Exploring new physics by loop-corrected decays of additional Higgs bosons

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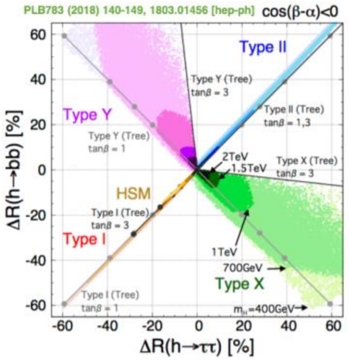

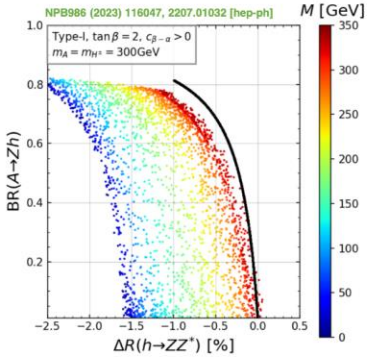

http://www-het.phys.sci.osaka-u.ac.jp/~hcoup/

What do we want to know?

What kinds of Higgs fields are in the Higgs sector?

Decoupling? or non-decoupling?

Additional symmetries

$\rho_{\mathrm{EW}} = 1$?

Why is FCNC suppressed?

Additional CP phases

- How much is "alignmentness" ?

$$g_{hXX} = \kappa_X \, g_{hXX}^{\mathrm{SM}}$$

$\kappa_X \to 1$ (Alignment limit)

- The mass scale of the 2nd Higgs boson

  Decoupling ? or Non-decoupling?

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$$g_{hXX} = \kappa_X \, g_{hXX}^{SM}$$

$\kappa_X \to 1$ (Alignment limit)

Indications from experiment

LHC results are consistent with SM predictions.

$\kappa_X \simeq 1$ (Nearly alignment)

- The mass scale of the 2nd Higgs boson

Decoupling ? or Non-decoupling?

Unknown.
No new particle has been discovered.

It does not mean decoupling scenario.
⇒ Direct search of additional Higgs bosons remains an important exploring method.

Two Higgs doublet models

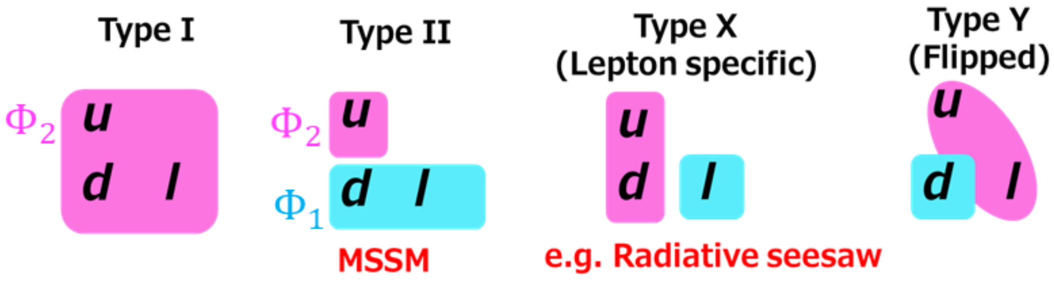
We investigate additional Higgs boson decays for direct searches.

- We show analyses of THDM with the softly broken Z_2 symmetry as an example.

$$\Phi_1 \to +\Phi_1$$
$$\Phi_2 \to -\Phi_2$$

Can avoid FCNC.

4 types of Yukawa interactions ⇒



- We focus on the CP-conserving case.

- Mass eigenstates

Higgs basis

h_{125} , $H, A, H^{\pm}$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h'_1 + v + iG^0) \end{pmatrix} \quad \Phi' = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA) \end{pmatrix} \quad \begin{pmatrix} h'_1 \\ h'_2 \end{pmatrix} = \begin{pmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

- h_{125} couplings

hWW, hZZ

$$\kappa_V^h = \frac{g_{hVV}^{\mathrm{THDM}}}{g_{hVV}^{\mathrm{SM}}} = \sin(\beta - \alpha) \quad \to 1$$

Alignment limit

How to Search Additional Higgs

In nearly alignment case, additional Higgs bosons' decays are very interesting !!

- Additional Higgs couplings with SM particles

Alignment limit

THDM Type-I

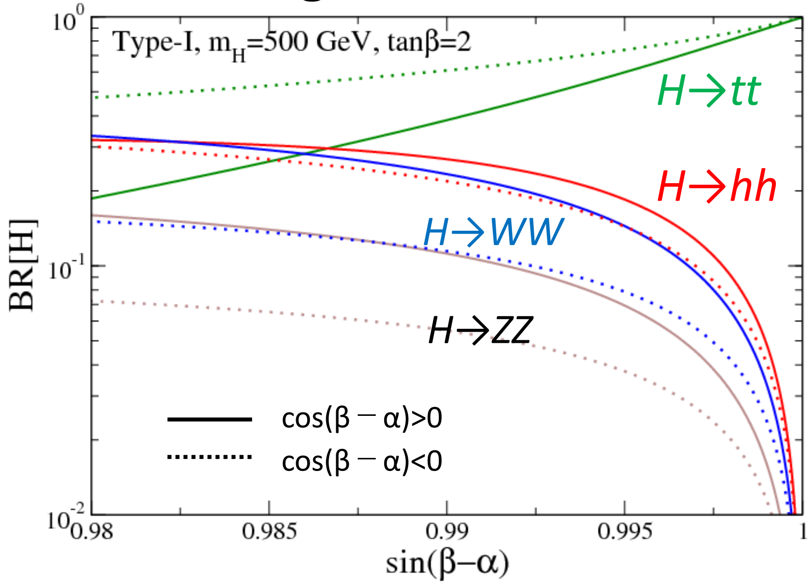
HWW, HZZ $\kappa_V^H = \frac{g_{HVV}^{NP}}{g_{hVV}^{SM}} = \cos(\beta-\alpha)$ → 0

Hhh $\lambda_{Hhh} = -\frac{\cos(\beta-\alpha)}{2v\sin 2\beta}\{(2m_h^2+m_H^2-3M^2)\sin 2\alpha + M^2\sin 2\beta\}$ → 0

In the nearly-alignment case they play important roles

Hff Type-I THDM $\kappa_f^H = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha)$ → $-\cot\beta$

- Branching ratio of *H*



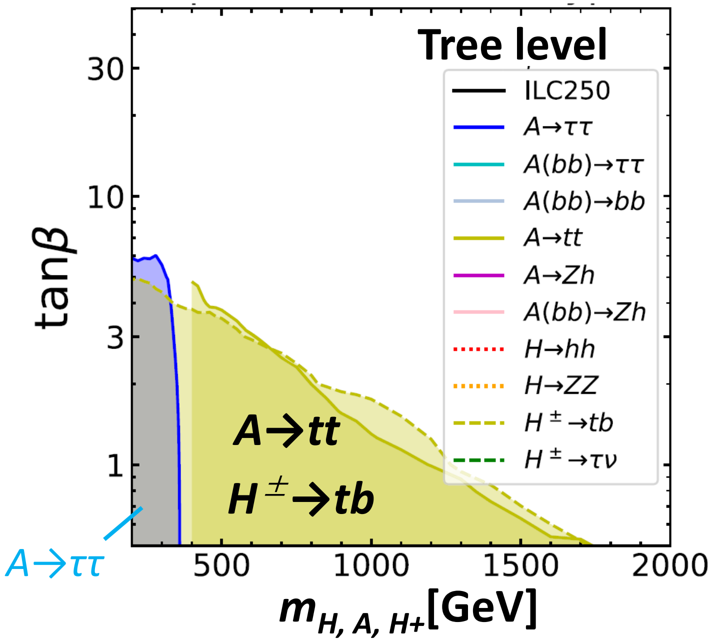
H decays are very sensitive to $\kappa_V^{\text{tree}} = \sin(\beta-\alpha)$.

Roughly, sin(β − α) can be determined by h_{125}-coupling measurements.
It is important to evaluate h_{125}-couplings and/or decays at the same time.

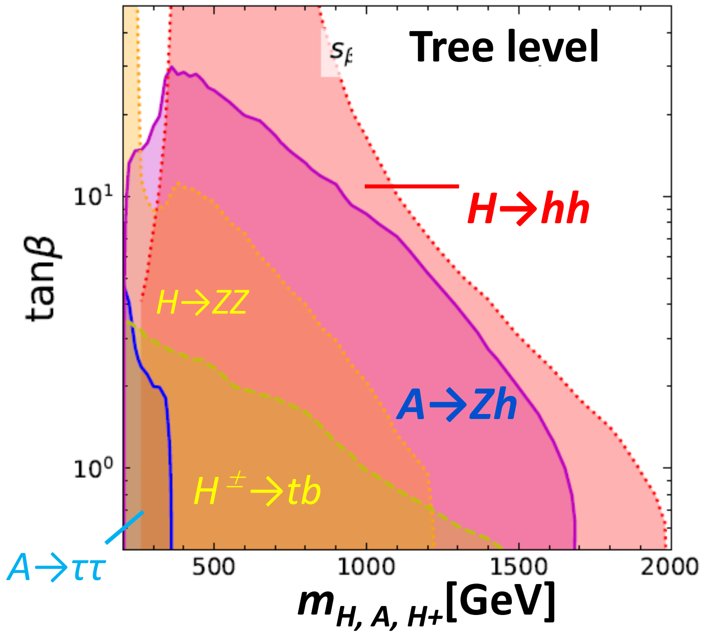
Searchable regions in nearly-alignment

Expected excluded parameter region by direct searches @**HL-LHC(3000fb^{-1})** (95%CL)

Type-I sin(β−α) = 1



Type-I sin(β−α) = 0.995 (cos(β-α) < 0)

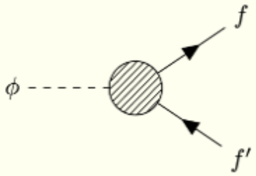


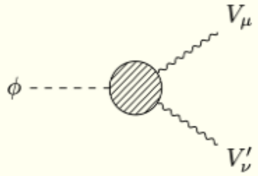
Aiko, Kanemura, MK, Mawatari, Sakurai, Yagyu [NPB966(2021)115375]

- Wide parameter region is expected to be surveyed by "Higgs to Higgs decays".
- Additional Higgs decays are very sensitive to sin(β−α).

