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BSM Physics in double Higgs production

Role of BSM triple Higgs couplings

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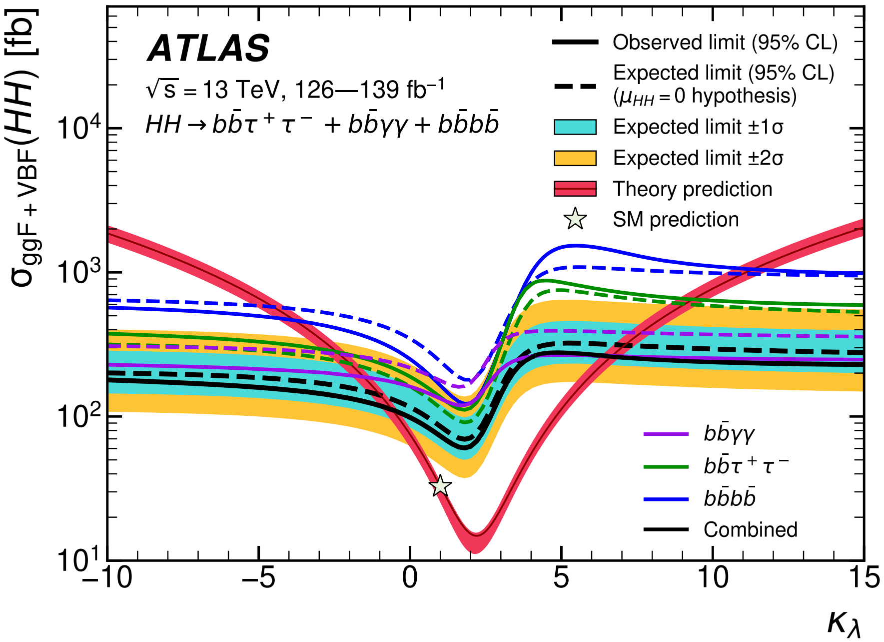
Based on:

- e^+e^- colliders: FA, S. Heinemeyer, M.J. Herrero, Eur.Phys.J.C 81 (2021) 10, 913, arXiv:2106.11105
- Hadron colliders: FA, S. Heinemeyer, M. Mühlleitner, K. Radchenko, Eur.Phys.J.C 81 (2021) 10, 913, arXiv:2106.11105

Motivation: the Higgs sector

- The discovered Higgs boson is consistent with the SM :(
- However self-interactions ***not*** measured with high accuracy



ATLAS bound at 95% CL:

ATLAS [arXiv:2211.01216]
CMS [arXiv:2207.00043]

$$-0.4 < \kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}} < 6.3$$

(Similar results in CMS)

Plenty of room for ***new physics***!

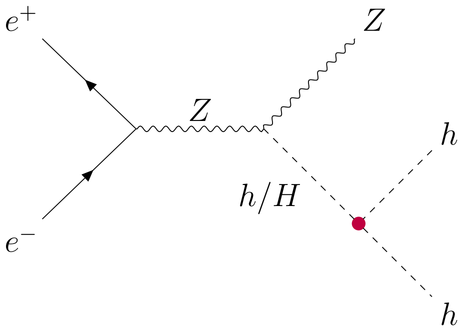
- Framework: two Higgs doublet model (2HDM)
- 5 Higgs bosons + complete new scalar sector

Why di-Higgs?

- Triple Higgs couplings (THC) can enter at **leading order (LO)** in di-Higgs production

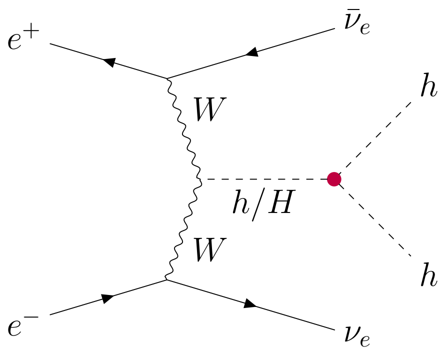
e^+e^- colliders

Hadron colliders



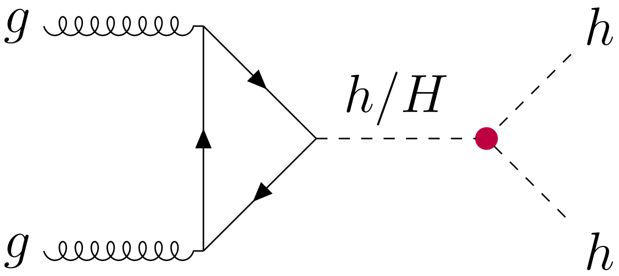
"Higgs-strahlung"

$$e^+e^- \to hhZ$$



Vector boson fusion (VBF)

$$e^+e^- \to hh\nu\bar{\nu}$$



Gluon-gluon fusion (ggF)

$$gg \to hh$$

Sensitivity to λ_{hhh} or κ_λ (non-resonant) and λ_{hhH} (resonant)

Two Higgs Doublet Model (2HDM)

- SM + second Higgs doublet

5 physical Higgs bosons: h, H, A and $H^\pm$

$$V_{2\mathrm{HDM}} = m_{11}^2\left(\Phi_1^\dagger\Phi_1\right) + m_{22}^2\left(\Phi_2^\dagger\Phi_2\right) - \left[m_{12}^2\left(\Phi_1^\dagger\Phi_2\right) + \mathrm{h.c.}\right] + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \mathrm{h.c.}\right]$$

  - CP conservation: (h, H even, A odd)
  - Z_2 symmetry to avoid FCNC (sofly broken by m_{12}^2) $\rightarrow$ only consider type I
- Input parameters:

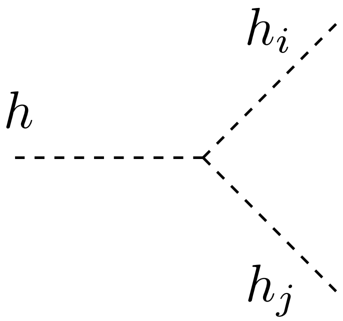
$$m_h\ (\sim 125\ \mathrm{GeV}),\ m_H, m_A, m_{H^\pm},\ \tan\beta, \cos(\beta-\alpha) \equiv c_{\beta-\alpha},\ m_{12}^2$$

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

Triple Higgs Couplings in the 2HDM

- Tree-level triple Higgs couplings (THC) given by:

[FA, Heinemeyer, Herrero, 2005.10576, 2203.12684]



$$= -ivn!\lambda_{hh_ih_j}$$

and $\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda^{\mathrm{SM}}_{hhh}}$

($n =$ # identical bosons)

Allowed ranges at the tree-level:

	Type I	Type II
κ_λ	[-0.5, 1.3]	[0.6, 1.0]
λ_{hhH}	[-1.7, 1.6]	[-1.8, 1.5]

In the alignment limit: $\kappa_\lambda = 1$ and $\lambda_{hhH} = 0$

- Constraints:
  - EWPO, mainly T parameter
  - Tree-level unitarity and potential stability
  - BSM Higgs boson searches @LHC, TeVatron and LEP
  - Properties of the SM-like Higgs boson
    - Close to alignment limit i.e. $c_{\beta-\alpha} \simeq 0$, less severe in type I
  - Flavor Observables $B_s \to \mu\mu, b \to s\gamma$

2HDMC, HiggsBounds, HiggsSignals, SuperISO were used

e^+e^- vs hadron collider

- Total XS presented in benchmark planes with large (and allowed) THC
  - Full computation with all LO diagrams, i.e. no NWA!

