Exploring new physics by comprehensive studies of loop-corrected decays of various Higgs bosons

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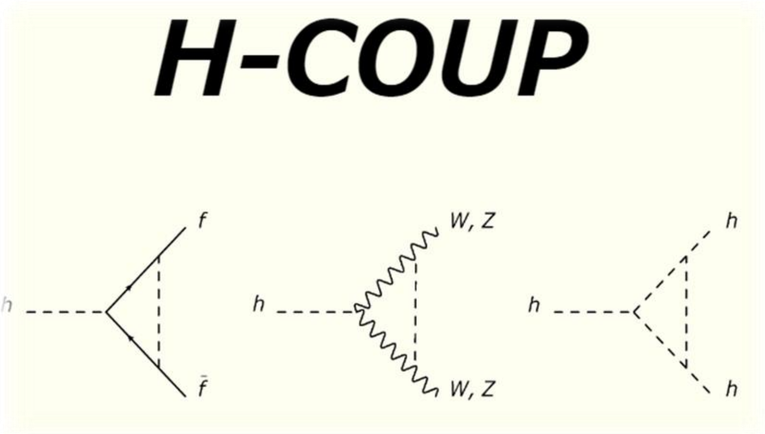
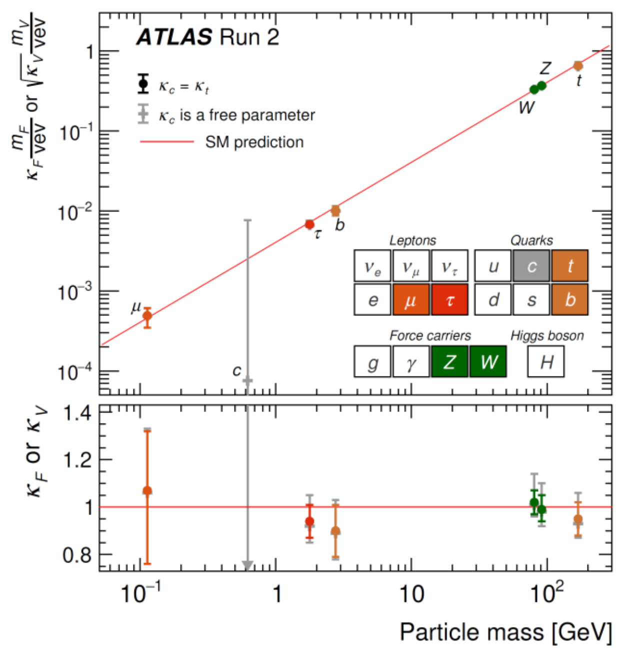


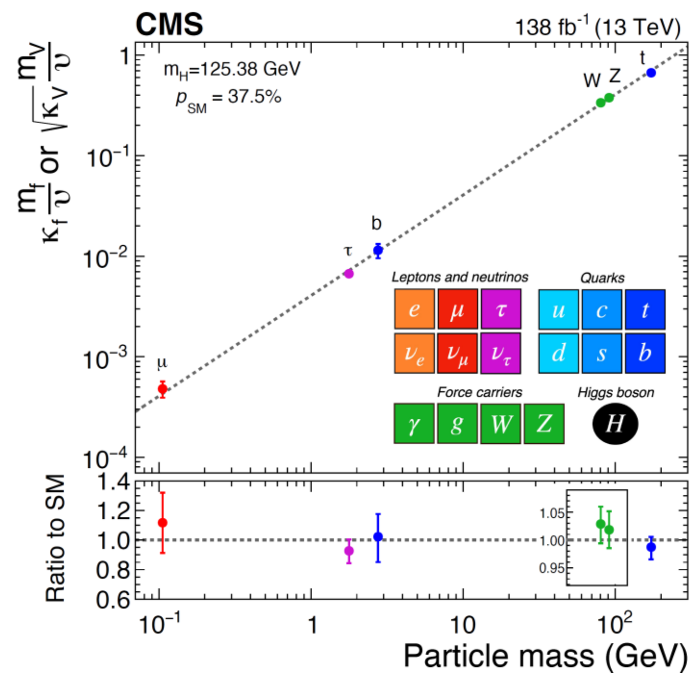
1. NPB 983(2022)115906, Kanemura, MK, Yagyu
2. In preparation, Aiko, Kanemura, MK, Sakurai, Yagyu

Current situation

- Discovery of Higgs boson 2012
- The Higgs boson is Standard Model-like



2207.00092 [hep-ex].



2207.00043 [hep-ex]

- New particles have not been discovered yet

Why is Higgs sector important?

- Higgs sector is still the black box.
  - ➢ What is origin of EWSB?
  - ➢ Elementary or Composite?
  - ➢ Are there no other Higgs bosons?

- "What is Structure of Higgs sector" ?
  - ➢ No principle to require the minimal Higgs sector.
  - ➢ Various extended Higgs sectors
  - ➢ Non-minimal Higgs sectors are often introduced in new physics models.

Structure of Higgs sector is related to new physics scenarios.

To explore Higgs sector is essentially important.

Extended Higgs sectors

- We focus on "2nd Simplest Higgs sector
  - General renormalizable models → There are many models.
  - 2nd Simplest Higgs sector → The number is not so much.

$$\Phi_1(I=1/2,\ Y=1/2) + \varphi_2\,(I,\ Y)$$

- Electroweak rho parameter
  - Electroweak precision measurements favor the theory with $\rho \simeq 1$.
  - Models with $\rho_{\mathbf{tree}} = 1$.

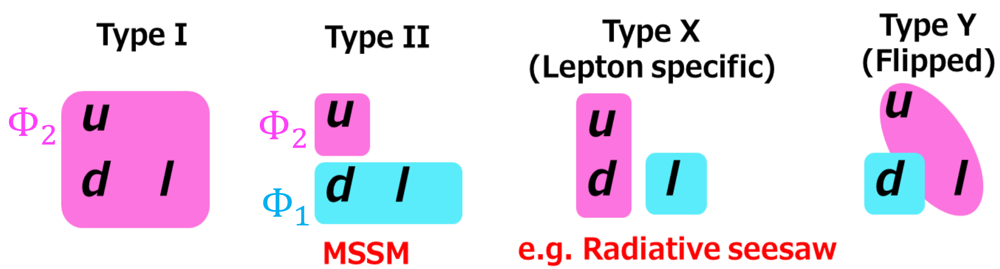
Higgs singlet model (HSM)	: Φ1 + singlet
Multi Higgs doublets	: Φ1 + Φ2 + …
Higgs septet model	: Φ1 + septet
Georgi-Machacek model	: Φ1 + real and complex triplet

We focus on 2nd Simplest Higgs sectors with $\rho_{\mathbf{tree}} = 1$.

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

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

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

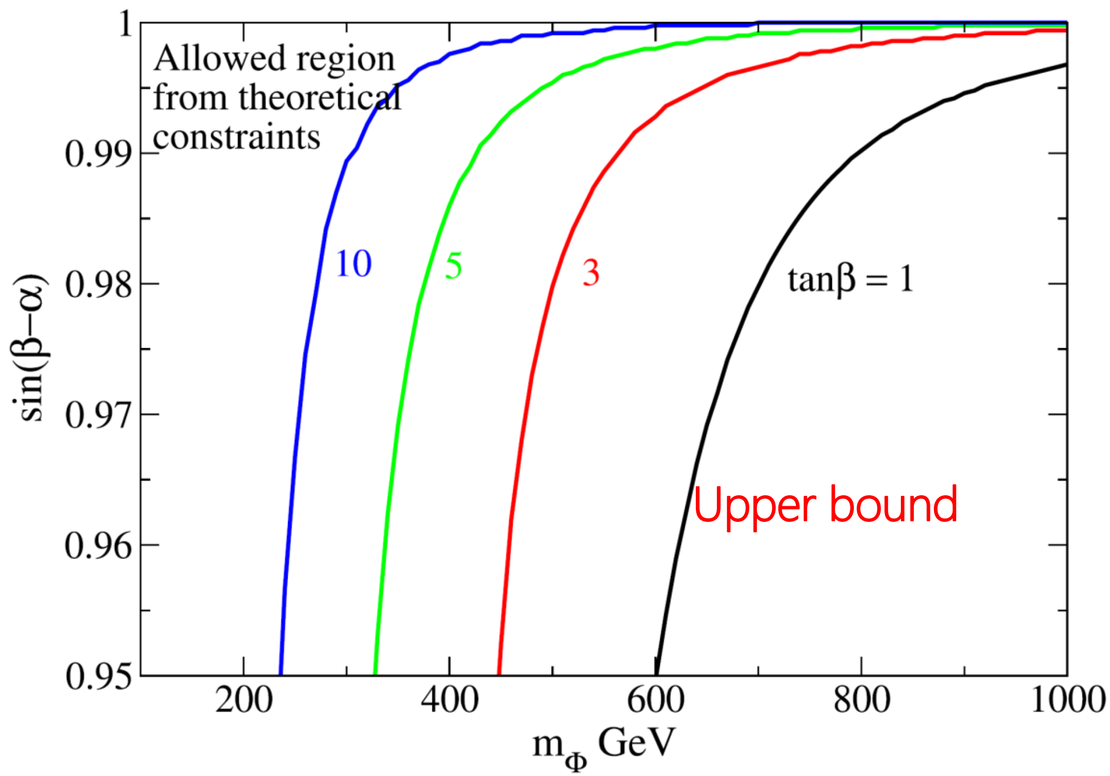
Coupling deviation 1

- Higgs boson coupling can deviate from SM predictions.

hWW, hZZ

$$\kappa_V^h = \frac{g_{hVV}^{NP}}{g_{hVV}^{SM}} = \sin(\beta - \alpha)$$

- If the deviations are detected, upper bounds on m_Φ are given by perturbative unitarity and vacuum stability.



Coupling deviation 2

- Deviation pattern depends on the structure of the Higgs sector.

