Neutrino Mass in light of the 750 GeV Diphoton Excess

Ivica Picek
University of Zagreb

Oslo, 3 February 2016

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 Z2 Symmetry

   V.Brdar, IP, B.Radovčić, PLB 728 (2014) 198

3. In Scotogenic Neutrino Models

   Derived dark Z2 Symmetry

   E.Ma, IP, B.Radovčić, PLB 726 (2013) 744

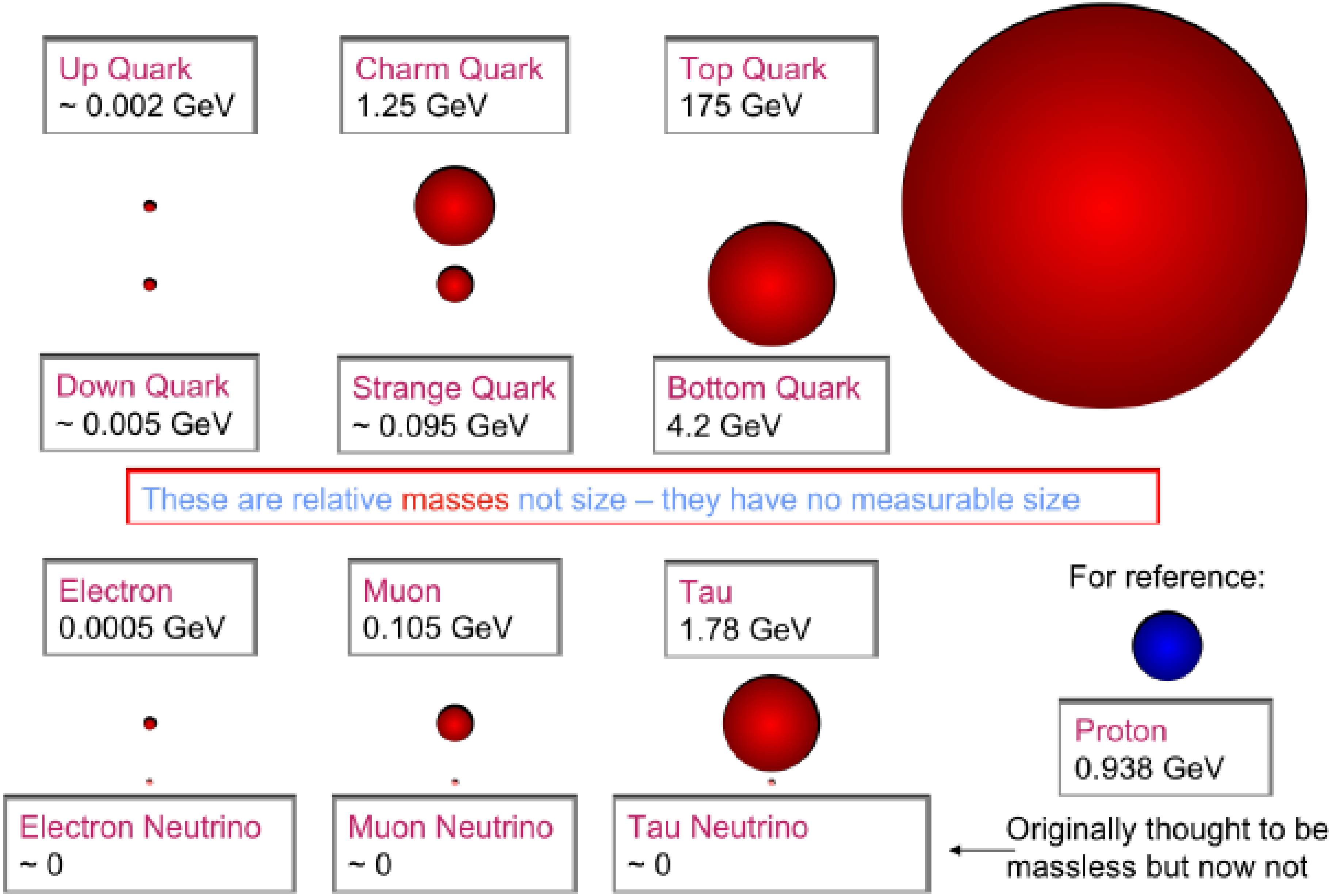
   Induced accidental Z2 Symmetry

