Probing the extended Higgs sector from precision measurements of the Higgs boson decays

1. S. Kanemura, M. Kikuchi, K. Yagyu, Nucl. Phys. B 896, 80 (2015).
2. S. Kanemura, M. Kikuchi, K. Yagyu, Nucl. Phys. B(2015).

May 24, 2016　Seminar @ Osaka University

Mariko Kikuchi

U. of Toyama　→ National Taiwan U. (Taipei) from August

Contents

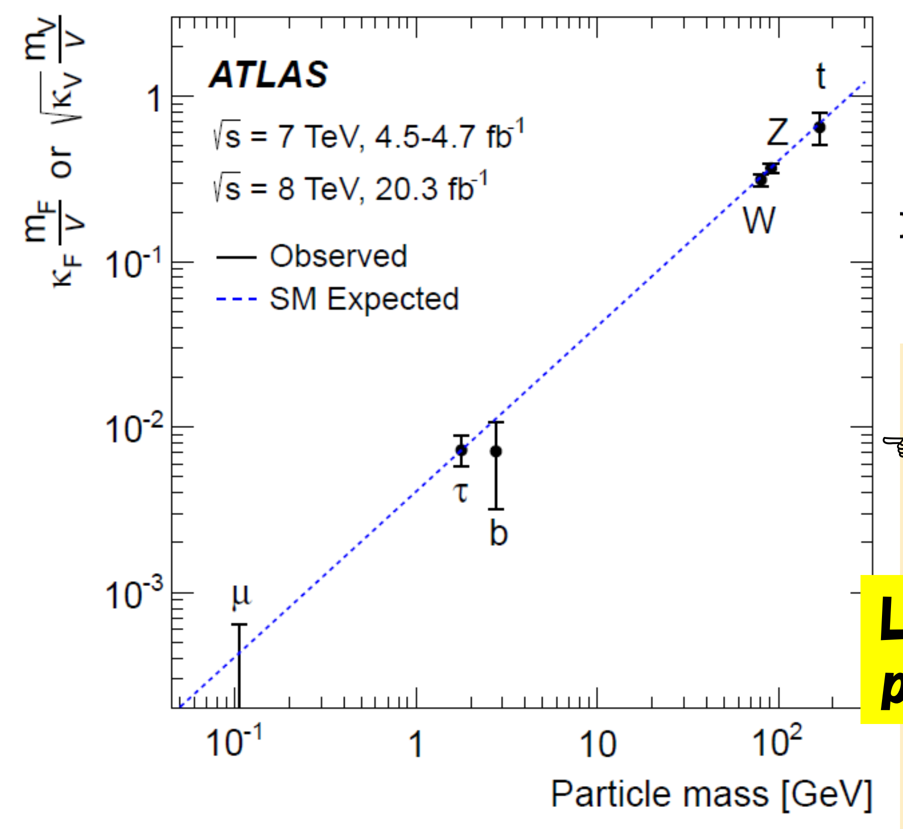
Introduction

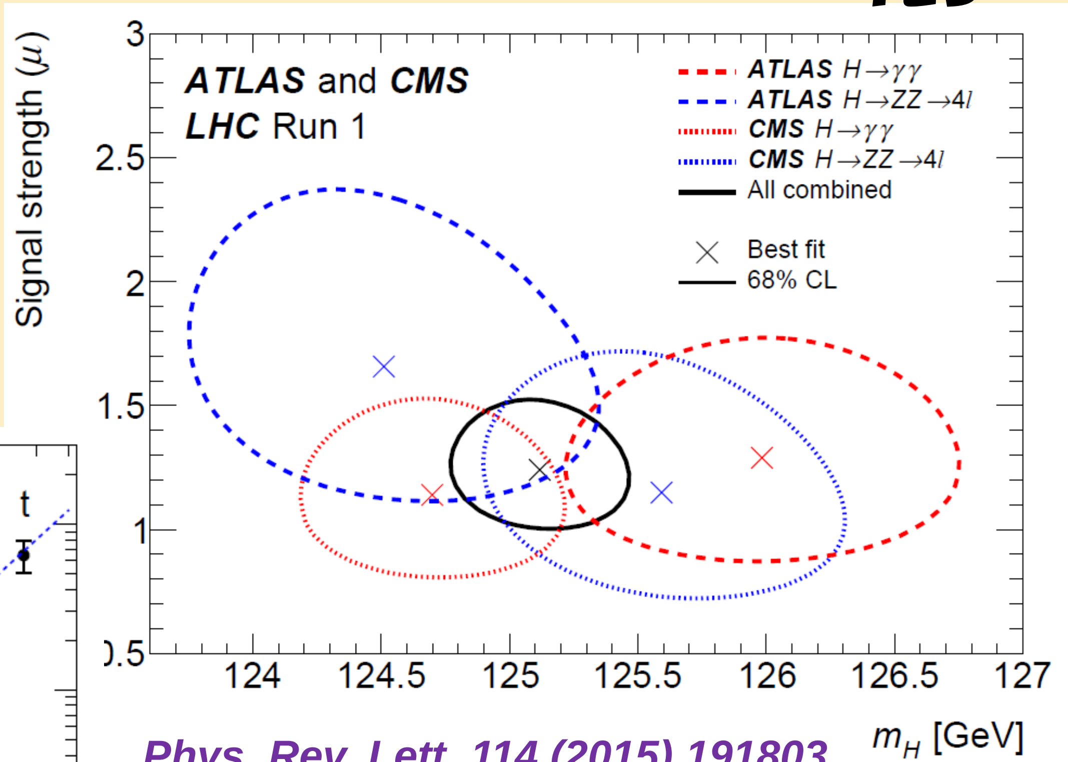
Current data of the Higgs boson h_{125}

Mass ≃ 125 GeV ☞

Spin parity : 0^+

ATLAS ePrint:1507.04548





Phys. Rev. Lett. 114 (2015) 191803

☜ **Strength of interaction**

LHC data are consistent with the predictions of the SM Higgs boson.

Mysteries in the Higgs sector

$$V = \mu^2|\Phi|^2 + \lambda|\Phi|^4. \qquad \mu^2 < 0$$

- # of scalar multiplets, their representations
- Negative mass term in the SM Higgs potential
- Hierarchy problem
- Elemental scalar? or Composite scalar?
- …

We don’t know the true Higgs sector!
We should consider not only the minimal one but also extended Higgs sectors.

