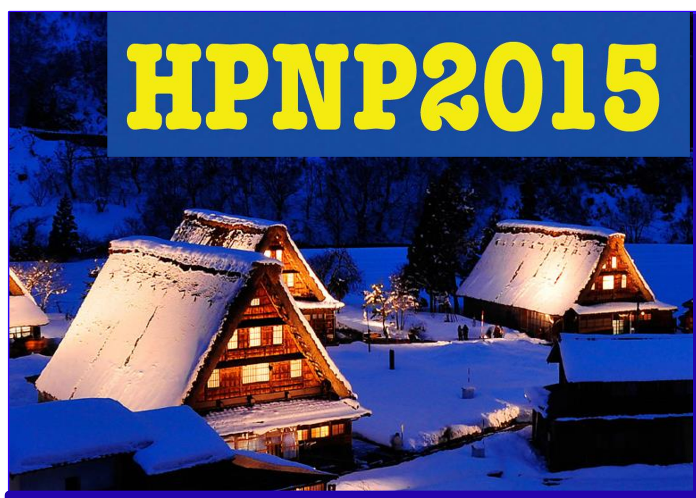

Exploring extended Higgs sectors by radiative corrections with future precision coupling measurements

1. Physics Letters B731(2014); 2. In preparation
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I. Introduction

Although m_h was found at the LHC, the structure of the Higgs sector is unknown.
(No principle to require a minimal Higgs sector)

New physics beyond the SM

Characteristic Higgs sector: Doublet, Triplet, Singlet

Direct searches $H, A, H^+, H^{++}, \ldots$ | Indirect searches Discovered 126 GeV h

Strong relation between NP and Higgs sector !

Higgs as a probe of NP !!

By bottom up using experimental data, Higgs sector can be reconstructed.

Direction of new physics beyond SM can be determined !!

II. Our project

Theoretical predictions of h-couplings at loop level × Precision measurements of Higgs couplings = Determination of Higgs sector

We calculate h-coupling with radiative corrections in extended Higgs sectors. (Higgs singlet model, Two Higgs doublet models, Higgs triplet model, Inert models…)

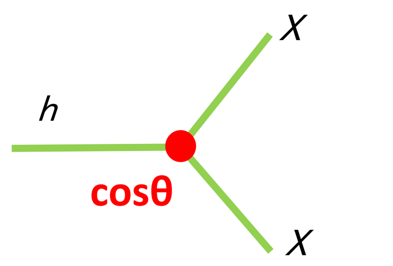
h-couplings can deviate from SM predictions by NP effects.

1. Mixing

The mixing factors depend on
- representations of Higgs fields
- symmetries in the theory

} Structure of Higgs sector

A pattern of deviations indicate the structure.

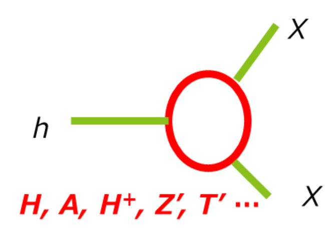


$h = \phi_1 \cos\theta + \phi_2 \sin\theta$

$hZZ, hWW, h\gamma\gamma, hgg, h\gamma Z, hbb, h\tau\tau, htt, hhh,\ldots$

2. Loop effects

Directions and magnitudes of the deviations depend on
- Spin
- Decoupling properties of New particle



By comparing future precision data, extract properties of Higgs sector.

⇒ Determine the Higgs sector !!

III. Two Higgs doublet models

To avoid FCNCs, we introduce a Z_2 symmetry.

$\Phi_1 \to +\Phi_1$

$\Phi_2 \to -\Phi_2$

Barger, Hewett, Phillips(1990), Aoki, Kanemura, Tsumura, Yagyu(2009)

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	+	−	+	+	−	+	−

● Higgs potential with Softly broken Z_2 & CP invariance

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

Soft-breaking scale of Z_2 sym. $M^2 = \dfrac{m_3^2}{\sin\beta\cos\beta}$

● Mass eigenstates h: SM-like Higgs, $H, A, H^\pm$: Extra Higgs, $G^0\, G^\pm$ NG bosons

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

● Parameters(8)

$m_H \;\; m_A \;\; m_{H^+} \;\; \alpha \;\; \beta \;\; M^2$ — 6 free parameters

$m_\Phi^2 \sim \lambda v^2 + M^2$

$v \simeq 246$ GeV $\quad m_h \simeq 126$ GeV $\quad \tan\beta = \dfrac{v_2}{v_1} \quad v^2 = v_1^2 + v_2^2 \sim (246{\rm GeV})^2$

IV. Higgs couplings at the tree level

● Gauge couplings (hWW, hZZ)

