Status of the Type-II 2HDM

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in collaboration with

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based on [arXiv:1305.1649], [arXiv:1403.1264]

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CKM fitter package

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Field Content and Symmetries

- Two scalar SU(2) doublets Φ_1 and Φ_2
- A softly broken $\mathbb{Z}_2$ symmetry which forbids FCNCs.
- No Higgs-sector CP violation
- Scalar potential:

$$\begin{aligned} V = \quad & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\ & + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \tfrac{1}{2}\lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2] \end{aligned}$$

- Scalar particle content: h, H, A, $H^\pm$.
- We assume $m_h = 126\,\text{GeV}$.

Parametrisation

- Lagrangian parametrisation:

$$v_2/v_1 \equiv \tan\beta,\ m_{12}^2,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5$$

- Physical parametrisation:

$$\tan\beta,\ \beta-\alpha,\ m_{12}^2,\ m_h,\ m_H,\ m_A,\ m_{H^\pm}$$

Limiting Cases

Custodial limit. The 2HDM Higgs sector has a custodial symmetry when $m_H = m_{H^\pm}$ or $m_A = m_{H^\pm}$.

Alignment limit. The light CP even Higgs h has SM-like couplings for

$$\beta - \alpha = \frac{\pi}{2}$$

Decoupling limit. The 2HDM is phenomenologically indistinguishable from the SM for $m_{12}^2 \gg v^2$.

Note that relations between Lagrangian and physical parameters are of the form

$$\lambda_1 = \frac{m_H^2 c_\alpha^2 + m_h^2 s_\alpha^2 - m_{12}^2 t_\beta}{v^2 c_\beta^2} \quad .$$

$\Rightarrow$ Perturbativity requires that in the decoupling limit $\beta - \alpha \to \pi/2$ and that heavy Higgs masses are “fine tuned”.

Theoretical Constraints

- The Higgs potential must be bounded from below

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

- The extremum of V with $v = 246\,\mathrm{GeV}$ must be the global minimum

$$m_h^2, m_H^2, m_A^2, m_{H^\pm}^2 \geq 0 \quad ,$$
$$m_{12}^2 (m_{11}^2 - m_{22}^2 \sqrt{\lambda_1 \lambda_2})(\tan\beta - (\lambda_1/\lambda_2)^{1/4}) > 0 \quad .$$

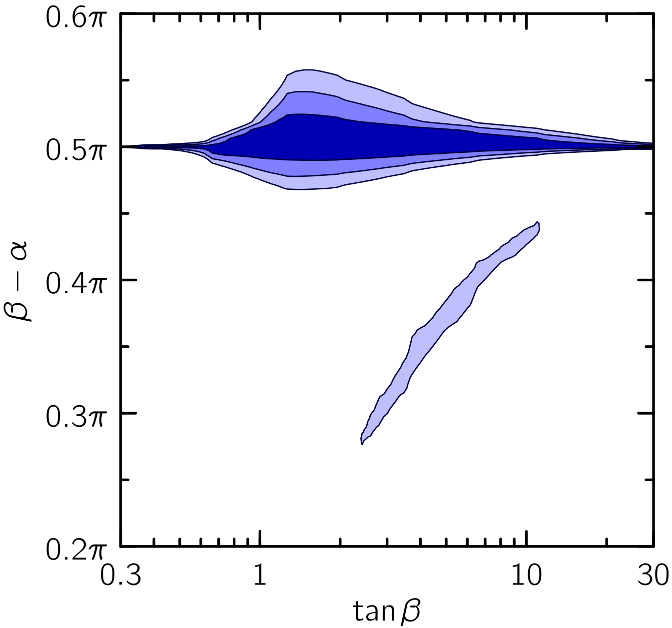
- The Higgs self-couplings must be perturbative

$$\| S_{\phi\phi \to \phi\phi} \| < \frac{1}{8} \text{ (1 for tree-level unitarity)} \quad .$$

