[2311.15892]

Precise calculations for decays of Higgs bosons in extended Higgs sectors

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In collaboration with

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The shape of the Higgs sector is unknown

- Extended Higgs sector is interesting possibility for new physics.

$$\Phi_{SM} + \Phi' + \ldots$$

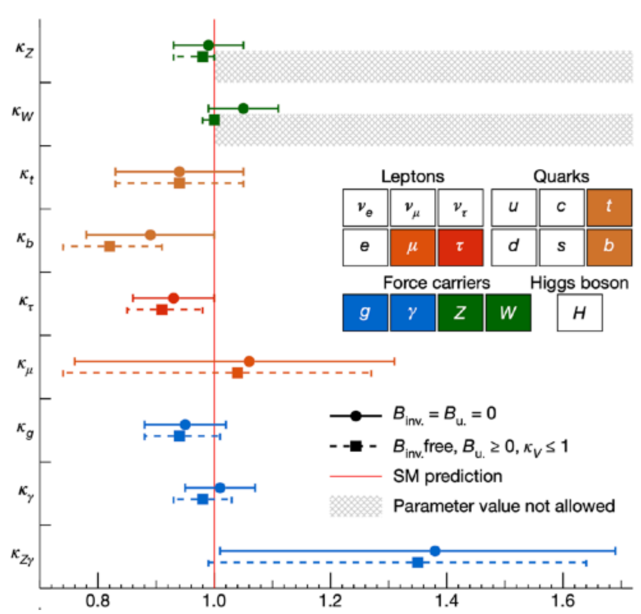
Dark matter, Neutrino masses,

Baryon asymmetry of the Universe,

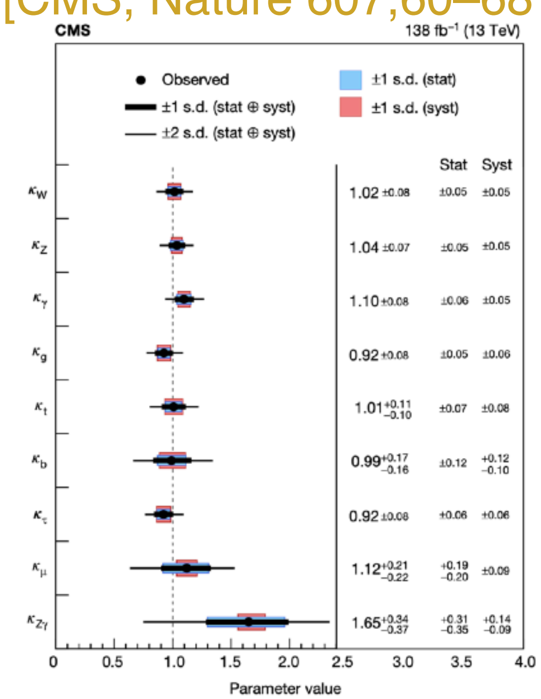
muon-2, W mass, GWs, …

- It is not completely excluded by the current LHC experiments.

[ATLAS, Nature 607,60–68 (2022)]

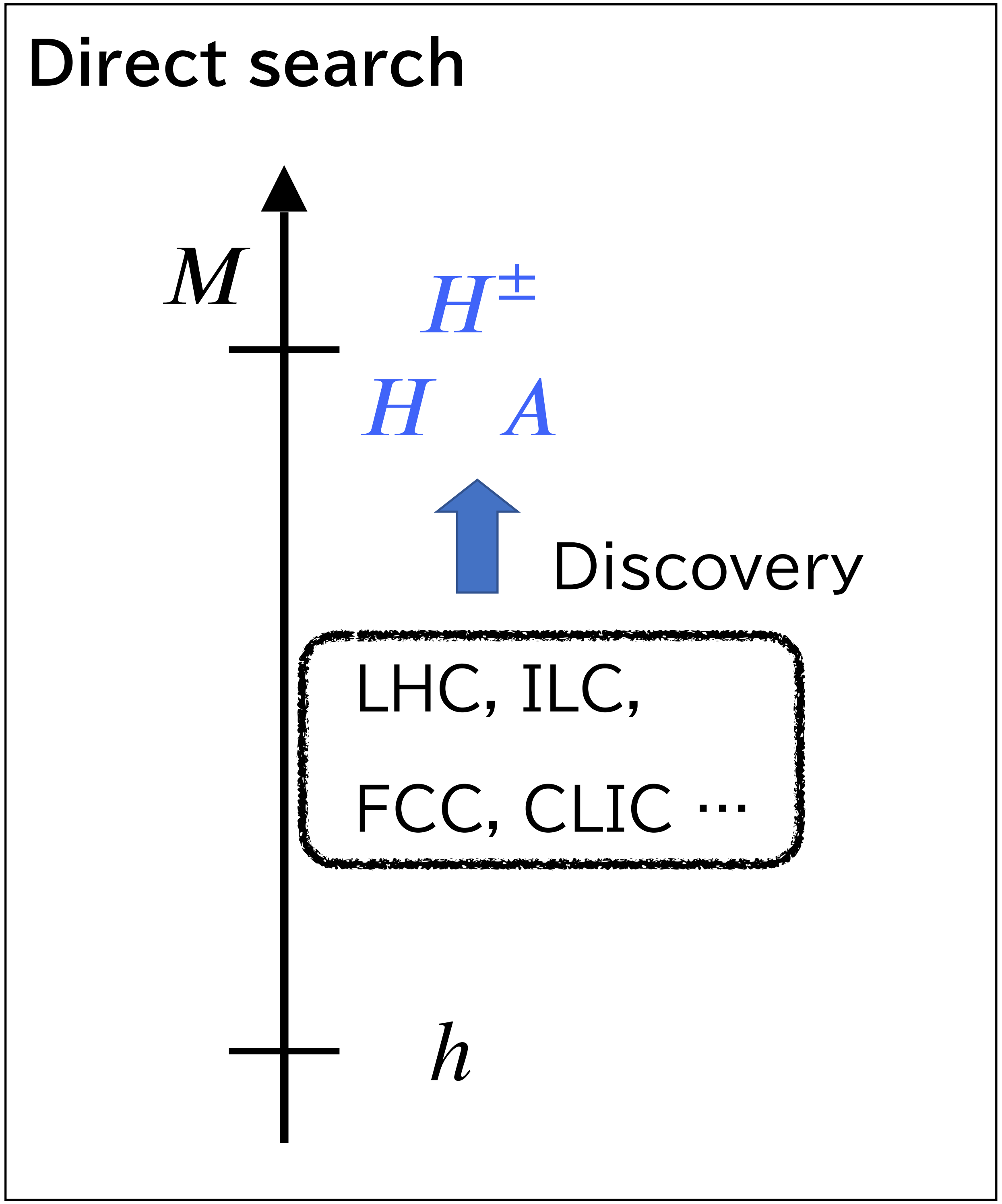


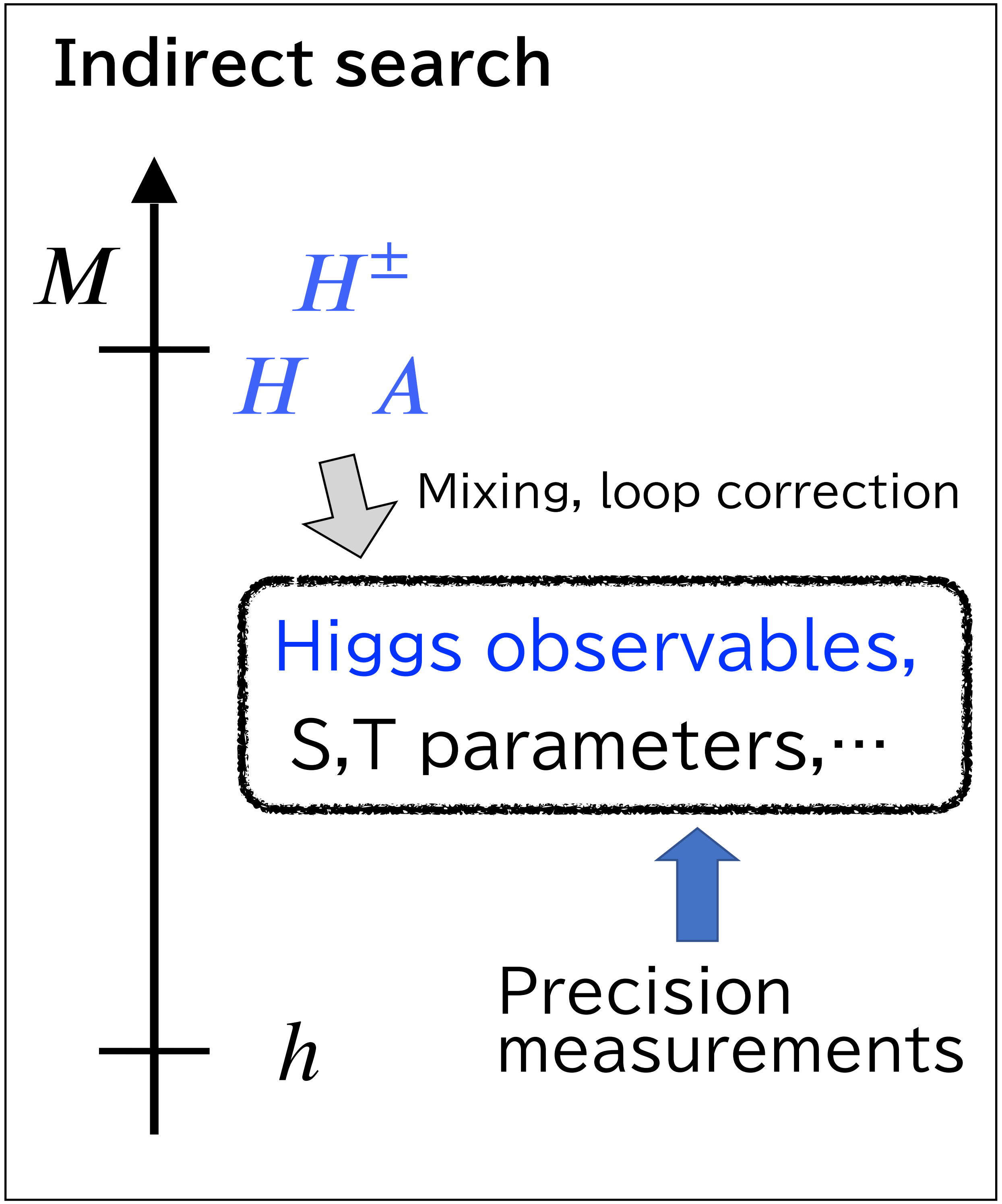
[CMS, Nature 607,60–68 (2022)]



Reconstructing Higgs sector is an important task for finding new physics.

How is the Higgs sector tested?





A combination of these two ways can test the Higgs sector.

Contents

- Introduction

- Model
  - 2HDM, motivations.

- Radiative corrections to Higgs decays
  - HCOUP, results for A—>Zh and h—>ZZ*

- Summary

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

2HDM is a simple example of the extended Higgs sector. It has several motivations to study.

- Higgs potential

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

- Softly broken Z_2 symmetry is imposed.

$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$$

- Component fields and physical states

$$\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{bmatrix}, \quad (i = 1, 2),$$

3 of 8 d.o.f are $G^0, G^\pm$

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

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha)\begin{pmatrix} H \\ h \end{pmatrix}, \quad R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

h : SM-like Higgs boson

$H, A, H^\pm$: Heavy Higgs bosons

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

- Model parameters

$$M^2 = \frac{m_3^2}{\cos\beta \sin\beta}$$

$$m_{1\text{-}3},\quad \lambda_{1\text{-}5} \quad \Rightarrow \quad m_{H,A,H^\pm},\quad M^2,\quad \sin(\beta-\alpha),\quad \tan\beta,$$

$$v\ (=246\mathrm{GeV}),\ m_h\ \ (=125\mathrm{GeV})$$

- Yukawa sector
  - Due to Z_2 symmetry, either Φ_1 or Φ_2 couple with each matter field.

    → Flavor-changing neutral current (FCNC) is forbidden at the tree level.
  - There are 4 types of interactions.

$$-\mathcal{L}_Y = Y_u \overline{Q}_L i\sigma_2 \Phi_u^* u_R + Y_d \overline{Q}_L \Phi_d d_R + Y_e \overline{L}_L \Phi_e e_R + \mathrm{h.c.}$$

	Φ_u	Φ_d	Φ_e	
Type I	Φ_2	Φ_2	Φ_2	Light $H^\pm$ scenario
Type II	Φ_2	Φ_1	Φ_1	MSSM
Type X	Φ_2	Φ_2	Φ_1	Radiative seesaw models
Type Y	Φ_2	Φ_1	Φ_2	

Decoupling limit and alignment limit

Alignment limit: $\alpha \to \beta - \pi/2$

- All scalars are diagonalized by β : $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = R(\beta) \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$ $\begin{matrix} \ni h \\ \ni H, A, H^\pm \end{matrix}$
- Higgs boson couplings coincide with the SM:

$$\begin{cases} \kappa_V = \sin(\beta - \alpha) \;\to\; 1 \\ \kappa_f = \sin(\beta - \alpha) + \zeta_f \cos(\beta - \alpha) \;\to\; 1 \end{cases}$$

Decoupling limit: $M^2 \to \infty$

- Heavy Higgs masses is governed by M^2 : $m_\Phi^2 \sim M^2 + f(\lambda_i)v^2$
- All effects of heavy Higgs is suppressed by $1/M^2$.