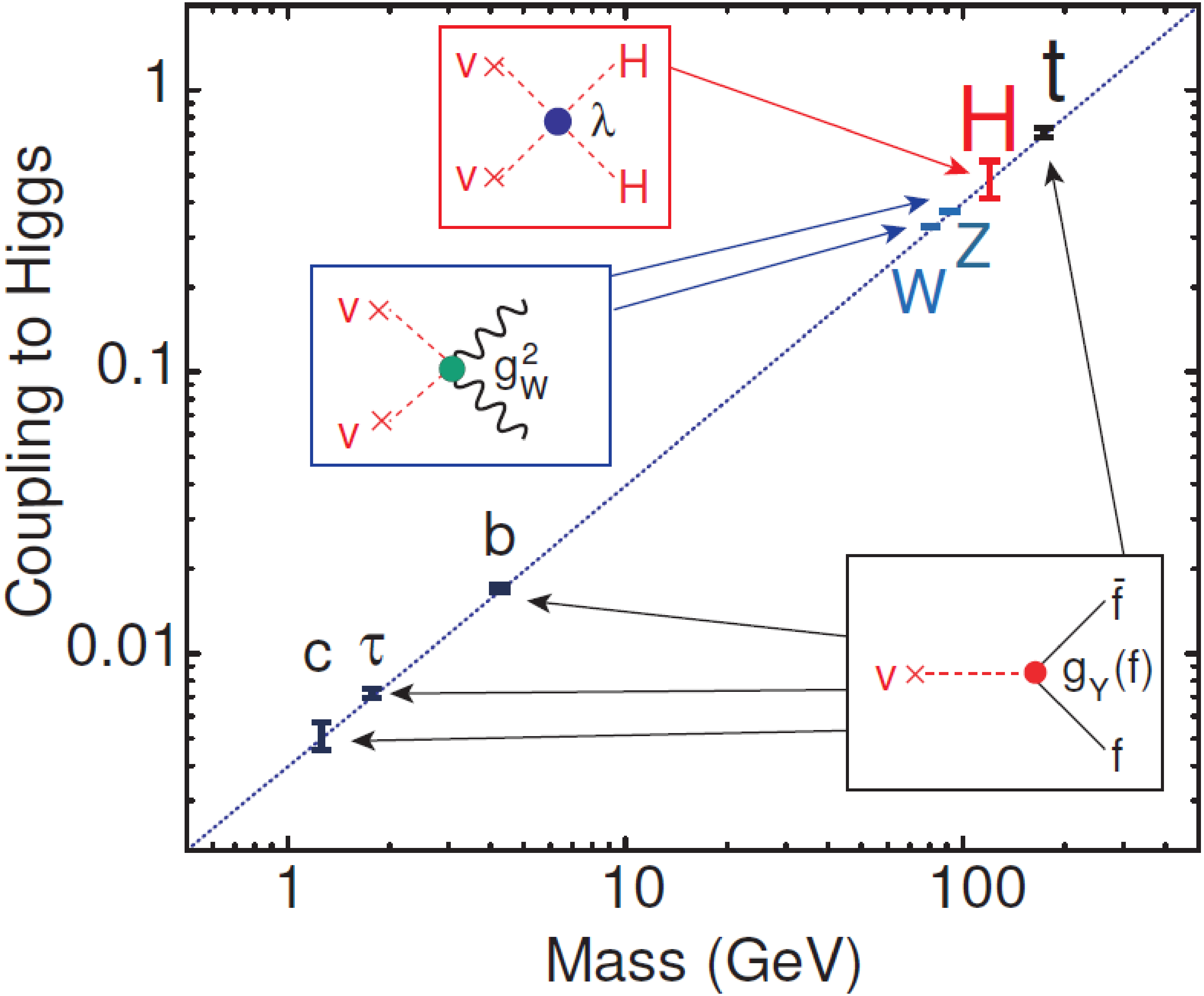
   P.Čuljak, IP, K.Kumerički, PLB 744 (2015) 237

1.The SM Higgs: Now, Then & in Future

1.1 On July 4, 2012, we learned of the discovery of SM Higgs

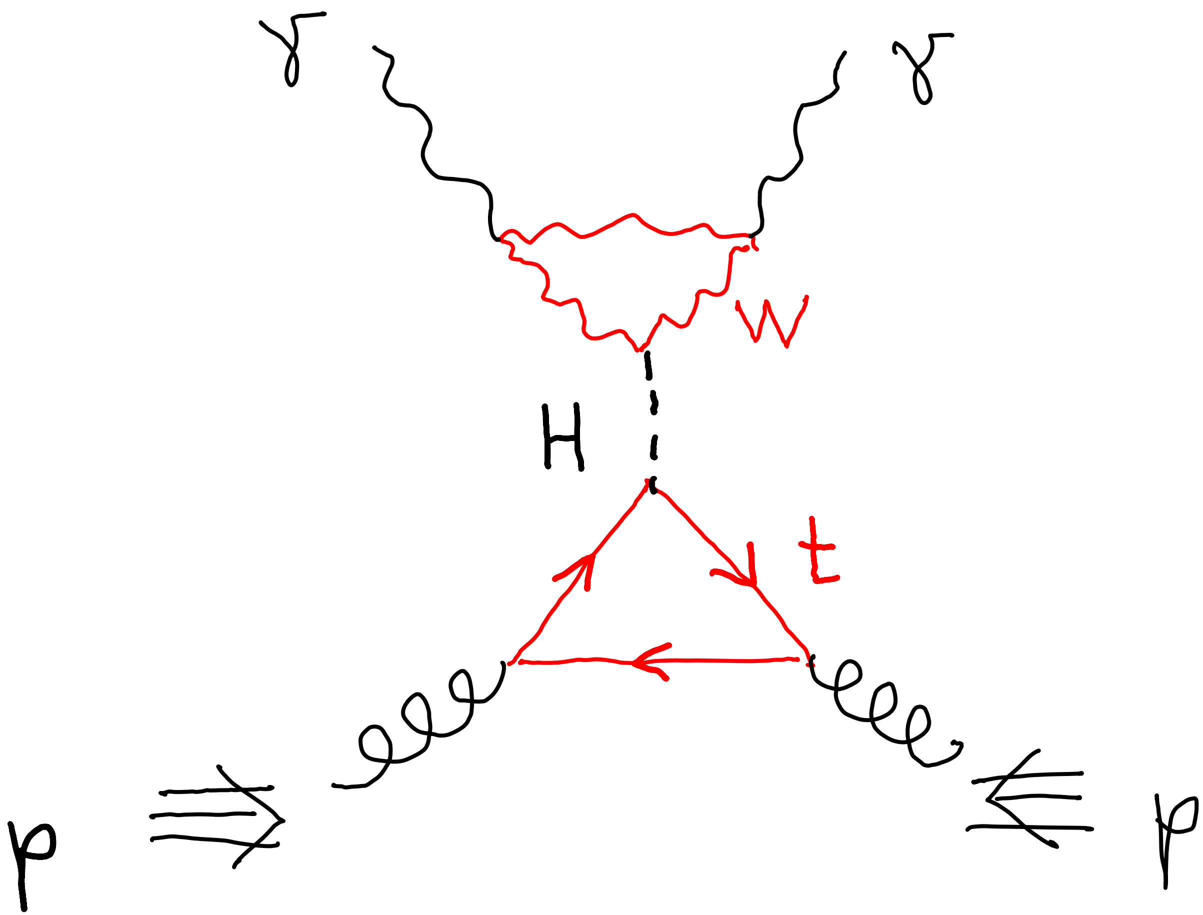
- An excitation of a field that cooled with the rest of the universe underwent a condensation;
- Massive fields in SM acquire their masses from this condensate

