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NLO corrections to heavy Higgs boson decays in 2HDM

Kodai Sakurai (U. of Warsaw)

Collaborators:

Masashi Aiko (KEK), Shinya Kanemura (Osaka U),

Mariko Kikuchi (Nihon U.), Kei Yagyu (Osaka U)

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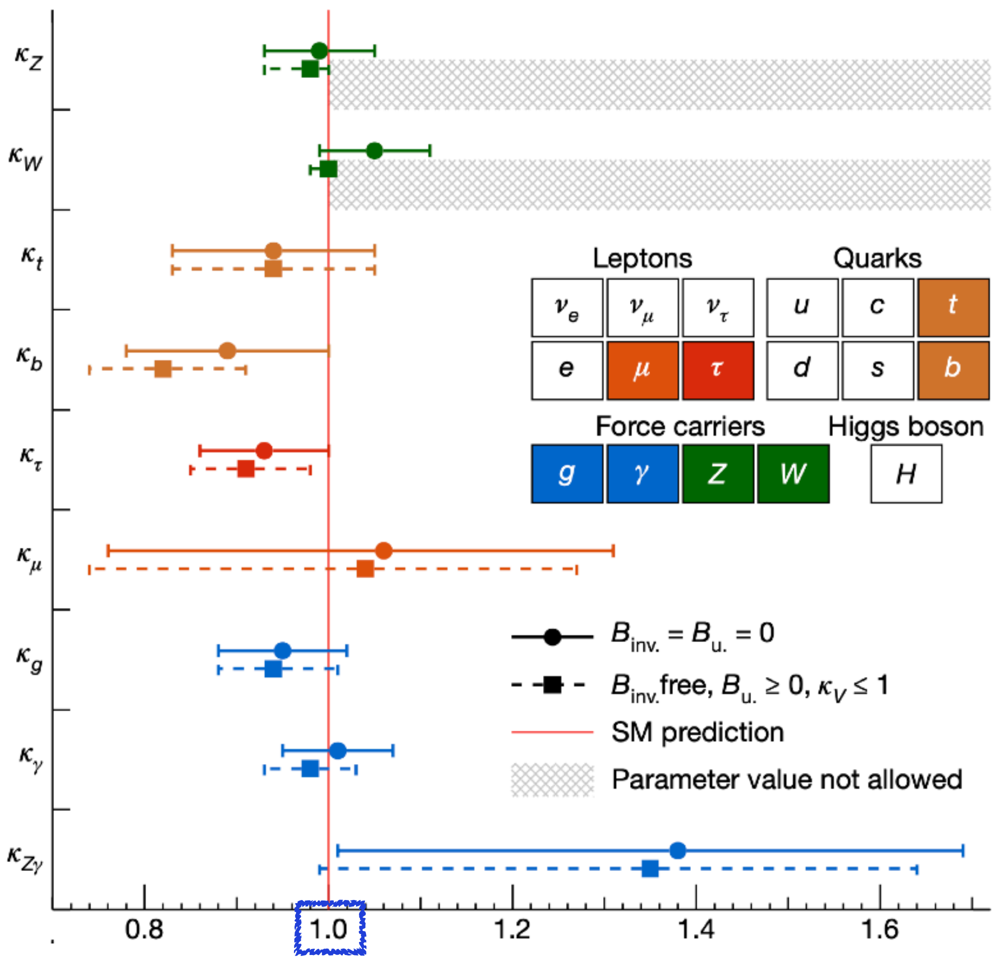
- Introduction
  - 2HDM, motivations.
- Detail of calculations
  - renormalization, scheme difference
- Results for A—>Zh and H—>hh
- Summary

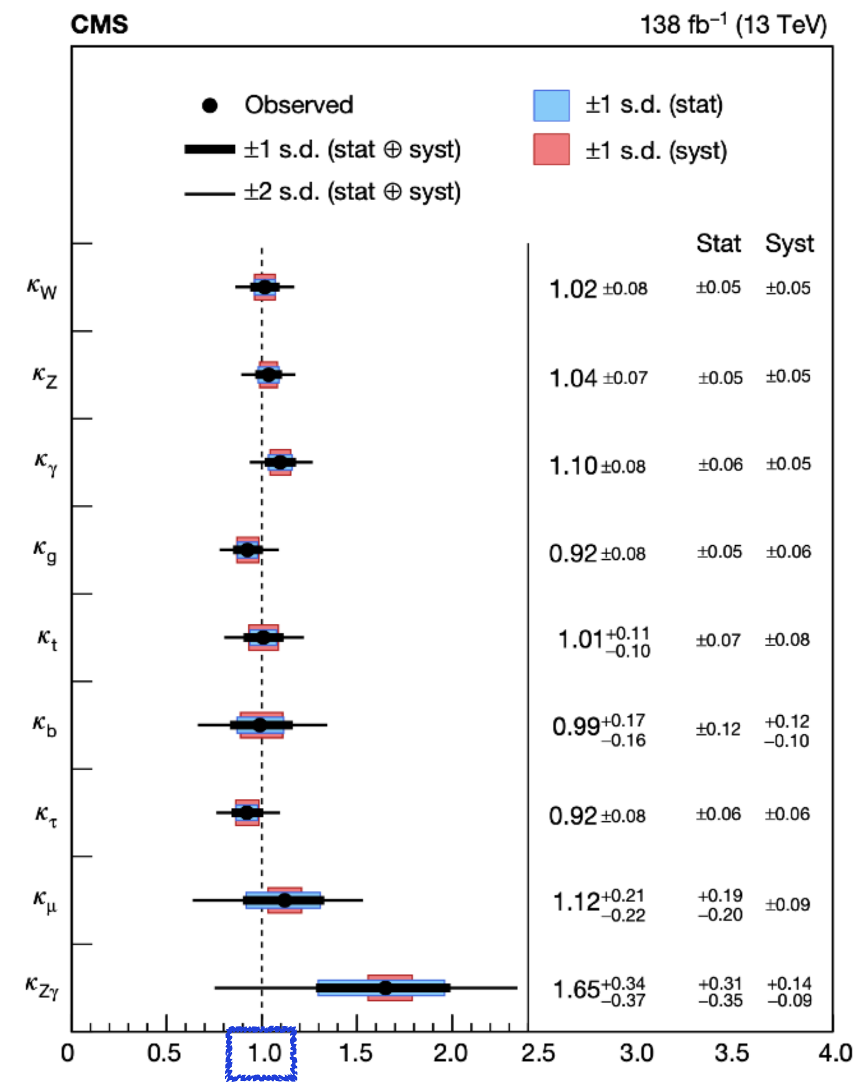
Current status of Higgs measurements

[ATLAS, Nature 607,60–68 (2022)]



SM prediction

[CMS, Nature 607,60–68 (2022)]



SM prediction

$$\kappa_X = g_{hXX}^{\mathrm{EX.}} / g_{hXX}^{\mathrm{SM.}}$$

- Discovered Higgs boson is consistent with the prediction of the SM.

→ This does not mean that Higgs sector of the SM is confirmed.

Extended Higgs sector [1/2]

- Many models can take SM-like limit.

$$\xrightarrow{M^2 \gg v} \quad \mathcal{L}_{\rm eff}^{NP} \simeq \mathcal{L}_{\rm SM} + \frac{1}{M^2}(\Phi^\dagger \Phi)^3 + \dots$$

$$\kappa_X \sim 1$$

- Mystery of extended Higgs sector

  - Number of Higgs, its representation
  - Decoupling feature (Nondecoupling/decoupling) $\quad m_\Phi^2 \simeq M^2 + \lambda_i v^2$
  - Symmetries ⟷ Shape of the Higgs potential
    ⟷ Decoupling limit
  - etc.

Extended Higgs sector [2/2]

- Relation between Higgs sector and BSM.

Extended Higgs sector

$$\Phi + S + \ldots$$
$$\cup$$
$$H,\ A,\ H^{\pm}, \ldots$$

→ ←

BSM phenomena

- DM (mediator, axion)
- Baryogenesis (strong 1st OPT, CPV)
- ν masses (Type-II seesaw, radiative seesaw)
- Anomalies (muon g-2, B-physics, W mass, …)

- Relating with structure of Higgs sectors, decoupling features

Probe of Higgs sector is a key to purse NP beyond the SM

Two Higgs doublet models (2HDMs) [1/2]

- Two Higgs doublet fields: $\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}w_1^+ \\ v_1 + h_1 + iz_1 \end{pmatrix}$ $\Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}w_2^+ \\ v_2 + h_2 + iz_2 \end{pmatrix}$

- Originally prosed by T.D. Lee to introduce CPV. [T.D. Lee, PRD 8 (1973) 1226]

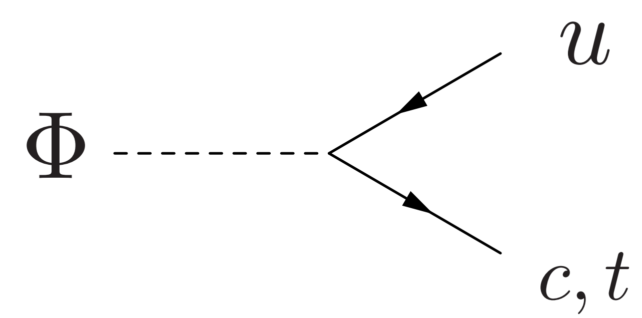
- Restrictions for the shape of Higgs sector

  - ρ parameter $\rho \equiv \left(\frac{m_W^2}{m_Z \cos\theta_W}\right)^2 = \frac{\sum v_i^2 (I_{3,i}(I_{3,i}+1) - \frac{1}{4}Y_i^2)}{\sum \frac{1}{2} v_i^2 Y_i^2} = 1$

  - FCNC

$$\mathcal{L}^Y \ni \bar{Q}\left(Y_{u,1}\Phi_1^c + Y_{u,2}\Phi_2^c\right)u_R + \bar{Q}\left(Y_{d,1}\Phi_1 + Y_{d,2}\Phi_2\right)d_R + \bar{L}\left(Y_{e,1}\Phi_1 + Y_{e,2}\Phi_2\right)\ell_R$$

Flavor changing neutral current (FCNC)



→ We impose softly broken Z_2 symmetry $\Phi_1 : +, \quad \Phi_2 : -$

→ 4 types of Yukawa interactions: Type I, Type II, Type X, Type Y

$(u_R, d_R, \ell_R) =$ $(-,-,-)$ $(-,+,+)$ $(-,-,+)$ $(-,+,-)$

Two Higgs doublet models (2HDMs) [2/2]

$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}],$$

$$\Phi_i = \begin{pmatrix} w_i^\pm \\ \frac{1}{\sqrt{2}}(v_1 + h_i + z_i) \end{pmatrix} \quad (i = 1, 2)$$

- Physical fields

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha)\begin{pmatrix} H \\ h \end{pmatrix}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta)\begin{pmatrix} G^0 \\ A \end{pmatrix}, \quad \begin{pmatrix} w_1^\pm \\ w_2^\pm \end{pmatrix} = R(\beta)\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

H, A, H^+, H^- :additional Higgs bosons, *h* : SM-like Higgs boson

- Input parameters: m_H, m_A, $m_{H^\pm}$, $\sin(\beta-\alpha)$, $\tan\beta$, M^2 ($=m_3^2/c_\beta s_\beta$)

Alignment limit and decoupling limit

Alignment limit

Higgs boson couplings : $\kappa_V = \sin(\beta-\alpha) \quad \kappa_f = \sin(\beta-\alpha) + \xi_f \cos(\beta-\alpha)$

$$\boxed{\sin(\beta-\alpha) \to 1} \quad \Longleftrightarrow \quad \kappa_V, \kappa_f \to 1$$

[$\rightleftarrows$ $\alpha = \beta - \frac{\pi}{2}$ All Higgs states are diagonalized by β.]

