Electroweak and Higgs physics

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Plan of the Lectures

1 EW Symmetry Breaking in the Standard Model (SM)

2 Physics of non-Minimal Higgs sectors

3 Higgs as a Probe of New Physics

Plan of the Lectures

1 EW Symmetry Breaking in the Standard Model (SM)

2 Physics of non-Minimal Higgs sectors
- 2-1: Motivation
- 2-2: Two Higgs doublet models
- 2-3: Other Models
- 2-4: Fingerprinting Higgs models
- 2-5: Decoupling/Non-decoupling
- 2-6: Radiative Corrections to Higgs couplings

3 Higgs as a Probe of New Physics

2 Physics of non-minimal Higgs Sectors

2-1 Motivation

Extended Higgs Sector

The “SM-like” does not necessarily mean the SM.
Every extended Higgs sector can contain the SM-like Higgs boson *h* in its decoupling regime.

General Extended Higgs models

Multiplet Structure

Φ_{SM}+Singlet, Φ_{SM}+Doublet (2HDM),
Φ_{SM}+Triplet, …

Additional Symmetry

Discrete or Continuous?
Exact or Softly broken?

Interaction

Weakly coupled or Strongly Coupled ?
Decoupling or Non-decoupling?

Multiplet Structure

If the Higgs sector contains more than one scalar bosons, possibility would be

- SM + extra Singlets   (NMSSM, B-L Higgs, 1st OPT, ...)
- SM + extra Doublets (MSSM, CPV, EW Baryogenesis, 1st OPT, Neutrino mass, …)
- SM + extra Triplets   (Type II seesaw, LR models….)
- ….

Basic data which strongly constrain the shape of extended Higgs sectors

- Electroweak rho parameter
- Flavor Changing Neutral Current (FCNC)

EW rho parameter

$\rho_{exp} = 1.0004^{+0.0003}_{-0.0004}$

$Q = I_3 + Y/2$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i \left[4T_i(T_i+1) - Y_i^2\right] |v_i|^2 c_i}{\sum_i 2Y_i^2 |v_i|^2}$$

T_i : $SU(2)_L$ isospin
Y_i : hypercharge
v_i : v.e.v.
c_i : 1 for complex representation
1/2 for real representation

N=1 SM Higgs doublet *Φ* (*T*=1/2, *Y*=1) $\rho = 1$!

N=2 What kind of (2 field) extended Higgs sector *Φ* + $X(T_X, Y_X)$ can satisfy $\rho = 1$?

We solve the equation

$$4\, T_X(T_X+1) = 3 Y_X^{\,2}$$

$(T_X,$	$Y_X)$	X
(0,	0)	Singlet
(1/2,	1)	Doublet
(3,	4)	Septet
(25/2,	15)	25-plet
….		….

EW rho parameter

$\rho_{exp} = 1.0004^{+0.0003}_{-0.0004}$

Possibility

1. **ρ=1 at tree** SM + doublets (ϕ) (+ singlets (S)), ...

2. **ρ≈1 at tree** SM + Triplets (Δ)

   a) $v_\Delta << v_\varphi$

   $$\rho_{\rm tree} = \frac{1+\frac{2v_\Delta^2}{v_\Phi^2}}{1+\frac{4v_\Delta^2}{v_\Phi^2}} \simeq 1 - \frac{2v_\Delta^2}{v_\Phi^2}$$

   b) Combination of several representations

   [(ex) Georgi-Machasek Model]

   $v_\Delta \approx v_\varphi$

Multi-doublets (+singlets) seem the most natural choice?

2-2 Two Higgs doublet models

Simplest extension
2 Higgs doublet model (2HDM)

$$\Phi_i = \begin{pmatrix} \omega_i^\pm \\ \frac{1}{\sqrt{2}}(v_i + h_i + i z_i) \end{pmatrix} \quad (i = 1, 2)$$

Sharing the VEV $\quad v = 246\ \mathrm{GeV} = \sqrt{v_1^2 + v_2^2} \qquad \tan\beta = \frac{v_2}{v_1}$

Field Mixing

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

$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix}$$

$$\begin{pmatrix} \omega_1^\pm \\ \omega_2^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \omega^\pm \\ H^\pm \end{pmatrix}$$

New Particles $\quad h \quad H \quad A \quad H^\pm$

CP-odd (A) Charged ($H^\pm$)

h ↑ *h*(125)

H, A, $H^\pm$: Additional bosons

Other three are unphysical Nambu-Goldstone bosons

Deviation in the coupolings of *h*(125)

SM			2HDM	
hVV	1	→	*hVV*	sin(β−α)

2 Higgs Doublet Model

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

$$\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + ia_i) \end{bmatrix} \quad (i = 1, 2)$$

Φ_1 and $\Phi_2 \Rightarrow h$, H, A^0, $H^\pm \oplus$ Goldstone bosons

↑ CPeven ↑ CPodd ↑charged

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}\begin{bmatrix} H \\ h \end{bmatrix} \qquad \begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

$$\begin{bmatrix} w_1^\pm \\ w_2^\pm \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} w^\pm \\ H^\pm \end{bmatrix}$$

$$\frac{v_2}{v_1} = \tan\beta$$

$$m_h^2 = v^2\left(\lambda_1\cos^4\beta + \lambda_2\sin^4\beta + \frac{\lambda}{2}\sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$

$$m_H^2 = M_{\text{soft}}^2 + v^2(\lambda_1 + \lambda_2 - 2\lambda)\sin^2\beta\cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$

