H-COUP: Towards determination of the Higgs sector via radiative corrections and future precision measurements

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Based on:

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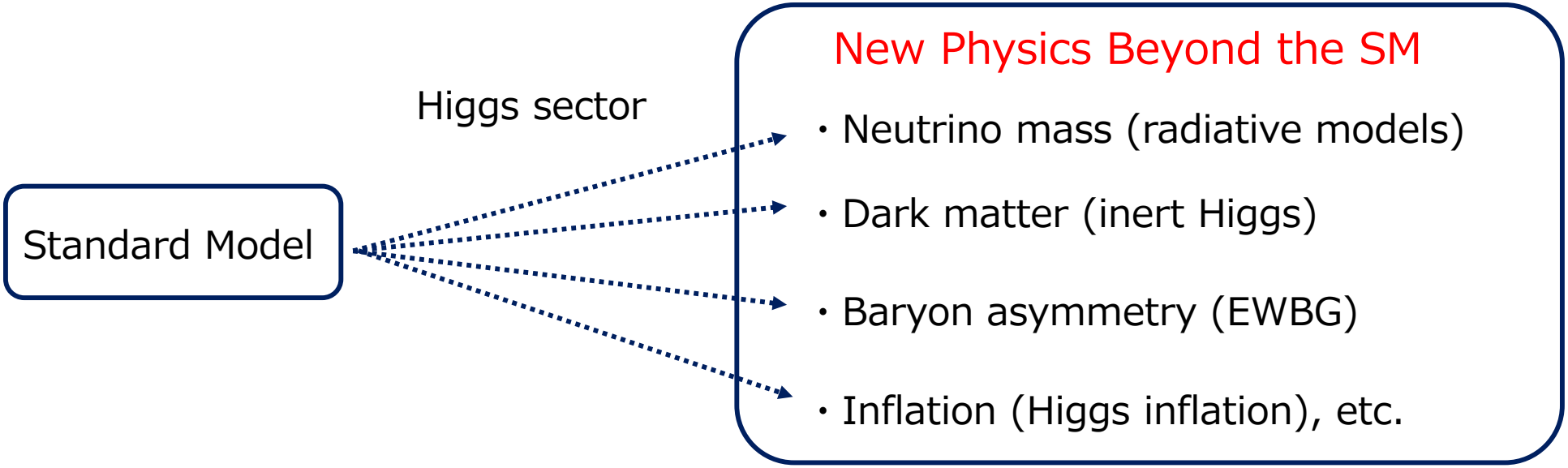
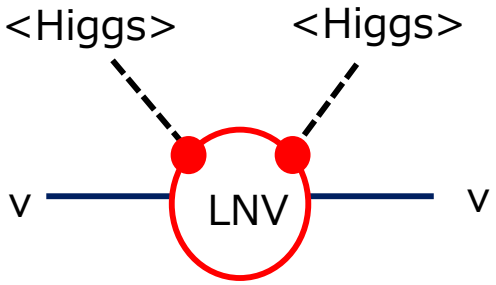
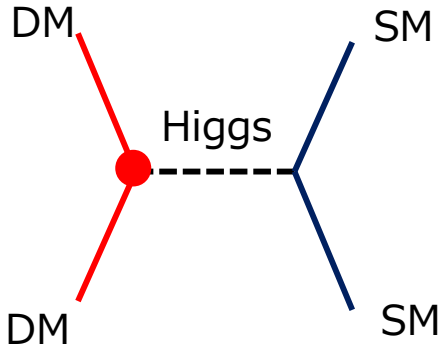
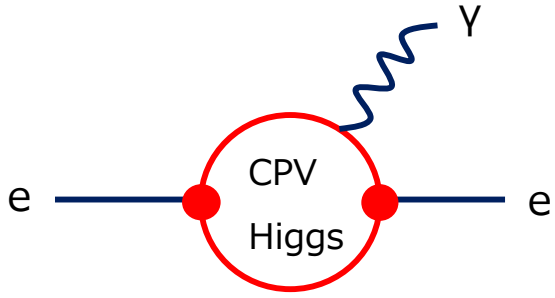
Higgs as a Probe of New Physics

- The Higgs sector can be a portal to the BSM sector.







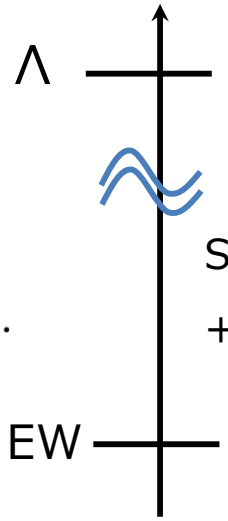


Clarifying the structure of the Higgs sector is important to know the BSM!

Bottom-Up Approach

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_i}{\Lambda^n}\mathcal{O}_i^{4+n} + \cdots$$



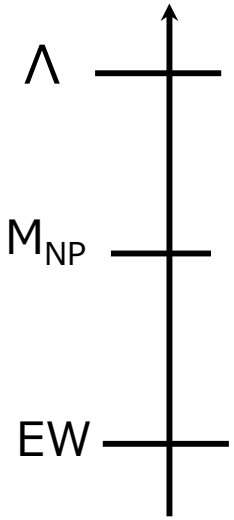
SM fields

+ High order OP.

