Triple Higgs couplings in the di-Higgs production in the 2HDM at future colliders

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Higgs Pairs Workshop 2022 - Future colliders: wildcard talks

Dubrovnik (Croatia), 2nd June 2022

e^+e^- part based on arXiv:2005.10576, arXiv:2106.11105, published in EPJC and arXiv:2203.12684 (to appear in EPJC), by FA, S. Heinemeyer and M.J. Herrero

HL-LHC part based on up-coming work, + M. Mühlleitner and K. Radchenko

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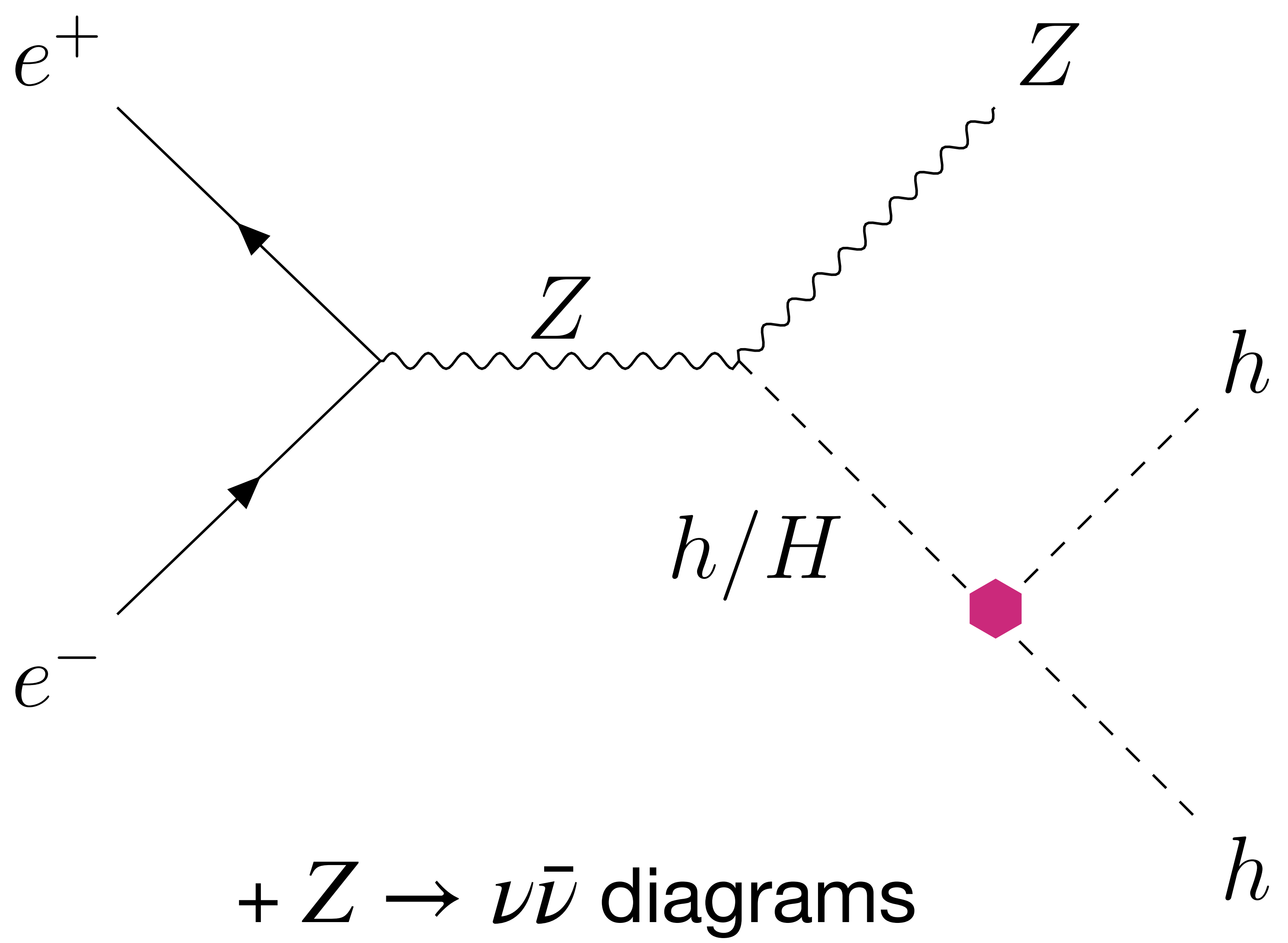
Motivation

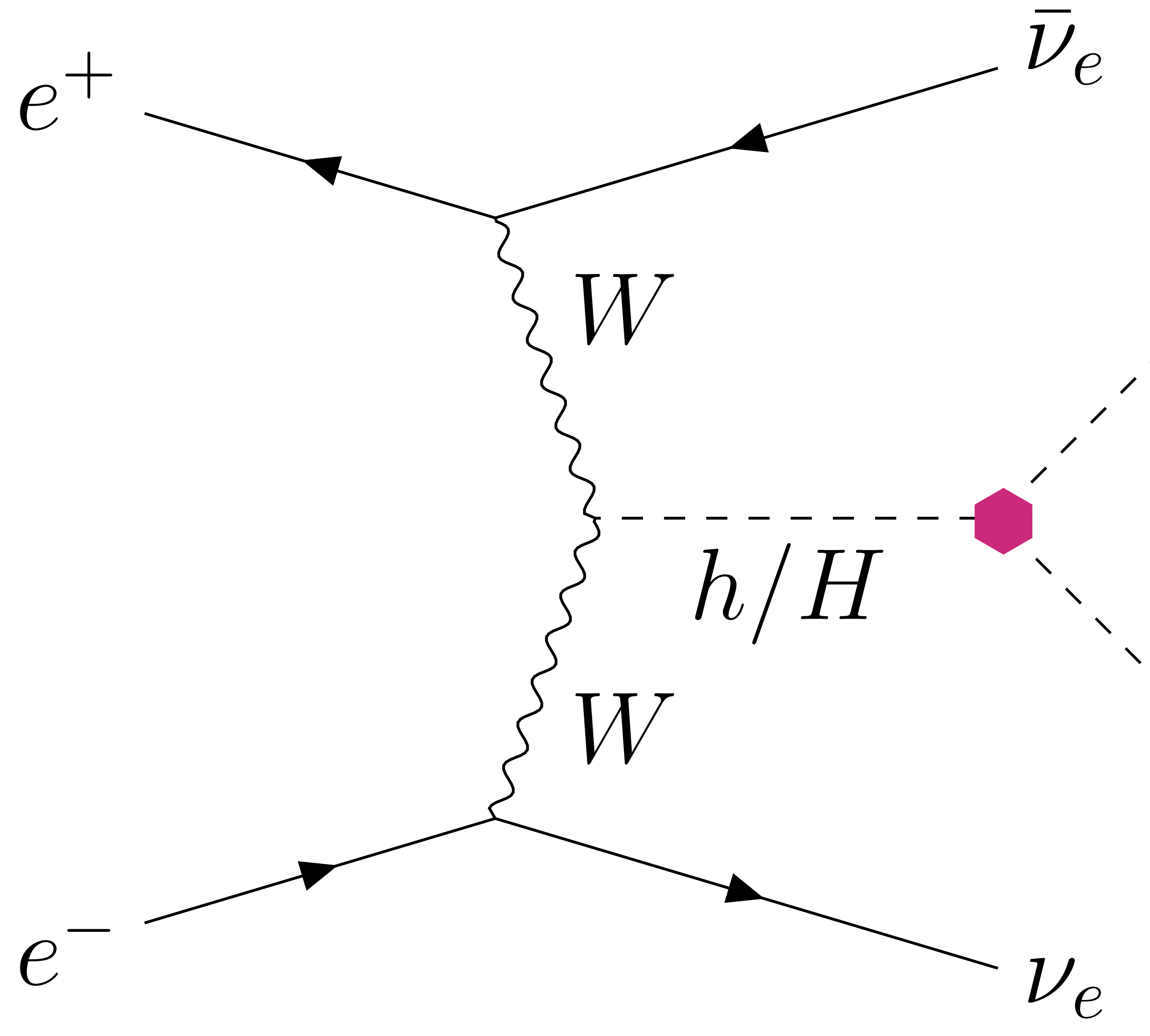
In the 2HDM, triple Higgs couplings $\lambda_{h_i h_j h_k}$ can be large while respecting all the relevant constraints (arXiv2005.10576, arXiv:2203.12684)

↓

Di-Higgs production could access to $\lambda_{h_i h_j h_k}$ at leading order

e^+e^- COLLIDERS (arXiv:2106.11105)

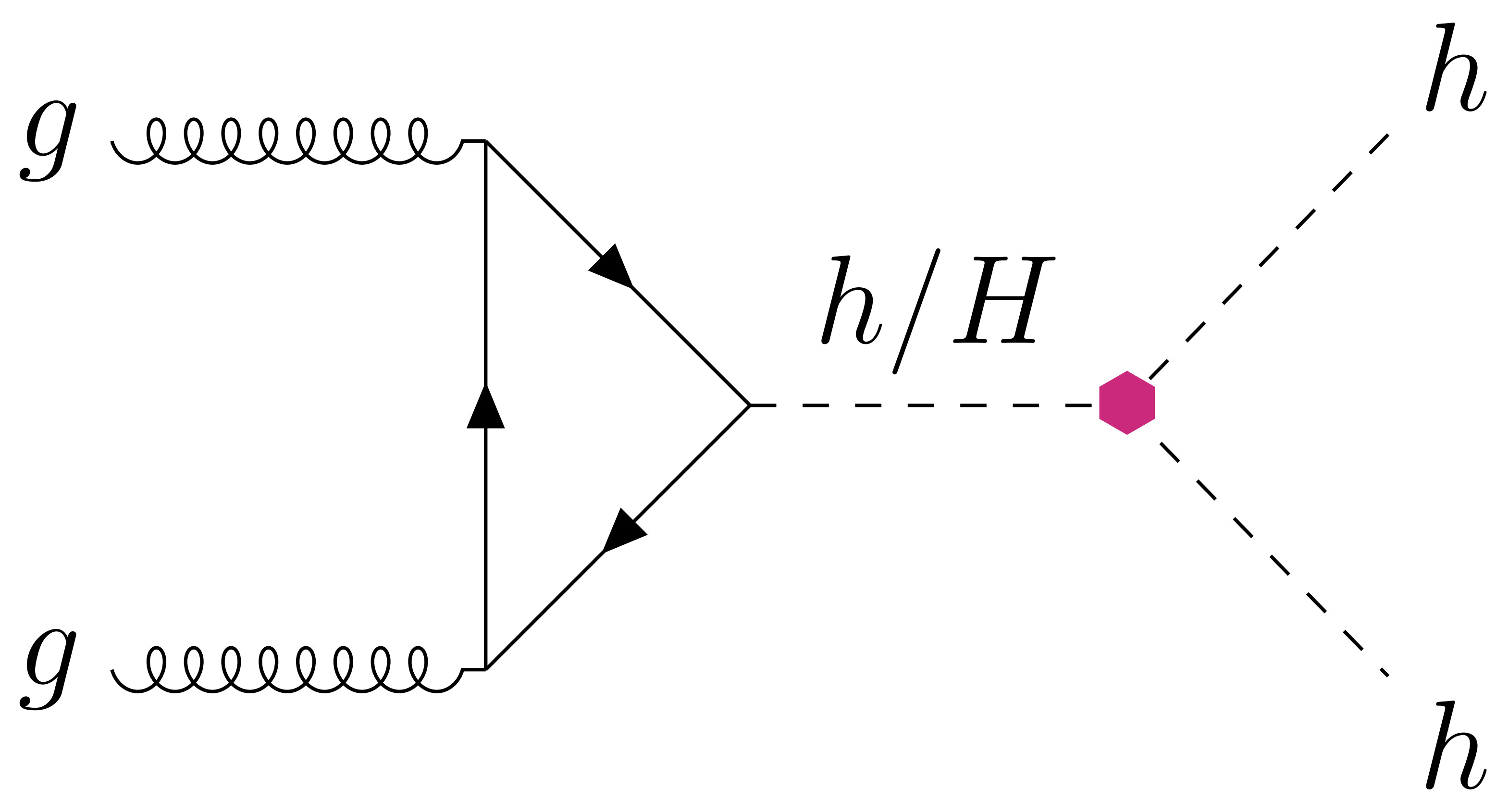




+ $Z \to \nu\bar{\nu}$ diagrams

HADRON COLLIDERS

(ongoing work)



hh but also hH, HH and AA production at e^+e^- colliders was studied

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 structure: we only consider mainly 2HDM type I in this talk

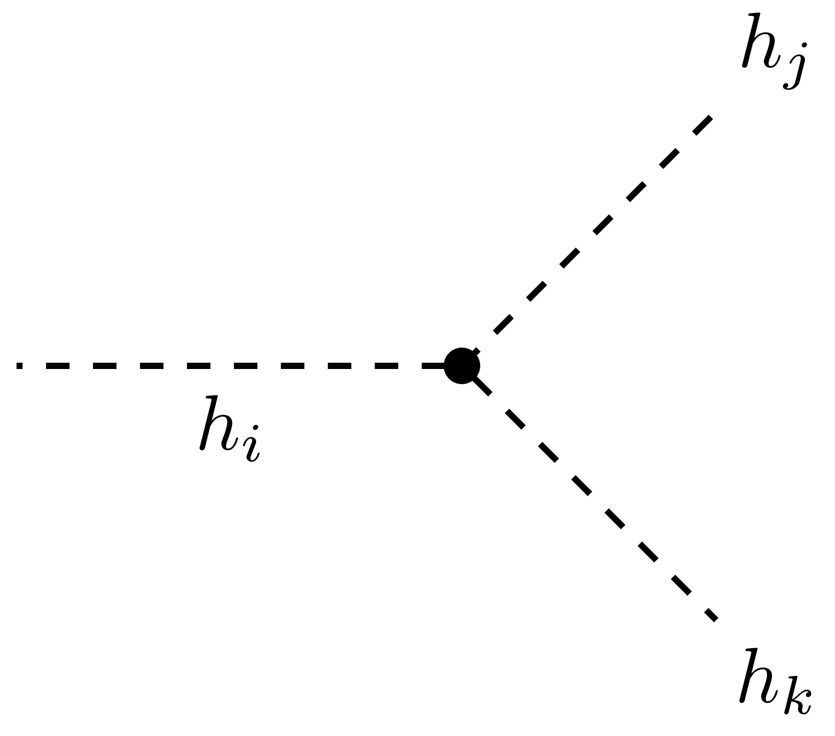
INPUT PARAMETERS:

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

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

Triple Higgs Couplings (THC)

Coupling definition



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

and

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

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
  - Usually 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 to enlarge the allowed region
- 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 $\mathrm{BR}(B_s \to \mu\mu)$

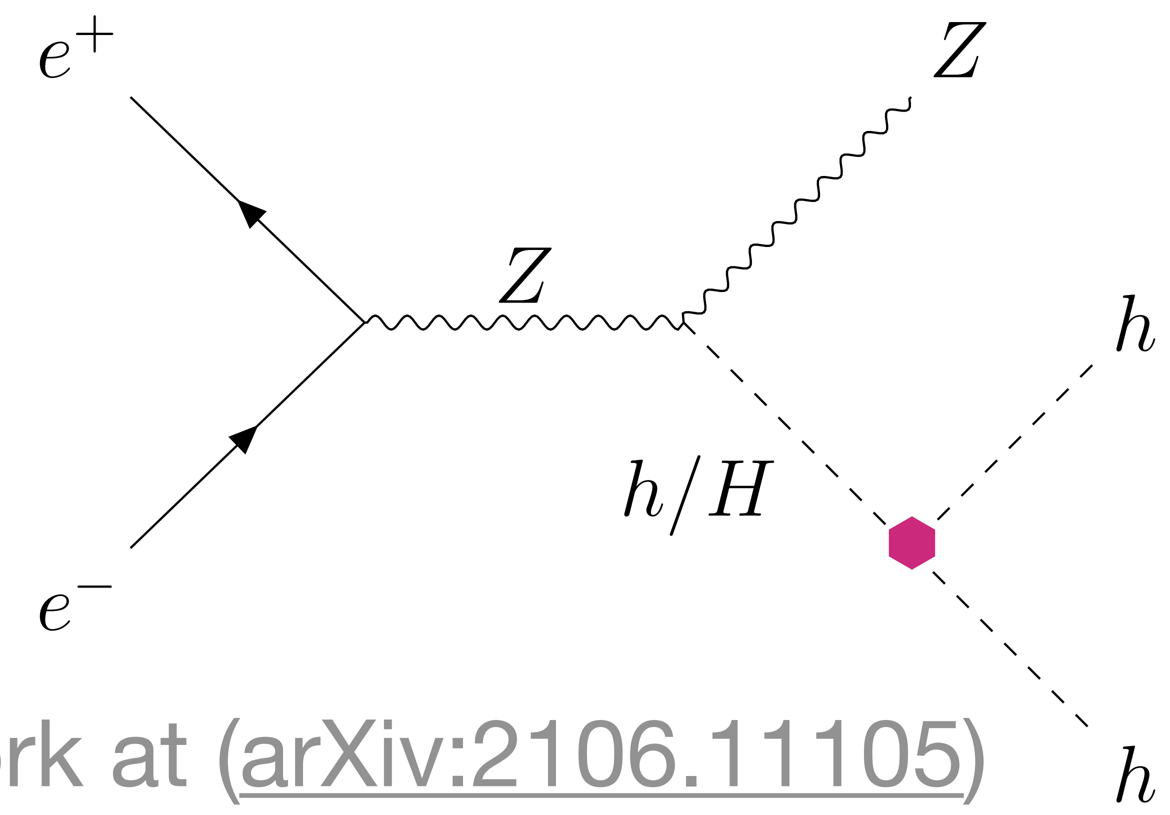
2HDMC, HiggsBounds, HiggsSignals and superISO were used

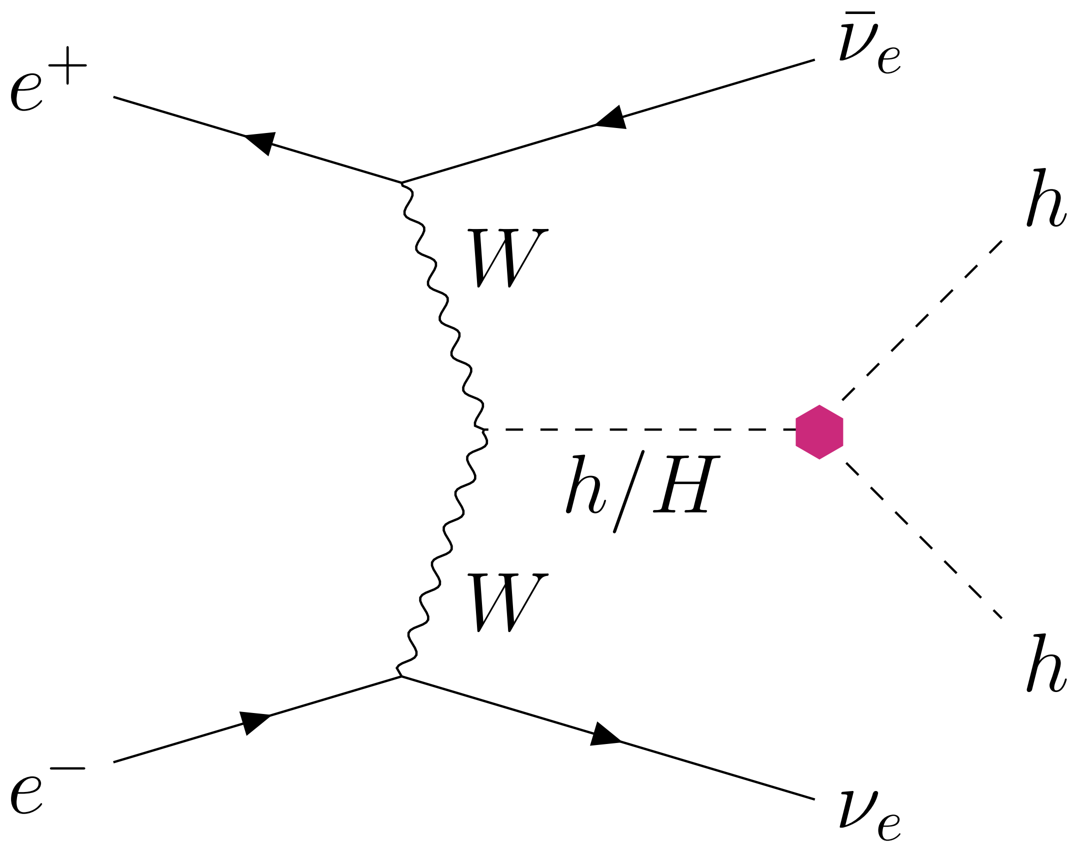
Methodology

XS presented in some **benchmark planes** with large (and allowed) THC (2005.10576, updated 2203.12684)

e^+e^- COLLIDER PRODUCTION: hhZ and $hh\nu\bar{\nu}$

- Tree level calculation: `Madgraph` + `FeynRules`
  - Study for ILC and CLIC (1405.0301)
- hhZ ($hh\nu\bar{\nu}$) dominates at low (large) energies
- Resonant diagrams mediated by H (w/ λ_{hhH}) and A

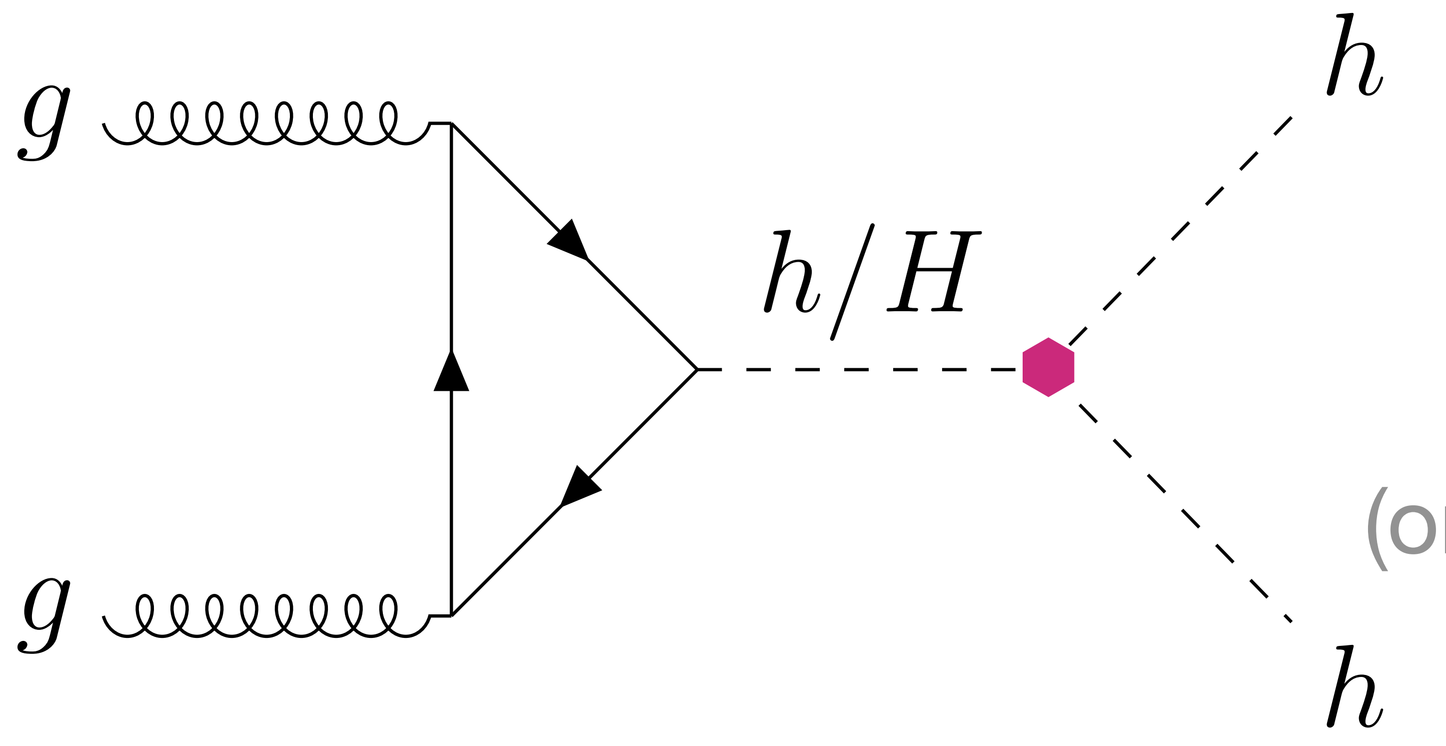




Full work at (arXiv:2106.11105)

HADRON COLLIDER PRODUCTION: Gluon fusion

- NLO calculation in the heavy top limit: `HPAIR` (1504.06577)
  - Study for HL-LHC
- Resonant diagrams mediated only by H (w/ λ_{hhH})

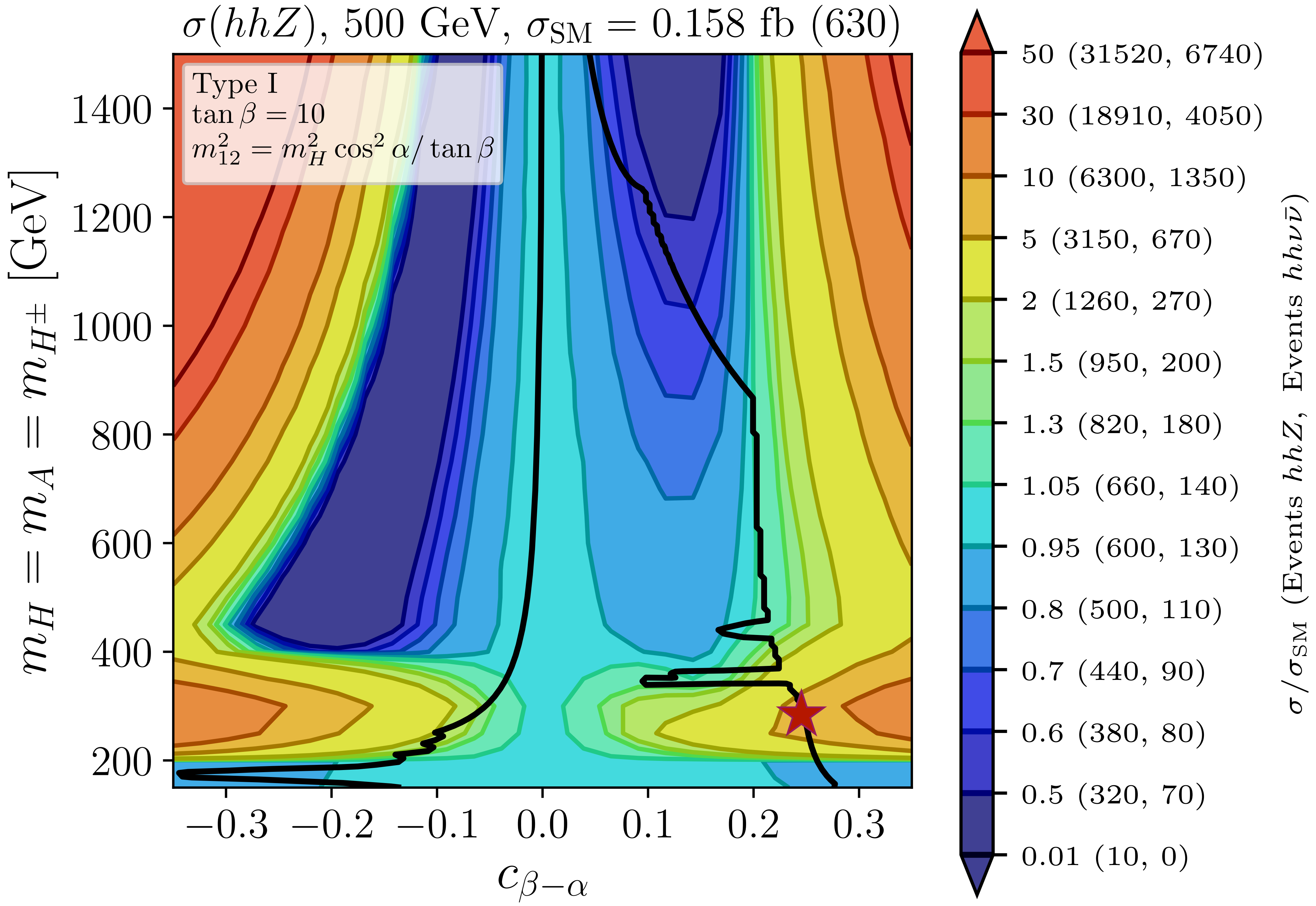


(ongoing work)

