Charged Higgs in a Hidden two-Higgs doublet model

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Two Higgs doublet models (2HDM)

Work together with Rikard Enberg and Johan Rathsman (Uppsala), basically same presentation as JR for SUSY 2010 (thanks for the slides and plots)

Why 2HDM?

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

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

General two Higgs doublet model potential

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

General potential

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

- 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 $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2 \Rightarrow m_{12}^2 = 0$, $\lambda_{6-7} = 0$ 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)

- No hard breaking of Z_2 symmetry $\Rightarrow$ relation for λ_2, λ_7 :

$$(\lambda_1 - \lambda_2)\left[\lambda_{345}(\lambda_6 + \lambda_7) - \lambda_2\lambda_6 - \lambda_1\lambda_7\right] \\ -2(\lambda_6 - \lambda_7)(\lambda_6 + \lambda_7)^2 = 0$$

$$(\lambda_1 - \lambda_2)m_{12}^2 + (\lambda_6 + \lambda_7)(m_{11}^2 - m_{22}^2) \neq 0$$

$(\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5\ )$

- $\lambda_{1,3,4,5}$ can be traded for the Higgs masses, m_{22} and the mixing angle:

$$\sin 2\alpha = 2v^2\lambda_6/(m_H^2 - m_h^2)$$

$$-\tan 2\alpha = 2v^2\lambda_6/(m_A^2 + v^2(\lambda_5 - \lambda_1))$$

- Parameterisation of potential: $\{ \; m_{22}^2, \; m_h, \; m_H, \; m_A, \; m_{H^\pm}, \; s_\alpha \; \}$
- We futher impose $\lambda_7 = \lambda_6$ and $\lambda_1 = \lambda_2$ to simply the phenomenological study
- for $mh = mH$ the mixing is undefined

Yukawa

- 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 $2 \rightarrow 2$ 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

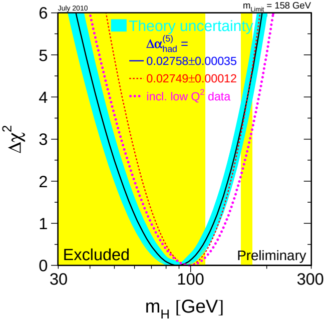
Naturalness (Barbieri, Hall, Rychkov)

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

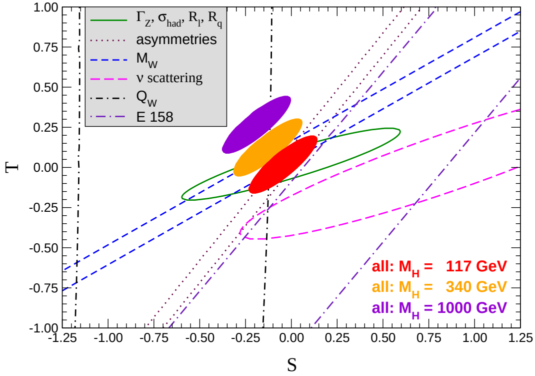
$$\left(\delta m_h^2\right)_{\rm top} = \frac{3m_t^2}{2\pi^2 v^2}\Lambda_t^2 < m_h^2 \qquad \Rightarrow \qquad \Lambda_t \lesssim \sqrt{4\pi}\, m_h$$

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

But EW precision measurements restrict m_h severely in SM



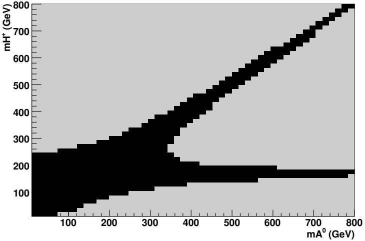
- Oblique parameters S, T, U sensitive to new physics
- Fixing the SM Higgs mass and $U = 0$ gives region of allowed (90% CL) points in the S - T plane



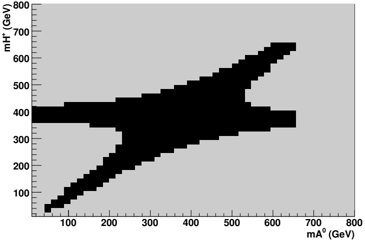
- If new physics increase T and/or decrease $S \Rightarrow$ lightest CP-even Higgs can be much heavier
- possible with an additional Higgs doublet (also in IDM and λSUSY)

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

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



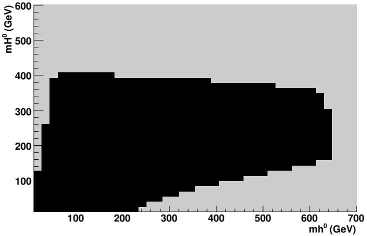
$$m_h = 400 \text{ GeV}$$
$$m_H = 200 \text{ GeV}$$
$$\sin\alpha = 0.3$$
$$m_{22} = 100 \text{ GeV}$$