Decoupling limit

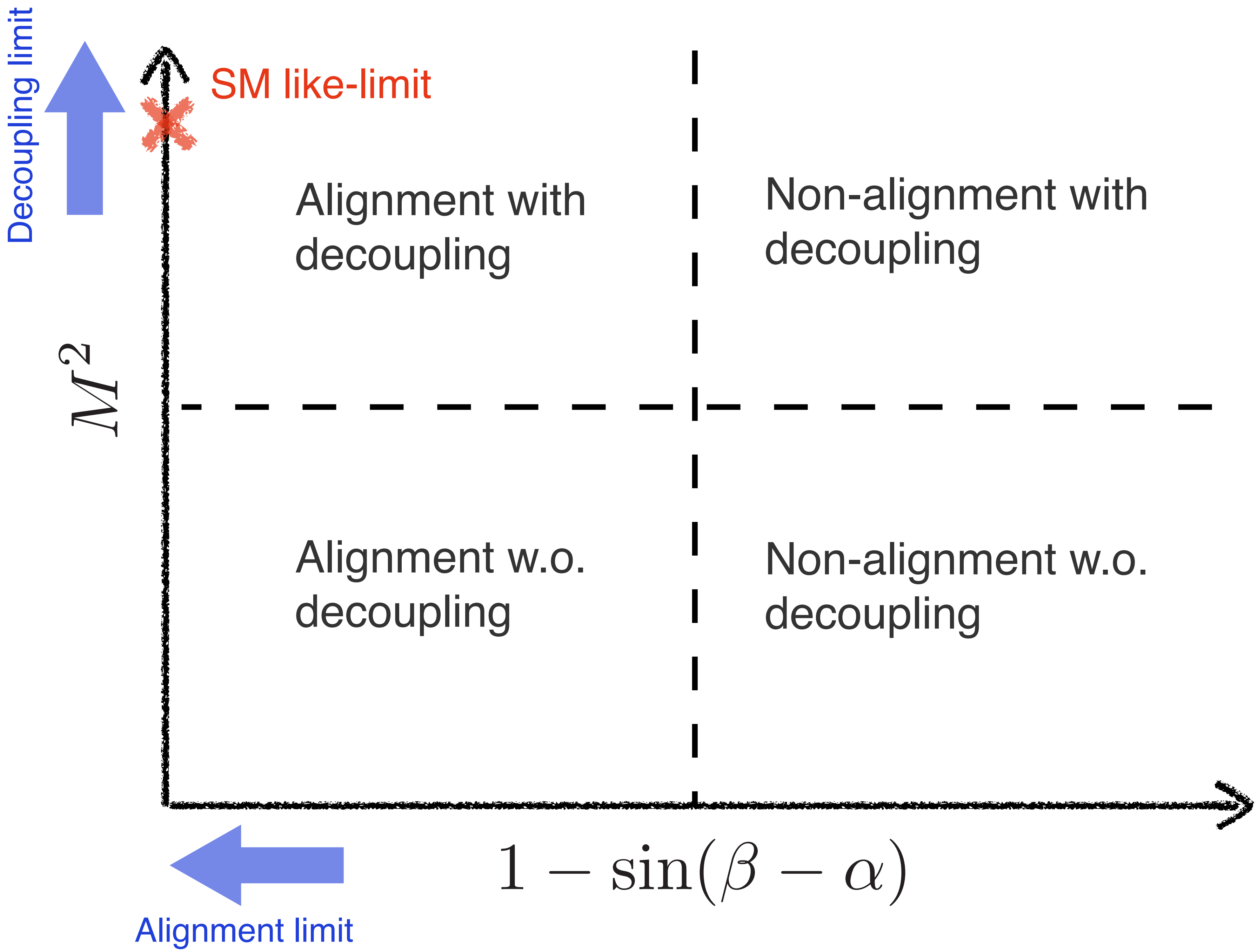
Mass of additional Higgs : $m_\Phi^2 \simeq M^2 + \lambda_i v^2$

$$\boxed{M^2 \to \infty}$$

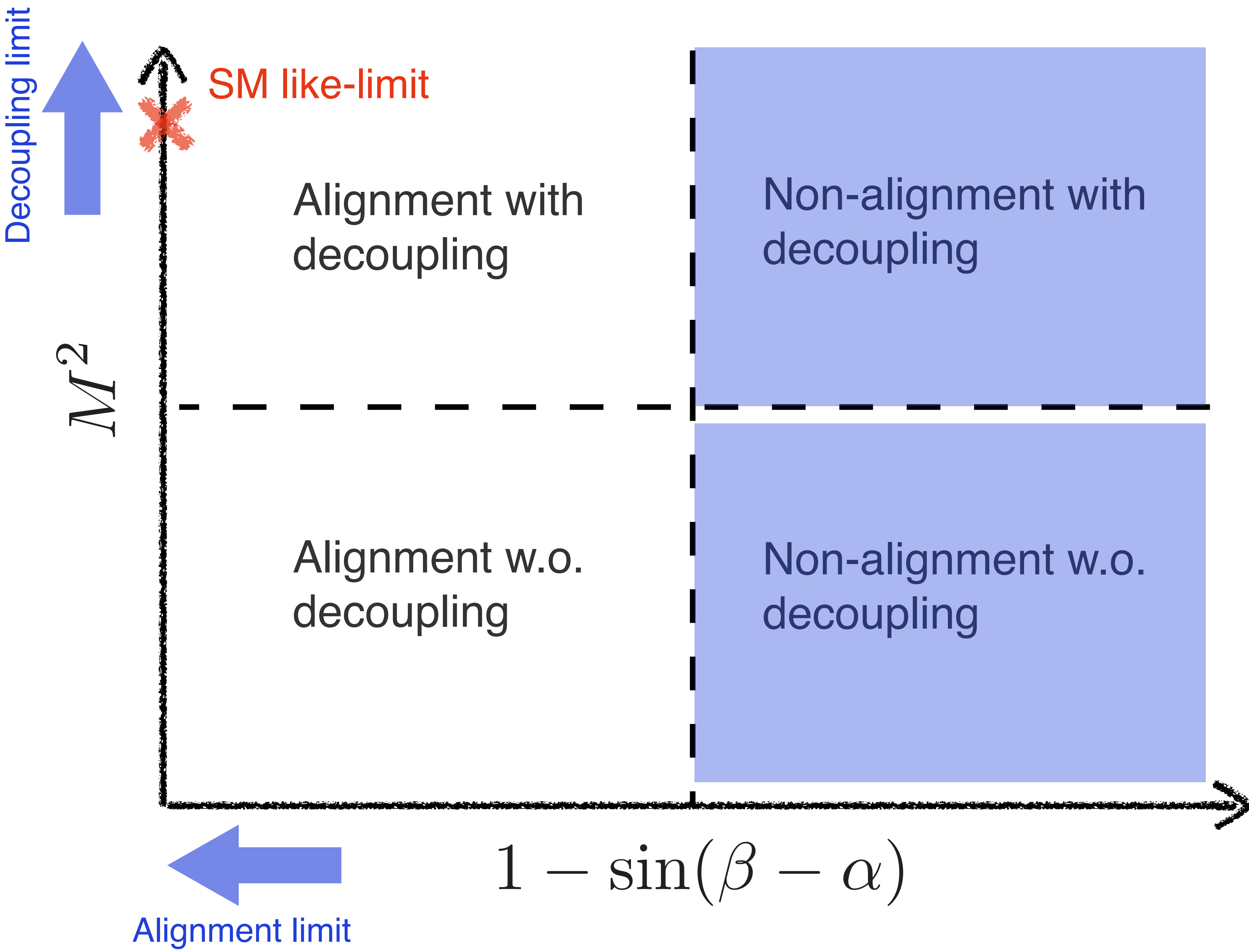
Definition of α: $\tan 2(\beta-\alpha) = \frac{\sum_i c_i \lambda_i v^2}{\sum_i c_i \lambda_i v^2 + M^2} \to 0$

Alignment limit is automatically satisfied by decoupling limit.

Distinct scenarios



Distinct scenarios



- $\sin(\beta - \alpha) \neq 0,\ M^2 \gg v^2$

$$\tan 2(\beta - \alpha) = \frac{\sum_i c_i \lambda_i v^2}{\sum_i c_i \lambda_i v^2 + M^2}$$

$$\longrightarrow \quad \lambda_i \gg 1$$

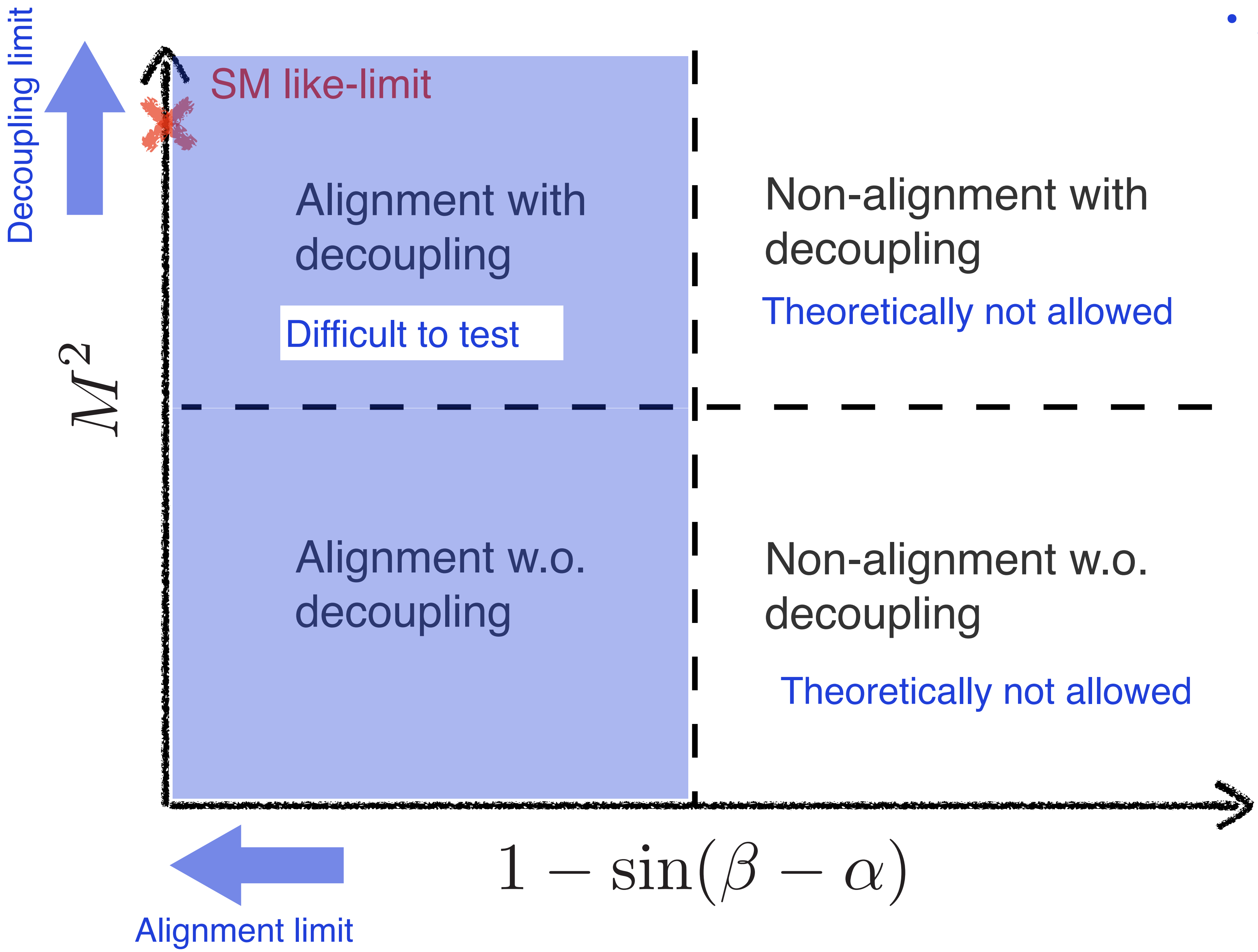
- $\sin(\beta - \alpha) \neq 0,\ M^2 \sim v^2$

$$\lambda_3 \sim t_\beta (1 - \lambda_{\rm SM}) s_{2(\beta-\alpha)} + \lambda_{\rm SM} c_{2(\beta-\alpha)}$$

$$\longrightarrow \quad \lambda_i \gg 1 \qquad (\ \text{if } t_\beta \gg 1\ )$$

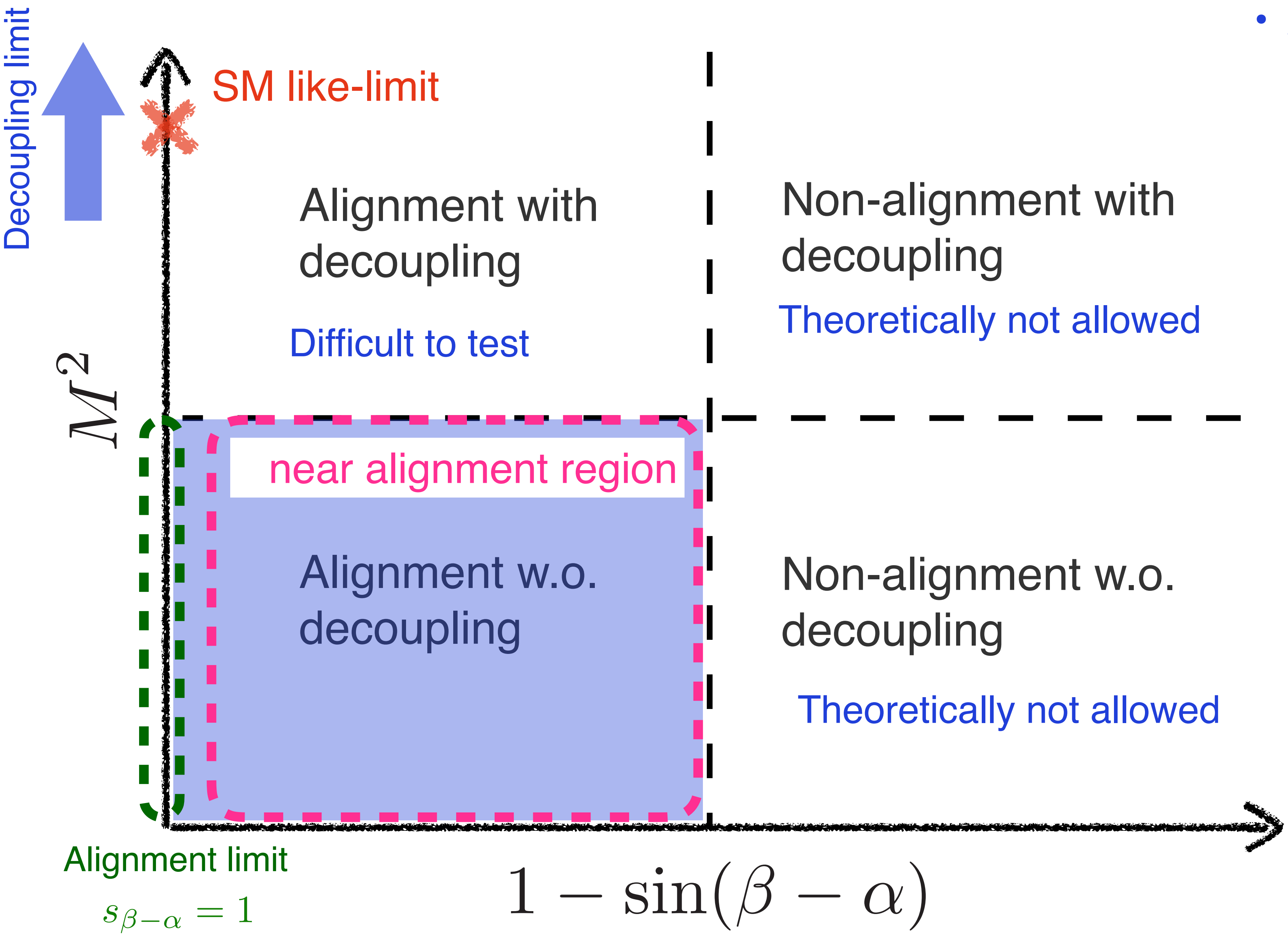
These are excluded by theoretical arguments (e.g. perturbativity)

Distinct scenarios



- Alignment w.o. decoupling is accessible by collider experiments.

