Triple Higgs couplings in the 2HDM

Based on [arXiv:2005.10576]
with S. Heinemeyer and M.J. Herrero

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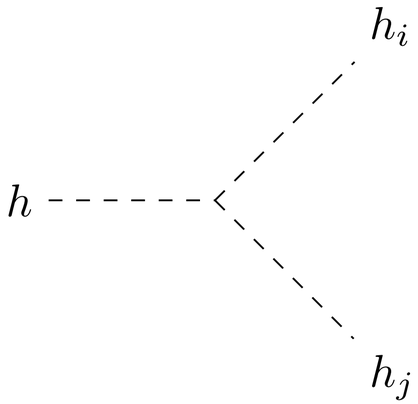
Preparatory Joint Sessions on “Open questions and New Ideas”, Energy Frontier *(from home)*
July 8th, 2020

Motivation

- ⋆ Di-Higgs production can be enhanced by BSM physics
- ⋆ Analysis in the 2HDM ⟶ new interactions in the scalar sector
  - How large can triple Higgs couplings be?
    - ✓ Taking all the constraints into account
- ⋆ Couplings studied:

hhH, hHH, hAA, hH^+H^- and hhh



$$= -i\,v\,n!\,\lambda_{hh_ih_j}$$

$$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{SM}$$

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

$$\boxed{7 \text{ free parameters} + 5 \text{ physical states: } h,\ H,\ A,\ H^+ \text{ and } H^-}$$

CP even

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-like interactions for h are recovered $\implies$ *Alignment limit*
  - ⋆ <u>Alignment limit $\neq$ SM</u>, 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

