Cornering the Two-Higgs-Doublet Type II Model

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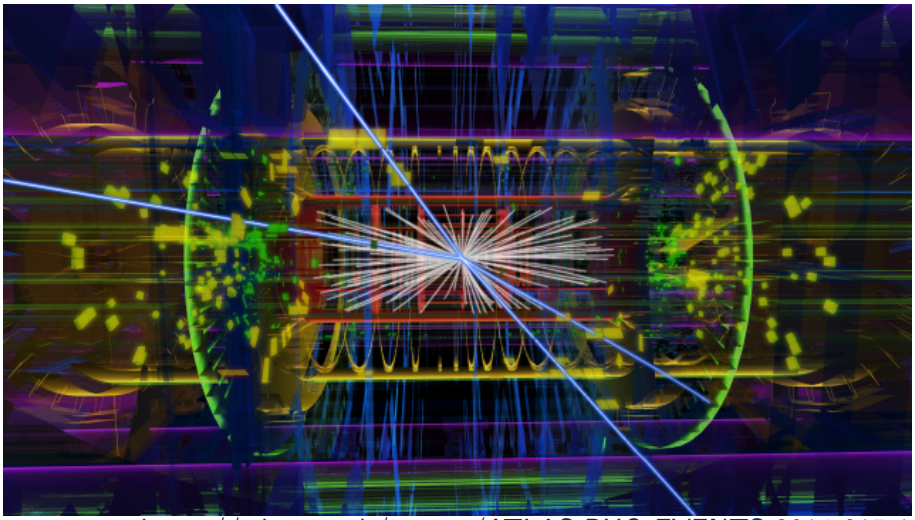
*All results are preliminary



https://cds.cern.ch/images/ATLAS-PHO-EVENTS-2014-015-1/

- For a review of 2HDMs, see e.g. [Branco et al. '11]
- 2HDM Potential:

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

- Two Doublets ($i = 1, 2$):

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i^0)/\sqrt{2} \end{pmatrix}$$

- Five Higgs particles: h^0, H^0, A^0, H^+, H^-
- $H^\pm$ couplings:

$$\epsilon_{\ell,d} \propto -\tan\beta, \quad \epsilon_u \propto \cot\beta$$

- h^0 couplings:

$$\kappa_V = \sin(\beta-\alpha)$$
$$\kappa_u = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$
$$\kappa_{d,\ell} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

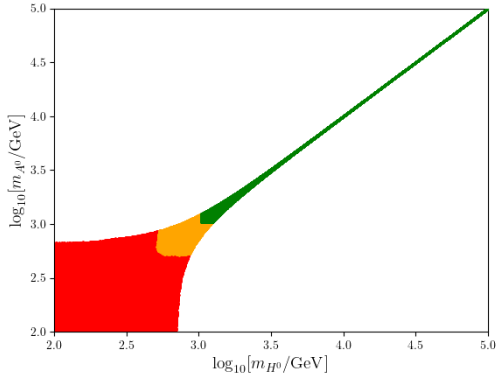
- Parameters:
  - $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}, m_{11}, m_{22}$ Convert with [Arnan et al. '17]
  - $m_{12}, m_{H^0}, m_{A^0}, m_{H^\pm}, \cos(\beta-\alpha), \tan\beta = \frac{v_2}{v_1}$
- $m_{h^0} = 125.1\,\text{GeV}$, $v_{SM}^2 = v_1^2 + v_2^2$
- Two ways to recover SM h^0 behaviour:
  - Alignment Limit $\rightarrow \cos(\beta-\alpha) = 0$
  - Wrong Sign Limit $\rightarrow \cos(\beta-\alpha) = \sin(2\beta)$ [Das, Kundu, Saha '17]
- CRC research on 2HDMs:
  - [Eberhardt, Nierste, Wiebusch '13]
  - [Basler, Dawson, Englert, Mühlleitner '19]
  - [Krause, Mühlleitner '19]

