Global fits of the Two-Higgs-Doublet models with a softly broken $\mathbb{Z}_2$ symmetry

Multi-Higgs Workshop

Lisbon, 4th September 2018

Otto Eberhardt (Instituto de Física Corpuscular, València)
in collaboration with D. Chowdhury
based on *JHEP 1805 (2018) 161*

Motivation

HEPfit – overview

Model $\longrightarrow$ Parameters & Observables

Priors $\pi(\boldsymbol{\theta})$ Likelihoods $L(\boldsymbol{x}|\boldsymbol{\theta})$

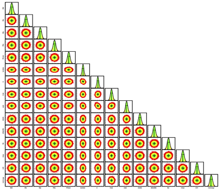
Output:

HEPfit – overview

Model $\longrightarrow$ Parameters & Observables

Priors $\pi(\boldsymbol{\theta})$ Likelihoods $L(\boldsymbol{x}|\boldsymbol{\theta})$

Output: Parameter and observable posterior distributions



HEPfit – overview

Model ⟶ Parameters & Observables

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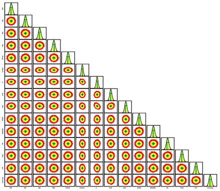
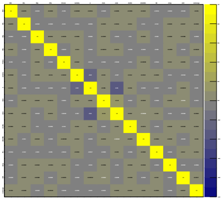
Output: Parameter and observable posterior distributions
Parameter correlations



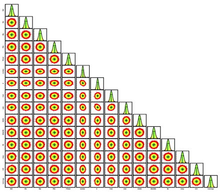


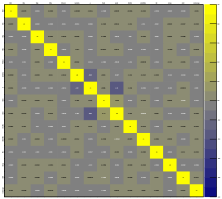
HEPfit – overview

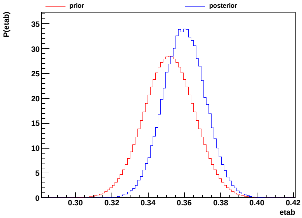
Model ⟶ Parameters & Observables

Priors $\pi(\boldsymbol{\theta})$ Likelihoods $L(\boldsymbol{x}|\boldsymbol{\theta})$

Output: Parameter and observable posterior distributions
Parameter correlations
Comparison of prior and posterior





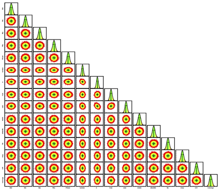


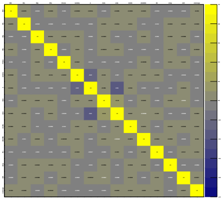
HEPfit – overview

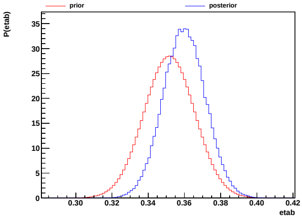
Model $\longrightarrow$ Parameters & Observables

Priors $\pi(\boldsymbol{\theta})$ Likelihoods $L(\boldsymbol{x}|\boldsymbol{\theta})$

Output: Parameter and observable posterior distributions
Parameter correlations
Comparison of prior and posterior
Global mode and normalisation, (D)IC values







HEPfit – models

- Standard Model with full flexibility [1512.07157,1608.01509]
- Various effective models [1608.01509,1803.00939]
- 2HDM with and without $\mathbb{Z}_2$ symmetry [1609.01290,1711.02095]
- Manohar-Wise model (+2HDM) [1808.05824]
- Georgi-Machacek model [1807.10660]
- Complex MSSM (work in progress)
- Left-Right symmetric model (work in progress)

HEPfit – models

Standard Model with full flexibility

Various effective models

2HDM with and without $\mathbb{Z}_2$ symmetry

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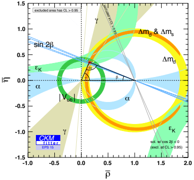
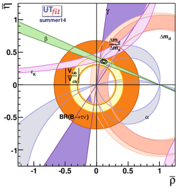
Left-Right symmetric model



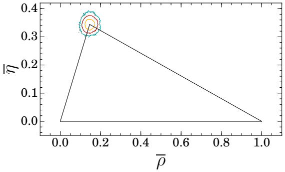
[CKMfitter '15]

$\mathcal{O}$(days)



[UTfit '14]

$\mathcal{O}$(days)



[HEPfit '17]

$\mathcal{O}$(hour)

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HEPfit – models

Standard Model with full flexibility

Various effective models

2HDM with and without $\mathbb{Z}_2$ symmetry

Manohar-Wise model (+2HDM)

Georgi-Machacek model

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Left-Right symmetric model (work in progress)

} Additional scalars!

