Large Triple Higgs Couplings in the 2HDM

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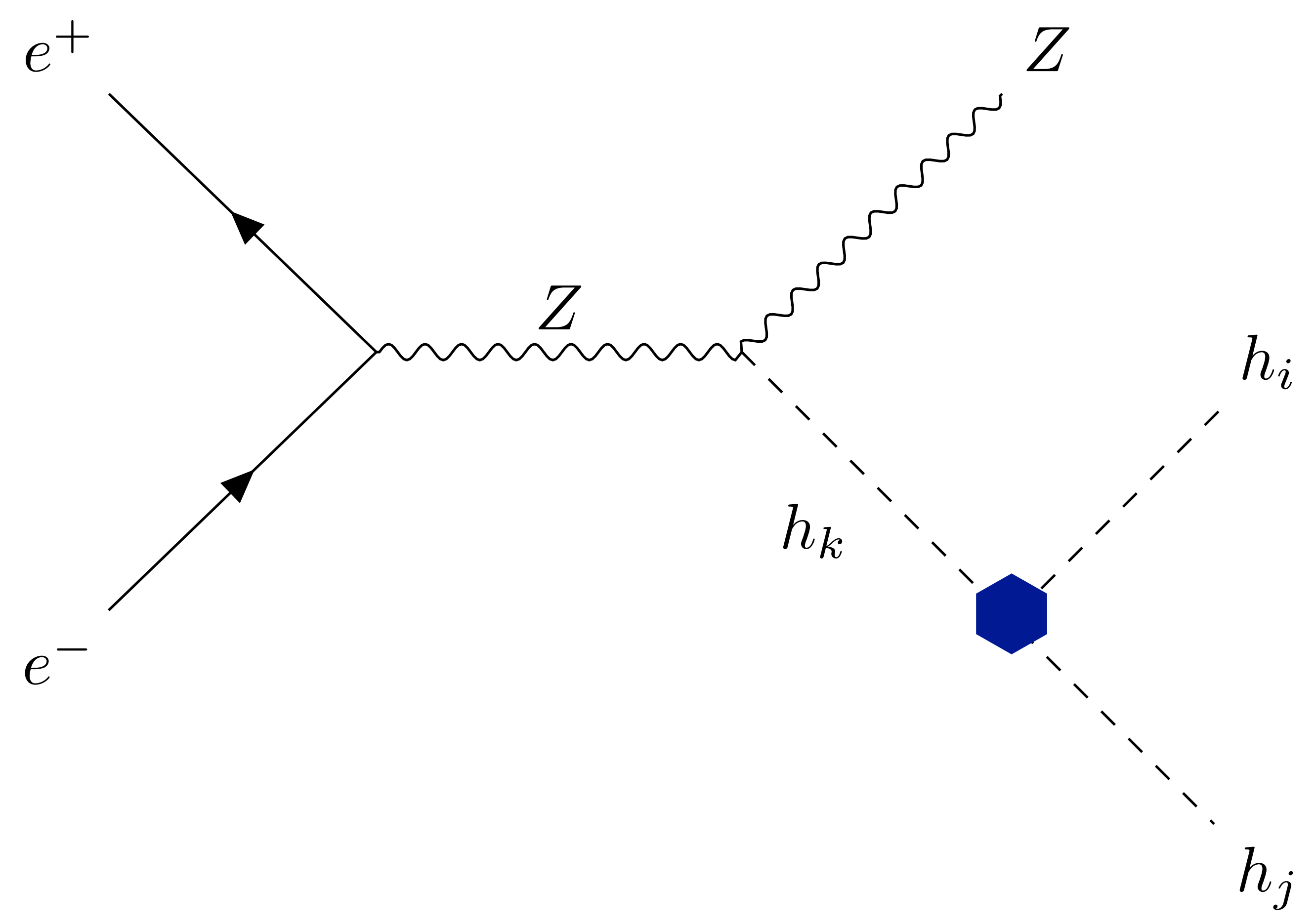
Motivation

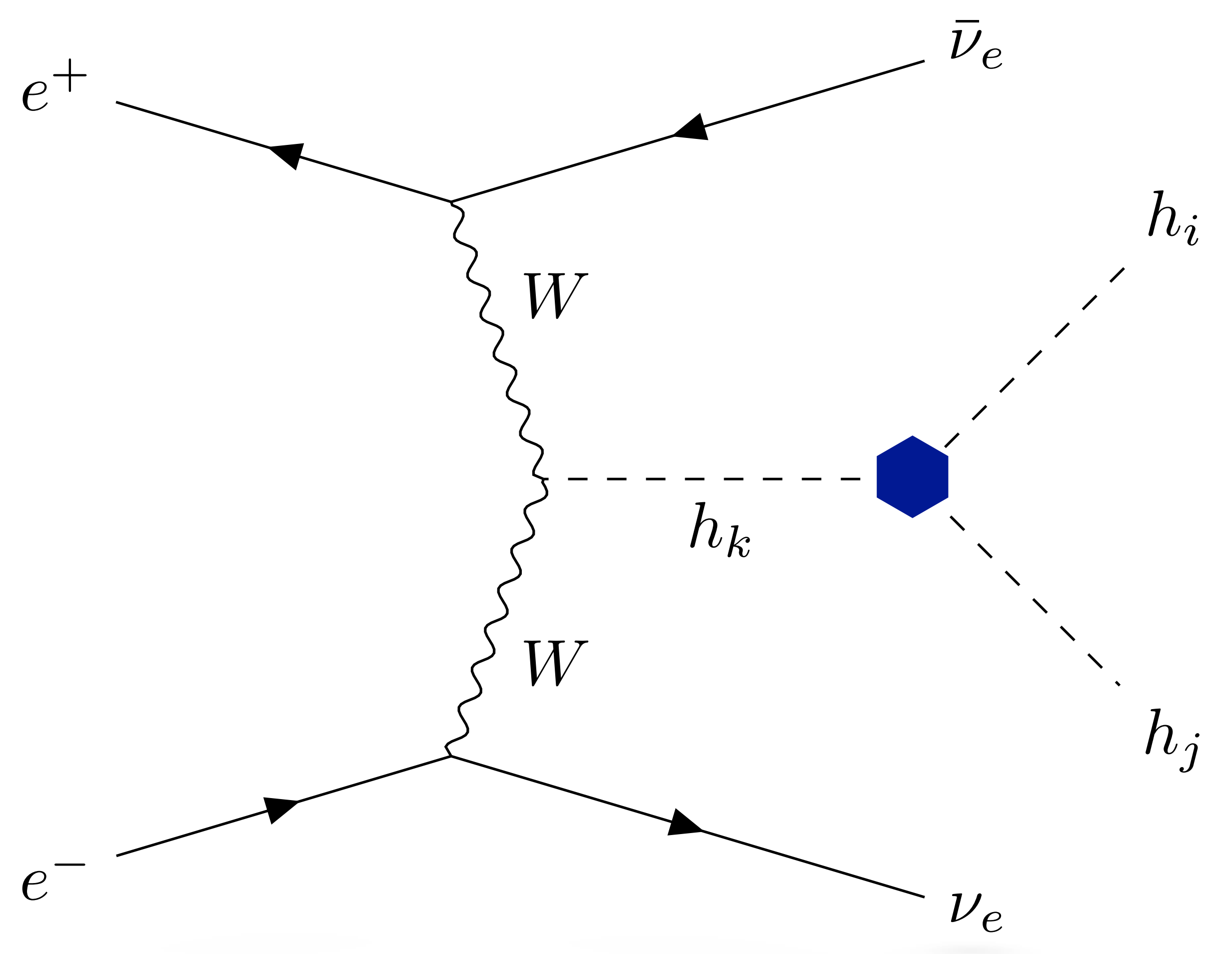
In the context of the 2HDM (type I and II), triple Higgs couplings $\lambda_{h_ih_jh_k}$, can be large while respecting all the relevant constraints (*Eur.Phys.J.C 80 (2020) 9, 884,* [arXiv2005.10576])

↓

$\lambda_{h_ih_jh_k}$ can affect the di-Higgs production at tree level

Two channels of interest: $e^+e^- \to h_ih_jZ$ and $e^+e^- \to h_ih_j\nu\bar{\nu}$ with $h_ih_j = hh, hH, HH, AA$





The Two Higgs Doublet Model (2HMD)

Adding a second Higgs doublet to the SM $\Longrightarrow$ 5 physical Higgs bosons: h, H, A and $H^{\pm}$

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* conservation: all parameters are real
- Z_2 symmetry to avoid FCNC: softly broken by m_{12}^2
  - 4 possible Yukawa structures: we only consider 2HDM type I and type II

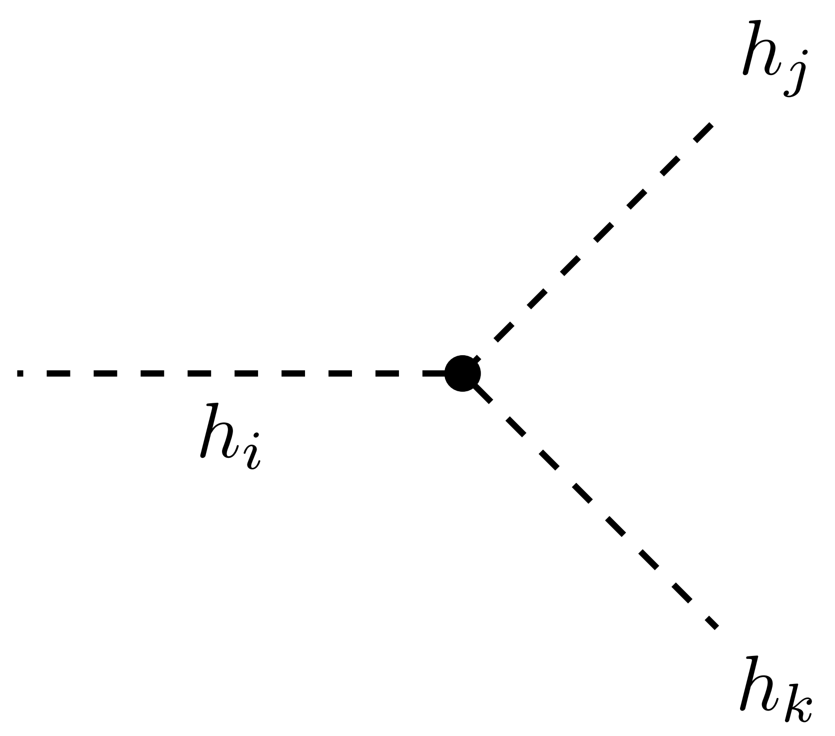
Input parameters:

$$m_h\ (=125\ \text{GeV}),\ m_H,\ m_A,\ m_{H^\pm},\ \tan\beta := v_2/v_1,\ \cos(\beta-\alpha) \equiv c_{\beta-\alpha} \text{ and } m_{12}^2$$

Alignment limit: $c_{\beta-\alpha} \to 0$, the SM interactions for h are recovered

Triple Higgs Couplings (THC)

Coupling definition:



$$= -\,i\,v\,n!\,\lambda_{h_i h_j h_k}$$

and

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

Final allowed ranges:

Type I	Type II
$\kappa_\lambda \in [-0.5,\ 1.5]$	$\kappa_\lambda \in [0.0,\ 1.0]$
$\lambda_{hhH} \in [-1.4,\ 1.5]$	$\lambda_{hhH} \in [-1.6,\ 1.8]$
$\lambda_{hHH} \in [0,\ 15]$	$\lambda_{hHH} \in [0,\ 15]$
$\lambda_{hAA} \in [0,\ 16]$	$\lambda_{hAA} \in [0,\ 16]$

