

# ACCESS TO TRIPLE HIGGS COUPLINGS IN THE 2HDM AT FUTURE $e^+e^-$ COLLIDERS

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Based on [arxiv:2005.10576](https://arxiv.org/abs/2005.10576) and [arxiv:2106.11105](https://arxiv.org/abs/2106.11105), published in EPJC



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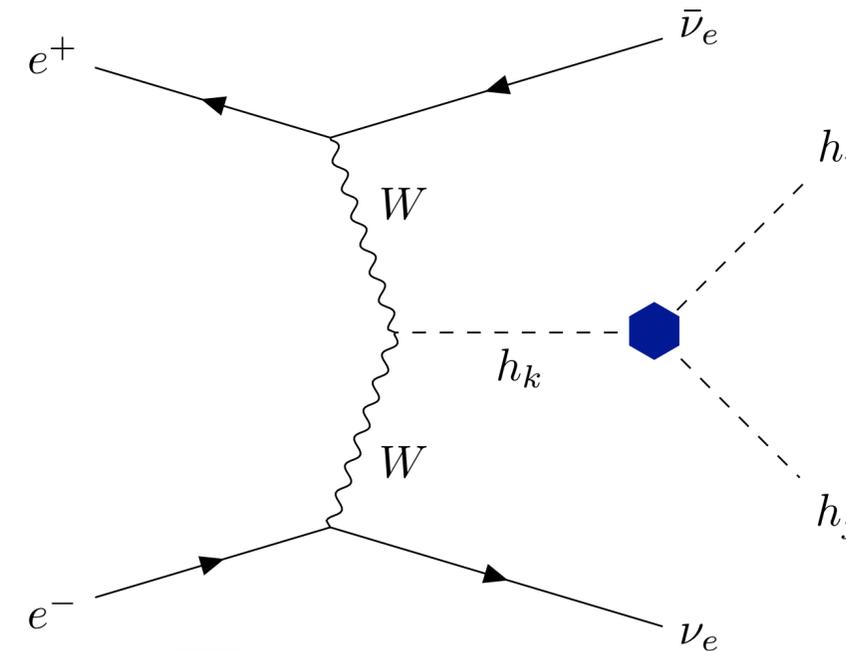
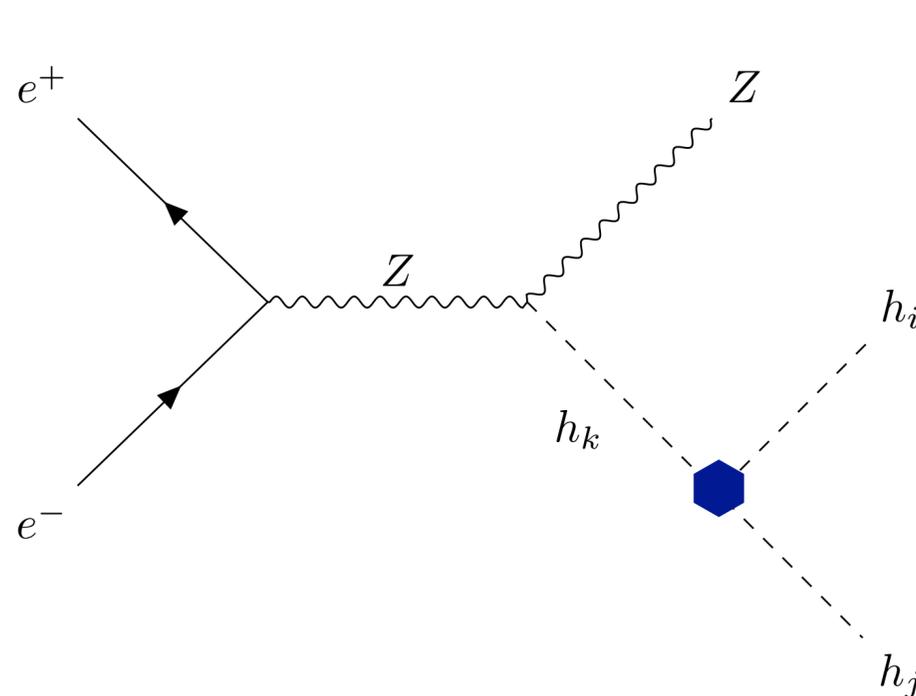
# MOTIVATION

In the context of the 2HDM (type I and II), triple Higgs couplings  $\lambda_{h_i h_j h_k}$ , can be large while respecting all the relevant constraints (*Eur.Phys.J.C* 80 (2020) 9, 884, [[arXiv2005.10576](https://arxiv.org/abs/2005.10576)])



$\lambda_{h_i h_j h_k}$  can affect the di-Higgs production at tree level

Two channels of interest:  $e^+e^- \rightarrow h_i h_j Z$  and  $e^+e^- \rightarrow h_i h_j \nu \bar{\nu}$  with  $h_i h_j = hh, hH, HH, AA$



# THE TWO HIGGS DOUBLET MODEL (2HDM)

Adding a second Higgs doublet to the SM  $\implies$  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

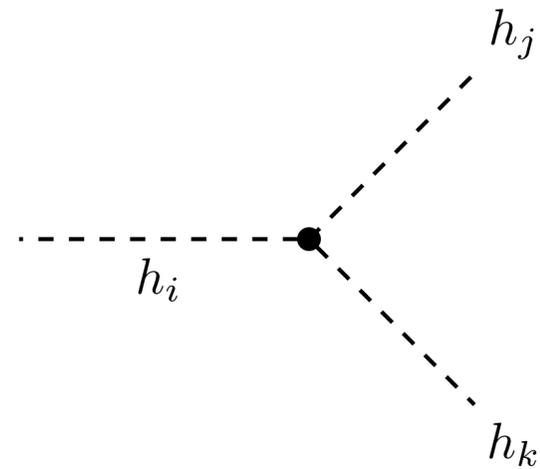
**INPUT PARAMETERS:**

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

**ALIGNMENT LIMIT:**  $c_{\beta-\alpha} \rightarrow 0$ , the SM interactions for  $h$  are recovered

# TRIPLE HIGGS COUPLINGS (THC)

## COUPLING DEFINITION:



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

and

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

## FINAL ALLOWED RANGES:

### TYPE I

$$\kappa_\lambda \in [-0.5, 1.5]$$

$$\lambda_{hhH} \in [-1.4, 1.5]$$

$$\lambda_{hHH} \in [0, 15]$$

$$\lambda_{hAA} \in [0, 16]$$

### TYPE II

$$\kappa_\lambda \in [0.0, 1.0]$$

$$\lambda_{hhH} \in [-1.6, 1.8]$$

$$\lambda_{hHH} \in [0, 15]$$

$$\lambda_{hAA} \in [0, 16]$$

## CONSTRAINTS

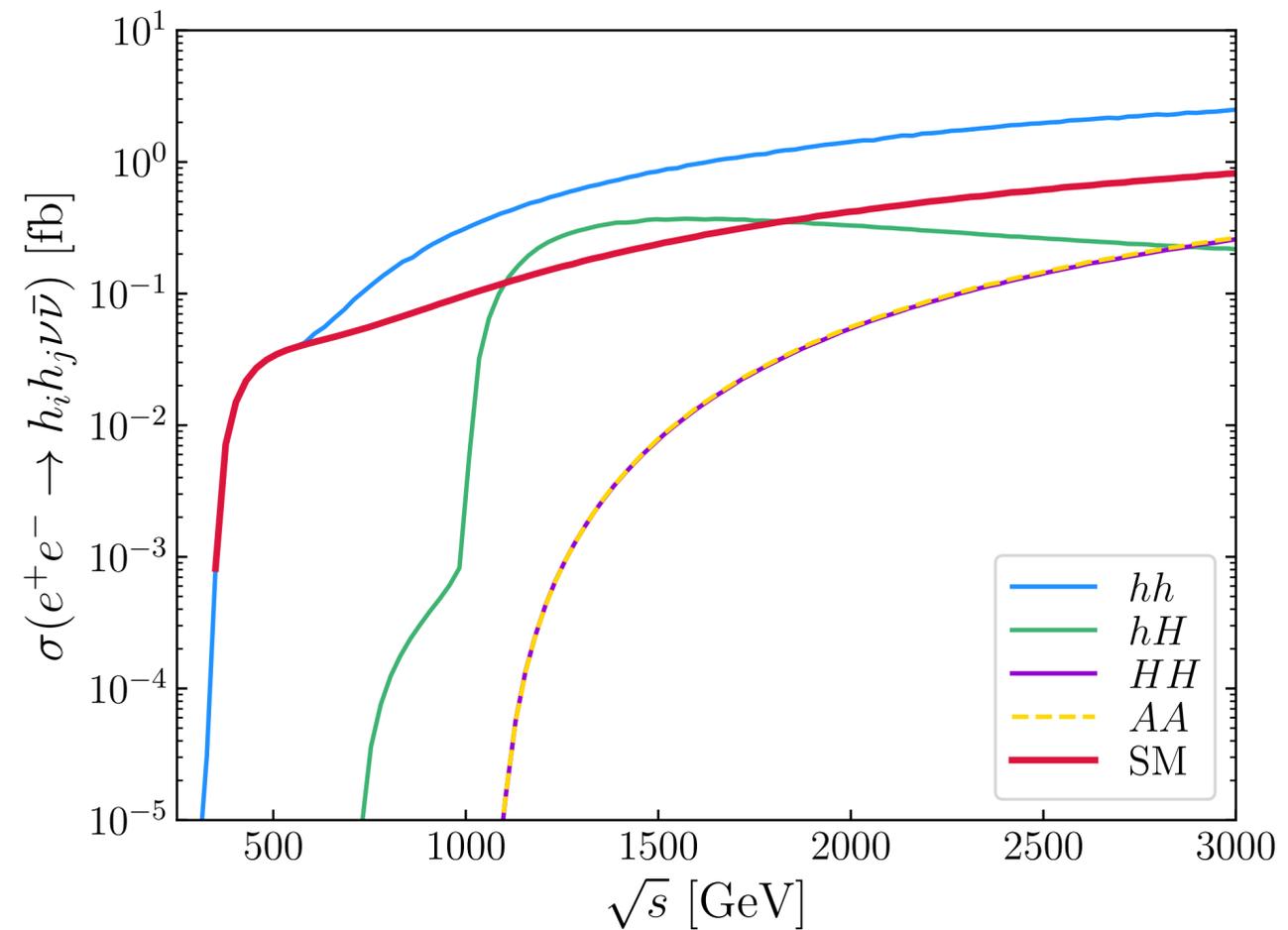
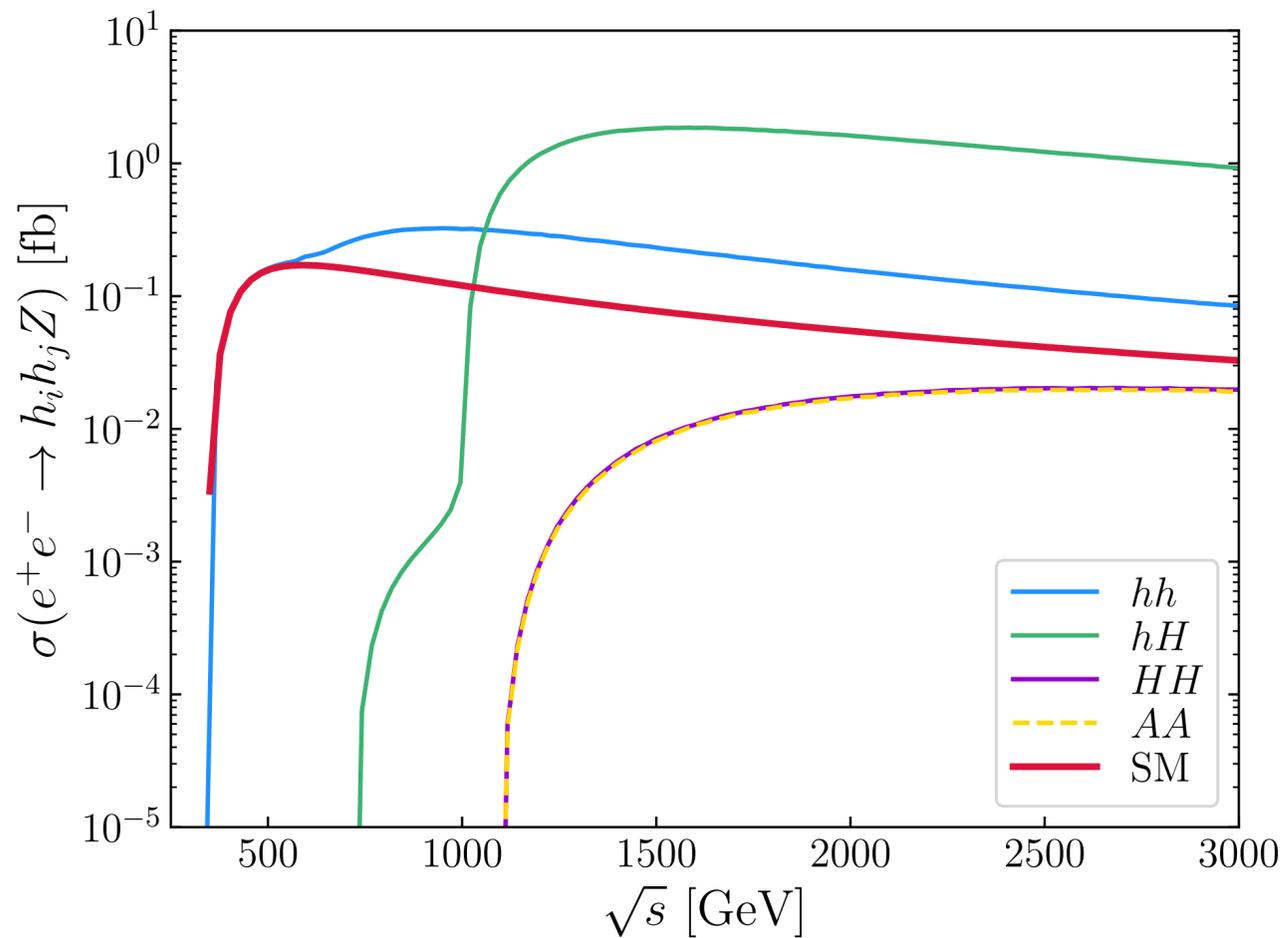
- Electroweak precision data,  $T$  parameter: motivates scenarios with degenerate masses
  - For us  $m_H = m_A = m_{H^\pm} \equiv m$
- Tree level unitarity and potential stability:  $m_{12}^2 = m_H^2 \cos^2 \alpha / \tan \beta$  helps reach large masses

- 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:  $\text{BR}(B \rightarrow X_s \gamma)$  and  $\text{BR}(B_s \rightarrow \mu\mu)$ 

2HDMC, HiggsBounds, HiggsSignals and superISO were used

(More detailed discussion to all these constraints in [[arXiv2005.10576](https://arxiv.org/abs/2005.10576)])

# DEPENDENCE WITH ENERGY



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

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

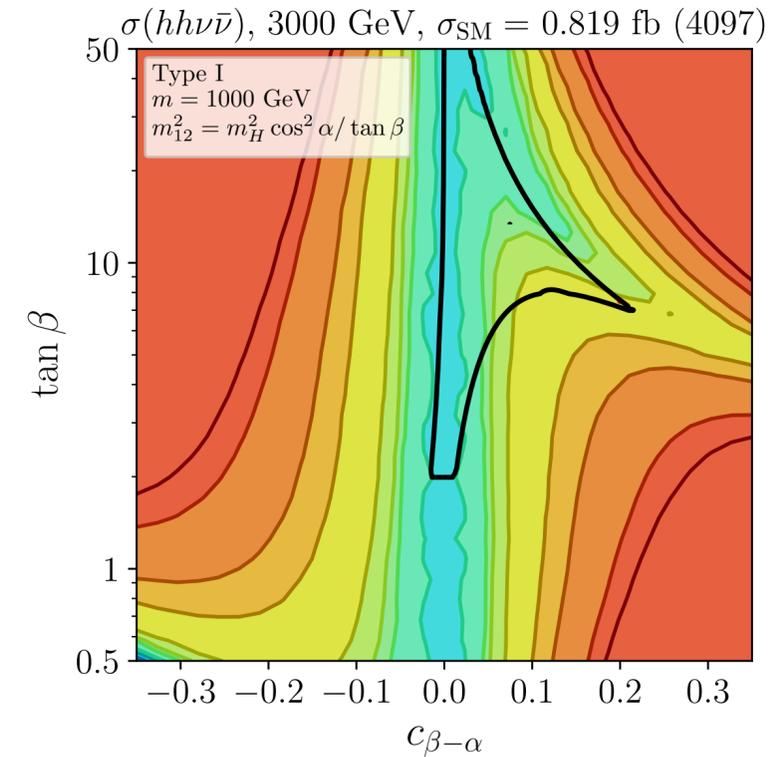
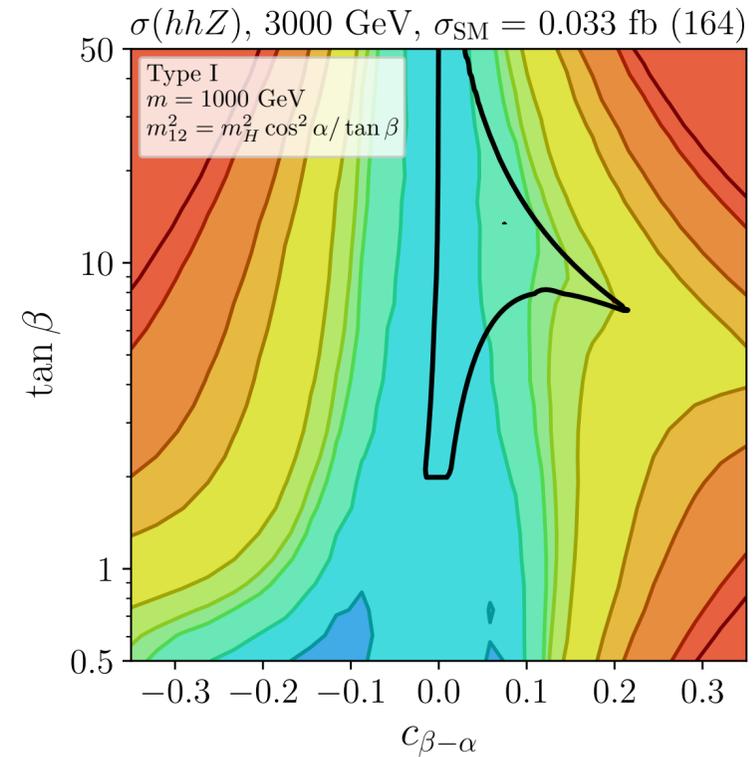
$Z$  channel  $\rightarrow$  decreases with the energy  
 $\nu\bar{\nu}$  channel  $\rightarrow$  increases with the energy (VBF topologies!)

