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Non-Abelian $SU(2)_H$ and Two-Higgs Doublets

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Plea

- Please do not take any photo during the talk

- Please do not scoop us, publishing a similar paper on arXiv tomorrow

- Any comments or suggestions would be very appreciated

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Outline

- Motivation and model features
- Model setup: Higgs potential, Yukawa couplings and anomaly cancelation
- Spontaneous symmetry breaking and mass spectra of scalar and gauge bosons
- (Very) Preliminary results
- Conclusions and outlook

Motivation

- After the Standard Model (SM) Higgs discovery at the LHC, one could ask if there exist other scalar particles. Additionally, what is dark matter (DM) is and where does the tiny neutrino mass come from?

- Two Higgs doublets can naturally arise such as H_u and H_d in SUSY due to anomaly cancelation and SUSY chiral structure

- Two Higgs doublets can also provide an additional *CP* phase to realize observed baron asymmetry, which can not be accounted for in the SM

Motivation

- Out of many two Higgs doublet models, the inert two Higgs doublet model (IHDM) (Deshpande and Ma '78) provides a DM candidate, features simpler Higgs potential and Yukawa couplings because of an ad-hoc Z_2 symmetry

- IHDM also avoids flavor-changing-neutral-current due to the Z_2 symmetry

- However, the Z_2 symmetry is imposed by hand without justification

Model features

- We introduce extra gauge groups $SU(2)_H \otimes U(1)_X$ into the SM
- $SU(2)_L$ symmetry breaking can be induced by $SU(2)_H$ symmetry breaking
- One of Higgs doublets can be inert and its stability are protected by $SU(2)_H$
- Unlike Left-Right (LR) symmetric models (Mohapatra and Pati '75, Senjanovic and Mohapatra '75 '80), the complex gauge fields are electrically neutral
- Neutrinos would be Dirac fermions unless additional lepton number violation terms are involved

LR symmetric models versus SU(2)$_H$

$$U_L \begin{pmatrix} h_1^0 & h_2^+ \\ h_1^- & h_2^0 \end{pmatrix} U_R^\dagger$$

$$U_L \begin{pmatrix} h_1^0 & h_2^0 \\ h_1^- & h_2^- \end{pmatrix} U_R^\dagger \qquad U_R \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

$$U_R \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$U_R \begin{pmatrix} u_R \\ u_R^H \end{pmatrix} \qquad U_R \begin{pmatrix} d_R^H \\ d_R \end{pmatrix}$$

$W_R^\pm$ and Z_R

$W'^{\{p,m\}}$ and Z'

Particle contents

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
$Q_L = (u_L \;\; d_L)^T$	3	2	1	1/6	0
$U_R = (u_R \;\; u_R^H)^T$	3	1	2	2/3	1
$D_R = (d_R^H \;\; d_R)^T$	3	1	2	−1/3	−1
$L_L = (\nu_L \;\; e_L)^T$	1	2	1	−1/2	0
$N_R = (\nu_R \;\; \nu_R^H)^T$	1	1	2	0	1
$E_R = (e_R^H \;\; e_R)^T$	1	1	2	−1	−1
χ_u	3	1	1	2/3	0
χ_d	3	1	1	−1/3	0
χ_ν	1	1	1	0	0
χ_e	1	1	1	−1	0
$H = (H_1 \;\; H_2)^T$	1	2	2	1/2	1
$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$	1	1	3	0	0
$\Phi_H = (\Phi_1 \;\; \Phi_2)^T$	1	1	2	0	1

TABLE I. Matter field contents and their quantum number assignments.

- H_1 and H_2 are embedded into a $SU(2)_H$ doublet
- $SU(2)_L$ doublet fermions are singlets under SU(2) while $SU(2)_L$ singlet fermions pair up with heavy fermions as $SU(2)_H$ doublets
- VEVs of Φ_H and Δ_H give a mass to $SU(2)_H$ gauge bosons
- VEV of Φ_H gives a Dirac mass to heavy fermions

