Effects from triple Higgs couplings in the 2HDM at e^+e^- colliders

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Based on arxiv:2005.10576 and arxiv:2106.11105, published in EPJC

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Motivation

The shape of the SM Higgs potential is ***NOT*** measured experimentally and there is not a precise measurement of the Higgs self-coupling

Actual measurements on $\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$

ATLAS	CMS
[-2.3, 10.3] at 95% CL	[-3.3, 8.5] at 95% CL
[ATLAS-CONF-2019-049]	[arXiv:2011.12373, CMS-HIG-19-018]

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

ILC	CLIC
500GeV: ±27% at 68% CL 1TeV: ±10% at 68% CL	3+1.4 TeV combination: -8% and 11% at 68% CL
[arXiv:1910.11775]	[arXiv:1901.05897]

All the above analysis assume the SM couplings

- There are analysis for FCC-hh [arXiv.2004.03505] and ILC [J. List et al., preliminary] with $\kappa_\lambda \neq 1$

Future e^+e^- colliders will play a crucial role to measure λ_{hhh}, but…

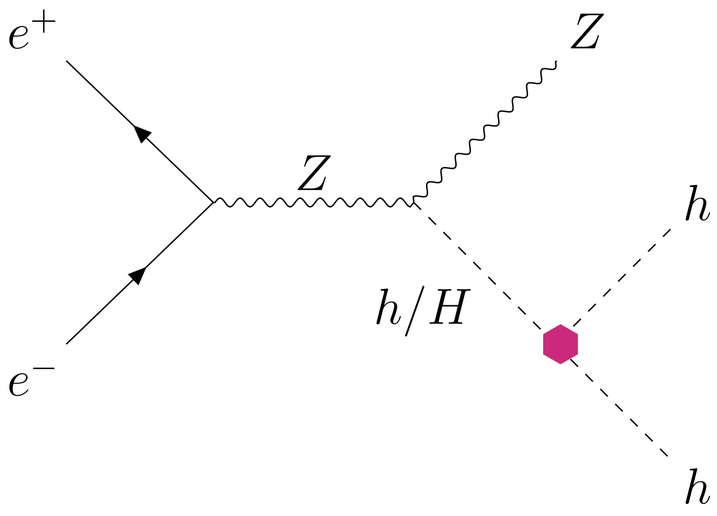
There is room for SM deviations in the scalar sector !!!

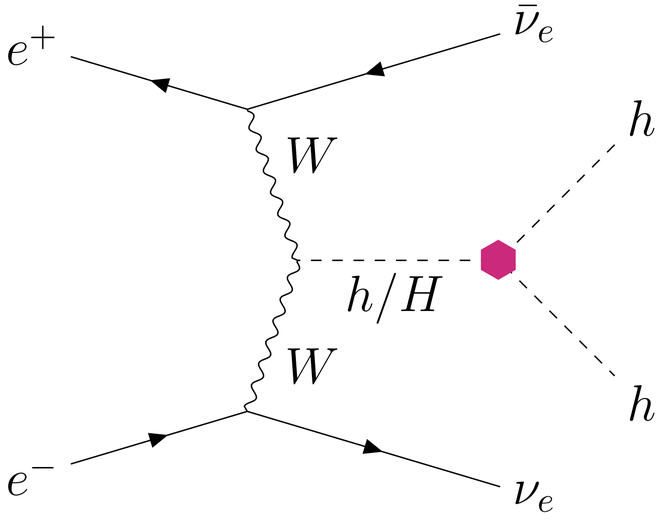
(More) motivation

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])

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

Two channels of interest: $e^+e^- \to hhZ$ and $e^+e^- \to hh\nu\bar{\nu}$





Production of hH, HH and AA at both channels were studied at [arxiv:2106.11105]

The Two Higgs Doublet Model (2HDM)

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

POTENTIAL:

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

$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

- *CP* conservation
- 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)

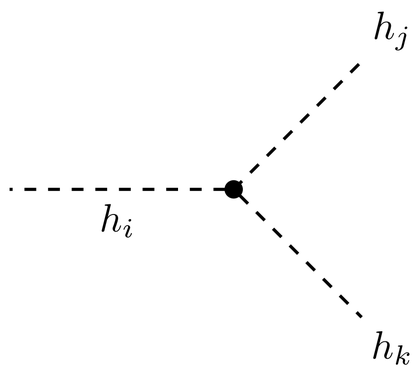
INPUT PARAMETERS:

m_h ($= 125$ GeV), m_H, m_A, $m_{H^\pm}$, $\tan\beta := v_2/v_1$, $\cos(\beta-\alpha) \equiv c_{\beta-\alpha}$ 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: $\mathrm{BR}(B \to X_s\gamma)$ and $\mathrm{BR}(B_s \to \mu\mu)$

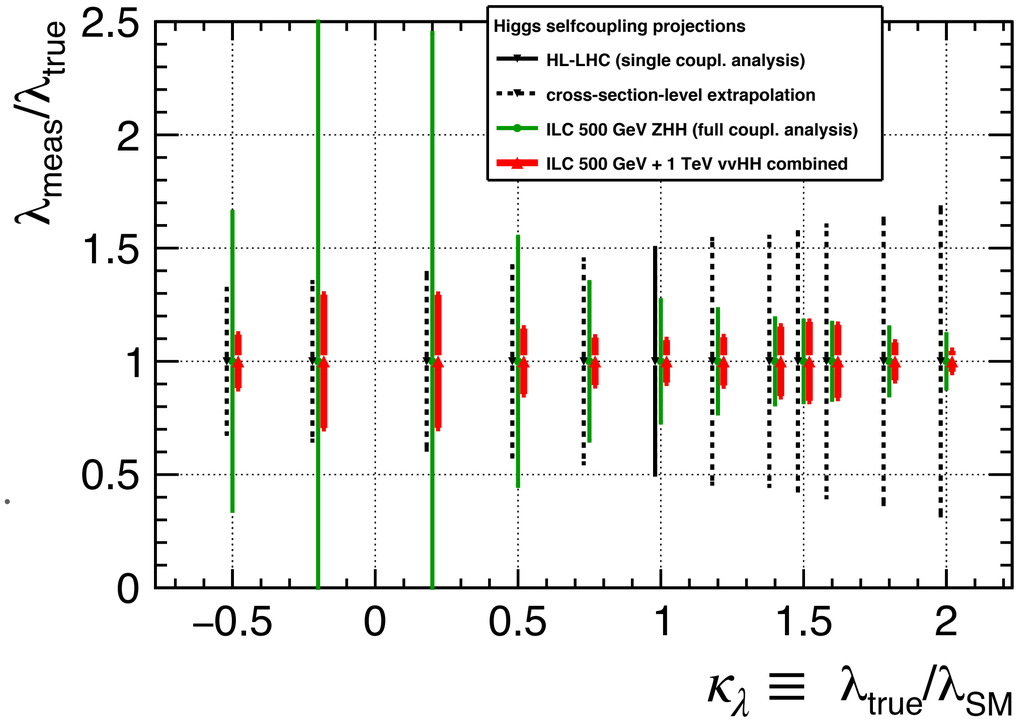
2HDMC, HiggsBounds, HiggsSignals and superISO were used

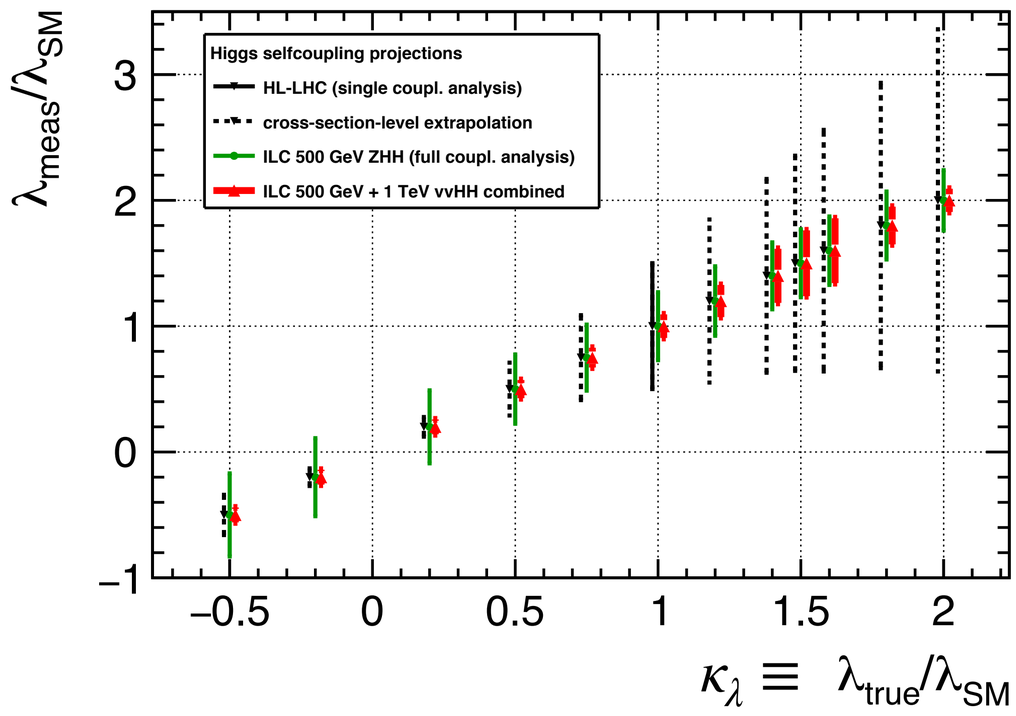
*smaller ranges with latest HiggsSignals updates

Experimental expectation for κ_λ at ILC

Sensitivity to κ_λ for the di-Higgs production at HL-LHC and ILC, also for $\kappa_\lambda \neq 1$:

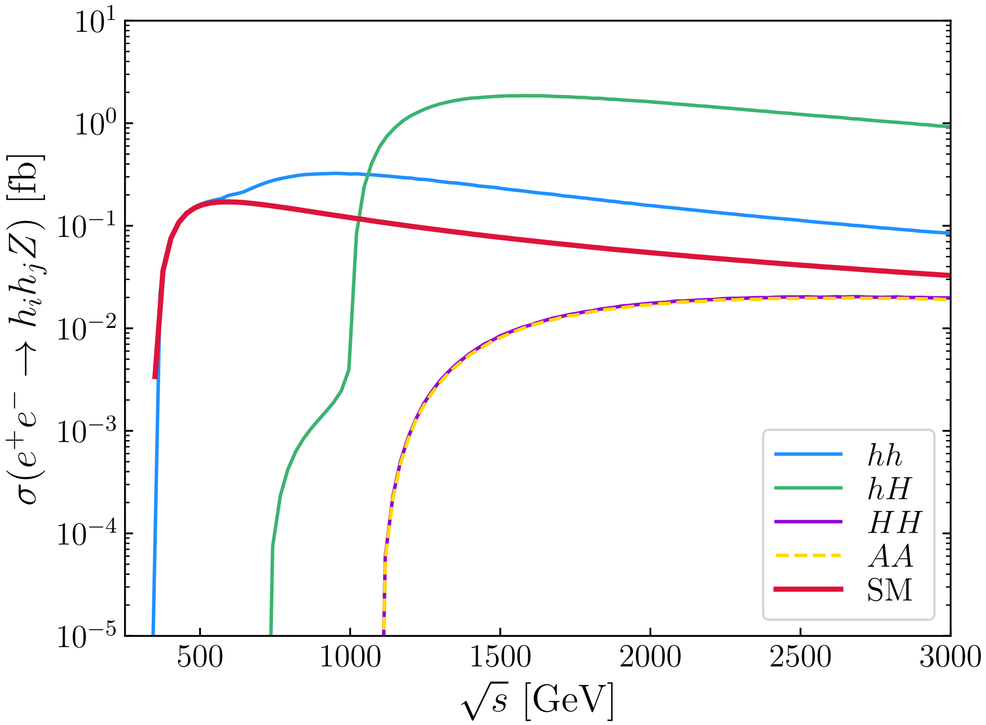
J. List priv. commun.

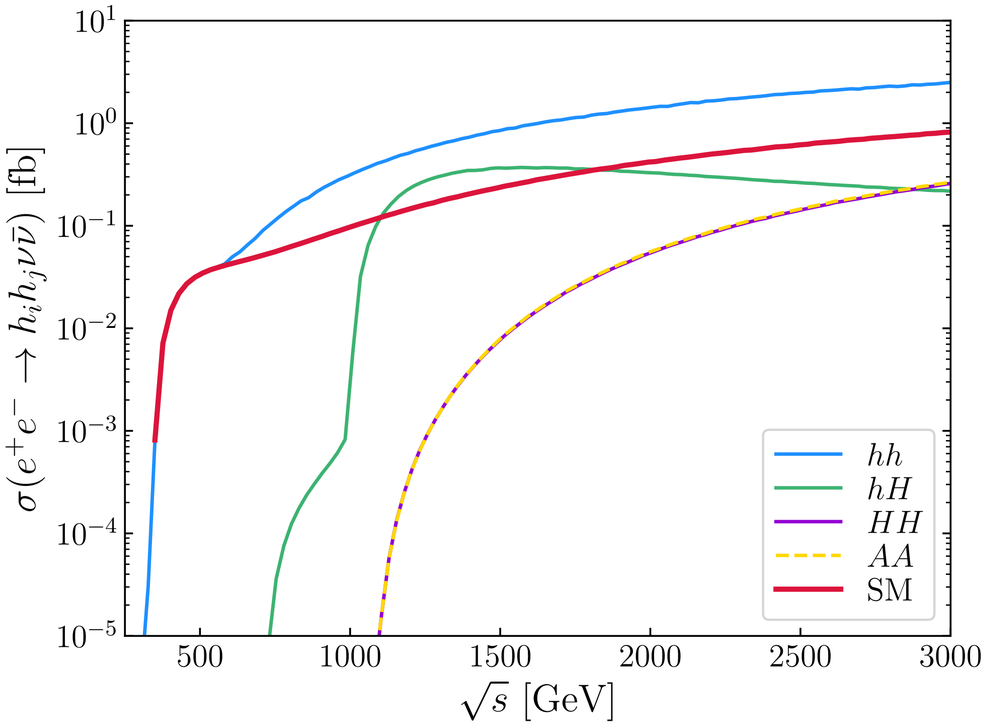




- Allowed ranges by type I and II are included
- ILC 500 + ILC 1000 is better to measure κ_λ except for $\kappa_\lambda \sim 0$, where HL-LHC competes (no BSM channels are included)

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

Methodology

- XS presented in some **benchmark planes** with large (and allowed) THC (inspired from [arXiv:2005.10576])
  - 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 $m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$
- **ALL** diagrams included (**no NWA!**)
- Access to THC via XS distributions on the **invariant mass of the final hh pair**
- We studied effects from THC in m_{hh} for 5 benchmark points (BP) with a wide range of BSM Higgs masses

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

MadGraph, FeynRules, 2HDMC and ROOT were used

hh production

Three main effects different from the SM:

1. Deviations from $\kappa_\lambda = 1$

   Diagrams with κ_λ has a positive interference in the Z channel and negative in the neutrino channel

2. H mediated resonant diagrams (contains λ_{hhH})

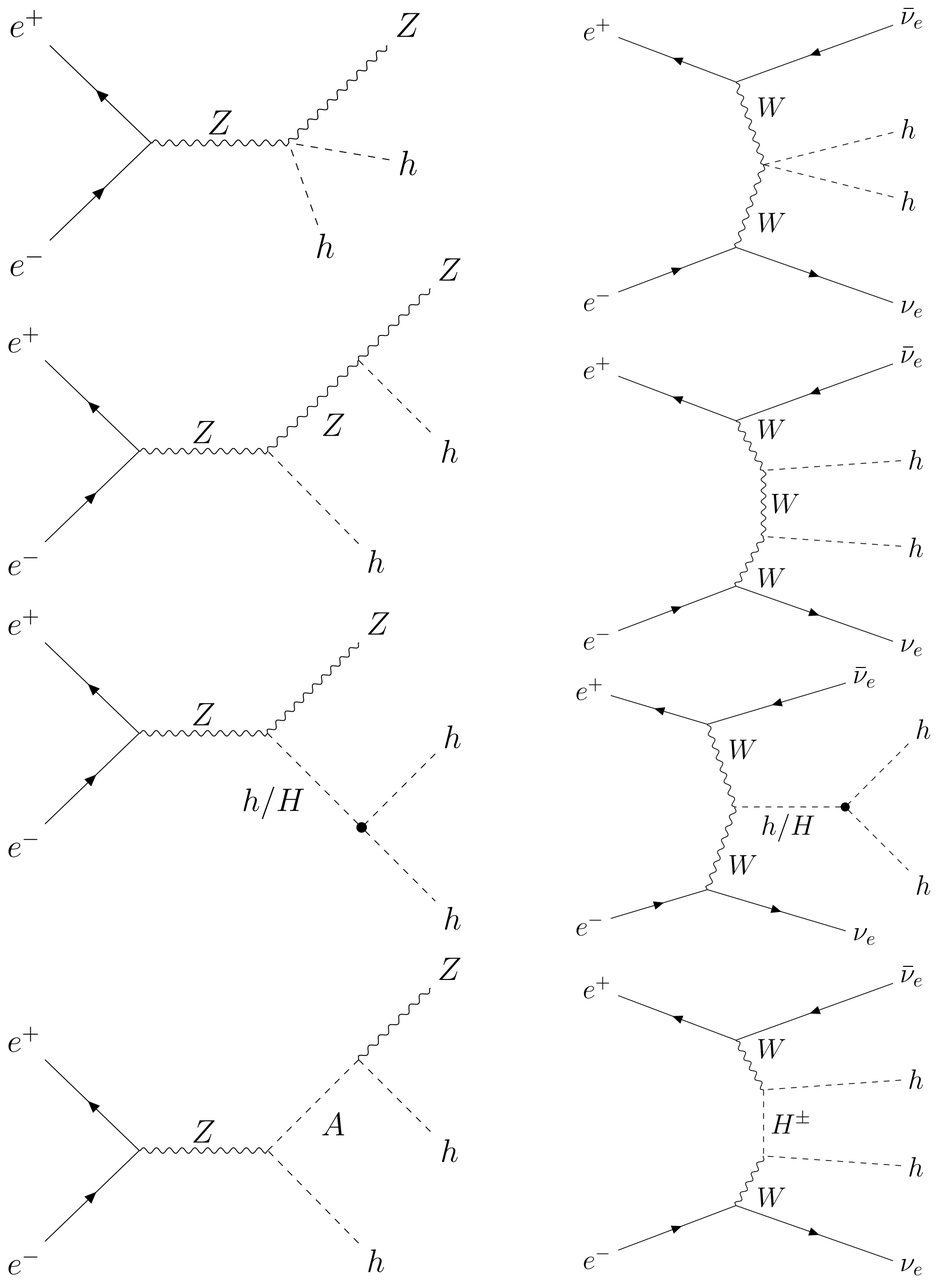
   $e^+e^- \to H^*Z \to hhZ\ (\to hh\nu\bar{\nu})$

   $e^+e^- \to H^*\nu_e\bar{\nu}_e \to hh\nu_e\bar{\nu}_e$

3. A mediated resonant diagrams (no sensitivity to THC)

   $e^+e^- \to hA^* \to hhZ\ (\to hh\nu\bar{\nu})$ (More relevant for the Z channel)