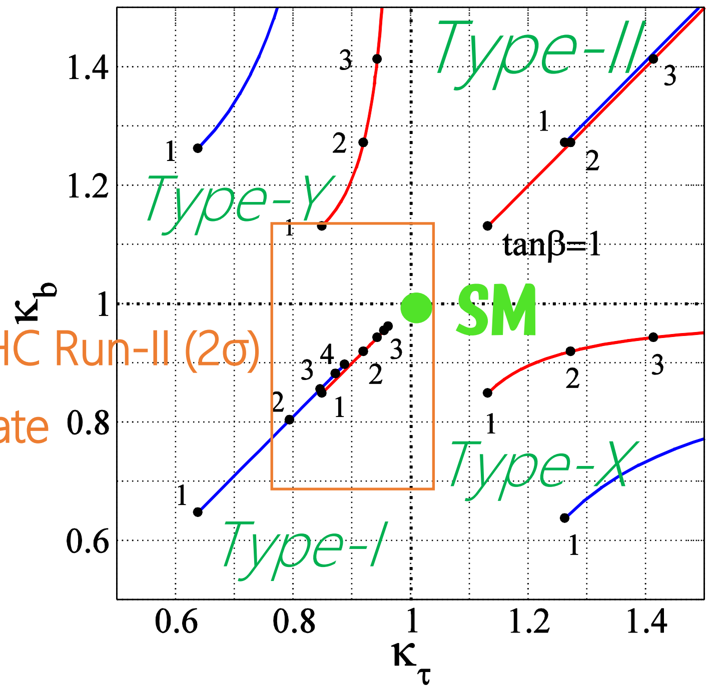
Yukawa interaction

THDM

If f couples to Φ_2 $\quad \kappa_f = \sin(\beta-\alpha) + \cot\beta \cos(\beta-\alpha)$

If f couples to Φ_1 $\quad \kappa_f = \sin(\beta-\alpha) - \tan\beta \cos(\beta-\alpha)$

$$\kappa_f = \frac{y^{NP}_{hff}}{y^{SM}_{hff}}$$



$\kappa_V = \sin(\beta-\alpha) = 0.99$

$\kappa_V = \sin(\beta-\alpha) = 0.95$

Current data at LHC indicate "nearly alignment" ($\sin(\beta-\alpha) \simeq 1$).

- In $\sin(\beta-\alpha) \to 1$ limit, all couplings of h are aligned to those of SM.

$\sin(\beta-\alpha) \to 1$: Higgs alignment limit

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

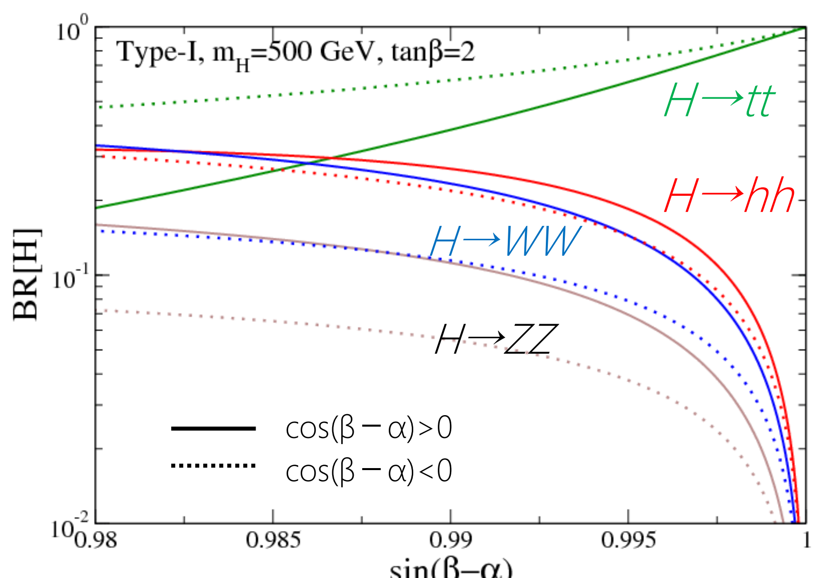
HWW, HZZ $$\kappa_V^H = \frac{g_{HVV}^{NP}}{g_{hVV}^{SM}} = \cos(\beta - \alpha) \rightarrow 0$$

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 $$\kappa_f^H = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha) \rightarrow -\cot\beta$$

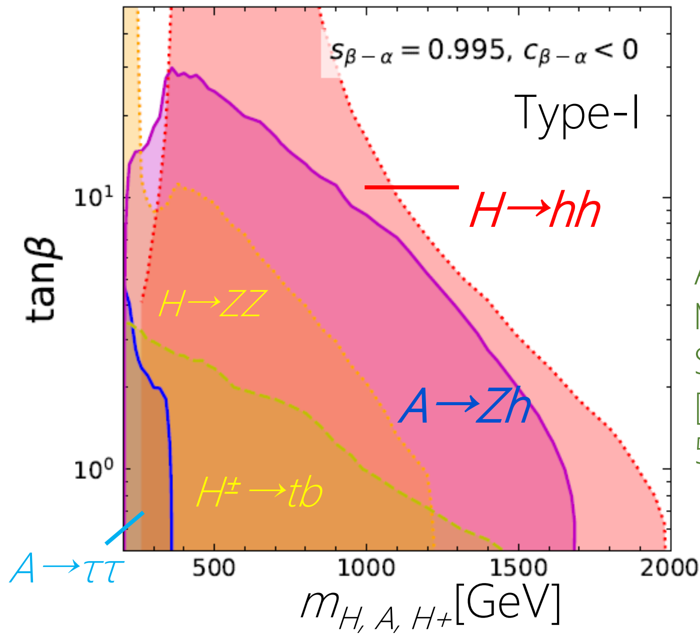
- Branching ratio of *H*



If sin(β − α) ≠ 1,
"Higgs to Higgs decays" channels can be main decay channels.

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" such as $H\to hh$ and $A\to Zh$.

But, they are results at tree level. ➡ Radiative corrections should be included in the analyses.

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

We are extending similar calculations for additional Higgs bosons' processes to **HSM** and **IDM**.

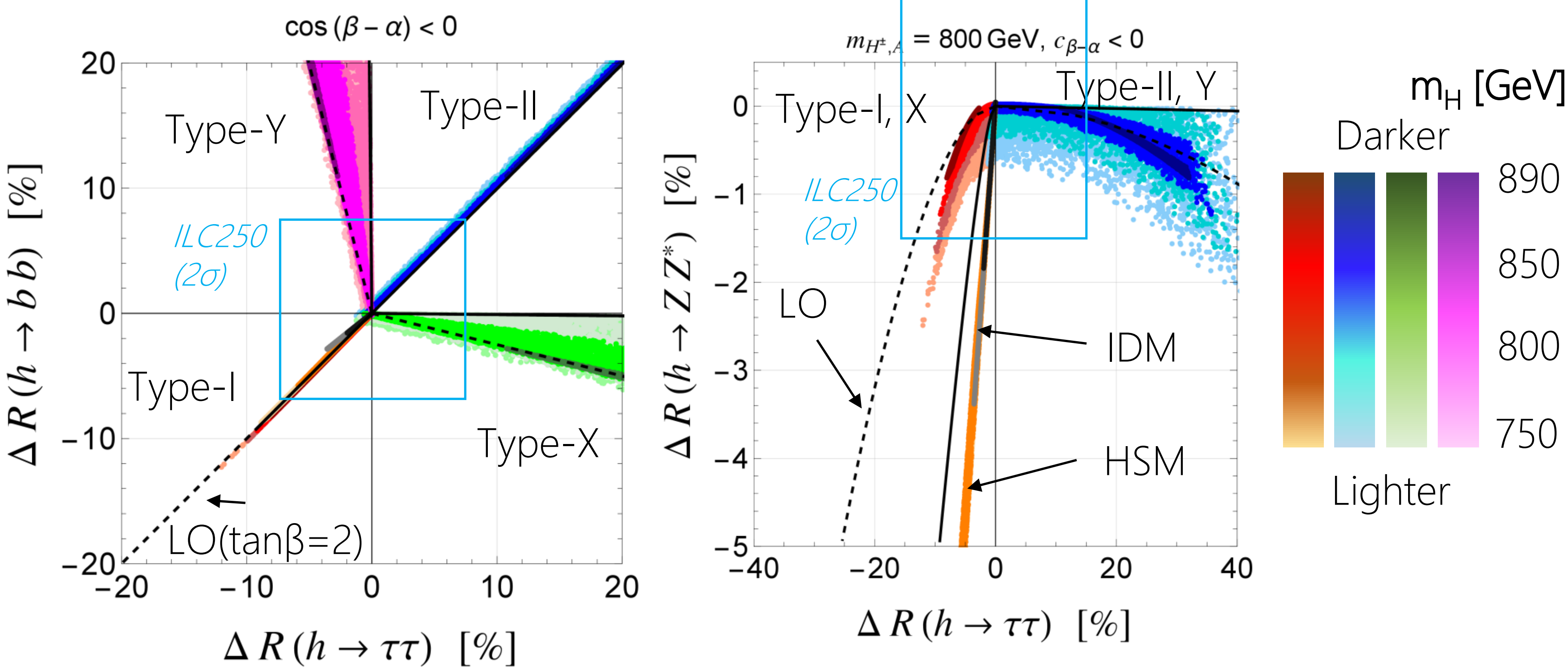
We show results for decays of *H→hh, A→Zh, h→VV*, h→ff* in THDMs.