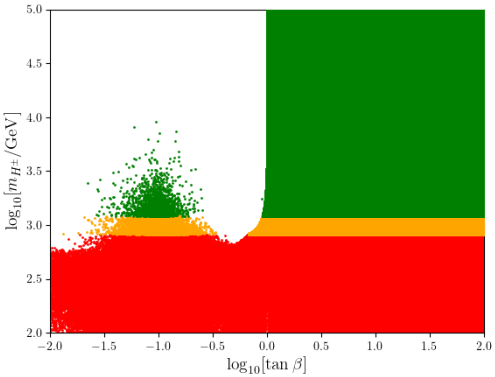
- Unitarity [Arhrub '00]
- Perturbativity: [Ginzburg & Ivanov '05]

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

- Vacuum Stability: [Deshpande & Ma '78]

$$\lambda_{1,2} > 0$$
$$\lambda_3 > -(\lambda_1\lambda_2)^{1/2}$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -(\lambda_1\lambda_2)^{1/2}$$





- Monte Carlo scans for allowed mass basis parameters – 10^8 points
- 3 regions based on $B \to X_s\gamma$ constraint
- Tight mass degeneracy for higher scales
- $\tan\beta \gtrsim 1$ for $m_{H^\pm} \gtrsim 1210\,\mathrm{GeV}$
  ➥ with the addition of flavour constraints
- Exact constraints on mass splittings and more in the paper

- We use the **flavio** package [flav-io.github.io, D. Straub '18]
- Signal strength:

$$\mu_i^f = \frac{(\sigma_i \cdot \mathcal{B}_f)_{\text{exp.}}}{(\sigma_i \cdot \mathcal{B}_f)_{\text{SM}}},$$

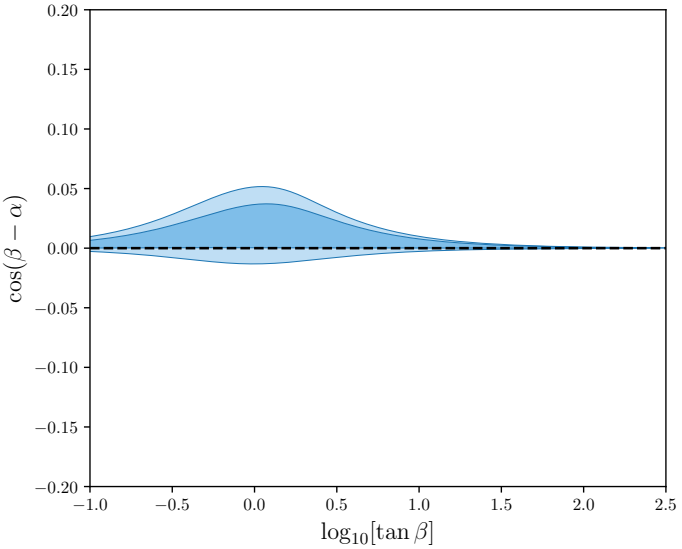
- 31 channels
- Signal strengths yield the result

$$|\cos(\beta - \alpha)| \leq 0.05\,(2\sigma)$$

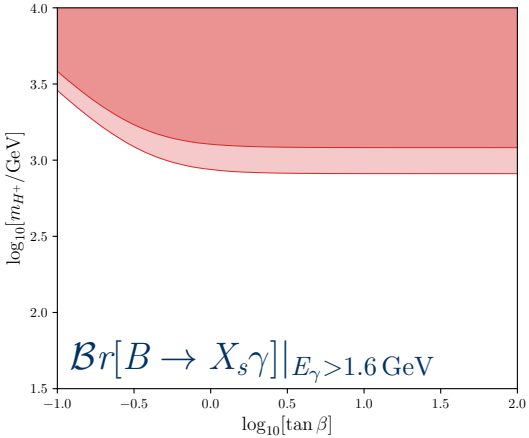
- Strong demand for $\cos(\beta - \alpha) > 0$
- This constraint is strengthened later in global fit
- In the Wrong Sign Limit,

$$\kappa_V = 1, \qquad \kappa_u = 1, \qquad \kappa_{d,\ell} = -1$$
$$\implies \cos(\beta - \alpha) = \sin(2\beta)$$