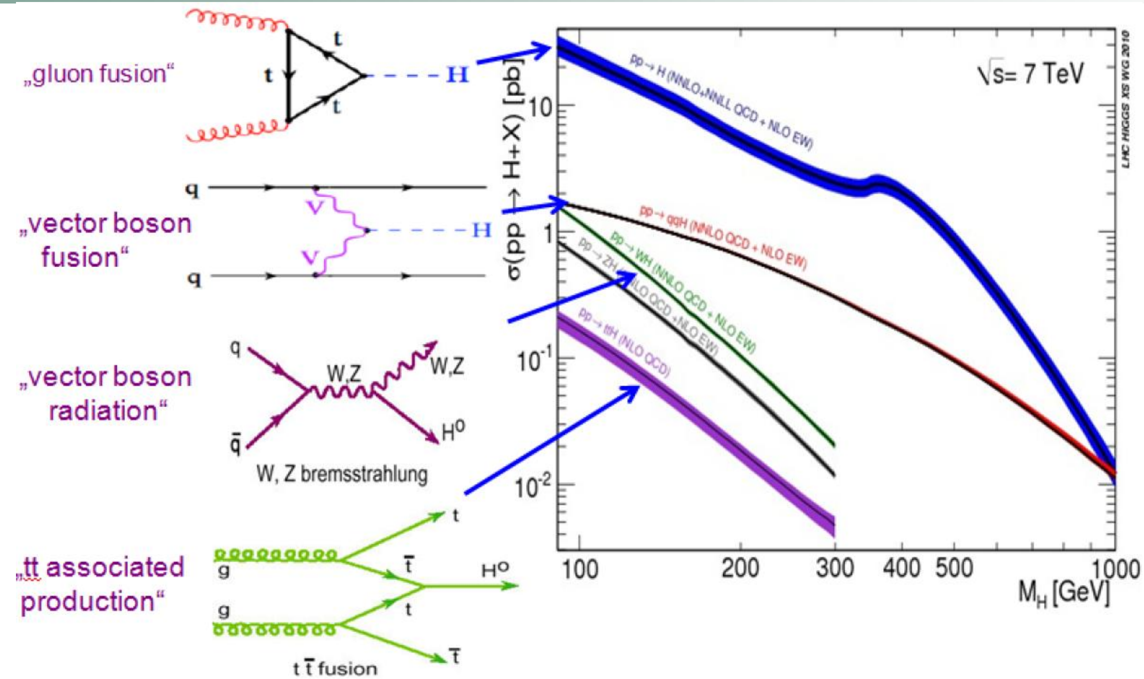

Up Quark
~ 0.002 GeV
Charm Quark
1.25 GeV
Top Quark
175 GeV
Down Quark
~ 0.005 GeV
Strange Quark
~ 0.095 GeV
Bottom Quark
4.2 GeV
These are relative masses not size – they have no measurable size
Electron
0.0005 GeV
Muon
0.105 GeV
Tau
1.78 GeV
For reference:
Proton
0.938 GeV
Electron Neutrino
~ 0
Muon Neutrino
~ 0
Tau Neutrino
~ 0
Originally thought to be massless but now not



Coupling to Higgs
1
0.1
0.01
1
10
100
Mass (GeV)
v
H
λ
H
g_W^2
H
t
W
Z
b
c
τ
$\bar{f}$
$g_Y(f)$
f