- $hhZ$  and  $hh\nu\bar{\nu}$ :  $\sim 3$  times the SM due to resonant diagrams mediated by  $H$  (contains  $\lambda_{hhH}$ ) 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
- $HH\nu\bar{\nu} \sim AA\nu\bar{\nu}$ : dominated at large energies by  $\lambda_{hHH}$  ( $\lambda_{hAA}$ ) if it is large enough (because  $m_H = m_A$ )

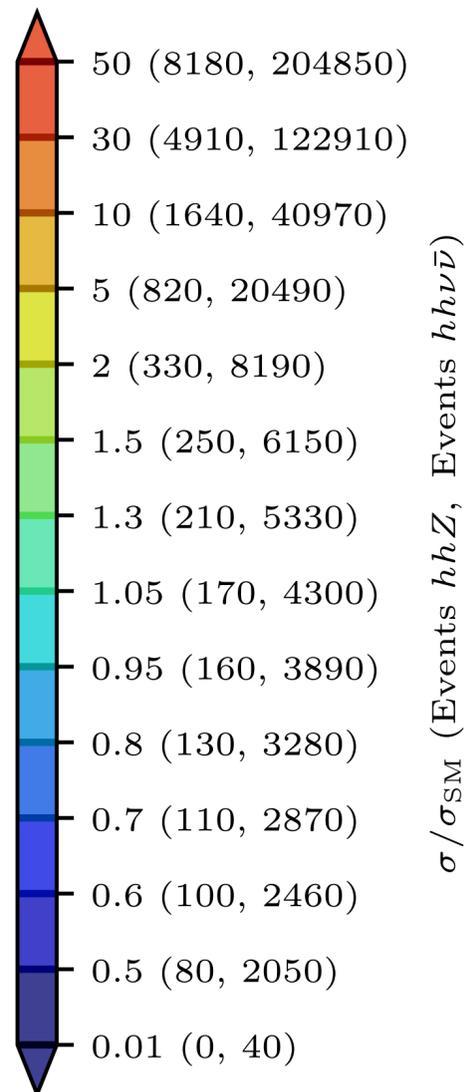
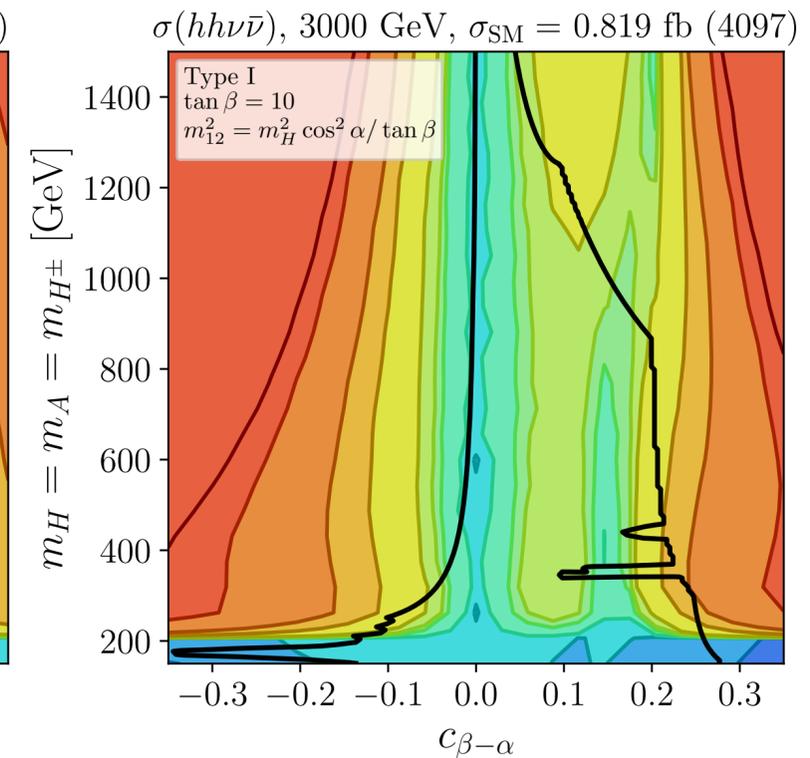
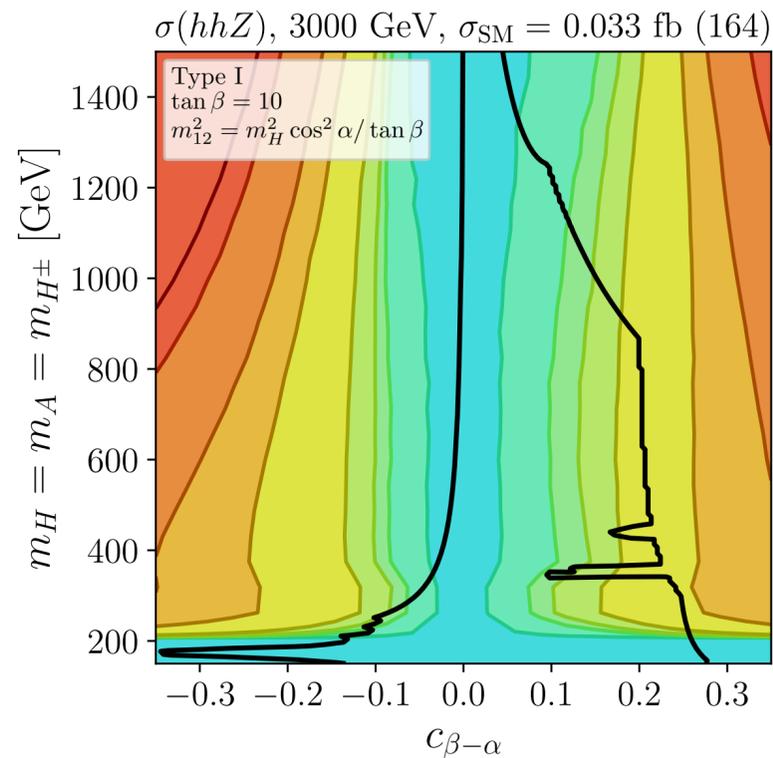
# $hh$ PRODUCTION, CLIC 3TEV (TYPE I)

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
- $hhZ$ : dominated by the  $A$  mediated diagrams
- $hh\nu\bar{\nu}$ : mediated diagrams (with  $\lambda_{hhH}$ ) are more important, for low masses  $\sigma_{2\text{HDM}} \sim 10\sigma_{\text{SM}}$
- For both channels  $\sigma_{2\text{HDM}} \sim 3\sigma_{\text{SM}}$  can be reach around  $c_{\beta-\alpha} \sim 0.2$



Black lines are the boundaries to the total allowed region



# $hh$ PRODUCTION, THC DEPENDENCE, CLIC 3TEV

## (TYPE I)

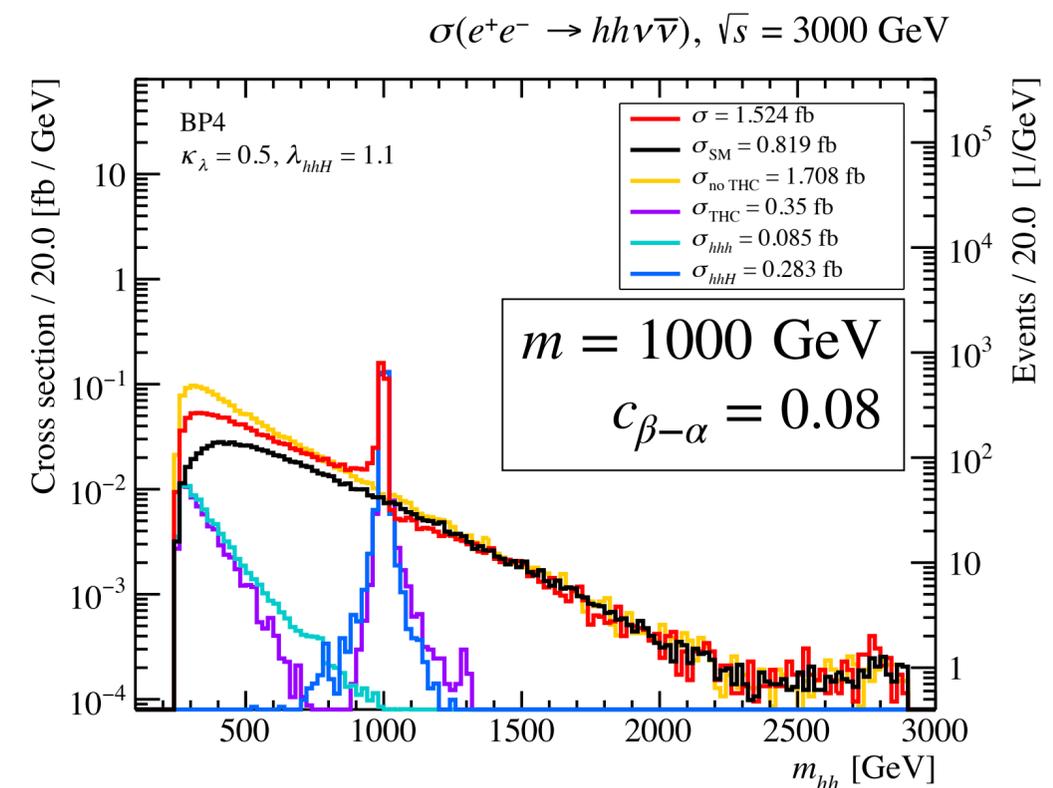
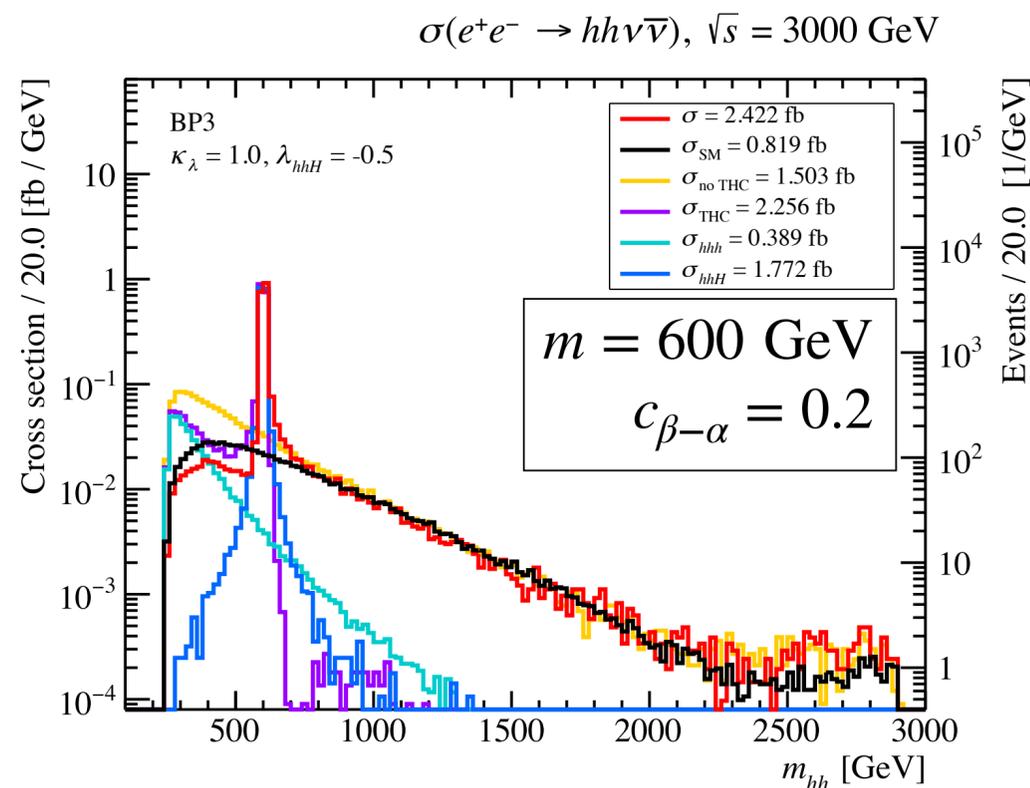
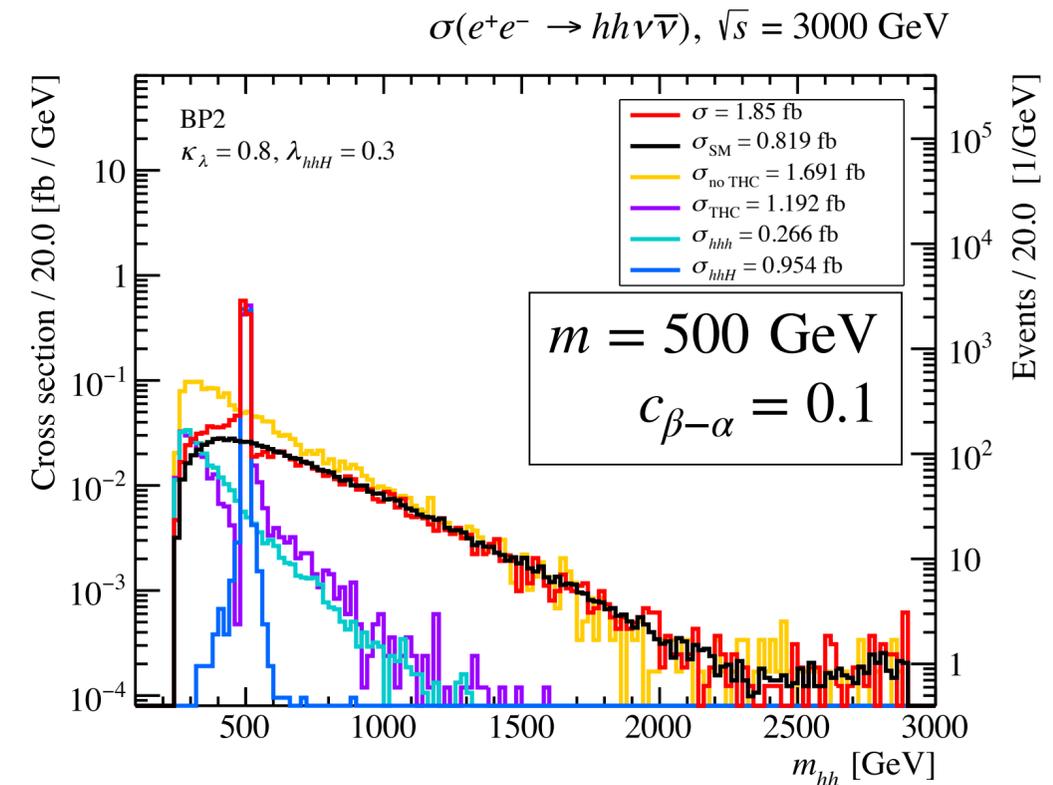
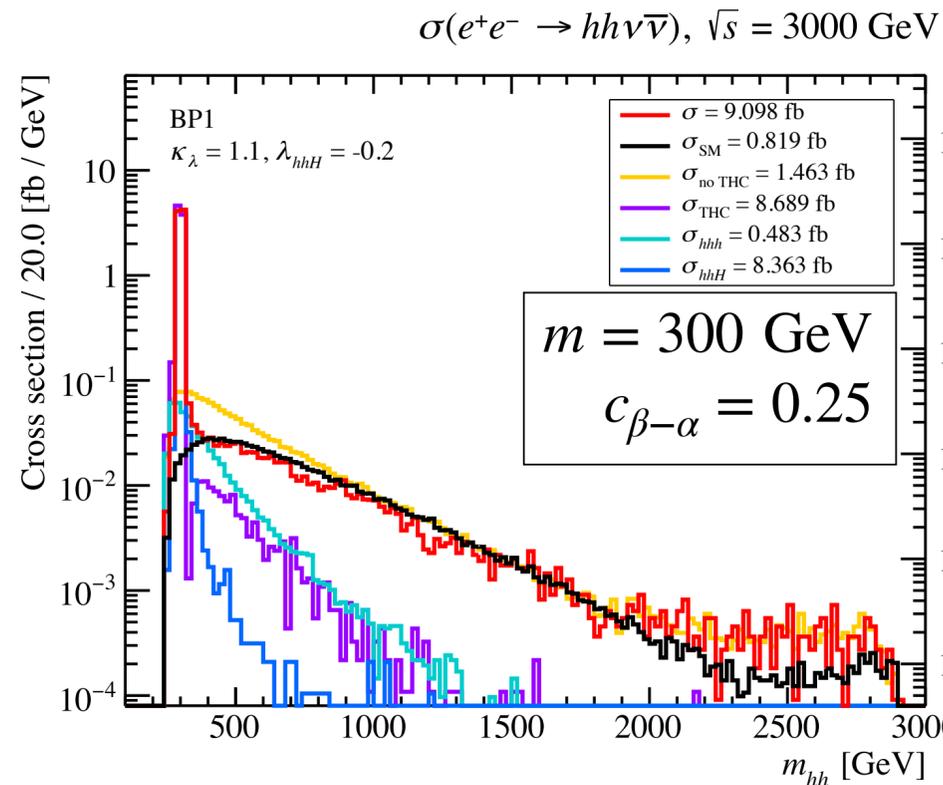
Cross section distribution on  $m_{hh}$  for