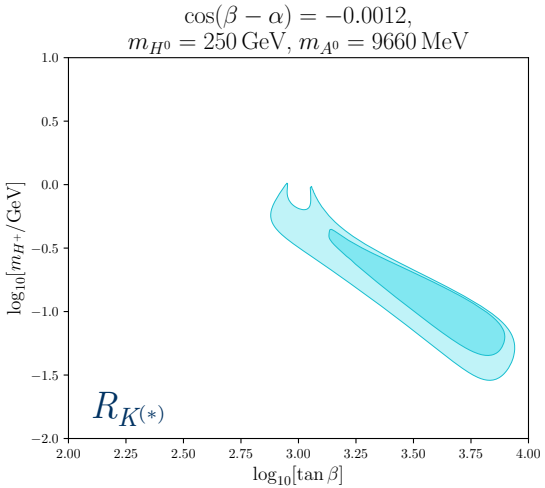
- Higgs Signals alone **exclude** the Wrong Sign Limit



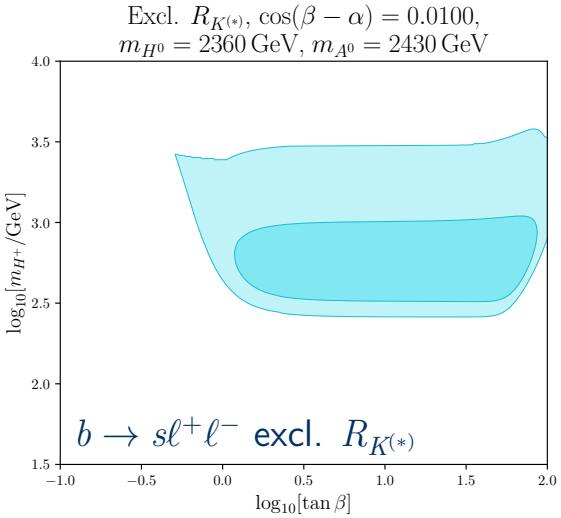
- We again use **flavio** here
- 241 flavour observables included overall
- $\mathcal{B}r[B \to X_s\gamma]|_{E_\gamma > 1.6\,\text{GeV}}$:
  - $m_{H^\pm} > 820\,(1210)$ GeV at $2\sigma\,(1\sigma)$
- [Misiak, Rehman, Steinhauser '20]
  - $m_{H^\pm} \geq 800$ GeV at 95% CL

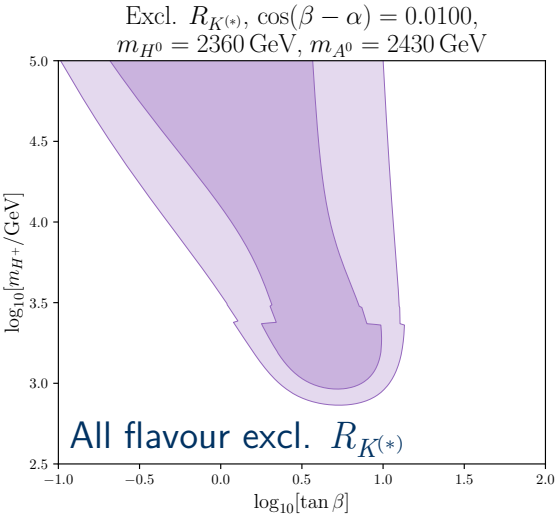


- Tree level leptonic and semileptonic B, D, K decays
- B-mixing
- $B \to X_s\gamma$
- $b \to s\ell^+\ell^-$ observables
- LFU observables: $R_{K^{(*)}}, R_{D^{(*)}}$
- $R_{K^{(*)}}$ cannot be resolved simultaneously with other observables



- Two scenarios: excluding and including $R_{K^{(*)}}$
- Flavour anomalies lead to upper bounds on $m_{H^\pm}$
- Small region of overlap between anomalies and others – some tension with theory constraints?





