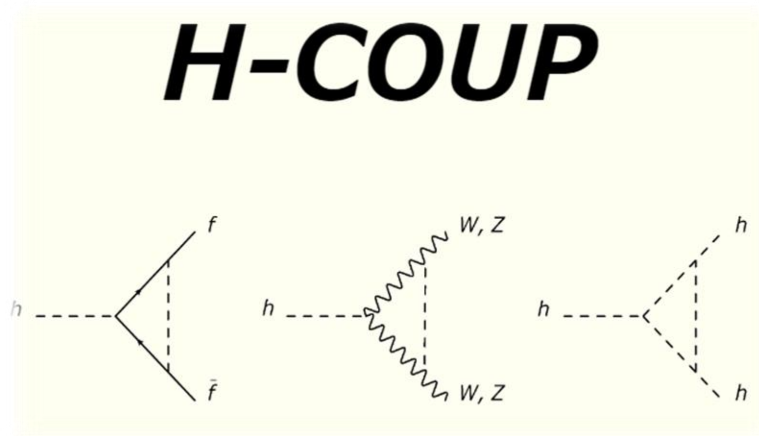
Comprehensive studies of loop-corrected decays of various Higgs bosons



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Collaborators;

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1. NPB 983(2022)115906, Kanemura, MK, Yagyu
2. In preparation, Aiko, Kanemura, MK, Sakurai, Yagyu

Why is Higgs sector important?

- What is Structure of Higgs sector ?

  Various extended Higgs sectors

Multi Doublets	Doublet + Singlet	Doublet + Triplet	・・・

Why is Higgs sector important?

- What is Structure of Higgs sector ?

  Various extended Higgs sectors

Multi Doublets | Doublet + Singlet | Doublet + Triplet | · · ·

$\Updownarrow$

Scalar DM | EWBG | CPV | 1st order PT | Tiny ν mass | · · ·

- Higgs sector is related to new physics scenarios.

  Each new physics model requires a characteristic Higgs sector.

It is important to explore Higgs sector
by bottom-up approach.

Why is Higgs sector important?

- What is Structure of Higgs sector ?

  Various extended Higgs sectors

Multi Doublets | Doublet + Singlet | Doublet + Triplet | ･･･

Scalar DM | EWBG | CPV | 1st order PT | Tiny ν mass | ･･･

- Higgs sector is related to new physics scenarios.

  Each new physics model requires a characteristic Higgs sector.

It is important to explore Higgs sector by bottom-up approach.

- We here focus on "Doublet + an additional scalar".

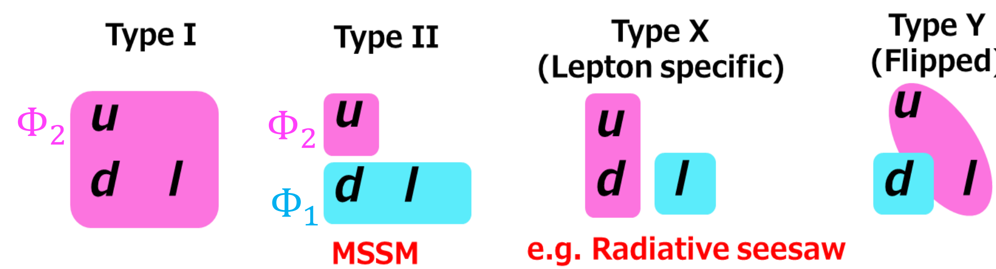
Higgs singlet model (HSM), Two Higgs doublet model (THDM), Inert doublet (IDM), …

Two Higgs double models (THDMs)

- Some new physics models contain two Higgs doublets.
  (MSSM, Inert DM, loop induced m_ν , CPV, …)

- We focus on THDM with softly broken Z2.
  Can avoid FCNC.

4 types of Yukawa interactions



- We focus on CP-conserving case

- Mass eigenstates

Higgs basis **h (125GeV Higgs), H, A, $H^\pm$**

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

- Parameters in potential

m_h v m_H m_A m_{H^+} $\sin(\beta-\alpha)$ $\tan\beta$ M^2

※ $M^2 = \dfrac{m_3{}^2}{\sin\beta\cos\beta}$ $\tan\beta = \dfrac{v_2}{v_1}$

Deviations from SM predictions

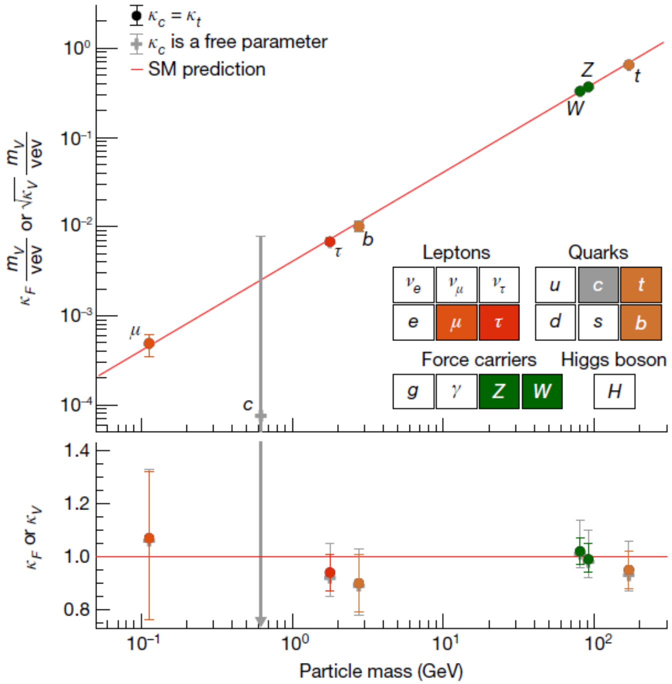
- h-couplings can change via field mixing (α, β)

$$\kappa_X = \frac{g_{hXX}^{NP}}{g_{hXX}^{SM}}$$

$\sin(\beta-\alpha) = \kappa_V \to 1$ ⋯(Higgs) alignment limit

[Couplings of h are aligned to those of SM.]

- LHC Run2 results of h_{125} measurement



Current data is consistent with SM prediction within experimental uncertainties.

We focus on "nearly-alignment" case.

ATLAS Nature 607, 52-59

Additional Higgs bosons' decay in nearly-alignment

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

- Additional Higgs couplings with SM particles

Alignment limit

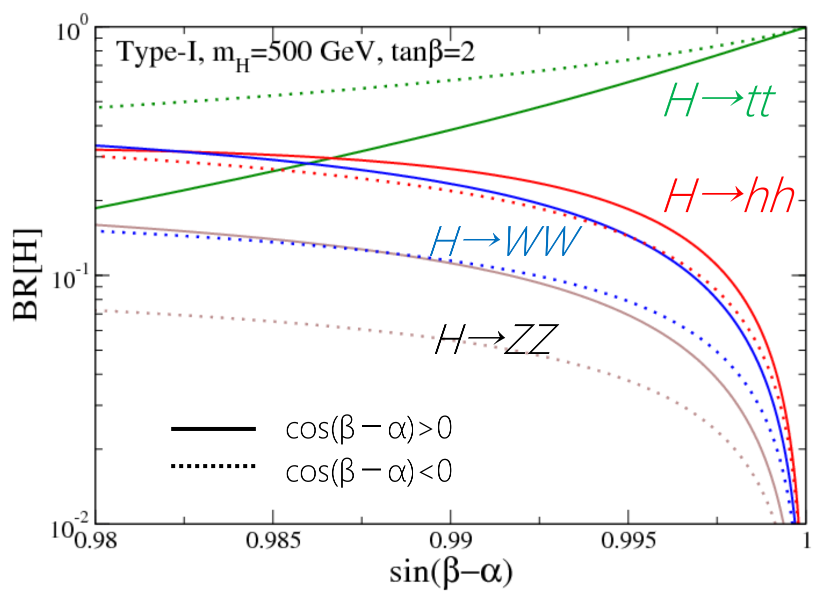
HWW, HZZ $$\kappa_V^H = \frac{g_{HVV}^{NP}}{g_{hVV}^{SM}} = \cos(\beta-\alpha) \quad \rightarrow 0$$