New physics via the Higgs sector

New physics models

MSSM, Inert DM, loop induce m_ν, CPV,
Strong 1st order phase transition, B-L Gauge,
Type-II seesaw、 LR model、…

require

determine

Higgs sector

Φ + S (singlet)	Φ + Φ (doublet)	Φ + Δ (triplet)

Φ: Isospin doublet

Bottom up

Experimentation

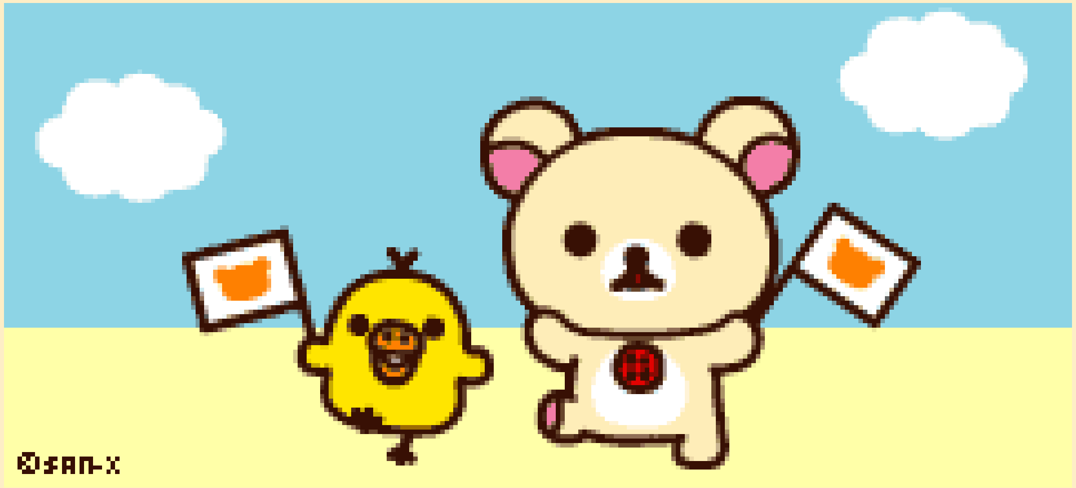
Direct searches of second Higgs boson
H, A, H^+, H^{++},…

Precision measurements of *h*

If we know the true Higgs sector,
we can determine the direction of new physics

To clarify the structure of the Higgs sector is one of the most important study of NP !

Indirect tests of extended Higgs models by precision measurements of the Higgs boson couplings



Extended Higgs sectors

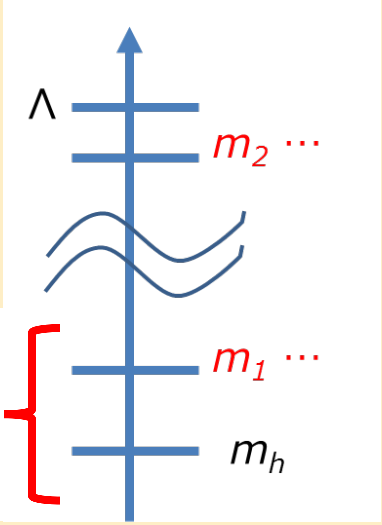
We focus on general extended Higgs sectors !

- Renormalizeble theory
- General models → There are many models.
- 2nd Simplest Higgs sector → The number is not so much.

$$\Phi_1(I=1/2,\ Y=1/2)\ +\ \Phi_2\ (I,\ Y)$$

- The model with the 2nd simplest can be the effective theory of the genera extended Higgs models.

2nd Simplest Higgs model may be the effective theory.



We investigate the possibility the Higgs sector is 2nd Simplest.

Second simplest Higgs sectors

$$\Phi = \begin{pmatrix} \omega^+ \\ \frac{1}{\sqrt{2}}(h+v+iz) \end{pmatrix}$$

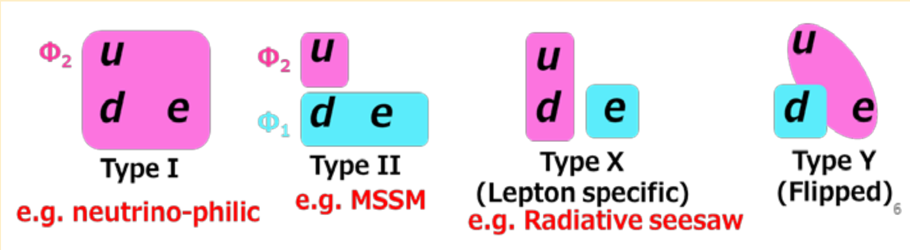
I=1/2, Y=1/2

+ additional Higgs field φ × New symmetries

HSM Φ + S (I=0, Y=0)

2HDM Φ + Φ' (I=1/2, Y=1/2)

Softly broken Z_2 sym. → 4 types models



IDM Unbroken Z_2 sym. Φ + Φ' (I=1/2, Y=1/2, Z_2-odd)

HTM Φ + Δ (I=1, Y=1)

Φ + Δ' (I=1, Y=0)

2 Higgs doublet models (2HDM)

Softly broken Z2 sym., CP invariance

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

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

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

- **Mass** (Φ : $H, A, H^\pm$)

$m_\Phi^2 \cong \lambda' v^2 + M^2$

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

- **Parameters (8)**

m_h v m_H m_A m_{H+} α β M^2

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

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

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

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

■ Parameters (8)

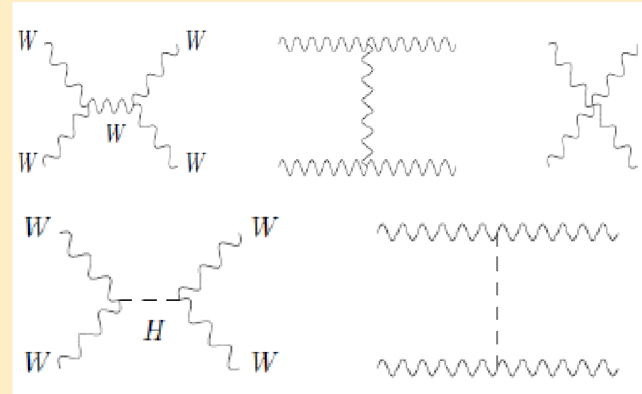
m_h v m_H α μ_S $\lambda_{\Phi S}$ λ_S v_S

Theoretical constraints

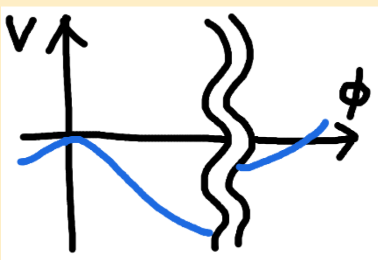
◆ Perturbative unitarity

$$|a_0(W_L^+W_L^- \to W_L^+W_L^-)| < 1/2$$

Kanemura, Kubota, Takasugi (1993),
Akeroyd, Arhrib, Naimi (2000).



◆ Vacuum stability



$$\lambda > 0, \quad \lambda_S > 0, \quad 4\lambda\lambda_S > \lambda_{\Phi S}^2$$

◆ Wrong vacuum conditions

Extrema except EW vacuum

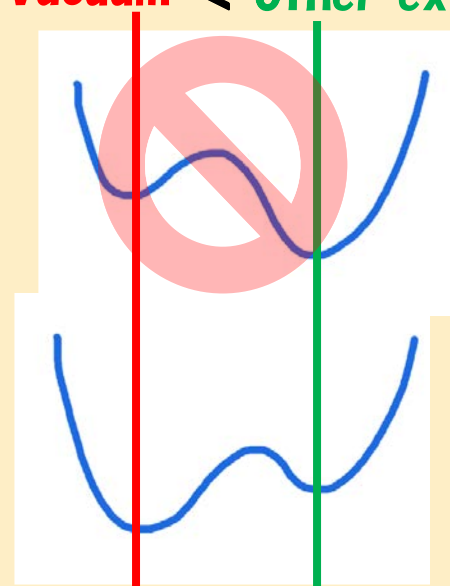
$$(v', v'_S) = (v_+, x_+), \ (v_-, x_-), \ (0, x_1^0), \ (0, x_2^0), \ (0, x_3^0)$$

