BSM Triple Higgs Couplings at future e^+e^- colliders

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Based on arxiv:2005.10576, arxiv:2106.11105 and arxiv:2203.12684

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Motivation

BSM Higgs sectors are still allowed by the measurements of the properties of the 125 GeV Higgs boson

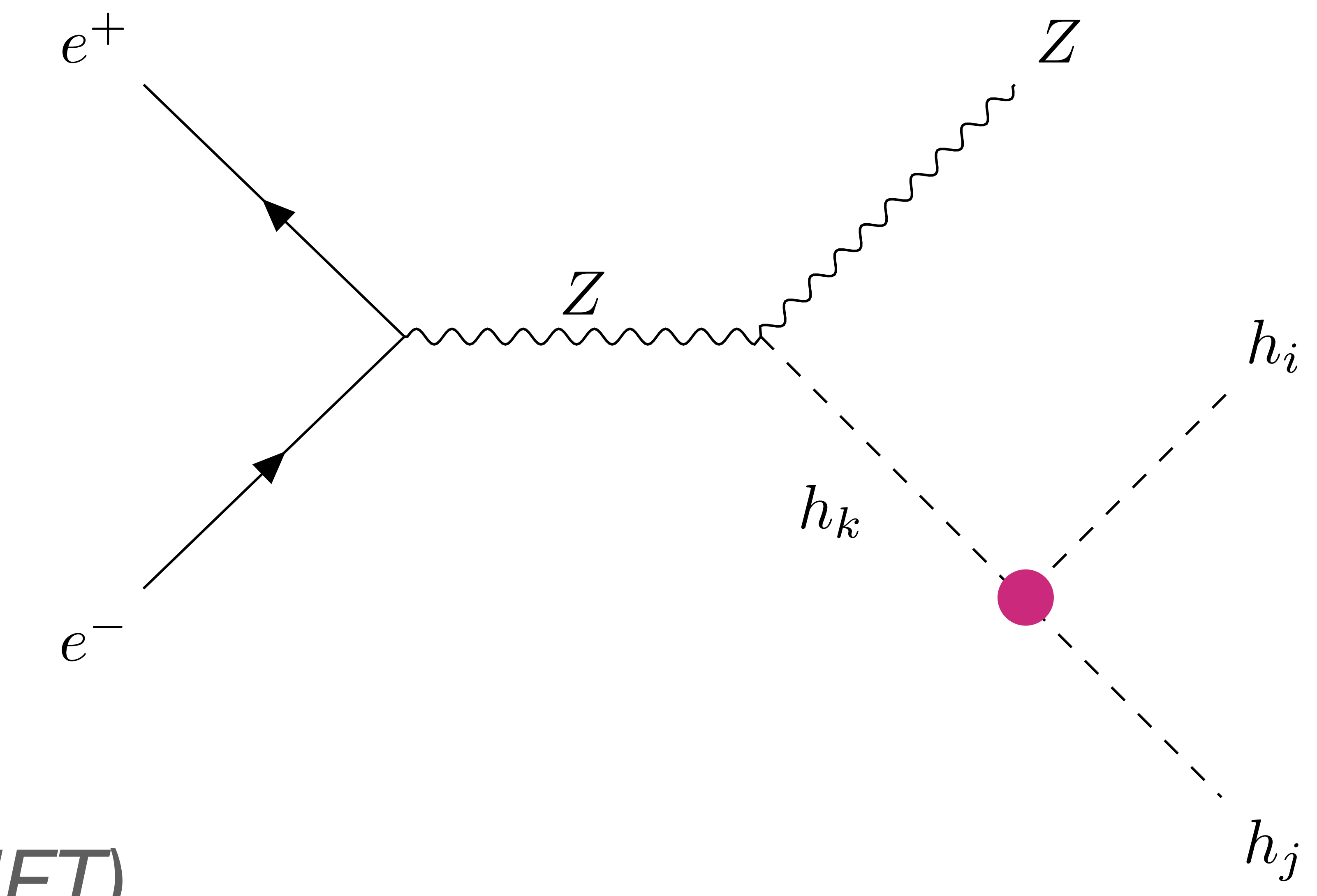
In the 2HDM, triple Higgs couplings $\lambda_{h_i h_j h_k}$ can be large while respecting all the relevant constraints

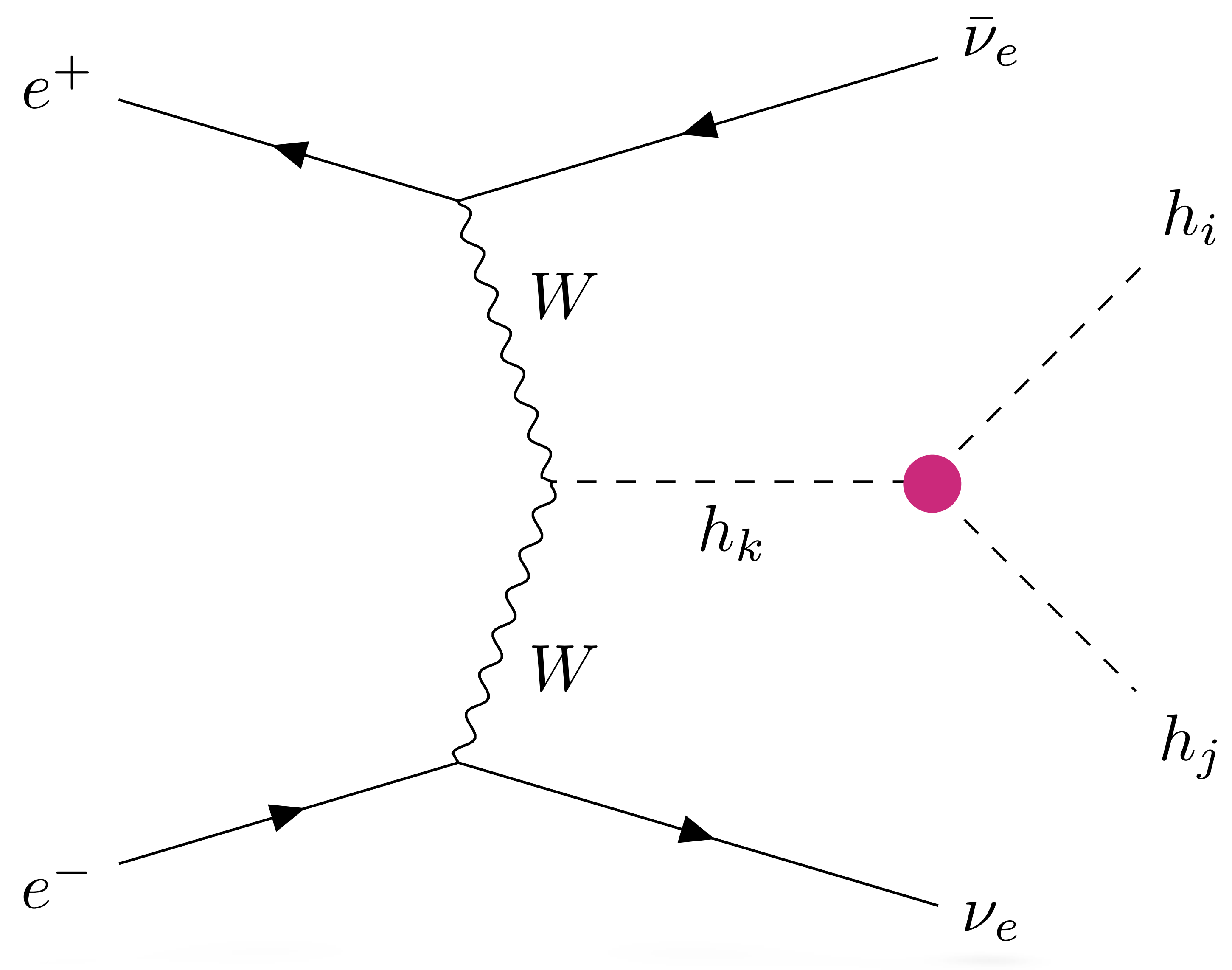
(Eur.Phys.J.C 80 (2020) 9, 884 arXiv:2005.10576 and Eur.Phys.J.C 82 (2022) 6, 536 arXiv:2203.12684)

↓

Di-Higgs production could give access to $\lambda_{h_i h_j h_k}$ 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 $h_i h_j = hh,\ hH,\ HH,\ AA$





(Eur.Phys.J.C 81 (2021) 10, 913 [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

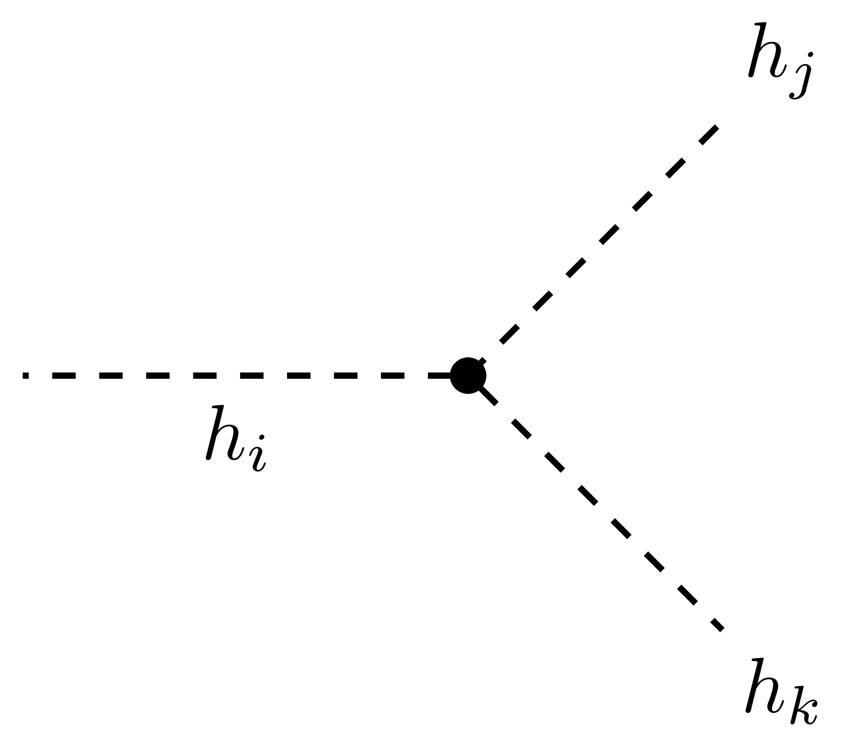
INPUT PARAMETERS:

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

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

Triple Higgs Couplings (THC)

Coupling definition



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

and

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

at tree level

Final allowed ranges

updated ranges from arXiv:2203.12684!