$$m_{H^\pm}^2 = M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2}v^2,$$

$$m_A^2 = M_{\text{soft}}^2 - \lambda_5 v^2.$$

M_{soft}: soft breaking scale

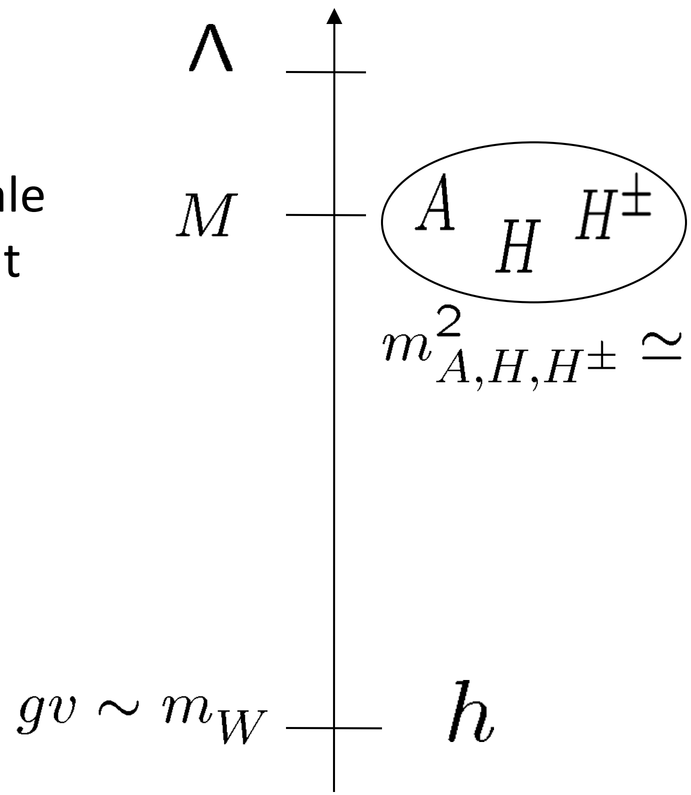
$M_{\text{soft}}\ \left(= \frac{m_3}{\sqrt{\cos\beta\sin\beta}}\right)$:

soft-breaking scale of the discrete symm.

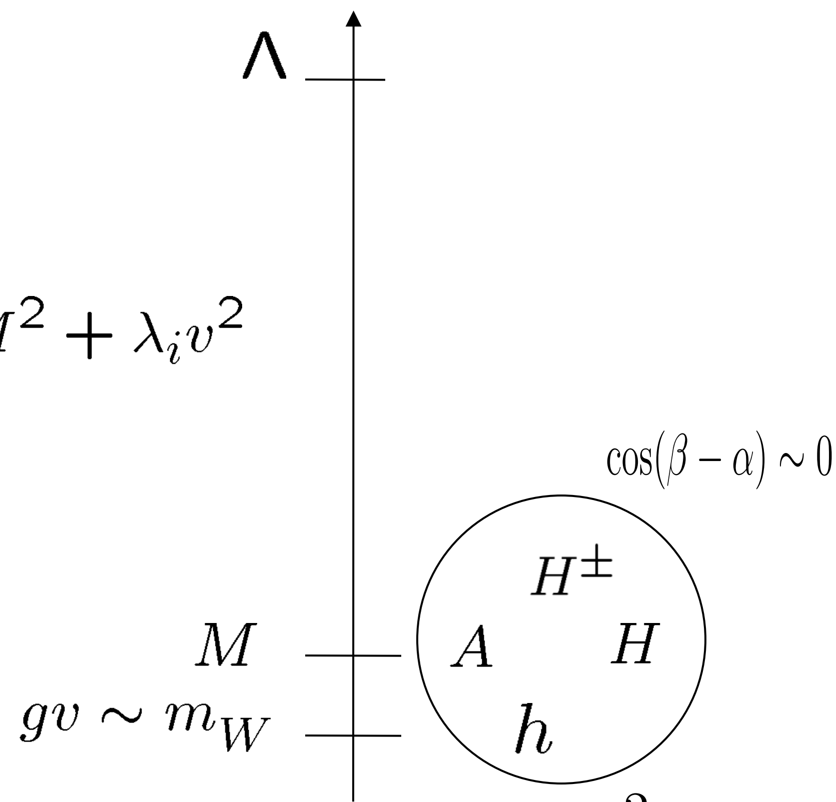
Two Possibilities

Λ: Cutoff

M: Mass scale irrelevant to VEV



$$m^2_{A,H,H^\pm} \simeq M^2 + \lambda_i v^2$$



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{nonSM}} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

Effective Theory is an extended Higgs sector

Non-decoupling effect

Gauge Couplings *hVV*

$L = g_{hVV} \sin(\beta-\alpha)\, hVV + g_{HVV} \cos(\beta-\alpha)\, HVV$

- Changed by mixing with the other scalars

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

- Sum-rule for a multi-doublet structure

  $g_{hVV}^2 + g_{HVV}^2 = g_V^2$

  $\sin^2(\beta-\alpha)<1 \Leftrightarrow \kappa_V^2 = (g_{hVV}/g_{hVV}^{SM})^2 < 1$

SM-like case
$\sin^2(\beta-\alpha) \approx 1$

- Higgs sector with an exotic representation

  $\kappa_V^2 > 1$ is also possible!

Higgs triplet model
Georgi-Machasek model
Models with a septet field, …

Yukawa Coupling in Extended Higgs Sectors

Multi-Higgs model: FCNC appears via Higgs mediation

2 Higgs doublet models:

to avoid FCNC, give different charges to Φ_1 and Φ_2

Discrete sym. $\Phi_1 \rightarrow +\Phi_{1,} \quad \Phi_2 = -\Phi_2$

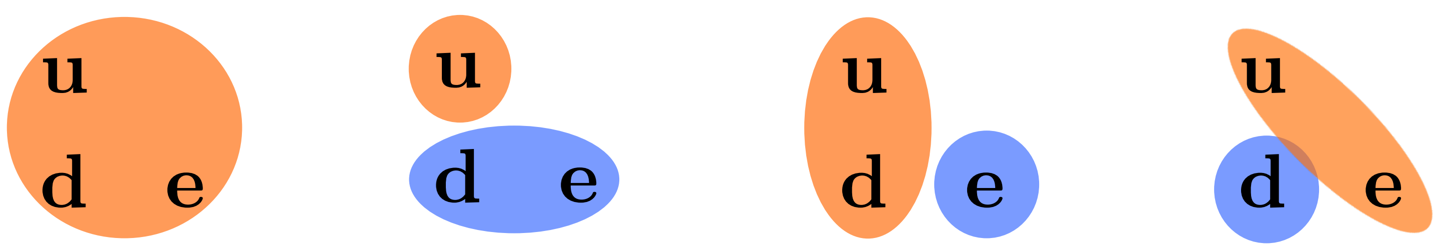
Each quark or lepton couples only one Higgs doublet