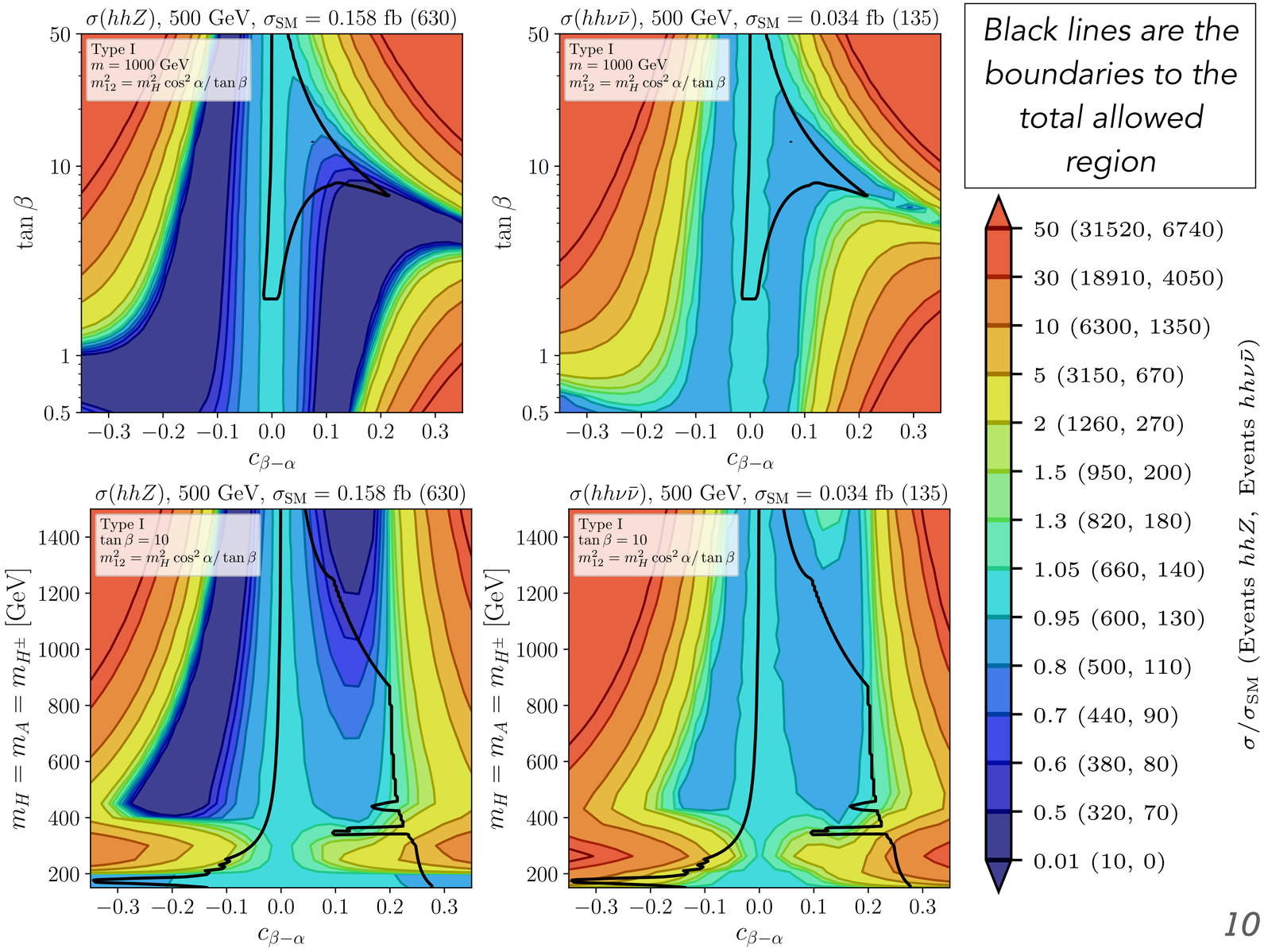
If $c_{\beta-\alpha} = 0$ we recover the SM prediction



diagrams with $Z \to \nu\bar{\nu}$ also included

hh production, ILC 500GeV (type I)

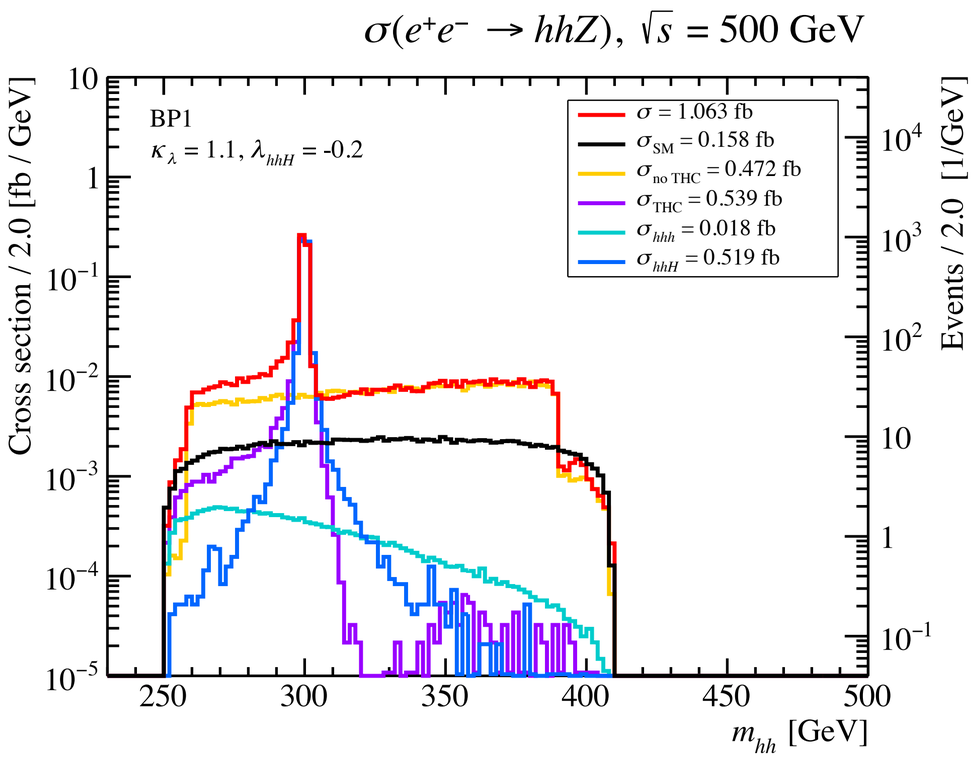
- At this energy, hhZ is the most important channel
- $c_{\beta-\alpha} - \tan\beta$ plane: H and A are too heavy $\Longrightarrow$ we see mainly the effect of κ_λ
- In the $c_{\beta-\alpha} - m$ plane, the H (λ_{hhH}) and A (no THC) resonances manifest for low masses
  - The enhancement wrt the SM in the neutrino channel is larger, but the absolute XS is smaller

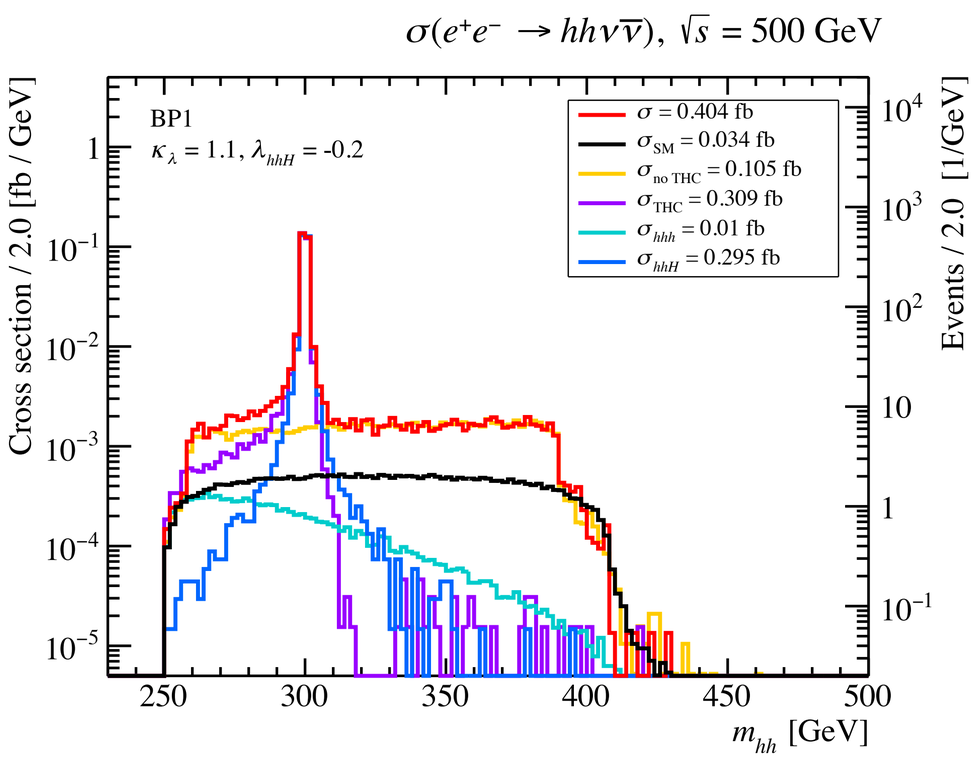


Black lines are the boundaries to the total allowed region

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

Cross section distribution on the invariant mass of hh:





BP1

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 when $m_{hh} \sim m_H = 300$ GeV (dark blue line): information from λ_{hhH}
- Plateau in the 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

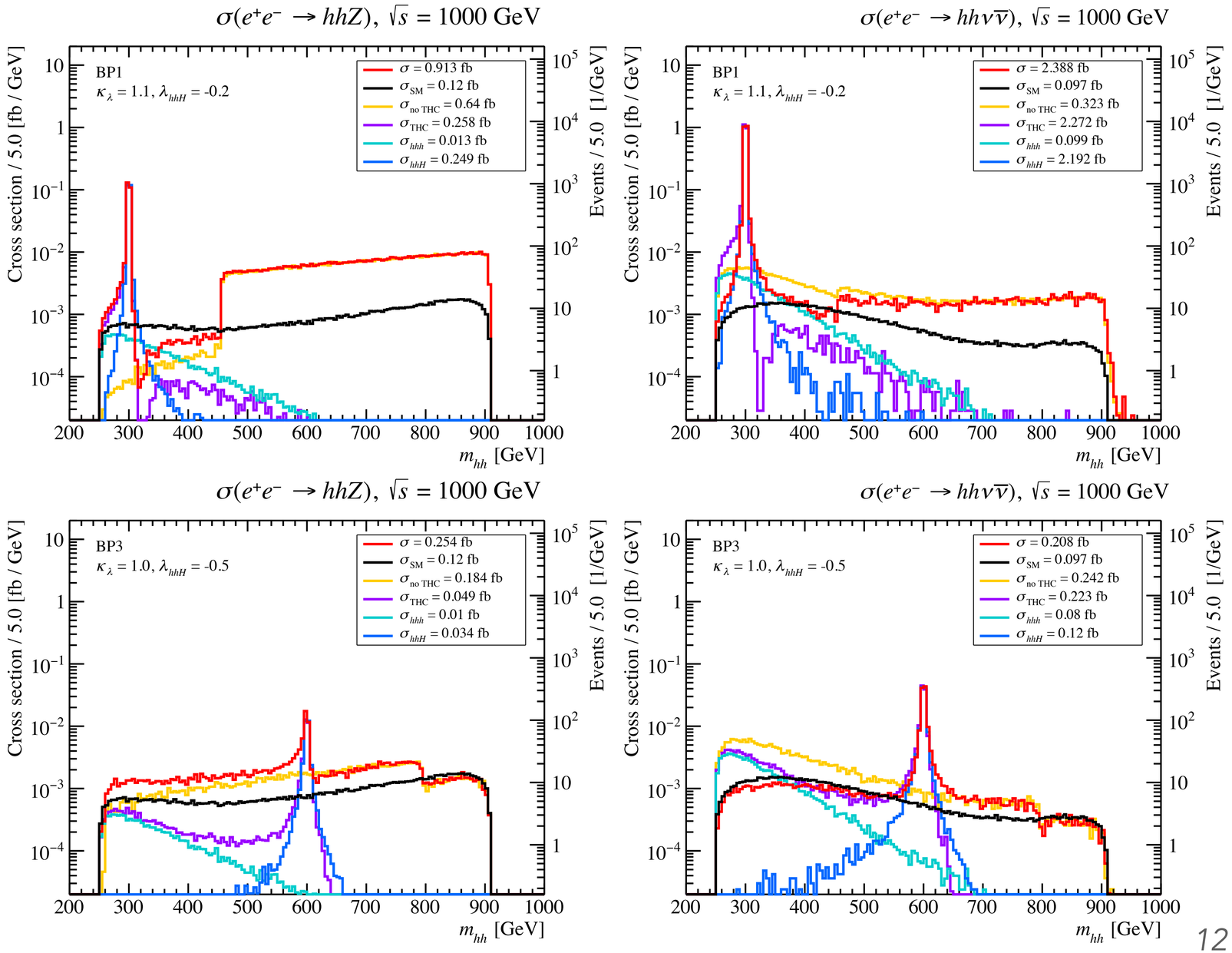
hh production, THC dependence, ILC 1TeV (type I)

