Exploring 2HDM with `Magellan`

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BSM searches

Aim:

- infer on the 'health' of the model (non-excluded regions)
- identify interesting regions/signals (where searches high sensitivity for exclusion/avenues for discovery)

Challenges:

- multiple constraints that are needed to be taken into account
- models usually have many parameters $\Longrightarrow$ high dimensionality. Attached problems:
  - computing power to explore the parameter space.
  - statistical interpretation
- sometimes it is hard to see the overall picture (various search channels, observables, ...)

Example for an approach within 2HDM.

Minimalistic extension of the Higgs sector: 2HDM

Doublet structure:

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{v\cdot cos(\beta)+h_1+i\eta_1}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{v\cdot sin(\beta)+h_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$$

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Scalars: h, H, A, $H^\pm$ (5 d.o.f) ✓

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2HDM properties:

- minimalistic extension of SM, adds only a few arbitrary parameters
- satisfies $\rho = \frac{m_W^2}{m_Z^2 \cos^2(\theta_W)} \sim 1$
- structure can be present in more complete theories (e.g. SUSY, Composite Higgs)

Recommended references:

Theory and phenomenology of two-Higgs-doublet models [Branco et al., 2012]

Higgs Hunters' guide [Gunion et al., 1990]

The anatomy of electroweak symmetry breaking Tome II [Djouadi, 2008]

2HDM - Counting # d.o.f of the potential

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

Parameters:

- m_{11}^2, m_{22}^2 and λ_i with $i = 1, ..., 4 \in \mathbb{R}$
- m_{12}^2, λ_i with $i = 5, 6, 7 \in \mathbb{C}$

General potential ($\mathcal{V}_{gen}$): **14 parameters**

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remaining:	**6 parameters**

2HDM Type-II hqq couplings

$$\kappa_{h\bar{d}d} = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta \xrightarrow[\beta-\alpha=\frac{\pi}{2}]{} 1 \text{ (middle-region)}$$

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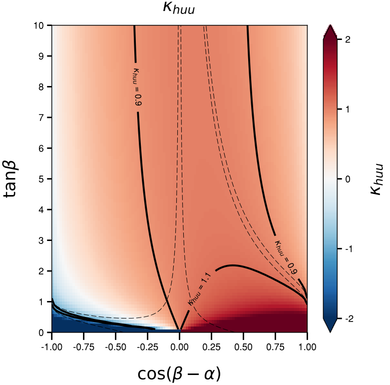
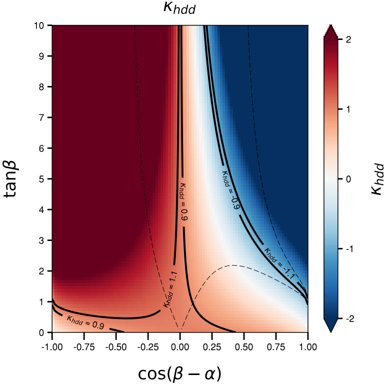




Constraints on the parameter space

Theoretical constraints:

- **Unitarity** of the scattering matrix S: upper bound on the eigenvalues of the matrix

$$|L_i| \leq 16\pi$$

[Ginzburg and Ivanov, 2005, Kanemura et al., 1993]

- **Perturbativity**: quartic Higgs couplings should be small

$$|C_{H_i H_j H_k H_l}| \leq 8\pi$$

- **Stability** of the potential: the quartic Higgs potential terms are bounded from below

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

[Deshpande and Ma, 1978]

Using 2HDMC [Eriksson et al., 2010]

Constraints on the parameter space

Experimental constraints:

- Experimental limits on flavour changing neutral currents (FCNC) $\Longrightarrow \mathbb{Z}_2$ symmetry of the dimension 4 terms of the Higgs potential.
- Observed **Higgs signal strengths**: χ^2 fit to data (with `HiggsSignals`) constructing $\Delta\chi^2 = \chi^2 - \chi^2_{min}$, and identifying the $1, 2$ and 3σ non-excluded regions
- **Non-observation of additional Higgs states**: negative LHC searches $\rightarrow$ 95 % exclusion limits (`HiggsBounds`)
- Electro-Weak Precision Observables (**EWPO**): Check on S, T, U parameters.
- **Constraint on $\mathbf{m_{H^\pm}}$**: From $\bar{B} \rightarrow X_s\gamma$ at CLEO, Belle and BABAR $\Longrightarrow$ $m_{H^\pm} > 480 GeV$ at 95 % [Misiak et al., 2015]

Existing 2HDM literature

Common problem of parameter scans in high dimensional parameter space (here d=6) is the CPU time, and to take into account all the constraints simultaneously.

See e.g.:
Haber et al (1507.04281) Bernon et al. (1507.00933) Dorsch et al. (1601.04545)

You usually find:

- Only benchmark points/planes
- Multi-dimensional scan is constrained in one of the parameters
- Some constraint is not taken into account. (e.g. flavour $b \to s\gamma$)

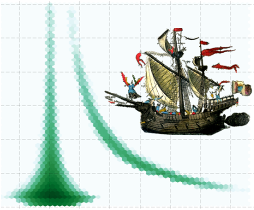
Natural evolution of the tools

Old framework: `awk` + `shell` + `gnuplot`. Ugh.

New framework: `Magellan`

Features:

- Use of parallel processing when doing scans (16 cores $\Longrightarrow$ 16 times speed increase) based on T3PS 1503.01073
- Data stored in pandas DataFrames, HDF5 file format, BLOSC compression (=fast read speed, much easier analysis)
- Fast pipeline, interactive visualisation, linked brushing



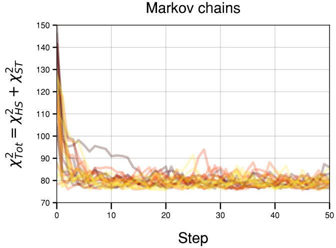
Physics tools: `2HDMC`, `HiggsBounds`, `HiggsSignals`, `SusHi`

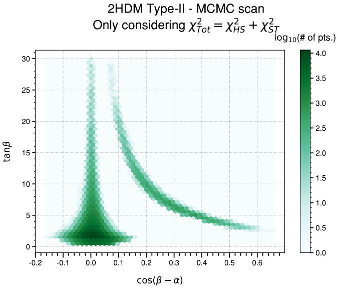
Parameter scan: `T3PS` (MCMC)

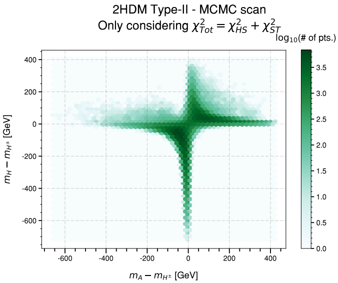
Data processing, visualisation: (standard instandard in data science) `pandas`, `jupyter`, `bokeh`, `holoviews`, `corner`

MCMC scan

Using vanilla-Metropolis Hastings sampler.

