E_6SSM inspired 6-Higgs-Doublet Models

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EWSB in the Standard Model

The Brout-Englert-Higgs-Hagen-Kibble-Guralnik mechanism of EWSB requires one doublet of complex scalar fields:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

with the gauge invariant potential:

$$V = -\frac{1}{2}m^2(\Phi^\dagger\Phi) + \frac{1}{2}\lambda(\Phi^\dagger\Phi)^2$$

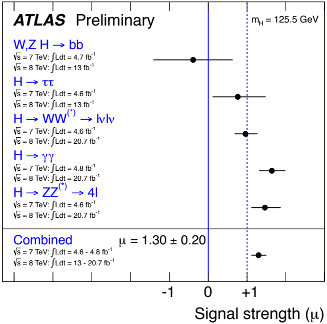
For positive m^2 it acquires a non-zero v.e.v.

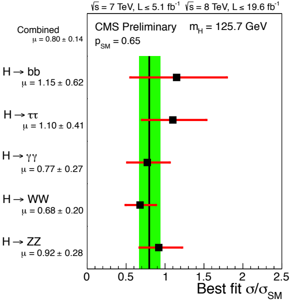
$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

The symmetry is spontaneously broken $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$

SMS discovery

There is evidence for an SM-like Scalar boson with mass 125 GeV:





Deviations from the SM hint at non-minimal Higgs sectors

Non-minimal Higgs sectors

- Many non-minimal Higgs sectors have been studied: [Accomando et al., arXiv:hep-ph/0608079]
- All BSM extensions have to abide to the existence of a Higgs boson at 125 GeV
- Typically these sectors involve several Higgs fields: IHDM (2 doublets), MSSM (2 doublets), E$_6$SSM (6 doublets)
- Many motivations for N-Higgs-Doublet models - the simplest BSM extensions
- Offer a richer particle spectrum with charged and neutral scalars - each of which could in principle be the scalar discovered at the LHC

Scalar sector in 2HDM

A second copy of the Higgs doublet

$$\Phi_\alpha = \begin{pmatrix} \phi_\alpha^+ \\ \frac{1}{\sqrt{2}}(\rho_\alpha + i\eta_\alpha) \end{pmatrix}, \qquad \alpha = 1,2$$

The most general $SU(2) \times U(1)$ scalar potential, has 14 free parameters:

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

- $m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4$ are real
- $m_{12}^2, \lambda_5, \lambda_6, \lambda_7$ can be complex → Explicit CPV

Symmetries of the scalar sector in 2HDM

All possible symmetry groups of 2HDM potential were found using geometrical approaches:

$$Z_2, \quad (Z_2)^2, \quad (Z_2)^3, \quad O(2), \quad O(2)\times Z_2, \quad O(3)$$

class	symmetry	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	n
I	U(2)		m_{11}^2	0		λ_1		$\lambda_1-\lambda_3$	0	0	0	3
II	CP3		m_{11}^2	0		λ_1			$\lambda_1-\lambda_3-\lambda_4$	0	0	4
III	CP2		m_{11}^2	0		λ_1					$-\lambda_6$	5
IV	U(1)			0					0	0	0	6
V	Z_2			0						0	0	7
VI	CP1			real					real	real	real	8

[Ivanov, Phys.Rev.D75 (2007)]

Inert Higgs Doublet Model

A Z_2-symmetric 2HDM with one inert doublet

$$\Phi_a = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{pmatrix}, \quad \Phi_i = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + iA^0\right) \end{pmatrix}$$

The most general scalar potential:

$$\begin{aligned} V \;=\; & -|\mu_1^2|(\Phi_a^\dagger\Phi_a) + \mu_2^2(\Phi_i^\dagger\Phi_i) + \lambda_1(\Phi_a^\dagger\Phi_a)^2 + \lambda_2(\Phi_i^\dagger\Phi_i)^2 \\ & +\lambda_3(\Phi_a^\dagger\Phi_a)(\Phi_i^\dagger\Phi_i) + \lambda_4(\Phi_a^\dagger\Phi_i)(\Phi_i^\dagger\Phi_a) + \frac{1}{2}\lambda_5\left[(\Phi_a^\dagger\Phi_i)^2 + h.c.\right] \end{aligned}$$