The relation between α and M

$$\tan 2(\beta - \alpha) = \frac{\sum_i c_i \lambda_i v^2}{\sum_i c_i \lambda_i v^2 + M^2} \xrightarrow[M^2 \to \infty]{} 0$$

- The decoupling limit leads to the alignment limit (if λ_i perturbative).

- The opposite is not true : $0 \underset{\text{Alignment limit}}{=} \sum_i c_i \lambda_i v^2$ This doesn't depend on *M.*

$$\boxed{\alpha \to \beta - \pi/2} \quad \Leftarrow \quad \not\Rightarrow \quad \boxed{M^2 \to \infty}$$

In 2HDM, alignment without decoupling scenario is possible.

[counterexample: MSSM

$$\boxed{\alpha \to \beta - \pi/2} \quad \rightleftarrows \quad \boxed{m_A^2 \to \infty}$$

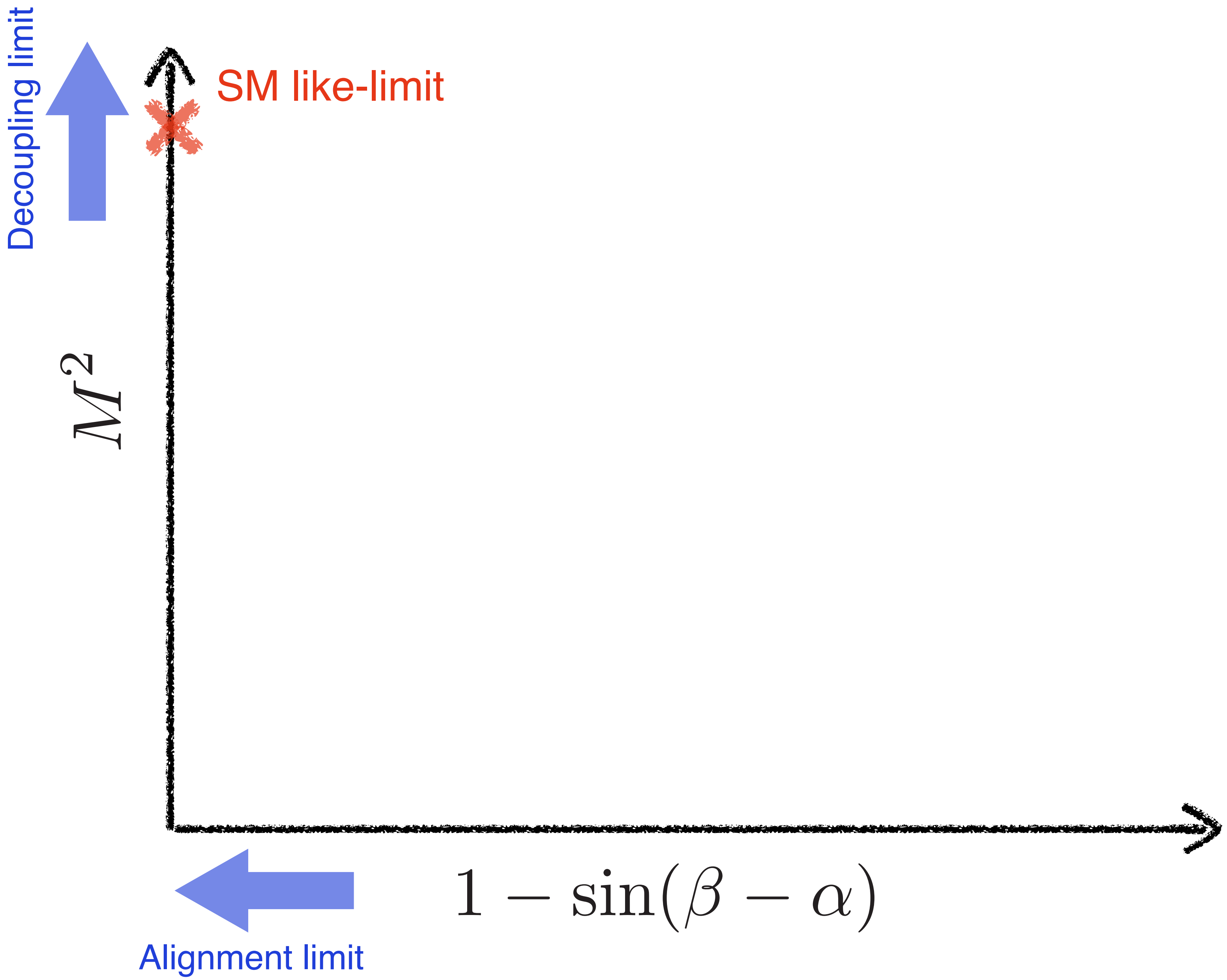
$$\frac{\tan 2\alpha}{\tan 2\beta} = \frac{m_H^2/m_A^2 + m_h^2/m_A^2}{1 + m_z^2/m_A^2}$$

$$m_H^2 = m_A^2 + m_Z^2(1 - \cos^2 2\beta)$$

]

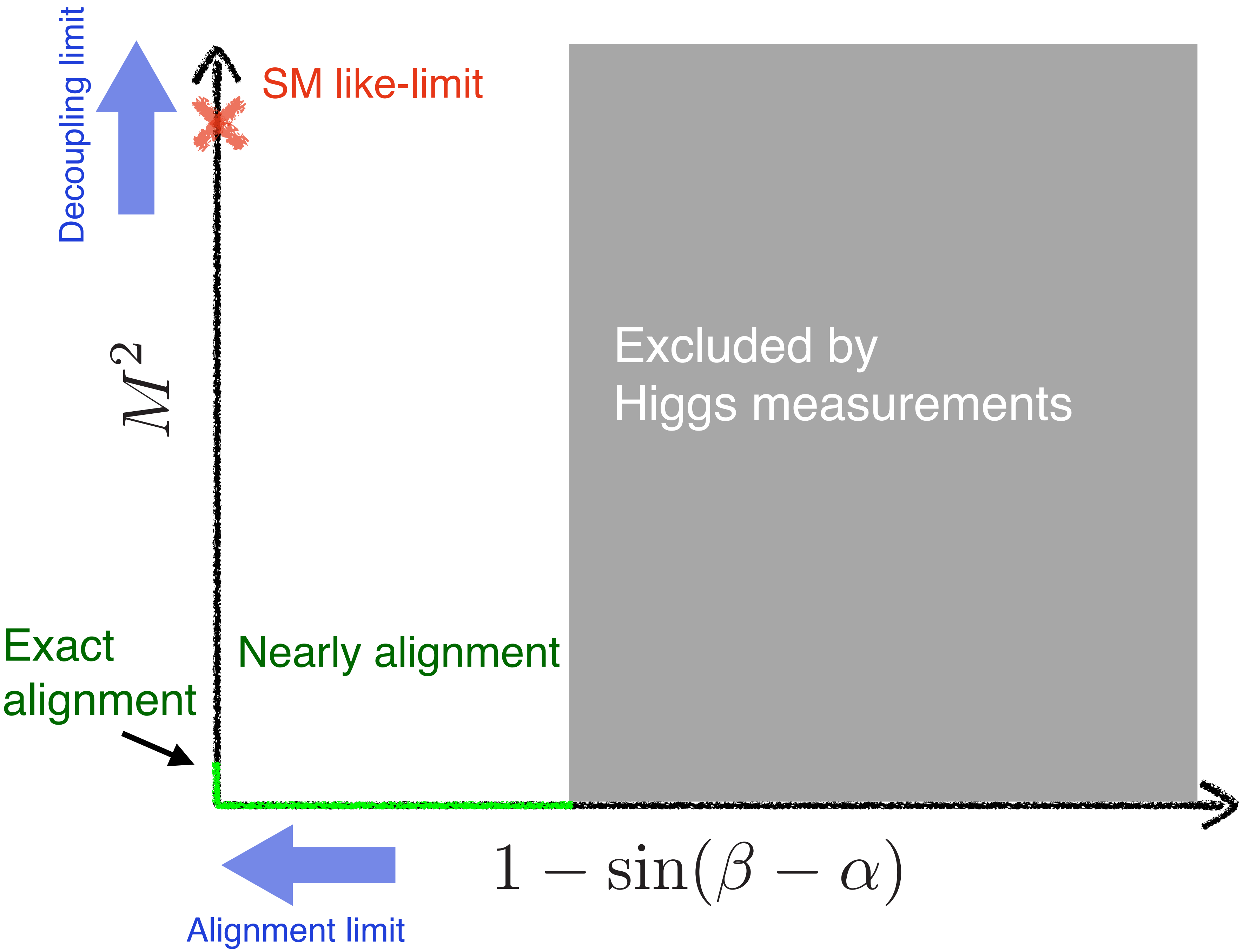
Distinct scenarios [1/3]

We can describe the model parameter space by the decoupling parameter and the alignment parameter.

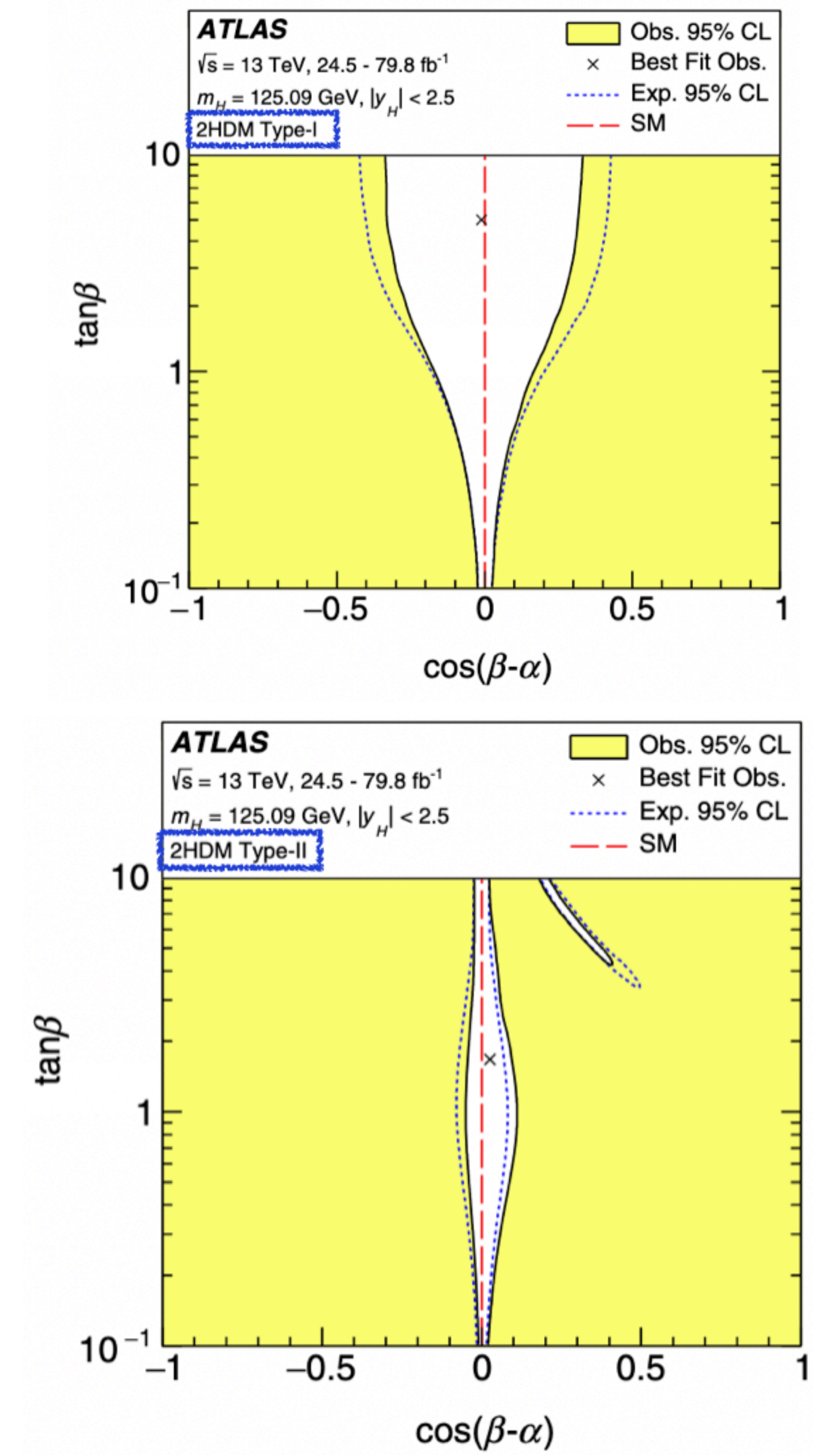


Distinct scenarios [2/3]