No FCNC at tree level

Four Types of Yukawa coupling

Barger, Hewett, Phillips

Classified by Z_2 charge assignment



Type-I — Neutrinophilic, Inert

Type-II — SUSY

Type-X — Radiative Seesaw, Lepton specific

Type-Y

Type2-2HDM (MSSM) Higgs couplings

VEV's: $v_1^2 + v_2^2 = v^2 \simeq (246\ \text{GeV})^2$

Higgs mixing

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

SM

2HDM Type2

Gauge coupling:

$\phi VV \quad (V = Z, W) \quad \Rightarrow$

hVV: $\sin(\beta - \alpha)$, HVV: $\cos(\beta - \alpha)$

Yukawa coupling:

$\phi b\bar{b} \quad \Rightarrow$

$hb\bar{b}$: $\dfrac{\sin\alpha}{\cos\beta}$, $Hb\bar{b}$: $\dfrac{\cos\alpha}{\cos\beta}$

$\phi t\bar{t} \quad \Rightarrow$

$ht\bar{t}$: $\dfrac{\cos\alpha}{\sin\beta}$, $Ht\bar{t}$: $\dfrac{\sin\alpha}{\sin\beta}$,

SM-like regime

hVV $\sin(\beta-\alpha)$ HVV $\cos(\beta-\alpha)$

$$\sin(\beta-\alpha) \simeq 1$$

Only the lightest Higgs *h* couples to weak gauge bosons

h **behaves like the SM Higgs**

$$g_{hVV} \to g^{\mathrm{SM}}_{\phi VV} \qquad g_{HVV} \to 0$$

$$y_{ht\bar{t}} \to y^{\mathrm{SM}}_{\phi t\bar{t}} \qquad y_{Ht\bar{t}} \to y^{\mathrm{SM}}_{\phi t\bar{t}} \cot\beta$$

$$y_{hb\bar{b}} \to y^{\mathrm{SM}}_{\phi b\bar{b}} \qquad y_{Hb\bar{b}} \to y^{\mathrm{SM}}_{\phi b\bar{b}} \tan\beta$$

$$y_{h\tau\tau} \to y^{\mathrm{SM}}_{\phi\tau\tau} \qquad y_{H\tau\tau} \to y^{\mathrm{SM}}_{\phi\tau\tau} \tan\beta$$

Type-II 2HDM

Theoretical Constraints on extended Higgs sectors

- Unitarity bound
- Vacuum Stability bound
- Triviality bound
- Wrong vacuum condition (singlet model)

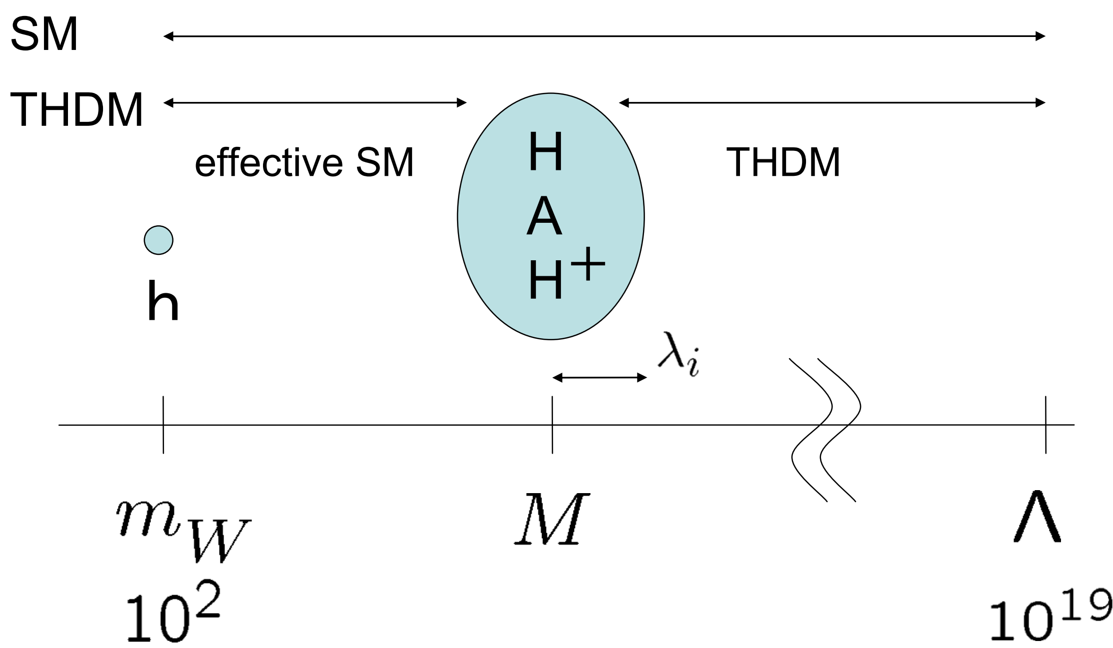
Many λcouplings → mass prediction changed