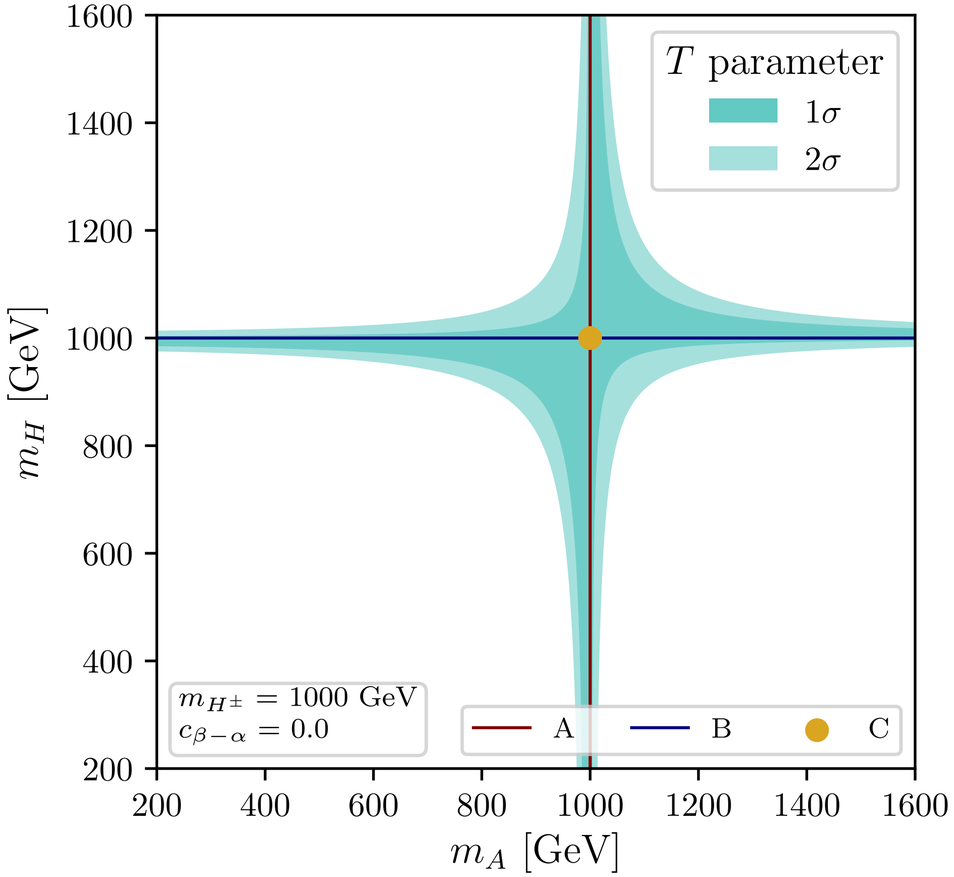
Constraints on the model

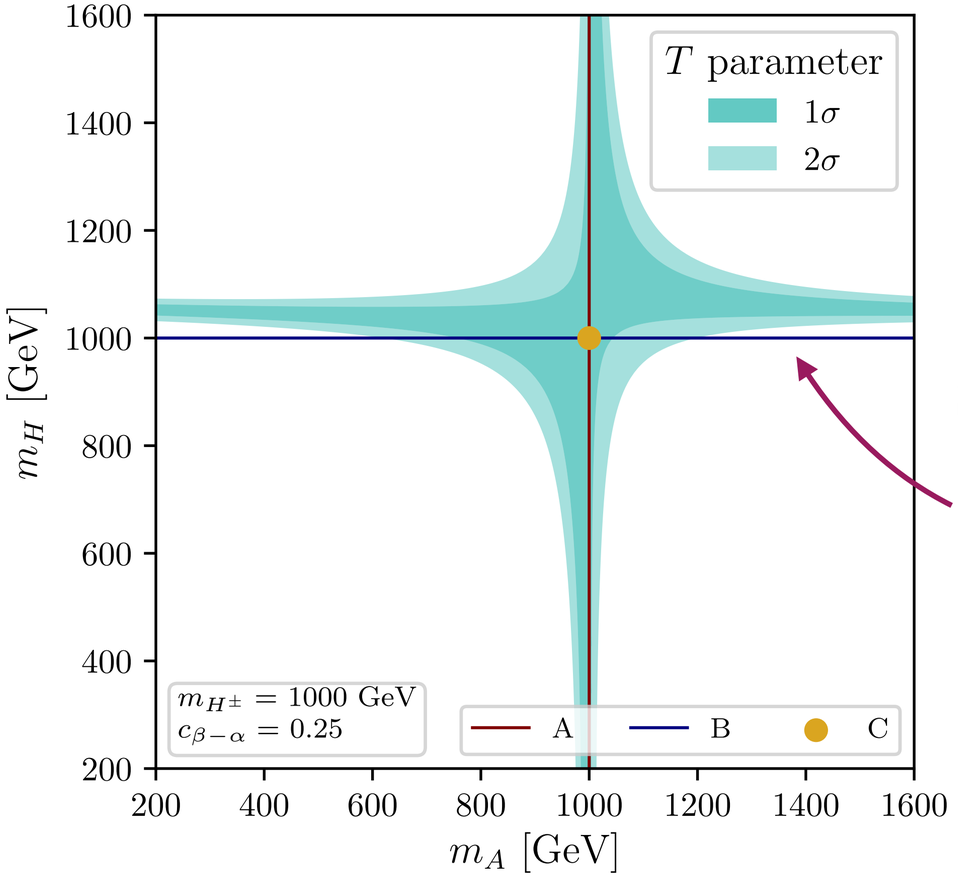
and the impact of m_{12}^2

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





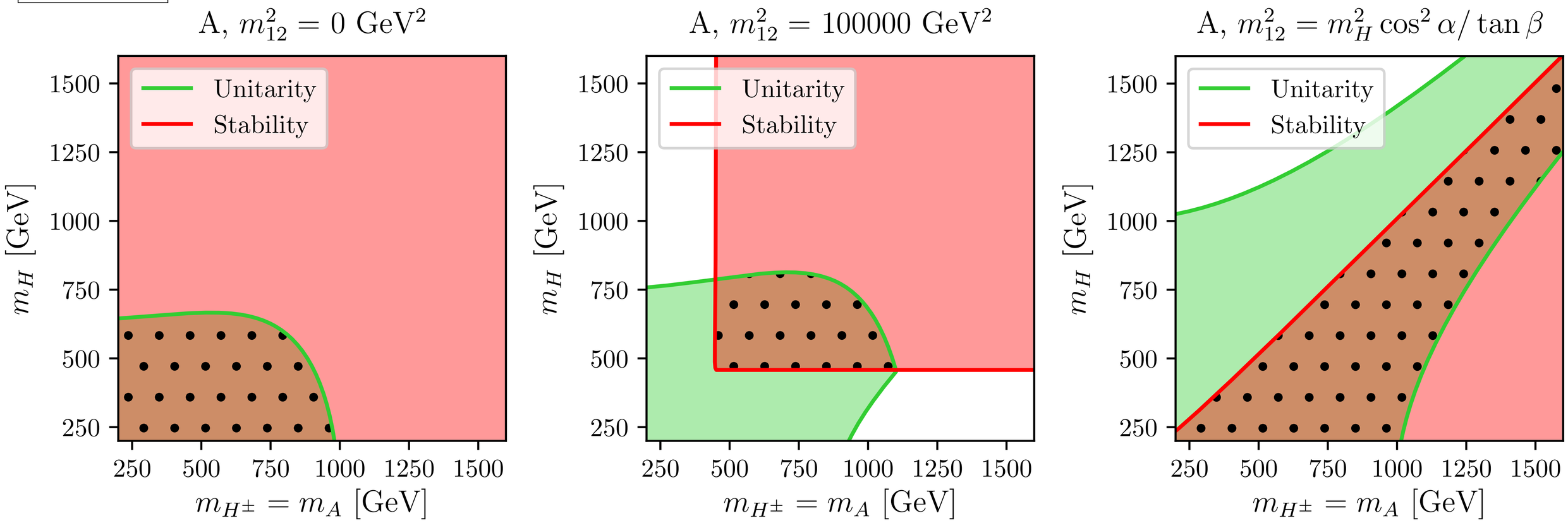
Scenario B may be in conflict with data outside the alignment limit

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

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!

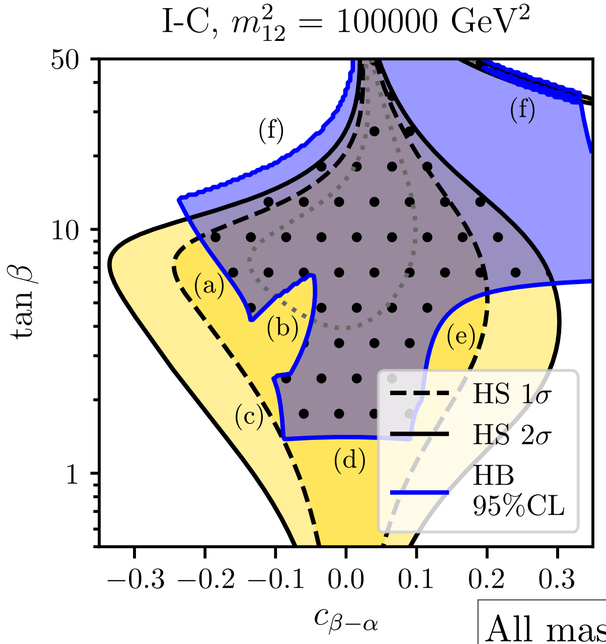
Similar for scenario B...

Experimental Constraints

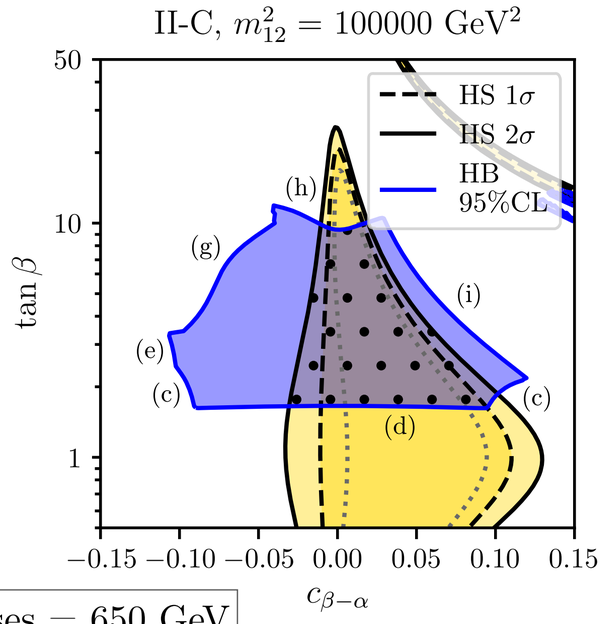
★ Higgs searches & collider measurements: HiggsBounds & HiggsSignals (w/2HDMC)
[arXiv:1311.0055,arXiv:1305.1933]

★ Flavor measurements: SuperISO (w/ 2HMDC + addition of Higgs penguins)
[arXiv:0808.3144,arXiv:1404.5865,arXiv:1703.03426]