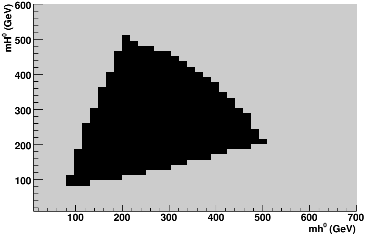
$\Rightarrow$ points with an custodial global $SU(2)$ symmetry allowed
$m_{H^\pm} \approx m_A$ or $m^2_{H^\pm} \approx m^2_H \sin^2\alpha + m^2_h \cos^2\alpha$

In m_h, m_H - plane

$$m_{H^+} = 500 \text{ GeV}$$
$$m_A = 50 \text{ GeV}$$
$$\sin\alpha = 0.3$$
$$m_{22} = 10 \text{ GeV}$$

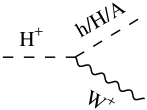


$$m_{H^+} = 400 \text{ GeV}$$
$$m_A = 300 \text{ GeV}$$
$$\sin\alpha = 1/\sqrt{2}$$
$$m_{22} = 100 \text{ GeV}$$



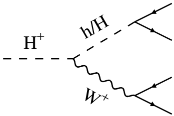
Non-standard H^+ decays

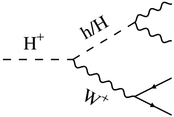
Basic decay vertex

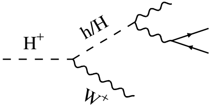


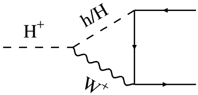
$\cos\alpha$ / $\sin\alpha$ / 1

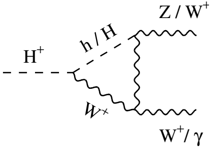
Decays into fermions and SM gauge bosons $(m_{H^\pm} < m_A)$



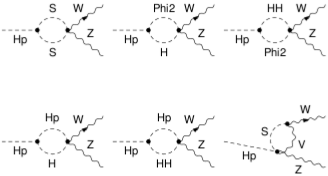








(cont.) H^+ into SM gauge bosons diagrams of these types also contribute (here shown $H^+ \to W^+ Z$)

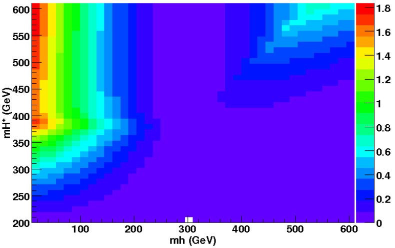


Note: all diagrams proportional to $\sin(2\alpha) \Rightarrow$ vanish in the Inert limit $\sin\alpha \to 0$ or $\cos\alpha \to 0$.
H$=h^0$, HH$=H^0$

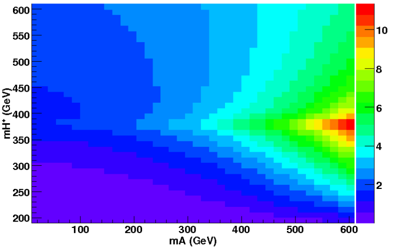
There are also UV-divergent diagrams contributing, ongoing work.

$H^+ \to t\bar{b}$ at one loop level, calculated with FormCalc (MeV)

$$
\begin{aligned}
m_H &= 300 \text{ GeV} \\
m_A &= 300 \text{ GeV} \\
\sin\alpha &= 0.3
\end{aligned}
$$

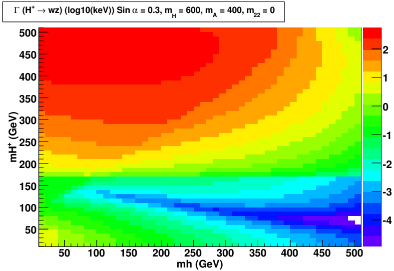


$$
\begin{aligned}
m_H &= 100 \text{ GeV} \\
m_h &= 300 \text{ GeV} \\
\sin\alpha &= 1/\sqrt{2}
\end{aligned}
$$



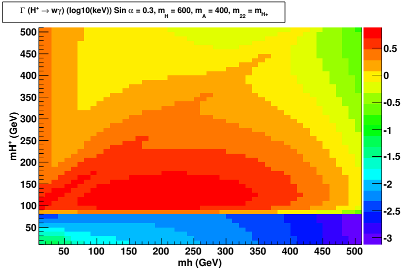
$H^+ \to W^+ Z$ at one loop level, calculated with FormCalc ($\log_{10}$ keV)

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

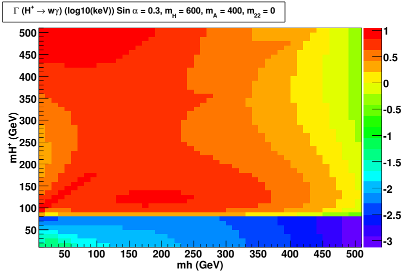


$H^+ \to W^+\gamma$ at one loop level, calculated with FormCalc ($\log_{10}$ keV)