☺ Generic

☹ No relation among coefficients

Renormalizable Models



SM fields

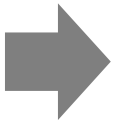
+ $H^{\pm}$, A, H, ⋯

☺ Concrete predictions

☹ Model dependent

What we know now

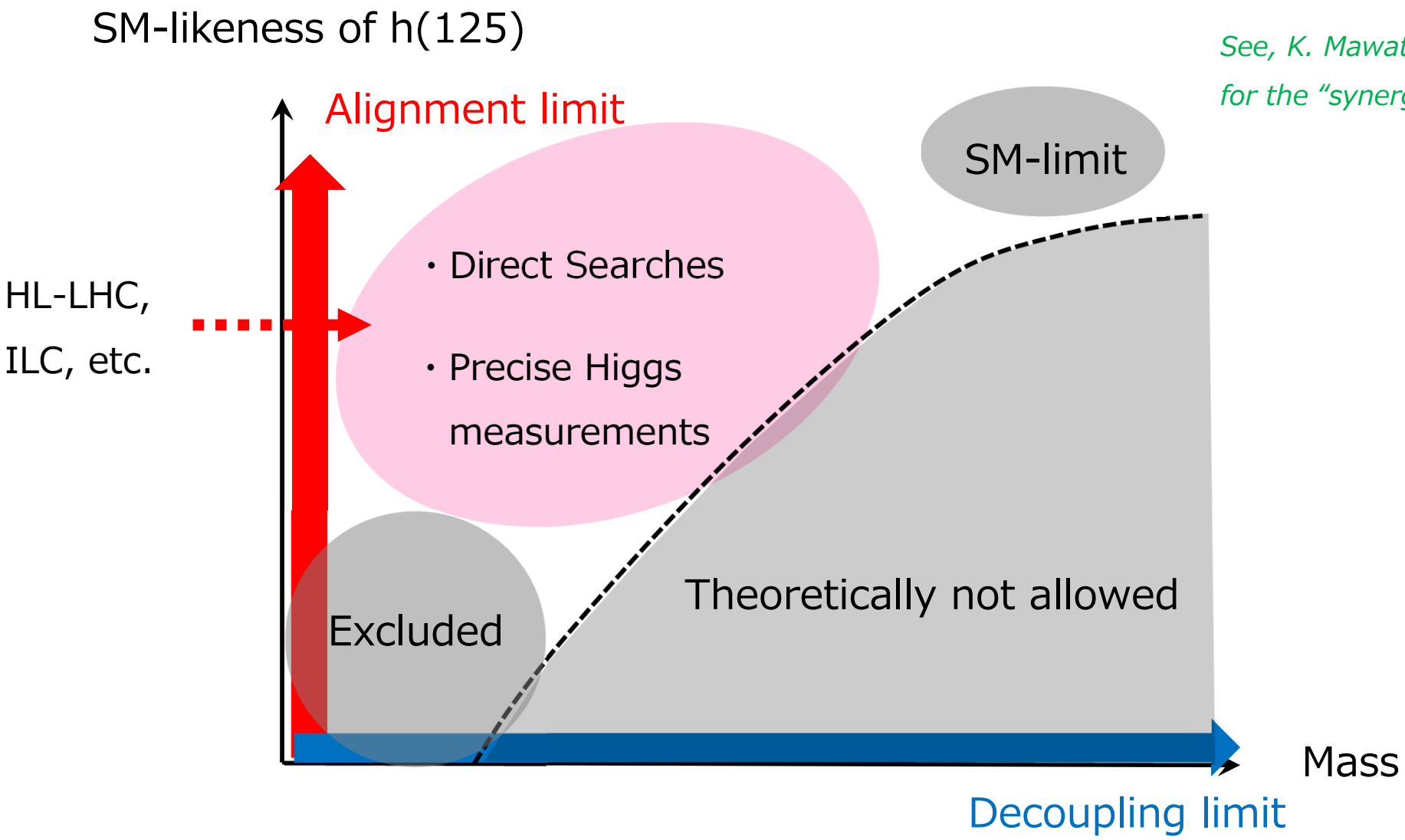
- Before the Higgs discovery
  - Electroweak ρ parameter: close to unity
  - Flavor changing neutral current: highly constrained
- After the Higgs discovery
  - Higgs mass 125 GeV
  - Alignment-like (SM Higgs-like)
  - (Currently) no discovery of the other Higgs bosons



Models with one Higgs doublet can explain all the above facts.
This does not exclude extended structures of the Higgs sector.

One doublet + singlets, doublets and/or triplets, ⋯ can be considered.

Keywords: Alignment/Decoupling



See, K. Mawatari's talk for the "synergy" analysis

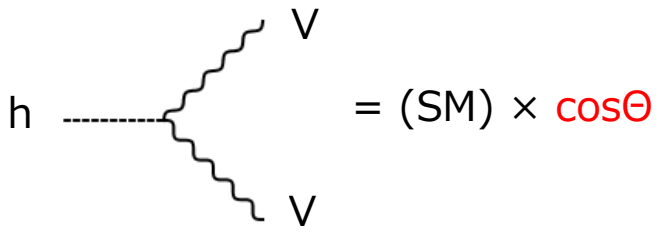
(Near) alignment without decoupling scenario becomes important.

What is alignment?

- It could be defined by the deviation in the Higgs decay rate :

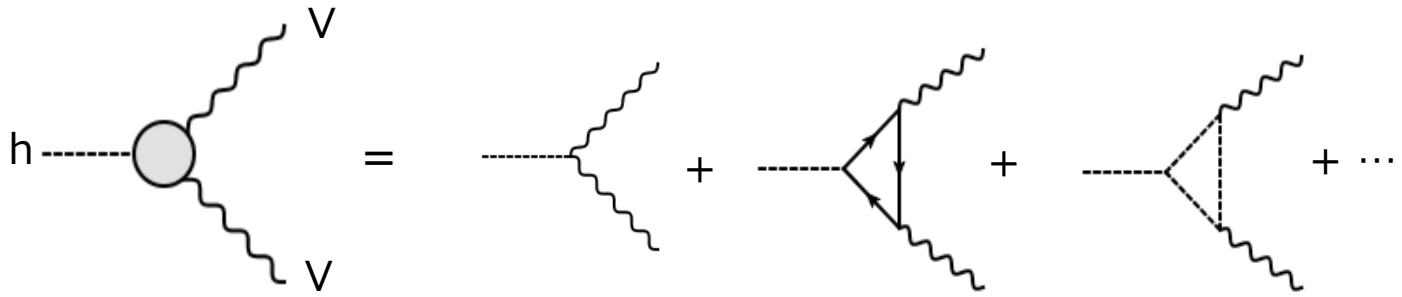
"Alignment-ness" = $\Gamma(h \to VV)^{\mathrm{NP}} / \Gamma(h \to VV)^{\mathrm{SM}}$

・Tree-level : This can be expressed by a mixing angle b/w h_{125} and an extra Higgs



= (SM) × cosΘ

・Loop-level: Many parameters (mass, coupling, ⋯) appear, and a mixing angle is no longer the "good parameter" to measure the alignment-ness.



For the determination of the Higgs sector, calculations beyond tree level are inevitable.