	Type I	Type II	Type III (Y)	Type IV (X)
$\kappa_\lambda \in$	$[-0.5,\ 1.3]$	$[0.6,\ 1.0]$	$[0.6,\ 1.0]$	$[0.5,\ 1.0]$
$\lambda_{hhH} \in$	$[-1.7,\ 1.6]$	$[-1.8,\ 1.5]$	$[-1.8,\ 1.3]$	$[-1.8,\ 1.4]$
$\lambda_{hHH} \in$	$[-0.7,\ 15]$	$[-0.5,\ 16]$	$[-0.3,\ 16]$	$[-0.6,\ 9]$
$\lambda_{hH^+H^-} \in$	$[-1.8,\ 33]$	$[-1.4,\ 33]$	$[-1.3,\ 33]$	$[-1.7,\ 33]$

$$\lambda_{hAA} = \lambda_{hH^+H^-}/2$$

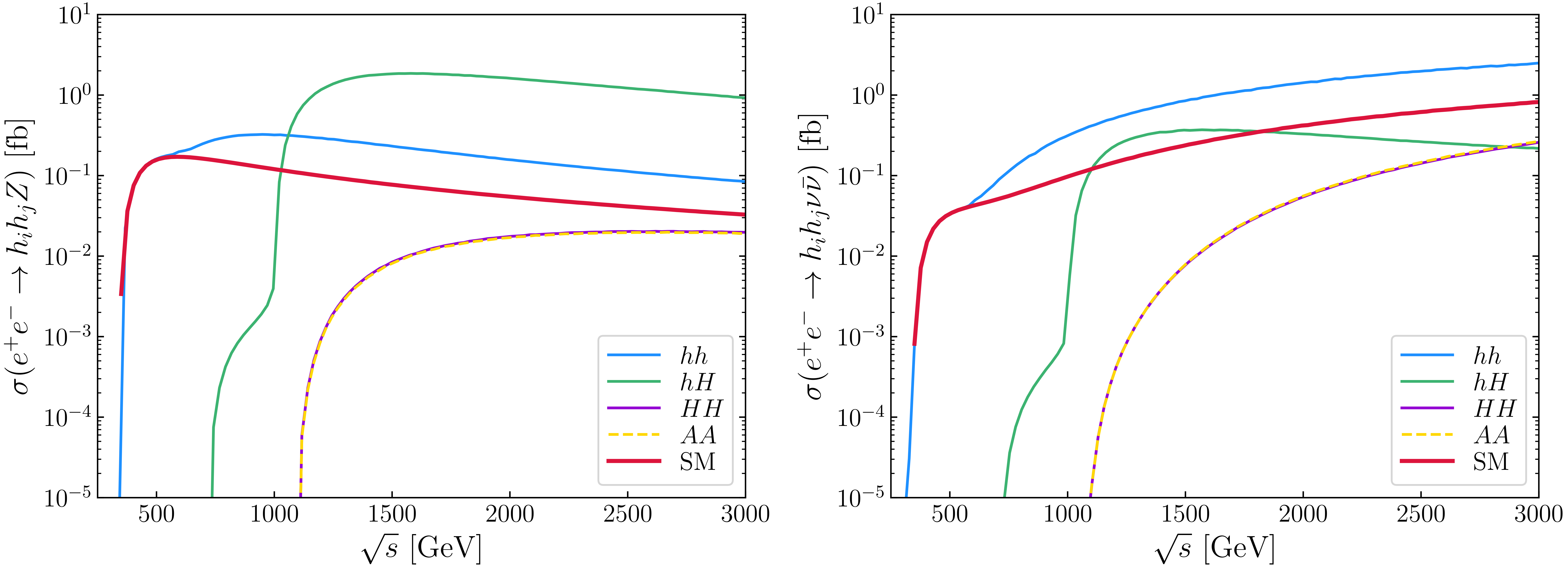
Constraints

- Electroweak precision data, T parameter: motivates (before CDF II) scenarios with degenerate masses, $m_H = m_A = m_{H^\pm} \equiv m$
- Tree level unitarity and potential stability:
  - $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$ helps to satisfy these constraints
- Collider measurements of the 125 GeV Higgs
  - Close to $\cos(\beta - \alpha) = 0$, specially for type II
- BSM Higgs searches at 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

Dependence with energy

Madgraph was used



Type I

$m = 500$ GeV

$\tan\beta = 10$

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

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

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

(num. 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 resonant diagrams mediated by H (contains λ_{hhH}) and A (without THC)
- hHZ and $hH\nu\bar{\nu}$: dominated by A mediated diagrams but still sensitive to THC at large energies
- $HH\nu\bar{\nu}$ ~ $AA\nu\bar{\nu}$: dominated at large energies by λ_{hHH} (λ_{hAA}) if large enough

Methodology

- XS presented in some **benchmark planes** with large (and allowed) THC
- **ALL** diagrams included (**no NWA!**)
- Access to THC via XS distributions on the **invariant mass of the final $h_i h_j$ pair**

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

- We studied effects from THC in $m_{h_i h_j}$ for 5 benchmark points (BP) with a wide range of BSM Higgs masses
- In the case of the sensitivity to λ_{hhH} at hh production we propose a theoretical estimator from **4-$b$jets** events

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})

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

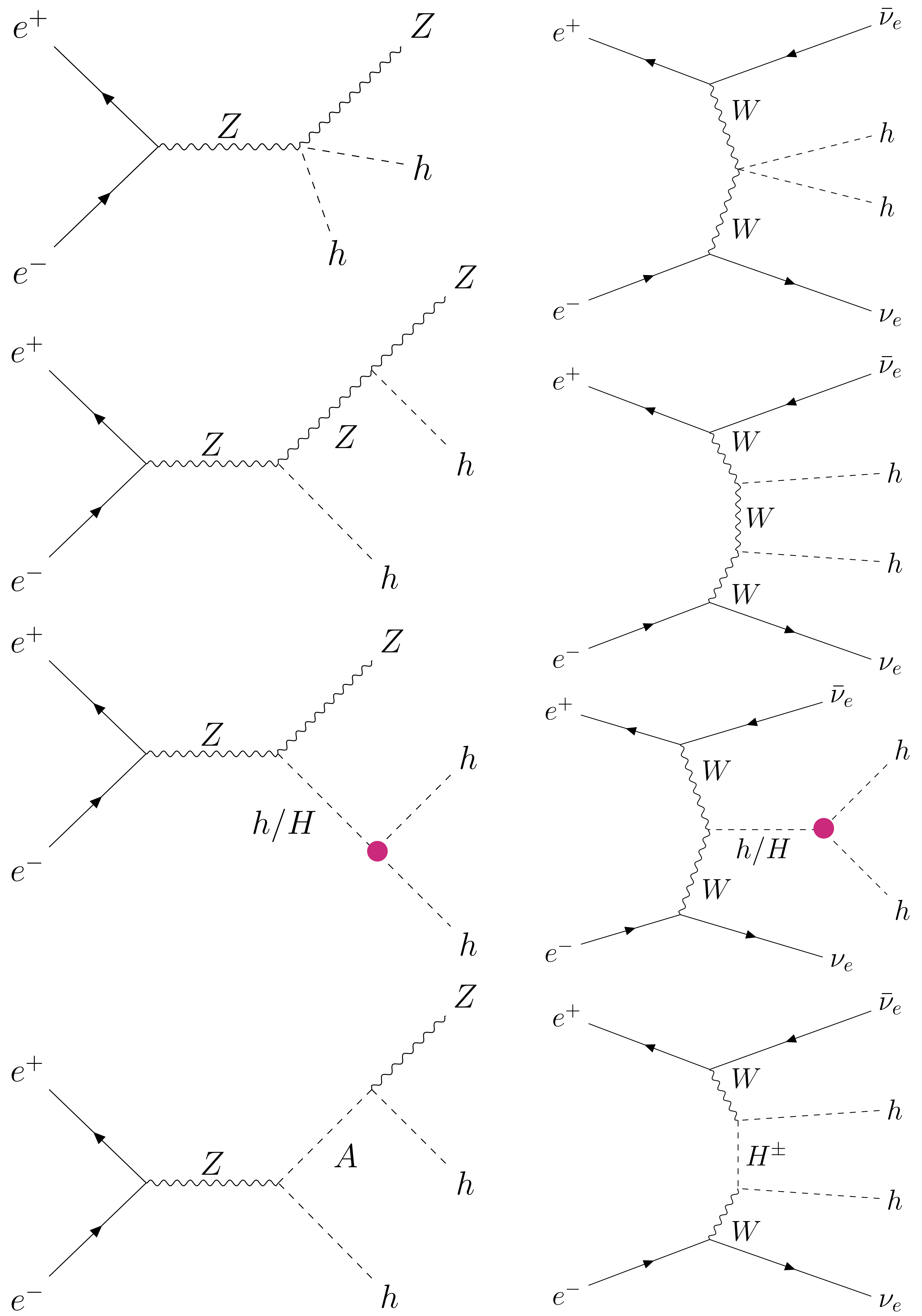
   $$e^+e^- \to H^*\nu_e\bar{\nu}_e \to hh\nu_e\bar{\nu}_e$$

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



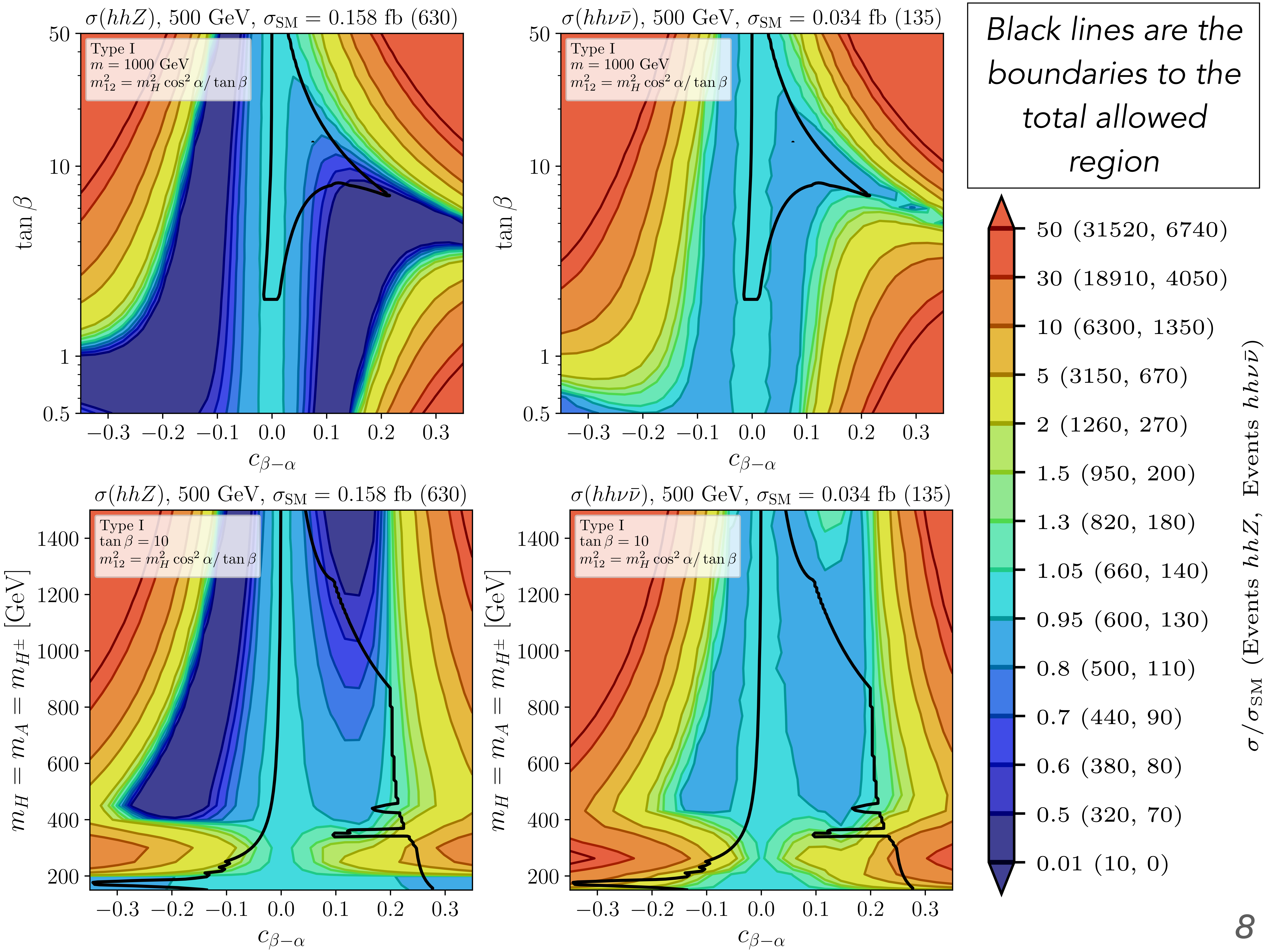
diagrams with $Z \to \nu\bar{\nu}$ included

hh production, ILC 500GeV (type I)

- Production XS for hhZ and $hh\nu\bar{\nu}$ wrt the SM @ILC500GeV
  - hhZ is the dominant channel
- $c_{\beta-\alpha} - \tan\beta$ plane: H and A are too heavy → effect of κ_λ
- $c_{\beta-\alpha} - m$ plane: the H (λ_{hhH}) and A (no THC) resonances manifest for low masses
  - The enhancement wrt the SM in $hh\nu\bar{\nu}$ is larger, but the absolute XS is smaller

