Access to Triple Higgs Couplings in the 2HDM with CLIC

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Based on arXiv2005.10576 and arXiv:2106.11105

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

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

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 !!!

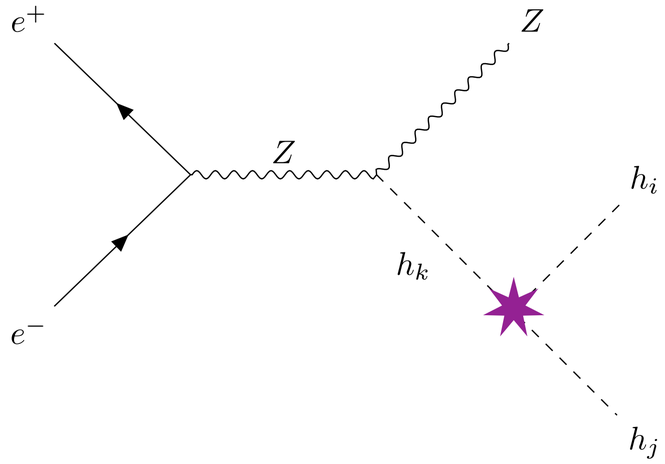
(More) motivation

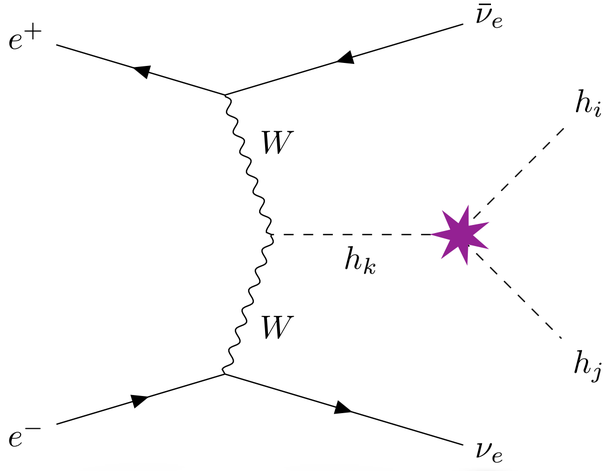
In the context of the 2HDM (type I and II), triple Higgs couplings $\lambda_{h_i h_j h_k}$, can be large while respecting all the relevant constraints (*Eur.Phys.J.C 80 (2020) 9, 884,* [arXiv2005.10576])

↓

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

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





The Two Higgs Doublet Model (2HDM)

Adding a second Higgs doublet to the SM $\Longrightarrow$ 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, $m_{H^\pm}$, $\tan\beta := v_2/v_1$, $\cos(\beta-\alpha) \equiv c_{\beta-\alpha}$ and m_{12}^2

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

Constraints

T parameter (2HDMC): Motivates degenerate masses.

In this work $m_H = m_A = m_{H^\pm} \equiv m$

Theoretical constraints: Tree level unitarity and potential stability.

$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$ helps to enlarge the allowed region (specially if $\tan\beta$ is large)

Collider Searches (HiggsBounds + 2HDMC)

125 GeV Higgs measurements at colliders

(HiggsSignals + 2HDMC): Allowed region within 2σ from the SM

$c_{\beta-\alpha}$ should be close to 0, specially for type II

new: inclusion of STXS to HiggsSignals

Flavor observables (superISO + corrections):

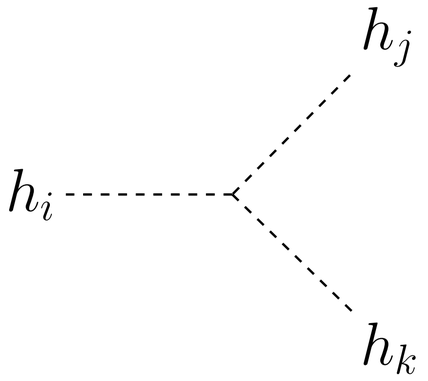
$B \to X_s\gamma$ and $B_s \to \mu\mu$ inside the 2σ region

They disallow regions of low $\tan\beta$ in both types (and also very large $\tan\beta$ in type II) and $m_{H^\pm} \gtrsim 600\ \mathrm{GeV}$ in type II

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

Triple Higgs couplings (THC)

Definition:



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

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

n is the number of identical particles

with this definition

$\lambda_{hhh} = \lambda_{hhh}^{\rm SM} = \dfrac{m_h^2}{2v^2}$ *in the alignment limit*

In [arXiv2005.10576] we found the following allowed ranges to the THC:

Type I	Type II
$\kappa_\lambda \in [-0.5,\ 1.5]$	$\kappa_\lambda \in [0.0,\ 1.0]$
$\lambda_{hhH} \in [-1.4,\ 1.5]$	$\lambda_{hhH} \in [-1.6,\ 1.8]$
$\lambda_{hHH} \in [0,\ 15]$	$\lambda_{hHH} \in [0,\ 15]$
$\lambda_{hAA} \in [0,\ 16]$	$\lambda_{hAA} \in [0,\ 16]$
$\lambda_{hH^+H^-} \in [0,\ 32]$	$\lambda_{hH^+H^-} \in [0,\ 32]$

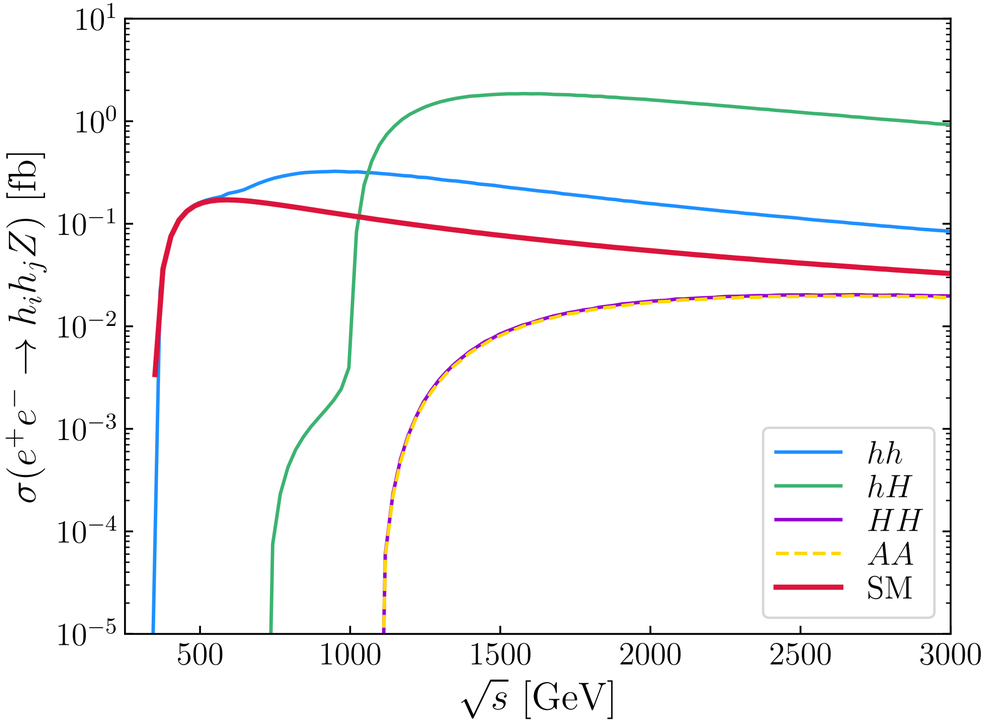
In the alignment limit ($c_{\beta-\alpha} \to 0$):

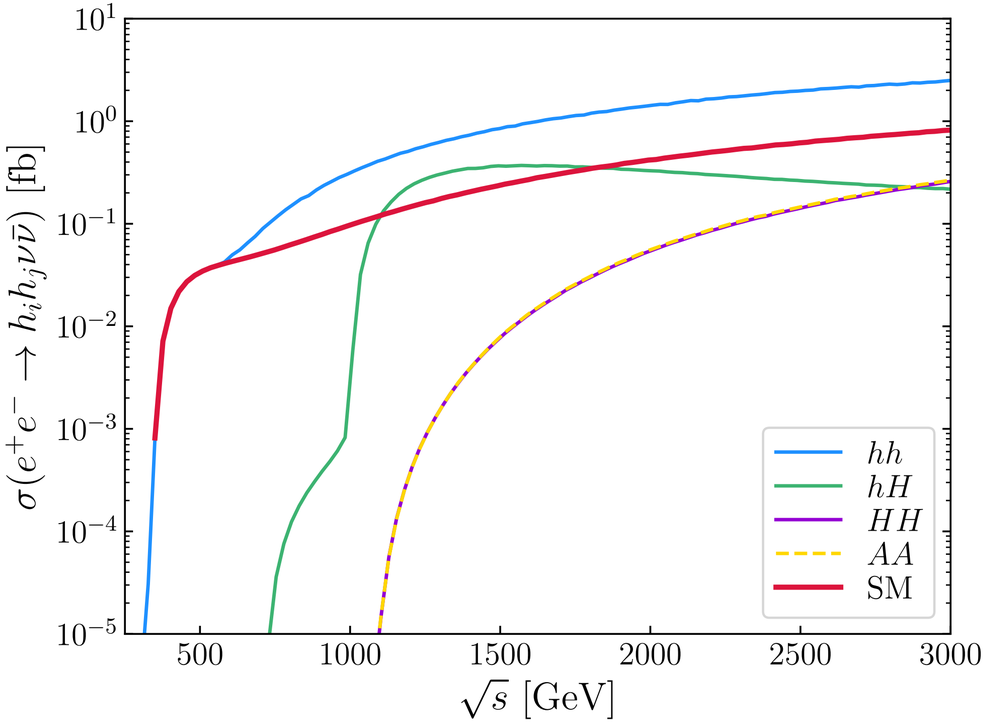
$\kappa_\lambda \to 1$, $\lambda_{hhH} \to 0$ but $\lambda_{hHH}, \lambda_{hAA}, \lambda_{hH^+H^-} \neq 0$

Disclaimer! Type II was affected more by the inclusion of the STXS observables ($|c_{\beta-\alpha}| < 0.05$)

$\Longrightarrow$ The allowed regions for κ_λ and λ_{hhH} are much smaller.