$\Gamma[h \to ff]$, $\Gamma[h \to ZZ^*]$

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

$$m_A = m_{H^\pm} = 800\ \text{GeV}, \quad \tan\beta \geq 2$$

$$\cos(\beta - \alpha) \leq 0$$

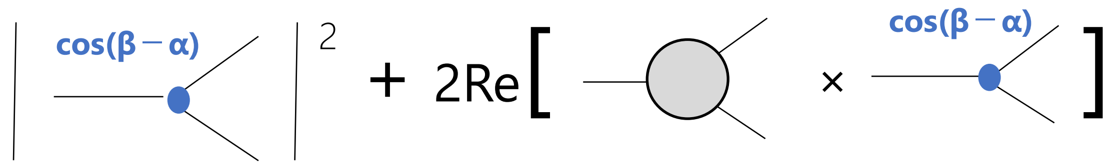


If $|\Delta R[h \to \mathrm{bb}/\tau\tau]|$ **> several %**, prediction of each Type does not overlap

Loop corrections to Γ[$H\to hh$]

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

$\Gamma_{\rm NLO}[H \to hh]$ =



- Decoupling? Or Non-decoupling? $\Phi = H, A, H^{\pm}$

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

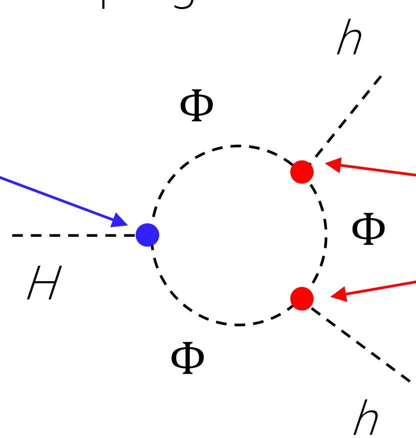
$M^2 \simeq \lambda' v^2$ ・・・ Non-decoupling

Scalar self couplings

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

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

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



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

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

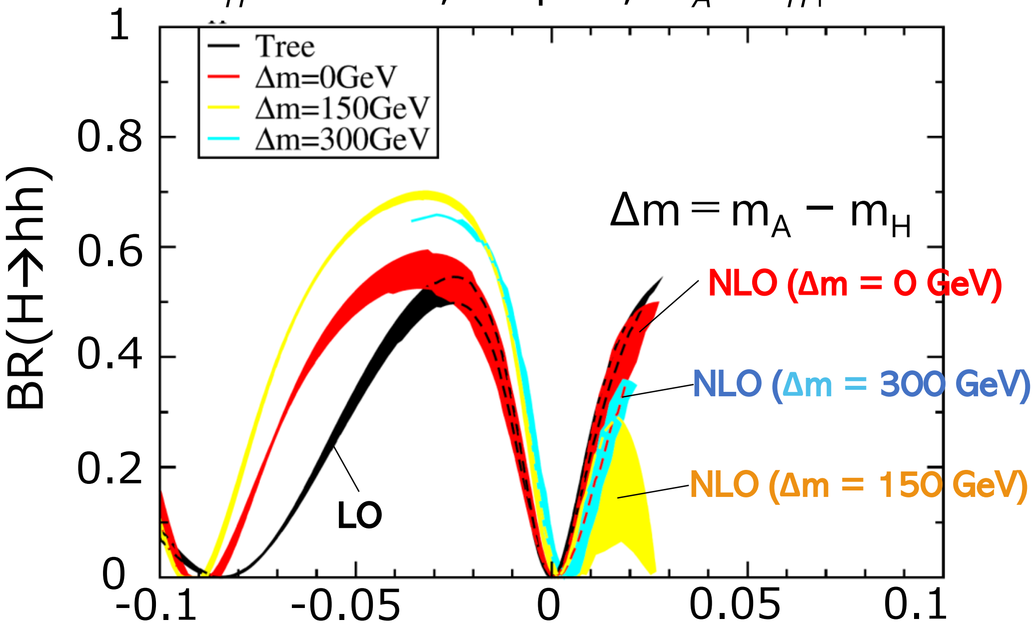
$(m_{A,H^{\pm}} - m_H \neq 0)$ case

Even if $m_{\rm H}^2 \simeq M^2$, 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+}



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

NPB 983(2022)115906
Kanemura, MK, Yagyu

ILC250 (2σ)
BR(h→WW) : 1.8 %

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

If cos(β−α)>0 ··· $\Gamma_h^{\mathrm{THDM}} > \Gamma_h^{\mathrm{SM}}$

If cos(β−α)<0 ··· $\Gamma_h^{\mathrm{THDM}} < \Gamma_h^{\mathrm{SM}}$

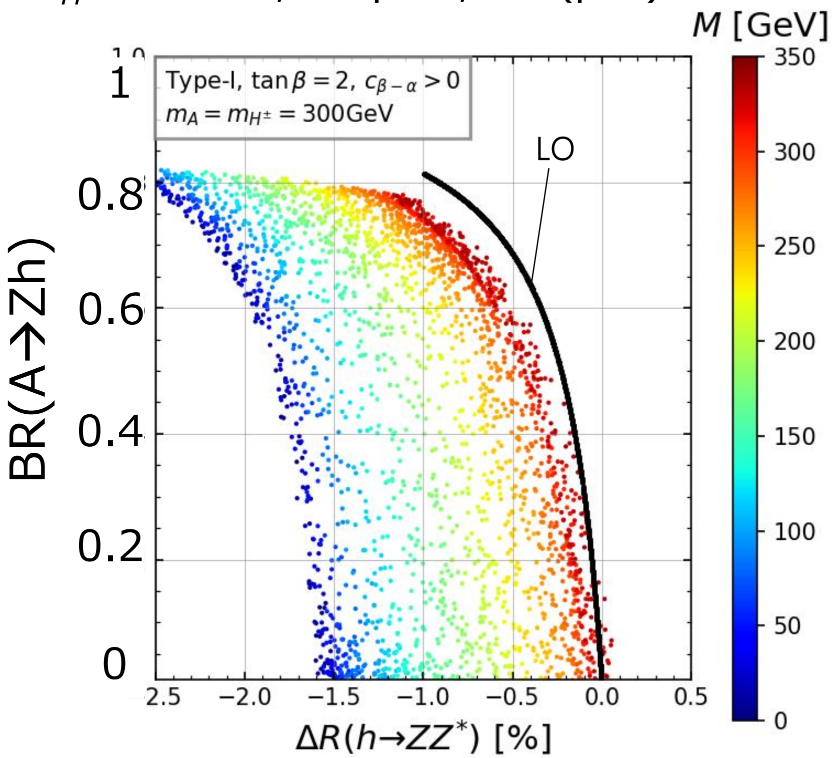
Correlation between BR(*H → hh)* and BR(*h → WW**) is changed from LO by O(10)%.

Study of radiative corrections is essentially important
for direct searches of additional Higgs bosons.

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

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

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



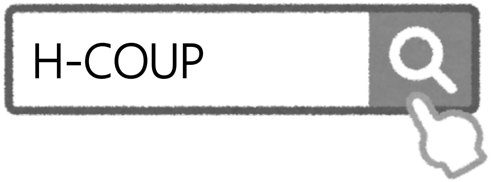
$$\Delta R[h \to ZZ^*] = \frac{\Gamma^{\rm THDM}_{\rm NLO}[h \to ZZ^*]}{\Gamma^{\rm SM}_{\rm NLO}[h \to ZZ^*]} - 1$$

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

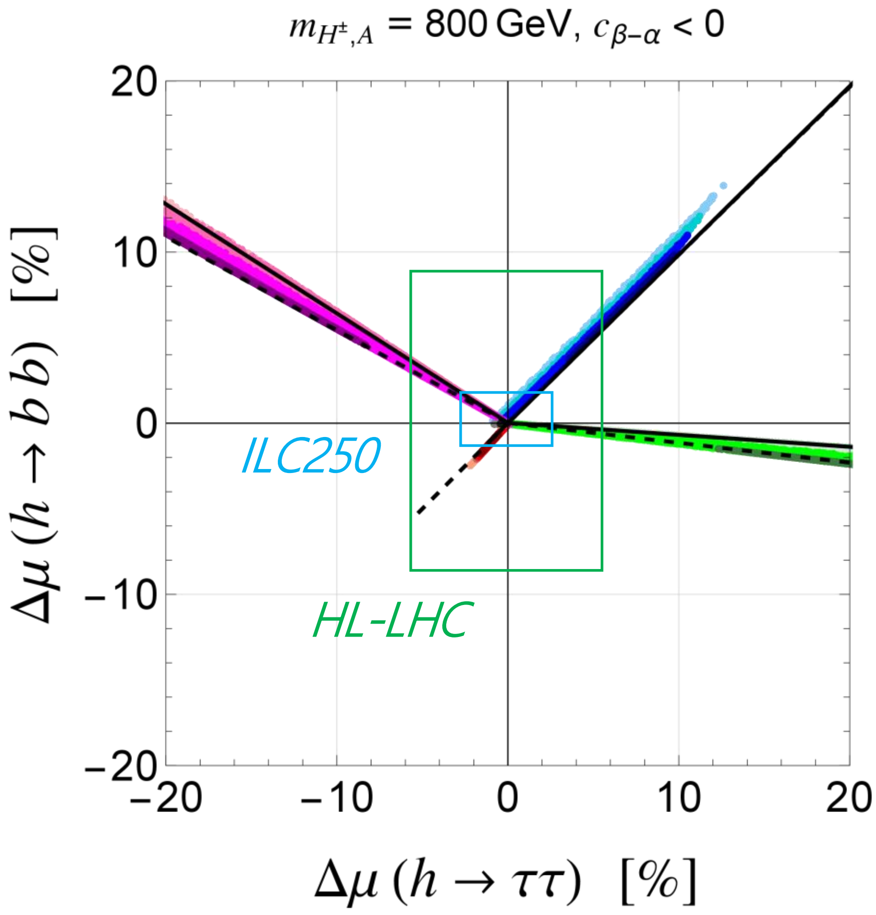
- LHC results of h_{125} measurements indicate "nearly alignment", where additional Higgs bosons' decays are very interesting !!
- Study of radiative corrections to decays of both additional Higgs bosons and h_{125} are essentially important.
- We show results of BR[Higgs to Higgs decays] and BR[h_{125}] including radiative corrections.
- BR[$H \rightarrow hh$] with NLO correction can change LO prediction by O(10)%.
  BR[$A \rightarrow Zh$] also also receives O(10)% correction if $\tan\beta \simeq 2$.
- Correlations between $A \rightarrow Zh$ / $H \rightarrow hh$ and $h \rightarrow VV^*$ are significantly changed from LO.
- We will provide H-COUP ver.3.