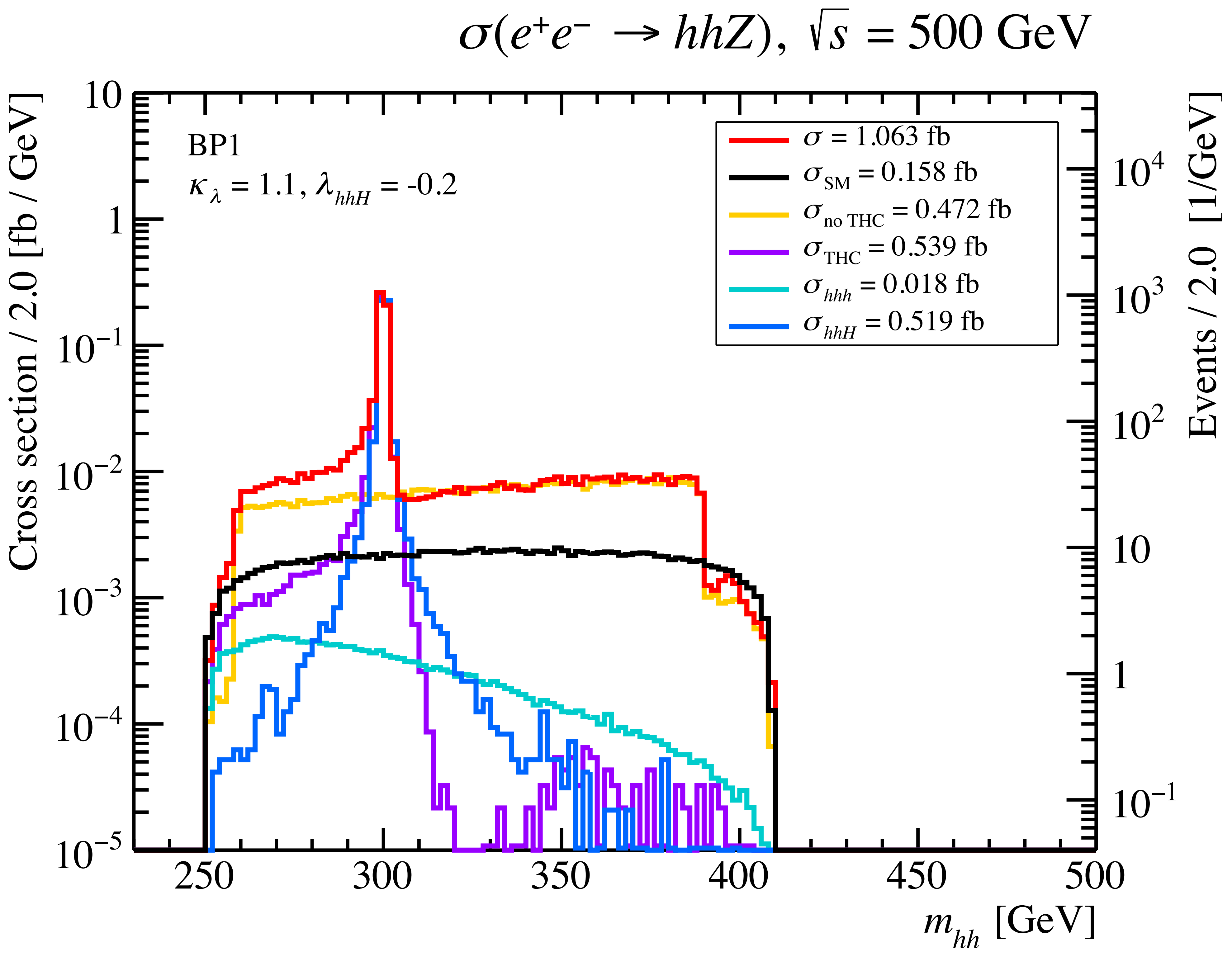
$\Longrightarrow$ Access to THC via the XS distributions on the invariant mass of hh

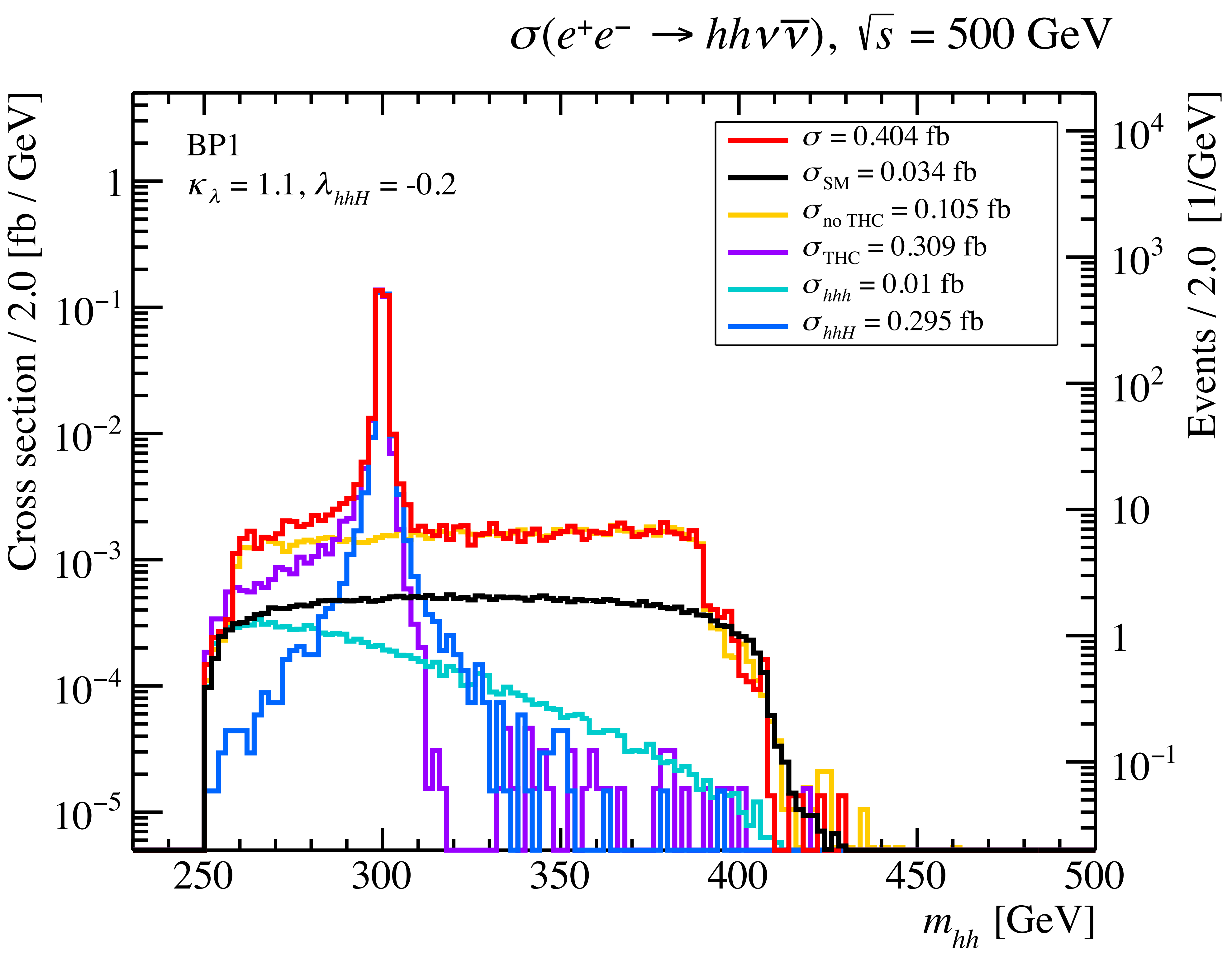
Black lines are the boundaries to the total allowed region



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

Cross section distribution on the invariant mass of hh:





BP1

Type I

$m = 300$ GeV

$\tan\beta = 10$

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

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

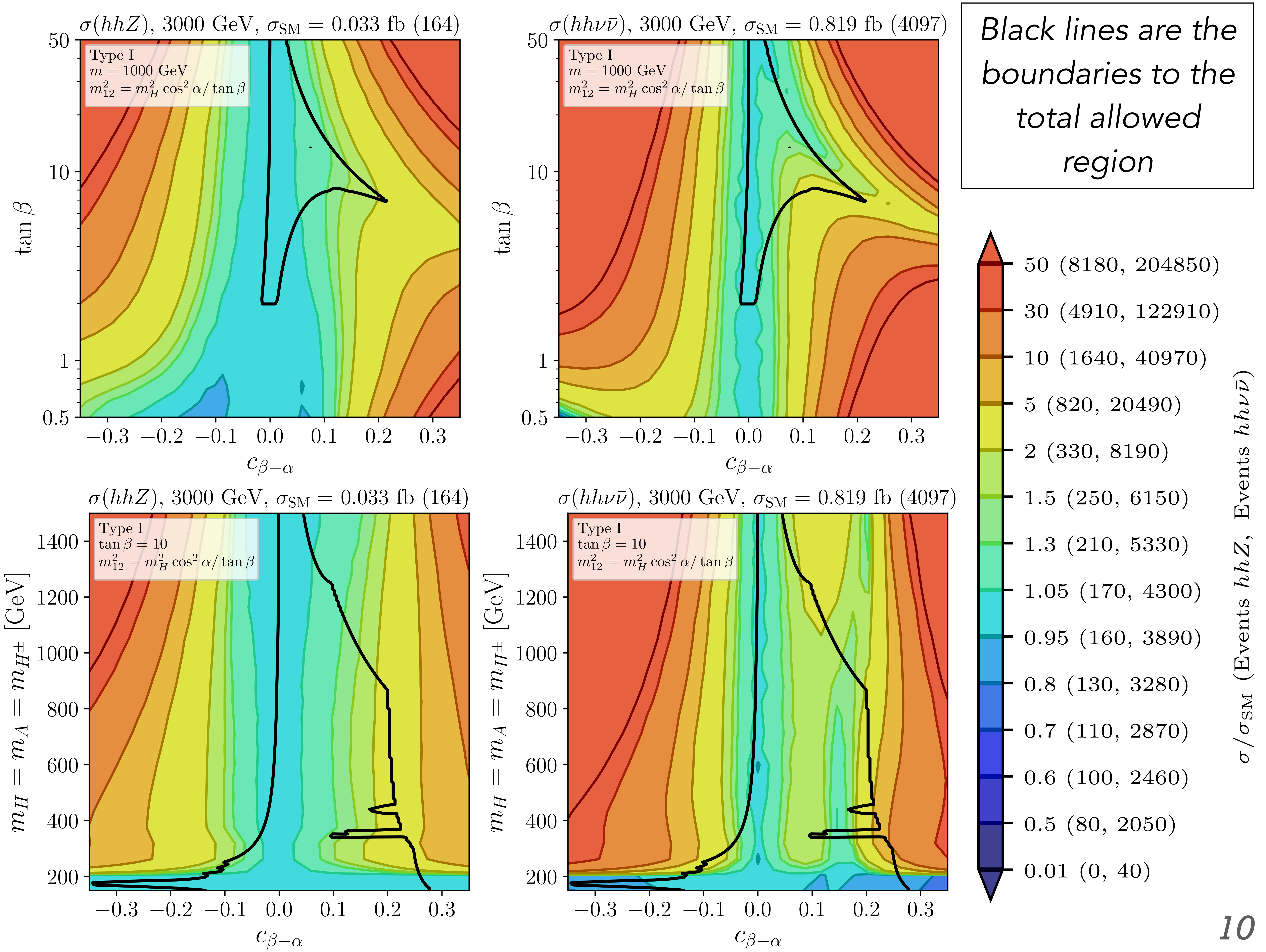
- Main effect from κ_λ at the threshold of m_{hh} (light blue line)
- H resonance when $m_{hh} \sim m_H = 300$ GeV (dark blue line) → access to λ_{hhH}
- Plateau wrt the SM from diagrams without THC (yellow line) → A resonant diagrams

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

hh production, CLIC 3TeV (type I)

- Production XS for hhZ and $hh\nu\bar{\nu}$ wrt the SM @CLIC 3TeV
    - Now $hh\nu\bar{\nu}$ is the dominant channel
- hhZ is dominated by A mediated diagrams → no THC info :(
- $hh\nu\bar{\nu}$ the H mediated diagrams are more important → access to λ_{hhH}
    - $\sigma(hh\nu\bar{\nu}) \sim 10\sigma_{\rm SM} = 9$ 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