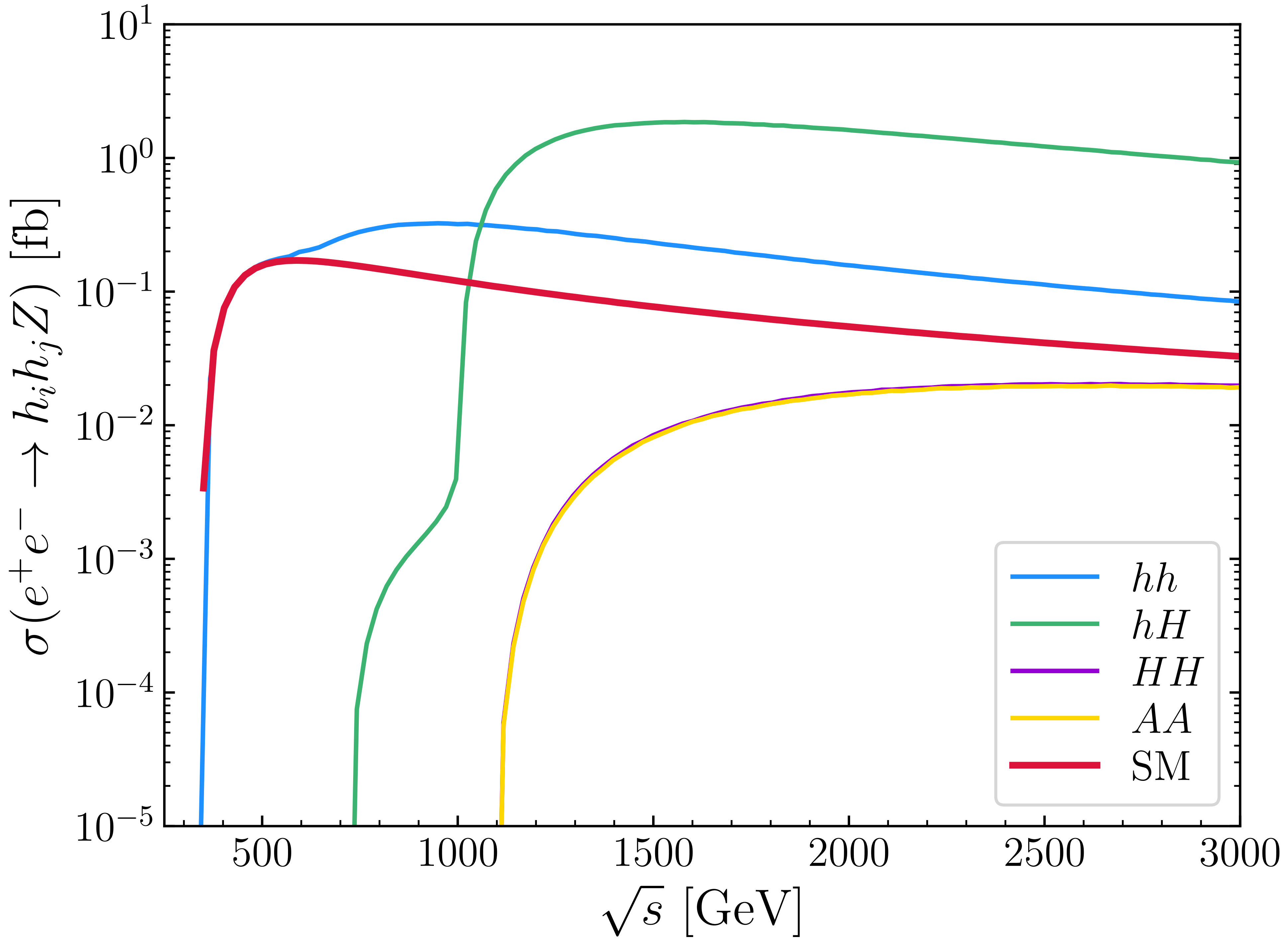
Constraints

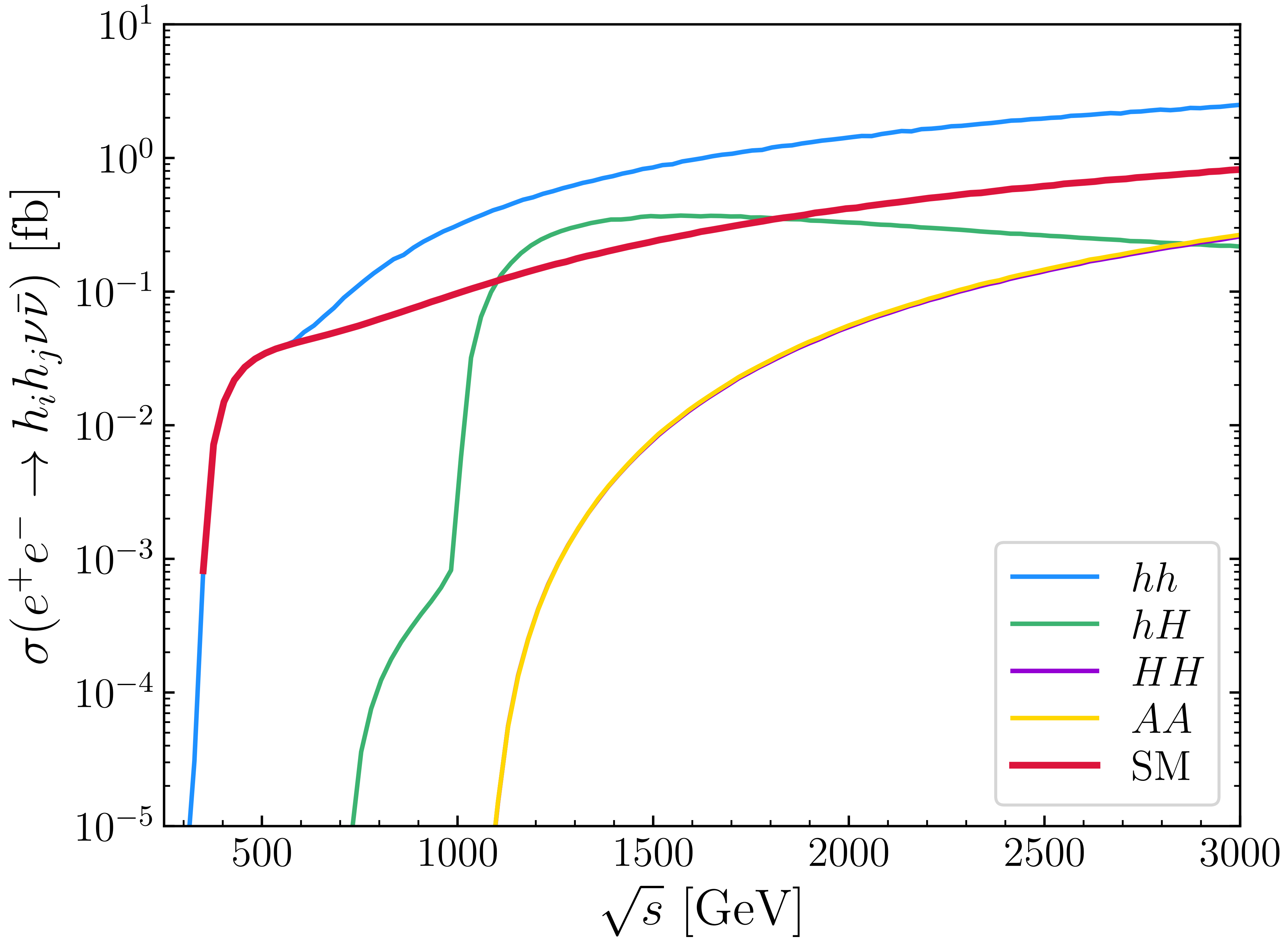
- Electroweak precision data, T parameter: motivates scenarios with degenerate masses
  - For us $m_H = m_A = m_{H^\pm} \equiv m$
- Tree level unitarity and potential stability: $m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$ helps reach large masses
- Collider measurements of the 125 GeV Higgs
  - Close to $\cos(\beta-\alpha)=0$, specially for type II
- BSM Higgs searches in LEP, TeVatron and LHC
- Flavor observables: ${\rm BR}(B\to X_s\gamma)$ and ${\rm BR}(B_s\to\mu\mu)$

2HDMC, HiggsBounds, HiggsSignals and superISO were used

(More detailed discussion to all these constraints in [arXiv2005.10576])

Dependence with energy





Type I
$m = 500$ GeV
$\tan\beta = 10$
$c_{\beta-\alpha} = 0.2$
$m_{12}^2 = 24000$ GeV^2

$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{SM} \simeq 1$
$\lambda_{hhH} = -0.5$
$\lambda_{hHH} = \lambda_{hAA} = 6$
$\lambda_{hH^+H^-} = 12$

Z channel → decreases with the energy

$\nu\bar{\nu}$ channel → increases with the energy (VBF topologies!)

- hhZ and $hh\nu\bar{\nu}$: ~ 3 times the SM due to resonant diagrams mediated by H (contains λ_{hhH}) and A (without THC)
- hHZ and $hH\nu\bar{\nu}$: A mediated diagrams are the dominant contribution but we can still have THC sensitivity at large energies
- $HH\nu\bar{\nu}$ ~ $AA\nu\bar{\nu}$: dominated at large energies by λ_{hHH} (λ_{hAA}) if it is large enough (because $m_H = m_A$)

Madgraph was used

hh production, ILC 500GeV (type I)

Production cross sections wrt the SM at ILC 500 GeV for hhZ (left) and $hh\nu\bar{\nu}$ (right)

- Here hhZ is the most important channel

1. κ_λ: positive interference in the Z channel and negative interference in the $\nu\bar{\nu}$ channel

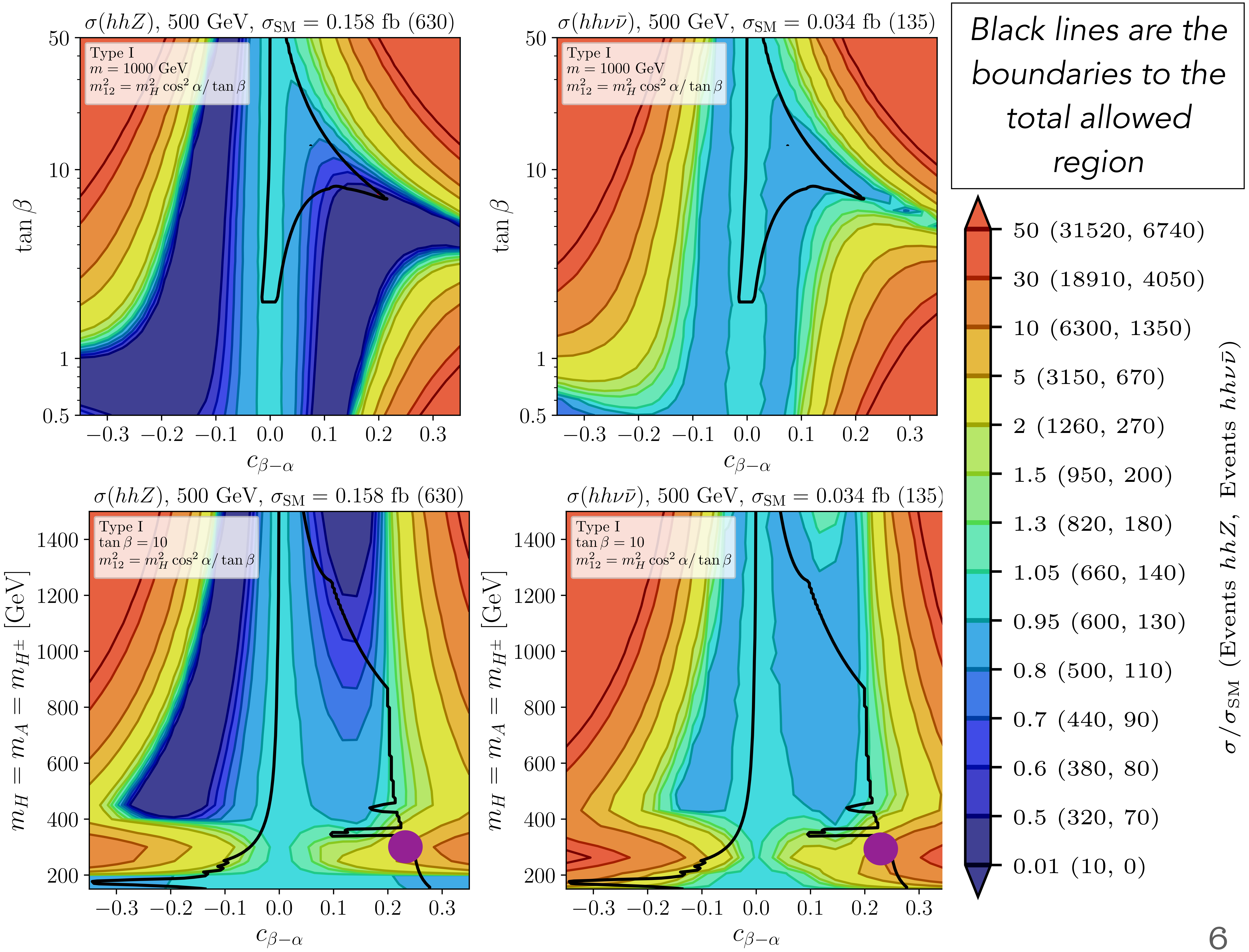
   Larger distortion wrt the SM at the "tip" ($\kappa_\lambda = -0.4$)

2. λ_{hhH}: through resonant diagrams mediated by H

   For low masses away from the alignment limit

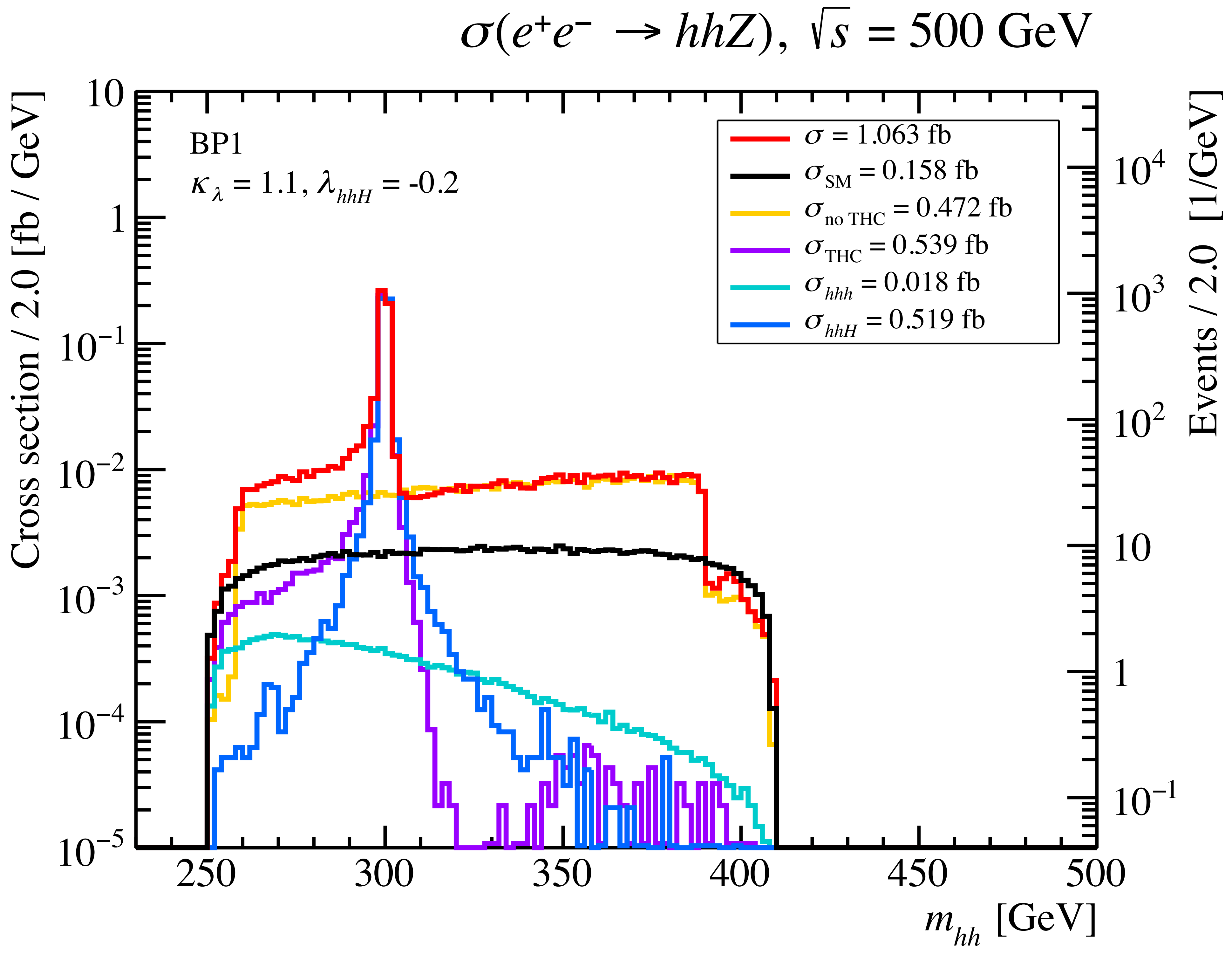
3. Extra contribution from resonant diagrams mediated by A, but no information about THC :(