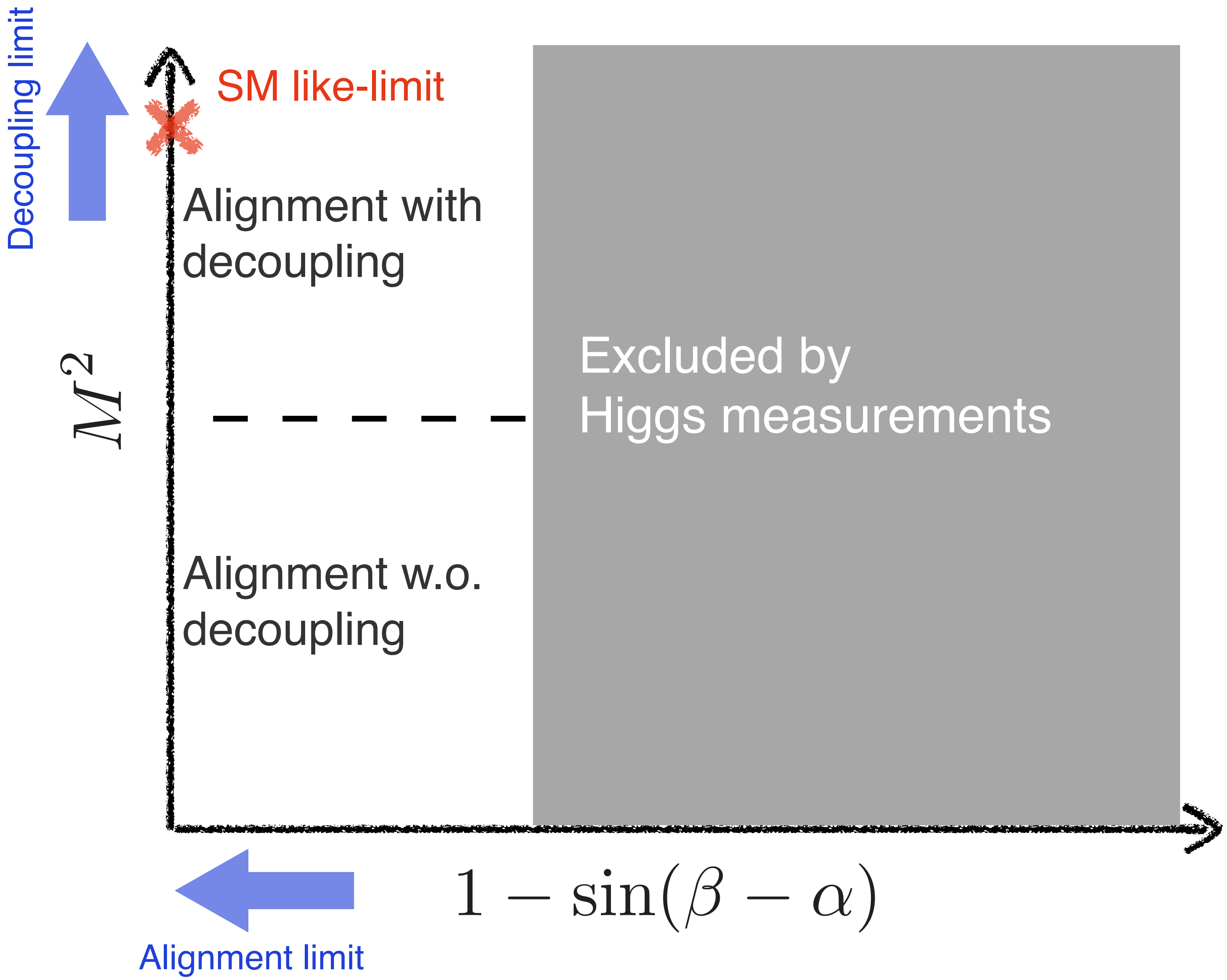
Exact alignment or nearly alignment scenarios are favored.



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



Distinct scenarios [3/3]



Alignment with decoupling

- It is difficult to test.

Alignment w.o. decoupling

- Deviations in the HCs.
- Strong1st EWPT
- Gravitational wave

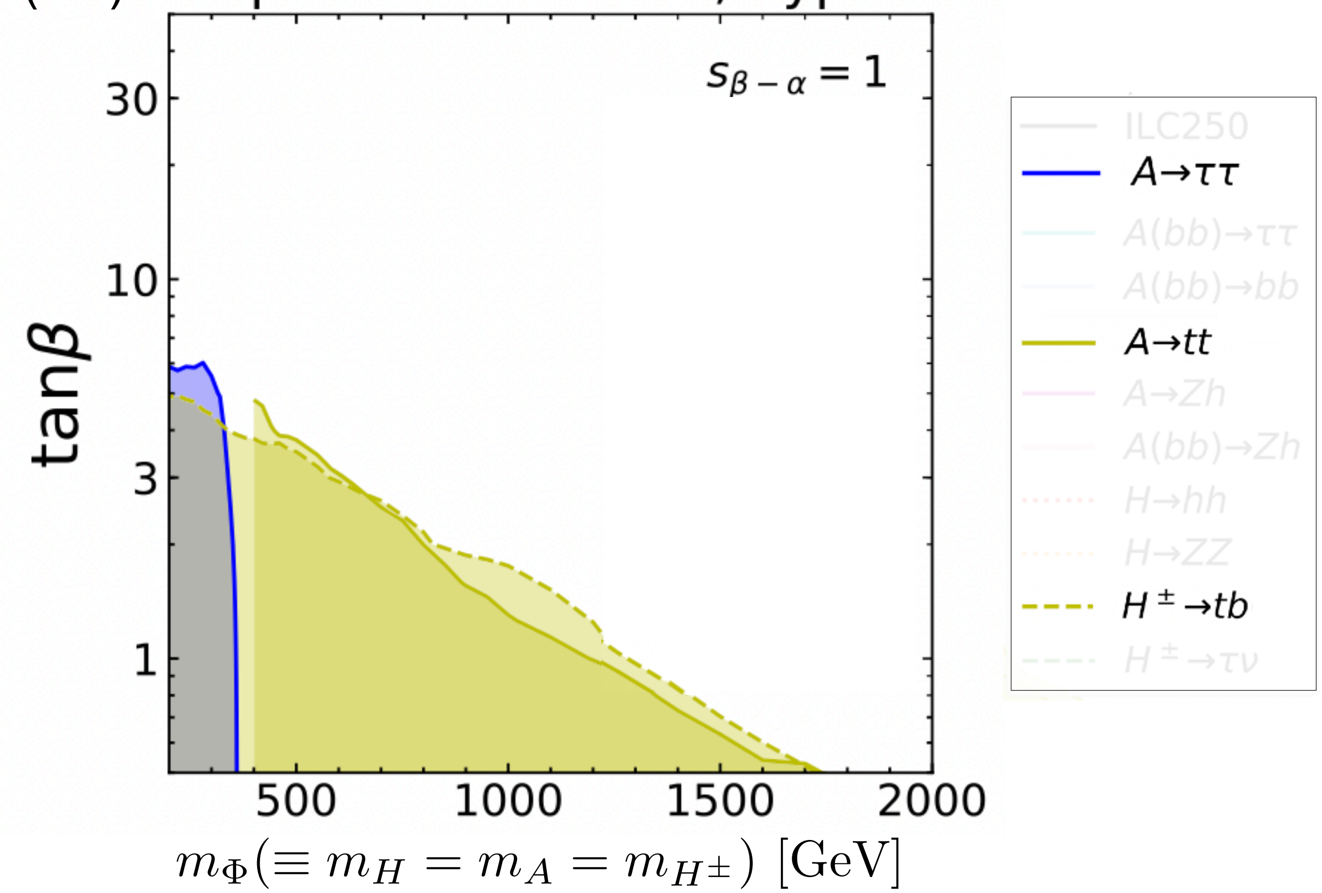
Intriguing scenario. The testability should be studied.

Synergy between direct and indirect searches[1/2]

Exact alignment scenario: $\sin(\beta-\alpha)=1$

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

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



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

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

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

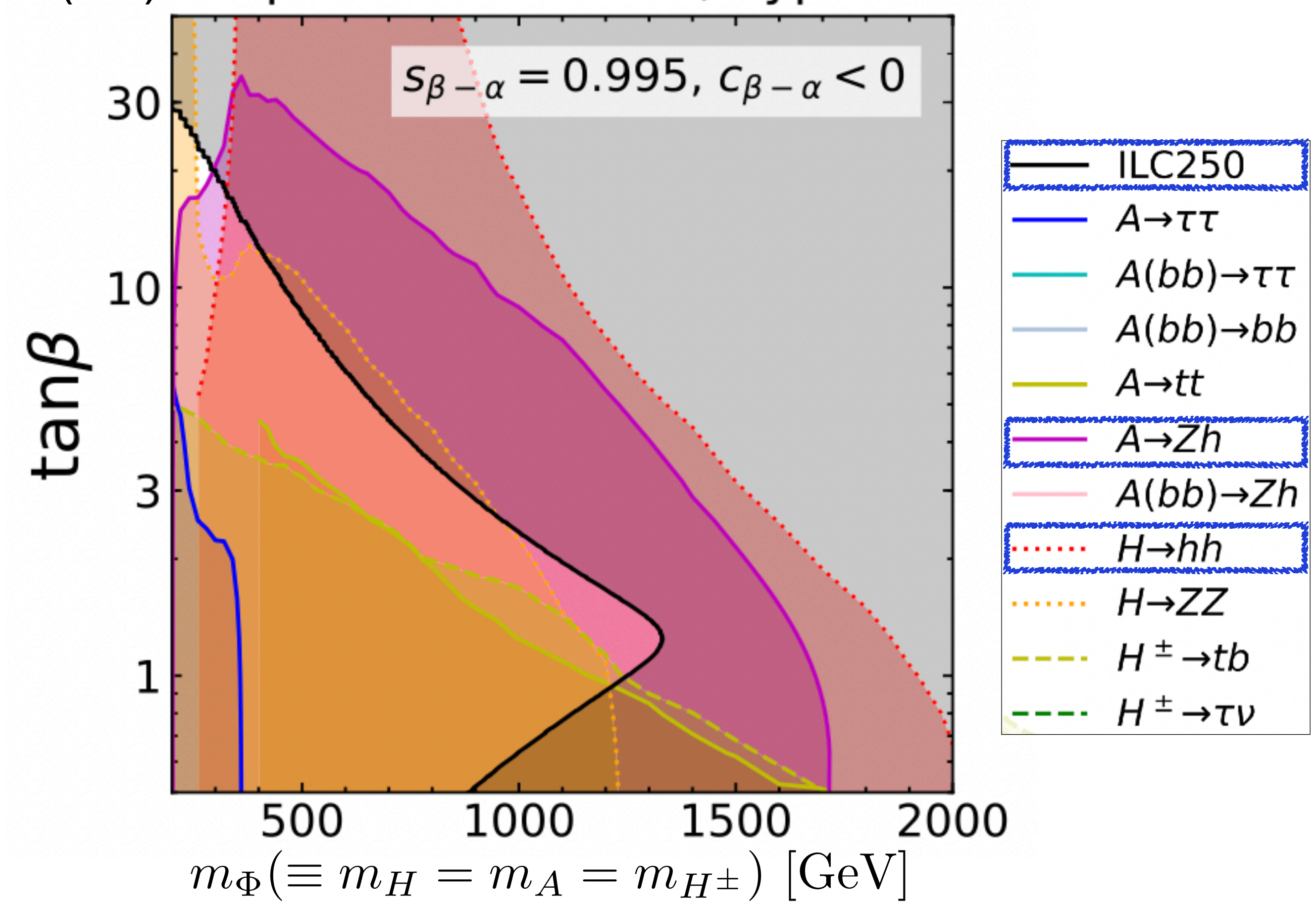
Indirect searches : No sensitivity since Higgs couplings do not deviate.

Synergy between direct and indirect searchesc [2/2]

Near alignment scenario: $\sin(\beta-\alpha) = 0.995\ (\cos(\beta-\alpha) \simeq -0.1)$

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

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



$\kappa_Z = \sin(\beta-\alpha)$

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

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

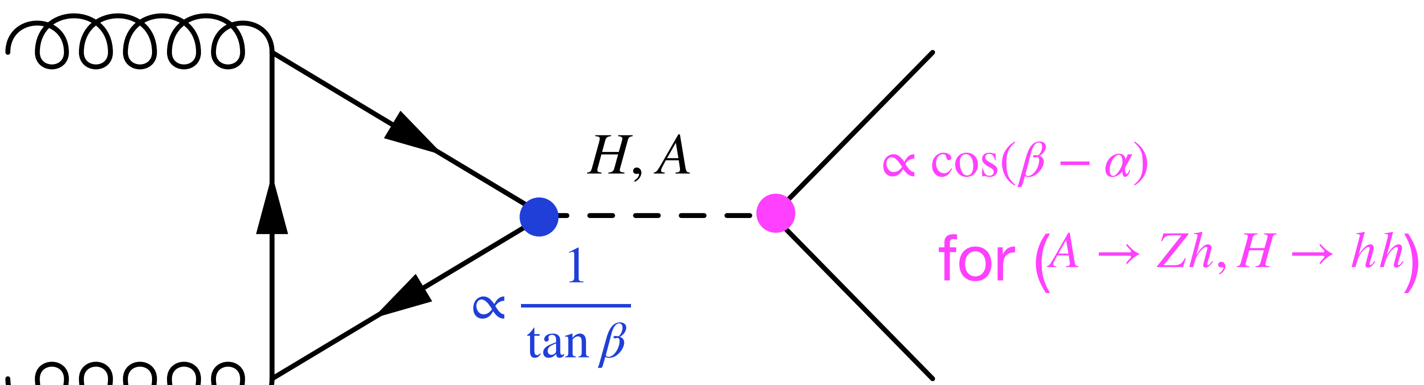
Direct searches: $A \to Zh$ and $H \to hh$ give wider sensitivity regions for $(m_\Phi,\ \tan\beta)$ plane.

