Fingerprinting non-minimal Higgs sectors with precision measurements of the Higgs boson couplings

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Higgs sector

- In SM, there is one iso-doublet scalar field ← Minimality

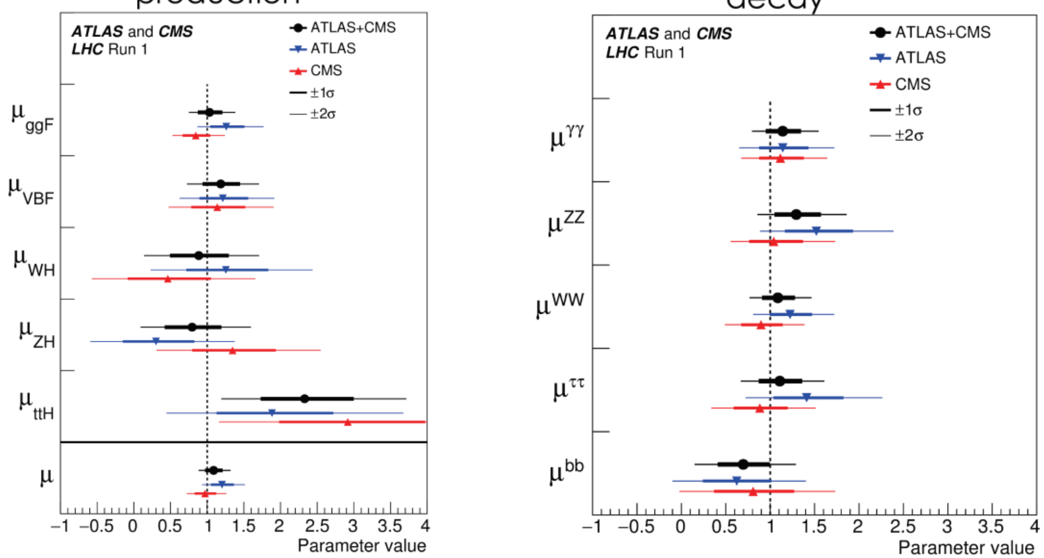
  Higgs sector may take the extended form because there is no principle

- LHC data ⇒ Discovered Higgs is SM-like one

signal strength $\mu=\sigma/\sigma_{SM}$

ATLAS+CMS JHEP 08 (2016) 045

production | decay

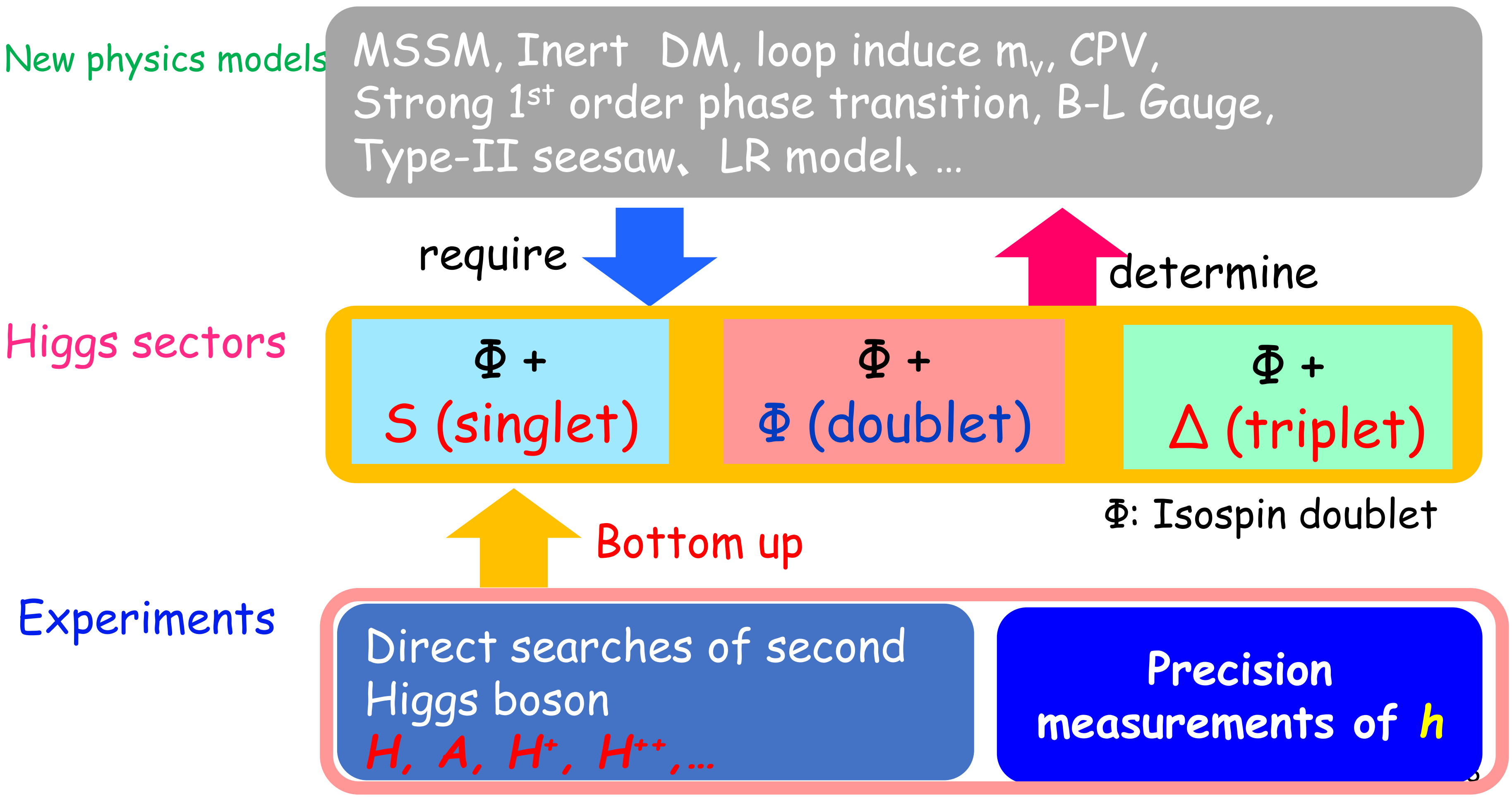


JHEP 1608, 045

- Data do not indicate SM Higgs sector is correct.

  Extended Higgs sectors also can explain current data of Higgs boson.

Higgs Sector is Window of New Physics !

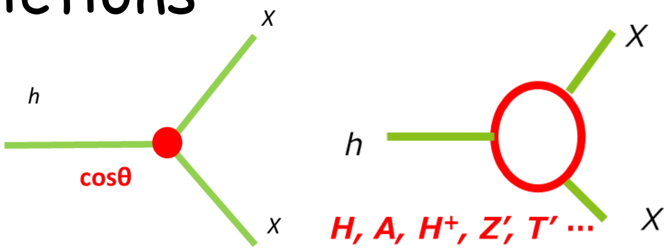


First step is determining Higgs sector by bottom up way

How to explore extra Higgs bosons

- Direct searches by collider experiments (*H*, *A*, H^+, …)

- Coupling deviations from SM predictions
  - Field mixing effects at the tree level
  - Loop effects of new particles



hZZ, hWW, hgg, hgg, hgZ, hbb, htt, htt, hhh, …

Coupling deviations might be detected in the future when the data will be more accumulated.