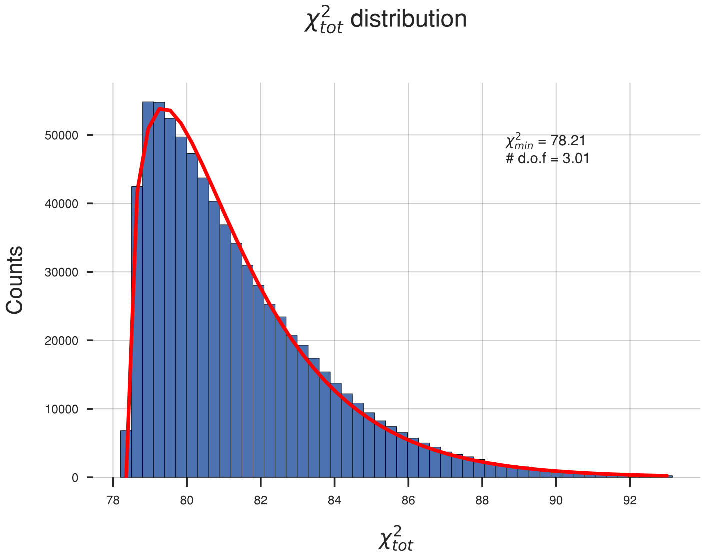






Demo

Extracting the relevant d.o.f from the χ^2 distribution



Summary and Outlook

Prelim findings of the study:

- Restricted parameter space if every constraint is applied.
- Depending on the parameters, alignment limit may not be allowed, while wrong-sign scenario is.
- Quicker iteration with the new framework.
- Idea is to make the dataset & interactive frontend public.

Todo:

- Proper Bayesian & frequentist analysis
- could test other samplers: `MultiNest`, `pymc3` (Hamiltonian, No-U-Turn sampler)

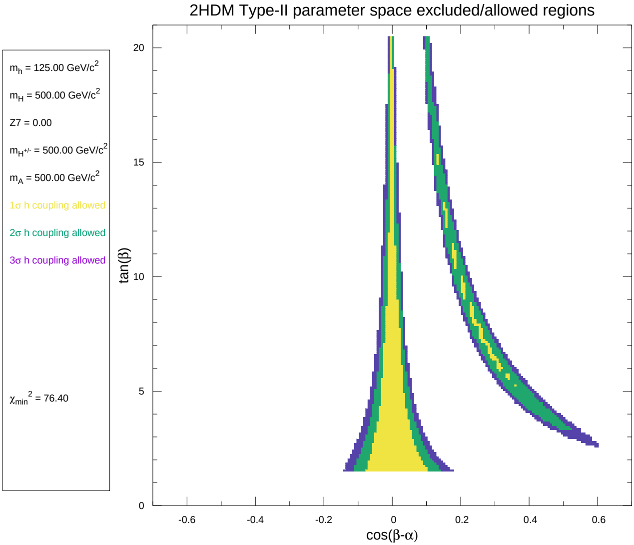
Thank you for your attention!

Backup

2HDM Parameter scans

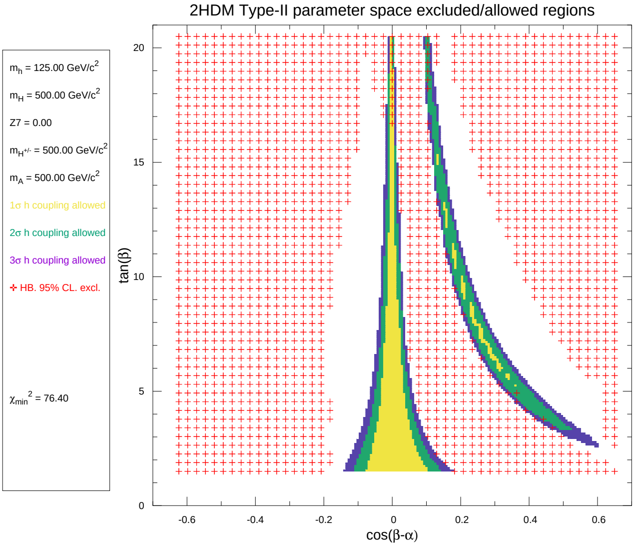
Let's take a look at the effect of the constraints.