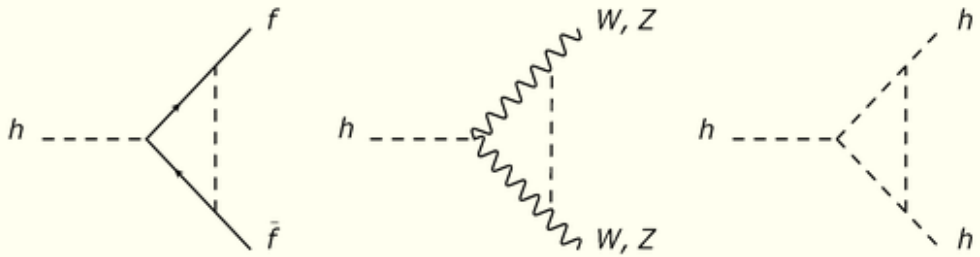
H-COUP

Kanemura, Kikuchi, Sakurai, KY (2017)

Kanemura, Kikuchi, Sakurai, Mawatari, KY (2019)

HCOUP

H-COUP



What is H-COUP?

A fortran code to calculate 1-loop corrected
Higgs couplings, decay rates, BRs
based on the improved OS renormalization scheme.

Downloads

- H-COUP version 2.3 : [HCOUP-2.3.zip] [The manual for H-COUP ver. 2 is here]
- H-COUP version 1.0 : [HCOUP-1.0.zip] [The manual for H-COUP ver. 1 is here]

In order to run H-COUP programs, you need to install LoopTools (www.feynarts.de/looptools/).

You can download the source code from here.

H-COUP Project

- Before publication of H-COUP *Kanemura, Senaha, Okada, Yuan, hep-ph/0408364 (PRD)* *Kanemura, Kikuchi, KY, arXiv:1502.07716 (NPB)*
  - Development of the OS-scheme in the 2HDM *Kanemura, Kikuchi, Sakurai, arXiv:1511.06211 (PRD)* *Kanemura, Kikuchi, KY, arXiv:1511.06211 (NPB)*
  - Development of the OS-scheme in the Higgs singlet model and the inert doublet model
  - Development of the gauge independent OS-scheme *Kanemura, Kikuchi, Sakurai, KY, arXiv:1705.05399 (PRD)*
- 2017: H-COUP Ver. 1 *Kanemura, Kikuchi, Sakurai, KY, arXiv:1710.04603 (CPC)*
  - 1-loop corrected h_{125} couplings can be calculated in the improved OS-scheme.

    4 types of the 2HDM, the Higgs singlet model and the inert doublet model are implemented.
- 2019: H-COUP Ver. 2 *Kanemura, Kikuchi, Mawatari, Sakurai, KY, arXiv:1910.12769 (CPC)*
  - h_{125} decay rates and BRs can be calculated at NLO EW/QCD.

Now

- 2021-: H-COUP Ver. 3 and beyond
  - We try to include decays of heavier Higgs bosons (H, A, $H^{\pm}$, ⋯).
  - Also, we try to implement cross sections, other models (triplets, etc.), other schemes (MS-bar, etc.), ⋯

Other Public Tools

2HDMC *Eriksson, Rathsman, Stal (2010)*

- 2HDMs
- Higgs decays at NLO QCD

(ewN)2HDECAY *Krause, Mühlleitner, Spira (2018)* *Krause, Mühlleitner (2019)*

- 2HDMs, N2HDM
- 2 body Higgs decays at NLO EW and NLO QCD

SHDECAY *Costa, Mühlleitner, Sampaio, Santos (2016)*

- HSM (Real & Complex)
- Higgs decays at NLO QCD

Prophecy4f *Altenkamp, Dittmaier, Rzehak (2018)*

- 2HDMs, HSM (Real)
- h → VV → 4f at NLO EW & NLO QCD

RECOLA2 *Denner, Lang, Uccirati (2018)*

- 2HDMs, HSM (Real & Complex)
- General one-loop amplitudes

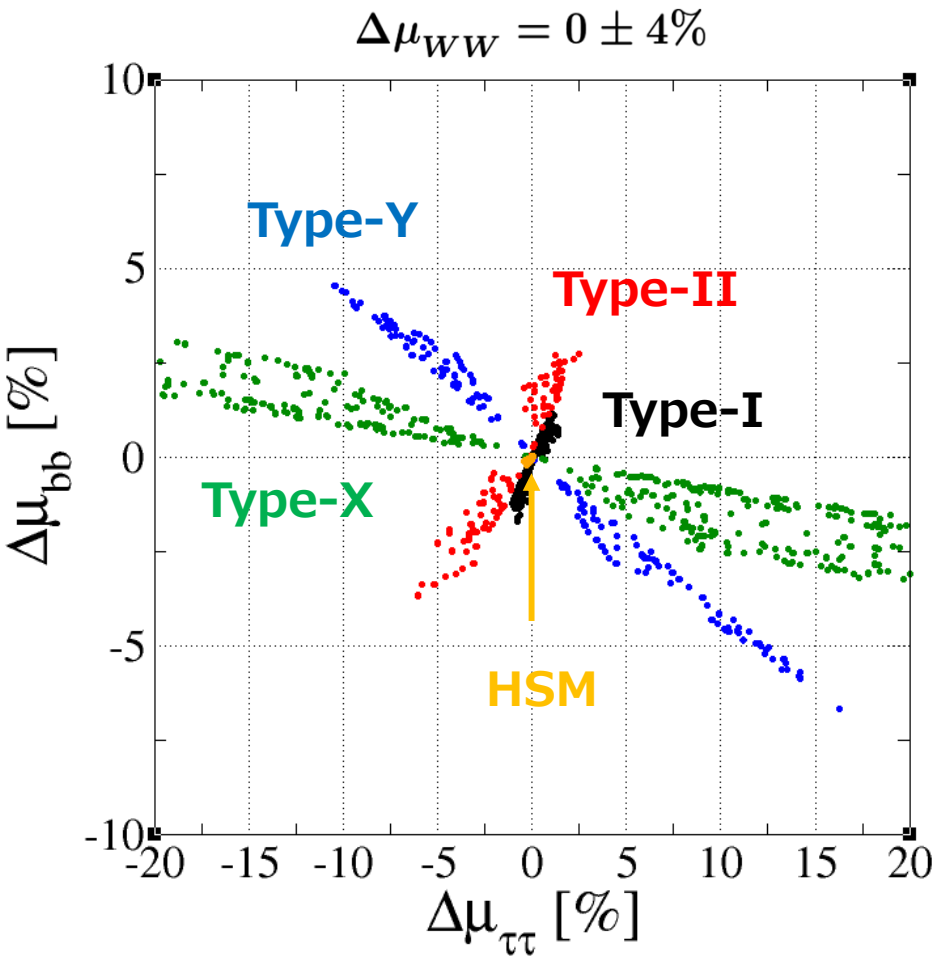
H-COUP *Kanemura, Kikuchi, Sakurai, KY (2017)* *Kanemura, Kikuchi, Sakurai, Mawatari, KY (2019)*

