Preparing Higgs Theory for Precision Measurements at Future Colliders

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Talk Plan

- Higgs Physics → New physics
- Future collider experiments
- Indirect test by Higgs precision measurements
  Precise calculations for 125 Higgs decay processes
- Our current research results (*Complex Triplet Model*)
- Summary

Unknown things in the Higgs sector

The origin of the Higgs field

The origin of mass and flavour?

Why $\mu^2 < 0$?

Meta-stability of the vacuum

Detail of EW phase transition

Connecting New Physics to the Higgs Sector

Higgs field	I	Y
Φ	1/2	1/2

$$\mathcal{L}_{\mathrm{SM}\ Higgs} = |D_\mu \Phi|^2$$

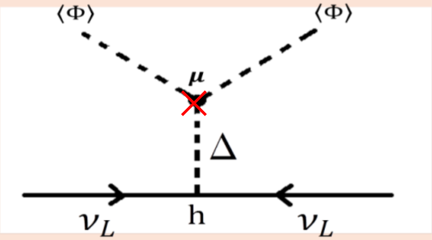
$$- y_f \bar{f}_L \Phi f_R + \mathrm{h.c.}$$

$$- (\mu^2 |\Phi|^2 + \lambda |\Phi|^4)$$

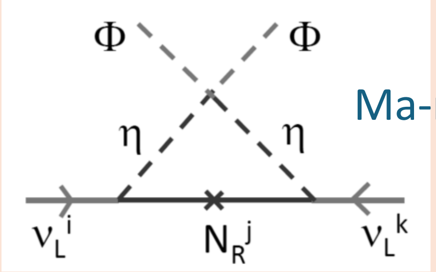
New Physics and Extended Higgs sectors

Neutrino and Higgs

Type Ⅱ Seesaw



Radiative seesaw



Ma-model

DM and Higgs

Spin-0 WIMP → Additional scalar boson

$$\mathbf{A} \rightarrow -\mathbf{A}$$

※ Strongly constrained by direct DM searches.
（In Singlet model, $m_{DM} \gtrsim$ 10TeV 共鳴領域以外）

EW Phase transition

Condition for 1st Order PT：
（sphaleron decoupling condition）

$$\boxed{\frac{\varphi_C}{T_C} \gtrsim 1}$$

Additional bosons loop can make sphaleron decoupling condition.

They are well-motivated !!

Φ + S (一重項場)

電弱一次相転移, 暗黒物質, CPの破れ, …

Φ + Φ’ (二重項場)

超対称模型, 暗黒物質,電弱一次相転移, CPの破れ, ニュートリノ質量（輻射シーソー）, …

Φ + Δ (三重項場)

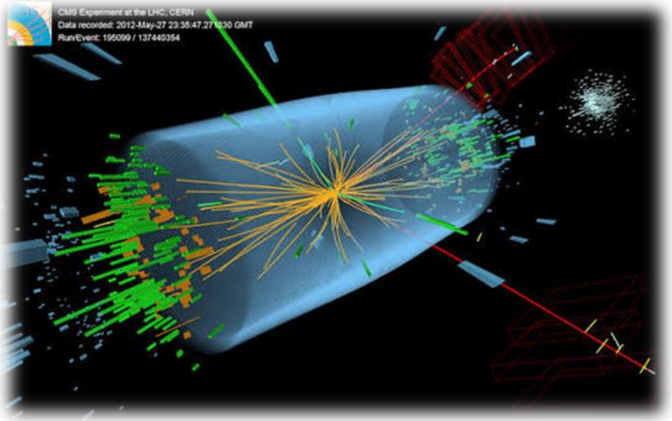
ニュートリノ質量（TypeIIシーソー）, 電弱一次相転移, 暗黒物質, …

Higgs precision measurements

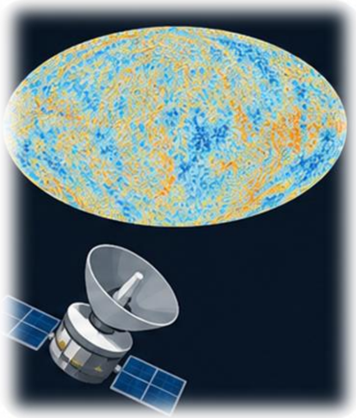
at future collider experiments

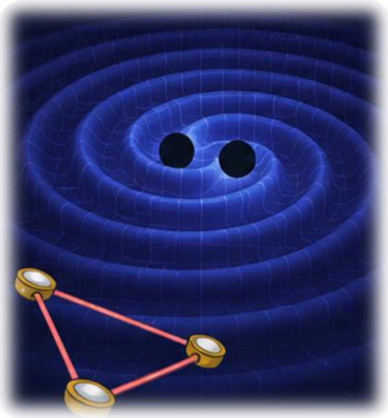
How do we approach these problems?

Collider experiments



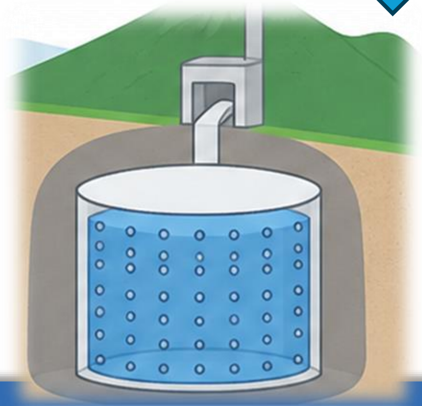
Cosmological survey(CMB, GW, DM, …)