$h_i h_j$ production in e^+e^-: energy dependence





Type I

$m = 500$ GeV

$\tan\beta = 10$

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

$m_{12}^2 = 24000$ GeV^2

$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{SM} \simeq 1$

(numerical cancelation)

$\lambda_{hhH} = -0.5$

$\lambda_{hHH} = \lambda_{hAA} = 6$

$\lambda_{hH^+H^-} = 12$

Z channel → decreases with the energy

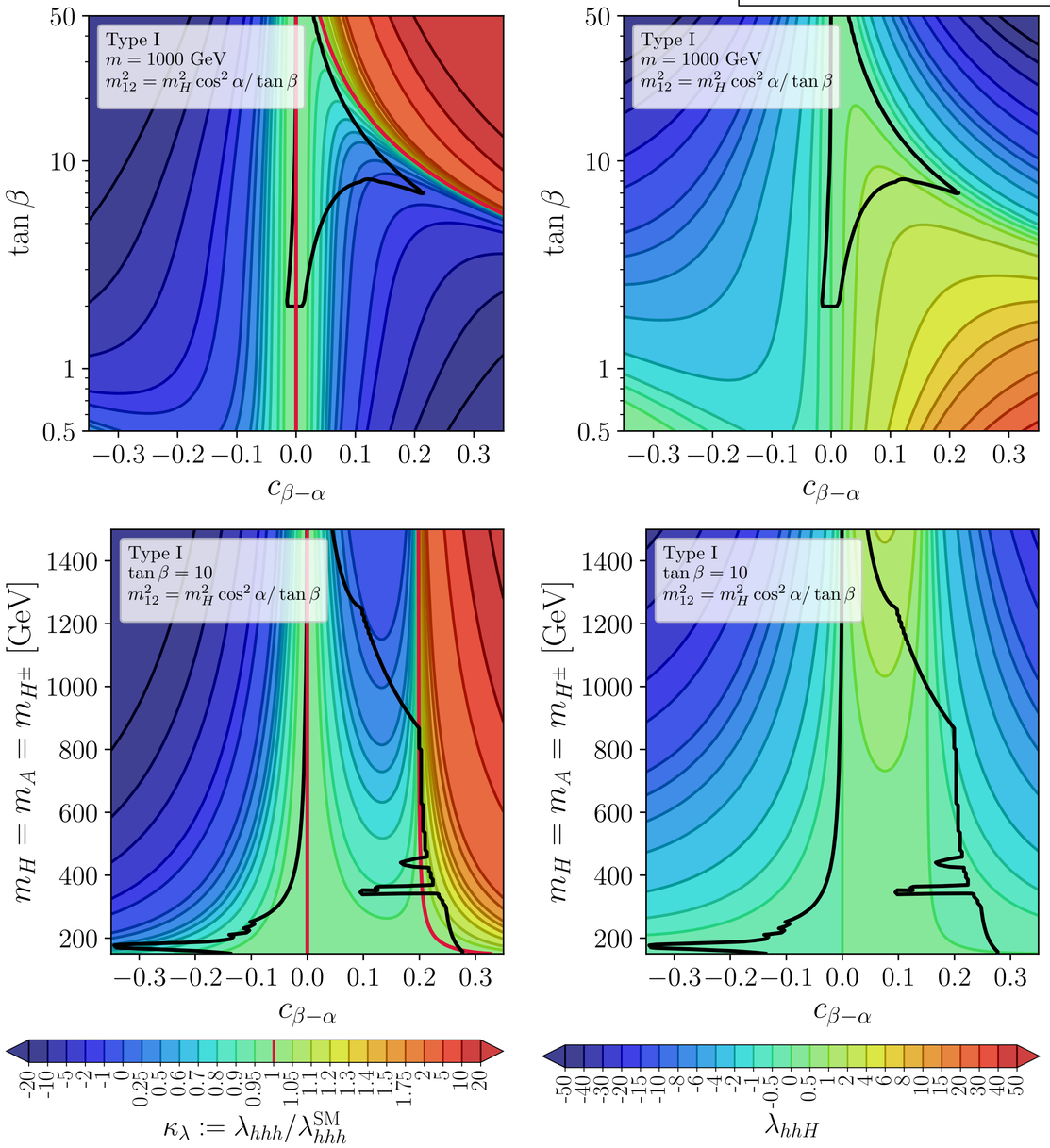
$\nu\bar{\nu}$ channel → increases with the energy (VBF topologies!)

- hhZ and $hh\nu\bar{\nu}$: ~3 times the SM due to 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
- $HH\nu\bar{\nu} \sim AA\nu\bar{\nu}$: dominated by λ_{hHH} (λ_{hAA}) if it is large enough (we have $m_H = m_A$)

Methodology

Black lines are the boundaries to the total allowed region

- 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 $m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$ (upper plots)
  - Plane $c_{\beta-\alpha} - m$: Type I with $\tan\beta = 10$ and $m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$ (lower plots)
  - 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 $c_{\beta-\alpha} = 0.02$
- Large deviations from $\kappa_\lambda = 1$ far from the alignment limit and larger values of λ_{hhH} around $c_{\beta-\alpha} \sim 0.1$



Methodology (II)

- Access to THC via XS distributions on the **invariant mass of the final** $h_i h_j$
  - We include **ALL** diagrams in the computation (i.e. resonant and non-resonant, no Narrow Width Approximation is used)
- We studied effects from THC in $m_{h_i h_j}$ for 5 benchmark points (BP) with a wide range of BSM Higgs masses
- For the non-resonant diagrams with THC the larger effects appear at low $m_{h_i h_j}$
- In the case of the sensitivity to λ_{hhH} at hh production we propose a theoretical estimator from 4-bjets events (discussed later)

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

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

MadGraph, FeynRules, 2HDMC and ROOT were used

hh production

Three main effects:

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})

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

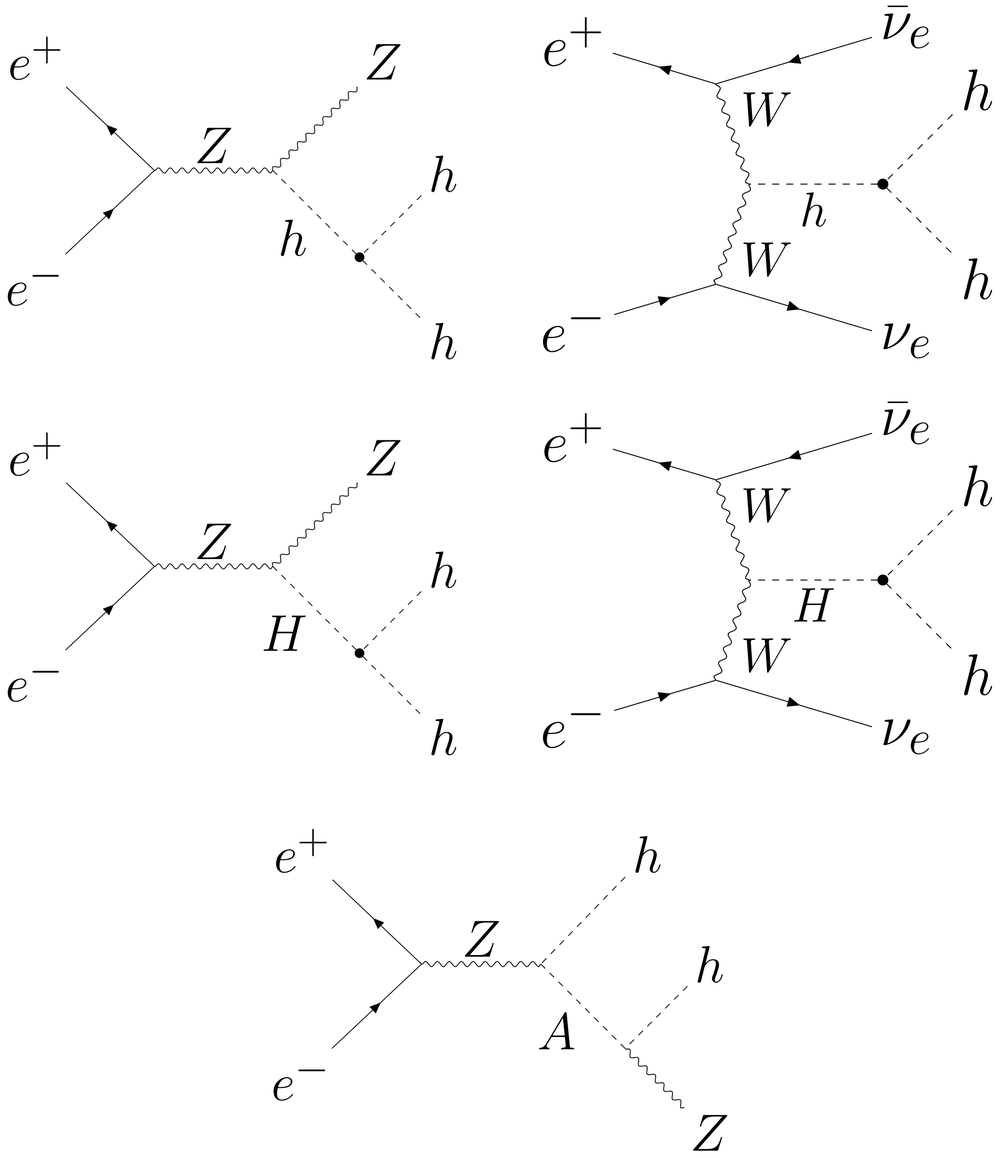
   $e^+e^- \to H^*\nu_e\bar{\nu}_e \to hh\nu_e\bar{\nu}_e$

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)

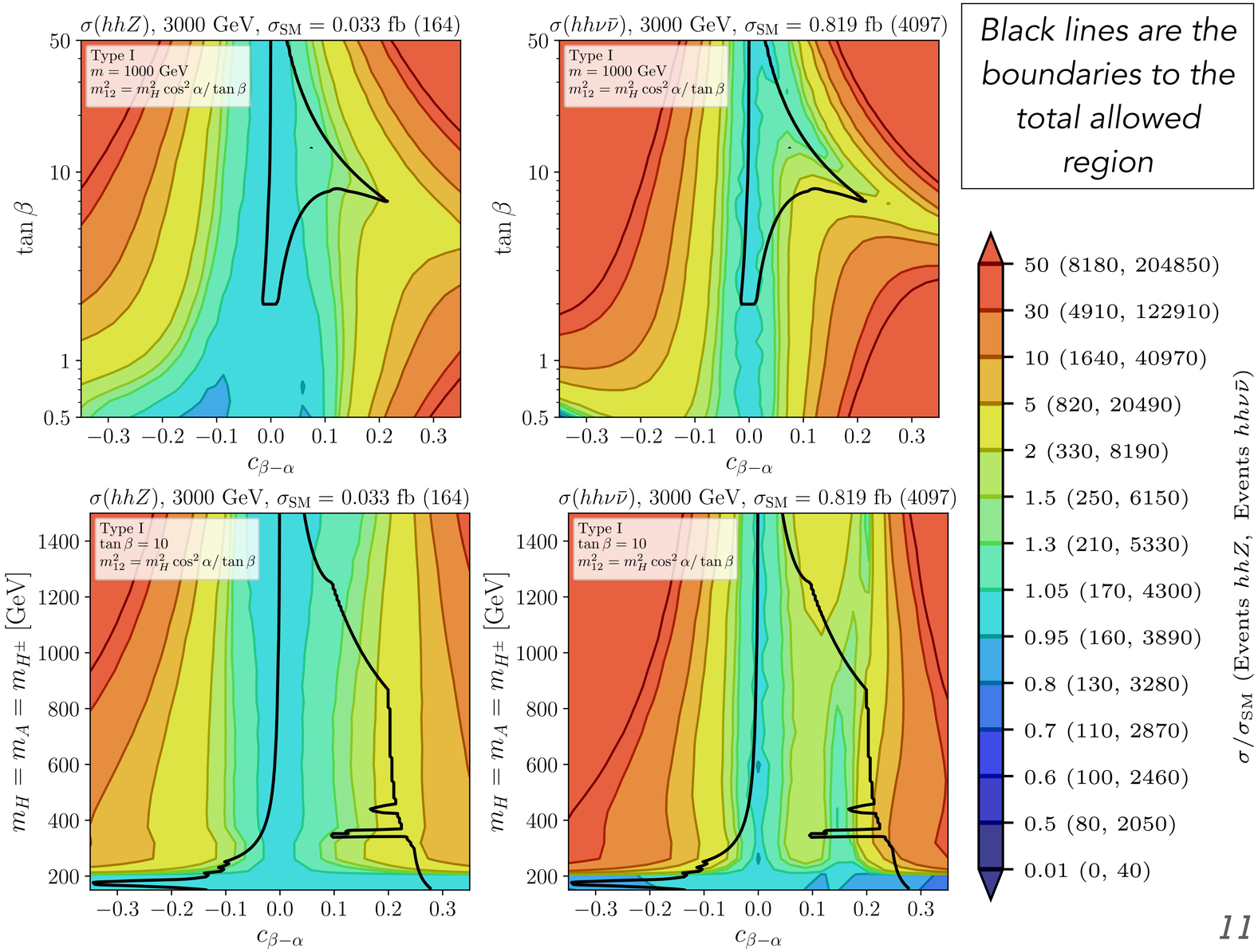
If $c_{\beta-\alpha} = 0$ we recover the SM prediction



diagrams with a final Z also enters in the neutrino channel with $Z \to \nu\bar{\nu}$

hh production, CLIC 3TeV (type I)

