Hidden two-Higgs doublet model

Johan Rathsman, Uppsala and Lund University

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Two Higgs doublet models (2HDM)

Work together with Rikard Enberg and Glenn Wouda (Uppsala)

Why 2HDM?

- Simplest non-trivial extension of the SM Higgs sector
- Realized in the MSSM (type II)
- Interesting phenomenology

Here: Hidden 2HDM where

- softly broken Z_2 symmetry imposed in Higgs basis (cf. Inert Doublet Model (IDM) by Barbieri, Hall and Rychkov)
- A and $H^\pm$ have
  - no tree-level couplings to fermions
  - usual couplings to h, H and γ, Z, W
- Interesting phenomenology:
  - electroweak precision tests can be fulfilled also with heavy h
  - non-std decays of $A/H^\pm$ such as $H^+ \to W^+\gamma$ can dominate
  - essentially no limits on A, $H^\pm$ from low-energy flavour experiments (B-decays etc)

General two Higgs doublet model potential

- Two complex $SU(2)_L$ doublets with hypercharge Y=1: Φ_1 ,Φ_2
- Invariance under global $SU(2)$: $\Phi_a \to U_{ab}\Phi_b$

General potential

$$\mathcal{V} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right] + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left\{\frac{1}{2}\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\left(\Phi_1^\dagger\Phi_2\right) + \mathrm{h.c.}\right\}$$

- Potential real $\Rightarrow \{m_{11}^2,\ m_{22}^2,\ \lambda_{1-4}\}$ real, $\{m_{12}^2,\ \lambda_{5-7}\}$ complex
- No explicit CP-violation $\Rightarrow \{m_{12}^2,\ \lambda_{5-7}\}$ real

Exact Z_2 symmetry (as in IDM)

Demanding that the potential is symmetric under $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2 \Rightarrow m_{12}^2 = 0$, $\lambda_{6-7} = 0$ in general basis

Electroweak symmetry breaking

- Higgs basis $\Rightarrow$ EW symmetry broken by non-zero vev of Φ_1

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ v - h \sin\alpha + H \cos\alpha + \mathrm{i} G^0 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} H^+ \\ h \cos\alpha + H \sin\alpha + \mathrm{i} A \end{pmatrix}$$

- Minimization $\Rightarrow \begin{cases} m_{11}^2 = -\frac{1}{2} v^2 \lambda_1 \\ m_{12}^2 = \frac{1}{2} v^2 \lambda_6 \end{cases}$ $(v \approx 246$ GeV $)$
- Three Goldstone bosons: $G^\pm$, $G^0 \Rightarrow$ masses to W and Z
- Five "Higgs" boson states: two CP-even, h, H with mixing angle α, one CP-odd A, and two charged $H^\pm$
- $\sin\alpha \propto m_{12}^2$ ($m_{12}^2 = 0$ restores Z_2 symmetry)
- Higgs-gauge couplings from $s_\alpha \equiv \sin\alpha$ $(\tan\beta = 0)$
- No hard breaking of Z_2 symmetry $\Rightarrow \lambda_2$, λ_7 fixed
- Parameterisation of potential: $\{ m_{22}^2, m_h, m_H, m_A, m_{H^\pm}, s_\alpha \}$

Yukawa sector

- In order for fermions to get mass they have to couple to Φ_1
- To avoid non-MFV CC and FCNC at tree-level, each fermion type can only couple to one Higgs doublet (Glashow & Weinberg)
- $\Rightarrow$ fermions cannot couple to Φ_2

Yukawa couplings for SM fermions with mass eigenstates $D = \{d, s, b\}$, $U = \{u, c, t\}$, $L = \{e, \mu, \tau\}$ and massless neutrinos

$$\mathcal{L}_{\mathrm{Y}} = \frac{1}{v}\left(\sum_D \overline{D} m_D D + \sum_U \overline{U} m_U U + \sum_L \overline{L} m_L L\right)(\sin\alpha h - \cos\alpha H)$$

Theoretical constraints

Positivity of potential

Demanding that the potential is bounded from below $\Rightarrow$

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

plus more complicated expressions

Perturbativity

Cross-section for $2 \to 2$ Higgs scattering processes $\propto \dfrac{\lambda_{HHHH}^2}{16\pi^2}$
$\Rightarrow$ the quartic Higgs couplings λ_{HHHH} cannot be too large for the perturbative series to make sense

Tree-level unitarity

requiring tree-level unitarity for HH and HV_L scattering $\Rightarrow$ limits on eigenvalues of the corresponding scattering matrices

Improved naturalness

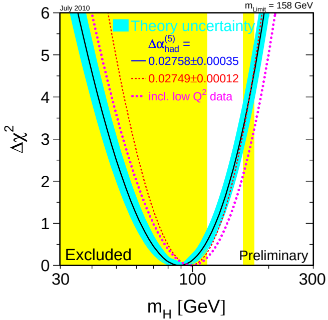
Naturalness (Barbieri, Hall, Rychkov)

The physics that cancels the quadratic corrections to m_h^2 must enter at a scale obtained from

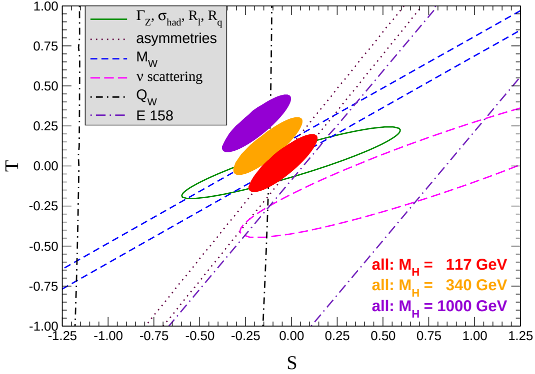
$$\left(\delta m_h^2\right)_{\rm top} = \frac{3m_t^2}{2\pi^2 v^2}\Lambda_t^2 < m_h^2 \qquad \Rightarrow \qquad \Lambda_t \lesssim \sqrt{4\pi}\, m_h$$