Lightest Higgs mass

$$m_h^2 = \lambda v^2$$

Additional Higgs masses

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

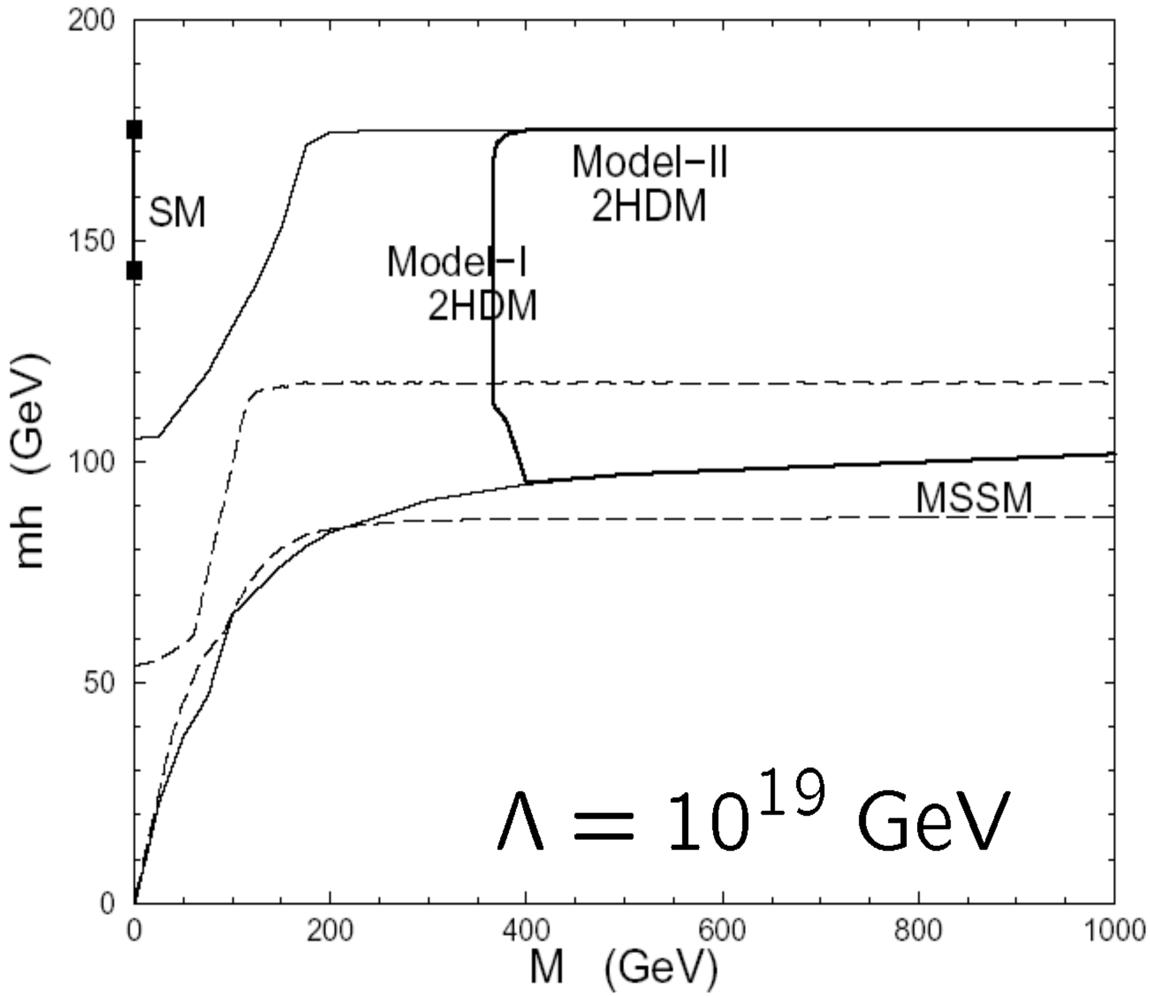


RGE

$$16\pi^2 \mu \frac{d}{d\mu}\lambda = 24\lambda^2 - 6y_t^2 + A(\lambda', \lambda'', \ldots)$$

Mass of the lightest Higgs boson

- SM
- 2HDM type1
- 2HDM type 2
- MSSM



The predicted region of mass can be differ even if all the other phenomena behave like the SM in the low energy.

Kanemura, Kasai, Okada 1999

Higgs singlet extension (HSM)

$$V_0 = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2} S^2 + \frac{\mu_S'}{3} S^3 + \frac{\lambda_S}{4} S^4$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + \phi_1 + iG^0) \end{pmatrix}, \quad S = v_S + \phi_2$$

Mass eigenstates and mixing angle

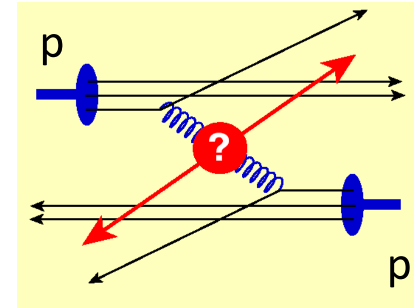
$(\phi_1, \phi_2) \rightarrow$ $(h,\ H)$ with θ

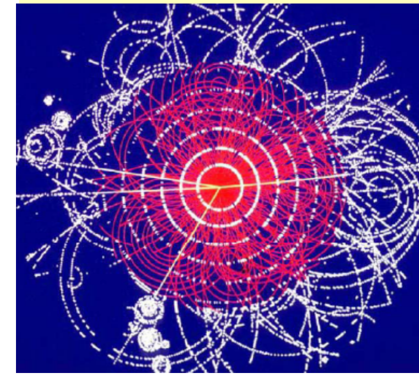
↑

125GeV Higgs boson

Fingerprinting

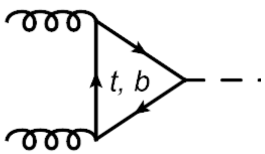
Direct search and indirect tests





- **Direct searches of additional Higgs bosons**

  $h(125)$, $H, A, H^+, H^{++}, \ldots$



$H, A, \ldots$

Machine for discovery!

Hadron Collider (LHC)

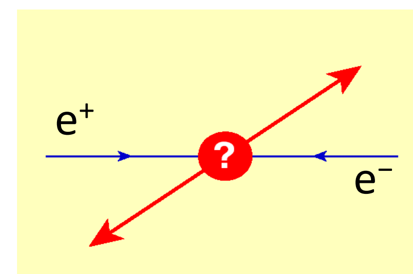
Run1	7-8 TeV	20fb^{-1}
Run 2,3	13-14 TeV	300fb^{-1}
HL-LHC	13-14 TeV	3000fb^{-1}

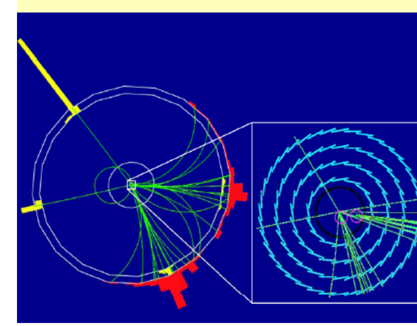
- **Indirect test by finding deviations from SM**

  EW parameters m_W, S, T, U, Zff, Wff', $WWV, \ldots$

  Couplings of $h(125)$ $hWW, hZZ, h\gamma\gamma, hff, hhh, \ldots$

Precision measurements!