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

- Effect from  $\kappa_\lambda$ : the region of low invariant mass
  - The neutrino channel can access to the  $H$  resonant peak (i.e. to  $\lambda_{hhH}$ ) for a wide range of  $m_H$  and  $c_{\beta-\alpha}$
- $\Rightarrow$  which collider and channel are best suited to access to  $\lambda_{hhH}$ ?

Fran Arco (UAM-IFT)



# 4-*b*JETS EVENTS FROM *hh* PRODUCTION: $\lambda_{hhH}$ “SENSITIVITY”

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

$\bar{N}^{R/C}$  are an estimation of the events nearby the *H* resonance from diagrams with  $\lambda_{hhH}$  and diagrams without THC resp.

Considered reduction factors:

- $h \rightarrow b\bar{b}$  decays + *b*-jet tagging efficiency of 80%

- Detection acceptance considering the following cuts:

$$p_T^b > 20 \text{ GeV}, |\eta^b| < 2, \Delta R_{bb} > 0.4, \begin{cases} p_T^Z > 20 \text{ GeV} \\ E_T > 20 \text{ GeV} \end{cases}$$

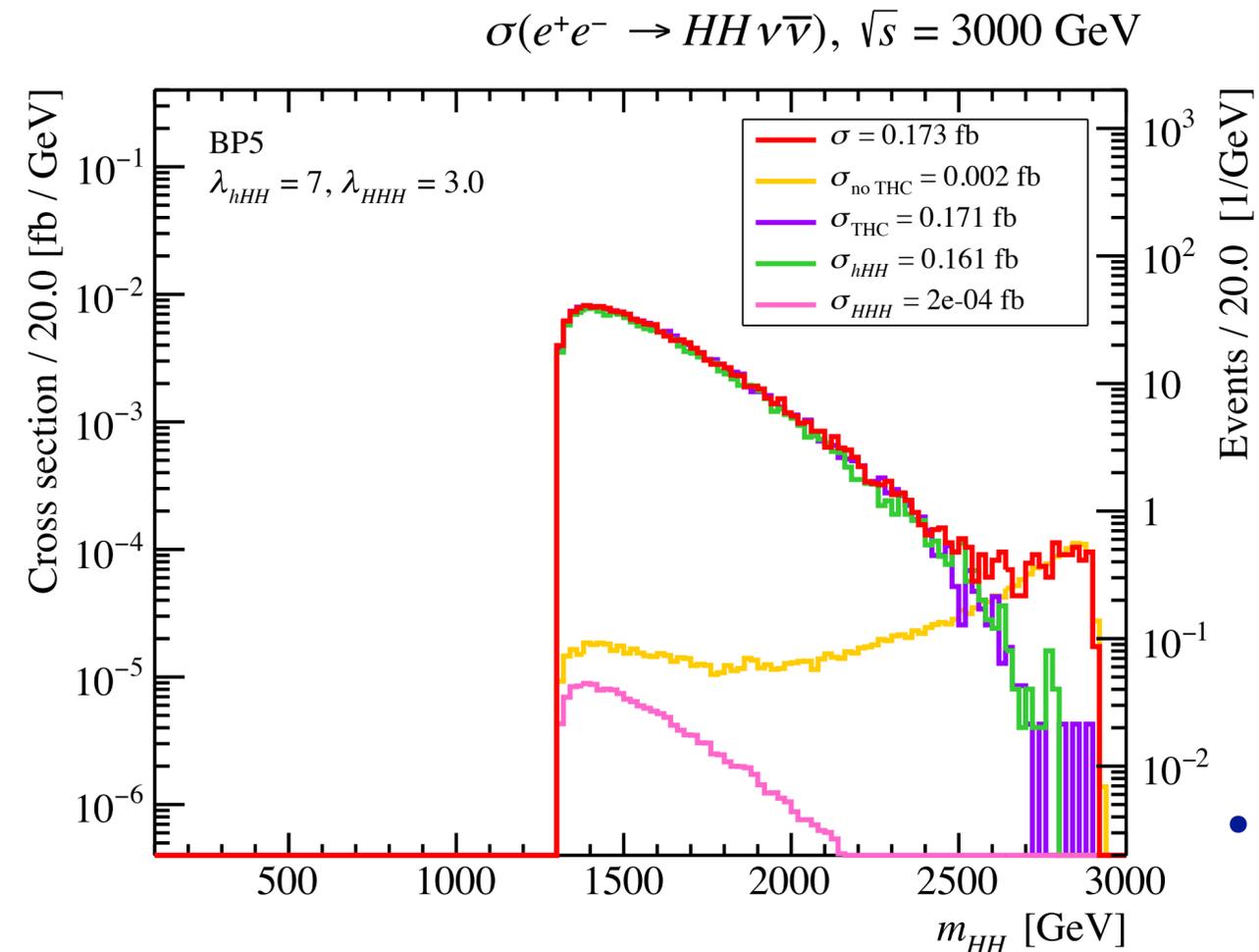
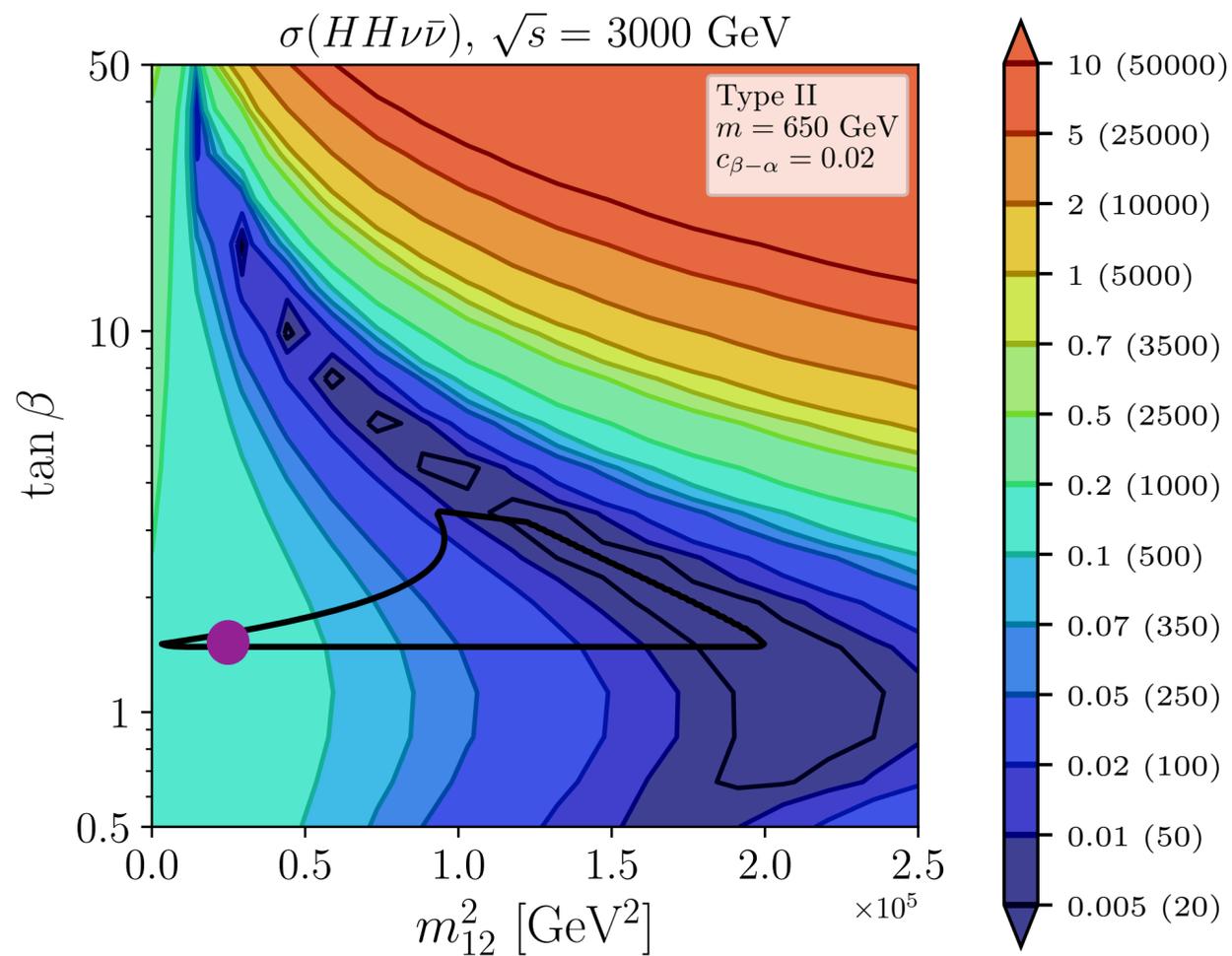
<i>hhZ</i>	$\sqrt{s}$ [GeV]	$\sigma_{2\text{HDM}} / \sigma_{\text{SM}}$ [fb]	$\bar{N}_{4bZ}^R / \bar{N}_{4bZ}^C / \bar{N}_{4bZ}^{\text{SM}}$	$R_{4bZ}$
BP1	500	1.063 / 0.158	193 / 10 / 3	58
	1000	0.913 / 0.120	206 / 1 / 4	205
	1500	0.493 / 0.077	22 / < 1 / 1	-
	3000	0.147 / 0.033	1 / < 1 / < 1	-
BP2	1000	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	-

<i>hh<math>\nu\bar{\nu}</math></i>	$\sqrt{s}$ [GeV]	$\sigma_{2\text{HDM}} / \sigma_{\text{SM}}$ [fb]	$\bar{N}_{4bE_T}^R / \bar{N}_{4bE_T}^C / \bar{N}_{4bE_T}^{\text{SM}}$	$R_{4bE_T}$
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  $\lambda_{hhH}$  (i.e. larger  $R$ ) in the neutrino channel at all studied points, specially at **CLIC 3 TeV**

# $HH \sim AA$ PRODUCTION, THC DEPENDENCE, CLIC 3TEV(TYPE II)

In type II only  $HH\nu\bar{\nu} \sim AA\nu\bar{\nu}$  production is relevant (because of collider constraints)



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

- XS is larger at low  $m_{12}^2$ , that is the region where  $\lambda_{hHH}$  is larger

- The dominant effect in  $HH\nu\bar{\nu}$  comes from  $\lambda_{hHH}$  (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  $\lambda_{hHH}$  can large (if  $m_H$  is light enough)

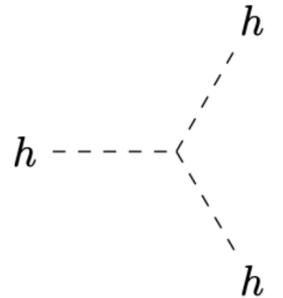
# SUMMARY & CONCLUSIONS

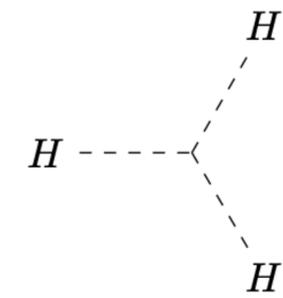
- The di-Higgs production of neutral Higgs bosons is studied at CLIC ( $e^+e^-$  colliders) in the 2HDM, with the aim to find effects coming from triple Higgs couplings (THC)
  - ▶ Two production channels were studied:  $e^+e^- \rightarrow h_i h_j Z$  and  $e^+e^- \rightarrow h_i h_j \nu \bar{\nu}$
- **IN  $hh$  PRODUCTION:** only sizable distortions at type I (type II is very constrained)
  - ▶ From  $\kappa_\lambda$ , at low invariant mass of the  $hh$  pair, similar to what happens in the SM (extensively studied in the literature)
  - ▶ From  $\lambda_{hhH}$ , through a resonant peak due to the  $H$  boson: a study on the final 4  $b$ -jets state shows that  $hh\nu\bar{\nu}$  channel is better at all energies (specially CLIC3TeV)
- **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  $\lambda_{hHH}$  ( $\lambda_{hAA}$ )

**THANKS FOR YOUR  
ATTENTION :)**

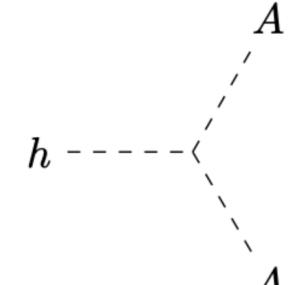
*Questions??*

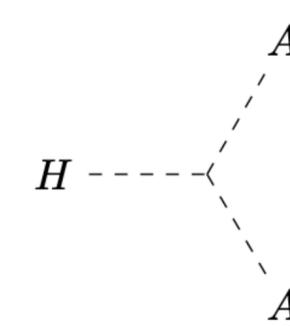
# BACK-UP, FEYNMAN RULES WITH THC



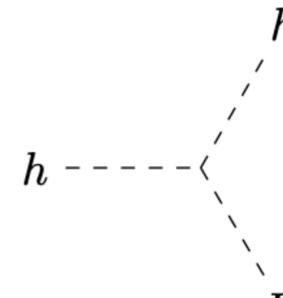
$$= -\frac{3i}{v} \left( 2 \cot 2\beta (m_h^2 - \bar{m}^2) c_{\beta-\alpha}^3 + (3m_h^2 - 2\bar{m}^2) c_{\beta-\alpha}^2 s_{\beta-\alpha} + m_h^2 s_{\beta-\alpha}^3 \right)$$