- HSM, 2HMDs, IDM
- Decays of h_{125} at NLO EW & NLO QCD

Applications of Ver. 2 [Higgs Inverse Problem]

Kanemura, Kikuchi, Mawatari, Sakurai, KY, arXiv:1906.10070 (NPB)

- Deviations in the h_{125} decay BRs at 1-loop level.



$$\Delta\mu_X \equiv \mathrm{BR}(h \to XX)_{\mathrm{NP}} / \mathrm{BR}(h \to XX)_{\mathrm{SM}} - 1$$

- 2HDM: $1.5 < \tan\beta < 10$,
  $m_\Phi > 600$ GeV (Φ=H, A, $H^\pm$),
  $0 < M < m_\Phi$

Characteristic patterns of the deviation with few % order can appear.

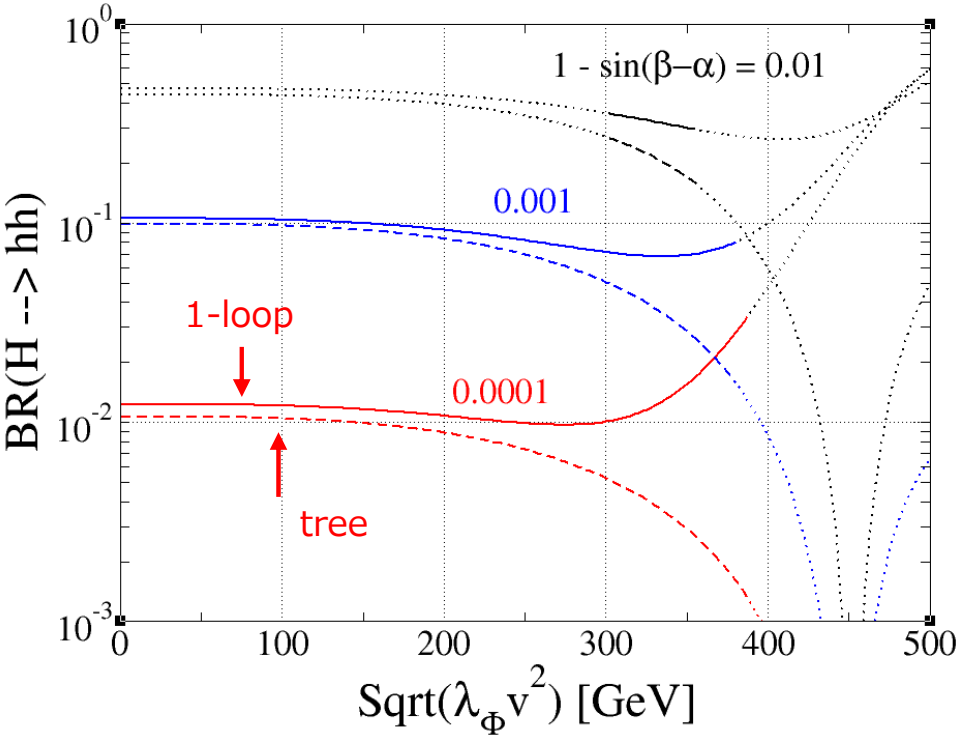
Towards Ver. 3 [Heavier Higgs Decays]

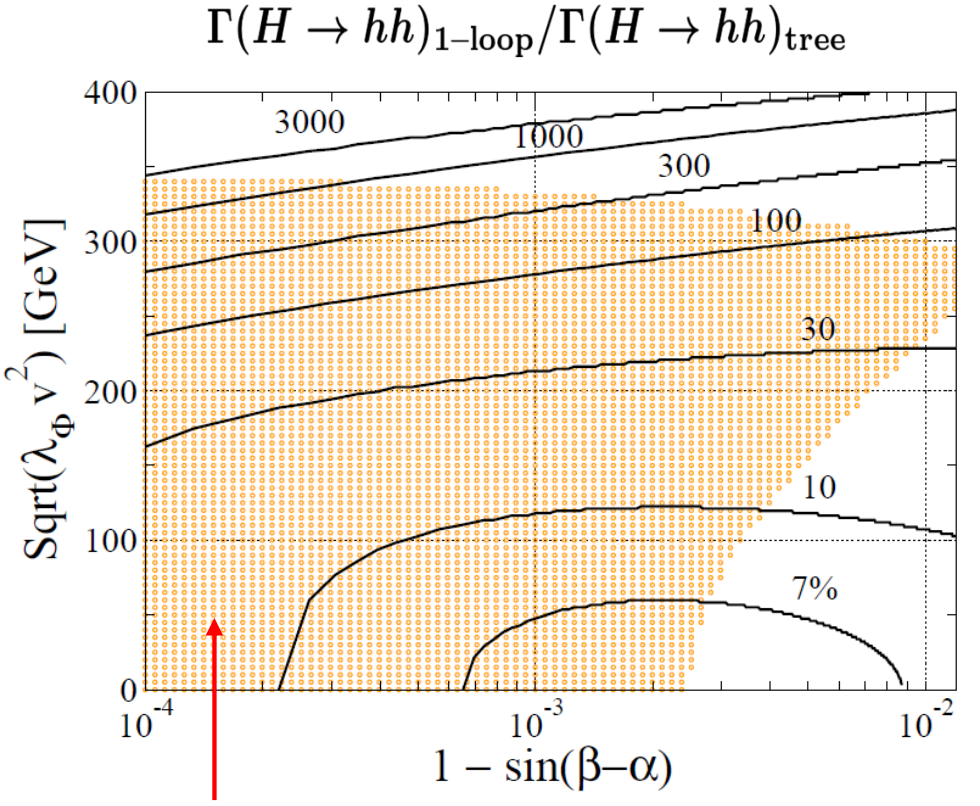
Preliminary

- Decay BR of H → hh at one-loop level.
  - 2HDM type-I, tanβ = 2, mH = mA = mH⁺ = 500 GeV, cos(β-α) > 0