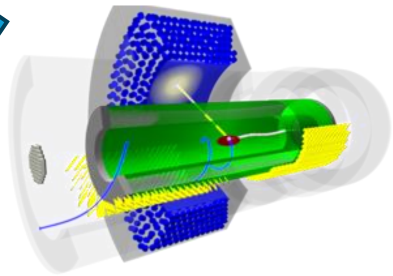


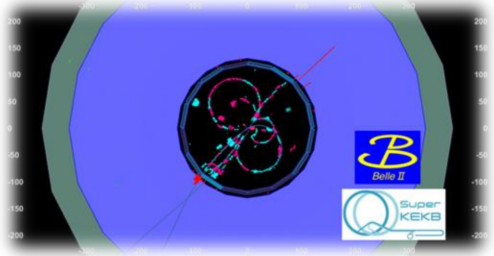
Higgs Physics

DM detection, ν-experiment



Flavor Physics Experiments





Current Status of Future Colliders

Near-term Timeline

- 2022–2026 : LHC Run 3
- 2026–2030 : Long Shutdown 3 (HL-LHC upgrade)
- 2030–2041 : High-Luminosity LHC (HL-LHC)

Candidate Future Colliders(e+e-)

FCC-ee → FCC-hh	**Preferred option in the 2026 European Strategy**
CEPC	Circular
ILC	Linear
CLIC	Linear

https://home.cern/the-cern-council-decided-to-update-the-european-strategy-for-particle-physics/

Expected Higgs coupling precisions

@ FCC-ee

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

2504.00672 [hep-ex]

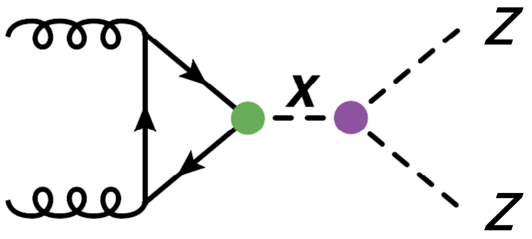
@ LCF(ILC)

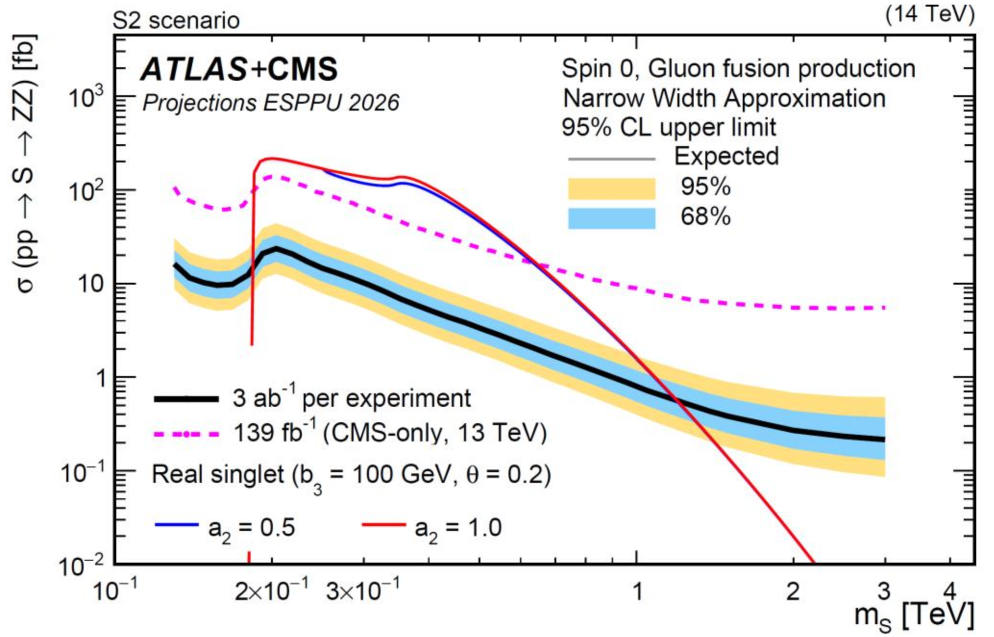
	LCF,	250 GeV	250 + 550 GeV	250 + 550 GeV
Higgs couplings	L[ab^{-1}]	3, pol.	3+4, pol.	3+8, pol.
$g(Hb\bar{b})$		0.72	0.46	0.38
$g(Hc\bar{c})$		1.45	1.04	0.87
$g(Hgg)$		1.31	0.86	0.70
$g(H\tau\tau)$		0.83	0.61	0.53
$g(HWW)$		0.34	0.24	0.22
$g(HZZ)$		0.34	0.24	0.22
$g(H\gamma\gamma)$		1.02	0.98	0.94
$g(H\gamma Z)$		7.51	5.75	5.41
$g(H\mu\mu)$		3.87	3.68	3.53
Higgs widths				
total width		1.39	0.97	0.85
width to invisible (95%CL)		0.36	0.33	0.31
width to unclassified (95%CL)		1.53	1.23	1.11

2503.19983 [hep-ex]

How to search at colliders

Direct searches of heavy Higgs





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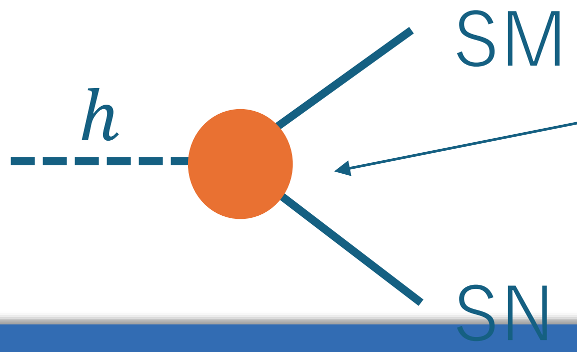
Indirect test by h –precision

In SM : couplings $\propto$ masses

Deviations from the SM predictions ＝ New physics effects



Precision measurements of h

Higgs factory !!