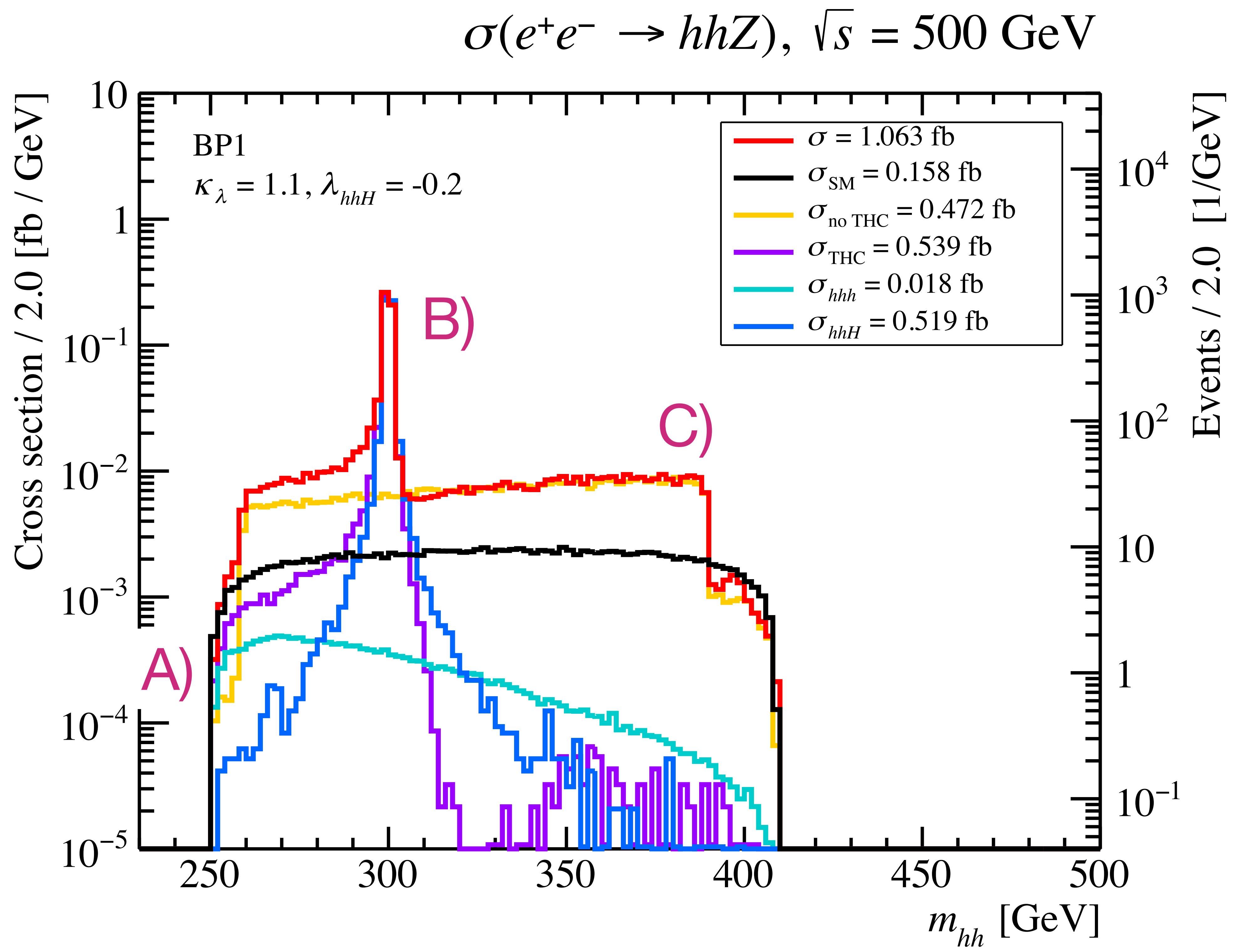
- Access to THC via XS distributions on the **invariant mass** m_{hh}
- **ALL** diagrams included (**no NWA!**)

For both colliders, in the alignment limit $\kappa_\lambda = 1$ and $\lambda_{hhH} = 0$, then $\sigma_{\rm 2HDM} = \sigma_{\rm SM}$

hhZ production, ILC 500GeV (type I)



Black lines are the boundaries to the total allowed region



Type I
$m = 300$ GeV
$\tan\beta = 10$
$c_{\beta-\alpha} = 0.25$
$$m_{12}^2 = \frac{m_H^2 \cos^2\alpha}{\tan\beta}$$

- hhZ is the dominant channel at this energy
- $\sigma(hhZ) \sim 7\sigma_{\rm SM} = 1$ fb for low masses due to H and A resonances

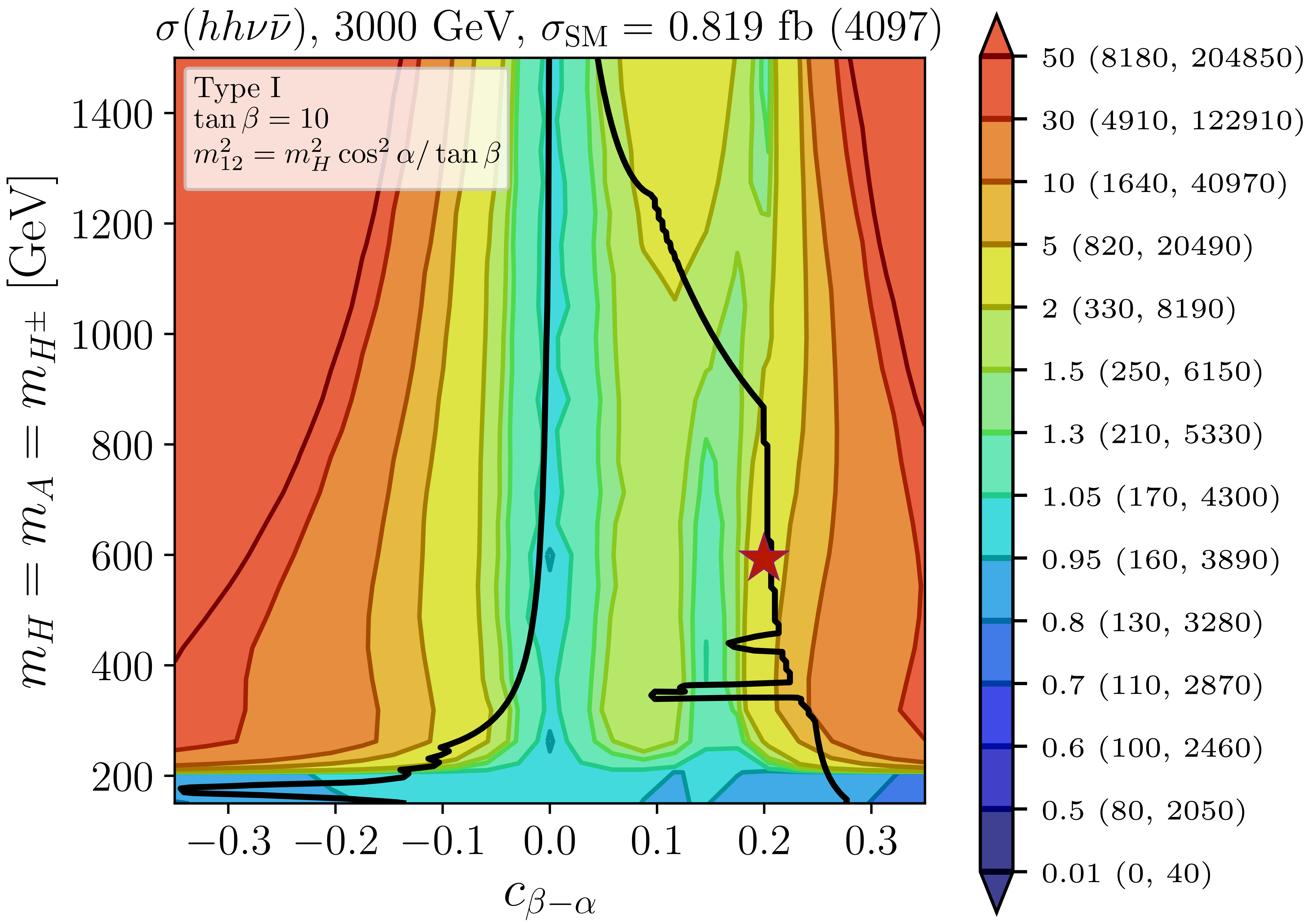
A) Main effect from κ_λ at the threshold of m_{hh}

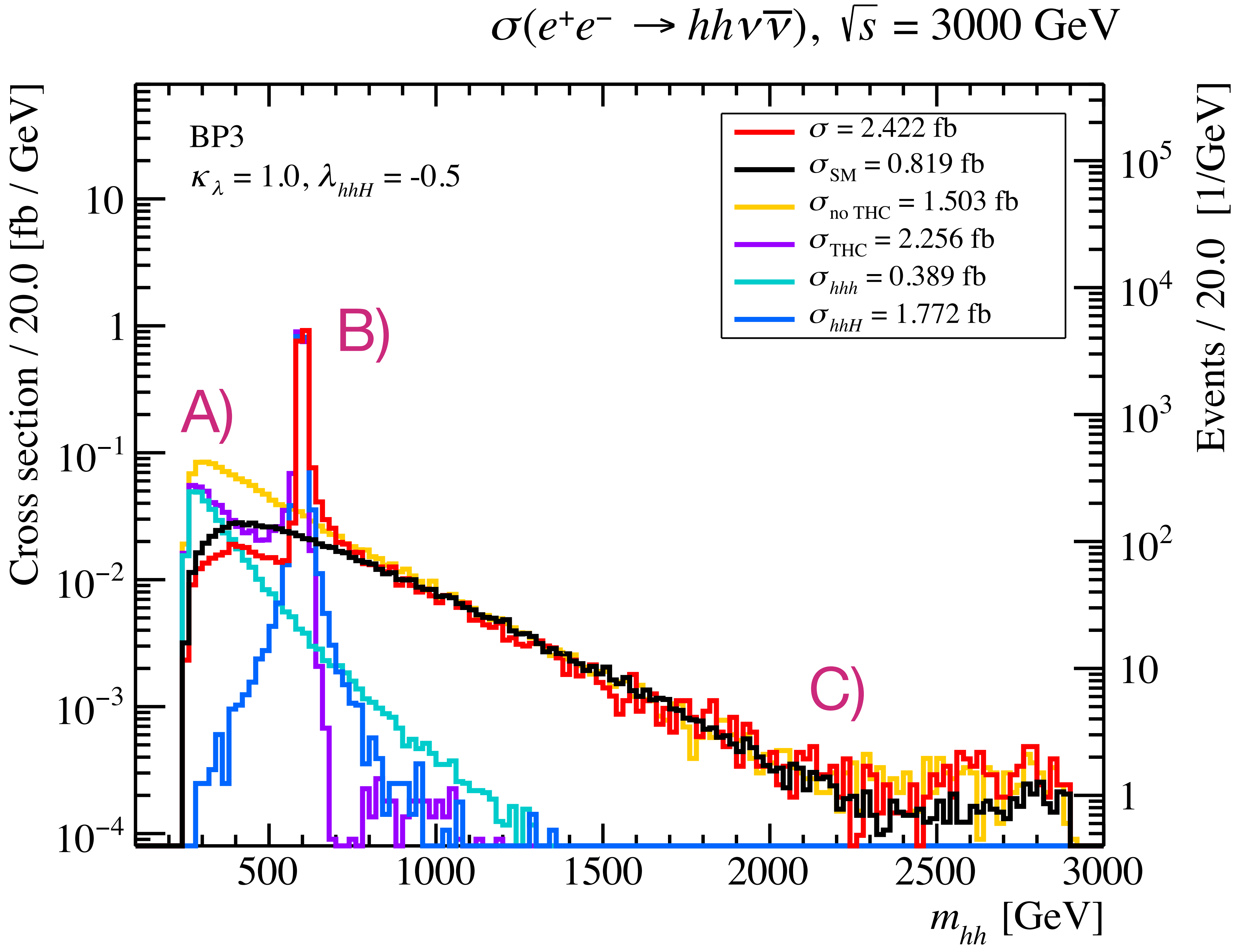
B) H resonance when $m_{hh} \sim m_H \to$ access to λ_{hhH}

Asymmetry around the H resonance $\to \lambda_{hhH}$ sign!