Type I

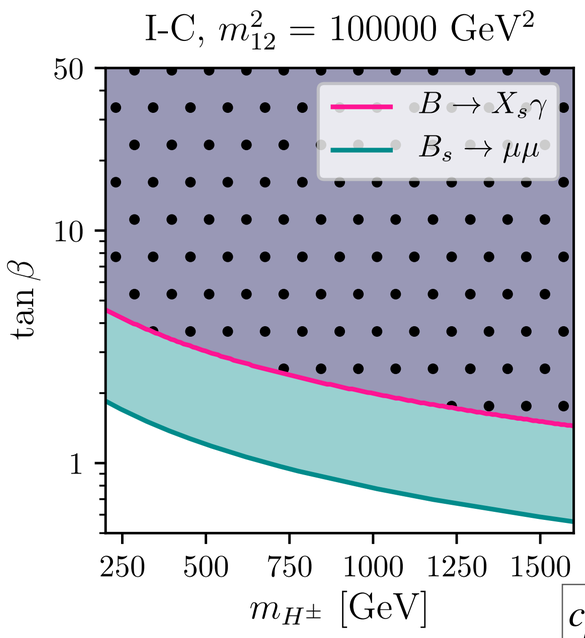


Type II

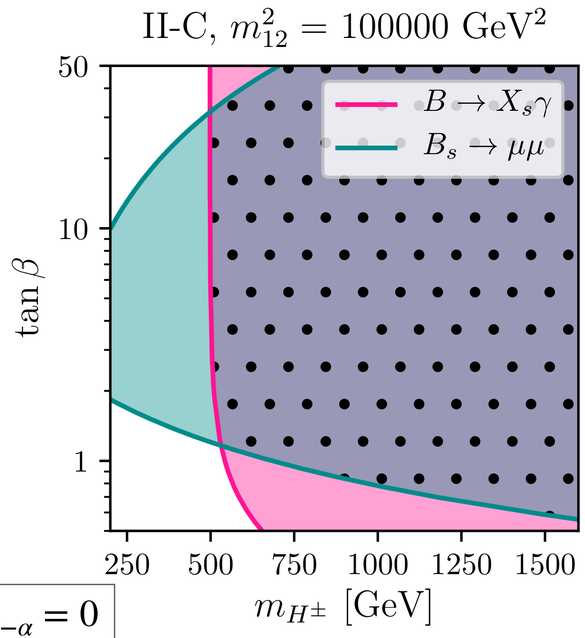


All masses = 650 GeV

Type I



Type II

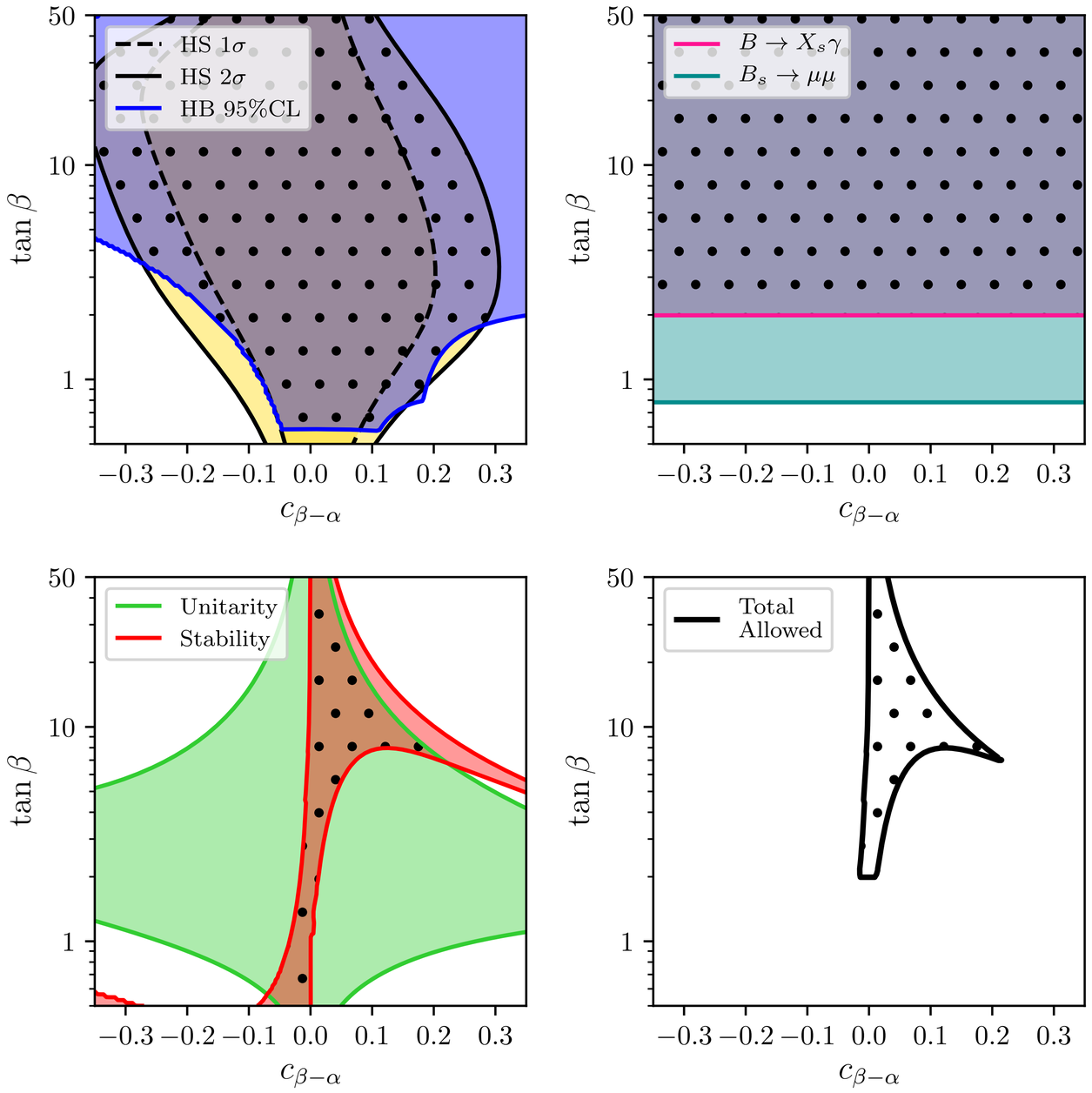


$c_{\beta-\alpha} = 0$

Allowed regions are affected in the large m_{12}^2 and large $\tan\beta$ region

Numerical Results

2HDM type I, scenario C

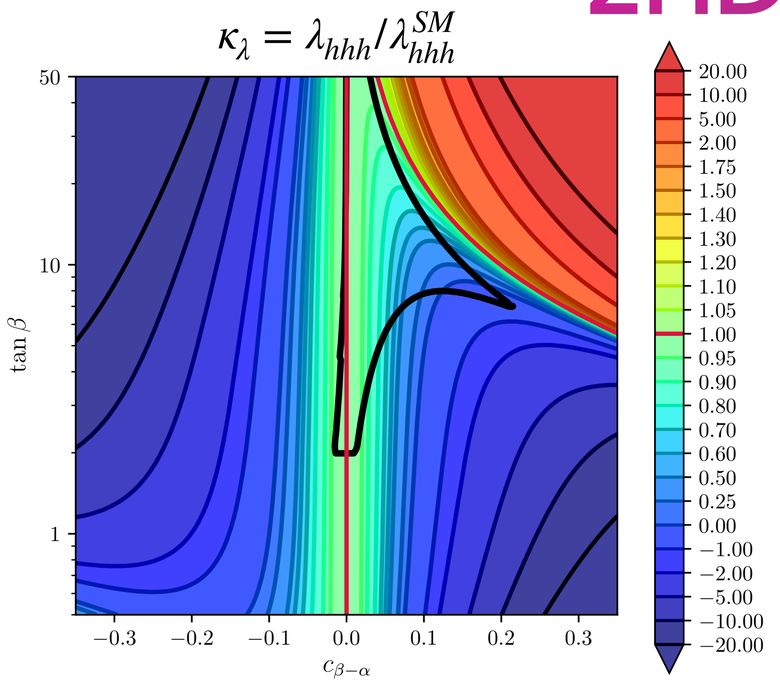


$$m_H = m_A = m_{H^\pm} = 1000 \text{ GeV (scenario C)}$$

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

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

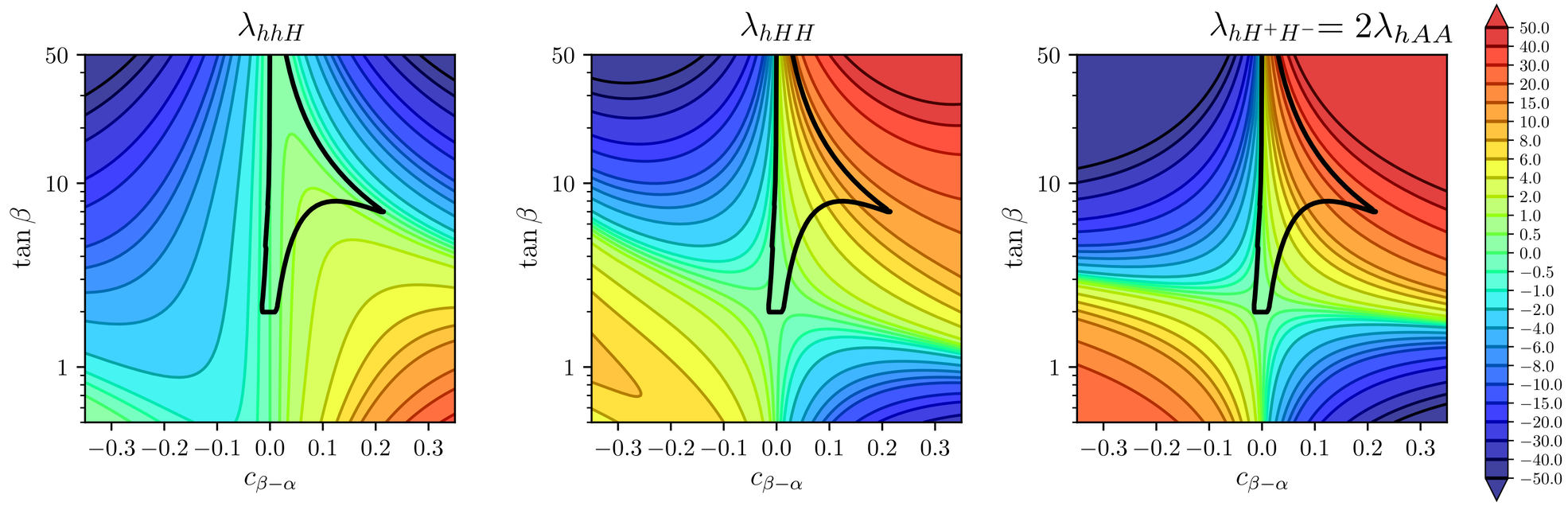
2HDM type I, scenario C



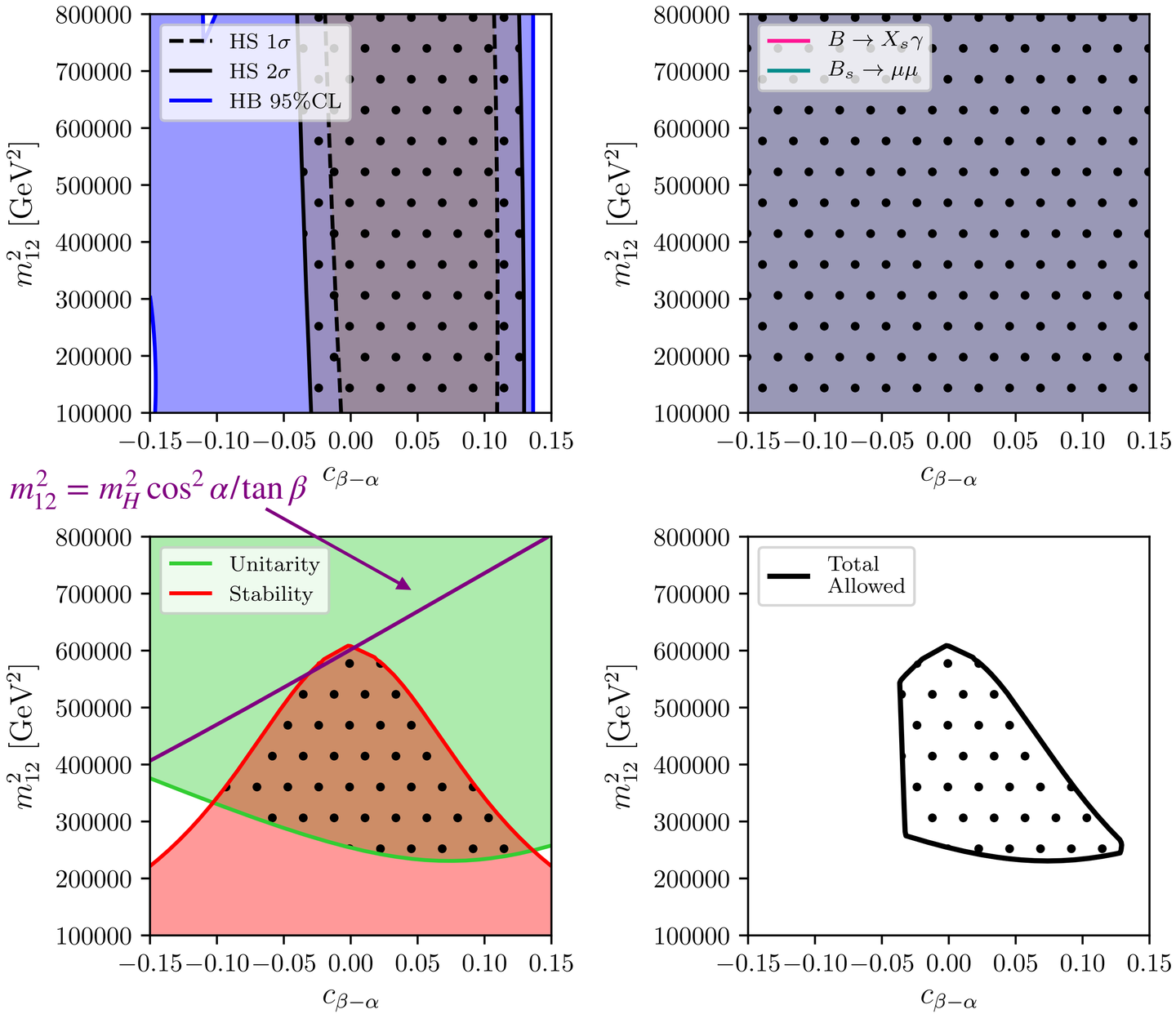
$$m_H = m_A = m_{H^\pm} = 1000 \text{ GeV (scenario C)}$$