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

But, in nearly alignment they play important roles

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

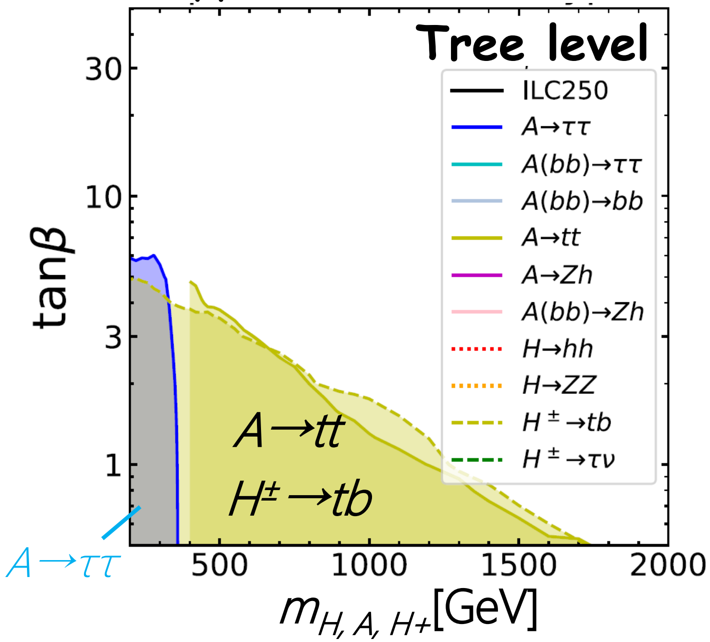
- Branching ratio of *H*

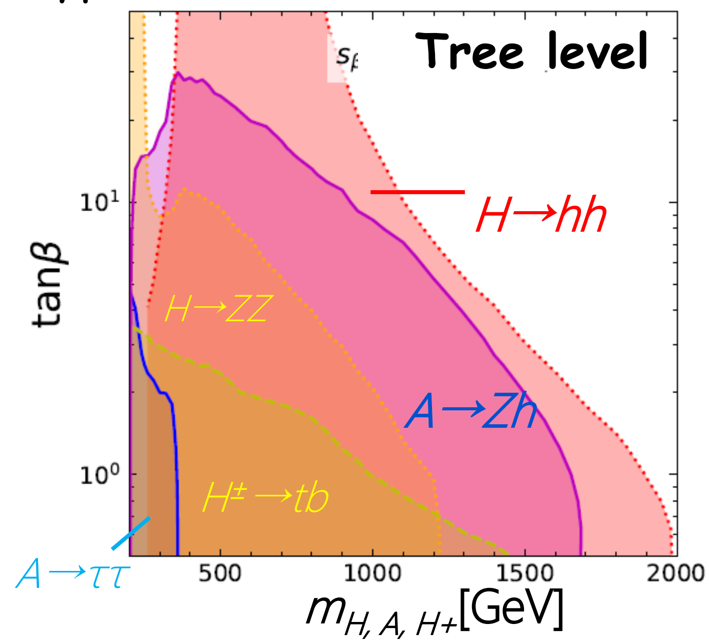


H-decays are very sensitive to sin(β − α).

Searchable regions in nearly-alignment

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





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 not only *h*-decays but also additional Higgs decays.

H-COUP project

Numerical program for Full set of BRs of Higgs bosons with radiative corrections.

H-COUP [éɪtʃ-kúː] *Aiko, Kanemura, MK, Sakurai, Yagyu*

Various observables

Couplings, BR, Γ, …

h→VV, h→ff, h→γγ, …

Including radiative corr.

SM
HSM (Φ+S)
THDMs ($\Phi_1+\Phi_2$)
(Type-I, II, X, Y)
IDM (Φ+η)

Model Variations

×

Future precision data

HL-LHC,
ILC, CEPC, FCC, …

Explore Higgs sector

- **EW and scalar-NLO by on-shell scheme**
  Kanemura, MK, Yagyu, NPB 896 (2015) 80, Kanemura, MK, Yagyu NPB 917 (2017) 154,
  Kanemura, MK, Mawatari, Sakurai, Yagyu, NPB 949 (2019) 114791,
  Kanemura, MK, Sakurai, PRD 94 (2016) , Kanemura, MK, Sakurai, Yagyu, PRD 96 (2017)
- **NNLO QCD corrections by MS-bar scheme**
  A. Djouadi, Phys. Rept., 457, 1 (2008), M. Spira, Prog. Part. Nucl. Phys., 95, 98 (2017),
  K. G. Chetyrkin, A. Kwiatkowski, Nucl. Phys., B461, 3 (1996)...

Ver.1 (2017) : Renormalized vertices of ***h*(125)**. Kanemura, MK, Sakurai, Yagyu, CPC.233(2018)134
Ver.2 (2019) : Decay BRs of ***h*(125)**. Kanemura, MK, Mawatari, Sakurai, Yagyu, CPC 257(2020) 107512
Ver.3(Coming soon) : Decay BRs of additional Higgs bosons

【Other public tools】
★2HDECAY : [M. Krause, M. Mühlleitner, M. Spira], ★Prophecy4f : [A. Denner, S. Dittmaier, A. Mück]

H-COUP ver.3

Processes in THDMs

NPB 973 (2021) 115581, Aiko, Kanemura, Sakurai
NPB 983(2022)115906 Kanemura, MK, Yagyu
NPB 986 (2023) 116047 Aiko, Kanemura, Sakurai,

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

HSM

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

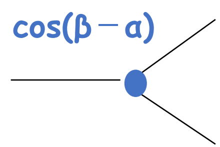
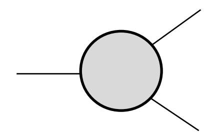
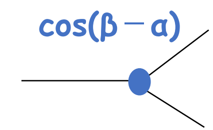
IDM

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

We show results for decays of $H\to hh$, $A\to Zh$, $h\to VV^*$, $h\to ff$ in THDMs.

Loop corrections to $\Gamma[H\to hh]$

- NLO contributions works constructively or destructively
  $\cos(\beta-\alpha) > 0$ ··· constructively, $\cos(\beta-\alpha) < 0$ ··· destructively

$\Gamma_{NLO}[H\to hh]$ = |  |^2 + 2Re[ × ]

- Decoupling? Or Non-decoupling?

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

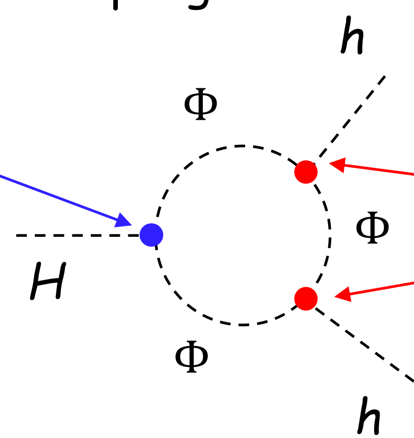
$M^2 \simeq \lambda' v^2$ ··· Non-decoupling