Distinct scenarios



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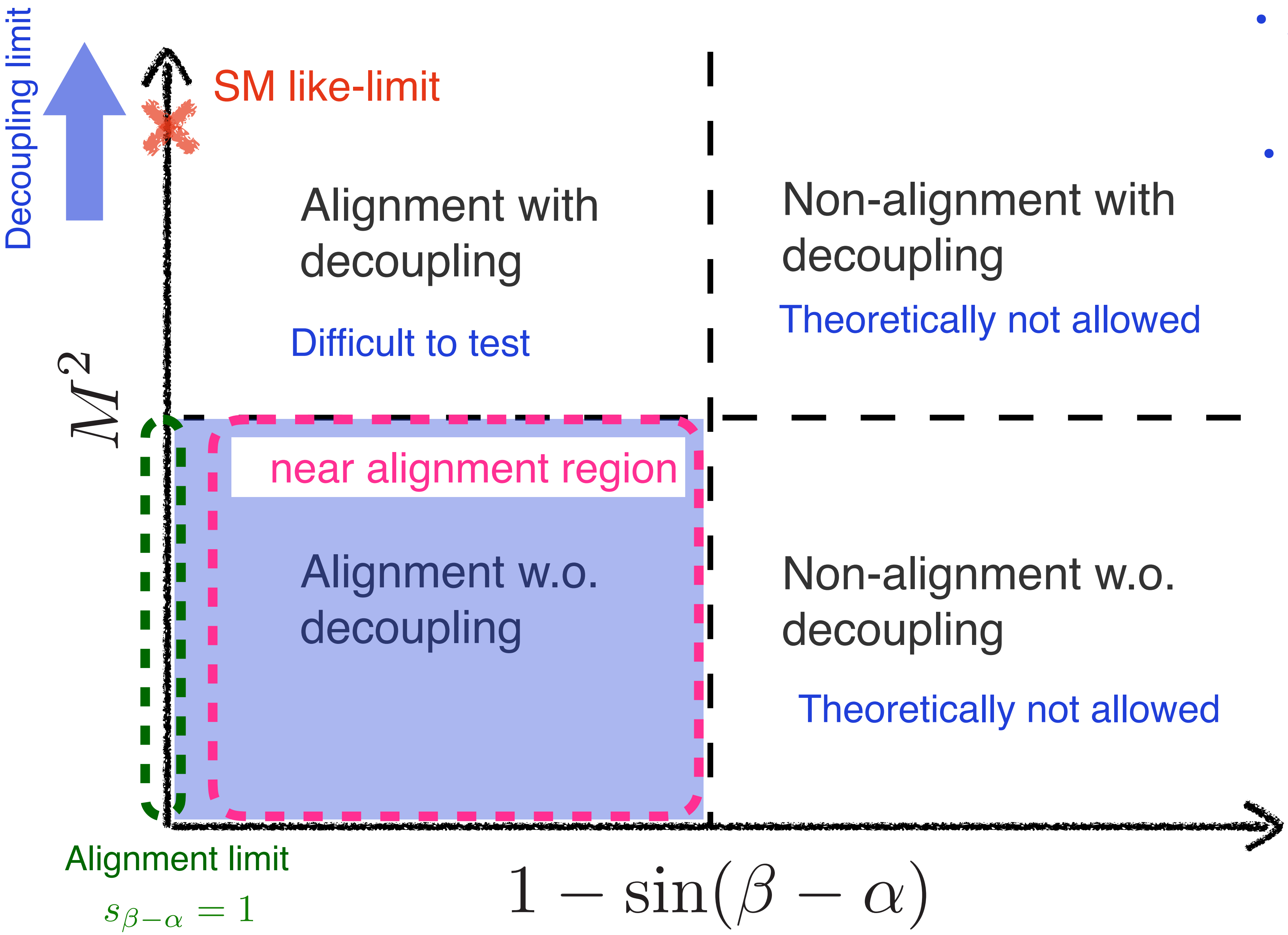
Distinct scenarios

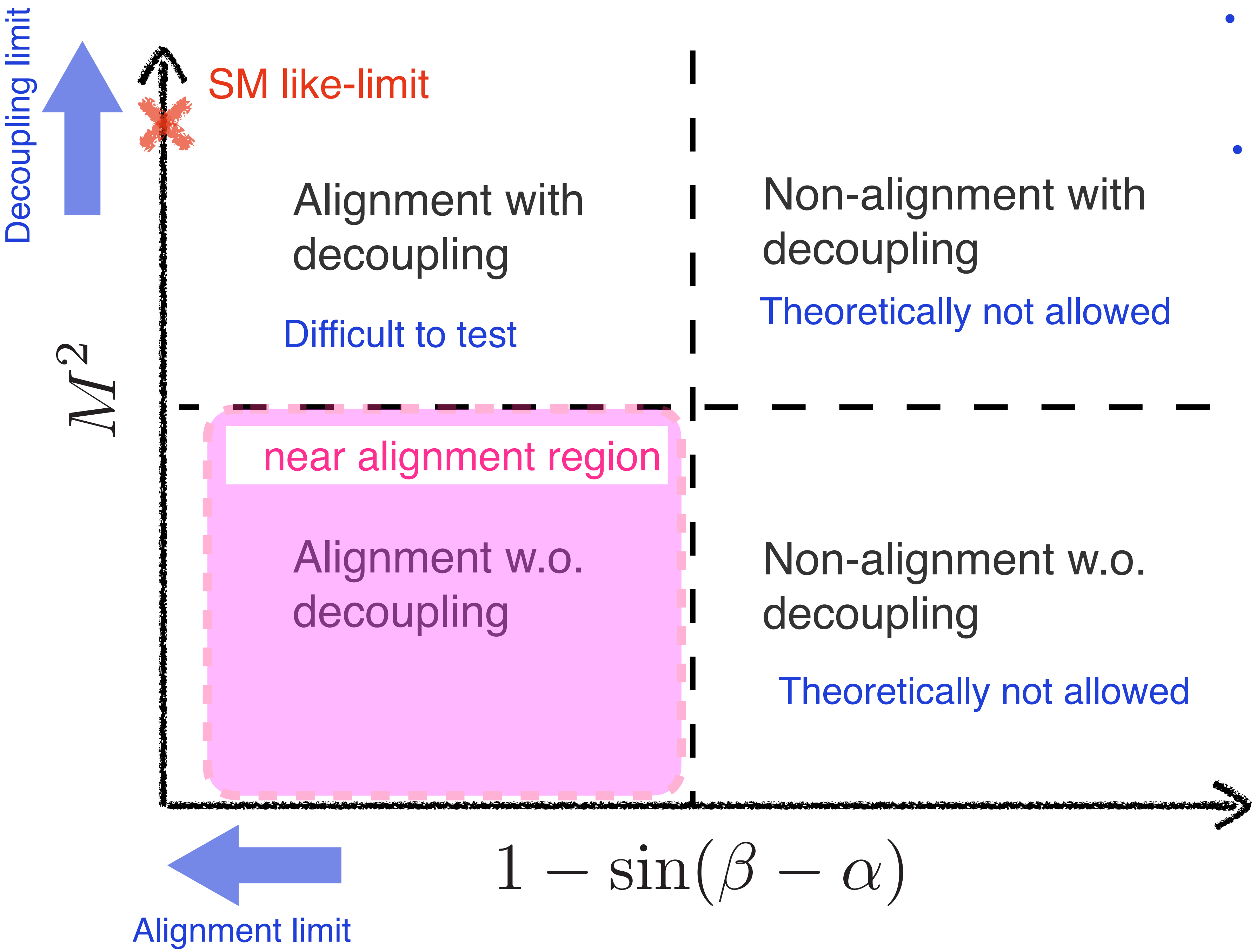


- Alignment w.o. decoupling is accessible by collider experiments.
- It is favored by measurements of the signal strength of h :

  $c_{\beta-\alpha} \lesssim 0.3\ (0.1)$ for Type I (II)

  [ATLAS collaboration, PRD 101, 012002 (2020)]

Distinct scenarios



- Alignment w.o. decoupling is accessible by collider experiments.
- It is favored by measurements of the signal strength of h :

$$c_{\beta-\alpha} \lesssim 0.3\ (0.1) \quad \text{for Type I (II)}$$

[ATLAS collaboration, PRD 101, 012002 (2020)]

- In near alignment region

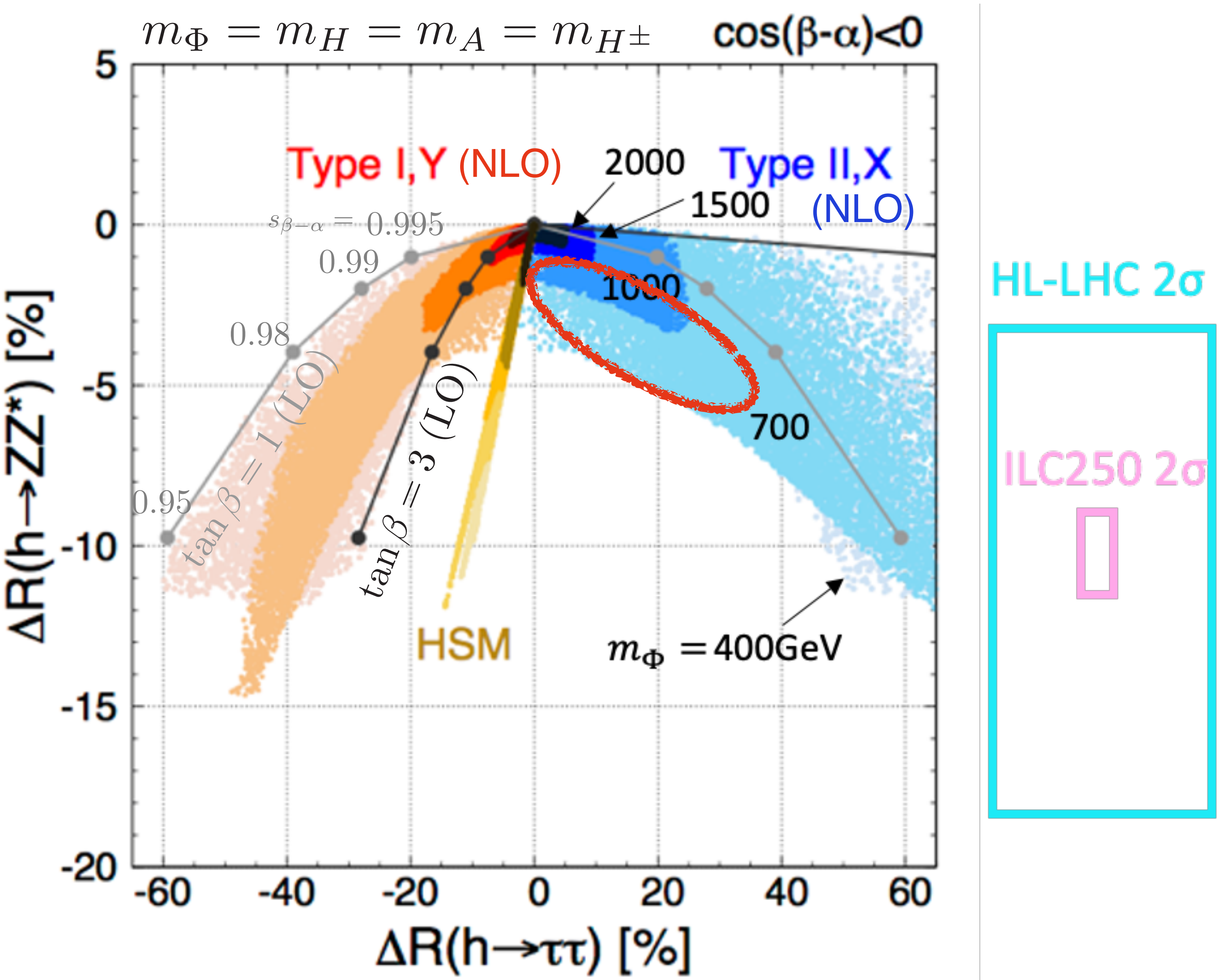
$$\kappa_X \neq 1$$

- The scenario can be tested by future precision measurements of κ_X .
- Importantly, non-decoupling effects can be comparable with the precision measurements.