Φ = H, A and H⁺

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



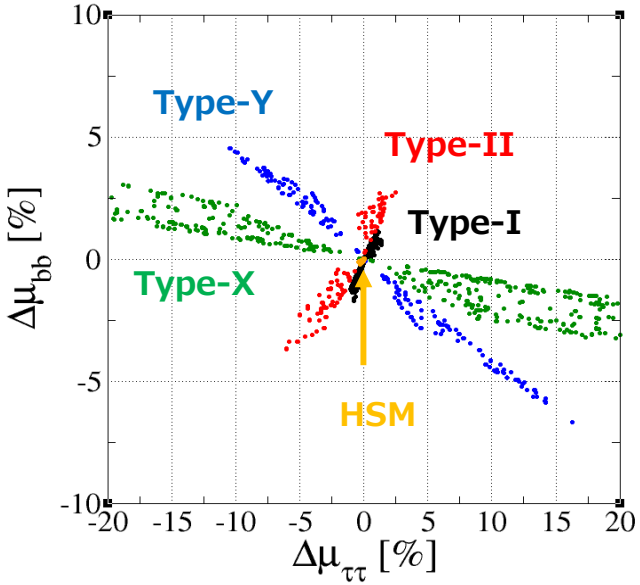


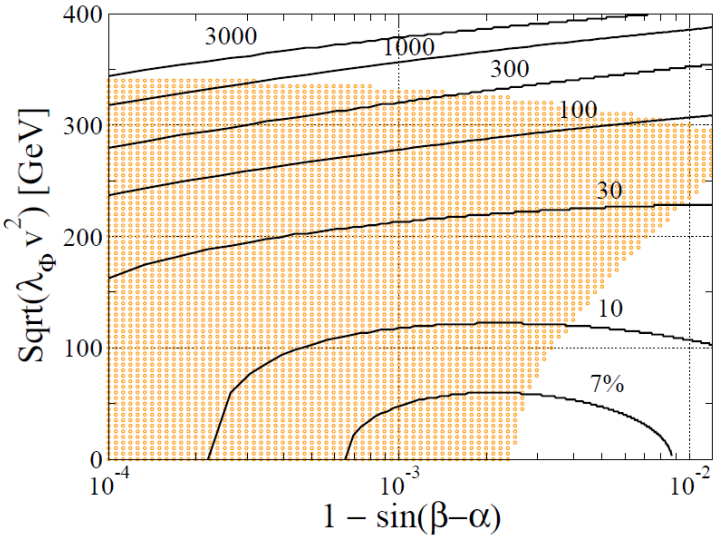
Allowed by perturbative unitarity & vacuum stability

Large corrections can appear due to the non-decoupling effects.

Summary

- Now, the alignment is an important key word to study the Higgs sector, and its meaningful definition is possible at loop levels.
- H-COUP (v2) provides one-loop corrected decay rates of the h_{125} in various extended Higgs sectors.
- H-COUP (v3) is now under construction, and it will be able to provide one-loop corrected heavier Higgs decays.