C) Plateau wrt the SM from A resonance (without THC)

$hh\nu\bar{\nu}$ production, CLIC 3TeV (type I)





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

Black lines are the boundaries to the total allowed region

- $hh\nu\bar{\nu}$ is now the dominant channel
- $\sigma(hh\nu\bar{\nu}) \sim 10\sigma_{SM} = 9$ fb at low masses and $\sim 3\sigma_{SM}$ for a wide range of masses

A) Main effect from κ_λ at the threshold of m_{hh}

B) H resonance when $m_{hh} \sim m_H \to$ access to λ_{hhH}

Asymmetry around the H resonance $\to \lambda_{hhH}$ sign!

C) No sign from A resonance!

$hh\nu\bar{\nu}$ production, CLIC 3TeV, THC (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)

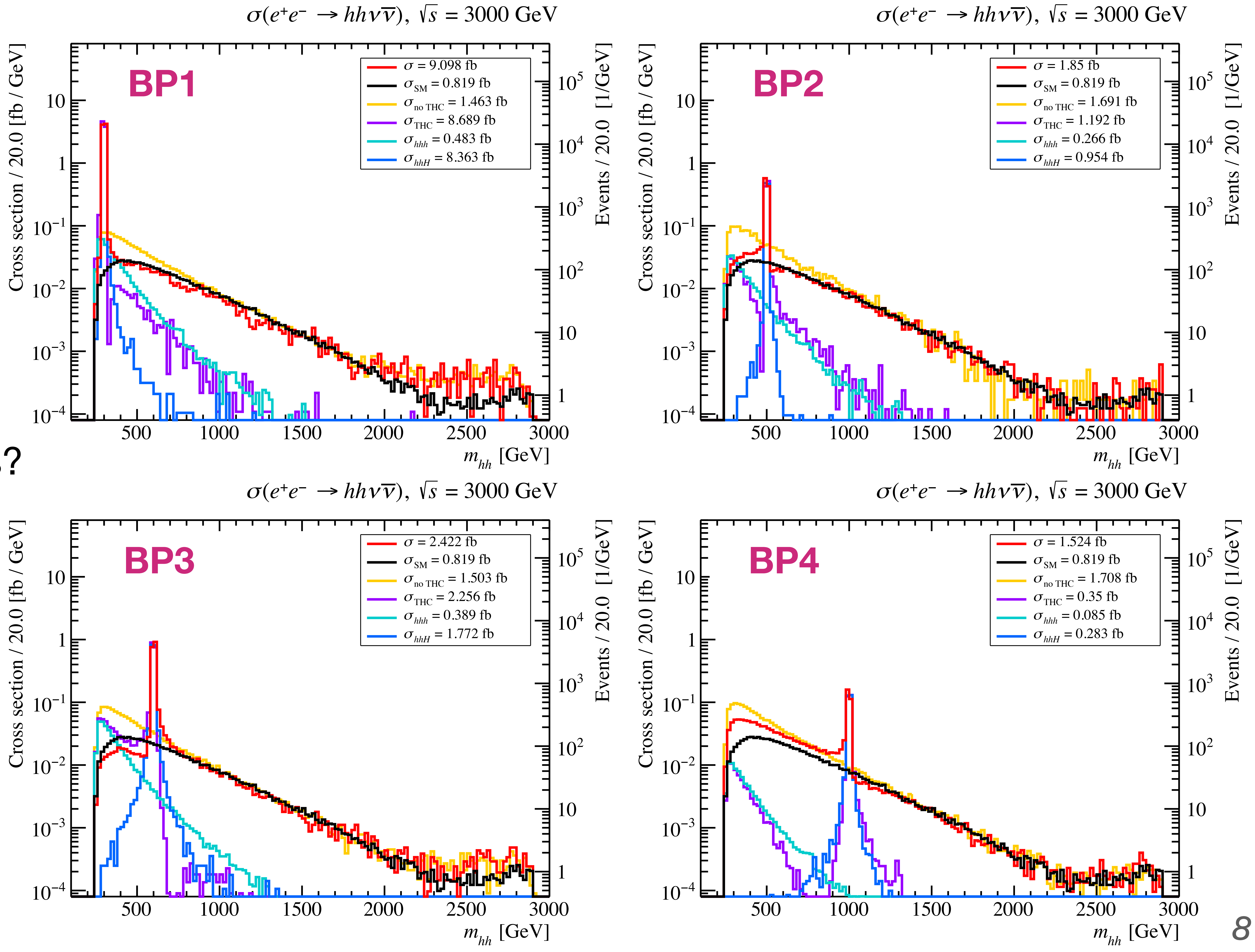
(Eq. (8) $\rightarrow m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$)

$\Longrightarrow$ Which collider and channel are best suited to access to λ_{hhH} at e^+e^- colliders?

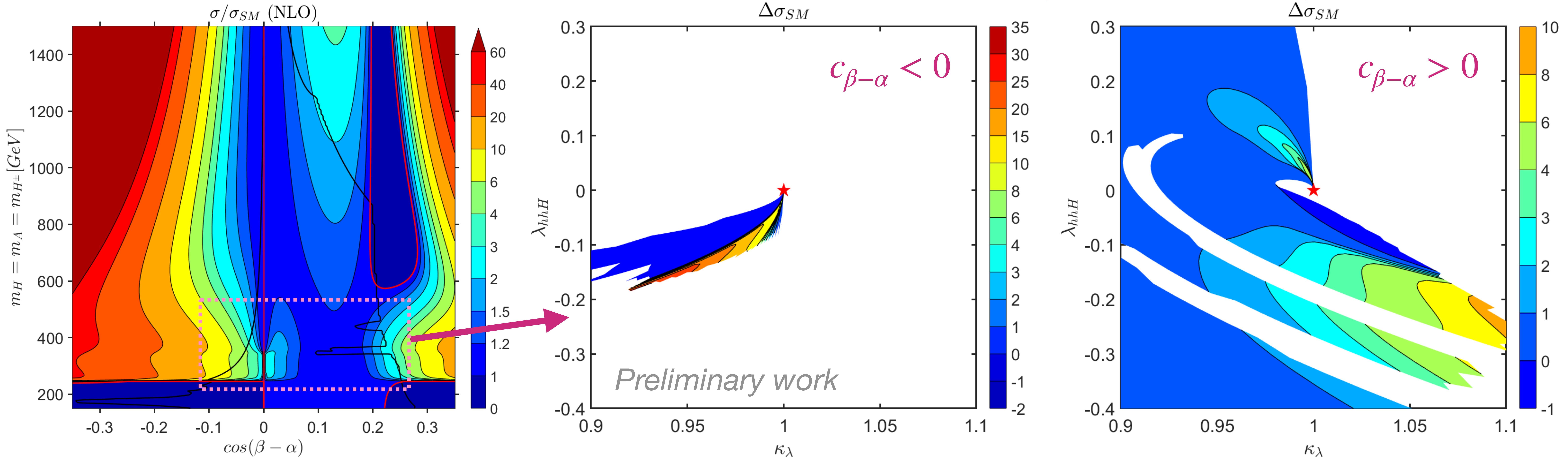
We estimated the final $4b$-jets events around the resonant peak (without backgrounds) and we found large "sensitivity" to λ_{hhH} at:

- $hh\nu\bar{\nu}$, specially at CLIC 3 TeV
- $hh\nu\bar{\nu}$ and hhZ for low m_H at ILC

More details at arXiv:2106.11105



hh production, HL-LHC (type I)



Black lines are the boundaries to the total allowed region

$$\Delta\sigma_{\rm SM} = \frac{\sigma_{\rm 2HDM} - \sigma_{\rm SM}}{\delta\sigma} \quad \text{with} \quad \delta\sigma = \sigma_{\rm SM}/4.5$$

the actual projected significance at HL-LHC for $\kappa_\lambda = 1$ (1910.00012)

- $\sigma(hh) \sim 8\sigma_{\rm SM} \sim 300$ fb for $c_{\beta-\alpha} < 0$ and low masses due, in part, to H resonant diagrams
- K-factors $= \sigma_{\rm NLO}/\sigma_{\rm LO} \sim 2$

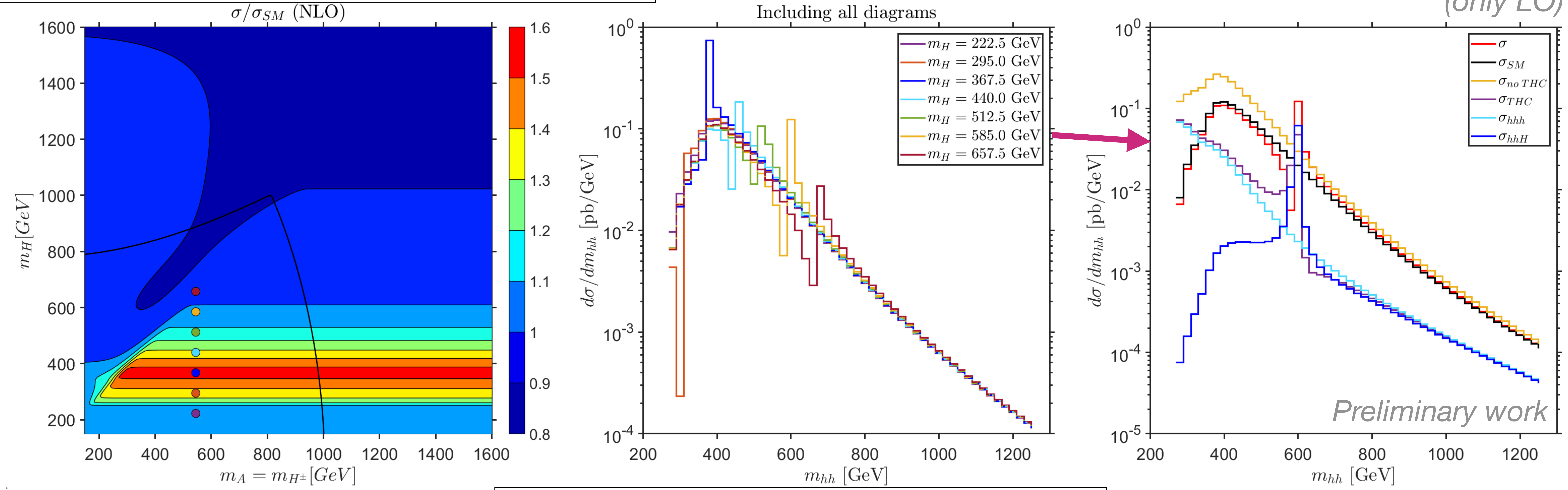
- Slight dependence on λ_{hhH} but strong dependence on κ_λ (also in other scenarios)
- Possible access thanks to the large luminosity of HL-LHC???

hh production, HL-LHC, THC (type I)

- Larger κ_λ effect, again, at the m_{hh} threshold
- Access H resonances at $m_{hh} = m_H$ for different values of m_H → info about λ_{hhH}
- Large asymmetry around the H resonant peak → sign of λ_{hhH}

Black lines are the boundaries to the total allowed region

(only LO)



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

Summary & Conclusions

- The hh production is studied at future e^+e^- colliders and at the HL-LHC in the 2HDM type I, with the aim to find **effects coming from BSM triple Higgs couplings (THC):** Only sizable distortions at **2HDM type I**
- From κ_λ, at low invariant mass of the hh pair, similar to what happens in the SM
- From λ_{hhH}, through a H boson resonant peak:
  - At e^+e^- **COLLIDERS:**
    - A study of the final 4 b-jets events shows that $hh\nu\bar{\nu}$ channel is better to access to λ_{hhH} at large energies (specially CLIC 3TeV), but large #events at ILC energies for a light H for $hh\nu\bar{\nu}$ and hhZ
  - At **HL-LHC:**
    - Upcoming work!! Looking for scenarios with larger sensitivity to λ_{hhH}
- Effects from THC in $hH\nu\bar{\nu}$, $HH\nu\bar{\nu}$ and $AA\nu\bar{\nu}$ at e^+e^- colliders could be seen at CLIC 3TeV, see [arxiv:2106.11105]!