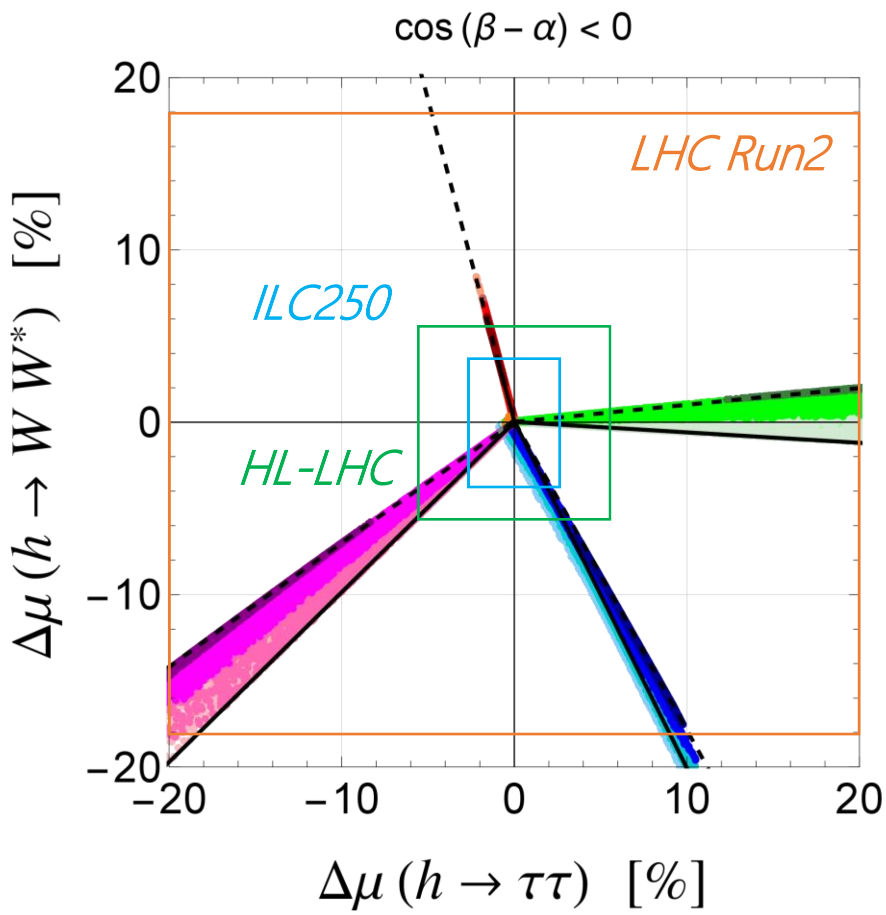


Thank you for your attention !!

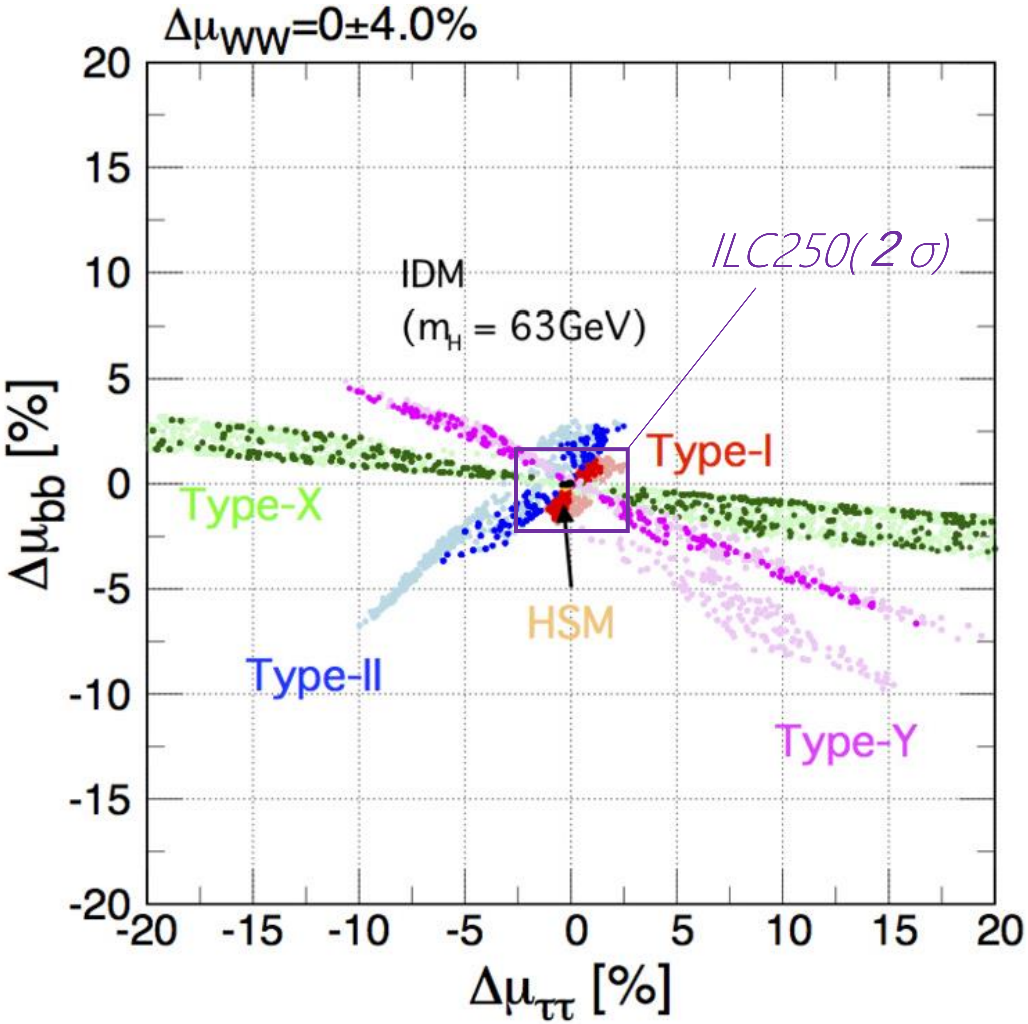
Backup

Deviations in BR



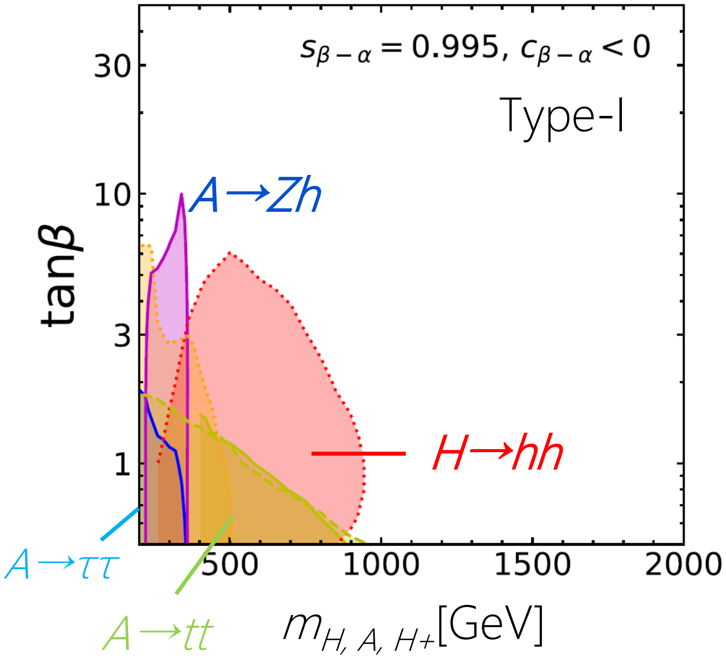


Deviations in BR

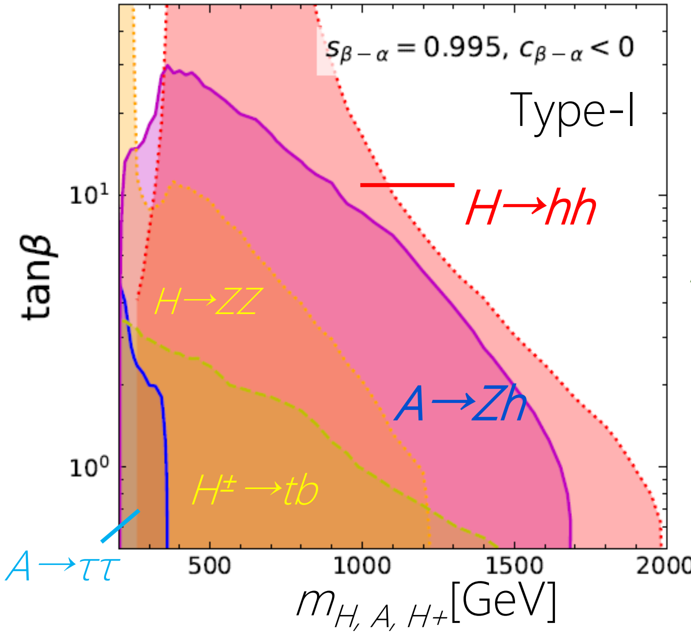


Searchable regions in nearly-alignment

Excluded region by direct searches
@LHC Run-II (36fb^{-1}) (95%CL)



Expected excluded region
@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” such as $H \to hh$ and $A \to Zh$.