[FA, Heinemeyer, Herrero, 2106.11105]

- **e^+e^- colliders: ILC and CLIC**
  - $e^+e^- \to hhZ,\ hh\nu\bar{\nu}$ (VBF)
  - Tree level computation: `Madgraph`
    - hhZ ($hh\nu\nu$) dominates at low (large) energies

[FA, Heinemeyer, Mühlleitner, Radchenko, 2212.11242]

- **Hadron colliders: HL-LHC**
  - Gluon-gluon fusion $gg \to hh$
  - One-loop calculation: `HPAIR`
    - NLO QCD corrections also included in the total XS (K-factor ~ 2)

- Access to triple Higgs couplings (THC) via the **differential cross section** distributions on the **invariant mass** of the final Higgs pair m_{hh}

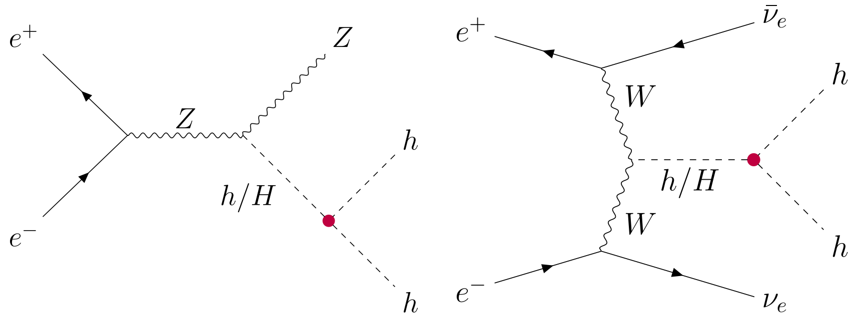
Main BSM effects from THC

A) **Non-resonant** diagram with $\boldsymbol{\kappa_\lambda}$ $\rightarrow$ important at low m_{hh}

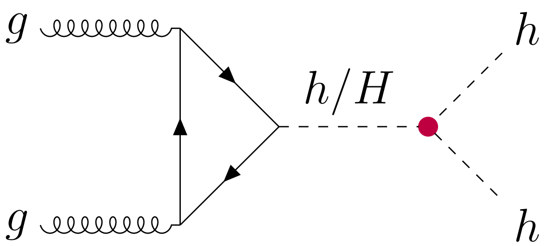
- Interference with the other diagrams

B) **Resonant** $\boldsymbol{H}$ diagram with $\boldsymbol{\lambda_{hhH}}$ $\rightarrow$ important when $m_{hh} \simeq m_H$

e^+e^- colliders



Hadron colliders

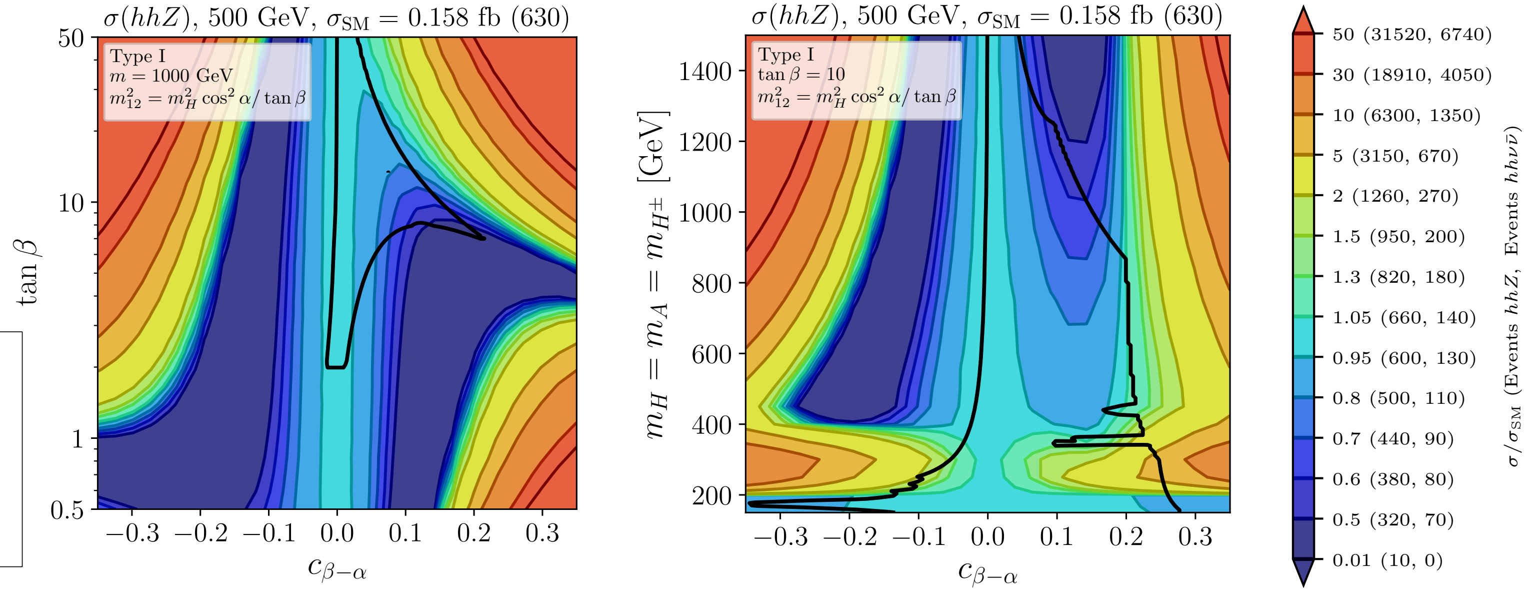


C) Only at $e^- e^+$ colliders, resonant A diagram (no THC)

At both colliders, in the alignment limit $\sigma_{\text{2HDM}} = \sigma_{\text{SM}}$ (at LO)