Scalar self couplings

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

$\boxed{\cos(\beta-\alpha) \ll 1 \text{ case}}$

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



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

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

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

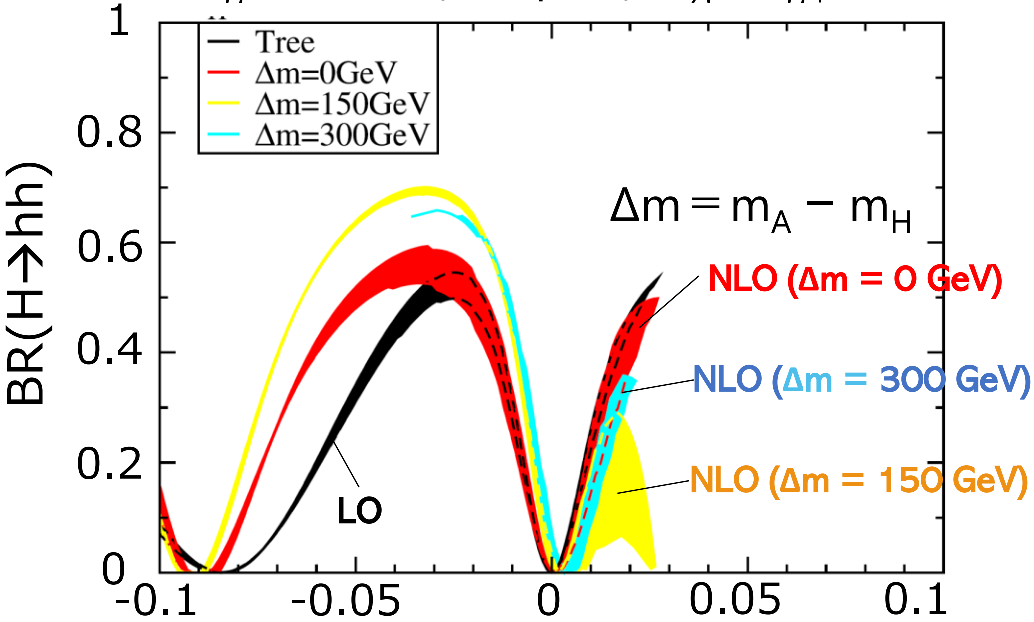
Even if $m_{\mathrm{H}}^2 \simeq M^2$, corrections of $H^\pm, A$ loop diagrams are not suppressed.

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

Type-I

m_H=500GeV, tanβ=5, m_A=m_{H+}

NPB 983(2022)115906
Kanemura, MK, Yagyu



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

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

If cos(β−α)>0 $\cdots$ $\Gamma^{\mathrm{THDM}}_h > \Gamma^{\mathrm{SM}}_h$

If cos(β−α)<0 $\cdots$ $\Gamma^{\mathrm{THDM}}_h < \Gamma^{\mathrm{SM}}_h$

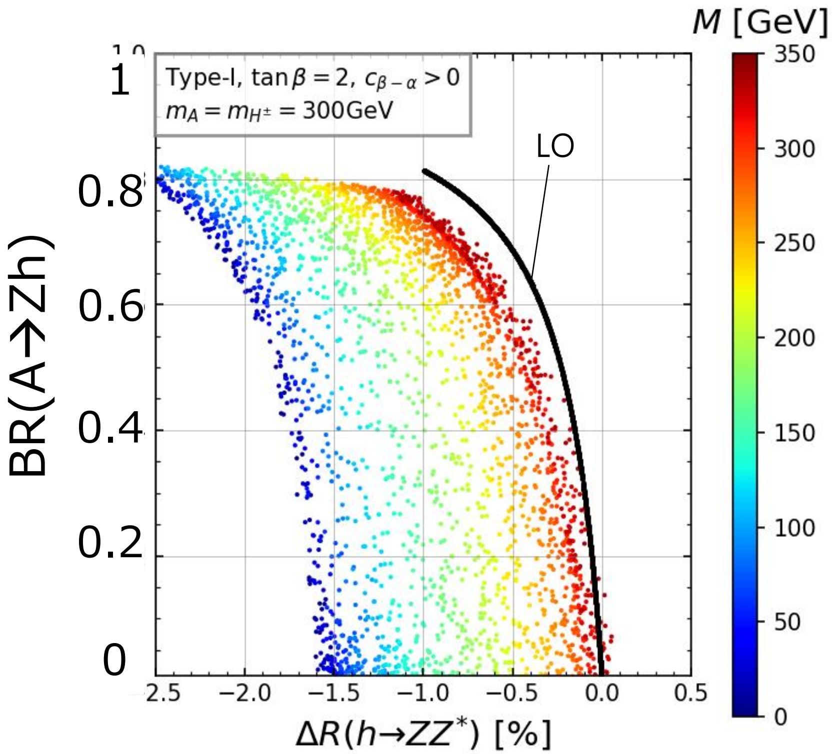
Correlation between BR($H \to hh$) and BR($h \to WW^*$) is changed from LO by $O(10)$%.

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

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

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

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



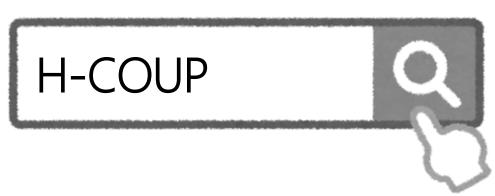
$$\Delta R[h \to ZZ^*] = \frac{\Gamma_{\rm NLO}^{\rm THDM}[h \to ZZ^*]}{\Gamma_{\rm NLO}^{\rm SM}[h \to ZZ^*]} - 1$$

BR[$A \to Zh$] also receives O(10)% correction if tanβ≃2.

Correlation between BR($A \to Zh$) and ΔR ($h \to ZZ^*$) is significantly changed from LO.

Summary

- LHC results of h_{125} measurements indicate "nearly alignment", where additional Higgs bosons' decays are very interesting !!
- Study of radiative corrections to decays of both additional Higgs bosons and h_{125} are essentially important.
- We show results of BR[Higgs to Higgs decays] and BR[h_{125}] including radiative corrections.
- 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 $h \to VV^*$ are significantly changed from LO.**
- We will release H-COUP ver.3.



Counter terms

Parameter shift ;

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

8

Field shift ;

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

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

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

6 + 6

8(parameters) + 6(fields) + 6(field mixing) = 20

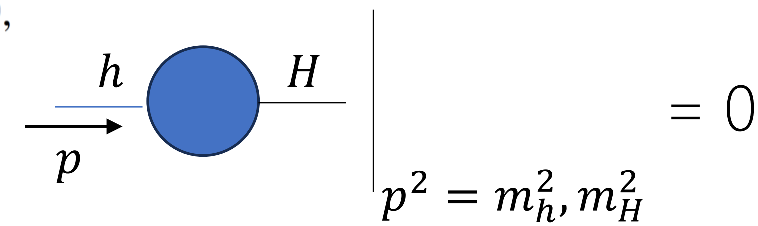
On-shell renormalization conditions

δm_i^2 δZ_i i = h, H, A, $H^\pm$

$$\hat{\Pi}_{ii}[m_i^2] = 0, \quad \frac{d}{dp^2}\hat{\Pi}_{ii}[p^2]\Big|_{p^2=m_i^2} = 1, \quad \Rightarrow \quad \delta m_i^2 = \tilde{\Pi}_{ii}^{1\mathrm{PI}}[m_i^2], \quad \delta Z_i = -\frac{d}{dp^2}\Pi_{ii}^{1\mathrm{PI}}[p^2]\Big|_{p^2=m_i^2}.$$

δC_h δC_A $\delta\alpha$ $\delta\beta$

$$\hat{\Pi}_{hH}[m_h^2] = \hat{\Pi}_{hH}[m_H^2] = 0, \quad \hat{\Pi}_{AG^0}[m_A^2] = \hat{\Pi}_{AG^0}[0] = 0,$$



$$\Downarrow$$

$$\delta C_h = \frac{1}{2(m_H^2 - m_h^2)}\left(\Pi_{Hh}^{1\mathrm{PI}}[m_h^2] - \Pi_{Hh}^{1\mathrm{PI}}[m_H^2]\right),$$

$$\delta C_A = -\frac{1}{2m_A^2}\left(\Pi_{Hh}^{1\mathrm{PI}}[m_A^2] - \Pi_{Hh}^{1\mathrm{PI}}[0]\right),$$

$$\delta\alpha_f = \frac{1}{2(m_H^2 - m_h^2)}\left(\tilde{\Pi}_{Hh}^{1\mathrm{PI}}[m_h^2] + \tilde{\Pi}_{Hh}^{1\mathrm{PI}}[m_H^2]\right),$$

$$\delta\beta_f = -\frac{1}{2m_A^2}\left(\tilde{\Pi}_{AG}^{1\mathrm{PI}}[m_A^2] + \tilde{\Pi}_{AG}^{1\mathrm{PI}}[0]\right),$$