Experimental Constraints

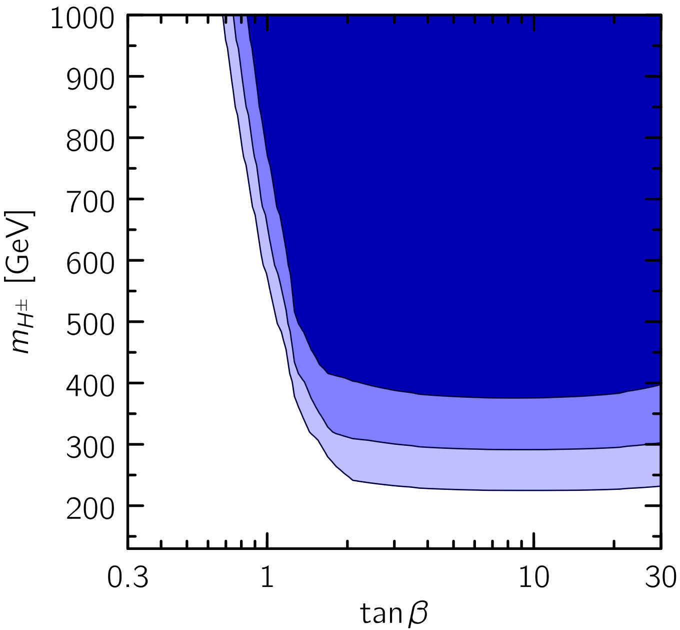
- Full set of electroweak precision observables.
  (Can't use S, T and U because of non-oblique corrections to $Zb\bar{b}$ vertex.)
- Signal strengths of the light Higgs boson (including correlations between different production mechanisms).
- Limits on heavy $H \to WW, ZZ$ and $H \to \tau\tau$ resonances.
- Flavour observables relevant for the low $\tan\beta$ region:
  B_s mixing and $B \to X_s\gamma$.

$\tan\beta$ vs. $\beta - \alpha$



- $1\,\sigma$ and $2\,\sigma$ contours close to the alignment limit.
- Region with wrong sign top Yukawa coupling ruled out at $2\,\sigma$ due to flavour constraints.
- No upper or lower limit on $\tan\beta$.

$\tan\beta$ vs. $m_{H^\pm}$



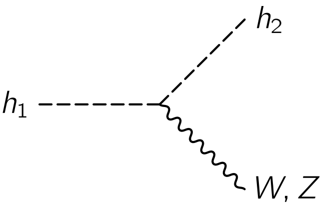
- $m_{H^\pm} \gtrsim 300\,\mathrm{GeV}$ due to $\mathrm{Br}(B \to X_s\gamma)$.
- Low $\tan\beta$ region constrained by Δm_{B_s}.

Similar Studies

[P. Ferreira, R. Santos, M. Sher, and J. P. Silva, arXiv:1112.3277], [K. Blum and R. T. D'Agnolo, arXiv:1202.2364], [L. Basso, A. Lipniacka, F. Mahmoudi, S. Moretti, P. Osland, arXiv:1205.6569], [H. Cheon and S. K. Kang, arXiv:1207.1083], [D. Carmi, A. Falkowski, E. Kuflik, T. Volansky, and J. Zupan, arXiv:1207.1718], [A. Drozd, B. Grzadkowski, J. F. Gunion, and Y. Jiang, arXiv:1211.3580], [J. Chang, K. Cheung, P.-Y. Tseng, and T.-C. Yuan, arXiv:1211.3849], [C.-Y. Chen and S. Dawson, arXiv:1301.0309], [A. Celis, V. Ilisie, and A. Pich, arXiv:1302.4022], [P. P. Giardino, K. Kannike, I. Masina, M. Raidal, and A. Strumia, arXiv:1303.3570], [B. Grinstein and P. Uttayarat, arXiv:1304.0028], [J. Shu and Y. Zhang, arXiv:1304.0773], [A. Barroso, P. Ferreira, R. Santos, M. Sher, and J. P. Silva, arXiv:1304.5225], [G. Belanger, B. Dumont, U. Ellwanger, J. Gunion, and S. Kraml, arXiv:1306.2941], [V. Barger, L. L. Everett, H. E. Logan, and G. Shaughnessy, arXiv:1308.0052], [D. López-Val, T. Plehn, and M. Rauch, arXiv:1308.1979], [G. Bhattacharyya, D. Das, P. B. Pal, and M. Rebelo, arXiv:1308.4297], [S. Chang, S. K. Kang, J.-P. Lee, K. Y. Lee, S. C. Park, et al., arXiv:1310.3374], [A. Celis, V. Ilisie, and A. Pich, arXiv:1310.7941], [L. Wang and X.-F. Han, arXiv:1312.4759],. . .