Cross section distributions 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)

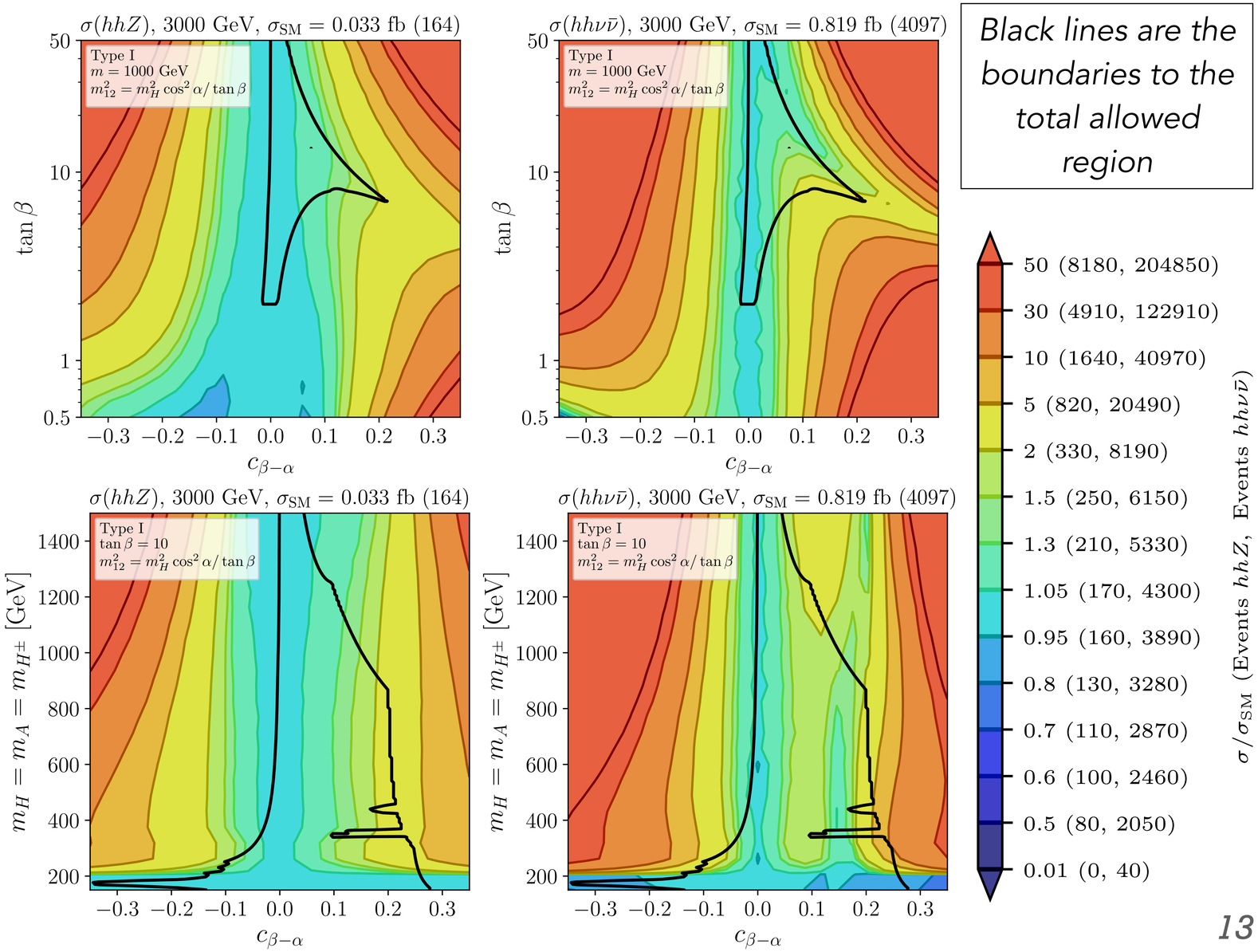
(Eq. (8) $\rightarrow m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$)

- Effect from κ_λ: the region of low invariant mass
- Effect from λ_{hhH}: H resonant peak at $m_{hh} \sim m_H$
- Extra events due to the A resonance



hh production, CLIC 3TeV (type I)

- 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 distributions 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
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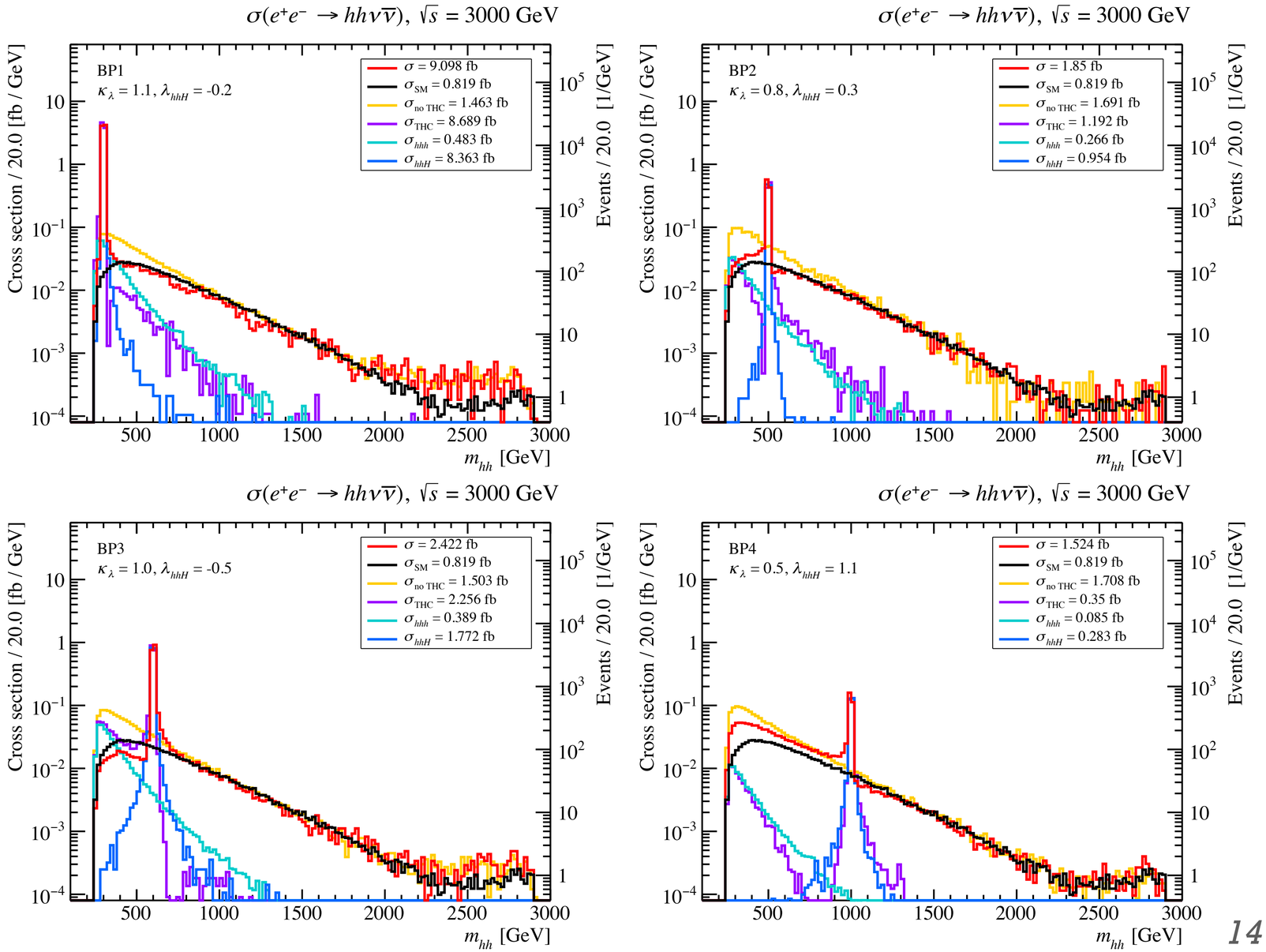
BP4	I	1000	8.5	0.08	Eq. (8)

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

- Effect from κ_λ: 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 $c_{\beta-\alpha}$

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



4-$b$jets in hh production: λ_{hhH} "sensitivity"

- We define a theoretical "sensitivity" R with an estimation of the final 4-$b$jets events that could be detected at a collider close to the H resonance:

$$R = \frac{\bar{N}^R - \bar{N}^C}{\sqrt{\bar{N}^C}}$$

N^R are events from the H mediated diagrams and N^C are events from diagrams without THC

where $\bar{N} = N \times \mathscr{A} \times \epsilon_b^4$ with N the number of total 4-$b$jets events, $\epsilon_b \sim 0.8$ the b-tagging efficiency and $\mathscr{A} = N_{\text{cuts}}/N_{\text{no cuts}}$ is the acceptance of the collider