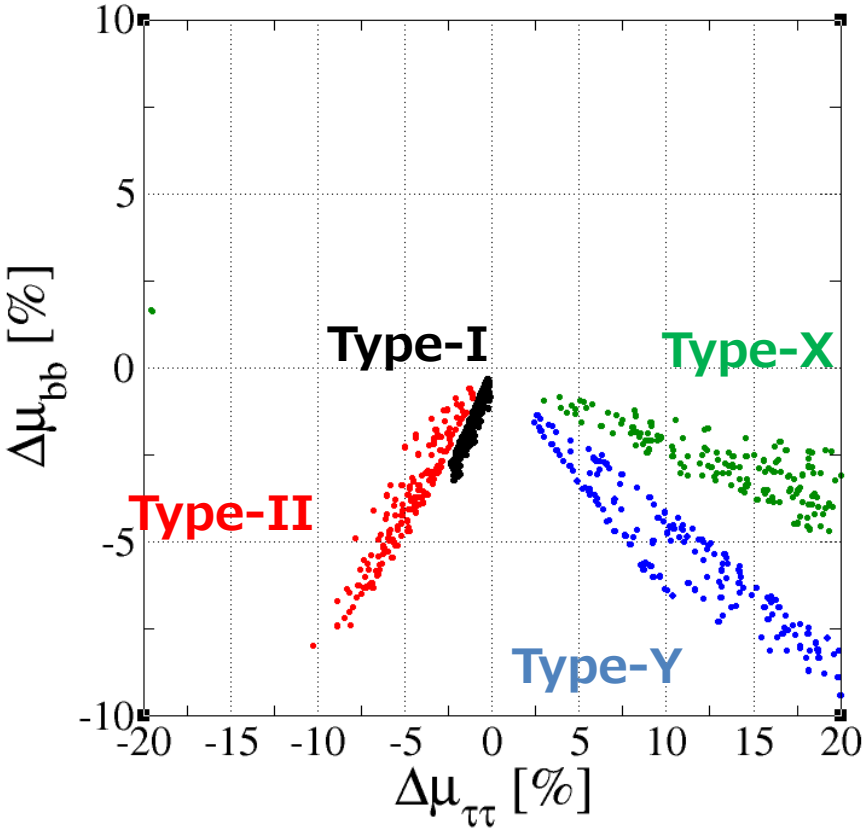




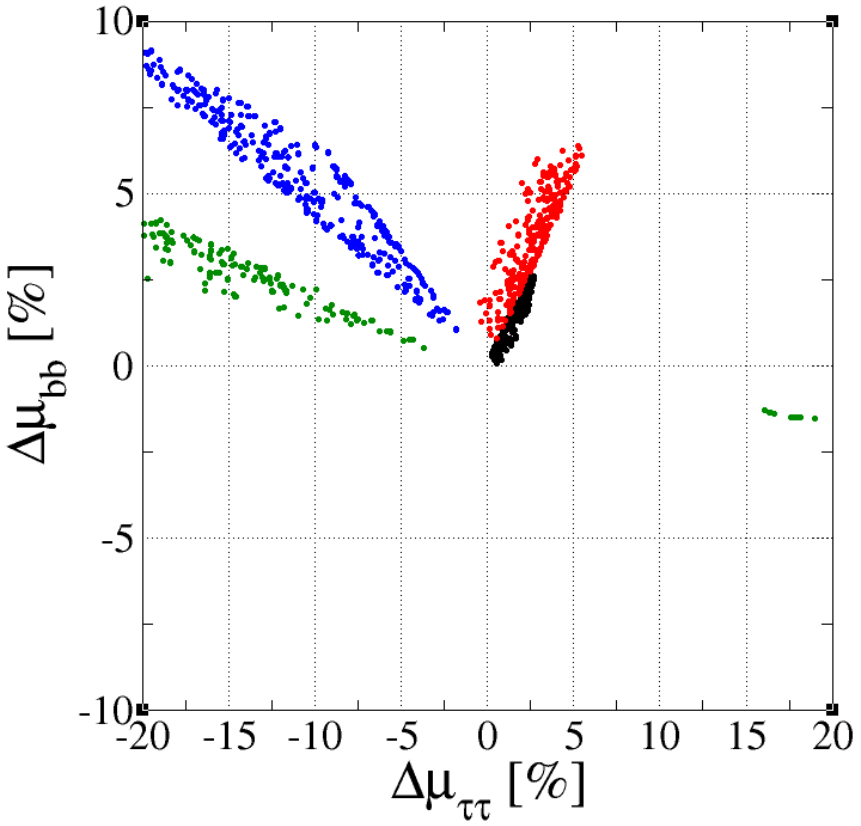
Applications

Kanemura, Kikuchi, Mawatari, Sakurai, KY, arXiv:1906.10070 (NPB)

$$\Delta\mu_{WW} = +5 \pm 4\%$$



$$\Delta\mu_{WW} = -5 \pm 4\%$$



$$\Delta\mu_X \equiv \mathrm{BR}(h \to XX)_{\mathrm{NP}}/\mathrm{BR}(h \to XX)_{\mathrm{SM}} - 1$$

Fingerprinting the Higgs Sector at NLO

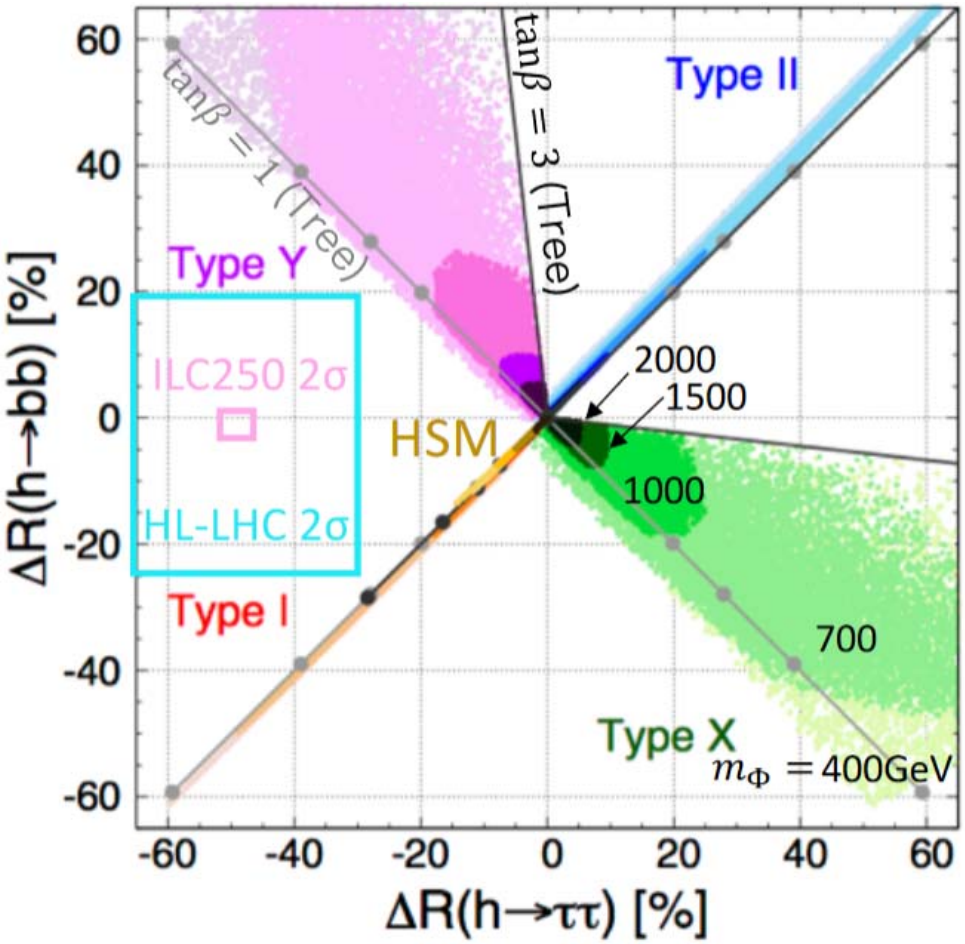
Kanemura, Kikuchi, Sakurai, Mawatari, KY, PLB783, 140 (2018)

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

Accuracies at the HL-LHC and ILC250 :

Fujii et al, 1710.07621 [hep-ph]