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HEPfit – models

- Standard Model with full flexibility
- Various effective models
- 2HDM with and without $\mathbb{Z}_2$ symmetry
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- Left-Right symmetric model (work in progress)

The general 2-Higgs-Doublet model

$$\begin{aligned} V_H^{\text{G2HDM}} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right] \\ & + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ & + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \tfrac{1}{2} \left[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right] \\ & + \tfrac{1}{2} \left[\lambda_6 (\Phi_1^\dagger \Phi_2)(\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_2) + \text{H.c.} \right] \end{aligned}$$

$$\mathcal{L}_Y^{\text{G2HDM}} = -\sum_{j=1}^{2} \left[Y_j^u \bar{Q}_L \tilde{\Phi}_j u_R + Y_j^d \bar{Q}_L \Phi_j d_R + Y_j^e \bar{L}_L \Phi_j \ell_R \right] + \text{H.c.}$$

SM + 11 new parameters in V_H^{G2HDM}

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The general 2-Higgs-Doublet model

$$V_H^{\text{G2HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right]$$
$$+ \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$
$$+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \tfrac{1}{2}\left[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right]$$
$$+ \tfrac{1}{2}\left[\lambda_6 (\Phi_1^\dagger \Phi_2)(\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_2) + \text{H.c.} \right]$$

$$\mathcal{L}_Y^{\text{G2HDM}} = -\sum_{j=1}^{2} \left[Y_j^u \bar{Q}_L \tilde{\Phi}_j u_R + Y_j^d \bar{Q}_L \Phi_j d_R + Y_j^e \bar{L}_L \Phi_j \ell_R \right] + \text{H.c.}$$

SM + 11 new parameters in V_H^{G2HDM}

→ see Ana Peñuela's talk later today

The 2-Higgs-Doublet model with a softly broken $\mathbb{Z}_2$

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

$$
\mathcal{L}_Y^{\text{2HDM}} = -Y_2^u \bar{Q}_L \tilde{\Phi}_2 u_R - \sum_{j=1}^{2} \left[Y_j^d \bar{Q}_L \Phi_j d_R + Y_j^e \bar{L}_L \Phi_j \ell_R \right] + \text{H.c.}
$$

	I	II
X	Y_2^d	Y_1^e
Y	Y_2^e	Y_1^d

SM + 6 new parameters in V_H^{2HDM}

Parametrizations in HEPfit

m_{11}^2

m_{22}^2

m_{12}^2

λ_1

λ_2

λ_3

λ_4

λ_5

Parametrizations in HEPfit

m_{11}^2 m_{22}^2 m_{12}^2 λ_1 λ_2 λ_3 λ_4 λ_5

Y_1 Y_2 Y_3 Z_1 Z_2 Z_3 Z_4 Z_5 Z_6 Z_7

$$V_H^{2HDM} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3 \left[H_1^\dagger H_2 + \text{H.c.}\right]$$
$$+ \tfrac{1}{2} Z_1 \left(H_1^\dagger H_1\right)^2 + \tfrac{1}{2} Z_2 \left(H_2^\dagger H_2\right)^2$$
$$+ Z_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + Z_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right)$$
$$+ \left[\tfrac{1}{2} Z_5 \left(H_1^\dagger H_2\right)^2 + Z_6 \left(H_1^\dagger H_1\right)\left(H_1^\dagger H_2\right)\right.$$
$$\left. + Z_7 \left(H_2^\dagger H_2\right)\left(H_1^\dagger H_2\right) + \text{H.c.}\right]$$

$$H_1 = \Phi_1 c_\beta + \Phi_2 s_\beta, \quad H_2 = -\Phi_1 s_\beta + \Phi_2 c_\beta$$

[Haber et al.]