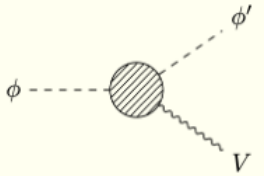
They are results at tree level. ⇨ Precise calculation is necessary for both h_{125}-decays and additional Higgs decays.

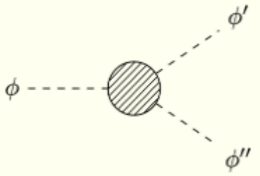
We evaluate the correlations with loop corrections by using H-COUP!





H-COUP





Fortran program for decay BRs of Higgs bosons with loop corrections in extended Higgs models.

You can obtain H-COUP at ⇒ http://www-het.phys.sci.osaka-u.ac.jp/~hcoup/

【 Characteristics of H-COUP】

- Various extended Higgs models : Higgs singlet model, THDMs (Type-I, II, X, Y) , Inert doublet model
- Full set of decay processes of all Higgs bosons:

  Ver.1 (2017) : Renormalized vertices of h_{125}. Kanemura, MK, Sakurai, Yagyu, CPC.233(2018)134

  Ver.2 (2019) : Two- and Three-body decays of h_{125}. Kanemura, MK, Mawatari, Sakurai, Yagyu, CPC 257(2020) 107512

  Ver.3 (2023) : Two-body decays of additional Higgs bosons ($H, A, H^\pm$) Aiko, Kanemura, MK, Sakurai, Yagyu, CPC 301 (2024) 109231

  ⇒ Evaluate correlations between behavior of various decay processes.

- Loop corrections : EW and scalar-NLO

  New renormalization scheme
  Yagyu's talk (Wed.)

  - UV div. → On-shell renormalizations
  - Gauge dependence → Remove by Pinch technique
  - IR div. via photon loop → Cancel by real photon emission

  QCD (NNLO, NLO) corrections (MS-bar scheme).

  A. Djouadi, Phys. Rept., 457, 1 (2008),
  B. M. Spira, Prog. Part. Nucl. Phys., 95, 98 (2017),
  K. G. Chetyrkin, A. Kwiatkowski, Nucl. Phys., B461, 3 (1996)

- Constraints : Vacuum stability(tree level, RGE improved), Tree-level unitarity, Triviality, True vacuum, ST parameters

H-COUP ver.3

Processes in THDMs

CP-even	CP-odd	Charged
$H \to VV$	$A \to ff$	$H^\pm \to ff'$
$H \to ff$	$A \to Zh, ZH$	$H^\pm \to AW$
$H \to hh$	$A \to H^\pm W$	$H^\pm \to HW, hW$
$H \to AA, H^+H^-$	$A \to ZZ, WW, \gamma\gamma, \gamma Z$	$H^\pm \to W\gamma, WZ$
$H \to AZ, H^\pm W$		
$H \to \gamma\gamma, \gamma Z, gg$		

NPB 973 (2021) 115581, Aiko, Kanemura, Sakurai

NPB 983(2022)115906 Kanemura, MK, Yagyu

NPB 986 (2023) 116047 Aiko, Kanemura, Sakurai,

IDM

CP-even	CP-odd	Charged
$H \to AZ$	$A \to ZH$	$H^\pm \to AW$
$H \to H^\pm W$	$A \to H^\pm W$	$H^\pm \to HW$

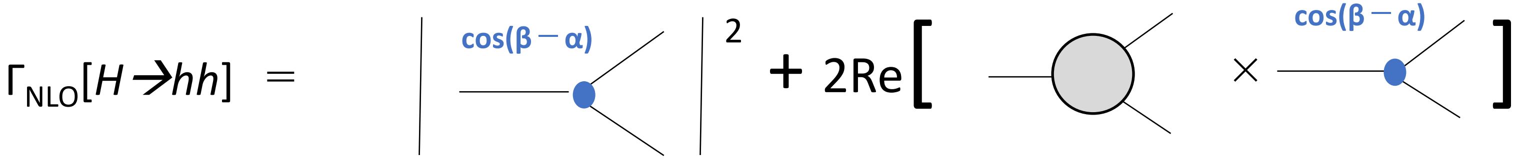
HSM

CP-even
$H \to VV$
$H \to ff$
$H \to hh$
$H \to \gamma\gamma, \gamma Z, gg$

We show results for decays of *$H \to hh$, $A \to Zh$, $h \to VV^*$* in Type-I THDM.

Loop corrections to Γ[*H*→*hh*]

- NLO contributions works constructively or destructively
  cos(β-α) > 0 ・・・ constructively, cos(β-α) < 0 ・・・ destructively



- Decoupling? Or Non-decoupling?

$M^2 \gg \lambda_\Phi v^2 \ (m_\Phi^2 \simeq M^2)$ ・・・ Decoupling

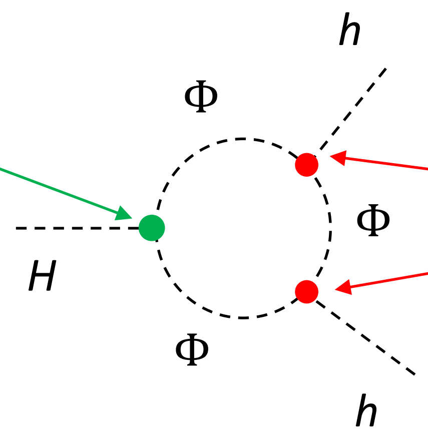
$M^2 \simeq \lambda_\Phi v^2$ ・・・ Non-decoupling

$m_\Phi^2 \cong \lambda_\Phi v^2 + M^2$

Scalar self couplings

$\cos(\beta-\alpha) \ll 1$ case

$\lambda_{H\Phi\Phi} \sim \frac{1}{v}(m_{\mathrm{H}}^2 - M^2)$



$\Phi = H, A, H^\pm$

$\lambda_{h\Phi\Phi} \sim \frac{1}{v}(m_\Phi^2 - M^2)$

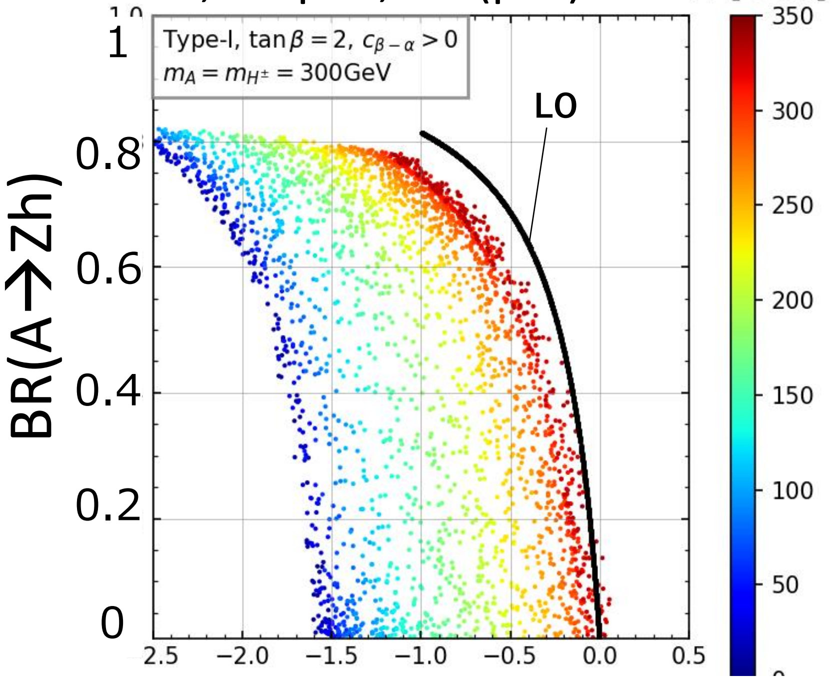
$(m_{A,H^\pm} - m_H \neq 0)$ case

Even if $m_{\mathrm{H}}^2 \simeq M^2$, corrections of $H^\pm, A$ loop diagrams are not suppressed.