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

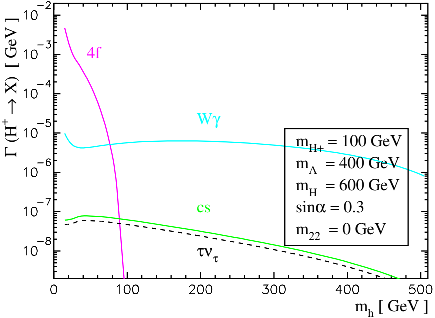


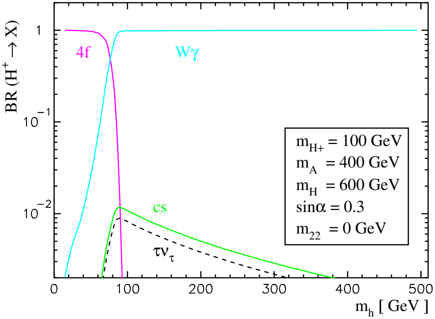
$$
\begin{aligned}
m_H &= 600 \text{ GeV} \\
m_A &= 400 \text{ GeV} \\
\sin\alpha &= 0.3 \\
m_{22} &= 0
\end{aligned}
$$



Example 1)

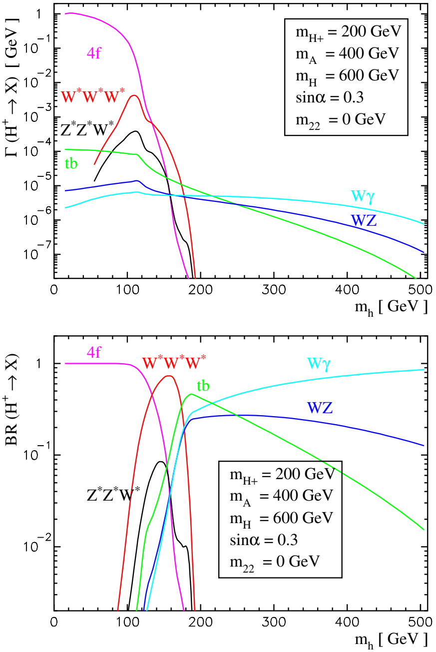
$$
\begin{aligned}
m_{H^\pm} &= 100 \text{ GeV} \\
m_H &= 600 \text{ GeV} \\
m_A &= 400 \text{ GeV} \\
\sin\alpha &= 0.3 \\
m_{22} &= 0
\end{aligned}
$$





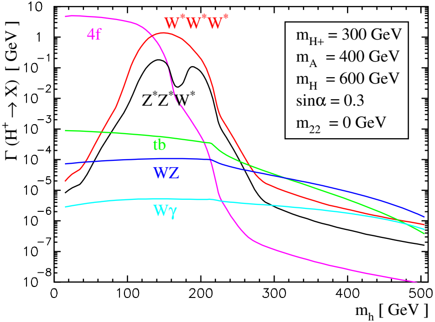
Example 2)

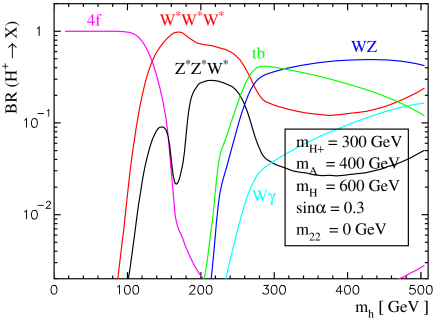
$$m_{H^\pm} = 200 \text{ GeV}$$
$$m_H = 600 \text{ GeV}$$
$$m_A = 400 \text{ GeV}$$
$$\sin\alpha = 0.3$$
$$m_{22} = 0$$



Example 3)

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





- Improved naturalness, lighest CP even Higgs boson can be sustansially heavy while still respecting EWPT.
- Since H^+, A^0 does not couple to fermions at tree-level, basically no limits from low-energy flavour experiments (B-decays etc)
- if $H^+ \to W^+ h/H/A$ is kinematically forbidden, decays such as W^+Z, $W^+\gamma$ and 3-body decay can dominate which changes collider searches drastically, e.g. H^+ (and A) might already been produced at LEP
- Consequenses for LHC? Heavy Higgses, non-standard H^+, A decays

Summary, Outlook

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

Ongoing

- Inclusion and renormalization of the UV-divergent diagrams to the above mentioned processes, severe influence?

Next steps

- A decays
- Look at lighter A and $H^{\pm}$ and see possible effects on LEP searches.
- $H^{+} \to W^{+}\gamma$ possible at LHC for $mH^{+} \sim 100 - 150$ GeV?
- Mechanism of soft Z_2 symmetry breaking?