Other potential of e+e- colliders

① Z-pole

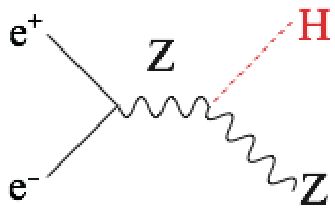
mZ, Flavor Phys. (Z→bb)

② WW threshold (m_W)

mW, Γ_W, EW parameters

③ 240 GeV (HZ)

hZZ, Higgs couplings, Γ_h

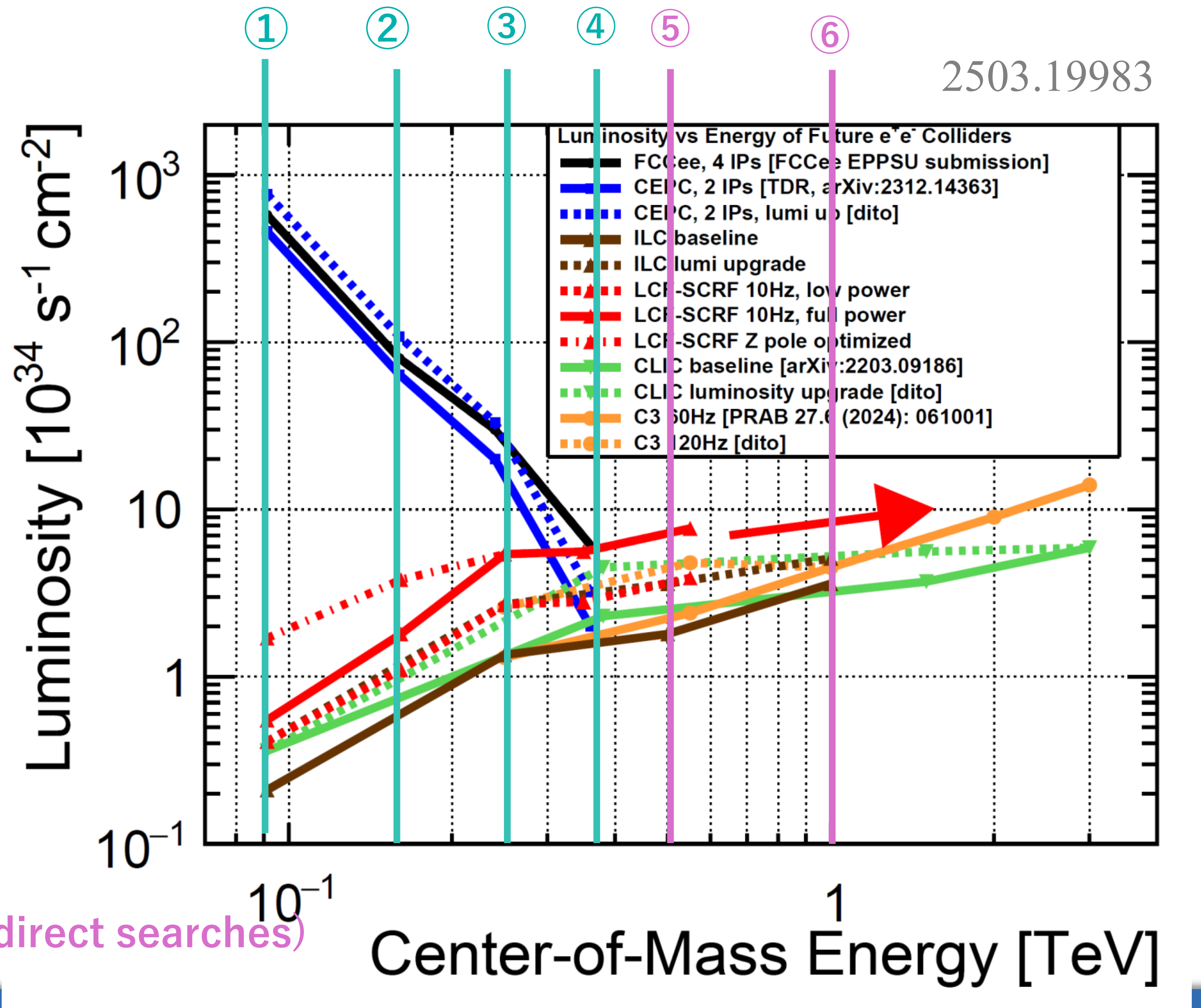


④ 365 GeV (tt)

Top mass

⑤ 500 GeV – 500 GeV
(Top-Yukawa, Double Higgs pro. , hhh)

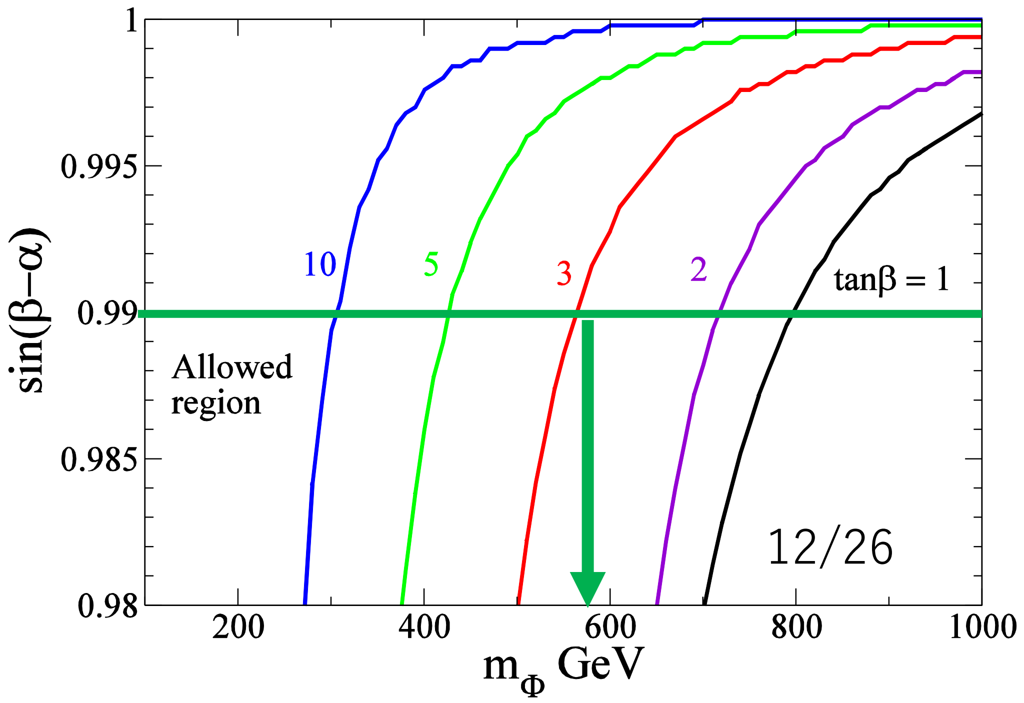
⑥ 1TeV
(More precise measure hhh, Heavy Higgs direct searches)