Correlation between "Higgs to Higgs decays" and h_{125}→VV^*

Type-I

$m_A = m_{H+}$ =300GeV, tanβ=2, cos(β-α)>0



$$\Delta R[h_{125} \to ZZ^*] = \frac{\Gamma^{\rm THDM}_{\rm NLO}[h_{125} \to ZZ^*]}{\Gamma^{\rm SM}_{\rm NLO}[h_{125} \to ZZ^*]} - 1$$

NPB 986 (2023) 116047
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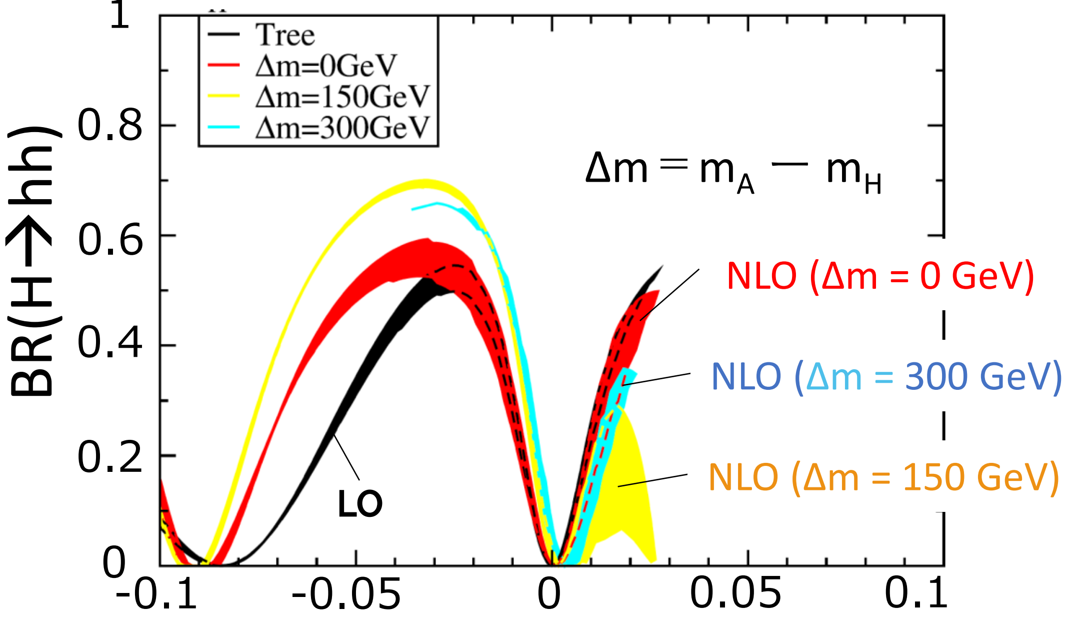
m_H=500GeV, tanβ=5, $m_A = m_{H+}$



$$\Delta\mu[h_{125} \to WW^*] = \frac{{\rm BR}^{\rm THDM}_{\rm NLO}[h_{125} \to WW^*]}{{\rm BR}^{\rm SM}_{\rm NLO}[h_{125} \to WW^*]} - 1$$

NPB 983(2022)115906
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Correlations between "Higgs to Higgs decays" and h_{125}→VV^* are significantly changed from LO (~O(10)%).

It is necessary to evaluate both h_{125}-decays and Heavy Higgs decays with loop corrections simultaneously.

Summary

- H-COUP is a good tool for determining the Higgs sector by comparing precise predictions of various processes in some extended Higgs models and future precision measurement.

- h_{125} measurements indicate "nearly alignment".

  ⇒ "Higgs to Higgs decays" can be main search modes.

- We show results of BR[Higgs to Higgs decays] and BR[h_{125}] including radiative corrections in Type-I THDM.

  BR[$H \to hh$] with NLO correction can change LO prediction by O(10)%.

  BR[$A \to Zh$] also receives O(10)% correction if $\tan\beta \simeq 2$.

- Correlations between $A \to Zh$ / $H \to hh$ and $h \to VV^*$ significantly change from LO.

Correlation between *H*→*hh* and *h*→*WW**

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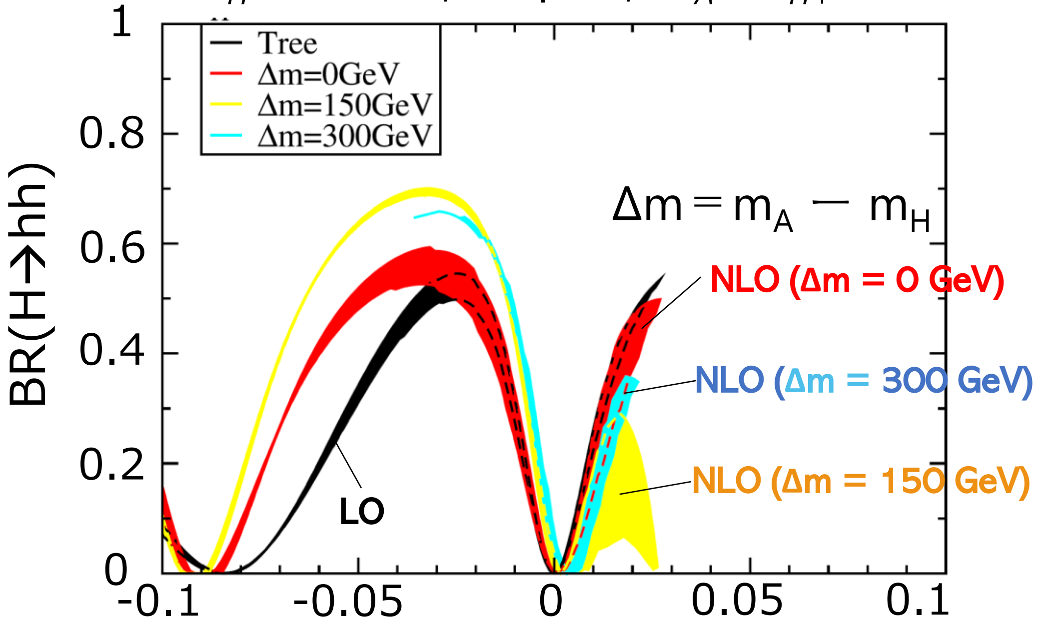
Type-I m_H=500GeV, tanβ=5, m_A=m_{H+}



$$\Delta\mu[h \to WW^*] = \frac{\mathrm{BR}^{\mathrm{THDM}}_{\mathrm{NLO}}[h \to WW^*]}{\mathrm{BR}^{\mathrm{SM}}_{\mathrm{NLO}}[h \to WW^*]} - 1$$

$$\Gamma^{\mathrm{THDM}}_{\mathrm{LO}}[h \to WW^*] \propto \sin^2(\beta - \alpha)$$

➡ $\Gamma^{\mathrm{THDM}}[h \to WW^*] \lesssim \Gamma^{\mathrm{SM}}[h \to WW^*]$

If $\cos(\beta - \alpha) > 0$ · · · $\Gamma^{\mathrm{THDM}}_{h,\mathrm{total}} > \Gamma^{\mathrm{SM}}_{h,\mathrm{total}}$

If $\cos(\beta - \alpha) < 0$ · · · $\Gamma^{\mathrm{THDM}}_{h,\mathrm{total}} < \Gamma^{\mathrm{SM}}_{h,\mathrm{total}}$

➡ Decrease in $\Gamma^{\mathrm{THDM}}_{\mathrm{partial}}$ is canceled by decrease in $\Gamma^{\mathrm{THDM}}_{\mathrm{h,total}}$.

Correlation between BR($H \to hh$) and BR($h \to WW^*$) is changed from LO by $O(10)$%.

It is important to evaluate both *h*-decays and *H*-decays with loop corrections simultaneously.

