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Exploring sizable triple Higgs Couplings in the 2HDM

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with *F. Arco and M.J. Herrero* [*arXiv:2005.10576*]

Many slides taken from talk by F. Arco (DESY, 06/20)

- Motivation
- Model and Constraints
- Results
- Implications for future colliders

1. Motivation

Di-Higgs production: λ_{hhh} or $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$

– deviations possible in BSM models
– which size is still allowed taking all constraints into account?
– implications for measurements at future colliders?

Di-Higgs production involving heavy Higgses: λ_{hhH}, λ_{hHH}, λ_{hAA}, $\lambda_{hH^+H^-}$

– large values of λ's possible?
– which size is still allowed taking all constraints into account?
– implications for searches at future colliders?

$\Rightarrow$ analysis in the 2HDM

2. Model and constraints

The 2HDM

Two Higgs Doublet Model CP conserving

The potential:

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

Considerations:

- ⋆ CP conserving $\longrightarrow$ all parameters are real
- ⋆ $\mathbb{Z}_2$ symmetry to avoid FCNC $\longrightarrow$ softly broken by m_{12}^2 **Very important!**
- ⋆ Four types of Yukawa structure (we will focus on type I and II)

CP odd

7 free parameters + 5 physical states: h, H, A, H^+ and H^-

CP even

Extension of Z_2 symmetry to fermions $\Rightarrow$ 4 types

$\Rightarrow$ analyzed: type I and type II

Possible choice for free parameters:

Free parameters of the 2HDM

- ⋆ Physical masses: m_h, m_H, m_A and $m_{H^\pm}$
  - ⋆ We set $m_h = 125$ GeV
  - ⋆ The rest Higgs bosons are assumed to be heavier
- ⋆ $\tan(\beta) := v_2/v_1$: Ratio of the Higgs doublets vevs
- ⋆ $\cos(\beta-\alpha)$: α diagonalizes the neutral CP even states h and H
  - ⋆ If $\cos(\beta-\alpha) \to 0$ the SM Higgs couplings to gauge bosons are recovered $\Longrightarrow$ *Alignment limit*
  - ⋆ Alignment limit $\neq$ SM, we can have hH^+H^-, ZHA or $H^+u\bar{d}$ interactions even if $\cos(\beta-\alpha)=0$
- ⋆ Soft $\mathbb{Z}_2$ breaking parameter m_{12}^2
  - ⋆ It only enters in the scalar sector

Alignment limit: $\cos(\beta-\alpha) \to 0$

$\Rightarrow$ more details on the model in the back-up

The constraints:

$\rightarrow$ applied to every point analyzed/scanned/...

- Tree-level perturbativity
- Stability: potential is bounded from below
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds (2HDMC)
- SM-like Higgs properties $\Rightarrow$ HiggsSignals (2HDMC)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso
- Electroweak precision data (S, T and U) $\Rightarrow$ 2HDMC

$\Rightarrow$ many details in the back-up

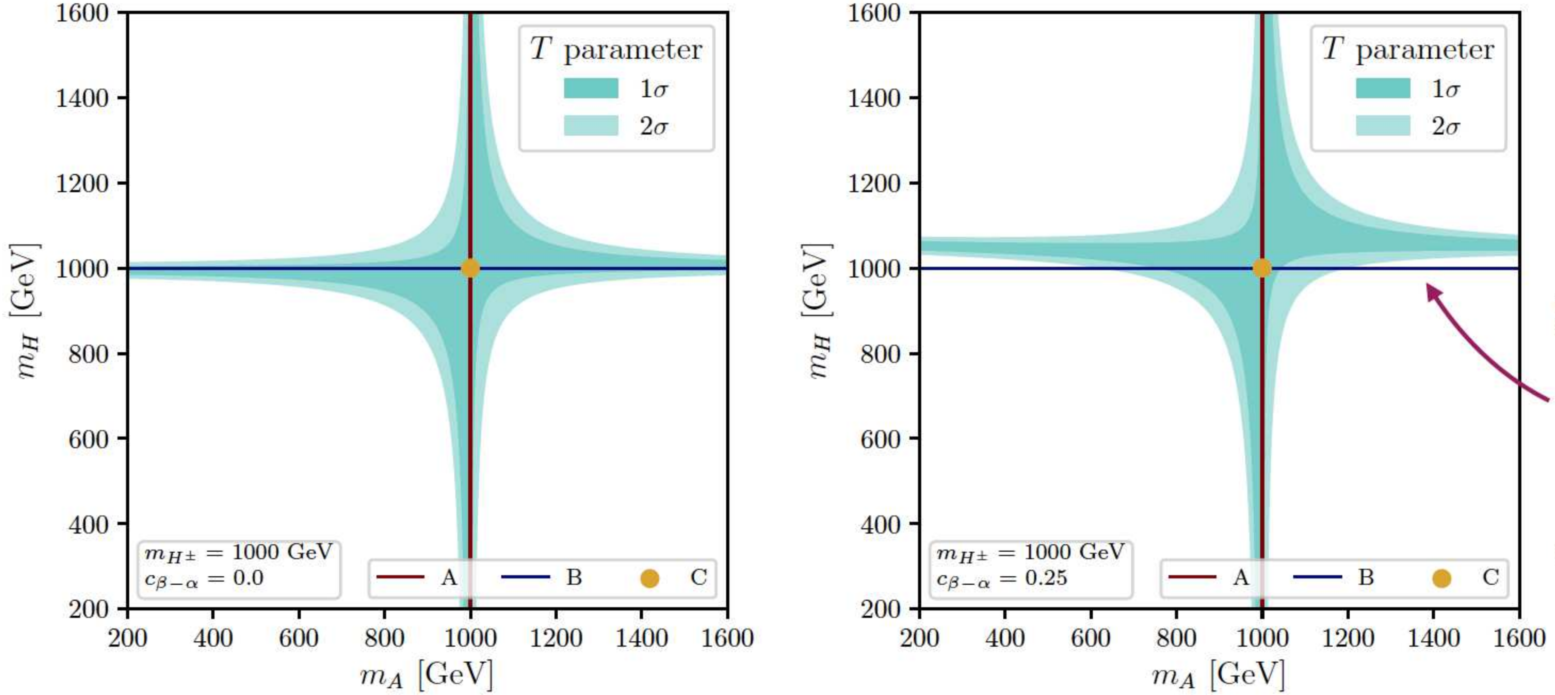
T parameter

T is sensitive to the mass splitting of the Higgs bosons $\Longrightarrow$ 3 simplified scenarios!