- At this energy, $hh\nu\bar{\nu}$ channel is the most important channel
  - hhZ: dominated by the A mediated diagrams
  - $hh\nu\bar{\nu}$: H mediated diagrams (with λ_{hhH}) are more important,
    $\sigma_{\text{2HDM}} \sim 10\sigma_{\text{SM}} = 9$ fb for low masses
- For both channels
  $\sigma_{\text{2HDM}} \sim 3\sigma_{\text{SM}}$ can be reach around $c_{\beta-\alpha} \sim 0.2$

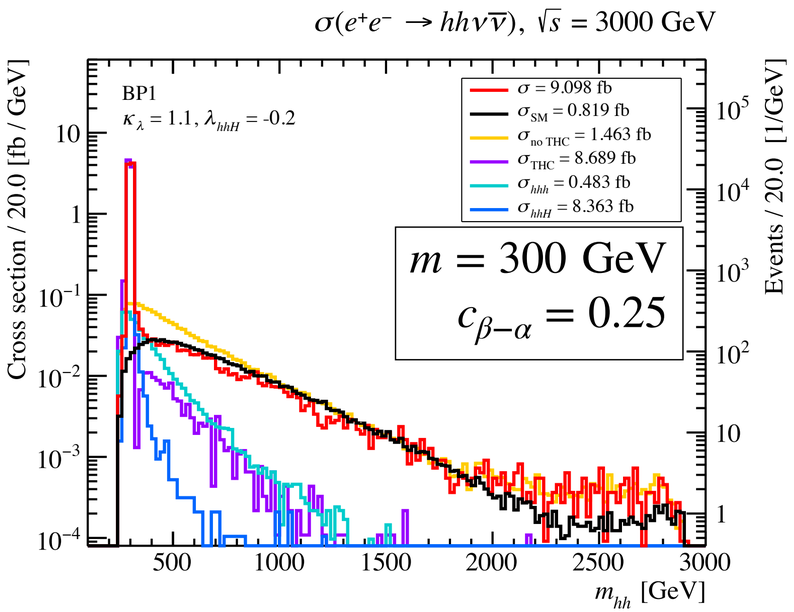


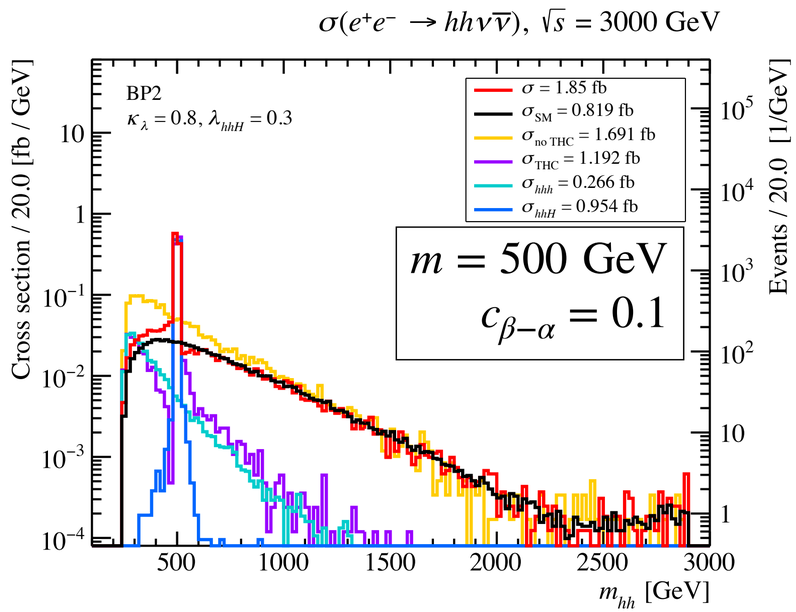
Black lines are the boundaries to the total allowed region

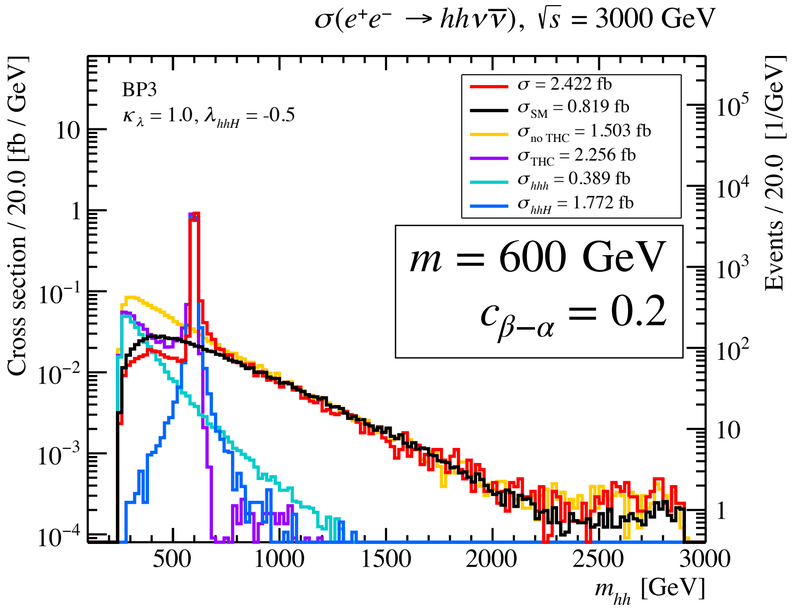
hh production, CLIC 3TeV, THC dependence (type I)

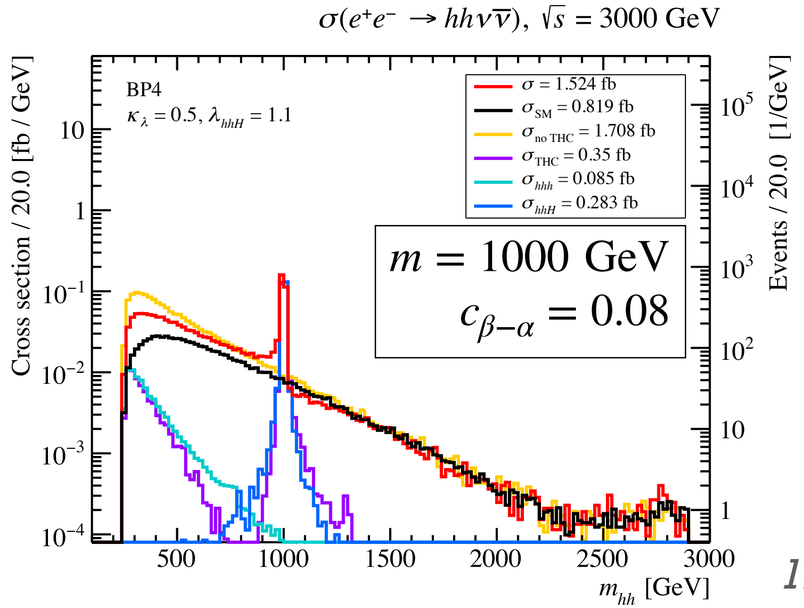
Cross section distribution on the invariant mass of hh for 4 benchmark points:

- The effect of κ_λ appear at the region of low invariant mass
- $hh\nu\bar{\nu}$ can give 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
- ***Question:*** Which resolution in m_{hh} do you expect to reach at CLIC?





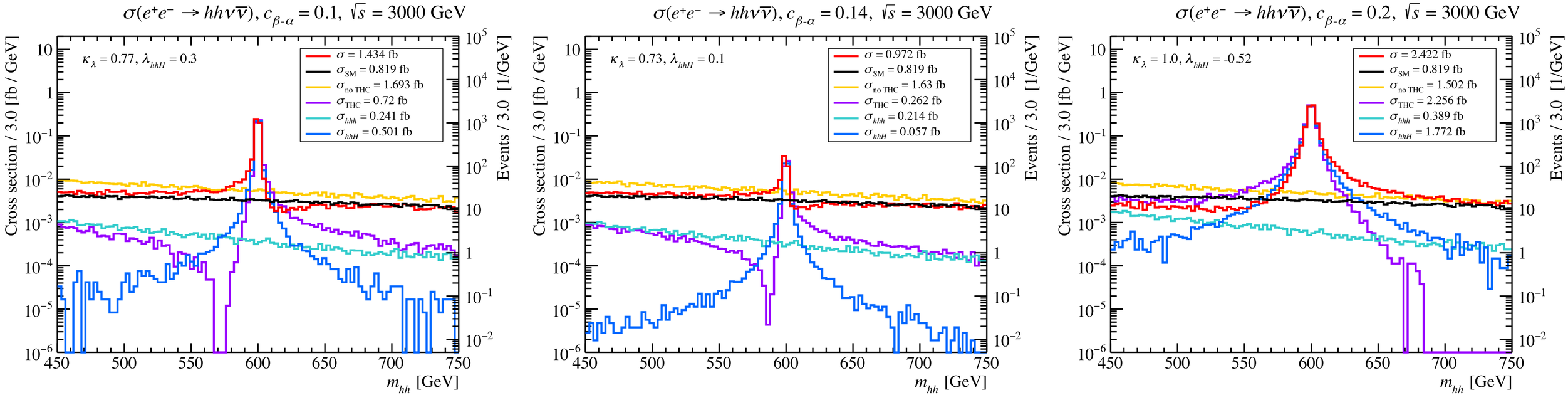




Sensitivity to $c_{\beta-\alpha}$ in the resonant region (type I)

Evolution of the H resonance with $c_{\beta-\alpha}$ (and with λ_{hhH}) in BP3

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

$\lambda_{hhH} > 0$:
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

4-bjets events from 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 4-bjets final 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, $\mathscr{A} = N_{\text{cuts}}/N_{\text{no cuts}}$ is the acceptance of the collider and $\epsilon_b \sim 0.8$ the b-tagging efficiency

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

λ_{hhH} "sensitivity" at hhZ from 4-bjet events (type I)

R_{4bZ} ratio: reconstruction of 4 b jets and a Z boson

- As expected, $\bar{N}^{R,C}$ decreases with the collider energy
- Only BP1 shows sensitivity to λ_{hhH} for ILC 500GeV and ILC 1TeV (larger at 1 TeV)
- 20-30 realistic events at the H peak are expected for BP2 and BP1 at 1 TeV and for BP3 at 1.5 TeV

hhZ	$\sqrt{s}$ [GeV]	$\sigma_{\rm 2HDM}$ / $\sigma_{\rm SM}$ [fb]	$\bar{N}^{R}_{4bZ}$ / $\bar{N}^{C}_{4bZ}$ / $\bar{N}^{\rm SM}_{4bZ}$	$\mathcal{A}_{\rm 2HDM}$/ $\mathcal{A}_{\rm SM}$	R_{4bZ}
BP1	500	1.063 / 0.158	193 / 10 / 3	0.70 / 0.68	58
	1000	0.913 / 0.120	206 / 1 / 4	0.70 / 0.71	205
	1500	0.493 / 0.077	22 / <1 / 1	0.51 / 0.62	-
	3000	0.147 / 0.033	1 / <1 / <1	0.05 / 0.05	-
BP2	1000	0.156 / 0.120	20 / 1 / 1	0.73 / 0.71	19
	1500	0.106 / 0.077	4 / <1 / <1	0.65 / 0.62	-
	3000	0.042 / 0.033	<1 / <1 / <1	0.07 / 0.05	-
BP3	1000	0.254 / 0.120	29 / 5 / 2	0.71 / 0.71	11
	1500	0.218 / 0.077	8 / 1 / <1	0.70 / 0.62	7
	3000	0.086 / 0.033	1 / <1 / <1	0.08 / 0.05	-
BP4	1500	0.075 / 0.077	1 / <1 / <1	0.64 / 0.62	-
	3000	0.038 / 0.033	<1 / <1 / <1	0.07 / 0.05	-