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

"Sensitivity" to λ_{hhH} at hhZ and $hh\nu\bar{\nu}$

More sensitivity to λ_{hhH} (i.e. larger R) in $hh\nu\bar{\nu}$, specially at CLIC 3 TeV

But good prospects for BP1 at ILC at both channels

hhZ	$\sqrt{s}$ [GeV]	$\sigma_{\rm 2HDM}$ / $\sigma_{\rm SM}$ [fb]	$\bar{N}^R_{4bZ}$ / $\bar{N}^C_{4bZ}$ / $\bar{N}^{\rm SM}_{4bZ}$	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]	$\sigma_{\rm 2HDM}$ / $\sigma_{\rm SM}$ [fb]	$\bar{N}^R_{4b\not{E}_T}$ / $\bar{N}^C_{4b\not{E}_T}$ / $\bar{N}^{\rm SM}_{4b\not{E}_T}$	$R_{4b\not{E}_T}$
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 details in [arxiv:2106.11105]

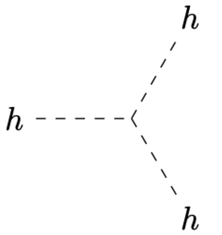
Summary & Conclusions

- The hh production is studied at e^+e^- colliders in the 2HDM type I, with the aim to find effects coming from triple Higgs couplings (THC)
  - Two production channels were studied: $e^+e^- \to hhZ$ and $e^+e^- \to hh\nu\bar{\nu}$
- 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
  - From λ_{hhH}, through a resonant peak due to the H boson:
    - A study of the final 4 b-jets events shows that $hh\nu\bar{\nu}$ channel is better at large energies (specially CLIC 3TeV)
    - Large #events at ILC energies for a light H at both channels
- Effects from THC on $hH\nu\bar{\nu}$, $HH\nu\bar{\nu}$ and $AA\nu\bar{\nu}$ can be seen at large energies (CLIC 3TeV), see [arxiv:2106.11105]!

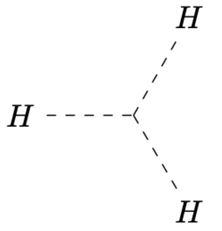
Thanks for your attention :)

Questions??

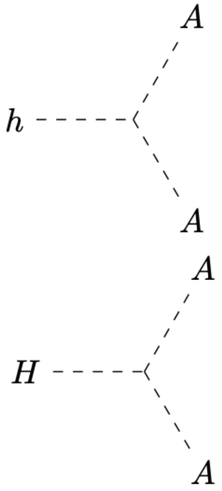
Back-up, Feynman Rules with THC



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

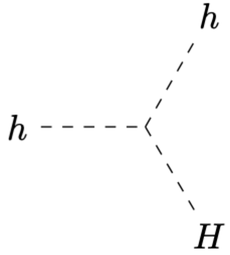


$$= -\frac{3i}{v}\left(\left(3m_H^2-2\bar{m}^2\right)c_{\beta-\alpha}s_{\beta-\alpha}^2+2\cot 2\beta\left(\bar{m}^2-m_H^2\right)s_{\beta-\alpha}^3+m_H^2 c_{\beta-\alpha}^3\right)$$

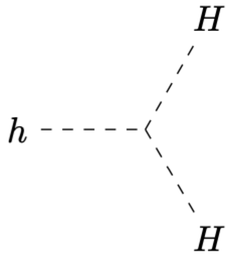


$$= -\frac{i}{v}\left(s_{\beta-\alpha}\left(-2\bar{m}^2+2m_A^2+m_h^2\right)+2\cot 2\beta\left(m_h^2-\bar{m}^2\right)c_{\beta-\alpha}\right)$$

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

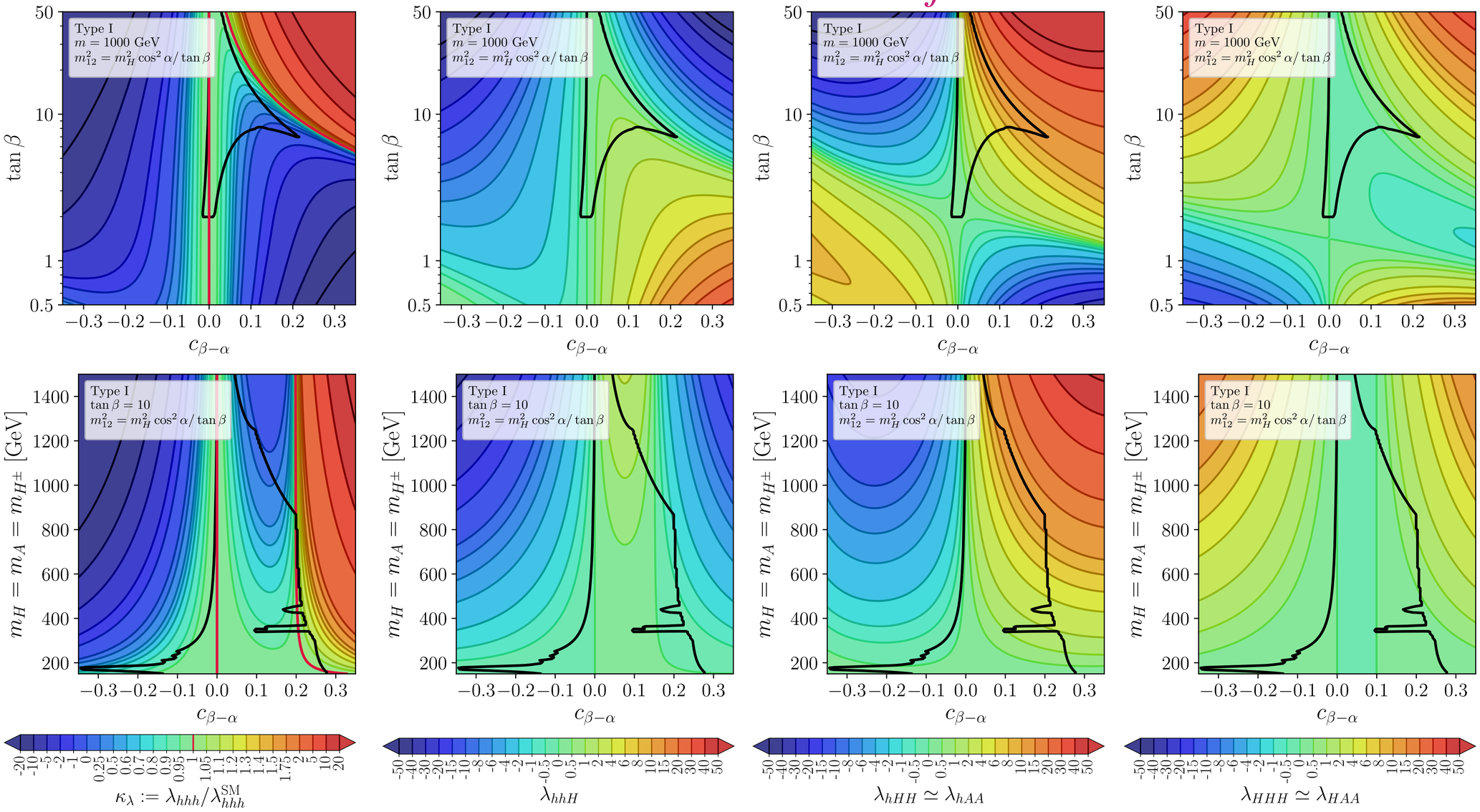


$$= \frac{ic_{\beta-\alpha}}{v}\left(2\bar{m}^2\left(c_{\beta-\alpha}^2-3\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}-2s_{\beta-\alpha}^2\right)+\left(2m_h^2+m_H^2\right)\left(-c_{\beta-\alpha}^2+2\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s_{\beta-\alpha}^2\right)\right)$$