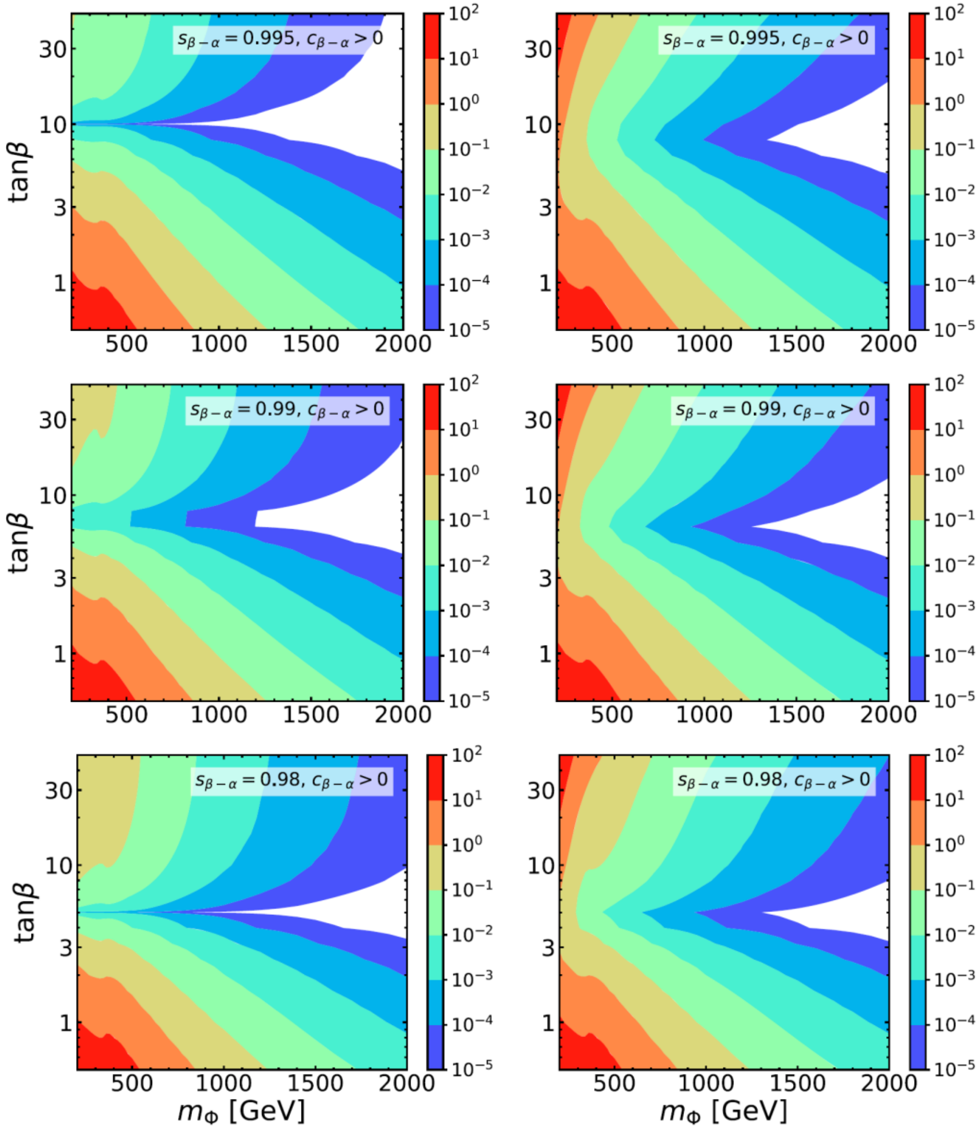
But, they are results at tree level. ➡ Radiative corrections should be included in the analyses.

H production

$\cos(\beta-\alpha)>0$

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

13TeV LHC

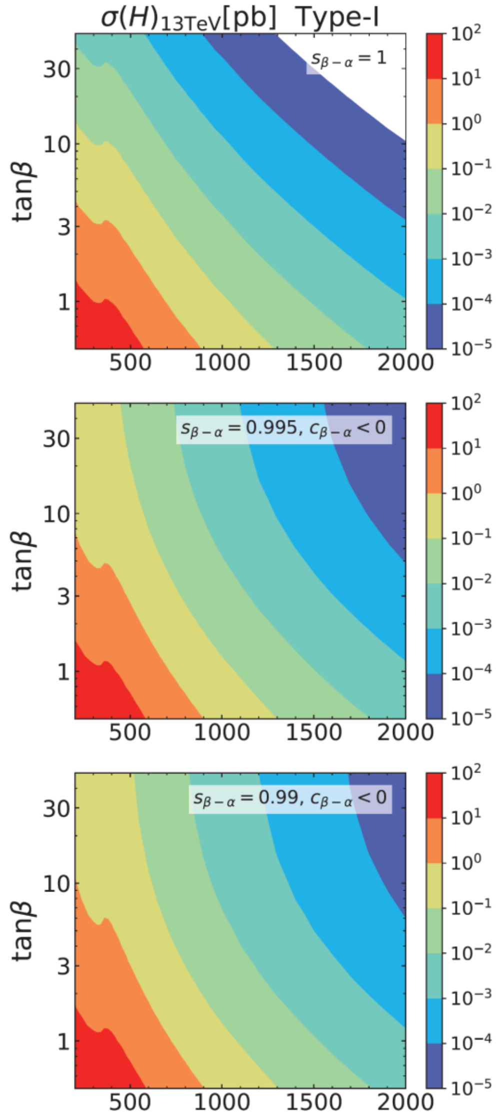


[pb]

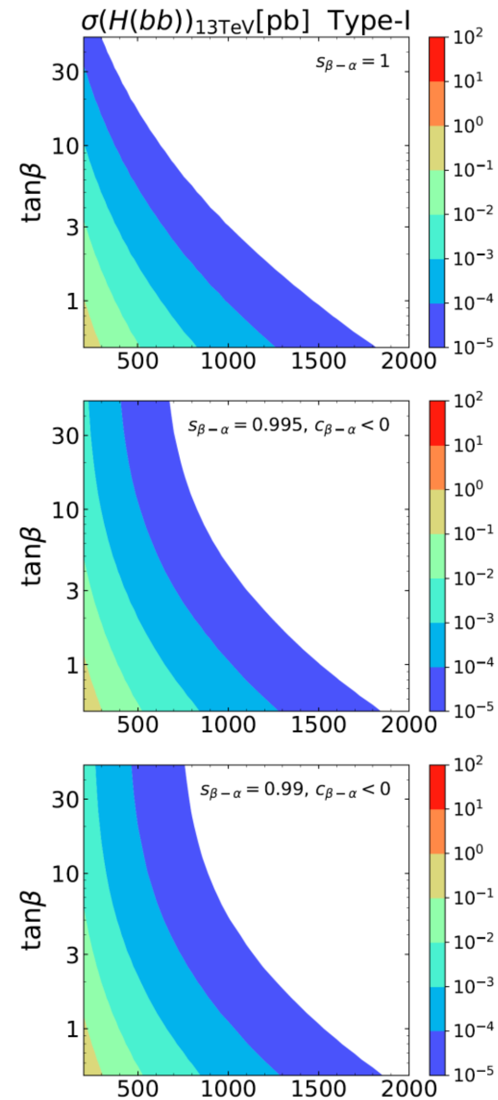
H production

$\cos(\beta-\alpha)<0$

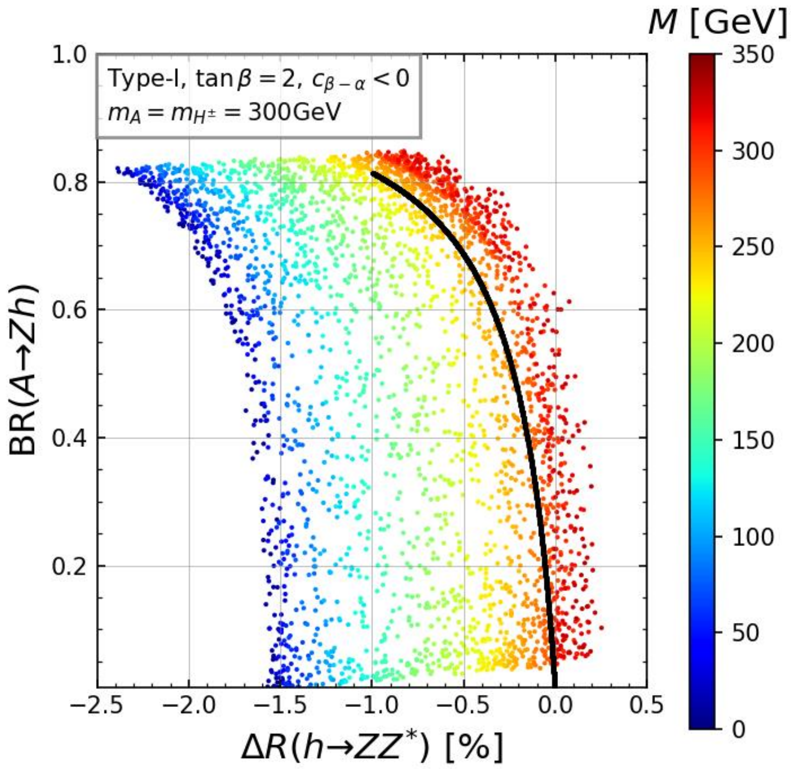
gluon-fusion process ($pp\rightarrow H$), [pb]