At e^+e^- colliders

hhZ cross section @ILC 500 GeV

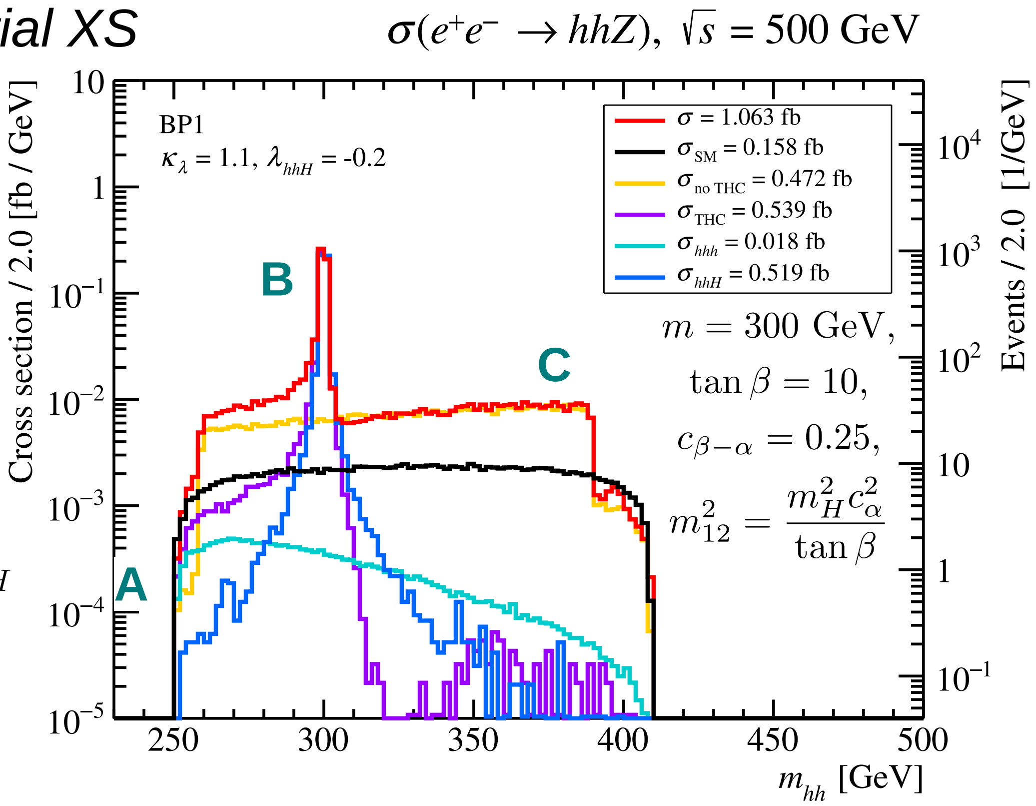


Black line is the boundary of the allowed region

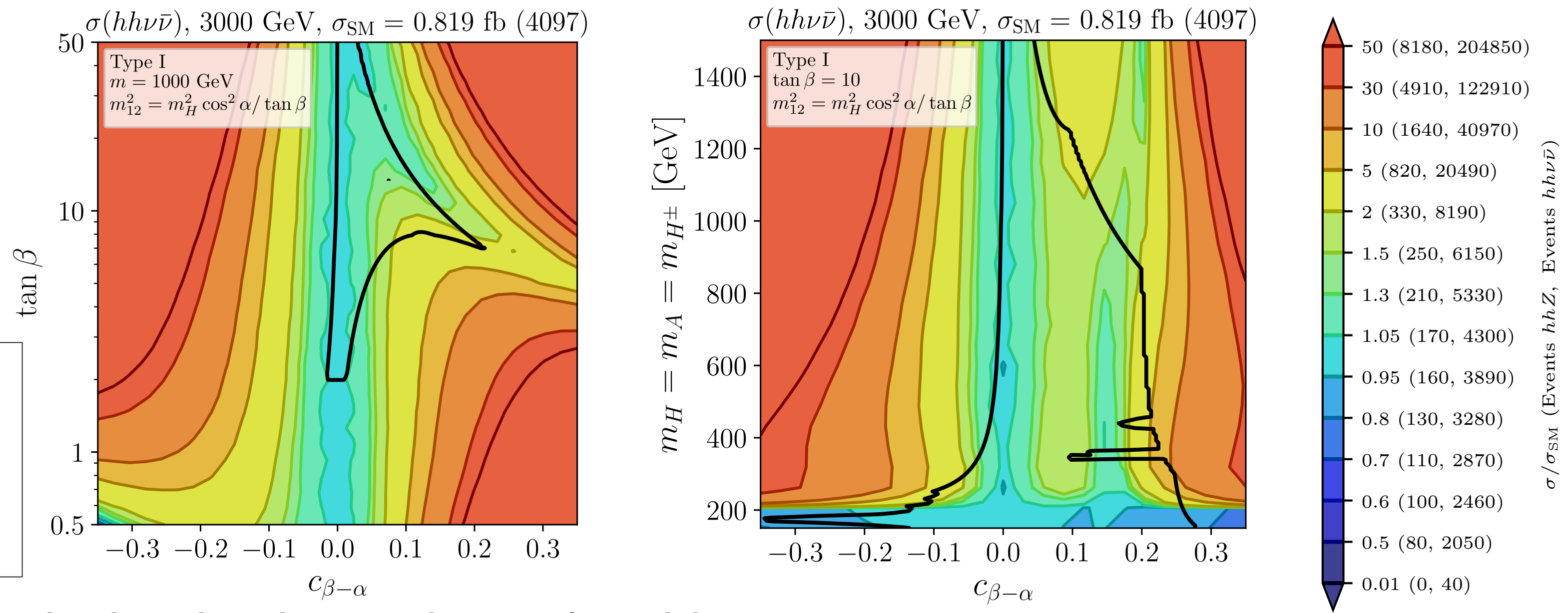
- hhZ is the dominant channel at this energy
  - $c_{\beta-\alpha} - \tan\beta$ plane (with large masses) → effect of $\kappa_\lambda \neq 1$
  - $c_{\beta-\alpha} - m$ plane (with low masses) → H and A resonances with $\sigma \sim 5\sigma_{\mathrm{SM}} \sim 0.8$ fb

Triple Higgs Couplings @ILC 500 GeV

- Access to THC via the *differential XS*
  - A) κ_λ → at the threshold (light blue line)
  - B) λ_{hhH} → resonant peak at $m_{hh} \simeq m_H$ (dark blue line)
  - C) A resonance → plateau wrt the SM (yellow line)
- κ_λ and λ_{hhH} effects "mixed" if m_H close to threshold
- Asymmetry of the H peak → λ_{hhH} sign



$hh\nu\bar{\nu}$ cross section @CLIC 3 TeV



Black line is the boundary of the allowed region

- $hh\nu\nu$ is the dominant channel at this energy
  - Now the H and A resonant production is sizable also for large Higgs masses
  - For moderate masses $\sigma \sim 3\sigma_{\rm SM}$ and for low masses up to $\sigma \sim 10\sigma_{\rm SM}$