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

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 $\kappa_\lambda \neq 1$

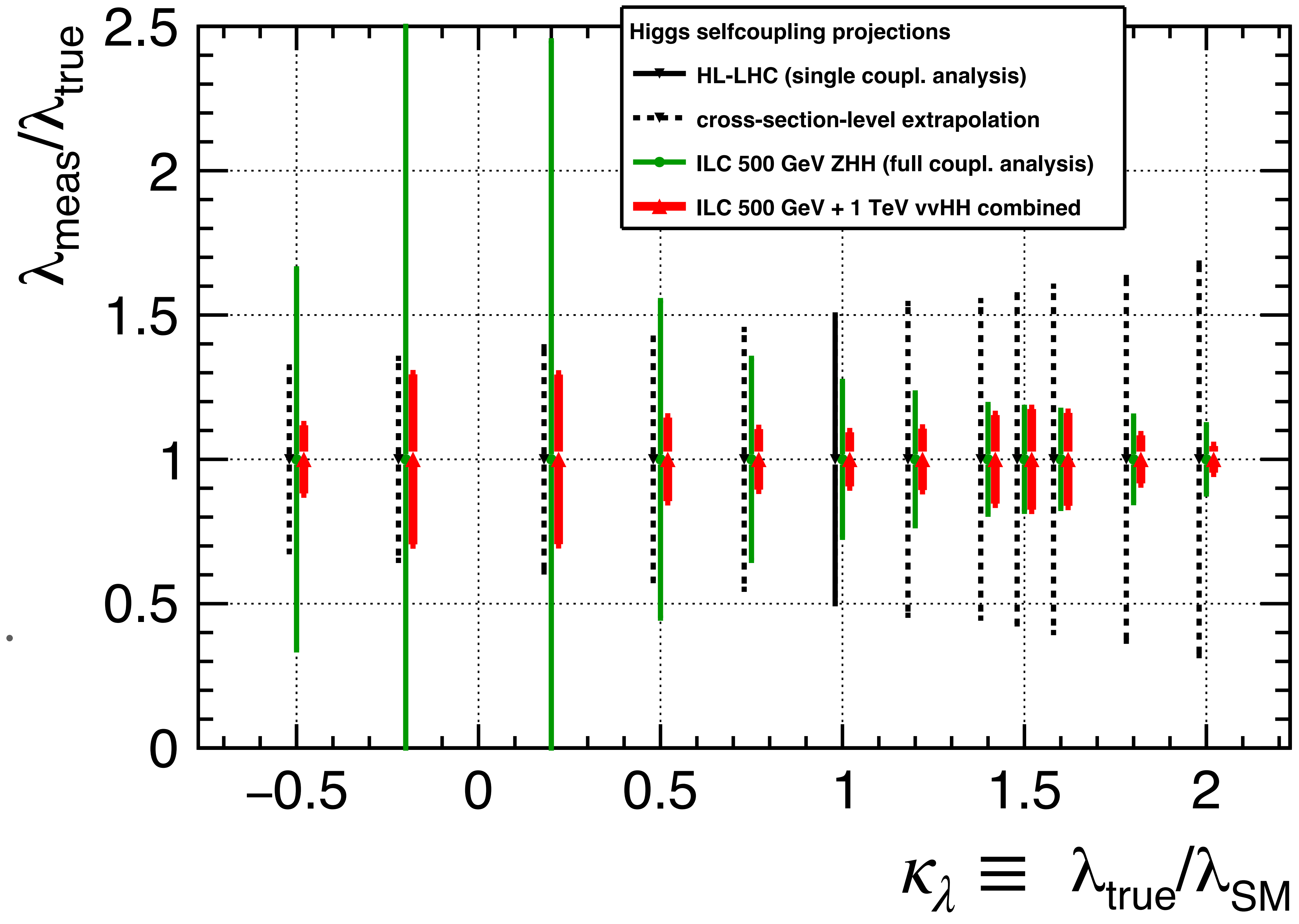
Future e^+e^- colliders will play a crucial role to measure λ_{hhh}, but…

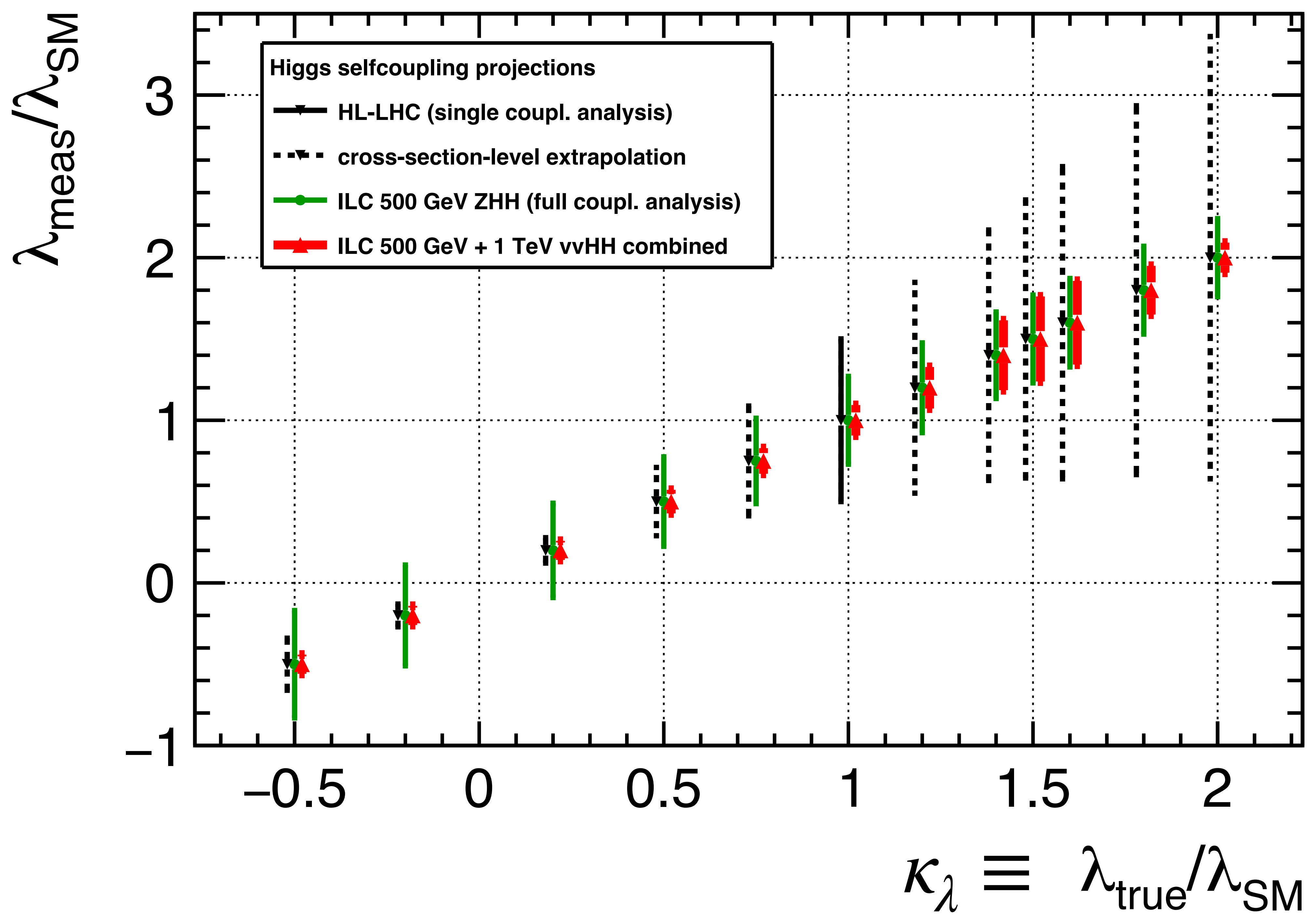
There is room for SM deviations in the scalar sector !!!

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)

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 $hh\nu\bar{\nu}$

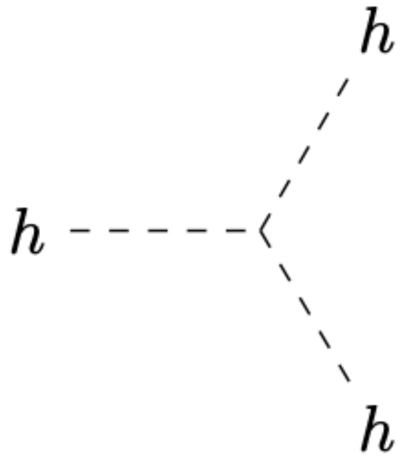
More sensitivity to λ_{hhH} (i.e. larger R) in $hh\nu\bar{\nu}$, specially at CLIC 3 TeV
But good prospects for BP1 at ILC at both channels

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	-

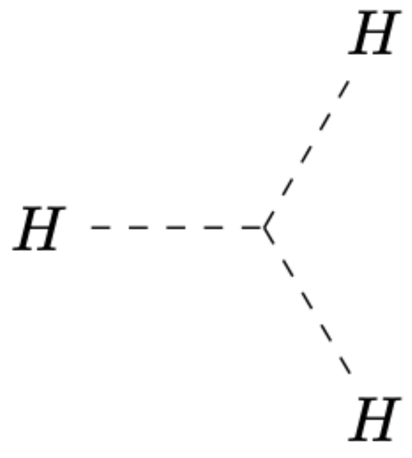
$hh\nu\bar{\nu}$	$\sqrt{s}$ [GeV]	$\sigma_{\rm 2HDM}$ / $\sigma_{\rm SM}$ [fb]	$\bar{N}^R_{4b\not{E}_T}$ / $\bar{N}^C_{4b\not{E}_T}$ / $\bar{N}^{\rm SM}_{4b\not{E}_T}$	$R_{4b\not{E}_T}$
BP1	500	0.404 / 0.034	119 / 4 / 1	58
	1000	2.391 / 0.097	1510 / 24 / 0	303
	1500	4.423 / 0.239	794 / 13 / 2	217
	3000	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]

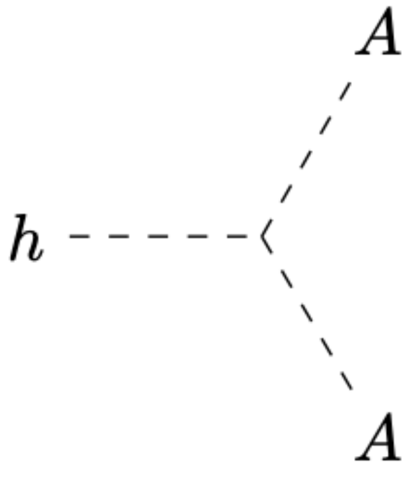
Back-up, Feynman Rules with THC



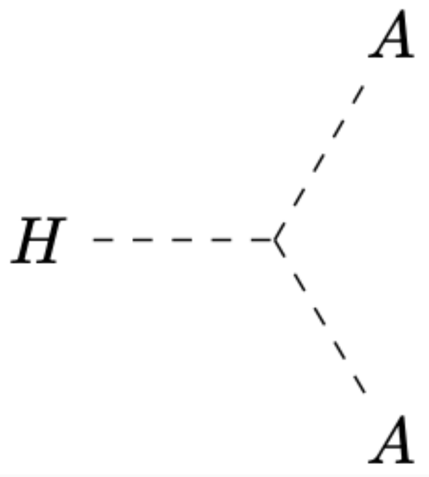
$$= -\frac{3i}{v}\left(2\cot 2\beta\left(m_h^2 - \bar{m}^2\right)c_{\beta-\alpha}^3 + \left(3m_h^2 - 2\bar{m}^2\right)c_{\beta-\alpha}^2 s_{\beta-\alpha} + m_h^2 s_{\beta-\alpha}^3\right)$$



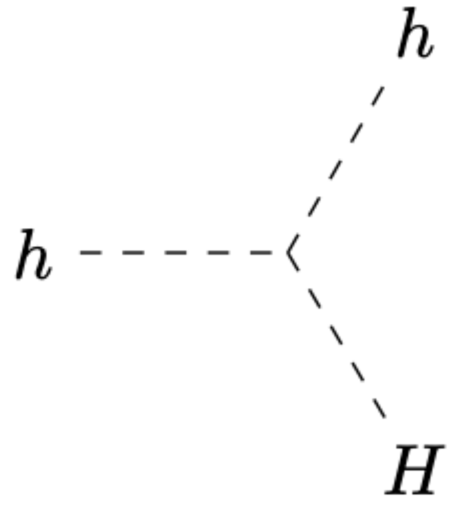
$$= -\frac{3i}{v}\left(\left(3m_H^2 - 2\bar{m}^2\right)c_{\beta-\alpha}s_{\beta-\alpha}^2 + 2\cot 2\beta\left(\bar{m}^2 - m_H^2\right)s_{\beta-\alpha}^3 + m_H^2 c_{\beta-\alpha}^3\right)$$



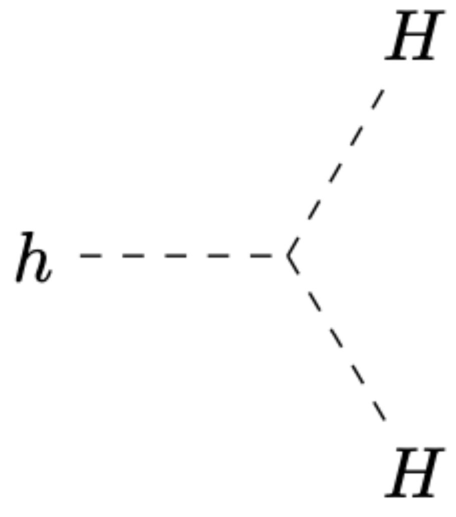
$$= -\frac{i}{v}\left(s_{\beta-\alpha}\left(-2\bar{m}^2 + 2m_A^2 + m_h^2\right) + 2\cot 2\beta\left(m_h^2 - \bar{m}^2\right)c_{\beta-\alpha}\right)$$