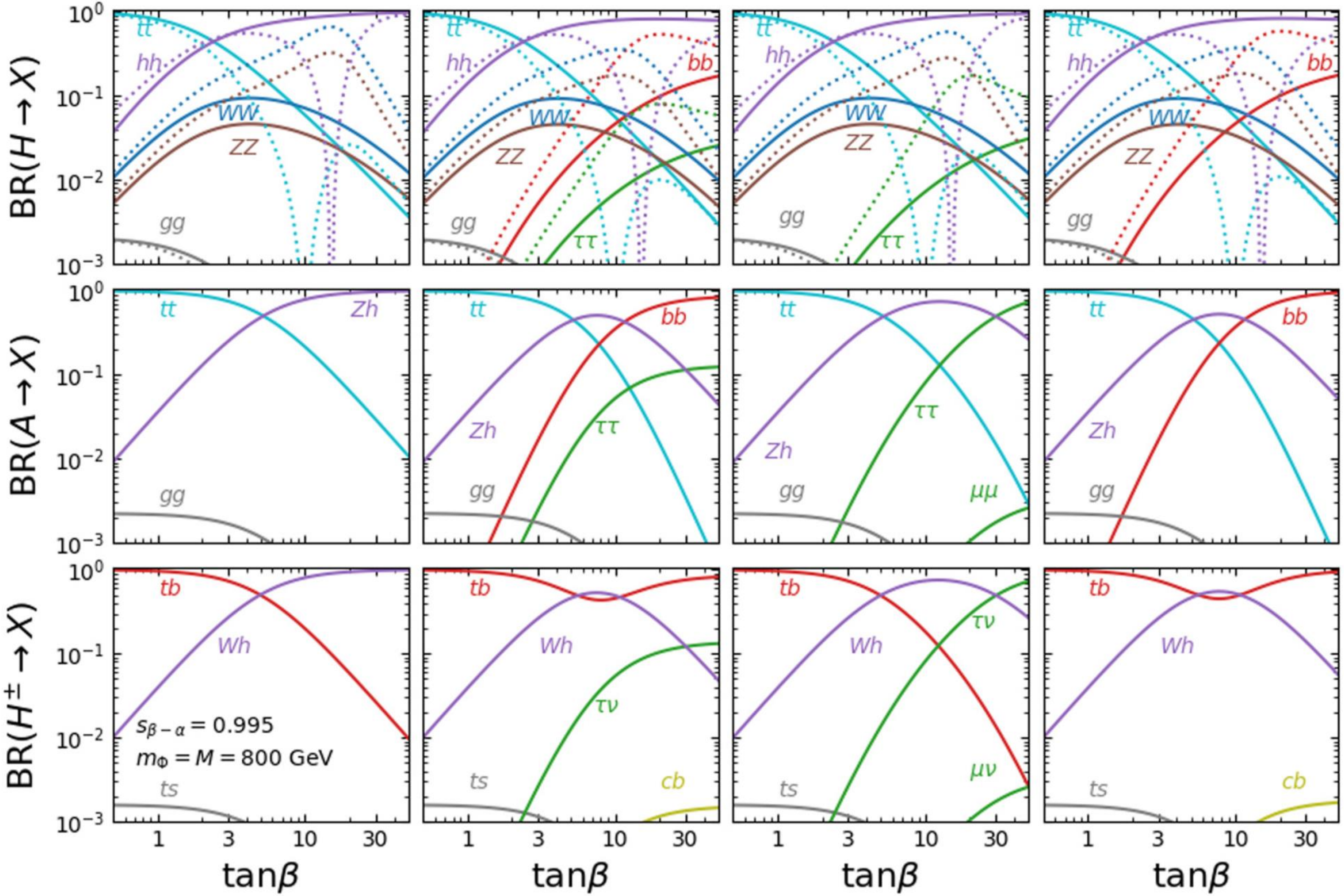


Fig. 5. Decay branching ratios for h, H, A and $H^\pm$ as a function of $\tan\beta$ in the case of $m_\Phi = M = 800$ GeV and $s_{\beta-\alpha} = 0.995$. Solid lines show results of $c_{\beta-\alpha} < 0$ and dotted lines are those of $c_{\beta-\alpha} > 0$. Results for Type-I, Type-II, Type-X and Type-Y of the THDM are shown from the left panels to the right panels.

Expected uncertainties of $\sigma\times$BR at ILC

ILC250 with 2 at^{-1} total integrated luminosity

arXiv:2203.07622 (Snowmass report2021)

$\sigma_{Zh}\times$ BR(h → bb)	0.7%
$\sigma_{Zh}\times$ BR(h → cc, gg)	4%
$\sigma_{Zh}\times$ BR(h → ττ)	2%
$\sigma_{Zh}\times$ BR(h → μμ)	38%
$\sigma_{Zh}\times$ BR(h → ZZ)	8%
$\sigma_{Zh}\times$ BR(h → WW)	2.4%

Table 2.4. Expected accuracies for cross section times branching ratio measurements for the 125 GeV h boson.

ILC TDR (2013)

	$\Delta(\sigma\cdot BR)/(\sigma\cdot BR)$				
$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	250 fb^{-1} at 250 GeV (-0.8,+0.3)		500 fb^{-1} at 500 GeV (-0.8,+0.3)		1 ab^{-1} at 1 TeV (-0.8,+0.2)
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$h\to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	0.47%
$h\to c\bar{c}$	7.4%	-	12%	6.2%	7.6%
$h\to gg$	9.1%	-	14%	4.1%	3.1%
$h\to WW^*$	6.4%	-	9.2%	2.6%	3.3%
$h\to\tau^+\tau^-$	4.2%	-	5.4%	14%	3.5%
$h\to ZZ^*$	19%	-	25%	8.2%	4.4%
$h\to\gamma\gamma$	29-38%	-	29-38%	20-26%	7-10%
$h\to\mu^+\mu^-$	100%	-	-	-	32%

ILC

Snowmass 2021 report [arXiv:2203.07622]

coupling	ILC250 full	ILC250 no BSM	ILC500 full	ILC500 no BSM	ILC1000 full	ILC1000 no BSM
hZZ	0.49	0.38	0.35	0.20	0.34	0.16
hWW	0.48	0.38	0.35	0.20	0.34	0.16
hbb	0.99	0.80	0.58	0.43	0.47	0.31
$h\tau\tau$	1.1	0.95	0.75	0.63	0.63	0.52
hgg	1.6	1.6	0.96	0.91	0.67	0.59
hcc	1.8	1.7	1.2	1.1	0.79	0.72
$h\gamma\gamma$	1.1	1.0	1.0	0.96	0.94	0.89
$h\gamma Z$	8.9	8.9	6.5	6.5	6.4	6.4
$h\mu\mu$	4.0	4.0	3.8	3.7	3.4	3.4
htt	—	—	6.3	6.3	1.0	1.0
hhh	—	—	20	20	10	10
Γ_{tot}	2.3	1.3	1.6	0.70	1.4	0.50
Γ_{inv}	0.36	—	0.32	—	0.32	—

Table 12.2: Projected uncertainties in the Higgs boson couplings for the ILC250, ILC500, and ILC1000, with precision LHC input. All values are *relative* errors, given in percent (%). The columns labelled "full" refer to a 22-parameter fit including the possibility of invisible and exotic Higgs boson decays. The columns labelled "no BSM" refer to a 20-parameter fit including only decays modes present in the SM.

Renormalization in potential (1)

Parameters in Higgs potential (8)

$$m_h^2, \quad m_H^2, \quad m_A^2, \quad m_{H^\pm}^2, \quad M^2(m_{12}^2), \quad v, \quad \alpha, \quad \beta$$

Parameter shift ;

$$m_\varphi^2 \to m_\varphi^2 + \delta m_\varphi^2 \quad M^2 \to M^2 + \delta M^2 \quad v \to v + \delta v \quad \alpha \to \alpha + \delta\alpha \quad \beta \to \beta + \delta\beta$$

8 counterterms via parameter shifts

Field shift ;

$$\begin{pmatrix} H \\ h \end{pmatrix} \to \begin{pmatrix} 1 + \delta Z_H & \delta C_{Hh} + \delta\alpha \\ \delta C_{hH} - \delta\alpha & 1 + \delta Z_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} \to \begin{pmatrix} 1 + \delta Z_G & \delta C_{GA} + \delta\beta \\ \delta C_{AG} - \delta\beta & 1 + \delta Z_A \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} \to \begin{pmatrix} 1 + \delta Z_{G^\pm} & \delta C_{G^\pm H^\mp} + \delta\beta \\ \delta C_{H^\pm G^\mp} - \delta\beta & 1 + \delta Z_{H^\pm} \end{pmatrix} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

12 counterterms via field shifts

Total : 20 counterterms

Renormalization in potential (2)

- On shell conditions

δm_ϕ^2	$\times 4$	$\hat{\Pi}_{\phi\phi}[m_\phi^2] = 0.$	$\times 4$	$\delta m_i^2 = \tilde{\Pi}_{ii}^{\rm 1PI}[m_i^2]$	$\times 6$
δZ_ϕ	$\times 6$	$\frac{d}{dp^2}\hat{\Pi}_{\phi\phi}[p^2]\|_{p^2=m_\phi^2} = 0,$	$\times 6$	$\delta Z_i = -\frac{d}{dp^2}\Pi_{ii}^{\rm 1PI}[p^2]\|_{p^2=m_i^2}$	$\times 6$
δC_{Hh} δC_{hH} $\delta\alpha$	3	$\delta C_{hH} = \delta C_{Hh}$ $\hat{\Pi}_{hH}[m_h^2] = \hat{\Pi}_{hH}[m_H^2] = 0,$	3	$\delta C_{hH} = \delta C_{Hh} = \frac{1}{m_H^2 - m_h^2}(\Pi_{hH}^{\rm 1PI}[m_h^2] - \Pi_{hH}^{\rm 1PI}[m_H^2])$ $\delta\alpha = \frac{1}{2(m_H^2 - m_h^2)}(\tilde{\Pi}_{Hh}^{1PI}[m_h^2] + \tilde{\Pi}_{Hh}^{1PI}[m_H^2])$	
δC_{GA} δC_{AG} $\delta\beta$	3	$\delta C_{GA} = \delta C_{AG}$ $\hat{\Pi}_{AG^0}[m_A^2] = \hat{\Pi}_{AG^0}[0] = 0$	3	$\delta C_{AG} = \delta C_{GA} = -\frac{1}{2m_A^2}(\Pi_{AG^0}^{1PI}[m_A^2] - \Pi_{AG^0}^{1PI}[0])$ $\delta\beta = \frac{1}{2m_A^2}(\tilde{\Pi}_{AG}^{1PI}[m_A^2] + \tilde{\Pi}_{AG}^{1PI}[0])$	
$\delta C_{H^\pm G^\mp}$ $\delta C_{G^\pm H^\mp}$	2	$\hat{\Pi}_{H^\pm G^\mp}[m_{H^\pm}^2] = \hat{\Pi}_{H^\pm G^\mp}[0] = 0$ $\delta C_{GA} = \delta C_{AG}$	2	$\delta C_{H^\pm G^\mp} = \delta C_{G^\pm H^\mp} = \delta\beta + \frac{1}{m_{H^\pm}^2}\tilde{\Pi}_{H^\pm G^\mp}^{1PI}[0]$	
δv is determined by EW renormalization.			1	Total : 19	

Renormalization in potential (3)

δM^2 is determined by the MS-bar scheme, which absorb only the divergent part in the *hhh* vertex at the one-loop level.

$$\hat{\Gamma}_{hhh} = 6\lambda_{hhh} + \delta\Gamma_{hhh} + \Gamma^{1\text{PI}}_{hhh}$$