NLO corrections should be included to compare the experiments.

Fingerprinting by Higgs boson decays

[Kanemura,Kikuchi,Mawatari,KS,Yagyu]

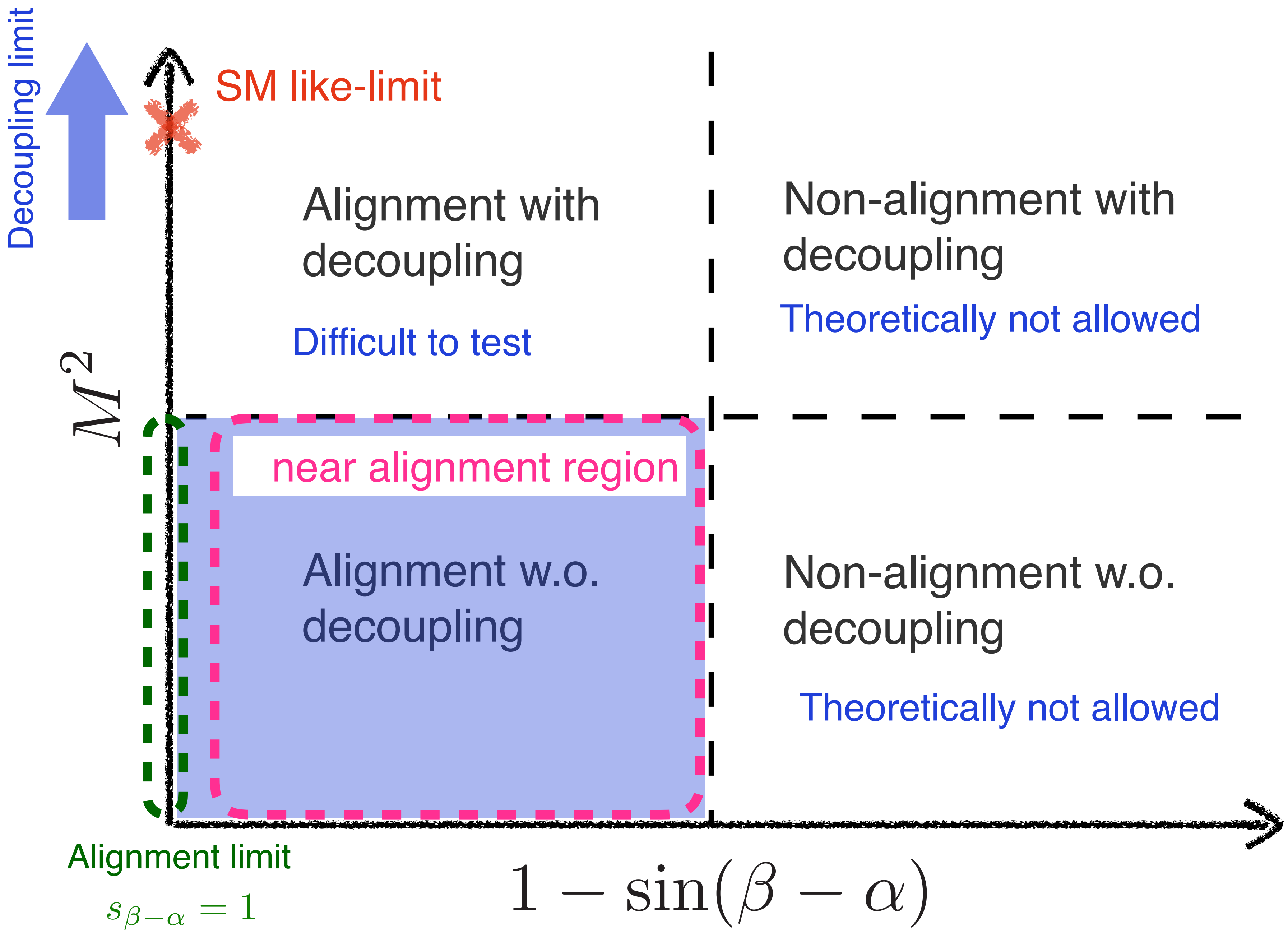


- We can distinguish the type of 2HDM.
- The size of deviation determine the upper bounds of m_Φ .
- Theoretical predictions can be changed by loop effects within several %.

→ Future precision measurements is needed to detect the loop effect.

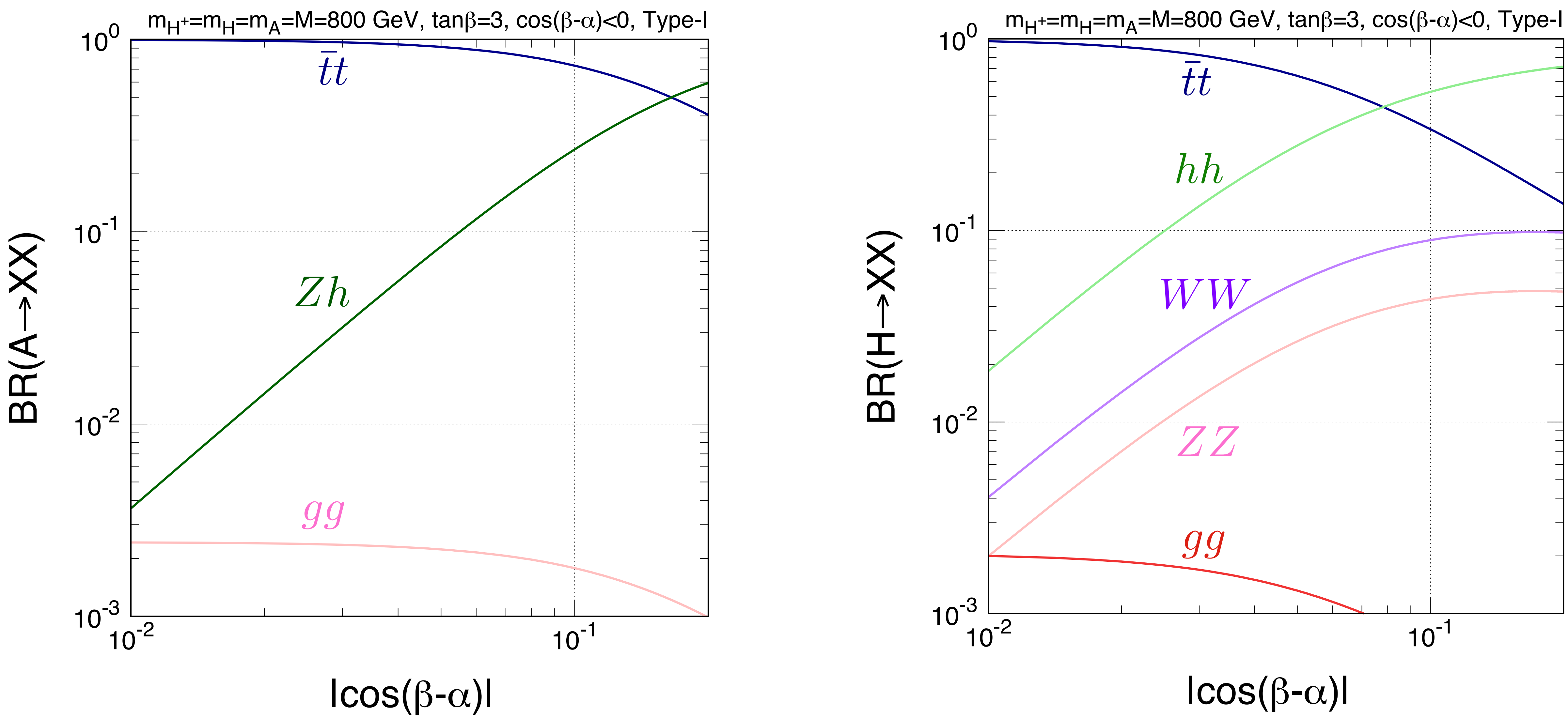
$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)}{\Gamma(h \to XX)_{\rm SM}} - 1$$

Distinct scenarios



- Heavy Higgs boson is relatively light.
- Large parameter regions can be probed by a synergy between direct searches of Φ and the indirect searches.

Branching ratios for the Heavy Higgs bosons



- $\sin(\beta-\alpha)=1: A, H \to \bar{t}t$ are dominant process. $\Gamma(A \to Zh) \propto \cos(\beta-\alpha)^2 \frac{m_A^3}{16\pi v^2}$
- $\sin(\beta-\alpha) \neq 1$: Scalar to scalar decays are important $\Gamma(H \to hh) \sim \cos(\beta-\alpha)^2 \frac{m_H^3}{16\pi v^2}$

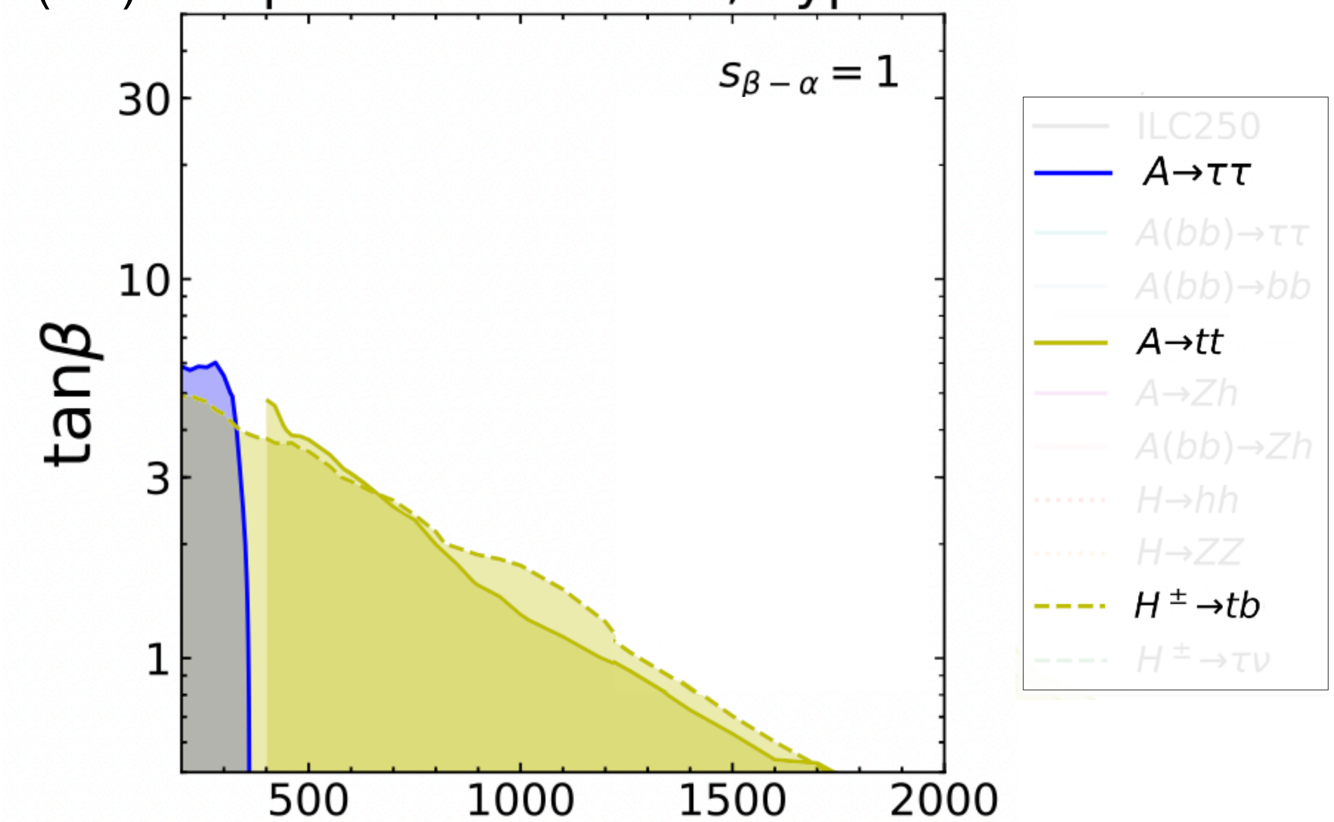
→ Behaviors of BRs strongly depend on the alignment parameter.

Synergy between direct and indirect searches[1/3]

Alignment limit: $\sin(\beta - \alpha) = 1$

[M. Aiko, S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu, NPB 966 (2021) 115375]

(Ex.): Expected exclusion; Type-I at HL-LHC



$s_{\beta-\alpha}$: $\sin(\beta-\alpha)$

$c_{\beta-\alpha}$: $\cos(\beta-\alpha)$

$$\Gamma(A \to f\bar{f}) \propto \frac{m_A}{\tan^2\beta}$$

$$\Gamma(H^+ \to t\bar{b}) \propto \frac{m_{H^\pm}}{\tan^2\beta}$$

Direct searches : Lower bounds for m_Φ and $\tan\beta$ are given.