Precision measurements

Future prospect

Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%

Most of the Higgs couplings will be measured more precise accuracy at future colliders!!

Snowmass Higgs Working Group Report (1310.8361)

Higgs coupling measurements will become a powerful procedure to test extended Higgs sectors.

In my talk …

Indirect test of extended Higgs sectors by
precision measurements of discovered Higgs boson couplings

- Two Higgs doublet models, Singlet extension model
- Coupling deviations at tree level
- One-loop corrections to Higgs boson couplings
  (Renormalization, Remove gauge dependence)
- Fingerprinting Higgs boson couplings
- Summary

Models

- Two Higgs doublet models (2HDM)
- Higgs Singlet Model (HSM)

Two Higgs doublet models (2HDMs)

Φ_1, Φ_2 (I=1/2, Y=1/2)

In general, multi-doublet structures cause FCNCs.

To avoid FCNCs, Φ_1 and Φ_2 should have different quantum numbers each other.

Discrete Z_2 symmetry

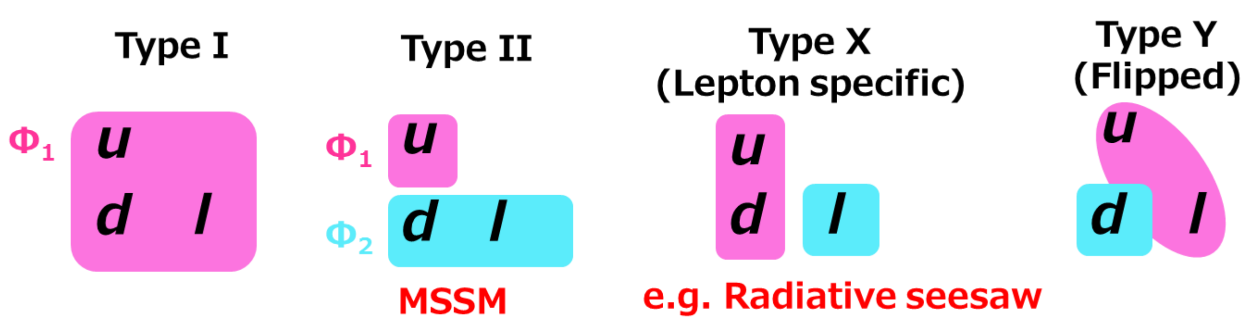
$$\Phi_1 \rightarrow +\Phi_1$$
$$\Phi_2 \rightarrow -\Phi_2$$

$$\mathcal{L}_Y = -\bar{Q}_{L,i}\left(\kappa_{ij}\Phi_1 + \cancel{\rho_{ij}\Phi_2}\right) f_{R,j} + h.c.$$

Glashow-Weinberg, '77

4 types of Yukawa interactions

	Z_2 charge						
	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R
Type-I	+	−	+	+	−	−	−
Type-II	+	−	+	+	−	+	+
Type-X	+	−	+	+	−	−	+
Type-Y	+	−	+	+	−	+	−



2HDMs : Higgs potential

Softly broken Z2 sym., CP invariance

$$\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + iZ_i) \end{pmatrix}$$

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

- Field mixing

Isospin state — Mass eigenstate

CP-odd component $\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} G^0 \\ A \end{pmatrix}$ $\tan\beta = \frac{v_2}{v_1}$

Charged component $\begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$ $v^2 = v_1^2+v_2^2 \sim (246\text{GeV})^2$

CP-even component $\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} H \\ h \end{pmatrix}$ → h : SM-like Higgs (125 GeV)

- Mass (Φ : H, A, $H^\pm$)

$m_\Phi^2 \cong \lambda' v^2 + M^2$ $M^2 = \frac{m_3^2}{\sin\beta\cos\beta}$

Higgs singlet model (HSM)

$$V(\Phi,S) = m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \lambda_{\Phi S}|\Phi|^2 S^2 + t_S S + m_S^2 S^2 + \mu_S S^3 + \lambda_S S^4,$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(\phi + v + iG^0) \end{pmatrix}, \quad S = s + v_S,$$

- **Mass eigenstates**

CP-even states : *h, H*

$$\begin{pmatrix} s \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

h, ***H***

SM-like Higgs boson — Extra Higgs boson

- **Mass formulae**

$$\tilde{M}^2 = 2m_S^2 + 12\lambda_S v_S^2 + 6 v_S \mu_S$$

$$m_h^2 = 2\lambda v^2 + \mathcal{O}\left(\frac{v^4}{\tilde{M}^2}\right)$$

$$m_H^2 = \tilde{M}^2 + \lambda_{\Phi S} v^2 + \mathcal{O}\left(\frac{v^4}{\tilde{M}^2}\right)$$

$$(\tilde{M}^2 \gg v^2)$$

Higgs couplings @ tree level

Pattern of deviations strongly depends on Higgs sector
- Representations (Φ, Δ, S, …)
- Number of Higgs fields
- Additional symmetries

Scaling factor

$$\kappa_X \equiv \frac{g_{hXX}}{g_{hXX}^{SM}}$$

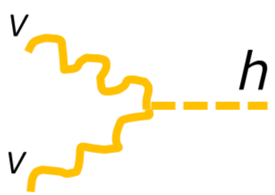
Field mixing

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

VEV sharing

$v^2 = v_1^2 + a_2 v_2^2 + \ldots$ ($v \simeq 246$ GeV)

- Gauge couplings (hWW, hZZ)



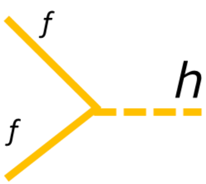
$$\leftarrow g^2 \sum_i c_i v_i h_i VV$$