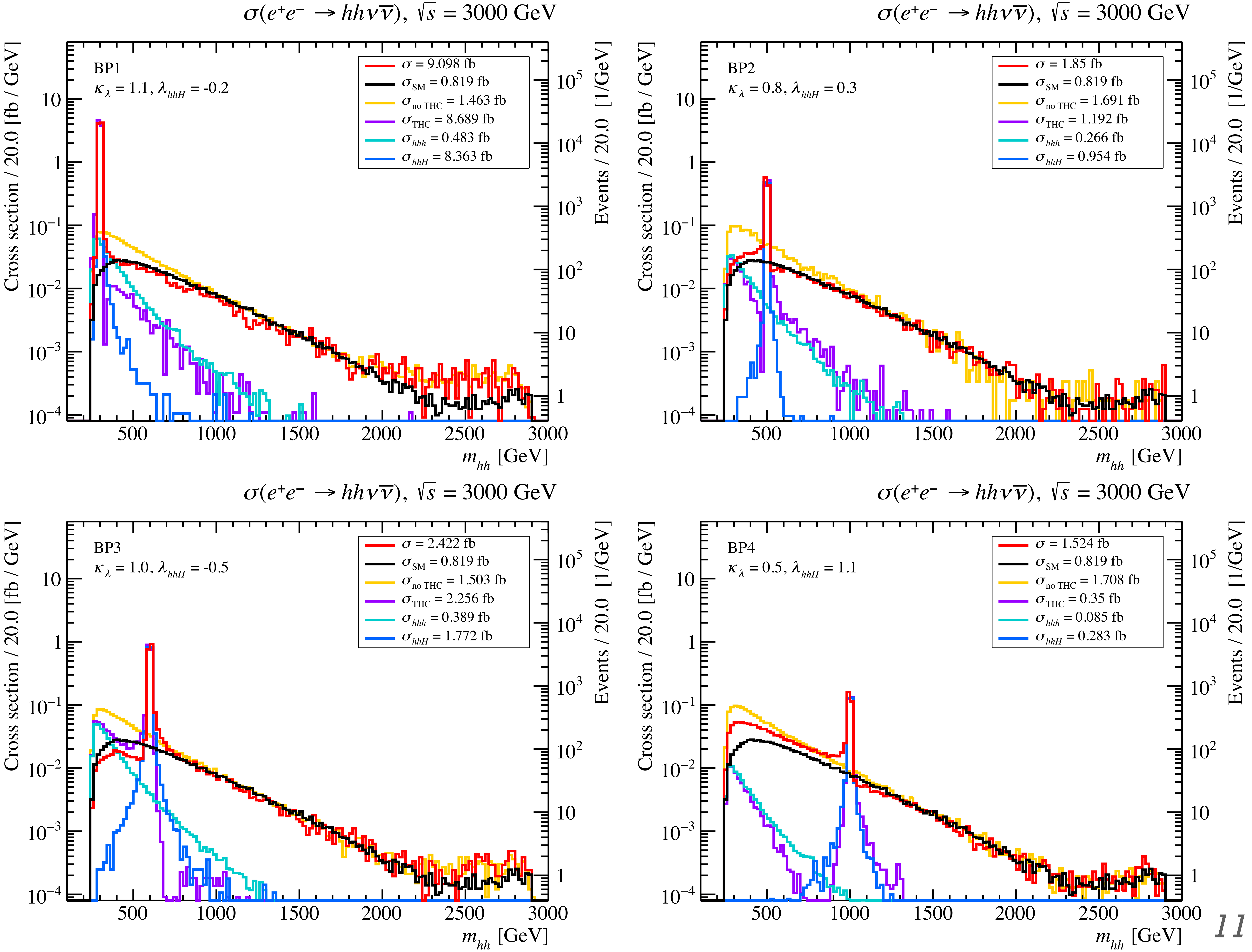
hh production, CLIC 3TeV, THC dependence (type I)

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
BP3	I	600	10	0.2	Eq. (8)
BP4	I	1000	8.5	0.08	Eq. (8)

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

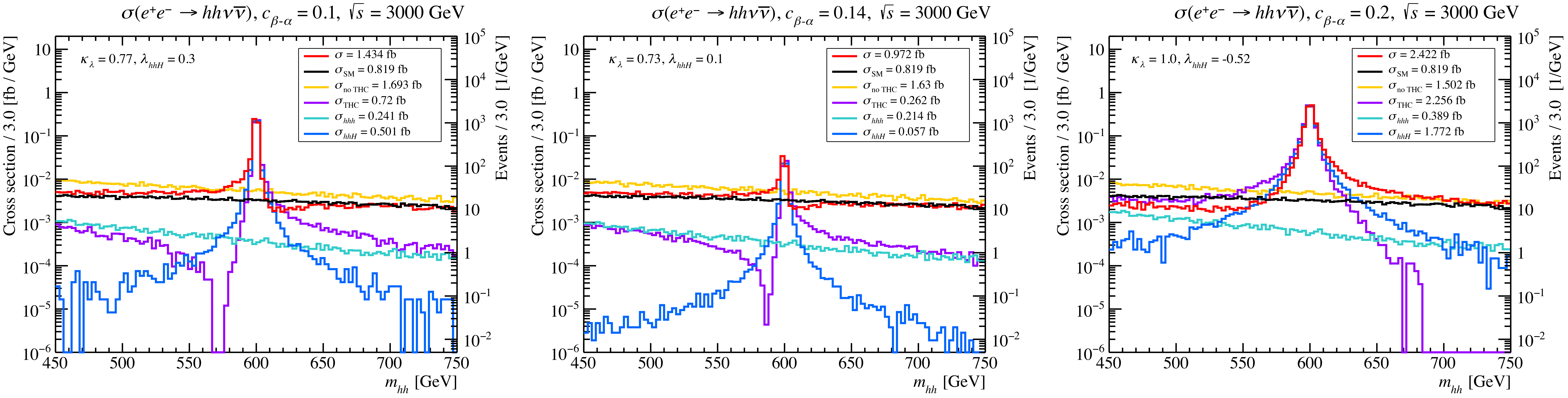
- Effect from κ_λ: the region of low invariant mass
- The neutrino channel can provide access to λ_{hhH} via the H resonant peak for a wide range of m_H and $c_{\beta-\alpha}$



hh production, CLIC 3TeV, THC sign 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

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

- Which collider and channel are best suited to access to λ_{hhH}?

- We define a theoretical "sensitivity" R ratio: estimation of the final 4-$b$jets events at a collider close to the H resonance:

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

$\bar{N}^R$ are events from the H mediated diagrams
$\bar{N}^C$ 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 with these cuts:

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

λ_{hhH} "sensitivity" at hhZ from 4-bjet events

- Large sensitivity @ILC for BP1 (lighter H)
- 20-30 events @ILC1TeV for BP2 and BP3
- Barely no events @CLIC

hhZ	$\sqrt{s}$ [GeV]	$\sigma_{2\text{HDM}}$ / σ_{SM} [fb]	$\bar{N}^R_{4bZ}$ / $\bar{N}^C_{4bZ}$ / $\bar{N}^{\text{SM}}_{4bZ}$	$\mathcal{A}_{2\text{HDM}}$/ $\mathcal{A}_{\text{SM}}$	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	-

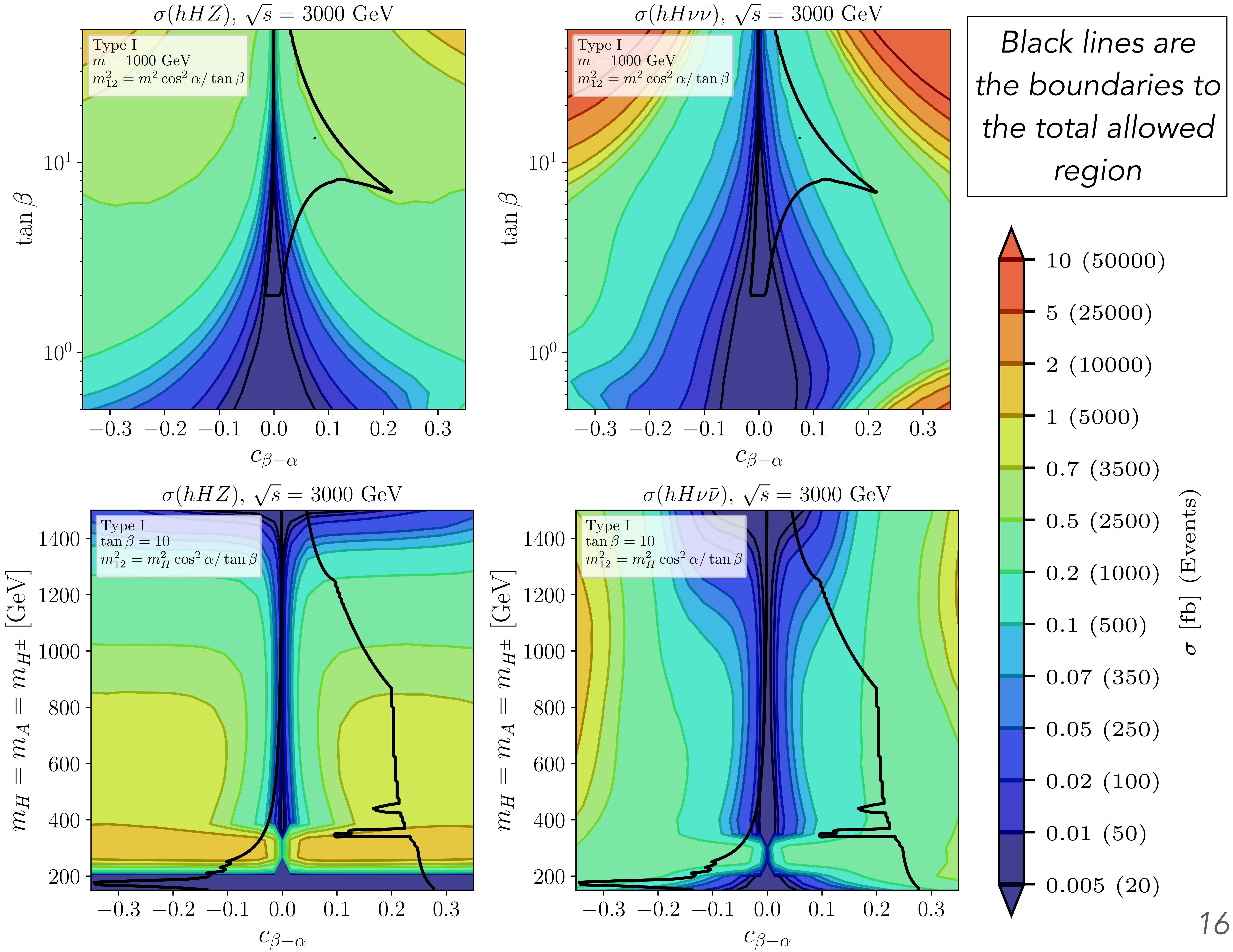
λ_{hhH} "sensitivity" at $hh\nu\bar{\nu}$ from 4-bjet events

- Better sensitivities for all BPs compared to hhZ
- Better R ratio @CLIC3TeV
- No significant events only for BP4 @CLIC1.5TeV

$hh\nu\bar{\nu}$	$\sqrt{s}$ [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

