Exploring Multi-Higgs Doublet Models

Theory, Simulation, and Phenomenology of Extended Higgs Sectors

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Overview

- Motivation
- The Standard Model (SM)
- Two Higgs Doublet Model (2HDM)
- Three Higgs Doublet Model (3HDM)
- Simulation Framework
- Results: Branching Ratio (BR), $\sigma \times$BR, exclusion maps (2HDM vs 3HDM)
- Conclusions

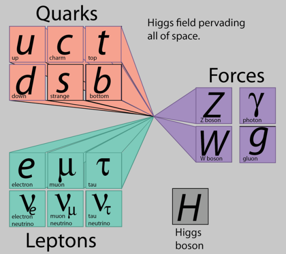
Motivation

Why extend the Higgs sector?

- The SM is extremely successful but leaves several phenomena unexplained:
  - Neutrino masses
  - Baryon asymmetry of the Universe
  - Dark matter (no viable SM candidate)

- Extended scalar sectors (2HDM, 3HDM, ...) provide:
  - Additional scalar states that could be discovered at colliders
  - New sources of CP violation (helpful for baryogenesis)
  - Possible dark-matter candidates (depending on symmetry)

The Standard Model (SM)



Source: [1]

- **Gauge symmetry:**
  $SU(3)_C \times SU(2)_L \times U(1)_Y$
- **Particle content:**
  - 3 generations of quarks and leptons
  - Gauge bosons: $W^{\pm}$, Z, γ and gluons
  - **One Higgs boson**
- SM contains only one Higgs doublet
  $\Phi = (\phi^{+}, \phi^{0})^{T}$

One Higgs — is that the whole story?

or could there be more scalars?

Electroweak Symmetry Breaking in the SM

- SM forbids explicit masses for fermions and gauge bosons due to $SU(2)_L \times U(1)_Y$ gauge symmetry.
- **Scalar potential:**

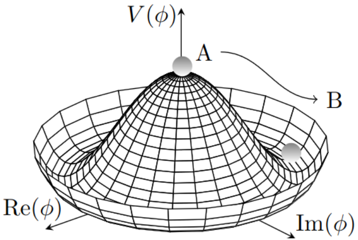
$$V(\Phi) = \mu^2\,\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2, \qquad \mu^2 < 0$$

- Spontaneous symmetry breaking (SSB) when

$$\langle\phi^0\rangle = \frac{v}{\sqrt{2}}$$

- Higgs doublet expansion:

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\,w^+ \\ v + h + iz\end{pmatrix}$$



Higgs potential showing SSB.

One physical scalar remains: the 125 GeV Higgs boson

2HDM Overview

Motivation

- Preserves the electroweak ρ parameter ($\rho \approx 1$) at tree level.
- Naturally accommodates the Alignment Limit.

Scalar Content

- Two Higgs doublets: Φ_1 and Φ_2
- 5 physical Higgs bosons
  - CP-even: h (SM-like in alignment limit), H
  - CP-odd: A
  - Charged: $H^{\pm}$

VEV Structure

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

Alignment Limit

The alignment limit is the regime where one neutral Higgs scalar has couplings identical to those of the Standard Model Higgs boson.

$$\alpha = \beta$$

where α is the mixing angles of CP-even sector.[2]

2HDM: Scalar Potential (CP-conserving)

CP-Conservation: All parameters (m_{ij}^2, λ_i) are taken to be real.

Z$_2$-Symmetric Scalar Potential:

$$V = m_{11}^2\, \Phi_1^\dagger \Phi_1 + m_{22}^2\, \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right] .$$

Key Features

- Z_2 symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$.
- Soft-breaking term: proportional to m_{12}^2.

2HDM Yukawa Sector and Z_2 Structure

Yukawa Structure

- Two Higgs doublets allow tree-level Flavor-Changing Neutral Currents(FCNCs).
- A Z_2 symmetry ensures that there is only one Yukawa matrix for each fermion.

Model	Φ_1	Φ_2	u_R	d_R	e_R
Type I	$+$	$-$	$-$	$-$	$-$
Type II	$+$	$-$	$-$	$+$	$+$
Lepton-spec.	$+$	$-$	$-$	$-$	$+$
Flipped	$+$	$-$	$-$	$+$	$-$

Z_2 assignments define the four 2HDM types and remove tree-level FCNC.

Z2HDM Yukawa Lagrangian

$$\mathcal{L}_Y = -\sum_{i,j=1}^{3}\Big[(Y_u)_{ij}\,\overline{Q}_{iL}\tilde{\Phi}_2 u_{jR} + (Y_d)_{ij}\,\overline{Q}_{iL}\Phi_1 d_{jR} + (Y_\ell)_{ij}\,\overline{L}_{iL}\Phi_1 \ell_{jR}\Big] + \text{h.c.}$$

where $i, j = 1, 2, 3$ are generation (flavor) indices, $\tilde{\Phi}_2 = i\sigma_2\Phi_2^*$ and σ_2 is a Pauli matrix.