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

- ★ 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 $c_{\beta-\alpha} \sim 0.05$
- ★ Max $\lambda_{hHH} \sim 12$ and $\lambda_{hH^+H^-} = 2\lambda_{hAA} \sim 24$ in the unitarity border



2HDM type II, scenario C

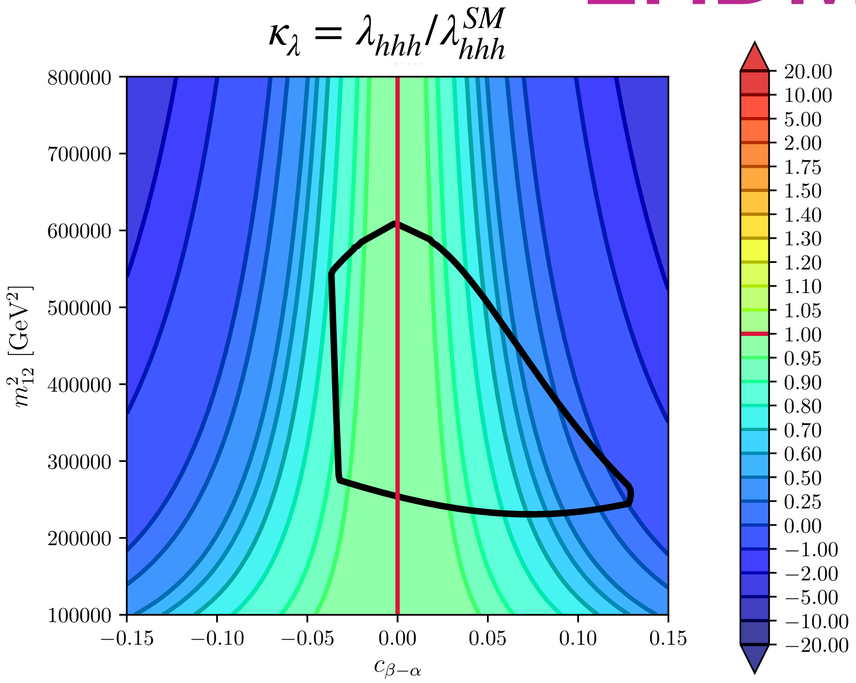


$m_H = m_A = m_{H^\pm} = 1100$ GeV (scenario C)

$\tan\beta = 0.9$

- ★ 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)

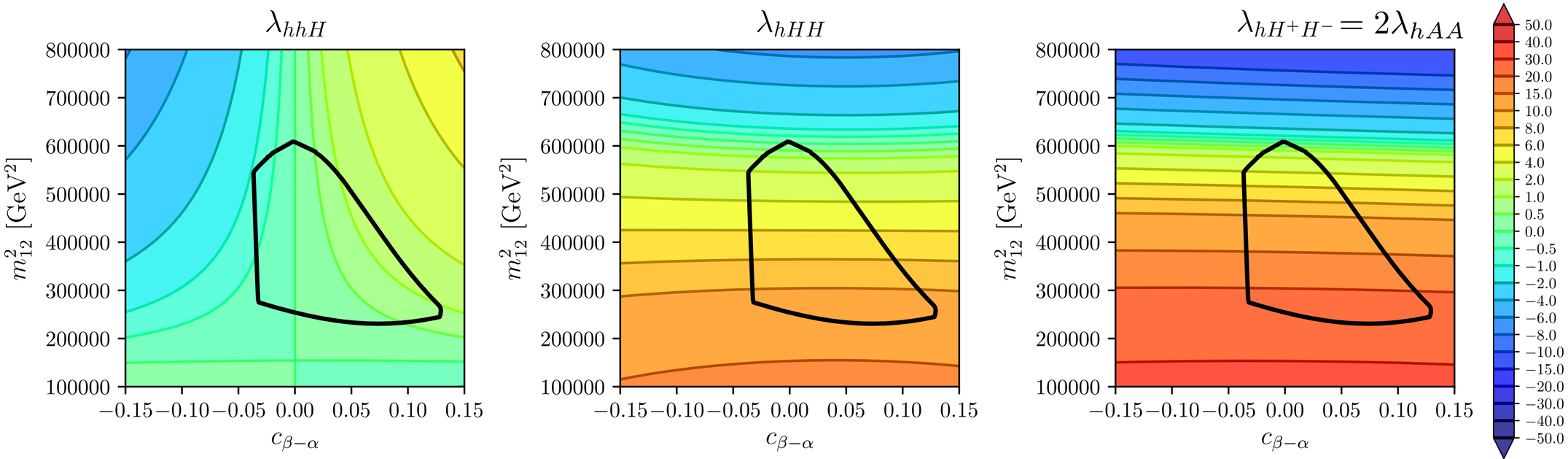
2HDM type II, scenario C



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

$\tan\beta = 0.9$

- ★ Min $\kappa_\lambda \sim 0.0$ 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