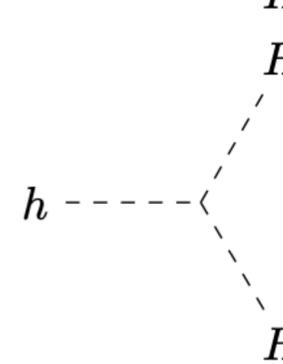
$$= -\frac{3i}{v} \left( (3m_H^2 - 2\bar{m}^2) c_{\beta-\alpha} s_{\beta-\alpha}^2 + 2 \cot 2\beta (\bar{m}^2 - m_H^2) s_{\beta-\alpha}^3 + m_H^2 c_{\beta-\alpha}^3 \right)$$



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


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



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


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

# 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  $m = 1$  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  $m = 650$  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]	$\mathcal{L}_{\text{int}}$ [ $\text{ab}^{-1}$ ]
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)  $\rightarrow m_{12}^2 = m_H^2 \cos^2 \alpha / \tan \beta$ )

# BACK-UP, $hh$ PRODUCTION: $\lambda_{hhH}$ “SENSITIVITY”

- We propose an estimator to try to determine when the effect of  $\lambda_{hhH}$  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  $\bar{N} = N \times \mathcal{A} \times \epsilon_b^4$  with  $N$  the number of total events,  $\mathcal{A} = N_{\text{cuts}}/N_{\text{no cuts}}$  is the acceptance of the collider and  $\epsilon_b \sim 0.8$  the  $b$ -tagging efficiency
- **Cuts:**  $p_T^b > 20 \text{ GeV}$ ,  $|\eta^b| < 2$ ,  $\Delta R_{bb} > 0.4$ ,  $p_T^Z > 20 \text{ GeV}$ ,  $E_T > 20 \text{ GeV}$

# $hh$ 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.  $\kappa_\lambda$ : positive interference in the  $Z$  channel and negative interference in the  $\nu\bar{\nu}$  channel

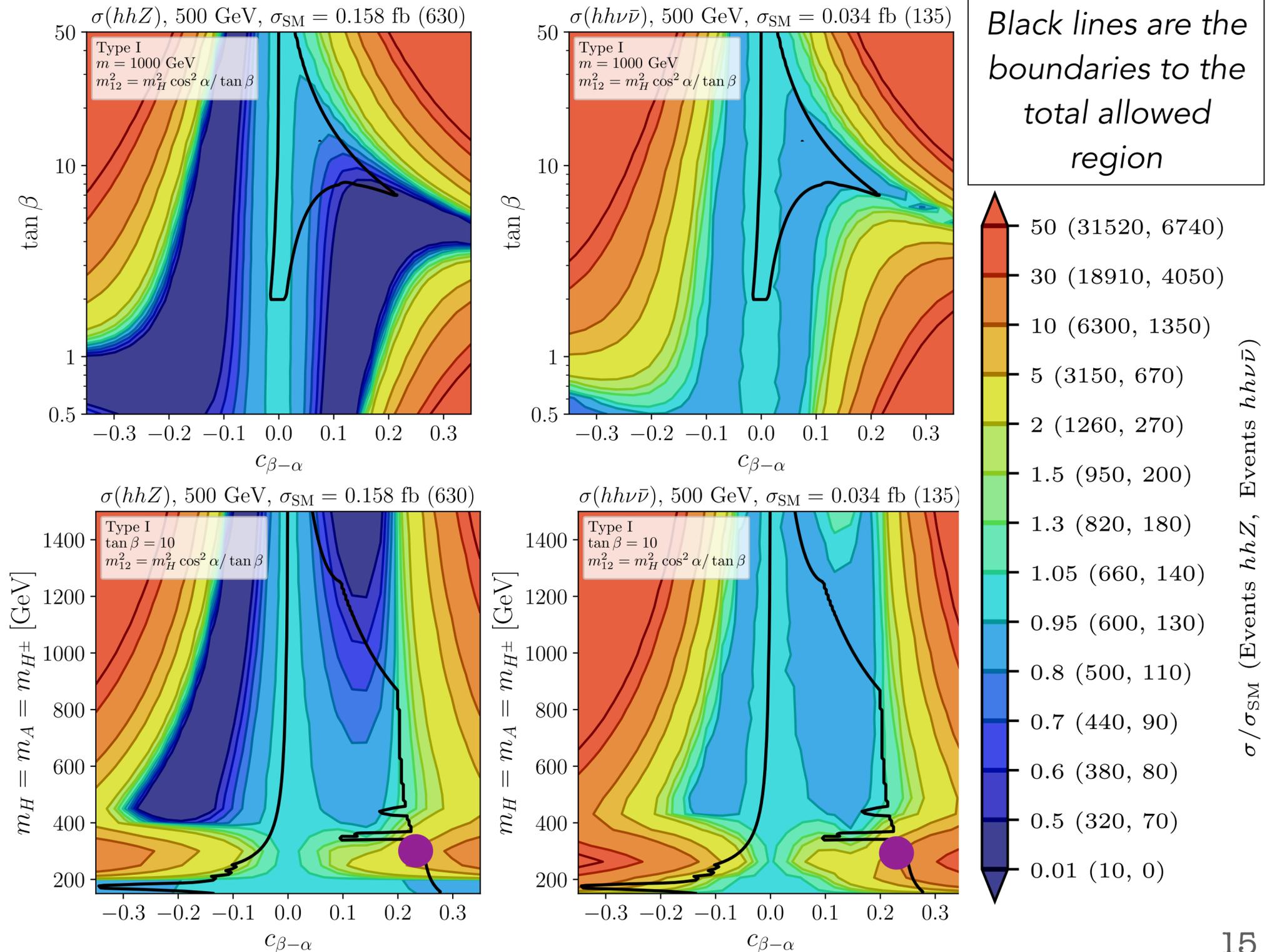
Larger distortion wrt the SM at the “tip”  
( $\kappa_\lambda = -0.4$ )

2.  $\lambda_{hhH}$ : 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 :(

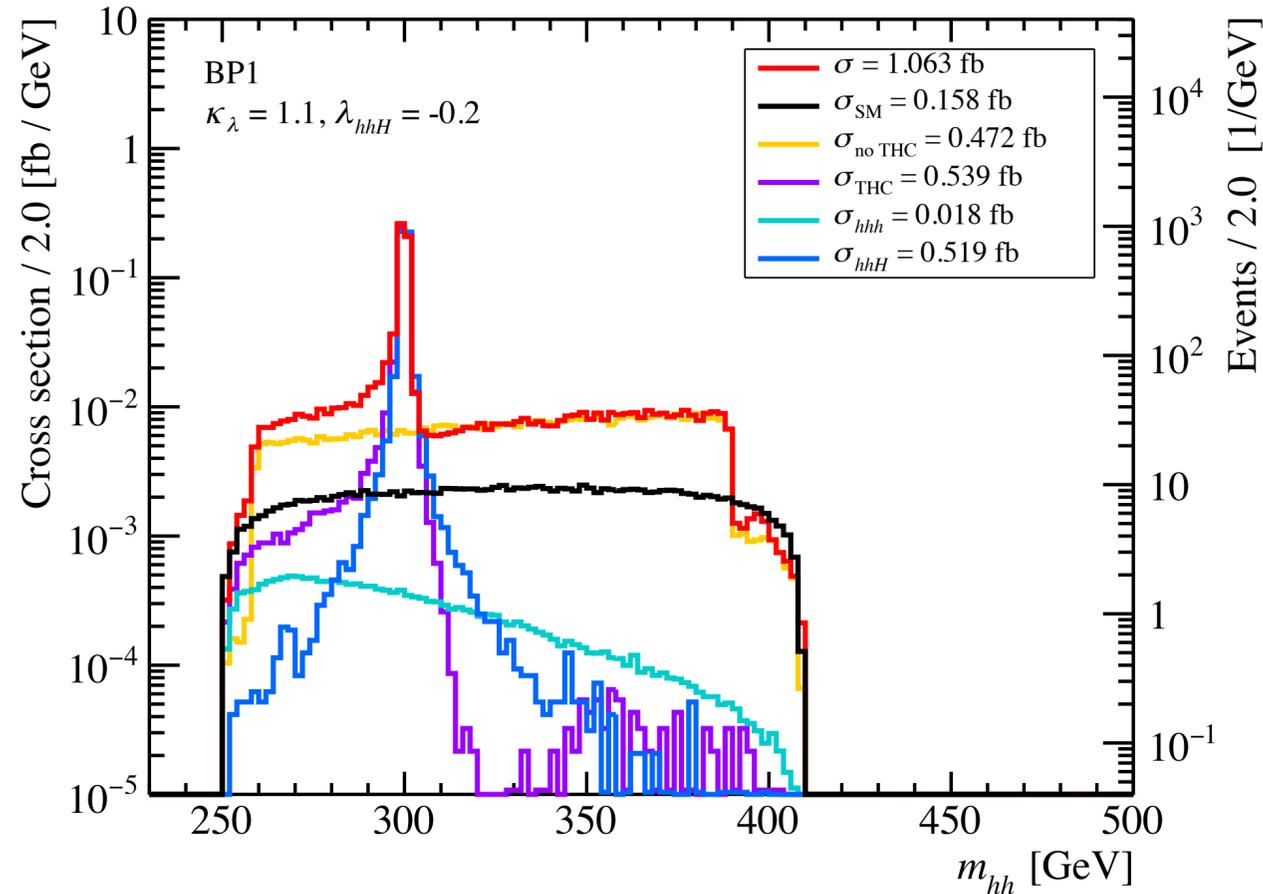
It is essential to look to the invariant mass of the final Higgs pair  $m_{hh}$  to see the effects of THC



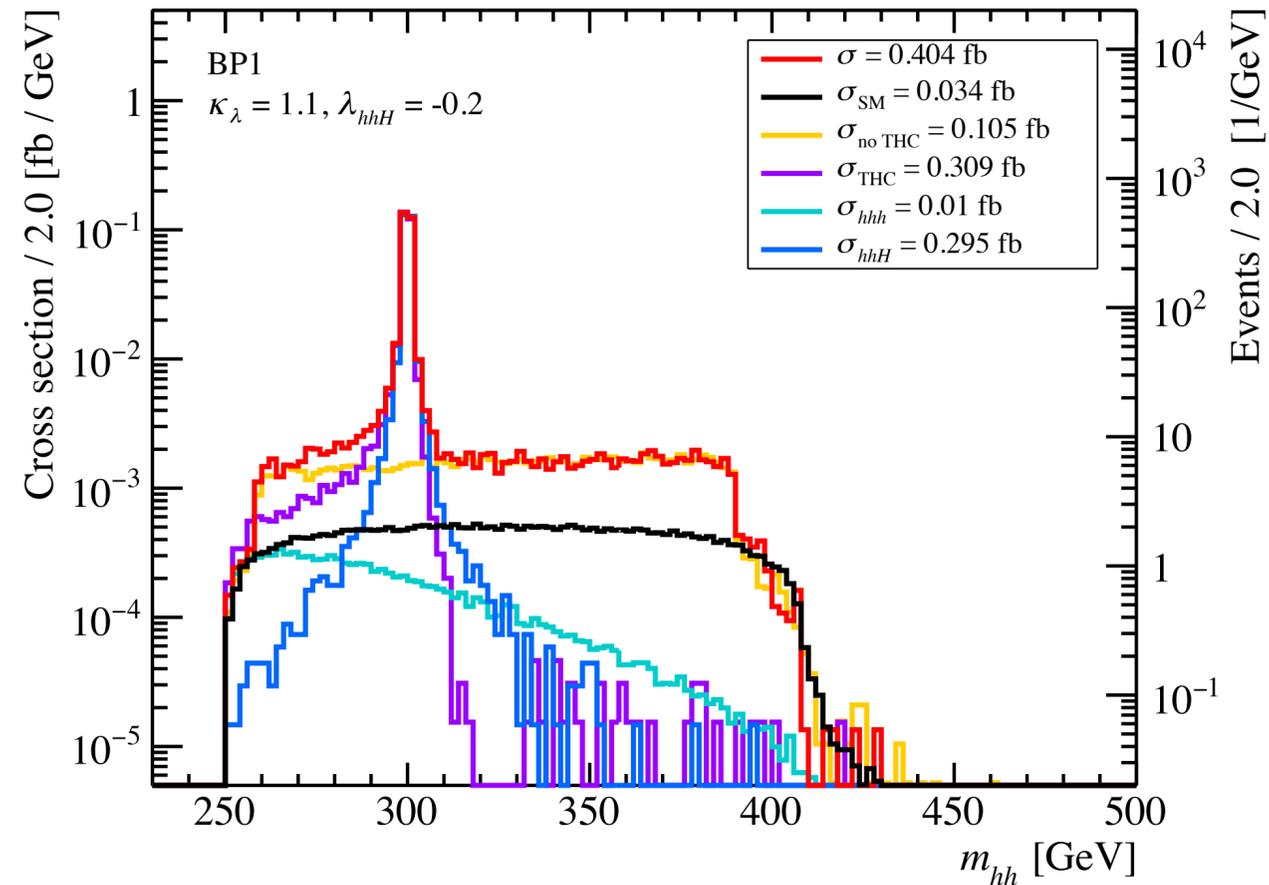
# $hh$ PRODUCTION, ILC 500GEV, THC DEPENDENCE (TYPE I)