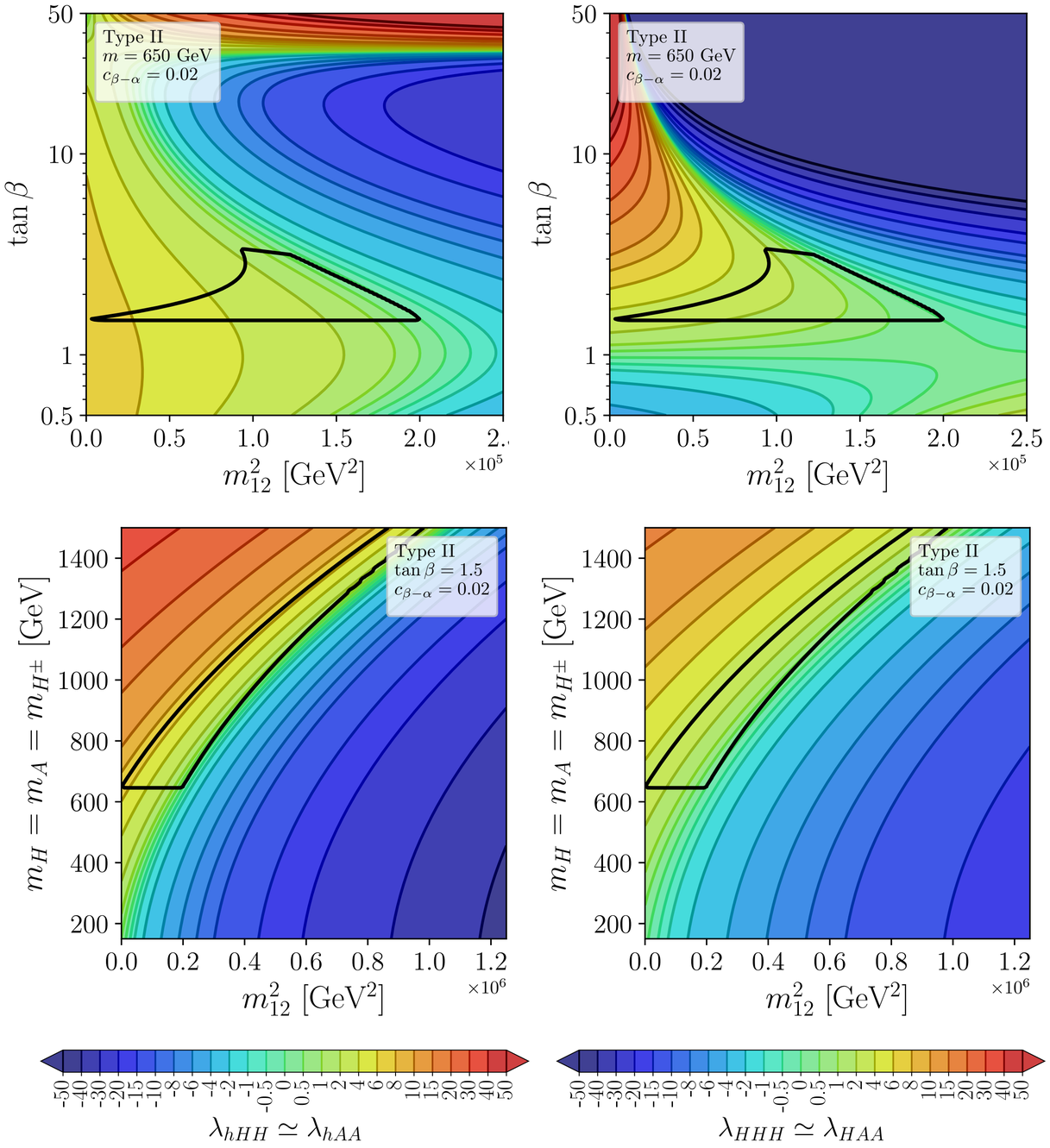


$$= -\frac{is_{\beta-\alpha}}{v}\left(\left(m_h^2+2m_H^2\right)\left(-c_{\beta-\alpha}^2+2\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s_{\beta-\alpha}^2\right)-2\bar{m}^2\left(-2c_{\beta-\alpha}^2+3\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s_{\beta-\alpha}^2\right)\right)$$

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

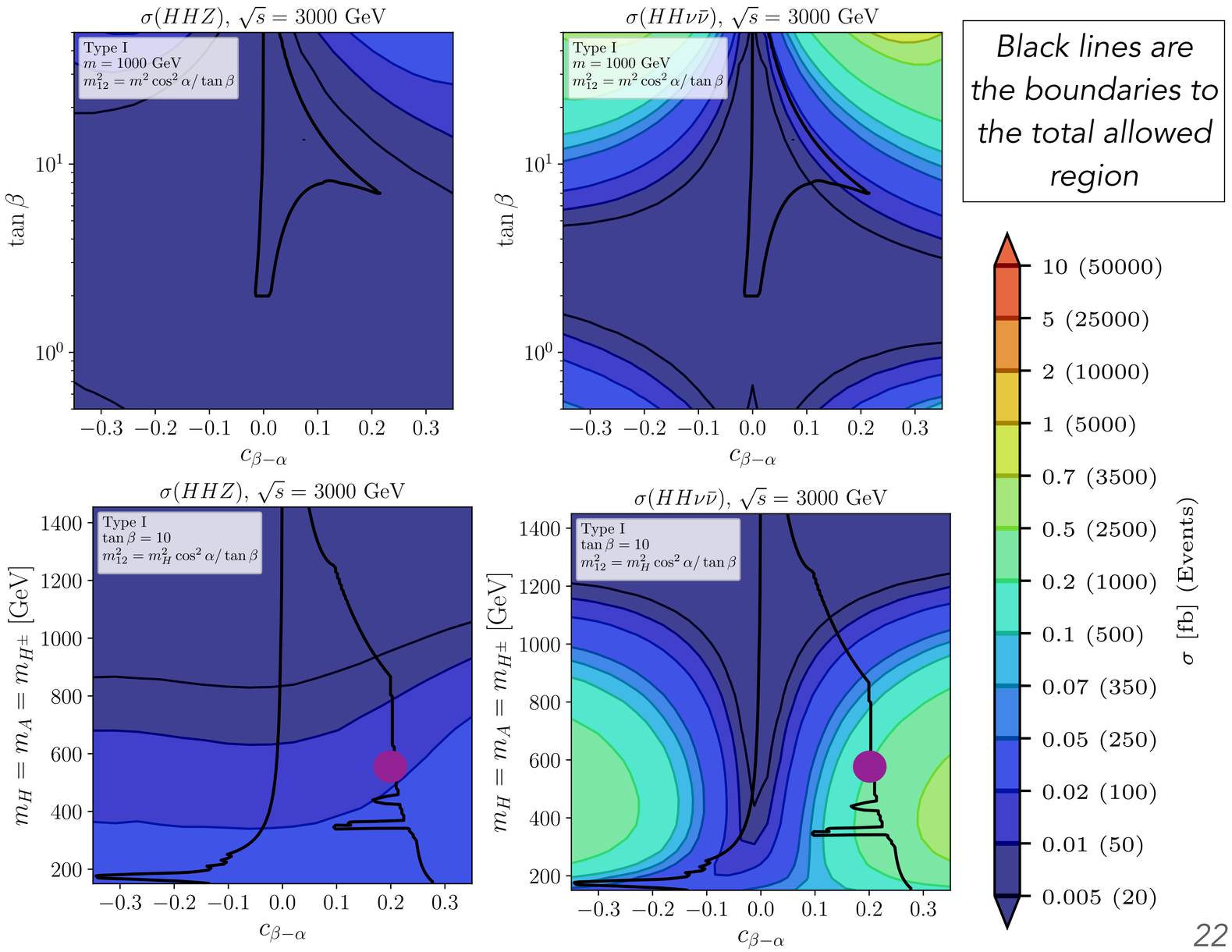


Back-up, $\lambda_{h_i h_j h_k}$



$HH \sim AA$ production, CLIC 3TeV

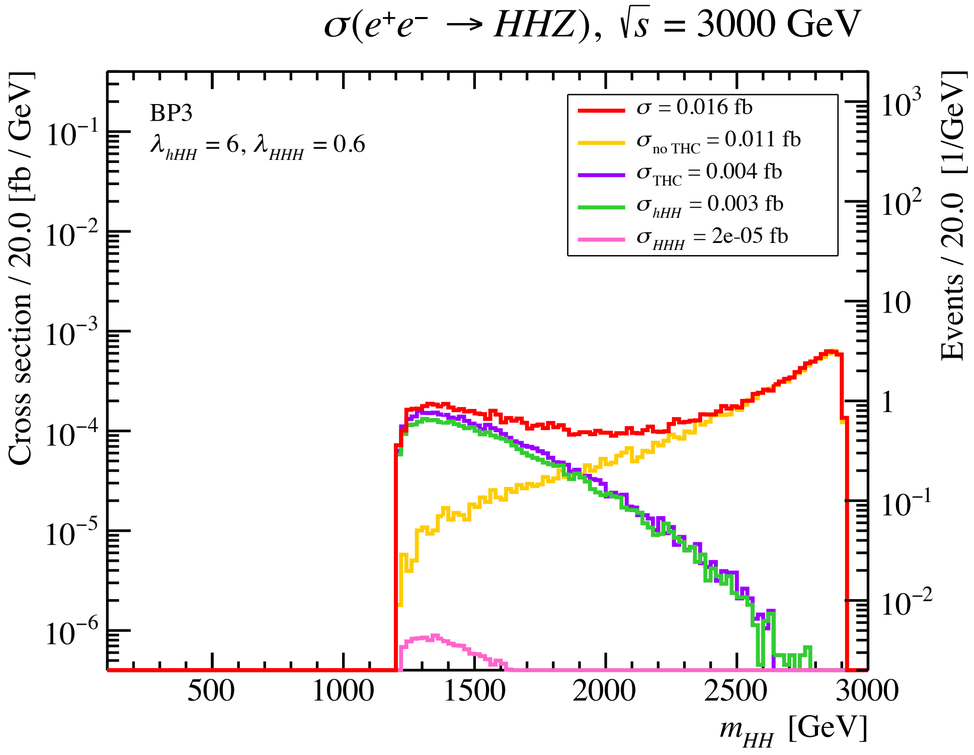
- The $HH \sim AA$ production can be non-zero even in the alignment limit ($c_{\beta-\alpha} \to 0$)
- Only sizable cross sections inside the allowed region for the neutrino channel
  - Not larger than 0.5 fb
- The sizable cross sections comes from the effect of λ_{hHH} (λ_{hAA})
  - Effects from λ_{HHH}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

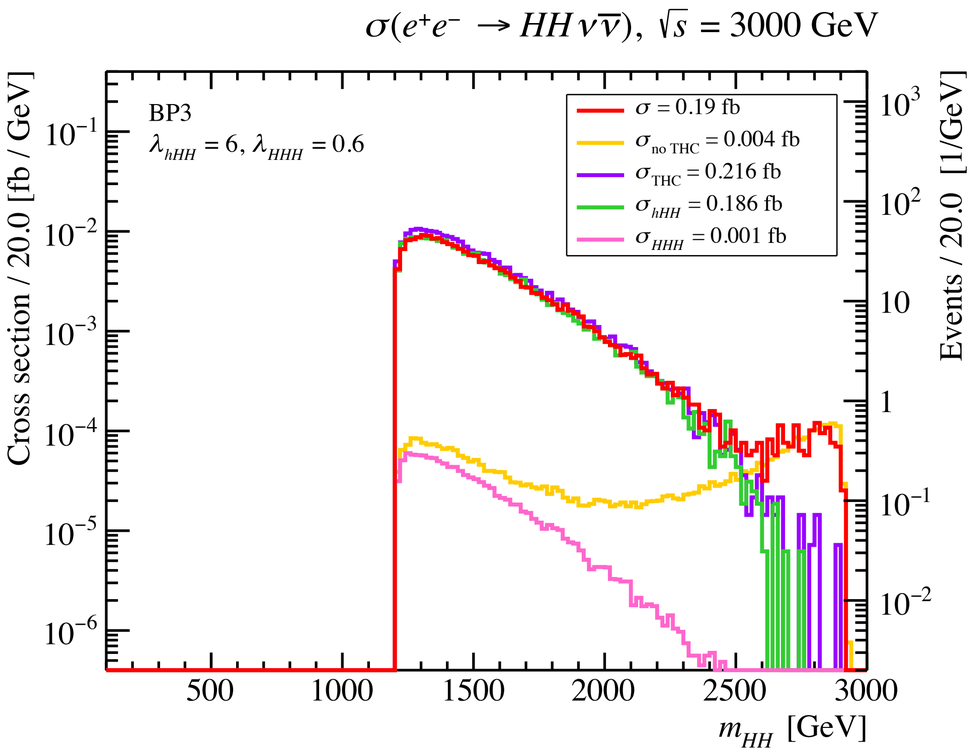


Black lines are the boundaries to the total allowed region

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

Cross section distribution on the invariant mass of HH:





