Two Higgs Doublet Models

Theoretical Overview

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Motivation for 2HDM

Why not?

The scalar sector is much more minimal than other sectors.

SUSY

Requires two Higgs doublets.
MSSM special case of one 2HDM

Dark Matter

Stable Higgs boson as DM?
Some models for dark matter candidates, e.g. axion models include two Higgs doublets

CP-violation

Needed to explain matter antimatter assymmetry.
Can have CP-violation in extended scalar sector

General Theory

Scalar sector constrained from parameter
ρ – experimentally close to one

$$\rho = \frac{\sum_{i=1}^{n}\left(I_i(I_i+1) - \frac{1}{4}Y_i^2\right)v_i}{\sum_{i=1}^{n}\frac{1}{2}Y_i^2 v_i}$$

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Introduce additional SU(2) doublet

$$Y_i = +1 \qquad I(I+1) = \frac{3}{4}Y^2$$

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix} \qquad a = 1, 2$$

Neutral scalars: h, H
Neutral pseudoscalar: A
2 charged scalars: $H^{\pm}$

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2HDM potential

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

- In CP-conserving case
- Couplings are real

General Theory

2HDM potential

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

→

Both doublets acquire a nonzero vev:

$$\langle \Phi_i \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_i}{\sqrt{2}} \end{pmatrix} \quad v_{SM} = \sqrt{v_1^2 + v_2^2}$$

General Theory

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Diagonalize mass matrices, mass eigenstates:

$$\alpha, \beta \qquad \tan\beta = \frac{v_2}{v_1}$$

Charged: $$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

CP-even: $$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

Pseudoscalar: $$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

General Theory

Theoretical Constraints

Perturbativity:

$$|\lambda_i| \leq 4\pi$$

Vacuum stability:

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_3 \geq -\sqrt{\lambda_1 \lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1 \lambda_2}$$

General Theory

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FCNC

Yukawa couplings not simultaneously diagonalizable

$$\mathcal{L}_Y = y^1_{ij} \bar{\psi}_i \psi_j \Phi_1 + y^2_{ij} \bar{\psi}_i \psi_j \Phi_2$$

2HDMs have tree-level FCNC
Heavily constrained by experiment

→ Avoid by introducing $\mathbb{Z}_2$ symmetries

Models

Type I 2HDM $\Phi_1 \to -\Phi_1$

No Yukawa couplings to first doublet

Model	u_R	d_R	e_R
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Inert	Φ_1	Φ_1	Φ_1

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Type II 2HDM $\Phi_1 \to -\Phi_1 \quad d_R \to -d_R$

Down type fermions and leptons couple to first doublet.
MSSM is a special case

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Lepton-specific 2HDM

Leptons couple to first Higgs doublet

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Lepton-specific 2HDM

Leptons couple to first Higgs doublet

Inert 2HDM $\langle\Phi_1\rangle_0 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \langle\Phi_2\rangle_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$

Second doublet has zero vev

→ DM candidate as lightest neutral scalar of inert doublet

Model	u_R	d_R	e_R
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
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Models
Couplings to SM particles

- Yukawa couplings depend on α and β
- Model dependent

$$\mathcal{L}_Y = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i\xi_A^f \bar{f}\gamma_5 f A\right) - \left(\frac{\sqrt{2}V_{ud}}{v}\bar{u}(m_u \xi_A^u P_L + m_d \xi_A^d P_R) d H^+ \frac{\sqrt{2} m_\ell \xi_A^\ell}{v} \overline{\nu_L} \ell_R H^+ + h.c.\right)$$

	Type I	Type II	Lepton-specific
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_h^l	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^l	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$
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- Couplings of neutral scalars to WW and ZZ are the same in all models

h: Multiply SM coupling with sin(β – α)
H: Multiply SM coupling with cos(β – α)
A: no coupling

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Alignment limit

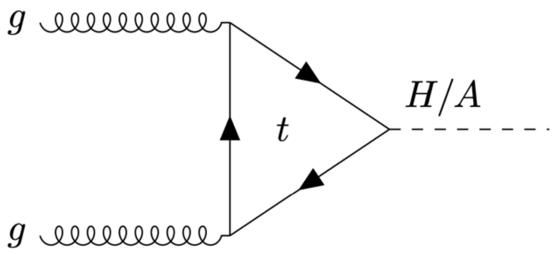
$\cos(\beta - \alpha) = 0$ SM Higgs = h

$\cos(\beta - \alpha) = 1$ SM Higgs = H

Experimental Signatures

Phenomenology varies between models, many free parameters and depend on masses and α and β

Similar to the SM Higgs, the dominant production mode for neutral Higgs bosons is ggF