These extrema must be higher than EW vacuum !

$$\boxed{V_{nor}(v_\pm, x_\pm) > 0, \quad V_{nor}(0, x_{1,2,3}) > 0,}$$

Chen, Dawson, Lewis (2015)

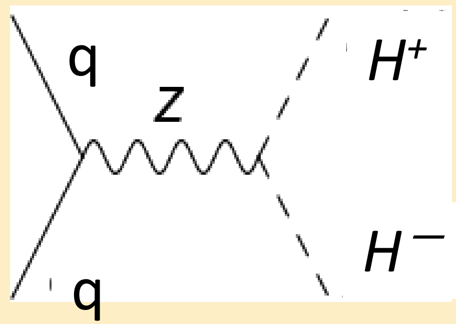
EW vacuum < Other extrema

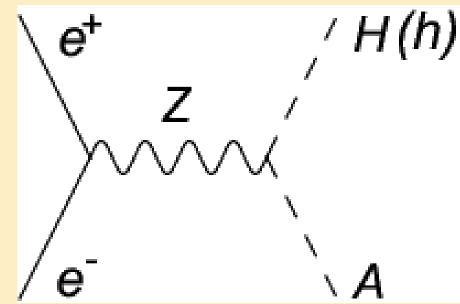


Test at collider experiments

Extended Higgs sectors are typically tested by collider experiments.

Direct search :

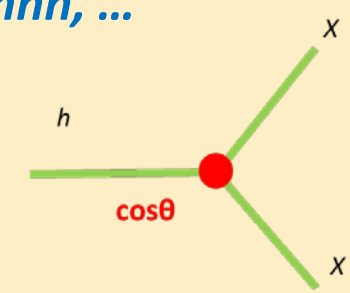


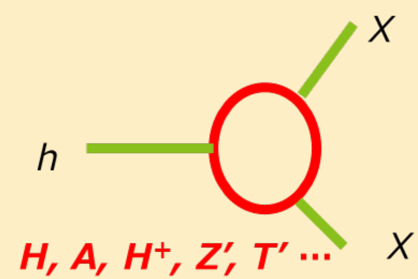


Indirect search : Precision measurements of 125GeV Higgs boson couplings

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

- Higgs boson coupling can deviate from the SM values.
- The deviation pattern depend on the Higgs sector.





→ We may discriminate extended models by using such characteristic deviation patterns.

We focus on the indirect search by the fingerprinting of the Higgs boson couplings !!

Higgs couplings @ tree level

Pattern of deviations strongly depends on Higgs sector

- Representations (Φ, Δ, S, ⋯)
- Number of Higgs fields
- Additional symmetries

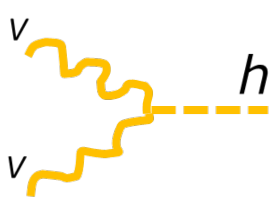
Field mixing

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

VEV sharing

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

■ Gauge couplings (*hWW, hZZ*)



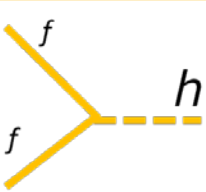
$\leftarrow g^2 \sum_i c_i v_i h_i VV$

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

Alignment limit

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

■ Yukawa couplings (*htt, hbb, h*$\tau\tau$, ⋯)



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

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 Higgs couplings

In the SM like limit, $\Delta\kappa_V = -(1/2)\,x^2 \quad (x << 1)$ $\qquad \Delta\kappa_a = \kappa_a - 1$

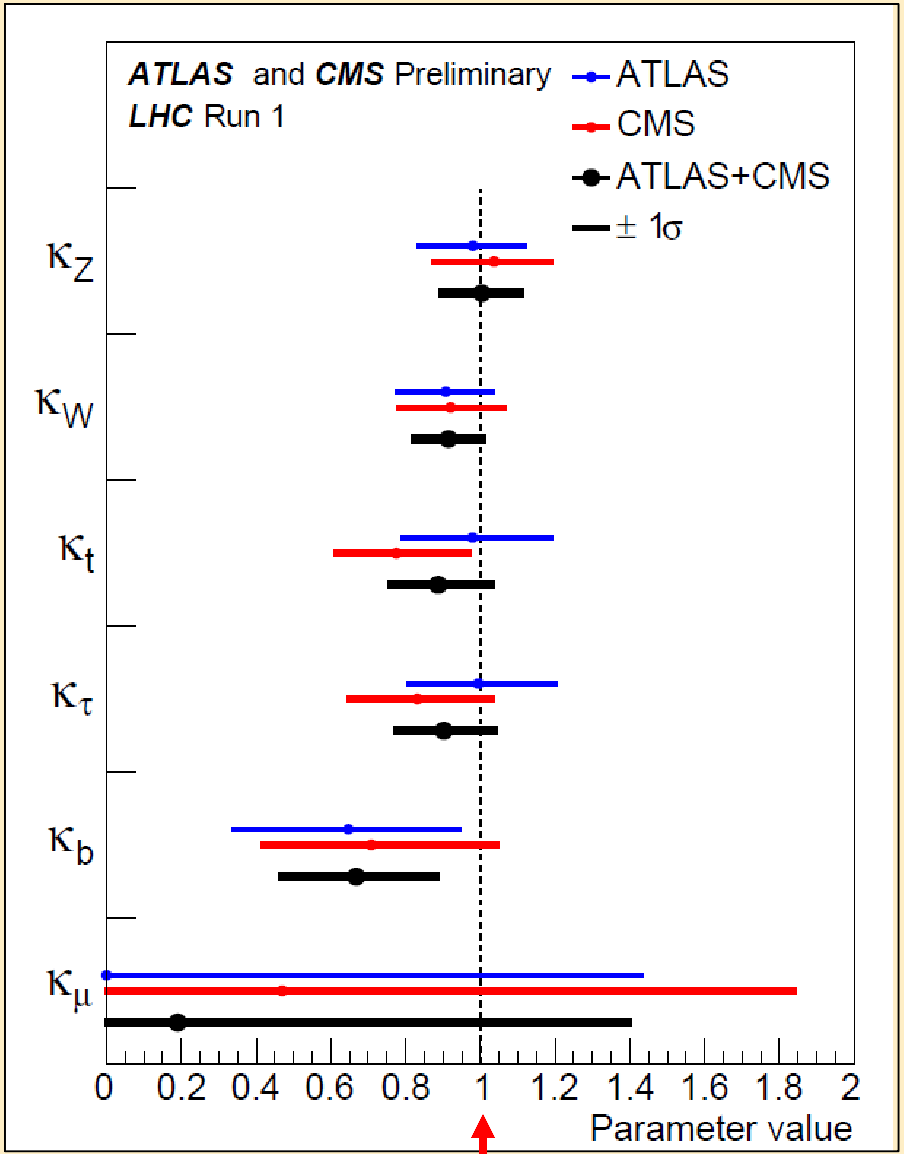
↑ Larger or ↓ Smaller than SM values

(x < 0)	$\Delta\kappa_u$	$\Delta\kappa_d$	$\Delta\kappa_e$	If $\Delta\kappa_V$= -1 %
Φ+S	$-(1/2)\,x^2$	$-(1/2)\,x^2$	$-(1/2)\,x^2$	-1 %
Type I 2HDM	$-\cot\beta\,\lvert x\rvert$	$-\cot\beta\,\lvert x\rvert$	$-\cot\beta\,\lvert x\rvert$	-O(10) %
Type X 2HDM	$-\cot\beta\,\lvert x\rvert$	$-\cot\beta\,\lvert x\rvert$	$+\tan\beta\,\lvert x\rvert$	O(10) %
MSSM (Type II 2HDM)	$-\cot\beta\,\lvert x\rvert$	$+\tan\beta\,\lvert x\rvert$	$+\tan\beta\,\lvert x\rvert$	O(10) %

We can discriminate models by pattern of deviations in *hXX* couplings except in decoupling limit.
→ We need to evaluate all measurable couplings of the Higgs boson.