Parametrizations in HEPfit

m_{11}^2	Y_1	v_1
m_{22}^2	Y_2	v_2
m_{12}^2	Y_3	λ_1^{HH}
λ_1	Z_1	λ_2^{HH}
λ_2	Z_2	λ_3^{HH}
λ_3	Z_3	λ_4^{HH}
λ_4	Z_4	λ_5^{HH}
λ_5	Z_5	λ_6^{HH}
	Z_6	
	Z_7	

$$
\begin{aligned}
V_H^{2HDM} = {} & \lambda_1^{HH}\left(\Phi_1^\dagger\Phi_1 - {v_1}^2\right)^2 \\
& + \lambda_2^{HH}\left(\Phi_2^\dagger\Phi_2 - {v_2}^2\right)^2 \\
& + \lambda_3^{HH}\left(\Phi_1^\dagger\Phi_1 - {v_1}^2 + \Phi_2^\dagger\Phi_2 - {v_2}^2\right)^2 \\
& + \lambda_4^{HH}\left[(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\right] \\
& + \lambda_5^{HH}\left[\mathrm{Re}\left(\Phi_1^\dagger\Phi_2\right) - v_1 v_2\right]^2 \\
& + \lambda_6^{HH}\left[\mathrm{Im}\left(\Phi_1^\dagger\Phi_2\right)\right]^2
\end{aligned}
$$

[Higgs Hunter's Guide]

Parametrizations in HEPfit

m_{11}^2	Y_1	v_1	ξ_0
m_{22}^2	Y_2	v_2	ξ_1
m_{12}^2	Y_3	λ_1^{HH}	ξ_3
λ_1	Z_1	λ_2^{HH}	η_{00}
λ_2	Z_2	λ_3^{HH}	η_3
λ_3	Z_3	λ_4^{HH}	E_{11}
λ_4	Z_4	λ_5^{HH}	E_{22}
λ_5	Z_5	λ_6^{HH}	E_{33}
	Z_6		
	Z_7		

$$V_H^{\mathrm{2HDM}} = \xi_0 K_0 + \xi_i K_i + \eta_{00} K_0^2 + 2\eta_i K_i K_0 + E_{ij} K_i K_j$$

$$K_0 = \Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2$$
$$K_1 = \Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1$$
$$K_2 = i\Phi_2^\dagger \Phi_1 - i\Phi_1^\dagger \Phi_2$$
$$K_3 = \Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2$$

[Maniatis, Nachtmann]

Parametrizations in HEPfit

m_{11}^2	Y_1	v_1	ξ_0	v
m_{22}^2	Y_2	v_2	ξ_1	m_h
m_{12}^2	Y_3	λ_1^{HH}	ξ_3	m_{12}^2
λ_1	Z_1	λ_2^{HH}	η_{00}	$\tan\beta$
λ_2	Z_2	λ_3^{HH}	η_3	$\beta-\alpha$
λ_3	Z_3	λ_4^{HH}	E_{11}	$m_H^{(2)}$
λ_4	Z_4	λ_5^{HH}	E_{22}	$m_A^{(2)}$
λ_5	Z_5	λ_6^{HH}	E_{33}	$m_{H^\pm}^{(2)}$
	Z_6			
	Z_7			

Parametrizations in HEPfit

m_{11}^2	Y_1	v_1	ξ_0	$v \approx 246$ GeV
m_{22}^2	Y_2	v_2	ξ_1	$m_h \approx 125$ GeV
m_{12}^2	Y_3	λ_1^{HH}	ξ_3	$-(1.5\ \mathrm{TeV})^2 \leq m_{12}^2 \leq (1.5\ \mathrm{TeV})^2$
λ_1	Z_1	λ_2^{HH}	η_{00}	$0.1 \leq \tan\beta \leq 50$
λ_2	Z_2	λ_3^{HH}	η_3	$0 \leq \beta - \alpha < \pi$
λ_3	Z_3	λ_4^{HH}	E_{11}	$130\ \mathrm{GeV} \leq m_H \leq 1.5$ TeV
λ_4	Z_4	λ_5^{HH}	E_{22}	$130\ \mathrm{GeV} \leq m_A \leq 1.5$ TeV
λ_5	Z_5	λ_6^{HH}	E_{33}	$130\ \mathrm{GeV} \leq m_{H^\pm} \leq 1.5$ TeV
	Z_6			
	Z_7			