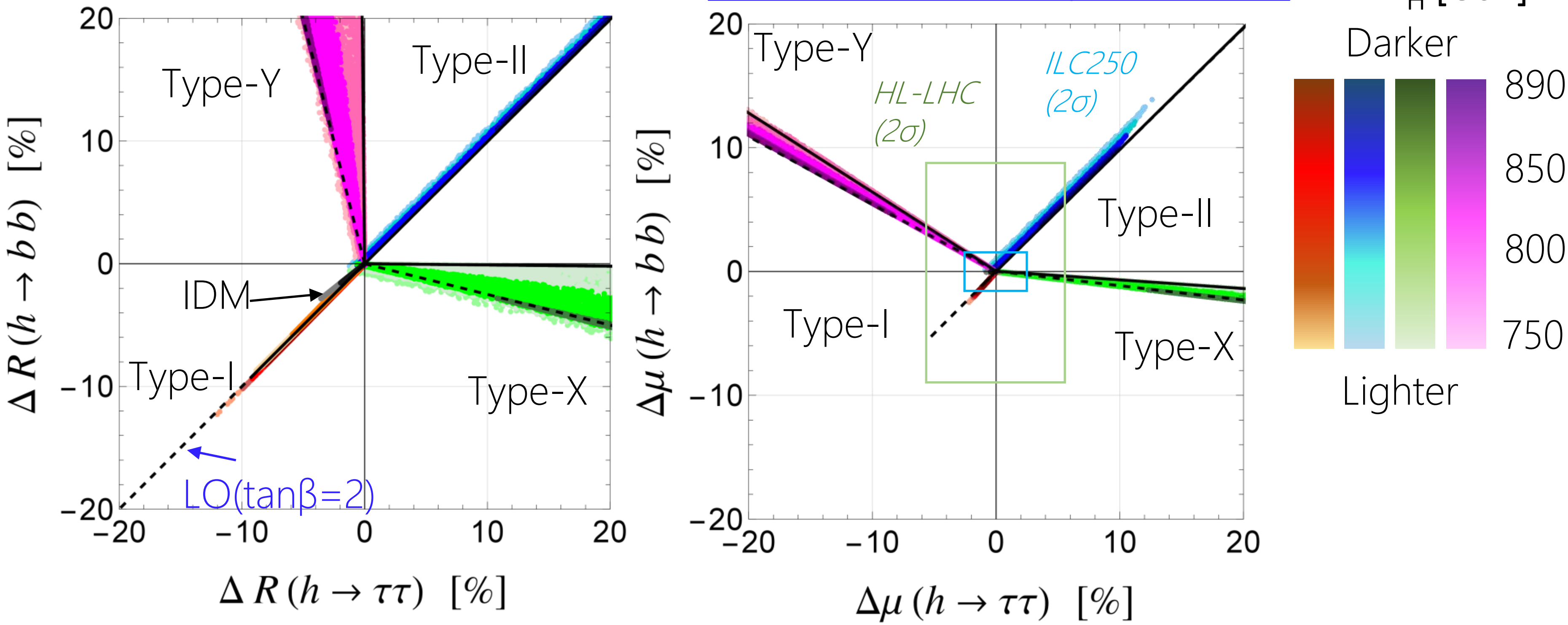
e we ake $\delta C_{hH} = \delta C_{Hh} \equiv \delta C_h$ and $\delta C_{AG^0} = \delta C_{G^0A} \equiv \delta C_A$.

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

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

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

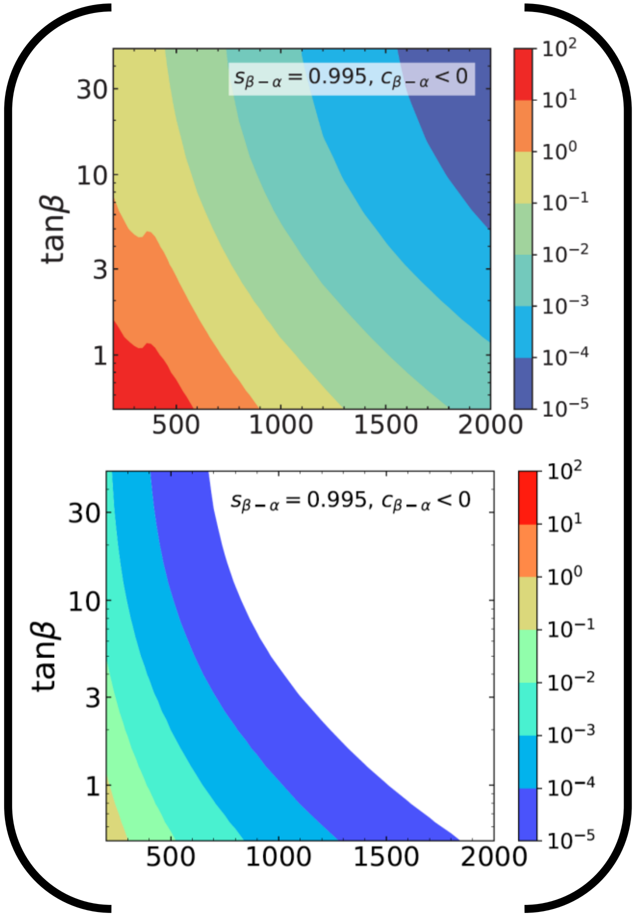
$$\Delta \mu[h \to XX] = \frac{\text{BR}^{\text{THDM}}_{\text{NLO}}[h \to XY]}{\text{BR}^{\text{SM}}_{\text{NLO}}[h \to XY]} - 1$$



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

Constraint from direct searches (Run2)

Production cross section



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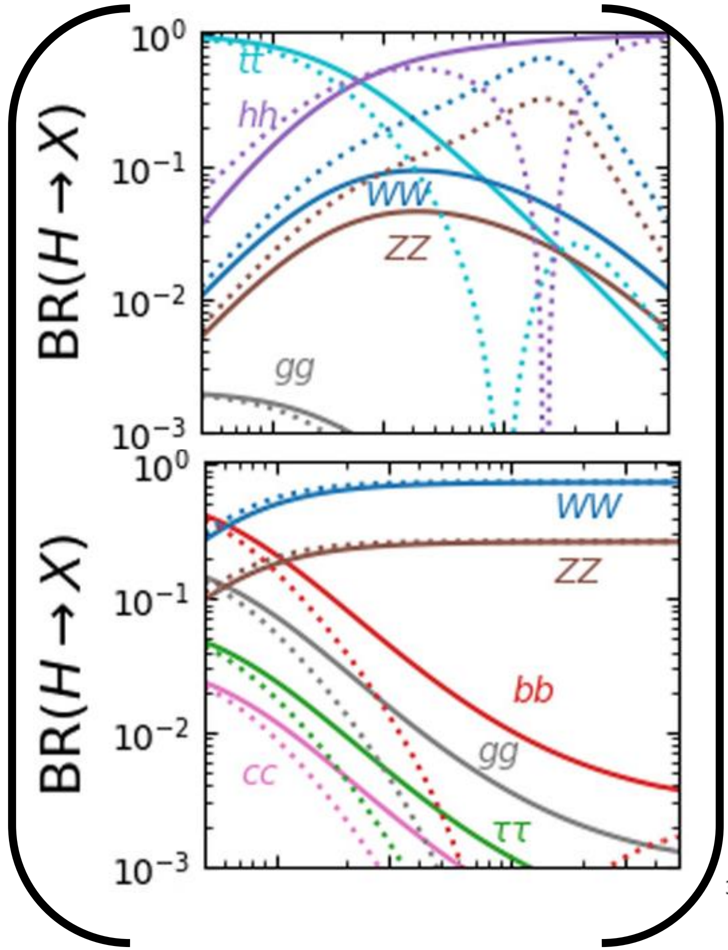
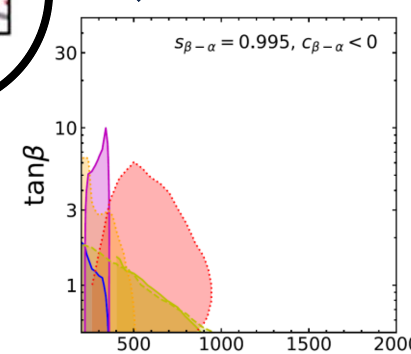
BR