Coupling measurements

Current data



SM prediction

Consistent with those of the SM within the 2σ uncertainties.
(accuracy:10%, 68%CL)

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Coupling 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)

We should investigate these couplings with higher order corrections in several extended Higgs sectors now !

Our project

Kanemura,
Kikuchi, Yagyu

- We calculate a full set of 125 GeV Higgs boson couplings with radiative corrections in the 7 models. (Without QCD corrections)

HSM, 2HDMs, IDM, HTM × hZZ, hWW, hbb, $h\tau\tau$, htt, hcc, $h\gamma\gamma$, $h\gamma Z$, hgg, hhh

- Our purpose : To determine the Higgs sector by comparing future precision data of various Higgs couplings with the precise calculations including one-loop corrections.

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

Radiative corrections

× Precision measurements → Determination of the Higgs sector !!

We make the program code group of the calculation for the 1-loop corrected Higgs boson couplings.
We will publish the 1-loop calculation codes named H-COUP.

Calculations have been almost done .

Singlet model (HSM)

Kanemura, MK, Yagyu, arXiv:1511.06211(2015)

Two Higgs doublet model (2HDM)

Kanemura, MK, Yagyu, NPB 896,80(2015)
Kanemura, MK, Yagyu, PLB731 (2014)27

Triplet model (HTM)

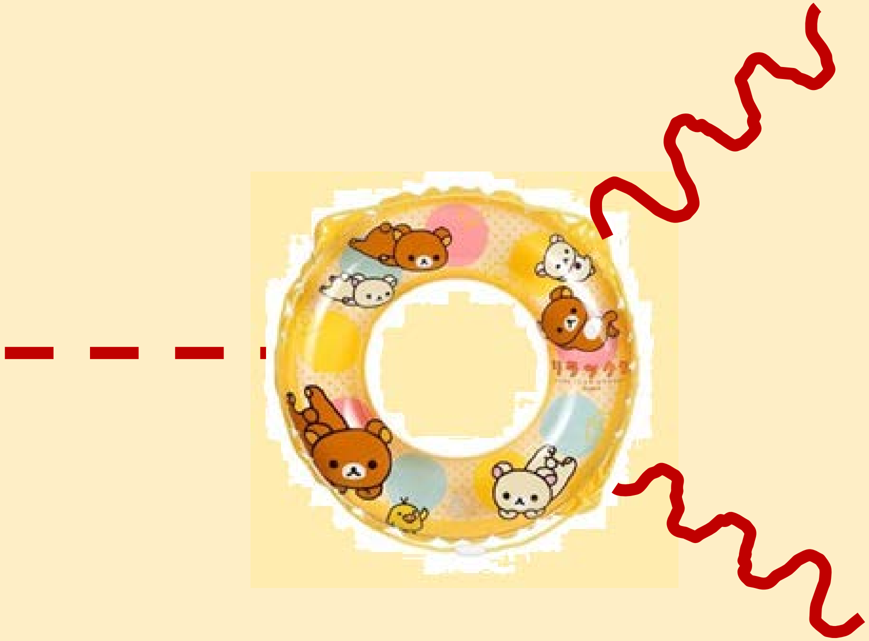
Kanemura, MK Yagyu, PRD87, 015012(2013)

Inert doublet model

Kanemura, MK, Sakurai, in preparation

	hWW	hZZ	htt	hbb	$h\tau\tau$	$h\gamma\gamma$	hgg	$h\gamma Z$	hhh
Φ+S	✔	✔	✔	✔	✔	✔	✔	✔	✔
Φ+Φ I	✔	✔	✔	✔	✔	✔	✔	✔	✔
Φ+Φ II	✔	✔	✔	✔	✔	✔	✔	✔	✔
Φ+Φ X	✔	✔	✔	✔	✔	✔	✔	✔	✔
Φ+Φ Y	✔	✔	✔	✔	✔	✔	✔	✔	✔
Φ+Δ	✔	✔				✔	✔	✔	✔
Inert	✔	✔	✔	✔	✔	✔	✔	✔	✔
…									

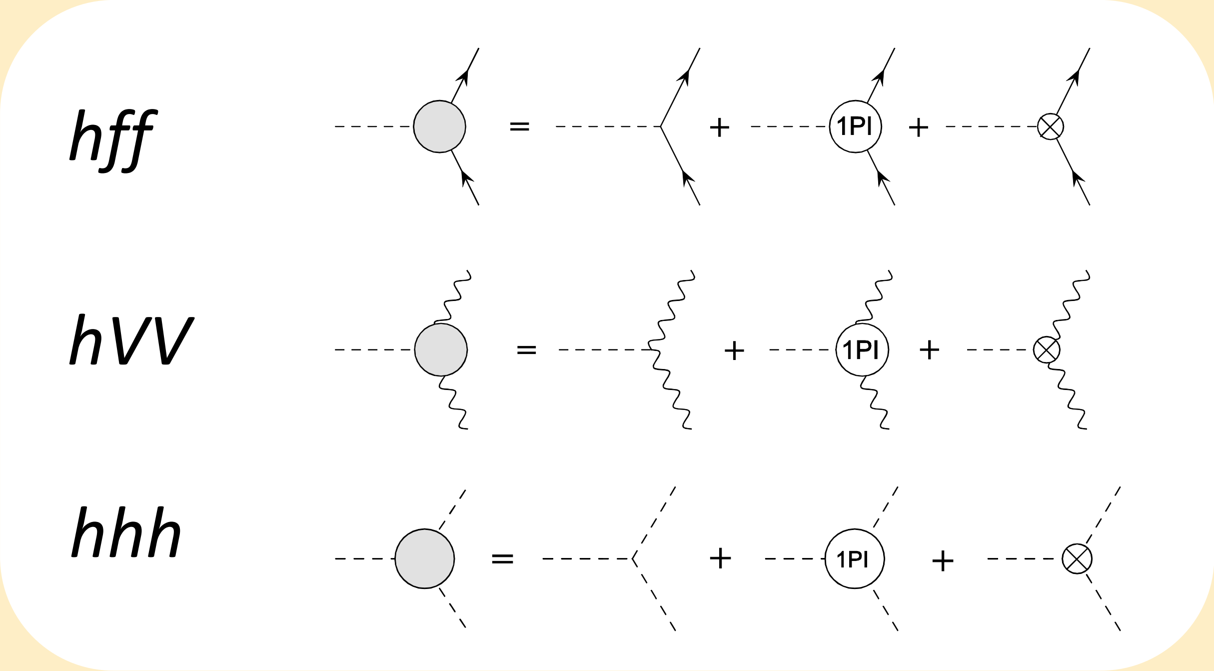
Radiative corrections to the Higgs boson couplings