Pure Quantum- Discovery @ LHC: gluon fusion + rare decay

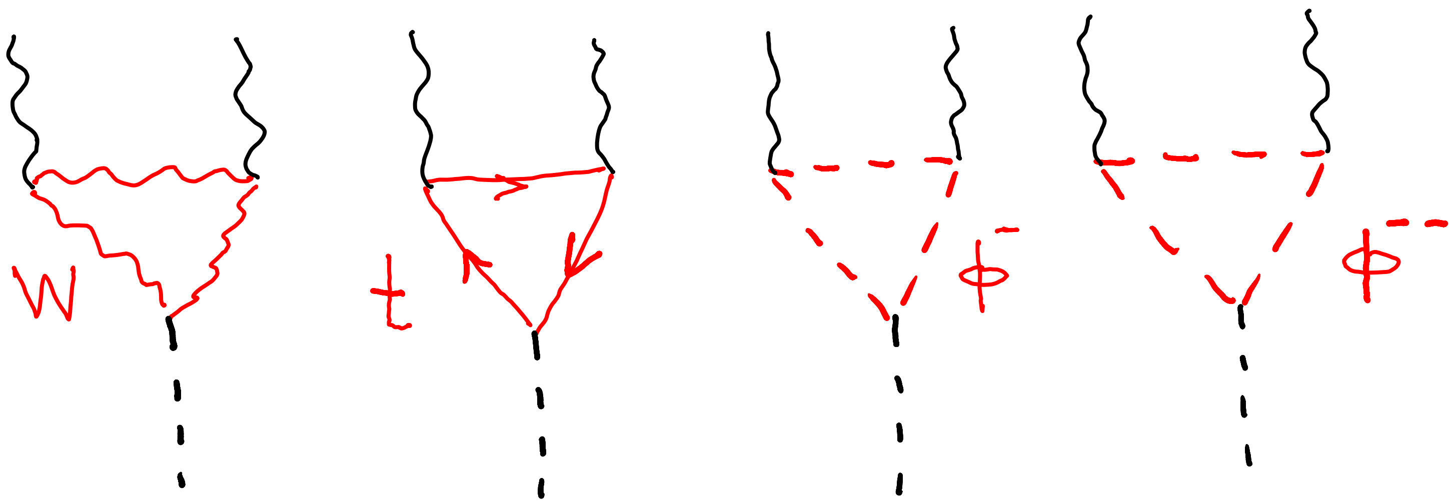




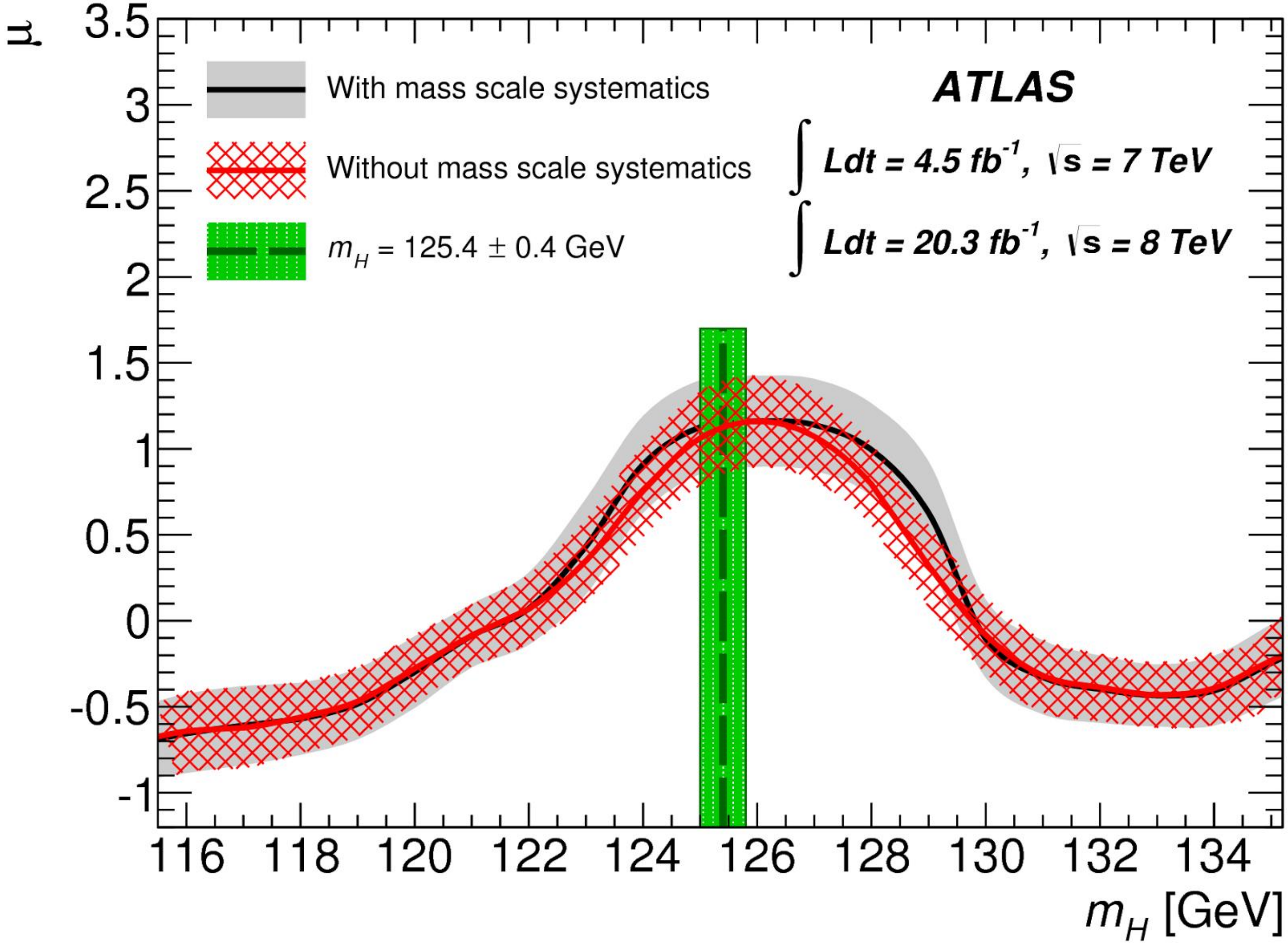
Decay mode	BR	Notes (as of early 2014)
$b\bar{b}$	58%	Observed at about 2σ at CMS
WW^*	22%	Observed at 4σ
gg	8.6%	
$\tau\tau$	6.3%	Observed at 1–2 σ
$c\bar{c}$	2.9%	
ZZ^*	2.6%	Discovery mode (in $ZZ^* \to 4\mu$, $2\mu 2e$, $4e$)
$\gamma\gamma$	0.23%	Discovery mode
$Z\gamma$	0.15%	
$\mu\mu$	0.022%	
Γ_{tot}	4.1 MeV	

BSM fields may give diphoton excess (important charged scalars)