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

$\sigma(e^+e^- \rightarrow hhZ), \sqrt{s} = 500 \text{ GeV}$



$\sigma(e^+e^- \rightarrow hh\nu\bar{\nu}), \sqrt{s} = 500 \text{ GeV}$



Type I

$m = 300 \text{ GeV}$

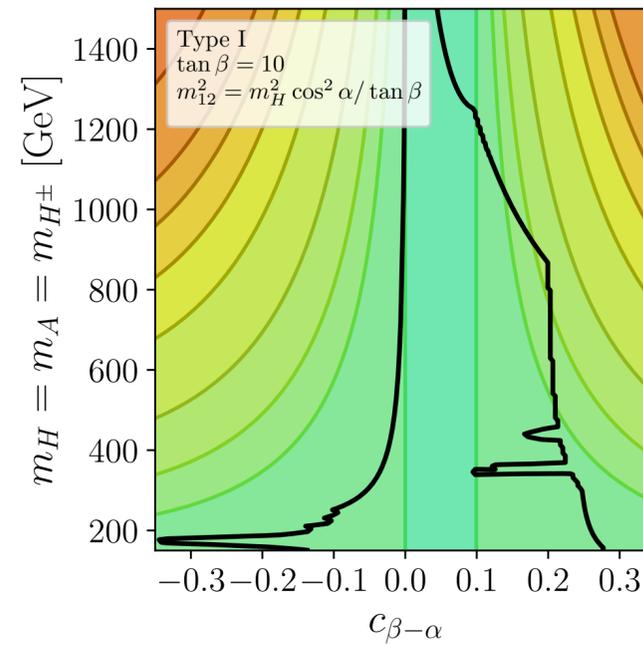
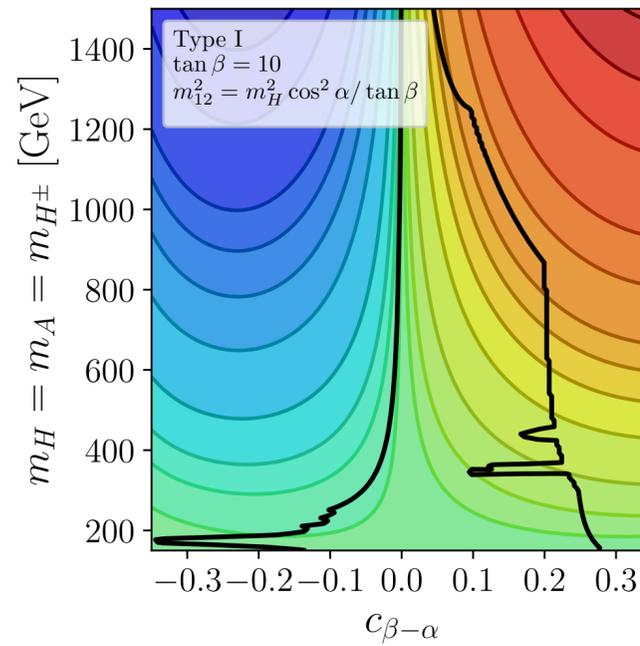
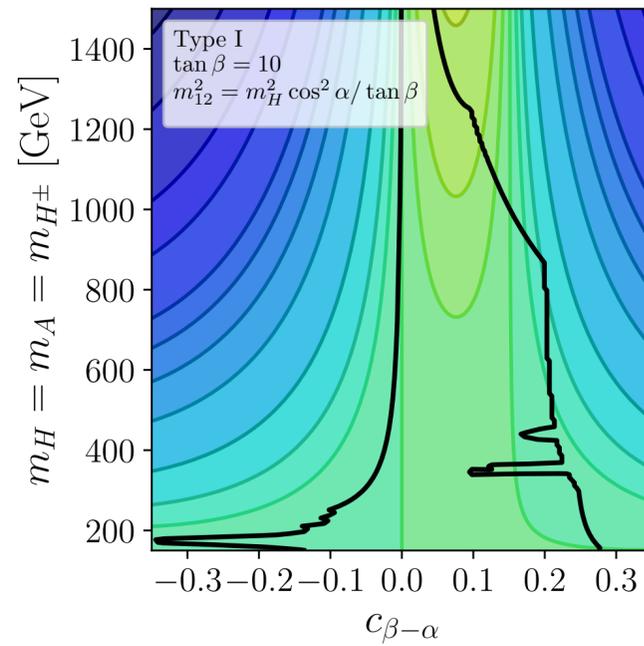
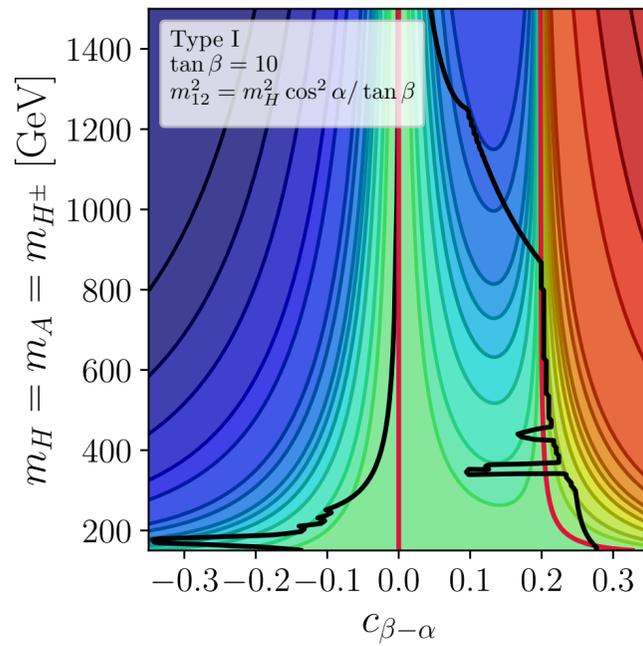
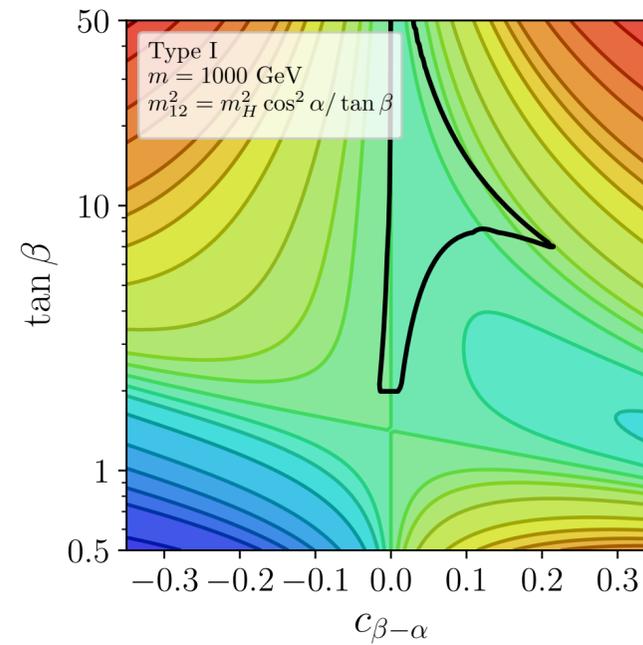
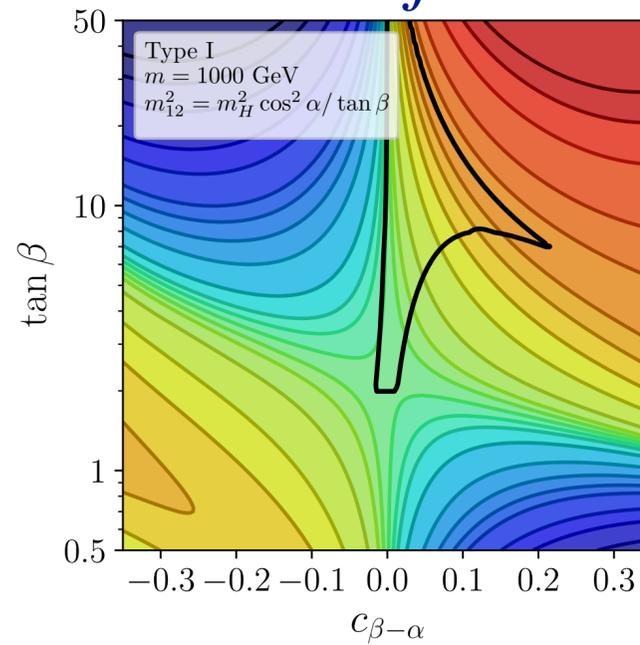
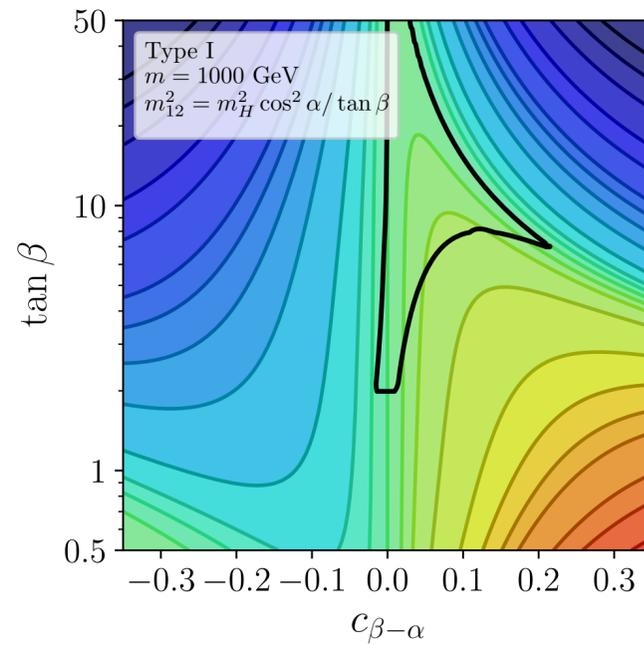
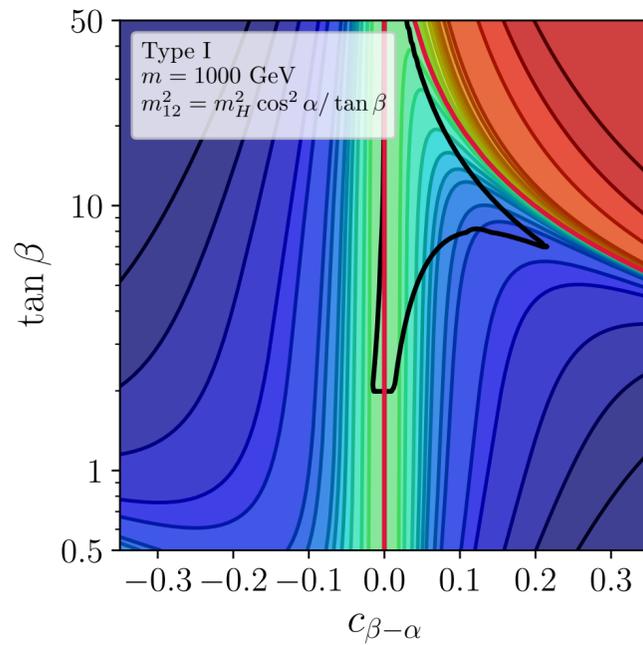
$\tan \beta = 10$

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

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

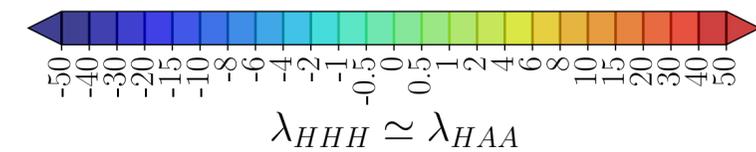
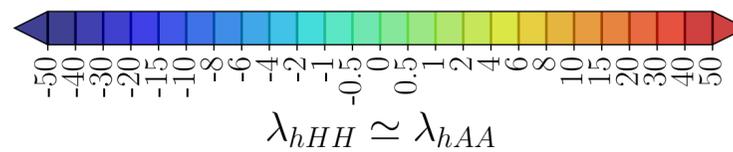
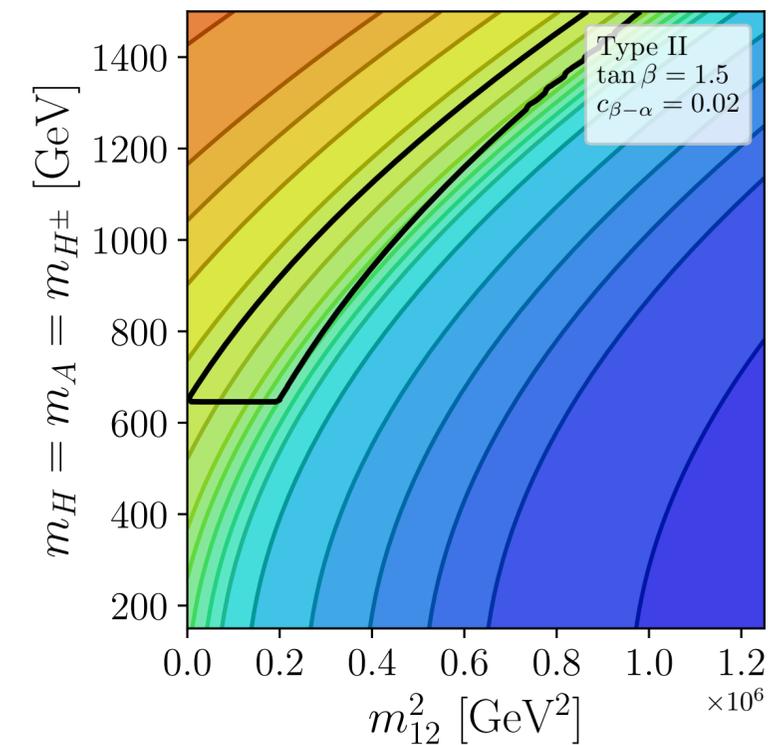
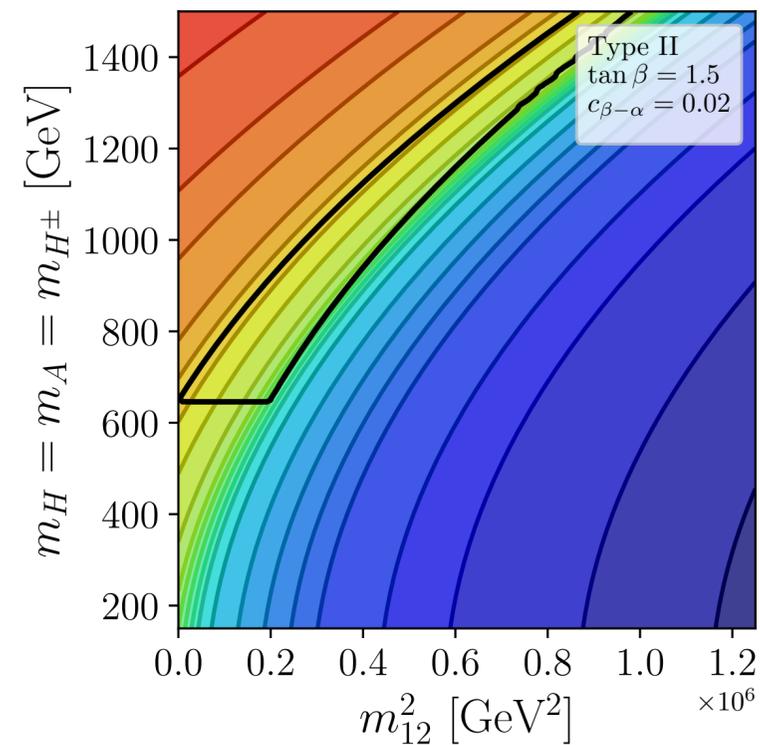
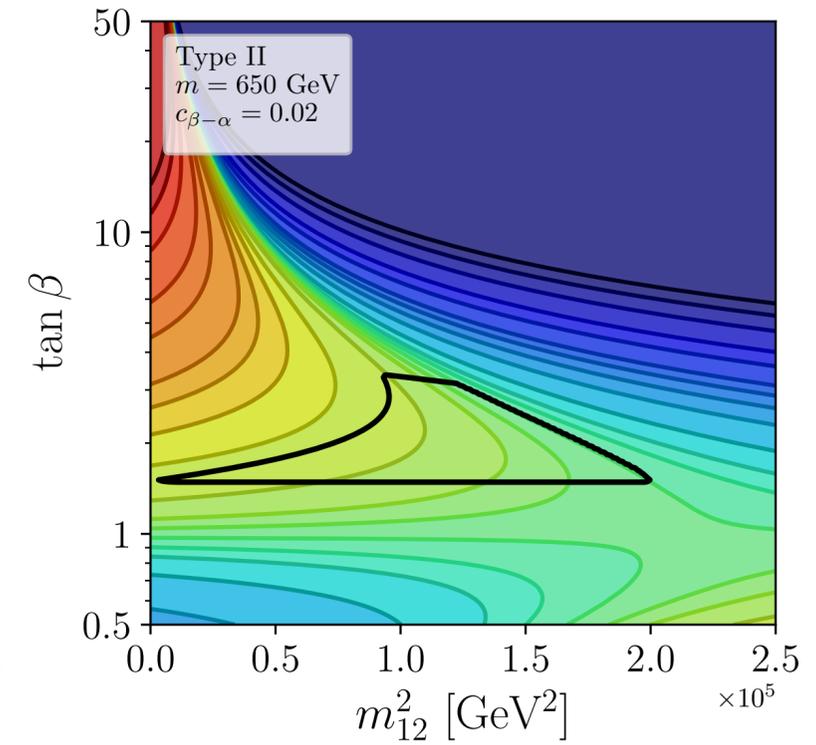
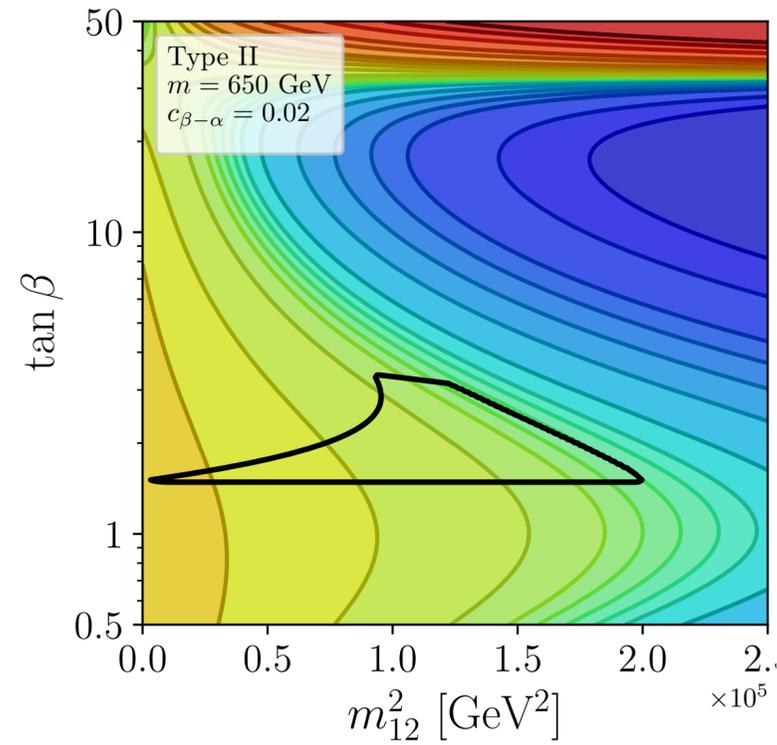
- Larger influence of  $\kappa_\lambda$  appears at the threshold of  $m_{hh}$  (light blue line)
- $H$  resonance (dark blue line): around  $m_{hh} = m_H \rightarrow$  information from  $\lambda_{hhH}$
- Plateau in the diagrams without THC (yellow line) wrt the SM (black line) due to the  $A$  resonant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