Scenario A: $m_A = m_{H^\pm}$

Scenario B: $m_H = m_{H^\pm}$

Scenario C: $m_H = m_A = m_{H^\pm}$



Scenario B may be in conflict with data outside the alignment limit

Predictions of T obtained with 2HDMC [arXiv:0902.0851]

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⇒ definition of Scenario A, B, C

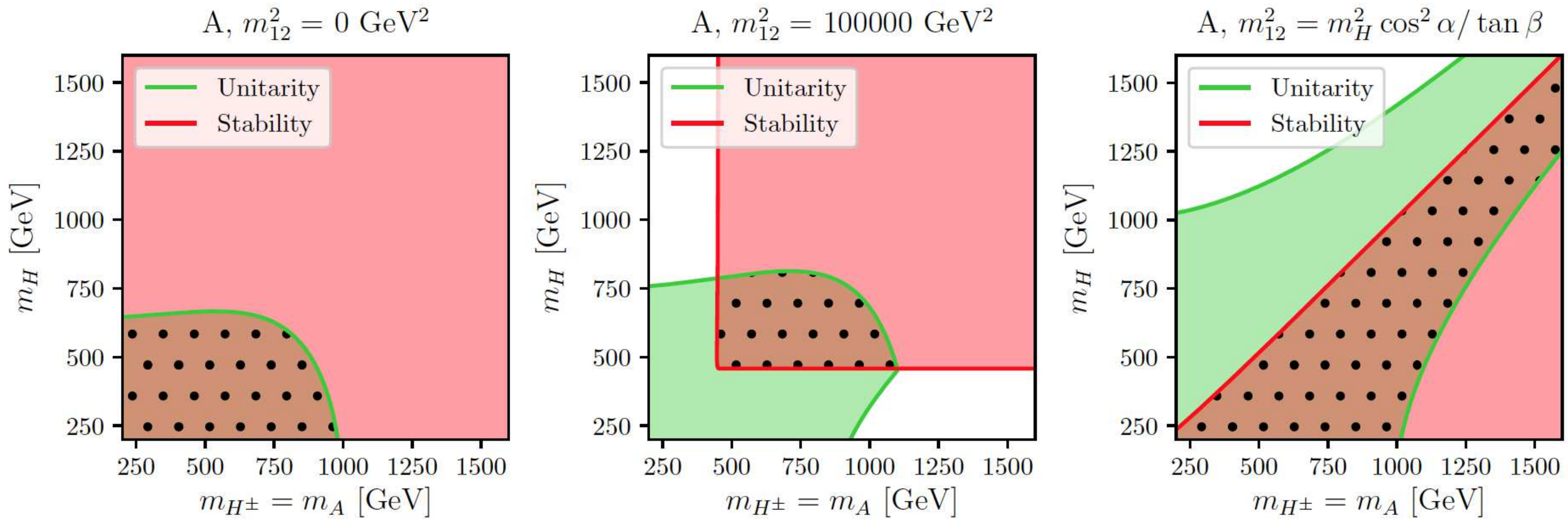
⇒ Once T is satisfied, also S and U are satisfied

Unitarity vs. Stability:

Unitarity + Stability

$\tan\beta = 1.5$
$c_{\beta-\alpha} = 0$

dotted region are allowed regions



★ m_{12}^2 controls the overlapping region between unitarity and stability

★ $m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$ enlarges the allowed region!

Similar for scenario B...