Alignment limit

2HDMs $\kappa_V = \sin(\beta - \alpha) \rightarrow 1$

HSM $\kappa_V = \cos\alpha \rightarrow 1$

- Yukawa couplings (hff, hbb, htt, …)



$$\leftarrow \frac{m_f}{v_i} h_i ff$$

2HDM

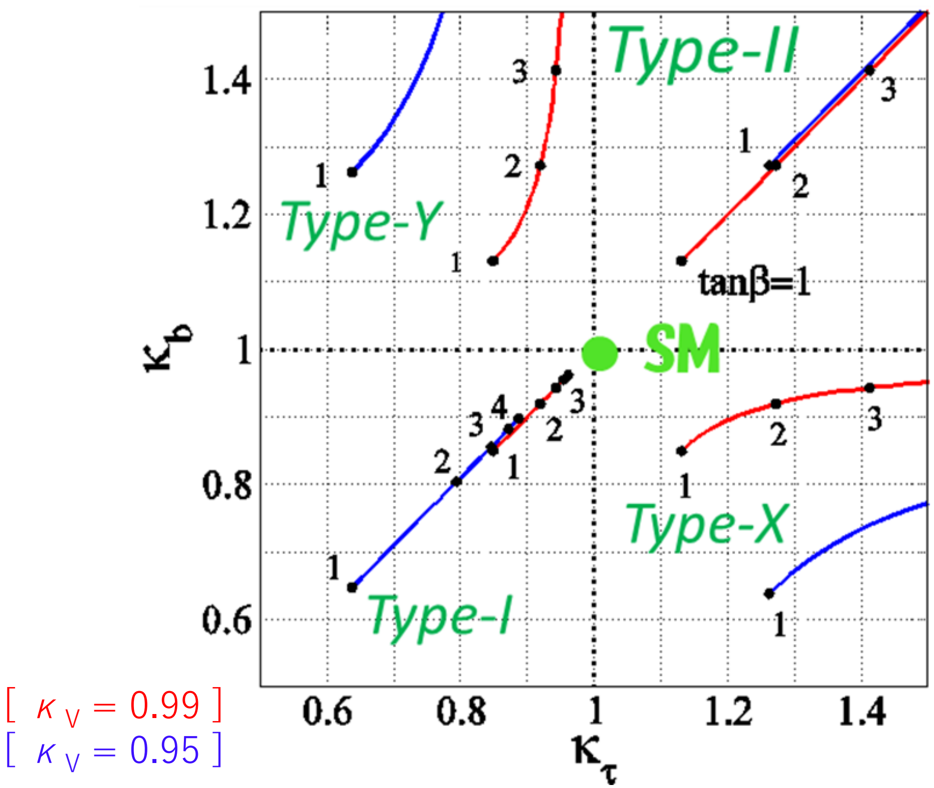
If f couples to Φ_2: $\kappa_f = \sin(\beta-\alpha) + \cot\beta \cos(\beta-\alpha)$

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

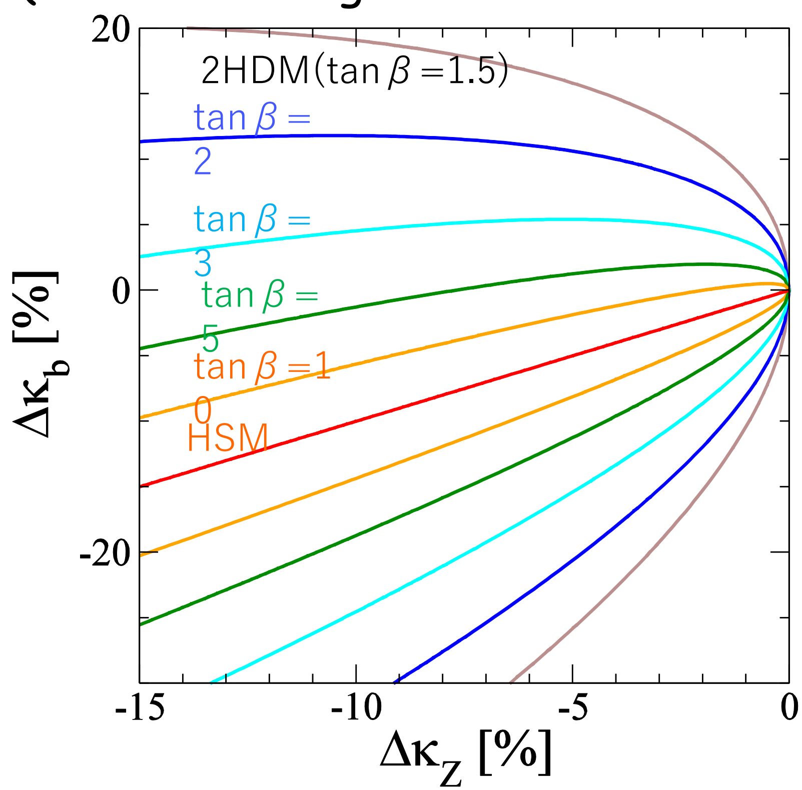
HSM $\kappa_f = \kappa_V = \cos\alpha \rightarrow 1$

Pattern of deviations

4types of 2HDMs



Type-I 2HDM , HSM
(Yukawa scaling factors are universal)



$\Delta\kappa_X \equiv \kappa_X - 1$

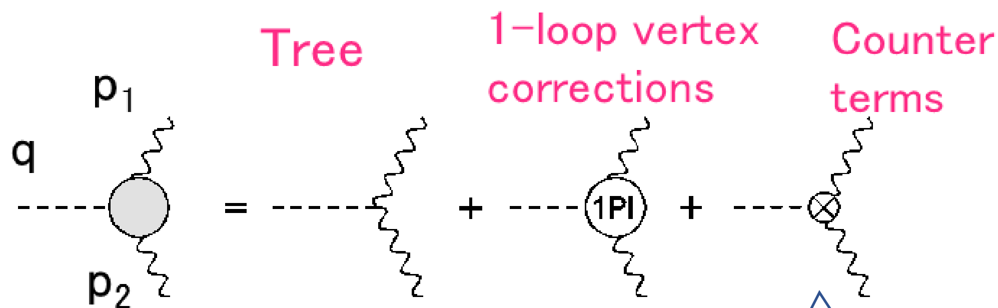
There are characteristic deviation pattern in each model at tree level .

Calculations of one-loop corrections

Calculations of one-loop corrections

We calculate renormalized couplings at the one-loop level by modified on-shell renormalization scheme.

$$\Gamma_{hZZ}^{THDM}[p_1^2, p_2^2, q^2] =$$



Involve divergence

Absorb the divergence

Flow to renormalized couplings

1. Introduce counter terms
2. Determine explicit forms of counter term
3. Calculate loop diagrams
4. Combine the three parts

Counter terms

Parameter shift ;

$$m_\varphi^2 \to m_\varphi^2 + \delta m_\varphi^2, \quad \alpha \to \alpha + \delta\alpha, \quad \beta \to \beta + \delta\beta, \quad M^2 \to M^2 + \delta M^2,$$

9

Field shift ;

$$\begin{pmatrix} H \\ h \end{pmatrix} \to \begin{pmatrix} 1 + \delta Z_H & \delta C_{Hh} + \delta\alpha \\ \delta C_{hH} - \delta\alpha & 1 + \delta Z_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

12

Tadpole shift ; $T_{\phi_1} \to T_{\phi_1} + \delta T_{\phi_1} \qquad T_{\phi_2} \to T_{\phi_2} + \delta T_{\phi_2}$ 2