Precise calculations for 125 Higgs decay processes

What Do Deviations Tell Us? (1)New physics scale

Constraints from perturbative unitarity



例えば

$\Delta\kappa_Z$ = - 1%

Deviations in Higgs couplings give upper bounds on Additional Higgs mass.

Characteristic deviation pattern

$\kappa_X = \frac{c_{hXX}}{c_{hXX}^{SM}}$	κ_Z	κ_d	κ_e
HSM	$\cos\alpha$	$\cos\alpha$	$\cos\alpha$
Type-I 2HDM	$\sin(\beta-\alpha)$ $(= \sin\beta\cos(-\alpha) + \cos\beta\sin(-\alpha))$	$\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	$\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$
Type-II 2HDM	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$	$\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$
Type-X 2HDM	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	$\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$
Triplet (Y=1)	$\cos\beta'\cos\alpha + 2\sin\beta'\sin\alpha$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$

If $\Delta\kappa_Z = -1\%$

	$\Delta\kappa_Z = \kappa_Z - 1 \ll 1$	$\Delta\kappa_d$		$\Delta\kappa_e$	
HSM	$-x^2/2$	$-x^2/2$	-1%	$-x^2/2$	-1%
Type-I 2HDM	$-x^2/2$	$+\cot\beta\, x$	$+\mathcal{O}(10)\%$	$+\cot\beta\, x$	$+\mathcal{O}(10)\%$
Type-II 2HDM	$-x^2/2$	$-\tan\beta\, x$	$-\mathcal{O}(10)\%$	$-\tan\beta\, x$	$-\mathcal{O}(10)\%$
Type-X 2HDM	$-x^2/2$	$+\cot\beta\, x$	$+\mathcal{O}(10)\%$	$-\tan\beta\, x$	$-\mathcal{O}(10)\%$
Triplet (Y=1)	$-(\alpha^2 + \beta^2 - 2\sqrt{2}\alpha\beta)/2$	$-(\alpha^2 - \beta^2)/2$		$-(\alpha^2 - \beta^2)/2$	

Decoupling & non-decoupling

<u>スカラー粒子</u>のループ効果 も デカップリング 効果になり得る

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

付加的ヒッグス場ϕの質量は2種類のソース

- $M^2 >> \lambda_i v^2$ デカップリングする
- $M^2 \sim \lambda_i v^2$ ノンデカップリング効果

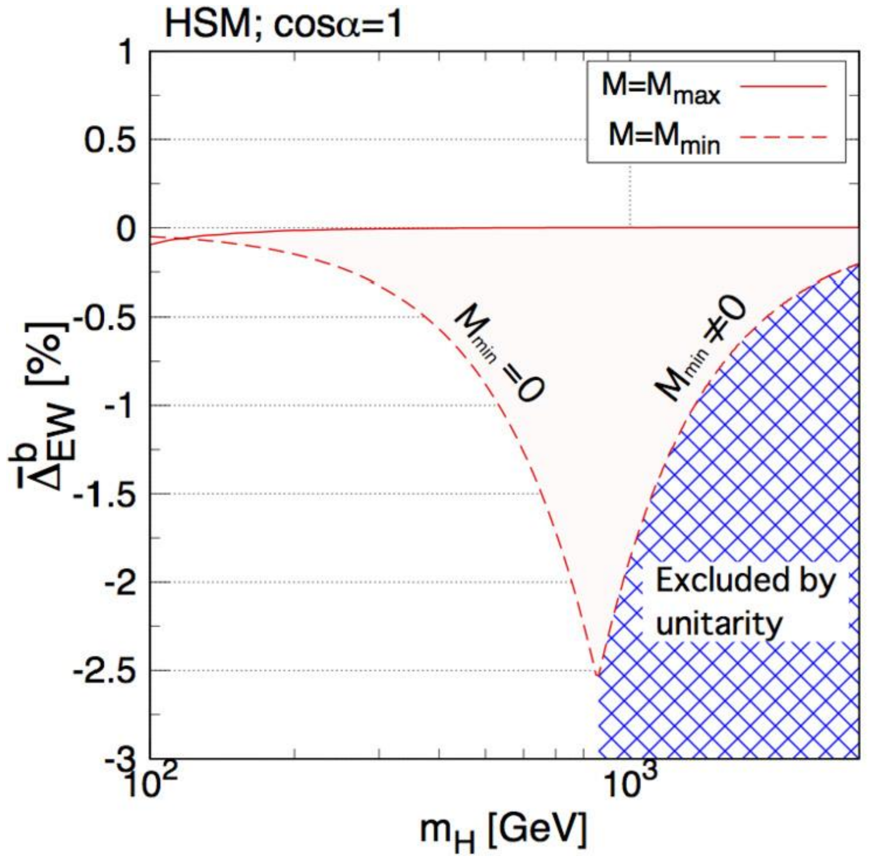
例 $$\Gamma(h \to f\bar{f}) = \Gamma_0(h \to f\bar{f})\left[1 + \Delta_{\mathrm{EW}}^f + \Delta_{\mathrm{QCD}}^f\right]$$

$$\overline{\Delta}_{EW}^X \simeq -\frac{1}{16\pi^2}\frac{1}{6}\sum_\Phi c_\Phi \frac{m_\Phi^2}{v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^2$$

$$m_\Phi^2\left(1 - \frac{M^2}{m_\Phi^2}\right)^2 \begin{cases} \propto \dfrac{1}{m_\Phi^2} & (M^2 \gg v^2) \\ \propto m_\Phi^2 & (M^2 \sim v^2) \end{cases}$$

デカップリング

ノンデカップリング



Kanemura, KM, Mawatari, Sakurai, Yagyu (2018)

H-COUP

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

Fortran program for decay BRs of Higgs bosons with loop corrections in extended Higgs models.