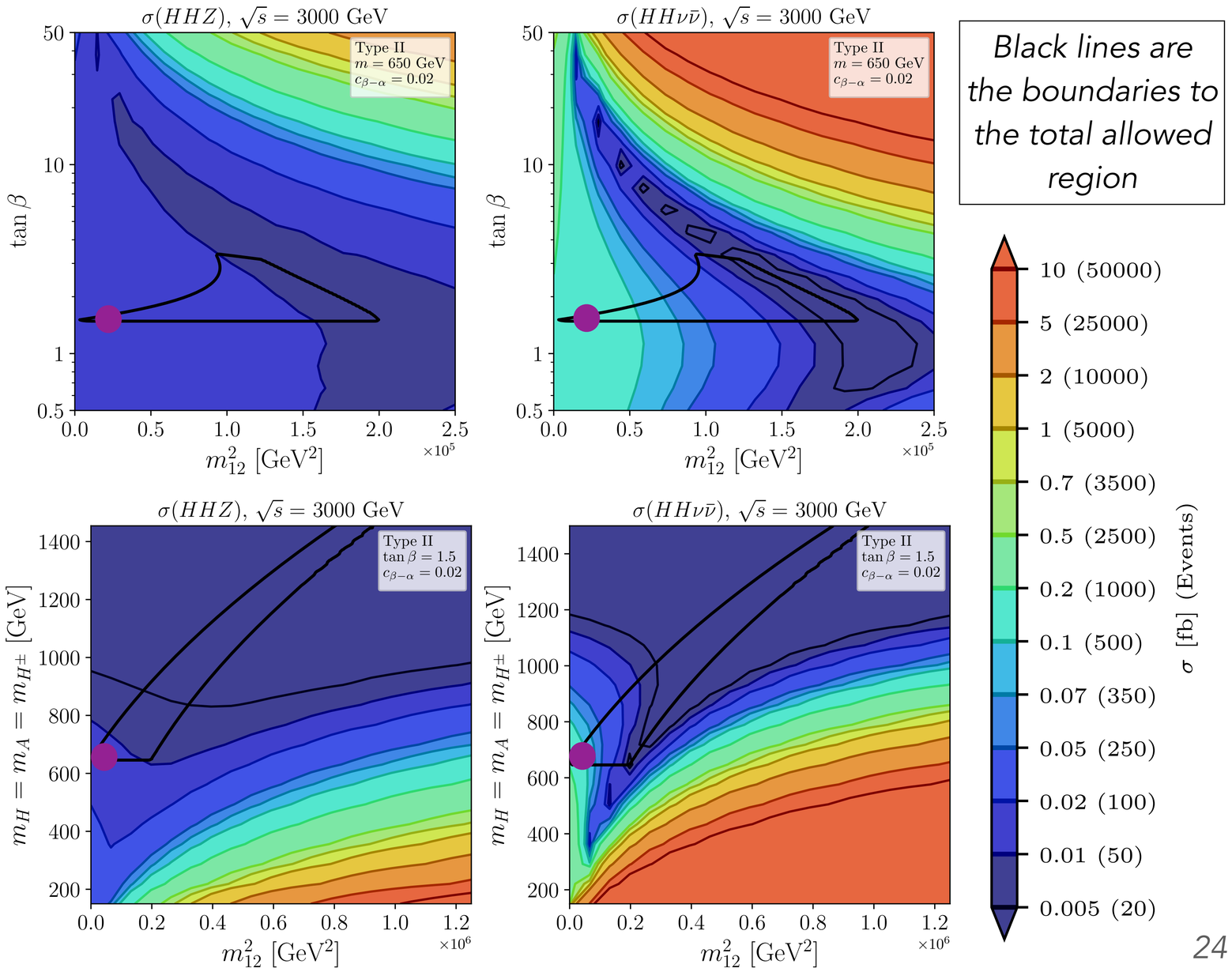
Type I
$m = 600$ GeV
$\tan\beta = 10$
$c_{\beta-\alpha} = 0.2$
$m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$

- 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

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

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

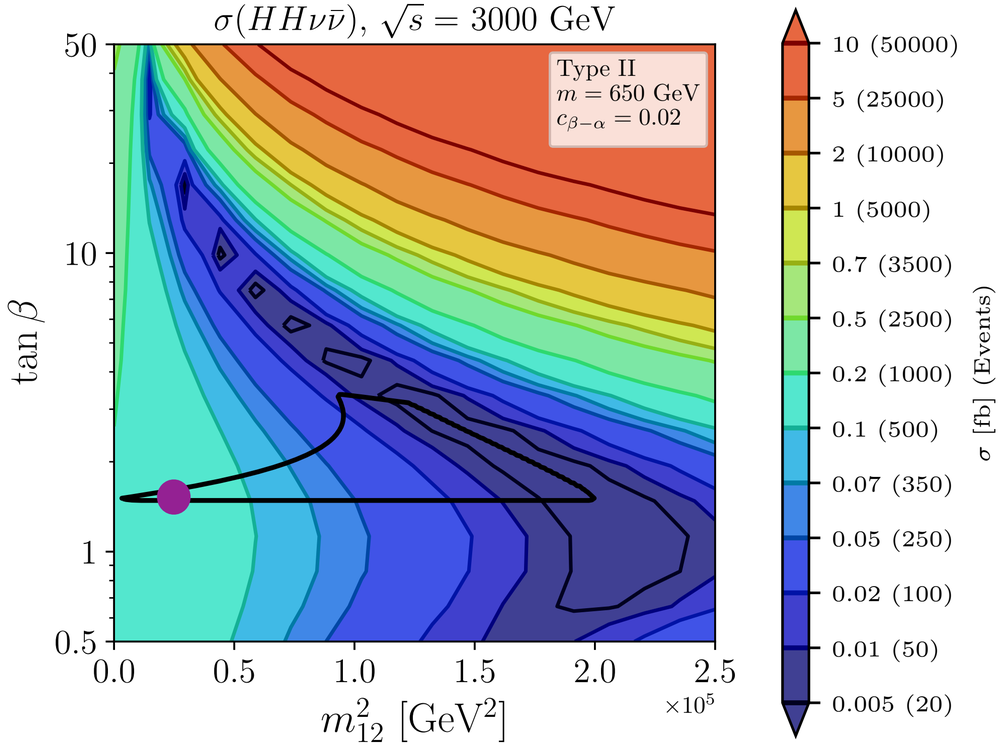
- In type II, due to the collider constraints, only $HH \sim AA$ production is relevant
- Only sizable XS, not larger than 0.5 fb, inside the allowed region for the neutrino channel
- Sizable XS comes from the effect of λ_{hHH} (λ_{hAA})
  - XS is larger at low m_{12}^2, that is the region where λ_{hHH}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

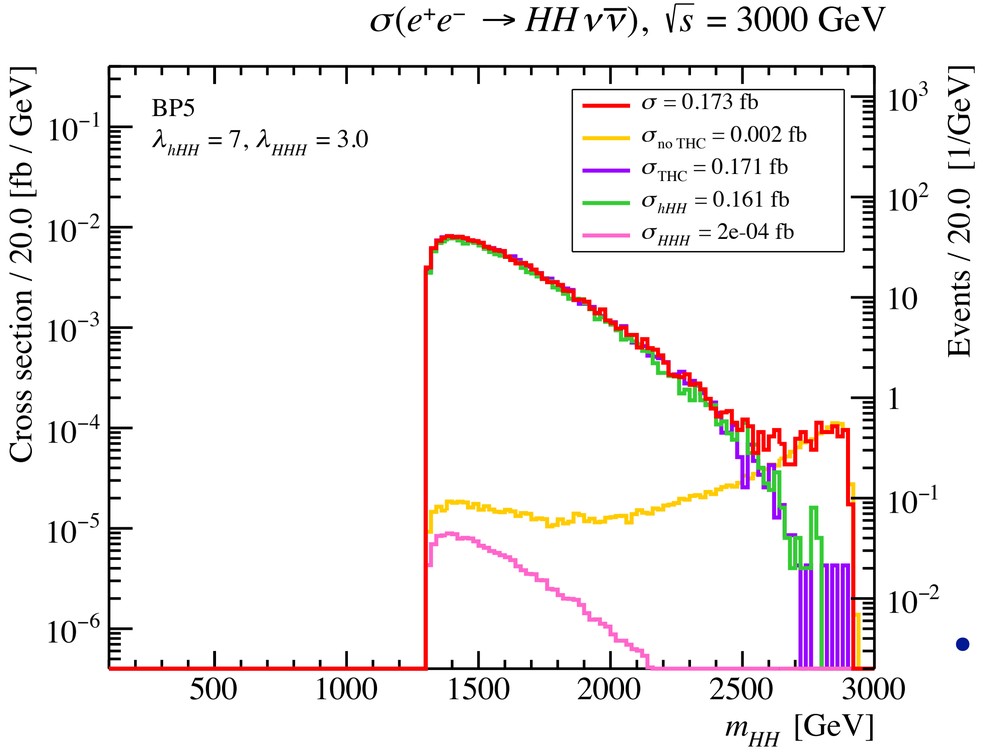


Black lines are the boundaries to the total allowed region

$HH \sim AA$ production, 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)