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$D_R = (d_R^H \;\; d_R)^T$	3	1	2	−1/3	−1
$L_L = (\nu_L \;\; e_L)^T$	1	2	1	−1/2	0
$N_R = (\nu_R \;\; \nu_R^H)^T$	1	1	2	0	1
$E_R = (e_R^H \;\; e_R)^T$	1	1	2	−1	−1
χ_u	3	1	1	2/3	0
χ_d	3	1	1	−1/3	0
χ_ν	1	1	1	0	0
χ_e	1	1	1	−1	0
$H = (H_1 \;\; H_2)^T$	1	2	2	1/2	1
$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$	1	1	3	0	0
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- VEVs of $\mathbf{\Phi}_H$ and $\mathbf{\Delta}_H$ give a mass to $SU(2)_H$ gauge bosons
- VEV of $\mathbf{\Phi}_H$ gives a Dirac mass to heavy fermions

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Higgs potential

$$V\left(H,\Delta_H,\Phi_H\right) = V(H) + V(\Phi_H) + V(\Delta_H) + V_{\text{mix}}\left(H,\Delta_H,\Phi_H\right)$$

$$\begin{aligned}
V(H) &= \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 \ , \\
&= \mu_H^2 \left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \lambda_H \left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 \ , \\
V(\Phi_H) &= \mu_\Phi^2 \Phi_H^\dagger \Phi_H + \lambda_\Phi \left(\Phi_H^\dagger \Phi_H\right)^2 \ , \\
&= \mu_\Phi^2 \left(\Phi_1^* \Phi_1 + \Phi_2^* \Phi_2\right) + \lambda_\Phi \left(\Phi_1^* \Phi_1 + \Phi_2^* \Phi_2\right)^2 \ , \\
V(\Delta_H) &= -\mu_\Delta^2 \operatorname{Tr}\left(\Delta_H^\dagger \Delta_H\right) + \lambda_\Delta \left(\operatorname{Tr}\left(\Delta_H^\dagger \Delta_H\right)\right)^2 \ , \\
&= -\mu_\Delta^2 \left(\frac{1}{2}\Delta_3^2 + \Delta_p \Delta_m\right) + \lambda_\Delta \left(\frac{1}{2}\Delta_3^2 + \Delta_p \Delta_m\right)^2 \ ,
\end{aligned}$$

$$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$$

$$\Delta_m = (\Delta_p)^* \ \text{and} \ (\Delta_3)^* = \Delta_3$$

Higgs potential

$$V(H,\Delta_H,\Phi_H) = V(H) + V(\Phi_H) + V(\Delta_H) + V_{\rm mix}(H,\Delta_H,\Phi_H)$$

$$\begin{aligned}
V_{\rm mix}(H,\Delta_H,\Phi_H) = & + M_{H\Delta}\left(H^\dagger \Delta_H H\right) - M_{\Phi\Delta}\left(\Phi_H^\dagger \Delta_H \Phi_H\right) \\
& + \lambda_{H\Delta}\left(H^\dagger H\right) \mathrm{Tr}\left(\Delta_H^\dagger \Delta_H\right) + \lambda_{H\Phi}\left(H^\dagger H\right)\left(\Phi_H^\dagger \Phi_H\right) \\
& + \lambda_{\Phi\Delta}\left(\Phi_H^\dagger \Phi_H\right) \mathrm{Tr}\left(\Delta_H^\dagger \Delta_H\right) , \\
= & + M_{H\Delta}\left(\frac{1}{\sqrt{2}} H_1^\dagger H_2 \Delta_p + \frac{1}{2} H_1^\dagger H_1 \Delta_3 + \frac{1}{\sqrt{2}} H_2^\dagger H_1 \Delta_m - \frac{1}{2} H_2^\dagger H_2 \Delta_3\right) \\
& - M_{\Phi\Delta}\left(\frac{1}{\sqrt{2}} \Phi_1^* \Phi_2 \Delta_p + \frac{1}{2} \Phi_1^* \Phi_1 \Delta_3 + \frac{1}{\sqrt{2}} \Phi_2^* \Phi_1 \Delta_m - \frac{1}{2} \Phi_2^* \Phi_2 \Delta_3\right) \\
& + \lambda_{H\Delta}\left(H_1^\dagger H_1 + H_2^\dagger H_2\right)\left(\frac{1}{2}\Delta_3^2 + \Delta_p \Delta_m\right) \\
& + \lambda_{H\Phi}\left(H_1^\dagger H_1 + H_2^\dagger H_2\right)\left(\Phi_1^* \Phi_1 + \Phi_2^* \Phi_2\right) \\
& + \lambda_{\Phi\Delta}\left(\Phi_1^* \Phi_1 + \Phi_2^* \Phi_2\right)\left(\frac{1}{2}\Delta_3^2 + \Delta_p \Delta_m\right) ,
\end{aligned}$$

