Probing extended Higgs sectors by precision measurements of the Higgs boson couplings

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S. Kanemura, MK, K. Yagyu, **arXiv:1511.06211**

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Introduction

- Although a Higgs boson was discovered, there remains a lot of mysteries in the Higgs sector.

Negative mass term, Elemental scalar? or Composite scalar?,
# of scalar multiplets, their representations, ⋯

We don't know the nature of the Higgs field and the structure of the Higgs sector!

- How can we determine the Higgs sector by collider experiments?
  - Direct search of the second Higgs boson
  - Indirect search through coupling constants of 125GeV Higgs boson!

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

- A pattern of deviations in Higgs couplings from the SM predictions depend on the structure of the Higgs sector.

  ⇨ It is useful to discriminate extended Higgs sectors by the deviation pattern among various Higgs boson couplings.

- Higgs boson couplings will be measured with high precision at future collider experiments (LHC Run-II, HL-LHC, ILC, …).

Typically O(1) % level

We should investigate these couplings with radiative corrections in various extended Higgs sectors.

Our projects

Project Authors:
S. Kanemura, M. Kikuchi, K.Yagyu

- We calculate a full set of 125 GeV Higgs boson couplings with radiative corrections in the 7 models.

  - Higgs Singlet Model (HSM)
    Kanemura, MK, Yagyu, in preparation
  - 4 types of Two Higgs Doublet Models (2HDMs)
    Kanemura, MK, Yagyu, NPB 896,80(2015)
    Kanemura, MK, Yagyu, PLB731 (2014)27
  - Inert Doublet Model (IDM)
    Kanemura, MK, Sakurai, in preparation
  - Higgs Triplet Model (HTM)
    Aoki, Kanemura, MK, Yagyu; PRD87,015012(2013),
    Kanemura, MK, Yagyu; arXiv:1511.06211

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

Radiative corrections to Higgs boson couplings in the 2HDM/MSSM

hZZ
hWW

Hollik, Penaranda (2002) [in the MSSM]
Hahn, Heinemeyer, Weiglein (2003) [in the MSSM]
Kanemura, Kiyoura, Okada, Senaha, Yuan PLB558, (2003);
Kanemura, Okada, Senaha, Yuan (2004).
Kanemura, Kikuchi, Yagyu (2015)

hff

Guasch, Hollik, Penaranda (2001) [in the MSSM]
Guasch, Hafliger, Spira (2003) [in the MSSM]
Haber, Logan, Penaranda, Temes, (2006) [in the MSSM]
Kanemura, Kikuchi, Yagyu (2014)
Kanemura, Kikuchi, Yagyu (2015)

hhh

Hollik, Penaranda (2002) [in the MSSM]
Dobado, Herrero, Hollik, Penaranda (2002) [in the MSSM]
Kanemura, Okada, Senaha, Yuan, PRD70 (2004).
Kanemura, Kikuchi, Yagyu NPB896 (2015)

Pattern of deviations in *h* couplings with radiative corrections

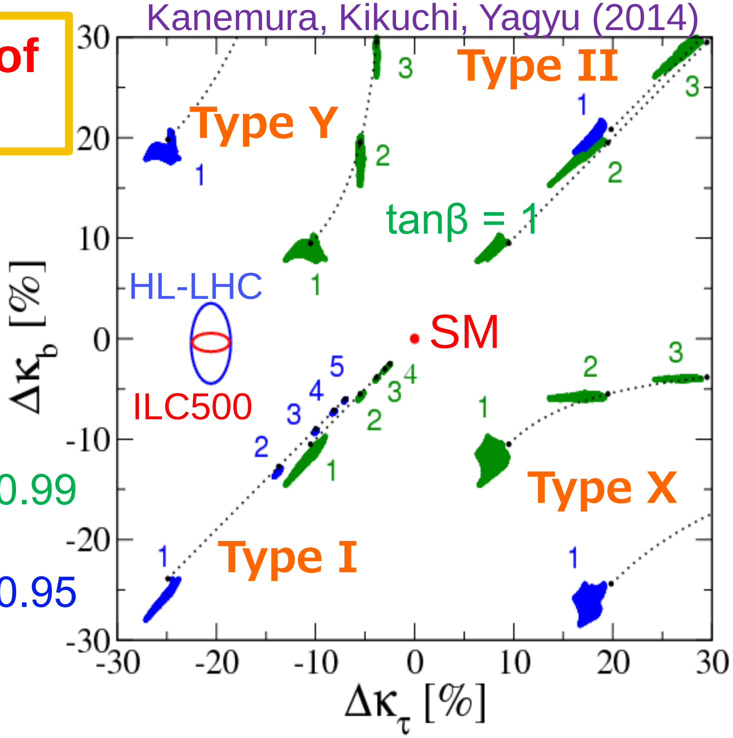
Deviations in scaling factors : $\Delta\kappa_X \equiv \frac{\hat{\Gamma}_{hXX}[p_1^2, p_2^2, q^2]}{\hat{\Gamma}_{hXX,SM}[p_1^2, p_2^2, q^2]} - 1$

We scan inner parameters under the constraints from perturbative unitarity, vacuum stability and wrong vacuum condition.