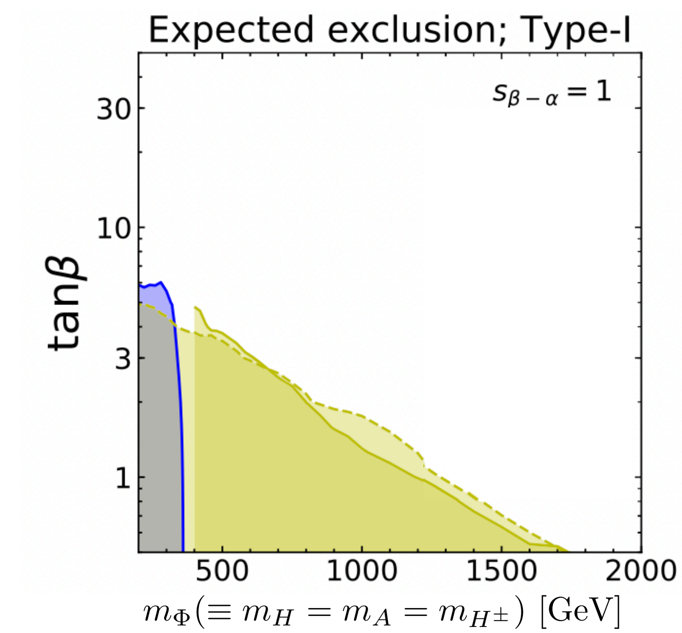
Indirect searches: If a deviation in *hZZ* founds, the upper bounds for m_Φ are given.

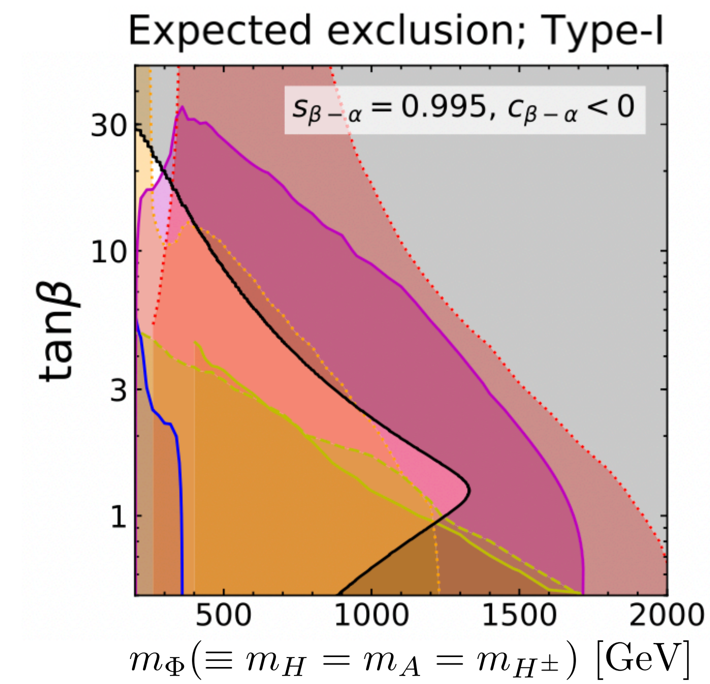
→ Most parameter space can be surveyed by the combination of scalar-to-scalar decays and precision measurements of the Higgs coupling.

Importance of NLO corrections to heavy Higgs

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







➡ The loop effect on heavy Higgs decays can be significant.

$$\Gamma^{\rm NLO}_{S\to SV} = \tilde{\Gamma}^{\rm LO}(c^2_{\beta-\alpha} + c_{\beta-\alpha}\Delta^{\rm NLO})$$

$$\Delta^{\rm NLO} > c_{\beta-\alpha}\ ?$$

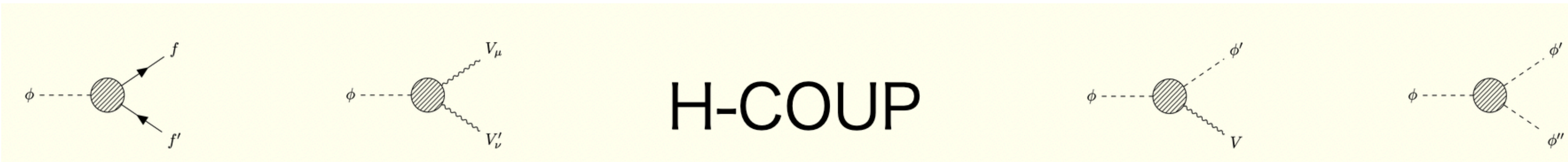
Our interest : impact of NLO corrections on heavy Higgs boson decays.

Correlation between decays of heavy Higgs and *h(125)*.

H-COUP ver. 3

[2311.15892]

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



- Fortran program to evaluate the NLO EW corrections and (N)NLO QCD corrections to various Higgs decays.

- Outputs (EW correction: On-shell scheme, QCD correction:MS scheme)

  h: On-shell 2-body decays (e.g., $h \to \bar{f}f$)

  Off-shell 3-body decays (e.g., $h \to ZZ^* \to Z\bar{f}f$)

  $H, A, H^{\pm}$: On-shell 2-body decays (e.g., $A \to \bar{f}f, Zh$)

- Model Two Higgs doublet models (Type I, Type II, Type X, Type Y)

  Inert doublet model

  Higgs singlet model (without global symmetry)

Other public tools

- 2HDECAY, sHDECAY, NHDECAY [M. Krause, M. Mühlleitner, M. Spira, CPC 246 (2020) 106852], [M. Krause, M. Mühlleitner, 1904.02103] [F. Egle, M. Mühlleitner, ,R. Santos,J. Viana, JHEP 11 (2023) 116]]
    - 2-body decays of all Higgs boson with NLO EW and the state of the art QCD corrections.
    - Model: THDMs (2HDECAY), the Singlet extension of the SM with Z_2 (sHDECAY), THDMs + real singlet (NHDECAY)
- PROPHECY4F [L. Altenkamp, S. Dittmaier, H. Rzehak,JHEP 1803 (2018) 110]
    - CP-even Higgs decays into 4fermions with NLO EW and QCD corrections.
    - Model: THDMs, the Singlet extension of the SM with Z_2.
- Flexibledecay [P. Athron, A. Büchner, et. al., Comput.Phys.Commun. 283, (2023) 108584]
    - 2-body decays of neutral Higgs bosons with SM QCD/EW corrections in HSM, Type II 2HDM, CMSSM,MRMSSM.
    - BSM effect is at LO.

Numerical analysis

h	H	A	$H^{\pm}$
$h \to f\bar{f}$	$H \to f\bar{f}$	$A \to f\bar{f}$	$H^{\pm} \to ff'$
$h \to ZZ^*$	$H \to ZZ,\ WW$	$A \to ZZ,\ WW$	$H^{\pm} \to Wh$
$h \to WW^*$	$H \to hh$	$A \to Zh$	$H^{\pm} \to WH,\ WA$
$h \to gg$	$H \to ZA, WH^{\pm}$	$A \to HZ,\ WH^{\pm}$	$H^{\pm} \to W\gamma,\ WZ$
$h \to \gamma\gamma, Z\gamma$	$H \to gg$	$A \to gg$	
	$H \to \gamma\gamma, Z\gamma$	$A \to \gamma\gamma, Z\gamma$	

- We chose $A \to Zh$ and $h \to ZZ^*$ to illustrate the NLO corrections.

  $A \to Zh$: Suppression of $\Gamma^{\rm LO}_{A\to Zh}$

  $h \to ZZ^*$: precise measurement in future colliders (e.g. 0.76% @ILC) [1710.07621]

- Benchmark scenarios for alignment w.o. decoupling ($|c_{\beta-\alpha}| < 0.1$)

  (I) $m_A = m_{H^\pm} = 300{\rm GeV}$ in Type I 2HDM

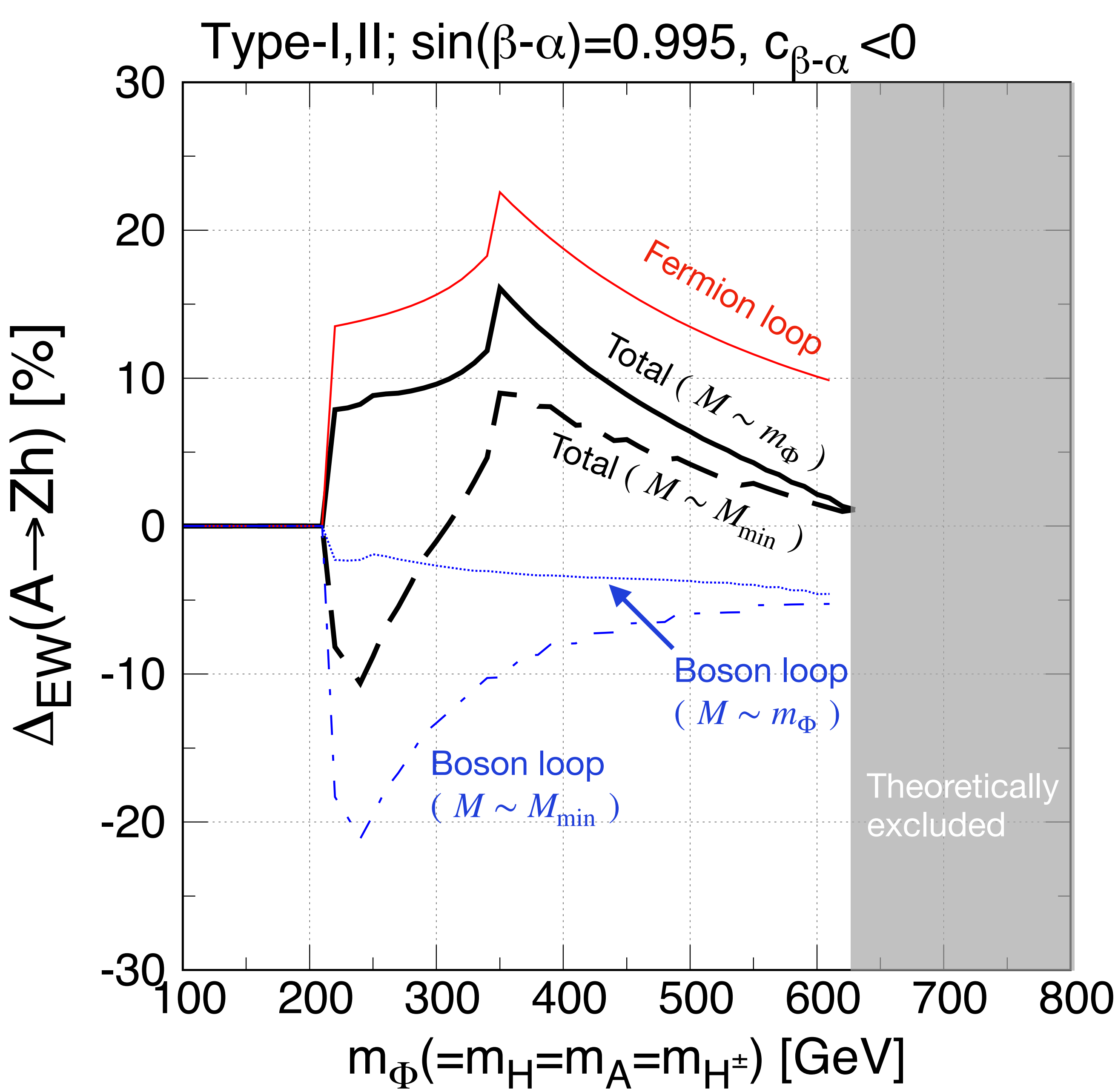
  The scenario can be explored by HL-LHC.

  (II) $m_A = m_{H^\pm} = 800{\rm GeV}$ in Type I,II 2HDMs

  A realistic scenario for Type II due to $B \to X_s\gamma$ ($m_{H^\pm} \gtrsim 600{\rm GeV}$).