Triple Higgs Couplings @CLIC 3 TeV

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A) κ_λ → at the threshold

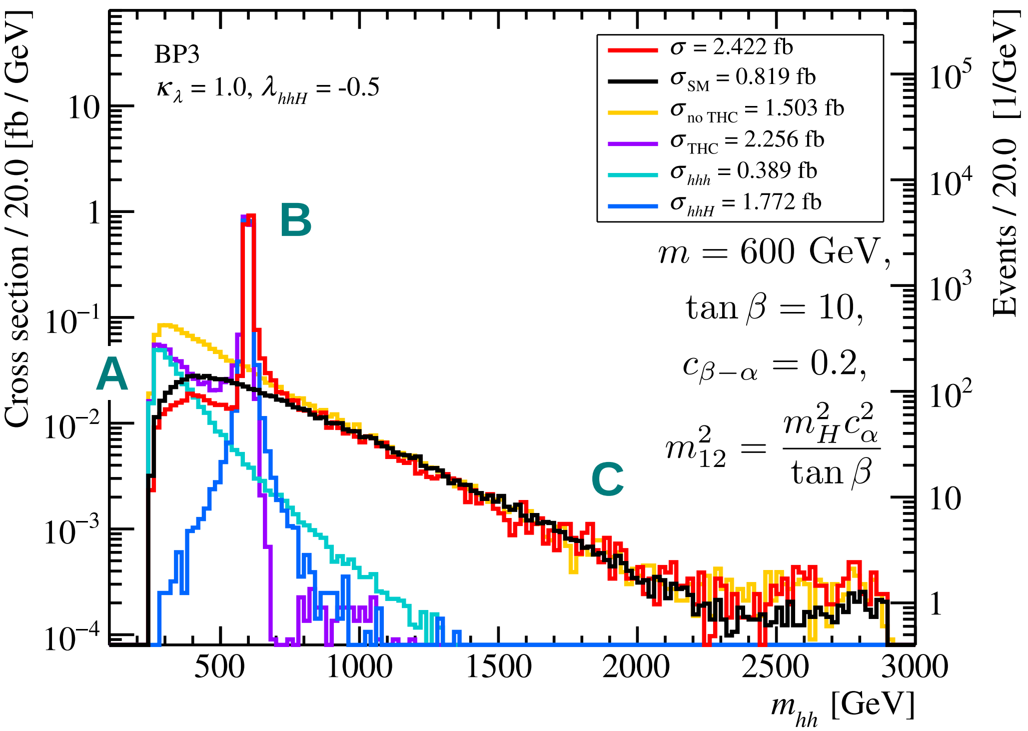
- Different from SM even with $\kappa_\lambda = 1$

B) λ_{hhH} → prominent resonant peak at $m_{hh} \simeq m_H$

- Dip-peak structure → sign of λ_{hhH}

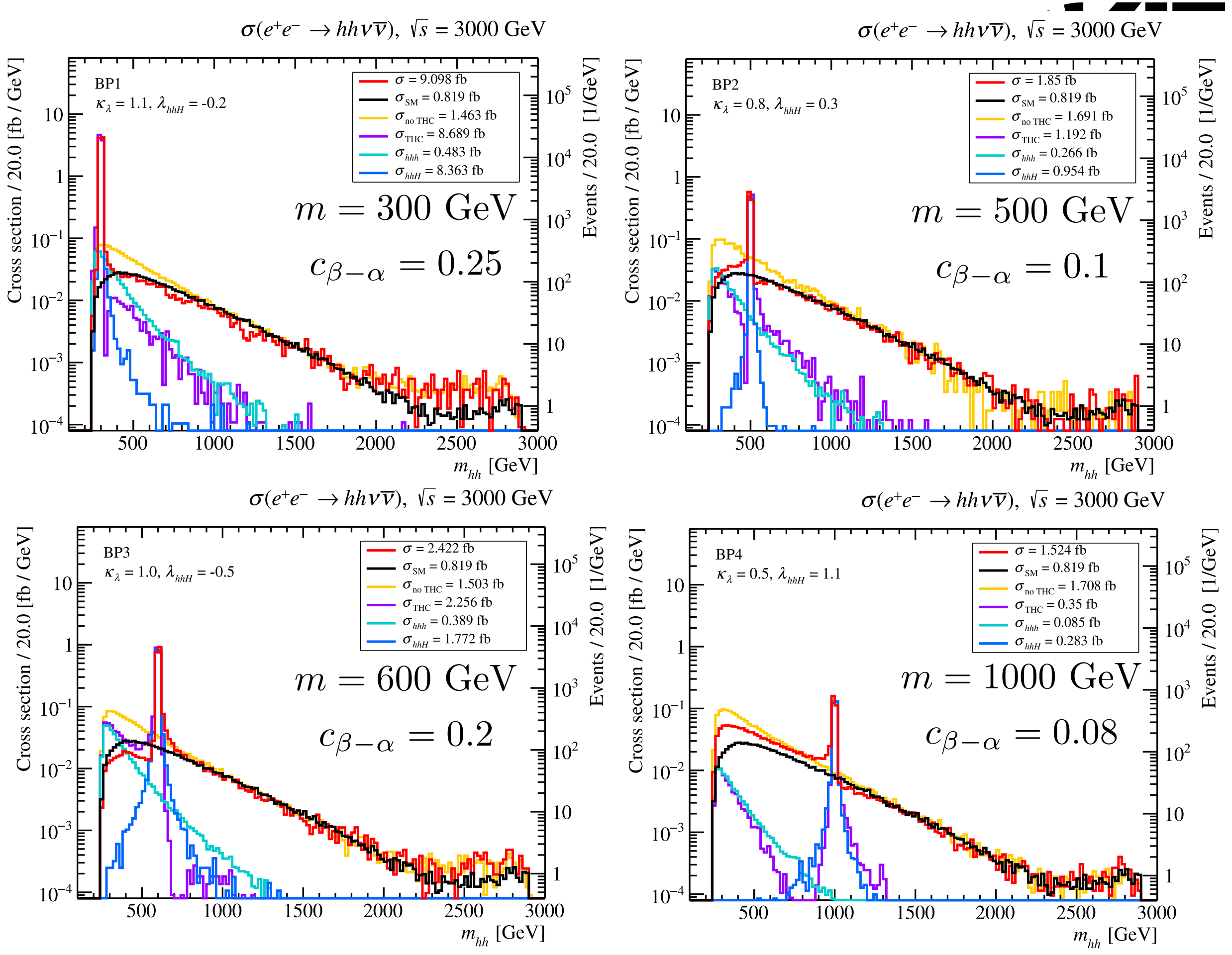
C) no A resonance

$\sigma(e^+e^- \to hh\nu\bar{\nu})$, $\sqrt{s}$ = 3000 GeV



Great access to λ_{hhH} @CLIC 3TeV !

- Estimated "sensitivity" to λ_{hhH} from the expected **final 4b jet events** at the H peak:
  - Overall, larger "sensitivity" to λ_{hhH} at VBF channel at @3TeV
  - Also good "sensitivity" if m_H is very low