9(parameters) + 2(Tadpole) + 6(fields) + 6(field mixing) = 23

Ex. >> *hZZ*

$$\Gamma_{hZZ}^{Tree} hZ^\mu Z^\nu = \frac{2m_Z^2}{v}\sin(\beta-\alpha)\, hZ^\mu Z^\nu$$

$$\to \frac{2m_Z^2}{v}\sin(\beta-\alpha)\underbrace{\left(1 + \frac{\delta m_Z^2}{m_Z^2} - \frac{\delta v}{v} + \delta Z_Z + \frac{1}{2}\delta Z_h + \frac{\cos(\beta-\alpha)}{\sin(\beta-\alpha)}(\delta C_{Hh} + \delta\beta)\right)}\, hZ^\mu Z^\nu$$

Counter term formula of *hZZ*

Renormalization conditions

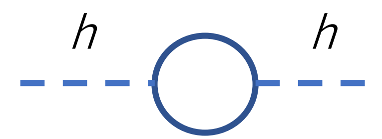
- On shell conditions

δm_h^2 $\quad \hat{\Pi}_{\phi\phi}[m_\phi^2] = 0.$

$$\delta m_h^2 = \frac{s_\gamma^2}{v}\delta T_1 - \frac{2 s_\gamma c_\gamma}{v}\delta T_2 + \Pi_{hh}^{\rm 1PI}[m_h^2],$$

δZ_h $\quad \frac{d}{dp^2}\hat{\Pi}_{\phi\phi}[p^2]|_{p^2=m_\phi^2} = 0,$

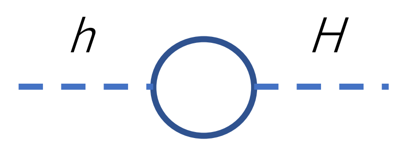
$$\boldsymbol{\delta Z_h = -\frac{d}{dp^2}\Pi_{hh}{}^{1PI}(m_h{}^2)}$$



δC_{Hh}, δC_{hH} $\quad \hat{\Pi}_{hH}[m_h^2] = \hat{\Pi}_{hH}[m_H^2] = 0,$

$\delta \alpha$ $\quad \hat{\Gamma}^1_{HZZ}[m_Z^2, m_Z^2, m_H^2]|_{\rm div.part} = 0,$

$$\delta C_{Hh} = \frac{1}{m_H^2 - m_h^2}\left(\Pi_{hH}^{\rm 1PI}[m_h^2] - \Pi_{hH}^{\rm 1PI}[m_H^2]\right)$$



δv $\quad \delta Z_Z$; Determined by renormalization in gauge sector
Composed of gauge boson two-point functions.

Gauge dependence in counter term

It is known that counter terms of mixing angle include gauge dep.

$$\delta m_{h_i}^2 = \Pi_{h_i h_i}(m_{h_i}^2) \qquad \delta\alpha = \frac{1}{2(m_H^2 - m_h^2)}\left[\Pi_{Hh}(m_h^2) + \Pi_{Hh}(m_H^2)\right]$$

Nielsen identity

N. K. Nielsen (1975).

$$\partial_\xi \Pi_{ij}(p^2) = F_{ij}(p^2)(p^2 - m_j^j) + (p^2 - m_i^2)F_{ji}^*(p^2),$$

For mass counter term, gauge dependence vanish because i=j.

$$\delta m_h^2 \propto (m_h^2 - m_h^2) * (F_{hh}(m_h^2) + F_{hh}^*(m_h^2))$$

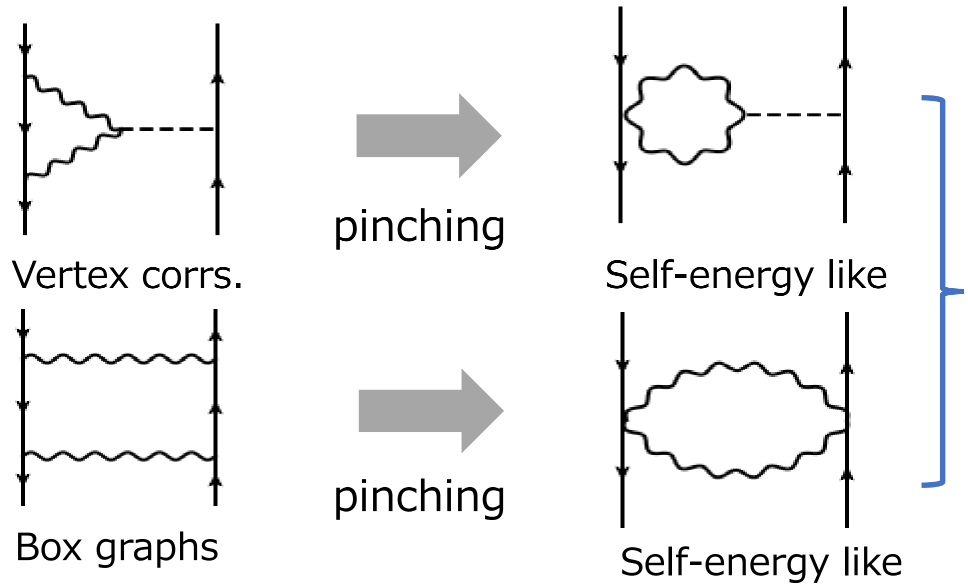
For counter terms of mixing angle, gauge dependence remains

$$\delta\alpha \propto F_{hH}(m_h^2) - F_{Hh}^*(m_H^2)$$

Pinch technique

In order to remove gauge dependence from counter terms, we pick up pinch terms from scattering amplitude $\bar{f}f \to \bar{f}f$.

Pinch tech.



We can extract **"pinch terms"**.

These cancel the δ_ξ part in 2p functions!

Gauge independent two-point functions

$$\Pi_{XY}{}^{1PI}(p^2) \longrightarrow \Pi_{XY}{}^{1PI}(p^2) + \Pi_{XY}{}^{PT}(p^2)$$