- For simplicity, we neglect the effect of mixing λ's which do not lift the degeneracy between H_1 and H_2

$U(1)_X$ is introduced mainly to simplify the scalar potential

Higgs potential

- If $<\Delta_3>= -v_\Delta \neq 0$, the quadratic terms for H_1 and H_2 read:

$$\mu_H^2 \mp \frac{1}{2} M_{H\Delta} \cdot v_\Delta + \frac{1}{2}\lambda_{H\Delta} \cdot v_\Delta^2 + \frac{1}{2}\lambda_{H\Phi} \cdot v_\Phi^2$$

- If $<\Delta_3>= -v_\Delta \neq 0$, the quadratic terms for Φ_1 and Φ_2 read:

$$\mu_\Phi^2 \pm \frac{1}{2} M_{\Phi\Delta} \cdot v_\Delta + \frac{1}{2}\lambda_{\Phi\Delta} \cdot v_\Delta^2 + \frac{1}{2}\lambda_{H\Phi} \cdot v^2$$

➢ Therefore, $SU(2)_H$ spontaneous symmetry breaking can trigger $SU(2)_L$ symmetry breaking even if μ_H^2 is positive

Quark Yukawa couplings

- We choose to pair SM SU(2)$_L$ singlet fermions with heavy fermions to form SU(2)$_H$ doublets as

$$\mathcal{L}_{\rm Yuk} \supset y_d \bar{Q}_L \left(D_R \cdot H\right) + y_u \bar{Q}_L \left(U_R \cdot \tilde{H}\right) + {\rm H.c.},$$
$$= y_d \bar{Q}_L \left(d_R^H H_2 - d_R H_1\right) - y_u \bar{Q}_L \left(u_R \tilde{H}_1 + u_R^H \tilde{H}_2\right) + {\rm H.c.},$$

$$U_R^T = (u_R \; u_R^H)_{2/3}$$
$$D_R^T = (d_R^H \; d_R)_{-1/3}$$

- To give a mass to heavy fermions, we add "left-handed" partners with the help of the SU(2)$_H$ scalar doublet $\mathbf{\Phi}_H$:

$$\mathcal{L}_{\rm Yuk} \supset y_d' \overline{\chi}_d \left(D_R \cdot \Phi_H\right) + y_u' \overline{\chi}_u \left(U_R \cdot \tilde{\Phi}_H\right) + {\rm H.c.},$$
$$= y_d' \overline{\chi}_d \left(d_R^H \Phi_2 - d_R \Phi_1\right) - y_u' \overline{\chi}_u \left(u_R \tilde{\Phi}_1 + u_R^H \tilde{\Phi}_2\right) + {\rm H.c.},$$

$$\Phi_H = (\Phi_1 \; \Phi_2)^T$$

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Lepton Yukawa couplings

- Similarly, for the lepton sector we have:

$$\mathcal{L}_{\rm Yuk} \supset y_e \bar{L}_L \left(E_R \cdot H\right) + y_\nu \bar{L}_L \left(N_R \cdot \tilde{H}\right) + y'_e \overline{\chi}_e \left(E_R \cdot \Phi_H\right) + y'_\nu \overline{\chi}_\nu \left(N_R \cdot \tilde{\Phi}_H\right) + {\rm H.c.},$$
$$= y_e \bar{L}_L \left(e_R^H H_2 - e_R H_1\right) - y_\nu \bar{L}_L \left(\nu_R \tilde{H}_1 + \nu_R^H \tilde{H}_2\right)$$
$$+ y'_e \overline{\chi}_e \left(e_R^H \Phi_2 - e_R \Phi_1\right) - y'_\nu \overline{\chi}_\nu \left(\nu_R \tilde{\Phi}_1 + \nu_R^H \tilde{\Phi}_2\right) + {\rm H.c.},$$

where we introduce the right-handed neutrino and its $SU(2)_H$ partner, $N_R = \left(\nu_R \;\; \nu_R^H\right)^T$

- The SM neutrinos have only Dirac masses unless the Majorana mass is introduced such as:

$$\overline{N_R^c} \Delta_N N_R \rightarrow$$

where $U(1)_X$ is broken because N_R carries $U(1)_X$ charge

Anomaly cancellation

- The anomaly cancellation for the SM gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$ is guaranteed since addition heavy particles of the same hypercharge form Dirac pairs. Therefore, contributions of the left-handed currents from χ_u, χ_d, χ_ν and χ_e cancel those of right-handed ones from u_R^H, d_R^H, ν_R^H and e_R^H respectively.