Compare

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

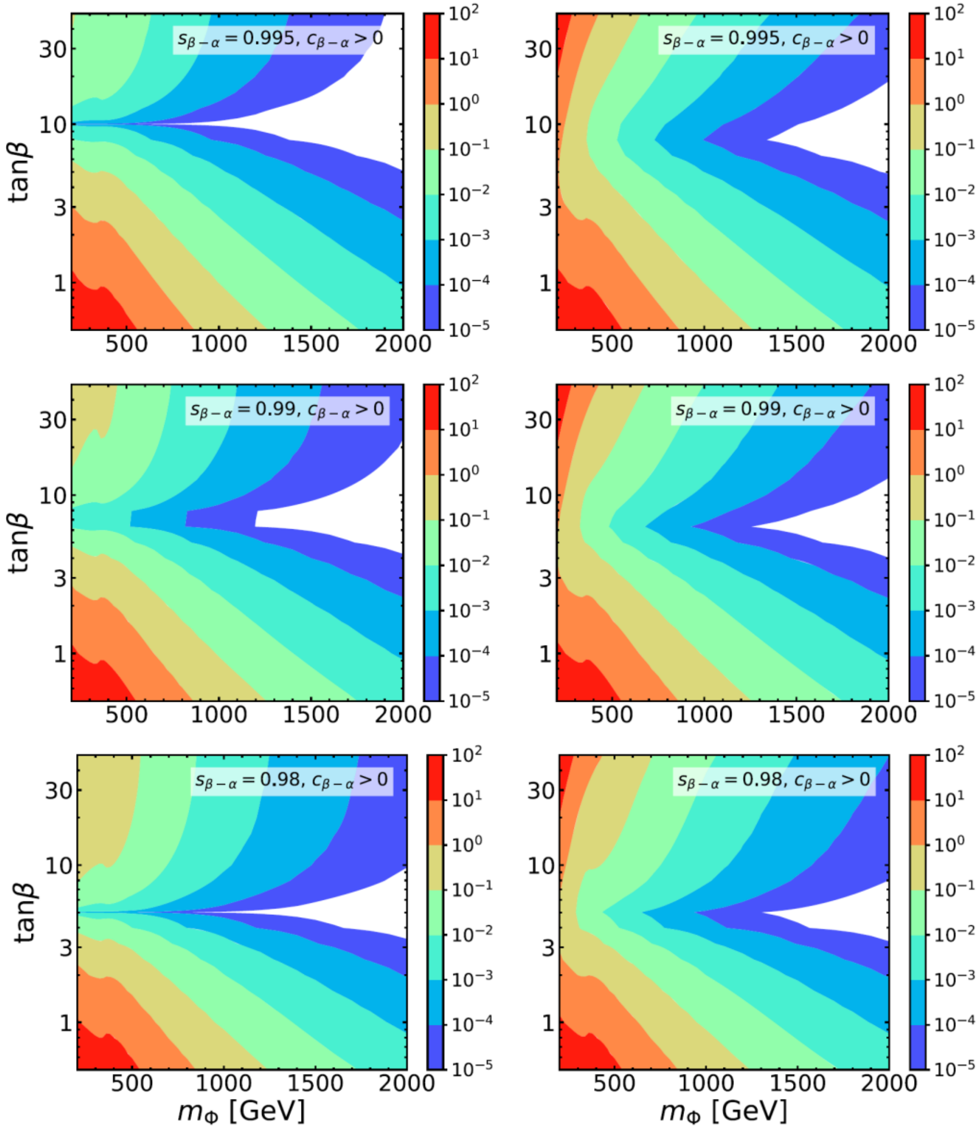
obtain Constraints



H production

Cos(β − α)>0

gluon-fusion process (pp→H), bottom associated process(pp→H(bb))



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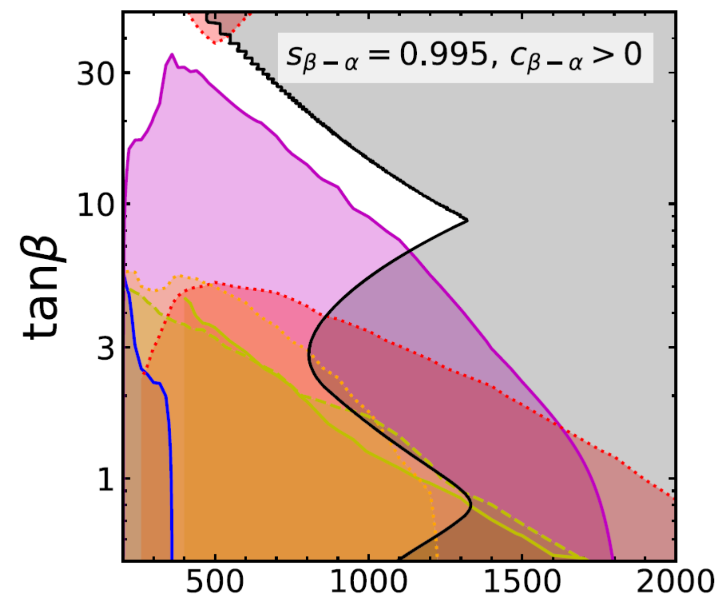
13TeV LHC



H production

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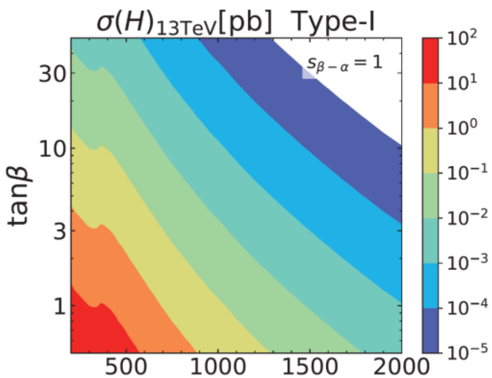

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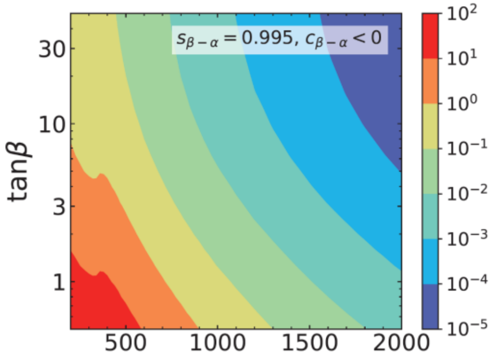
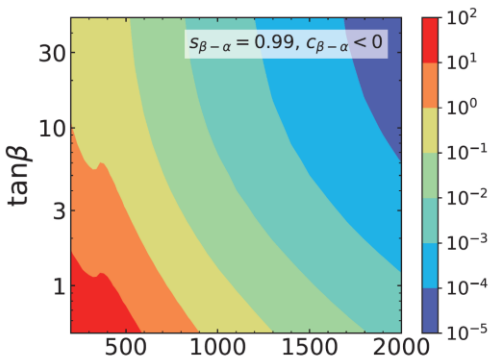
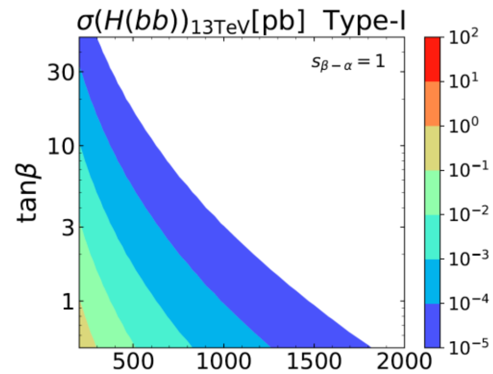
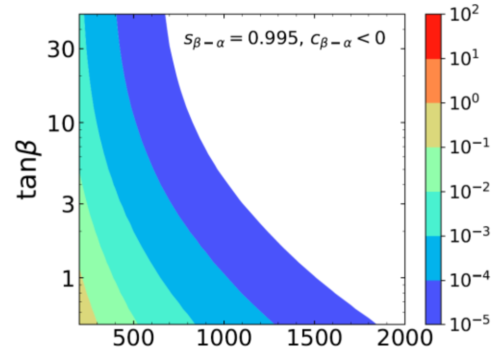
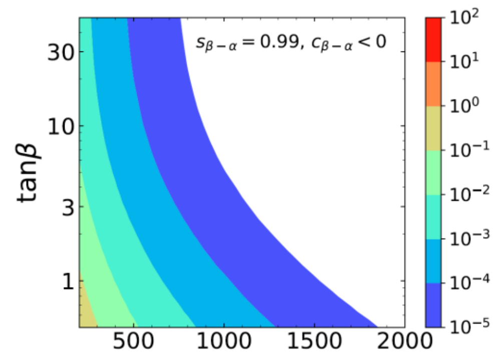