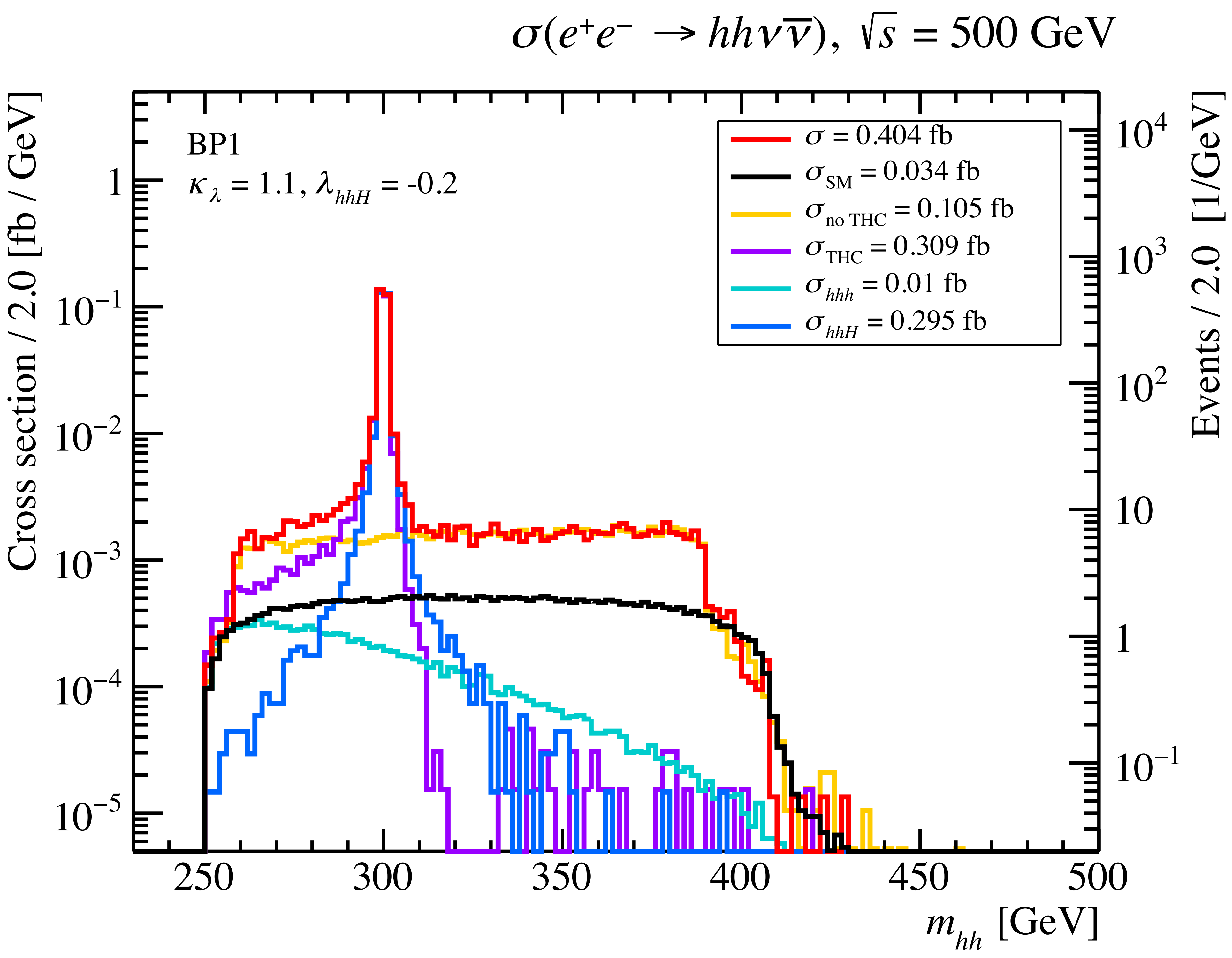
It is essential to look to the invariant mass of the final Higgs pair m_{hh} to see the effects of THC



hh production, ILC 500GeV, THC dependence (type I)

Cross section distribution on the invariant mass of hh, contribution from different diagrams:





Type I

$m = 300$ GeV

$\tan\beta = 10$

$c_{\beta-\alpha} = 0.25$

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

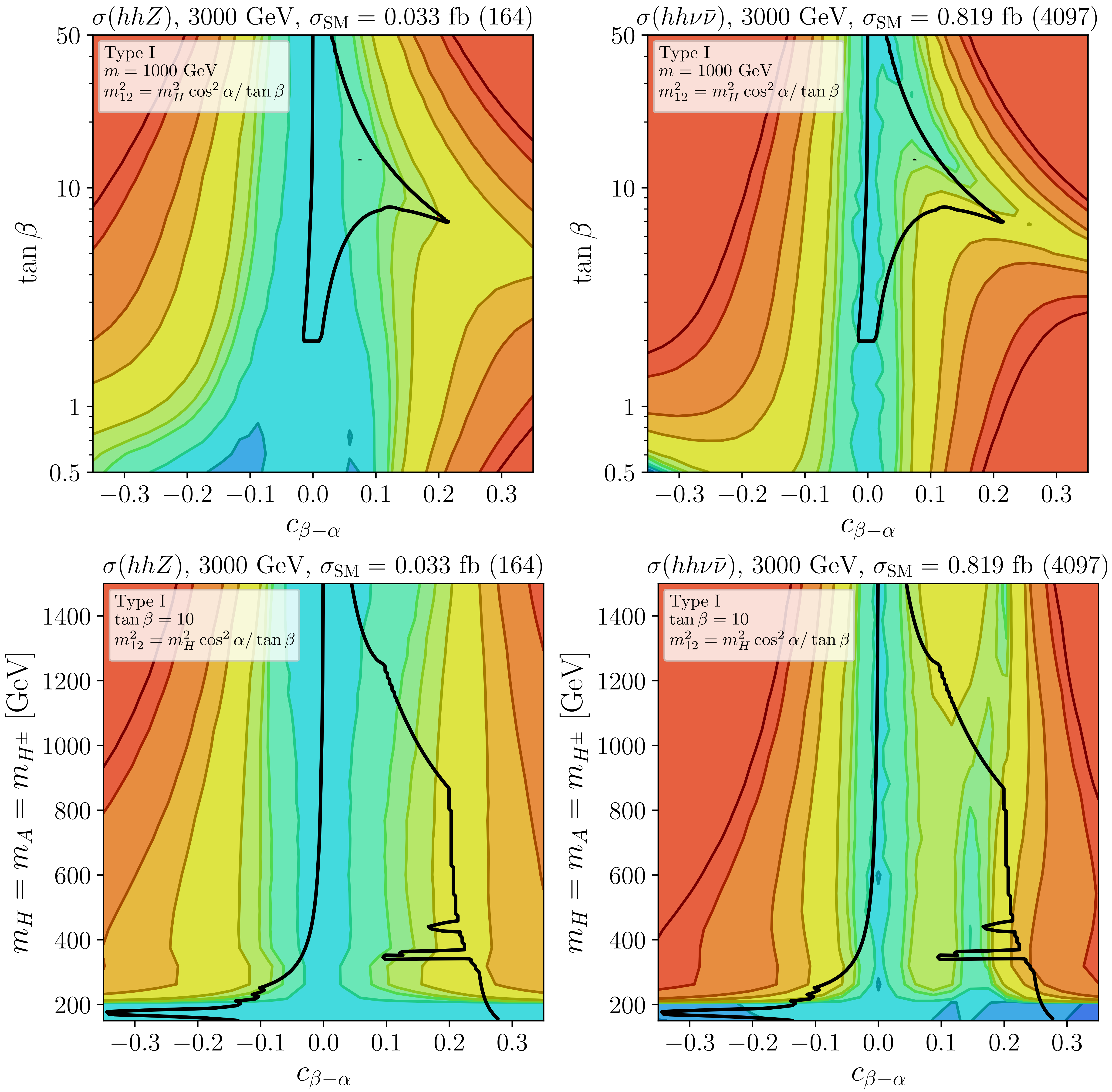
- Larger influence of κ_λ appears at the threshold of m_{hh} (light blue line)
- H resonance (dark blue line): around $m_{hh} = m_H \to$ information from λ_{hhH}
- Plateau in the diagrams without THC (yellow line) wrt the SM (black line) due to the A resonant diagrams

The effect from κ_λ and λ_{hhH} can be “mixed” if m_H is small

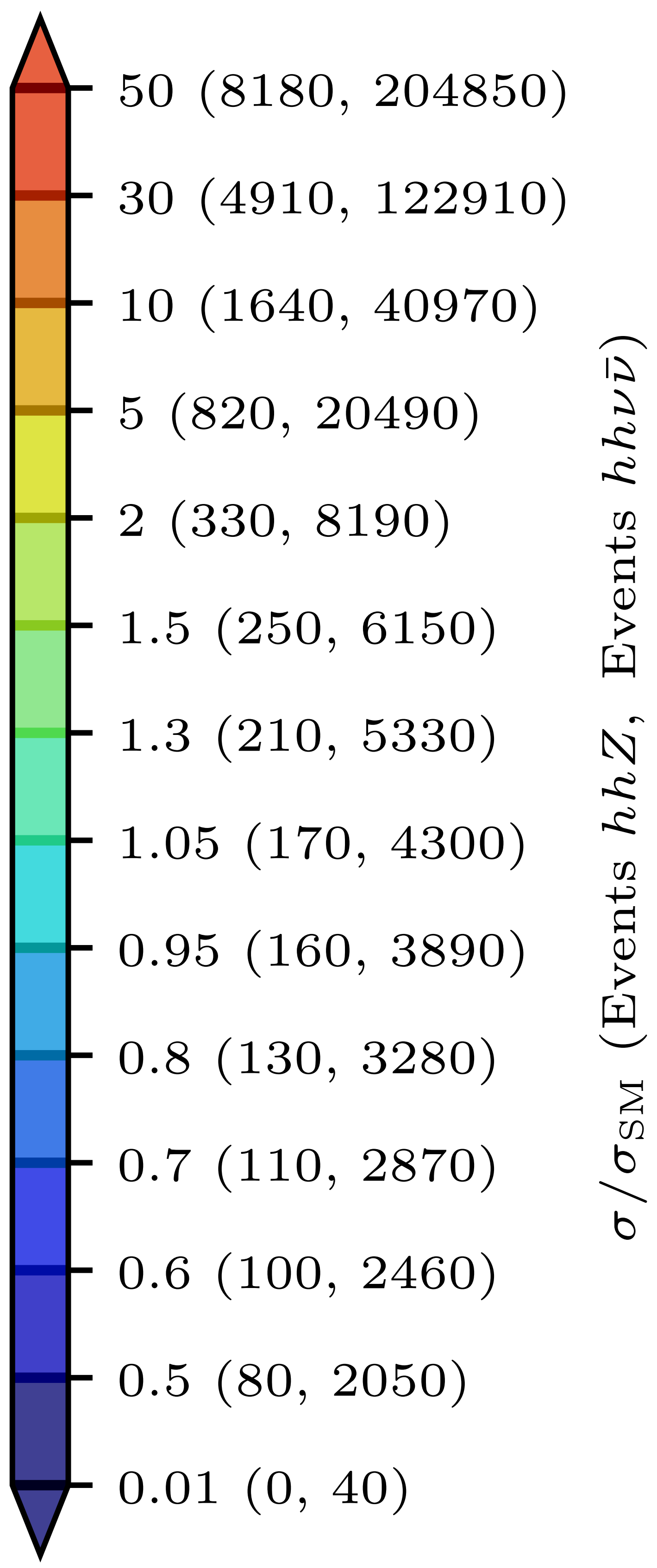
hh production, CLIC 3TeV (type I)

Production cross sections wrt the SM at CLIC 3 TeV for hhZ (left) and $hh\nu\bar{\nu}$ (right)

- At this energy, $hh\nu\bar{\nu}$ channel is the most important channel
- hhZ is very dominated by the A mediated diagrams, while in $hh\nu\bar{\nu}$ the H mediated diagrams are more important
- In the neutrino channel we can find very large XS: $\sim 10\sigma_{\rm SM} = 9$ fb at low masses and $\sim 3\sigma_{\rm SM}$ for a wide range of masses