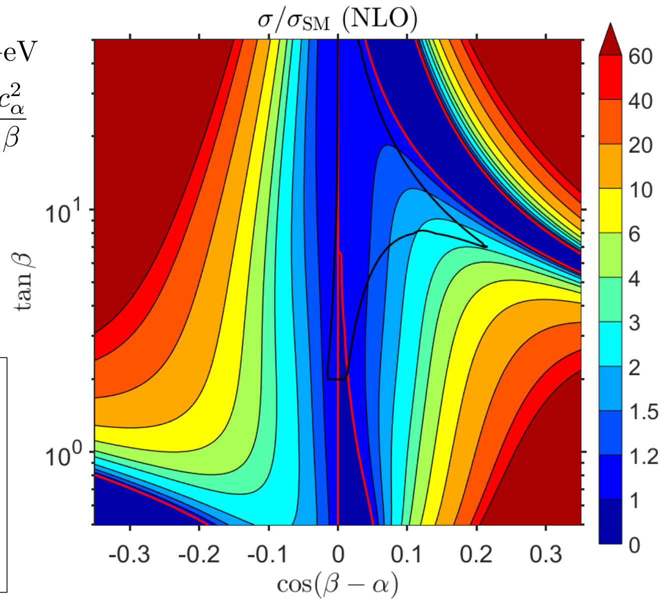


At the HL-LHC

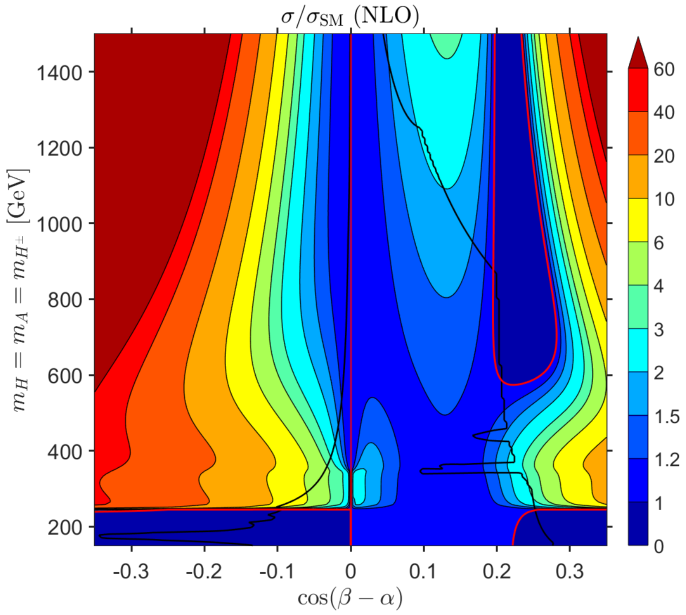
hh production via ggF @HL-LHC

$m = 1000$ GeV

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



Black line is the boundary of the allowed region



$\sigma_{\mathrm{SM}}^{\mathrm{LO}} = 19.76$ fb

$\sigma_{\mathrm{SM}}^{\mathrm{NLO}} = 38.24$ fb

$\tan\beta = 10$

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

- XS shows effects from κ_λ and λ_{hhH} in both planes
- Effect from H resonant production only important for m_H below ~600 GeV

Effect of κ_λ @HL-LHC

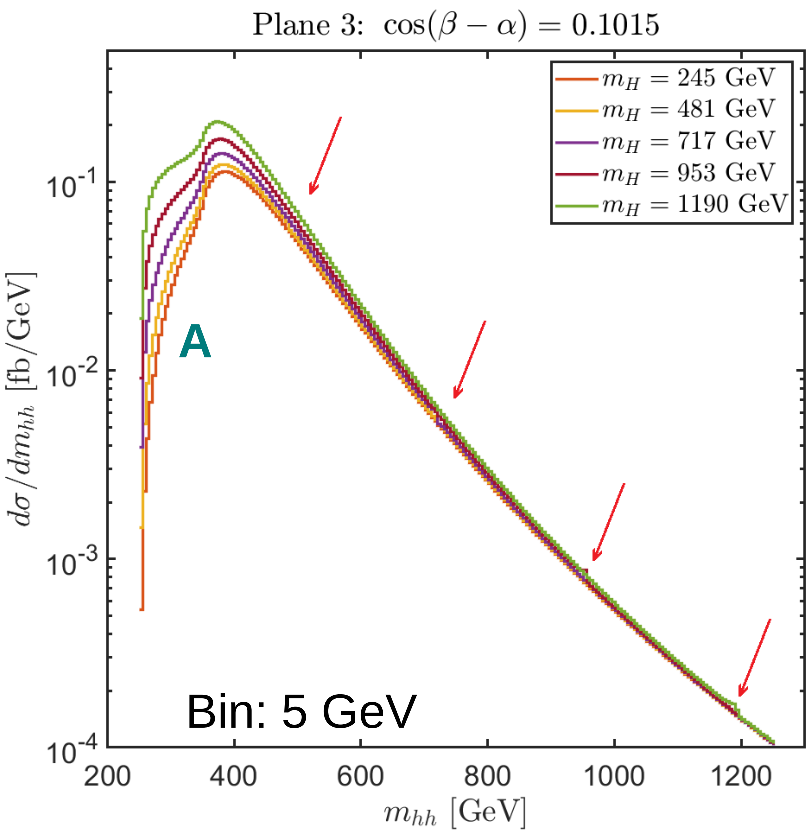
- ➔ Access to κ_λ via the *differential XS*

A) κ_λ → at the threshold

Larger XS for $\kappa_\lambda < 1$

B) λ_{hhH} → No resonant peak at $m_{hh} \simeq m_H$ (red arrows)

Very small H Yukawa coupling



$$\kappa_\lambda = 0.97$$
$$\downarrow$$
$$\kappa_\lambda = -0.04$$

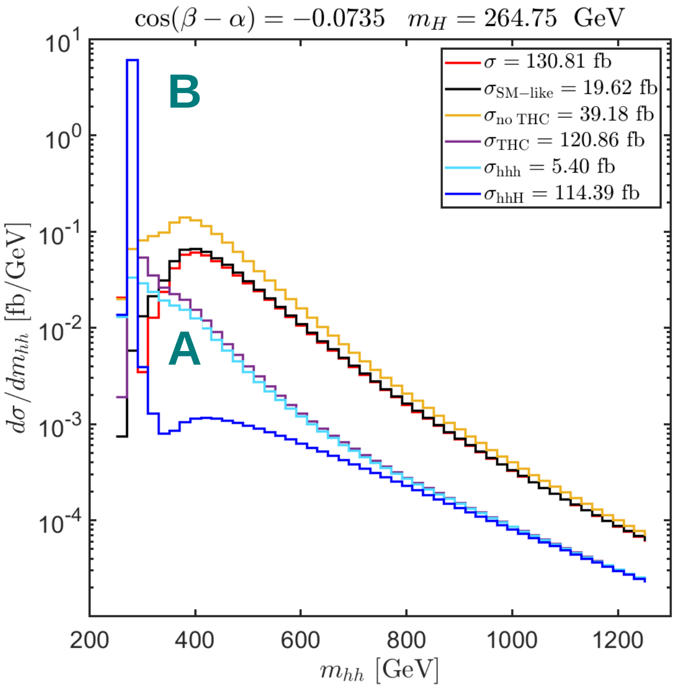
$$\tan\beta = 10$$
$$m_{12}^2 = \frac{m_H^2 c_\alpha^2}{\tan\beta}$$

Effect of λ_{hhH} @HL-LHC

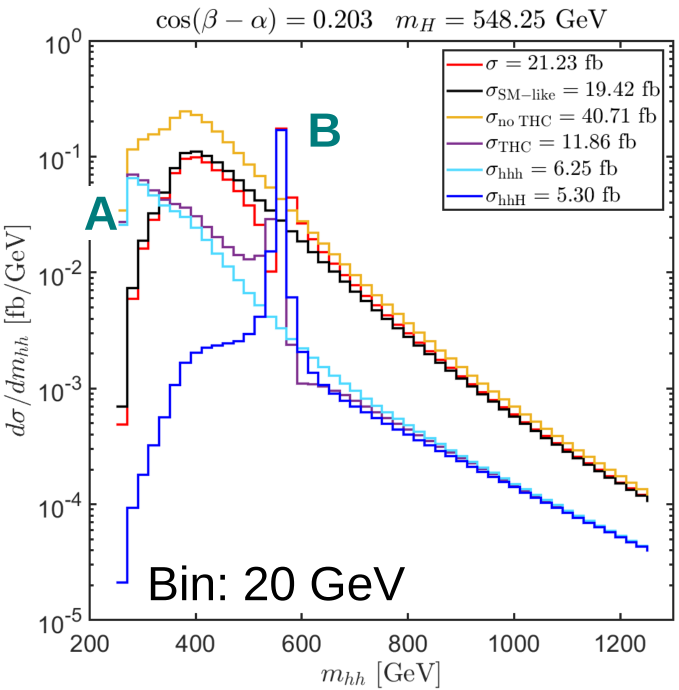
A) $\kappa_\lambda \simeq 1$ then BSM effect mainly from H diagram