- For $[SU(2)_H]^2 U(1)_Y$ from the doublets U_R, D_R, N_R and E_R with the following result, one has

$$\begin{aligned} 2\mathrm{Tr}[T^a\{T^b, Y\}] =& 2\delta^{ab}\left(\sum_l Y_l - \sum_r Y_r\right) = -2\delta^{ab}\sum_r Y_r \\ =& -2\delta^{ab}\left(3\cdot 2\cdot Y(U_R) + 3\cdot 2\cdot Y(D_R) + 2\cdot Y(N_R) + 2\cdot Y(E_R)\right) \end{aligned}$$

Anomaly cancellation

- In terms of $U(1)_X$, one has to check $[SU(3)_C]^2U(1)_X$, $[SU(2)_H]^2U(1)_X$, $[U(1)_X]^3$, $[U(1)_Y]^2U(1)_X$ and $[U(1)_X]^2U(1)_Y$. The first three terms are zero due to cancellation between U_R and D_R and between E_R and N_R with opposite $U(1)_X$ charges. For $[U(1)_Y]^2U(1)_X$ and $[U(1)_X]^2U(1)_Y$, one has respectively

$$2 \cdot \left(3 \cdot \left(Y(U_R)^2X(U_R) + Y(D_R)^2X(D_R)\right) + Y(E_R)^2X(E_R)\right)$$
$$2 \cdot \left(3 \cdot \left(X(U_R)^2Y(U_R) + X(D_R)^2Y(D_R)\right) + X(E_R)^2Y(E_R)\right).$$

- One can also check the perturbative gravitational anomaly associated with the hypercharge and $U(1)_X$-charge current couples to two gravitons is proportional to the following sum of the hypercharge

$$3 \cdot (2 \cdot Y(Q_L) + Y(\chi_u) + Y(\chi_d) - 2 \cdot Y(U_R) - 2 \cdot Y(D_R))$$
$$+2 \cdot Y(L_L) + Y(\chi_\nu) + Y(\chi_e) - 2 \cdot Y(N_R) - 2 \cdot Y(E_R),$$

and $U(1)_X$-charge

$$X(U_R) + X(D_R) + X(E_R) + X(N_R).$$

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Scalar mass spectrum

- First, we Taylor expand scalar fields around the vacua

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + iG^0 \end{pmatrix} \quad , \quad \Phi_H = \begin{pmatrix} G_H^p \\ \frac{v_\Phi+\phi_2}{\sqrt{2}} + iG_H^0 \end{pmatrix} \quad , \quad \Delta_H = \begin{pmatrix} \frac{-v_\Delta+\delta_3}{2} & \frac{1}{\sqrt{2}}\Delta_p \\ \frac{1}{\sqrt{2}}\Delta_m & \frac{v_\Delta-\delta_3}{2} \end{pmatrix}$$

$$H_2 = (H_2^+ \; H_2^0)^T$$

$\Psi_G \equiv \{G^+, G^0, G_H^p, G_H^0\}$ are Goldstone bosons

$\Psi \equiv \{h, H_2, \Phi_1, \phi_2, \delta_3, \Delta_p\}$ are the physical fields

➢ We have 6 Goldstone bosons, absorbed by 3 SM gauge bosons and 3 $SU(2)_H$ ones, yielding the massless photon and dark photon