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



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



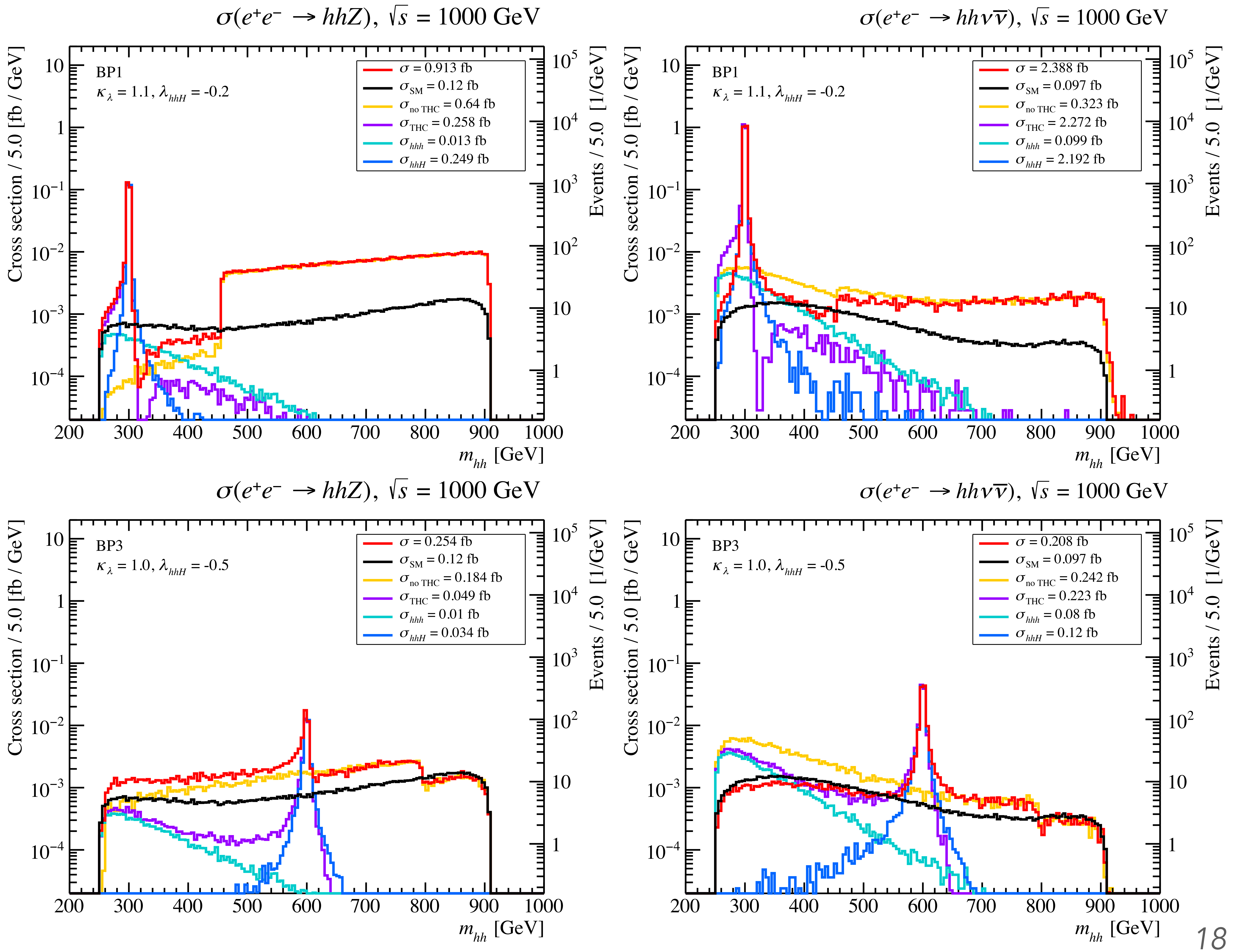
$$= -\frac{is_{\beta-\alpha}}{v}\left(\left(m_h^2 + 2m_H^2\right)\left(-c_{\beta-\alpha}^2 + 2\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha} + s_{\beta-\alpha}^2\right) - 2\bar{m}^2\left(-2c_{\beta-\alpha}^2 + 3\cot 2\beta c_{\beta-\alpha}s_{\beta-\alpha} + s_{\beta-\alpha}^2\right)\right)$$

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

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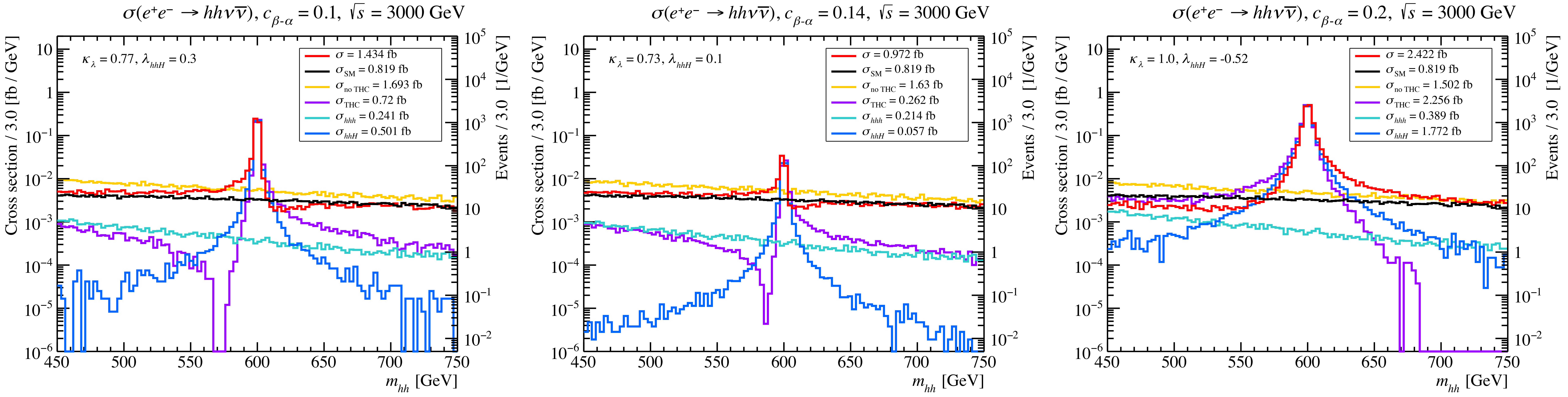
hh production, CLIC 3TeV, THC dependence (type I)

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

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



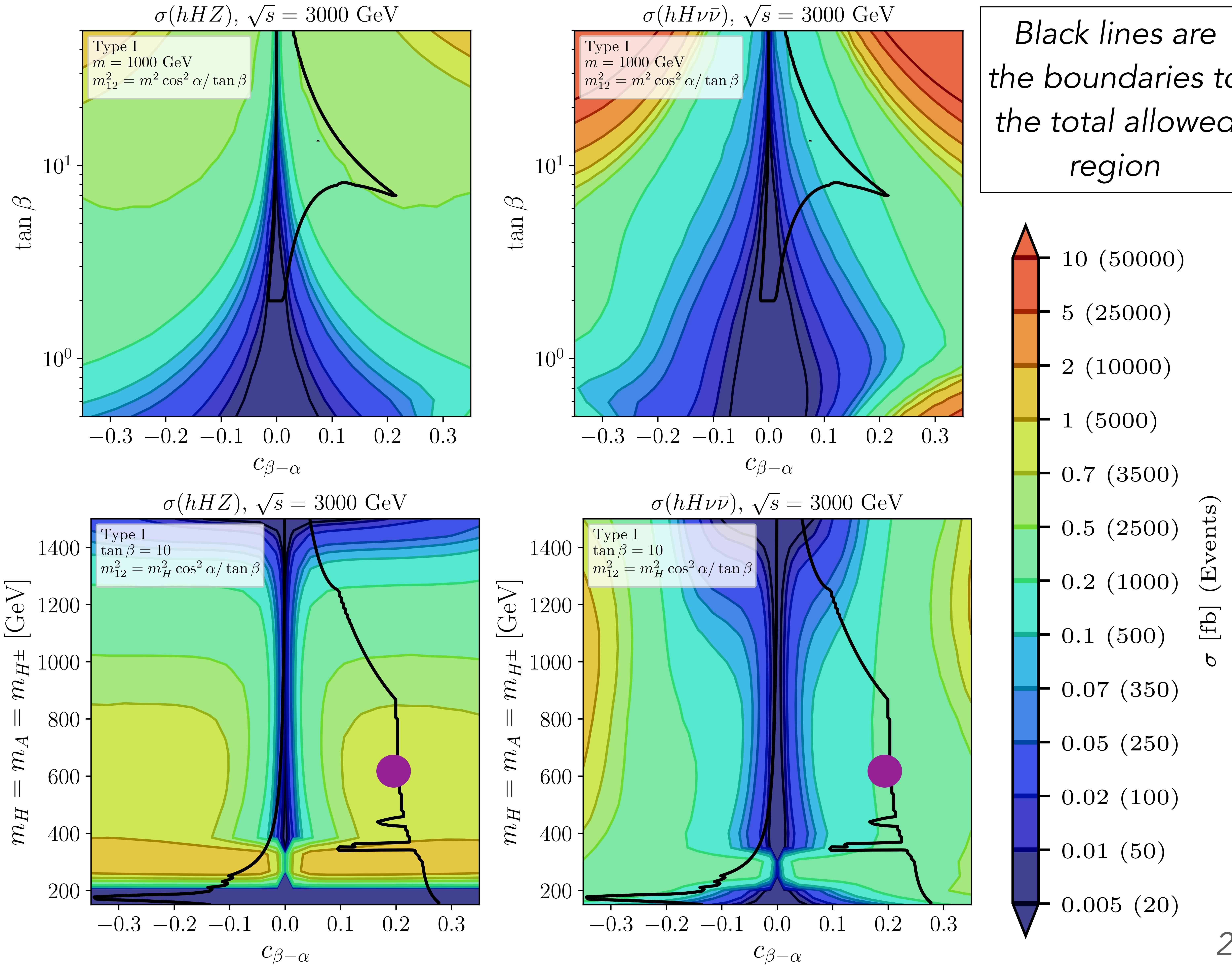
- Height of the resonance depends on λ_{hhH}
- For large $c_{\beta-\alpha}$ the resonance is wider because Γ_H is larger

$\lambda_{hhH} > 0$: 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)

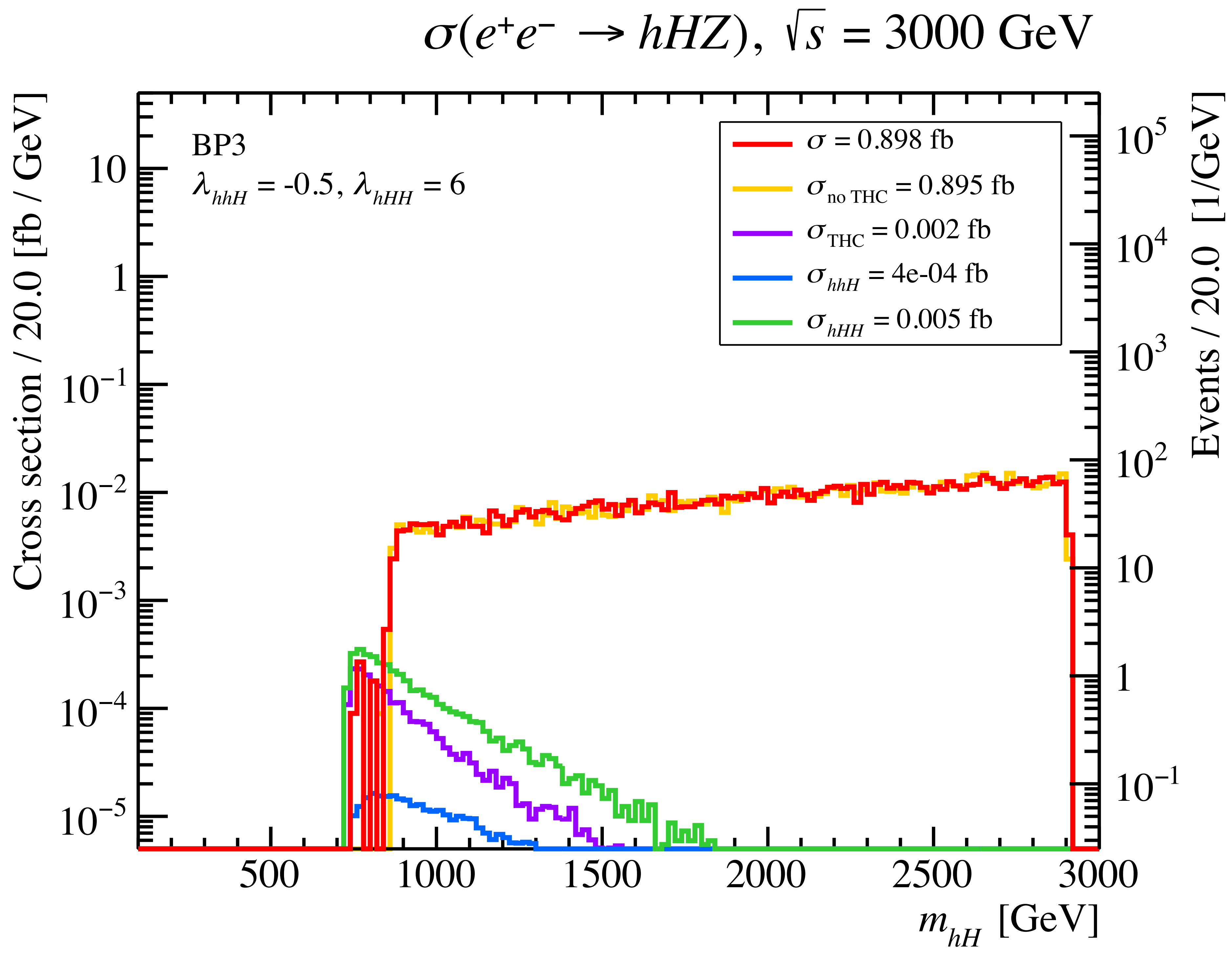
- The hH production channels disappear in the alignment limit
- Very strong contribution from resonant A diagrams in the hHZ channel
- In the neutrino channel, the effects from A mediated diagrams mixes with the effects coming from the THC (for this process: λ_{hhH} and λ_{hHH})