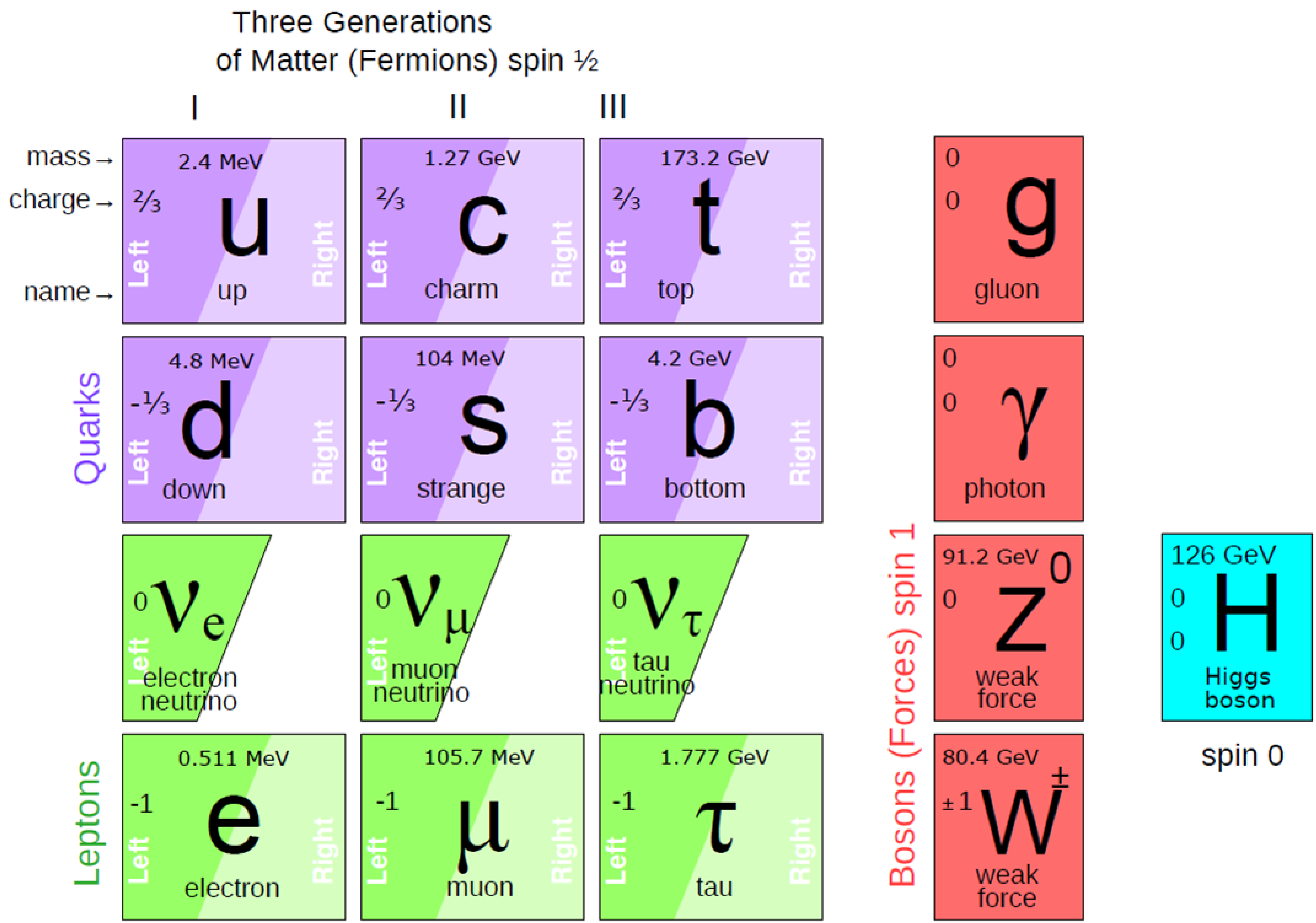
$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{256\pi^3 v_H^2} \left| A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t) + N_{c,S} Q_S^2 \frac{c_S}{2} \frac{v_H^2}{m_S^2} A_0(\tau_S) \right|^2$$



No more Diphoton Excess at 125 GeV in 2014



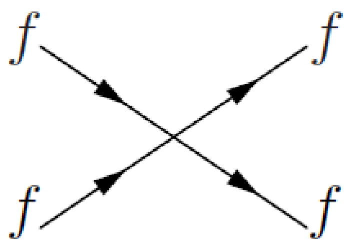
"The SM Periodic Table"



1.2 Perturbative hints for the "BSM" discoveries in the past

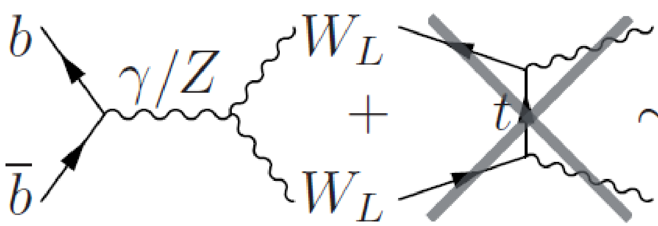
(dim 6 op's leading to E^2 scatt. ampl.)

- NP beyond the Fermi theory



$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \longrightarrow m_W < 4\pi v$$

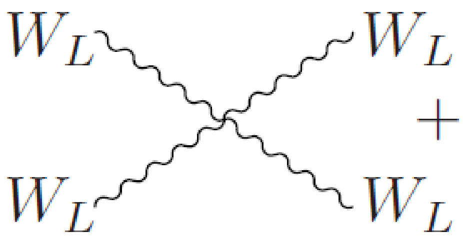
- The search for the top quark, because



$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \longrightarrow m_t < 4\pi v$$

new theory must show up at an energy scale below $4\pi/\sqrt{G_F} \simeq 4\pi v$, having expressed $G_F = 1/\sqrt{2}v^2$ in terms of the EWSB scale $v \simeq 246$ GeV.

The expectation of the Higgs, because of the quadratic term in the scatt. ampl.



$$+ \ldots \sim g_W^2 E^2 / m_W^2 < 16\pi^2 \longrightarrow m_H < 4\pi v$$

the critical threshold of $4\pi v \sim 3$ 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

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \qquad \rho_{\exp} = 1.0004^{+0.0003}_{-0.0004}$$

- **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 $Y_i = 1/2$, and 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

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

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

- **Masses for W and Z** the terms proportional to v_X^2

$$(\mathcal{D}_\mu X)^\dagger (\mathcal{D}^\mu X) \supset X^\dagger \left[\frac{g^2}{4} W_\mu^+ W^{-\mu} (T^+ T^- + T^- T^+) + g^2 W_\mu^3 W^{3\mu} (T^3)^2 + g'^2 B_\mu B^\mu (Y)^2 + 2gg' B_\mu W^{3\mu} (Y T^3) \right] X,$$

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

$$\begin{aligned} T^+T^- + T^-T^+ &= \sqrt{2}(T^1 + iT^2)\sqrt{2}(T^1 - iT^2) + \sqrt{2}(T^1 - iT^2)\sqrt{2}(T^1 + iT^2) \\ &= 4\left[(T^1)^2 + (T^2)^2\right] \\ &= 4\left[|\vec{T}|^2 - (T^3)^2\right] \\ &= 4\left[T(T+1) - (T^3)^2\right], \end{aligned}$$

- Contributions – in convention Q=T+Y

$$\begin{aligned} (\mathcal{D}_\mu X)^\dagger(\mathcal{D}^\mu X) \supset\ & X^\dagger \{g^2 W_\mu^+ W^{-\mu}\left[T(T+1) - Y^2\right] + g^2 W_\mu^3 W^{3\mu}(Y)^2 \\ & + g'^2 B_\mu B^\mu (Y)^2 - 2gg' B_\mu W^{3\mu}(Y)^2\} X. \end{aligned}$$