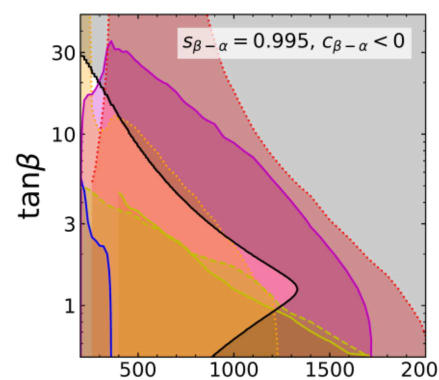




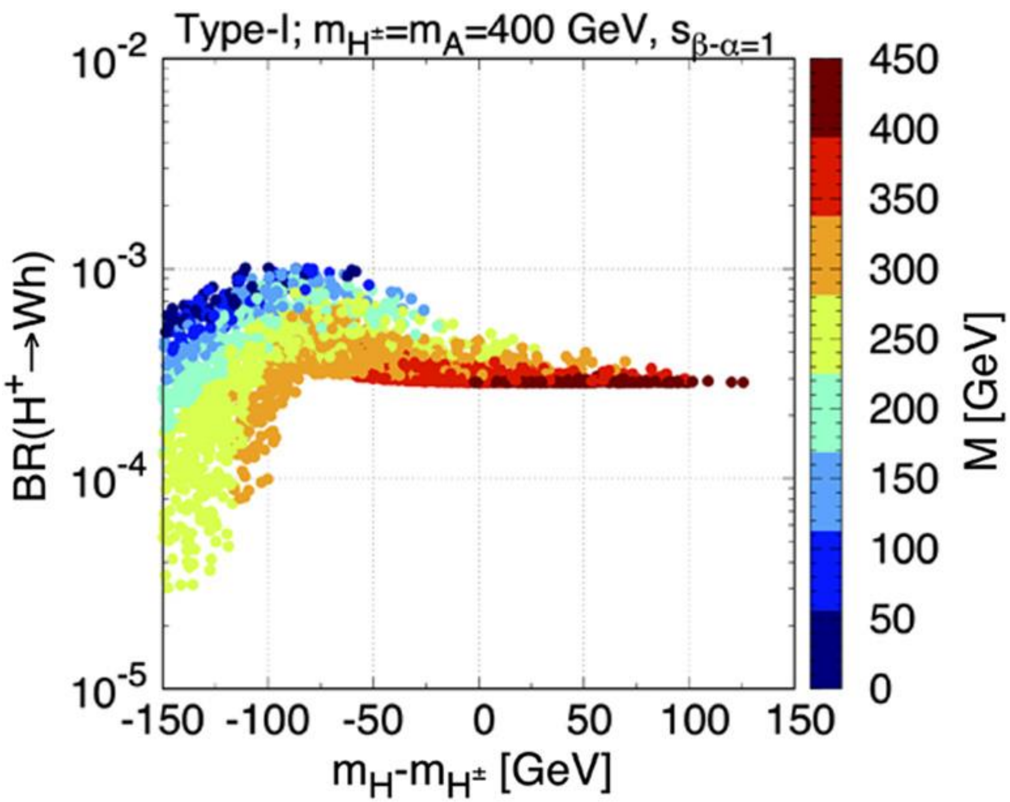
13TeV LHC





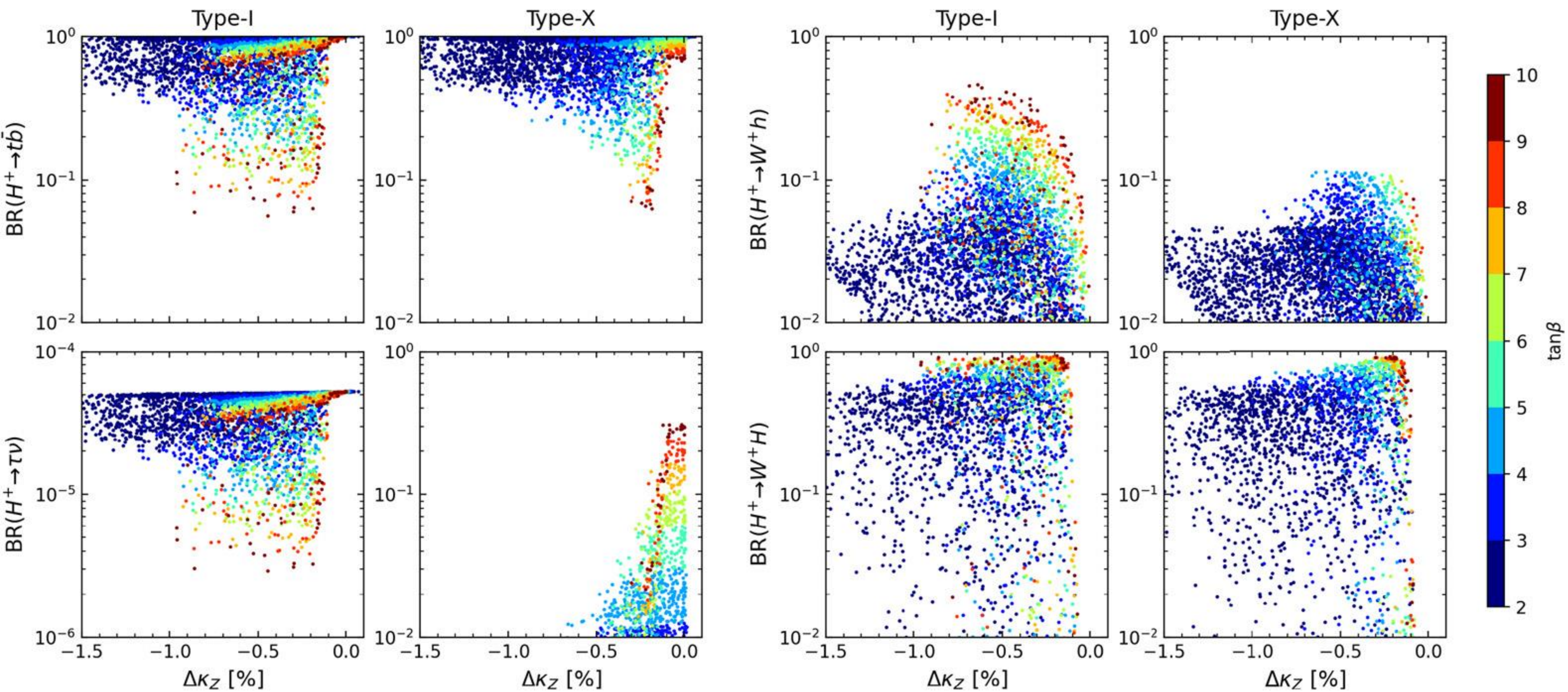


H^+ decays



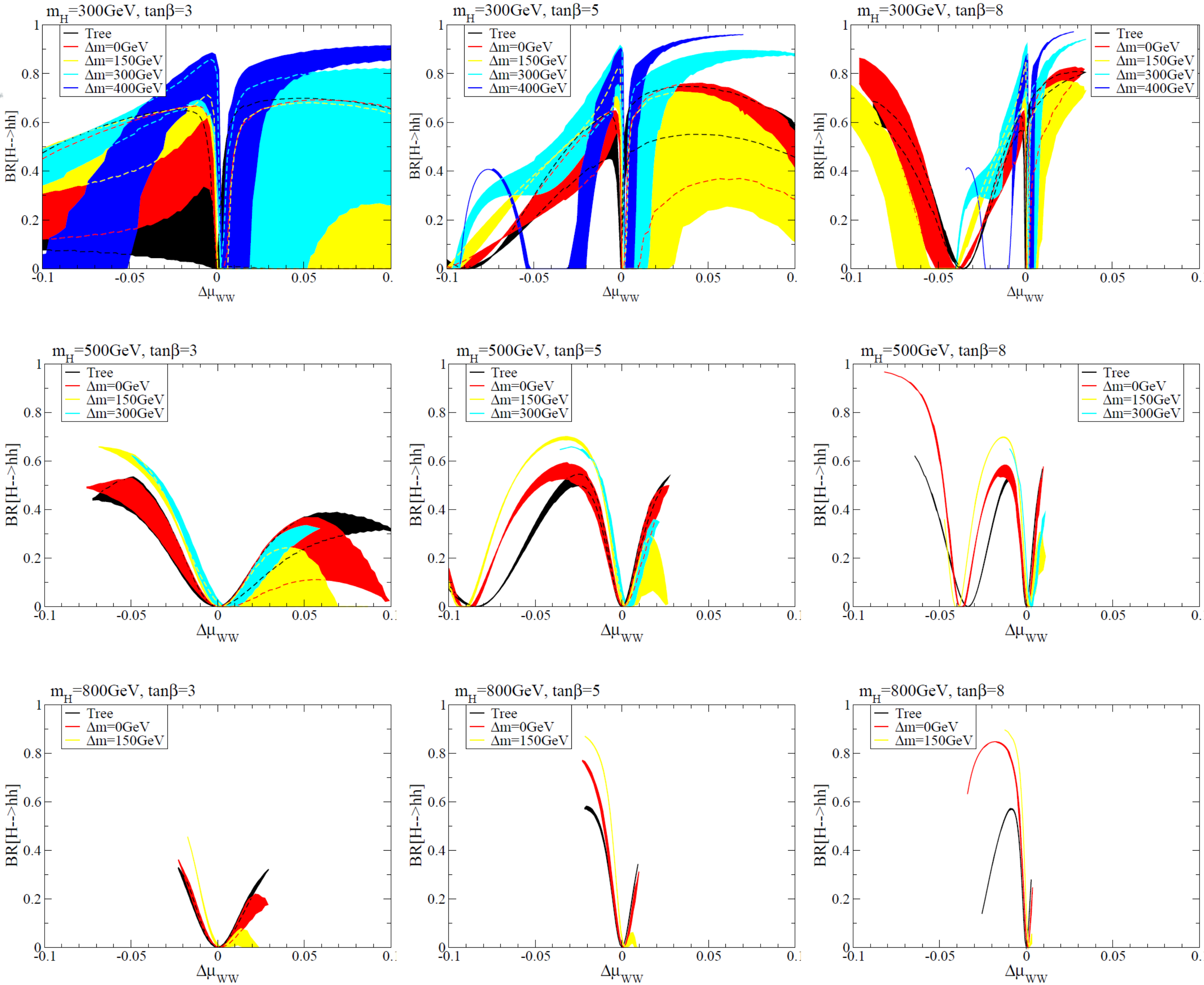
Type-I; $m_{H^\pm}=m_A=400$ GeV, $s_{\beta-\alpha}=1$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
BR($H^+ \to Wh$)
-150
-100
-50
0
50
100
150
$m_H - m_{H^\pm}$ [GeV]
450
400
350
300
250
200
150
100
50
0
M [GeV]