Counter terms can be expressed by gauge independent correlation functions

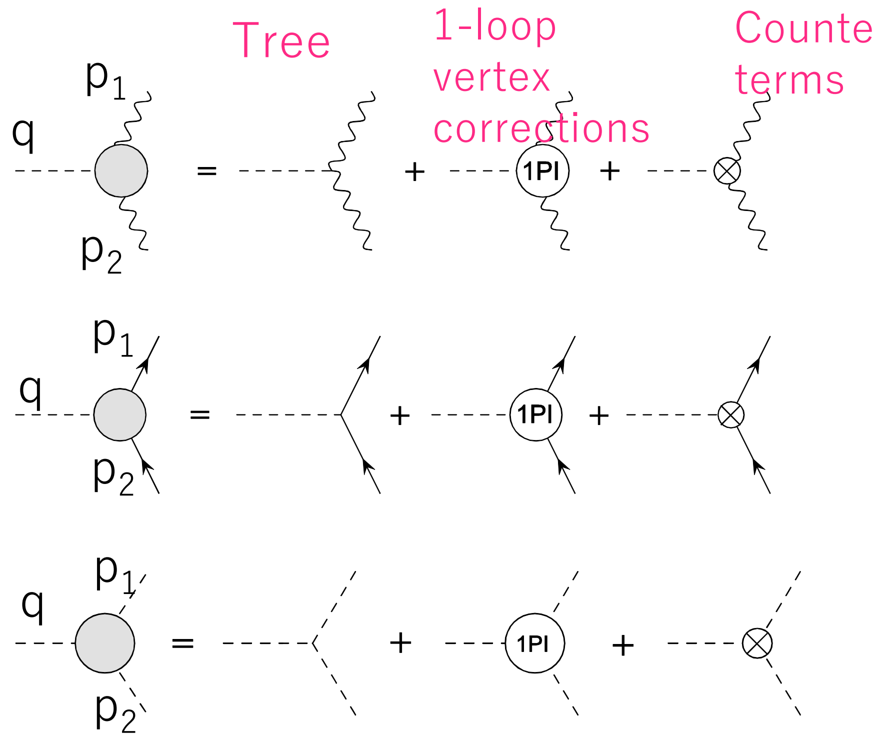
$$\delta\alpha = \frac{1}{2(m_H^2 - m_h^2)}\left[\Pi_{Hh}(m_h^2) + \Pi_{Hh}(m_H^2)\right]$$

Numerical calculations

$$\Gamma^{HSM}_{hVV}[p_1^2, p_2^2, q^2] =$$

$$\Gamma^{HSM}_{hff}[p_1^2, p_2^2, q^2] =$$

$$\Gamma^{HSM}_{hhh}[p_1^2, p_2^2, q^2] =$$



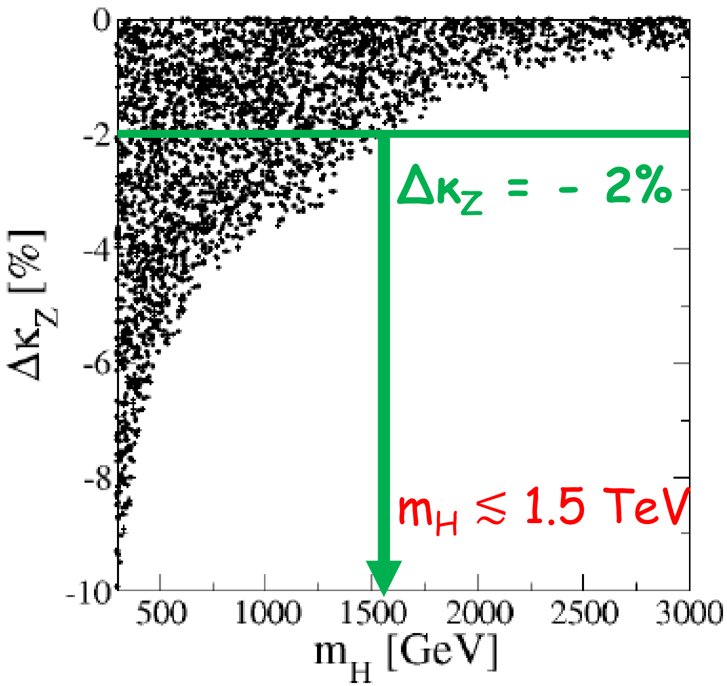
We numerically evaluate deviations of 1-loop scaling factors from 1 Δκ.

$$\Delta\kappa_V \equiv \frac{\Gamma^{HSM}_{hVV}\left[(m_h + m_V)^2, m_V^2, m_h^2\right]}{\Gamma^{SM}_{hVV}\left[(m_h + m_V)^2, m_V^2, m_h^2\right]} - 1 \qquad \Delta\kappa_f \equiv \frac{\Gamma^{HSM}_{hff}\left[m_f^2, m_f^2, m_h^2\right]}{\Gamma^{SM}_{hff}\left[m_f^2, m_f^2, m_h^2\right]} - 1$$

$$\Delta\kappa_h \equiv \frac{\Gamma^{HSM}_{hhh}\left[m_h^2, m_h^2, 4m_h^2\right]}{\Gamma^{SM}_{hhh}\left[m_h^2, m_h^2, 4m_h^2\right]} - 1$$