3HDM Overview

Scalar Content

- Three $SU(2)_L$ doublets $\Rightarrow$ 9 physical Higgs states:
- CP-even: h (lightest, SM-like in alignment), H_1, H_2
- CP-odd: A_1, A_2
- Charged: $H_1^{\pm}$, $H_2^{\pm}$

VEV Structure

$$v_1 = v\cos\beta_1\cos\beta_2, \quad v_2 = v\sin\beta_1\cos\beta_2, \quad v_3 = v\sin\beta_2$$

Alignment Limit

$$\alpha_1 = \beta_1, \qquad \alpha_2 = \beta_2 \quad \Rightarrow \quad h \text{ is SM-like [2]}$$

where α_1 and α_2 are the mixing angles of CP-even sector.

3HDM Scalar Potential with Z_3 Symmetry

Field transformation:

$$\Phi_1 \to \Phi_1, \qquad \Phi_2 \to \omega\,\Phi_2, \qquad \Phi_3 \to \omega^2\,\Phi_3, \quad \omega = e^{2\pi i/3}.$$

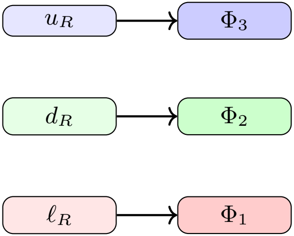
Scalar Potential

$$\begin{aligned}
V_{Z_3} = {} & m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) + m_{33}^2(\Phi_3^\dagger\Phi_3) \\
& - \left[m_{12}^2(\Phi_1^\dagger\Phi_2) + m_{23}^2(\Phi_2^\dagger\Phi_3) + m_{13}^2(\Phi_1^\dagger\Phi_3) + \text{h.c.}\right] \\
& + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_3^\dagger\Phi_3)^2 \\
& + \lambda_4(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_5(\Phi_1^\dagger\Phi_1)(\Phi_3^\dagger\Phi_3) + \lambda_6(\Phi_2^\dagger\Phi_2)(\Phi_3^\dagger\Phi_3) \\
& + \lambda_7(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \lambda_8(\Phi_1^\dagger\Phi_3)(\Phi_3^\dagger\Phi_1) + \lambda_9(\Phi_2^\dagger\Phi_3)(\Phi_3^\dagger\Phi_2) \\
& + \left[\lambda_{10}(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_3) + \lambda_{11}(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_3) + \lambda_{12}(\Phi_3^\dagger\Phi_1)(\Phi_3^\dagger\Phi_2) + \text{h.c.}\right].
\end{aligned}$$

- three soft-breaking terms $(m_{12}^2, m_{23}^2, m_{13}^2)$.

Yukawa Structure: The Type-Z Model

$\mathbf{Z}_3$ symmetry assigns each fermion type to a different Higgs doublet, leading to a unique Type-Z (democratic) Yukawa structure with Natural Flavor Conservation.



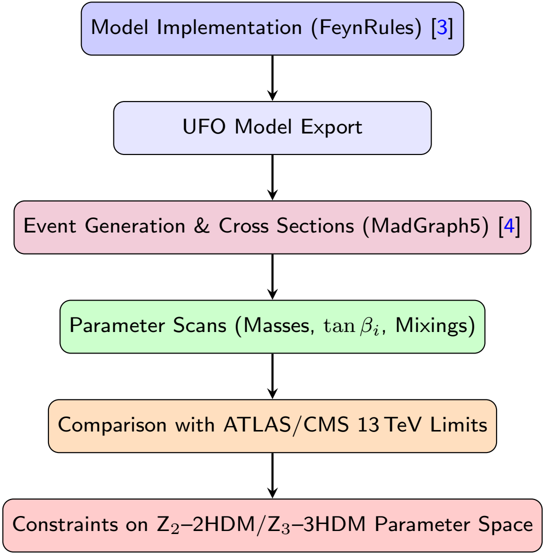
Each fermion type couples to a different Higgs doublet (unique to 3HDM).

Z3HDM Yukawa Lagrangian

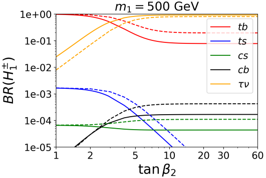
$$\mathcal{L}_Y = -\sum_{i,j=1}^{3}\left[(y_u)_{ij}\,\overline{Q}_{iL}\,\tilde{\Phi}_3\,u_{jR} + (y_d)_{ij}\,\overline{Q}_{iL}\,\Phi_2\,d_{jR} + (y_\ell)_{ij}\,\overline{L}_{iL}\,\Phi_1\,\ell_{jR}\right] + \text{h.c.}$$

where $i, j = 1, 2, 3$ are generation (flavor) indices, and $\tilde{\Phi}_3 = i\sigma_2\Phi_3^*$.