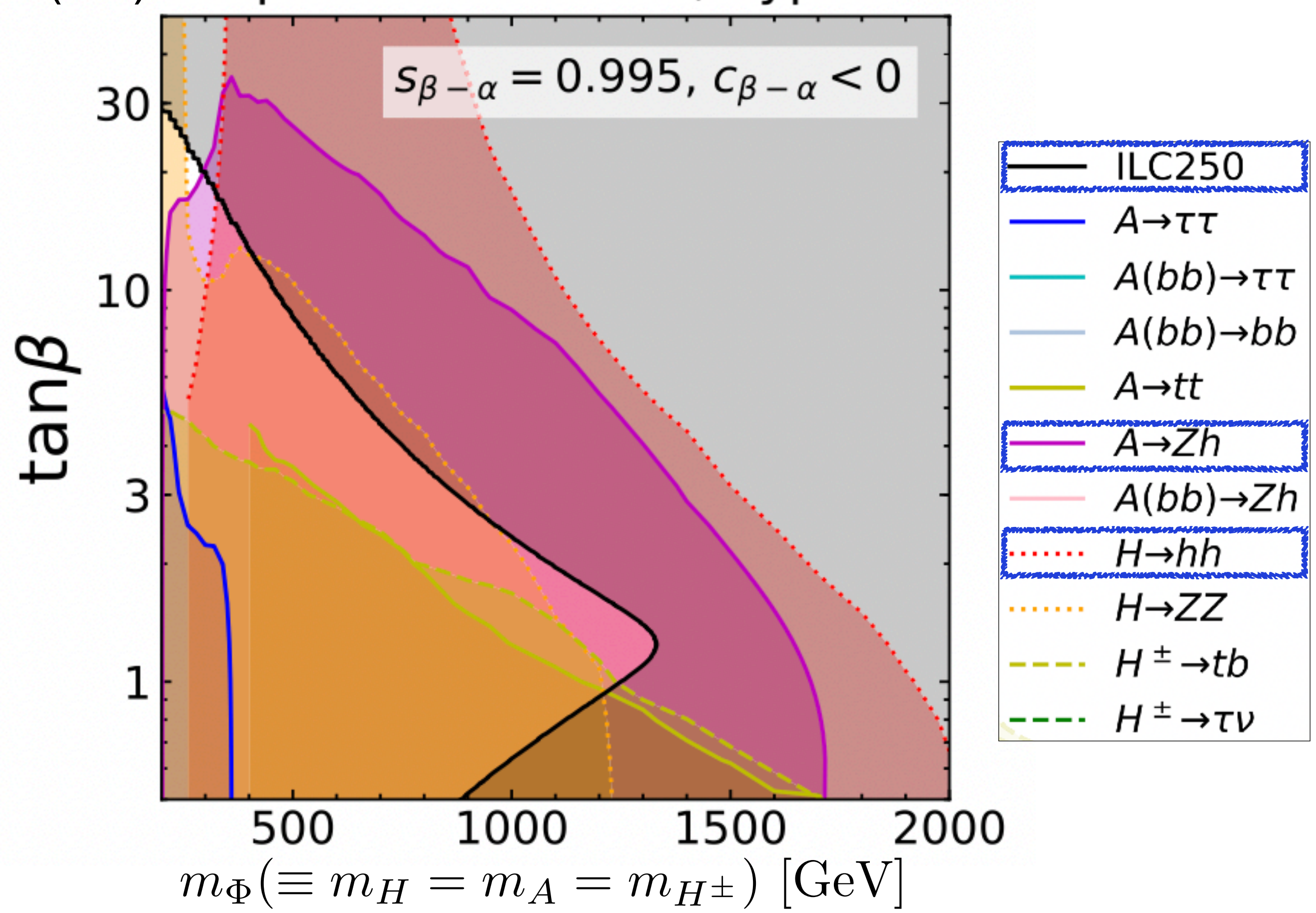
Indirect searches : No sensitivity since Higgs couplings do not deviate.

Synergy between direct and indirect searches[2/3]

Near alignment scenario: $\sin(\beta-\alpha)=0.995$

[M. Aiko, S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu, NPB 966 (2021) 115375]

(Ex.): Expected exclusion; Type-I at HL-LHC



$s_{\beta-\alpha}:\ \sin(\beta-\alpha)$

$c_{\beta-\alpha}:\ \cos(\beta-\alpha)$

$\Gamma(A\to Zh)\propto\cos(\beta-\alpha)^2\frac{m_A^3}{16\pi v^2}$

$\Gamma(H\to hh)\sim\cos(\beta-\alpha)^2\frac{m_H^3}{16\pi v^2}$

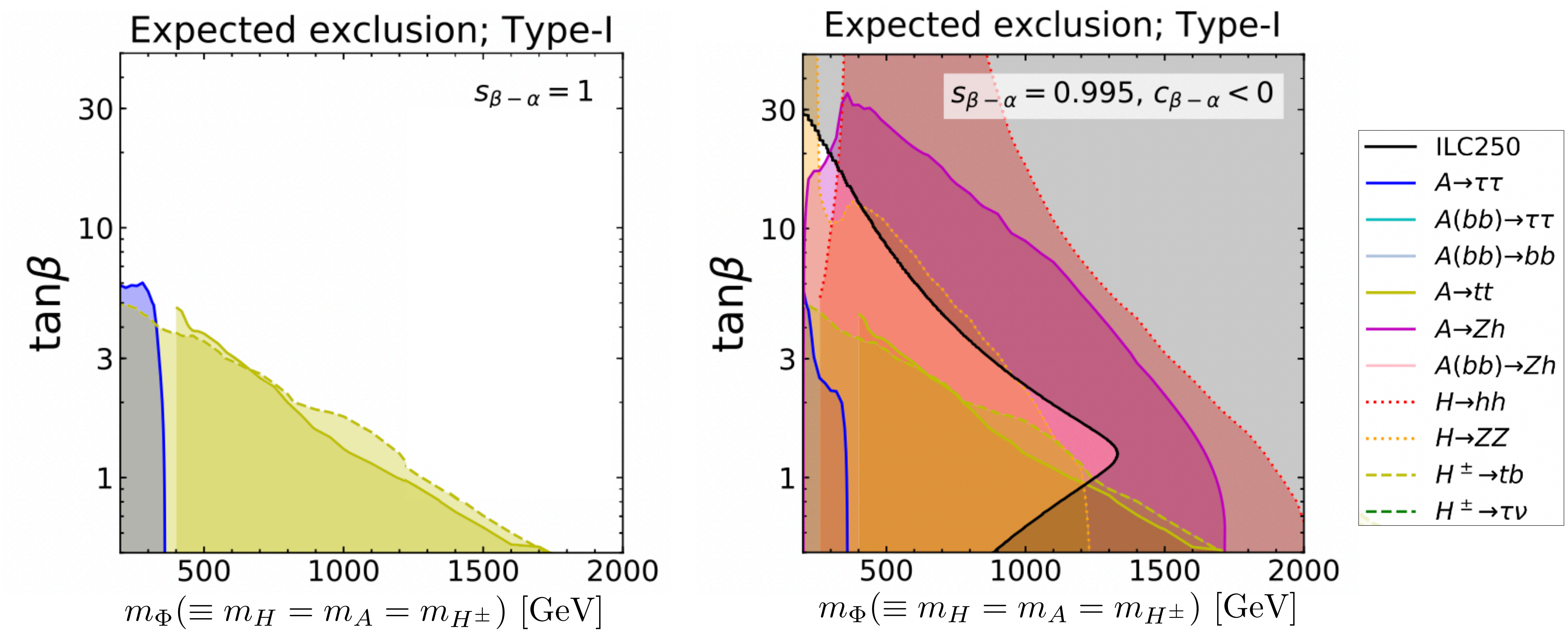
Direct searches : $A\to Zh$ and $H\to hh$ give wider sensitivity regions for $(m_\Phi,\ \tan\beta)$ plane.

Indirect searches : If a deviation in *hZZ* founds, the upper bounds for m_Φ are given.

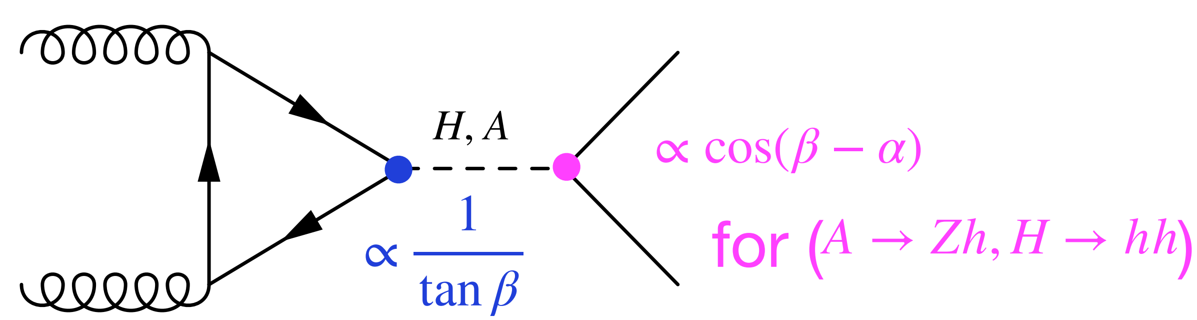
→ Most parameter space can be surveyed by the combination of Scalar-to scalar decays and precision measurements of the Higgs coupling.

Importance of NLO corrections to heavy Higgs

[M. Aiko, S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu, NPB 966 (2021) 115375]



Sensitivity regions by direct searches are drastically changed by $\sin(\beta-\alpha)$, especially for BRs.



➡ Loop effect to heavy Higgs decays can be significant. We should include it in alignment w.o the decoupling scenario.

H-COUP

We have calculated full NLO corrections to two-body decays of $H, A, H^{\pm}$.
They will be implemented in H-COUP ver. 3.

H-COUP Fortran program to evaluate loop-corrected Higgs observables in the improved on-shell scheme.

[Kanemura, Kikuchi, KS, Mawatari, Yagyu]

[Aiko, Kanemura, Kikuchi, KS, Yagyu]

Observables (NLO EW+NNLO QCD)	Model
(v2.0): $\mathrm{BR}(h \to ff), \mathrm{BR}(h \to VV^*), \lambda_{hhh}$	• Higgs Singlet model
(v3.0): $\mathrm{BR}(\Phi \to ff), \mathrm{BR}(\Phi \to SV/VV), \mathrm{BR}(\Phi \to SS)$	• Two Higgs doublet models
	• Inert doublet model

- Heavy Higgs decays for all models

Predictions for each model are evaluated in the same scheme

Open questions

Impact of NLO corrections to scalar-to-scalar decays (e.g, $A \to Zh, H \to hh$)

- How large is the size of NLO corrections?

  What is the origin of sizable corrections?

- Correlation between heavy Higgs boson decays and observables for h_{125} at 1-loop level.

Definition of Alignment limit: $\kappa_V = 1$

(tree): $\kappa_V = \sin(\beta - \alpha)$

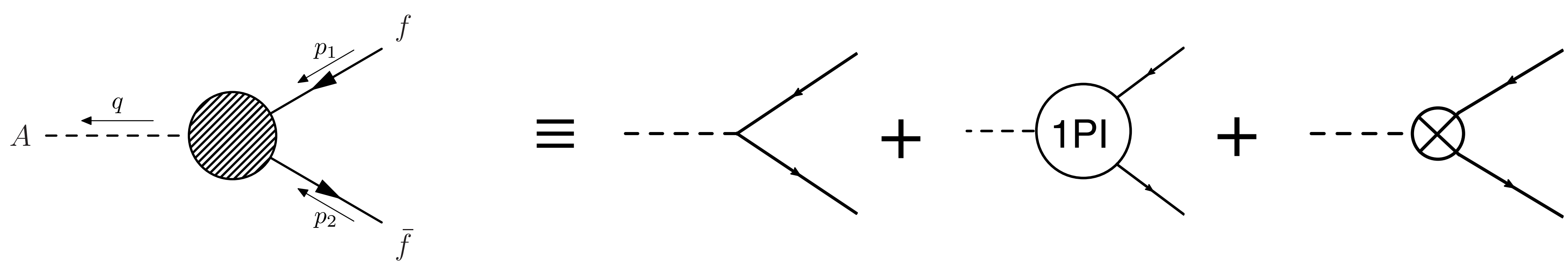
(loop): $\kappa_V = \sin(\beta - \alpha) + (\text{loop corrections})$

The dependence of $\Gamma_{A\to Zh, H\to hh}$ on κ_V may change from the tree-level analysis.

Detail of calculations

Details of the calculations of NLO EW corrections

Ex). A—>ff



Renormalization scheme : on-shell scheme

δm_Φ , $\delta Z_{\Phi 1 \Phi 2}$:
$\delta\alpha$, $\delta\beta$:
} On-shell ⟵ The CTs are renormalized by $\hat{\Pi}_{ij}(p^2)$

δM^2 : $\overline{\text{MS}}$ scheme

[Another choice: $\hat{\Gamma}_{\Phi\to SS} = 0$

- Limit for parameter space by kinematics
- Numerical instability [M. Krause, M. Muhlleitner, R. Santos, H. Ziesche]]

δT_h, δT_H : standard tadpole scheme, alternative tadpole scheme

Renormalization of tadpoles

- Standard tadpole scheme (STS) [W.F.L. Hollik, Fortschr. Phys. 38 (1990) 165.]

$$\begin{cases} t_i^B = t_i^R + \delta t_i \quad (i = h, H) \\ \hat{\Gamma}_i = t_R + \delta t_i + \Gamma_i^{1PI} \end{cases} \xrightarrow{(t_i^R = 0,\, \hat{\Gamma}_i = 0)} \delta t_i = -\Gamma_i^{1PI}$$

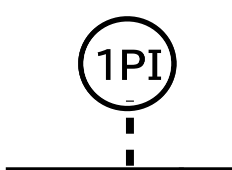
- Alternative tadpole scheme (ATS) [J. Fleischer and F. Jegerlehner, PRD23, 2001 (1981)]

$$\begin{cases} \Phi_m \to \Phi_m + \Delta v_m \quad (m = 1,2) \\ \hat{\Gamma}_i = t^B + f(\Delta v_m) + \Gamma_i^{1PI} \end{cases} \xrightarrow{(t_i^B = 0,\, \hat{\Gamma}_i = 0)} \Delta v_m = \sum_i R_{mi} \Gamma_i^{1PI} / m_i^2$$

- Difference between STS and ATS

- While in STS tadpole affects only scalar self-energy, in ATS all self-energy has tadpole contributions.

$$\hat{\Pi}_{ij}^{ATS} = \hat{\Pi}_{ij} +$$



- This makes self-energy gauge-independent at on-shell mass.