# BACK-UP, $\lambda_{h_i h_j h_k}$



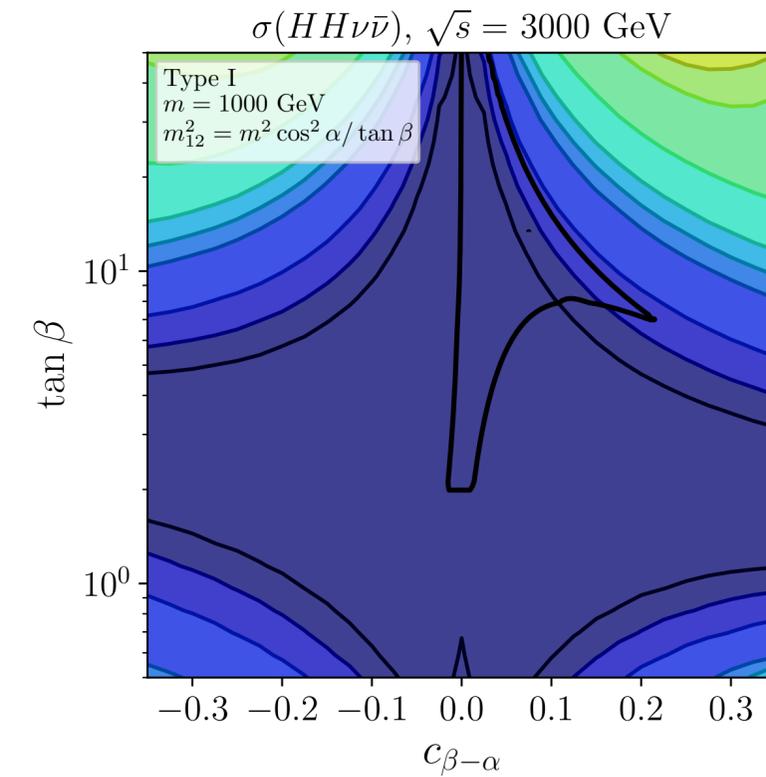
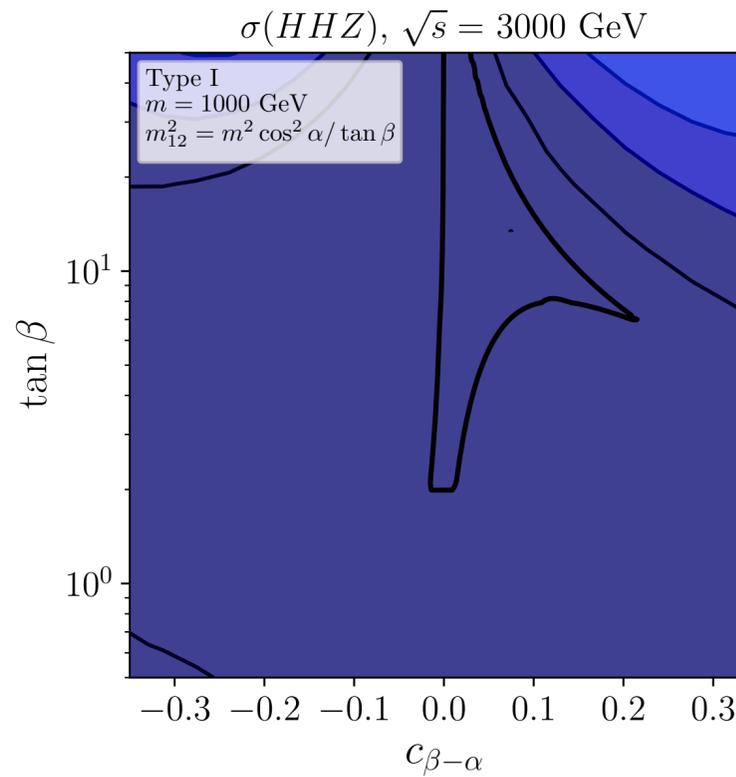
# BACK-UP,

$$\lambda_{h_i h_j h_k}$$

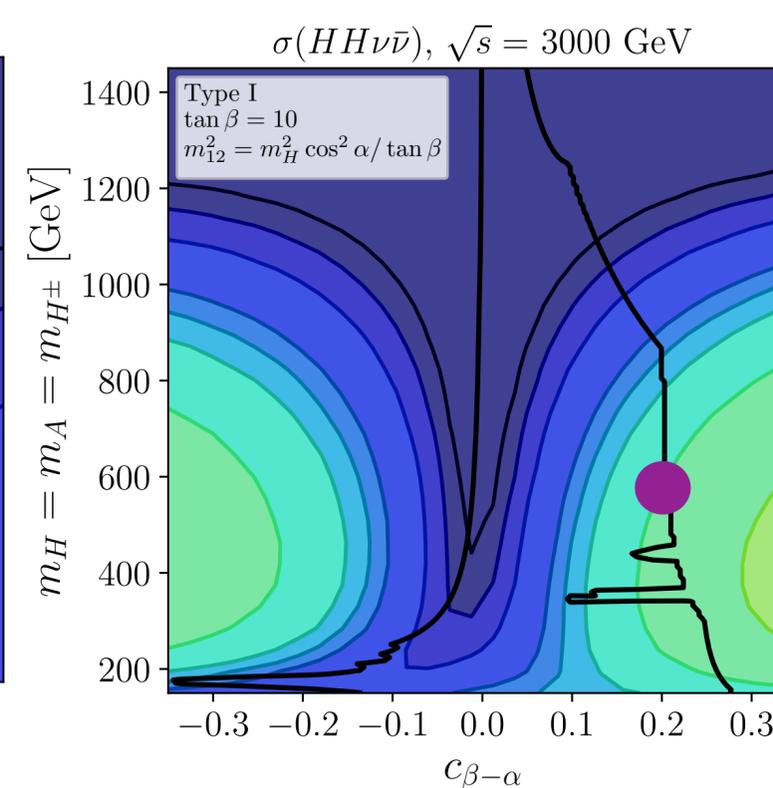
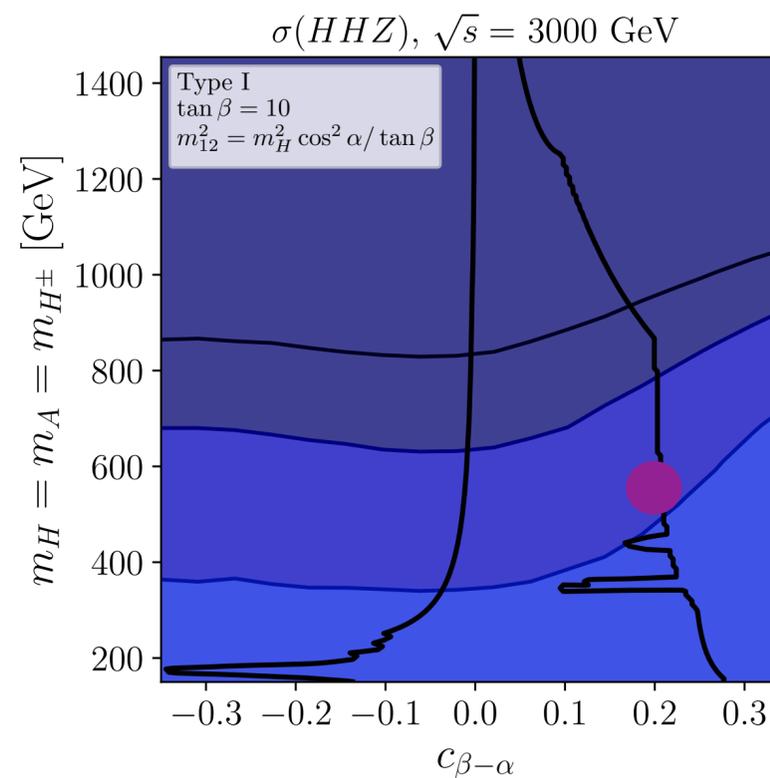
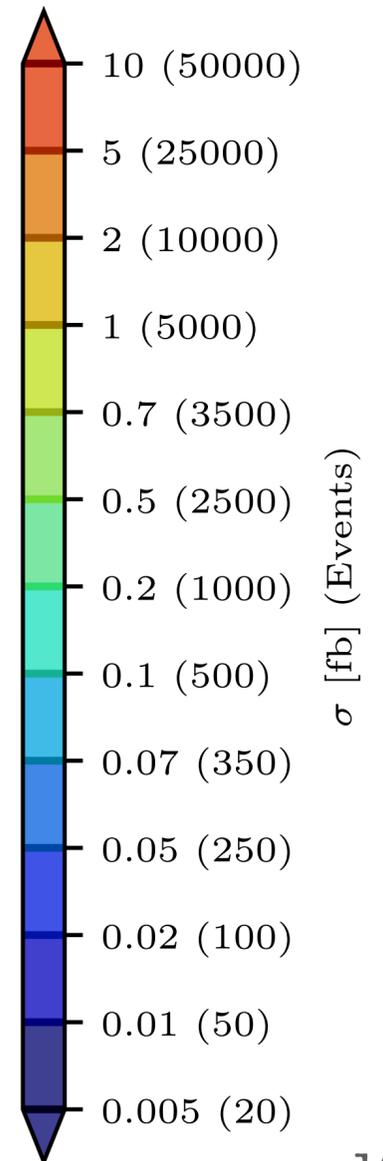


# $HH \sim AA$ PRODUCTION, CLIC 3TEV

- The  $HH \sim AA$  production can be non-zero even in the alignment limit ( $c_{\beta-\alpha} \rightarrow 0$ )
- 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  $\lambda_{hHH}$  ( $\lambda_{hAA}$ )
  - Effects from  $\lambda_{HHH}$  ( $\lambda_{HAA}$ ) could be important only for larger values of  $c_{\beta-\alpha}$



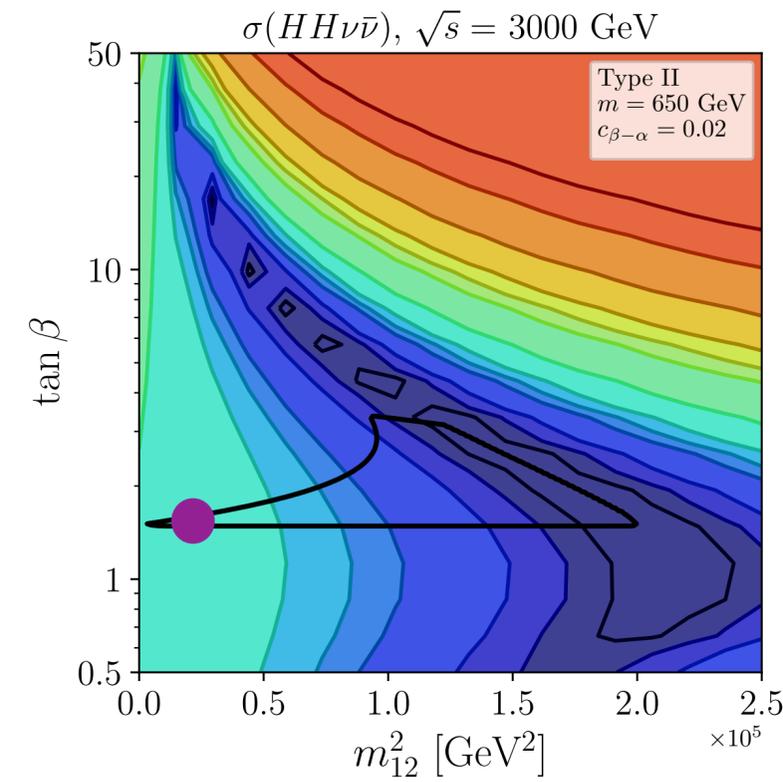
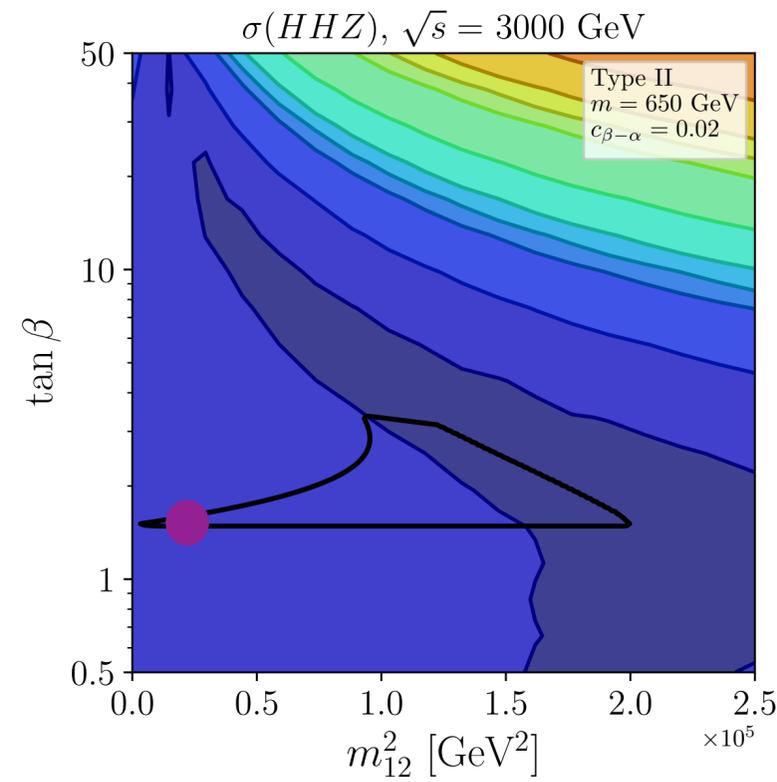
Black lines are the boundaries to the total allowed region



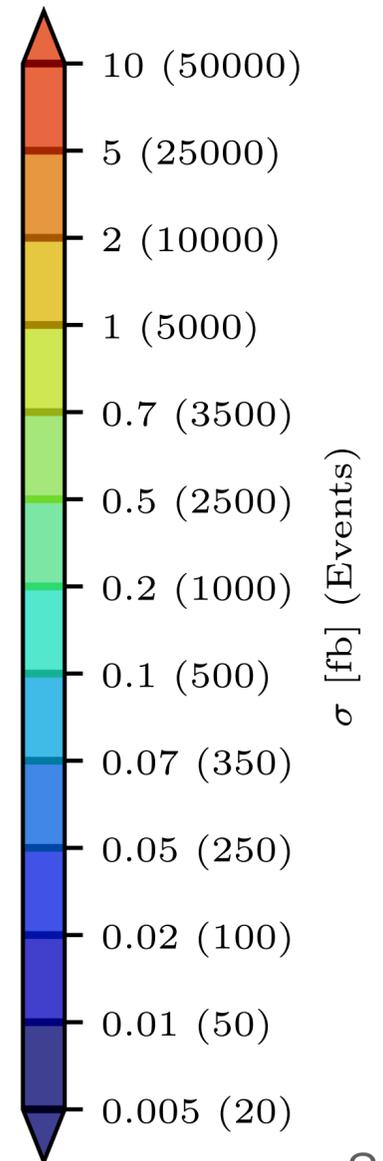
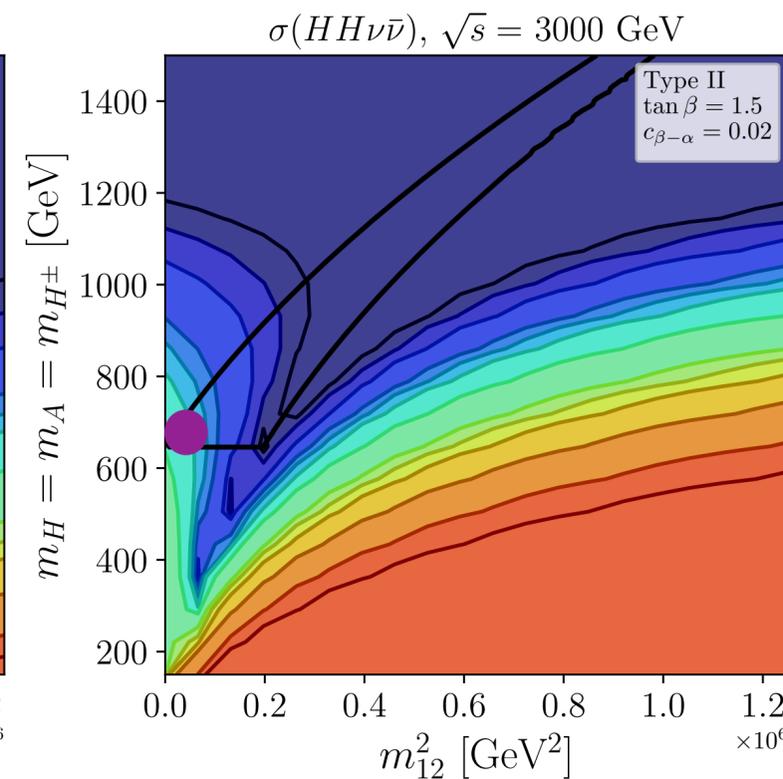
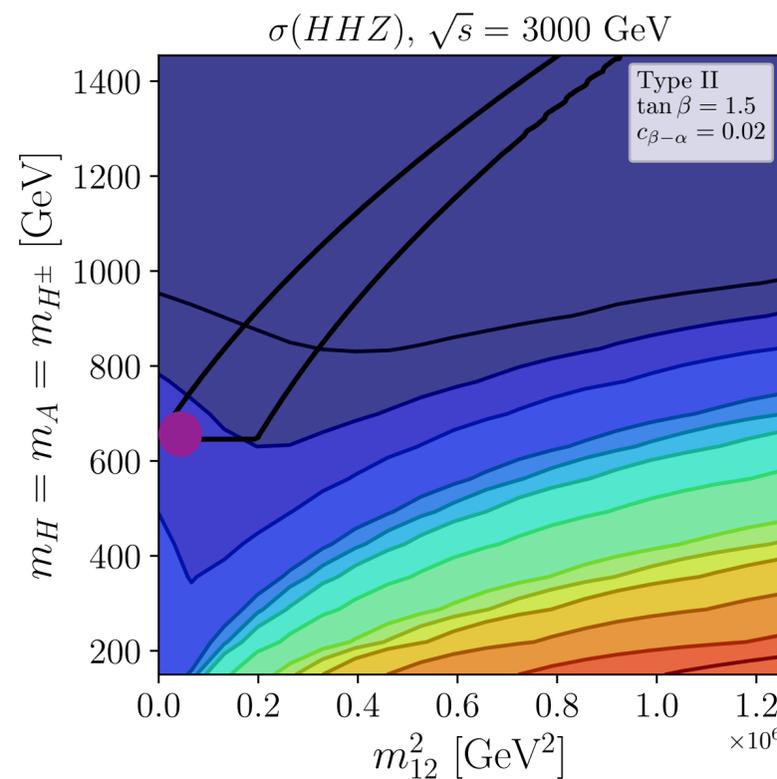
# $HH \sim AA$ PRODUCTION, CLIC 3TEV (TYPE II)