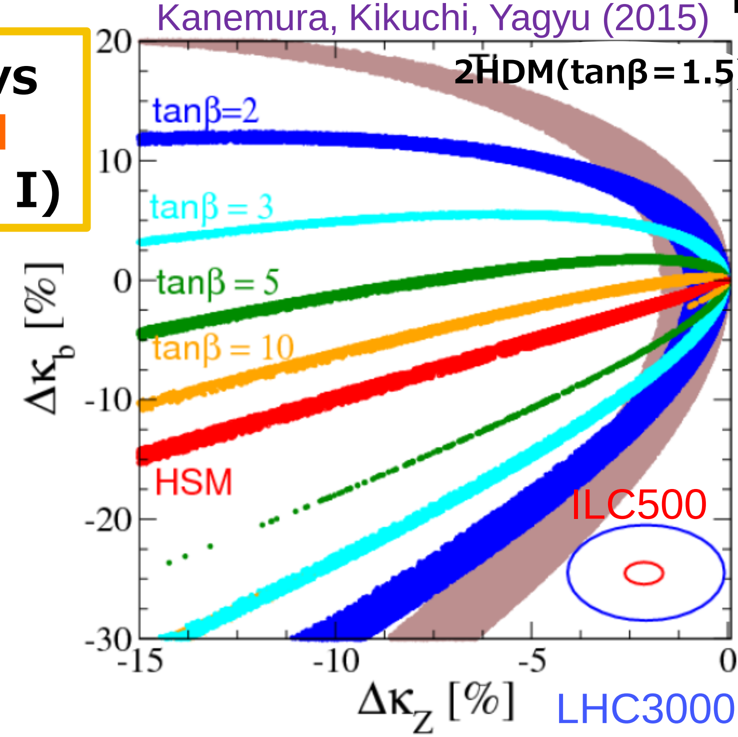
4 Types of 2HDMs

Sin(β−α)=0.99

Sin(β−α)=0.95



HSM vs 2HDM (Type I)



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.

Determination of inner parameters

How much precise can we extract values of inner parameters by using future precision data?

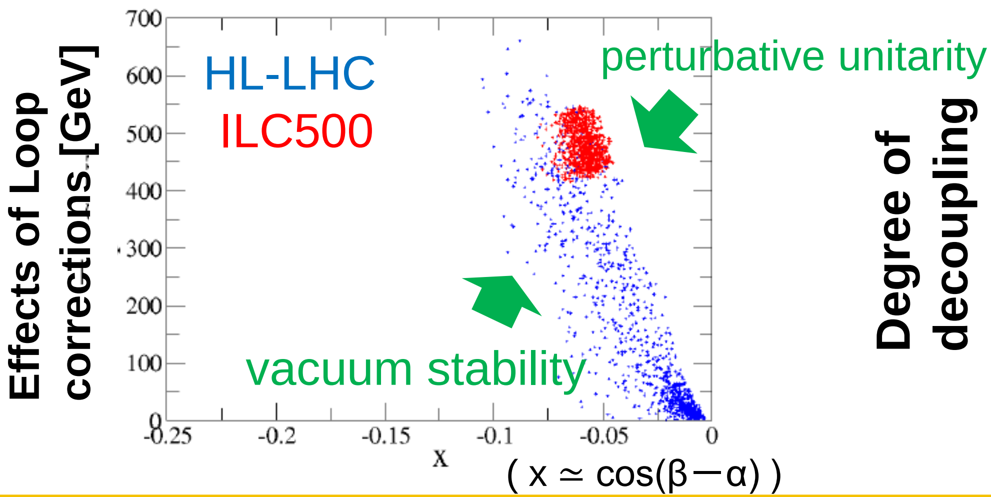
Bench mark set
Ex.))