One-loop corrected h-couplings

We calculate 1-loop corrected Higgs couplings by on-shell scheme,
(EW corrections + scalar sector corrections)

hZZ, hWW, hbb, hττ, htt, hcc, hγγ, hγZ, hgg, hhh



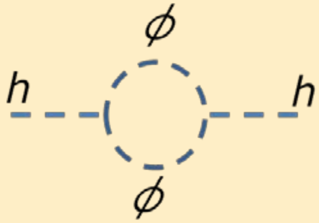
Approximate formulae

Approximate formulae (SM like limit) x << 1

$\Delta\kappa_X = \kappa_X - 1$ (1-loop level) $(\Phi = H^\pm, A, H)$

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

mixing Loop



$$\boxed{m_\Phi^2 \sim \lambda v^2 + M^2}$$

Loop effects

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

($M>>v$) **Decoupling!** ($\eta \to 0$)

($M \sim v$) **Non-decoupling!** ($\eta \to 1$)

Decoupling property : $\eta = 1 - \dfrac{M^2}{m_\Phi^2}$

$$\Delta\hat{\kappa}_b \simeq \Delta\hat{\kappa}_V + \xi_d\, x - \frac{1}{16\pi^2}\xi_u\xi_d\frac{2m_t^2}{v^2}\left(1-\frac{m_t^2}{m_{H^\pm}^2}-\frac{M^2}{m_{H^\pm}^2}\right) - \frac{1}{16\pi^2}\frac{1}{6}\xi_d^2\sum_{\Phi=A,H,H^\pm}\frac{m_b^4}{v^2 m_\Phi^2},$$

$$\Delta\hat{\kappa}_t \simeq \Delta\hat{\kappa}_V + \xi_u\, x - \frac{1}{16\pi^2}\frac{1}{6}\left[\xi_u^2\sum_{\Phi=A,H,H^\pm}\frac{m_t^4}{v^2 m_\Phi^2} + \xi_d^2\frac{m_b^2 m_t^2}{v^2 m_{H^\pm}^2}\right],$$

$$\Delta\hat{\kappa}_\tau \simeq \Delta\hat{\kappa}_V + \xi_e\, x,$$

$$\Delta\hat{\kappa}_c \simeq \Delta\hat{\kappa}_V + \xi_u\, x,$$

Numerical calculation

Kanemura, Okada, Senaha, Yuan (2002), Kanemura, MK, Yagyu

$$\boxed{\Delta\Gamma_{hVV} \equiv \frac{\Gamma^{\rm THDM}_{hVV} - \Gamma^{\rm SM}_{hVV}}{\Gamma^{\rm SM}_{hVV}}}$$

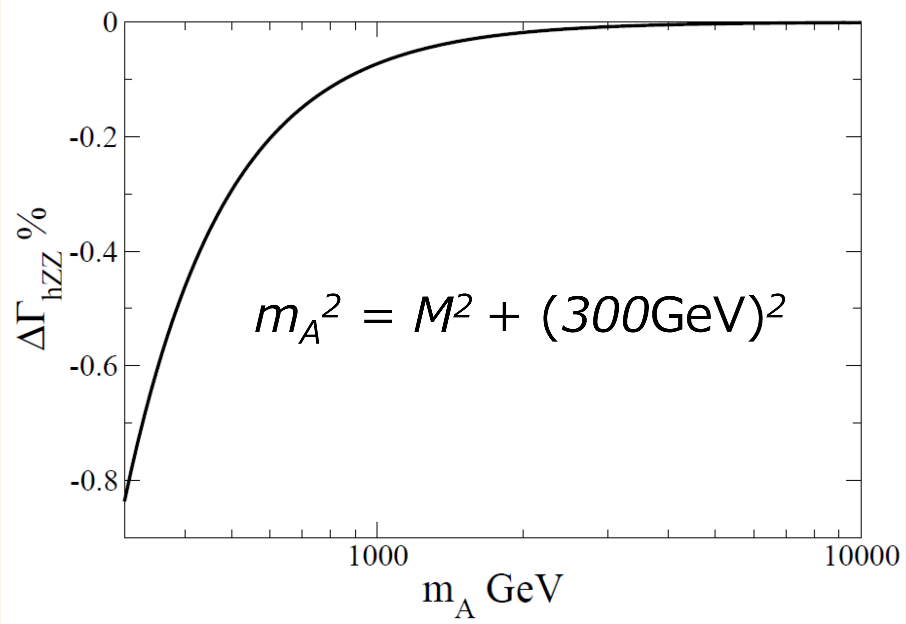
$$A(m_\Phi, M) = \frac{1}{16\pi^2}\frac{1}{6}\sum_\Phi c_\Phi \frac{m_\Phi^2}{v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^2$$

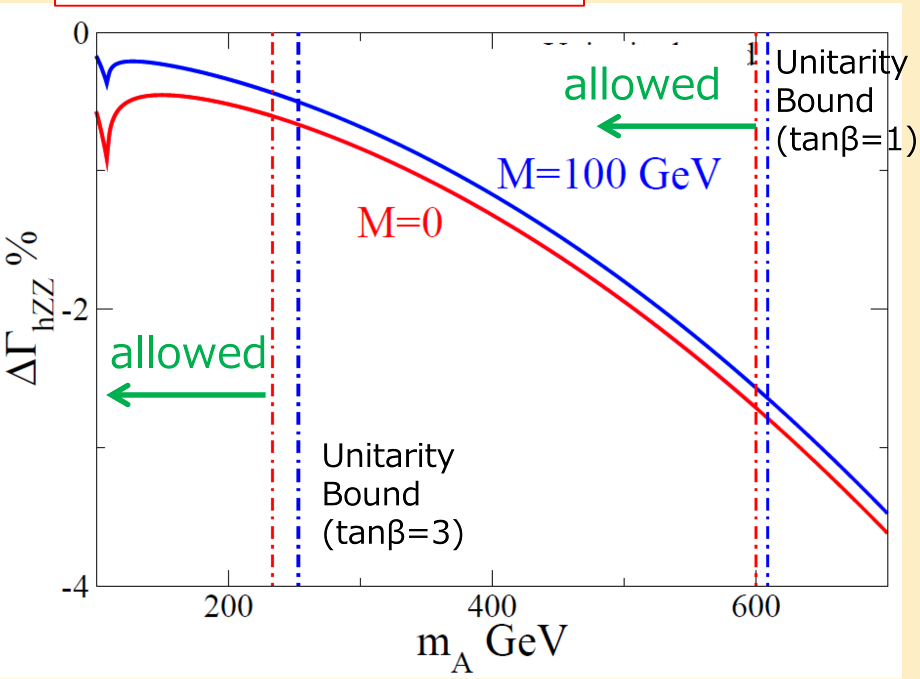
$m_\Phi^2 \sim \lambda_i v^2 + M^2$

THDMs $\sin(\beta-\alpha)=1$

Decoupling ($M>>v$)