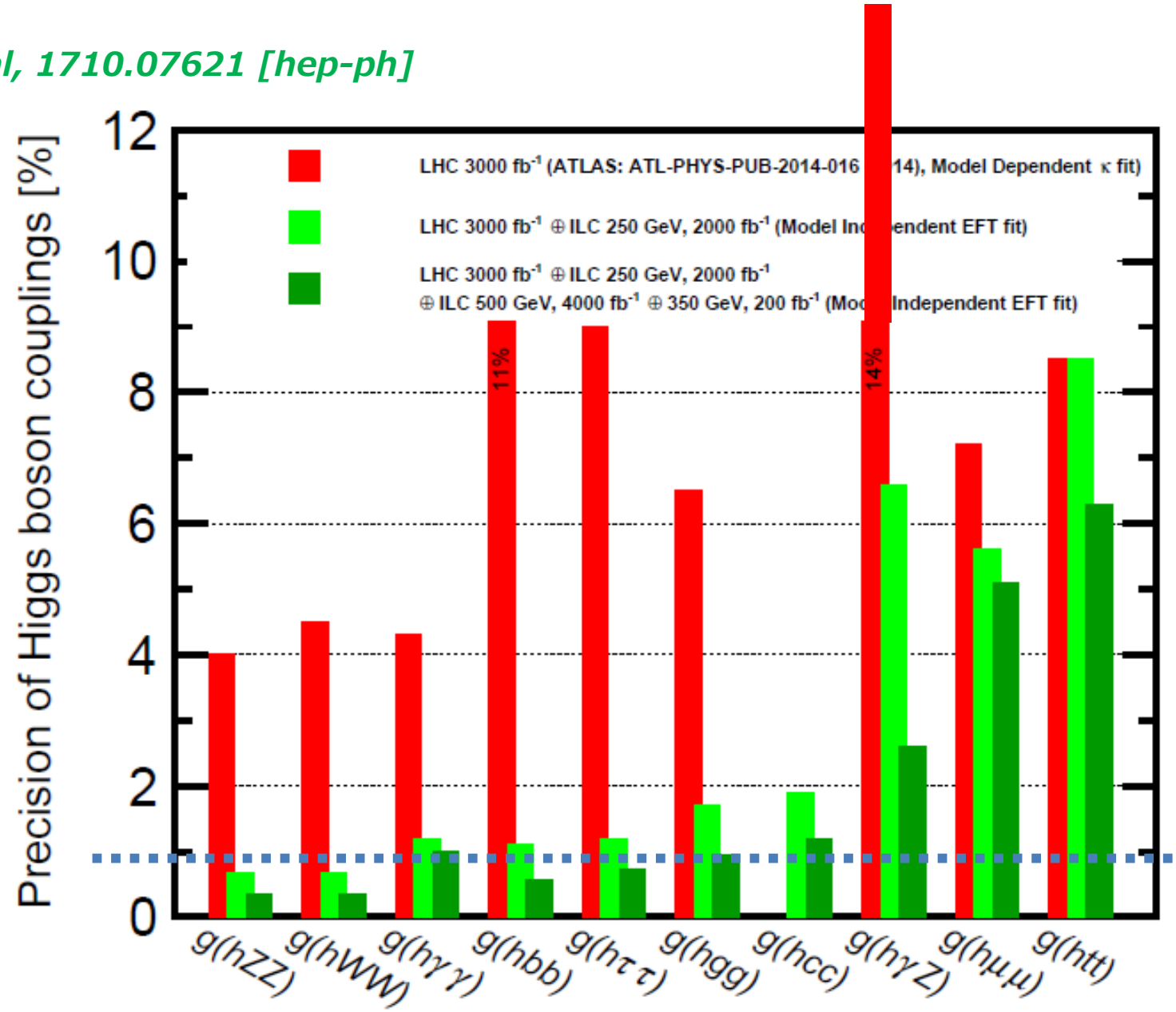
cos(β-α) < 0



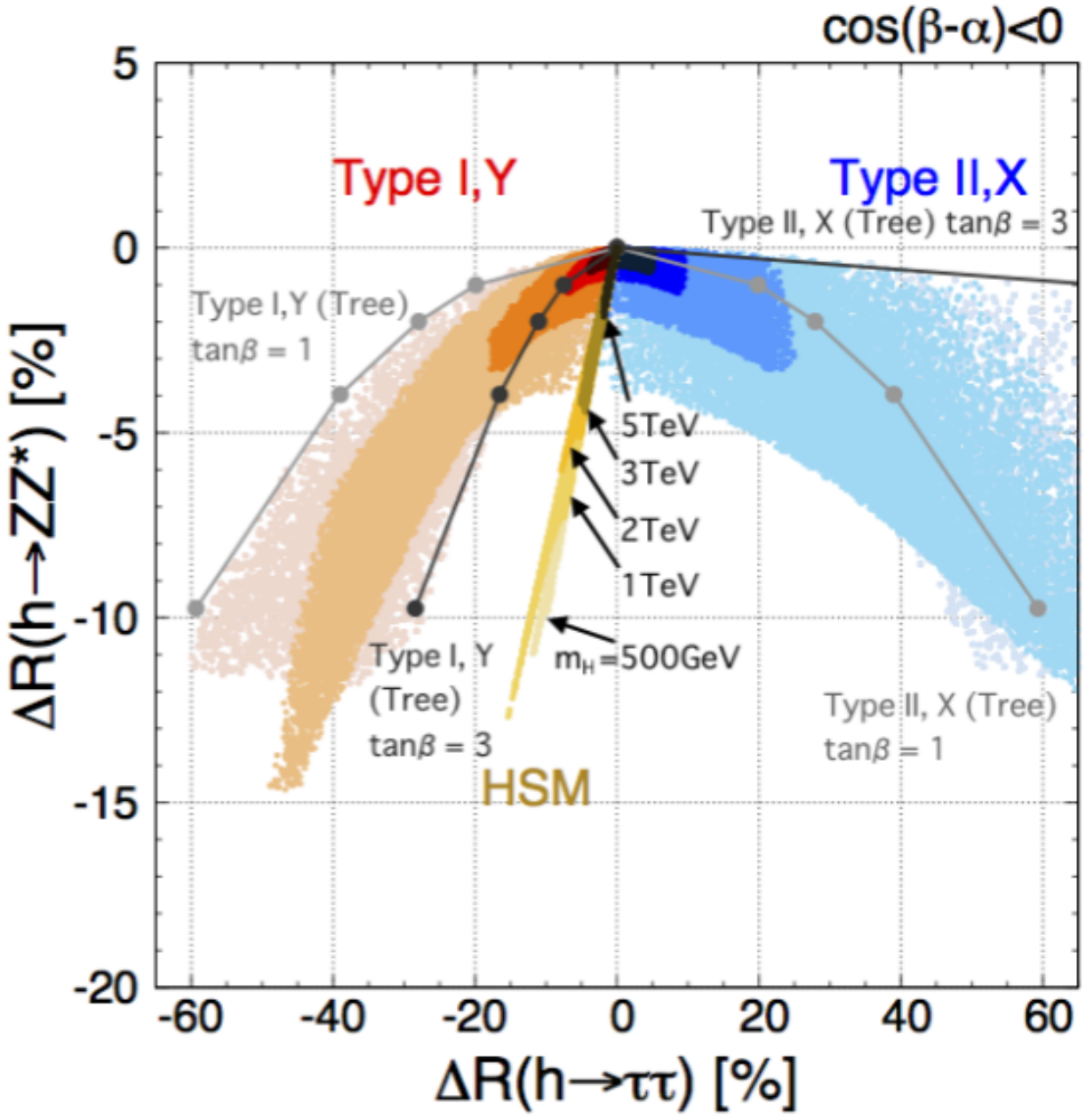
HL-LHC: **O(10)%** deviation is needed for discrimination.