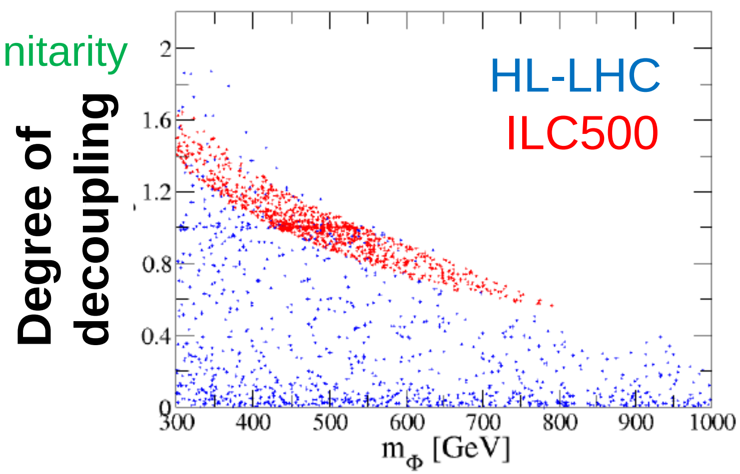
	LHC3000	ILC500
$\Delta\hat{\kappa}_V = -2.0$	± 2.0	$\pm 0.4\%$
$\Delta\hat{\kappa}_\tau = +5$	± 2.0	$\pm 1.9\%$
$\Delta\hat{\kappa}_b = +5$	± 4.0	$\pm 0.9\%$

⇒ **Type-II 2HDM**

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

We survey parameter regions in which Δκ are agreement with the future data within 1σ uncertainties, by scanning inner parameters.





- At ILC, inner parameters can be extracted more precise.
- We can obtain information of upper limit on m_Φ and the magnitude of loop corrections and so on.

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.
  - Higgs Singlet Model
  - 4 types of 2HDMs
  - Inert Doublet Model
  - Higgs Triplet Model

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

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

Radiative corrections × **Precision measurements** → Determination of the Higgs sector !!

A full set of fortran code for Higgs couplings in extended Higgs sectors had been completed.

- 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.

- In order to determine inner parameters by using future precision data of various Higgs boson couplings, studies of radiative corrections to Higgs boson couplings are critically important.

Higgs singlet model

$$V(\Phi,S)=m_\Phi^2|\Phi|^2+\lambda|\Phi|^4+\mu_{\Phi S}|\Phi|^2S+\lambda_{\Phi S}|\Phi|^2S^2+t_SS+m_S^2S^2+\mu_SS^3+\lambda_SS^4,$$

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

- **Mass eigenstates**

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

h*, *H

SM-like Higgs boson

Extra Higgs boson

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

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

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

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

- **Parameters(8)**

$v\simeq 246$ GeV $\quad m_h\simeq 126$ GeV $\quad m_H \quad \alpha \quad \mu_S \quad \lambda_{\Phi S} \quad \lambda_S \quad v_S$

- **Scaling factors of h_{125} couplings at tree level**

$$\kappa_V=\kappa_f=\cos\alpha,$$

$$\kappa_h=c_\alpha^3+\frac{2v}{m_h^2}s_\alpha^2(\lambda_{\Phi S}vc_\alpha-\mu_Ss_\alpha-4s_\alpha\lambda_Sv_S).$$

< Parameter range in HSM >

$300\text{GeV} < m_H < 1000\text{GeV}$,
$-15 < \lambda_{\Phi S} < 15$,
$-15 < \lambda_S < 15$,
$0.80 < \cos\alpha < 1$,
$-2000\text{GeV} < \mu_S < 2000\text{GeV}$.

< Parameter range in 2HDM >

$300\text{GeV} < m_H (= m_A = m_{H^\pm}) < 1000\text{GeV}$,
$0 < M^2< (1000\text{GeV})$^2,
$0.80 < \sin(\beta - \alpha) < 1$.

< Parameter range in IDM>

$300\text{GeV} < m_H (= m_A = m_{H^\pm}) < 1000\text{GeV}$,
$0 < \mu_2$^2 $< (1000\text{GeV})$^2

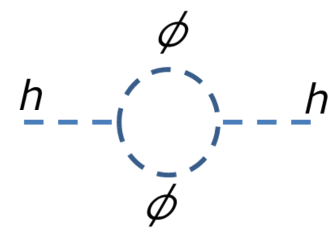
One-loop contributions

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

$$m_\Phi^2\left(1-\frac{M^2}{m_\Phi^2}\right)^2 \begin{cases} \propto \dfrac{1}{m_\Phi^2} & (M>>v) \quad \textbf{Decoupling!} \quad (\eta \to 0) \\ \propto m_\Phi^2 & (M \sim v) \quad \textbf{Non-decoupling!} \quad (\eta \to 1) \end{cases}$$

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

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

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

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

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

PARAMETRIC UNCERTAINTIES

Parametric Uncertainties of *hXX* couplings

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	*hbb*,	*hcc*,	*hgg* [%]
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

Lepage, Mackenzie, Peskin [1401.0319]