Black lines are the boundaries to the total allowed region

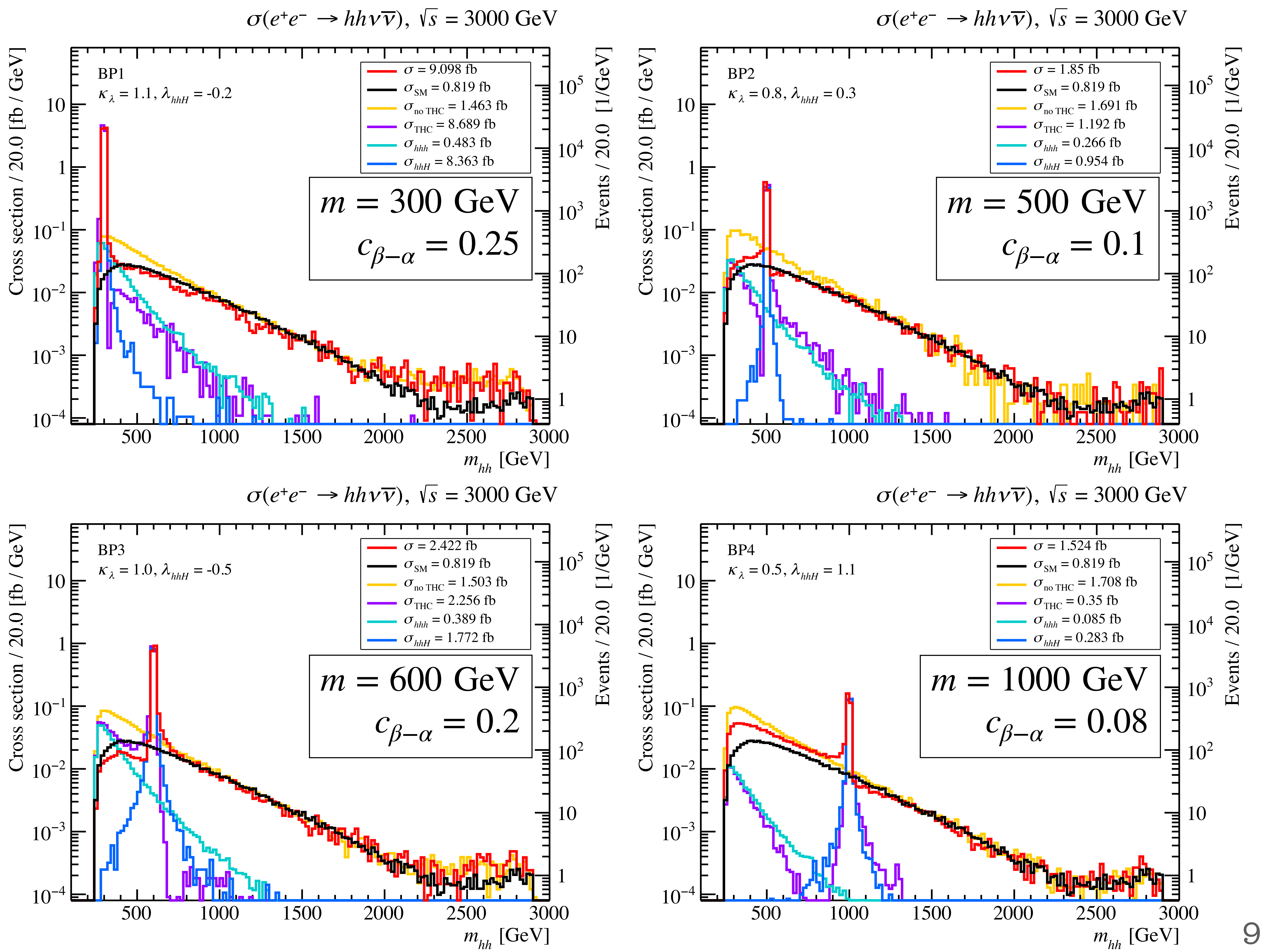


hh production, CLIC 3TeV, THC dependence (type I)

Cross section distribution on the invariant mass of hh, contribution from different diagrams:

- The effect of κ_λ appear at the region of low invariant mass
- The neutrino channel can access to the H resonant peak (i.e. to λ_{hhH}) for a wide range of m_H and $c_{\beta-\alpha}$
- Sign of λ_{hhH}: asymmetry around the H peak

$\Longrightarrow$ which collider and channel are best suited to access to λ_{hhH}?



hh production, "sensitivity" to λ_{hhH} (type I)

We define our theoretical sensitivity as: $R = \frac{\bar{N}^R - \bar{N}^C}{\sqrt{\bar{N}^C}}$

R estimates the sensitivity to λ_{hhH} via 4 b-jets events in the m_{hh} region close to the H resonance

$\bar{N}^{R/C}$ are the expected realistic events from the H resonance and from diagrams without THC, considering the b-tagging efficiency and detection acceptance at the collider with the following cuts:

$p_T^b > 20$ GeV, $|\eta^b| < 2$, $\Delta R_{bb} > 0.4$, $p_T^Z > 20$ GeV, $\not{E}_T > 20$ GeV

hhZ	$\sqrt{s}$ [GeV]	$\sigma_{2\mathrm{HDM}}$ / σ_{SM} [fb]	$\bar{N}^R_{4bZ}$ / $\bar{N}^C_{4bZ}$ / $\bar{N}^{\mathrm{SM}}_{4bZ}$	R_{4bZ}
BP1	500	1.063 / 0.158	193 / 10 / 3	58
	1000	0.913 / 0.120	206 / 1 / 4	205
	1500	0.493 / 0.077	22 / < 1 / 1	-
	3000	0.147 / 0.033	1 / < 1 / < 1	-
BP2	1000	0.156 / 0.120	20 / 1 / 1	19
	1500	0.106 / 0.077	4 / < 1 / < 1	-
	3000	0.042 / 0.033	< 1 / < 1 / < 1	-
BP3	1000	0.254 / 0.120	29 / 5 / 2	11
	1500	0.218 / 0.077	8 / 1 / < 1	7
	3000	0.086 / 0.033	1 / < 1 / < 1	-
BP4	1500	0.075 / 0.077	1 / < 1 / < 1	-
	3000	0.038 / 0.033	< 1 / < 1 / < 1	-

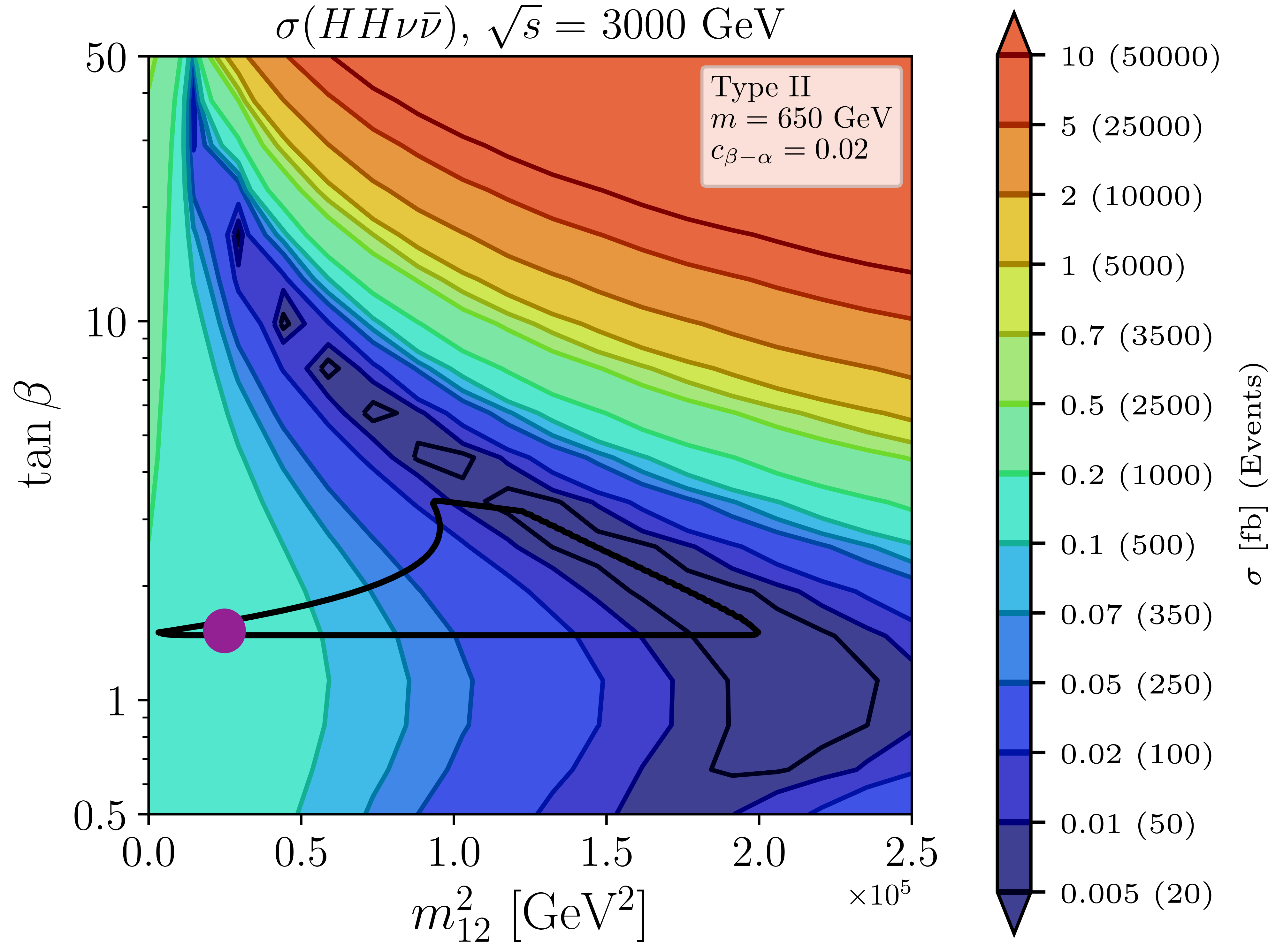
$hh\nu\bar{\nu}$	$\sqrt{s}$ [GeV]	$\sigma_{2\mathrm{HDM}}$ / σ_{SM} [fb]	$\bar{N}^R_{4b\not{E}_T}$ / $\bar{N}^C_{4b\not{E}_T}$ / $\bar{N}^{\mathrm{SM}}_{4b\not{E}_T}$	$R_{4b\not{E}_T}$
BP1	500	0.404 / 0.034	119 / 4 / 1	58
	1000	2.391 / 0.097	1510 / 24 / 0	303
	1500	4.423 / 0.239	794 / 13 / 2	217
	3000	9.098 / 0.819	2425 / 46 / 6	351
BP2	1000	0.234 / 0.097	79 / 3 / 1	44
	1500	0.625 / 0.239	70 / 3 / 1	39
	3000	1.850 / 0.819	282 / 28 / 9	48
BP3	1000	0.208 / 0.097	85 / 5 / 3	36
	1500	0.709 / 0.239	111 / 5 / 3	47
	3000	2.422 / 0.819	577 / 30 / 11	100
BP4	1500	0.428 / 0.239	4 / < 1 / < 1	-
	3000	1.523 / 0.819	72 / 4 / 3	34

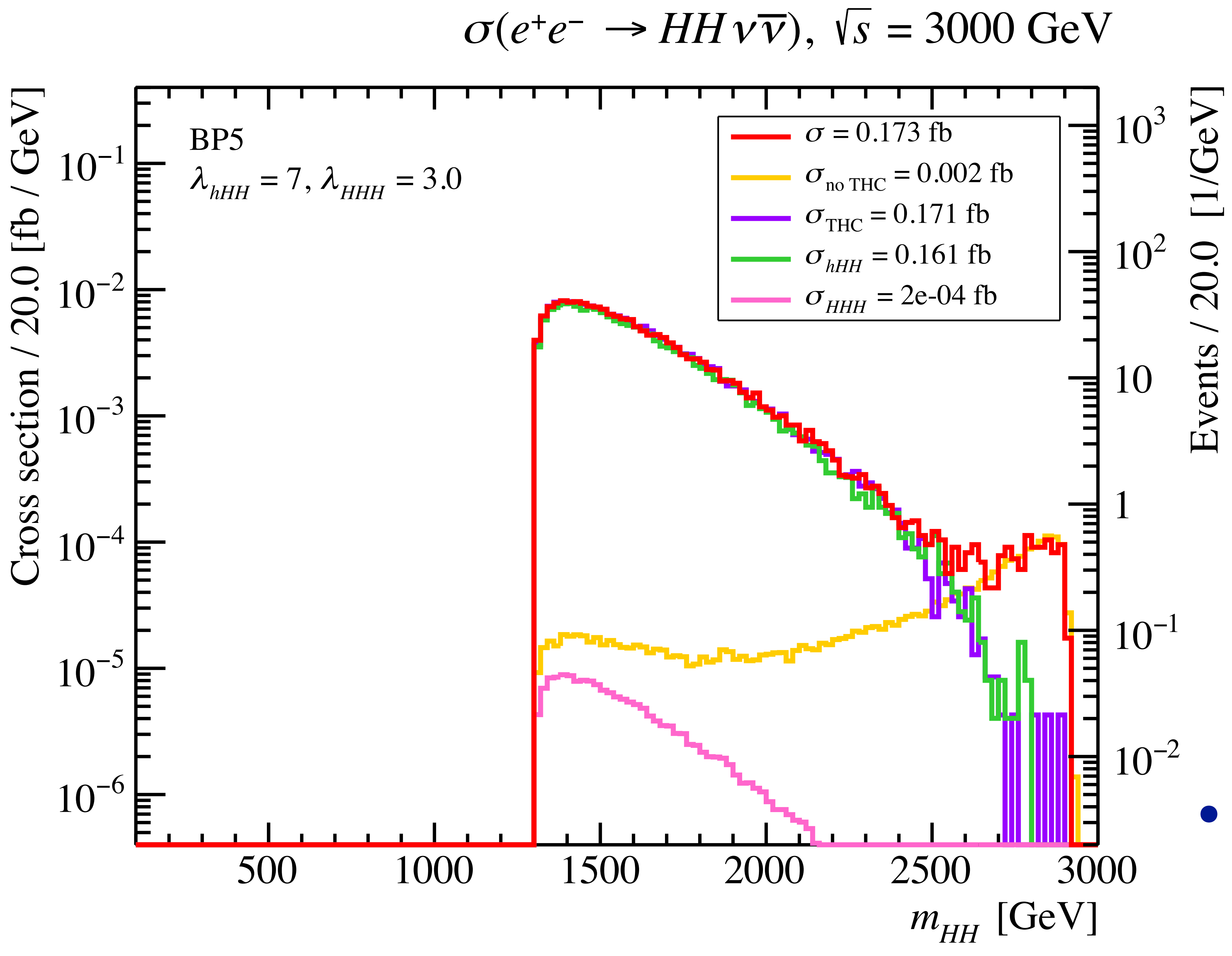
More sensitivity to λ_{hhH} (i.e. larger R) in the neutrino channel at all studied points, specially at CLIC 3 TeV

more details in [arxiv:2106.11105]