2HDM Parameter scans



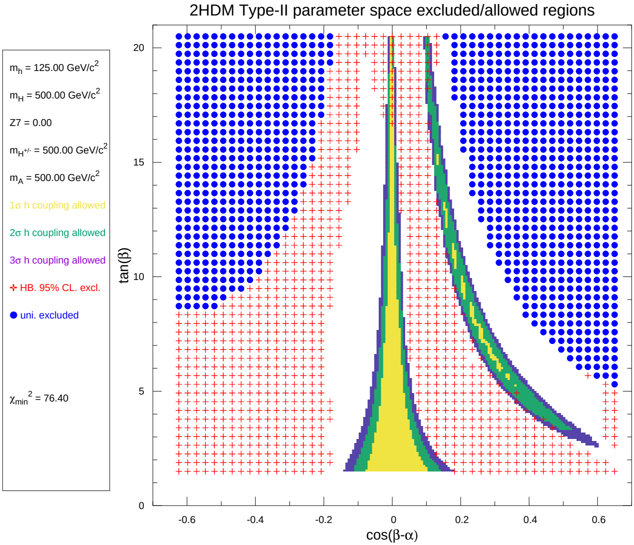
Considering bounds from Higgs signal strengths only

2HDM Parameter scans



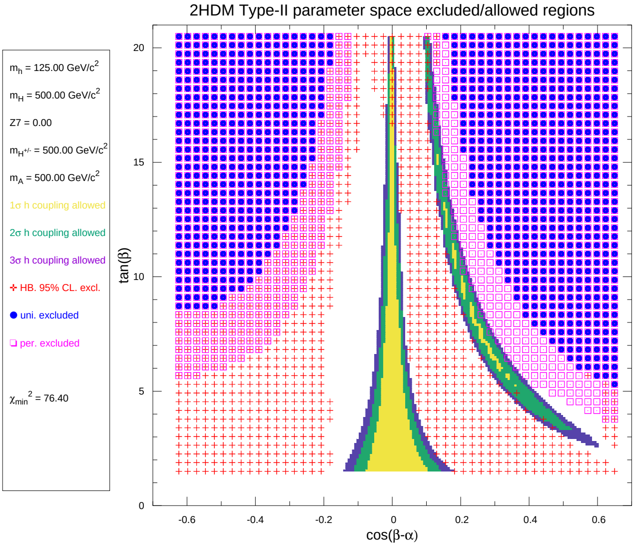
+ applying exclusion limits from the non-observation of additional Higgs

2HDM Parameter scans



Applying unitarity bounds.

2HDM Parameter scans



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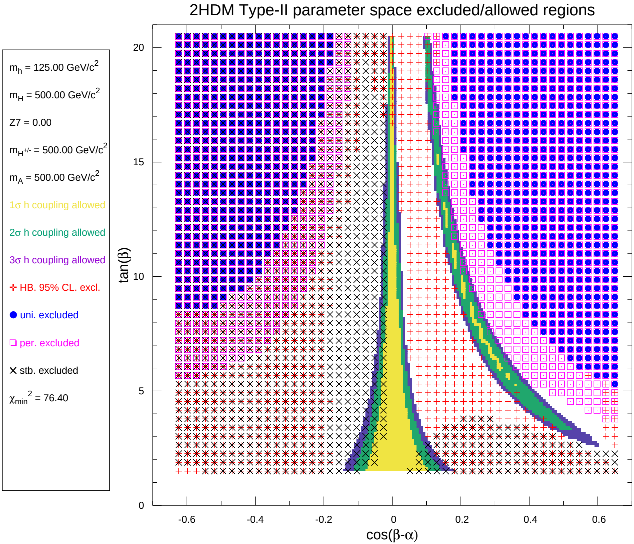
2HDM Parameter scans



Applying stability constraint.

2HDM Parameter scans

Viable region of parameter space is limited - to construct prospective signals at LHC, constraints have to be taken into account.