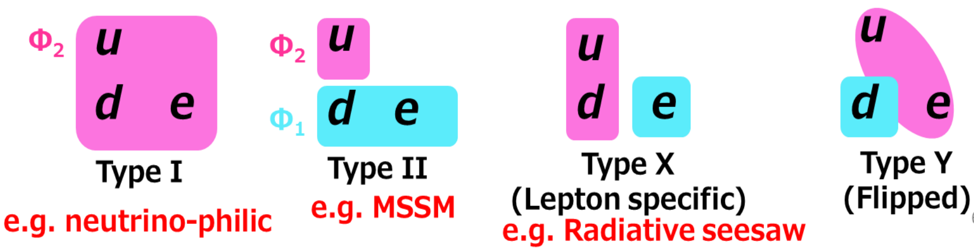
PT ; 4th order QCD perturbative theory
LS, LS^2; reduction of lattice spacing
ST; increasing the statistics of simulation

2HDM, IDM

2HDMs

- Softly breken Z2 sym.

$$\Phi_1 \to +\Phi_1$$
$$\Phi_2 \to -\Phi_2$$



- Mass eigenstates

  h, H A $H^{\pm}$

(Φ : H, A, $H^{\pm}$)

Soft breaking scale of Z2 sym.

- $h(125)$ coupling constants (tree level)

  κ_V = sin(β - α)