$HH \sim AA$ production, CLIC 3TeV, THC dependence (type II)

In type II, due to the collider constraints, only $HH\nu\bar{\nu} \sim AA\nu\bar{\nu}$ production is relevant





Type II
$m = 650$ GeV
$\tan\beta = 1.5$
$c_{\beta-\alpha} = 0.02$
$m_{12}^2 = 10000$ GeV^2

- XS is larger at low m_{12}^2, that is the region where λ_{hHH} is larger
- The dominant effect in $HH\nu\bar{\nu}$ comes from λ_{hHH} (green line) and it is responsible for almost all the cross section
- In both type I and type II, we will see a sizable XS in $HH\nu\bar{\nu}$ where λ_{hHH} can large (if m_H is light enough)

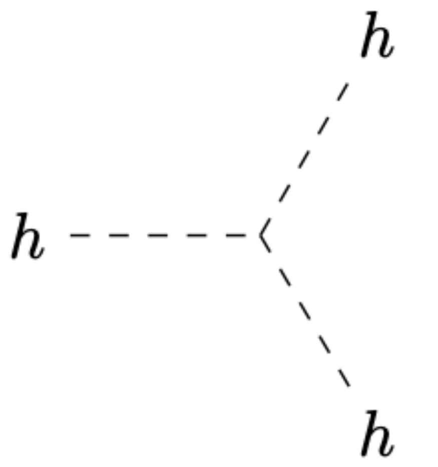
Summary & Conclusions

- The di-Higgs production of neutral Higgs bosons is studied at ILC and CLIC (e^+e^- colliders) in the 2HDM, with the aim to find effects coming from triple Higgs couplings (THC)
    - Two production channels were studied: $e^+e^- \to h_i h_j Z$ and $e^+e^- \to h_i h_j \nu\bar{\nu}$
- In hh production: only sizable distortions at type I (type II is very constrained)
    - From κ_λ, at low invariant mass of the hh pair, similar to what happens in the SM (extensively studied in the literature)
    - From λ_{hhH}, through a resonant peak due to the H boson: a "realistic" study shows that the neutrino channel is better to access this coupling at all center-of-mass energies (specially at CLIC 3TeV)
- The $HH\nu\bar{\nu} \sim AA\nu\bar{\nu}$ production can have sizable cross sections (around 0.2 fb), in both 2HDM type I and II, mainly because the effects from λ_{hHH} (λ_{hAA}) (and if the H boson is light enough to produce two of them)
    - What about a "future" $\mu^+\mu^-$ collider???

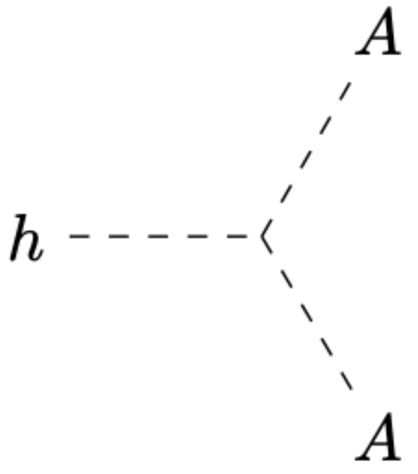
Thanks for your attention :)

Questions??

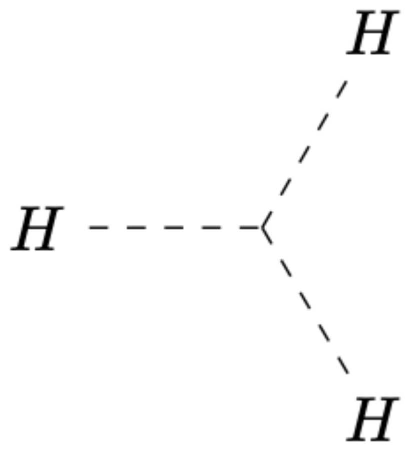
Back-up, Feynman Rules with THC



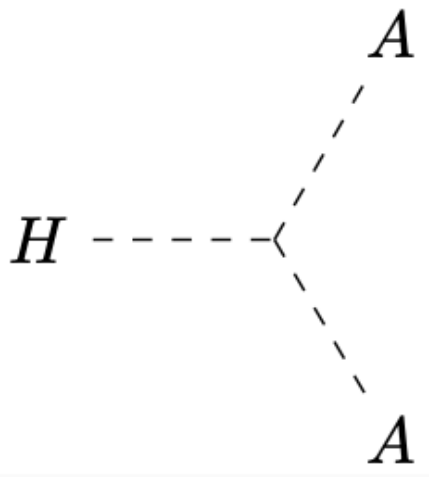
$$= -\frac{3i}{v}\left(2\cot 2\beta\left(m_h^2-\bar{m}^2\right)c^3_{\beta-\alpha} + \left(3m_h^2-2\bar{m}^2\right)c^2_{\beta-\alpha}s_{\beta-\alpha} + m_h^2 s^3_{\beta-\alpha}\right)$$



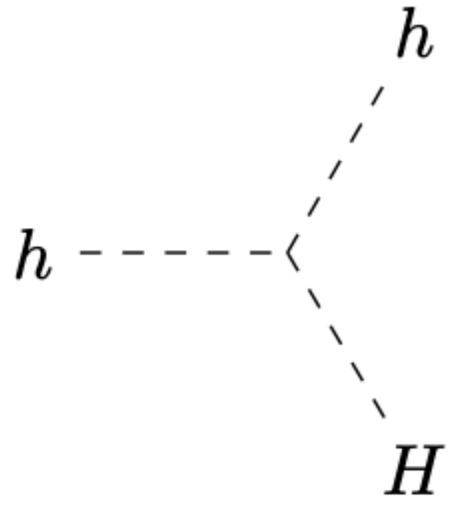
$$= -\frac{i}{v}\left(s_{\beta-\alpha}\left(-2\bar{m}^2+2m_A^2+m_h^2\right) + 2\cot 2\beta\left(m_h^2-\bar{m}^2\right)c_{\beta-\alpha}\right)$$



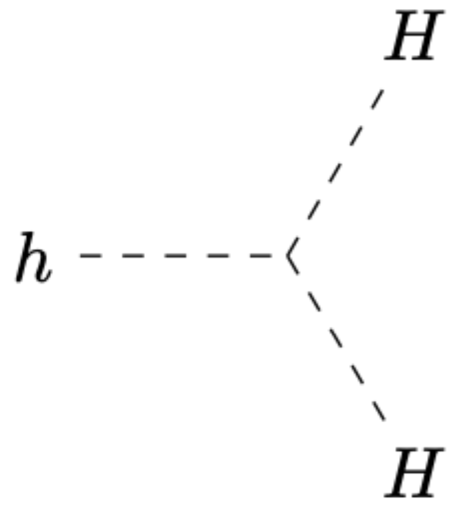
$$= -\frac{3i}{v}\left(\left(3m_H^2-2\bar{m}^2\right)c_{\beta-\alpha}s^2_{\beta-\alpha} + 2\cot 2\beta\left(\bar{m}^2-m_H^2\right)s^3_{\beta-\alpha} + m_H^2 c^3_{\beta-\alpha}\right)$$



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



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



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

Methodology

- Model implemented with FeynRules and computation of the cross section with MadGraph and obtain the Higgs widths with 2HDMC
  - We do NOT use the Narrow Width Approximation
- Cross sections presented in some benchmark planes that present large THC within the allowed region (based on [arXiv2005.10576]):
  - Plane $c_{\beta-\alpha} - \tan\beta$: Type I with $m = 1\ \text{TeV}$ and $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$
  - Plane $c_{\beta-\alpha} - m$: Type I with $\tan\beta = 10$ and $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$
  - Plane $m_{12}^2 - \tan\beta$: Type II with $m = 650\ \text{GeV}$ and $c_{\beta-\alpha} = 0.02$
  - Plane $m_{12}^2 - m$: Type II with $\tan\beta = 1.5$ and $c_{\beta-\alpha} = 0.02$
- Access to THC with the XS distributions on the invariant mass of the final $h_i h_j$ (with ROOT) of some Benchmark Points (BP)

We use the projected luminosities and center-of-mass for ILC and CLIC:

Collider	$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [ab^{-1}]
ILC	500	4
ILC	1000	8
CLIC	1500	2.5
CLIC	3000	5

Point	Type	m	$\tan\beta$	$c_{\beta-\alpha}$	m_{12}^2
BP1	I	300	10	0.25	Eq. (8)
BP2	I	500	7.5	0.1	32000
BP3	I	600	10	0.2	Eq. (8)
BP4	I	1000	8.5	0.08	Eq. (8)
BP5	II	650	1.5	0.02	10000

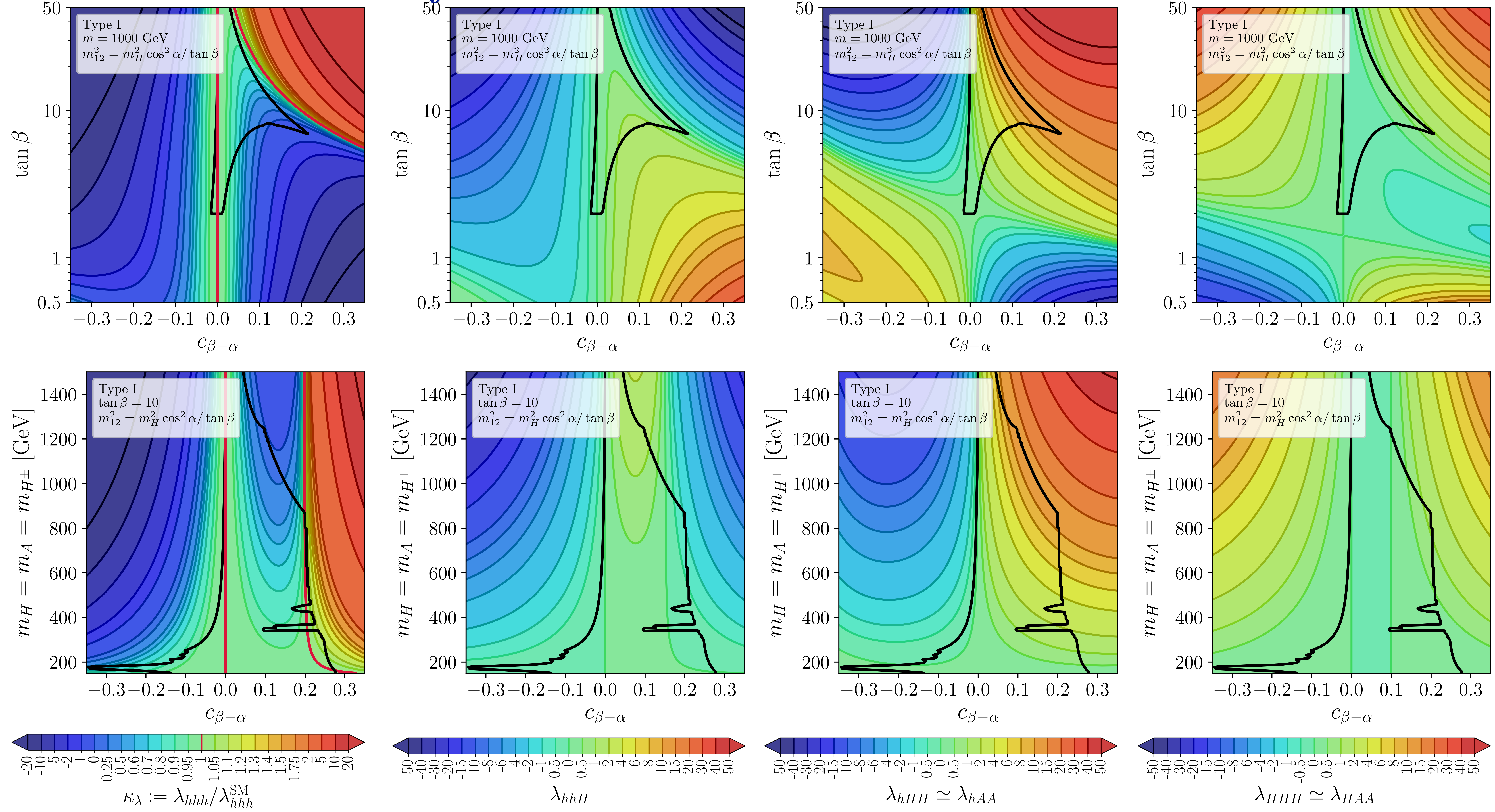
(Eq. (8) $\to m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$)

back-up, hh production: λ_{hhH} "sensitivity"