⇒ special condition for m_{12}^2 helps

⇒ more details in the back-up

3. Results

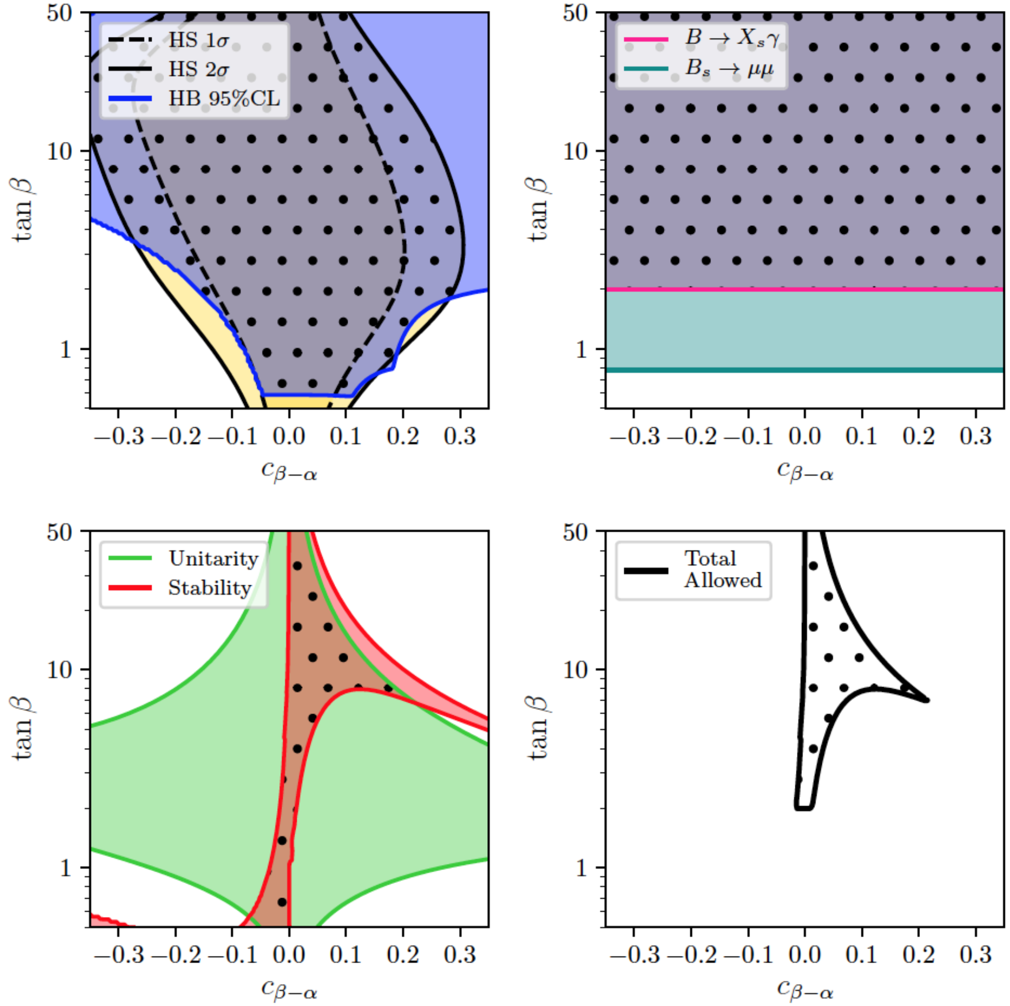
1. understanding of analytical depences of constraints and λ's on the input parameters

2. based on this: parameter scan to find extreme, but allowed points

3. based on this: 2-dim parameter planes to explore

4. parameter planes represent (contain) most "extreme" points we could find

2HDM type I, scenario C

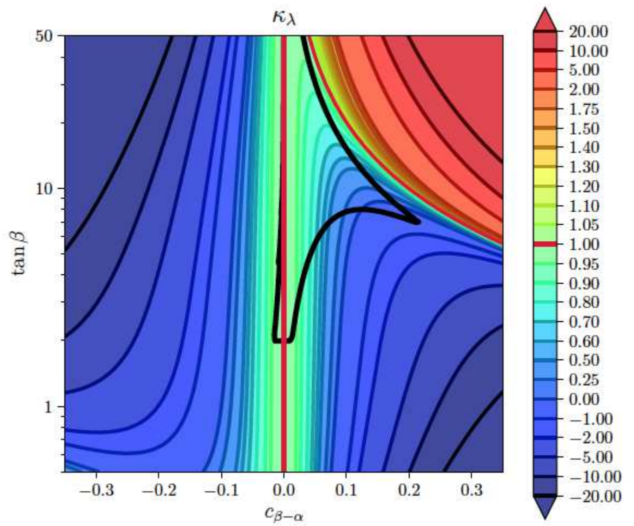


$$m_H = m_A = m_{H^\pm} = 1000 \text{ GeV (scenario C)}$$
$$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$$

- ⋆ Collider searches imposes $|c_{\beta-\alpha}| \lesssim 0.3$
- ⋆ Low $\tan\beta$ disallowed by $B \to X_s\gamma$
- ⋆ Most stringent bounds from theoretical constraints, but helped by $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$