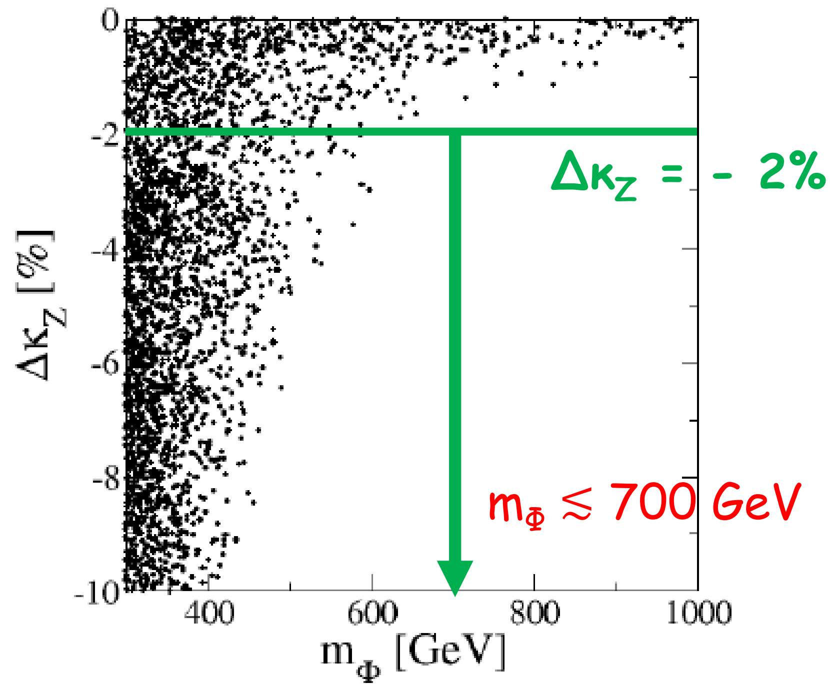
Decoupling behavior

HSM



2HDMs

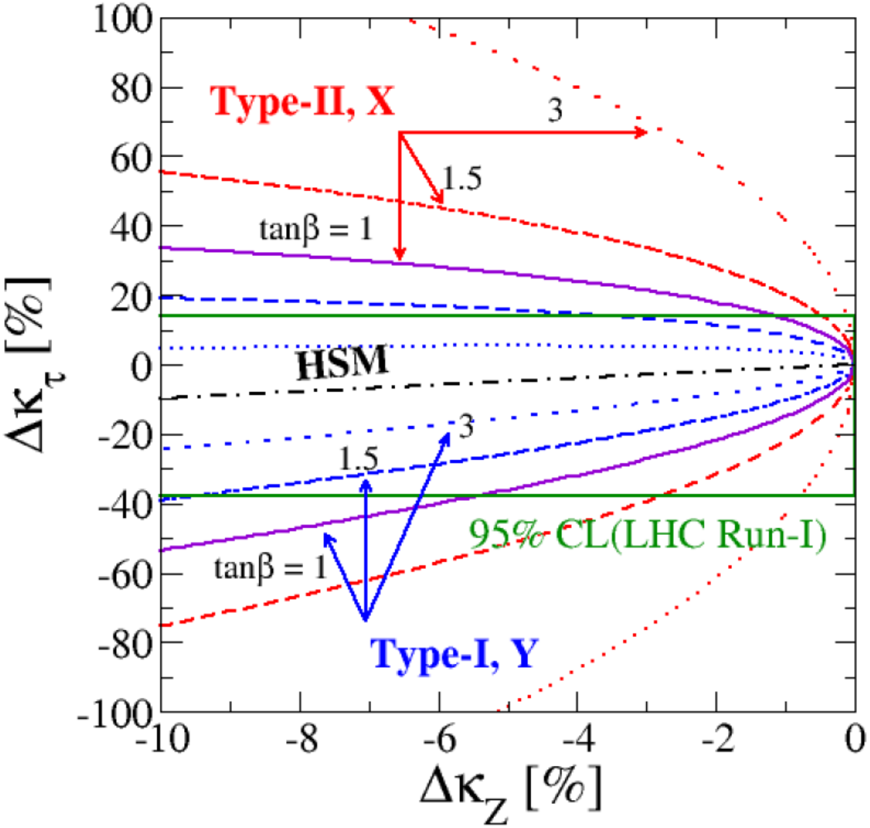
$m_\Phi = m_H = m_A = m_{H+}$



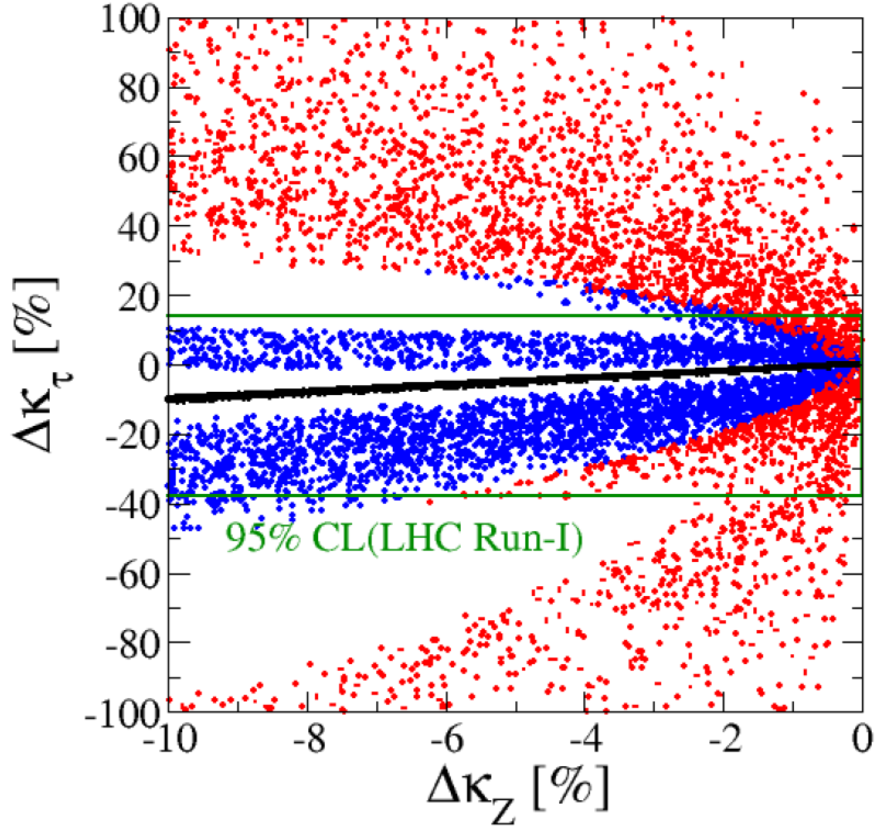
- Coupling deviations indicate new physics scale in each model
- $\Delta\kappa_X$ in 2HDMs more quickly reduces compared with case in HSM

$\Delta\kappa_Z$ VS $\Delta\kappa_\tau$

Tree level



One-loop level



Extended Higgs sectors can be discriminated by using characteristic patterns of coupling deviations.