Gauge invariant CTs can be obtained in ATS.

Gauge dependence in mixing angles

- In renormalization of mixing angle, there is a technical issue, namely, gauge dependence appears. [Yamada, PRD64(2001)036008]

- We can check gauge dependence from Nielsen identify:

$$\partial_\xi \Pi_{ij} = (2p^2 - m_i^2 - m_j^2)\tilde{\Pi}_{ij}$$

$i, j = h, H, A, H^\pm$

$\tilde{\Pi}_{ij}$: function of loop functions

- $i = j = h$: $\delta m_h^2 = \Pi_{hh}^{\rm 1PI}(m_h^2)$

$\partial_\xi \Pi_{hh}(p^2) = 0$ at $p^2 = m_h^2$ ➡ δm_h^2 is gauge-independent.

- $i = h, j = H$: $\delta\alpha = \{\Pi_{hH}^{\rm 1PI}(m_h^2) + \Pi_{hH}^{\rm 1PI}(m_H^2)\}/(m_H^2 - m_h^2)$

$\partial_\xi \Pi_{Hh} \neq 0$ at $p^2 = m_H^2 = m_h^2$, ➡ Gauge dependence for $\delta\alpha$

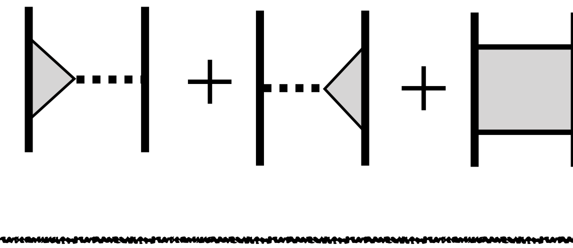
- Though this , the decay amplitudes are also gauge-dependent.

$$\frac{\partial \mathcal{M}_{A\to Zh}}{\partial \xi} = \frac{\partial}{\partial \xi}\left(\mathcal{M}^{\rm tree}_{A\to Zh} + \mathcal{M}^{\rm 1PI}_{A\to Zh} + \delta\mathcal{M}_{A\to Zh}\right)$$

$$= \frac{\partial}{\partial \xi}\left(\underbrace{\mathcal{M}^{\rm 1PI}_{A\to Zh} + f(\delta Z_i)}_{=0} + g(\delta\alpha, \delta\beta) + h(\delta m_i)\right) = \frac{\partial}{\partial \xi} g(\delta\alpha, \delta\beta) \neq 0$$

Gauge independent renormalization of mixing angles

- In order to remove the gauge dependence in $\delta\alpha,\ \delta\beta$, we utilize pinch technique.

Basic idea: $\Pi_{Hh} \to \Pi_{Hh} + \Pi_{Hh}^{\rm Pinch}$ ⟵ T = 

This should arise from the full NLO amp.

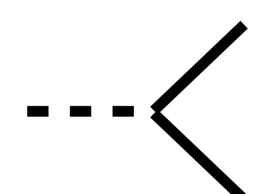
e.g., $gg \to A/H \to \bar{f}f$

$$\mathcal{M}^{\rm NLO}_{gg\to h/H\to \bar{f}f} \ni \mathcal{M}^{\rm SE-like}_{gg\to h/H\to \bar{f}f}$$

➡ $\partial_\xi \delta\alpha = 0,\ \partial_\xi \delta\beta = 0$

- Another scheme for mixing angles in gauge invariant way
  - p$_*$ scheme : $\hat{\Pi}_{Hh}\left(p^2 = [m_H^2 + m_h^2]/2\right) = 0$ [Espinosa, Yamada, PRD67(2003) 036003]
  - On-shell conditions with S matrix (THDM+ ν_{Ri} (i=1,2), $y_{\nu i} \to 0$) [Denner, Dittmaier, Lang, JHEP 1811(2018)104]

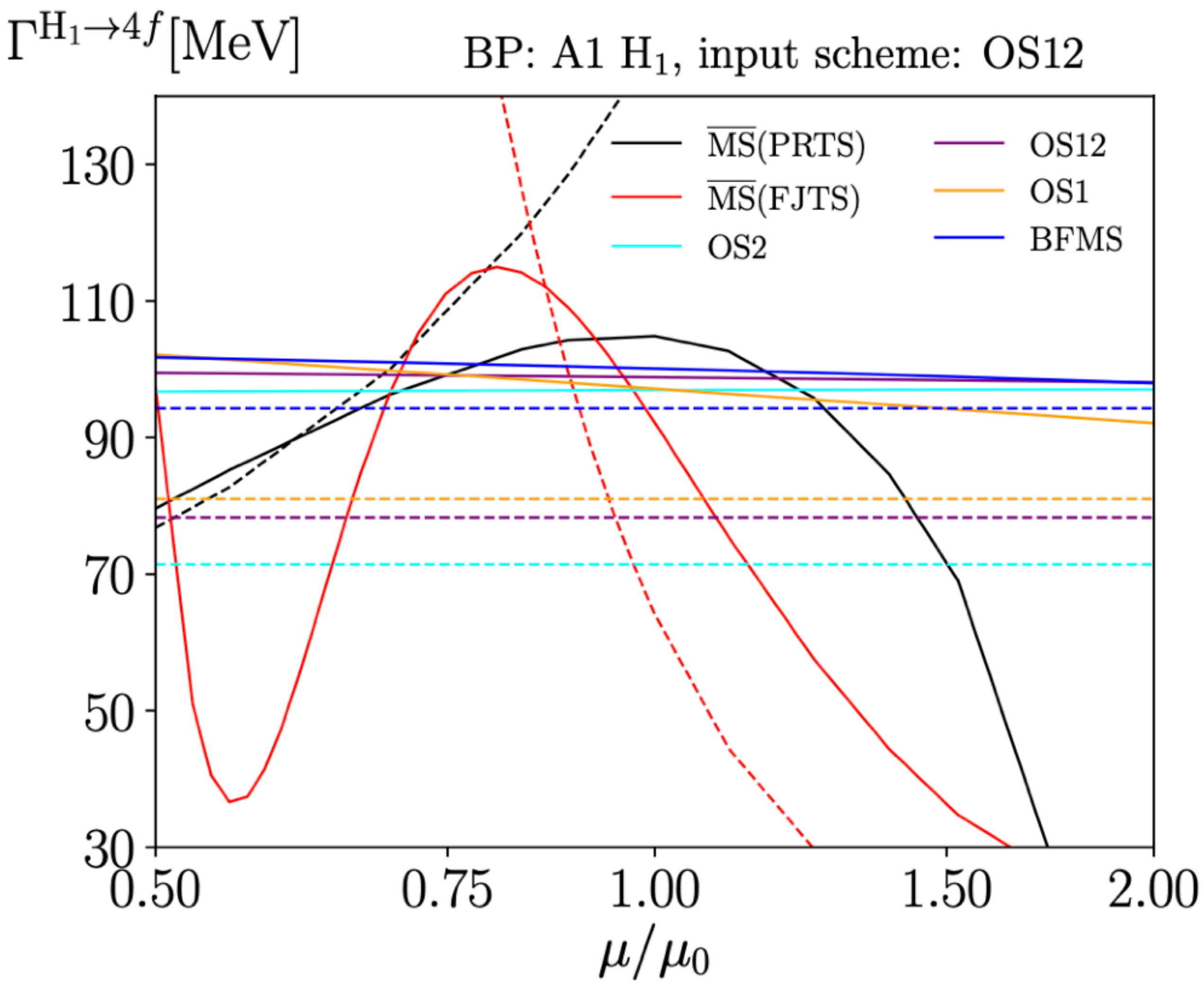
$$\frac{\mathscr{M}^{\rm loop}_{H\to \nu_{R1}\nu_{R1}}}{\mathscr{M}^{\rm loop}_{h\to \nu_{R1}\nu_{R1}}} = \frac{\mathscr{M}^{\rm tree}_{H\to \nu_{R1}\nu_{R1}}}{\mathscr{M}^{\rm tree}_{h\to \nu_{R1}\nu_{R1}}} = \frac{c_\alpha}{s_\alpha}$$

$h\ (H)$  ν_{Ri}, ν_{Ri} $= y_{\nu_i} c_\alpha\ (s_\alpha)$

Scheme difference in counterterms of mixing angles

[A. Denner, S. Dittmaier, J.N. Lang,1808.03466]

BP: *A1* $M_{H_2} = 125\text{GeV},\ M_{H_1} = 300\text{GeV},\ M_{A,H^+} = 460\text{GeV},$
$\lambda_5 = -1.9,\ t_\beta = 2,\ c_{\beta-\alpha} = 0.1$, $\mu_0 = (m_{H_2} + m_{H_1} + M_A + 2M_{H^\pm})/5$



Scheme	A1 LO	A1 NLO
$\overline{\text{MS}}$(PRTS)	$147.102(4)^{>+100\%}_{-47.8\%}$	$104.86(2)^{<-100\%}_{-24.1\%}$
$\overline{\text{MS}}$(FJTS)	$64.096(2)^{-86.9\%}_{>+100\%}$	$92.17(1)^{-81.4\%}_{+5.6\%}$
OS1	80.992(2)	$97.145(7)^{-5.2\%}_{+5.1\%}$
OS2	71.429(2)	$96.95(1)^{+0.1\%}_{-0.2\%}$
OS12	78.304(2)	$98.812(8)^{-0.8\%}_{+0.7\%}$
BFMS	94.265(2)	$100.117(5)^{-2.2\%}_{+1.6\%}$

OS1,2,12: On shell with $H, h \to \nu_{Ri}\bar{\nu}_{Ri}$

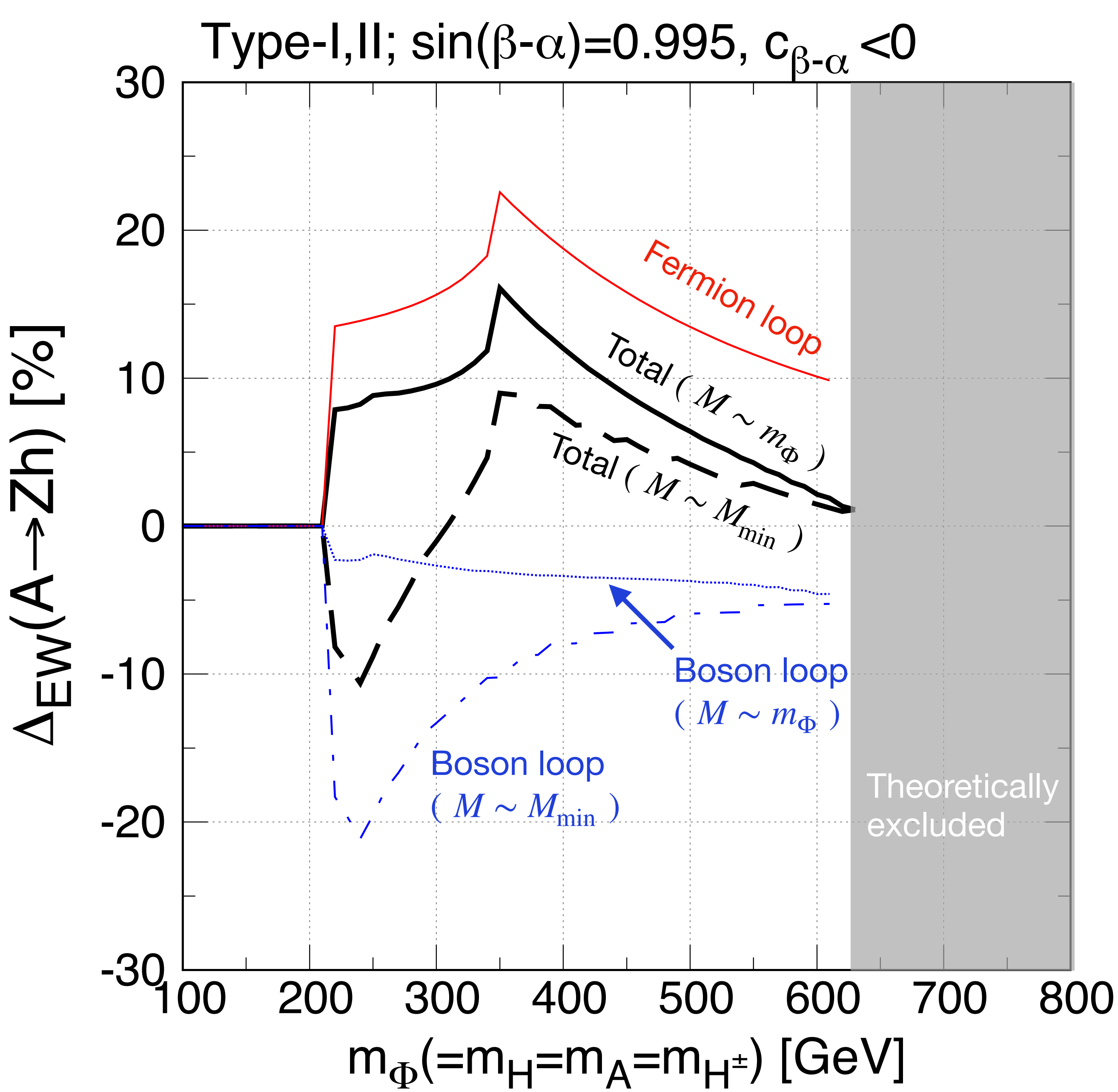
BFMS: On-shell with $\hat{\Pi}_{Hh}$ and the PT

Theoretical uncertainty (scheme difference) for on-shell scheme is a few %.