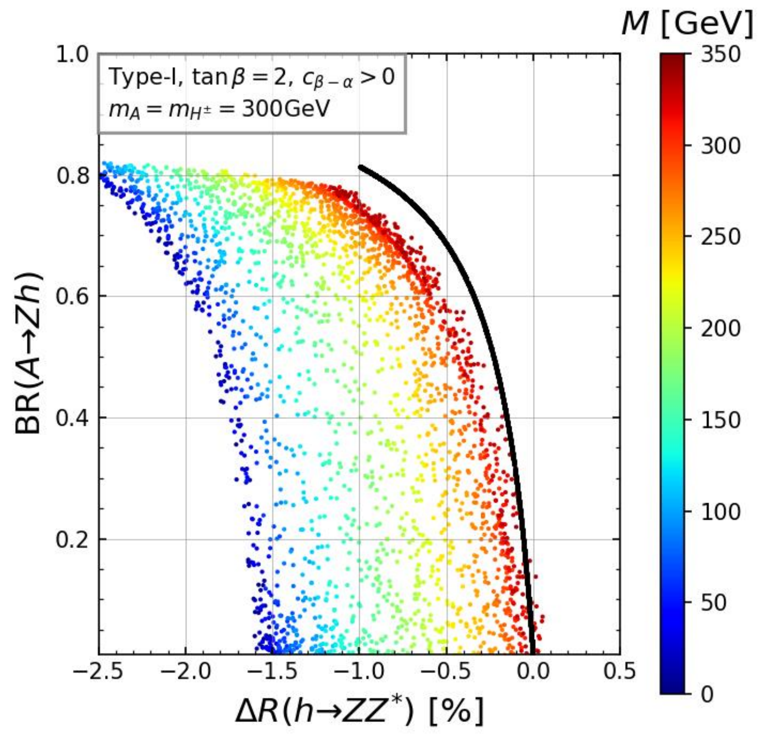


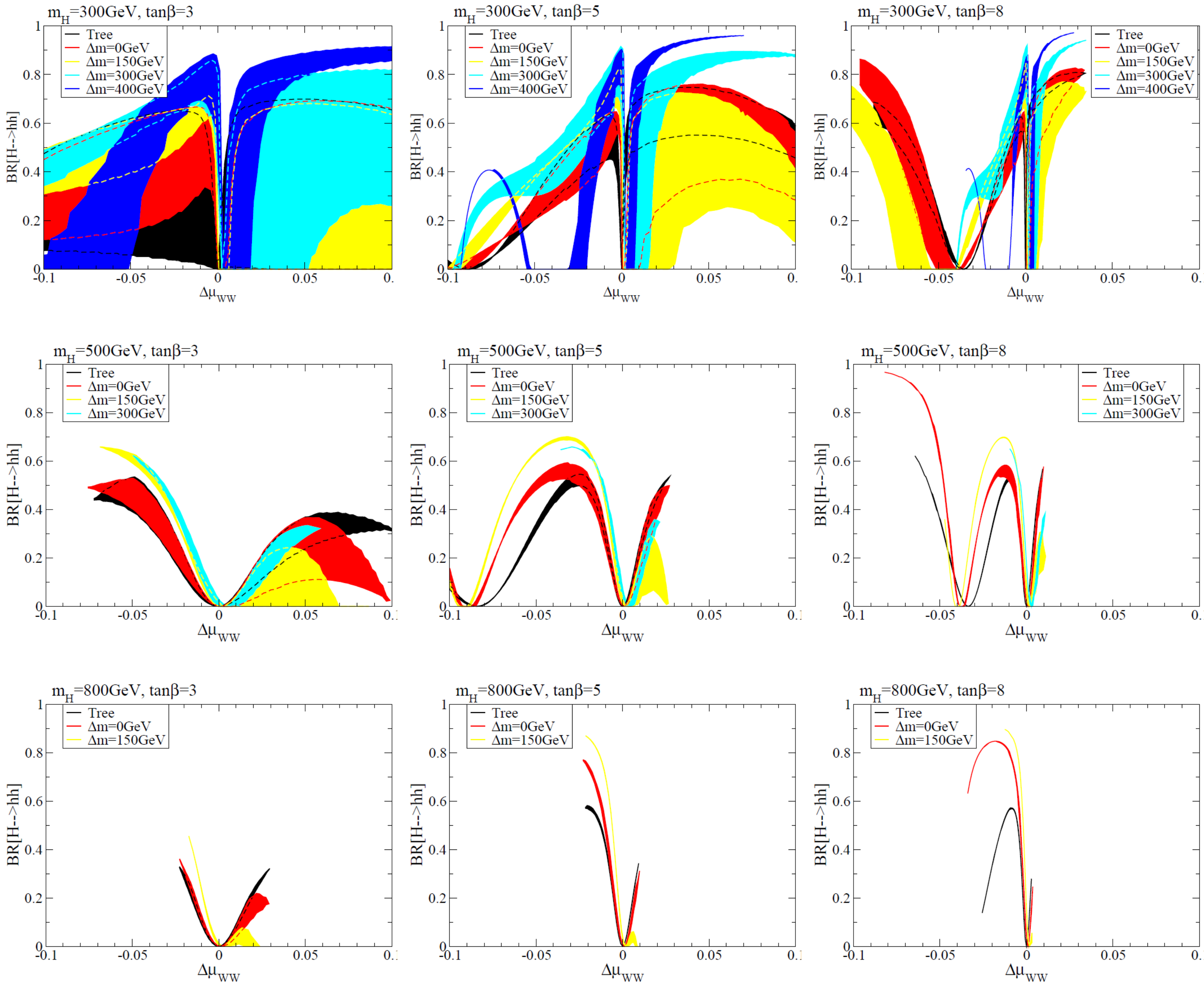
bottom associated process($pp\rightarrow H(bb)$) 13TeV LHC



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






mH=300GeV, tanβ=3
mH=300GeV, tanβ=5
mH=300GeV, tanβ=8
Tree
Δm=0GeV
Δm=150GeV
Δm=300GeV
Δm=400GeV
mH=500GeV, tanβ=3
mH=500GeV, tanβ=5
mH=500GeV, tanβ=8
Tree
Δm=0GeV
Δm=150GeV
Δm=300GeV
mH=800GeV, tanβ=3
mH=800GeV, tanβ=5
mH=800GeV, tanβ=8
Tree
Δm=0GeV
Δm=150GeV
BR[H-->hh]
ΔμWW

H^+ decays

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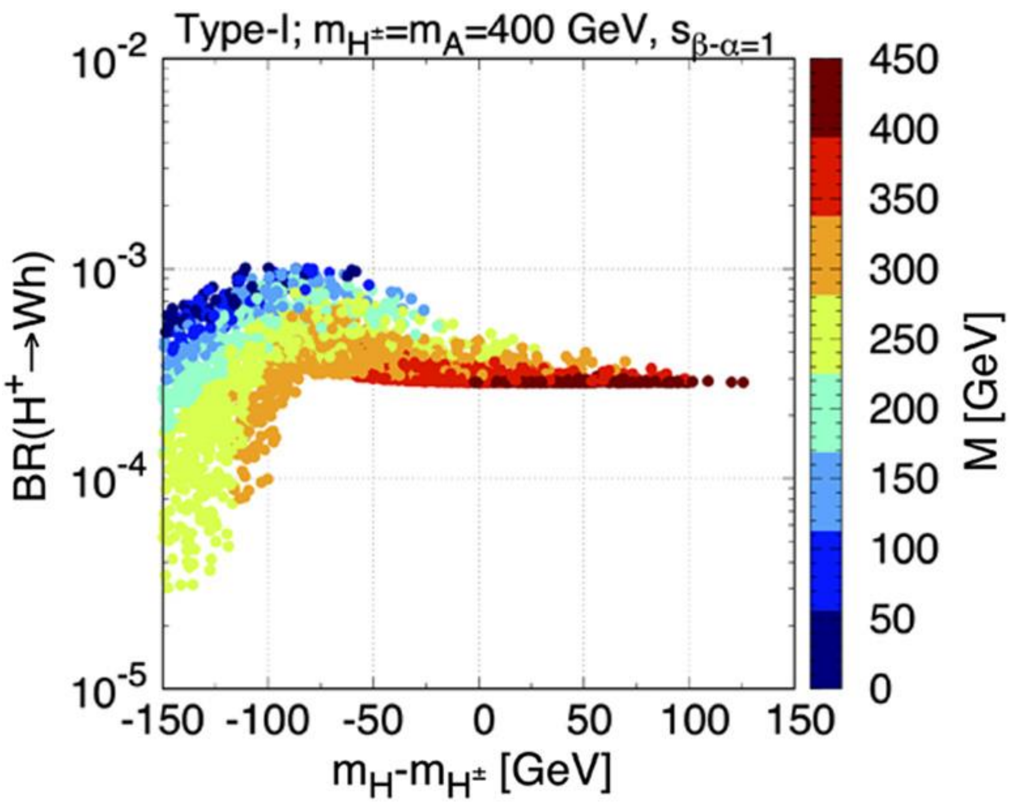
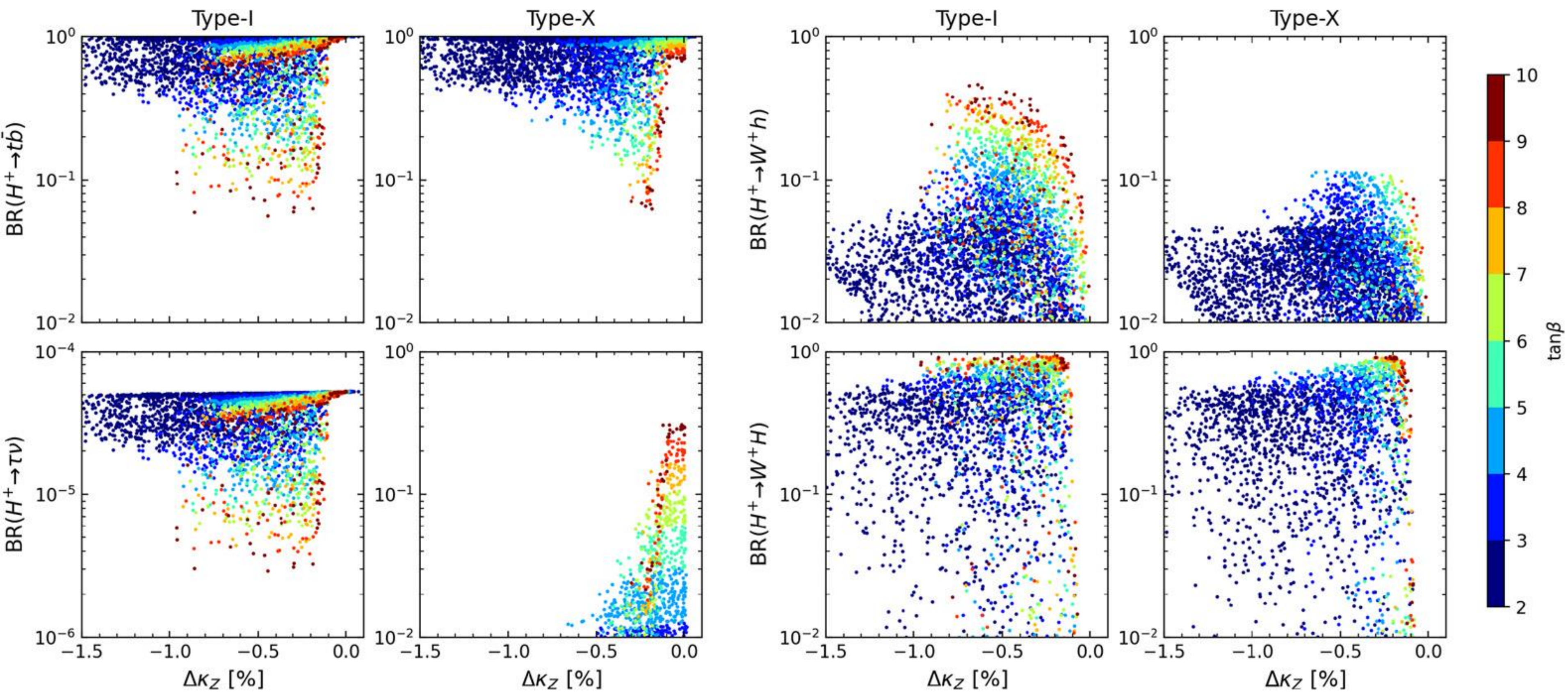