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

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

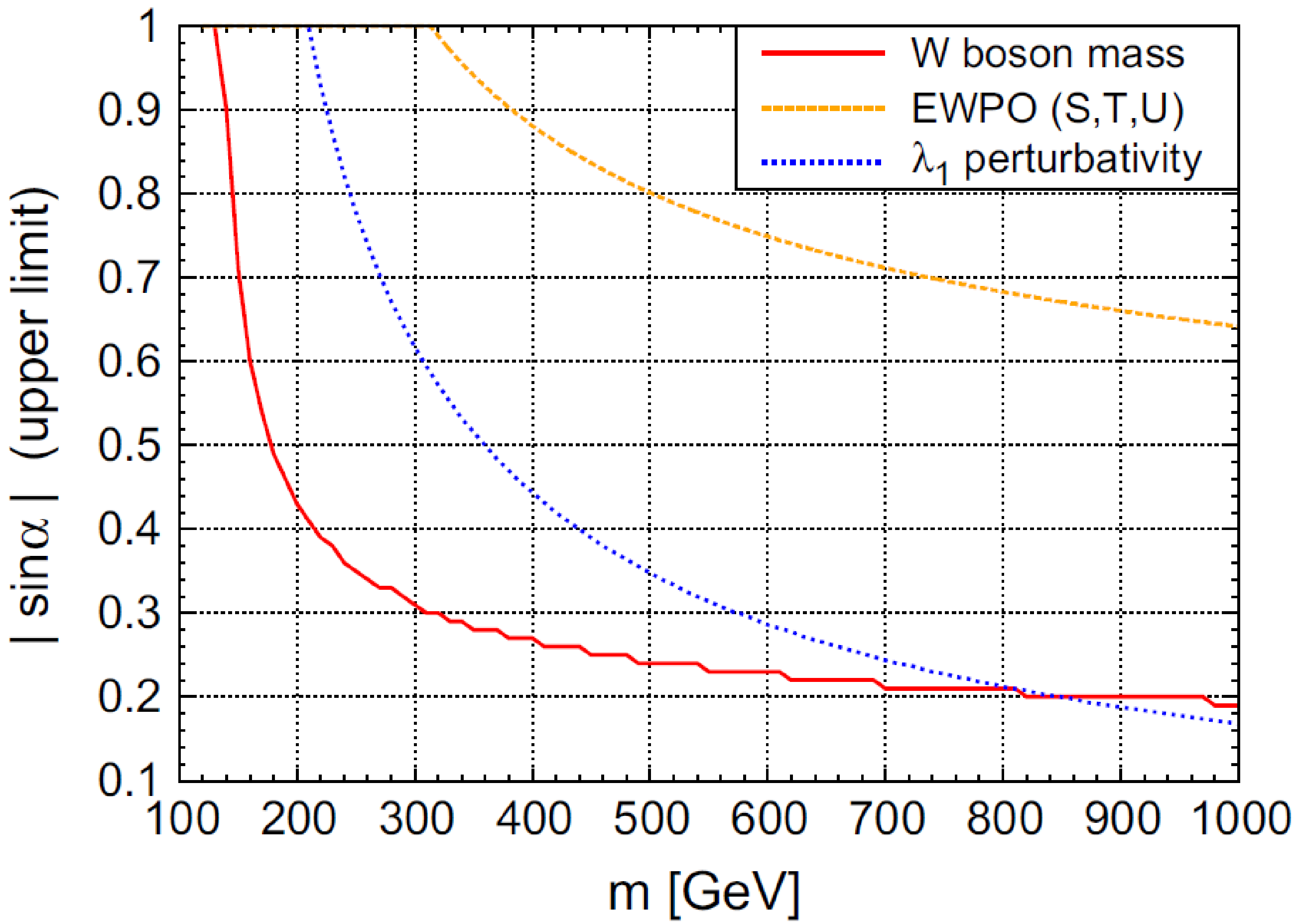
IDM

- Additional scalar field Φ_2 is Z_2-odd
- Eigenstates h, H A $H^{\pm}$ $m_\Phi{}^2 \cong \lambda' v^2 + \mu_2^2$
- $h(125)$ coupling constants (tree level) $\kappa_X = 1$

ELECTROWEAK PRECISION DATA

Higgs Singlet Model with a spontaneously broken Z2 sym

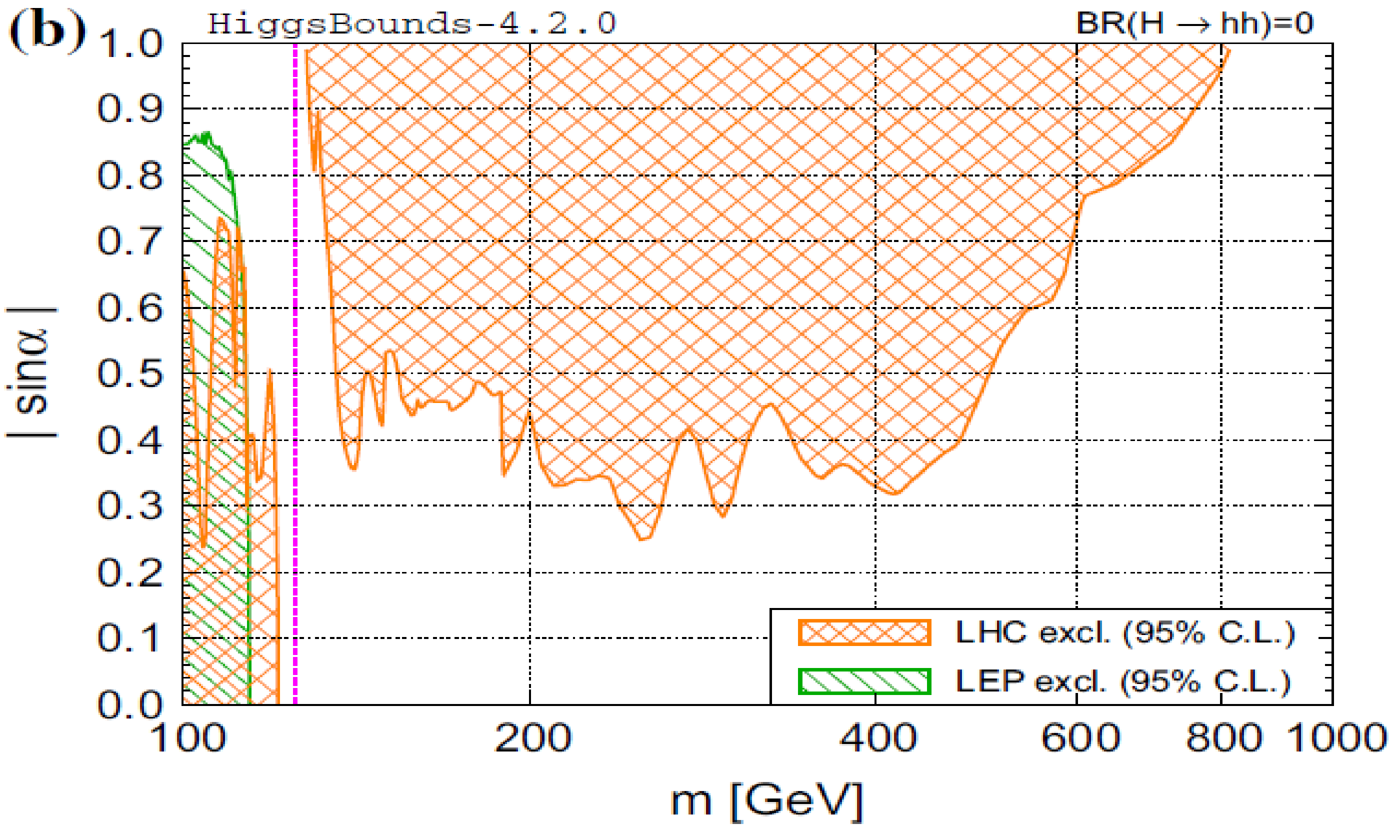
T. Robens and T. Stefaniak, Eur. Phys. J. C75, 104,(2015)