***preliminary**

- Excluding $R_{K^{(*)}}$:

  $\tan\beta \lesssim 13.4\,(9.7)$ at $2\sigma\,(1\sigma)$

  $m_{H^\pm} \gtrsim 740\,(930)$ GeV at $2\sigma\,(1\sigma)$

- Including $R_{K^{(*)}}$:

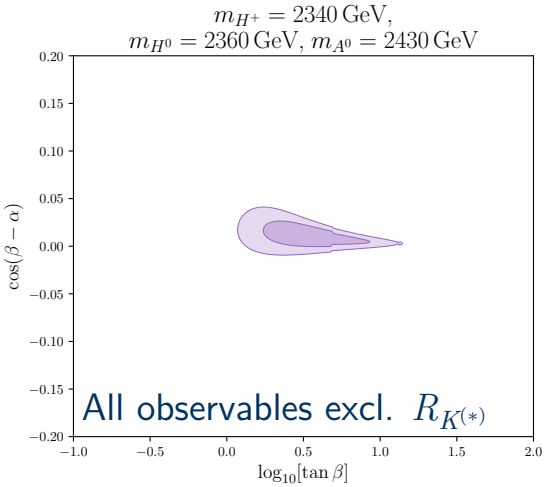
  $\tan\beta \lesssim 13.4\,(9.7)$ at $2\sigma\,(1\sigma)$

  $m_{H^\pm} \gtrsim 640\,(810)$ GeV at $2\sigma\,(1\sigma)$

- Now also include EWPOs: S,T,U
- 275 observables total; 10 $R_{K^{(*)}}$ bins

Best fit, $\{\tan\beta, m_{H^\pm}, m_{H^0}, m_{A^0}, \cos(\beta-\alpha)\}$:

- Excl. $R_{K^{(*)}}$:
  - $\{4.1, 2340\,\text{GeV}, 2360\,\text{GeV}, 2430\,\text{GeV}, 0.0100\}$
  - $\chi^2/\text{dof} = 1.10$ p-value $= 13.7\%$
- Incl. $R_{K^{(*)}}$:
  - $\{4.0, 2310\,\text{GeV}, 2230\,\text{GeV}, 2320\,\text{GeV}, 0.0098\}$
  - $\chi^2/\text{dof} = 1.16$ p-value $= 4.0\%$
- Wrong Sign Limit disfavoured by global fit
  - $\chi^2/\text{dof} \sim 10$



- Excluding $R_{K^{(*)}}$:

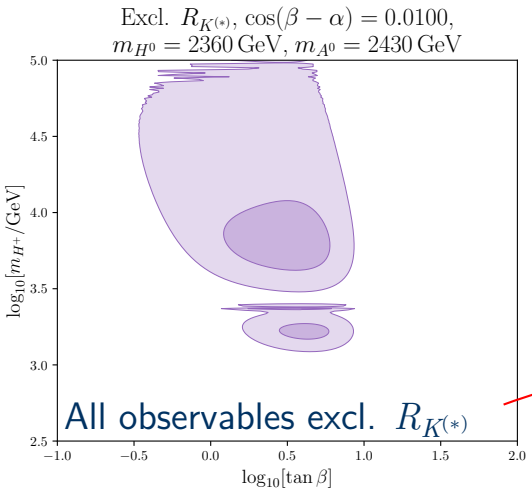
  $\cos(\beta-\alpha) \lesssim 0.041\,(0.026)$ at $2\sigma\,(1\sigma)$