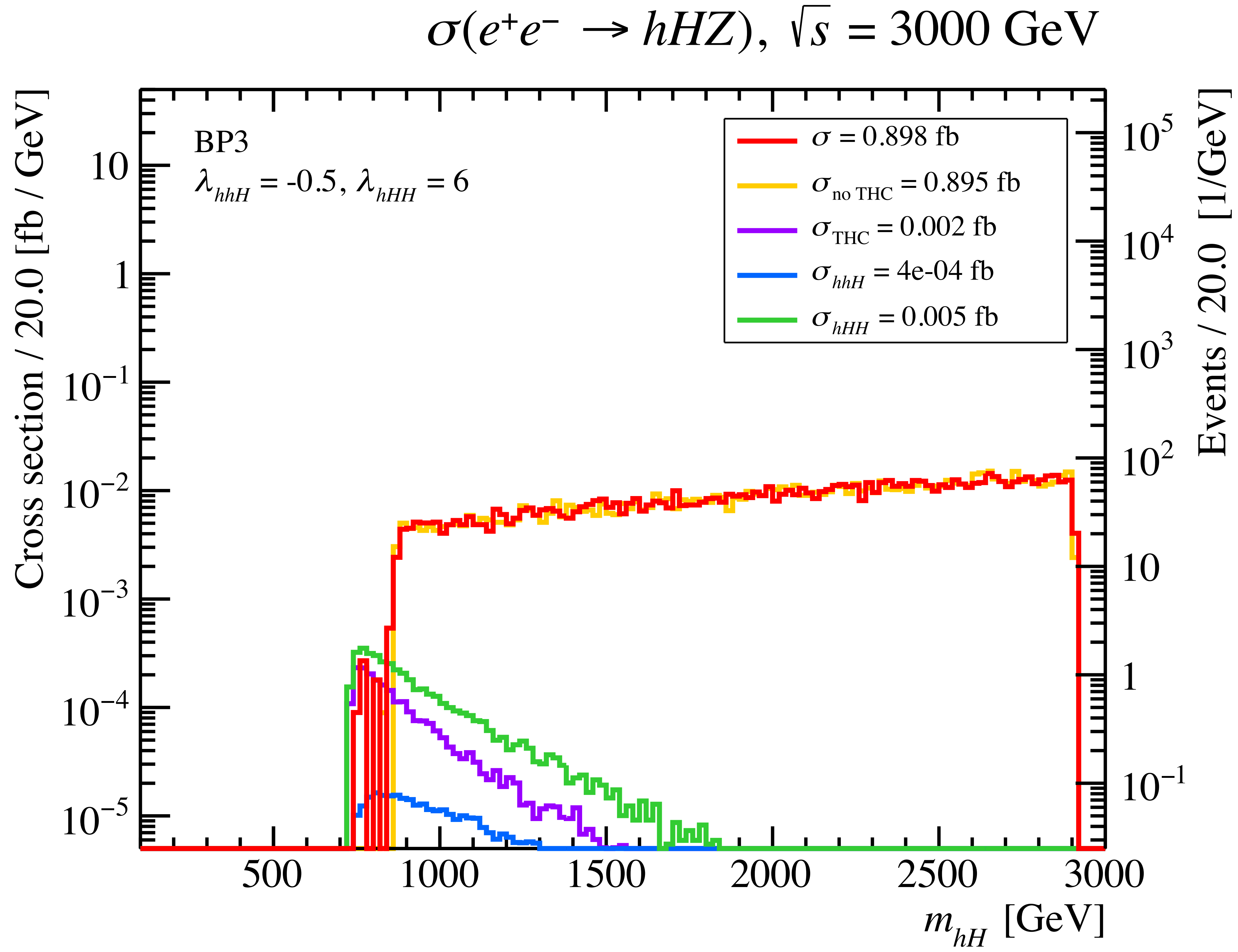
hH production, CLIC 3TeV (type I)

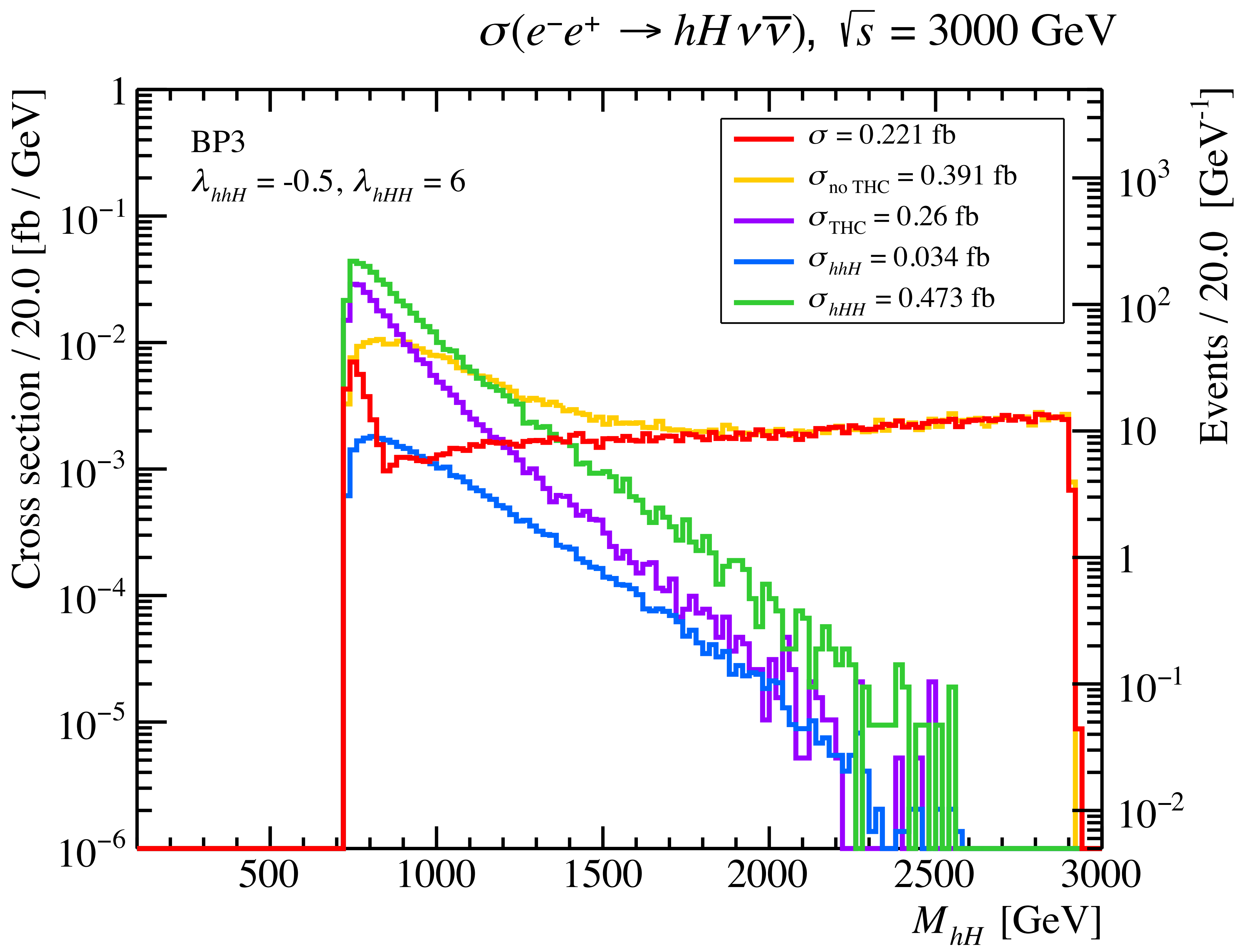
- Production XS for hHZ and $hH\nu\bar{\nu}$ @CLIC 3TeV
- $\sigma = 0$ in the alignment limit
- Very strong contribution from resonant A diagrams in the hHZ channel
- In the $hH\nu\bar{\nu}$ channel, the effects from diagrams with THCs (λ_{hhH} and λ_{hHH}) are mixed with the effects from A mediated diagrams



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

Cross section distribution on the invariant mass of hH:





BP3

Type I

$m = 600$ GeV

$\tan\beta = 10$

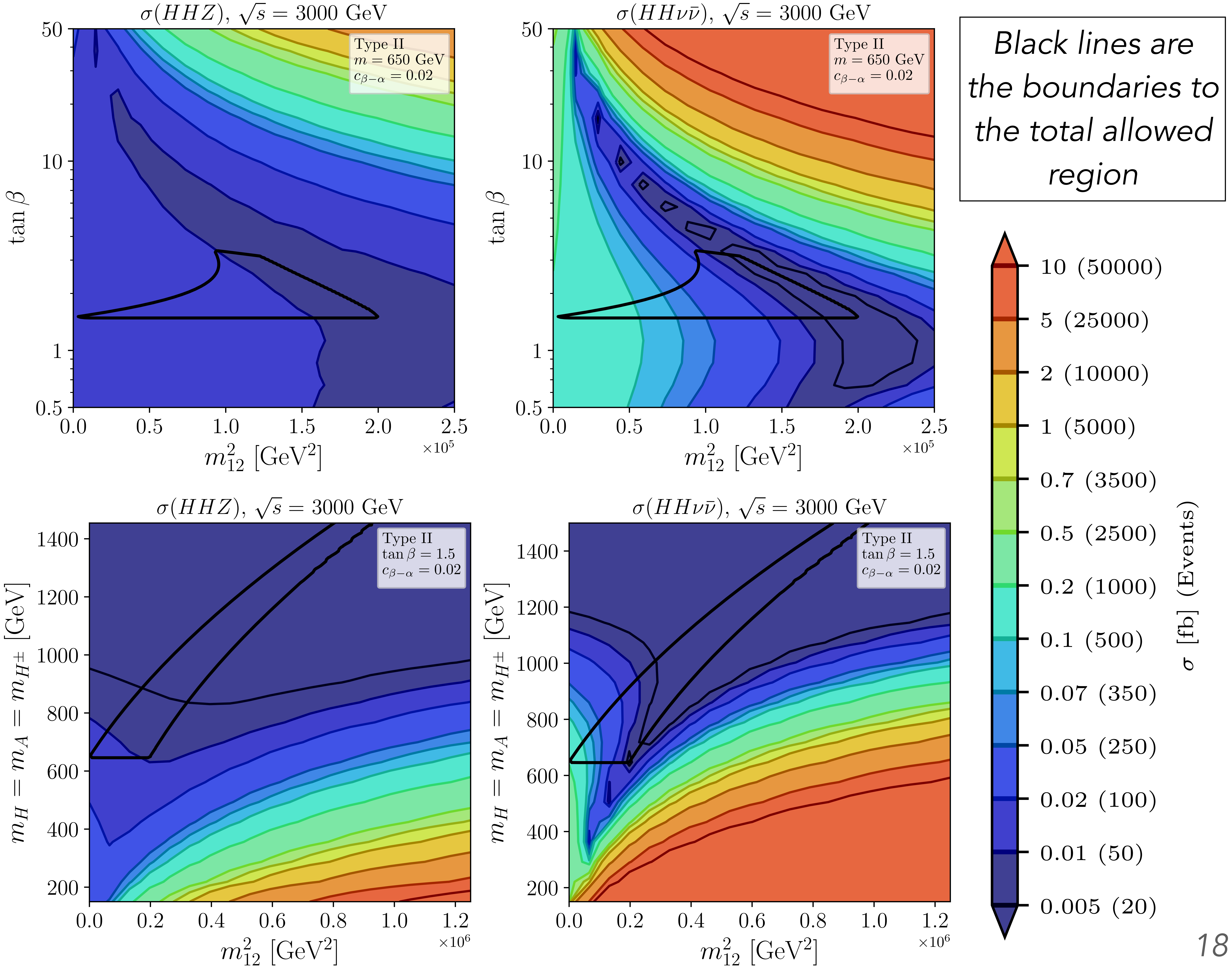
$c_{\beta-\alpha} = 0.2$

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

- Large plateaus of events coming from A resonant diagrams
- Large effects from diagrams with λ_{hhH} and λ_{hHH} 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)