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We also find that theory constraints play a crucial role: the stability condition excludes the alignment limit region in certain scenarios. (see in the following)

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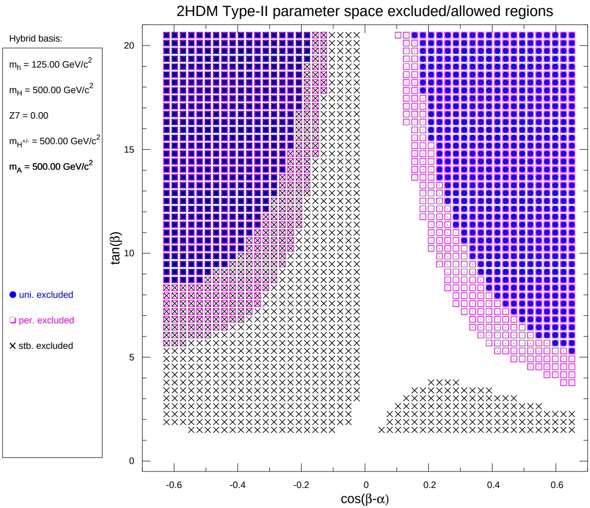

$m_A = 500$ GeV

Alignment limit region is allowed.

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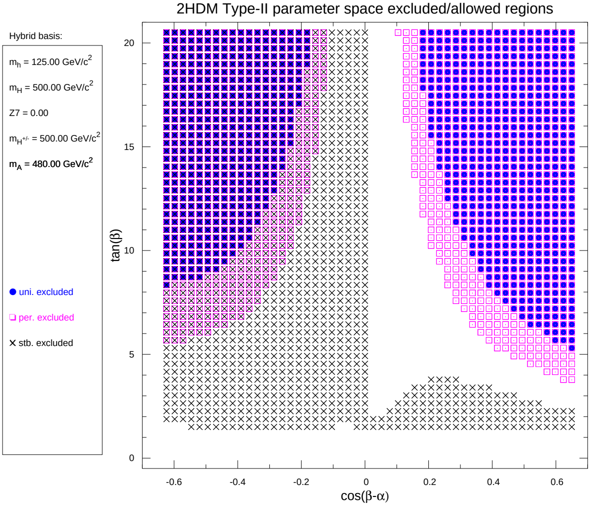
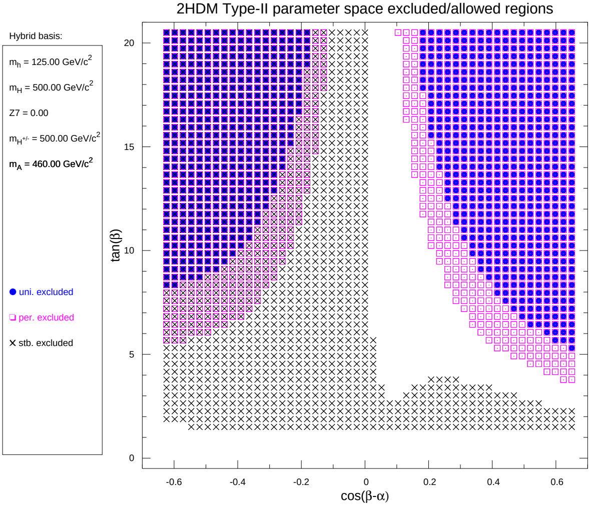


$$m_A = 480 \text{ GeV}$$

Stability condition starting to close the alignment limit region.

2HDM Parameter scans



$$m_A = 460 \text{ GeV}$$

... closing the alignment limit region.

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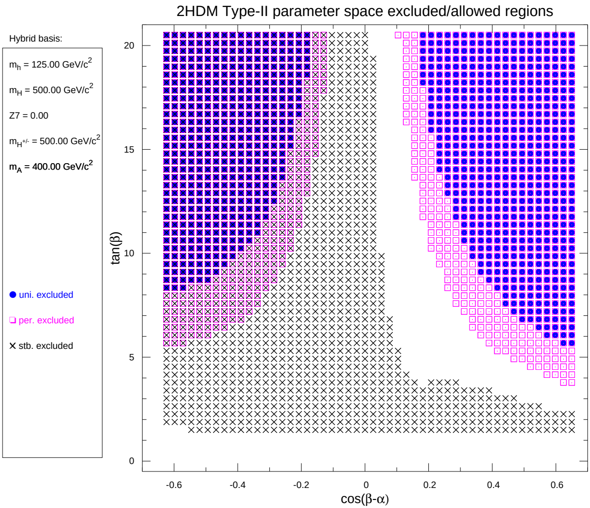

$$\mathbf{m_A = 400\ GeV}$$

Alignment limit region excluded.