Non-decoupling ($M\sim v$)



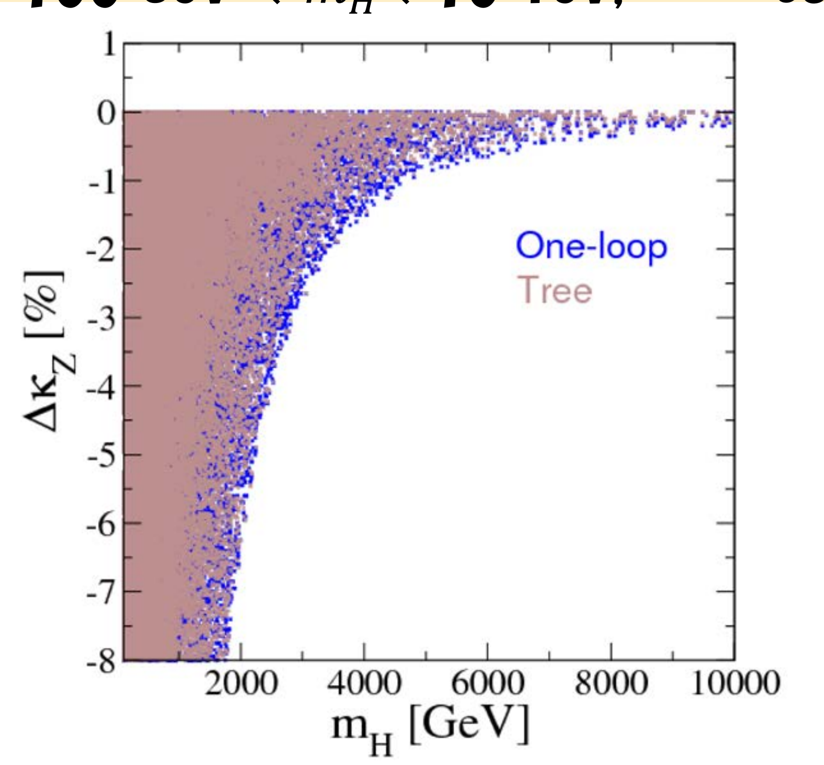


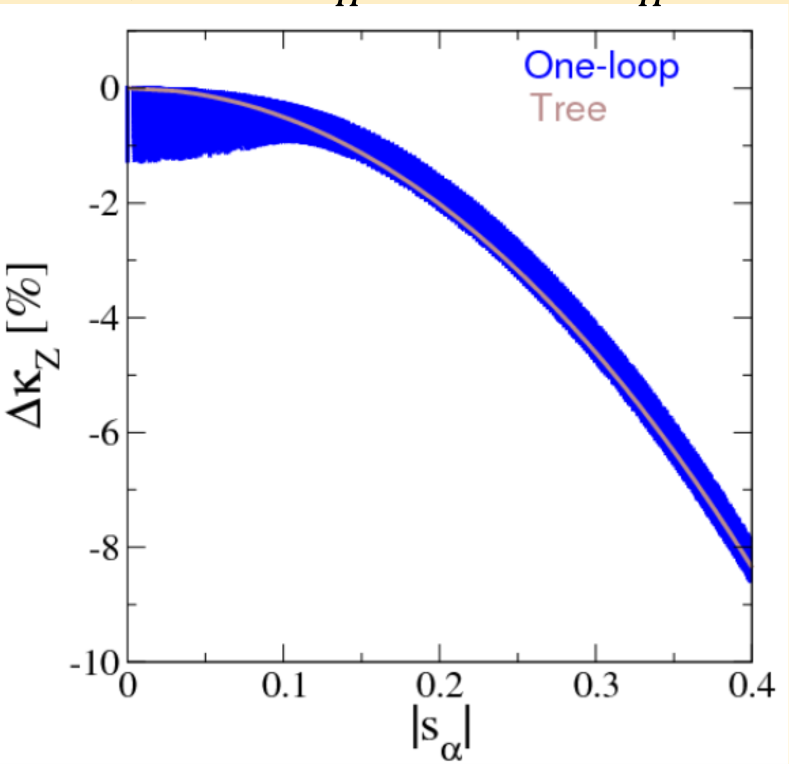
Numerical calculation

HSM **Relation between $\Delta\kappa_V$ and m_H, $\sin\alpha$**

We scan inner parameters :

100 GeV $< m_H <$ **10 TeV,** $\cos\alpha < 1$, $-m_H^2 \leq \widetilde{M}^2 \leq m_H^2$





- Non-zero negative value of $\Delta\kappa_Z \Rightarrow$ Upper bound on m_H
- The maximal value of the one-loop corrections (at most -1% or maximally less than -2%) is realized in alpha $\simeq$ 0.

Discrimination of HSM 2HDM(Type I) IDM

Can these extended Higgs models be discriminated by the deviation patterns of the Higgs boson couplings ?

Inner parameters m_Φ, mixing parameters, … → h_{125} couplings, κ_X, $\Delta\kappa_X$

We investigate how large *h* couplings deviate from the SM predictions at 1-loop level by scanning inner parameters

< Parameter range in HSM >
300GeV < m_H < 1000GeV,
0.80 < cos α <1,
–15 < $\lambda_{\Phi S}$ < 15, –15 < λ_S < 15, –2000GeV < μ_S < 2000GeV.
< Parameter range in 2HDM >
300GeV < m_H (= m_A = $m_{H\pm}$) < 1000GeV,
0 < M^2< (1000GeV)^2,
0.80 < sin($\beta - \alpha$) < 1.
< Parameter range in IDM>
300GeV < m_H (= m_A = $m_{H\pm}$) < 1000GeV,
0 < μ_2^2 < (1000GeV)^2

HSM

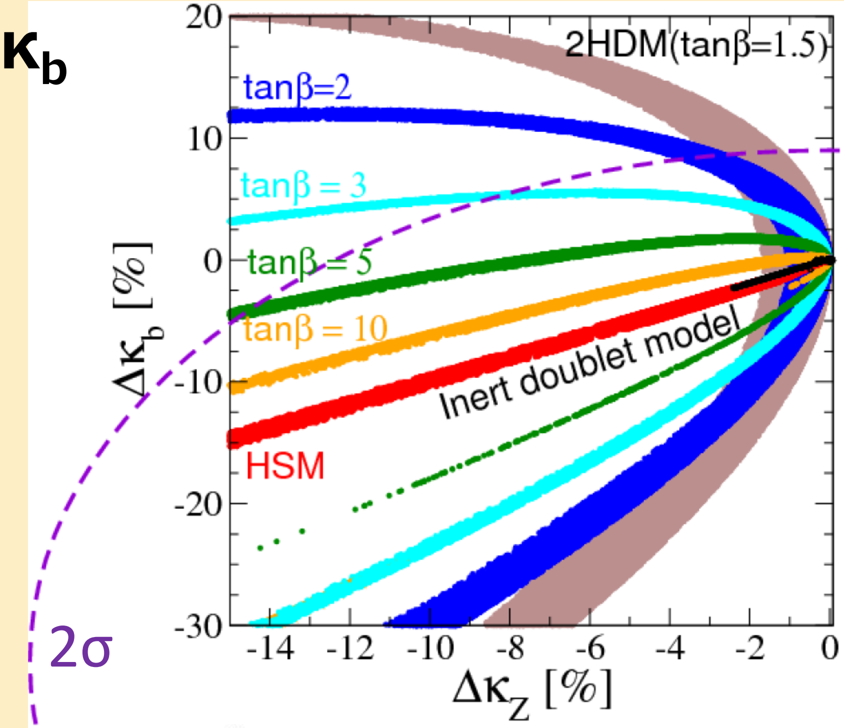
2HDM(Type I)

IDM

Scaling factors of all Yukawa couplings are Universal.