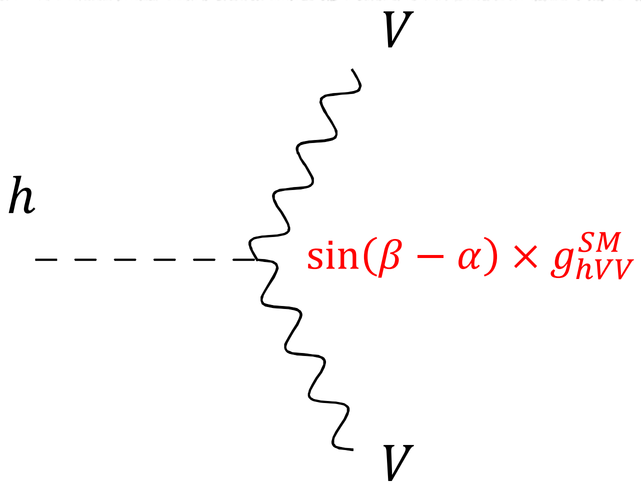
$$\delta\Gamma_{hhh} = 6\delta\lambda_{hhh} + 9\lambda_{hhh}\delta Z_h + 6\lambda_{Hhh}(\delta C_{Hh} + \delta\alpha)$$

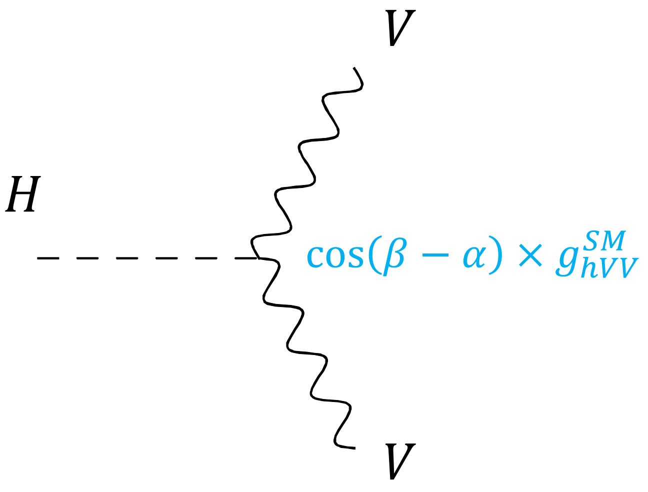
$$\delta\lambda_{hhh} = -\lambda_{hhh}\frac{\delta v}{v} - \frac{c_{3\alpha-\beta} + 3c_{\alpha+\beta}}{4vs_{2\beta}}\delta m_h^2 + F_\alpha\delta\alpha + F_\beta\delta\beta + \frac{c^2_{\beta-\alpha}c_{\alpha+\beta}}{vs_{2\beta}}\delta M^2$$

Remove only divergent part

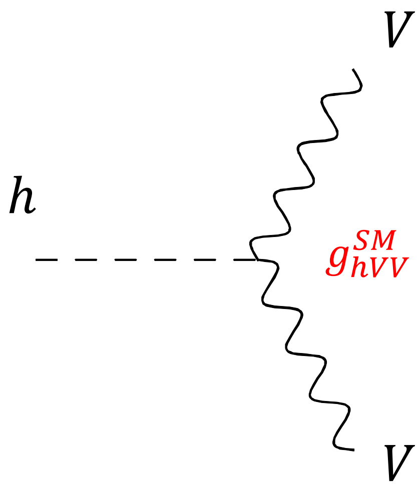
$$\delta M^2 = \frac{M^2}{16\pi^2 v^2}\Big[2\sum_f N_c^f m_f^2\kappa_f^2 + 4M^2 - 2m_{H^\pm}^2 - m_A^2 + \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2)$$
$$- 3(2m_W^2 + m_Z^2)\Big]\Delta_{\text{Div}} + \frac{2c_{2\beta}}{s_{2\beta}}\frac{M^2}{v}\left(\frac{c_{\beta-\alpha}}{m_h^2}\text{Div}(T_h^{1\text{PI}}) - \frac{s_{\beta-\alpha}}{m_H^2}\text{Div}(T_H^{1\text{PI}})\right)$$

Alignment limit at tree level

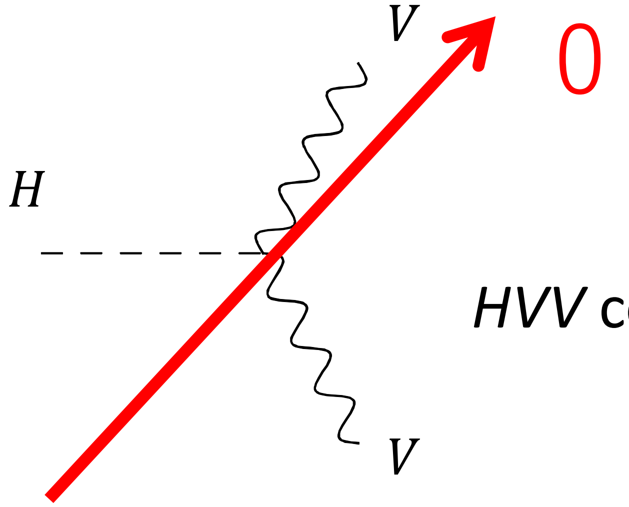




Alignment limit



hVV coupling is exactly that of the SM.

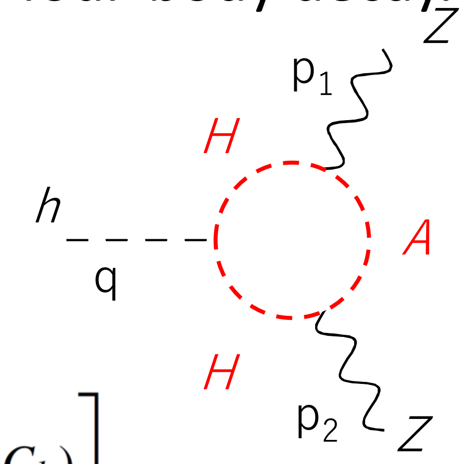


HVV coupling vanishes.

Alignment limit at loop level（*hVV*）

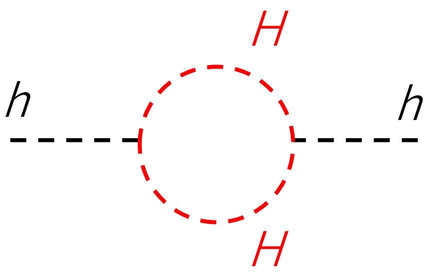
At loop level, sin(β-α) is no longer a parameter that represents "alignmentness".
One cannot take the exact alignment limit at loop level.

Since the renormalized *hVV* vertex cannot take the on-shell momentum, we have to calculate not the renormalized vertex but the three-body decay or the four-body decay.



$$\hat{\Gamma}^i_{hVV}(p_1^2, p_2^2, q^2) = \Gamma^{i,\text{tree}}_{hVV} + \delta\Gamma^i_{hVV} + \Gamma^{i,\text{1PI}}_{hVV}(p_1^2, p_2^2, q^2)$$

$$\delta\Gamma^1_{hVV} = \frac{2m_V^2}{v}\left[\sin(\beta-\alpha)\left(\frac{\delta m_V^2}{m_V^2} + \delta Z_V + \frac{1}{2}\delta Z_h - \frac{\delta v}{v}\right) + \cos(\beta-\alpha)(\delta\beta + \delta C_h)\right]$$



Alignment limit at loop level（*HVV*）

Renormalized *HVV* vertex

$$\hat{\Gamma}^{i}_{HVV}(p_1^2, p_2^2, q^2) = \Gamma^{1.Tree}_{HVV} + \delta\Gamma^{i}_{HVV} + \Gamma^{i,1PI}_{HVV}\ (p_1^2, p_2^2, q^2)$$

Renormalized *HVV* vertex

$$\delta\Gamma^{1}_{HVV} = \frac{2m_V^2}{v}\left[\cos(\beta-\alpha)\left(\frac{\delta m_V^2}{m_V^2} - \frac{\delta v}{v} + \delta Z_V + \frac{1}{2}\delta Z_H\right) + \sin(\beta-\alpha)(\delta C_{hH} - \delta\beta\ )\right]$$

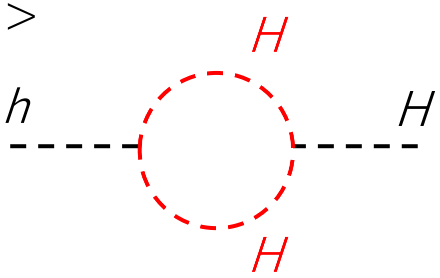
In the case with $\sin(\beta-\alpha) = 1$

$$\delta\Gamma^{1}_{HVV} = \frac{2m_V^2}{v}[(\delta C_{hH} - \delta\beta\ )] \neq 0$$

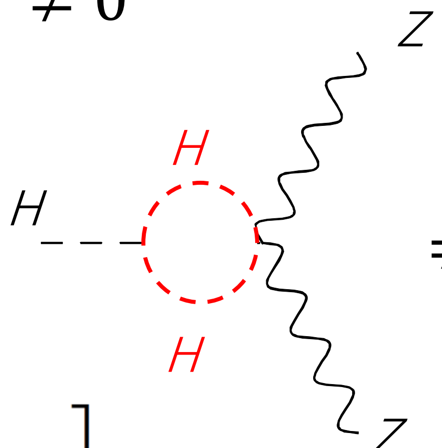
$$\Gamma^{i,1PI}_{HVV}\ (p_1^2, p_2^2, q^2) \neq 0$$

Only taking sin(b-a) = 1 does not realize *HVV* = 0.

ex.>>



$\neq 0$



$\neq 0$

In the case with $m^2_{H,A,H^\pm} = M^2$, these loop contributions vanish.