λ_{hhH} "sensitivity" at $hh\nu\bar{\nu}$ from 4-bjet events (type I)

$R_{4b\not{E}_T}$ ratio: reconstruction of 4 b jets and missing energy from the neutrinos

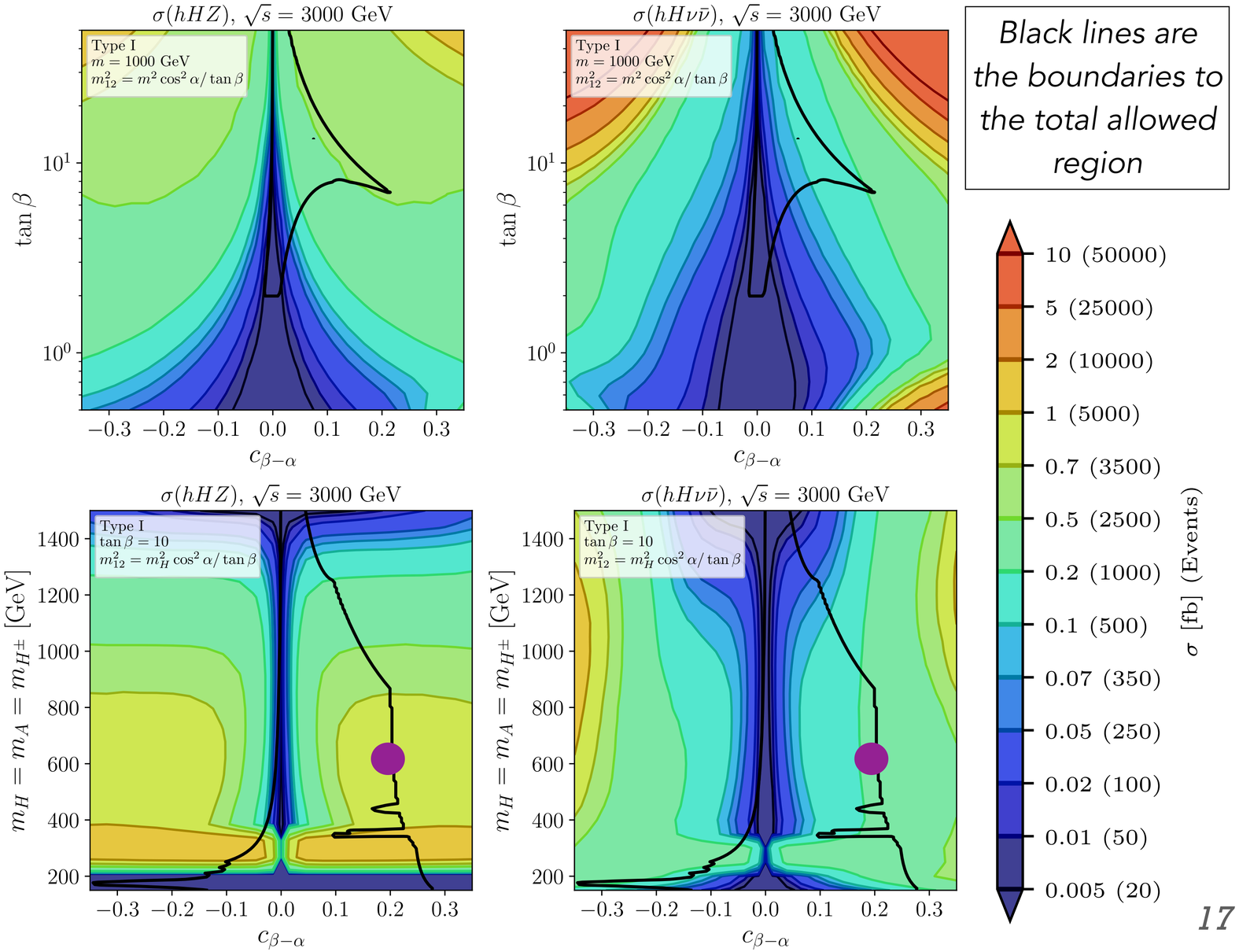
- Now, $\bar{N}^{R,C}$ increases with the collider energy
- Much larger $R_{4b\not{E}_T}$ is found for all BP's (except BP1 at ILC 500GeV)
  - High sensitivity to λ_{hhH} at all BP's and energies (except at BP4 at CLIC 1.5TeV)

$hh\nu\bar{\nu}$	$\sqrt{s}$ [GeV]	$\sigma_{\rm 2HDM}$ / $\sigma_{\rm SM}$ [fb]	$\bar{N}^R_{4b\not{E}_T}$ / $\bar{N}^C_{4b\not{E}_T}$ / $\bar{N}^{\rm SM}_{4b\not{E}_T}$	$\mathcal{A}_{\rm 2HDM}$/ $\mathcal{A}_{\rm SM}$	$R_{4b\not{E}_T}$
BP1	500	0.404 / 0.034	119 / 4 / 1	0.70 / 0.68	58
	1000	2.391 / 0.097	1510 / 24 / 0	0.65 / 0.55	303
	1500	4.423 / 0.239	794 / 13 / 2	0.58 / 0.41	217
	3000	9.098 / 0.819	2425 / 46 / 6	0.44 / 0.25	351
BP2	1000	0.234 / 0.097	79 / 3 / 1	0.65 / 0.55	44
	1500	0.625 / 0.239	70 / 3 / 1	0.56 / 0.41	39
	3000	1.850 / 0.819	282 / 28 / 9	0.41 / 0.25	48
BP3	1000	0.208 / 0.097	85 / 5 / 3	0.66 / 0.55	36
	1500	0.709 / 0.239	111 / 5 / 3	0.61 / 0.41	47
	3000	2.422 / 0.819	577 / 30 / 11	0.47 / 0.25	100
BP4	1500	0.428 / 0.239	4 / <1 / <1	0.50 / 0.41	-
	3000	1.523 / 0.819	72 / 4 / 3	0.38 / 0.25	34

- Sometimes, the number of events is smaller at CLIC 1.5 TeV than at ILC 1TeV due to the different luminosities ($2.5\ \text{ab}^{-1}$ vs $8\ \text{ab}^{-1}$)

hH production, CLIC 3TeV (type I)

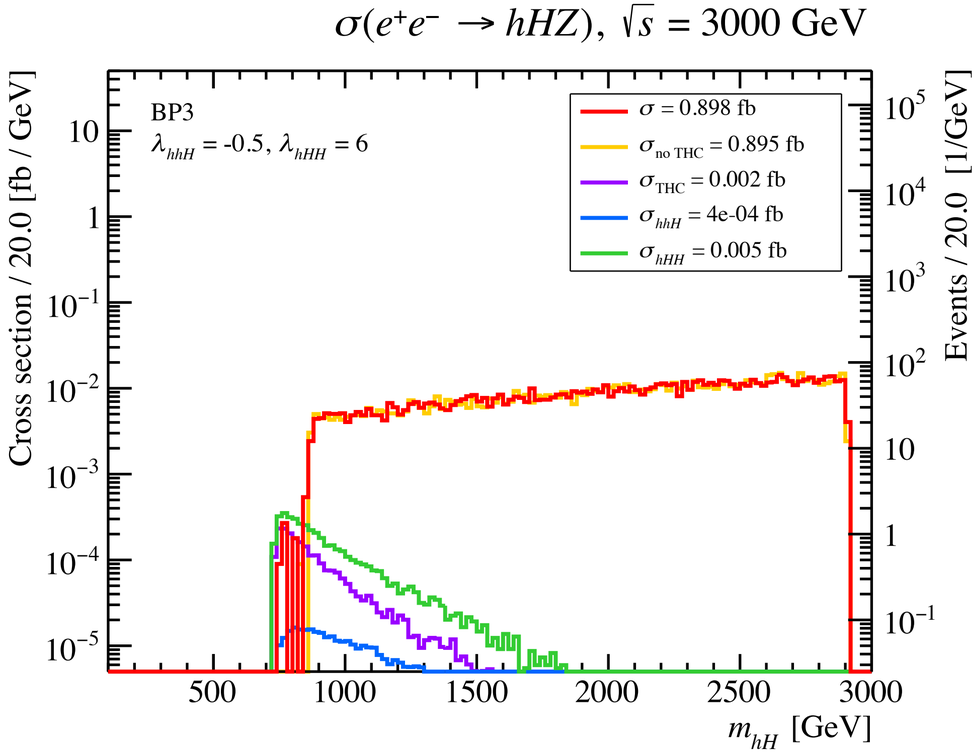
- The hH production channels disappear in the alignment limit
- Very strong contribution from resonant A diagrams in the hHZ channel
- In the neutrino channel, the effects from A mediated diagrams mixes with the effects coming from the THC (for this process: λ_{hhH} and λ_{hHH})

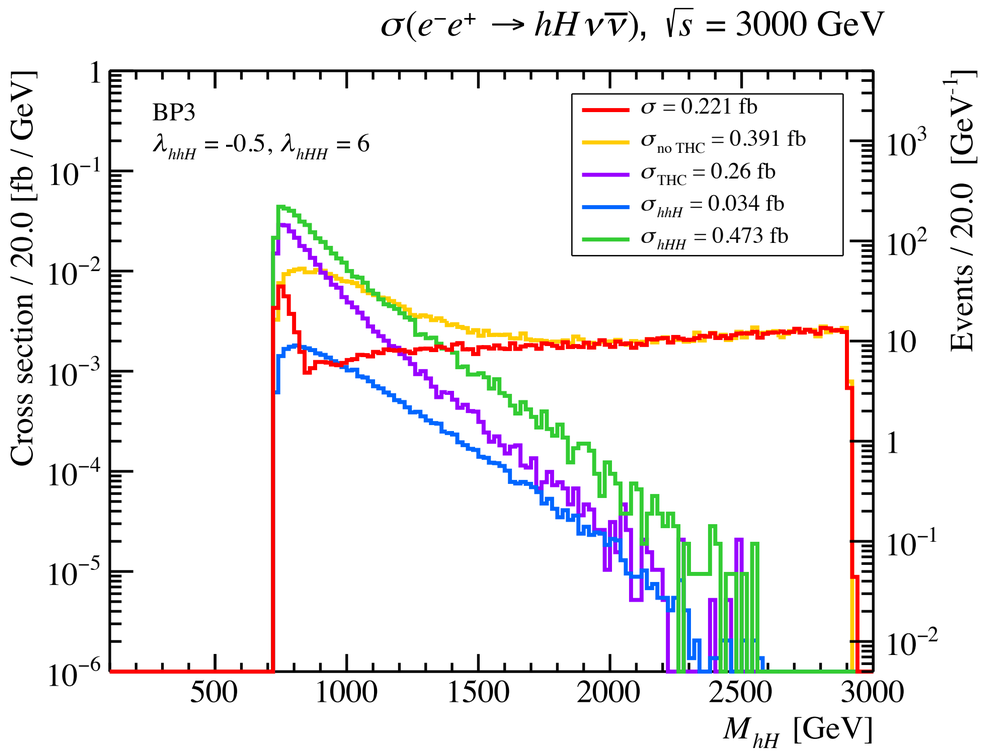


Black lines are the boundaries to the total allowed region

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

Cross section distribution on the invariant mass of hH:



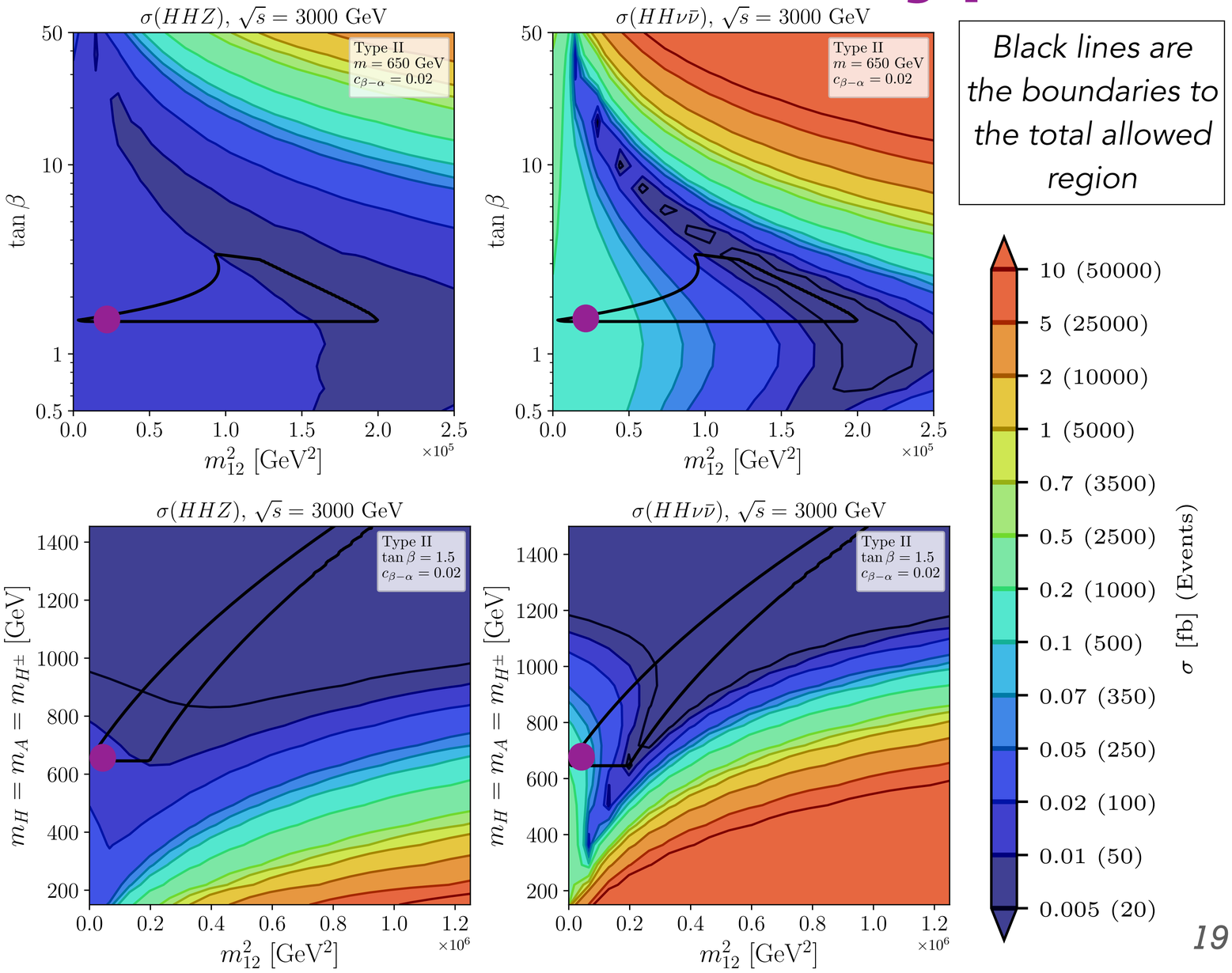


Type I
$m = 600$ GeV
$\tan\beta = 10$
$c_{\beta-\alpha} = 0.2$
$m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$

- 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

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

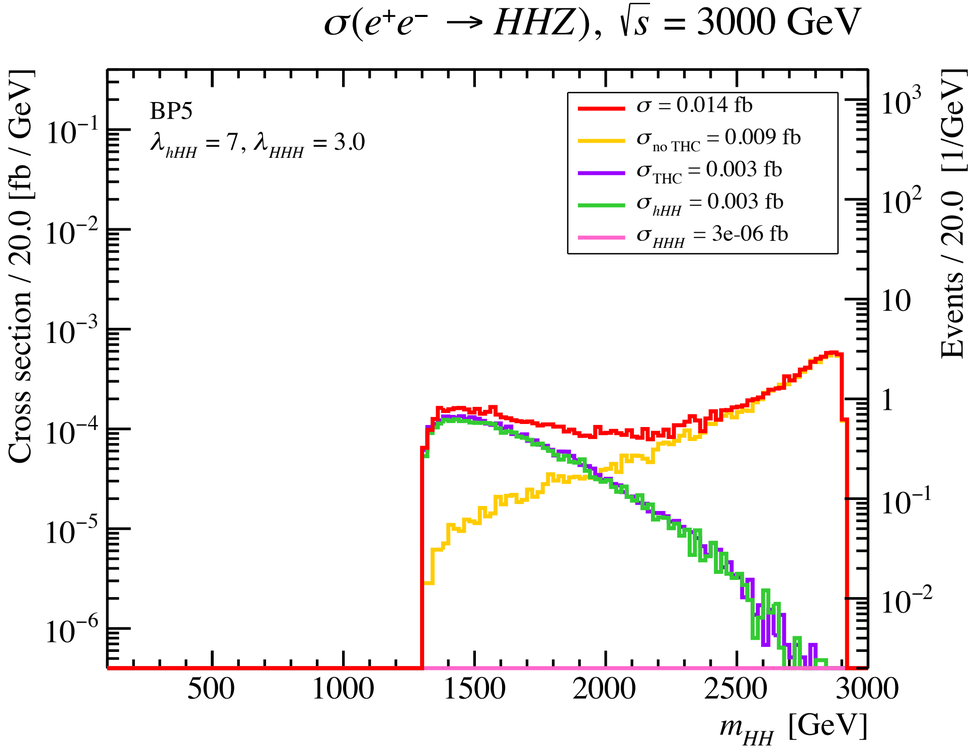
- In type II, due to the collider constraints, only $HH \sim AA$ production is relevant
- Only sizable XS, not larger than 0.5 fb, inside the allowed region for the neutrino channel
- Sizable XS comes from the effect of λ_{hHH} (λ_{hAA})
  - XS is larger at low m_{12}^2, that is the region where λ_{hHH}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

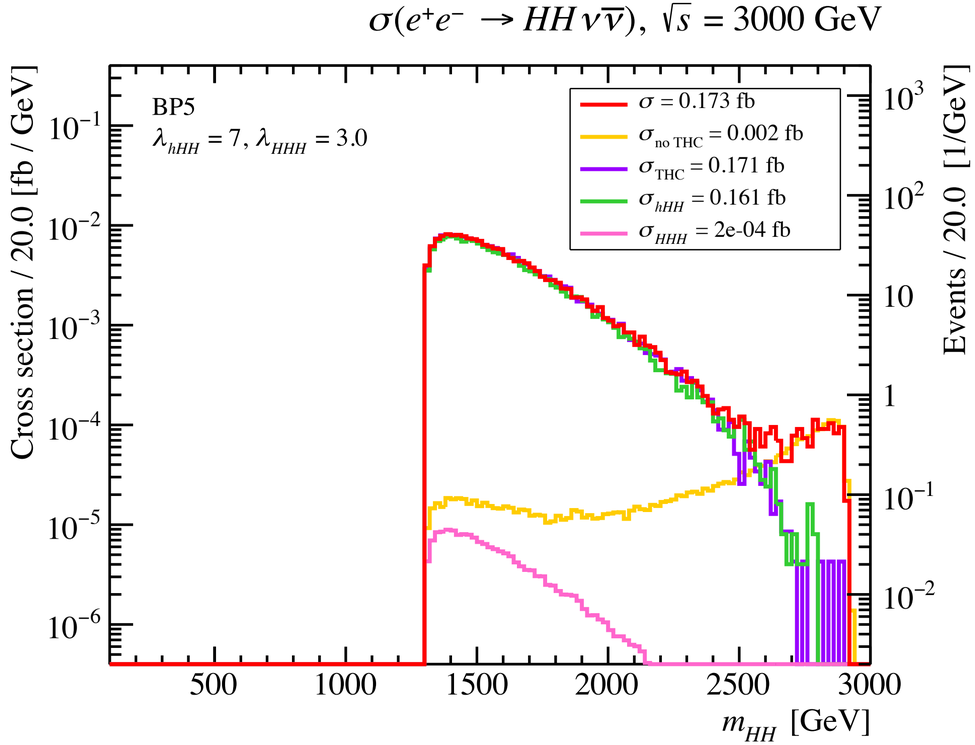


Black lines are the boundaries to the total allowed region

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

Cross section distribution on the invariant mass of HH:





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

- Very small XS and number of events in the HHZ channel
- The dominant effect in $HH\nu\bar{\nu}$ comes from λ_{hHH} and it is responsible for almost all the cross section
- In both type I and II, we will see a sizable XS in $HH\nu\bar{\nu}$ where λ_{hHH} can large (if m_H is light enough)

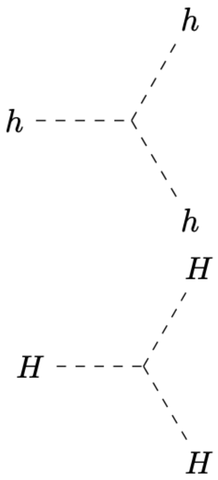
Summary & Conclusions

- The di-Higgs production of neutral Higgs bosons is studied at ILC and CLIC in the 2HDM
  - We propose to study the $m_{h_i h_j}$ invariant mass distributions to access the triple couplings (THC)
- **In hh production:**
  - κ_λ, at low invariant mass of the hh pair, similar to what happens in the SM (extensively studied in the literature)
  - λ_{hhH}, through a resonant peak due to the H boson and 4-bjets final events:
    - A realistic study shows that $hh\nu\bar{\nu}$ at CLIC (3TeV) provides the best access to λ_{hhH}
- **$hH\nu\bar{\nu}$ production** can display effects from λ_{hhH} and λ_{hHH} at large center-of-mass energies
- **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 H (A) is light enough to produce two of them)
- **CLIC (3TeV) + $h_i h_j \nu\bar{\nu}$** will be crucial to probe 2HDM Higgs couplings in the future

Thanks for your attention :)

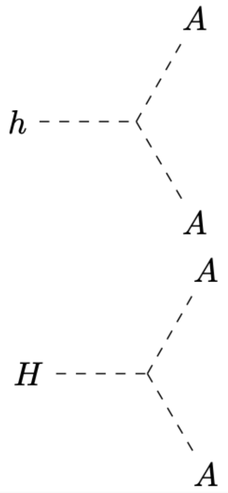
Questions??