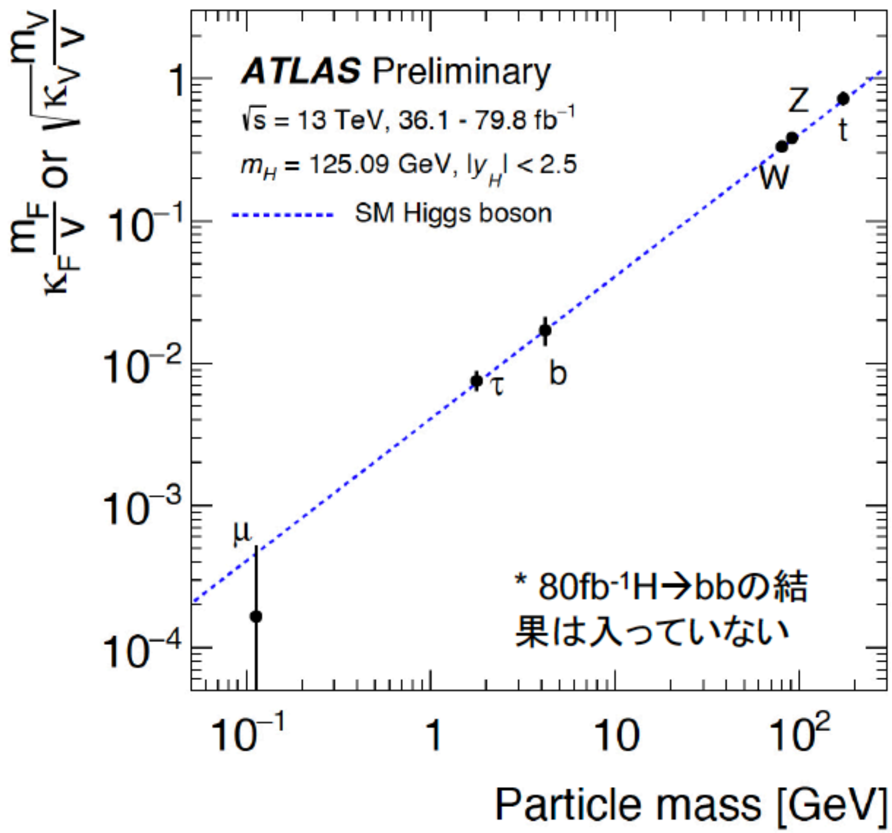


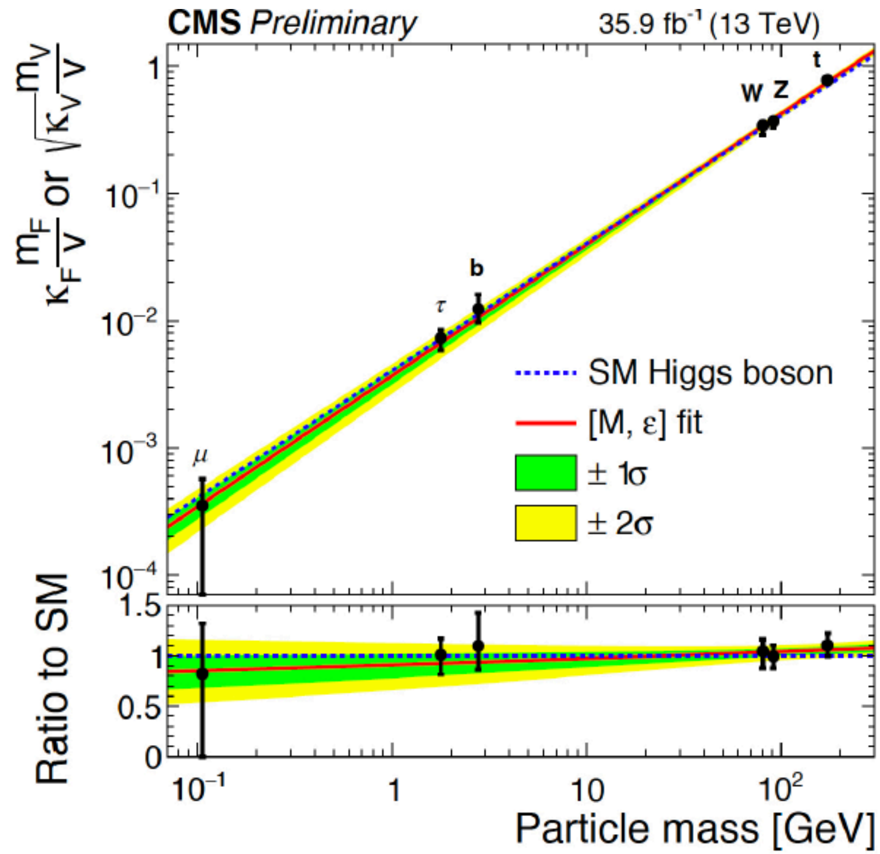


Advantage for lepton colliders

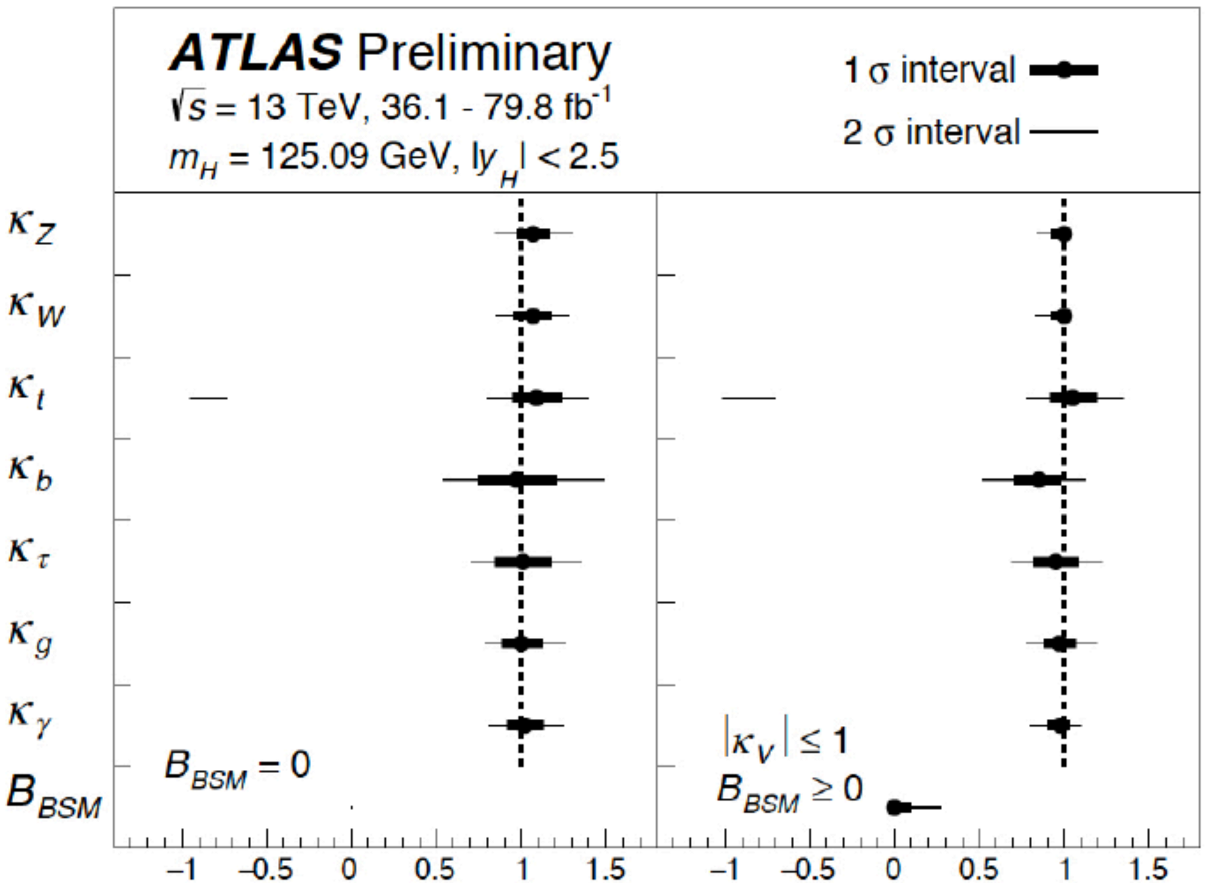
Future International Collider (ILC), CEPC, FCCee,

E = 240-250 GeV, (500GeV, 1 TeV, …)


ATLAS Preliminary
√s = 13 TeV, 36.1 - 79.8 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