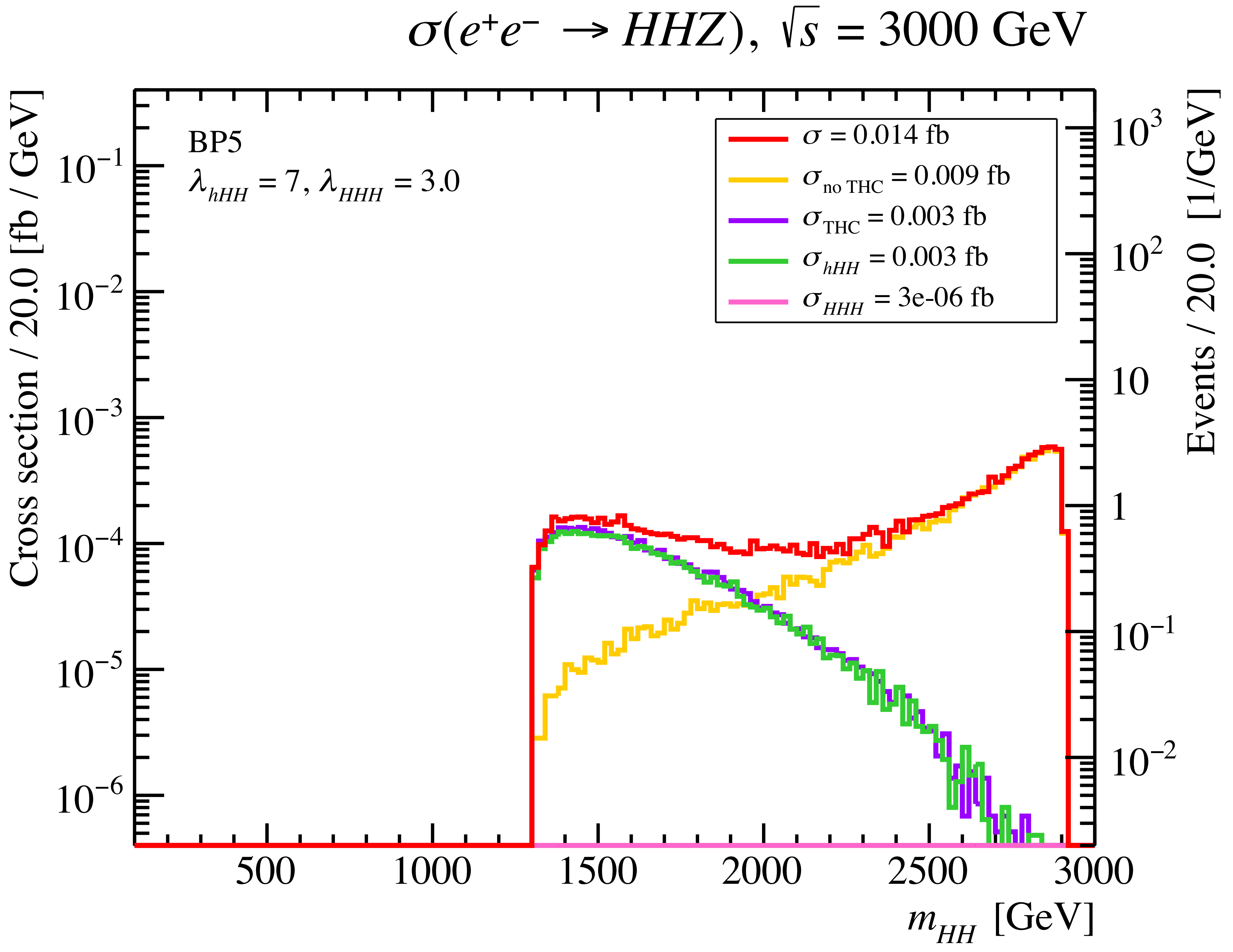
- Production XS for HHZ and $HH\nu\bar{\nu}$ @ILC500GeV
- In type II only $HH \sim AA$ production is relevant (because $c_{\beta-\alpha} \sim 0$)
- $HH\nu\bar{\nu}$ production up to 0.5 fb inside the allowed region
  - Effect coming from λ_{hHH} !
- In type I we can obtain similar XS with similar values for λ_{hHH}

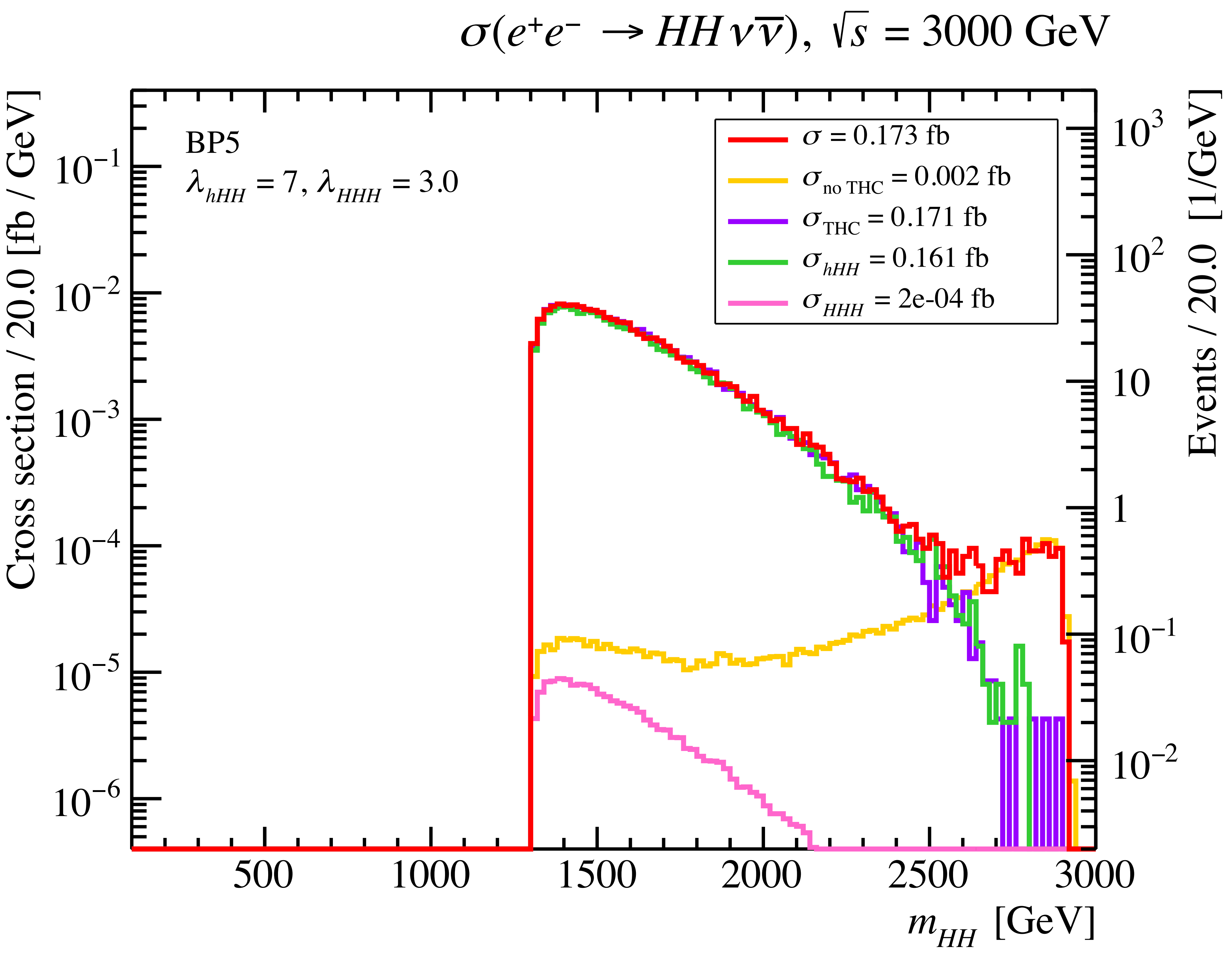


Black lines are the boundaries to the total allowed region

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

Cross section distribution on the invariant mass of HH:





BP5

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
- In the neutrino channel the diagram with λ_{hHH} dominates
- Sizable XS in both types if λ_{hHH} is large (and m_H light enough)

Summary & Conclusions

- The di-Higgs production is studied at e^+e^- **colliders** in the 2HDM, with the aim to find effects coming from BSM triple Higgs couplings (THC)
  - Two production channels were studied: $e^+e^- \to h_i h_j Z$ and $e^+e^- \to h_i h_j \nu\bar{\nu}$
- For ***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
  - From λ_{hhH}, through a resonant peak due to the H boson:
    - A study of the final 4 b-jets events hints that $hh\nu\bar{\nu}$ channel is better at large energies (specially @CLIC 3TeV)
    - Large #events @ILC energies for a light H at both channels
- Effects from THC on $hH\nu\bar{\nu}$ and $HH\nu\bar{\nu} \sim AA\nu\bar{\nu}$ could be potentially seen @CLIC 3TeV in both types, even at the alignment limit! $\to$ μ collider (?)

Thanks for your attention :)

Questions??

Prospects on κ_λ

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

ATLAS	CMS	ILC	CLIC
[-2.3, 10.3] at 95% CL	[-3.3, 8.5] at 95% CL	500GeV: ±27% at 68% CL 1TeV: ±10% at 68% CL	3+1.4 TeV combination: -8% and 11% at 68% CL
[ATLAS-CONF-2019-049]	[arXiv:2011.12373, CMS-HIG-19-018]	[arXiv:1910.11775]	[arXiv:1901.05897]

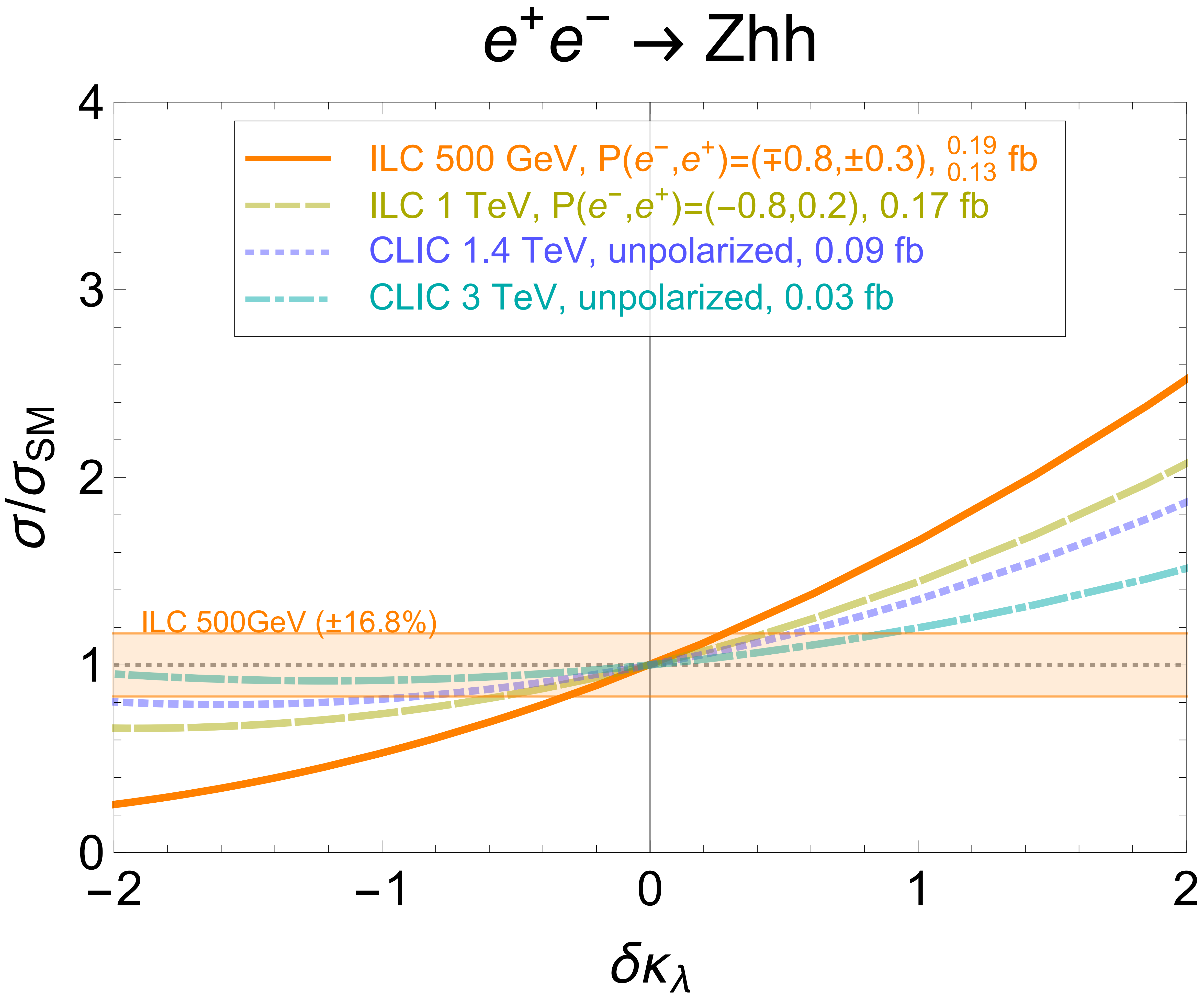
All the above analysis assume the SM couplings