The Two-Higgs-Doublet Model – constraints

Positivity of V_H^{2HDM} v as global minimum Perturbative NLO unitarity	} Theory constraints
h signal strengths Searches for H, A and $H^{\pm}$ Oblique parameters Flavour observables	} Experimental constraints

The Two-Higgs-Doublet Model – constraints

Positivity of V_H^{2HDM}

v as global minimum

Perturbative NLO unitarity

h signal strengths

Searches for H, A and $H^\pm$

Oblique parameters

Flavour observables

$$\lambda_1 > 0, \qquad \lambda_2 > 0,$$

$$\lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$

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

[Deshpande, Ma '78]

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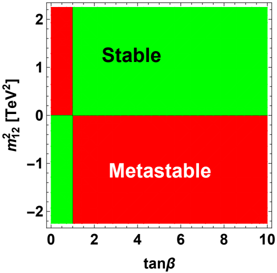
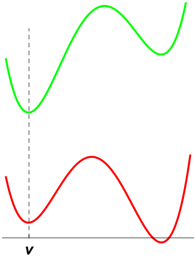
$$m_{12}^2 \left(m_{11}^2 - \sqrt{\frac{\lambda_1}{\lambda_2}} m_{22}^2 \right) \left(\tan\beta - \sqrt[4]{\frac{\lambda_1}{\lambda_2}} \right) > 0$$

For example, if $m_{11} > m_{22}$ and $\lambda_1 = \lambda_2$:





[Barroso, Ferreira, Ivanov, Santos '13]

The Two-Higgs-Doublet Model – constraints

Positivity of V_H^{2HDM}

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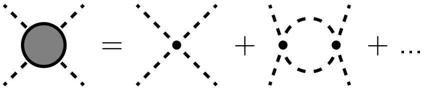
$$P(\phi_i\phi_j \to \phi_k\phi_\ell) \leq 1$$



LO $\geq$ NLO

[Grinstein, Murphy, Uttayarat '15]
[Cacchio, Chowdhury, OE, Murphy '16]

The Two-Higgs-Doublet Model – constraints

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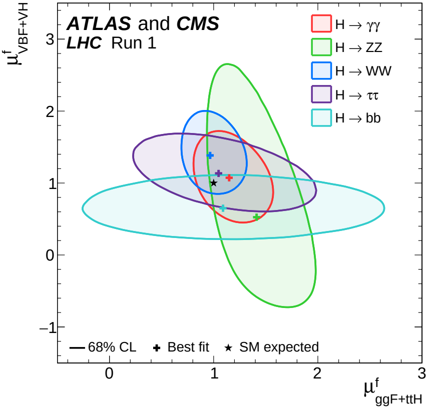
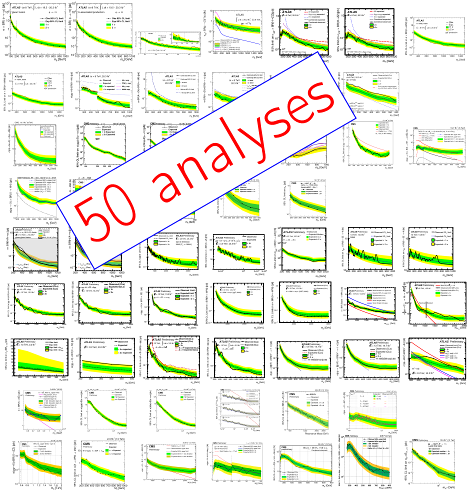


+ run II data

[ATLAS, CMS '14–'17]

The Two-Higgs-Doublet Model – constraints

- Positivity of V_H^{2HDM}
- v as global minimum
- Perturbative NLO unitarity
- h signal strengths
- Searches for H, A and $H^{\pm}$
- Oblique parameters
- Flavour observables



[ATLAS, CMS '14–'17]

The Two-Higgs-Doublet Model – constraints

- Positivity of V_H^{2HDM}
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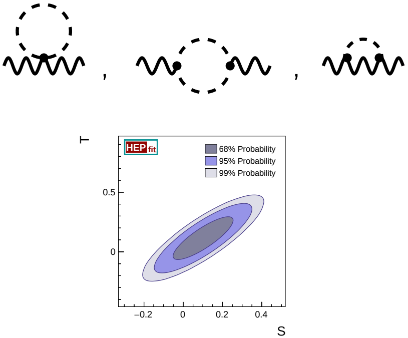
S, T, U are functions of