Example I: 2HDM type I: results

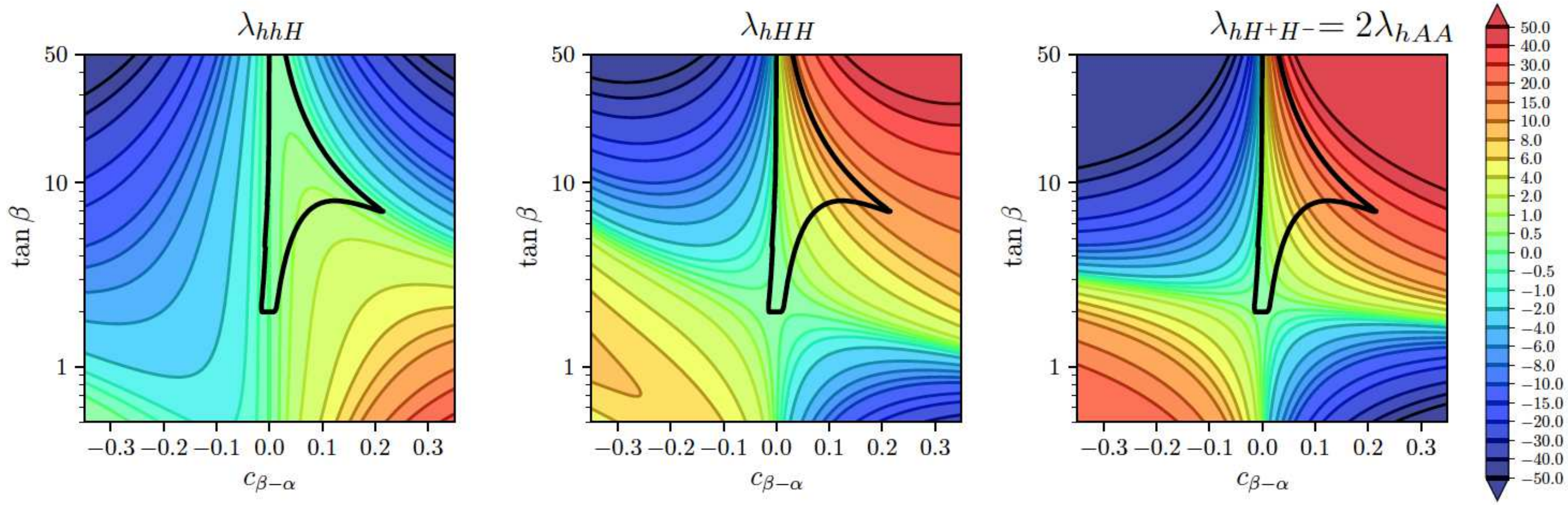
2HDM type I, scenario C



$$m_H = m_A = m_{H^\pm} = 1000\ \text{GeV (scenario C)}$$

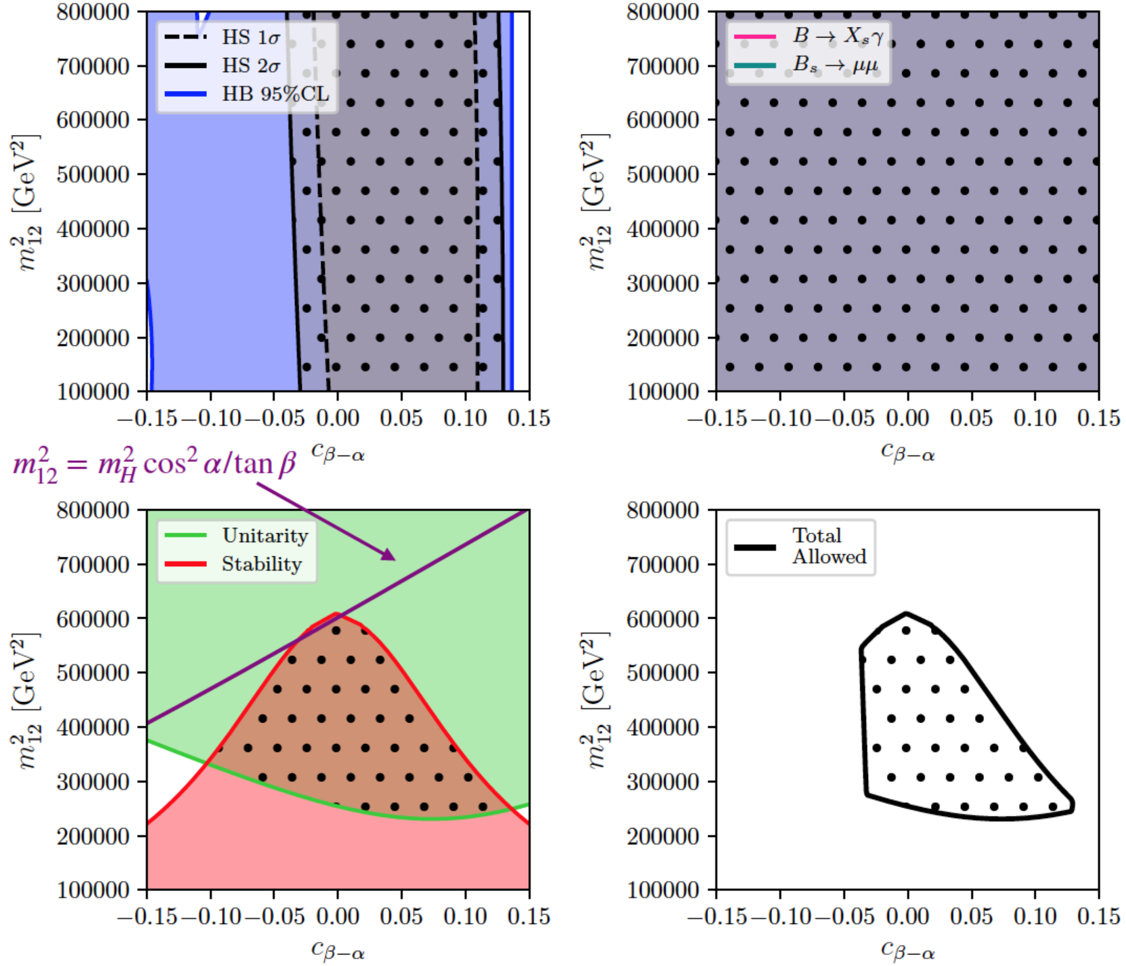
$$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$$

- ⋆ Min $\kappa_\lambda \sim -0.4$ in the "tip" with $\tan\beta \sim 7$ and $c_{\beta-\alpha} \sim 0.2$
- ⋆ Max $\lambda_{hhH} \sim 1.2$ for $c_{\beta-\alpha} \sim 0.1$
- ⋆ Max $\lambda_{hHH} \sim 12$ and $\lambda_{hH^+H^-} = 2\lambda_{hAA} \sim 24$ in the unitarity border



⇒ large deviations for κ_λ ⇒ large values for BSM λ's

2HDM type II, scenario C



$m_H = m_A = m_{H^\pm} = 1100$ GeV (scenario C)

$\tan\beta = 0.9$

- ⋆ Collider measurements $c_{\beta-\alpha} \in [-0.05, 0.13]$ nearly independent of m_{12}^2
- ⋆ No bounds from flavor
- ⋆ Overlapped allowed region by unitarity and stability ($m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$ does not work here)