All the parameters in this potential can be chosen real

This potential is symmetric under the Z_2 group

$$\Phi_a \to \Phi_a \qquad \Phi_i \to -\Phi_i \qquad\qquad g = \frac{2i\pi}{2}(0,1)$$

Dark Matter candidate in IHDM

The active and inert doublets

$$\Phi_a = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{pmatrix}, \quad \Phi_i = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + iA^0\right) \end{pmatrix}$$

• The v.e.v. alignment $(v, 0)$ leaves the Z_2 symmetry with generator $(0, 1)$ unbroken

• All other SM fields are even under this Z_2 group $\rightarrow$ Z_2 is conserved after EWSB

• DM candidate: the neutral CP-even state from the inert doublet, H^0 - stabilised by the conserved Z_2 symmetry

[Ma, et.al, Phys.Rev.D18,2574 (1978)], [Krawczyk, et.al, Phys.Rev.D72,115013 (2005)]

N-Higgs-Doublet models

N copies of the Higgs doublet with identical electroweak quantum numbers:

$$\phi_a = \begin{pmatrix} \phi_a^+ \\ \phi_a^0 \end{pmatrix} \qquad a = 1, \ldots, N$$

Many specific variants of NHDM for $N \geq 3$ have been suggested;

- Weinberg's 3HDM

[Weinberg,et al. Phys.Rev.D15,1958 (1977)], [Paschos, Phys.Rev.D15,1966 (1977)]

- Adler's 3HDM - 6HDM

[Adler, Phys.Rev.D60,015002 (1999)]

- Zee's private Higgs model

[Zee,et al., Phys.Lett.B666,491 (2008)]

The focus is usually on the fermion mass matrices. The scalar sector has been barely explored yet.

Symmetries of the scalar sector in NHDM

The most general scalar potential in NHDM contains $\frac{N^2(N^2+3)}{2}$ free parameters:

$$V = Y_{ab}(\phi_a^\dagger \phi_b) + Z_{abcd}(\phi_a^\dagger \phi_b)(\phi_c^\dagger \phi_d)$$

All Abelian symmetry groups in NHDM

[Keus, et al., J.Phys.A 45,215201 (2012)]

All finite symmetry groups in 3HDM

[Ivanov, et al., Eur.Phys.J.C 73,2309 (2013)]

Symmetry groups with triplet representations in 3HDM

[Ma, et al., Phys.Lett.B 552, (2003)], [Altarelli, et al., Nucl.Phys.B 720, (2005)]
[Lam, Phys.Rev.Lett. 101, (2008)], [Morisi, et al., Phys.Rev.D 80, (2009)]
[King, et al., Phys.Lett.B 687, (2010)]

List of symmetries in 3HDM

- Continuous Abelian symmetry groups

$$U(1), \quad U(1) \times U(1), \quad U(1) \times Z_2$$

- Finite Abelian symmetry groups

$$Z_2, \quad Z_3, \quad Z_4, \quad Z_2 \times Z_2$$

- Finite non-Abelian unitary symmetry groups

$$D_6, \quad D_8, \quad T \simeq A_4, \quad O \simeq S_4$$
$$(Z_3 \times Z_3) \rtimes Z_2 \simeq \Delta(54)/Z_3, \quad (Z_3 \times Z_3) \rtimes Z_4 \simeq \Sigma(36)$$

- Finite non-Abelian anti-unitary symmetry groups

$$Z_2^*, \quad Z_4^*, \quad Z_2 \times Z_2^*, \quad Z_2 \times Z_2 \times Z_2^*, \quad Z_3 \rtimes Z_2^* \simeq D_6$$
$$Z_4 \rtimes Z_2^* \simeq D_8 \quad D_6 \times Z_2^*, \quad D_8 \times Z_2^*, \quad A_4 \rtimes Z_2^* \simeq T_d$$
$$S_4 \times Z_2^* \simeq O_h \quad (Z_3 \times Z_3) \rtimes (Z_2 \times Z_2^*), \quad \Sigma(36) \rtimes Z_2^*$$

We aim to study these symmetries in 6HDMs

Particle content of E_6SSM

The Exceptional Supersymmetric Standard Model is based on the $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ gauge group, a subgroup of E_6.