(κ_t = κ_b = κ_τ @ tree level)

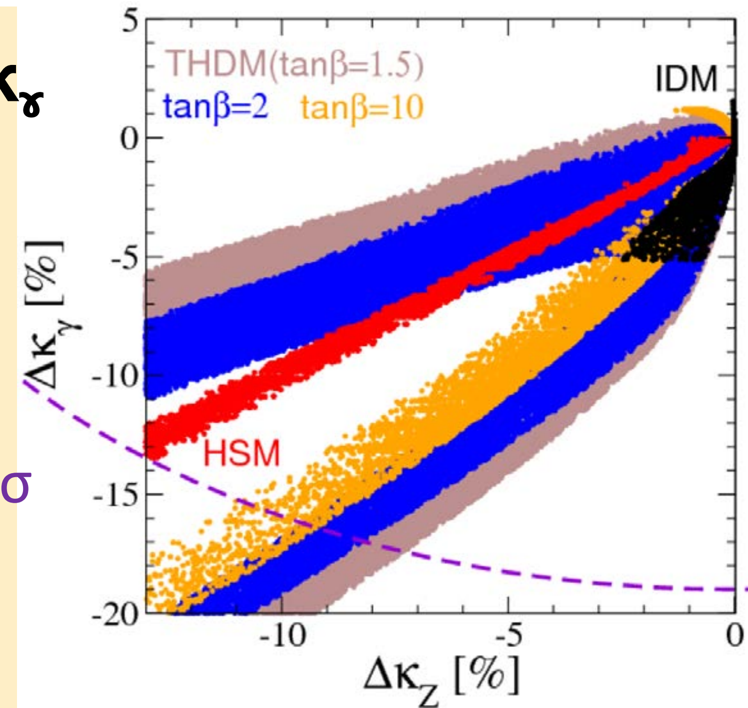
$\Delta\kappa_Z$ VS $\Delta\kappa_b$



LHC Run-I Data (ATLAS + CMS)

ATLAS-CONF-2015-044

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



2σ

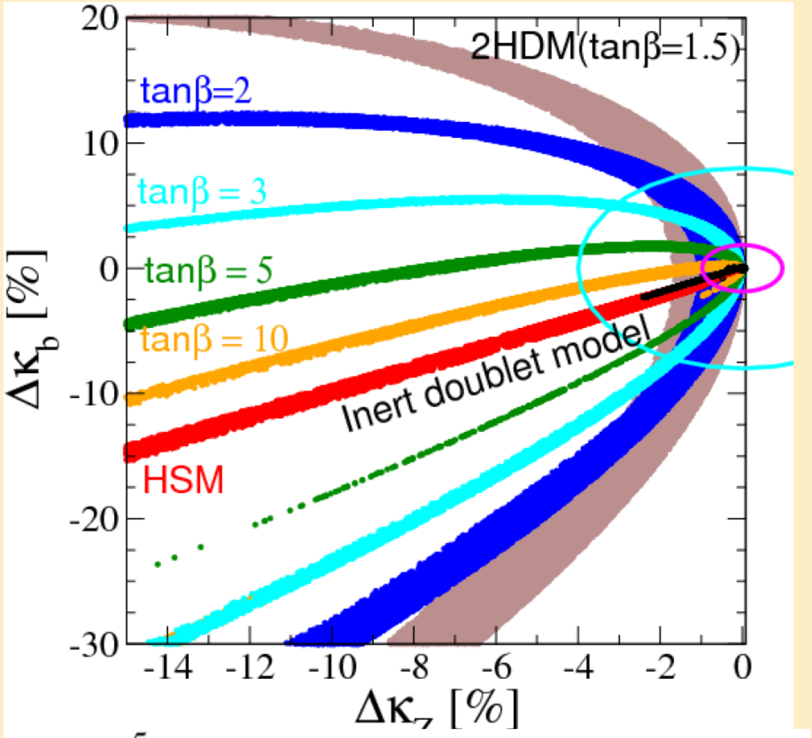
LHC Run-I Data (ATLAS + CMS)

HSM
2HDM(Type I)
IDM

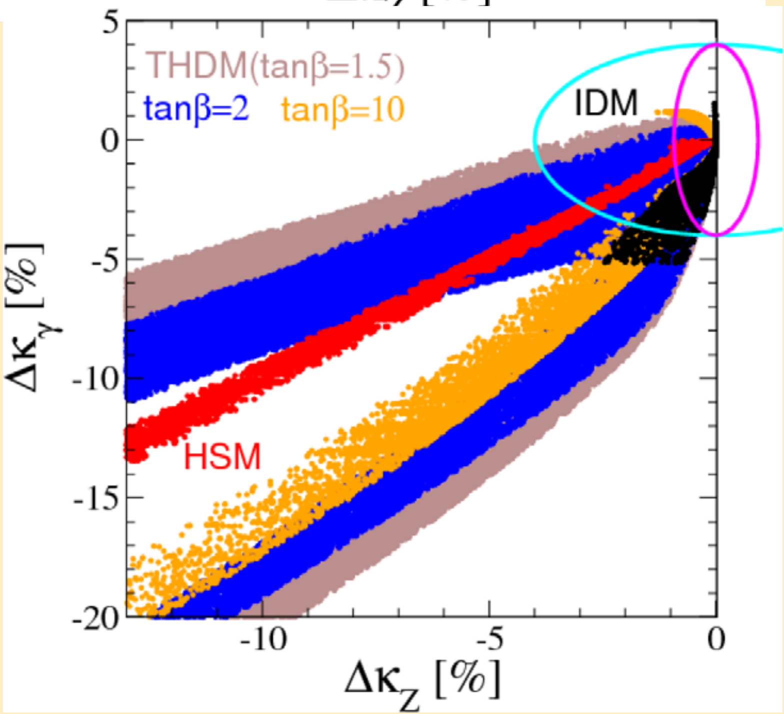
Scaling factor of all Yukawa couplings are Universal.

($\kappa_t = \kappa_b = \kappa_\tau$ @ tree level)

Δκ$_Z$ VS Δκ$_b$



Δκ$_Z$ VS Δκ$_\gamma$



Ellipses :
±2σ at HL-LHC, ILC500

Characteristic pattern of Δκ

These models may be distinguished, as long as $\Delta\kappa_Z$ is detected at ILC500.