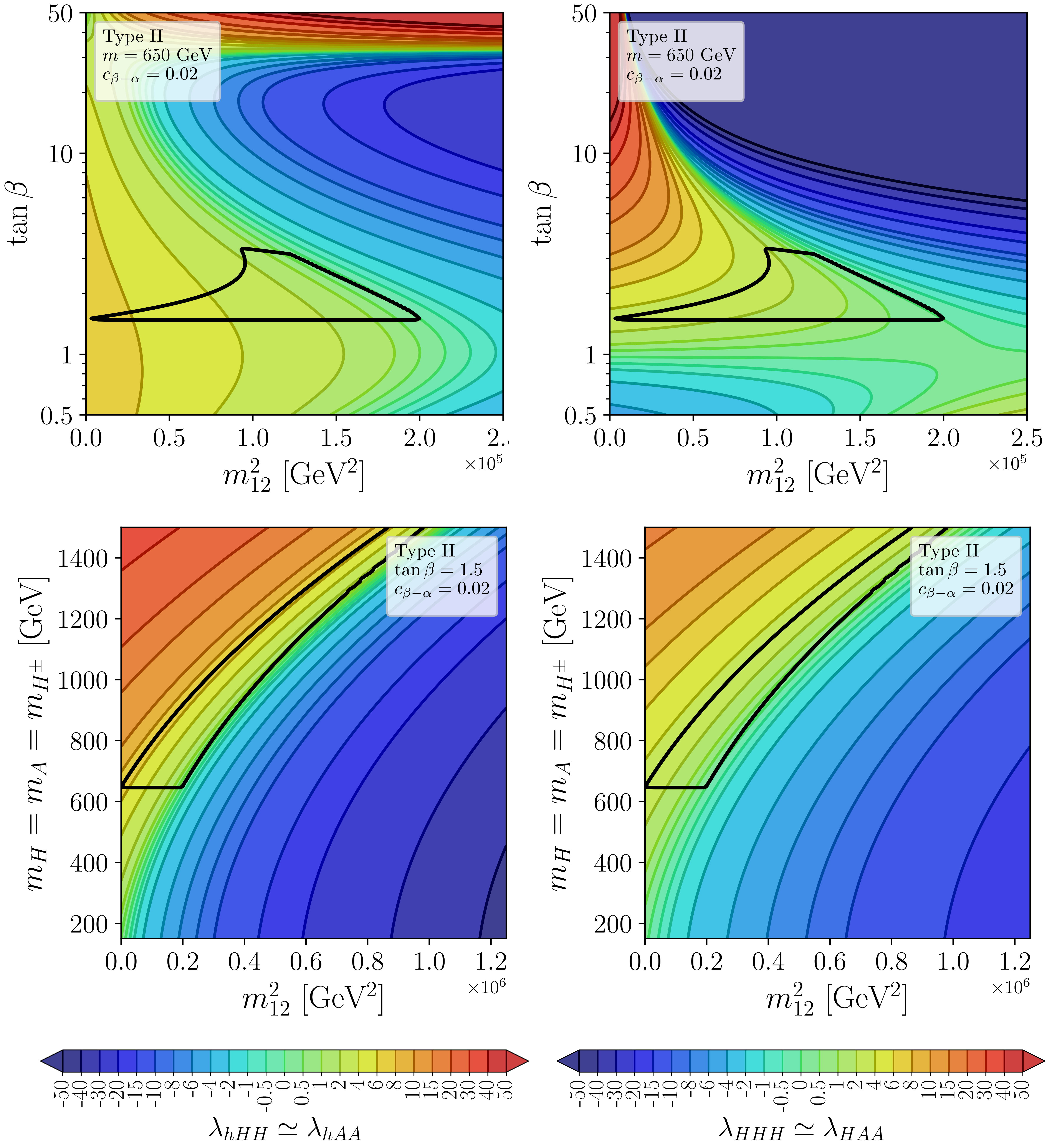
- We propose a estimator to try to determine when the effect of λ_{hhH} will be more prominent
  - Considering a realistic collider situation to reconstruct the experimental signal
  - We consider the events in the range where the XS distribution of the H mediated diagrams (dark blue lines) is larger than the XS distribution of the diagrams without THC (yellow lines)
- $$R = \frac{\bar{N}^R - \bar{N}^C}{\sqrt{\bar{N}^C}}$$

  N^R refers to the resonance and N^C to the "continuum"
  - where $\bar{N} = N \times \mathscr{A} \times \epsilon_b^4$ with N the number of total events, $\mathscr{A} = N_{\rm cuts}/N_{\rm no\ cuts}$ is the acceptance of the collider and $\epsilon_b \sim 0.8$ the b-tagging efficiency
- *Cuts:* $p_T^b > 20$ GeV, $|\eta^b| < 2$, $\Delta R_{bb} > 0.4$, $p_T^Z > 20$ GeV, $\not{E}_T > 20$ GeV

Back-up, $\lambda_{h_i h_j h_k}$

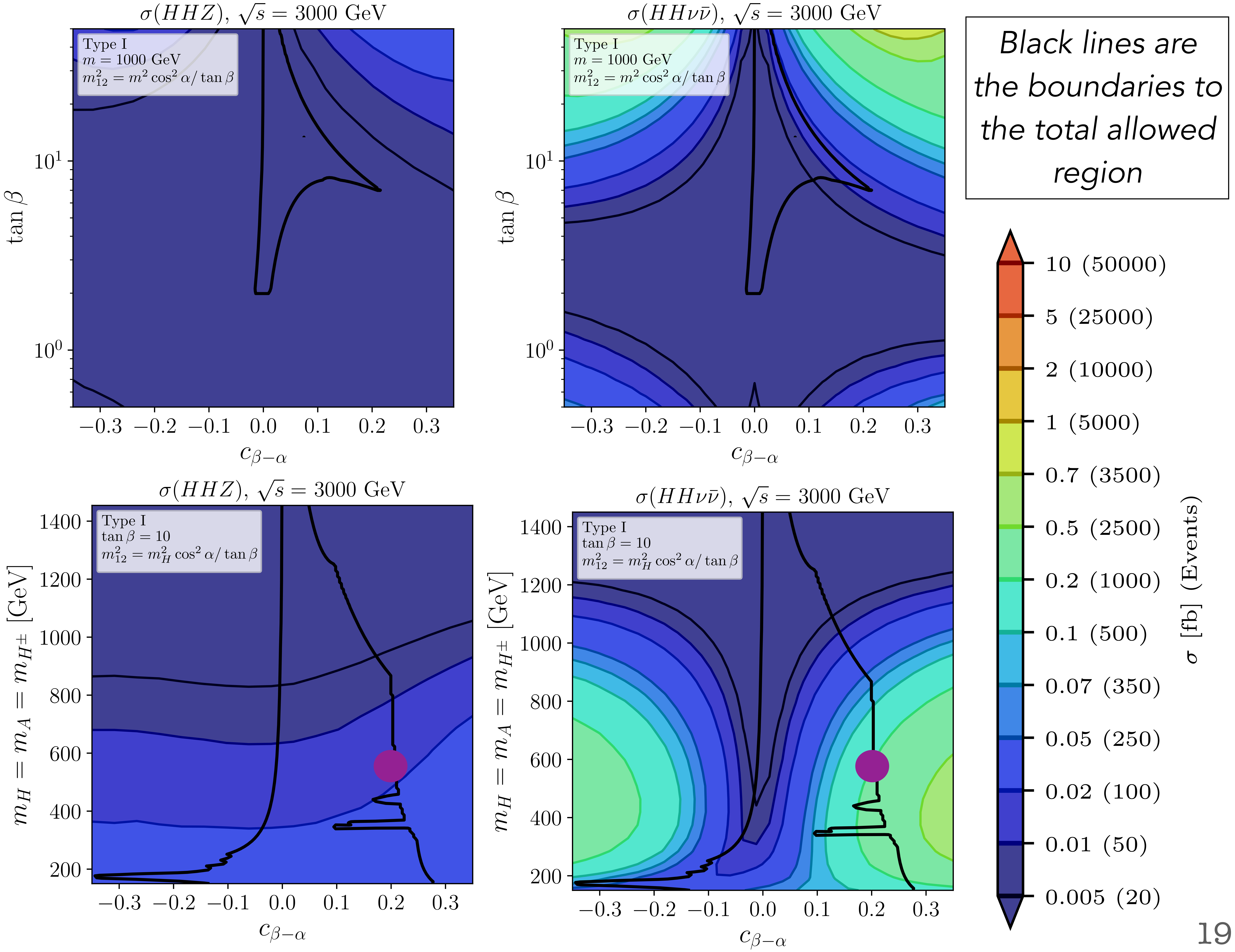


Back-up, $\lambda_{h_i h_j h_k}$



$HH \sim AA$ production, CLIC 3TeV

- The $HH \sim AA$ production can be non-zero even in the alignment limit ($c_{\beta-\alpha} \to 0$)
- Only sizable cross sections inside the allowed region for the neutrino channel
  - Not larger than 0.5 fb
- The sizable cross sections comes from the effect of λ_{hHH} (λ_{hAA})
  - Effects from λ_{HHH} (λ_{HAA}) could be important only for larger values of $c_{\beta-\alpha}$

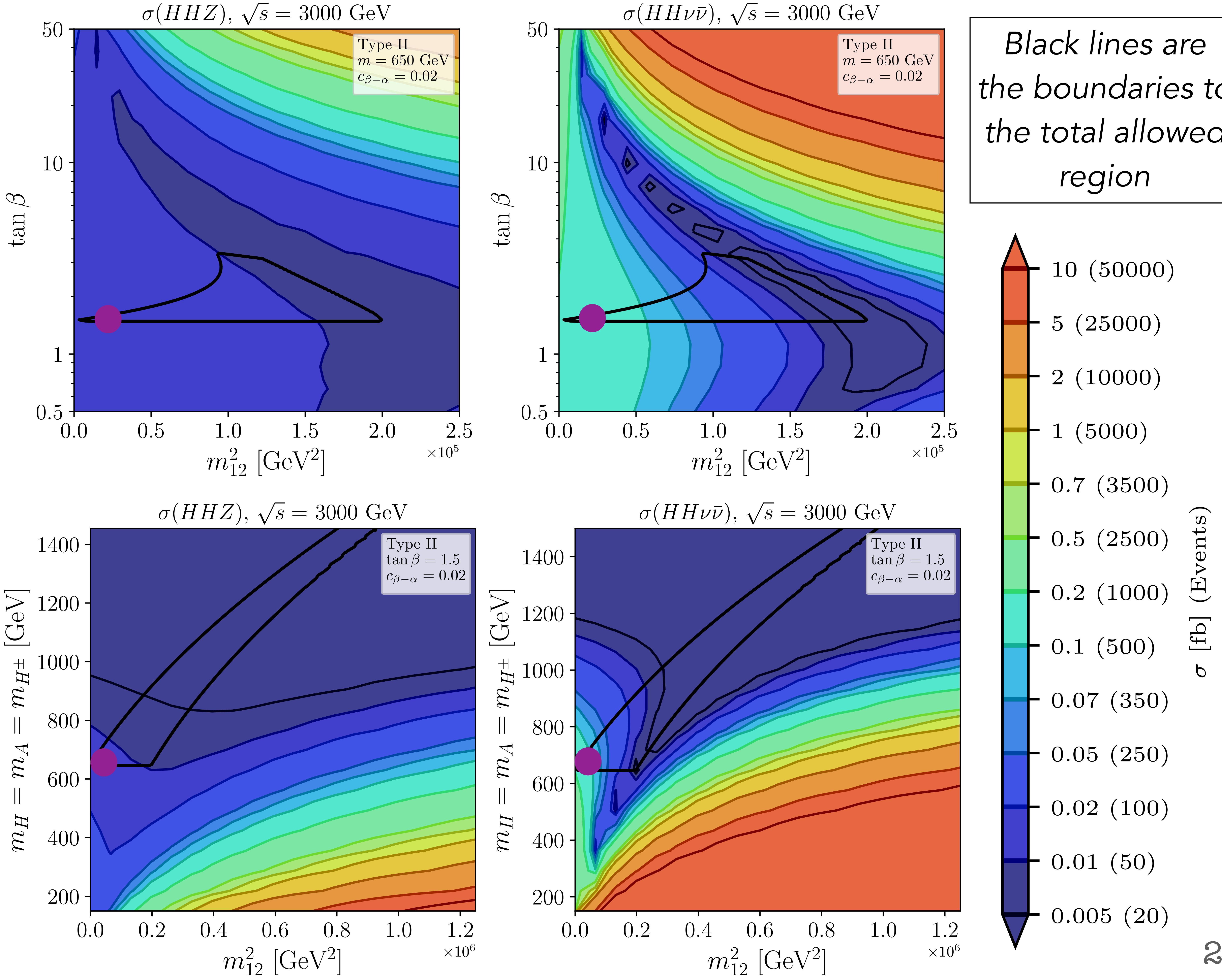


Black lines are the boundaries to the total allowed region

$HH \sim AA$ production, CLIC 3TeV (type II)

Production cross sections wrt the SM at ILC 500 GeV for HHZ (left) and $HH\nu\bar{\nu}$ (right)