Final allowed ranges

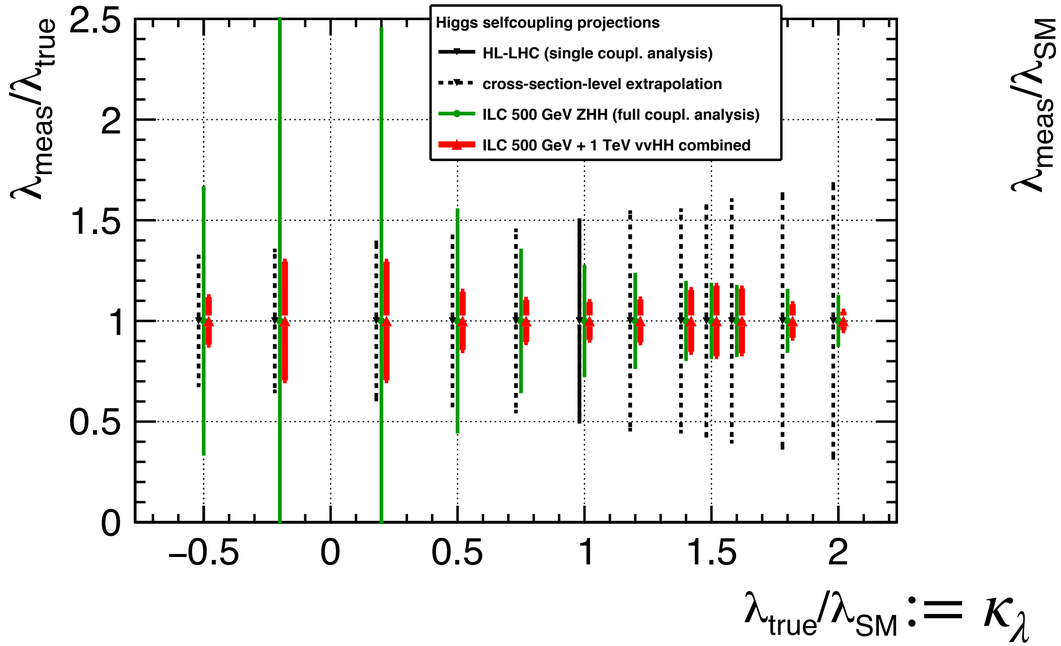
Type I	Type II	
$\kappa_\lambda \in [-0.5,\ 1.5]$	$\kappa_\lambda \in [0.0,\ 1.0]$	Far from the alignment limit and playing with m_{12}^2
$\lambda_{hhH} \in [-1.4,\ 1.5]$	$\lambda_{hhH} \in [-1.6,\ 1.8]$	For $c_{\beta-\alpha} \sim \pm 0.05$
$\lambda_{hHH} \in [0,\ 15]$	$\lambda_{hHH} \in [0,\ 15]$	Large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

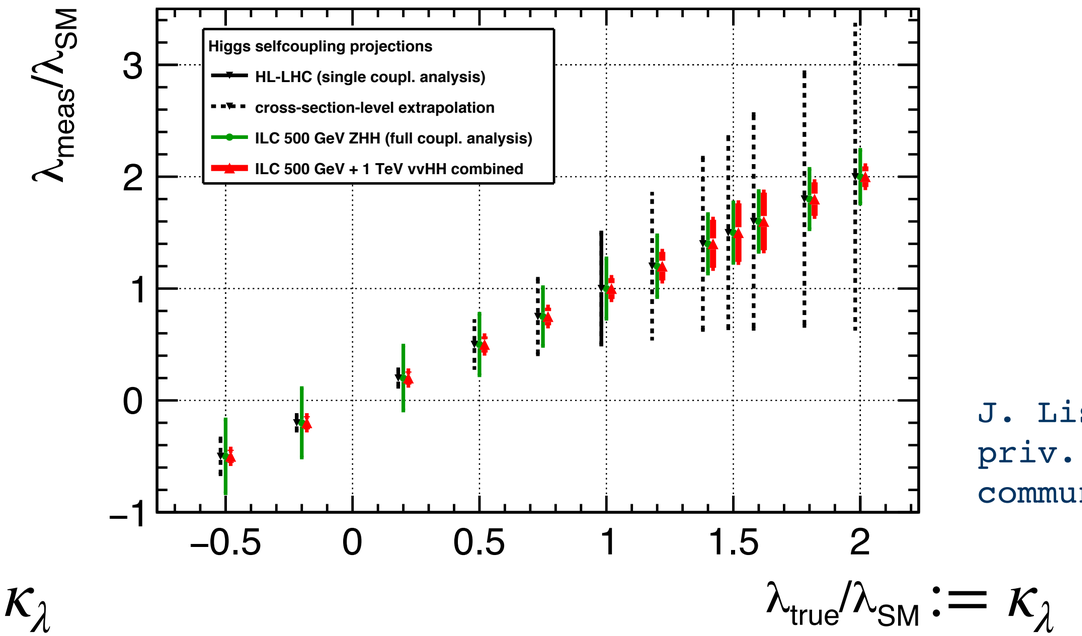
Generally extremes are find for large value of the masses

✨ 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 $\longrightarrow$ large masses $\longrightarrow$ propagator suppression

Predictions only for variations of λ_{hhh}

Thank you all for your attention :)

Back-up

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]

Unitarity + Stability

★ Tree-level unitarity

Eigenvalues of the lowest partial wave scattering matrices of 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

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

[arXiv:1303.5098]

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

★ Perturbativity

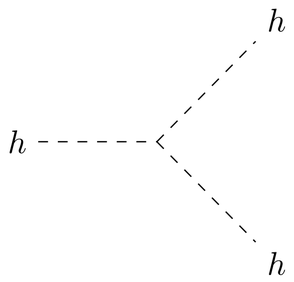
Unitarity limits the maximum size of λ_i's, so indirectly we satisfy perturbativity

Triple Higgs couplings

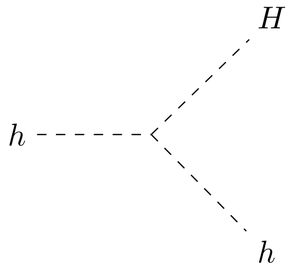
Triple Higgs couplings with at least one h

Definition:

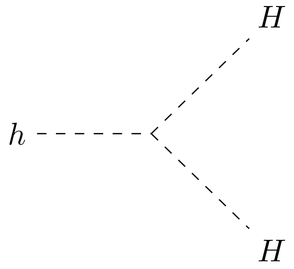
$$\bar{m}^2 = \frac{m_{12}^2}{s_\beta c_\beta}$$



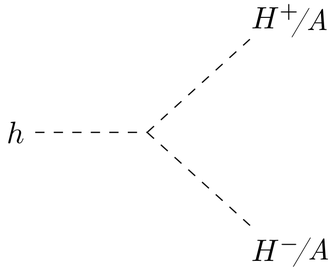
$$= -\frac{3i}{v}\left\{ m_h^2 s_{\beta-\alpha}^3 + \left(3m_h^2 - 2\bar{m}^2\right) c_{\beta-\alpha}^2 s_{\beta-\alpha} + 2\cot 2\beta \left(m_h^2 - \bar{m}^2\right) c_{\beta-\alpha}^3 \right\}$$



$$= \frac{ic_{\beta-\alpha}}{v}\left\{ \left(2m_h^2 + m_H^2 - 4\bar{m}^2\right) s_{\beta-\alpha}^2 + 2\cot 2\beta \left(2m_h^2 + m_H^2 - 3\bar{m}^2\right) s_{\beta-\alpha} c_{\beta-\alpha} - \left(2m_h^2 + m_H^2 - 2\bar{m}^2\right) c_{\beta-\alpha}^2 \right\}$$



$$= -\frac{is_{\beta-\alpha}}{v}\left\{ \left(m_h^2 + 2m_H^2 - 2\bar{m}^2\right) s_{\beta-\alpha}^2 + 2\cot 2\beta \left(m_h^2 + 2m_H^2 - 3\bar{m}^2\right) c_{\beta-\alpha} s_{\beta-\alpha} - \left(m_h^2 + 2m_H^2 - 4\bar{m}^2\right) c_{\beta-\alpha}^2 \right\}$$



$$= -\frac{i}{v}\left\{ \left(m_h^2 + 2m_{H^\pm/A}^2 - 2\bar{m}^2\right) s_{\beta-\alpha} + 2\cot 2\beta \left(m_h^2 - \bar{m}^2\right) c_{\beta-\alpha} \right\}$$