- 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 $\quad \bar{\theta}\, G^{\mu\nu}\tilde{G}_{\mu\nu} \quad (D=4) \quad \rightarrow \quad \bar{\theta} \lesssim 10^{-11}$
- EW naturalness $\quad \Lambda^2\, H^\dagger H \quad (D=2) \quad \rightarrow \quad \Lambda \approx 100\ \mathrm{GeV}$
- Cosmological constant $\quad \Lambda^4 \sqrt{g} \quad (D=0) \quad \rightarrow \quad \Lambda \approx 10^{-3}\ \mathrm{eV}$
- 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

2.1 Simplest scalar extensions

i) Real triplet T=1, Y=0 (VEV):

$$\Xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix} \to \begin{pmatrix} \xi^+ \\ \xi^0 + v_\xi \\ \xi^- \end{pmatrix}$$

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

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

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

$$M_\Xi^2 = v_\xi^2 \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

ii) Complex triplet T=1, Y=1 (VEV):

$$\langle X \rangle = \begin{pmatrix} 0 \\ 0 \\ v_\chi \end{pmatrix}$$

$$X = \begin{pmatrix} \chi^{++} \\ \chi^{+} \\ \chi^{0} \end{pmatrix} \to \begin{pmatrix} \chi^{++} \\ \chi^{+} \\ v_\chi + (h_\chi + i a_\chi)/\sqrt{2} \end{pmatrix}$$

$$(\mathcal{D}_\mu X)^\dagger (\mathcal{D}^\mu X) \supset g^2 v_\chi^2 W_\mu^+ W^{-\mu} + g^2 v_\chi^2 W_\mu^3 W^{3\mu} + g'^2 v_\chi^2 B_\mu B^\mu - 2 g g' v_\chi^2 B_\mu W^{3\mu}$$

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

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

the lower 2×2 block of this matrix is still diagonalized by the same weak mixing angle θ_W

does not generate the same masses for the W and Z in the limit $g' \to 0$

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 rotation symmetry

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 $v_\xi = v_\chi$

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

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

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

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

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," Nucl. Phys. B **262**, 463 (1985)

2.2 Two Higgs Doublet - 2HDM

the most explored benchmark model

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (h_1 + v_1 + i a_1)/\sqrt{2} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (h_2 + v_2 + i a_2)/\sqrt{2} \end{pmatrix}$$

- 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*-inv-ce, to cancel the unitarity growth

Most general non-SuSy 2HDM with CP conserving potential

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

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

$$\begin{aligned} \mathcal{V}_{2\mathrm{HDM}} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \\ & + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} . \end{aligned}$$

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

TABLE I. Four types of the charge assignment of the Z_2 symmetry.

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type-I	+	−	−	−	−	+
Type-II	+	−	−	+	+	+
Type-X	+	−	−	−	+	+
Type-Y	+	−	−	+	−	+

2.3 Custodial Triplet (GMM)

contains a singlet resonance that can take part in EWSB and still belong to a perturbative regime

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

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 $v_\phi^2 + 8v_\Delta^2 = v^2 = 1/\sqrt{2}\,G_F \simeq (246\,\mathrm{GeV})^2$

- C-W Chiang, A-L Kuo/1601.06394 **fit the 750 diphoton resonance with the Singlet of Custodial Triplet Model**

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

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

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

diagonalizes the adjoint rep of SU(2)

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

$$(\mathbf{2},\mathbf{2}) \sim \mathbf{1} \oplus \mathbf{3}, \text{ and } (\mathbf{3},\mathbf{3}) \sim \mathbf{1} \oplus \mathbf{3} \oplus \mathbf{5}$$

$SU(2)_C$ 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 3.6σ local excess in diphotons with invariant masses near $m_{\gamma\gamma} \sim 750$ GeV

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

[1] The ATLAS collaboration, ATLAS-CONF-2015-081.
[2] CMS Collaboration [CMS Collaboration], collisions at 13TeV," CMS-PAS-EXO-15-004.

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

[4] S. Knapen, T. Melia, M. Papucci and K. Zurek, arXiv:1512.04928 [hep-ph].
[5] R. S. Gupta, S. Jger, Y. Kats, G. Perez and E. Stamou, arXiv:1512.05332 [hep-ph].
[6] A. Falkowski, O. Slone and T. Volansky, arXiv:1512.05777 [hep-ph].

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

- **2HDMs cannot accomodate without additional massive particles**

A. Angelescu, A. Djouadi and G. Moreau, *Scenarii for interpretations of the LHC diphoton excess: two Higgs doublets and vector-like quarks and leptons*, [arXiv:1512.04921[hep-ph]]. 2

W. Altmannshofer, J. Galloway, S. Gori, A. L. Kagan, A. Martin and J. Zupan, *On the 750 GeV di-photon excess*, [arXiv:1512.07616[hep-ph]].

- **A need to go beyond purely scalar explanations**

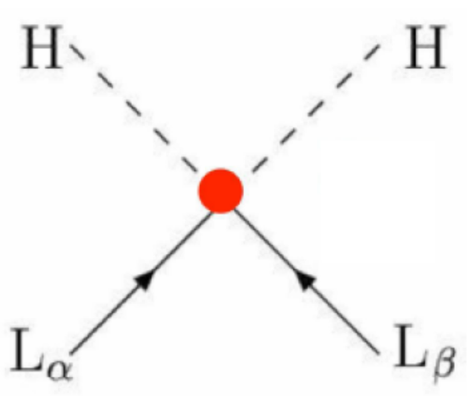
C. W. Murphy, *Vector Leptoquarks and the 750 GeV Diphoton Resonance at the LHC*, [arXiv:1512.06976[hep-ph]]. 2

3.2 Radiative Neutrino Models

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

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\lambda}{M}\underbrace{\bar{L}\tilde{H}\tilde{H}^T L^c}_{dim-5} + O(\frac{1}{M^2})$$