CONSTRAINTS BY HIGGS SEARCH

Higgs Singlet Model with a spontaneously broken Z2 sym

T. Robens and T. Stefaniak, Eur. Phys. J. C75, 104,(2015)



THDMs

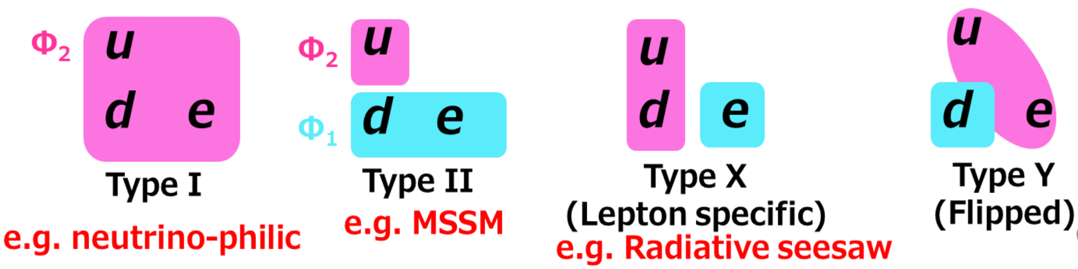
Φ_1, Φ_2

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

$$\Phi_1 \to +\Phi_1$$
$$\Phi_2 \to -\Phi_2$$



4 types of Yukawa interactions

Barger, Hewett, Phillips(1990), Aoki, Kanemura, Tsumura, Yagyu(2009), Logan, Su, Haber, ⋯.

- **Softly broken Z_2 & CP invariance**

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

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

Mass eigenstates : h $H, A, H^\pm$

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

$\tan\beta = \frac{v_2}{v_1}$ $v^2 = v_1^2 + v_2^2 \sim (246\text{GeV})^2$

Soft breaking scale of Z2 sym.

Renormalization

$$\rho = \frac{m_W{}^2}{m_Z{}^2 \cos^2\theta_W} = 1$$

➢ Kinetic term

- Parameters in Lagrangian ・・・ *g, g′, v*
- Physical parameters ・・・ m_W , m_Z , $\sin\theta_W$, G_F , α_{em} .

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2},$$

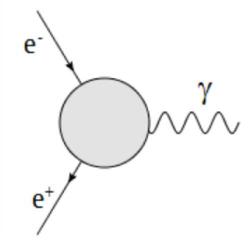
$$G_F = \frac{\pi\alpha_{em}}{\sqrt{2} m_W^2 \sin^2\theta_W}$$

- Counter-terms ・・・ δm_W, δm_Z, δs_W, δG_F, $\delta \alpha_{em}$,…
- Renormalized conditions ・・・

$$Re\Pi_{WW}(p^2)|_{p^2=m_W^2} = 0, \qquad \delta m_W^2 = Re\Pi_{WW}^{1PI}(m_W^2),$$

$$Re\Pi_{ZZ}(p^2)|_{p^2=m_Z^2} = 0, \qquad \delta m_Z^2 = Re\Pi_{ZZ}^{1PI}(m_Z^2),$$

On-shell conditions



$$= -ie\gamma^\mu$$

$$\frac{\delta\alpha_{em}}{\alpha_{em}} = \frac{d}{dp^2}\Pi_{\gamma\gamma}^{1PI}(p^2)|_{p^2=0} - \frac{2s_W}{c_W}\frac{\Pi_{\gamma Z}^{1PI}(0)}{m_Z^2}$$

- Counter term of *v*

$$v^2 = \frac{m_W{}^2 \sin^2\theta_W}{\pi\, \alpha_{em}}$$

$$\frac{\delta v}{v} = \frac{1}{2}\left(\frac{\delta m_W^2}{m_W^2} - \frac{\delta\alpha_{\rm em}}{\alpha_{\rm em}} + \frac{\delta s_W^2}{s_W^2}\right)$$

Counter terms in V

Parameters ; m_h v m_H a μ_S λ_S λ_S v_S 8

Tadpoles ; T_φ T_s 2

Mass eigenstates ; h H G^0 $G^\pm$ 4

Filed mixing ;
H-h 1

Paramater shift ; $m \rightarrow m + \delta m$

Field mixing ;
$$\begin{pmatrix} H \\ h \end{pmatrix} \to \begin{pmatrix} 1+\frac{1}{2}\delta Z_H & \delta C_{Hh}+\delta\alpha \\ -\delta\alpha+\delta C_{hH} & 1+\frac{1}{2}\delta Z_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