H^{+} decays

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

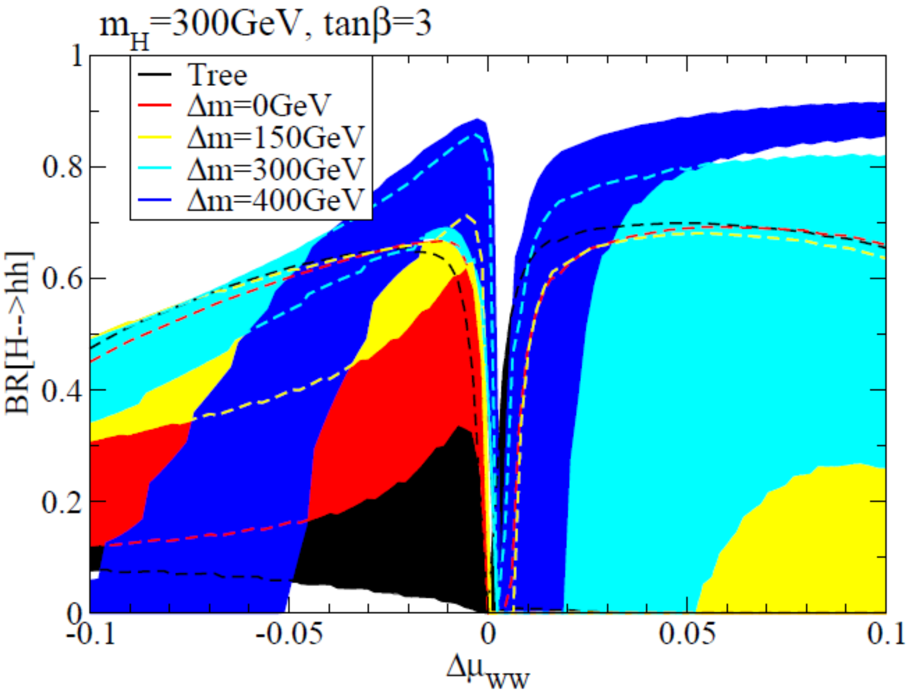


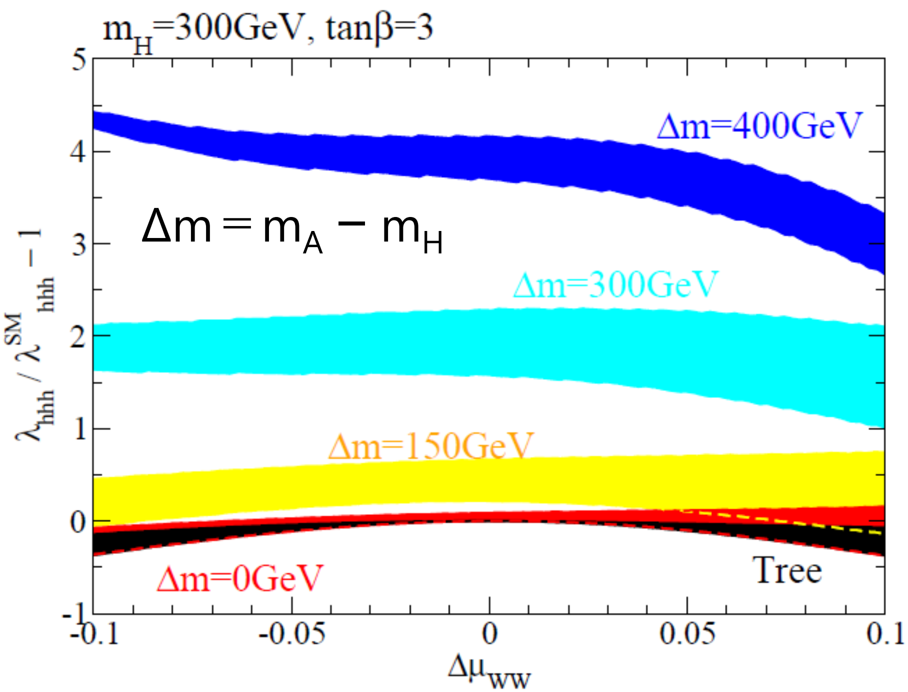
$m_{H+} = m_A = 400GeV$

$$\Delta\kappa_Z = \sqrt{\frac{\Gamma_{THDM}[h \to ZZ^*]}{\Gamma_{SM}[h \to ZZ^*]}} - 1$$