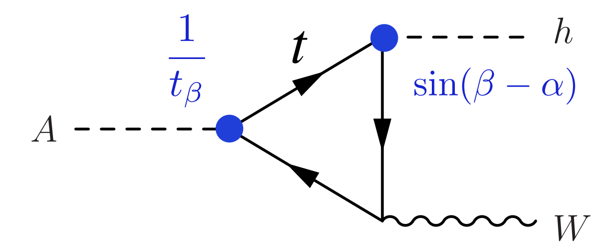
Non-decoupling effects in $\Gamma_{A\to Zh}$

[M. Aiko, S. Kanemura, KS]



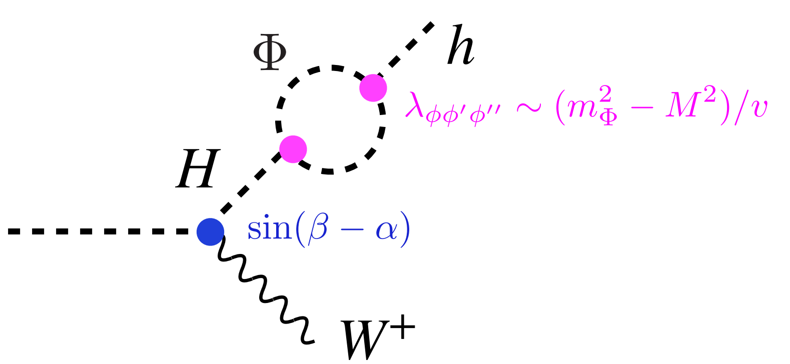
Typical graph :

fermion loop Suppression by t_β, m_Φ^2



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

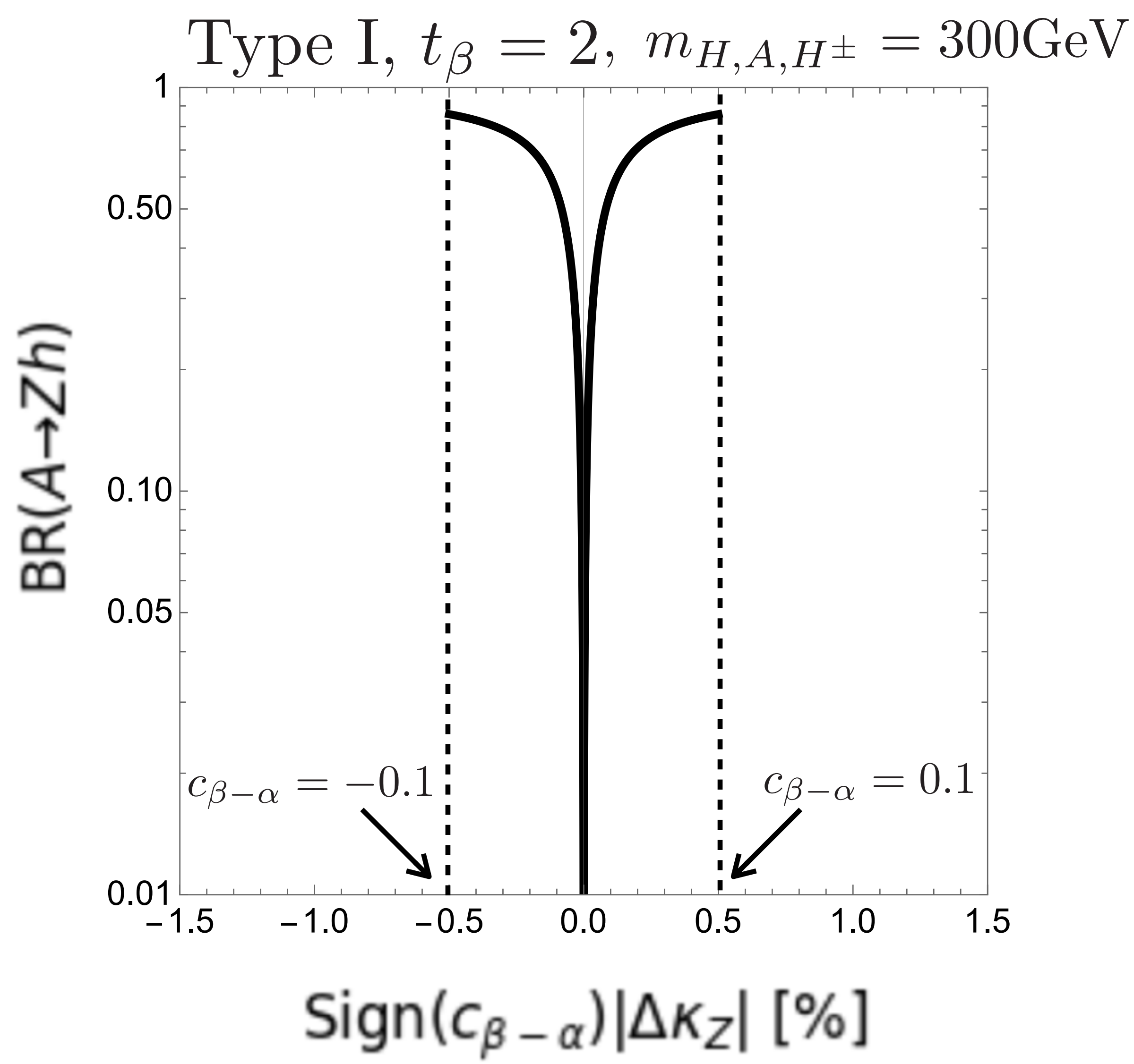
Boson loop Nondecoupling effects



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

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

Scenario I: BR(A —> Zh) vs $\Delta\kappa_V$ at LO [M. Aiko, S. Kanemura, KS]



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

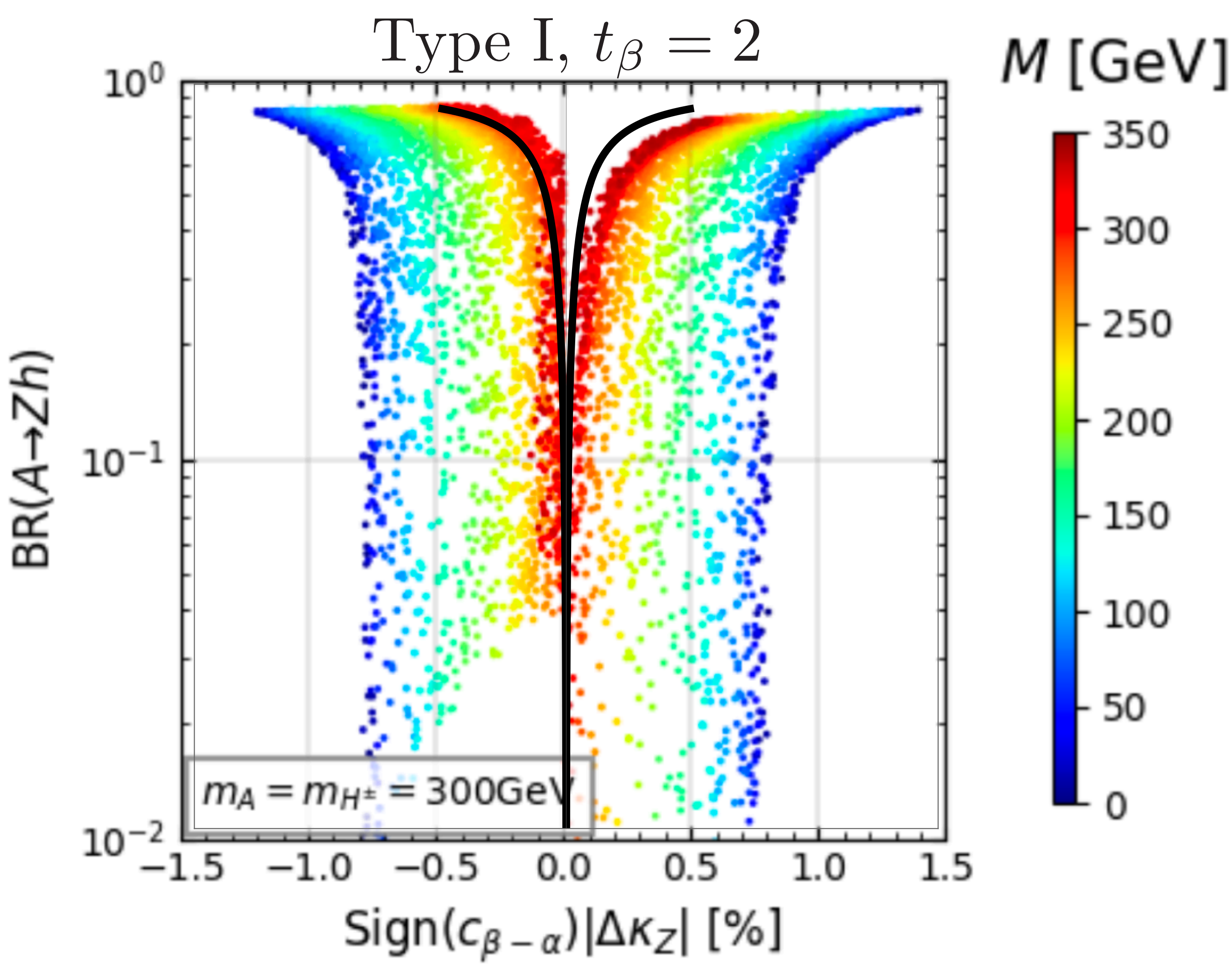
- $\Delta\kappa_Z$ and BR($A \to Zh$) are governed by $c^2_{\beta-\alpha}$. Positive correlation.

$$\Delta\kappa_Z = s_{\beta-\alpha} - 1 \simeq -c^2_{\beta-\alpha}/2 \ , \quad BR(A \to Zh) \simeq c^2_{\beta-\alpha}\frac{m_A^3}{16\pi\Gamma^A_{tot}v^2}$$

- The maximum of $\Delta\kappa_Z$ is 0.5% at LO.

Scenario I: BR(A —> Zh) vs $\Delta\kappa_V$ at NLO

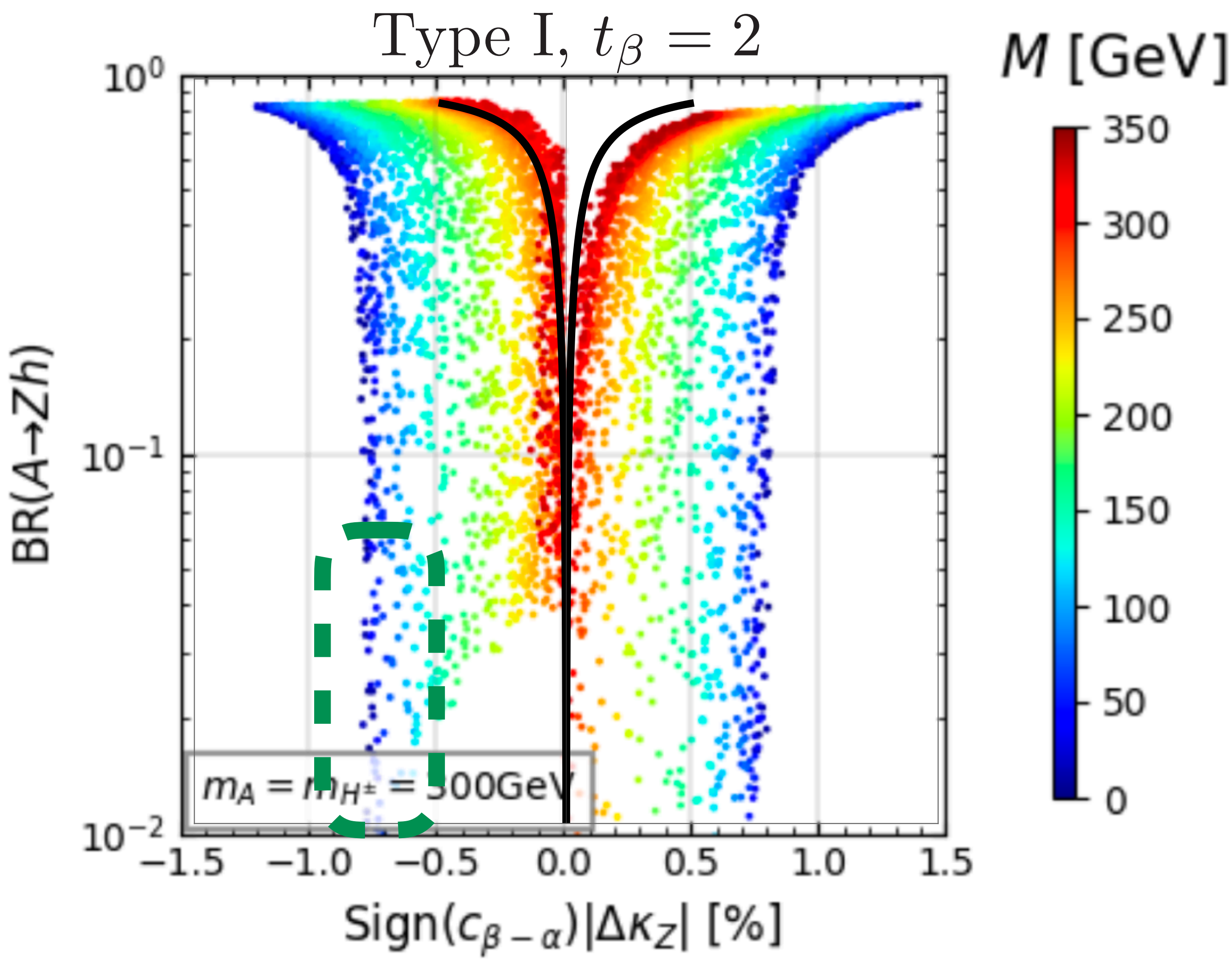
[M. Aiko, S. Kanemura, KS]



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

Scenario I: BR(A —> Zh) vs Δκ$_V$ at NLO

[M. Aiko, S. Kanemura, KS]