B) λ_{hhH} → Resonant peak at $m_{hh} \simeq m_H$

Sign of λ_{hhH} → structure of the resonance



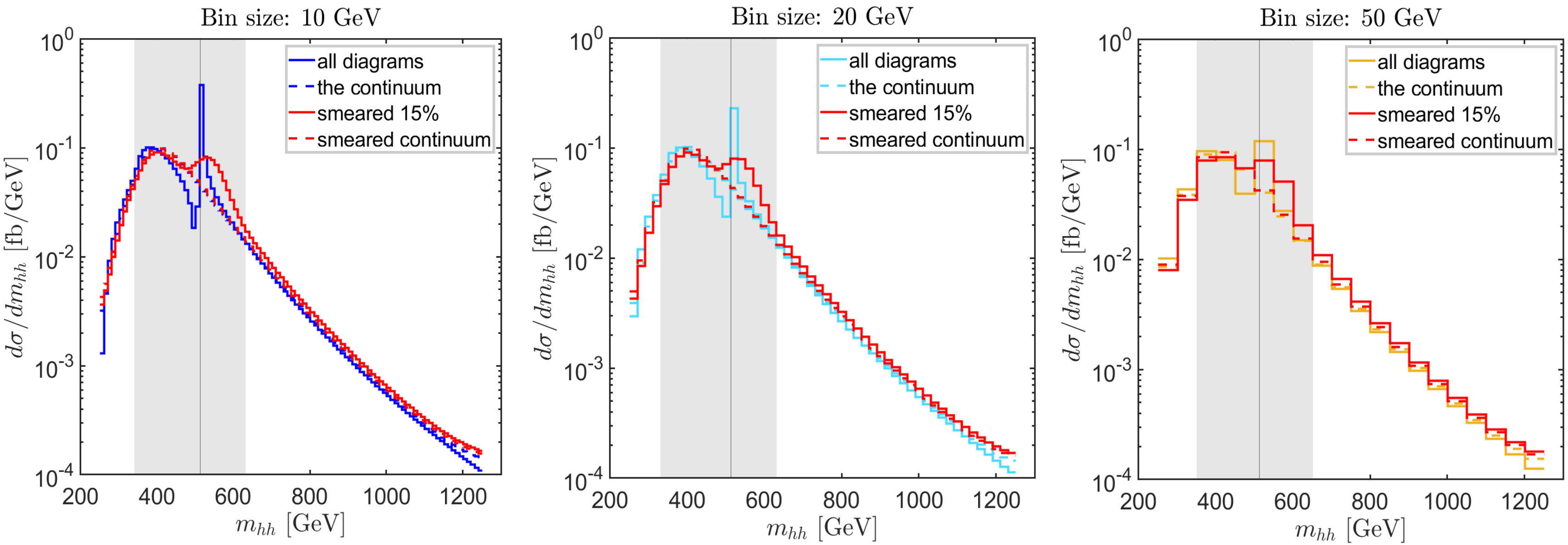
- m_H very close to threshold → $\sigma \sim 6\sigma_{\text{SM}}$



- "Conservative" m_H → $\sigma \sim 1.1\sigma_{\text{SM}}$

Effect of experimental uncertainties

- **Smearing**: uncertainty from the finite resolution of the detectors
- More realistic bin size: ~ 50 GeV



- **Smearing + bin size** can make the signal reconstruction challenging :(

Summary & Conclusions

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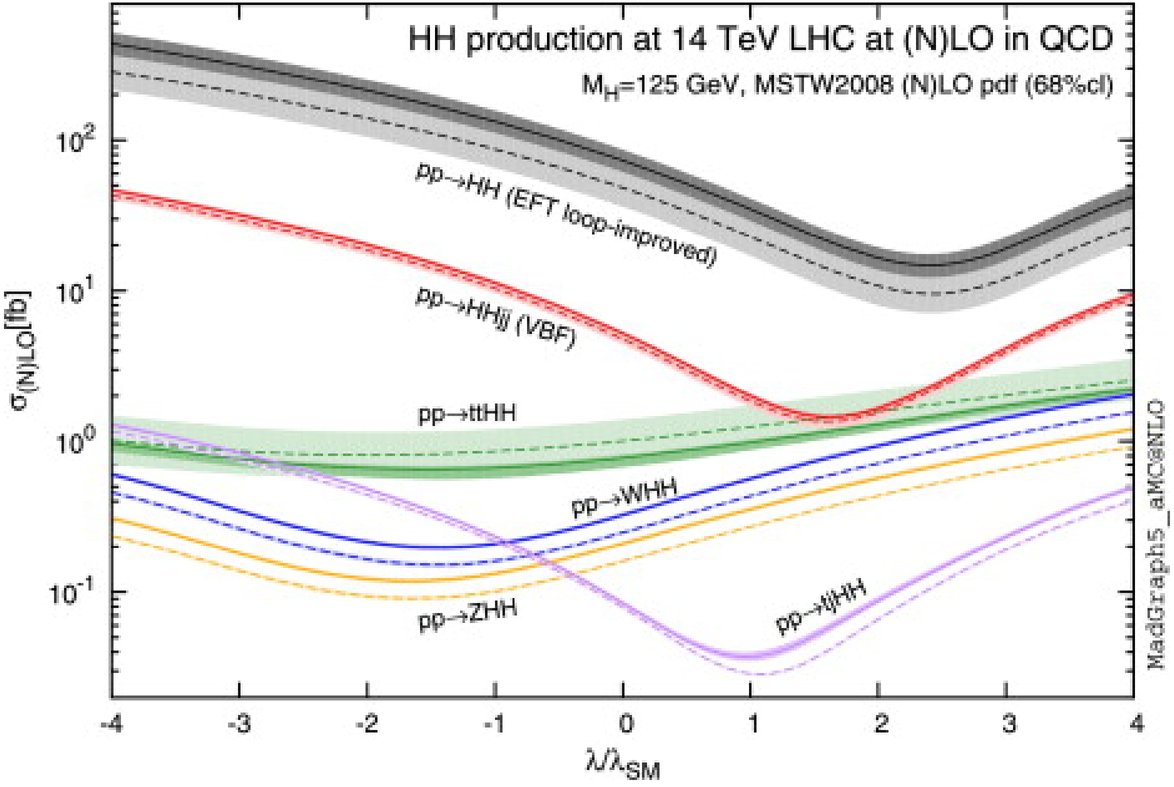
- Overview of the BSM effects from **triple Higgs couplings** (THC) in **double Higgs production** in the 2HDM (type I), still allowed by present constraints
- κ_λ $\rightarrow$ non-resonant effect, important at low m_{hh} (similar to SM unless H is light)
- λ_{hhH} $\rightarrow$ resonant effect, experimental access via resonant production
  - At e^+e^- colliders: good prospects for the VBF channel @CLIC 3TeV, ILC could be competitive if H is light
  - At HL-LHC: resonant H contributions possible if H is relatively light below ~ 600 GeV
    - Challenging reconstruction of the final signature (bin resolution + smearing)
- **Future directions!** 1-loop effects to κ_λ can be sizable even in the alignment limit! *To be continued...*