	Real Singlet	Softly broken Z2 2HDM (Type)	IDM	Complex Triplet	SM
h_{125}-decays Couplings, BR, Γ	✓	✓	✓	New !!	✓
Heavy Higgs decays BR, Γ	✓	✓	✓		✓

- Loop corrections : EW and scalar-NLO
  - UV div. → On-shell renormalizations
  - Gauge dependence → Remove by Pinch technique
  - IR div. via photon loop → Cancel by real photon emission

  QCD (NNLO, NLO) corrections (MS-bar scheme).

  A. Djouadi, Phys. Rept., 457, 1 (2008),
  B. M. Spira, Prog. Part. Nucl. Phys., 95, 98 (2017),
  K. G. Chetyrkin, A. Kwiatkowski, Nucl. Phys., B461, 3 (1996)
- Constraints : Vacuum stability(tree level, RGE improved), Tree-level unitarity, Triviality, True vacuum, ST parameters

H decays with loop corrections in Complex Triplet Model

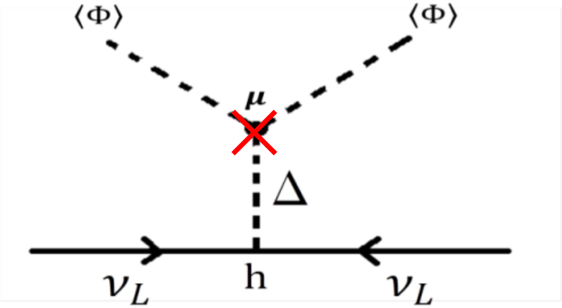
Complex Triplet Higgs model

	$SU(2)_L$	$U(1)_Y$
Φ	2	1/2
Δ	3	1

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & \frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \qquad \phi^0 = \frac{1}{\sqrt{2}}(\phi + v_\phi + i\,\chi) \qquad \Delta^0 = \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\,\eta)$$

- Neutrino mass (Type-II seesaw)

$$\boxed{\mathcal{L}_\nu = h_{ij}\overline{L_L^i}^c i\tau_2 \Delta L_L^j + hc} \qquad \boxed{M_\nu^{ij} = \frac{h^{ij}\mu v_\Phi^2}{M_\Delta^2}}$$



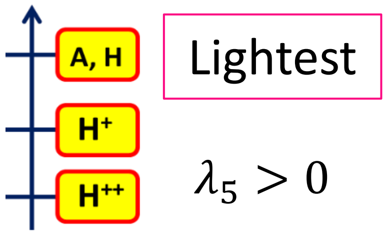
Cheng, Li (1980), Mohapatra, Senjanovic(1981)

- Mass eigenstates

h — SM-like Higgs boson

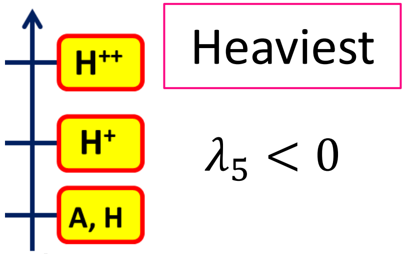
$H^{\pm\pm}$ $H^{\pm}$ A H — triplet-like Higgs bosons

$$\Delta m = m_{H^\pm} - m_{\text{lightest}}$$



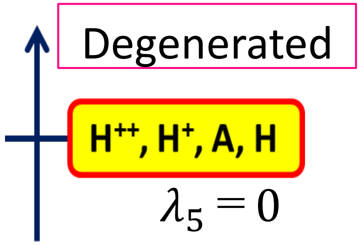
$\lambda_5 > 0$

$\Delta m = m_{H^\pm} - m_{H^{\pm\pm}}$



$\lambda_5 < 0$

$\Delta m = m_{H^\pm} - m_A$



$\lambda_5 = 0$

$\Delta m = 0$

- EW rho parameter

$$\rho_{\text{Tree}} = \frac{{m_W}^2}{{m_Z}^2 cos^2\theta_W} = \frac{v_\phi^2 + 2v_\Delta^2}{v_\phi^2 + 4v_\Delta^2} \neq 1$$