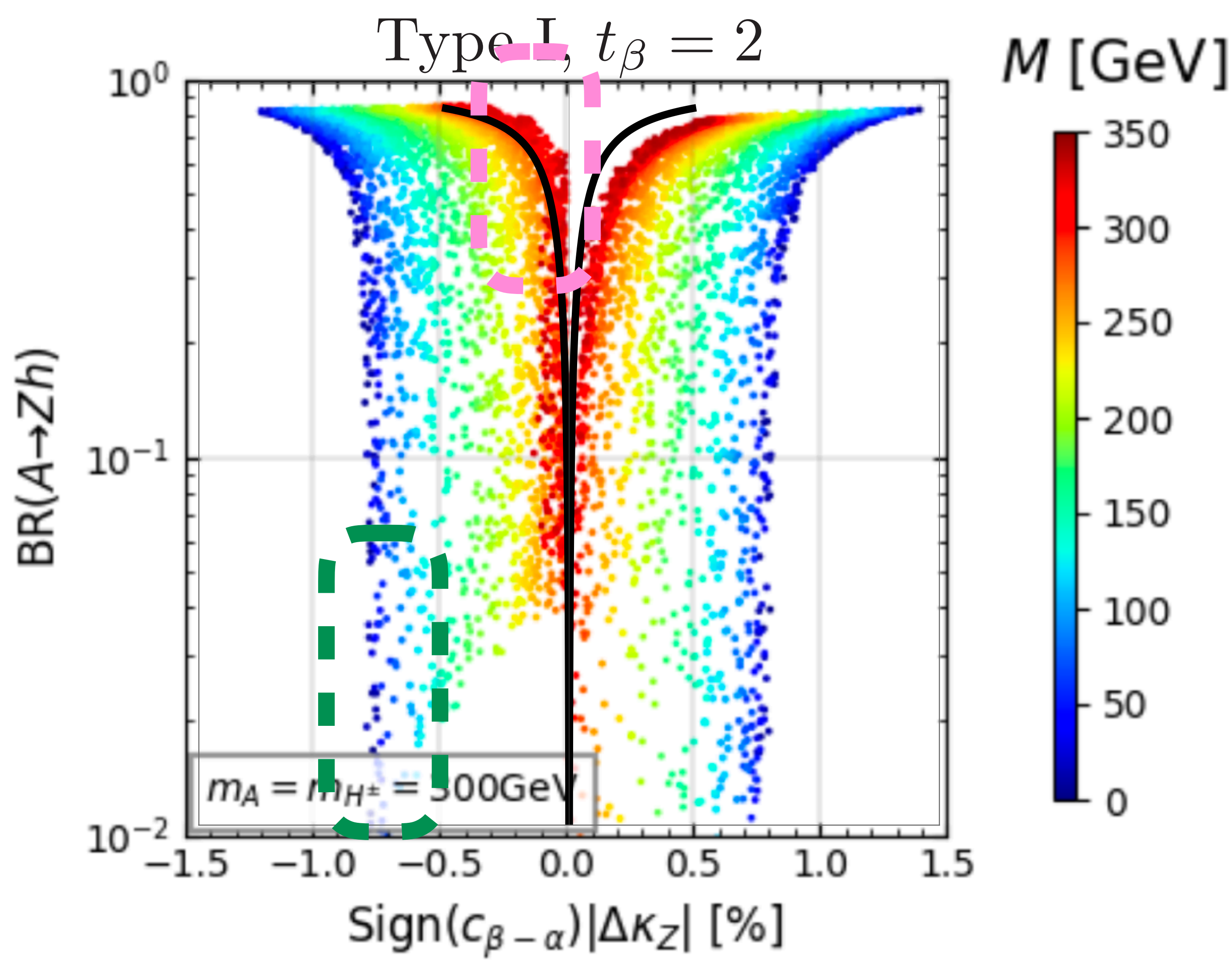


$$\Delta\kappa_Z = \sqrt{\frac{\Gamma^{\rm 2HDM}_{h\to ZZ^*}}{\Gamma^{\rm SM}_{h\to ZZ^*}}} - 1$$

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

Scenario I: BR(A —> Zh) vs $\Delta\kappa_V$ at NLO

[M. Aiko, S. Kanemura, KS]

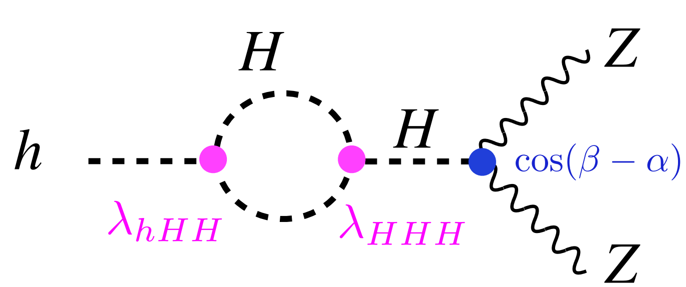


$$\Delta\kappa_Z = \sqrt{\frac{\Gamma^{\text{2HDM}}_{h\to ZZ^*}}{\Gamma^{\text{SM}}_{h\to ZZ^*}}} - 1$$

$M^2 \simeq 0, c_{\beta-\alpha} \simeq 0$: 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* → $\Delta\kappa_Z \sim 0$ but BR~*O*(10)%

Dominant diagrams : for h—>ZZ*

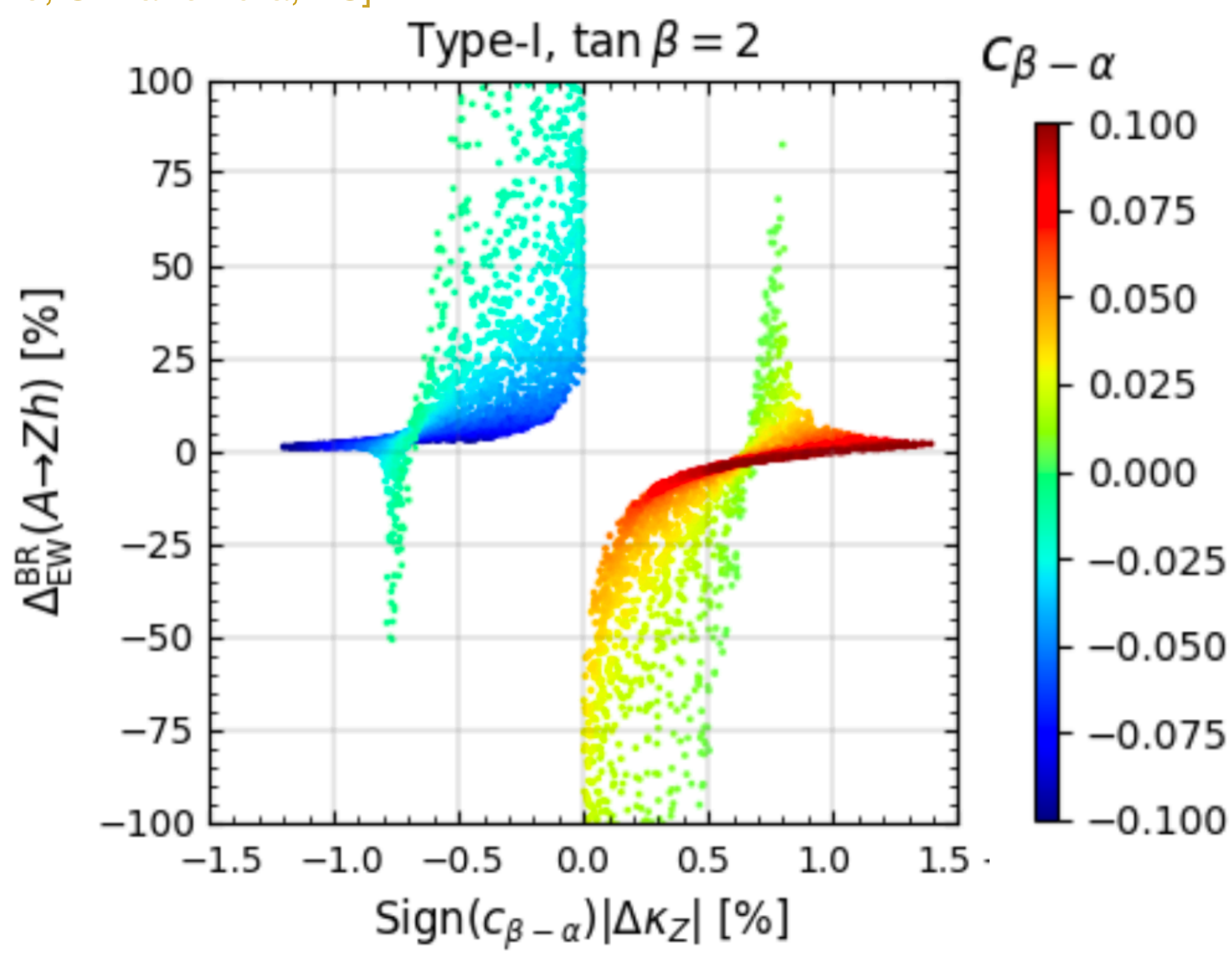


$$\sim \frac{1}{16\pi^2}(m_H^2 - M^2)^2 c_{\beta-\alpha}$$

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

Scenario I: NLO corrections for BR(A —> Zh)

[M. Aiko, S. Kanemura, KS]



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

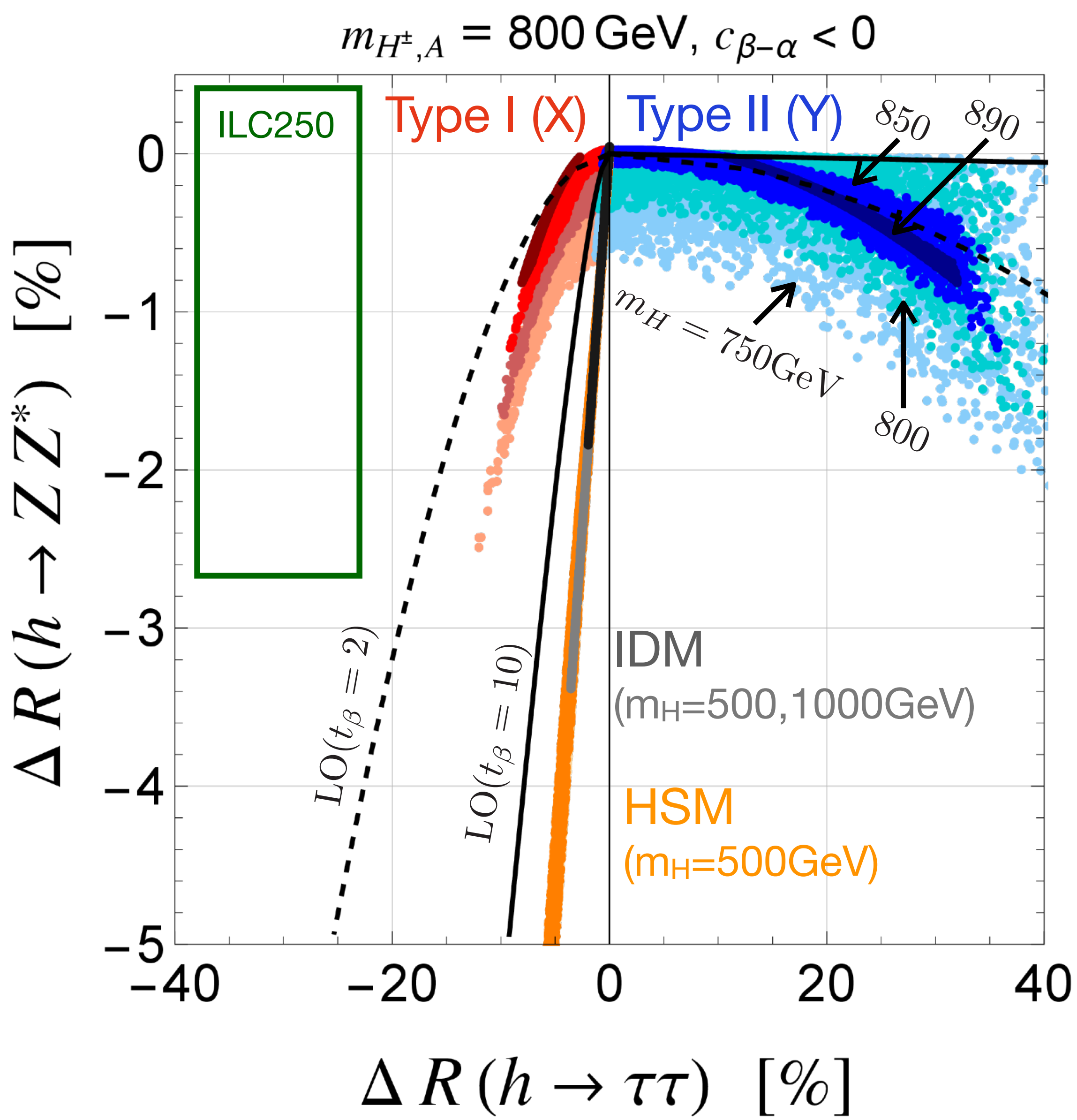
$|c_{\beta-\alpha}| \sim 0.1$: $\Delta^{\rm BR}$ is close to 0%

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

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

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

Scenario II: Correlation in h(125) decays



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

- HSM, IDM: $\Delta R_{h\to\tau\tau} \simeq \Delta R_{h\to ZZ}$, 2HDMs: $|\Delta R_{h\to\tau\tau}| \gg \Delta R_{h\to ZZ}$

  → The models can be distinguished from the difference in the gradients

- If $m_A - m_H \simeq 50\mathrm{GeV}$, the loop effect of $A, H^\pm$ make $\Delta R_{h\to ZZ^*}$ small.