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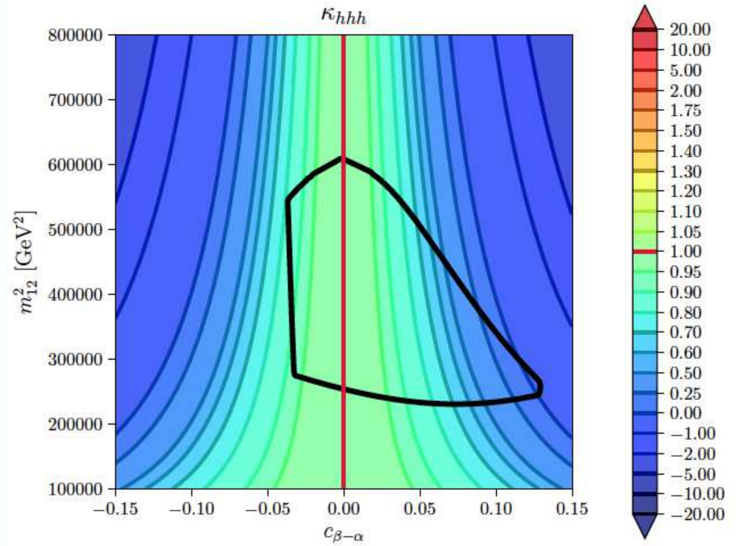
Example II: 2HDM type II: results

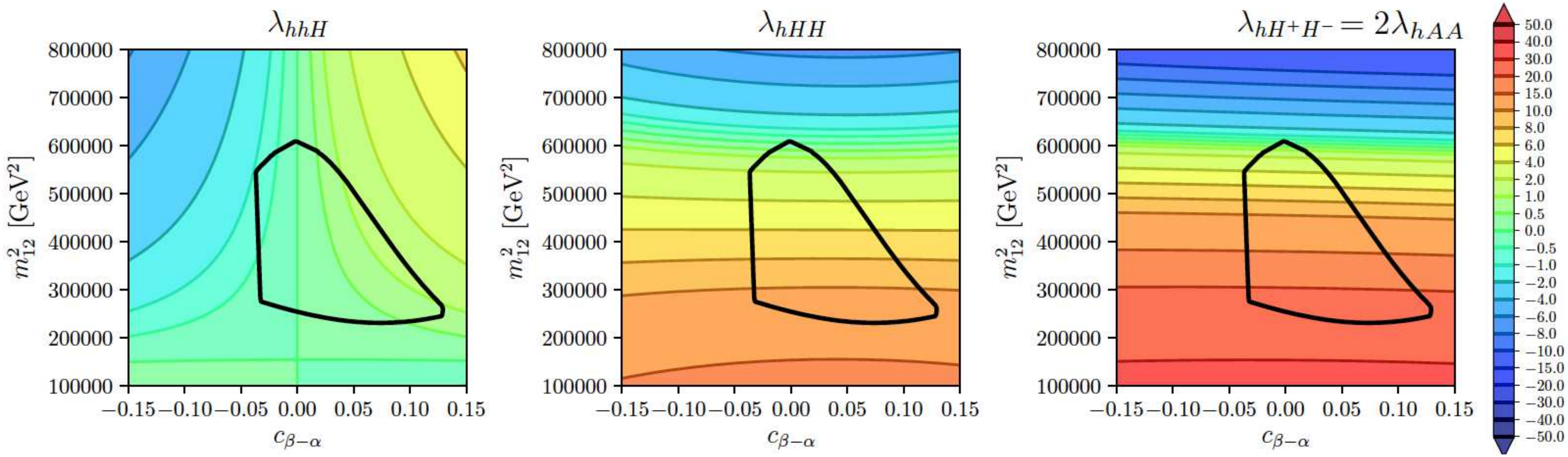
2HDM type II, scenario C



$m_H = m_A = m_{H^\pm} = 1100$ GeV (scenario C)

$\tan\beta = 0.9$

- ⋆ Min $\kappa_\lambda \sim -1.0$ for max $c_{\beta-\alpha} \sim 0.13$
- ⋆ Allowed $\lambda_{hhH} \in [-1,\ 1.4]$
- ⋆ Max $\lambda_{hHH} \sim 12$ and $\lambda_{hH^+H^-} = 2\lambda_{hAA} \sim 24$ for min $m_{12}^2 \sim 2 \times 10^5$ GeV^2



$\Rightarrow$ large deviations for κ_λ $\Rightarrow$ large values for BSM λ's

Result overview:

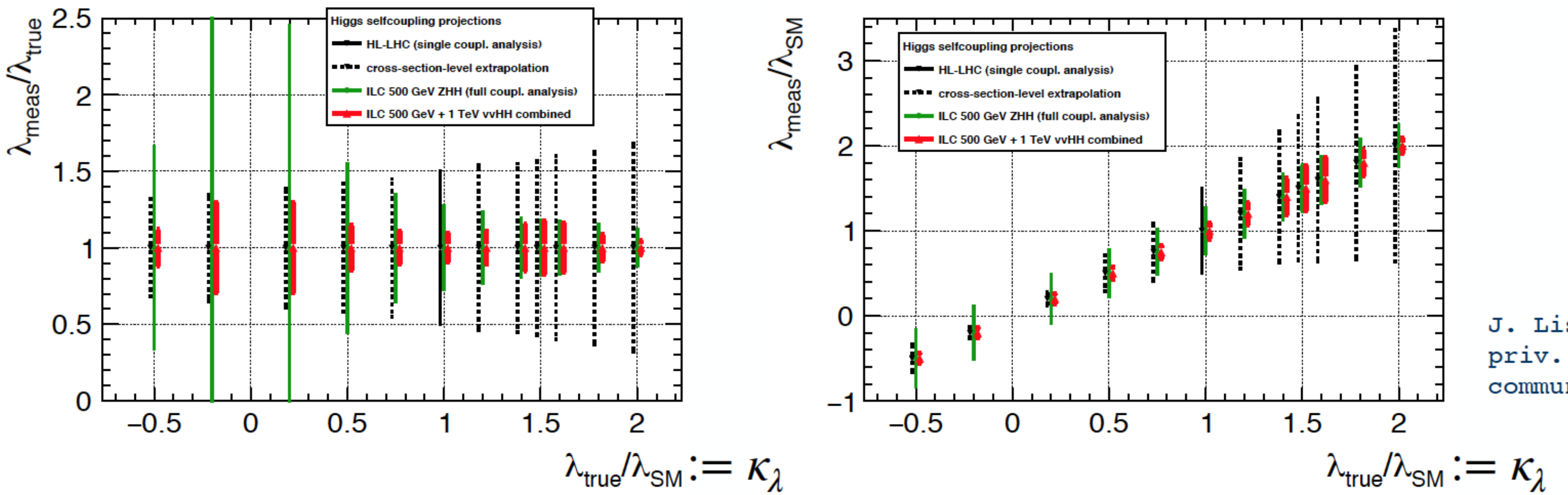
Final allowed ranges

Type I	Type II	
$\kappa_\lambda \in [-0.5,\ 1.5]$	$\kappa_\lambda \in [0.0,\ 1.0]$	→ Far from the alignment limit and playing with m_{12}^2
$\lambda_{hhH} \in [-1.4,\ 1.5]$	$\lambda_{hhH} \in [-1.6,\ 1.8]$	→ For $c_{\beta-\alpha} \sim \pm 0.05$
$\lambda_{hHH} \in [0,\ 15]$	$\lambda_{hHH} \in [0,\ 15]$	Large masses and nearly independent of $c_{\beta-\alpha}$ and scenario A or B
$\lambda_{hAA} \in [0,\ 16]$	$\lambda_{hAA} \in [0,\ 16]$	
$\lambda_{hH^+H^-} \in [0,\ 32]$	$\lambda_{hH^+H^-} \in [0,\ 32]$	

✨ Interesting points are shown in our paper [arXiv:2005.10576] ✨

Experimental determination of λ_{hhh}

Sensitivity of λ_{hhh} for the di-Higgs production in HL-LHC and future ILC:



J. List, priv. commun.

- ⋆ ILC500 + ILC1000 better except for $\kappa_\lambda \sim 0$ where HL-LHC competes

  This analysis does not take into account channels $\neq$ SM

- ⋆ Heavy Higgs production:

  large couplings ⟶ large masses ⟶ propagator suppression

Predictions only for variations of λ_{hhh}

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Further Questions?

The 2HDM

The lagrangian that respects the $\mathbb{Z}_2$ symmetry is given by:

$$\mathscr{L}_{\rm Yuk} = -\sum_{f=u,d,l} \frac{m_f}{v}\left[\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H + i \xi_A^f \bar{f}\gamma_5 f A\right] - \left[\frac{\sqrt{2}}{v}\bar{u}\left(m_u V_{\rm CKM}\xi_A^u P_L + V_{\rm CKM} m_d \xi_A^d P_R\right) d H^+ + \frac{\sqrt{2} m_l}{v}\xi_A^l \bar{\nu} P_R l H^+ + {\rm h.c.}\right]$$

	Type I	Type II
ξ_h^u	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$
$\xi_h^{d,l}$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$
ξ_H^u	$c_{\beta-\alpha} - s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\tan\beta$
$\xi_H^{d,l}$	$c_{\beta-\alpha} - s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$
ξ_A^u	$-\cot\beta$	$-\cot\beta$
$\xi_A^{d,l}$	$\cot\beta$	$-\tan\beta$

Definitions:

$c_{\beta-\alpha} = \cos(\beta-\alpha)$

$s_{\beta-\alpha} = \sin(\beta-\alpha)$

Unitarity + Stability

★ **Tree-level unitarity**

Eigenvalues of the lowest partial wave scattering matrices scalar processes below 16π

$$|\lambda_3 \pm \lambda_4| \leq 16\pi,$$
$$|\lambda_3 \pm \lambda_5| \leq 16\pi,$$
$$|\lambda_3 + 2\lambda_4 \pm 3\lambda_5| \leq 16\pi,$$
$$\left|\frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right)\right| \leq 16\pi,$$
$$\left|\frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2}\right)\right| \leq 16\pi,$$
$$\left|\frac{1}{2}\left(3\lambda_1 + 3\lambda_2 \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2}\right)\right| \leq 16\pi.$$

★ **Stability** [arXiv:1507.06424]

Potential bounded from below

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

+ true minimum

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

$$m_{12}^2 \geq 0$$

★ **Perturbativity**

Unitarity limits the maximum size of λ_i's, so indirectly we satisfy perturbativity

Unitarity + Stability

How to satisfy the theoretical constraints + have large triple Higgs couplings?

- ⋆ Masses can not be too large due to unitarity or be nearly degenerated
- ⋆ m_{12}^2 usually enters with a negative sign in the stability conditions

Problem: λ_1 grows with $\tan\beta$ and gets negative for large m_{12}^2

$$\lambda_1 = \frac{1}{v^2 \cos^2\beta}\left(m_h^2 \sin^2\alpha + m_H^2 \cos^2\alpha - m_{12}^2 \tan\beta\right)$$

$$m_{12}^2 = \frac{m_H^2 \cos^2\alpha}{\tan\beta}$$

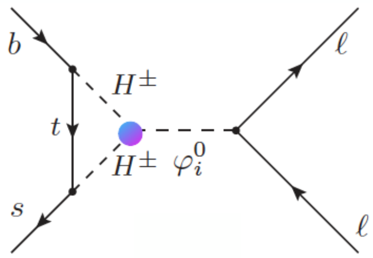
[arXiv:1706.05980]

Experimental Constraints

- Collider measurements & Higgs searches
  - HiggsBounds[arXiv:1311.0055]: 95% C.L. exclusion bounds on searches of BSM bosons at LEP, Tevatron and LHC
  - HiggsSignals[arXiv:1305.1933]: χ^2 statistical test of the 125 GeV Higgs measurements at LHC (Run II included) and Tevatron $\longrightarrow$ 2σ from the SM ($\chi^2_{SM} = 43.6$)
- Flavor measurements
  - SuperISO[arXiv:0808.3144]: Computes flavour observables in a general 2HDM
  - We have included penguin Higgs diagrams to C_S [arXiv:1404.5865] [arXiv:1703.03426]
  - More sensitive observables:
    - $\mathrm{BR}(B \to X_s \gamma) = (3.1 \pm 1.1) \times 10^{-4}$
    - $\mathrm{BR}(B_s \to \mu^+ \mu^-) = \left(2.7\,^{+0.6}_{-0.5}\right) \times 10^{-9}$