2HDM Phenomenology

- Non-standard decay modes of heavy Higgs resonances:



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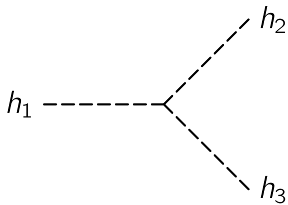
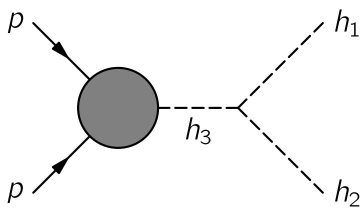


- New contributions to (light) Higgs pair production:



Triple Higgs Couplings

Define 2HDM/SM coupling ratios:

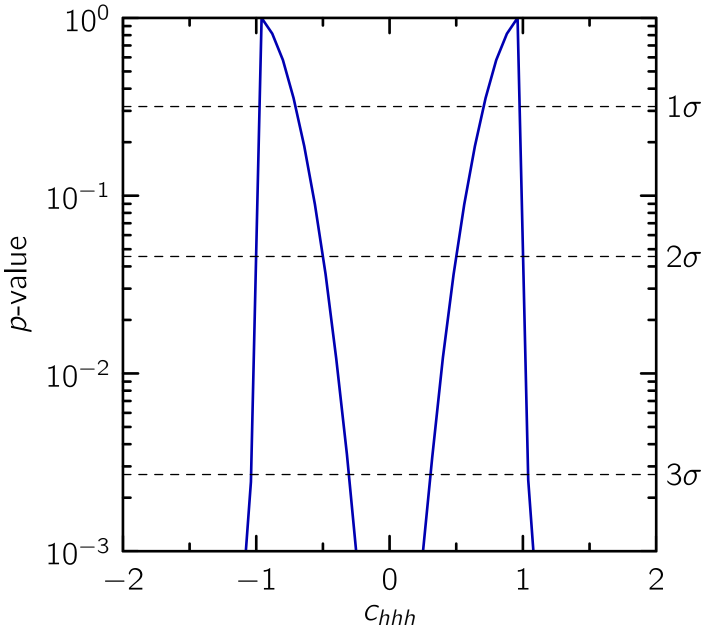
$$c_{h_1 h_2 h_3} = \frac{g^{\mathrm{2HDM}}_{h_1 h_2 h_3}}{g^{\mathrm{SM}}_{hhh}|_{m_h = 126\,\mathrm{GeV}}}$$

In the alignment limit $\beta - \alpha = \pi/2$:

$$c_{hhh} = 1 \quad , \quad c_{hhH} = 0 \quad .$$

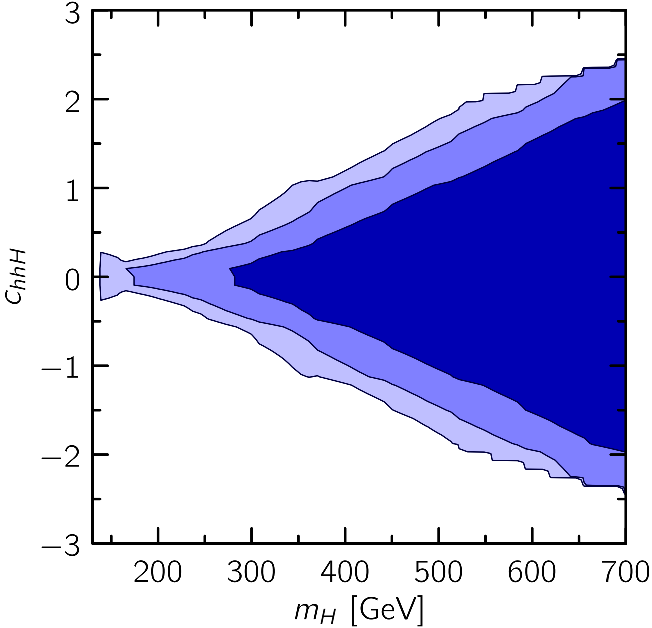
⇒ Strong constraints on these couplings from Higgs signal strengths.