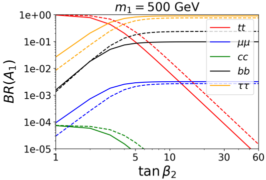
Simulation Framework and Parameter Scans



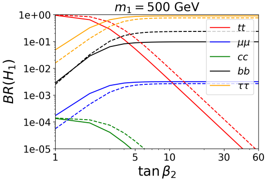
3HDM: Branching Ratios of Heavy Higgs bosons



$H_1^\pm$ Decay Channels



A_1 Decay Channels

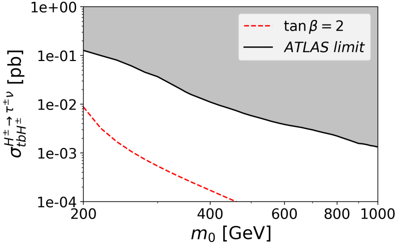


H_1 Decay Channels

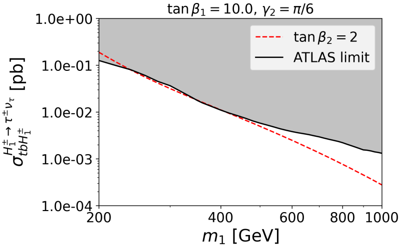
Parameters: $m_{H_1^\pm} = m_{H_1} = m_{A_1} = m_1; \quad m_{H_2^\pm} = m_{H_2} = m_{A_2} = m_2 = 5\,\mathrm{TeV};$
$\tan\beta_1 = 10; \quad \gamma_1 = \gamma_2 = -\alpha_3 = \alpha = \pi/6, \pi/4$ [5]

- Two free VEV ratios and mixing angle choices enable richer variation in branching ratios compared to 2HDM.
- Solid($\alpha = \pi/6$)/dashed($\alpha = \pi/4$) curves show the impact of mixing angle on decay patterns.

Exclusion Limits from $\tau\nu$ Channel



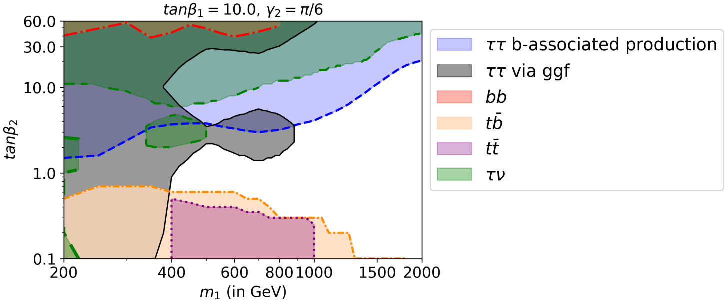
2HDM



3HDM

- Dashed lines show model predictions for $\tan\beta$ (2HDM) or $\tan\beta_2$ (3HDM) values
- ATLAS experimental limits are shaded.[6]
- For 2HDM, exclusion depends strongly on $\tan\beta$; for 3HDM, additional dependence on mixing angles and $\tan\beta_2$ provides more flexibility.

3HDM Parameter Exclusion from LHC Searches



Mass Range

$m_1 = 200\,\mathrm{GeV} - 2000\,\mathrm{GeV}$
$\tan\beta_2 = 0.1 - 60$
$\tan\beta_1 = 10$
$\alpha = \pi/6$

Mass Hierarchy

$m_{H_1^\pm} = m_{H_1} = m_{A_1} = m_1$
$m_{H_2^\pm} = m_{H_2} = m_{A_2} = m_2 = 5\,\mathrm{TeV}$ [5]

- Exclusion contours based on direct LHC search constraints.[7][8][9][10]

Conclusion

- Multi-Higgs models offer rich physics beyond the SM.
- 2HDM provides a minimal, testable extension with controlled FCNC.
- 3HDM introduces exotic signatures and expanded parameter space.

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Backup 2HDM

Mixing Angles and Mass Eigenstates

- After EWSB: **Higgs Doublets**

$$\Phi_i = \begin{pmatrix} \omega_i^{\pm} \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix}, \qquad i = 1, 2$$

  Each doublet contributes:
  - One charged field: $\omega_i^{\pm}$
  - One CP-even neutral field: h_i
  - One CP-odd neutral field: z_i
- The CP-even fields (h_1, h_2) mix with angle α via the mass matrix:

$$M^2_{\text{CP-even}} = \begin{pmatrix} M^2_{11} & M^2_{12} \\ M^2_{12} & M^2_{22} \end{pmatrix}$$

- Diagonalized by a rotation through angle α:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

- $\tan\beta = v_2/v_1$ defines the ratio of VEVs — rotation in the Higgs doublet space.