The particle content involves three fundamental 27 representations of E_6:

$$E_6 \to SU(5) \times U(1)_N \to SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$$

$$\underbrace{\left(10, \frac{1}{\sqrt{40}}\right)_i}_{Q_i, u_i^c, e_i^c} \oplus \underbrace{\left(5^*, \frac{2}{\sqrt{40}}\right)_i}_{d_i^c, L_i} \oplus \underbrace{\left(5^*, -\frac{3}{\sqrt{40}}\right)_i}_{H_{iu}, \overline{D}_i} \oplus \underbrace{\left(5, -\frac{2}{\sqrt{40}}\right)_i}_{H_{id}, D_i} \oplus \underbrace{\left(1, \frac{5}{\sqrt{40}}\right)_i}_{S_i} \oplus \underbrace{(1,0)_i}_{N_i^c}$$

The family index i runs from 1 to 3.

The Higgs sector in E_6SSM

The E_6SSM contains 6 Higgs doublets, with the same quantum numbers as the SM Higgs doublet, grouped into 3 doublets of doublets:

$$\begin{pmatrix} H_{iu} \\ H_{id} \end{pmatrix} \quad i = 1,2,3, \qquad \text{where} \quad H_{iu} = \begin{pmatrix} H_{iu}^{+} \\ H_{iu}^{0} \end{pmatrix}, \quad H_{id} = \begin{pmatrix} H_{id}^{+} \\ H_{id}^{0} \end{pmatrix}$$

and 3 Higgs singlets:

$$S_1, \quad S_2, \quad S_3$$

- Two of the doublets are active: $\langle H_{3u} \rangle = \langle H_{3d} \rangle = v$
- The other four are inert: $\langle H_{1u} \rangle = \langle H_{1d} \rangle = \langle H_{2u} \rangle = \langle H_{2d} \rangle = 0$
- The v.e.v alignment: $(0,0,0,0,v,v)$

Z_2^H symmetry in E$_6$SSM

To suppress the FCNCs arising from extra Higgs doublets, a Z_2^H symmetry is imposed on the superpotential, under which:

	H_{1u}	H_{1d}	H_{2u}	H_{2d}	H_{3u}	H_{3d}
Z_2^H	$+$	$+$	$+$	$+$	$-$	$-$

• The lightest CP-even neutral field from the inert doublets, is a viable dark matter candidate:

$$H_{1u} = \begin{pmatrix} H_{1u}^+ \\ \frac{1}{\sqrt{2}}(H_{1u}^0 + iA_{1u}^0) \end{pmatrix}$$

• H_{1u}^0 is stabilised by Z_2^H, and does not couple to fermions

Symmetric 3HDMs → symmetric 6HDMs

- Extending all 3HDM symmetries to 6HDM, by treating each doublet as a doublet of doublets:

$$\Phi_\alpha = \begin{pmatrix} H_{\alpha u} \\ H_{\alpha d} \end{pmatrix} \qquad i = 1, 2, 3$$

- Avoiding extra massless particles by adding an MSSM-inspired term:

$$\mu'^2 \left(H_{1u}^\dagger H_{1d} + H_{2u}^\dagger H_{2d} + H_{3u}^\dagger H_{3d} \right) + h.c.$$

We study the v.e.v alignment $(0, 0, 0, 0, v, v)$, and pick the CP-even neutral scalar from the first doublet to be the DM candidate

The DM is protected by either the original symmetry of the potential or the remnant of the symmetry after EWSB

Constructing a Z_2-symmetric 6HDM

A Z_p-symmetric potential has two parts:

$$V = V_0 + V_{Z_p}$$

where V_0 is invariant under any phase rotation, and V_{Z_p} is a collection of extra terms which ensure the chosen symmetry group