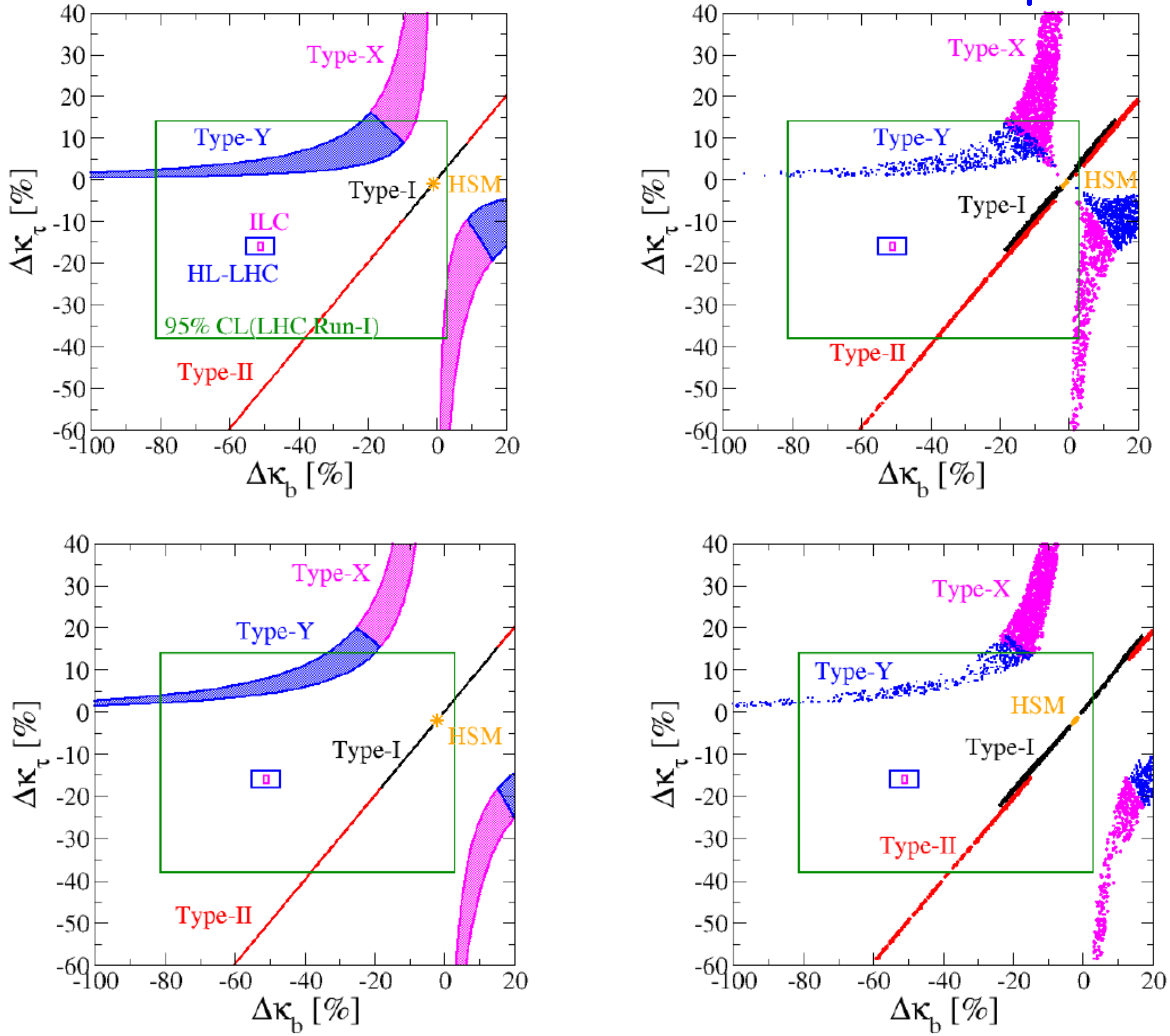
Fingerprinting

$\Delta\kappa_b$ VS $\Delta\kappa_\tau$

Tree level | One-loop level

$\Delta\kappa_Z = -1 \pm 0.58\%$

$\Delta\kappa_Z = -2 \pm 0.58\%$



$\Delta\kappa_Z$ VS $\Delta\kappa_\gamma$

HSM

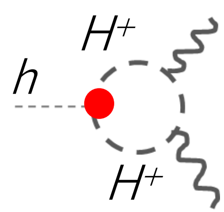
- There is no charged new particle.

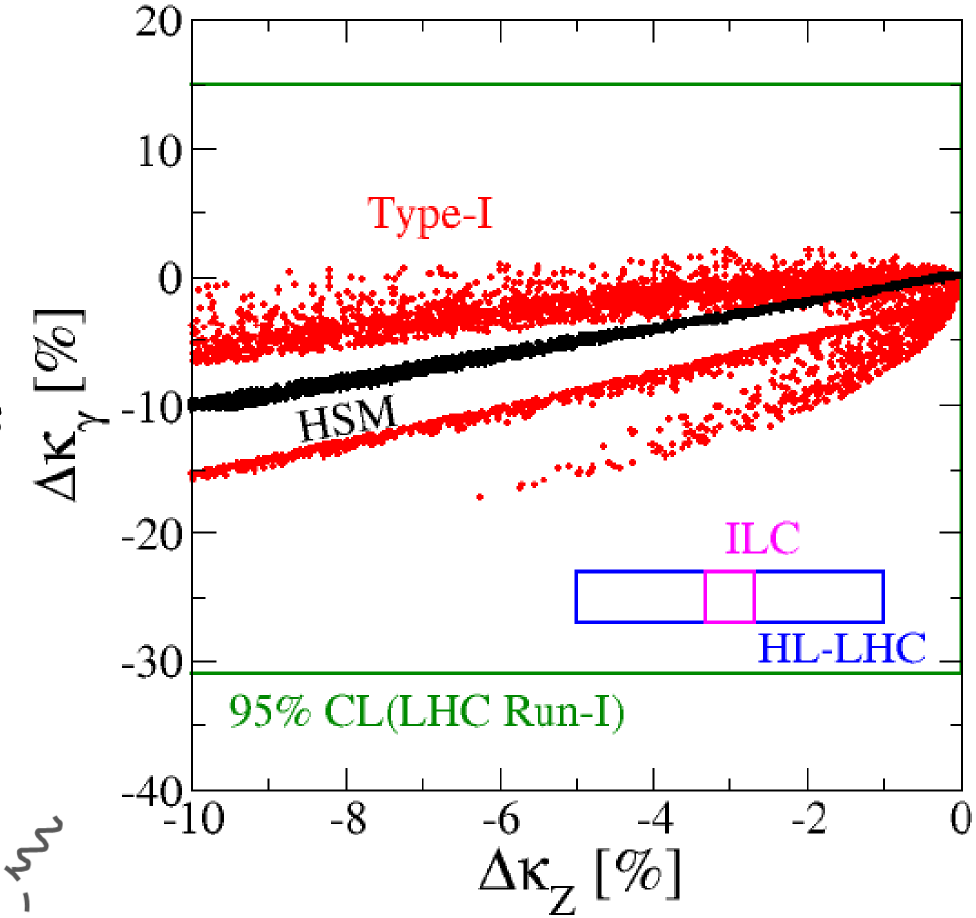
→ $\Delta\kappa_\gamma$ is made by mixing effects.

- *hZZ* and *hγγ* deviate to directions with the rate 1 : 1 by the mixing effect.