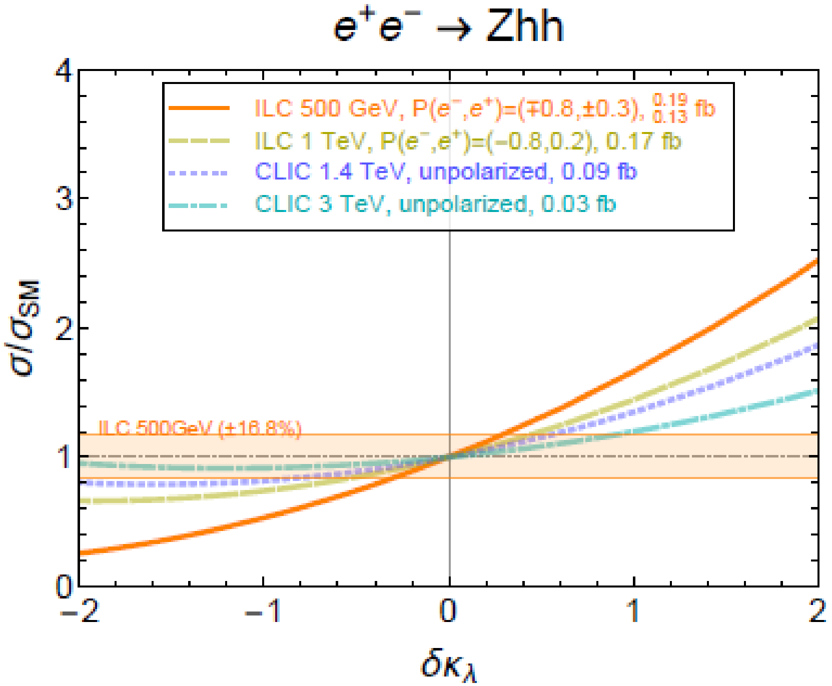
Thanks for your attention! :)