The most general phase invariant 6HDM potential:

$$V_0 = \sum_{i=1}^{6}\left[-|\mu_i^2|(\Phi_i^\dagger\Phi_i) + \lambda_{ii}(\Phi_i^\dagger\Phi_i)^2\right] + \sum_{i,j=1}^{6}\left[\lambda_{ij}(\Phi_i^\dagger\Phi_i)(\Phi_j^\dagger\Phi_j) + \lambda'_{ij}(\Phi_i^\dagger\Phi_j)(\Phi_j^\dagger\Phi_i)\right]$$

Constructing a Z_2-symmetric 6HDM

To reduce the number of parameters in the phase invariant part of the potential, we impose an $SO(4) \times SO(6)$ symmetry

$$
\begin{aligned}
V_0 \quad = \quad & -|\mu_a^2|(\Phi_a^\dagger \Phi_a) + \mu_i^2(\Phi_i^\dagger \Phi_i) \\
& +\lambda_a(\Phi_a^\dagger \Phi_a)^2 + \lambda_i(\Phi_i^\dagger \Phi_i)^2 \\
& +\lambda_{ai}(\Phi_a^\dagger \Phi_a)(\Phi_i^\dagger \Phi_i) + \lambda'_{ai}(\Phi_a^\dagger \Phi_i)(\Phi_i^\dagger \Phi_a)
\end{aligned}
$$

where Φ_is are the inert doublets and Φ_as are the active doublets (IHDM-like)

Constructing a Z$_2$-symmetric 6HDM

The construction of the V_{Z_2} part depends on the generator

$$g^{E_6SSM-like} = \mathrm{diag}\left(-1,-1,-1,-1,1,1\right)$$

$$V'_{Z_2} = \lambda_1\left[(H^\dagger_{1u}+H^\dagger_{1d}+H^\dagger_{2u}+H^\dagger_{2d})(H_{3u}+H_{3d})\right]^2 + h.c.$$

Or

$$g^{IHDM-like} = \mathrm{diag}\left(-1,1,1,1,1,1\right)$$

$$\begin{aligned} V_{Z_2} \quad = \quad & \lambda_1\left[H^\dagger_{1u}(H_{1d}+H_{2u}+H_{2d})\right]\left[(H^\dagger_{3u}+H^\dagger_{3d})H_{1u}\right] \\ & +\lambda_2\left[(H^\dagger_{1d}+H^\dagger_{2u}+H^\dagger_{2d})(H_{3u}+H_{3d})\right]^2 + h.c. \end{aligned}$$

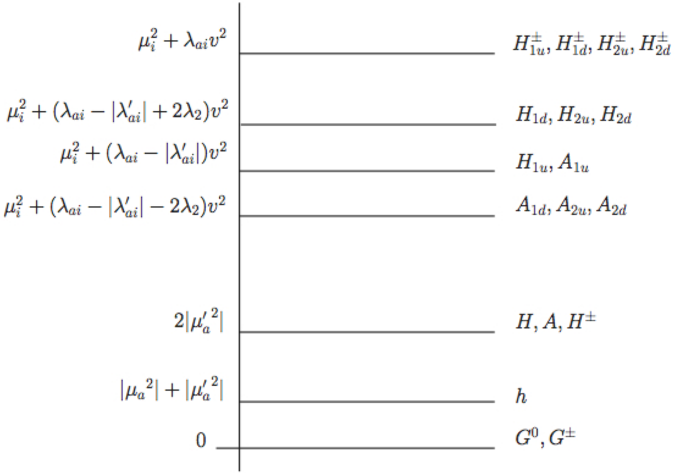
The IHDM-like scalar potential

The CP-conserving potential has 9 free parameters:

$$
\begin{aligned}
V \;=\; & -|\mu_a^2|\Big(|H_{3u}|^2+|H_{3d}|^2\Big)+\mu_i^2\Big(|H_{1u}|^2+|H_{1d}|^2+|H_{2u}|^2+|H_{2d}|^2\Big)\\
& +\mu_a'^2\Big(H_{3u}^\dagger H_{3d}+H_{3d}^\dagger H_{3u}\Big)\\
& +\lambda_a\Big(|H_{3u}|^2+|H_{3d}|^2\Big)^2+\lambda_i\Big(|H_{1u}|^2+|H_{1d}|^2+|H_{2u}|^2+|H_{2d}|^2\Big)^2\\
& +\lambda_{ai}\Big[(|H_{3u}|^2+|H_{3d}|^2)(|H_{1u}|^2+|H_{1d}|^2+|H_{2u}|^2+|H_{2d}|^2)\Big]\\
& +\lambda'_{ai}\Big[|H_{3u}^\dagger H_{1u}|^2+|H_{3u}^\dagger H_{1d}|^2+|H_{3u}^\dagger H_{2u}|^2+|H_{3u}^\dagger H_{2d}|^2\\
& \qquad +|H_{3d}^\dagger H_{1u}|^2+|H_{3d}^\dagger H_{1d}|^2+|H_{3d}^\dagger H_{2u}|^2+|H_{3d}^\dagger H_{2d}|^2\Big]\\
& +\lambda_1\Big[(H_{1u}^\dagger H_{1d}+H_{1u}^\dagger H_{2u}+H_{1u}^\dagger H_{2d})(H_{3u}^\dagger H_{1u}+H_{3d}^\dagger H_{1u})\Big]\\
& +\lambda_2\Big[H_{1d}^\dagger H_{3u}+H_{1d}^\dagger H_{3d}+H_{2u}^\dagger H_{3u}+H_{2u}^\dagger H_{3d}+H_{2d}^\dagger H_{3u}+H_{2d}^\dagger H_{3d}\Big]^2+h.c.
\end{aligned}
$$

The scalar mass spectrum

The mass eigenstates with $v^2 = |\mu_a^2|/(2\lambda_a + \lambda_5)$



Higgs boson couplings

The physical Higgses:

$$h = \frac{H^0_{3u} + H^0_{3d}}{\sqrt{2}}, \qquad H = \frac{H^0_{3u} - H^0_{3d}}{\sqrt{2}}$$

have the gauge couplings:

$$g^{hVV} = g^{h_{SM}VV}, \qquad g^{HVV} = 0$$

and the Yukawa couplings are TypeII-2HDM-like:

$$\xi_h^{u,d,l} = \frac{\cos\alpha}{\sin\beta}, \quad -\frac{\sin\alpha}{\cos\beta}, \quad -\frac{\sin\alpha}{\cos\beta}$$
$$\xi_H^{u,d,l} = \frac{\sin\alpha}{\sin\beta}, \quad \frac{\cos\alpha}{\cos\beta}, \quad \frac{\cos\alpha}{\cos\beta}$$
$$\xi_A^{u,d,l} = \cot\beta, \quad \tan\beta, \quad \tan\beta$$

with $\beta = -\alpha = \frac{\pi}{4}$

Production channels

The new particles are produced through:

$$pp \to W^{\mp *} \to H^{\pm}_{1u} A^0_{1u} \quad \text{or} \quad H^{\pm}_{1u} H^0_{1u}$$

$$pp \to W^{\mp *} \to H^{\pm}_{1d,2u,2d} A^0_{1d,2u,2d} \quad \text{or} \quad H^{\pm}_{1d,2u,2d} H^0_{1d,2u,2d}$$

$$pp \to Z^*(\gamma^*) \to H^0_{1d,2u,2d} A^0_{1d,2u,2d}$$

The fields from the first doublet have different production (and decay) rates from the fields from the other inert doublets

And similar to the IHDM:

$$pp \to W^{\mp *} \to H^{\pm} A \quad \text{or} \quad H^{\pm} H$$

$$pp \to Z^*(\gamma^*) \to HA \quad \text{or} \quad H^+ H^-$$

Signals

The new fields could affect the width of the SM Higgs:

$$h \to A^0_{1u,1d,2u,2d} A^0_{1u,1d,2u,2d}$$

$$H^0_{1u,1d,2u,2d} H^0_{1u,1d,2u,2d} \to h$$

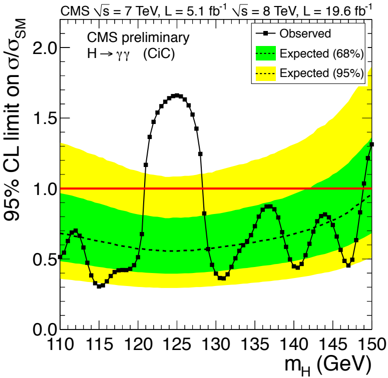
$$H^-_{1u,1d,2u,2d} H^+_{1u,1d,2u,2d} \to h$$