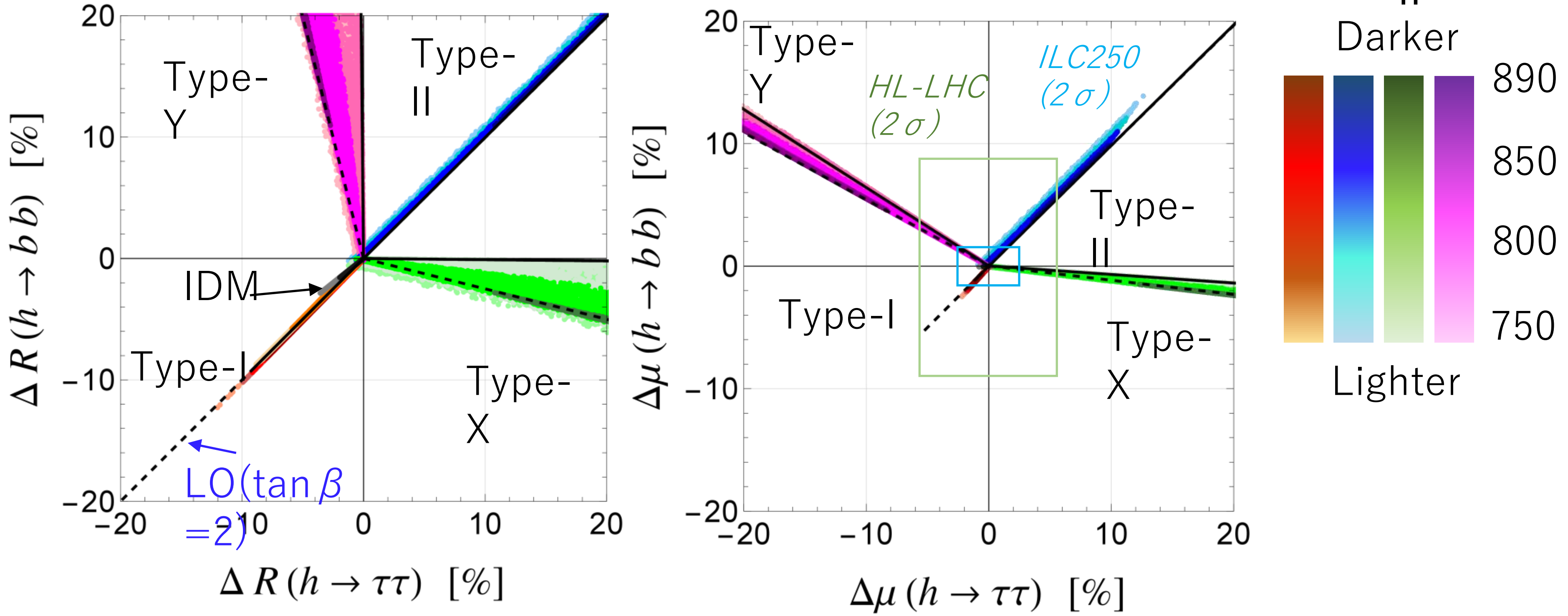
$$\lambda_{HHH} = -\frac{1}{2v}\left[2(M^2 - m_H^2)\cot 2\beta s^3_{\beta-\alpha} - 2(M^2 - m_H^2)c_{\beta-\alpha}s^2_{\beta-\alpha} + m_H^2 c_{\beta-\alpha}\right]$$

$h \to bb$, $h \to \tau\tau$

$$m_A = m_{H^\pm} = 800\ \text{GeV},\ \cos(\beta - \alpha) < 0$$

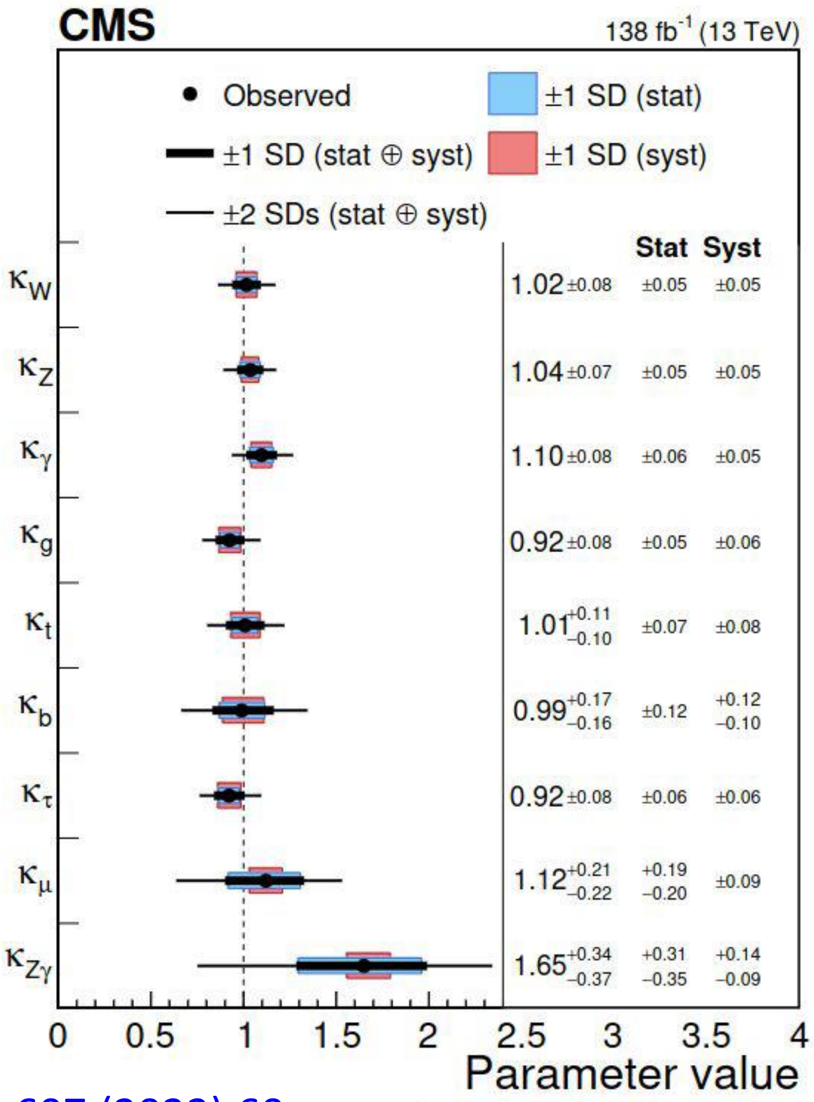
$$\Delta R[h \to XX] = \frac{\Gamma_{\text{NLO}}^{\text{THDM}}[h \to XX]}{\Gamma_{\text{NLO}}^{\text{SM}}[h \to XX]} - 1$$

$$\Delta \mu[h \to XX] = \frac{\text{BR}_{\text{NLO}}^{\text{THDM}}[h \to XY]}{\text{BR}_{\text{NLO}}^{\text{SM}}[h \to XY]} - 1$$



If $|\Delta R[h \to \text{bb}/\tau\tau]| > \text{several}\ \%$, prediction of each Type does not overlap

Combined scale factor results



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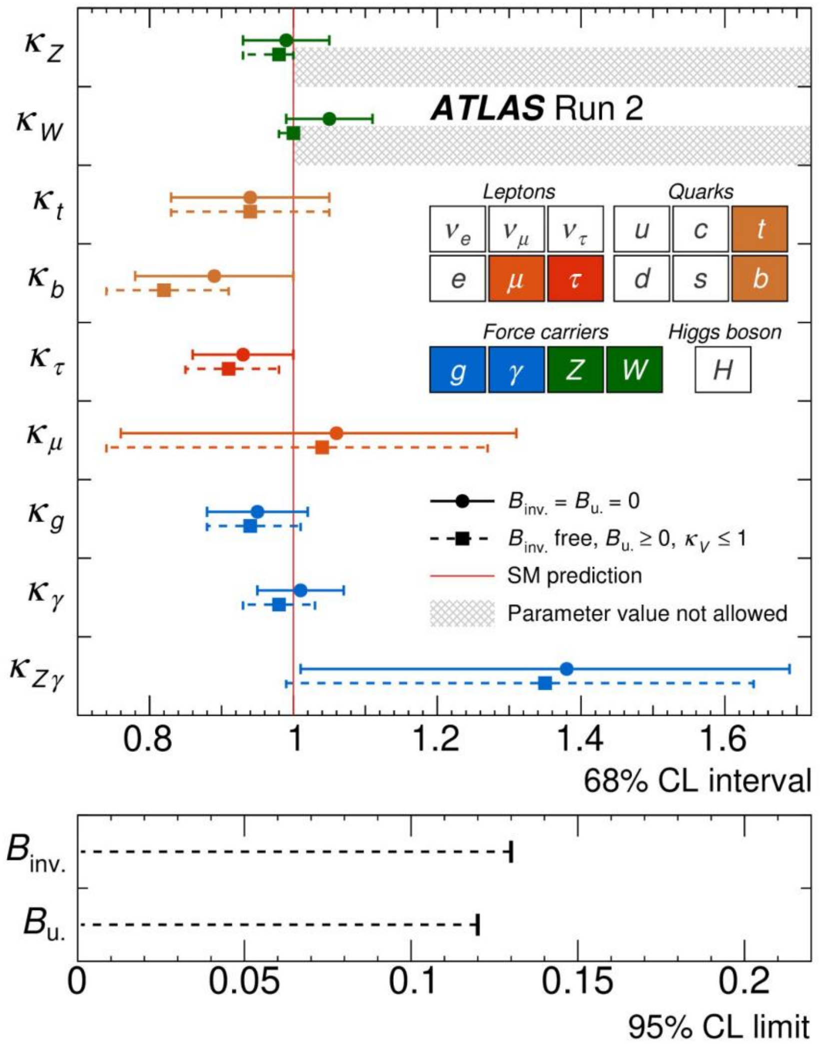