[Peskin, Takeuchi, '90, '91; Haber '92; HEPfit '16]

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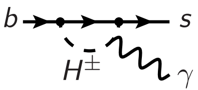
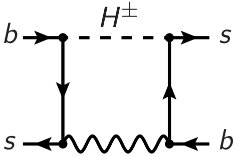


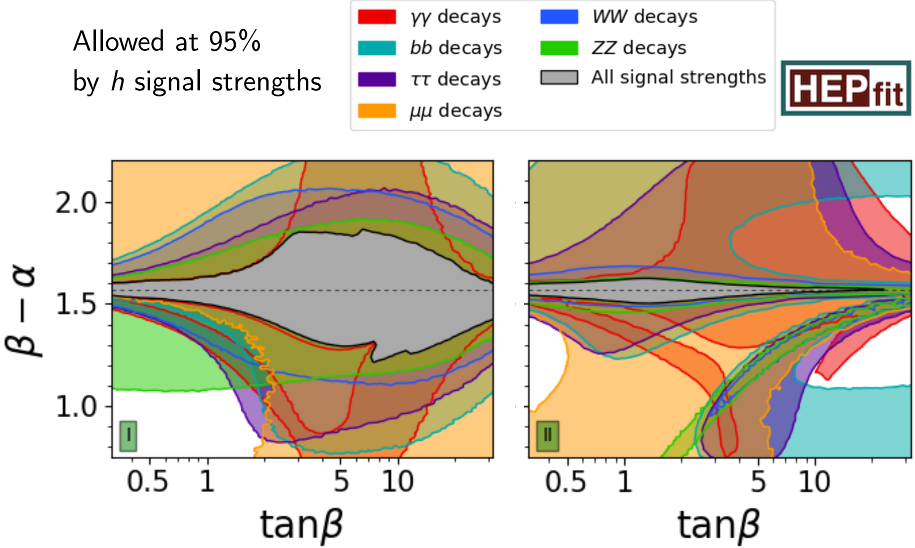
[Misiak et al. '15; HFLAV '17]



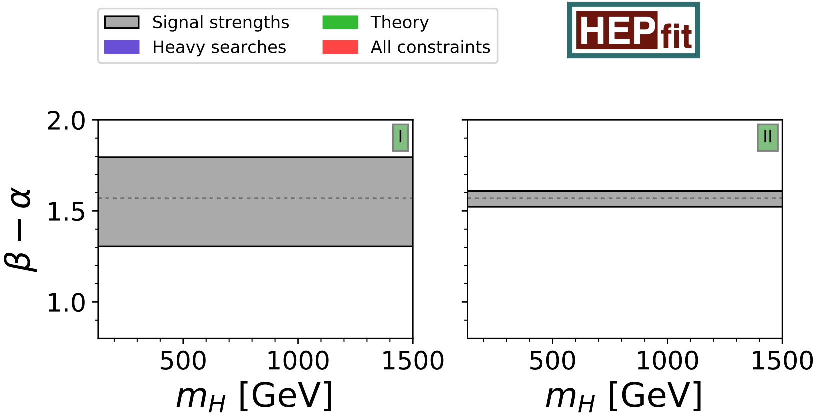
[Deschamps et al. '09; HFLAV '17]

Fit with h signal strengths only

Allowed at 95%
by h signal strengths



H mass fits with all constraints



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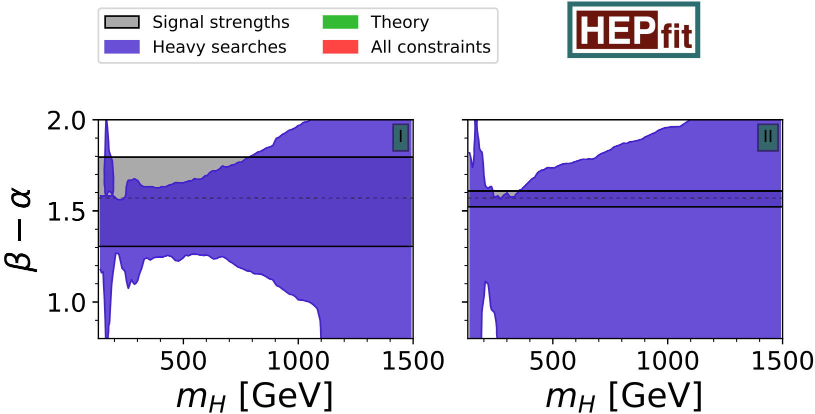