As well as the following channels, similar to the IHDM case

$$h \to AA,\, GG,\, G^\pm G^\pm$$

Signals

The charged scalars from extra doublets contribute the the $h \to \gamma\gamma$ plot through loops



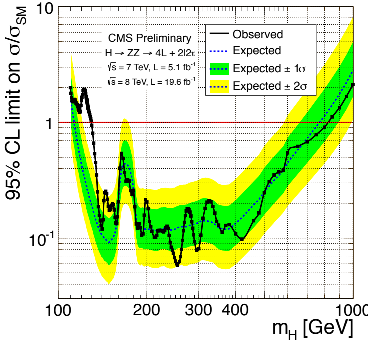
Signals

With $v_1 = v_2 \to \beta = -\alpha = \frac{\pi}{4}$ therefore:

$$g^{hVV} = g^{h_{SM}VV}, \quad g^{HVV} = 0$$

In the case of $v_1 \neq v_2$:

$$g^{hVV} : g^{SM}\sin(\beta-\alpha), \qquad g^{HVV} : g^{SM}\cos(\beta-\alpha)$$



Dark matter annihilation channels to SM particles

The dark matter candidate, H^0_{1u} can (co)annihilate through the following channels:

- to gauge boson final states:

$$H^0_{1u}H^0_{1u} \to W^+W^-, ZZ \qquad H^0_{1u}H^\pm_{1u} \to hW^\pm, ZW^\pm$$

- to Higgs final states:

$$H^0_{1u}H^0_{1u} \to hh$$

$$H^0_{1u}H^0_{1u} \to h^* \to hh$$

- to fermion anti-fermion final states:

$$H^0_{1u}H^0_{1u} \to h^* \to f\bar{f}$$

$$H^0_{1u}H^\pm_{1u} \to W^{\pm *} \to f\bar{f}$$

Dark matter annihilation channels to BSM particles

H^0_{1u} also (co)annihilates through the following channels:

$$H^0_{1u}H^0_{1u} \to HH,\, AA,\, H^0_{1d,2u,2d}H^0_{1d,2u,2d},\, A^0_{1u,1d,2u,2d}A^0_{1u,1d,2u,2d}$$

$$H^0_{1u}H^0_{1u} \to H^+H^-,\, H^+_{1u,1d,2u,2d}H^-_{1u,1d,2u,2d}$$

$$H^0_{1u}h \to H^0_{1u}H^0_{1d,2u,2d},\, A^0_{1u}A^0_{1d,2u,2d},\, H^\pm_{1u}H^\mp_{1d,2u,2d}$$

$$H^0_{1u}G \to H^0_{1u}A^0_{1d,2u,2d},\, H^0_{1d}A^0_{1u,2u,2d},\, H^\pm_{1u}H^\mp_{1d,2u,2d}$$

$$H^0_{1u}G^\pm \to H^\pm_{1u}H^0_{1d,2u,2d},\, H^\pm_{1d}A^0_{1d,2u,2d}$$

Summary and outlook

N-Higgs-doublet models are among popular extensions of the Standard Model.

Inspired by the E_6SSM, we study the complete list of symmetries realizable in 3HDMs extended to 6HDMs.

We simplify the problem of defining the parameter space, by imposing extra symmetries on the doublets.

Using common tools (HiggsBounds, HiggsSignals, 2HDMc) we are studying the constraint on the model, and the characteristics of each symmetry pattern.

Outlook

These models contain viable dark matter candidates. Exploring the observational consequences, relic abundance, the sensitivity of the evolution of Universe to the exact microscopic dynamics is among interesting directions of research.

Having explored the scalar sector, one would extend the symmetry to the fermionic sector. Family symmetries A_4 and S_4 have been studied and predict large θ_{13}.

Adding 3 higgs singlets to the story, helps studying the scalars sector of E$_6$SSM which contains 3 singlets as well as 6 doublets.

Thank you for your attention!