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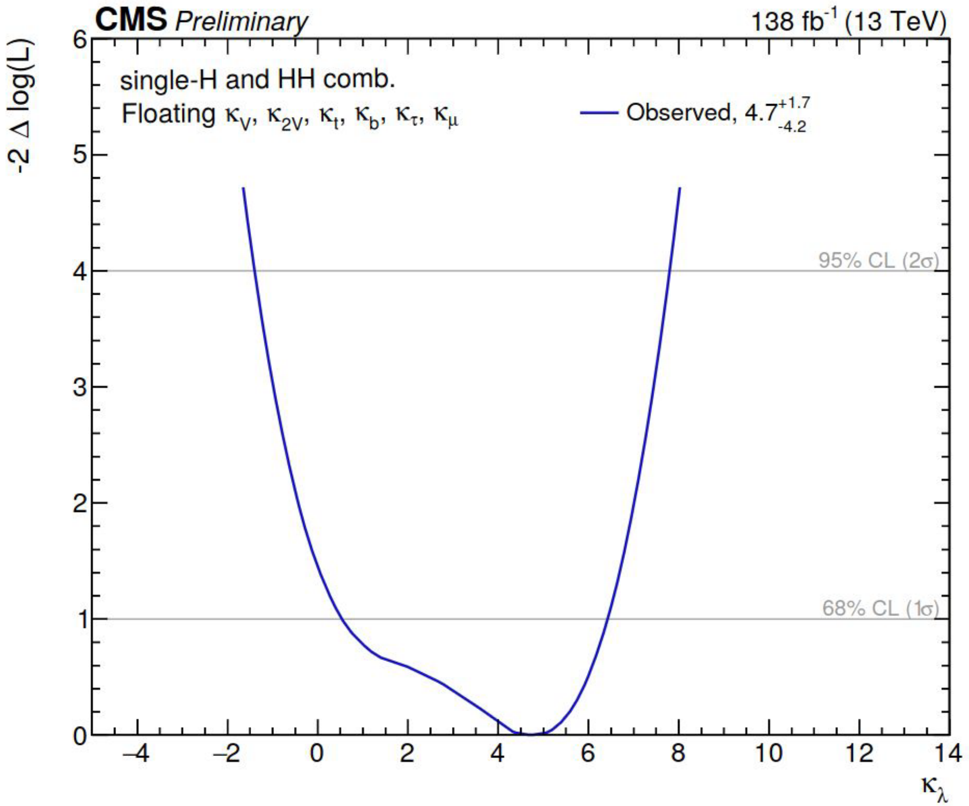
hhh coupling measurement



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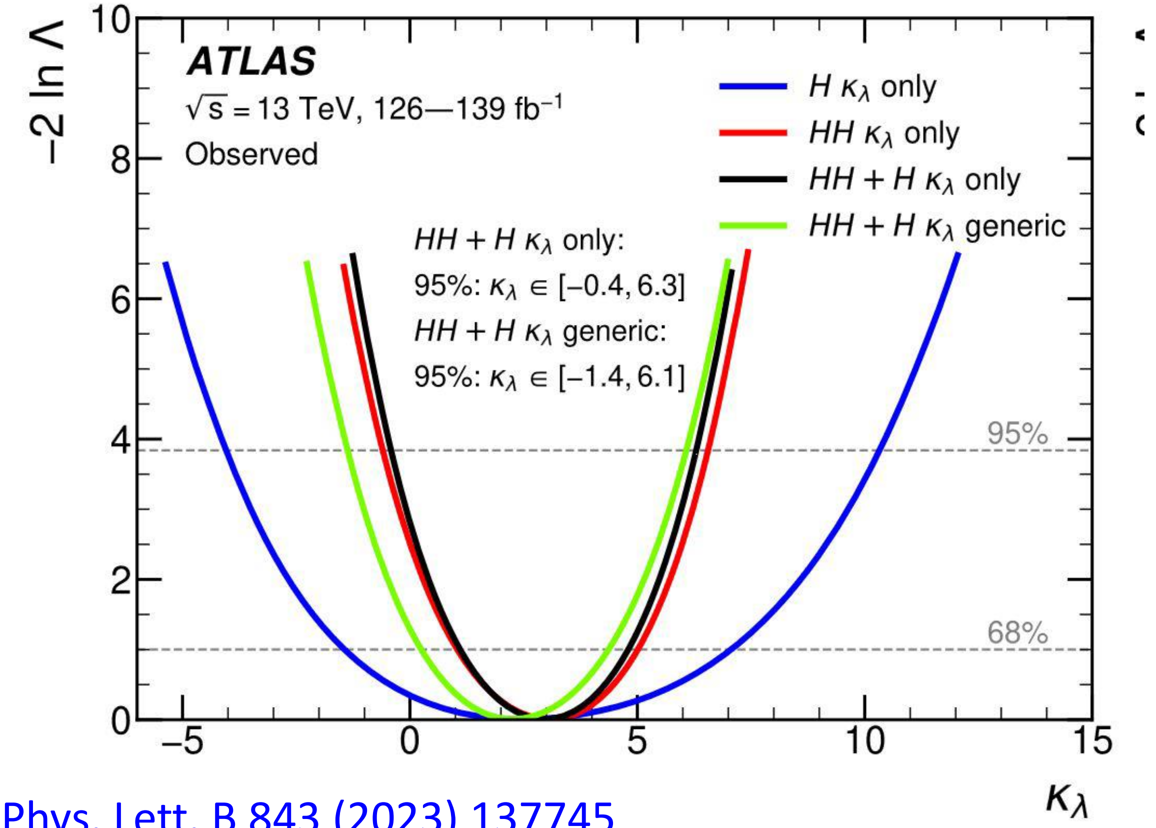

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$-1.2 < \kappa_\lambda < 7.5$ at 95% CL

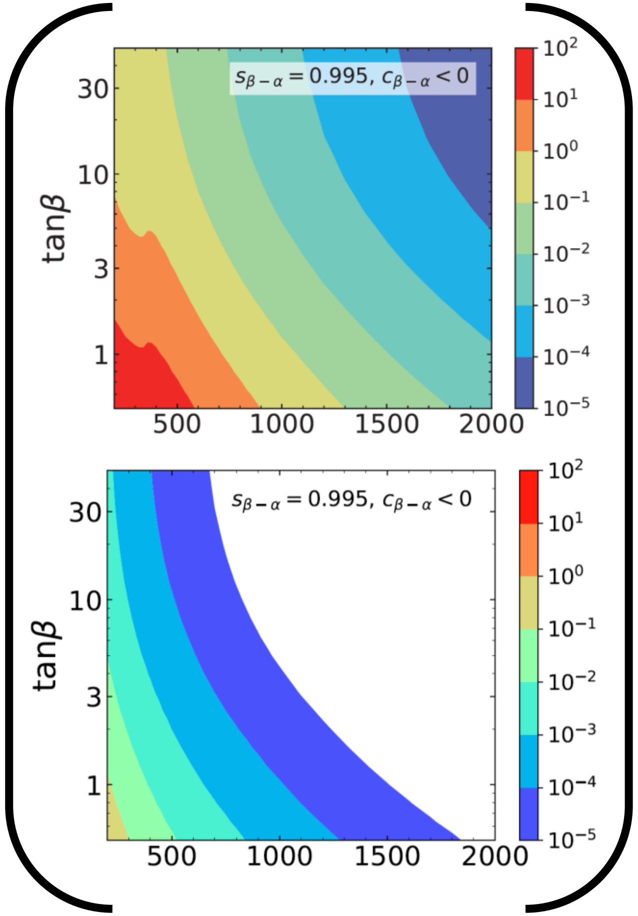
$-1.4 < \kappa_\lambda < 6.1$ at 95% CL

Constraint from direct searches (Run2)

Production cross section

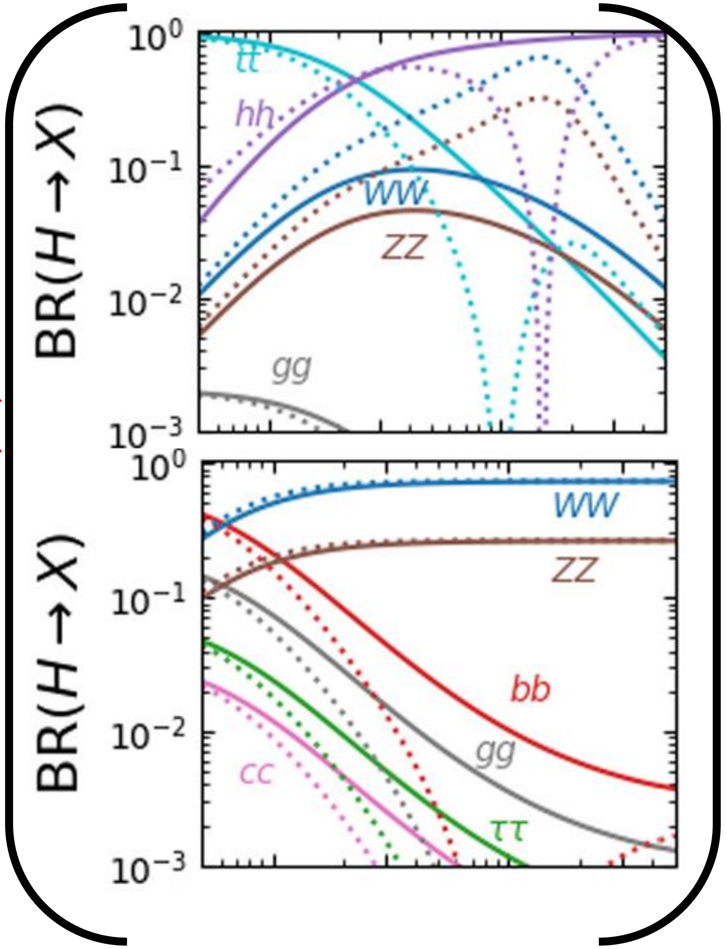
gluon-fusion process (pp→H)

bottom associated process(pp→H(bb))