Summary

- The tree-level contributions to scalar-to-scalar decays ($A \to Zh$ and $H \to hh$) are suppressed by the scalar mixing $c_{\beta-\alpha}$.

- We evaluated the NLO corrections by using H-COUP.

- We investigated the impact of NLO corrections to $A \to Zh$ and $h \to ZZ^*$.

- We found that the NLO corrections to $A \to Zh$ dominate if $|(\Gamma_{h\to ZZ^*}/\Gamma^{\rm SM}_{h\to ZZ^*})^{1/2} - 1| < 0.5\,\%$.

- Also, the correlation between $A \to Zh$ and $h \to ZZ^*$ can be different from the tree-level result.

Back up

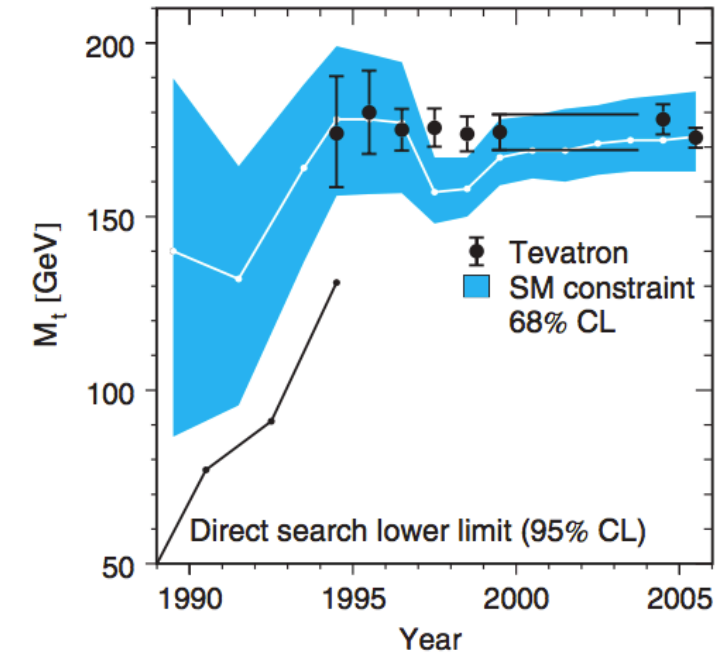
Impact of the precise measurements

Ex.) S, T parameter

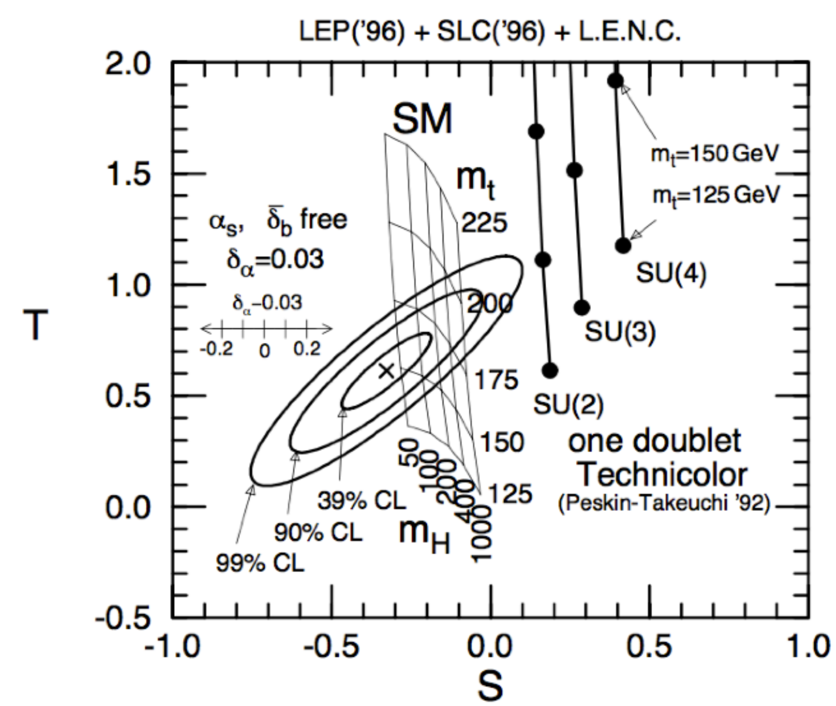
Top mass had been severely restricted
before the discovery.

$$\alpha_{\rm EM} T \simeq \frac{3G_F}{8\sqrt{2}\pi^2}\left(m_t^2 - m_Z^2 s_W^2 \log\frac{m_h^2}{m_Z^2}\right)$$

Non-decoupling effect



[Physics Reports 427(2006)257]



[Hagiwara, Haidt Matsumoto]

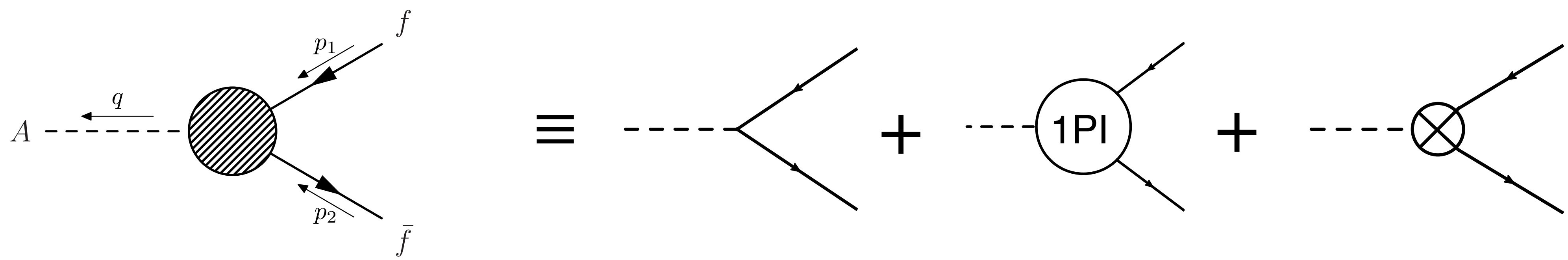
Same things can be applied to the Higgs physics.

Renormalization

Details of the calculations of NLO EW corrections

Ex). A—>ff

Tree 1-loop Counter terms (CTs)



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.]

$$\left[\begin{array}{l} t_i^B = t_i^R + \delta t_i \qquad (i = h, H) \\ \hat{\Gamma}_i = t_R + \delta t_i + \Gamma_i^{1\mathrm{PI}} \end{array}\right. \xrightarrow{(t_i^R = 0,\ \hat{\Gamma}_i = 0)} \delta t_i = -\Gamma_i^{1\mathrm{PI}}$$

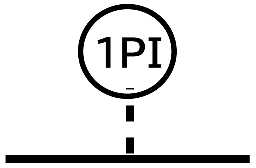
- Alternative tadpole scheme (ATS) [J. Fleischer and F. Jegerlehner, PRD23, 2001 (1981)]

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

- Difference between STS and ATS

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

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



- 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

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

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

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

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

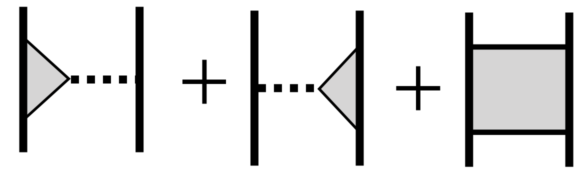
- Though this , the decay amplitudes are also gauge-dependent.

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

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

Gauge independent renormalization of mixing angles

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

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

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

This should arise from the full NLO amp.

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

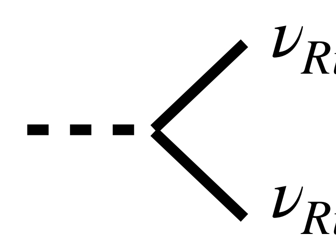
$$\mathcal{M}^{\text{NLO}}_{gg\to h/H\to \bar{f}f} \ni \mathcal{M}^{\text{SE-like}}_{gg\to h/H\to \bar{f}f}$$

- 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]

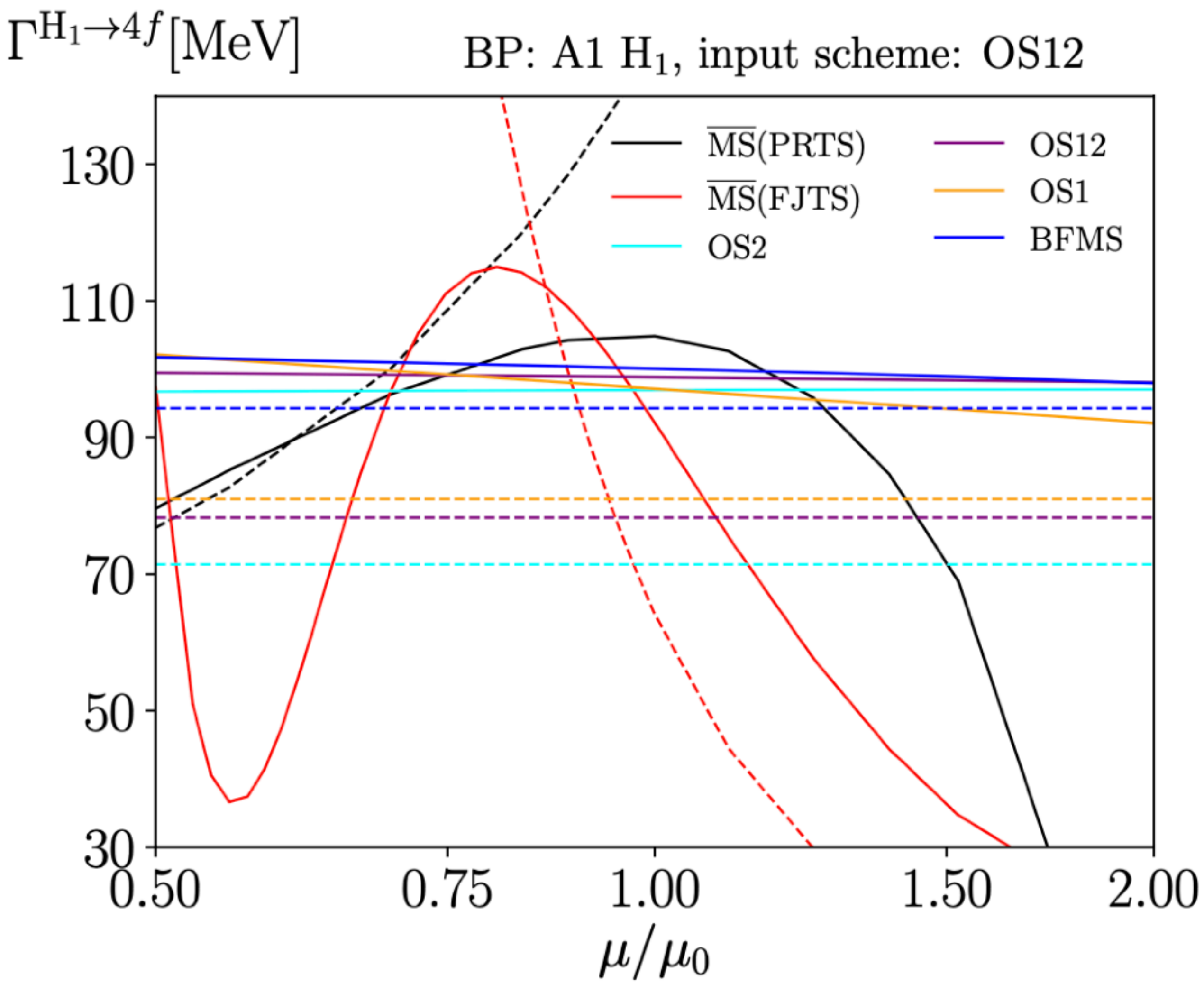
$$\frac{\mathcal{M}^{\text{loop}}_{H\to\nu_{R1}\nu_{R1}}}{\mathcal{M}^{\text{loop}}_{h\to\nu_{R1}\nu_{R1}}} = \frac{\mathcal{M}^{\text{tree}}_{H\to\nu_{R1}\nu_{R1}}}{\mathcal{M}^{\text{tree}}_{h\to\nu_{R1}\nu_{R1}}} = \frac{c_\alpha}{s_\alpha}$$