Constraints from ρ_{exp} $v_\Delta{}^2 << v_\phi{}^2$

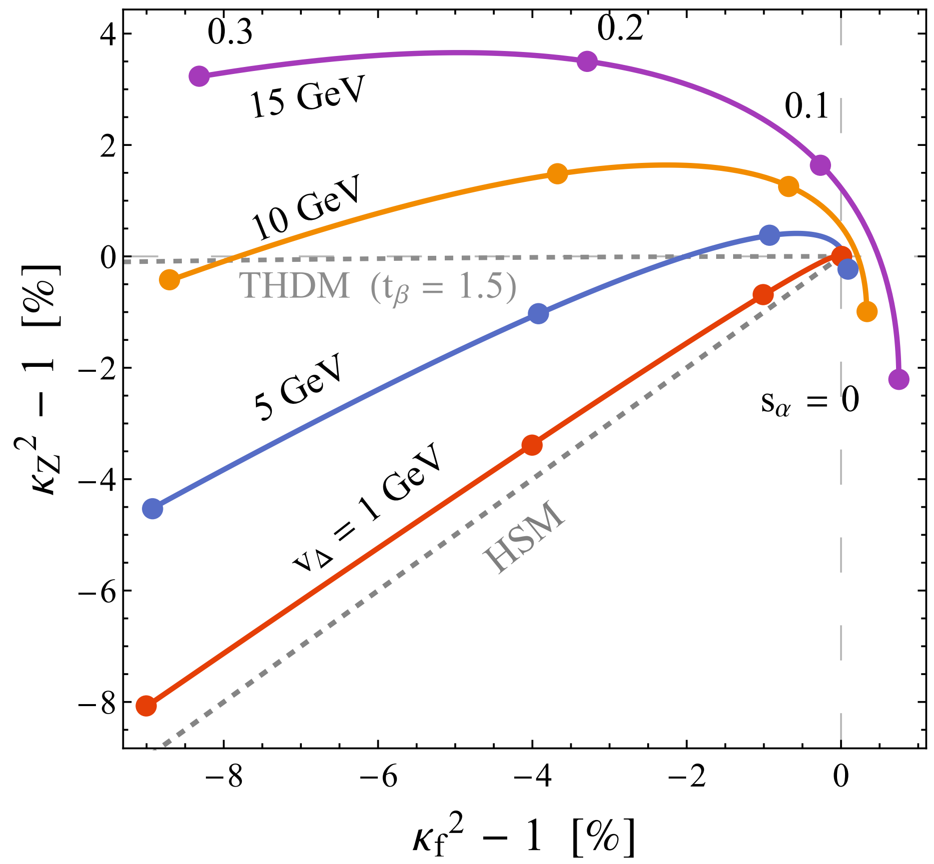
ρ= 1.00031 ± 0.00019 （PDG2024）

Coupling deviations

- hVV couplings can be larger than SM values.

$$K_{hZZ} = \cos\beta' \cos\alpha + 2\sin\beta' \sin\alpha$$
$$K_{hWW} = \cos\beta \cos\alpha + \sqrt{2}\sin\beta \sin\alpha$$

$$\left(\tan\beta = \frac{\sqrt{2}v_\Delta}{v_\phi}, \tan\beta' = \frac{2v_\Delta}{v_\phi}\right)$$



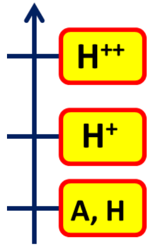
- A larger value of v_Δ leads to larger deviations in hVV couplings.

$$K_{hZZ} \simeq \cos\alpha + \frac{4v_\Delta}{v}\sin\alpha$$

$$K_{hff} = \cos\alpha/\cos\beta$$

Does the characteristic deviation pattern appear even with radiative correction?

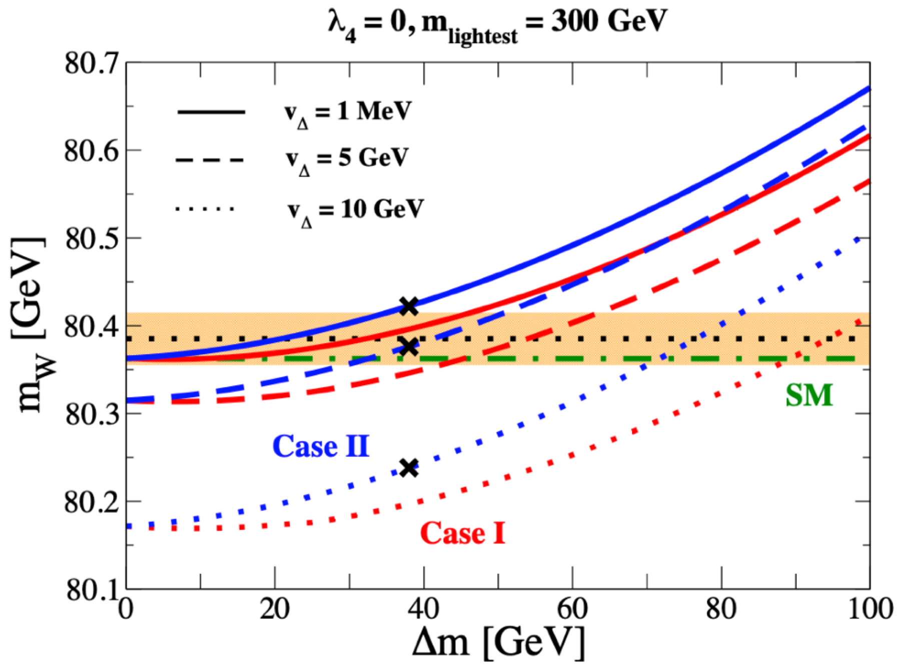
Constrains



Heaviest

$\lambda_5 < 0$

$\Delta m = m_{H^\pm} - m_A$



Aoki, Kanemura, MK, Yagyu (2012)

- EW precision observables

$$(m_W^{\rm rem})^2 = \frac{m_Z^2(1+c_{\beta'}^2)}{4}\left[1+\sqrt{1-\frac{8\pi\alpha_{\rm em}}{\sqrt{2}G_F m_Z^2(1+c_{\beta'}^2)(1-\Delta r)}}\right]$$

$$\Delta r \supset -\frac{1}{16\pi^2}\ln\left(m_{H^\pm}-m_A\right)^2$$

⇒ Large Δm is required.

- $h \to \gamma\gamma$

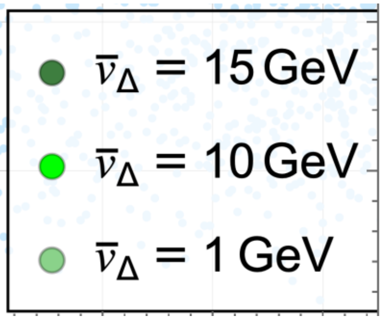
$$\Gamma(h \to \gamma\gamma)_{HTM} = \left| \quad \right|^2$$

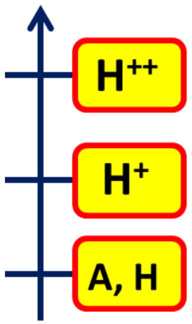
⇒ Larger $m_{H^{++}}$ is preferred.