- We have the mixing between $\{h, \delta_3, \phi_2\}$ and $\{G_H^p, \Delta_p, H_2^{0*}\}$ due to:

$$V_{\rm mix}(h, \delta_3, \phi_2) \supset + M_{H\Delta}\left(\frac{1}{2}H_1^\dagger H_1 \Delta_3\right) + \lambda_{H\Delta}\left(H_1^\dagger H_1\right)\left(\frac{1}{2}\Delta_3^2\right) + \lambda_{H\Phi}\left(H_1^\dagger H_1\right)\left(\Phi_2^*\Phi_2\right) + \lambda_{\Phi\Delta}\left(\Phi_2^*\Phi_2\right)\left(\frac{1}{2}\Delta_3^2\right) - M_{\Phi\Delta}\left(\frac{1}{2}\Phi_2^*\Phi_2\Delta_3\right)$$

$$V_{\rm mix}(G_H^p, \Delta_p, H_2^{0*}) \supset + M_{H\Delta}\left(\frac{1}{\sqrt{2}}H_1^\dagger H_2 \Delta_p + \frac{1}{\sqrt{2}}H_2^\dagger H_1 \Delta_m\right) - M_{\Phi\Delta}\left(\frac{1}{\sqrt{2}}\Phi_1^*\Phi_2\Delta_p + \frac{1}{\sqrt{2}}\Phi_2^*\Phi_1\Delta_m\right)$$

Scalar mass spectrum

- We have two mixing matrices for $\{h, \delta_3, \phi_2\}$ and $\{G_H^p, \Delta_p, H_2^{0*}\}$

$$\mathcal{M}_0^2 = \begin{pmatrix} 2\lambda_H v^2 & \frac{v}{2}\left(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta\right) & \lambda_{H\Phi} v v_\Phi \\ \frac{v}{2}\left(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta\right) & \frac{1}{4v_\Delta}\left(8\lambda_\Delta v_\Delta^3 + M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) & \frac{v_\Phi}{2}\left(M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta\right) \\ \lambda_{H\Phi} v v_\Phi & \frac{v_\Phi}{2}\left(M_{\Phi\Delta} - 2\lambda_\Phi v_\Delta\right) & 2\lambda_\Phi v_\Phi^2 \end{pmatrix}$$

$$\mathcal{M}_0'^2 = \begin{pmatrix} M_{\Phi\Delta} v_\Delta & -\frac{1}{2} M_{\Phi\Delta} v_\Phi & 0 \\ -\frac{1}{2} M_{\Phi\Delta} v_\Phi & \frac{1}{4v_\Delta}\left(M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) & \frac{1}{2} M_{H\Delta} v \\ 0 & \frac{1}{2} M_{H\Delta} v & M_{H\Delta} v_\Delta \end{pmatrix}$$

Scalar mass spectrum

- All VEVs are actually functions of the parameters in the scalar potential, where v is required to be 246 GeV and m_h=125 GeV

- The mixing of SM Higgs boson with δ_3 and ϕ_2 is suppressed by v/v_{Φ} , which turns out to be very small since $v_{\Phi} \gtrsim 10$ TeV from LEP constraints ⇒ satisfy LHC Higgs coupling measurements

$$\mathcal{M}_0^2 = \begin{pmatrix} 2\lambda_H v^2 & \frac{v}{2}\left(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta\right) & \lambda_{H\Phi} v v_\Phi \\ \frac{v}{2}\left(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta\right) & \frac{1}{4v_\Delta}\left(8\lambda_\Delta v_\Delta^3 + M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) & \frac{v_\Phi}{2}\left(M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta\right) \\ \lambda_{H\Phi} v v_\Phi & \frac{v_\Phi}{2}\left(M_{\Phi\Delta} - 2\lambda_\Phi v_\Delta\right) & 2\lambda_\Phi v_\Phi^2 \end{pmatrix}$$

$\{h, \delta_3, \phi_2\}$

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Scalar mass spectrum

- The determinant of the mass matrix is zero since one of the mass eigenstates and its complex conjugate correspond to the Goldstone bosons, eaten by $SU(2)_H$ W'

- For H_2^0 to be the DM candidate, one has to make sure it is lighter than its charged component $H_2^\pm$ of mass $M_{H\Delta}v_\Delta$

$$\mathcal{M}_0'^2 = \begin{pmatrix} M_{\Phi\Delta}v_\Delta & -\frac{1}{2}M_{\Phi\Delta}v_\Phi & 0 \\ -\frac{1}{2}M_{\Phi\Delta}v_\Phi & \frac{1}{4v_\Delta}\left(M_{H\Delta}v^2 + M_{\Phi\Delta}v_\Phi^2\right) & \frac{1}{2}M_{H\Delta}v \\ 0 & \frac{1}{2}M_{H\Delta}v & M_{H\Delta}v_\Delta \end{pmatrix}$$