Back-up, Feynman Rules with THC



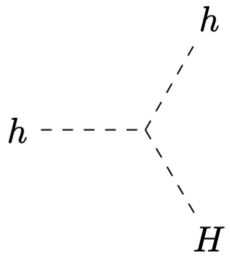
$$= -\frac{3i}{v}\left(2\cot 2\beta\left(m_h^2-\bar{m}^2\right)c_{\beta-\alpha}^3+\left(3m_h^2-2\bar{m}^2\right)c_{\beta-\alpha}^2 s_{\beta-\alpha}+m_h^2 s_{\beta-\alpha}^3\right)$$

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

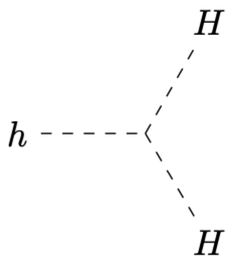


$$= -\frac{i}{v}\left(s_{\beta-\alpha}\left(-2\bar{m}^2+2m_A^2+m_h^2\right)+2\cot 2\beta\left(m_h^2-\bar{m}^2\right)c_{\beta-\alpha}\right)$$

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

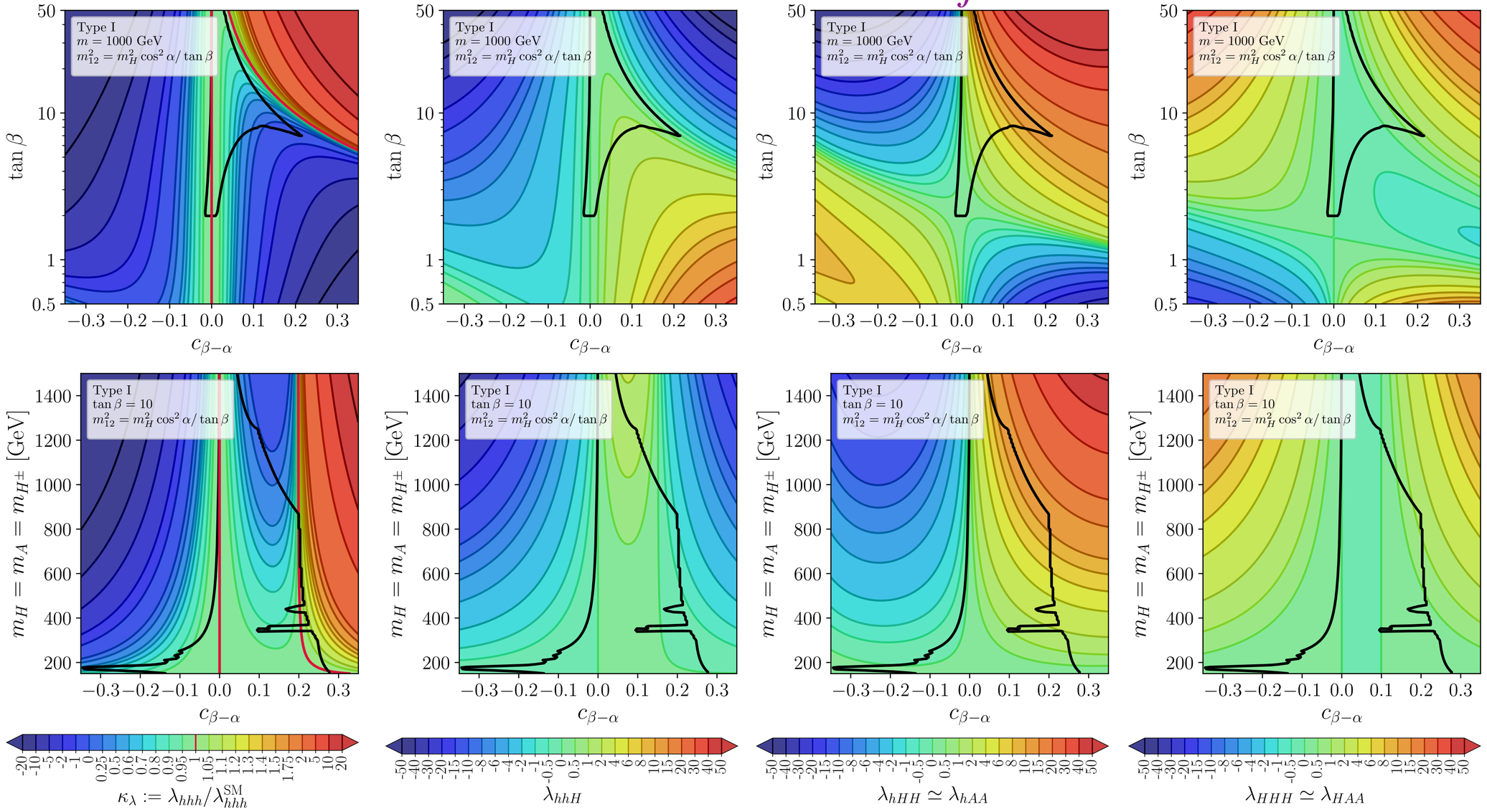


$$= \frac{ic_{\beta-\alpha}}{v}\left(2\bar{m}^2\left(c_{\beta-\alpha}^2-3\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}-2s_{\beta-\alpha}^2\right)+\left(2m_h^2+m_H^2\right)\left(-c_{\beta-\alpha}^2+2\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s_{\beta-\alpha}^2\right)\right)$$



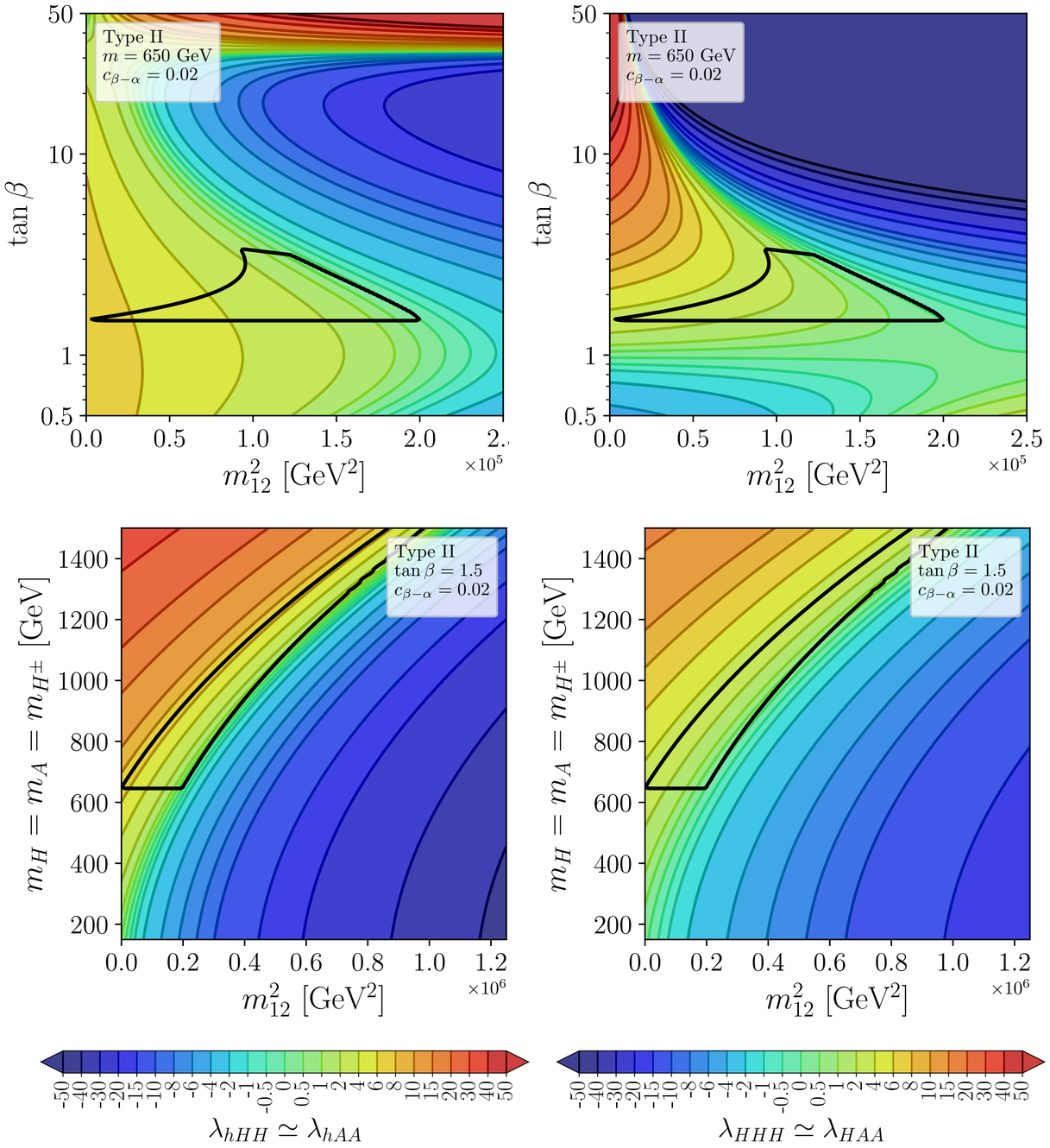
$$= -\frac{is_{\beta-\alpha}}{v}\left(\left(m_h^2+2m_H^2\right)\left(-c_{\beta-\alpha}^2+2\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s_{\beta-\alpha}^2\right)-2\bar{m}^2\left(-2c_{\beta-\alpha}^2+3\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s_{\beta-\alpha}^2\right)\right)$$

