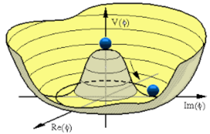
2/Two-Higgs-doublet models

2HDM/THDM

Why go beyond SM?

SM is minial but artificial

$$V = -\mu |H|^2 + \lambda |H|^4$$



[1201.6045]

Motivations for extended scalar sectors:

- Why not?
- Susy
- Sources of (spontaneous CP violation) for baryogenesis
- Inflation
- Mass hierarchy of SM fermions
- Strong CP problem - axions
- GUTs
- Dark matter relic abundance
- Vacuum stability

BUT: The SM works very well $\rightarrow$ Do not mess things up

In particular: $\rho = \frac{M_W^2}{M_Z^2 c_W^2} = 1.00039$, FCNC

Singlets and SU(2) doublets with $Y = 1/2$ do not spoil $\rho_{\text{tree level}} = 1$

2-Higgs-doublet model

Introduce 2 identical Higgs doublets with $Y = 1/2$:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix},$$

Demand global Z_2 symmetry usually softly broken in scalar potential:

$$\Phi_1 \to \Phi_1\,,\ \Phi_2 \to -\Phi_2\,,\ \text{broken by } m_{12}\Phi_1^\dagger\Phi_2 + m_{21}\Phi_2^\dagger\Phi_1$$

Why is the Z_2 symmetry demanded?

$$\mathcal{L}_Y \sim Y_f \Phi \bar{f}_i f_j \xrightarrow{\langle\Phi\rangle = v} M_{ij} = Y_f v \bar{f}_i f_j$$

$$\mathcal{L}_Y \sim Y_f^1 \Phi_1 \bar{f}_i f_j + Y_f^2 \Phi_2 \bar{f}_i f_j \xrightarrow[\langle\Phi_2\rangle = v_2]{\langle\Phi_1\rangle = v_1} M_{ij} = Y_f^1 v_1 \bar{f}_i f_j + Y_f^2 v_2 \bar{f}_i f_j$$

Z_2 symmetry avoids FCNC at tree level

Scalar potential

CP conserving for simplicity:

$$V_{\rm 2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + {\rm h.c.} \right] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$

$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left\{ \tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + {\rm h.c.} \right\},$$

EWSB:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

⇒ Presence of physical charged Higgs bosons $H^\pm$!
⇒ Presence of two physical CP even Higgs boson h and H
⇒ Presence of CP odd Higgs boson A

Independent parameters: m_h, m_H, m_A, $m_{H^\pm}$, α, β, m_{12}^2

Scalar spectrum

CP odd Higgs boson:

$$A = -\eta_1 \sin\beta + \eta_2 \cos\beta$$

$$M_A^2 = \frac{2m_{12}^2}{\sin(2\beta)} - \lambda_5 v^2$$

Charged Higgs boson:

$$H^+ = -\Phi_1^+ \sin\beta + \Phi_2^+ \cos\beta \quad \text{with} \quad \tan\beta = \frac{v_2}{v_1}$$

$$M_{H^\pm}^2 = M_A^2 + \frac{1}{2} v^2 (\lambda_4 - \lambda_5)$$

CP even Higgs bosons:

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

$$\mathcal{M}^2 = \begin{pmatrix} \lambda_1 v^2 c_\beta^2 + \left(M_A^2 + \lambda_5 v^2\right) s_\beta^2 & \left[\lambda_{345} v^2 - \left(M_A^2 + \lambda_5 v^2\right)\right] s_\beta c_\beta \\ \left[\lambda_{345} v^2 - \left(M_A^2 + \lambda_5 v^2\right)\right] s_\beta c_\beta & \lambda_2 v^2 s_\beta^2 + \left(M_A^2 + \lambda_5 v^2\right) c_\beta^2 \end{pmatrix}$$

Different types of the 2HDM

$$-\mathcal{L}_{\text{Yuk}} = \sum_{i=1}^{2} \left[\overline{Q}_L \widetilde{\Phi}_i \eta_i^U U_R + \overline{Q}_L \Phi_i \eta_i^D D_R + \overline{L}_L \Phi_i \eta_i^L E_R + \text{h.c.} \right]$$

Due to the different Z_2 charges each SM fermion type can couple only to Φ_1 or to Φ_2 $\rightarrow \eta_1^F = 0$ or $\eta_2^F = 0$

There are 4 different possibilities to realize consistent Z_2 charges of the SM fermions, defining the 4 types of the 2HDM:

	u-type	d-type	leptons	Q	u_R	d_R	L	l_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	$+$	$-$	$+$	$+$	$-$
flipped	Φ_2	Φ_1	Φ_2	$+$	$-$	$-$	$+$	$+$

[1612.01309]

Phenomenological consequences

The presence of additional Higgs bosons leads to modifications of SM predictions.