Results for A—>Zh and H—>hh

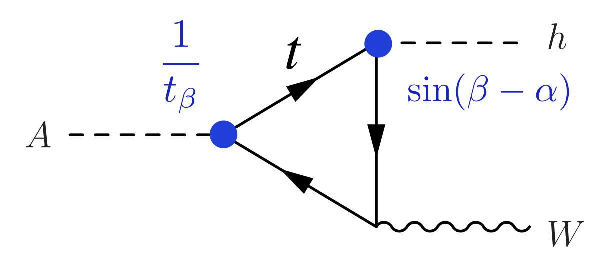
Non-decoupling effects in $\Gamma_{A\to Zh}$

[M. Aiko, S. Kanemura, KS]



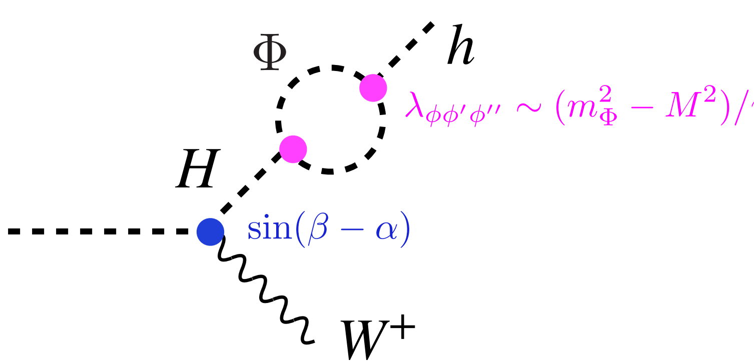
Typical graph :

fermion loop Suppression by t_β, m_Φ^2



$$\mathcal{M}^F_{A\to Zh} \sim -\frac{1}{16\pi^2}\frac{s_{\beta-\alpha}}{t_\beta}\frac{m_t^4}{v^2 m_\Phi^2} \quad (m_t \ll m_\Phi)$$

Boson loop Nondecoupling effects

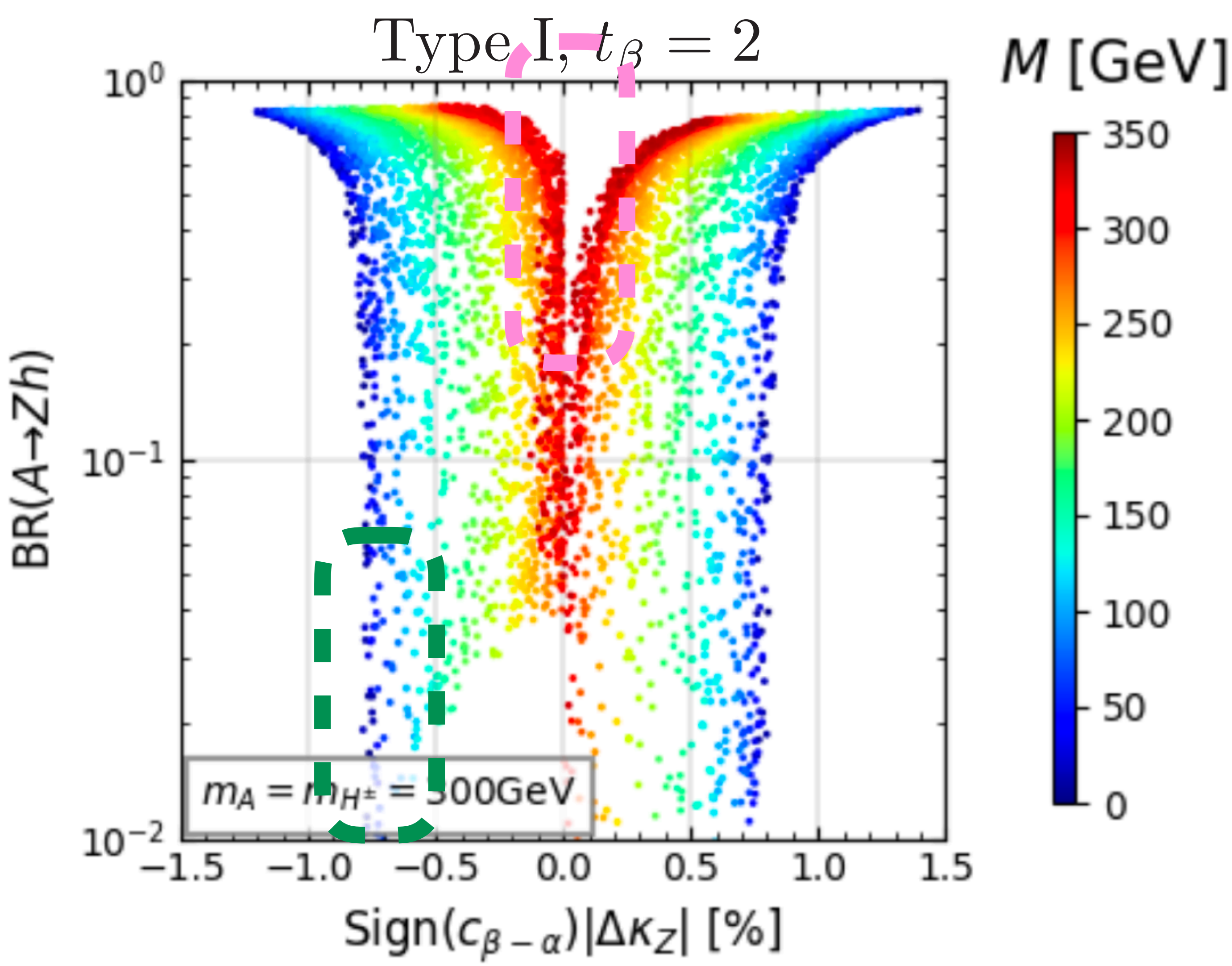


$$\mathcal{M}^B_{A\to Zh} \sim \left[\begin{array}{ll} \frac{1}{16\pi^2}s_{\beta-\alpha}\frac{m_\Phi^2}{v^2} & (M\sim v) \\ \frac{1}{16\pi^2}s_{\beta-\alpha}\frac{m_h^4}{v^2 m_\Phi^2} & (M\gg v) \end{array}\right.$$

- Some diagrams are not suppressed by $c_{\beta-\alpha}$.
- Fermion loop and Boson loop are destructive. → Total corrections reach ~15%.

BR(A —> Zh) vs $\Delta\kappa_V$

[M. Aiko, S. Kanemura, KS]

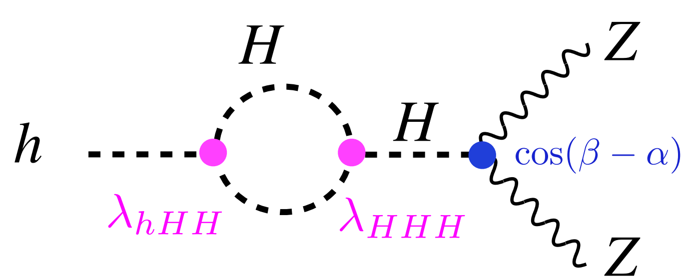


$$\Delta\kappa_Z = \frac{\Gamma^{\rm 2HDM}_{h\to ZZ^*}}{\Gamma^{\rm SM}_{h\to ZZ^*}} - 1$$

$M^2 \simeq 0, c_{\beta-\alpha} \simeq 0$: Nondecoupling effect of H,*A*,*H*$^\pm$ enhances $\Delta\kappa_Z$ → $\Delta\kappa_Z \neq 0$ but BR~1%

$M^2 \simeq m_A^2, |c_{\beta-\alpha}| \sim 0.1$: Nondecoupling effect of H *can affect* → $\Delta\kappa_Z$ ~ 0 but BR~*O*(10)%

Dominant diagrams : for h—>ZZ*

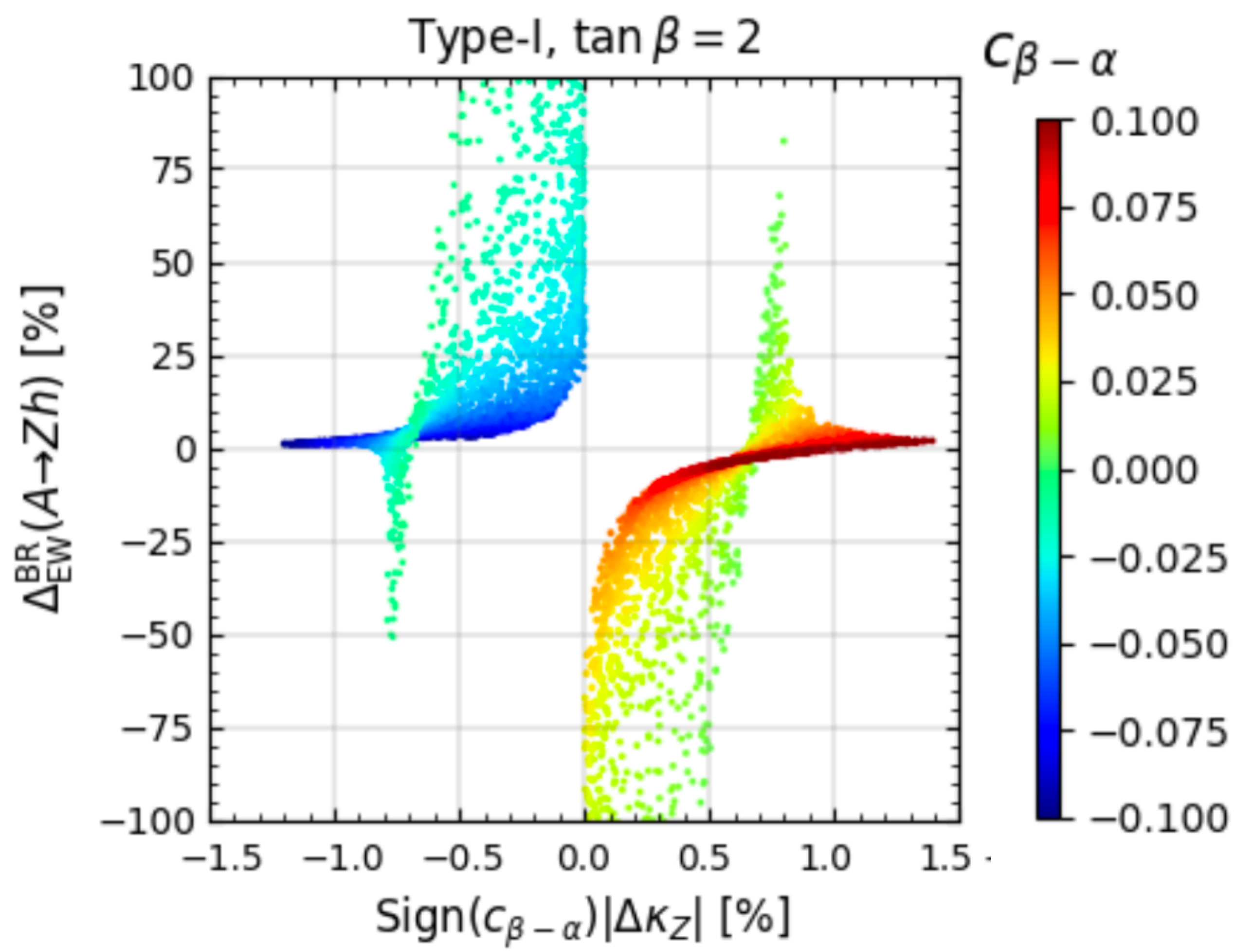


$$\sim \frac{1}{16\pi^2}(m_H^2 - M^2)^2 c_{\beta-\alpha}$$

This compensates tree level contributions in $\Delta\kappa_Z$.