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



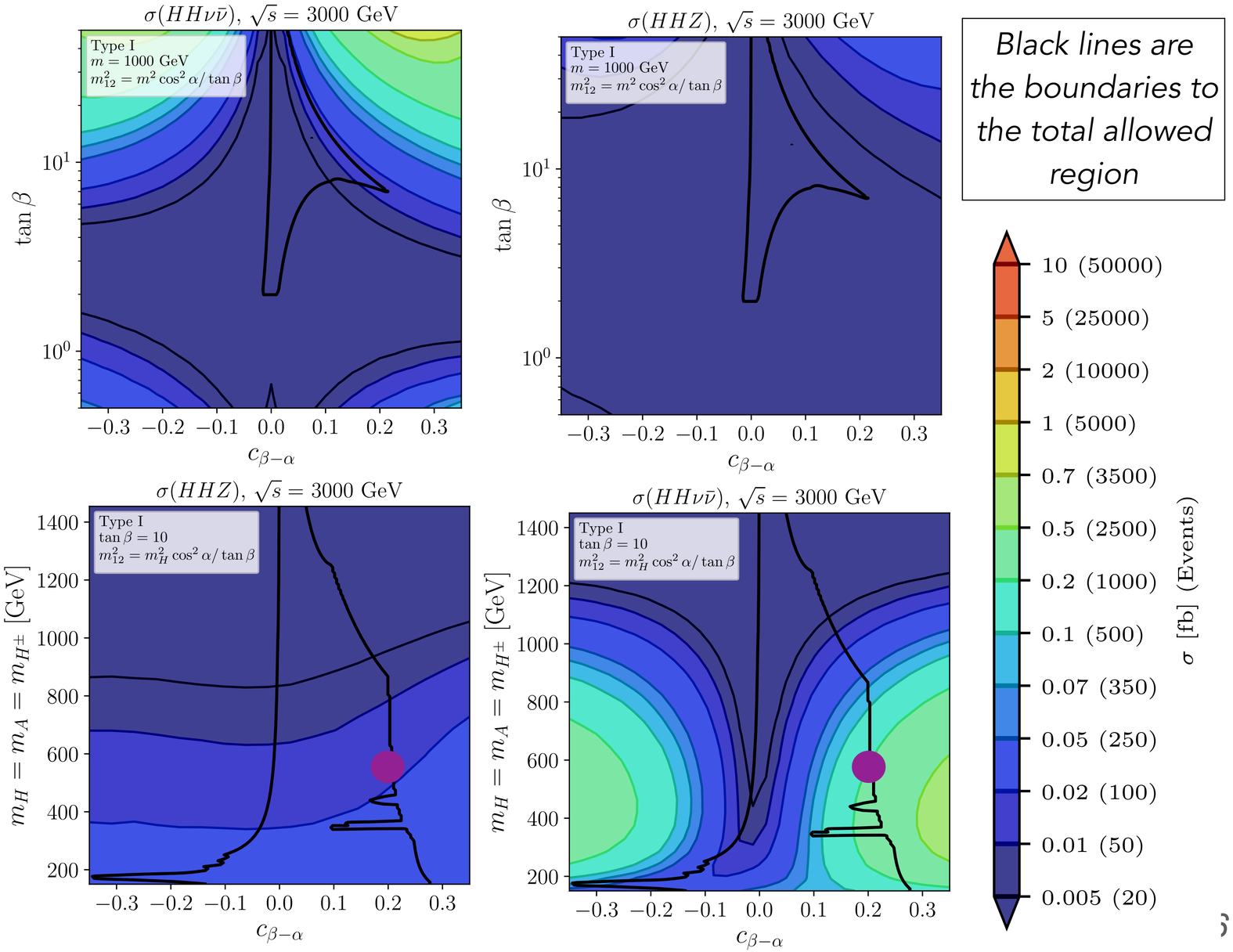
Back-up,

$\lambda_{h_i h_j h_k}$



$HH \sim AA$ production, CLIC 3TeV

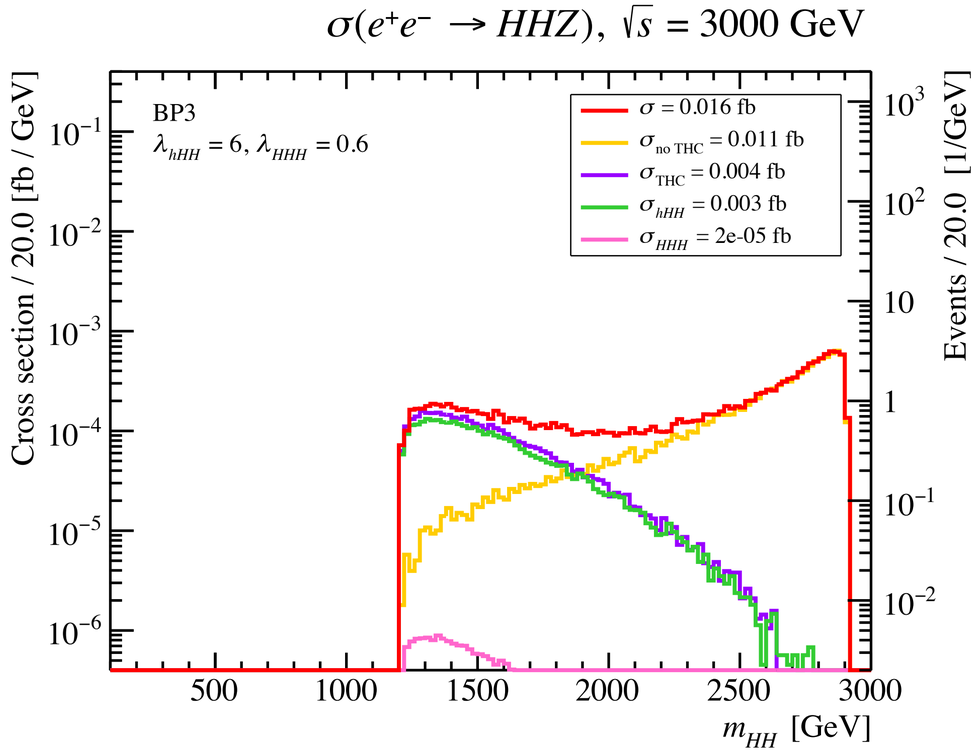
- The $HH \sim AA$ production can be non-zero even in the alignment limit ($c_{\beta-\alpha} \to 0$)
- Only sizable cross sections inside the allowed region for the neutrino channel
  - Not larger than 0.5 fb
- The sizable cross sections comes from the effect of λ_{hHH} (λ_{hAA})
  - Effects from λ_{HHH}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

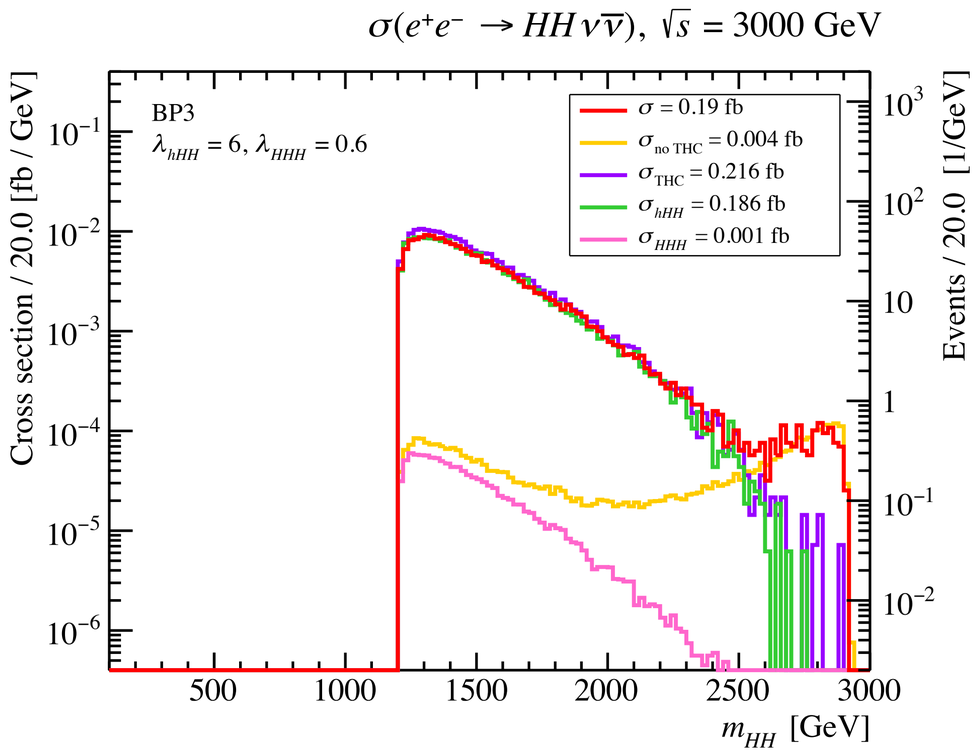


Black lines are the boundaries to the total allowed region

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

Cross section distribution on the invariant mass of HH:



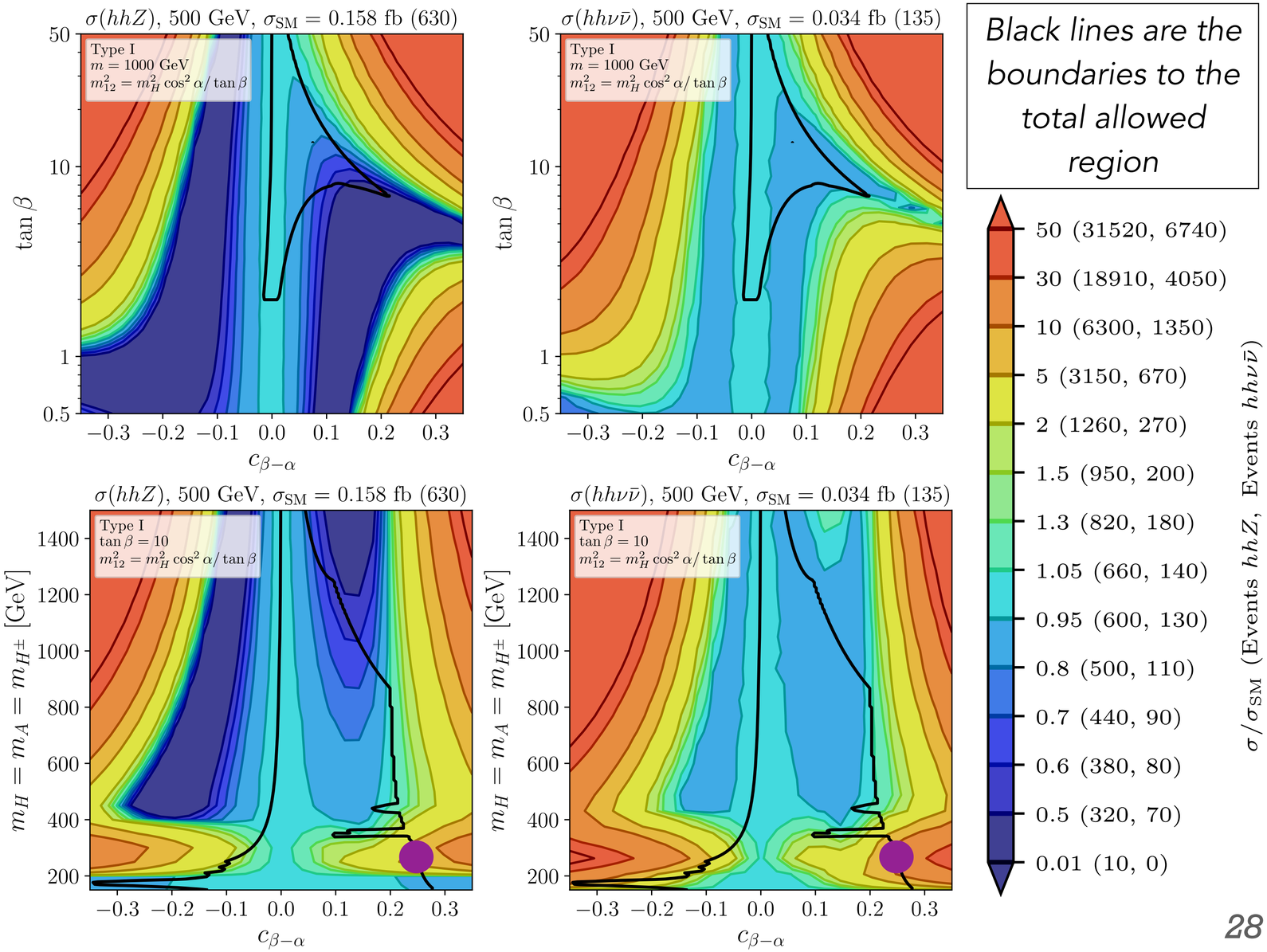


Type I
$m = 600$ GeV
$\tan\beta = 10$
$c_{\beta-\alpha} = 0.2$
$m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$

- 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

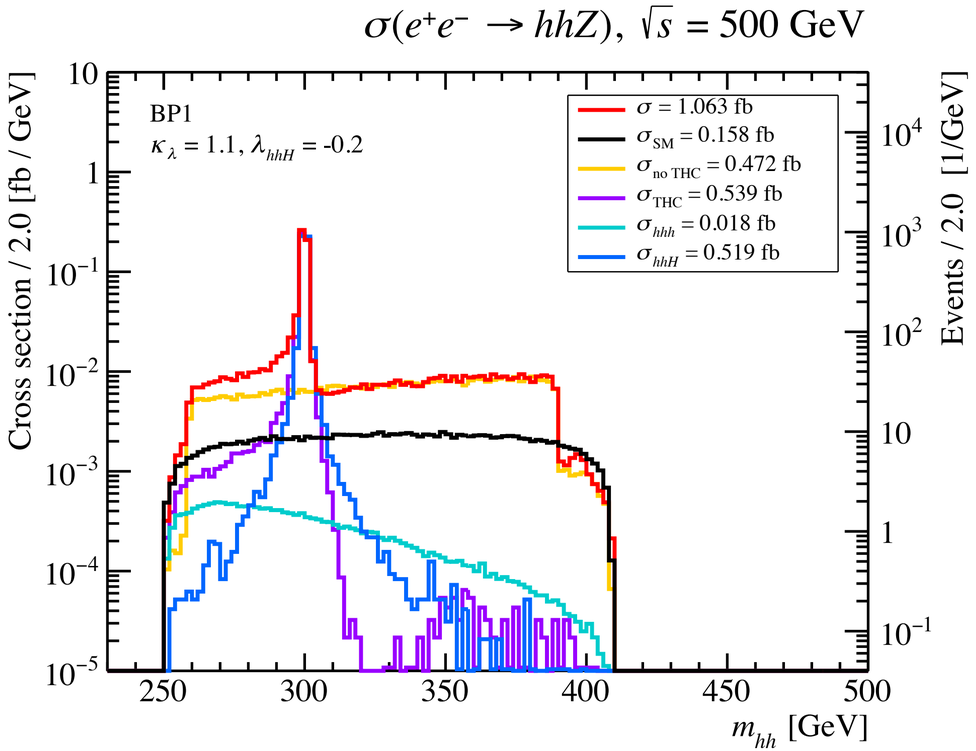
hh production, ILC 500GeV (type I)