×

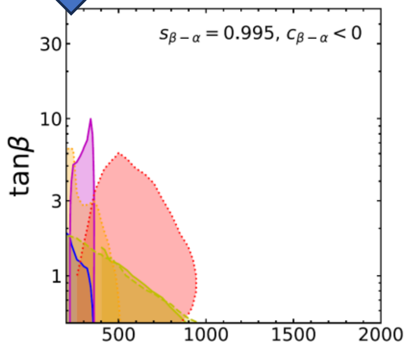
BR



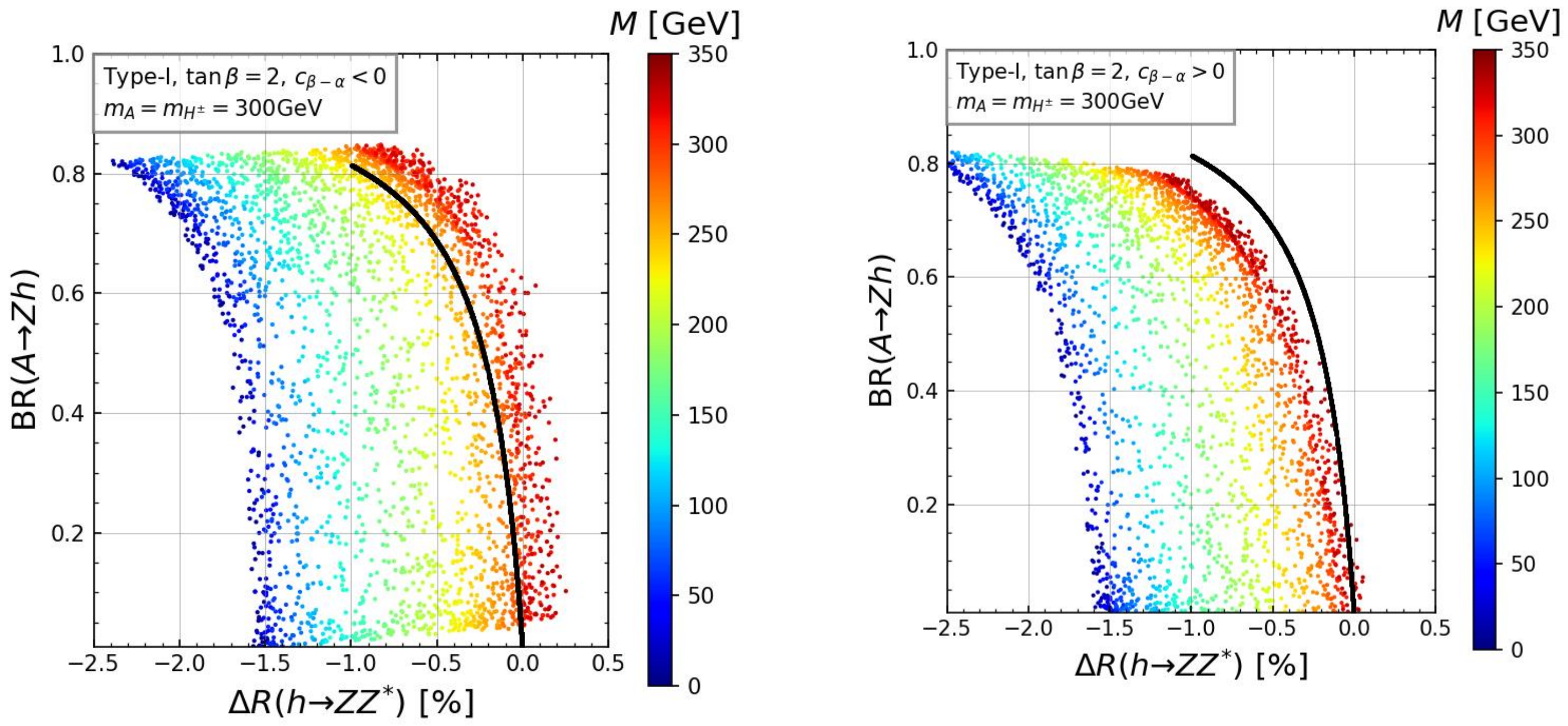
Compare

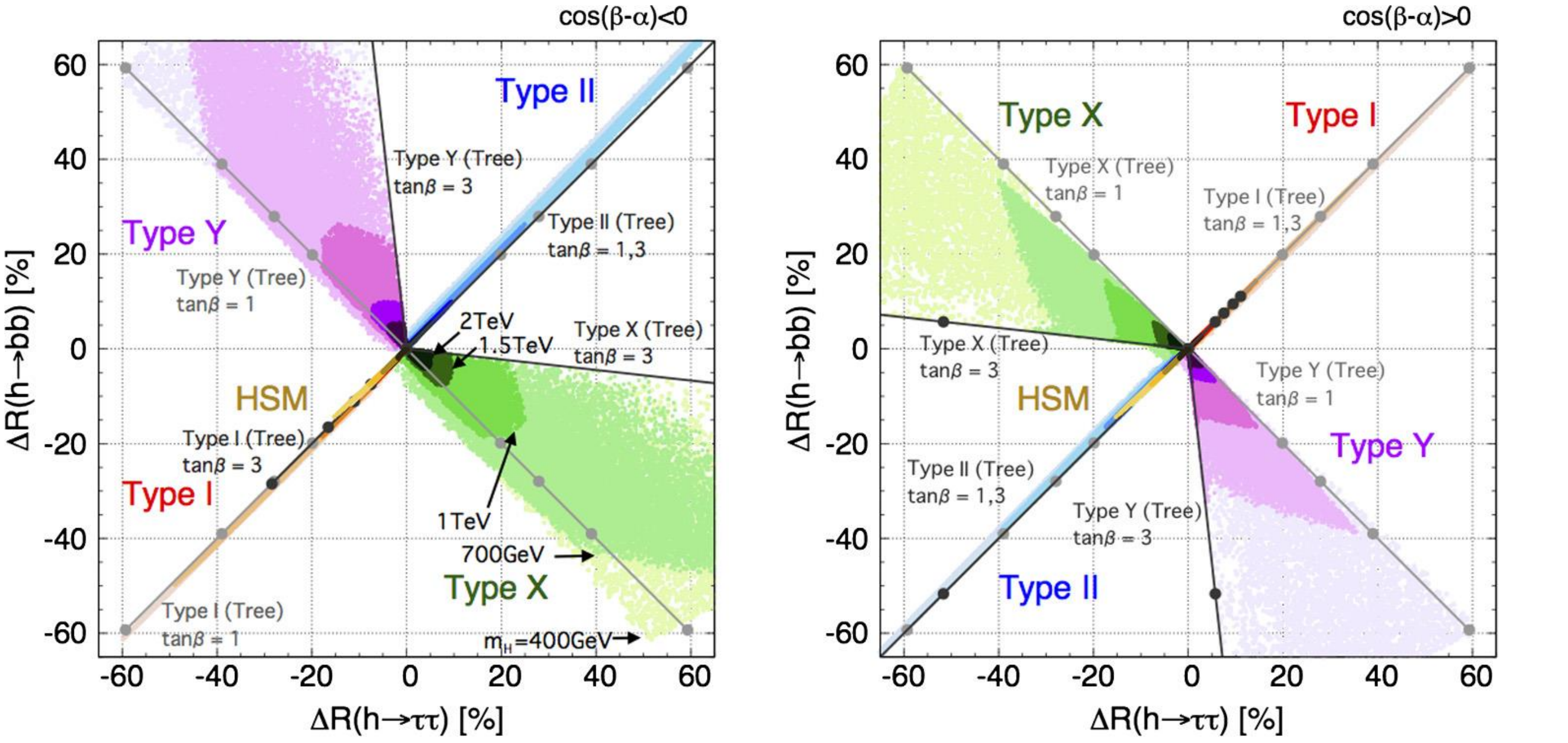
Upper limits at 95% CL with 36fb^{-1} data

obtain Constraints



Correlation between $A \to Zh$ and $h \to ZZ^*$




cos(β-α)<0
Type II
Type Y (Tree)
tanβ = 3
Type II (Tree)
tanβ = 1,3
Type Y
Type Y (Tree)
tanβ = 1
2TeV
1.5TeV
Type X (Tree)
tanβ = 3
HSM
Type I (Tree)
tanβ = 3
Type I
1TeV
700GeV
Type X
Type I (Tree)
tanβ = 1
m_H=400GeV
ΔR(h→bb) [%]
ΔR(h→ττ) [%]
cos(β-α)>0
Type X
Type I
Type X (Tree)
tanβ = 1
Type I (Tree)
tanβ = 1,3
Type X (Tree)
tanβ = 3
HSM
Type Y (Tree)
tanβ = 1
Type Y
Type II (Tree)
tanβ = 1,3
Type Y (Tree)
tanβ = 3
Type II
ΔR(h→bb) [%]
ΔR(h→ττ) [%]