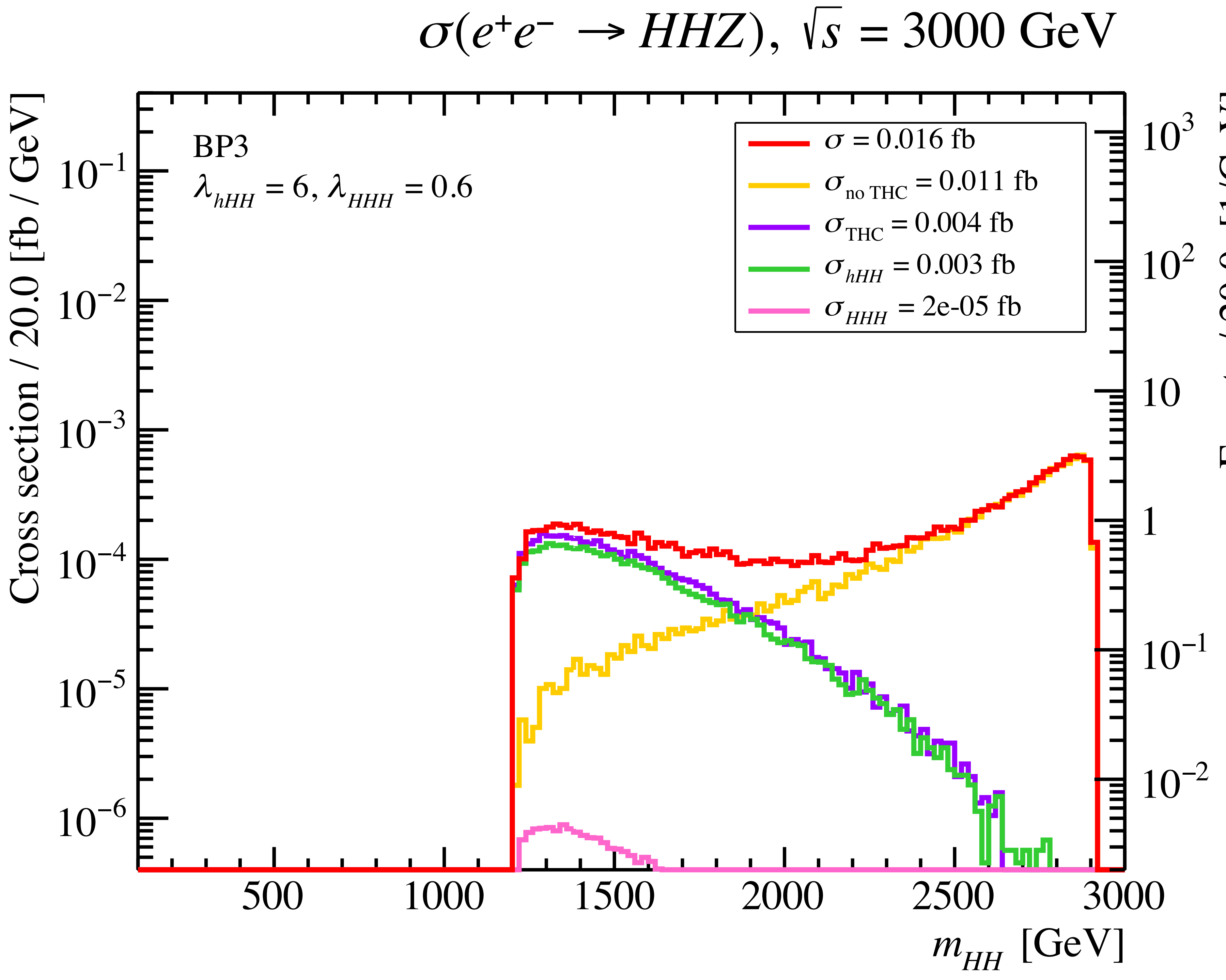
- In type II, due to the collider constraints, only $HH \sim AA$ production is relevant
- Only sizable XS, not larger than $0.5\ \mathrm{fb}$, inside the allowed region for the neutrino channel
- Sizable XS comes from the effect of λ_{hHH} (λ_{hAA})
  - XS is larger at low m_{12}^2, that is the region where λ_{hHH} is larger!
- In type I we can obtain similar XS (in other regions of the parameter space)

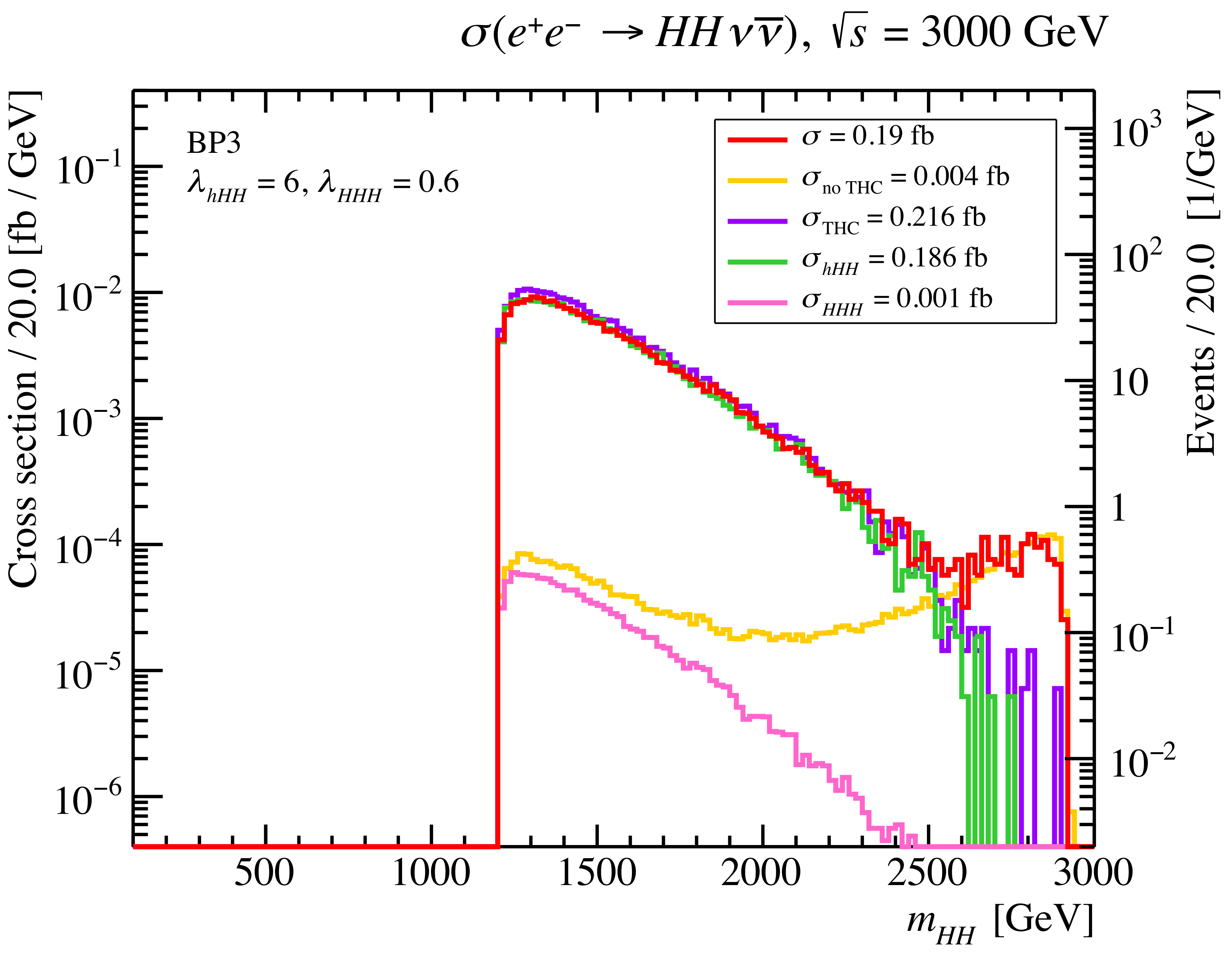


Black lines are the boundaries to the total allowed region

$HH \sim AA$ production, CLIC 3TeV, THC dependence

Cross section distribution on the invariant mass of HH:





Type I

$m = 600$ GeV

$\tan\beta = 10$

$c_{\beta-\alpha} = 0.2$

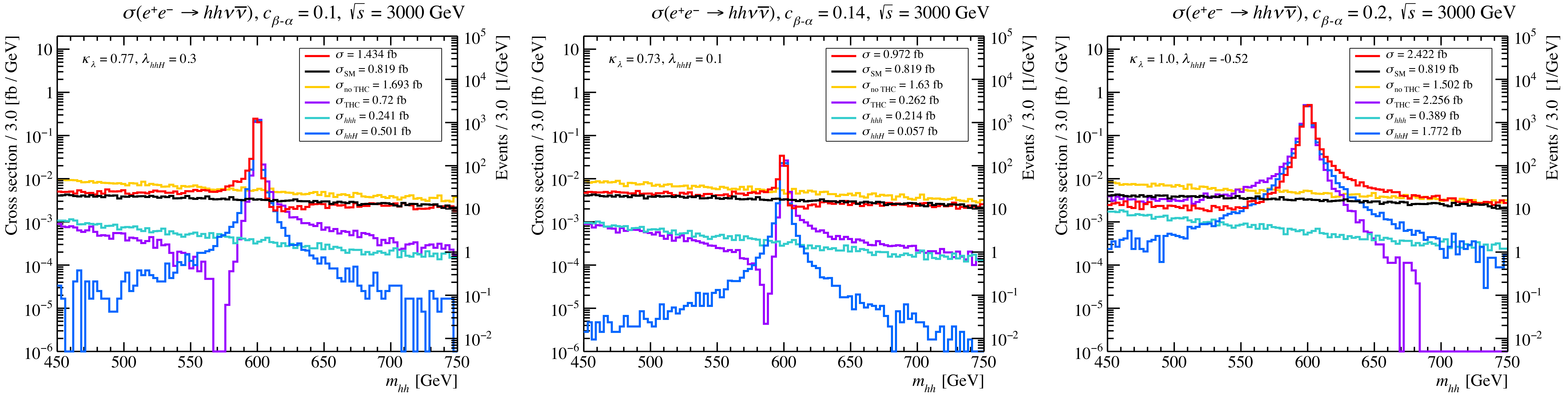
$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$

- Very small XS and number of events in the HHZ channel
- Dominant effect in $HH\nu\bar{\nu}$ comes from λ_{hHH} and it is responsible for almost all the cross section

hh production, CLIC 3TeV, THC dependence (type I)

Evolution of the H resonance with $c_{\beta-\alpha}$ (and indirectly with λ_{hhH})

Type I, $m = 600$ GeV, $\tan\beta = 10$, $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$

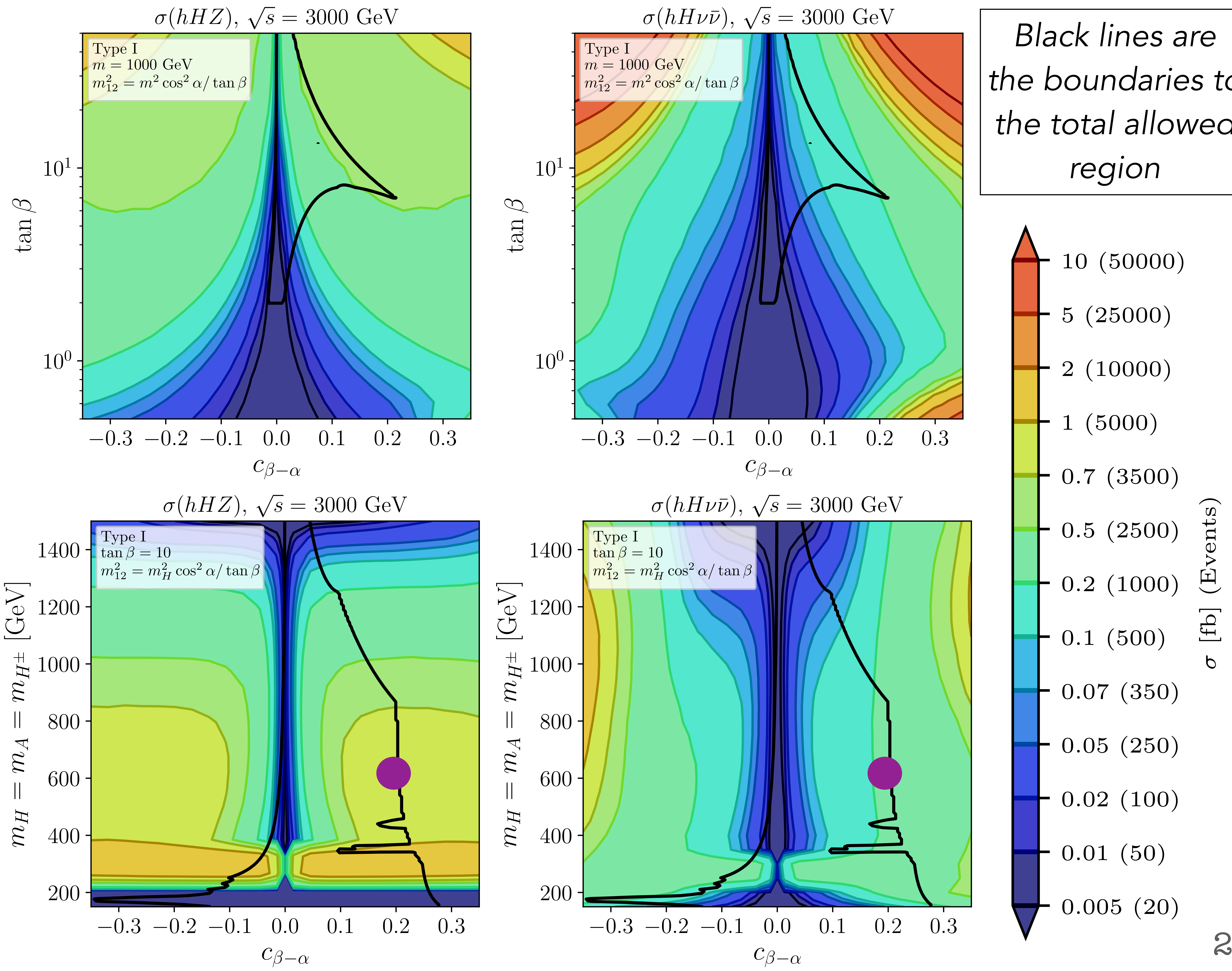


- Height of the resonance depends on λ_{hhH}
- For large $c_{\beta-\alpha}$ the resonance is wider because Γ_H is larger