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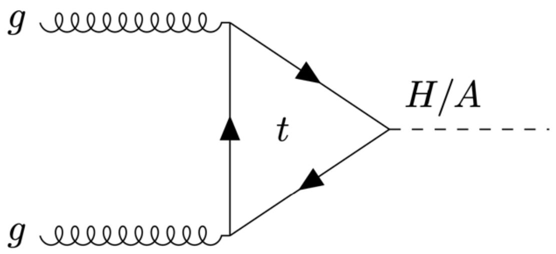
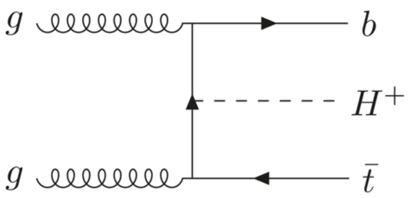
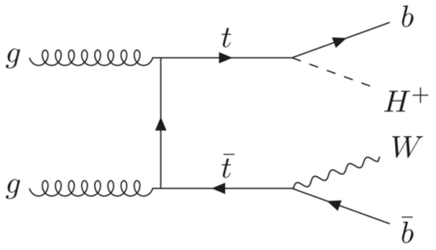


Charged Higgs bosons produced through ggF and from top quark decays





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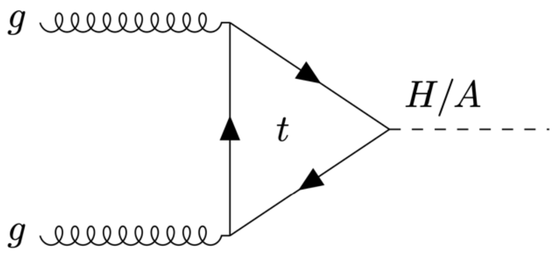

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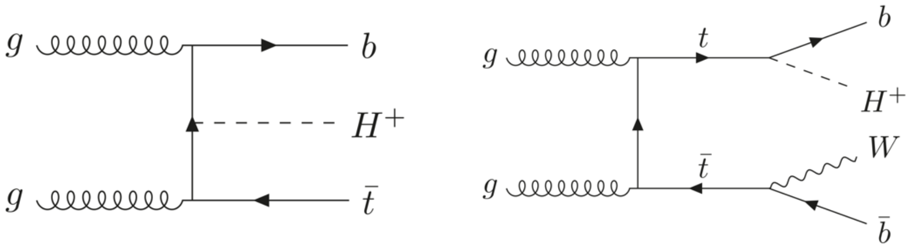


ATLAS and CMS have searched for additional neutral scalars in many decay channels

Experimental Signatures

Decays of neutral Higgs bosons

$$H/A \to f\bar{f}$$

- Largest branching ratio to the heaviest available fermion pair
- Search for decays into t, b, τ and μ
- No distinction between CP-even and CP-odd scalar – Degenerate masses

$$H \to W^+W^-,\ ZZ,\ \gamma\gamma,\ Z\gamma$$

- Not favored for pseudoscalar – CP conservation

$$A \to ZH,\ Zh \qquad H \to hh$$

- Assuming $m_A > m_H$

Experimental Signatures

Decays of charged Higgs bosons

$H^+ \to \tau^+ \nu_\tau \quad H^+ \to t\bar{b}$

- Decay into tau relevant for large mass range
- If allowed tb channel will dominate

$H^+ \to W^+ Z$

- Enhanced in certain models

Experimental Signatures

Decays of charged Higgs bosons

$$H^+ \to \tau^+ \nu_\tau \quad H^+ \to t\bar{b}$$

- Decay into tau relevant for large mass range
- If allowed tb channel will dominate

$$H^+ \to W^+ Z$$

- Enhanced in certain models

Searches have been carried out by the experiments considering many different final states

Have they found any additional scalars?

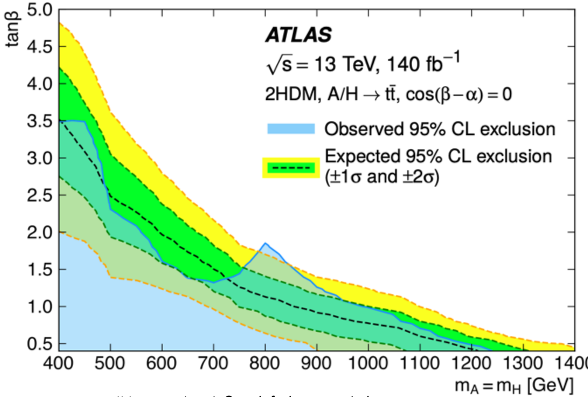
Experimental constraints

Phenomenology model dependent

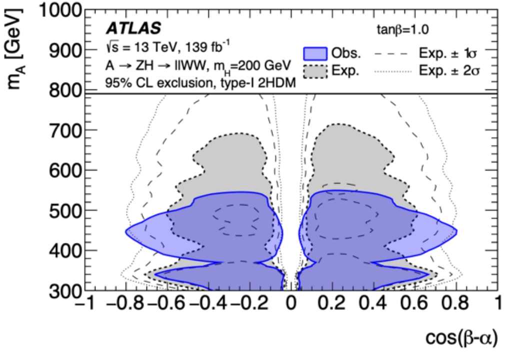
→ Difficult to place general constraints