    Data from PDG

    } no further than 2σ from the central value



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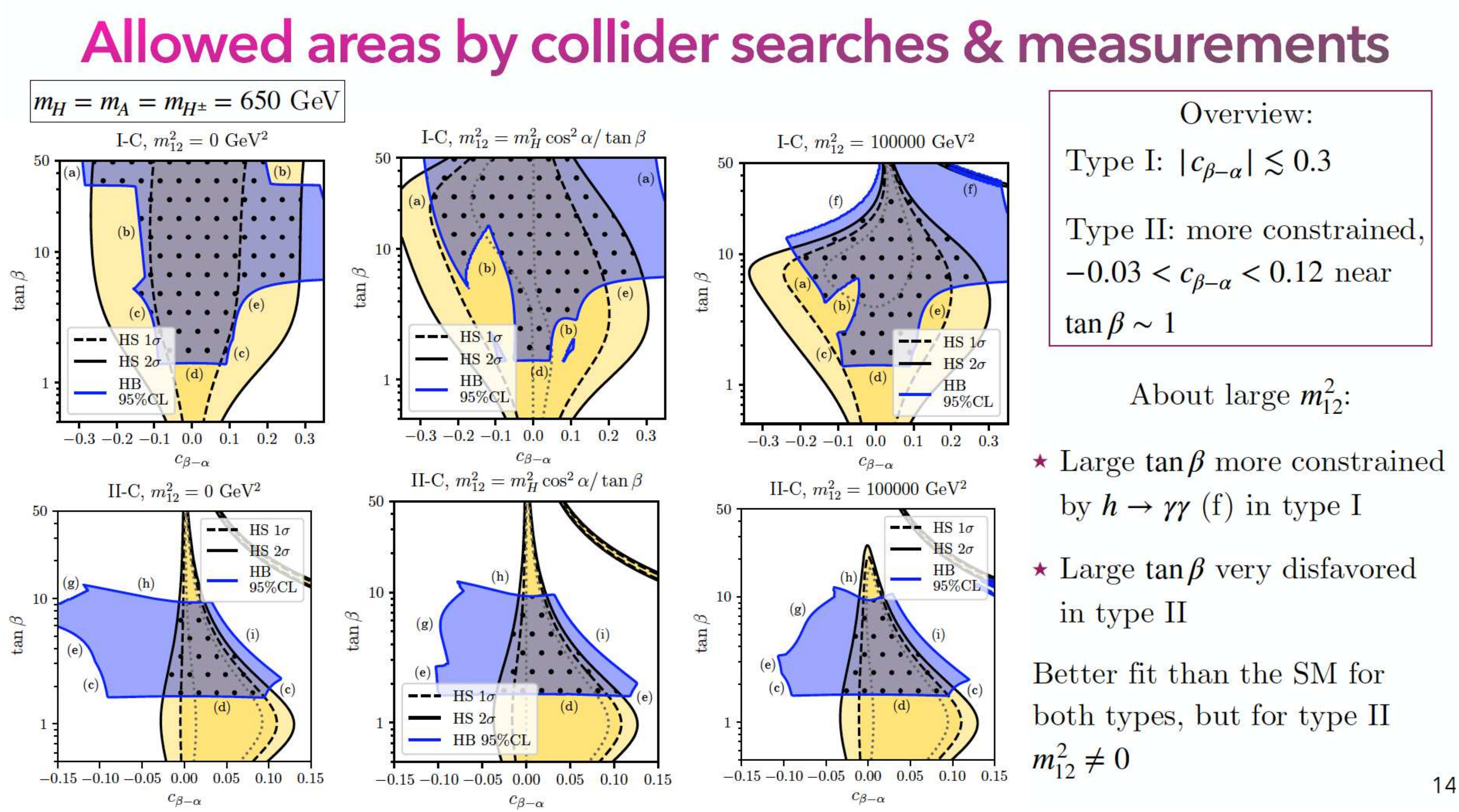
BSM Higgs searches and LHC rate measurements:



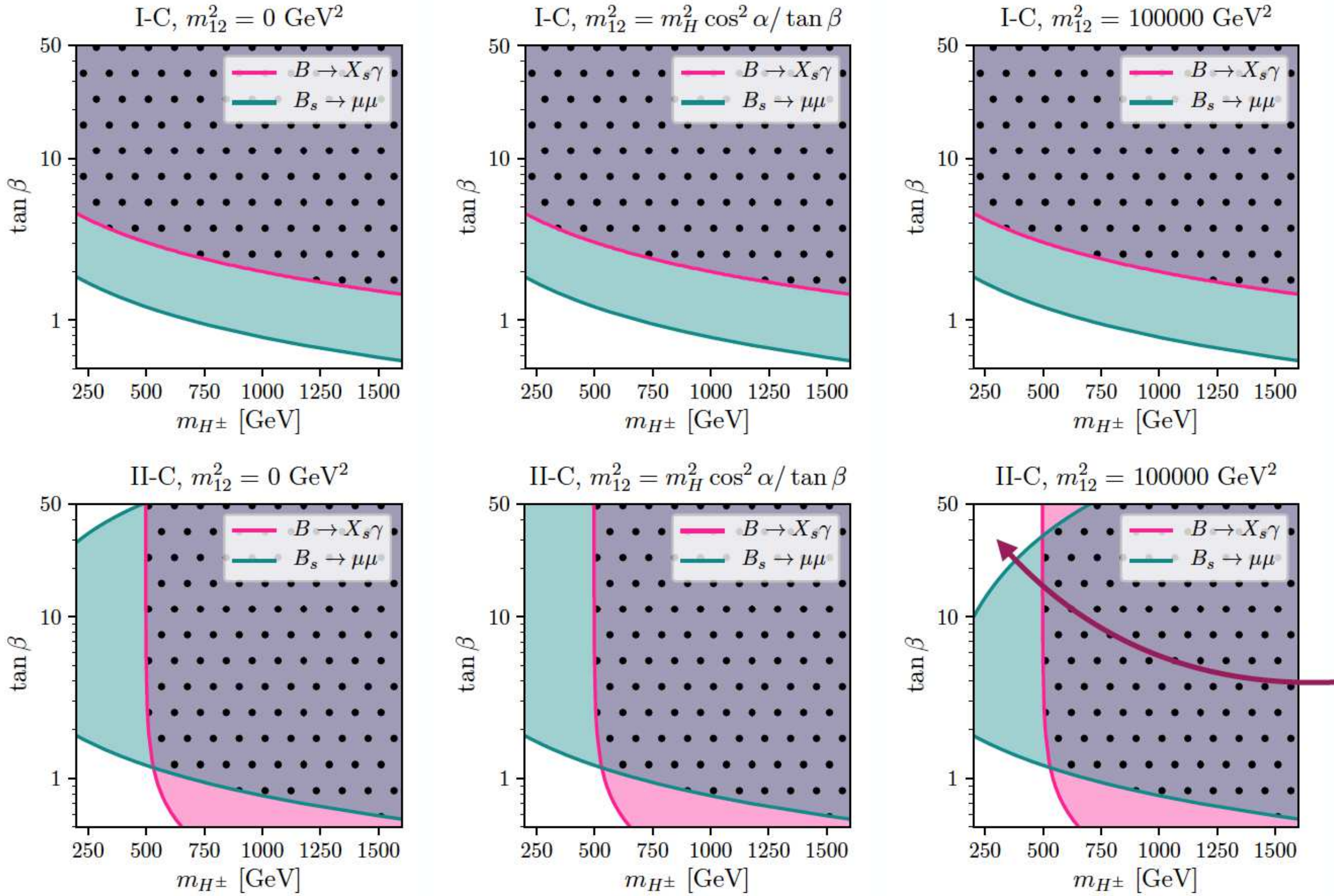
BSM Higgs searches: ⇒ HiggsBounds

LHC rate measurements of h_{125}: ⇒ HiggsSignals

Flavor constraints:

Allowed areas for flavor measurements

$m_H = m_A = m_{H^\pm}$, $c_{\beta-\alpha} = 0$



Overview:

Low $\tan\beta$ disallowed in both types

Type II has a $\tan\beta$ independent bound $m_{H^\pm} \gtrsim 500$ GeV

About large m_{12}^2:

Disallowed by Higgs-penguin diagrams, dominated by H

$\Rightarrow$ very different for type I and type II $\Rightarrow$ SuperIso

Interesting points for type I

Eq. m_{12}^2 means $m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$

m_H	m_A	$m_{H^\pm}$	$\tan\beta$	$c_{\beta-\alpha}$	m_{12}^2	κ_λ	λ_{hhH}	λ_{hHH}	λ_{hAA}	$\lambda_{hH^+H^-}$
750	750	750	5.5	0.25	Eq. m_{12}^2	**-0.4**	0.4	7	6	12
1000	1000	1000	7.5	0.2	Eq. m_{12}^2	**-0.3**	0.1	13	12	24
650	650	650	6.0	0.2	Eq. m_{12}^2	0.1	0.5	4	4	8
300	300	300	15.0	0.25	Eq. m_{12}^2	**1.5**	-0.6	2	2	5
400	400	400	12.5	0.2	12500	1.2	-0.4	3	3	6
600	600	600	10.0	0.2	Eq. m_{12}^2	1.0	-0.5	6	6	12
* 1500	1500	1500	2.0	-0.025	820000	0.8	**-1.2**	3	3	6
650	400	400	12.0	0.15	Eq. m_{12}^2	0.9	-0.3	6	2	4
300	600	600	2.5	0.1	5000	1.0	0.0	1	6	12
300	600	600	12.5	0.2	Eq. m_{12}^2	1.1	-0.2	2	6	12
* 700	1200	1200	2.0	0.0	Eq. m_{12}^2	1.0	0.0	0.0	**16**	**32**
700	1000	700	7.0	0.2	Eq. m_{12}^2	0.3	0.2	6	14	11
350	600	350	10.0	0.2	Eq. m_{12}^2	1.0	-0.1	2	6	4
600	350	600	10.0	0.2	Eq. m_{12}^2	1.0	-0.5	6	2	11

Valid also for Type II

Example points type II:

Interesting points for type II

m_H	m_A	$m_{H^\pm}$	$\tan\beta$	$c_{\beta-\alpha}$	m_{12}^2	κ_λ	λ_{hhH}	λ_{hHH}	λ_{hAA}	$\lambda_{hH^+H^-}$
1100	1100	1100	0.9	0.13	260000	**-0.1**	0.9	11	11	23
1500	1500	1500	0.8	0.05	775000	0.5	**1.7**	11	11	21
600	600	600	1.5	0.02	25000	**1.0**	0.0	5	5	10
1150	1000	1000	0.95	0.025	210000	**1.0**	0.1	**15**	10	19
400	600	600	1.5	0.04	10000	**1.0**	0.0	2	6	11
1350	1000	1350	0.9	0.05	460000	0.7	0.8	**15**	1	30
600	400	600	1.5	0.05	8000	**1.0**	-0.1	6	2	12