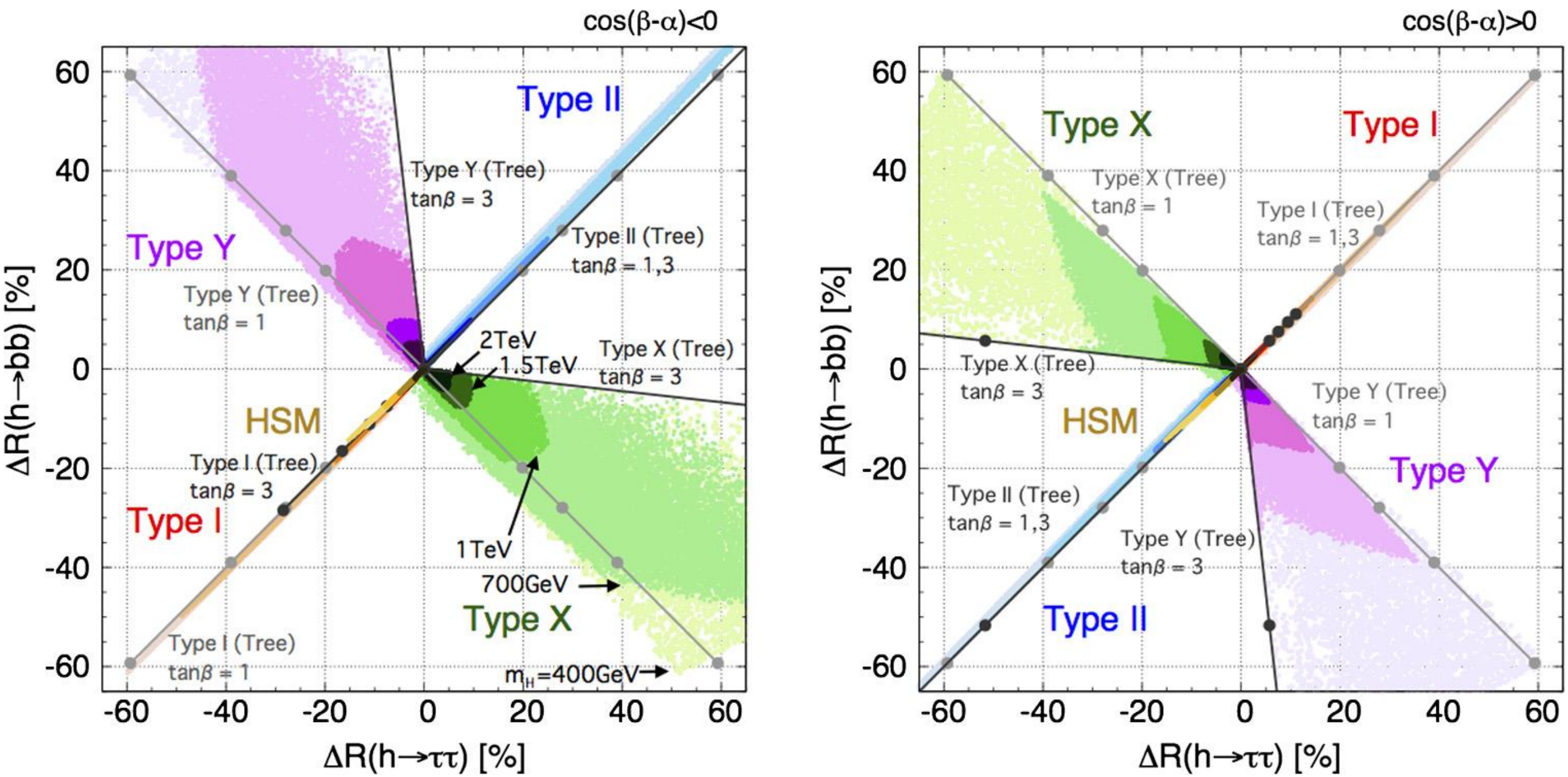
Correlation between *H→hh* and *hhh*

Kanemura, MK, Yagyu



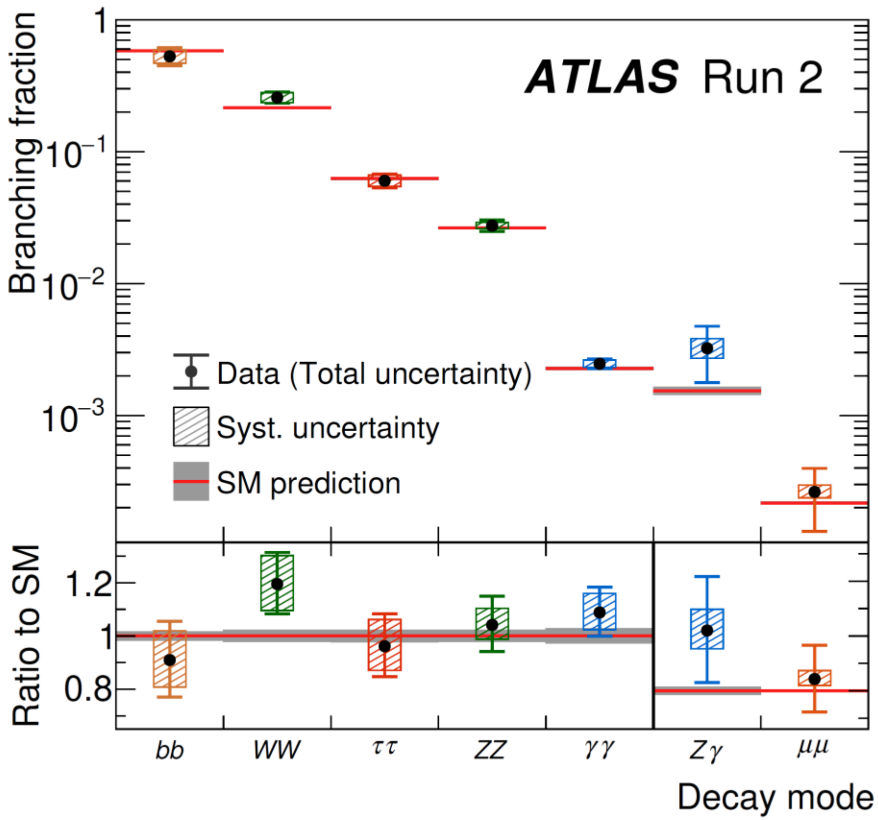


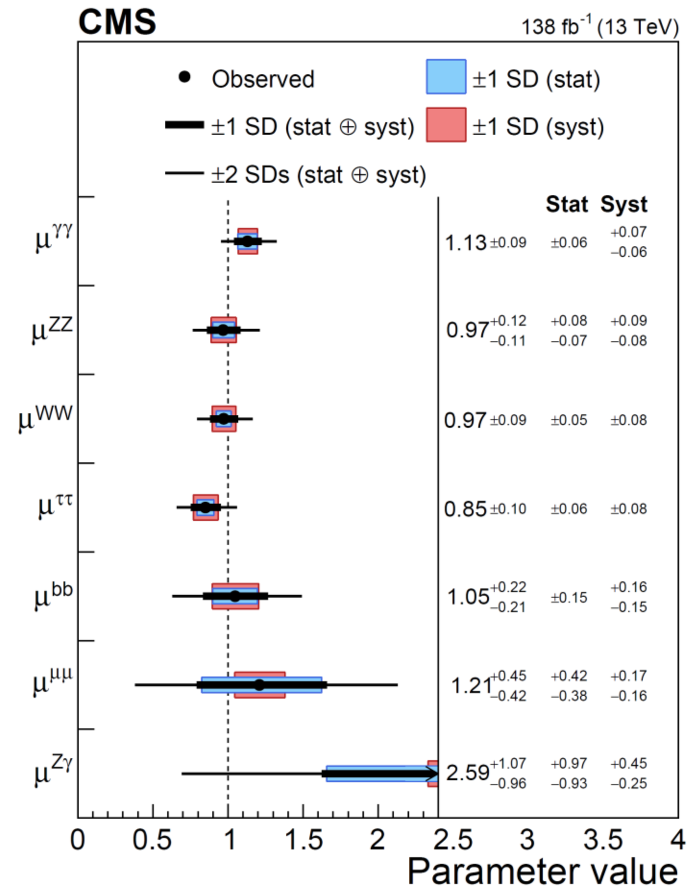
Radiative corrections to λ_{hhh} and BR[*H*→*hh*] are correlated strongly



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) [%]

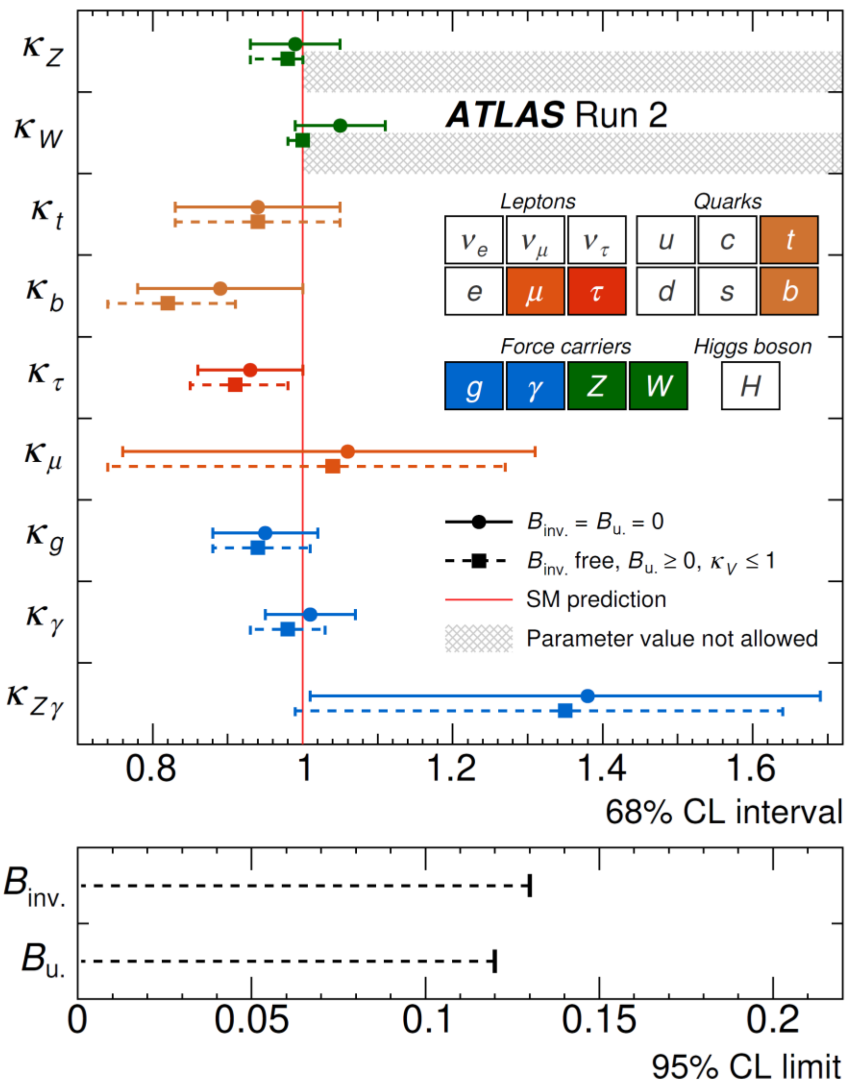
Signal strength

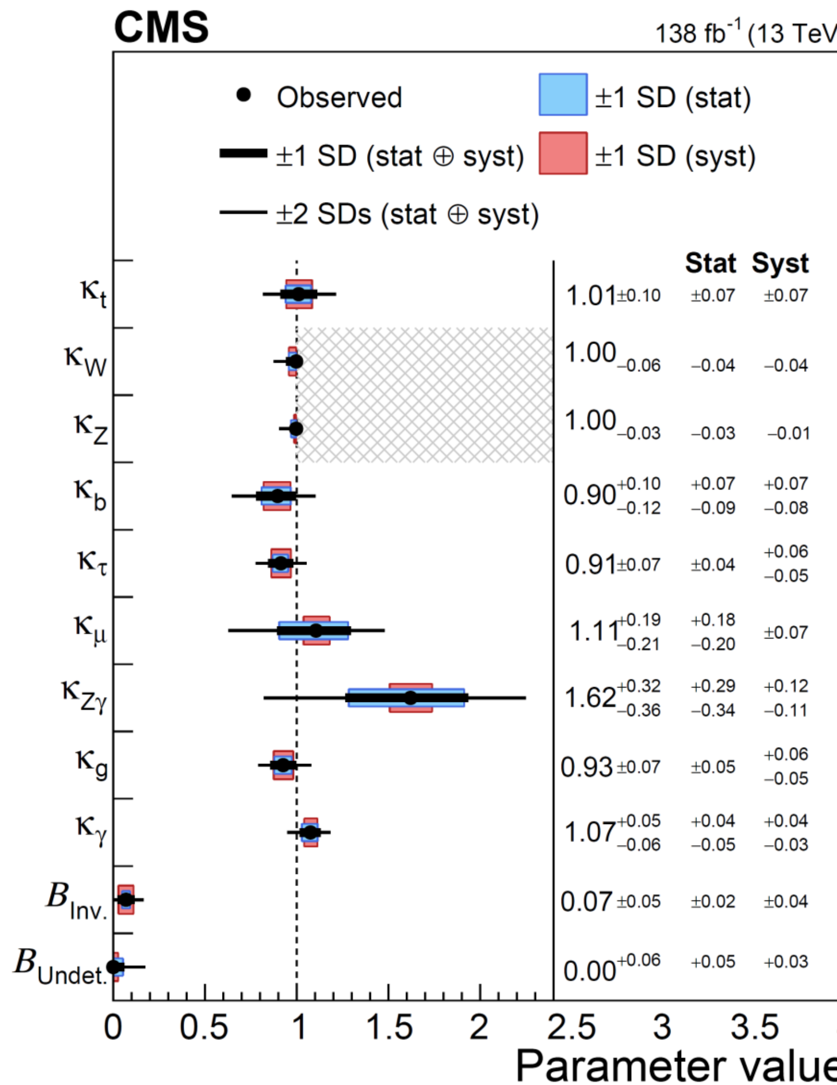




hep-ph: 2209.07510

Coupling measurements





hep-ph: 2209.07510