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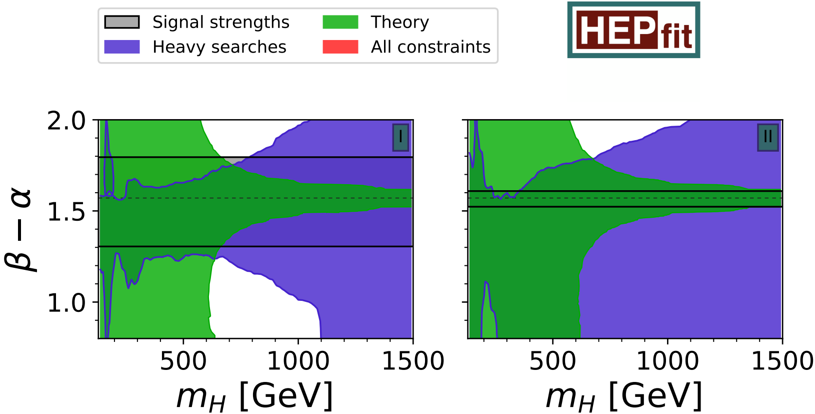

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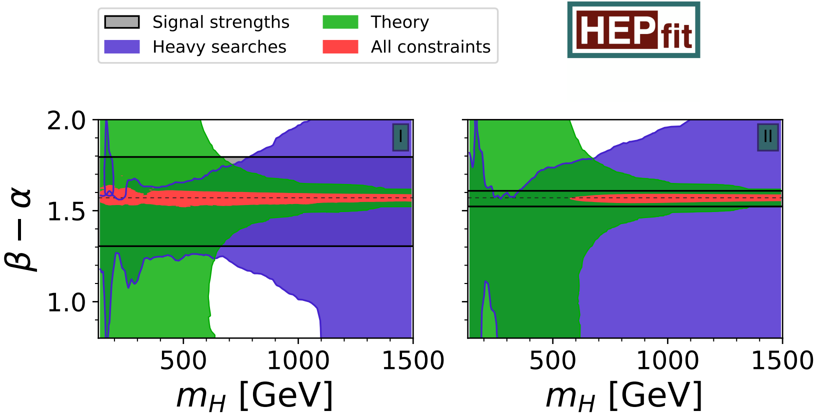
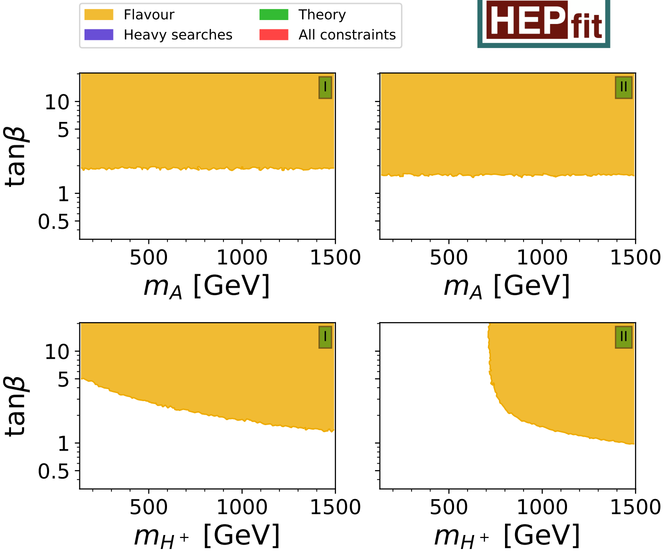