2HDM - Higgs potential parametrization

General potential parameters:

m_{12}^2, λ_1, λ_2, λ_3, λ_4, λ_5

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- not very convenient when looking at scaling of the couplings

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Hybrid parametrization: (1507.04281)

$$\underbrace{m_H,}_{\text{CP-even Higgs mass}} \quad \underbrace{\cos(\beta-\alpha),}_{\substack{\text{determines} \\ g_{hVV} \text{ \& } g_{HVV} \text{ couplings}}} \quad \underbrace{\tan(\beta),}_{\text{ratio of the vevs.}} \quad \underbrace{Z_4, \quad Z_5, \quad Z_7}_{\substack{\text{Higgs self-coupling} \\ \text{parameters}}}$$

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Parametrization in this study:

$$\underbrace{m_H, m_A, m_{H^\pm}}_{\text{Higgs masses}} \quad \underbrace{\cos(\beta-\alpha),}_{\text{determines } g_{hVV} \text{ \& } g_{HVV} \text{ couplings}} \quad \underbrace{\tan(\beta),}_{\text{ratio of the vevs.}} \quad \underbrace{Z_7}_{\text{Higgs self-coupling parameter}}$$

2HDM - Yukawa sector

Scaling of couplings with respect to SM in 2HDM:

Model	h			H			A		
	u	d	l	u	d	l	u	d	l
Type-I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{-\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\cot\beta$	$\tan\beta$	$\tan\beta$

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Type-II case:

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$$\kappa_{h\bar{d}d} = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta \xrightarrow[\beta-\alpha=\frac{\pi}{2}]{} 1 \text{ (middle-region)}$$

$$= -\sin(\beta+\alpha) + \cos(\beta+\alpha)\tan\beta \xrightarrow[\beta+\alpha=\frac{\pi}{2}]{} -1 \text{ (right-arm)}$$

$$\kappa_{h\bar{u}u} = \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cos(\beta-\alpha)\cot\beta \xrightarrow[\beta-\alpha=\frac{\pi}{2}]{} 1 \text{ (middle-region)}$$

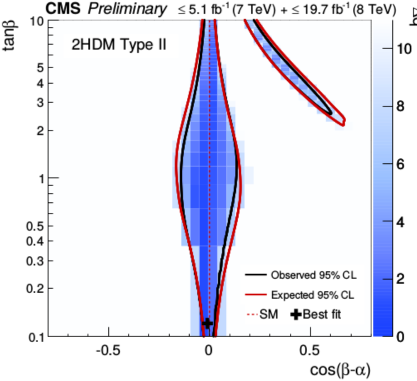
$$= \sin(\beta+\alpha) + \cos(\beta+\alpha)\cot\beta \xrightarrow[\beta+\alpha=\frac{\pi}{2}]{} 1 \text{ (right-arm)}$$

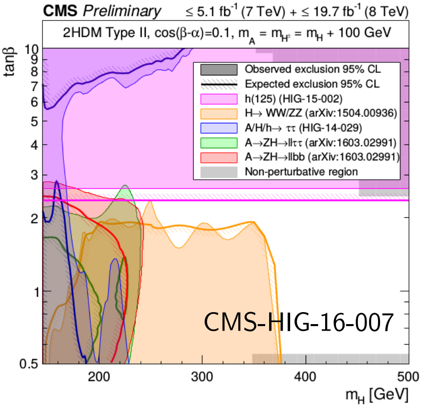
Type-II wrong-sign scenario $\kappa_{h\bar{d}d} = -1$ (right arm):

$$\tan\beta = \sqrt{\frac{1}{\cos^2(\beta-\alpha)} - 1} + \frac{1}{\cos(\beta-\alpha)}$$