Exclusion channels

(a) $pp \to H \to hh \to (b\bar{b})(\tau^+\tau^-)$

(b) $pp \to H \to hh \to (b\bar{b})(b\bar{b}/\tau^+\tau^-/W^+W^-/\gamma\gamma)$

(c) $pp \to H \to VV$

(d) $pp \to H^{\pm}tb \to (tb)tb$

(e) $gg \to A \to Zh \to (l^+l^-)(b\bar{b})$

(f) $pp \to hX \to \gamma\gamma X$

(g) $pp \to H \to hh \to (b\bar{b})(b\bar{b})$

(h) $pp \to H \to \tau^+\tau^-$

(i) $pp \to h \to ZZ \to (l^+l^-)(l^+l^-)$

Interesting points for type I

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

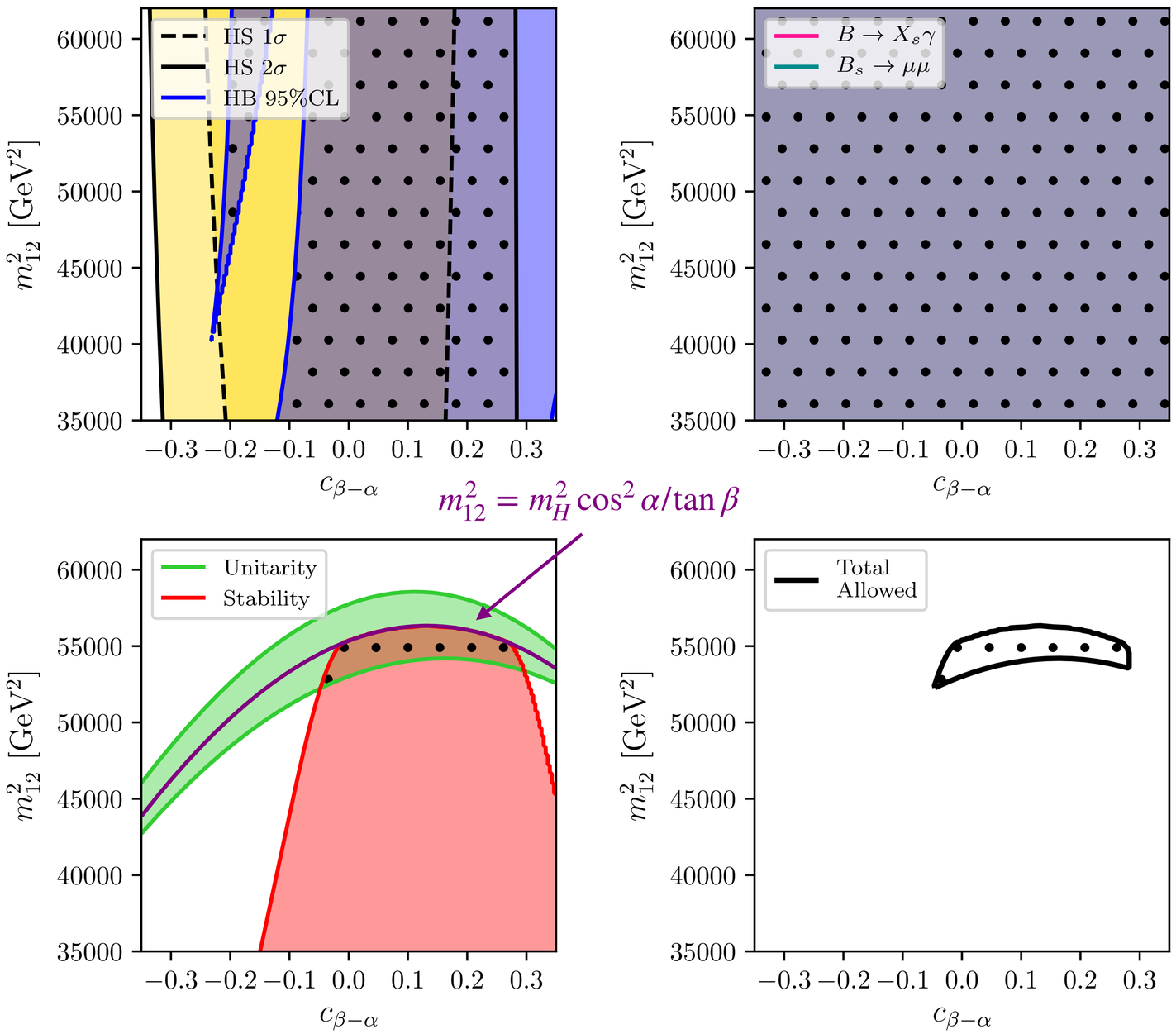
m_H	m_A	$m_{H^\pm}$	$\tan\beta$	$c_{\beta-\alpha}$	m_{12}^2	κ_λ	λ_{hhH}	λ_{hHH}	λ_{hAA}	$\lambda_{hH^+H^-}$
750	750	750	5.5	0.25	Eq. m_{12}^2	**-0.4**	0.4	7	6	12
1000	1000	1000	7.5	0.2	Eq. m_{12}^2	**-0.3**	0.1	13	12	24
650	650	650	6.0	0.2	Eq. m_{12}^2	0.1	0.5	4	4	8
300	300	300	15.0	0.25	Eq. m_{12}^2	**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

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

2HDM type I, scenario C



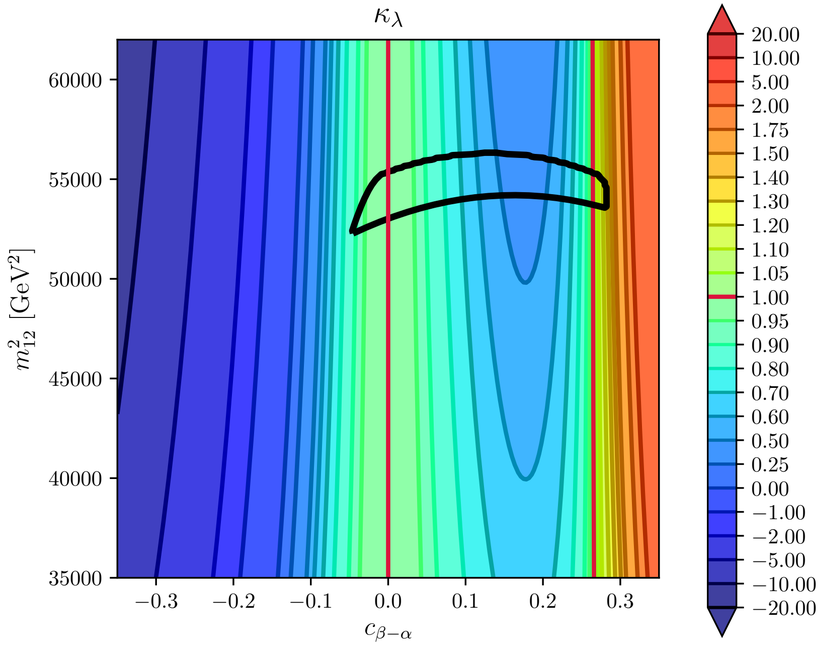
$m_H = m_A = m_{H^\pm} = 650$ GeV (scenario C)

$\tan\beta = 7.5$

- ★ Collider $c_{\beta-\alpha} \in [-0.1, 0.3]$ nearly independent of m_{12}^2
- ★ No bounds from flavor
- ★ Narrow allowed region by unitarity ($m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$ works!)

Again theoretical constraints are the most stringent ones!