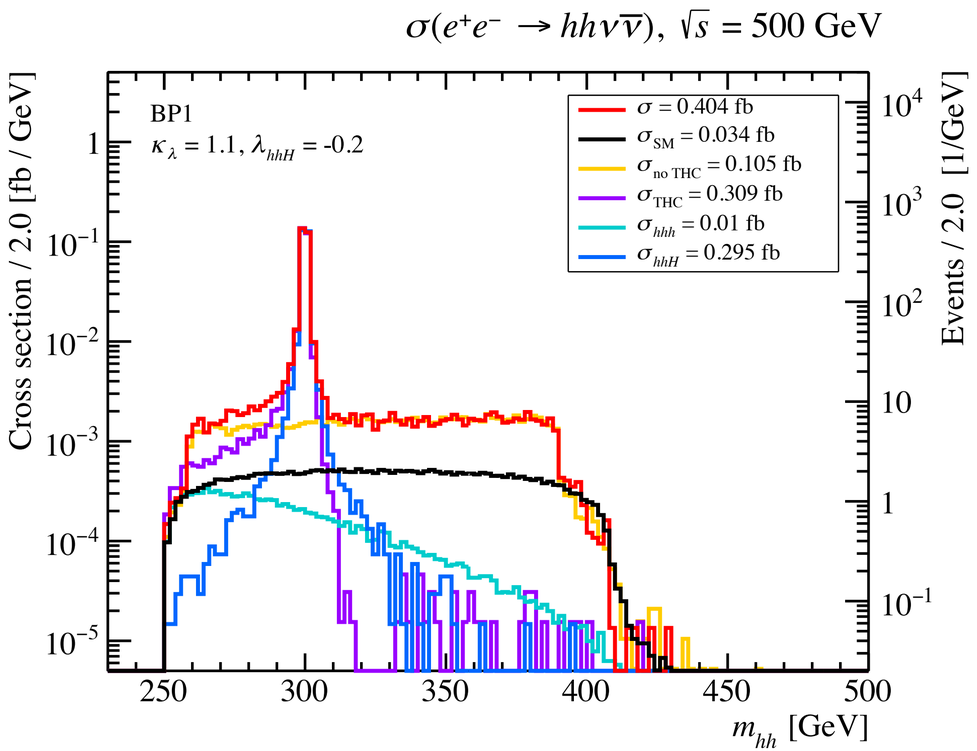
- At this energy, hhZ is the most important channel
- $c_{\beta-\alpha} - \tan\beta$ plane: H and A are too heavy $\Longrightarrow$ we see mainly the effect of κ_λ
- In the $c_{\beta-\alpha} - m$ plane, the H (λ_{hhH}) and A (no THC) resonances manifest for low masses
  - The enhancement wrt the SM in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



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

Cross section distribution on the invariant mass of hh:





Type I

$m = 300$ GeV

$\tan\beta = 10$

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

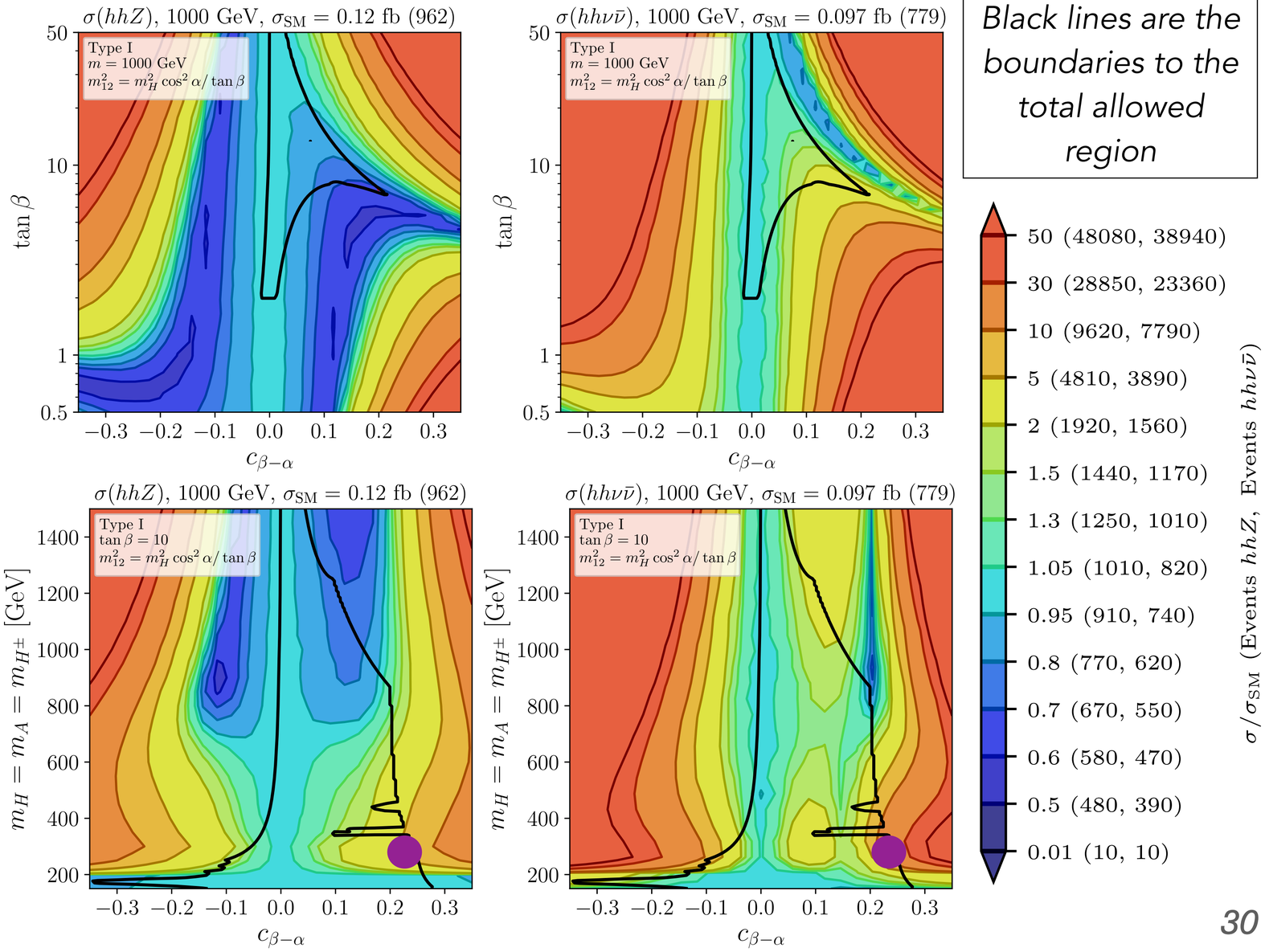
$$m_{12}^2 = \frac{m_H^2 \cos^2\alpha}{\tan\beta}$$

- 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, ILC 1TeV (type I)

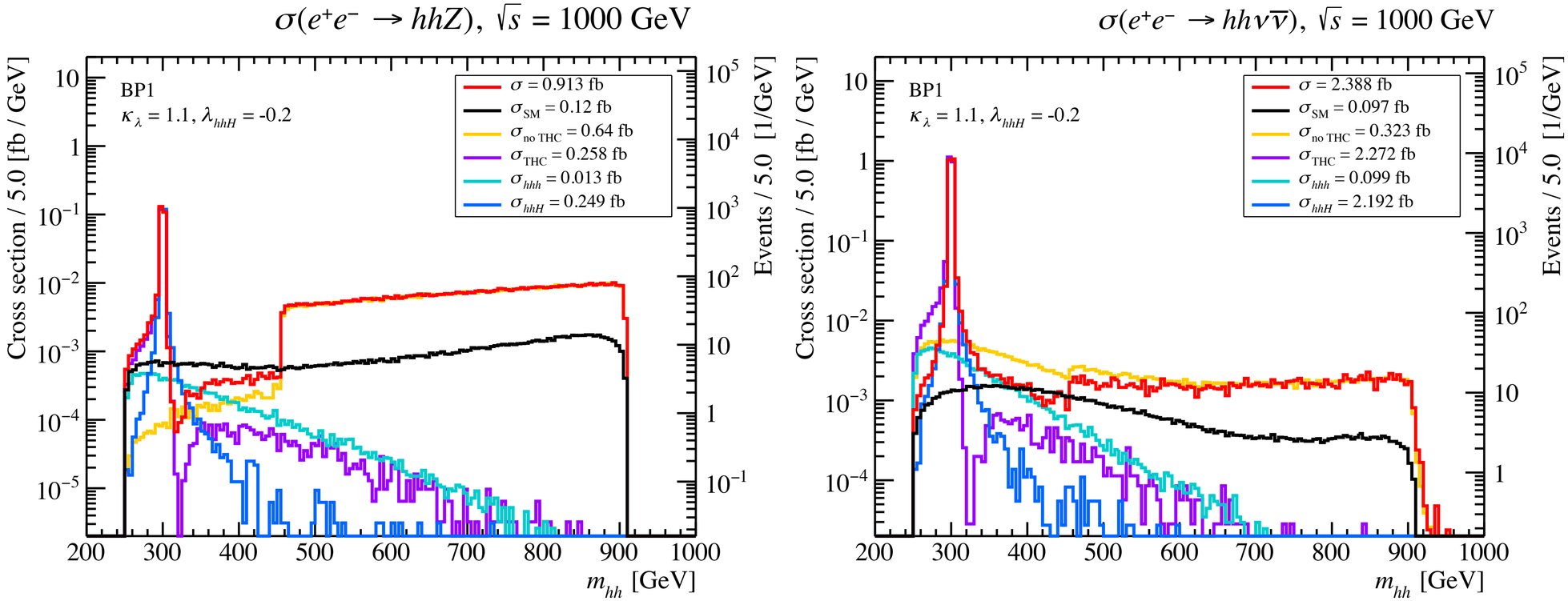
- At this energy, both channels are comparable
- $c_{\beta-\alpha} - \tan\beta$ plane: H and A are still too heavy
  - In the "tip", the Z channel is $\sim 0.6\sigma_{\rm SM}$ and the neutrino channel is $\sim 6\sigma_{\rm SM}$
- In the $c_{\beta-\alpha} - m$ plane, the resonant effects manifest for larger masses
  - The enhancement wrt the SM in the neutrino channel is even larger than at 500 GeV



Black lines are the boundaries to the total allowed region

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

Cross section distribution on the invariant mass of hh:



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 again at the threshold of m_{hh} (light blue line)
- H resonance (dark blue line) is taller in the neutrino channel
- Now the A resonance (yellow line) is responsible of the “step” behavior far from the H peak
  - The “step” extends through the kinematic allowed region for $e^+e^- \to hA \to hhZ\ (\to hh\nu\bar{\nu})$