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

Scheme difference in counterterms of mixing angles

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

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



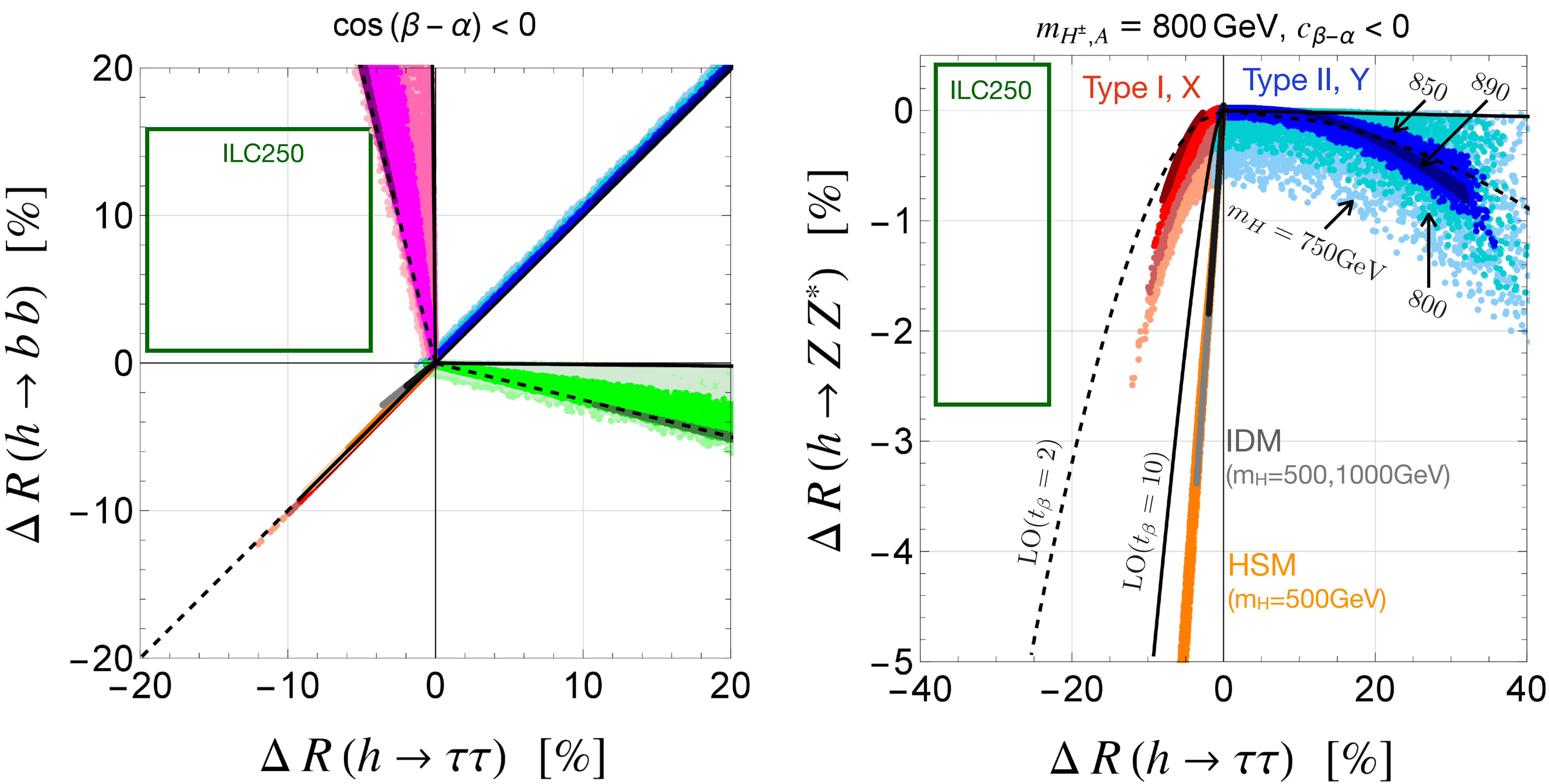
Scheme	A1 LO	A1 NLO
$\overline{\text{MS}}$(PRTS)	$147.102(4)^{>+100\%}_{-47.8\%}$	$104.86(2)^{<-100\%}_{-24.1\%}$
$\overline{\text{MS}}$(FJTS)	$64.096(2)^{-86.9\%}_{>+100\%}$	$92.17(1)^{-81.4\%}_{+5.6\%}$
OS1	80.992(2)	$97.145(7)^{-5.2\%}_{+5.1\%}$
OS2	71.429(2)	$96.95(1)^{+0.1\%}_{-0.2\%}$
OS12	78.304(2)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

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

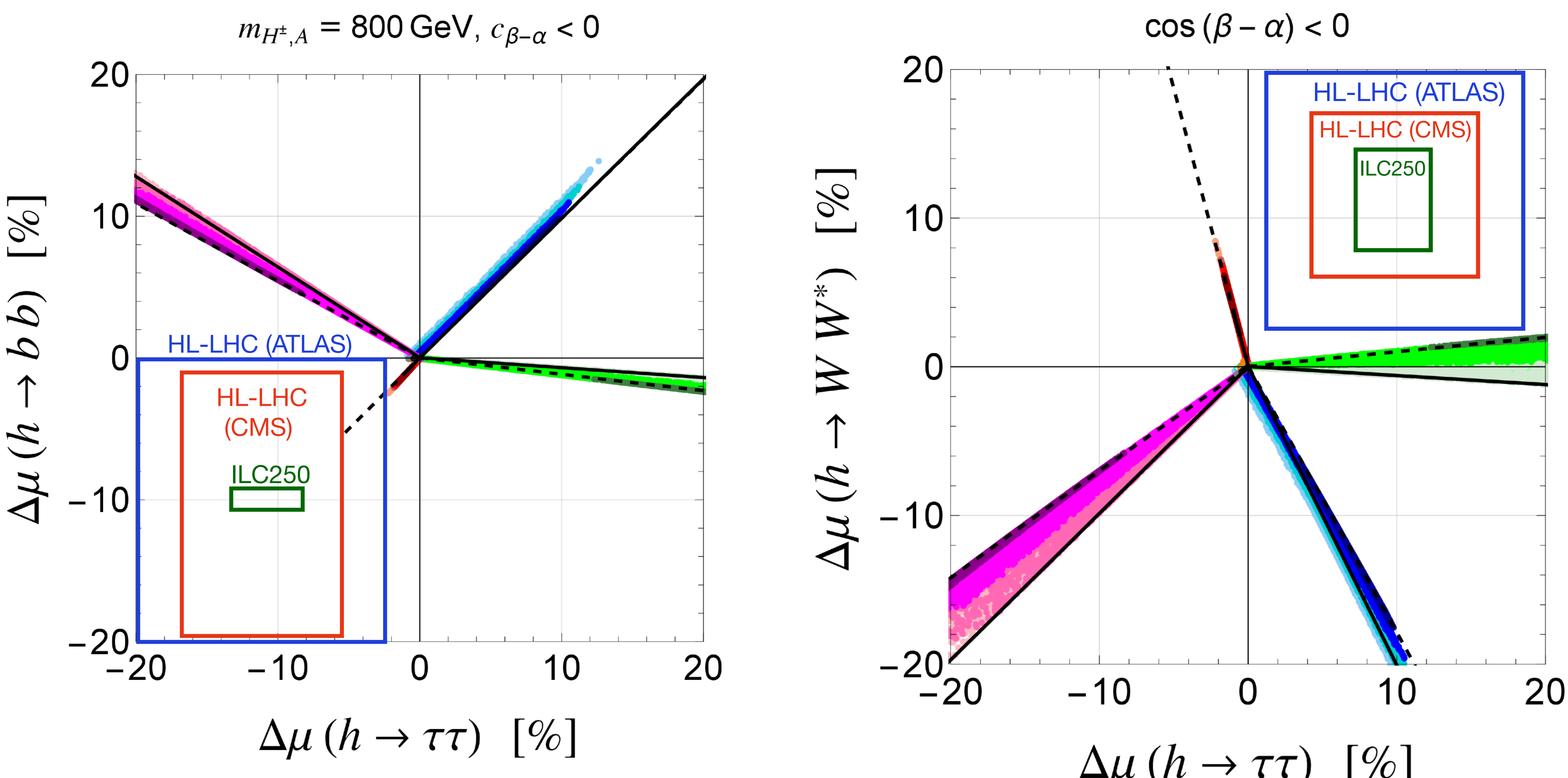
BFMS: On-shell with $\hat{\Pi}_{Hh}$ and the PT

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

Other plots



cos (β – α) < 0
ILC250
ΔR(h → bb) [%]
ΔR(h → ττ) [%]
$m_{H^\pm,A}$ = 800 GeV, $c_{\beta-\alpha}$ < 0
ILC250
Type I, X
Type II, Y
850
890
m_H = 750GeV
800
ΔR(h → ZZ*) [%]
LO(t_β = 2)
LO(t_β = 10)
IDM
(mH=500,1000GeV)
HSM
(mH=500GeV)



$m_{H^\pm,A}$ = 800 GeV, $c_{\beta-\alpha}$ < 0
HL-LHC (ATLAS)
HL-LHC (CMS)
ILC250
$\Delta\mu\,(h \to b\,b)$ [%]
$\Delta\mu\,(h \to \tau\tau)$ [%]
20
10
0
−10
−20
cos (β − α) < 0
HL-LHC (ATLAS)
HL-LHC (CMS)
ILC250
$\Delta\mu\,(h \to W\,W^*)$ [%]
$\Delta\mu\,(h \to \tau\tau)$ [%]

[1710.07621]

	ILC250		+ILC500	
	κ fit	EFT fit	κ fit	EFT fit
$g(hbb)$	1.8	1.1	0.60	0.58
$g(hcc)$	2.4	1.9	1.2	1.2
$g(hgg)$	2.2	1.7	0.97	0.95
$g(hWW)$	1.8	0.67	0.40	0.34
$g(h\tau\tau)$	1.9	1.2	0.80	0.74
$g(hZZ)$	0.38	0.68	0.30	0.35
$g(h\gamma\gamma)$	1.1	1.2	1.0	1.0
$g(h\mu\mu)$	5.6	5.6	5.1	5.1
$g(h\gamma Z)$	16	6.6	16	2.6
$g(hbb)/g(hWW)$	0.88	0.86	0.47	0.46
$g(h\tau\tau)/g(hWW)$	1.0	1.0	0.65	0.65
$g(hWW)/g(hZZ)$	1.7	0.07	0.26	0.05
Γ_h	3.9	2.5	1.7	1.6
$BR(h \to inv)$	0.32	0.32	0.29	0.29
$BR(h \to other)$	1.6	1.6	1.3	1.2

ATLAS						
		3000 fb^{-1} relative uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
$B^{\gamma\gamma}$	S1	6.0	1.2	4.7	3.3	1.4
	S2	3.7	1.2	2.9	1.8	0.6
B^{WW}	S1	5.8	1.0	2.8	4.3	2.6
	S2	4.4	1.0	2.4	3.2	1.6
B^{ZZ}	S1	5.3	1.6	3.0	3.7	1.7
	S2	3.8	1.6	2.7	1.9	1.0
B^{bb}	S1	7.6	2.0	2.4	5.0	4.7
	S2	5.0	2.0	1.9	2.8	3.2
$B^{\tau\tau}$	S1	6.0	1.7	2.7	4.4	2.4
	S2	4.4	1.7	2.5	2.8	1.7
$B^{\mu\mu}$	S1	14.9	12.7	3.2	6.8	0.3
	S2	13.7	12.7	3.2	3.7	0.3
$B^{Z\gamma}$	S1	24.2	20.3	4.5	12.2	0.0
	S2	24.2	20.3	4.5	12.2	0.0

CMS						
		3000 fb^{-1} relative uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
$B^{\gamma\gamma}$	S1	4.4	1.3	2.6	3.3	0.3
	S2	3.0	1.3	1.7	1.9	0.3
B^{WW}	S1	4.0	1.0	1.4	3.5	1.0
	S2	2.8	1.0	1.1	2.2	0.9
B^{ZZ}	S1	5.0	1.6	2.5	3.5	1.9
	S2	3.2	1.6	1.7	2.1	0.7
B^{bb}	S1	7.0	2.1	2.3	5.2	3.6
	S2	4.7	2.1	1.7	2.4	2.9
$B^{\tau\tau}$	S1	3.9	1.6	1.9	2.6	1.5
	S2	2.9	1.6	1.4	1.9	0.6
$B^{\mu\mu}$	S1	12.8	9.1	7.6	4.7	0.8
	S2	9.6	9.1	1.7	2.6	0.8

[1902.00134]

ILC 250 fb^{-1}

-80% e^-, +30% e^+ polarization:						
	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ [50–53]	2.0		1.8		4.2	
$h \to invis.$ [54, 55]	0.86		1.4		3.4	
$h \to b\bar{b}$ [56–59]	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$ [56, 57]	8.3		11	19	18	8.8
$h \to gg$ [56, 57]	7.0		8.4	7.7	15	5.8
$h \to WW$ [59–61]	4.6		5.6 *	5.7 *	7.7	3.4
$h \to \tau\tau$ [63]	3.2		4.0 *	16 *	6.1	9.8
$h \to ZZ$ [2]	18		25 *	20 *	35 *	12 *
$h \to \gamma\gamma$ [64]	34 *		39 *	45 *	47	27
$h \to \mu\mu$ [65, 66]	72 *		87 *	160 *	120 *	100 *
a [27]	7.6		2.7 *		4.0	
b	2.7		0.69 *		0.70	
$\rho(a, b)$	-99.17		-95.6 *		-84.8	
+80% e^-, -30% e^+ polarization:						

[1708.08912]