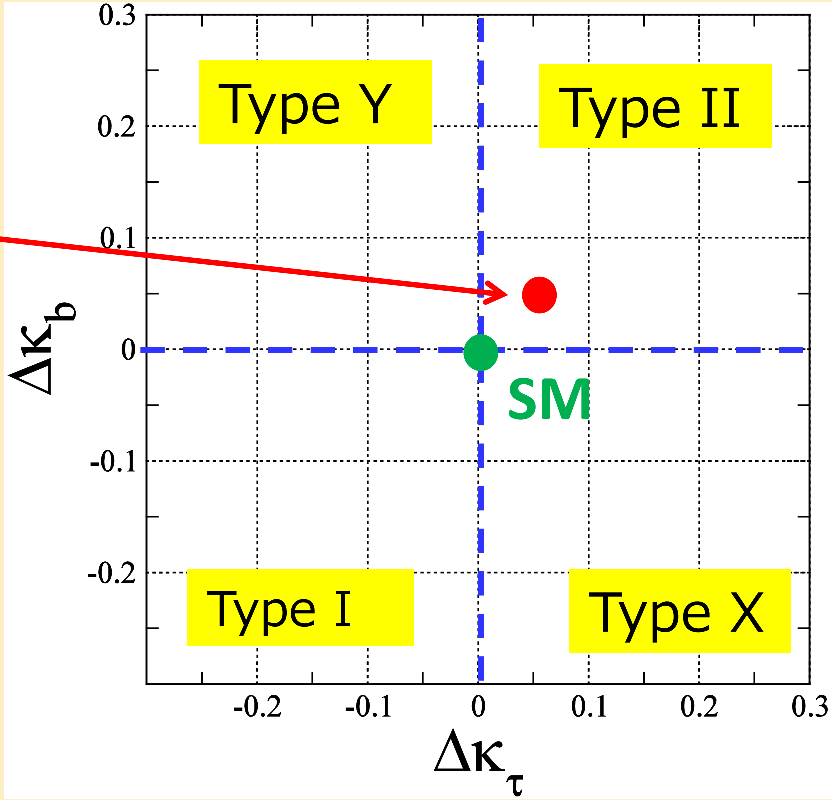
Extraction of parameters

In the future,
how much precise can we extract values of inner parameters by using LHC3000 and ILC500 data ?

Case A

		LHC3000	ILC500	1σ
$\Delta\hat{\kappa}_V$	= -2.0	±2.0	±0.4%	
$\Delta\hat{\kappa}_\tau$	= +5	±2.0	±1.9%	
$\Delta\hat{\kappa}_b$	= +5	±4.0	±0.9%	

Errors are from ILC(500) *in Snowmass 2014 Rep.*



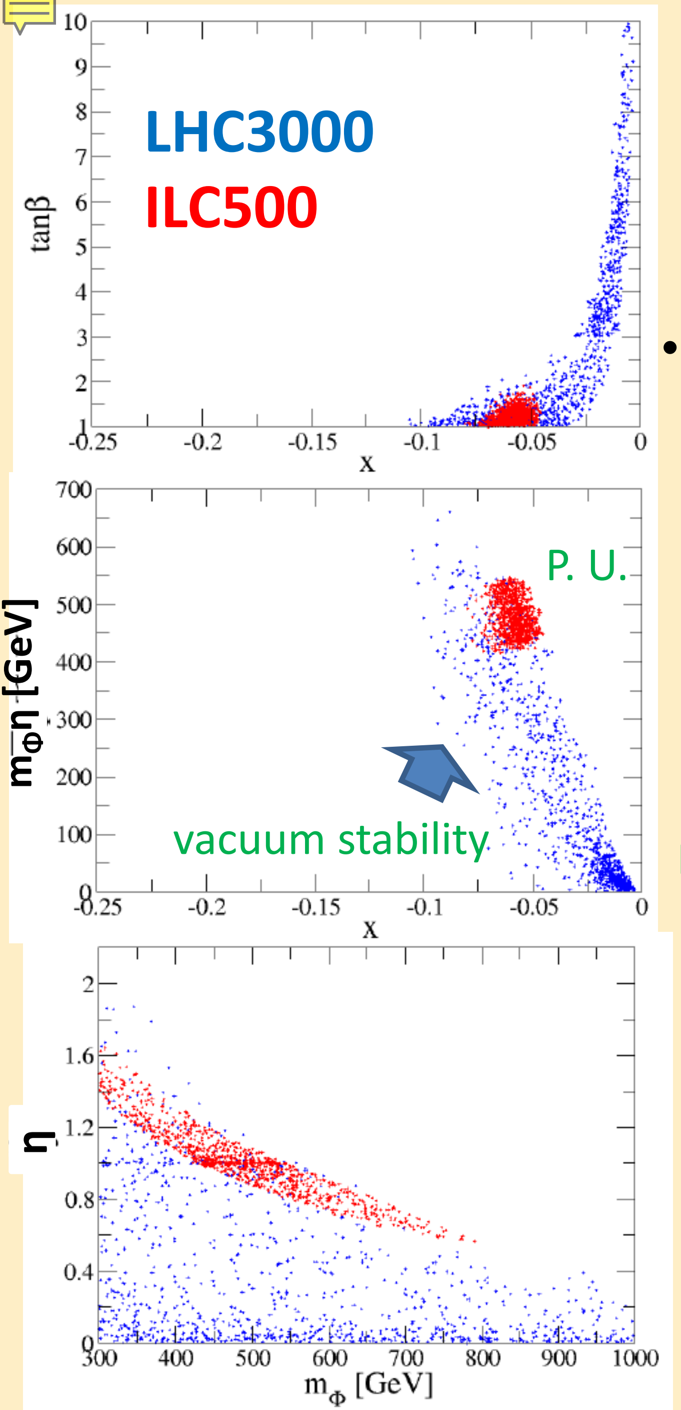
Type-II

We survey parameter regions by scanning inner parameters

x, $\tan\beta$, m_Φ, M

Φ = H⁺, H, A

Parameter extraction



Kanemura, MK, Yagyu (2015)

$$\Delta\hat{\kappa}_\tau - \Delta\hat{\kappa}_V \simeq -\tan\beta\, x$$

- At LHC3000, x→0 (tanβ→∞) is allowed because value of hVV includes SM limit within measurement uncertainties (x, tanβ can not be determined precisely.)

At ILC, x and tan β can be extracted more precise. -0.075 < x < -0.05, 1 < tanβ <1.7

P. U. : Perturbative unitarity bound

Extraction of upper value of m_Φ

$\Delta\hat{\kappa}_V$ =	-2.0	±2.0	±0.4%
$\Delta\hat{\kappa}_\tau$ =	+5	±2.0	±1.9%
$\Delta\hat{\kappa}_b$ =	+5	±4.0	±0.9%

⇨ m_Φ < **800 GeV**

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.

HSM, 2HDMs, IDM, HTM

×

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

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

Radiative corrections

×

Precision measurements

→

Determination of the Higgs sector !!

We may determine the structure of the Higgs sector by fingerprinting of the Higgs boson couplings even if additional Higgs bosons do not discovered directly.

We will publish the 1-loop calculation codes named H-COUP.

- Future work
  - Calculation of signal strength
  - Incorporating QCD corrections
  - …