SM Higgs boson
* 80fb-1H→bbの結
果は入っていない
Particle mass [GeV]


CMS Preliminary
35.9 fb⁻¹ (13 TeV)
SM Higgs boson
[M, ε] fit
± 1σ
± 2σ
Ratio to SM
Particle mass [GeV]

Coupling Measurements

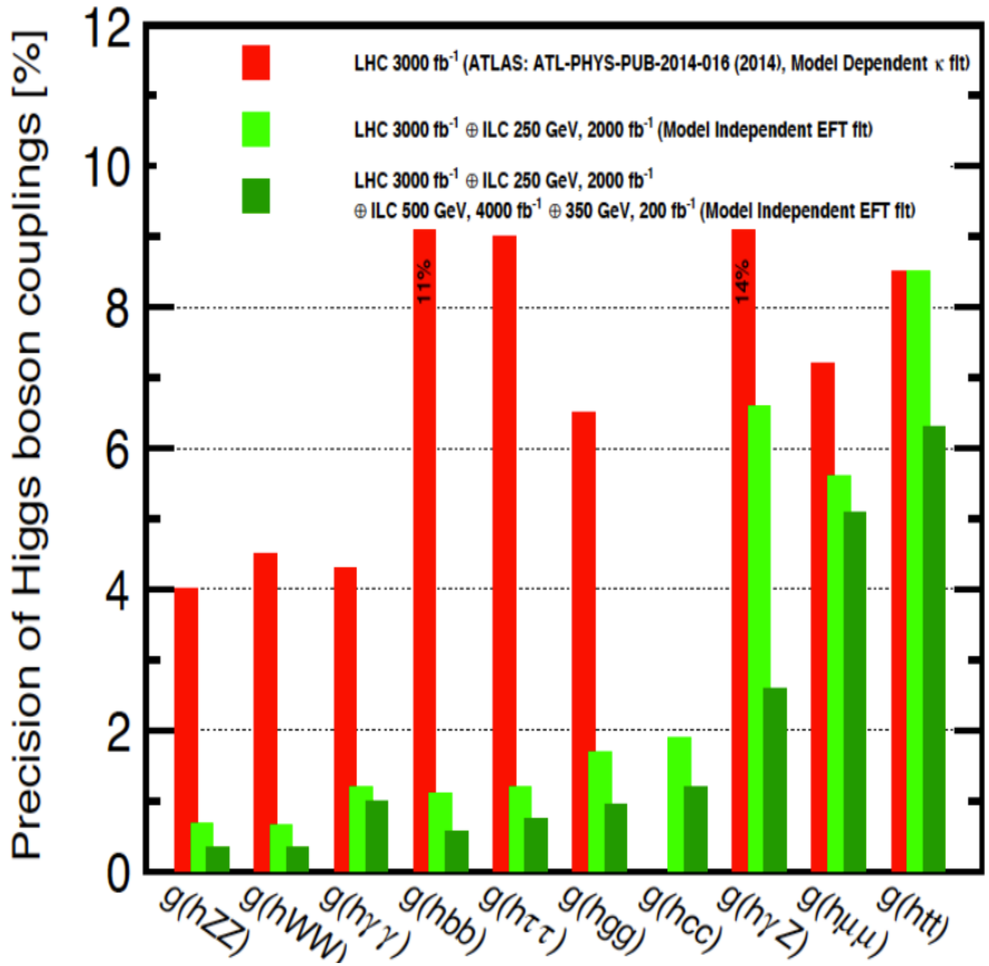


$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{1 - BR_{BSM}}$$

$B_{BSM} < 0.26$(95% C.L.)