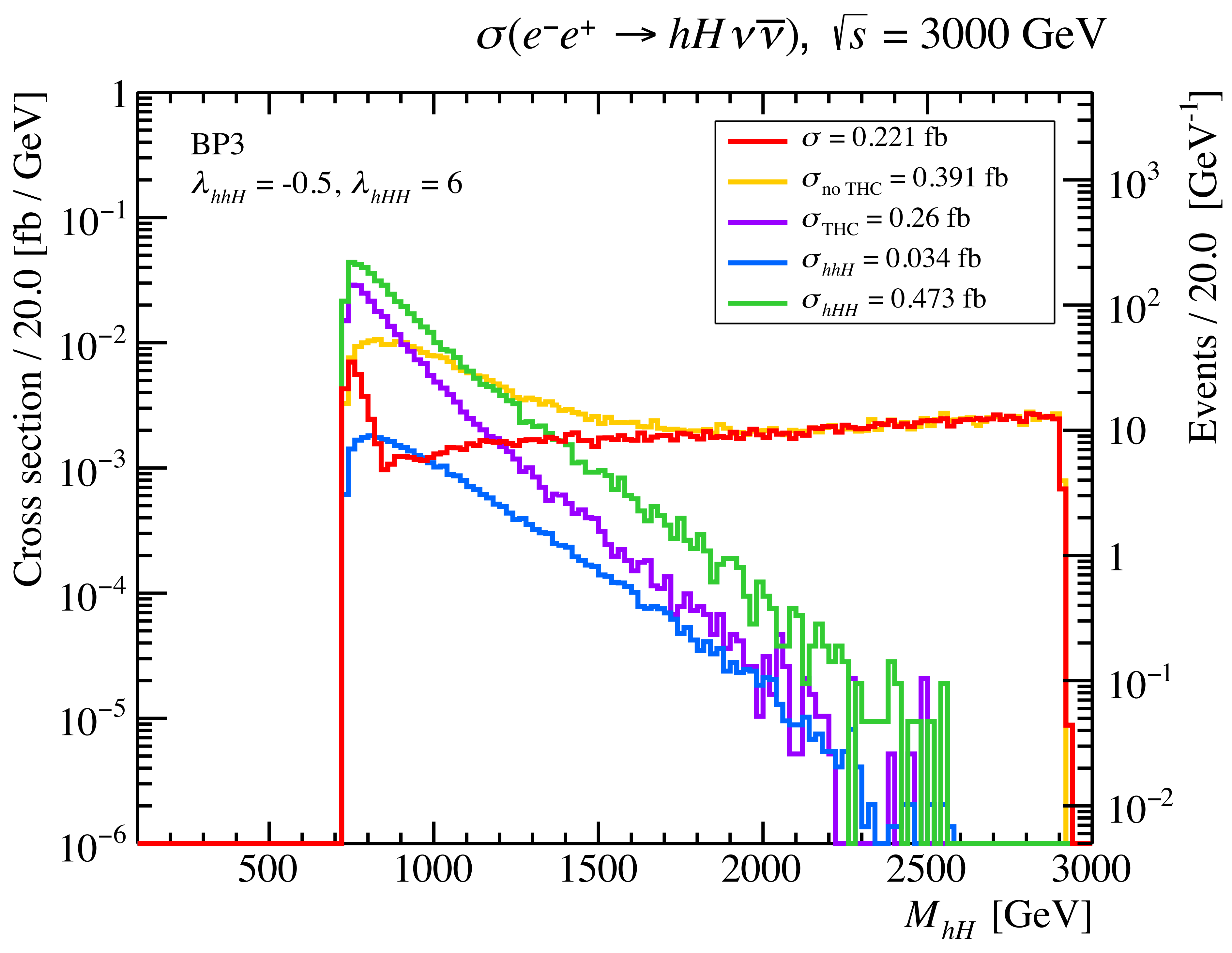


Black lines are the boundaries to the total allowed region

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

Cross section distribution on the invariant mass of hH:





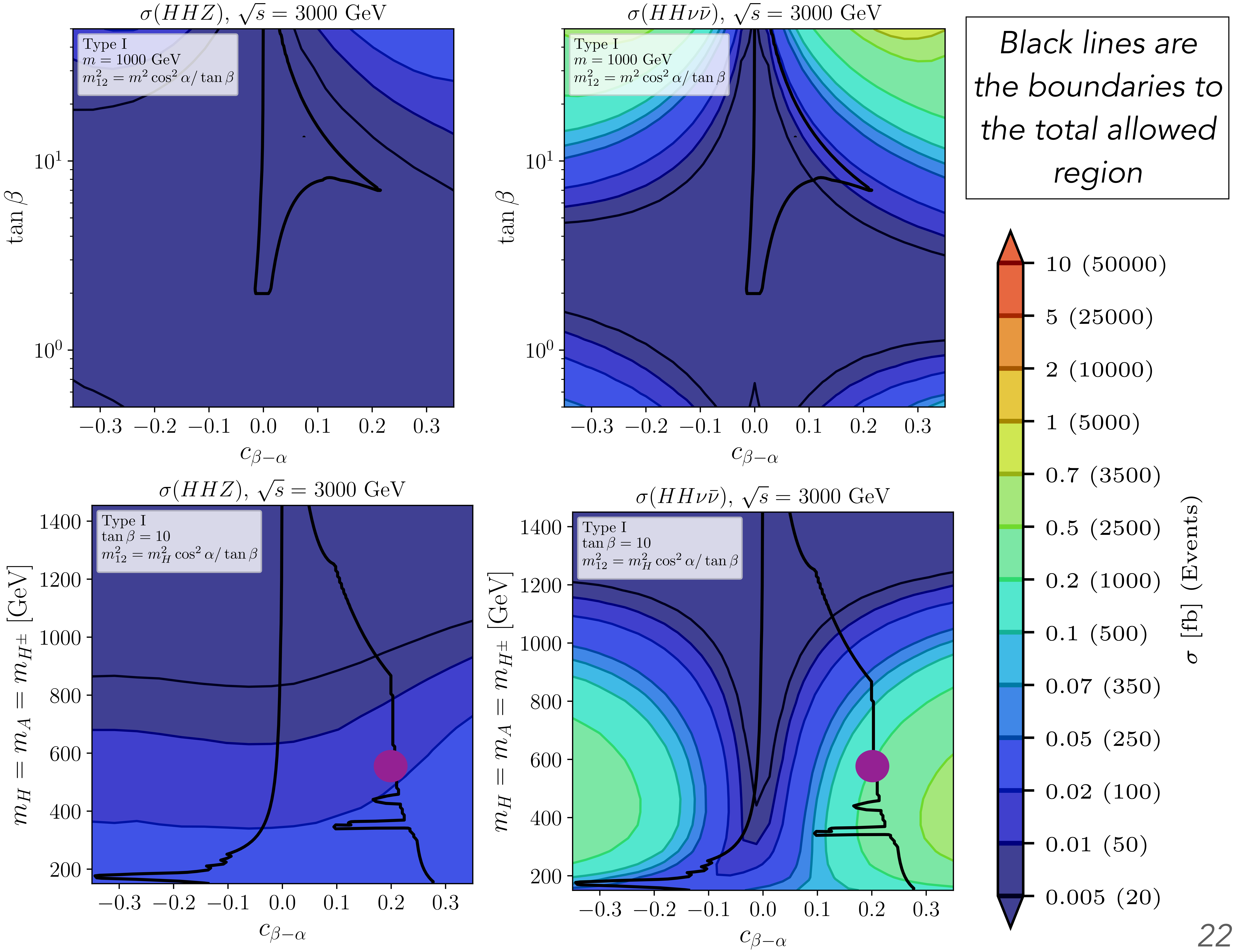
Type I
$m = 600$ GeV
$\tan\beta = 10$
$c_{\beta-\alpha} = 0.2$
$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$

- 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

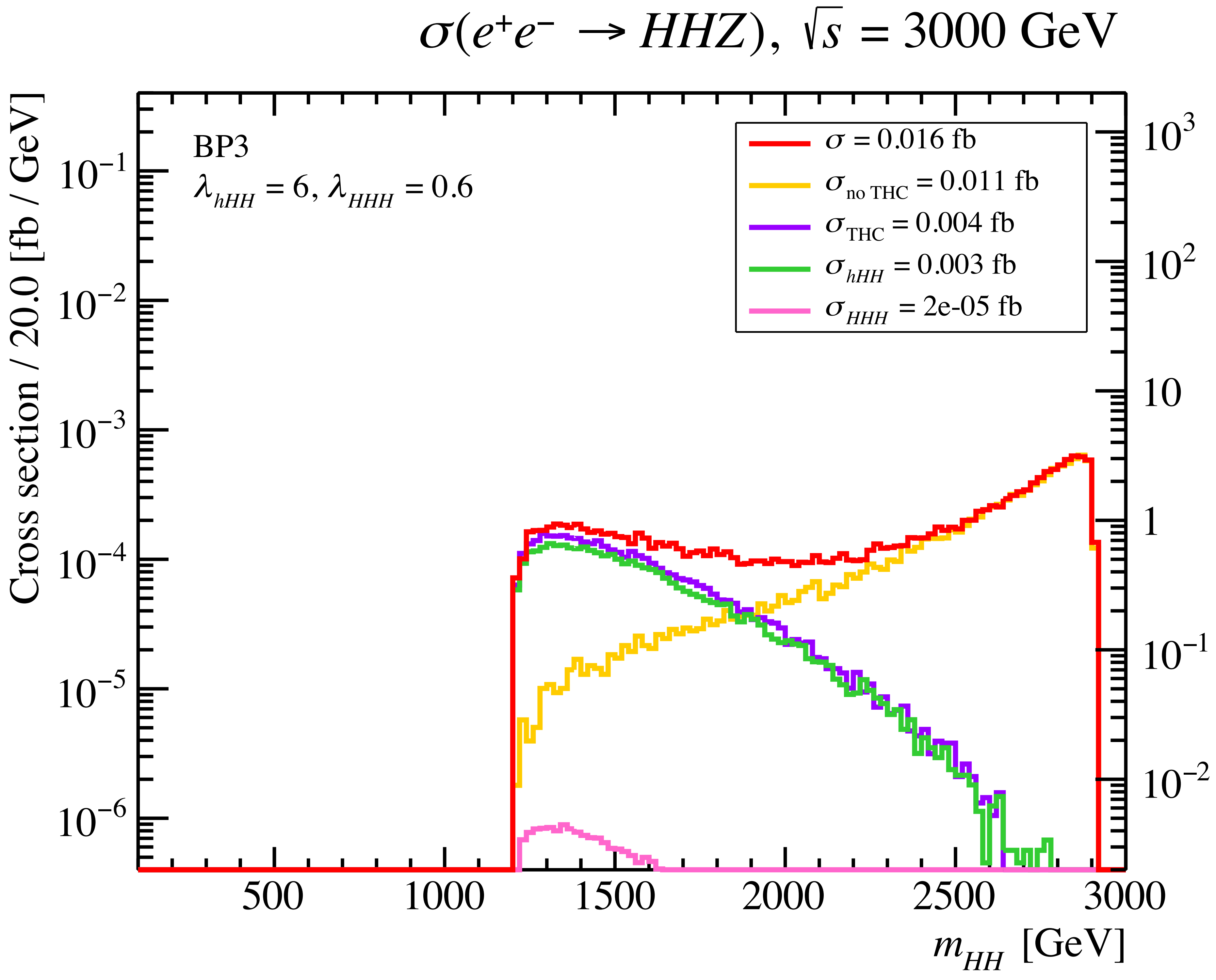
- The $HH \sim AA$ production can be non-zero even in the alignment limit ($c_{\beta-\alpha} \to 0$)
- Only sizable cross sections inside the allowed region for the neutrino channel
  - Not larger than 0.5 fb
- The sizable cross sections comes from the effect of λ_{hHH} (λ_{hAA})
  - Effects from λ_{HHH}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

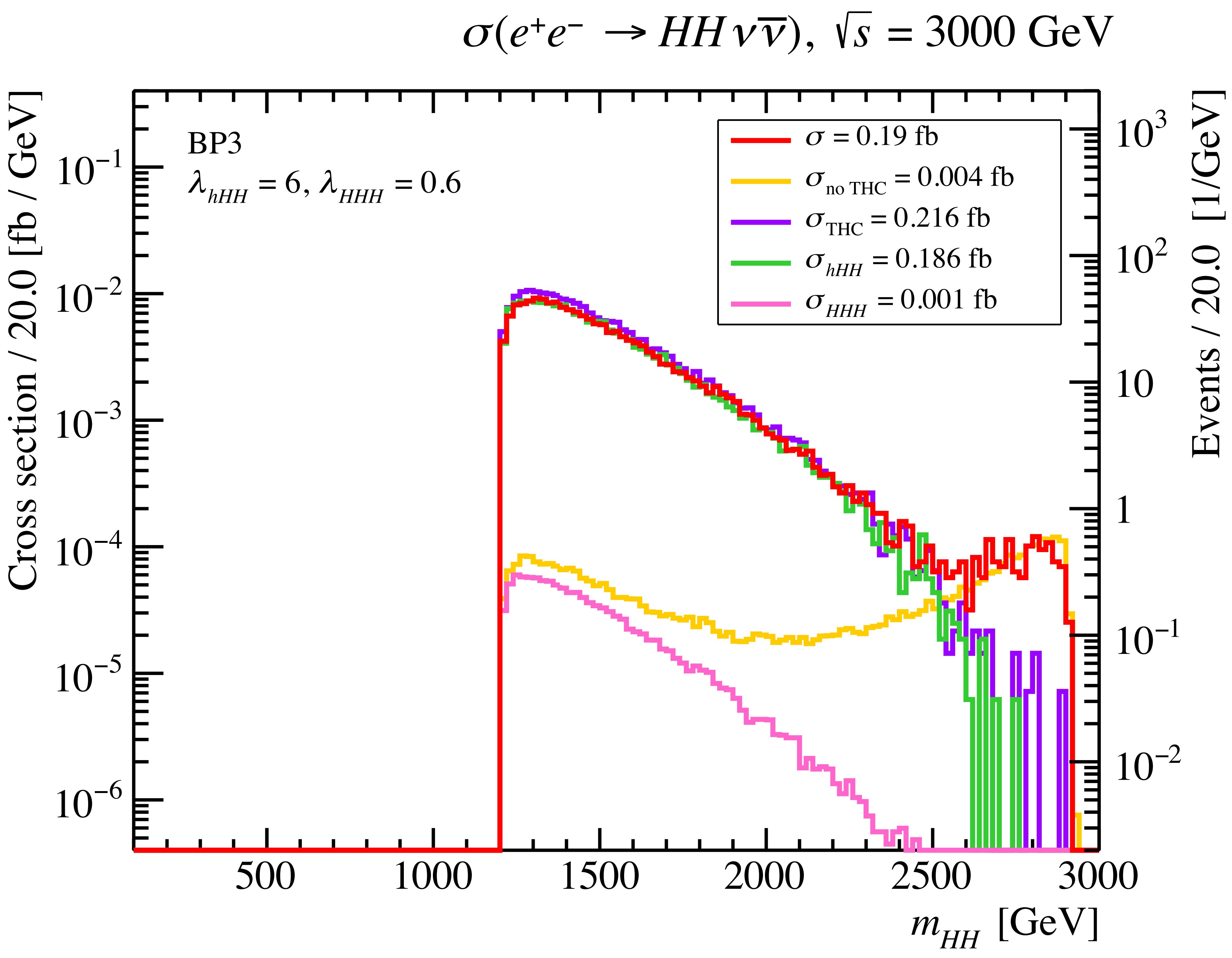
Black lines are the boundaries to the total allowed region