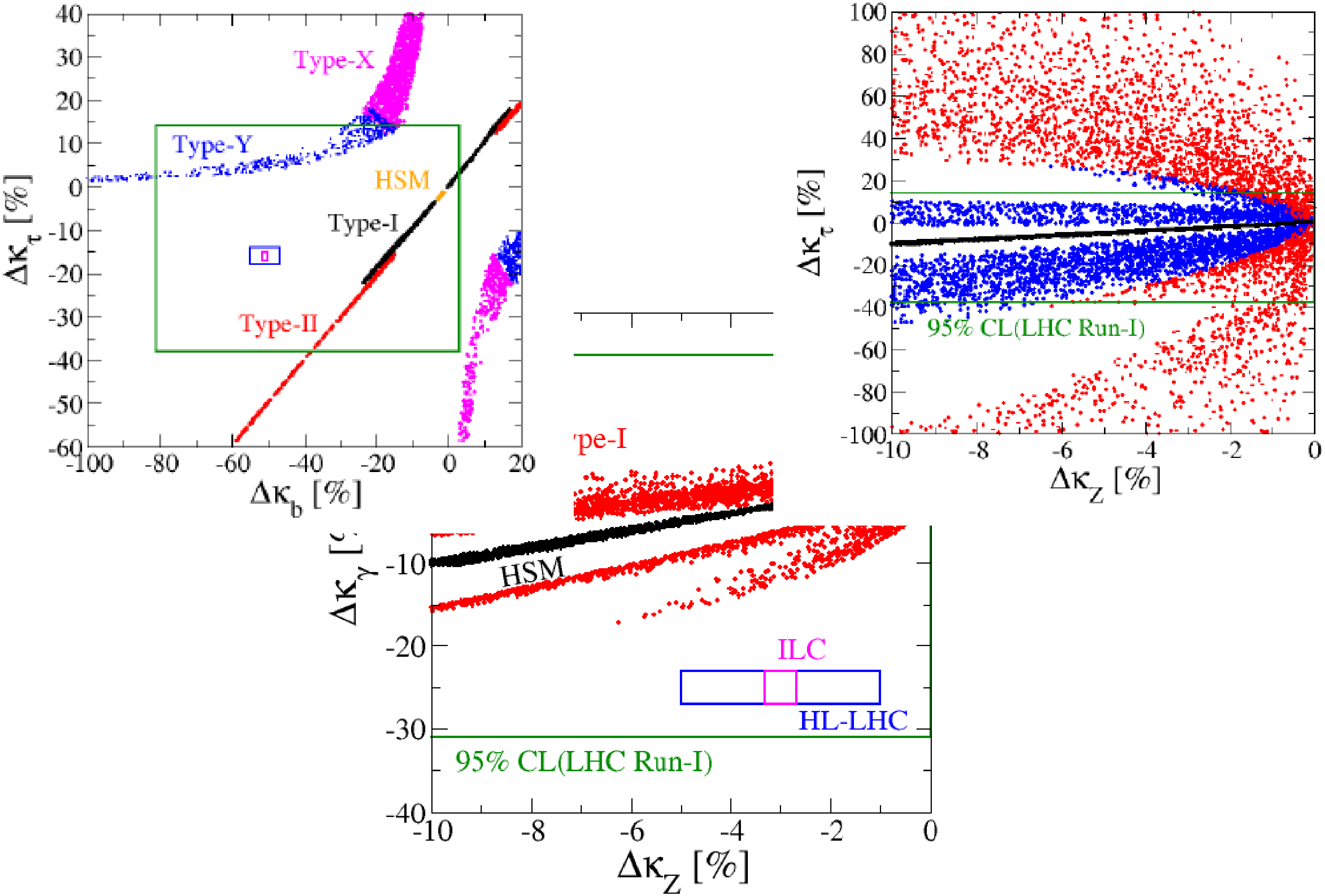
2HDM(Type I)

- Mixing effects and singly H+ loop contributions modify *hγγ*





Even in the region with $|\kappa_Z|$ ~ several %, predictions in 2HDMs can be largely different from those in the HSM because there is H+ loop effect in only 2HDMs.



In most of parameter regions except the decoupling limit,
we can discriminate models by using the pattern of deviations in various Higgs couplings, even if there is no discovery of new particles.

Summary

- Our purpose is to determine the Higgs sector by comparing future precision data of the Higgs boson couplings with the precise predictions with radiative corrections in various models.

hZZ, *hWW*, *h***gg**, *hgg*, *h***g***Z*, *hbb*, *h***tt**, *htt*, *hhh*,…

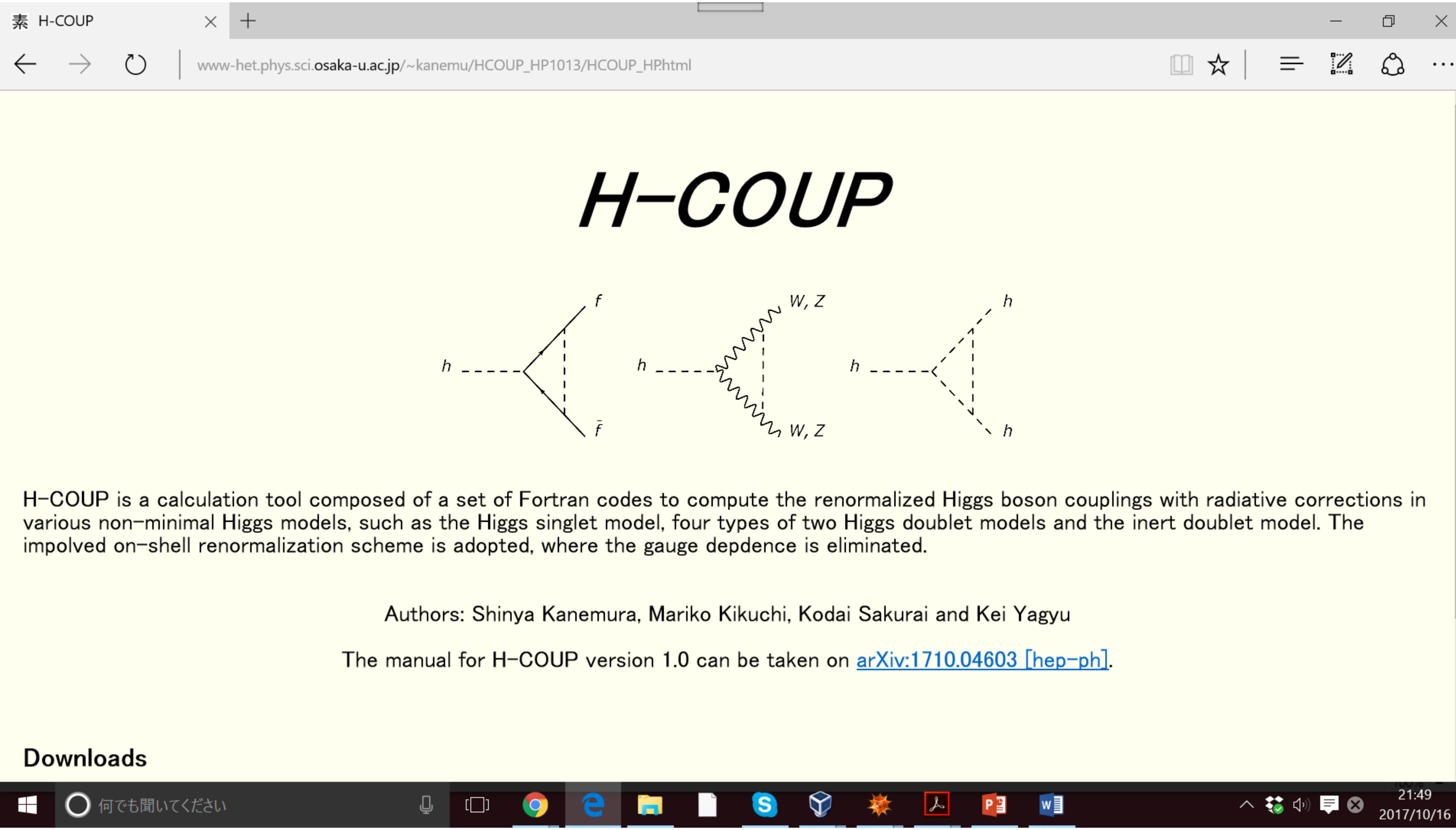
Radiative corrections

× Precision measurements ➡ Determination of the Higgs sector !!

- Fingerprinting ⇒

In most of parameter regions except the decoupling limit, we can discriminate models by using the pattern of deviations in various Higgs couplings, even if there is no discovery of new particles.

Notice !!



http://www-het.phys.sci.osaka-u.ac.jp/~kanemu/HCOUP_HP1013/HCOUP_HP.html