Back up slides

The μ-problem

The MSSM superpotential:

$$W = y_u \overline{u} Q H_u + y_d \overline{d} Q H_d + y_e \overline{e} L H_d + \mu H_u H_d$$

Minimization of Higgs potential results in:

$$\frac{1}{2} m_Z^2 = -|\mu^2| + m_{H_d}^2 - \frac{m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1}$$

where $m_{H_d}^2$ and $m_{H_u}^2$ are soft SUSY breaking Higgs mass parameters

One expects μ to be of the soft SUSY breaking order ~ 1 TeV

But the μ-term is SUSY preserving $\Rightarrow$ μ is of the M_{Pl} order

Solving the μ-problem

- A common way to solve this problem is to introduce a scalar S:

$$\lambda_s S H_u H_d \qquad \text{where} \qquad < S >= \frac{s}{\sqrt{2}} \quad \sim m_{soft} \quad \sim \ 1 \text{ TeV}$$

A new global $U(1)$ symmetry has been introduced and broken, resulting in a massless axion

- NMSSM: A cubic term S^3 is added, breaking the $U(1) \to Z_3$, which could lead to cosmological domain walls and overclosure of the Universe

- USSM: The $U(1)$ is gauged and a massive Z' appears, but the theory is not anomaly free

- E_6SSM: The gauged $U(1)$ is a remnant of a broken E_6. Anomaly cancellation is ensured by having particles in complete 27 representations of E_6 at the TeV scale

Scalar sector in 2HDM

A second copy of the Higgs doublet

$$\Phi_\alpha = \begin{pmatrix} \phi_\alpha^+ \\ \frac{1}{\sqrt{2}}(\rho_\alpha + i\eta_\alpha) \end{pmatrix}, \qquad \alpha = 1,2$$

The most general $SU(2) \times U(1)$ scalar potential, has 14 free parameters:

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

- $m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4$ are real
- $m_{12}^2, \lambda_5, \lambda_6, \lambda_7$ can be complex → Explicit CPV

Scalar sector in 2HDM

In general, minimizing the potential gives

$$< \Phi_1 >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad < \Phi_2 >= \frac{1}{\sqrt{2}} \begin{pmatrix} u_2 \\ v_2 e^{i\xi_2} \end{pmatrix}$$

- Non-zero u_2 $\rightarrow$ Charge-breaking vacuum
- Non-zero ξ_2 $\rightarrow$ Spontaneous CPV

A common basis choice

$$< \Phi_1 >= \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \cos\beta \end{pmatrix}, \quad < \Phi_2 >= \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin\beta \end{pmatrix}, \qquad \tan\beta = \frac{v_2}{v_1}$$

where $v = (\sqrt{2} G_F)^{-1/2} \approx 246$ GeV , with $0 \leq \beta \leq \pi/2$

Scalar sector in 2HDM

We define

$$\Phi_n = \begin{pmatrix} \phi_n^+ \\ \frac{1}{\sqrt{2}}(v_n + \rho_n + i\eta_n) \end{pmatrix}, \qquad n = 1, 2$$

with $v_1 = v\cos\beta, \quad v_2 = v\sin\beta$

The neutral Goldstone boson and the physical pseudo-scalar state

$$G^0 = \eta_1 \cos\beta + \eta_2 \sin\beta, \quad A = -\eta_1 \sin\beta + \eta_2 \cos\beta$$

And the physical scalars

$$h = -\rho_1 \sin\alpha + \rho_2 \cos\alpha, \quad H = \rho_1 \cos\alpha + \rho_2 \sin\alpha$$

with $-\pi/2 \leq \alpha \leq \pi/2$.

The independent variables of the model are $\tan\beta$ and $\sin\alpha$ which are single valued in the allowed regions

Different types of 2HDM

To avoid the FCNCs resulted from the extra doublets, a Z_2 symmetry is imposed on the scalar doublets

$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$$

and a corresponding symmetry to the fermions, leading to four types

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

[Branco,et al., Phys.Rept.516 (2012)]

Fermion and gauge couplings

The fermion couplings normalized to their SM values:

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

And the gauge couplings:

$$g^{hVV} : g^{SM}\sin(\beta-\alpha), \qquad g^{HVV} : g^{SM}\cos(\beta-\alpha)$$