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 fb, inside the allowed region for the neutrino channel
- Sizable XS comes from the effect of  $\lambda_{hHH}$  ( $\lambda_{hAA}$ )
  - XS is larger at low  $m_{12}^2$ , that is the region where  $\lambda_{hHH}$  is larger!
- In type I we can obtain similar XS (in other regions of the parameter space)



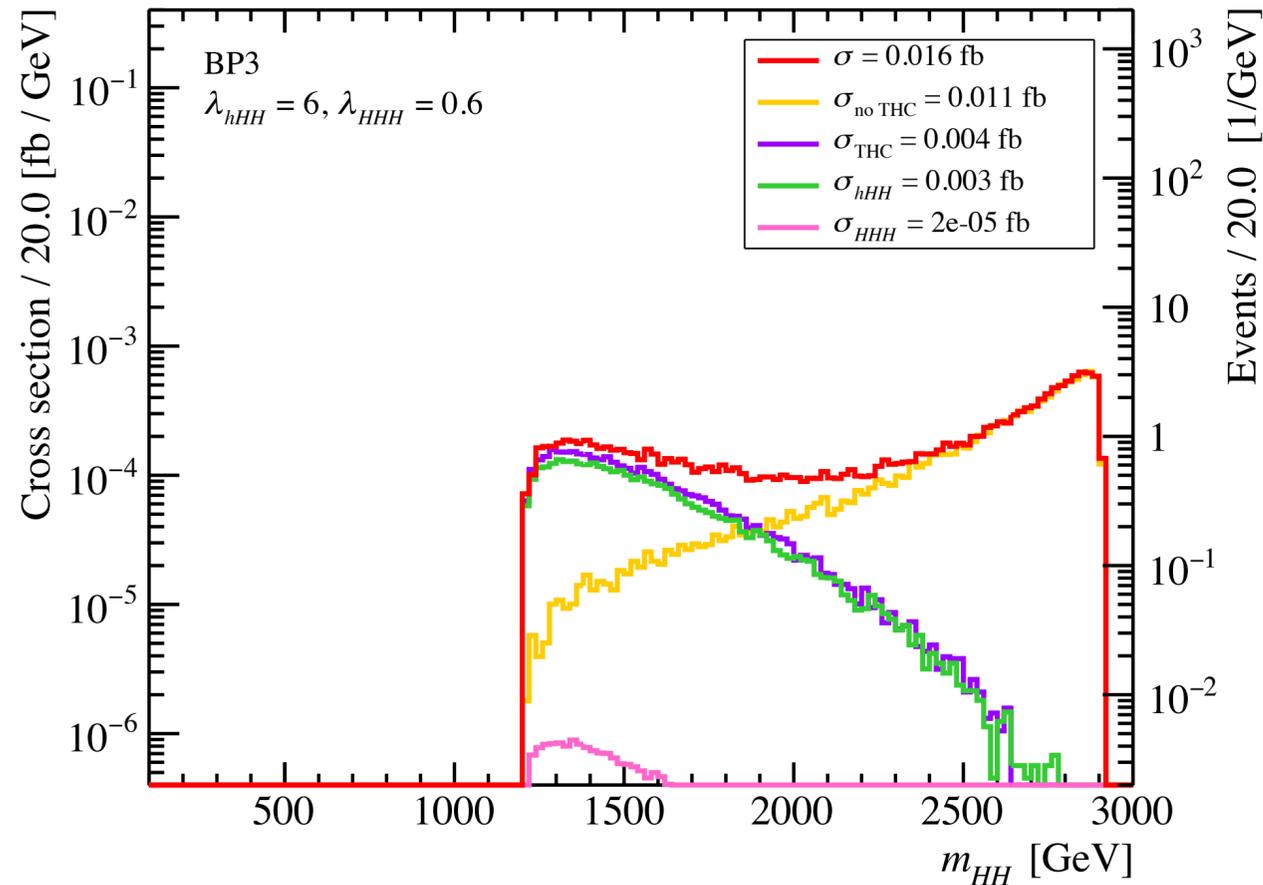
Black lines are the boundaries to the total allowed region



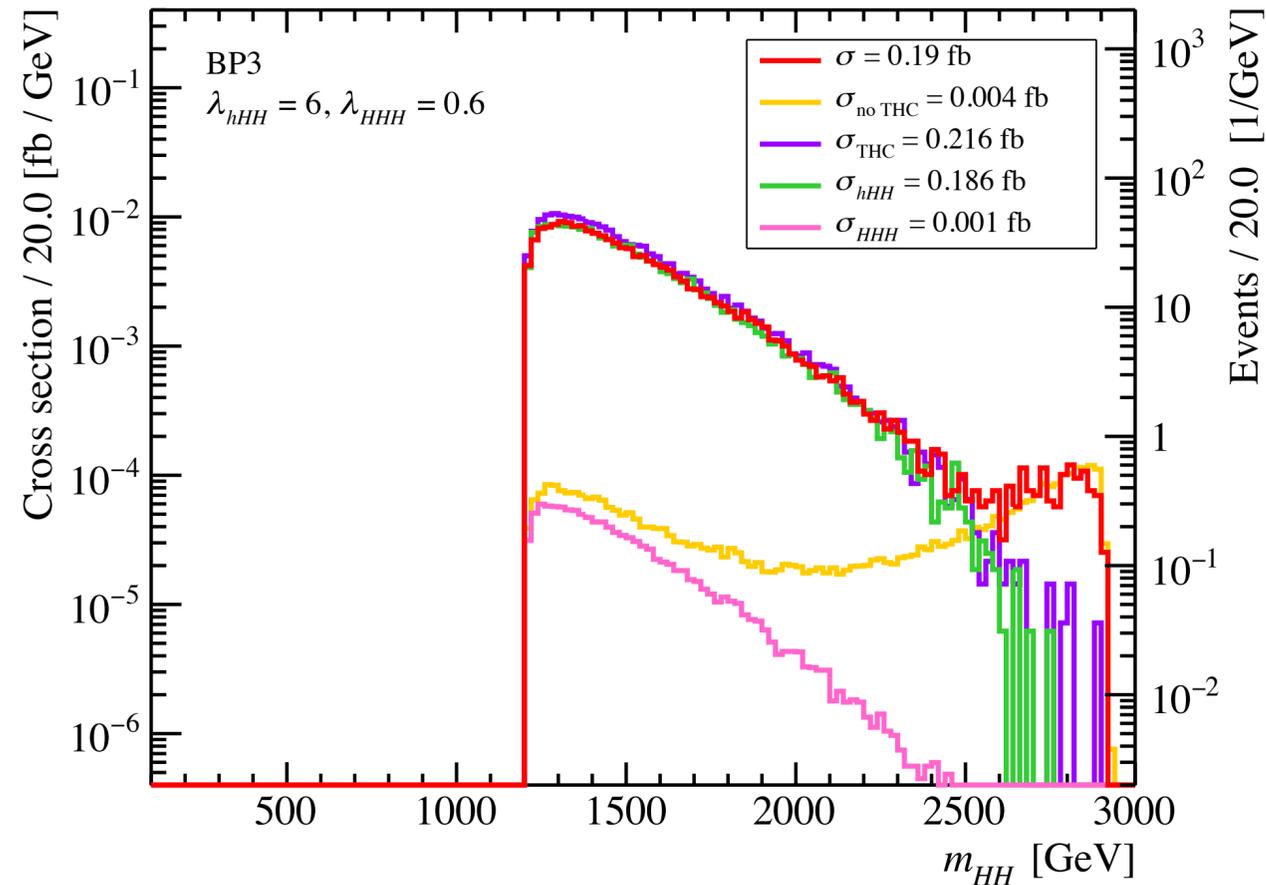
# $HH \sim AA$ PRODUCTION, CLIC 3TEV, THC DEPENDENCE

Cross section distribution on the invariant mass of  $HH$ :

$\sigma(e^+e^- \rightarrow HHZ), \sqrt{s} = 3000 \text{ GeV}$



$\sigma(e^+e^- \rightarrow HH\nu\bar{\nu}), \sqrt{s} = 3000 \text{ GeV}$



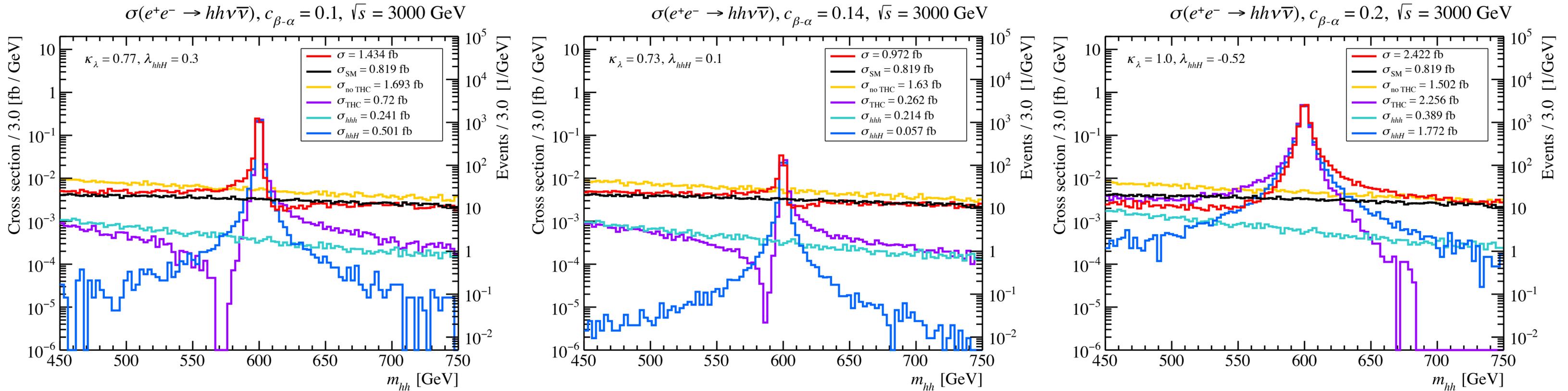
Type I  
 $m = 600 \text{ GeV}$   
 $\tan \beta = 10$   
 $c_{\beta-\alpha} = 0.2$   
 $m_{12}^2 = m_H^2 \cos^2 \alpha / \tan \beta$

- Very small XS and number of events in the  $HHZ$  channel
- Dominant effect in  $HH\nu\bar{\nu}$  comes from  $\lambda_{hHH}$  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  $\lambda_{hhH}$ )

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  $\lambda_{hhH}$
- For large  $c_{\beta-\alpha}$  the resonance is wider because  $\Gamma_H$  is larger

$\lambda_{hhH} > 0$ :

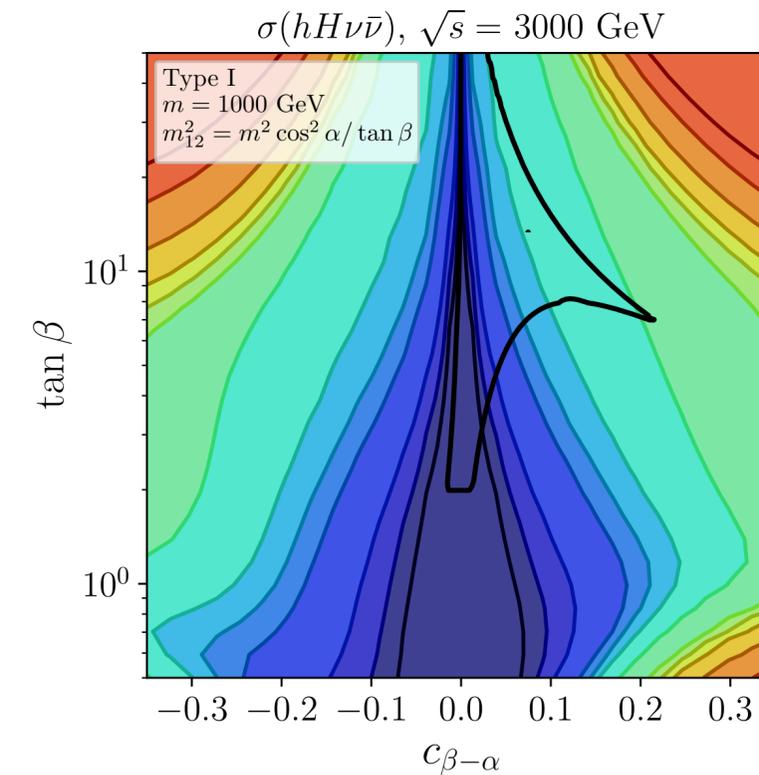
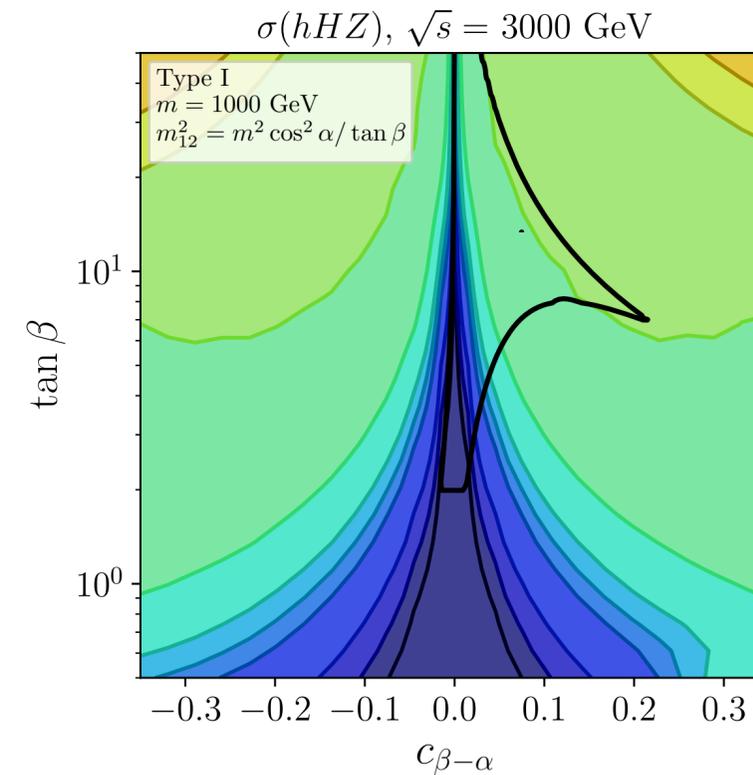
More events at the left of the peak than at the right