$$\{G_H^p, \Delta_p, H_2^{0*}\}$$

Scalar mass spectrum

- The charged components of H_2 do not mix with other neutral scalars:

$$m_{H_2^\pm}^2 = M_{H\Delta} v_\Delta$$

- The rest is the Goldstone bosons:

$$m_{G^\pm}^2 = m_{G^0}^2 = m_{G_H^0}^2 = 0$$

Gauge boson mass spectrum

- We have 6 Goldstone bosons: 2 absorbed by SM W, 2 eaten by $SU(2)_H$ W' and the rest two by Z and Z'.

- The SM W bosons acquire a mass by eating the charged components of H_1 as in the SM since H_2 does not get a VEV and the other scalars ($\mathbf{\Phi}_H$ and $\mathbf{\Delta}_H$) are neutral

$$M_{W^\pm} = \frac{1}{2} g v$$

- $SU(2)_H$ W' bosons receive a mass from all VEVs, $\langle \mathbf{\Delta}_3 \rangle$, $\langle \mathbf{\Phi}_2 \rangle$ and $\langle H_1 \rangle$:

$$m^2_{W'(p,m)} = \frac{1}{4} g_H^2 \left(v^2 + v_\Phi^2 + 4 v_\Delta^2 \right)$$

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Gauge boson mass spectrum

- $\langle\mathbf{\Delta}_3\rangle$ gives a mass to $SU(2)_H$ W' bosons but not W'^3 while one linear combination of W'^3 and X obtains a mass from $\langle\mathbf{\Phi}_2\rangle$

- $\langle H_1\rangle$ also gives a mass to W'^3 and X because of its quantum numbers. Hence, W'^3 and X mix with the SM W_3 and Y.

$$\mathcal{M}_1^2 = \begin{pmatrix} \frac{g'^2 v^2}{4} & -\frac{g' g\, v^2}{4} & \frac{g' g_H v^2}{4} & \frac{g' g_X v^2}{2} \\ -\frac{g' g\, v^2}{4} & \frac{g^2 v^2}{4} & -\frac{g g_H v^2}{4} & -\frac{g g_X v^2}{2} \\ \frac{g' g_H v^2}{4} & -\frac{g g_H v^2}{4} & \frac{g_H^2 \left(v^2+v_\Phi^2\right)}{4} & \frac{g_H g_X \left(v^2-v_\Phi^2\right)}{2} \\ \frac{g' g_X v^2}{2} & -\frac{g g_X v^2}{2} & \frac{g_H g_X \left(v^2-v_\Phi^2\right)}{2} & g_X^2 \left(v^2+v_\Phi^2\right) \end{pmatrix}$$

Gauge boson mass spectrum

- The mass matrix contains 2 massive particles, identified as SM Z and additional Z' and also two massless photon γ and dark photon γ'

- γ' also couples to SM fermions and are thermally produced in the early universe. It would be excluded, for instance, by CMB observables

- There exist at least two solutions: Stueckelberg mass terms (Kors and Nath '04 '05) or setting g_X zero.

- In the following, we present preliminary results for the second solution.

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Gauge boson mass spectrum

- The 3-by-3 mass matrix can be diagonalized by only 2 mixing angles:

$$\begin{pmatrix} m_\gamma^2 & 0 & 0 \\ 0 & m_Z^2 & 0 \\ 0 & 0 & m_{Z'}^2 \end{pmatrix} = R_{23}\left(\theta_{ZZ'}\right)^T R_{12}\left(\theta_w\right)^T \begin{pmatrix} \frac{g'^2 v^2}{4} & -\frac{g' g\, v^2}{4} & \frac{g' g_H v^2}{4} \\ -\frac{g' g\, v^2}{4} & \frac{g^2 v^2}{4} & -\frac{g g_H v^2}{4} \\ \frac{g' g_H v^2}{4} & -\frac{g g_H v^2}{4} & \frac{g_H^2 \left(v^2 + v_\Phi^2\right)}{4} \end{pmatrix} R_{12}\left(\theta_w\right) R_{23}\left(\theta_{ZZ'}\right)$$