Direct constraints

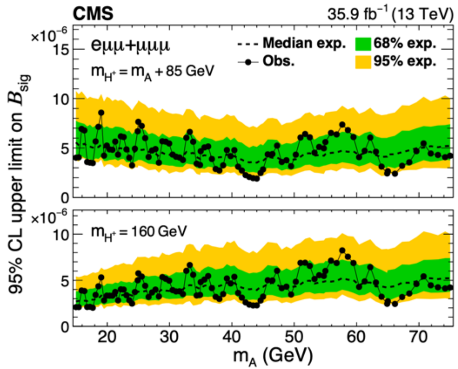
Measured cross-sections in agreement with SM give constraints on parameter space in the different models



ATLAS Collaboration. (2024). *Search for heavy neutral Higgs bosons decaying into a top quark pair in 140 fb⁻¹ of proton-proton collision data at √s = 13 TeV with the ATLAS detector.* arXiv:2404.18986



ATLAS Collaboration. (2021) *Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the ℓℓbb and ℓℓWW final states in pp collisions at √s = 13 TeV with the ATLAS detector.* arXiv:2011.05639



CMS Collaboration. (2019). "Search for a light charged Higgs boson decaying to a W boson and a CP-odd Higgs boson in final states with eμμ or μμμ in proton-proton collisions at √s = 13 TeV." arXiv:1905.07453.

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Phenomenology model dependent

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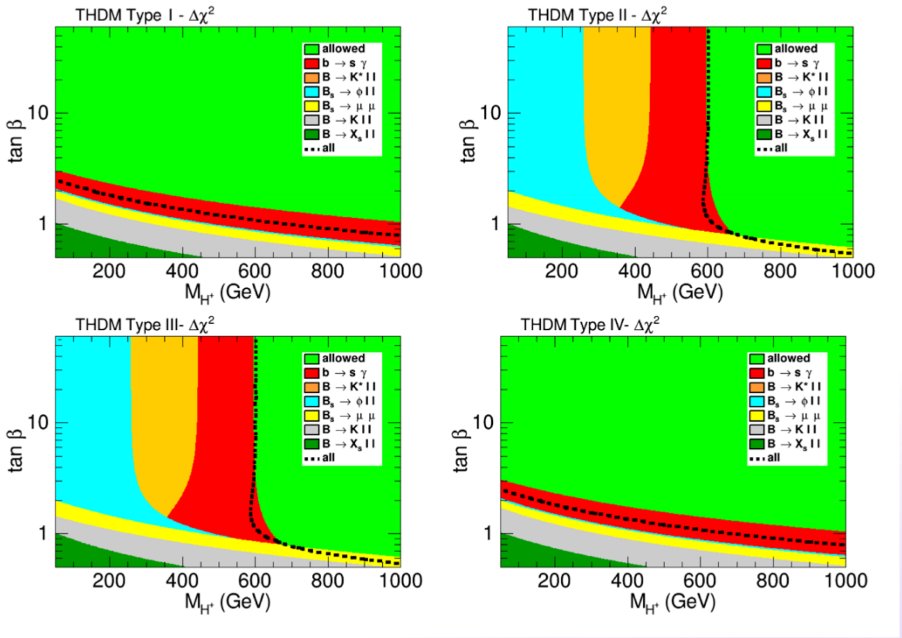
Direct constraints

Measured cross-sections in agreement with SM give constraints on parameter space in the different models

Indirect constraints

Flavour physics – Highly constrains mass of charged scalar in type II 2HDM

Measurements of SM-like Higgs properties



Arbey, A., Mahmoudi, F., Stål, O., & Stefaniak, T. (2018). Status of the Charged Higgs Boson in Two Higgs Doublet Models. arXiv:1706.07414

Summary and Outlook

- 2HDMs are simple extensions of SM scalar sector that can provide solutions to some of the limitations of the SM
- There are many models with many free parameters which gives varying phenomenology
- Direct searches have been performed, without statistically significant results
- EW precision measurements at HL-LHC might give insight into scalar sector.

Thanks for listening!

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