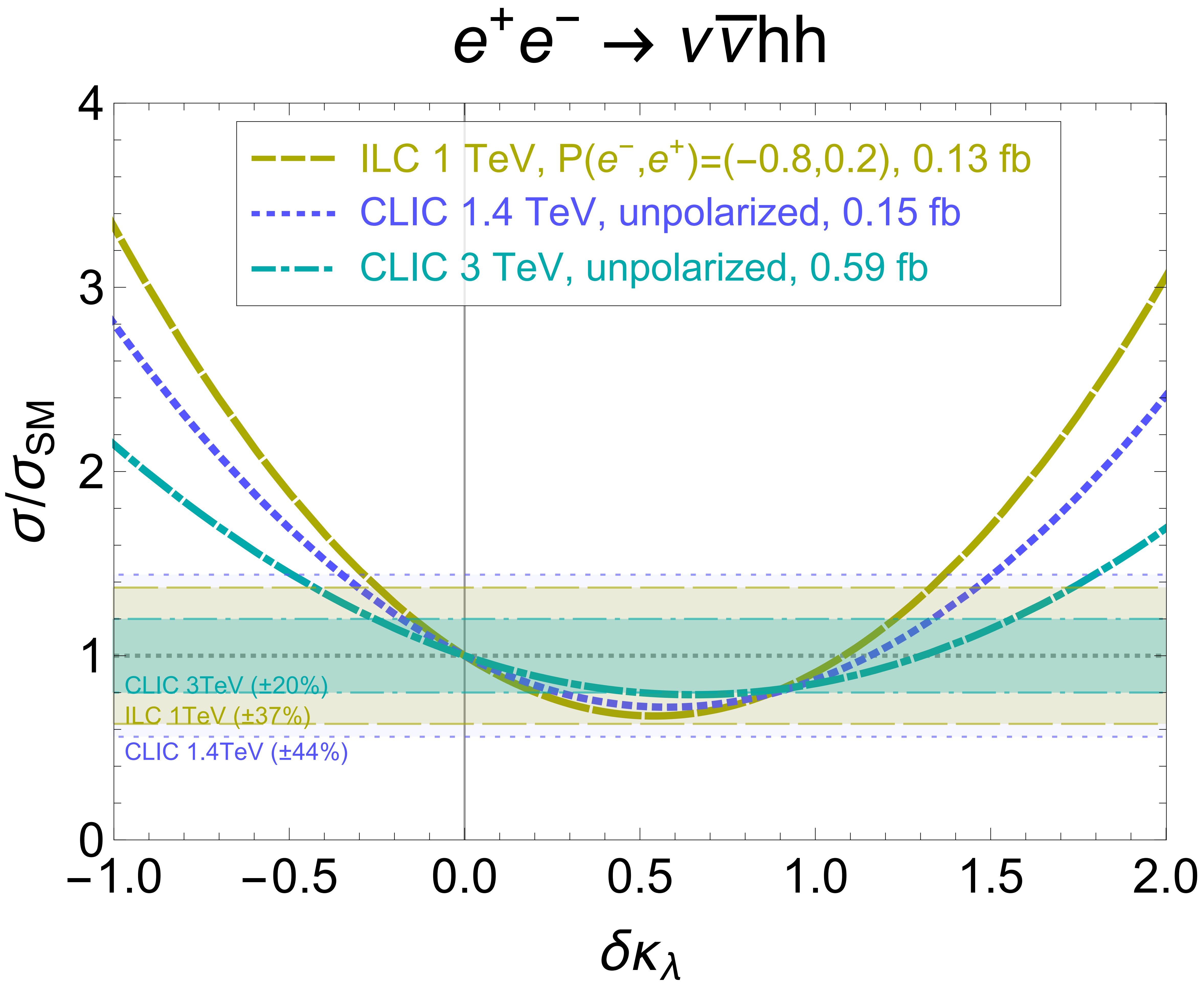
- There are analysis for FCC-hh [arXiv.2004.03505] and ILC [J. List et al., preliminary] with $\kappa_\lambda \neq 1$

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

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

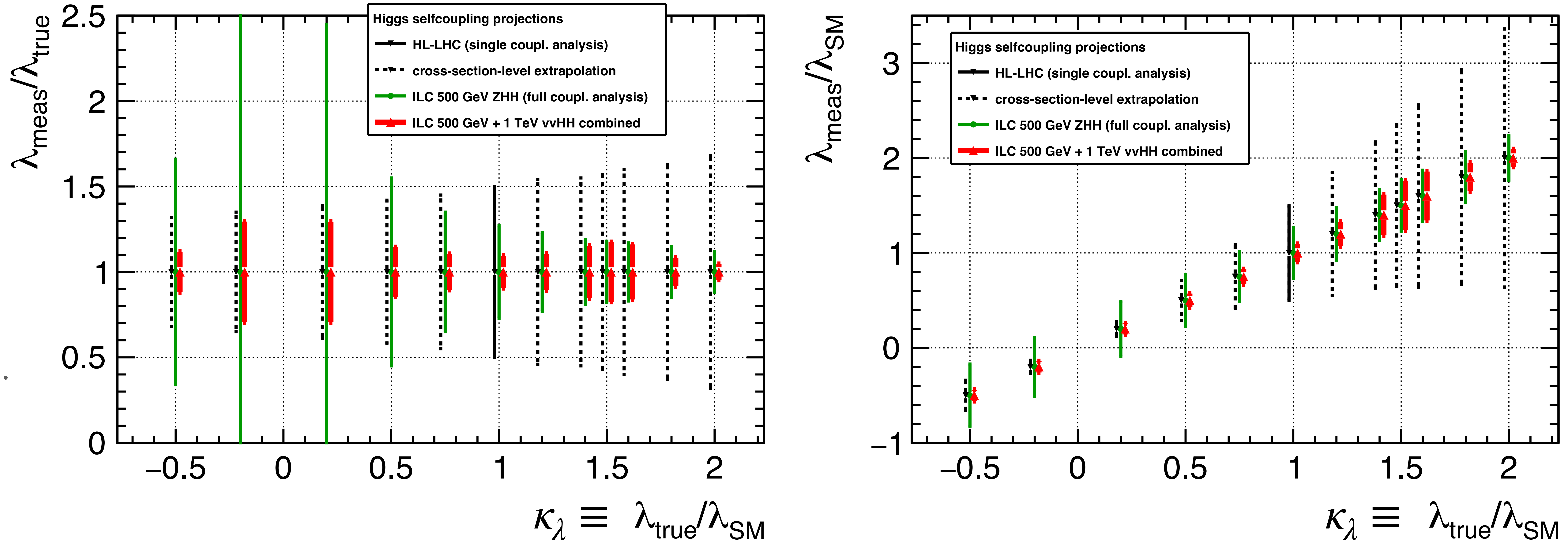
Back-up, κ_λ sensitivity on the SM





Prospects for κ_λ at ILC

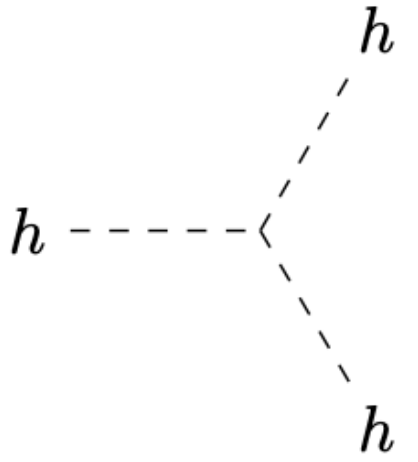
Sensitivity to κ_λ for the di-Higgs production at HL-LHC and ILC, also for $\kappa_\lambda \neq 1$:



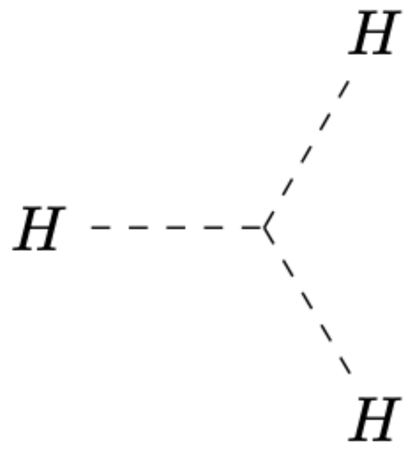
J. List priv. commun.

- 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)

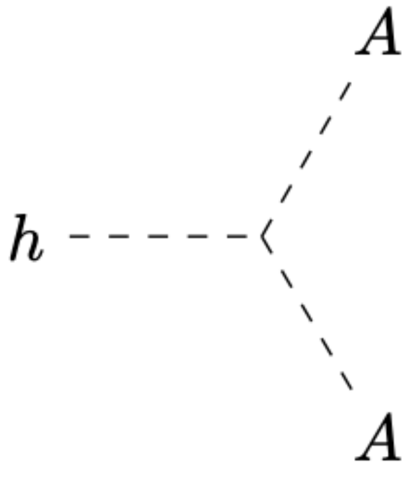
Back-up, Feynman Rules with THC



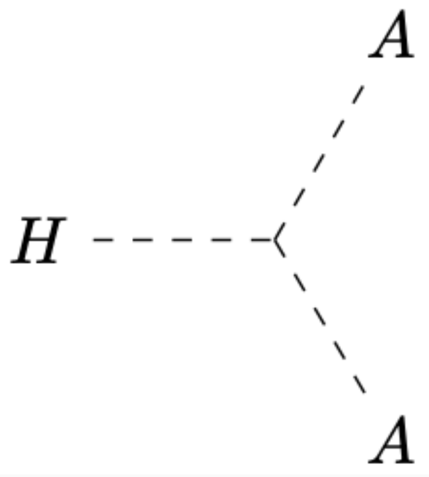
$$= -\frac{3i}{v}\left(2\cot 2\beta\left(m_h^2-\bar{m}^2\right)c^3_{\beta-\alpha} + \left(3m_h^2-2\bar{m}^2\right)c^2_{\beta-\alpha}s_{\beta-\alpha} + m_h^2 s^3_{\beta-\alpha}\right)$$



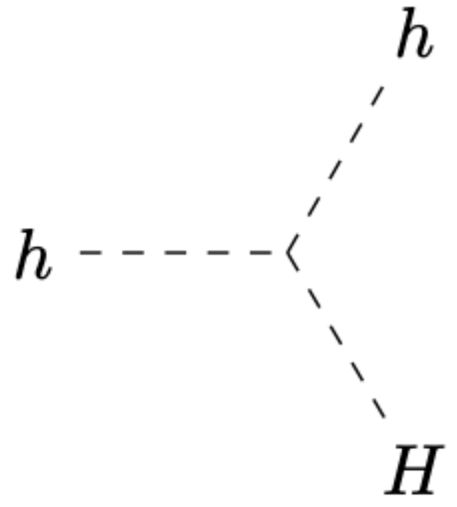
$$= -\frac{3i}{v}\left(\left(3m_H^2-2\bar{m}^2\right)c_{\beta-\alpha}s^2_{\beta-\alpha} + 2\cot 2\beta\left(\bar{m}^2-m_H^2\right)s^3_{\beta-\alpha} + m_H^2 c^3_{\beta-\alpha}\right)$$



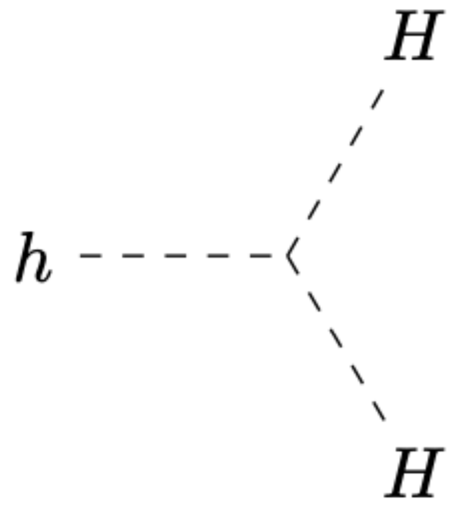
$$= -\frac{i}{v}\left(s_{\beta-\alpha}\left(-2\bar{m}^2+2m_A^2+m_h^2\right) + 2\cot 2\beta\left(m_h^2-\bar{m}^2\right)c_{\beta-\alpha}\right)$$