$\lambda_{hhH} < 0$ :

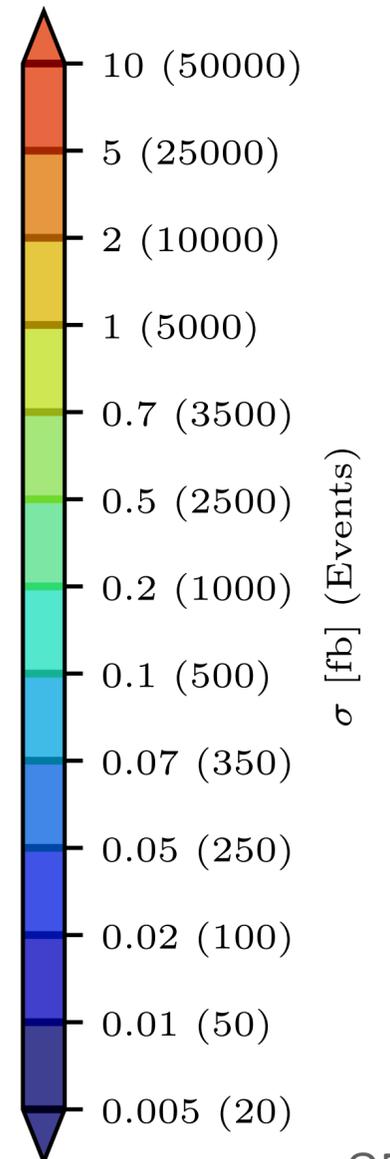
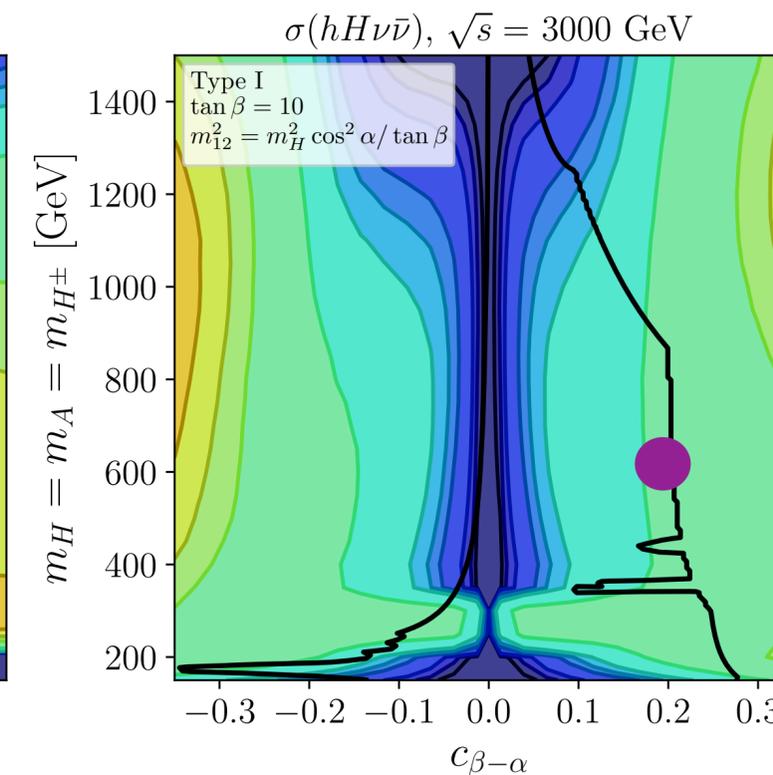
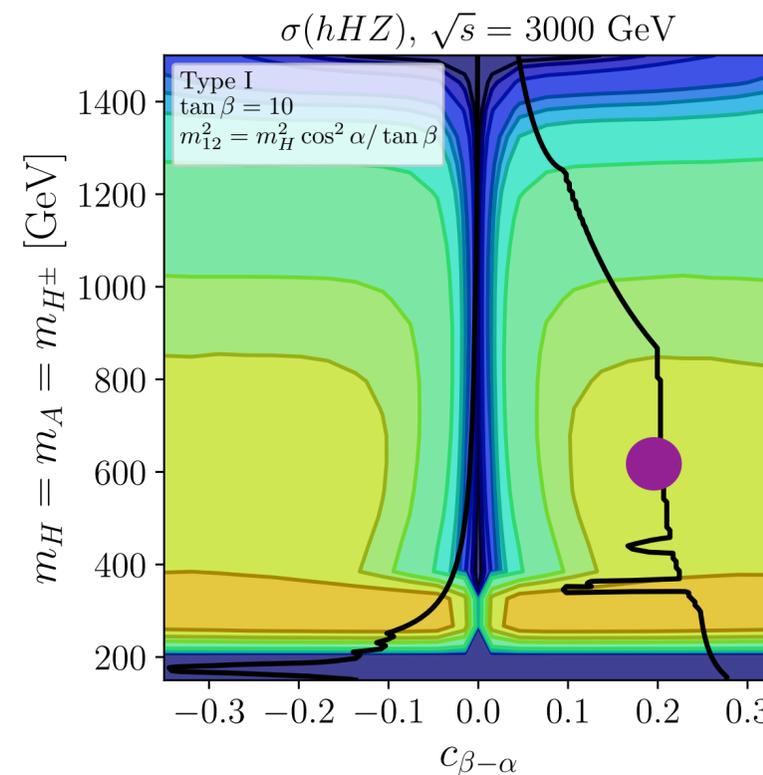
More events at the right of the peak than at the left

# $hH$ 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:  $\lambda_{hhH}$  and  $\lambda_{hHH}$ )



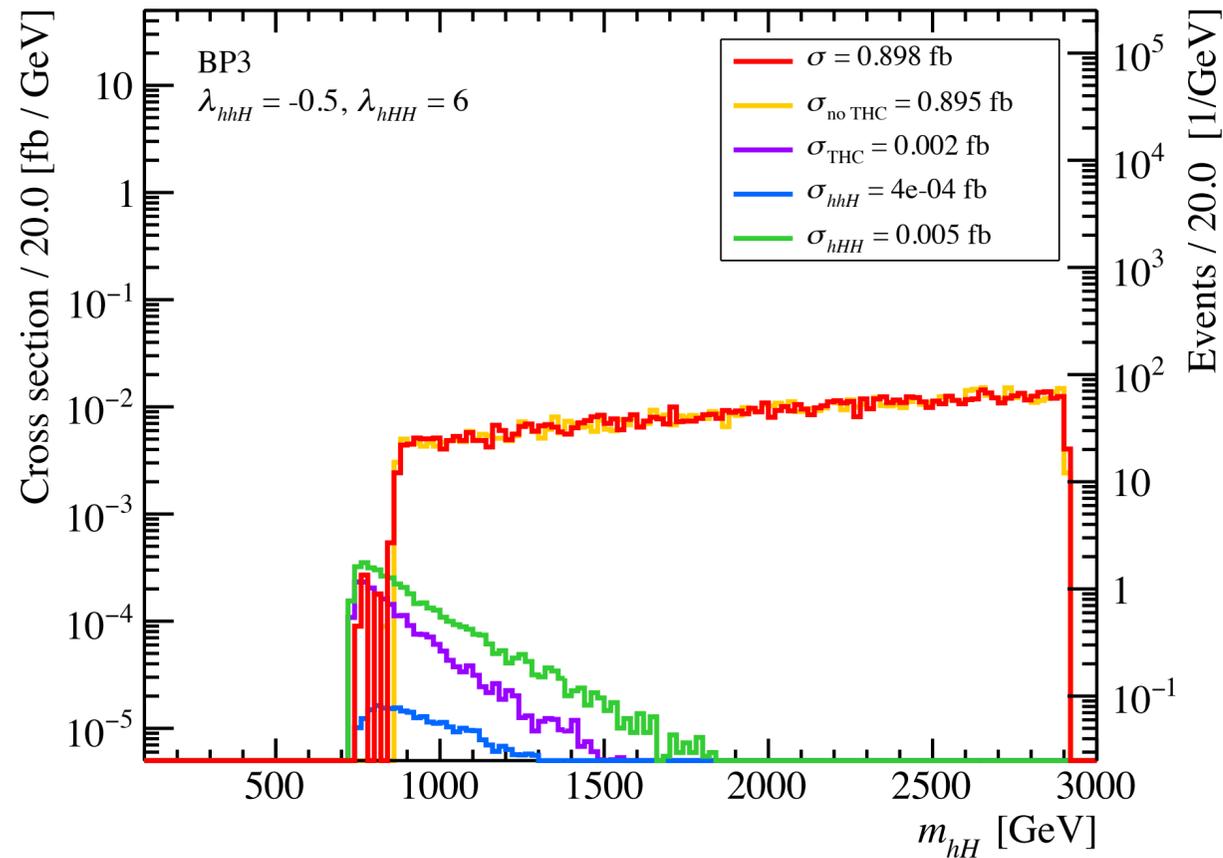
Black lines are the boundaries to the total allowed region



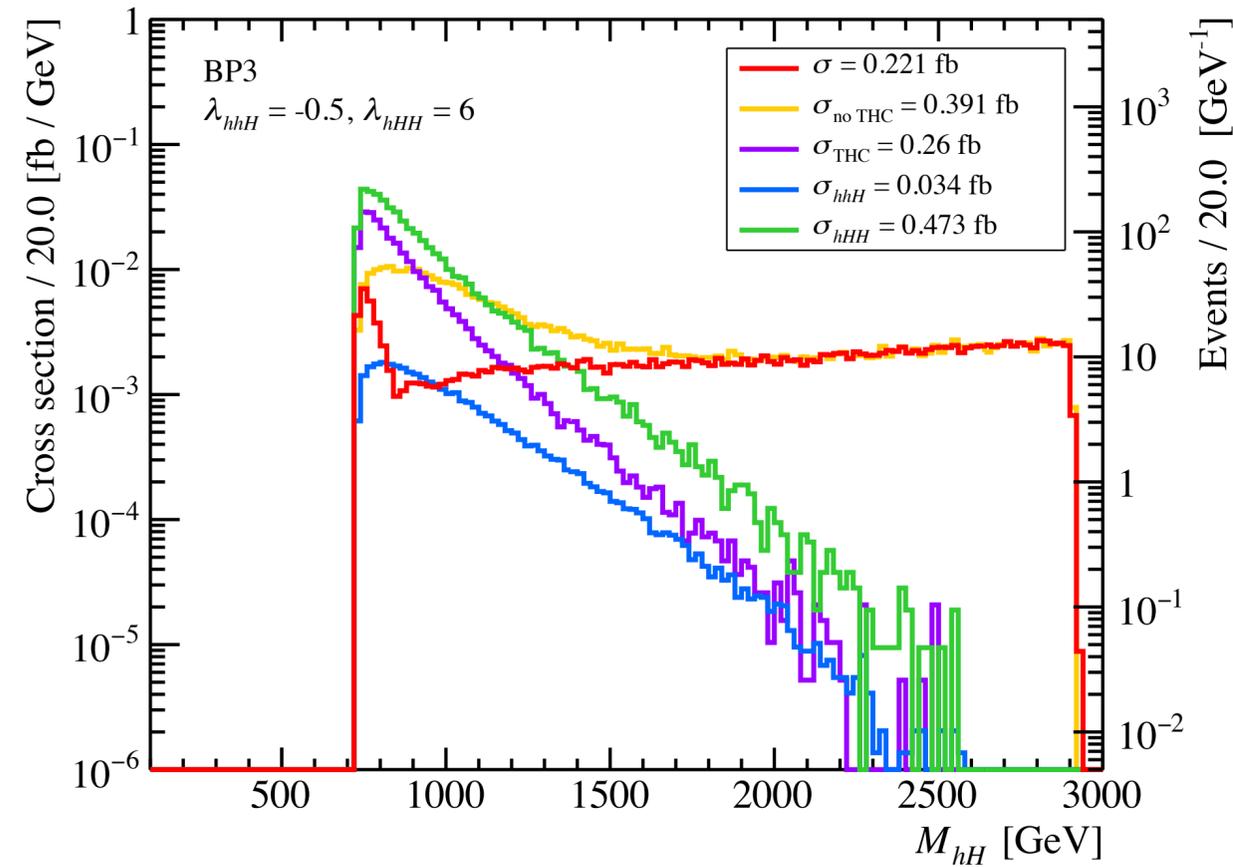
# $hH$ PRODUCTION, CLIC 3TEV, THC DEPENDENCE (TYPE I)

Cross section distribution on the invariant mass of  $hH$ :

$\sigma(e^+e^- \rightarrow hHZ), \sqrt{s} = 3000 \text{ GeV}$



$\sigma(e^-e^+ \rightarrow hH\nu\bar{\nu}), \sqrt{s} = 3000 \text{ GeV}$



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

- Large “steps” in both channels coming from  $A$  resonant diagrams

- Large effects from  $\lambda_{hhH}$  (dark blue line) and  $\lambda_{hHH}$  (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  $m = 1$  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  $m_{12}^2 = m_H^2 \cos^2 \alpha / \tan \beta$

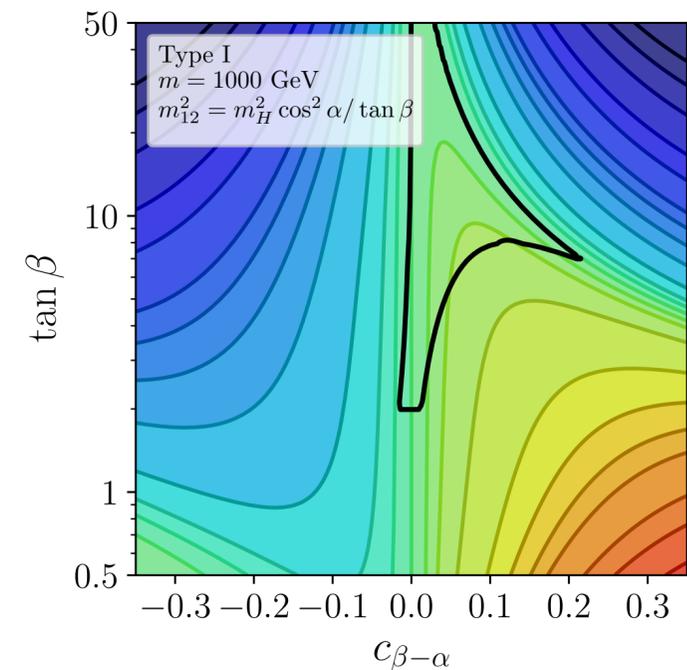
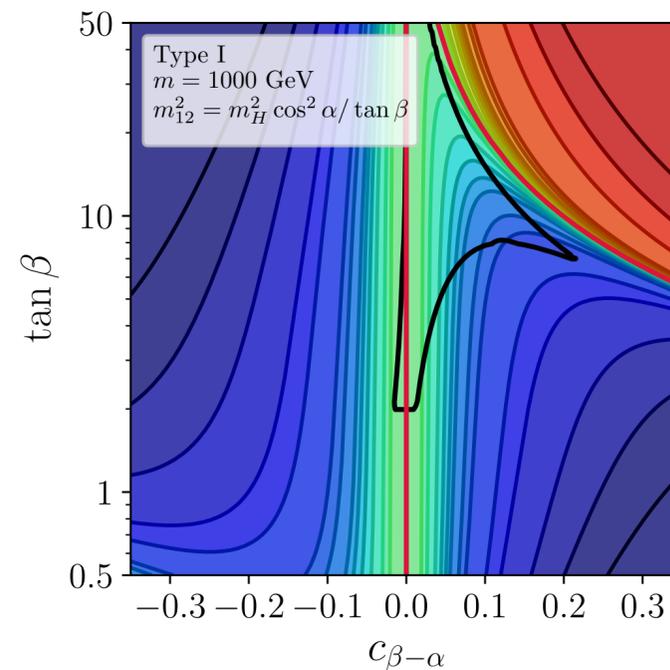
- $\kappa_\lambda := \lambda_{hhh} / \lambda_{hhh}^{\text{SM}}$

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

- $\lambda_{hhH}$

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

⇒ 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