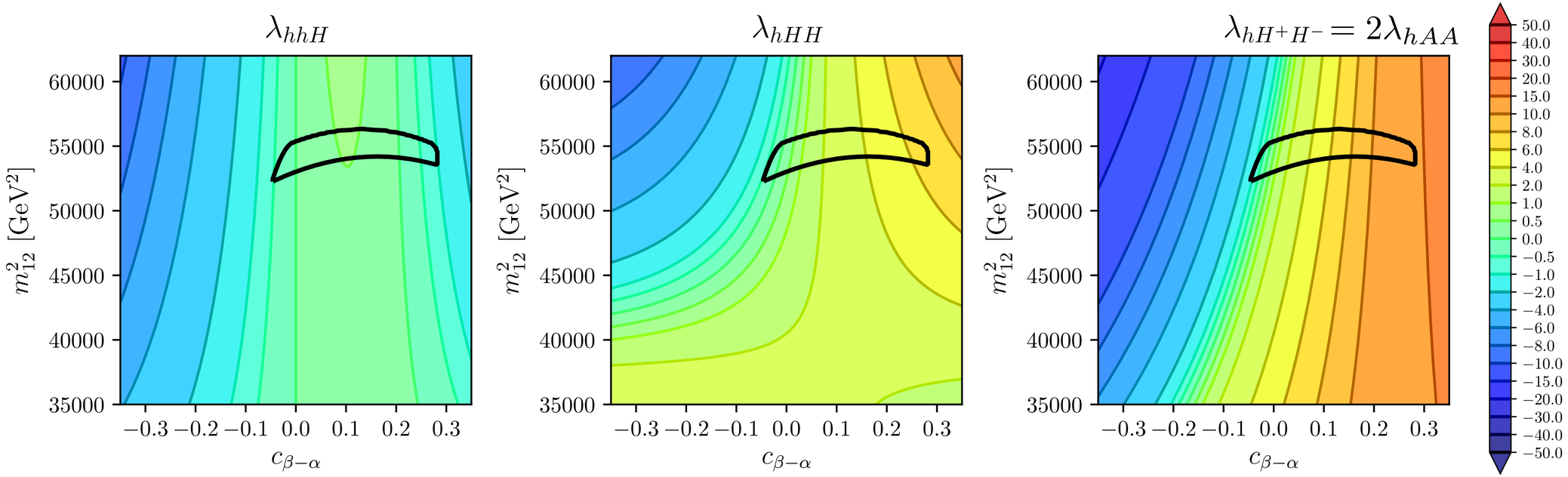
2HDM type I, scenario C



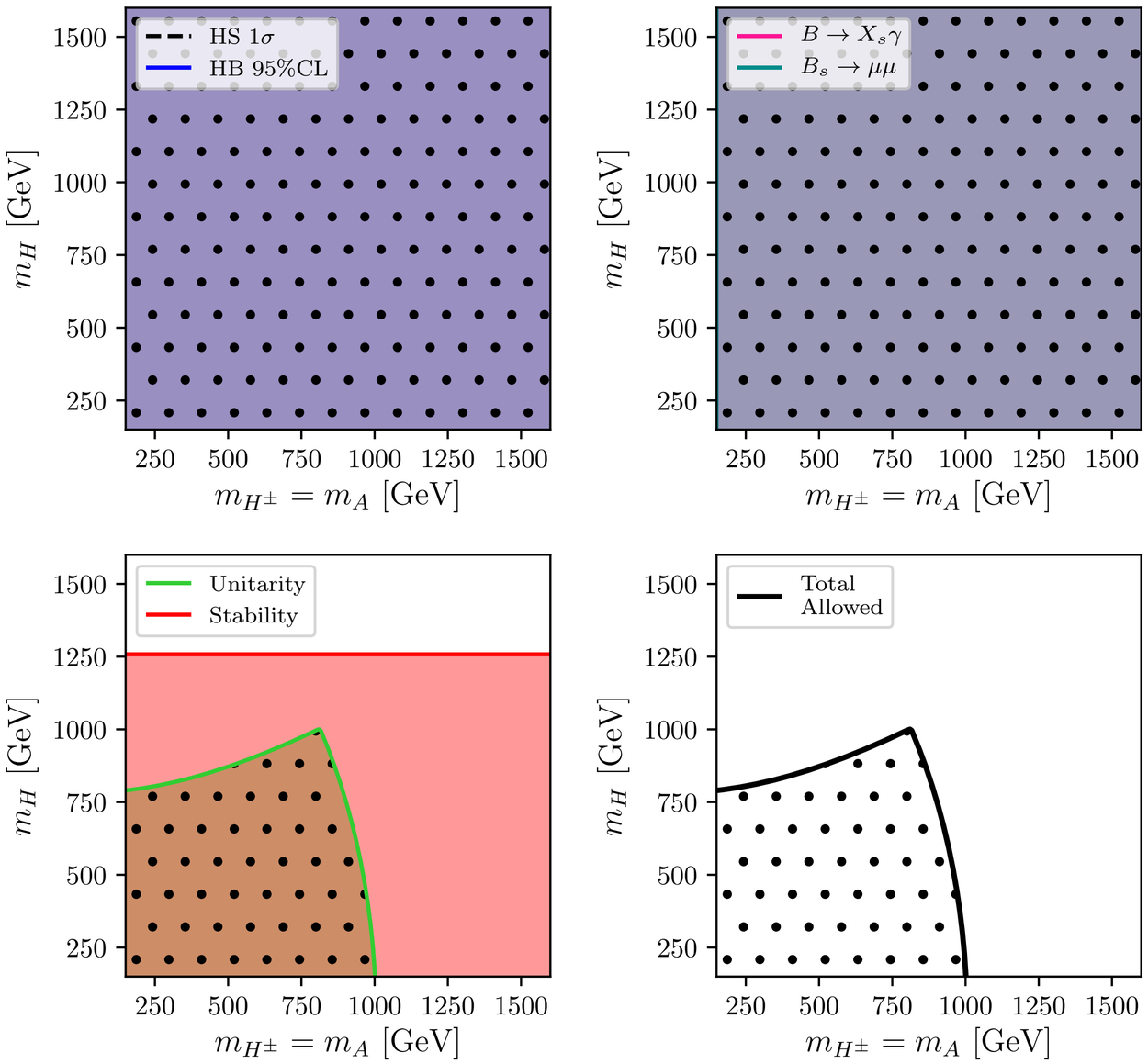
$m_H = m_A = m_{H^\pm} = 650$ GeV (scenario C)

$\tan\beta = 7.5$

- ★ Allowed $\kappa_\lambda \in [0.5, 1.2]$ (> 1 deviations for $c_{\beta-\alpha} > 0.25$)
- ★ Allowed $\lambda_{hhH} \in [-1, 0.3]$ with max at $c_{\beta-\alpha} \sim 0.1$
- ★ Max $\lambda_{hHH} \sim 7$ and $\lambda_{hH^+H^-} = 2\lambda_{hAA} \sim 14$ in max $c_{\beta-\alpha}$



2HDM type I, scenario A



$$\cos(\beta - \alpha) = 0.2,\ \tan\beta = 10$$
$$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$$

- ★ No bounds from collider
- ★ No bounds from flavor
- ★ Stability allows a "square" with $m_H, m_A = m_{H^\pm} \lesssim 1000$ GeV

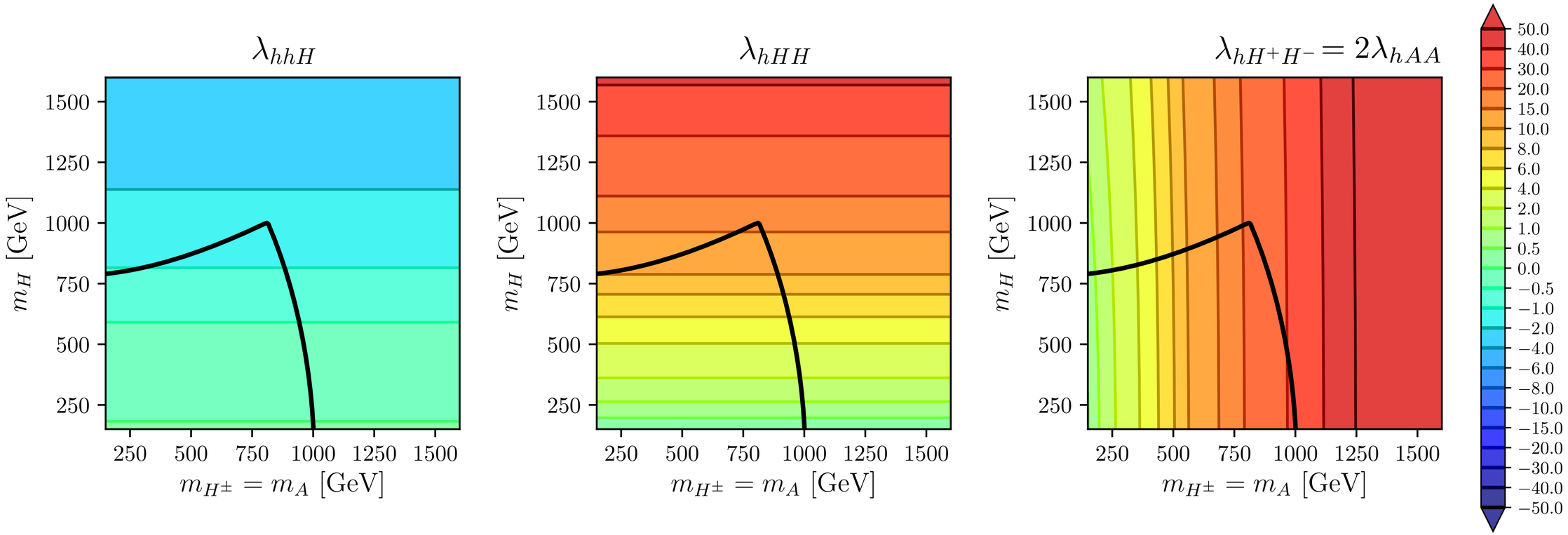
2HDM type I, scenario A

$$\cos(\beta-\alpha) = 0.2,\ \tan\beta = 10$$
$$m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$$