ILC250: **O(1)%** deviation could be enough for discrimination!!

Fujii et al, 1710.07621 [hep-ph]



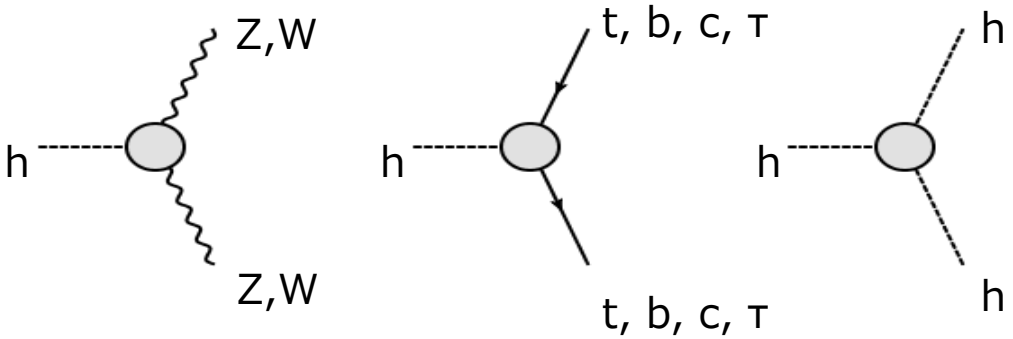
1%!!


cos(β-α)<0
Type I,Y
Type II,X
Type II, X (Tree) tanβ = 3
Type I,Y (Tree)
tanβ = 1
5TeV
3TeV
2TeV
1TeV
Type I, Y
(Tree)
tanβ = 3
m_H =500GeV
HSM
Type II, X (Tree)
tanβ = 1
ΔR(h→ZZ*) [%]
ΔR(h→ττ) [%]
5
0
-5
-10
-15
-20
-60
-40
-20
0
20
40
60

Higgs Couplings at 1-loop Level

Kanemura, Kikuchi, Sakurai, KY, Comp. Phys. Comm. 233, 134-144 (2018)

- H-COUP: A fortran90 code to calculate 1-loop corrected h(125) couplings based on the on-shell renormalization scheme



- ✓ UV finiteness
- ✓ IR finiteness
- ✓ Gauge invariance

Aoki, Kanemura, Kikuchi , KY, PRD87 (2013)
Chiang, Kuo, KY, PRD98 (2018)

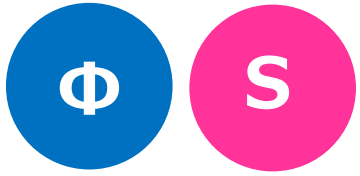
H-COUP_v1

- Models

SM

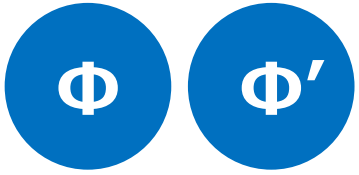
Fleischer, Jegerlehner, PRD23 (1981)
Kniehl, Phys. Rept. 240 (1994)

Higgs Singlet Model



Kanemura, Kikuchi, KY, NPB907 (2016)
Kanemura, Kikuchi, KY, NPB917 (2017)

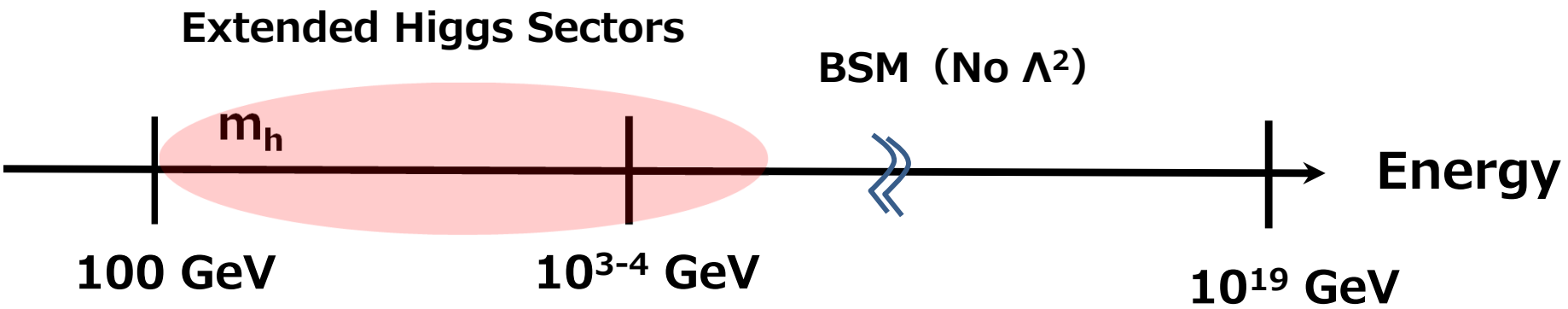
2 Higgs Doublet Models



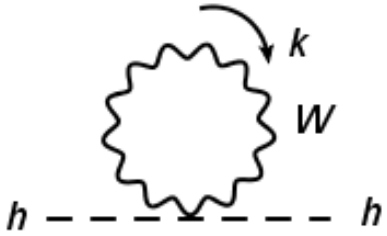
Kanemura, Okada, Senaha, Yuan, PRD70 (2004)
Kanemura, Kikuchi, KY, NPB896 (2015)
Krause, Lorenz, Santos, Muhlleitner, Ziesche, JHEP1609 (2016)

Triplet Models

Nature of the Higgs



$$(125\ \mathrm{GeV})^2 \sim (m_h^0)^2 + \frac{\Lambda^2}{16\pi^2} - \delta m_h^2$$



- Nature of the Higgs boson → New physics beyond the SM

Higgs is a
- Scalar boson (Supersymmetry) : Chiral Symmetry
- Fermion (Compositeness) : Chiral Symmetry
- Gauge boson (Gauge-Higgs Unification): Gauge Symmetry

Indirect Search = Higgs Precision Physics

HL-LHC, ILC, …

Loop level calculation

Precise measurements/calculations of h(125) properties

(couplings, width, BRs, cross sections, …)

When deviations are found

We can extract

2^{nd} Higgs mass scale and Higgs structure!!

”No-Loose Theorem” of the Higgs Physics