Counter terms; δm_h δv δm_H δa $\delta\mu_S$ $\delta\lambda_S$ $\delta\lambda_S$ δv_S
δT_φ δT_s
δZ_h δZ_H δZ_{G+} δZ_{G0}
δC_{hH} δC_{Hh}

16

Counter terms of Higgs couplings

$$\delta\Gamma^1_{hVV} = \frac{2m_V^2}{v}\cos\alpha\left(\frac{\delta m_V^2}{m_V^2} - \frac{\delta v}{v} + \frac{\sin\alpha}{\cos\alpha}\delta C_h + \delta Z_V + \frac{1}{2}\delta Z_h\right)$$

$$\delta\Gamma^S_{hff} = -\frac{m_f}{v}\cos\alpha\left(\frac{\delta m_f}{m_f} - \frac{\delta v}{v} + \frac{\sin\alpha}{\cos\alpha}\delta C_h + \delta Z_f^V + \frac{1}{2}\delta Z_h\right)$$

$$\delta\Gamma_{hhh} = \delta\lambda_{hhh} + \lambda_{hhH}(\delta C_h + \delta\alpha) + \frac{3}{2}\lambda_{hhh}\delta Z_h.$$

where

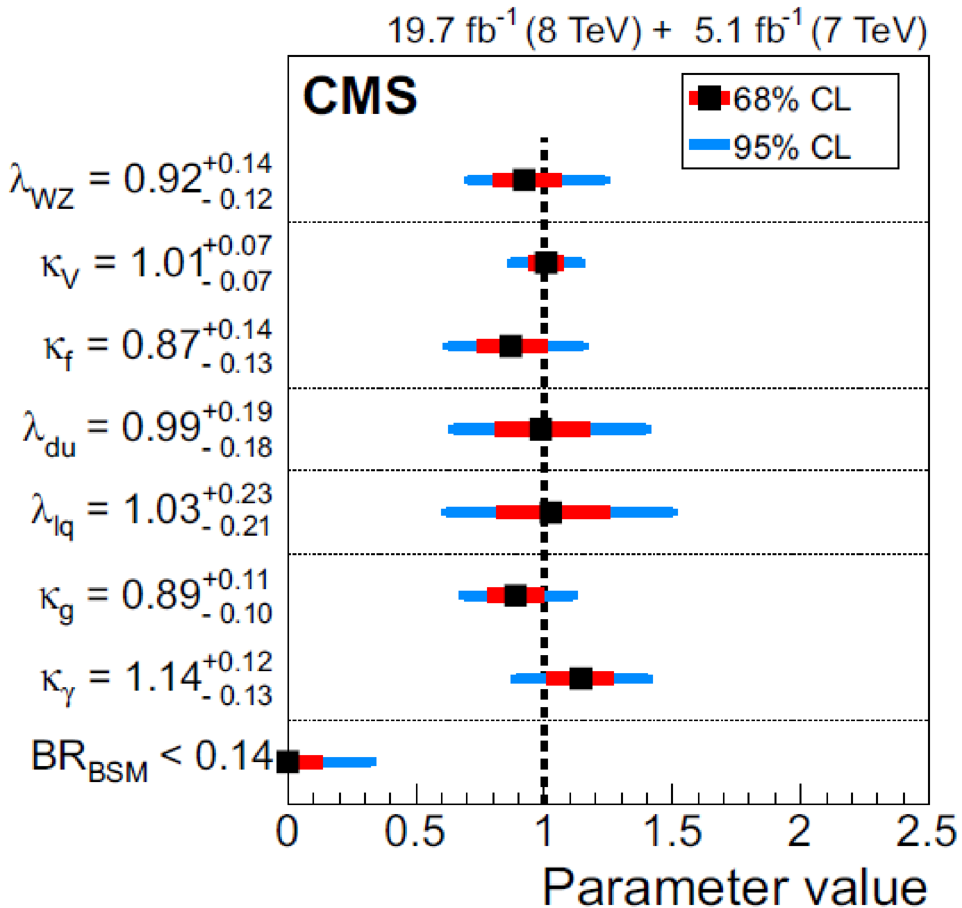
$$\delta\lambda_{hhh} = -\frac{c_\alpha^3}{2v}\delta m_h^2 + \left(\frac{m_h^2 c_\alpha^3}{2v^2} - s_\alpha^2 c_\alpha \lambda_{\Phi S}\right)\delta v$$
$$+ \left(\frac{3m_h^2}{2v}s_\alpha c_\alpha^2 + \lambda_{\Phi S} v(s_\alpha^3 - 2s_\alpha c_\alpha^2) + 3s_\alpha^2 c_\alpha \mu_S + 12\lambda_S v_S s_\alpha^2 c_\alpha\right)\delta\alpha + s_\alpha^2\delta\Lambda,$$

$$\delta\Lambda = -(c_\alpha v\delta\lambda_{\Phi S} - s_\alpha\delta\mu_S - 4s_\alpha v_S\delta\lambda_S).$$

☜ Combine $\delta\mu_S$ $\delta\lambda_S$ $\delta\lambda_S$ into $\delta\Lambda$

δΛ is determined by the minimal subtraction condition.