SM more natural (less fine-tuned) if m_h larger

But EW precision measurements restrict m_h severely in SM



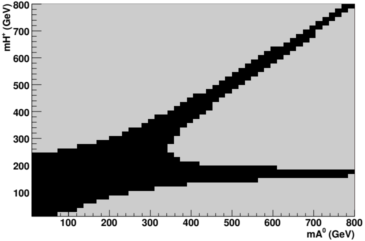
- Oblique parameters S, T, U sensitive to new physics
- Fixing the SM Higgs mass and $U = 0$ gives region of allowed (90% CL) points in the S - T plane



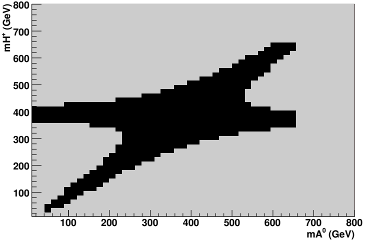
- If new physics increase T and/or decrease S $\Rightarrow$ lightest CP-even Higgs can be much heavier
- possible with an additional Higgs doublet (also in IDM and λSUSY)

Examples of allowed regions from S, T as well as positivity, perturbativity and tree-level unitarity in m_A-$m_{H^\pm}$ plane

$$\begin{aligned} m_h &= 150 \text{ GeV} \\ m_H &= 200 \text{ GeV} \\ \sin\alpha &= 1/\sqrt{2} \\ m_{22} &= 50 \text{ GeV} \end{aligned}$$



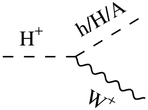
$$\begin{aligned} m_h &= 400 \text{ GeV} \\ m_H &= 200 \text{ GeV} \\ \sin\alpha &= 0.3 \\ m_{22} &= 100 \text{ GeV} \end{aligned}$$



$\Rightarrow$ points with an custodial global $SU(2)$ symmetry allowed $m_{H^\pm} \approx m_A$ or $m_{H^\pm}^2 \approx m_H^2 \sin^2\alpha + m_h^2 \cos^2\alpha$

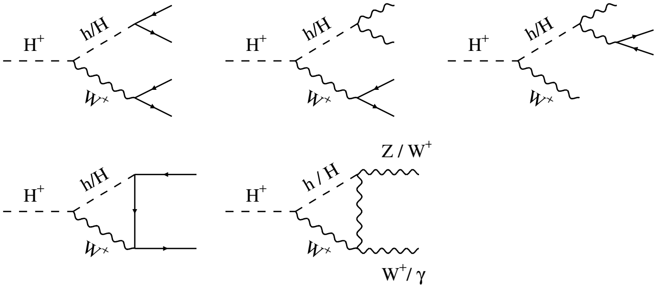
Non-standard H^+ decays

Basic decay vertex



cosα / sinα / 1

Decays into fermions and SM gauge bosons ($m_{H^\pm} < m_A$)



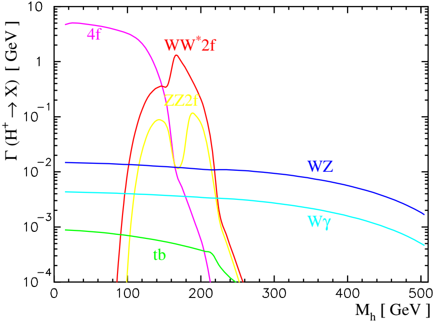
Note: all diagrams proportional to $\sin(2\alpha) \Rightarrow$ vanish in no-mixing limit $\sin\alpha \to 0$ or $\cos\alpha \to 0$

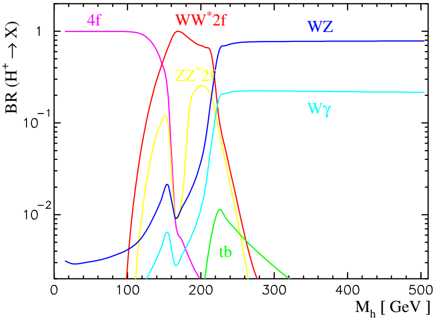
Example:

$$
\begin{aligned}
m_{H^\pm} &= 300 \text{ GeV} \\
m_H &= 600 \text{ GeV} \\
m_A &= 400 \text{ GeV} \\
\sin\alpha &= 0.3 \\
m_{22} &= 0
\end{aligned}
$$

- $H^+ \to 4f$ dominates for $m_h \lesssim 2m_V$ GeV
- $H^+ \to VV^{(*)}2f$ dominates for $2m_V \lesssim m_h \lesssim m_{H^\pm} - m_V$
- $H^+ \to WZ$ dominates for $m_h > m_{H^\pm} - m_V$

For smaller $m_{H^\pm}$ ($\sim$ 100 GeV) $H^+ \to W\gamma$ dominate for all m_h





Conclusions

Hidden two Higgs Doublet model

- softly broken Z_2 symmetry in Higgs basis
- no Yukawa couplings for A and $H^\pm$

Phenomenological consequences

- offers improved naturalness (m_h larger)
- non-standard decay modes of A and $H^\pm$ can dominate

Next step

- look at lighter A and $H^\pm$ and see possible effects on LEP searches