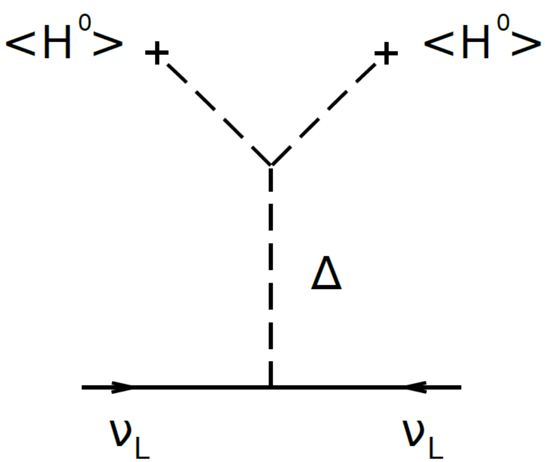
L_L — lepton doublet
H — Higgs boson doublet
M — heavy mass

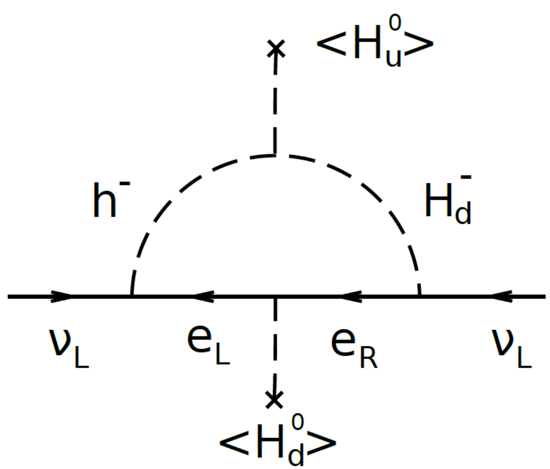


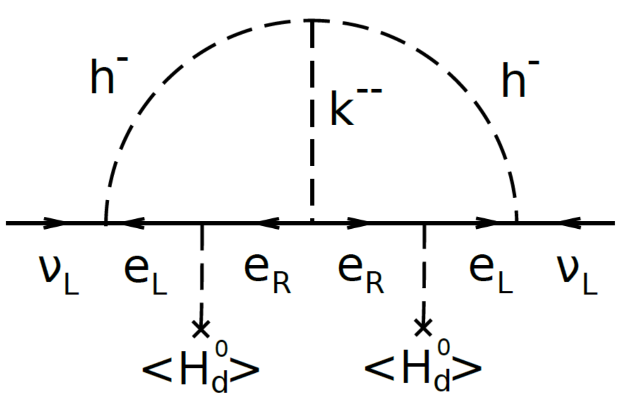
$$\langle H \rangle_0 = v \quad \longrightarrow \quad m_\nu \sim \lambda v \left(\frac{v}{M}\right)$$

Dim 5 op. in scalar extensions:
weak triplet w.r.t. 2nd doublet + charged scalars @ loop level

$(\ell\ell HH)/\Lambda$ $(\ell\ell\ell e^c H)/\Lambda^3$ $(\ell\ell\ell e^c \ell e^c)/\Lambda^5$







[Schechter, Valle (1980), Cheng, Li (1980), Lazarides, Shafi, Wetterich (1981), Mohapatra, Senjanovic (1981)]

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

[Zee (1986), Babu (1988)]

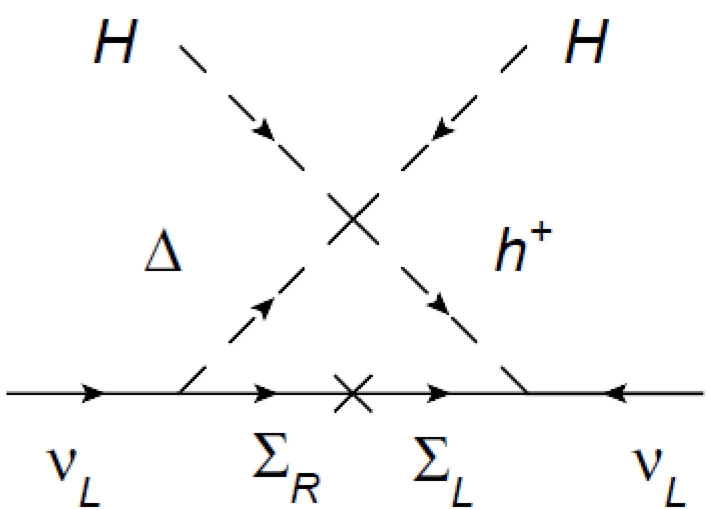
Radiative mass with real (Y=0) Triplet Scalar

BPR, PLB 728 (2014) 198

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

- **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**

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

- **The neutrino mass matrix**

$$\mathcal{M}_{ij} = \sum_{k=1}^{3} \frac{[(g_1)_{ik}(g_2)_{jk} + (g_2)_{ik}(g_1)_{jk}]}{8\pi^2} \lambda_7 \, v_H^2 \, M_{\Sigma_k} \frac{M_{\Sigma_k}^2 m_{h^+}^2 \ln \frac{M_{\Sigma_k}^2}{m_{h^+}^2} + M_{\Sigma_k}^2 m_{\Delta^+}^2 \ln \frac{m_{\Delta^+}^2}{M_{\Sigma_k}^2} + m_{h^+}^2 m_{\Delta^+}^2 \ln \frac{m_{h^+}^2}{m_{\Delta^+}^2}}{(m_{h^+}^2 - m_{\Delta^+}^2)(M_{\Sigma_k}^2 - m_{h^+}^2)(M_{\Sigma_k}^2 - m_{\Delta^+}{}^2)}$$

3.3 Inert-Scotogenic variants - as a link to DM problem

- **Scotogenic model with Z2 symmetry**

  V.Brdar, IP, B.Radovčić, 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 U(1)D gauge symm.**