hhh Coupling

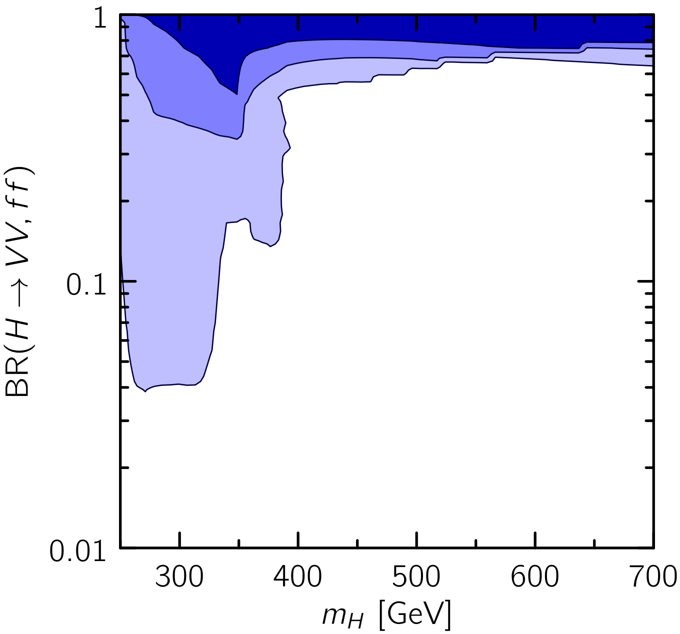


No enhanced coupling possible!

hhH Coupling

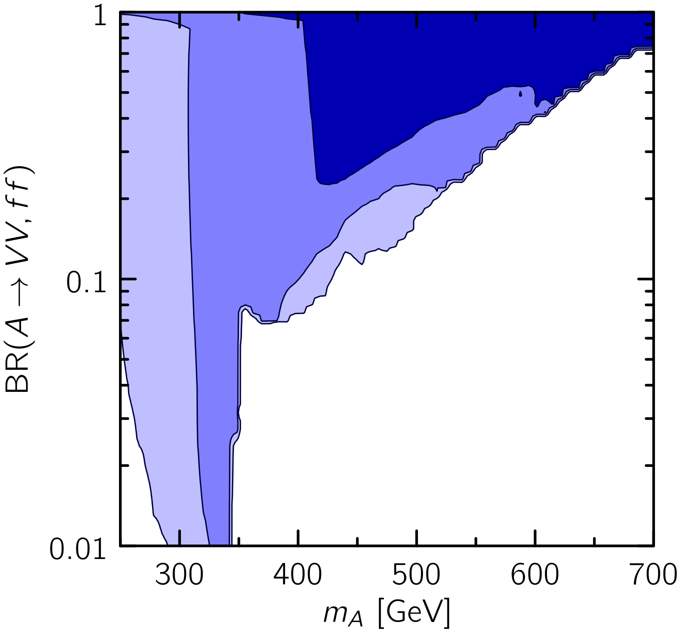


$\mathrm{Br}(H \to VV, f\bar{f})$



- Largest effects for m_H below the $t\bar{t}$ threshold.
- $Br(H \to VV, f\bar{f}) \gtrsim 40\%$ at $2\,\sigma$
- Non-standard decays mostly $H \to hh$.

Br($A \to VV, f\bar{f}$)



- Br($A \to ZH$) > 99% possible for m_A between 300 GeV and $2m_t$ (due to non-trivial interplay between all constraints).
- For $m_A \gtrsim 400$ GeV the $A \to H^{\pm}W^{\mp}$ decays can have branching fractions as large as 70%.

Benchmarks

- Scenarios with large triple Higgs couplings or large $h_i \to h_j h_k, h_j V$ branching fractions have interesting phenomenology.
- Detailed studies require the full set of 7 2HDM parameters for the allowed points.
- In [arXiv:1403.1264] we provide a list of benchmark scenarios which exhibit these features and pass all other constraints.

	$\tan\beta$	$(\beta-\alpha)/\pi$	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	m_{12}^2 [GeV^2]
H-1	1.75	0.522	300	441	442	38300
H-2	2.00	0.525	340	470	471	44400
H-3	4.26	0.519	450	546	548	43200
H-4	4.28	0.513	600	658	591	76900
A-1	4.61	0.505	346	300	345	23600
A-2	2.74	0.503	131	340	339	6200
A-3	7.02	0.508	290	450	446	11700
A-4	7.44	0.504	490	600	598	31620

Conclusions (I)

- Present data strongly constrains the parameter space of the type-II 2HDM.
  - Higgs signal strengths push us close to the alignment limit.
  - Flavour data puts a lower bound on the charged Higgs mass.
  - Electroweak precision data requires $m_H \approx m_{H^\pm}$ or $m_A \approx m_{H^\pm}$.

Conclusions (II)

- This has implications for possible signals in $h_i \to h_j h_k, h_j V$ decays and Higgs pair production.
  - hhh coupling can only be reduced.
  - Non-standard H branching fractions at most 40% at $2\,\sigma$.
  - Large non-standard A branching fractions only for $300\,\text{GeV} < m_A < 2m_t$.
- In [arXiv:1403.1264] we provide the parameter values for scenarios with these features.