2HDM - Current status

CMS BSM Higgs Run-1 Summary result:





"Although the data slightly prefer a positive sign of $\lambda_{du} = \kappa_{hu\bar{u}}/\kappa_{hd\bar{d}}$, the positive and negative signs can not be distinguished at the 95% CL."

$\Longrightarrow$ Right arm still well and alive.

Parameter scans - Unstable alignment

Stability conditions:

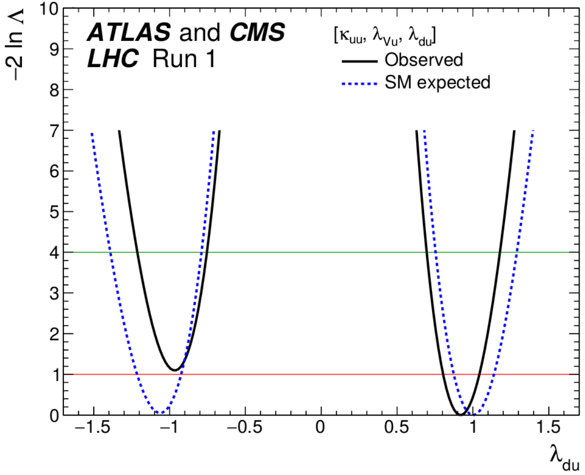
$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \quad \underbrace{\lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1 \lambda_2} > 0}_{\text{violated}}$$

Near the alignment limit we find:

- $|\lambda_4| \sim |\lambda_5| \gg \lambda_i$
- $\lambda_4 < 0$
- $\lambda_5 > 0$

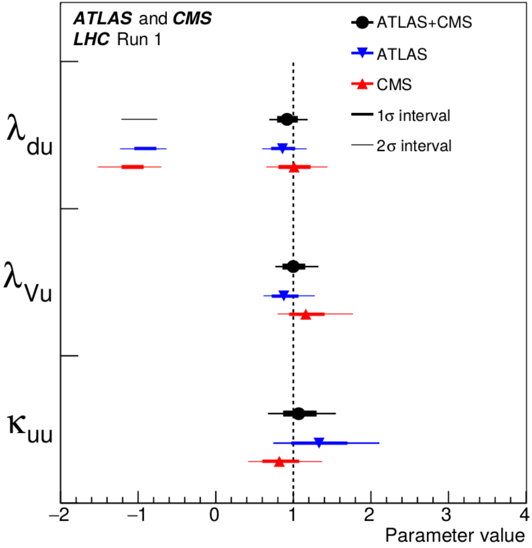
Some recent papers on stability condition with loop renormalisation:
[Bagnaschi et al., 2016] [Das and Saha, 2015]

ATLAS-CMS Higgs boson measurements - λ_{du}



1507.04548

ATLAS-CMS Higgs boson measurements - λ



1507.04548

2HDM bases and parametrizations

General	λ_i, $i = 1, \ldots, 7$, m_{12}^2, $\tan\beta$	
Higgs basis	Λ_i, $i = 1, \ldots, 7$, $m_{H^\pm}$	$\tan\beta = 0$
Physical basis	m_h, m_H, m_A, $m_{H^\pm}$, $\sin(\beta-\alpha)$, λ_6, λ_7, $\tan\beta$	

$$Z_5 = (m_h^2 \cos^2(\beta-\alpha) + m_H^2 \sin(\beta-\alpha) - m_A^2)/v^2$$
$$Z_4 = 2(m_A^2 - m_{H^\pm}^2)/v^2 + Z_5$$

(1507.04281)