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

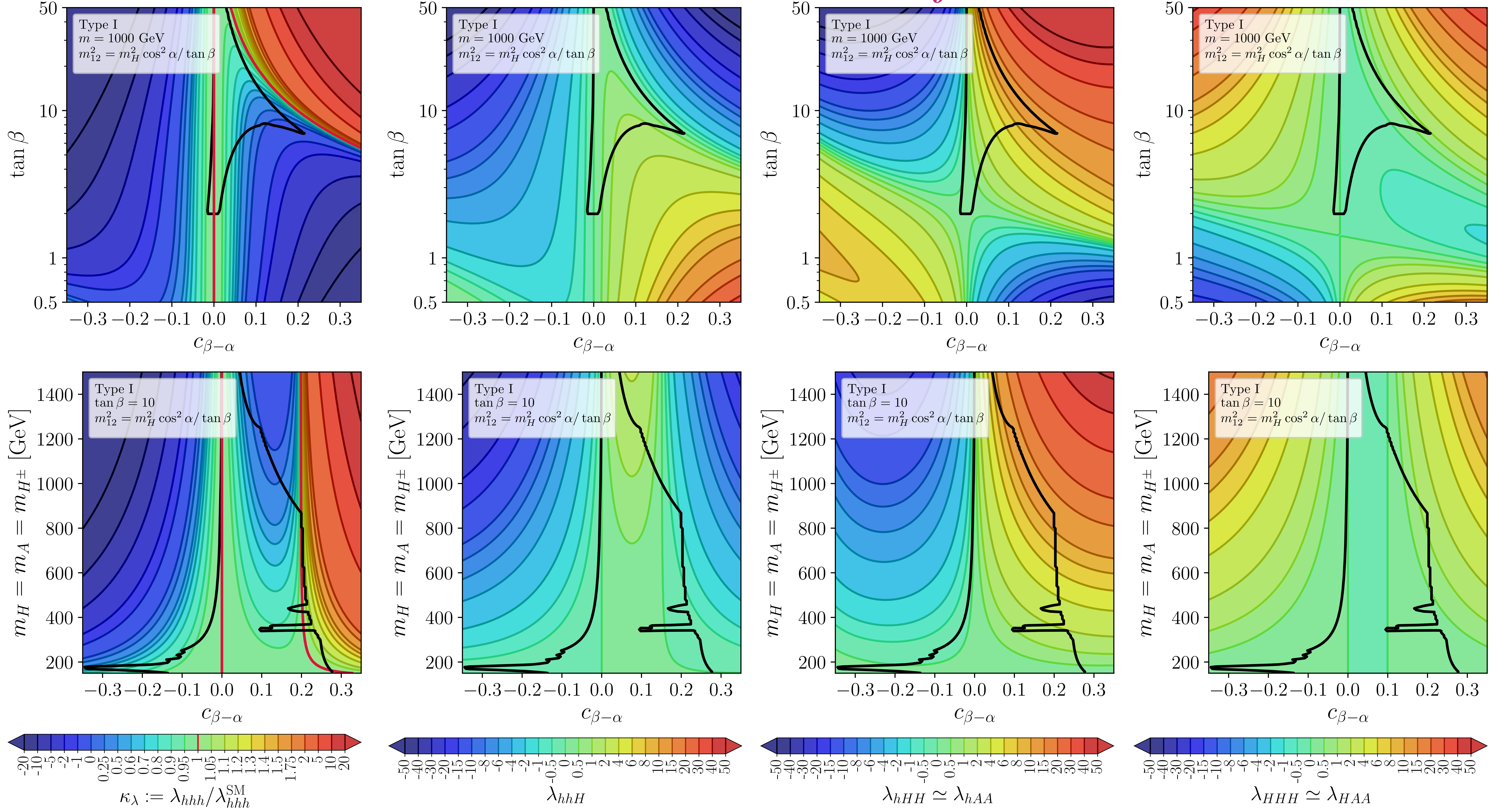


$$= \frac{ic_{\beta-\alpha}}{v}\left(2\bar{m}^2\left(c^2_{\beta-\alpha}-3\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}-2s^2_{\beta-\alpha}\right) + \left(2m_h^2+m_H^2\right)\left(-c^2_{\beta-\alpha}+2\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s^2_{\beta-\alpha}\right)\right)$$

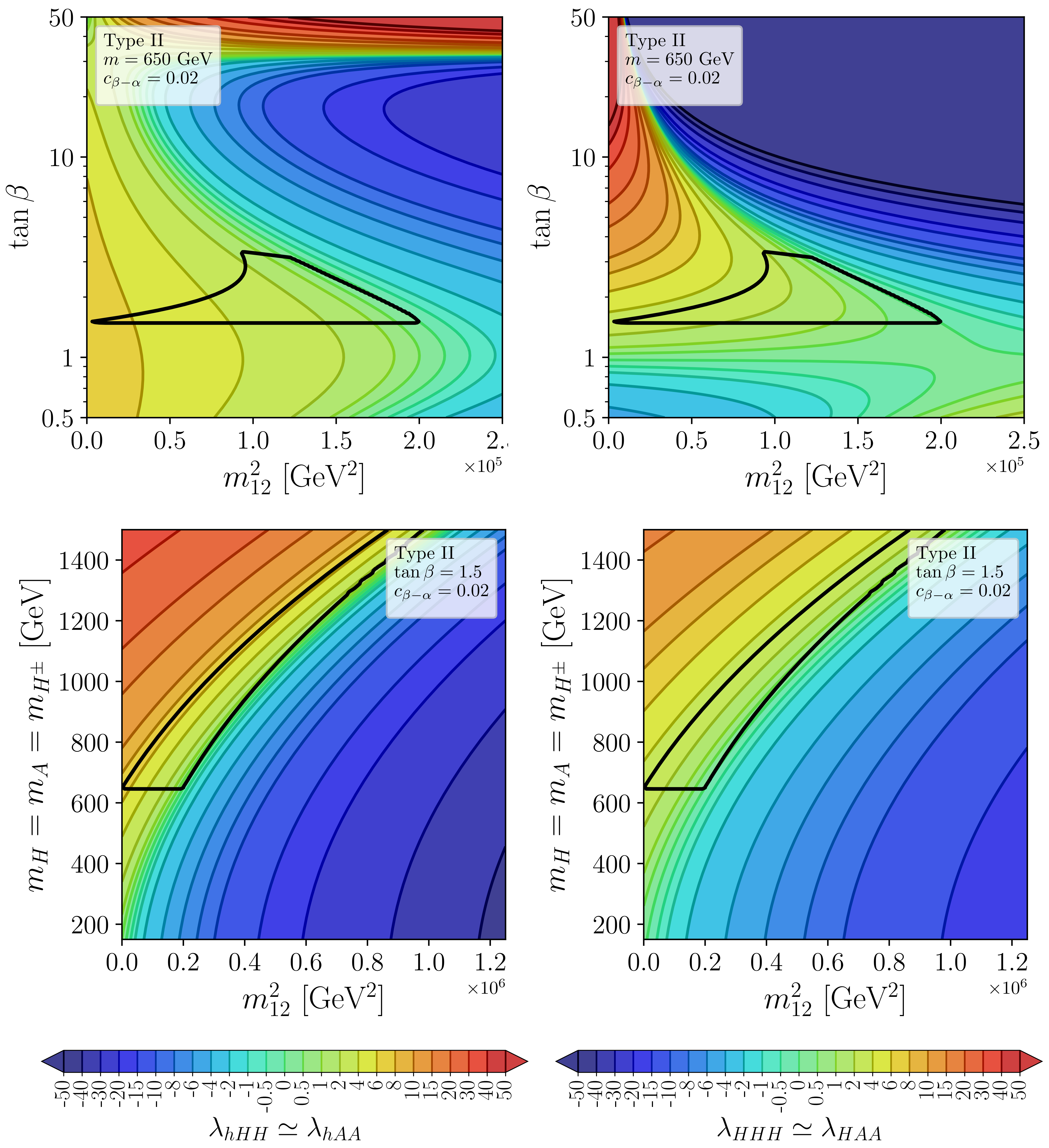


$$= -\frac{is_{\beta-\alpha}}{v}\left(\left(m_h^2+2m_H^2\right)\left(-c^2_{\beta-\alpha}+2\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s^2_{\beta-\alpha}\right) - 2\bar{m}^2\left(-2c^2_{\beta-\alpha}+3\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha}+s^2_{\beta-\alpha}\right)\right)$$

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



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

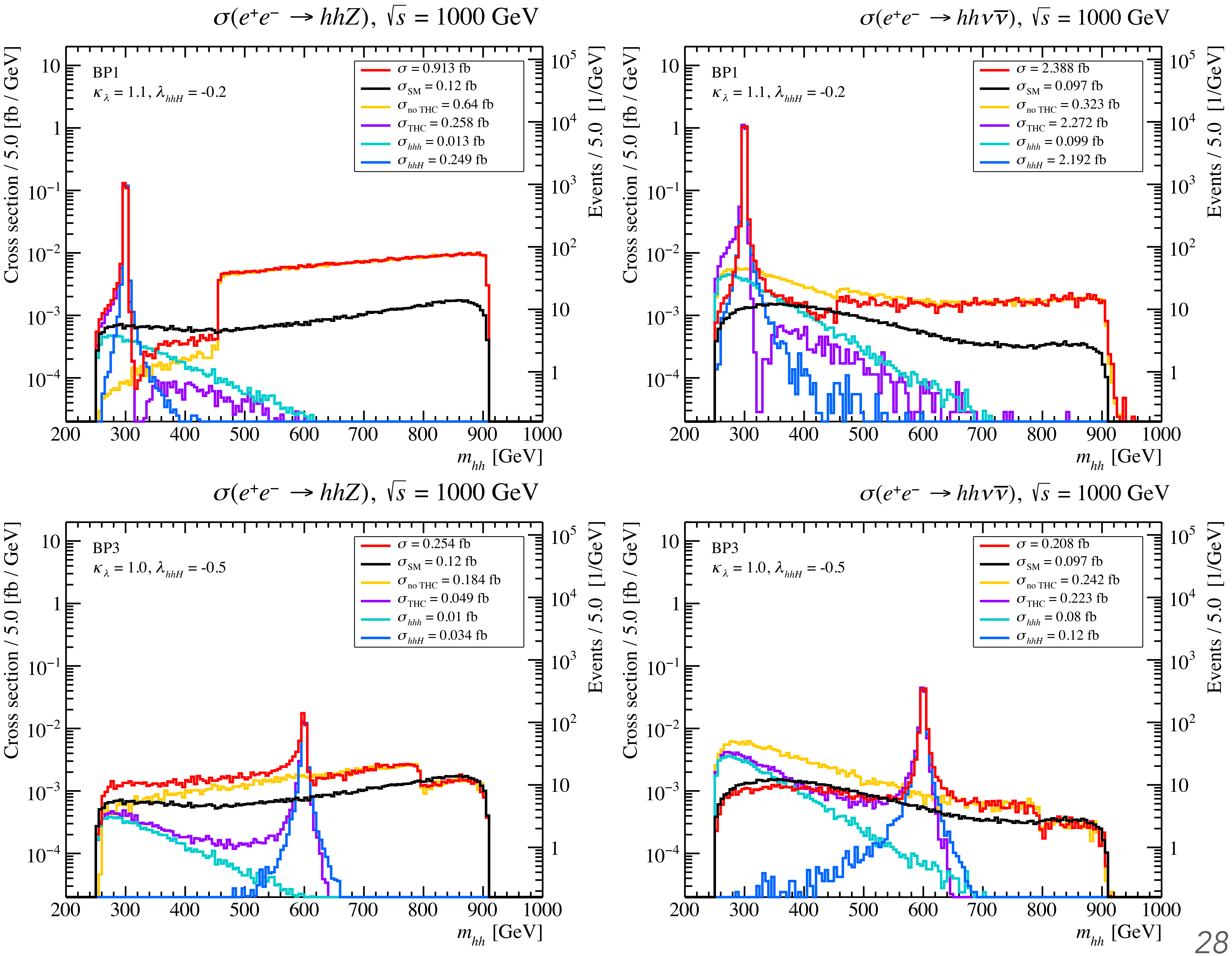


hh production, THC dependence, ILC 1TeV (type I)

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