H^+ decays



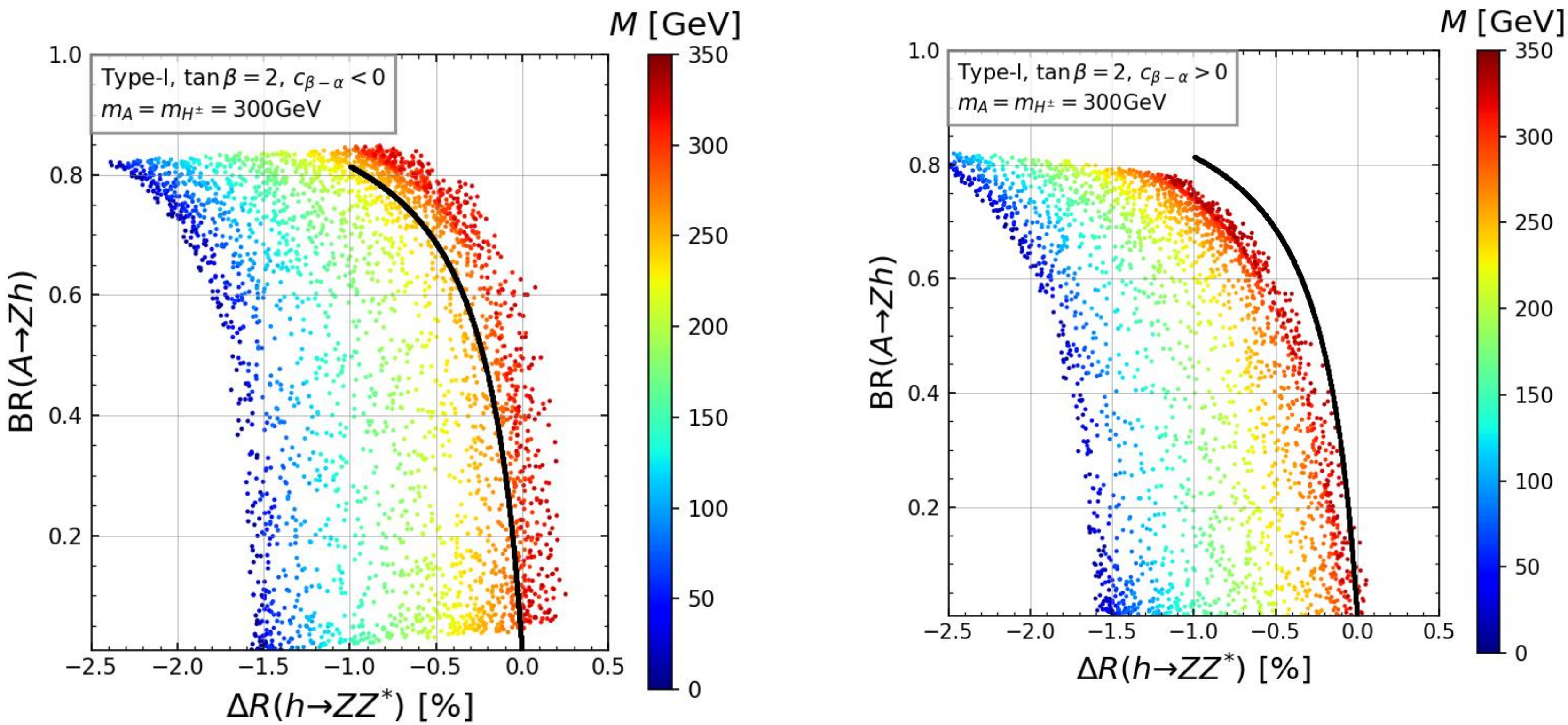
m_{H+} $=m_A=$ 400GeV

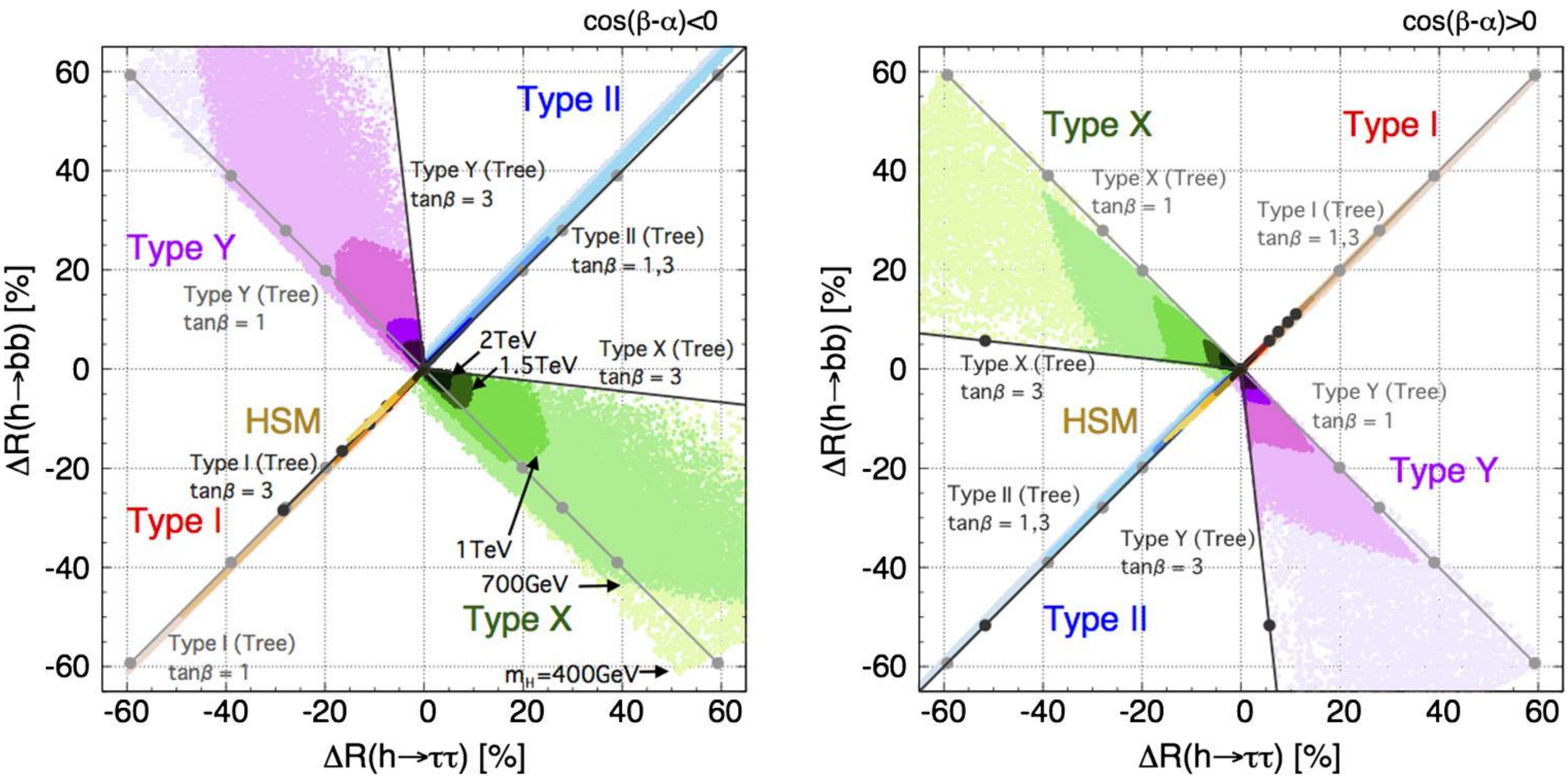
$$\Delta\kappa_Z = \sqrt{\frac{a}{b}}$$

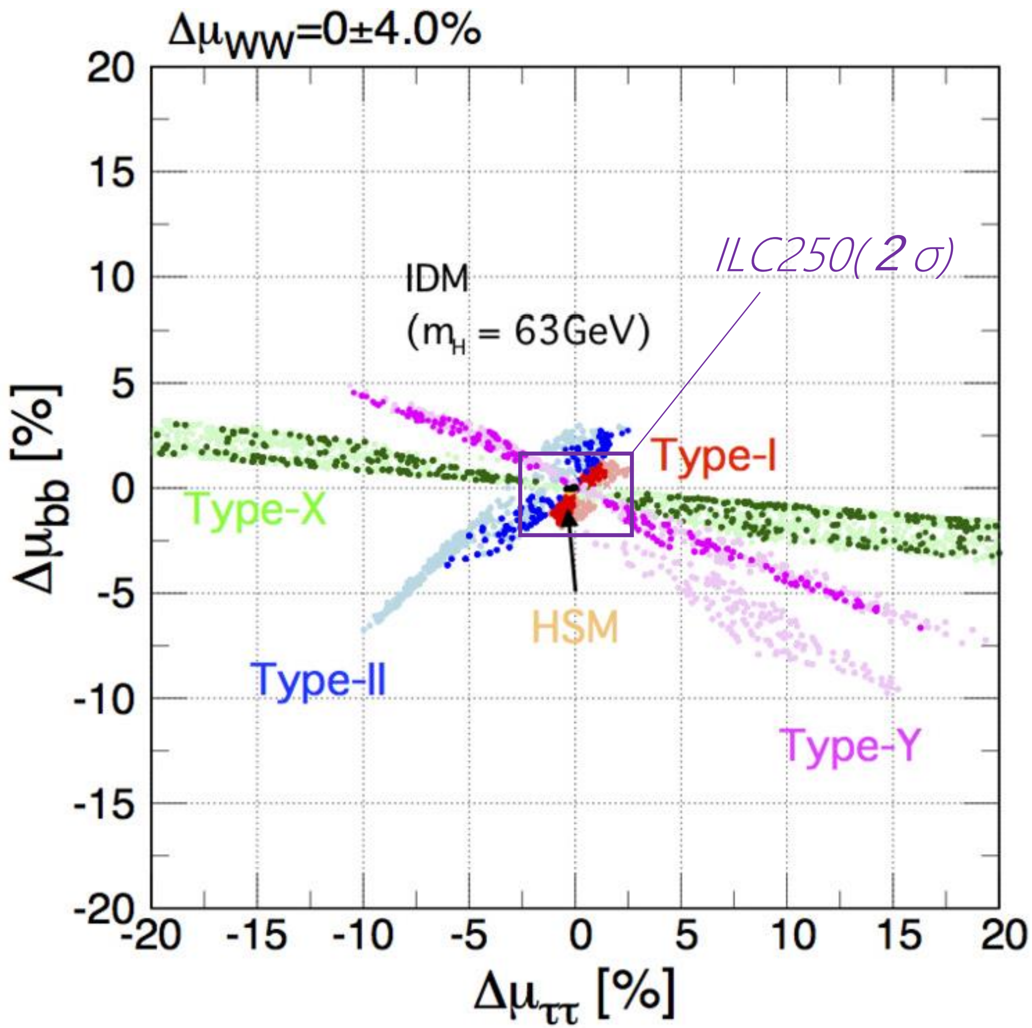


m_H=300GeV, tanβ=3
m_H=300GeV, tanβ=5
m_H=300GeV, tanβ=8
m_H=500GeV, tanβ=3
m_H=500GeV, tanβ=5
m_H=500GeV, tanβ=8
m_H=800GeV, tanβ=3
m_H=800GeV, tanβ=5
m_H=800GeV, tanβ=8
Tree
Δm=0GeV
Δm=150GeV
Δm=300GeV
Δm=400GeV
BR[H-->hh]
$\Delta\mu_{WW}$

Correlation between *A→Zh* and *h→ZZ**




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



$\Delta\mu_{WW}$=0±4.0%
IDM
(m_H = 63GeV)
ILC250(2σ)
Type-I
Type-X
Type-II
HSM
Type-Y
$\Delta\mu_{bb}$ [%]
$\Delta\mu_{\tau\tau}$ [%]