- Perturbative unitarity

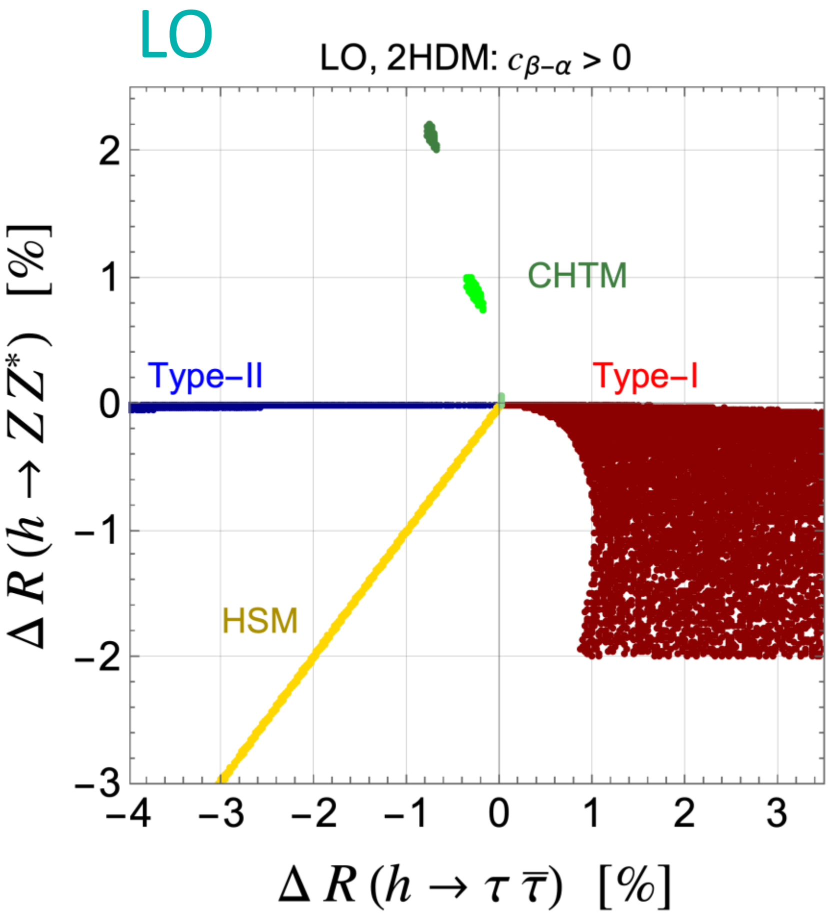
⇒ Upper bound for $m_{H^{++}}$

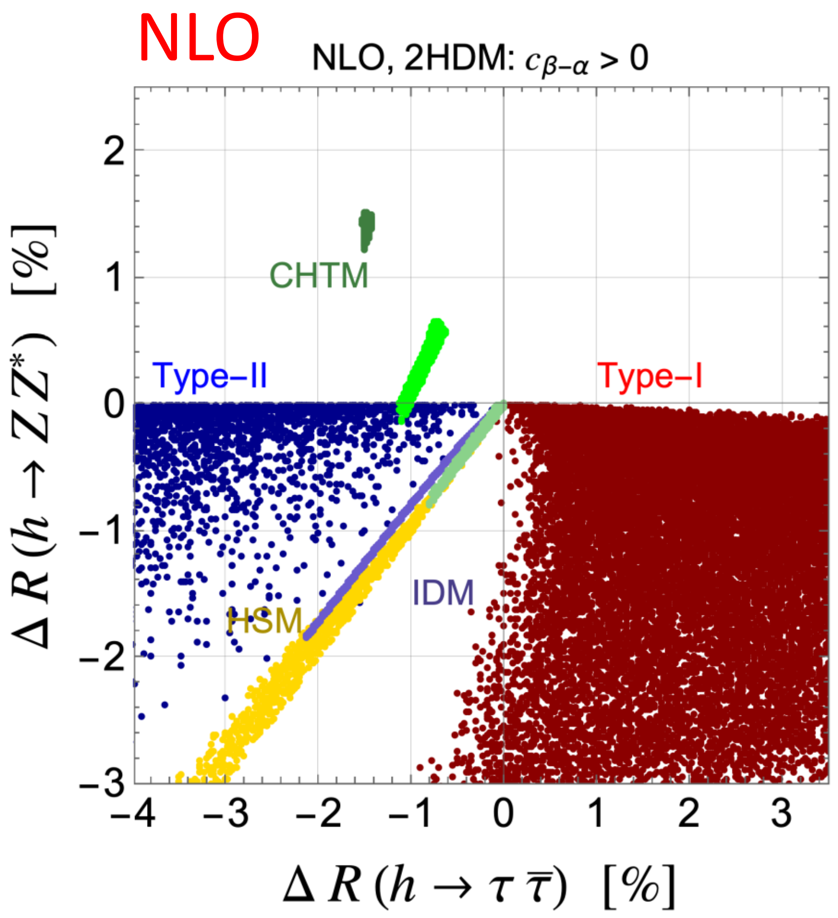
Decays of h→ZZ* and h→ττ with NLO corr.