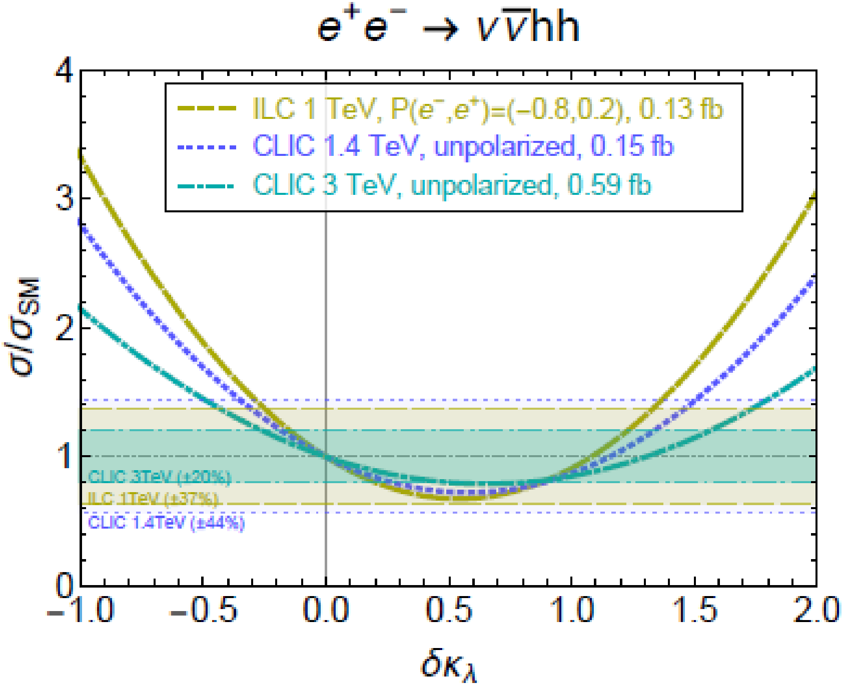
Back up

XS vs κ_λ in the SM at LHC



XS vs κ_λ in the SM at e^+e^- colliders





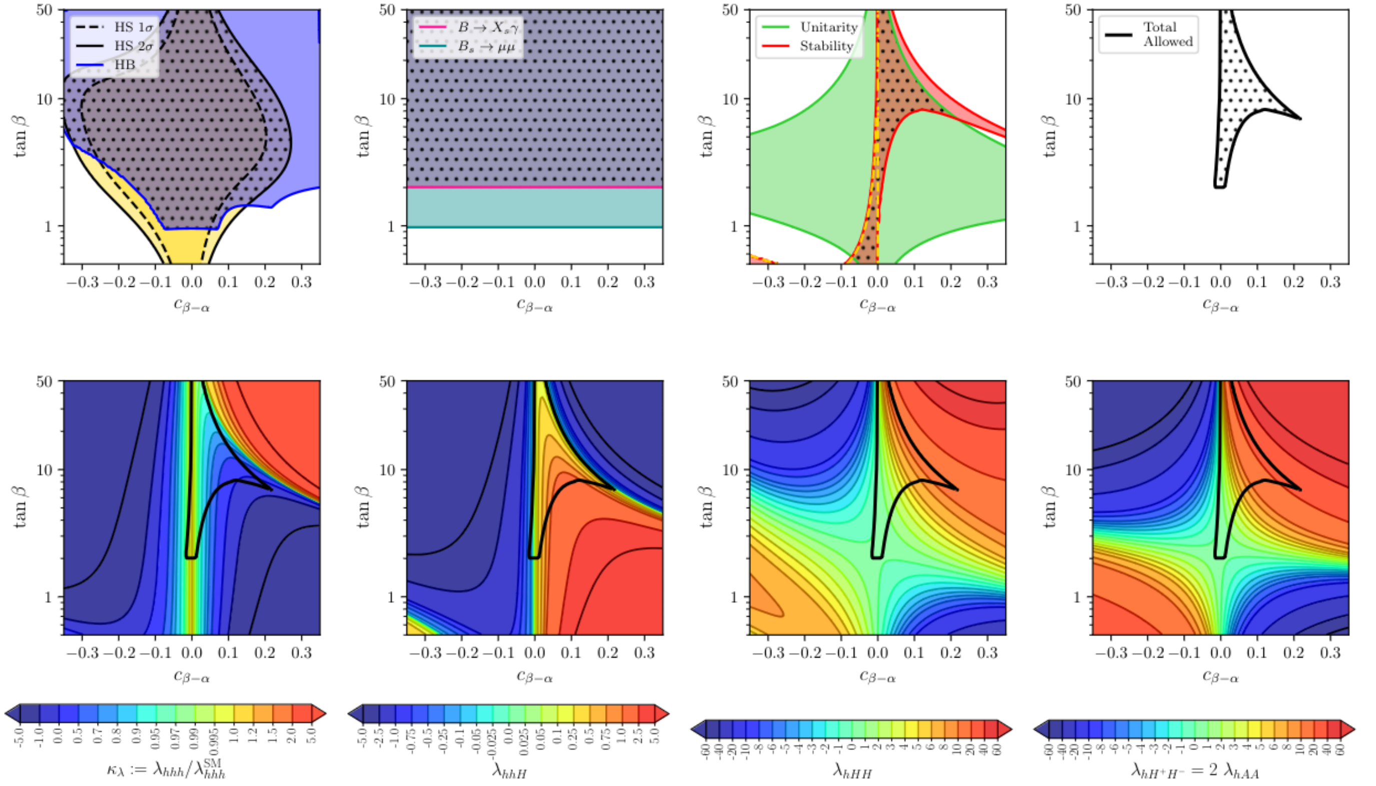
2HDM Yukawa couplings

$$\mathrm{L}_{\text{Yukawa}} \supset -\sum_{f=u,d,l} \frac{m_f}{v} \left[\xi_f^h \bar{f} f h + \xi_f^H \bar{f} f H + \xi_f^A \bar{f} \gamma_5 f A\right]$$
$$- \frac{\sqrt{2}}{v} \left[\bar{u} \left(\xi_d V_{\text{CKM}} m_d P_R - \xi_u m_u V_{\text{CKM}} P_L\right) d H^+ + \xi_l \bar{\nu} m_l P_R l H^+ + \text{h.c.}\right]$$

	Type I	Type II	Type III	Type IV
ξ_u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_d	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
ξ_l	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$

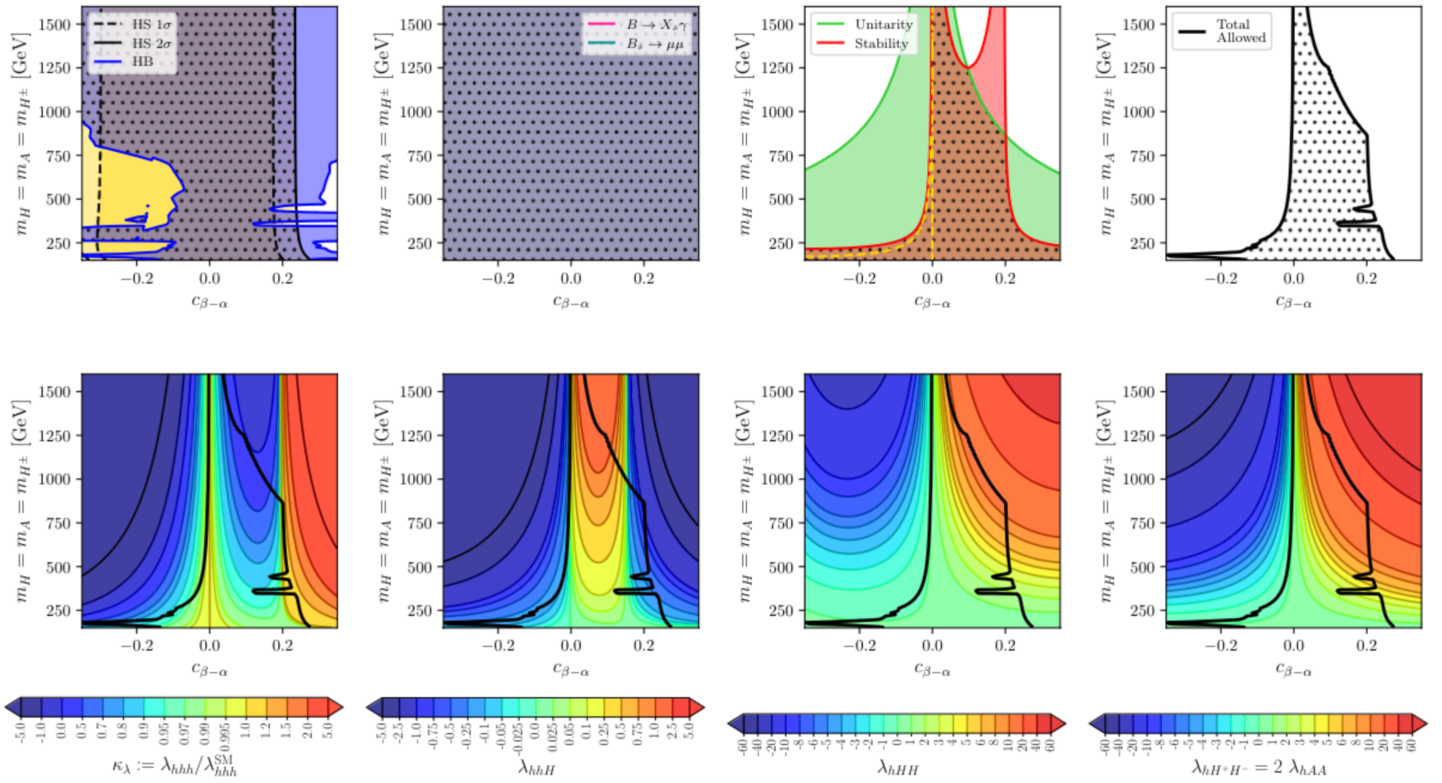
with $\xi_f^h = s_{\beta-\alpha} + \xi_f c_{\beta-\alpha}\,, \xi_f^H = c_{\beta-\alpha} - \xi_f s_{\beta-\alpha}\,, \xi_u^A = -i\xi_u\,, \xi_{d,l}^A = i\xi_{d,l}$

Plane 1



HS 1σ
HS 2σ
HB
B → X_s γ
B_s → μμ
Unitarity
Stability
Total
Allowed
tan β
c_{β−α}
κ_λ := λ_{hhh}/λ_{hhh}^{SM}
λ_{hhH}
λ_{hHH}
λ_{hH^+H^-} = 2 λ_{hAA}

Plane 3


HS 1σ
HS 2σ
HB
B → X_s γ
B_s → μμ
Unitarity
Stability
Total Allowed
m_H = m_A = m_H± [GeV]
c_β−α
κ_λ := λ_hhh / λ_hhh^SM
λ_hhH
λ_hHH
λ_hH+H− = 2 λ_hAA

R "sensitivity" at e^+e^- colliders

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$$R = \frac{\bar{N}^R - \bar{N}^C}{\sqrt{\bar{N}^C}} \,, \qquad \bar{N} = N \times \mathcal{A} \times (\epsilon_b)^4, \qquad \mathcal{A} = \frac{N_{\text{with cuts}}}{N_{\text{without cuts}}}$$

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

$hh\nu\bar{\nu}$	$\sqrt{s}$ [GeV]	$\sigma_{2\text{HDM}}$ / σ_{SM} [fb]	$\bar{N}^R_{4b\not{E}_T}$ / $\bar{N}^C_{4b\not{E}_T}$ / $\bar{N}^{\text{SM}}_{4b\not{E}_T}$	$\mathcal{A}_{2\text{HDM}}$/ $\mathcal{A}_{\text{SM}}$	$R_{4b\not{E}_T}$
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

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	-