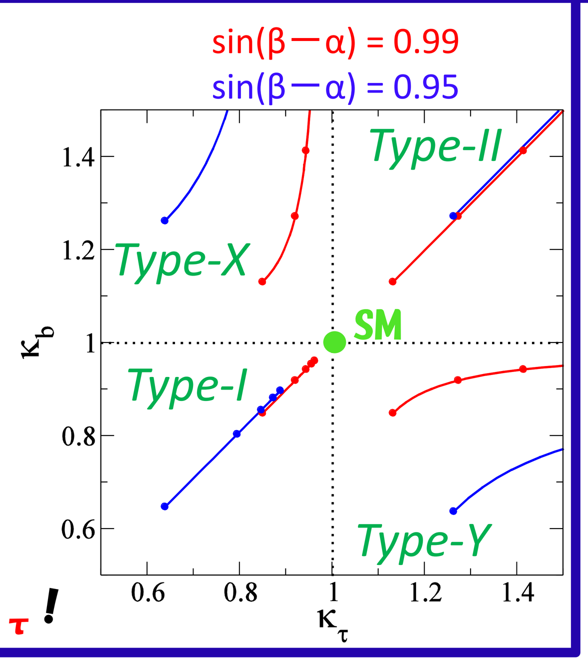
$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \sin(\beta-\alpha)$$

SM-like limit; $\kappa_V = \sin(\beta-\alpha) \to 1$

● Yukawa couplings ($htt, hbb, h\tau\tau,\ldots$)

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

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



Discriminate types by a pattern of deviations in κ_b and κ_τ !

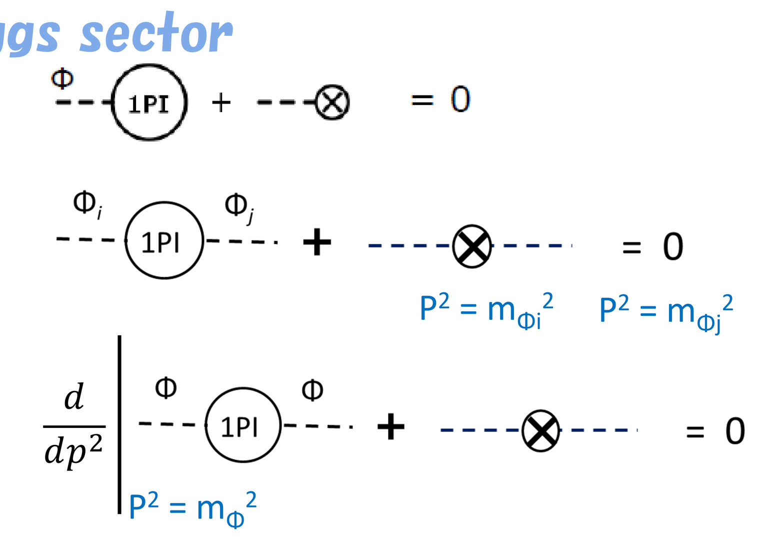
V. Method (Renormalization)

• # of counter-term : 5 (Gauge) + 3 × # of fermion (Yukawa) + 21 (Higgs)

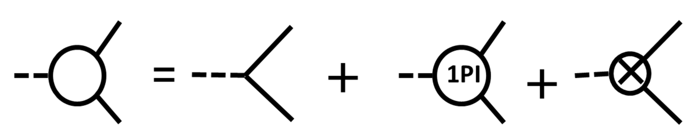
• On-shell renormalization conditions

Ex.>> Higgs sector

δT_h, δT_H | δm_Φ^2, $\delta\alpha$, $\delta\beta$ … | δZ_h, δZ_H, δZ_A, δZ_{H^+}, δZ_{G^0}, δZ_{G^+}



Using the counter terms, we calculate **Renormalized Higgs couplings.**



VI. Radiative corrections to h-couplings

$\beta - \alpha \equiv \frac{\pi}{2} - x$

$$\Delta\hat\kappa_X \equiv \frac{\hat\Gamma_{hXX}}{\hat\Gamma_{hXX}^{SM}} - 1$$

Deviations in scale factors at 1-loop level

Approximate formulae

SM-like; $x \ll 1$ $\quad \cos(\beta-\alpha) = x \quad [\, \sin(\beta-\alpha) = 1 - \frac{x^2}{2}\,]$

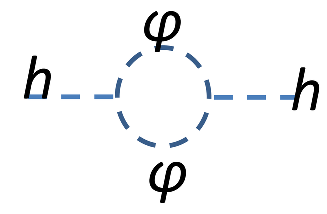
Gauge couplings

$$\Delta\hat\kappa_V \simeq -\frac{1}{2}x^2 - \frac{1}{16\pi^2}\frac{1}{6}\sum_{\Phi=A,H,H^\pm} c_\Phi \frac{m_\Phi^2}{v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^2, \qquad (\Phi = H^\pm, A, H)$$

Loop corrections

$$m_\Phi^2\left(1 - \frac{M^2}{m_\Phi^2}\right)^2 \begin{cases} \propto \dfrac{1}{m_\Phi^2} & (M \gg v) \text{ Decoupling! } \cdots\cdots \eta = 0 \\ \propto m_\Phi^2 & (M \sim v) \text{ Non-decoupling! } \cdots \eta = 1 \text{ (or more)} \end{cases}$$