A, H^+ mass fits with all constraints



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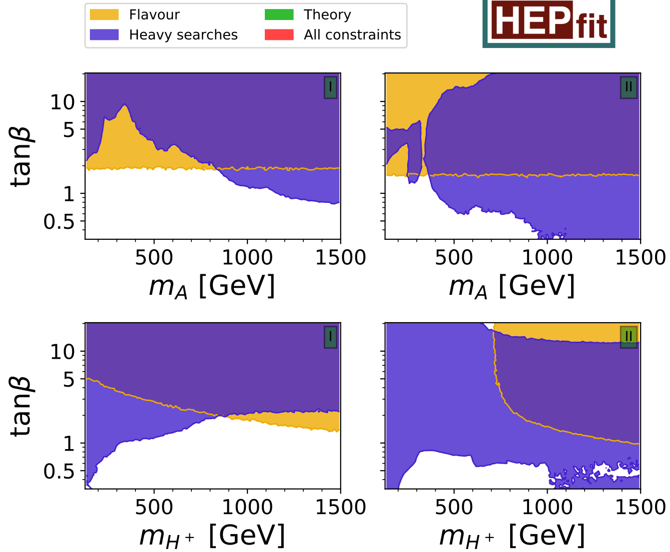

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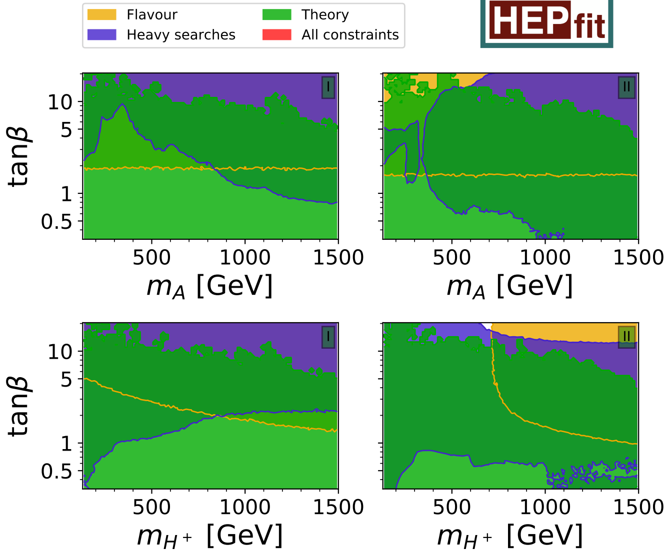

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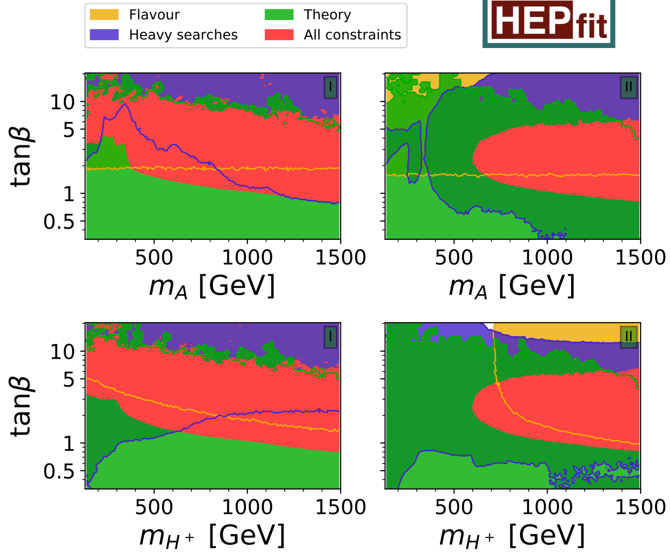

Mass differences, widths, $\mathbb{Z}_2$ breaking

	Type I	Type II
Mass differences:		
$\|m_H - m_A\|$	< 200 GeV	< 130 GeV
$\|m_H - m_{H^+}\|$	< 160 GeV	< 120 GeV
$\|m_A - m_{H^+}\|$	< 180 GeV	< 110 GeV
Decay widths:		
Γ_{H_i}/m_{H_i} for $H_i = H, A, H^+$	$\lesssim 7\%$	$\lesssim 5\%$
$\mathbb{Z}_2$ breaking:		
m_{12}^2	–	$> (280\text{ GeV})^2$

Conclusions

Use HEPfit:

http://hepfit.roma1.infn.it

2HDM with a softly broken $\mathbb{Z}_2$ symmetry are strongly constrained:

$|\beta - \alpha - \pi/2| < 0.03$.

$m_{H_i} > 700$ GeV in type II with $H_i = H, A, H^+$

Exotic decays $H_1 \to H_2 H_3$ can be excluded.

For more information: *JHEP 1805 (2018) 161*