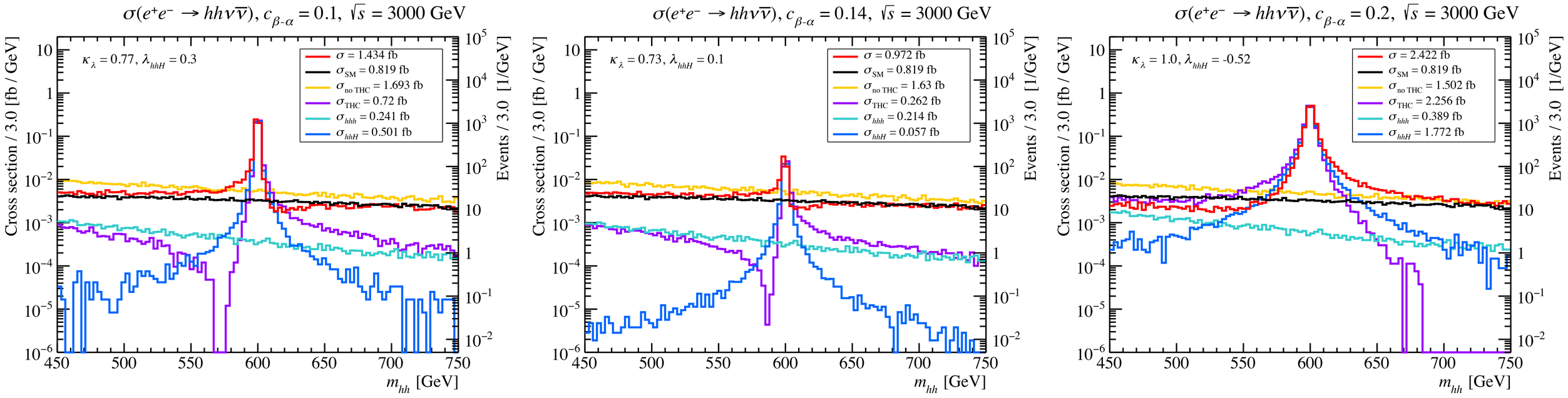
Type II
$m = 650$ GeV
$\tan\beta = 1.5$
$c_{\beta-\alpha} = 0.02$
$m_{12}^2 = 10000$ GeV^2

- 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)

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

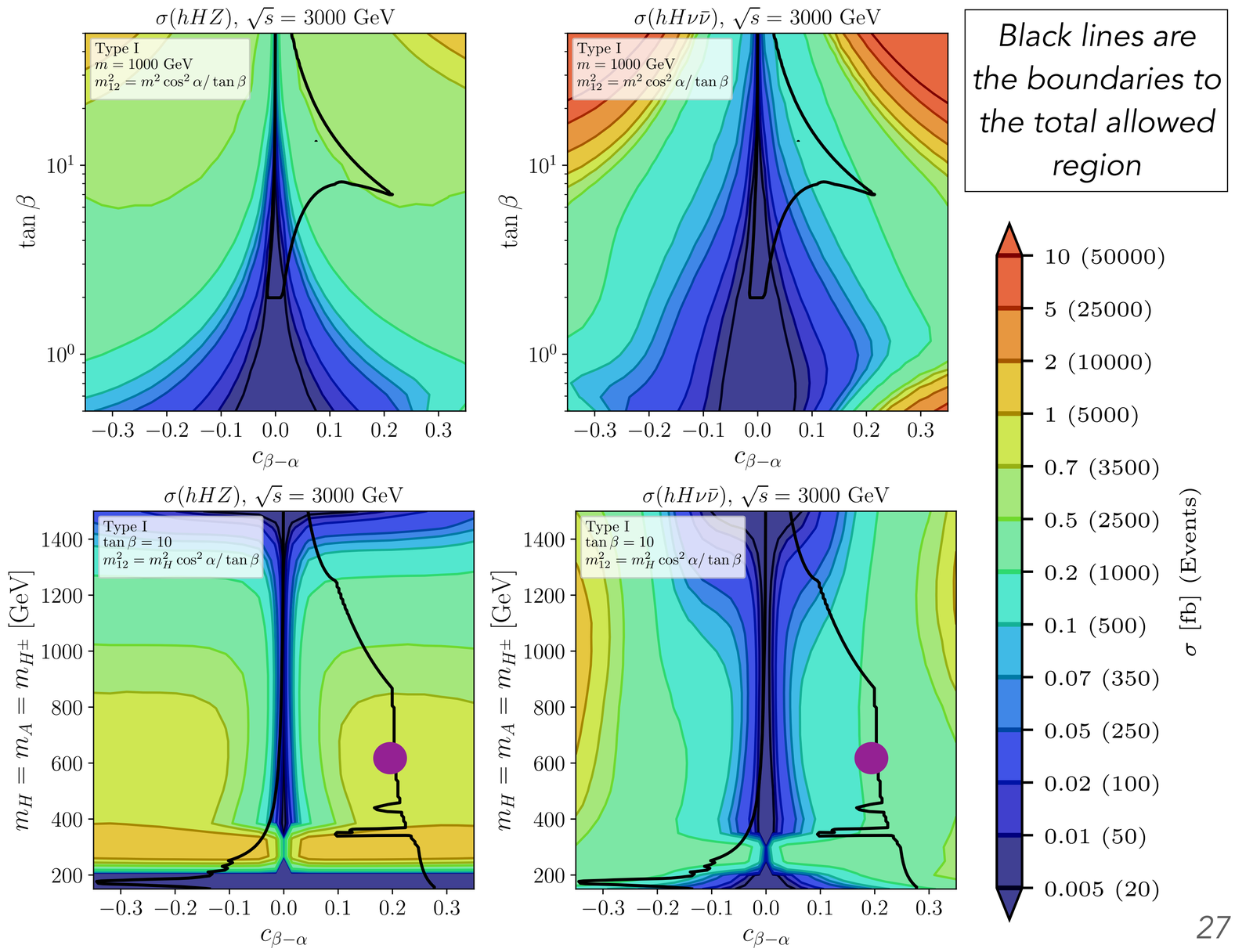


- Height of the resonance depends on λ_{hhH}
- For large $c_{\beta-\alpha}$ the resonance is wider because Γ_H is larger

$\lambda_{hhH} > 0$:	$\lambda_{hhH} < 0$:
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)

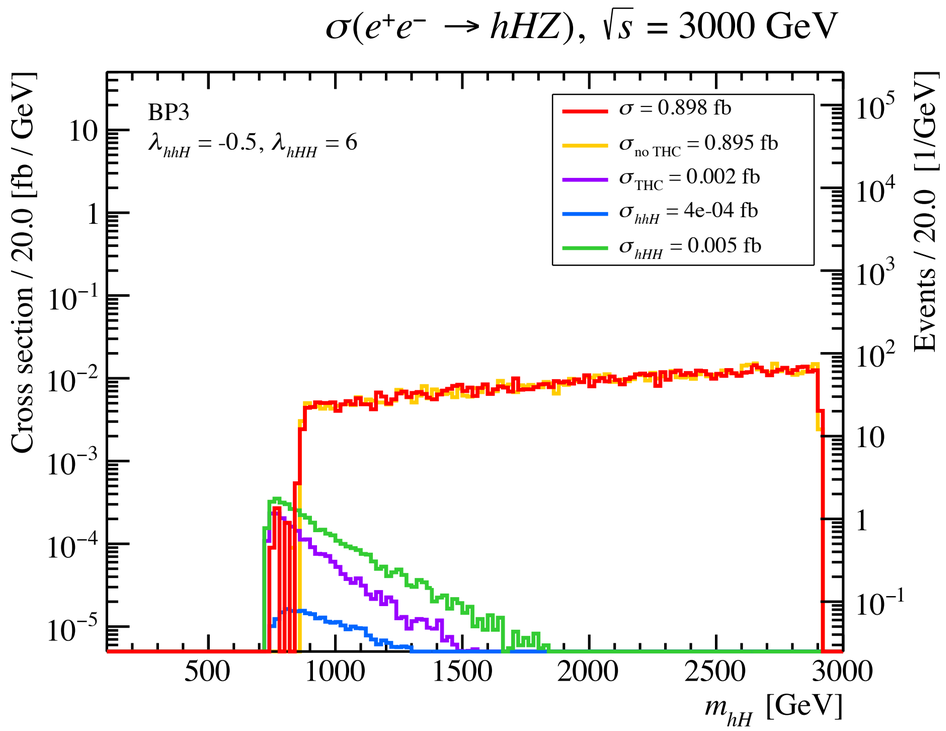
- The hH production channels disappear in the alignment limit
- Very strong contribution from resonant A diagrams in the hHZ channel
- In the neutrino channel, the effects from A mediated diagrams mixes with the effects coming from the THC (for this process: λ_{hhH} and λ_{hHH})

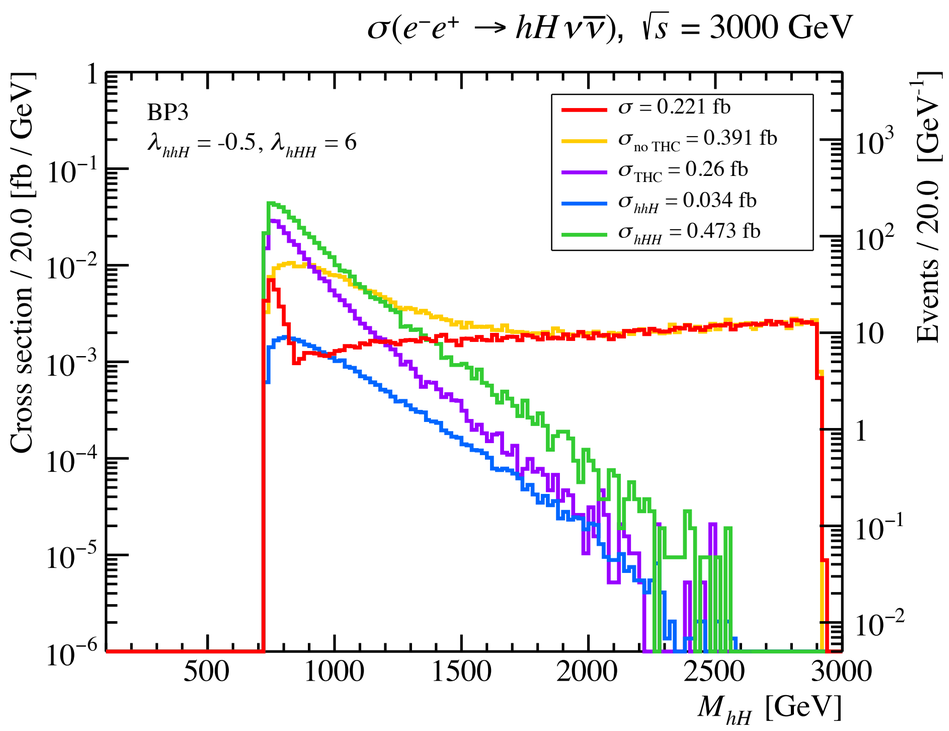


Black lines are the boundaries to the total allowed region

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