NLO corrections for BR(A —> Zh)

[M. Aiko, S. Kanemura, KS]



$$\Delta^{\rm BR}_{\rm EW} = \frac{{\rm BR}^{\rm NLO}_{A\to Zh}}{{\rm BR}^{\rm LO}_{A\to Zh}} - 1$$

$|c_{\beta-\alpha}| \sim 0.1$: Δ^{BR} is close to 0%

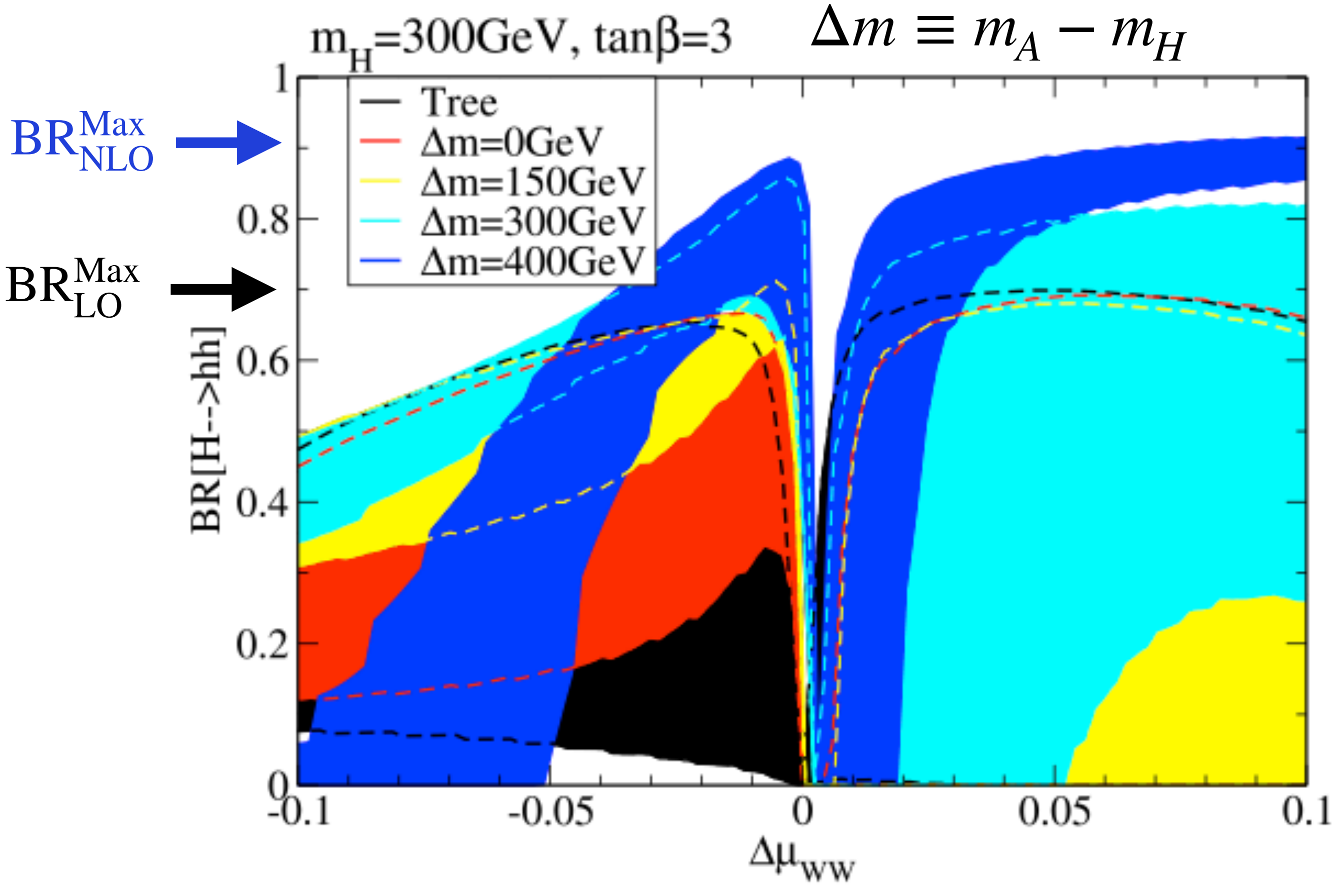
$$\Delta^{\rm BR}_{\rm EW} = \frac{1+\Delta^{\rm EW}_{A\to Zh}}{1+\underbrace{\Delta^{\rm EW}_{\rm tot}}_{\sim\Delta^{\rm EW}_{A\to Zh}}} - 1 \simeq 0$$

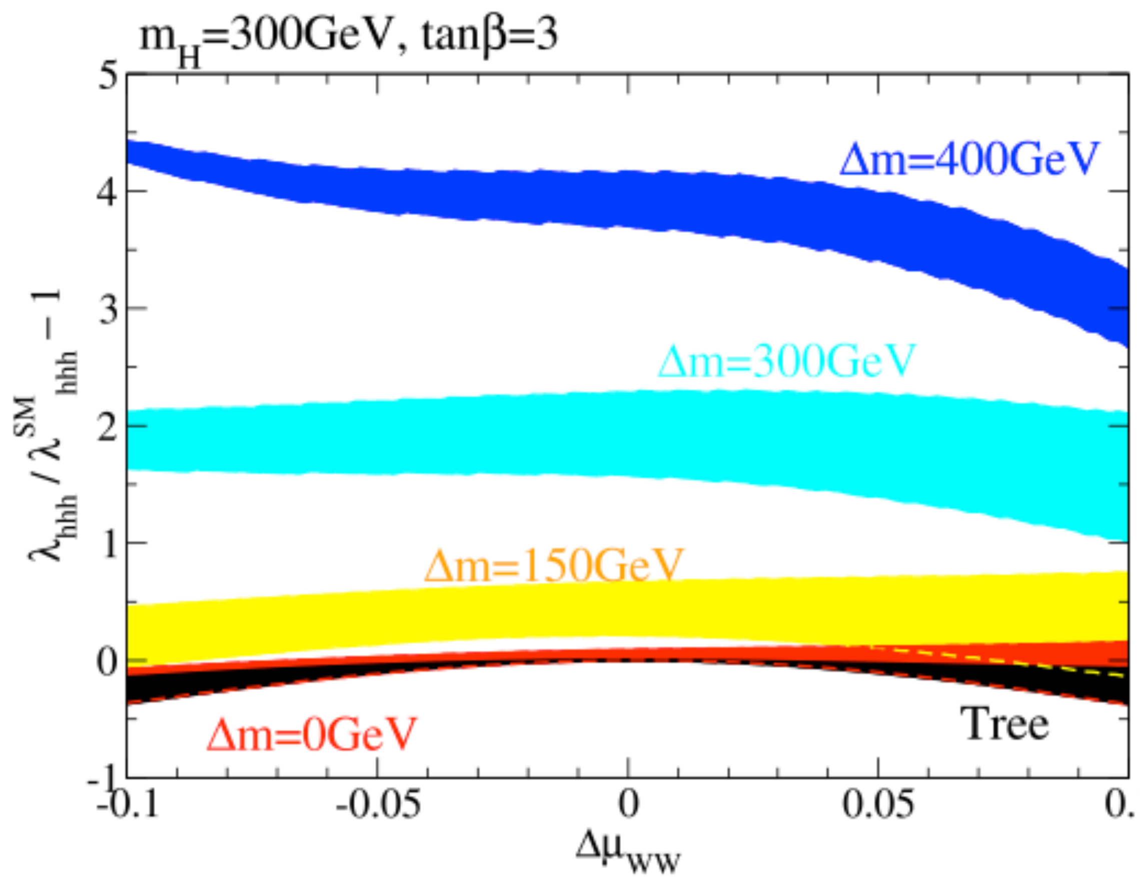
$|\Delta\kappa_Z| \lesssim 0.5\%$: Δ^{BR} can exceed 100%

$$|\mathcal{M}(A\to Zh)|^2 = C_{AZh}\left(\underbrace{\frac{g_Z^2}{4}c^2_{\beta-\alpha}}_{\text{Tree}} + \underbrace{g_Z c_{\beta-\alpha}{\rm Re}\Gamma^{\rm loop}_{\rm AZh} + |\Gamma^{\rm loop}_{\rm AZh}|^2}_{\text{1-loop}}\right)$$

Correlation between $\Gamma_{H\to hh}$ and λ_{hhh}

[Kanemura, Kikchi, Yagyu]





Nondecoupling effect in $\Gamma_{H\to hh}$ predicts sizable deviation in λ_{hhh} .

→ if *H* is discovered and the BRs are precisely determined, the scenario of EWBG can be tested.

[Realization of strong 1st OPT ⇄ $\frac{\lambda_{hhh}}{\lambda^{SM}_{hhh}} - 1 \gtrsim 10\,\%$]

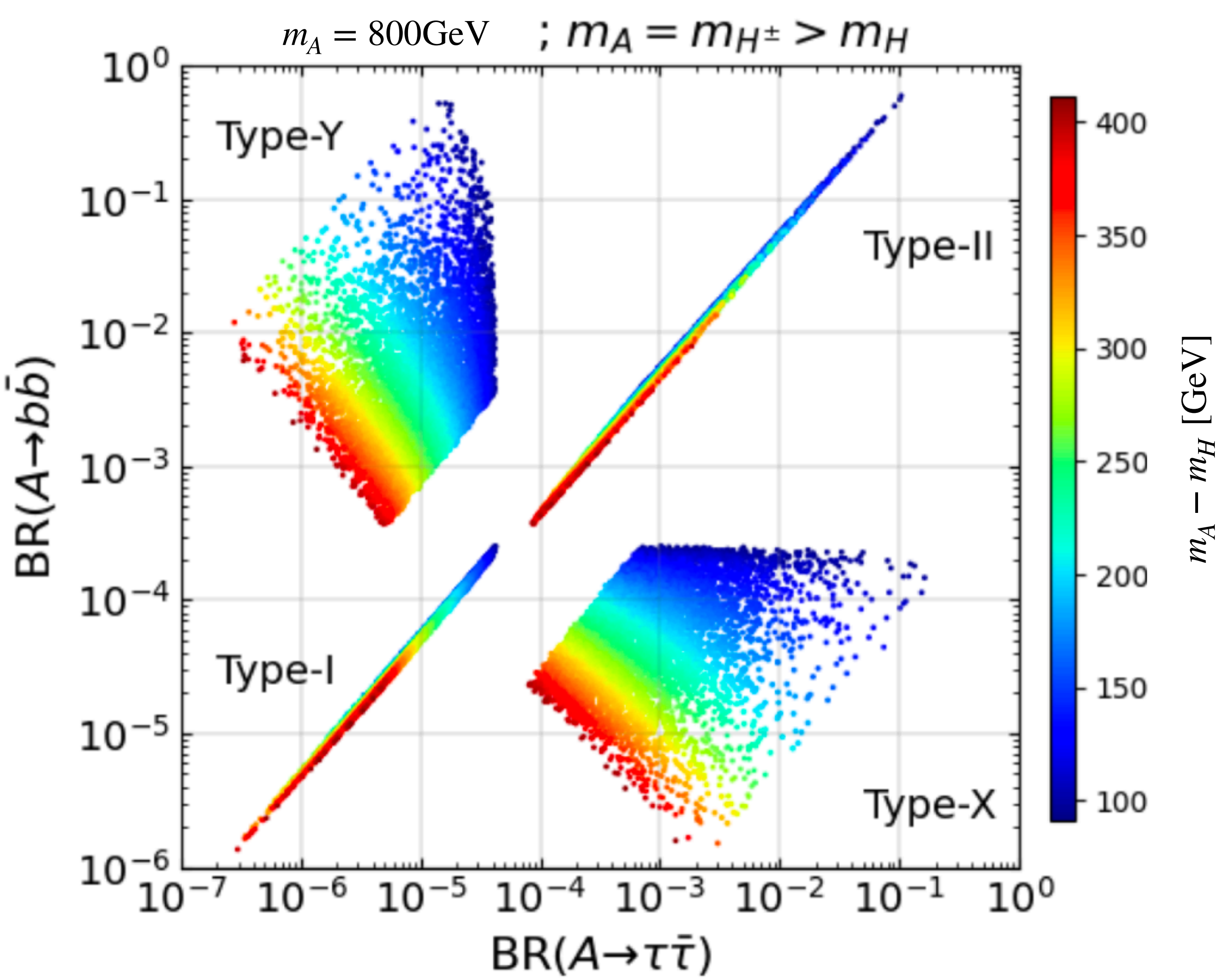
[S. Kanemura, Y. Okada, E. Senaha, *Phys.Lett.B* 606 (2005) 361]

How can we discriminate types of 2HDMs?

Near alignment regions $\left(\sin(\beta-\alpha)\neq 1\right)$ —> precise measurements of *h* (ILC, CLIC, FCC-ee, etc.)

Exact alignment regions $\left(\sin(\beta-\alpha)=1\right)$ —> Decay pattern of *A* (HL-LHC, FCC-hh, μ collider, etc.)

[M. Aiko, S. Kanemura, KS]



- Different $\tan\beta$ dependence.

$$\Gamma_{A\to f\bar{f}} \propto \begin{cases} \dfrac{m_A}{t_\beta^2} & \text{(type I)} \\ m_A t_\beta^2 & \text{(type II)} \end{cases}$$

- Suppression by $\Gamma_{A\to ZH} \propto (m_A - m_H)^2$

- $\Gamma_{A\to f\bar{f}}$ does not depends on $\sin(\beta-\alpha)$

→ Characteristic decay pattern of *A* even in alignment limit

→ Direct search of *A* and precision measurements of *h* are complimentary to determine Type.

Summary

- Scalar-to-scalar decays (e.g., A—>Zh,H —>hh) are proportional to cos(β-α).In near alignment region (sin(β-α)≠1), loop corrections to those processes can be significant.
- We calculated NLO corrections to two-body decays of heavy Higgs in 2HDMs.
- We discussed the correlation between heavy Higgs decays and observables for h_{125} at the 1-loop level.

Loop corrections can affect both of them. Correlations at loop level are changed from the tree-level analysis.