  E.Ma, IP, B.Radovčić, PLB 726 (2013) 744

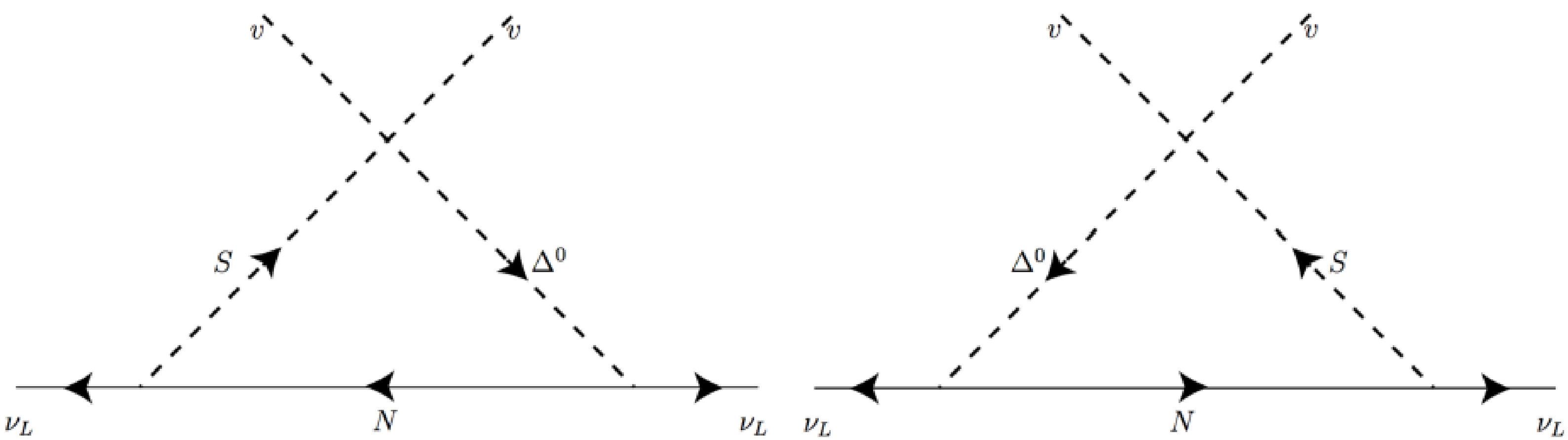
$$\Delta V(H, \Delta) = \lambda_8 (\Delta^\dagger \tau_a^{(3)} \Delta)^2 + \lambda_9 (H^\dagger \tau_a^{(2)} H)(\Delta^\dagger \tau_a^{(3)} \Delta)$$

Radiative mass with Y=2 Inert Triplet Scalar

- **Particle content**

H.Okada,Y.Orikasa: 1512.06687

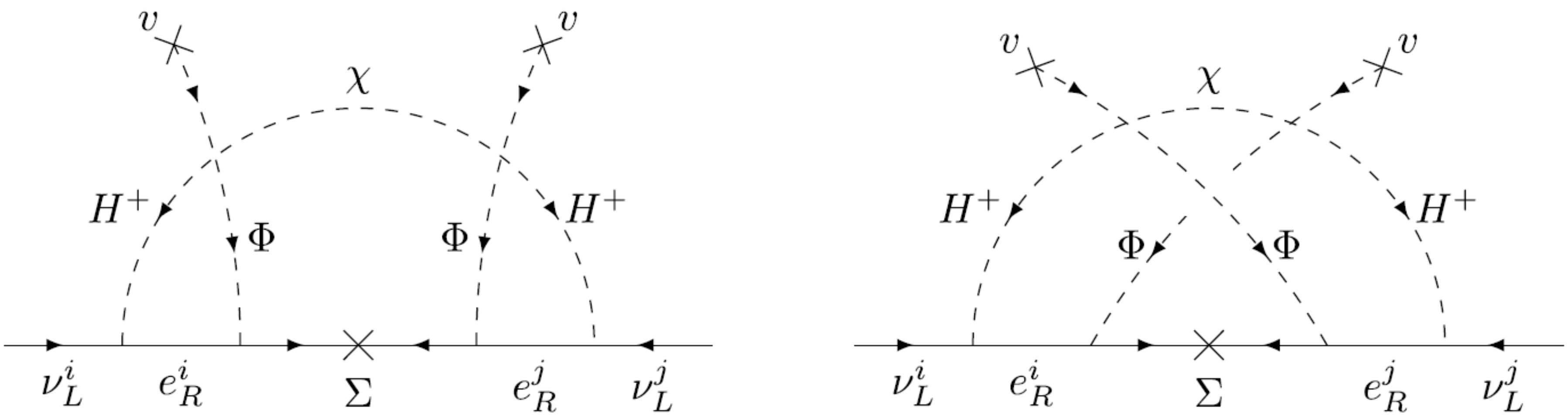
	Lepton Fields			Scalar Fields		
	L_L	e_R	L'	Φ	Δ	S
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{3}$	$\mathbf{1}$
$U(1)_Y$	$-1/2$	-1	$-1/2$	$1/2$	1	0
Z_2	$+$	$+$	$-$	$+$	$-$	$-$



Baroque Scotogenic Model

P.Čuljak, IP, K.Kumerički, PLB 744 (2015) 237

Three-loop RνMDM model



Yukawa interaction

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

$\tilde{Z}_2$-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

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

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

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

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

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

$$(H_{\mathbf{1}}, H_{\mathbf{2}}) \to (H_{\mathbf{1}}, -H_{\mathbf{2}})$$

In the "lepton-specific" (Type X or Type IV) model

$H_{\mathbf{2}}$ couples to all quarks whereas $H_{\mathbf{1}}$ couples to all leptons

	Q_i	u_{iR}	d_{iR}	L_{iL}	e_{iR}	$H_{\mathbf{1}}$	$H_{\mathbf{2}}$	Φ	χ	Σ_α
Z_2 accidental	+	+	+	+	+	+	+	−	−	−
$\tilde{Z}_2$ exact, imposed	+	−	−	+	+	+	−	+	−	+

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