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

Cross section distribution on the invariant mass of HH:





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

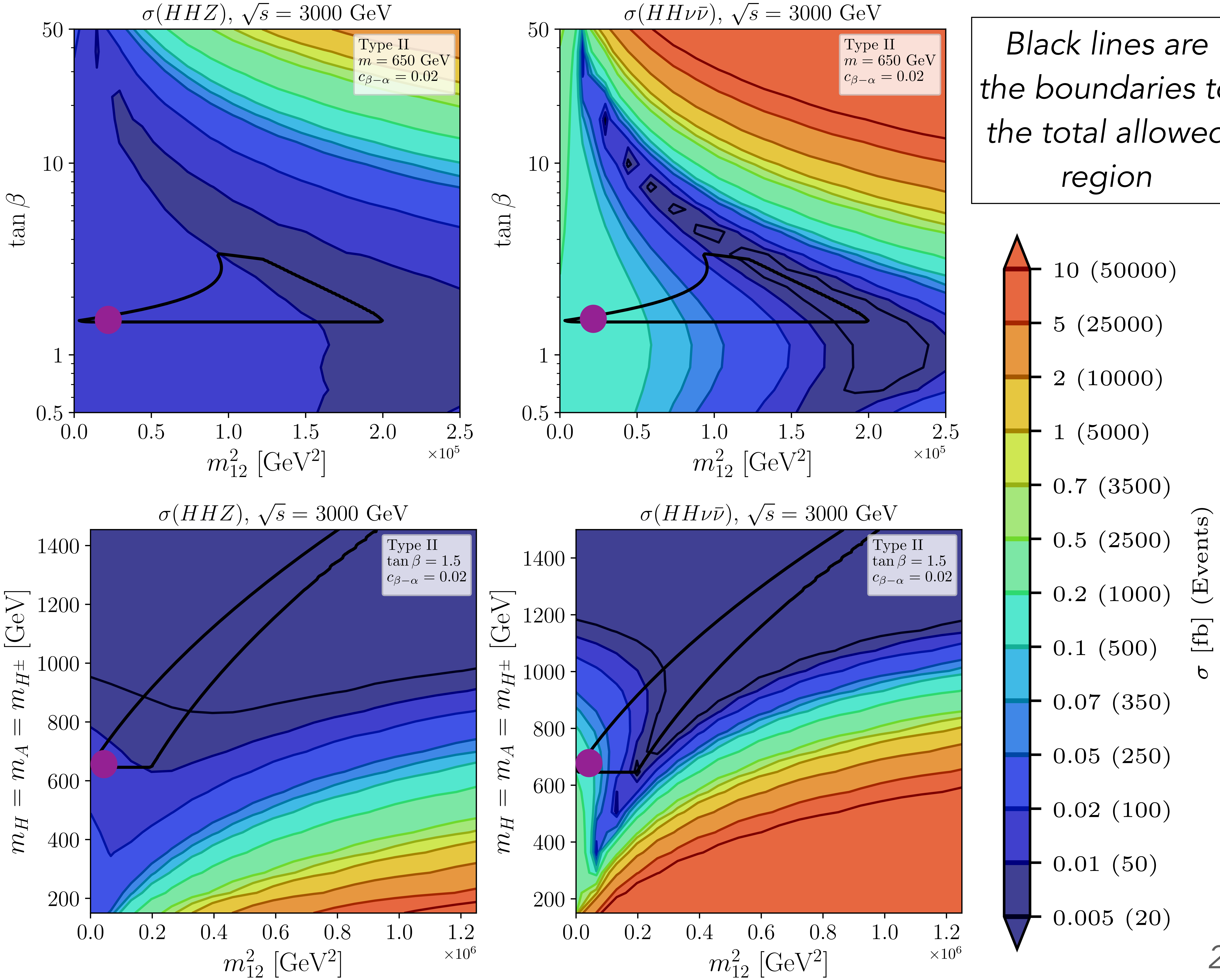
- Very small XS and number of events in the HHZ channel
- Dominant effect in $HH\nu\bar{\nu}$ comes from λ_{hHH} and it is responsible for almost all the cross section

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

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

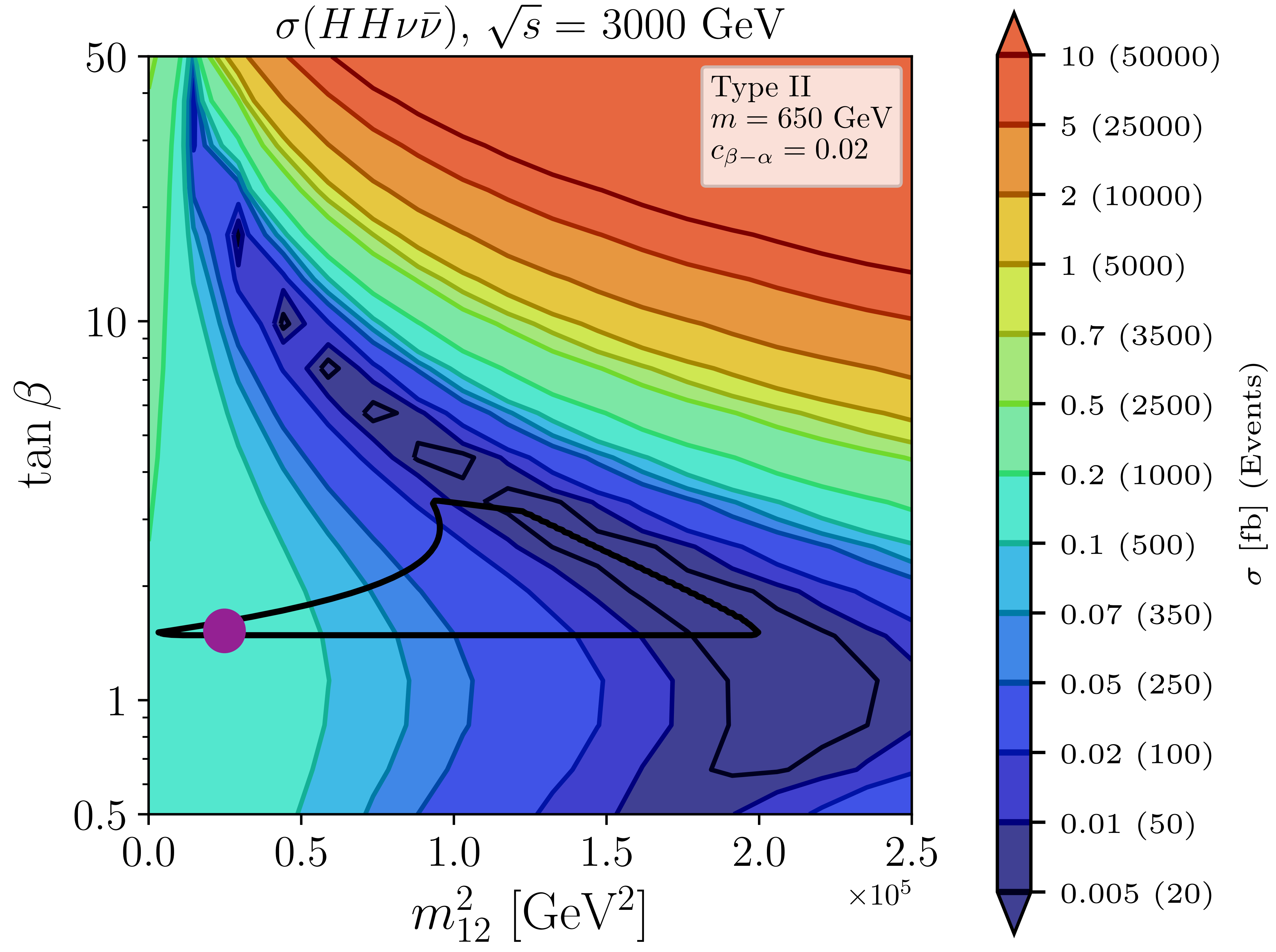
- In type II, due to the collider constraints, only $HH \sim AA$ production is relevant
- Only sizable XS, not larger than 0.5 fb, inside the allowed region for the neutrino channel
- Sizable XS comes from the effect of λ_{hHH} (λ_{hAA})
  - XS is larger at low m_{12}^2, that is the region where λ_{hHH}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

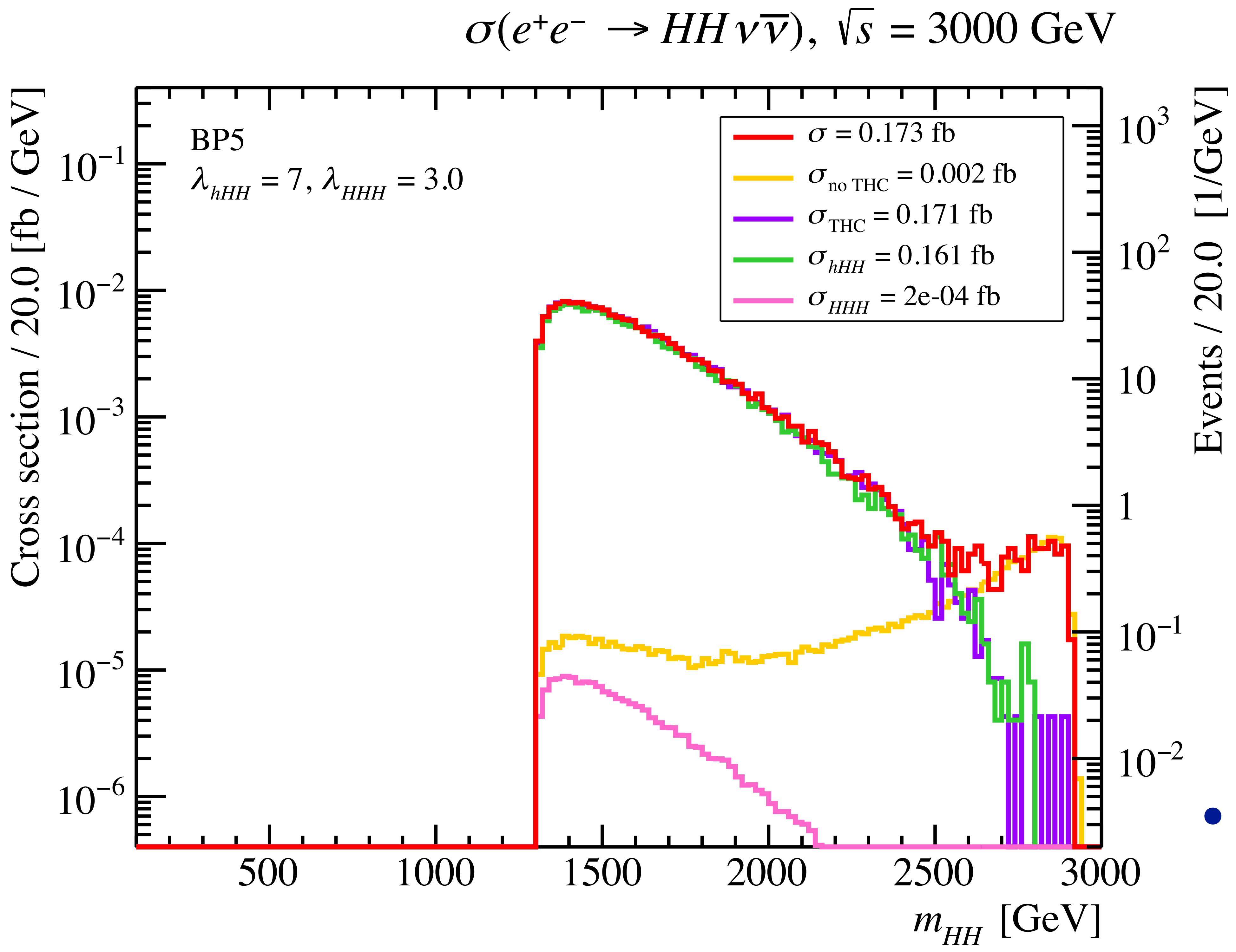
Black lines are the boundaries to the total allowed region



$HH \sim AA$ 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)