  $\tan\beta \in [1.2\,(1.8), 13.7, (8.4)]$ at $2\sigma\,(1\sigma)$

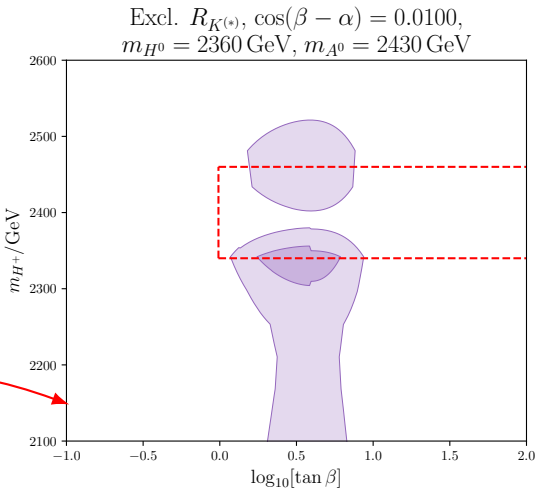
- Including $R_{K^{(*)}}$: ***preliminary**

  $\cos(\beta-\alpha) \lesssim 0.041\,(0.025)$ at $2\sigma\,(1\sigma)$

  $\tan\beta \in [1.2\,(1.7), 13.4\,(9.9)]$ at $2\sigma\,(1\sigma)$



+ theory constraints



- Excluding $R_{K^{(*)}}$:

  $m_{H^\pm} \gtrsim 1240\,(1480)$ GeV at $2\sigma\,(1\sigma)$

  $\tan\beta \in [0.3\,(1.2), 8.6\,(6.1)]$ at $2\sigma\,(1\sigma)$

- Including $R_{K^{(*)}}$:

  $m_{H^\pm} \gtrsim 1150\,(1370)$ GeV at $2\sigma\,(1\sigma)$

  $\tan\beta \in [0.6\,(1.7), 8.8\,(6.7)]$ at $2\sigma\,(1\sigma)$

- Excluding $R_{K^{(*)}}$: ***preliminary**

  $m_{H^\pm} \in [2350, 2450]$ GeV

  $\tan\beta \in [1.2\,(1.7), 9.2\,(7.2)]$ at $2\sigma\,(1\sigma)$

- Including $R_{K^{(*)}}$:

  $m_{H^\pm} \in [2240, 2320]$ GeV

  $\tan\beta \in [1.2\,(1.8), 9.2\,(7.1)]$ at $2\sigma\,(1\sigma)$

*preliminary

- Sakharov criteria for Baryogenesis ➡ Strongly First-Ordered EWPT (SFOEWPT) needed [Sakharov '91]
- Only in SM for $m_{h^0} \lesssim 70\,\text{GeV}$ [Kajantie et al. '96]
- Recent studies find SFOEWPT possible for $m_{H^\pm} \lesssim 1\,\text{TeV}$ [Basler et al. '16] [Su, Williams, Zhang '20]
- We use the **BSMPT** package to find [Basler & Mühlleitner '18] [Basler, Mühlleitner, Müller '20] $\xi_c = \frac{\omega_c}{T_c} > 1$ for SFOEWPT
- Best fit points yield $\xi_c \sim 0.14$ ➡ SFOEWPT incompatible with other 2HDM-II constraints?
- We plan to test ξ_c across our parameter space
- To what confidence could we find $\xi_c > 1$?

- We have presented a comprehensive study of the 2HDM-II
- Tested its parameter space using theory constraints, Higgs signals, flavour observables, and EWPOs
  - ➥ 275 observables in total
  - ➥ with fits including and excluding 10 $R_{K^{(*)}}$ bins
- Excluding theory constraints, we find lower bounds on m_{H^+}
- Including theory constraints, we find a small region still allowed for fixed $m_{H^0}, m_{A^0}, \cos(\beta - \alpha)$
- In all scenarios, $\tan\beta \sim \mathcal{O}(1) - \mathcal{O}(10)$
- Only small deviations from the alignment limit are allowed, and the Wrong Sign Limit is excluded
- So far, we do not find a SFOEWPT within 2σ
- Outlook: ➥ Extend to other 2HDMs: I,X,Y ➥ Collider searches

Thank you for listening!