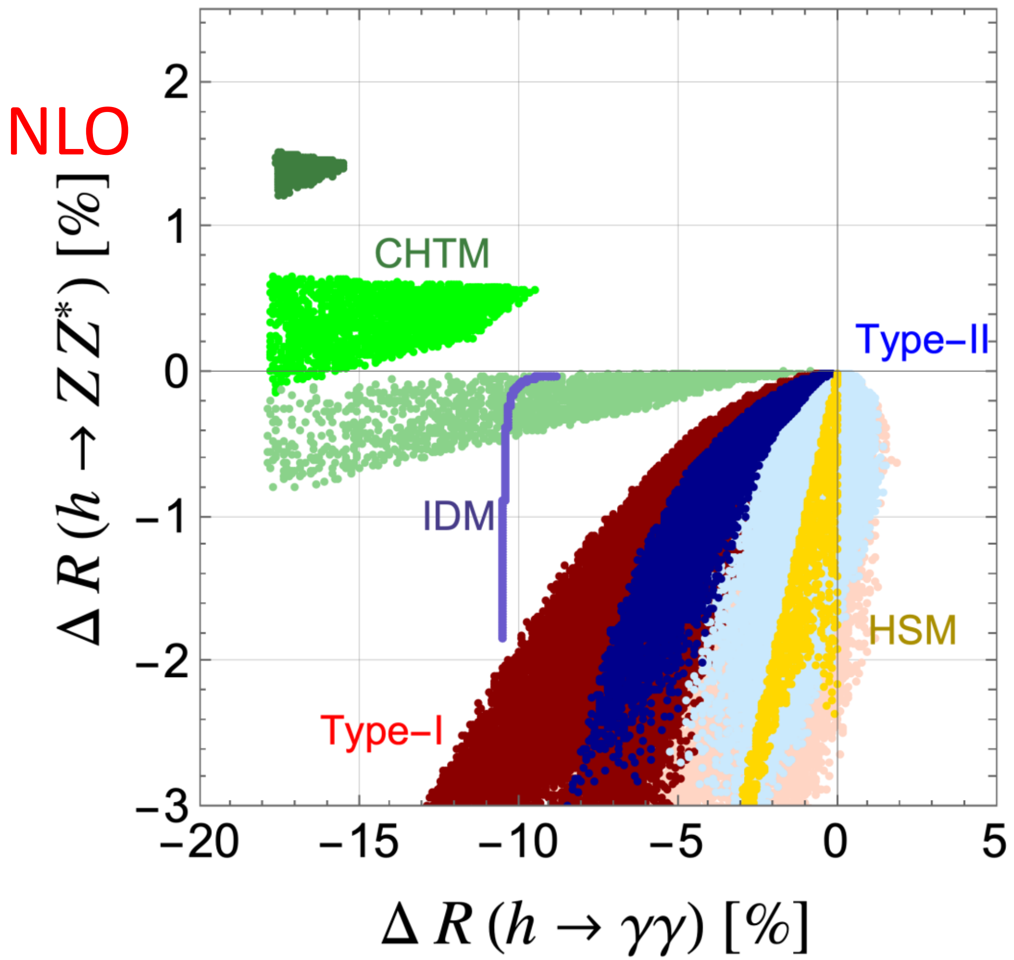
$$300\ \text{GeV} \leq m_A \leq 1\text{TeV},$$
$$0 \leq \Delta m \leq 150\text{GeV}$$
$$0 \leq \lambda_4 \leq 4\pi$$

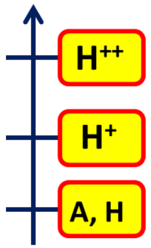




At NLO level, $\Delta R(h \to ZZ^*) \gtrsim 1\%$, by which CHTM is separable from other models.

Decays of h→ZZ* and h→γγ





h → γγ can be significantly deviated from SM.

$\Delta R(h \to \gamma\gamma) \simeq -20\,\%$ in $m_{H^{++}} > m_{H^+} > m_H$

$\Delta R(h \to \gamma\gamma) \simeq +10\,\%$ in $> m_H > m_{H^+} > m_{H^{++}}$

Current bound : $|\Delta\mu_{\gamma\gamma}| < 0.18$ at 2σ,

Future measurements :

$\Gamma(h \to \gamma\gamma)$ ~ 2.6% @ HL-LHC [2504.00672]

$\Gamma(h \to ZZ^*)$ ~ 0.5% @ ILC250+550 [2503.19983]

The characteristic deviation patterns are expected to be detected at HL LHC or future e+e- Collide

Summary

- Future e+e− colliders will provide not only Higgs precision measurements, but also EW and flavour precision.

- Precise theoretical calculations are essential to the future precision measurements.

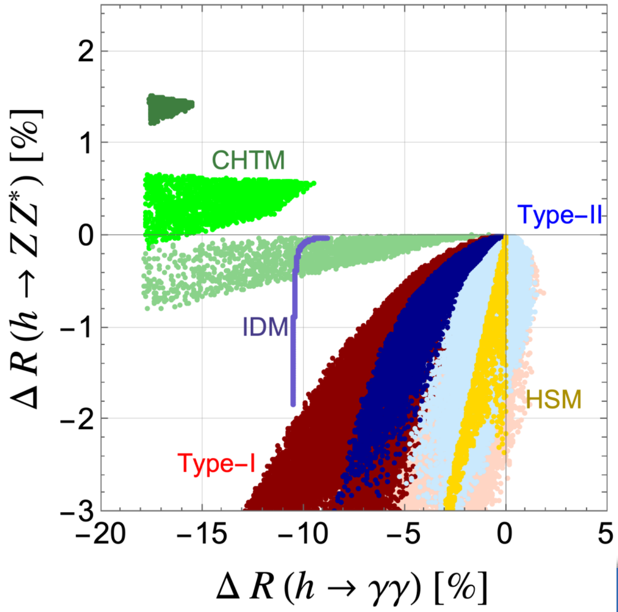
- H-COUP provides loop-corrected Higgs decay predictions in a variety of extended Higgs models.

- Comparing characteristic patterns of Higgs coupling deviations enables us to discriminate among different Higgs sectors.

- Current our result → Complex Triple model

$\Delta R(h \to VV^*) \sim +1\%$, $\Delta R(h \to \gamma\gamma) \sim -20\%$ [H++ Heaviest scenario]

$\Delta R(h \to \gamma\gamma) \sim +10\%$ [H++ Lightest scenario]



Indirect searches can probe heavy Higgs bosons beyond the direct-search reach !!