$\lambda_{hhH} > 0$:	$\lambda_{hhH} < 0$:
More events at the left of the peak than at the right	More events at the right of the peak than at the left

hH production, CLIC 3TeV (type I)

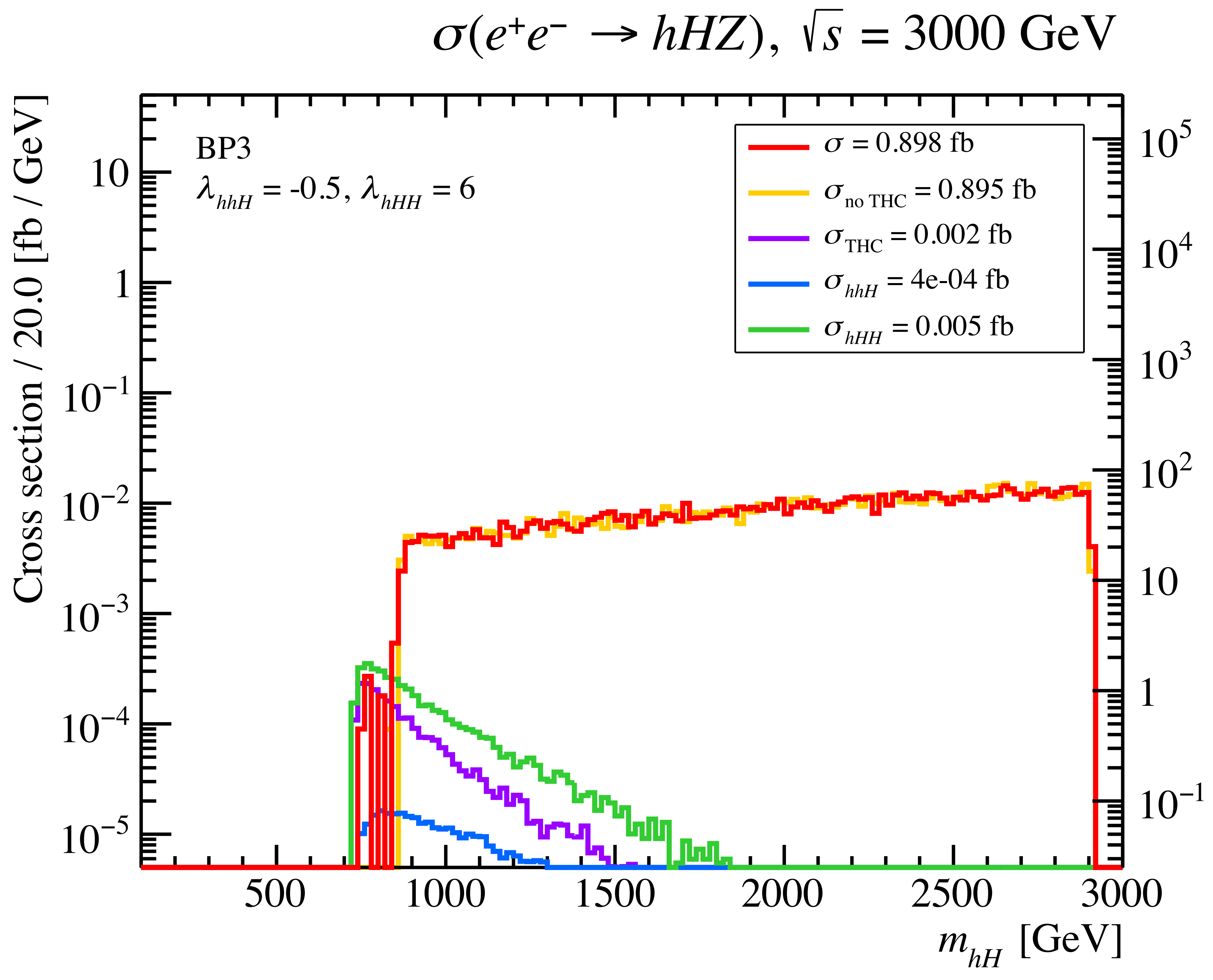
- The hH production channels disappear in the alignment limit
- Very strong contribution from resonant A diagrams in the hHZ channel
- In the neutrino channel, the effects from A mediated diagrams mixes with the effects coming from the THC (for this process: λ_{hhH} and λ_{hHH})

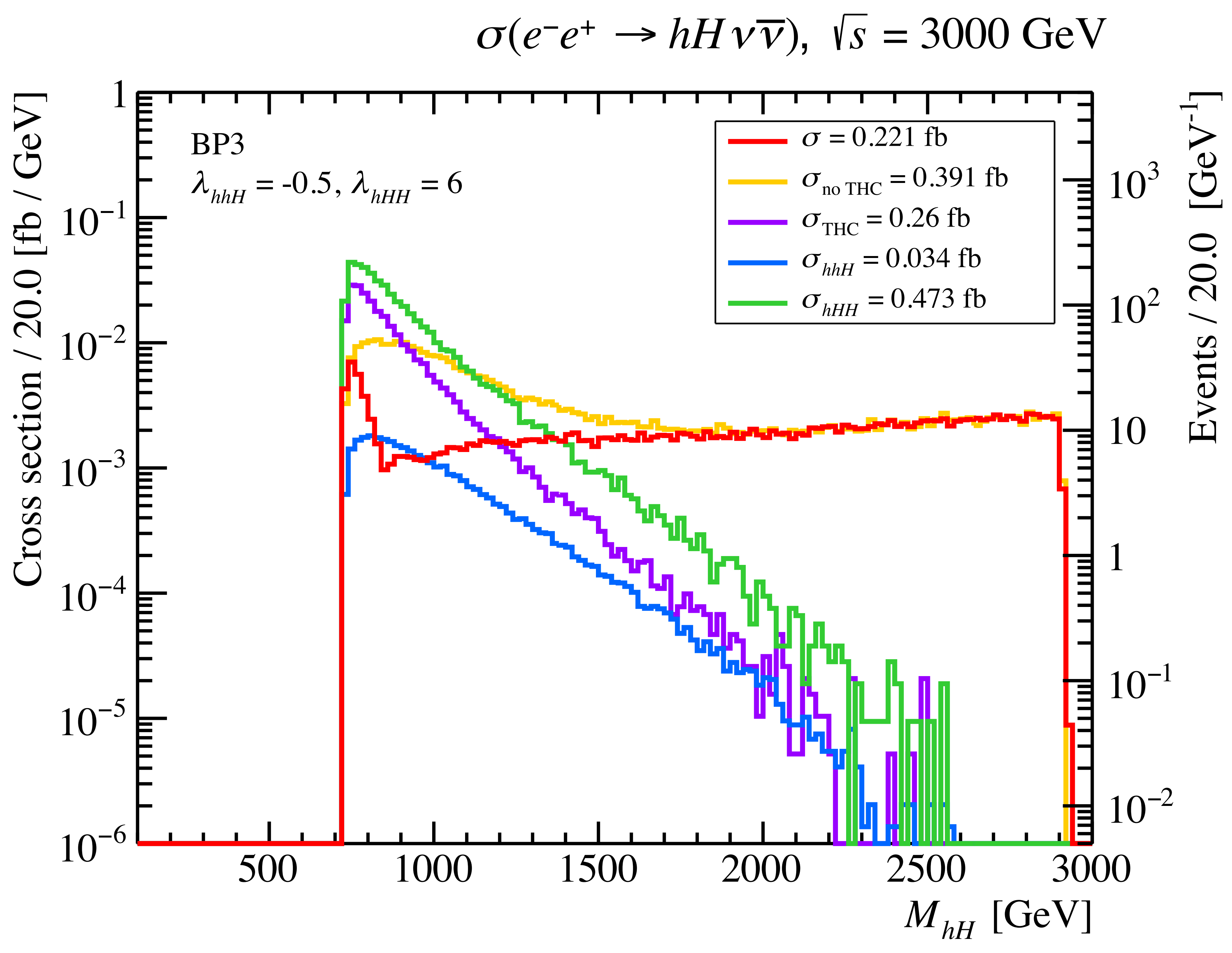


Black lines are the boundaries to the total allowed region

hH production, CLIC 3TeV, THC dependence (type I)

Cross section distribution on the invariant mass of hH:





Type I
$m = 600$ GeV
$\tan\beta = 10$
$c_{\beta-\alpha} = 0.2$
$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$

- Large “steps” in both channels coming from A resonant diagrams
- Large effects from λ_{hhH} (dark blue line) and λ_{hHH} (green line) at low m_{hH} only in the neutrino channel at the m_{hH} threshold
- The combined effect of both THC (purple line) depends on their relative sign

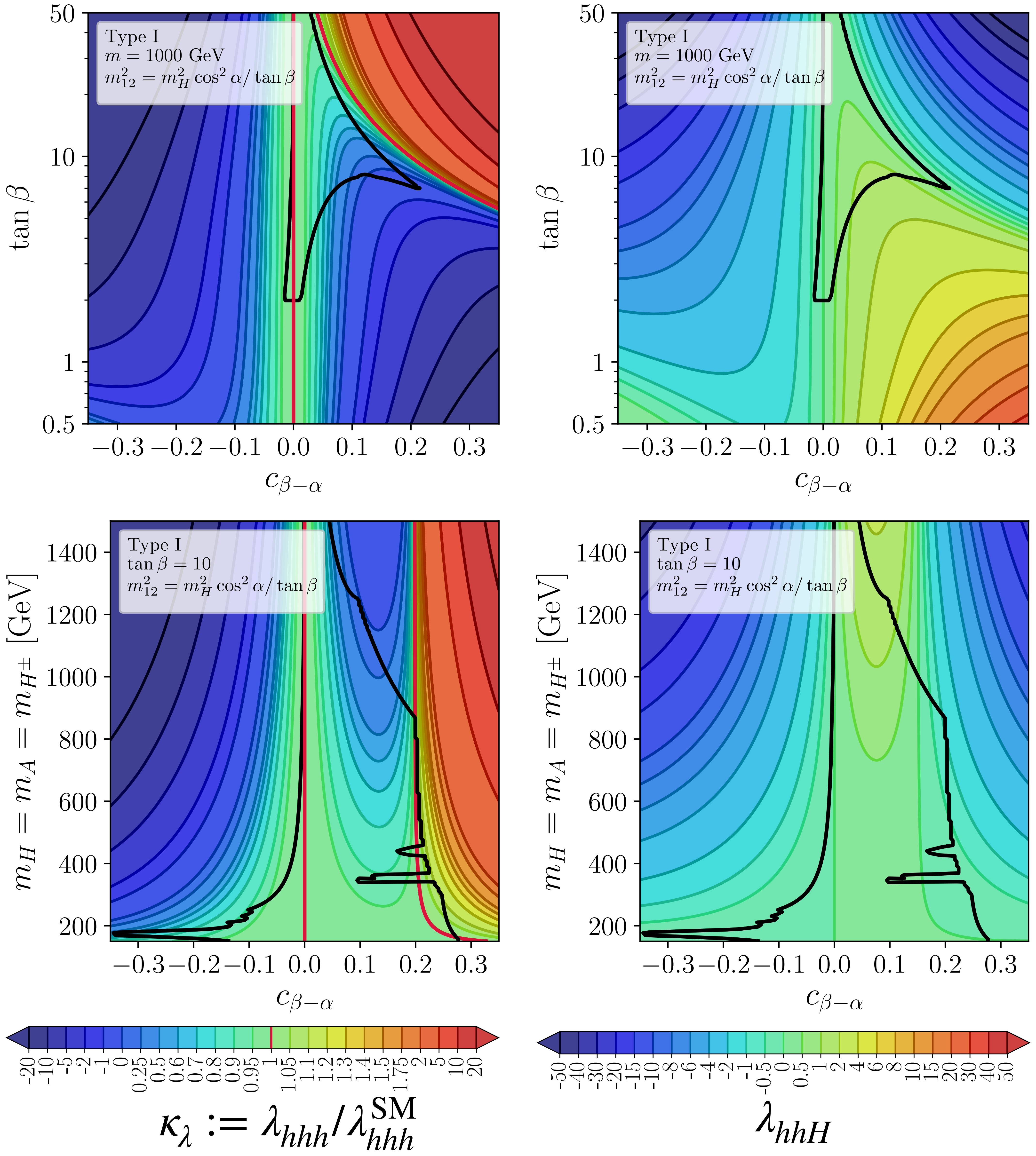
Triple Higgs Couplings (THC), Type I

- Two benchmark planes:
  - Plane $c_{\beta-\alpha} - \tan\beta$: Type I with $m = 1\ \mathrm{TeV}$ and $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$
  - Plane $c_{\beta-\alpha} - m$: Type I with $\tan\beta = 10$ and $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$
- $\kappa_\lambda := \lambda_{hhh} / \lambda_{hhh}^{\mathrm{SM}}$

  Lowest value $\kappa_\lambda = 1$ at the "tip" of $c_{\beta-\alpha} - \tan\beta$ plane
- λ_{hhH}

  Larger positive values around $c_{\beta-\alpha} \simeq 0.05$ and large negative values at large $c_{\beta-\alpha}$ in $c_{\beta-\alpha} - m$ plane

$\Longrightarrow$ Explore the production cross section of hhZ and $hh\nu\bar{\nu}$ in this planes



Black lines are the boundaries to the total allowed region