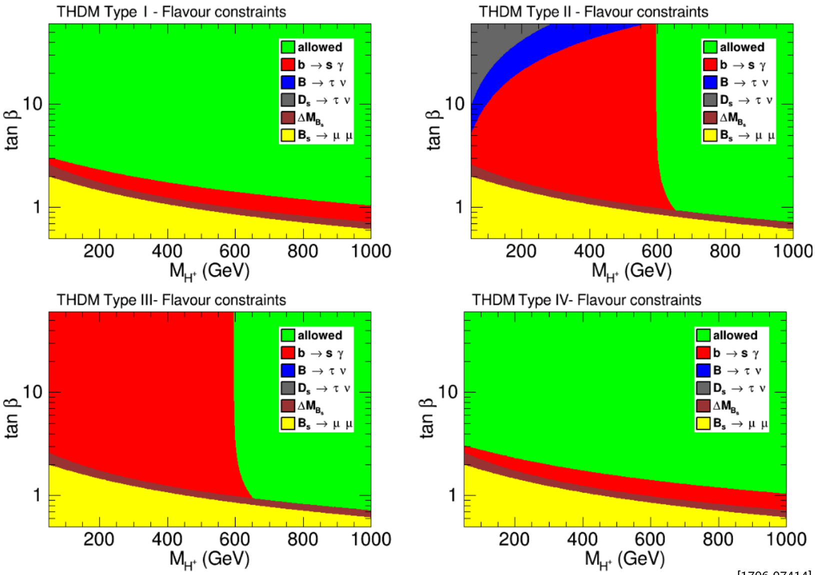
Various constraints have to be taken into account:

- Flavour physics observables
- Electroweak precision observables
- Collider searches
- SM Higgs-boson mass and signal strengths
- $Zb\bar{b}$ vertex corrections

Constraints from theoretical considerations:

- Stability of the vacuum
- Perturbativity
- Perturbative unitarity

Constraints from flavour physics observables



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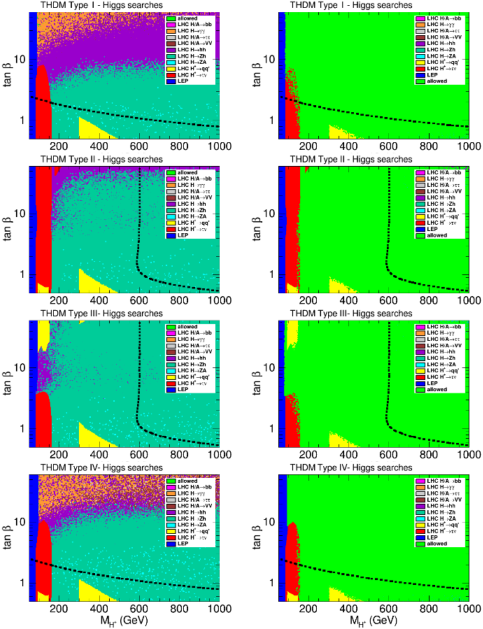
Constraints from collider searches



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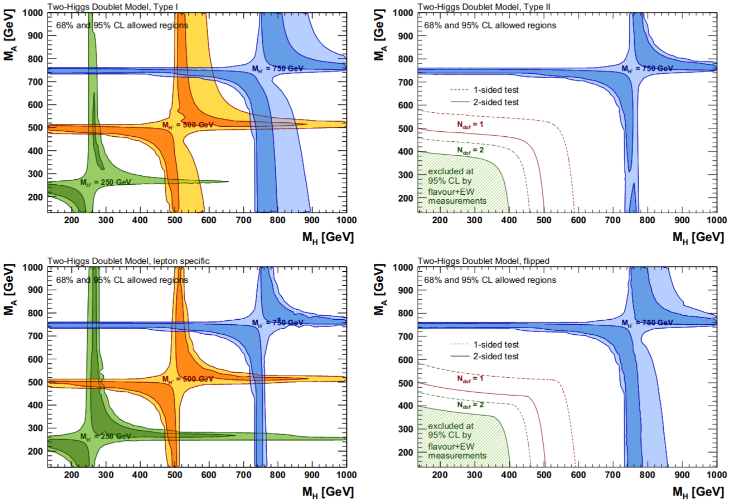
Constraints from the STU parameters



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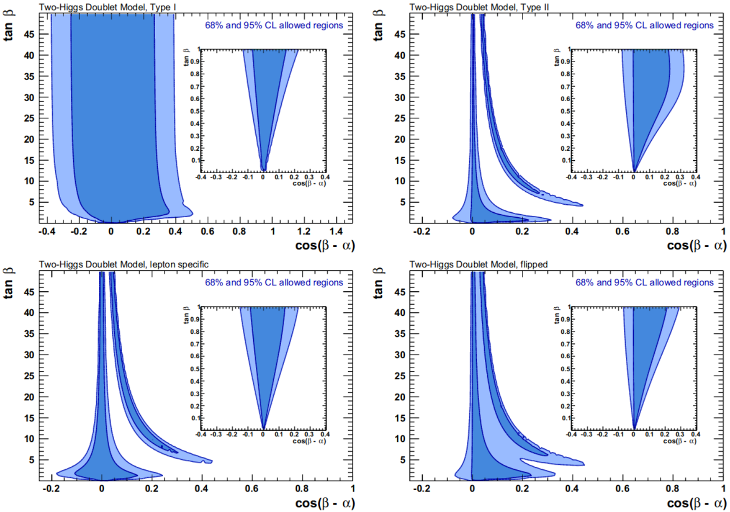
$$M_{H^\pm} \approx M_A \text{ or } M_{H^\pm} \approx M_H$$

The SM Higgs boson as a probe



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$\cos(\beta - \alpha) \to 0$ "Alignment limit"

What I did not talk about:

- CP violation and leptogenesis
- UV completions (axion models, Susy, . . .)
- Cosmological history: Phase transitions, inflation and gravitational waves
- Dark matter
- . . .

Questions or comments?