Loop corrections show decoupling property ! $\quad \eta = 1 - \dfrac{M^2}{m_\Phi^2}$



Yukawa couplings

$$\Delta\hat\kappa_\tau \simeq \Delta\hat\kappa_V + \xi_e x \qquad \Delta\hat\kappa_c \simeq \Delta\hat\kappa_V + \xi_u x$$

$$\Delta\hat\kappa_b \simeq \Delta\hat\kappa_V + \xi_d x - \frac{1}{16\pi^2}\xi_u\xi_d\frac{2m_t^2}{v^2}\left(1 - \frac{m_t^2}{m_{H^\pm}^2} - \frac{M^2}{m_{H^\pm}^2}\right)$$

$$\Delta\hat\kappa_t \simeq \Delta\hat\kappa_V + \xi_u x - \frac{1}{16\pi^2}\frac{1}{6}\xi_u^2\sum_{\Phi=A,H,H^\pm}\frac{m_t^4}{v^2 m_\Phi^2}$$

	ξ_u	ξ_d	ξ_ℓ
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Mixing factors

Decay rate of loop induce process

$$\Gamma(h\to\gamma\gamma) \simeq \frac{G_F\alpha_{\rm em}^2 m_h^3}{128\sqrt{2}\pi^3}\left|-\frac{1}{3}\left(1 - \frac{M^2}{m_{H^\pm}^2}\right) + Q_f N_c^f(1 + \xi_f x - \frac{x^2}{2})I_f + (1 - \frac{x^2}{2})I_W\right|^2$$

VII. Extractions of inner parameters

Kanemura, MK, Yagyu, in preparation

Set A	LHC3000 1σ	ILC(250+500) 1σ	
$\Delta\hat\kappa_V = -1.0$	±2 ,	±0.4	%
$\Delta\hat\kappa_\tau = +18$	±2 ,	±1.9	%
$\Delta\hat\kappa_b = +18$	±4 ,	±0.9	%

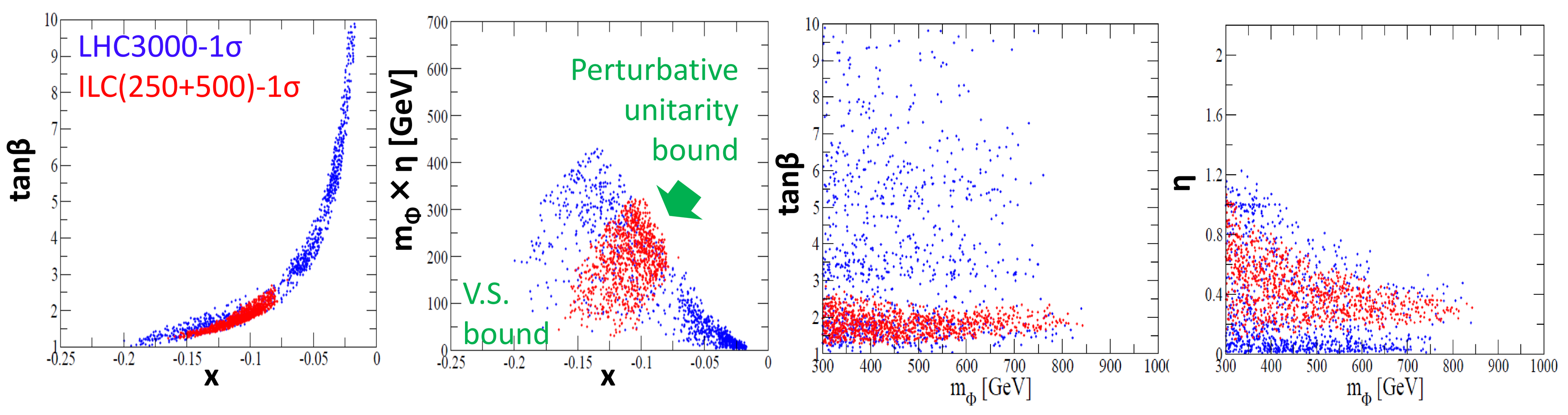
- We assume Set A.

⇒ Type II THDM !!

- How we can extract values of inner parameters?

Simulation results

V.S. ≡ vacuum stability



- **Mixing factors can deviate from tree level prediction.**
  ⇒ **We extract precise values of mixing factor.**
- **Upper limit for the mass of 2nd Higgs boson.**

VIII. Summary

$hZZ, hWW, h\gamma\gamma, hgg, h\gamma Z, hbb, h\tau\tau, htt, hhh,\ldots$

Radiative corrections

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Precision measurements

- Structure of the Higgs sector
- Decoupling property
- Inner parameters

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Determination of the Higgs sector !

Direction of new physics !!