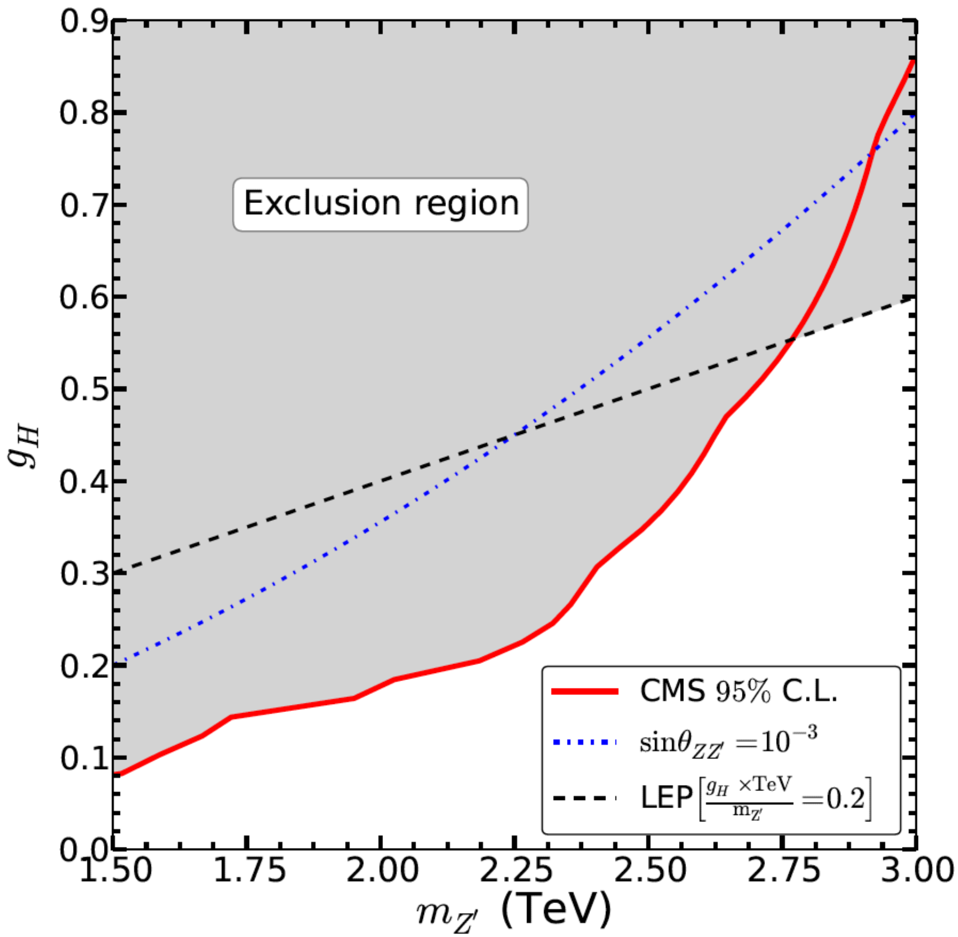
$$m_Z \simeq \sqrt{g^2 + g'^2}\frac{v}{2}$$

$$m_{Z'} \simeq g_H \frac{v_\Phi}{2}$$

$$\sin\theta_w = \frac{g'}{\sqrt{g^2 + g'^2}} \,,$$ Q= Y + I_3 is a good quantum number

$$\sin\theta_{ZZ'} \approx \frac{\sqrt{g^2 + g'^2}\, v^2}{g_H\, v_\Phi^2} \quad (\text{in the limit of } v_\Phi \gg v) \,,$$

Experimental constraints on Z’



- The red line comes from direct Z’ resonance searches (1412.6302)
- The black dashed line comes from LEP constraints on the cross-section of $e^+ e^- \to e^+ e^-$ (hep-ex/0312023) $\Rightarrow v_\Phi > 10$ TeV
- The blue dotted line comes from EWPT data and collider constraints on the Z-Z’ mixing(0906.2435, 1406.6776)