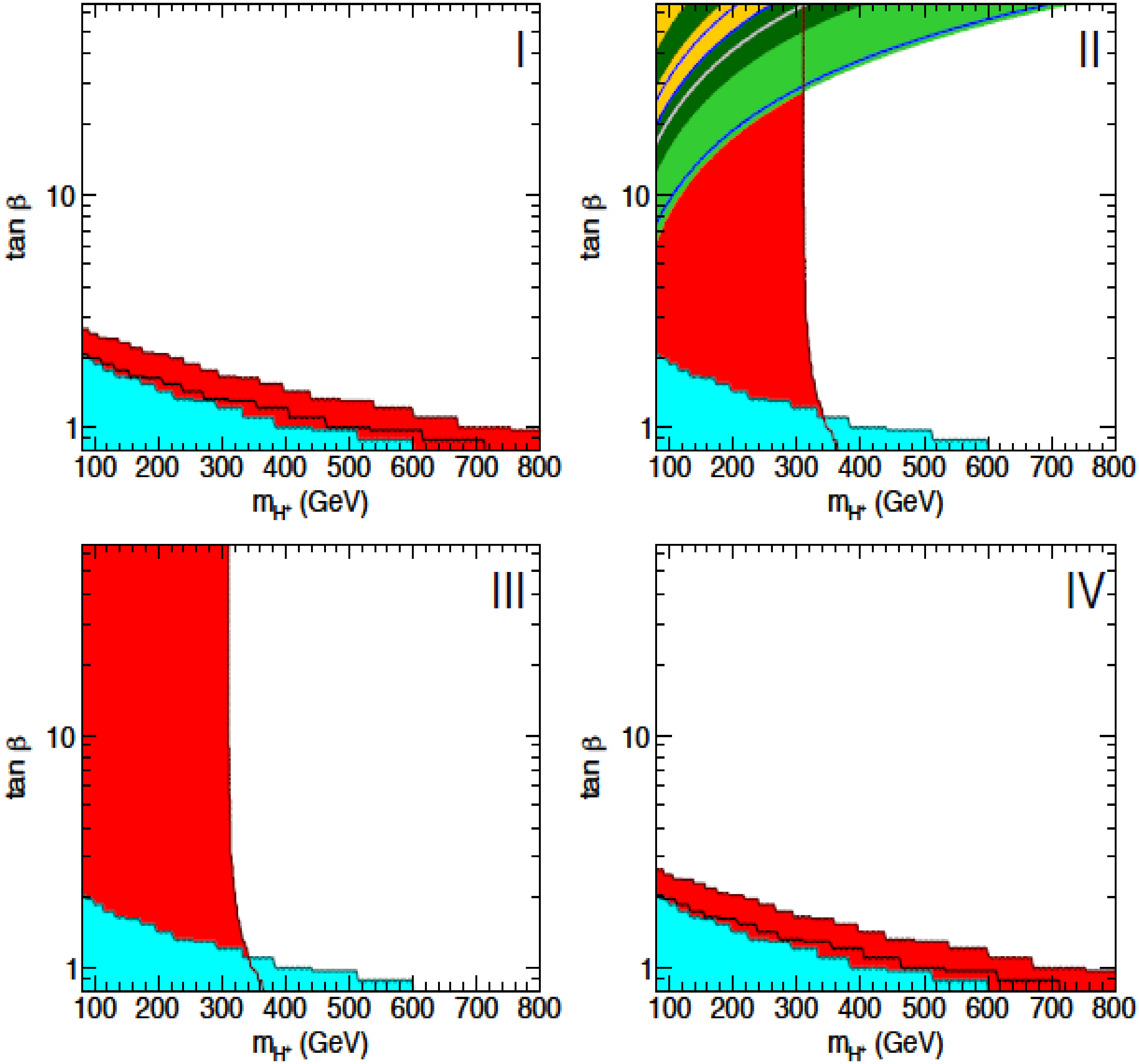
CURRENT DATA OF SCALING FACTORS



Eur. Phys. J. C (2015) 75:212

Flavor experiments

F. Mahmoudi and O. Stal, (2010)



$b \to s\gamma$

B_0–B_0 mixing

$D_s \to \tau\nu_\tau$

$D_s \to \mu\nu_\mu$

$B \to D\tau\nu_\tau$