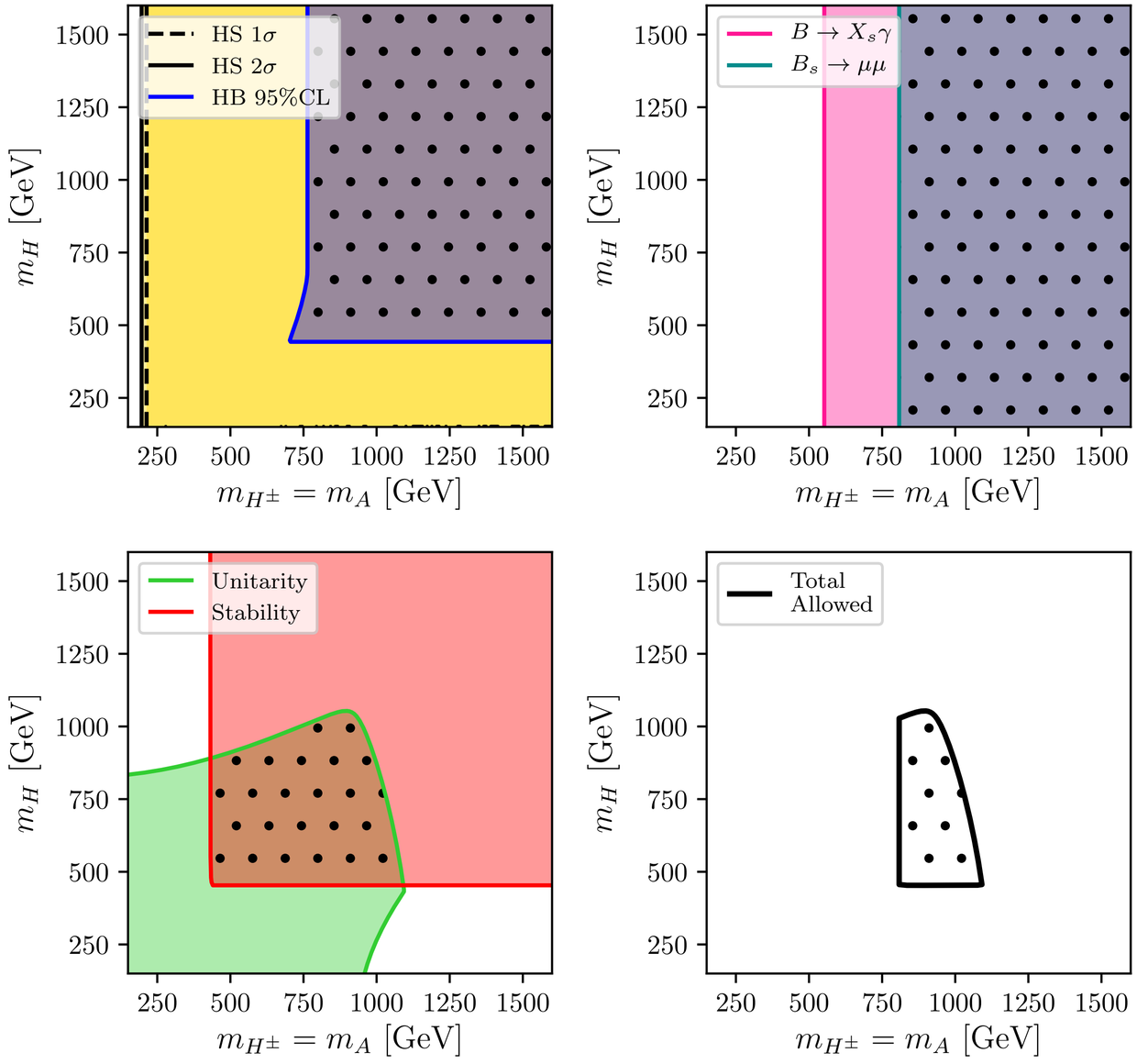
- ★ Allowed $\lambda_{hhH} \in [-1.5,0]$
- ★ Max $\lambda_{hHH} \sim 16$ for max m_H
- ★ Max $\lambda_{hH^+H^-} = 2\lambda_{hAA} \sim 32$ for max $m_A = m_{H^\pm}$

Deviations from $\kappa_\lambda = 1$ very small (will not be shown from now on)

Results from scenario B are very similar



2HDM type II, scenario A



$$\cos(\beta - \alpha) = 0.05, \ \tan\beta = 0.9$$
$$m_{12}^2 = 10^5 \text{ GeV}^2$$

- ★ BSM searches constrains $m_H \gtrsim 400$ GeV and $m_A = m_{H^+} \gtrsim 750$ GeV
- ★ $B_s \to \mu^+\mu^-$ imposes $m_A = m_{H^+} \gtrsim 800$ GeV
- ★ Theoretical constraints allows a "square" with $500 \text{ GeV} \lesssim m_H, m_A = m_{H^\pm} \lesssim 1100$ GeV

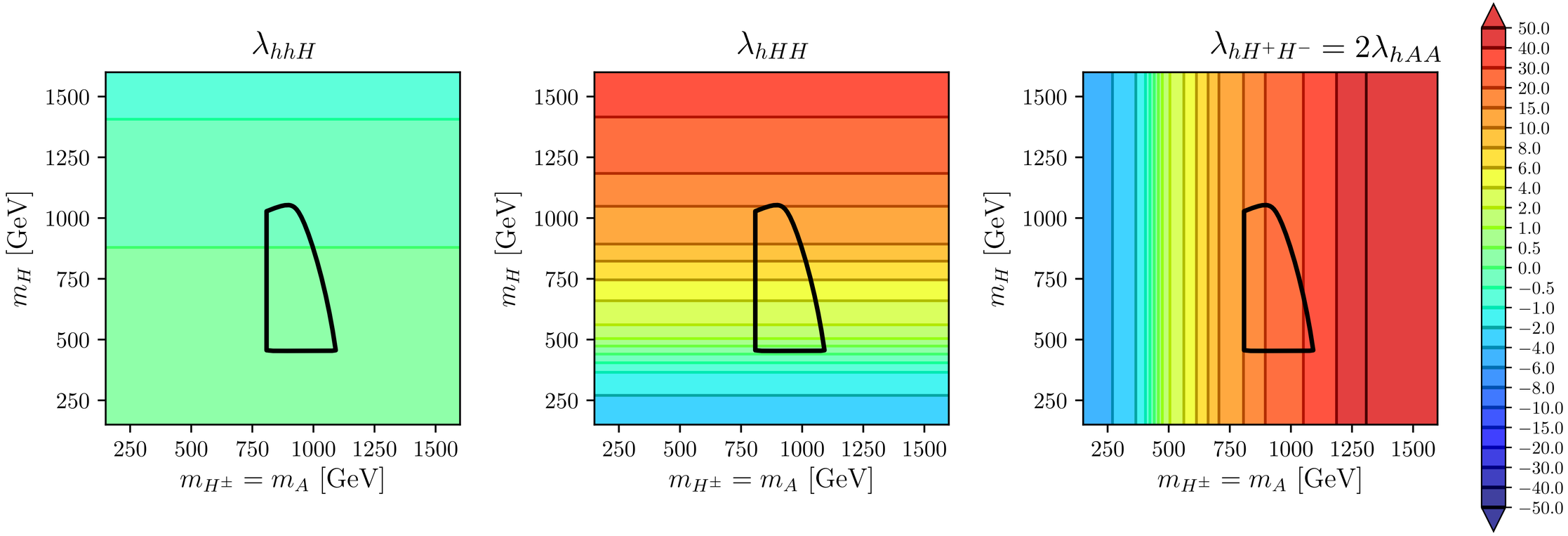
Final allowed region

$500 \text{ GeV} \lesssim m_H \lesssim 1000$ GeV and

$800 \text{ GeV} \lesssim m_A = m_{H^\pm} \lesssim 1100$ GeV

2HDM type II, scenario A

$\cos(\beta - \alpha) = 0.05,\ \tan\beta = 0.9$
$m_{12}^2 = 10^5\ \mathrm{GeV}^2$

- ★ Allowed $\lambda_{hhH} \in [-0.14,\ 0.23]$
- ★ Allowed $\lambda_{hHH} \in [8,\ 16]$ for max m_H
- ★ Allowed $\lambda_{hH^+H^-} = 2\lambda_{hAA} \in [16,\ 32]$ for max $m_A = m_{H^\pm}$

Results from scenario B are very similar