Backup: 2HDM — Higgs Doublets and Mass Spectrum

Mass terms after EWSB

$$V_{\rm mass} = (z_1\ z_2)\,\frac{M_P^2}{2}\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} + (\omega_1^+\ \omega_2^+)\,\frac{M_C^2}{2}\begin{pmatrix} \omega_1^- \\ \omega_2^- \end{pmatrix} + (h_1\ h_2)\,\frac{M_S^2}{2}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Goldstone isolation and mixing

- One neutral Goldstone (G^0) and one charged Goldstone ($G^\pm$) are eaten by Z and $W^\pm$.
- Use O_β to rotate into the Higgs basis:

$$D_P^2 = O_\beta M_P^2 O_\beta^T, \quad D_C^2 = O_\beta M_C^2 O_\beta^T$$

leading to $\mathrm{diag}(0, m_A^2)$ and $\mathrm{diag}(0, m_{H^\pm}^2)$.

Full diagonalization

$$D_S^2 = O_\alpha M_S^2 O_\alpha^T, \qquad D_S^2 = \mathrm{diag}(m_H^2, m_h^2)$$

Physical states

$$(G^0,\ A)^T = O_\beta (z_1, z_2)^T,$$

$$(G^\pm,\ H^\pm)^T = O_\beta (\omega_1^\pm, \omega_2^\pm)^T,$$

$$(H,\ h)^T = O_\alpha (h_1, h_2)^T$$

Notes

- The soft term m_{12}^2 prevents an additional Goldstone boson (ensures one CP-odd state A acquires mass).
- β defines the direction of EWSB: $\tan\beta = v_2/v_1$.
- α diagonalizes the CP-even sector.
- In the alignment limit ($\alpha = \beta$), h is SM-like.
- Electroweak precision fits prefer nearly degenerate heavy scalars: $m_H \simeq m_A \simeq m_{H^\pm}$.

backup: 3HDM — Mass Spectrum

mass terms

$$V_{\text{mass}} = (z_1\ z_2\ z_3)\,\frac{M_P^2}{2}\begin{pmatrix} z_1 \\ z_2 \\ z_3 \end{pmatrix} + (\omega_1^+\ \omega_2^+\ \omega_3^+)\,\frac{M_C^2}{2}\begin{pmatrix} \omega_1^- \\ \omega_2^- \\ \omega_3^- \end{pmatrix} + (h_1\ h_2\ h_3)\,\frac{M_S^2}{2}\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

Goldstones & block-diagonalization

- One neutral and one charged Goldstone ($\zeta,\ G^\pm$) are eaten by $Z, W^\pm$.
- Use O_β to isolate Goldstone direction: $B_P^2 = O_\beta M_P^2 O_\beta^T$ (similarly for M_C^2).
- B_P^2 and B_C^2 take the form $\mathrm{diag}(0,\ *_{2\times 2})$ after this rotation.

Full diagonalization

$$D_P^2 = O_{\gamma_1}\, B_P^2\, O_{\gamma_1}^T \quad , \quad D_C^2 = O_{\gamma_2}\, B_C^2\, O_{\gamma_2}^T \quad , \quad D_S^2 = O_\alpha\, M_S^2\, O_\alpha^T$$

$$D_P^2 = \mathrm{diag}(0, m_{A_1}^2, m_{A_2}^2), \quad D_C^2 = \mathrm{diag}(0, m_{H_1^\pm}^2, m_{H_2^\pm}^2), \quad D_S^2 = \mathrm{diag}(m_h^2, m_{H_1}^2, m_{H_2}^2)$$

Physical states

$$(\,\zeta,\ A_1,\ A_2\,)^T = O_{\gamma_1}\, O_\beta\, (z_1, z_2, z_3)^T,$$

$$(\,G^\pm,\ H_1^\pm,\ H_2^\pm\,)^T = O_{\gamma_2}\, O_\beta\, (\omega_1^\pm, \omega_2^\pm, \omega_3^\pm)^T,$$

$$(\,h,\ H_1,\ H_2\,)^T = O_\alpha\, (h_1, h_2, h_3)^T.$$

Notes

- Soft-breaking masses $m_{12}^2, m_{13}^2, m_{23}^2$ shift non-SM scalar masses upward (avoid extra Goldstones).
- In the alignment limit ($\alpha_1 = \beta_1,\ \alpha_2 = \beta_2$) the light state h is SM-like.