$$m_{Z'} \simeq g_H \frac{v_\Phi}{2}$$

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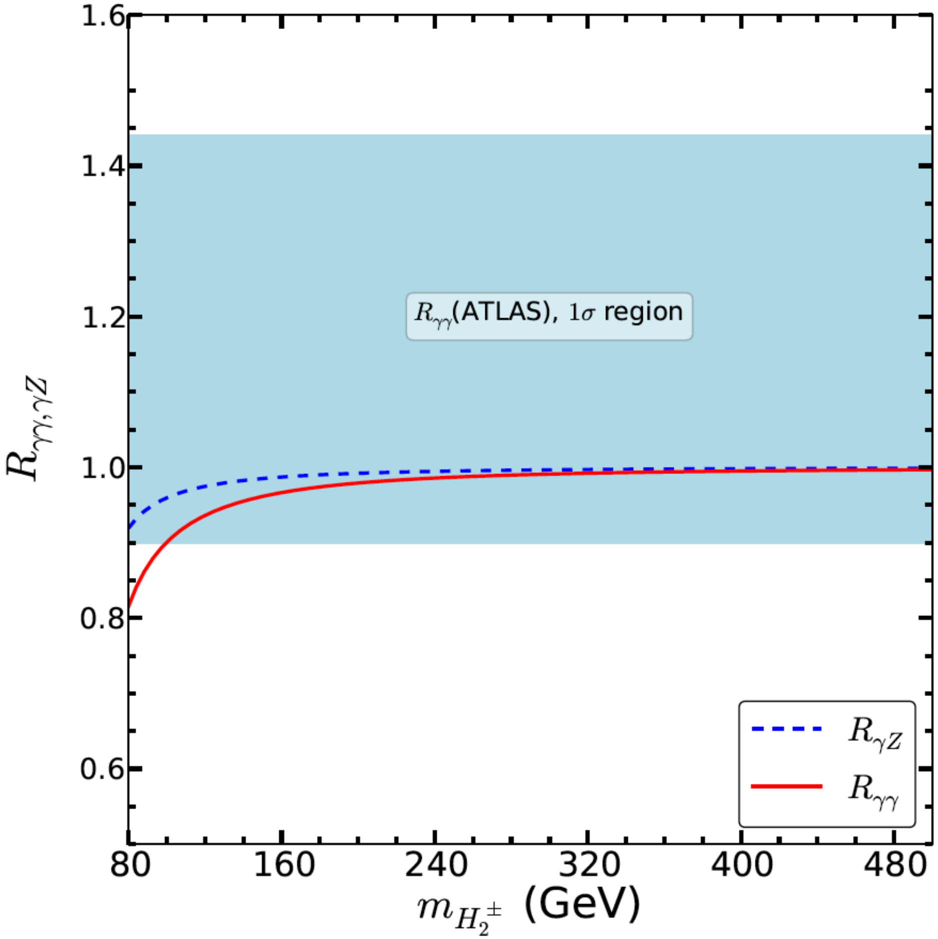
$h \to H_2^{\pm}$ loop $\to \gamma\gamma$ or $Z\gamma$



Predictions of $h \to \gamma\gamma$ and $h \to Z\gamma$ in this model. Due to the fact $\lambda_H (\approx m_h^2/2v^2)$ is positive, $R_{\gamma\gamma}$ is always less than the SM prediction while $R_{Z\gamma}$ ranges from 0.9 to 1, given the ATLAS and CMS measurements on $R_{\gamma\gamma}$:

CMS: 1.13 ± 0.24 and ATLAS: 1.17 ± 0.27 (1408.7084 and CMS-PAS-HIG-14-009 (2014)).

$$V(H) = \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 \,,$$
$$= \mu_H^2 \left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \lambda_H \left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 \,,$$

Conclusions and outlook

- We present the model with two Higgs doublets embedded into a doublet under the new non-abelian $SU(2)_H$ gauge group
- Spontaneous $SU(2)_H$ symmetry breaking triggers $SU(2)_L$ breaking
- The stability of H_2^0 as DM is protected by $SU(2)_H$ symmetry instead of the Z_2 symmetry
- Additional gauge bosons are all electrically neutral unlike Left-Right symmetric models

Conclusions and outlook

- The mixing between SM Higgs boson with heavy scalars are suppressed by a large $SU(2)_H$ VEV (v_Φ~ TeV)
- Z-Z' mixing are constrained to be small from various bounds which force v_Φ>10 TeV
- $h \rightarrow \gamma\gamma$ and $Z\gamma$ constraints are consistent with the LHC measurements as long as $H_2^\pm$ are heavier than 100 GeV
- DM phenomenology? Neutrino physics? Exact gauge boson mass spectrum with $g_X \neq 0$? Collider signatures? S T U?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