Higgs Precision at HL-LHC, ILC250, …

[K. Fujii, et al., arXiv:1710.07621]



Future lepton colliders ILC, CEPC, FCCee, CLIC, …

Deviation = New Physics scale

Scaling factor κ_i : factor of deviation from the SM value

Coupling of *h*(125) and weak bosons

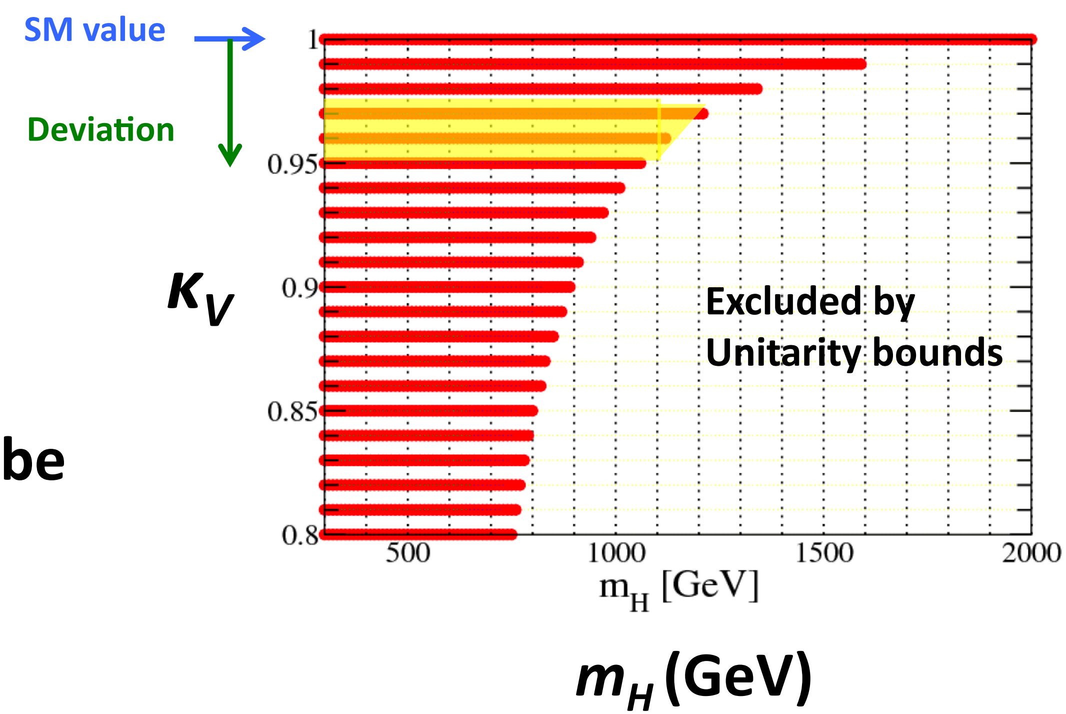
V (=W, Z) hVV

$$\kappa_V = \sin(\beta - \alpha)$$

If a 3% deviation in κ_V

⬇

The second Higgs *H* should be lighter than 1200 GeV



Precision test has the similar power to the direct search

Scaling factors

$$\kappa_X = g_{hXX}^{EX} / g_{hXX}^{SM}$$

2HDM :

	Mixing factor		
	ξ_u	ξ_d	ξ_e
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	$\cot\beta$	$-\tan\beta$	$\cot\beta$

$$\kappa_V = \sin(\beta - \alpha)$$

$$\kappa_f = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)$$

HSM :

$$\kappa_V = \cos\alpha$$

$$\kappa_f = \cos\alpha$$

$$\frac{\Gamma(h \to VV^*)_{EX.}}{\Gamma(h \to VV^*)_{SM}} \sim \kappa_V^2$$

$$\frac{\Gamma(h \to ff)_{EX.}}{\Gamma(h \to ff)_{SM}} \sim \kappa_f^2$$

Pattern of deviations

Gauge couplings: *hVV*

Yukawa couplings: *hττ*, *hbb*, *hcc*

cos(β-α) < 0

	κ_V	κ_τ	κ_b	κ_c
Type-I	↓	↓	↓	↓
Type-II	↓	↑	↑	↓
Type-X	↓	↑	↓	↓
Type-Y	↓	↓	↑	↓

Direction of deviation in each coupling

We can fingerprint extended Higgs models from the pattern of deviation in Higgs couplings

SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014

Fingerprinting the 2HDM

$$\kappa_V \equiv \frac{g_{hVV(2HDM)}}{g_{hVV(SM)}} = \sin(\beta - \alpha)$$

$x = \cos(\beta-\alpha)$ **SM-like: $|x| \ll 1$**

$\kappa_V = 1 - (1/2)\, x^2 + \ldots$

When a Fermion couples to Φ_1

$$\kappa_f = 1 + \cot\beta\, x + \cdots$$

and if it couples to Φ_2

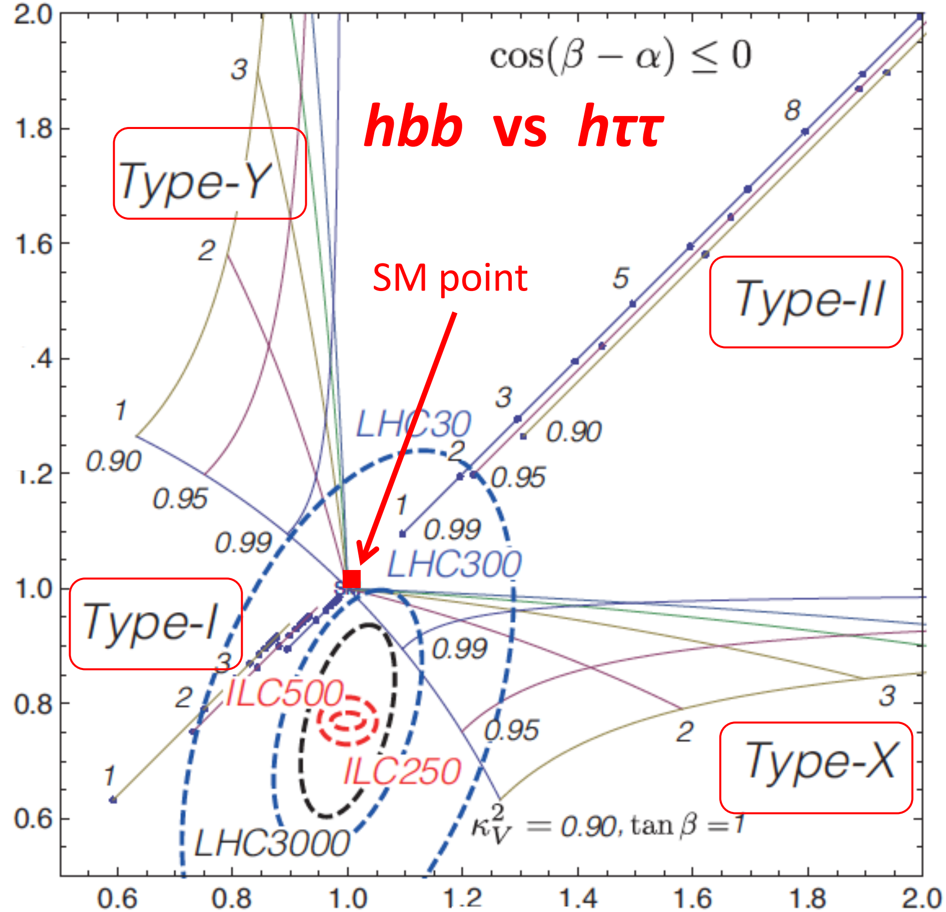
$$\kappa_f = 1 - \tan\beta\, x + \cdots$$

If deviation in κ^2_V can be large enough to be detected at future collider

4-models can be separated by looking at deviations in Yukawa couplings κ_τ, κ_b, κ_c, …

SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014

κ_b

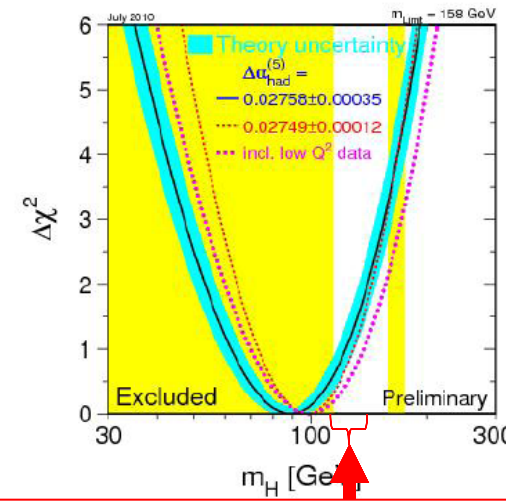


κ_τ

Ellipse = 68.27% CL

Radiative Correction
Decoupling/Non-decoupling

Higgs discovery in 2012



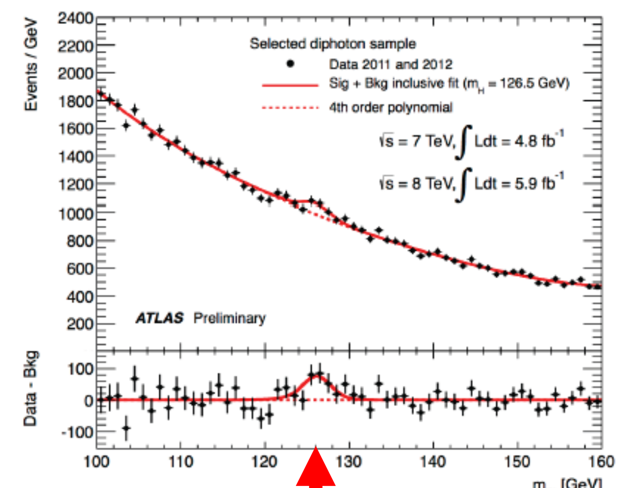
The mass is 125 GeV

Spin/Parity 0^+

It couples to ***γγ, ZZ, WW, bb, ττ, …***

Higgs Mass indicated by LEP/SLC

This is really a Higgs!



Measured couplings look consistent with the SM Higgs within the current errors

ATLAS/CMS July 2012

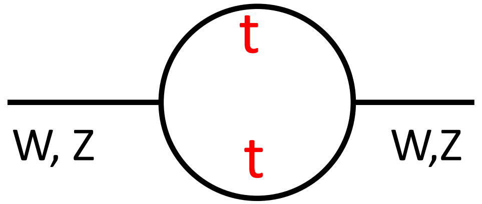
New Particle！

Radiative Corrections

Rho parameter（unity in the SM）

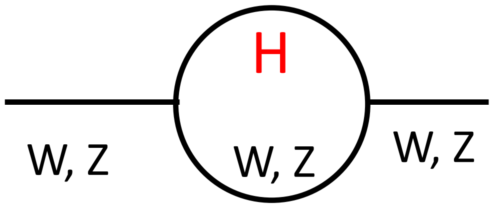
$\rho_{exp} = 1.0008^{+0.0017}_{-0.0007}$

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \; (= 1)$$



Loop corrections

$$\Delta\rho = 4\sqrt{2}G_F\left[\Pi_T^{33}(p^2=0) - \Pi_T^{11}(p^2=0)\right]$$



Loop effect of m_t and m_H

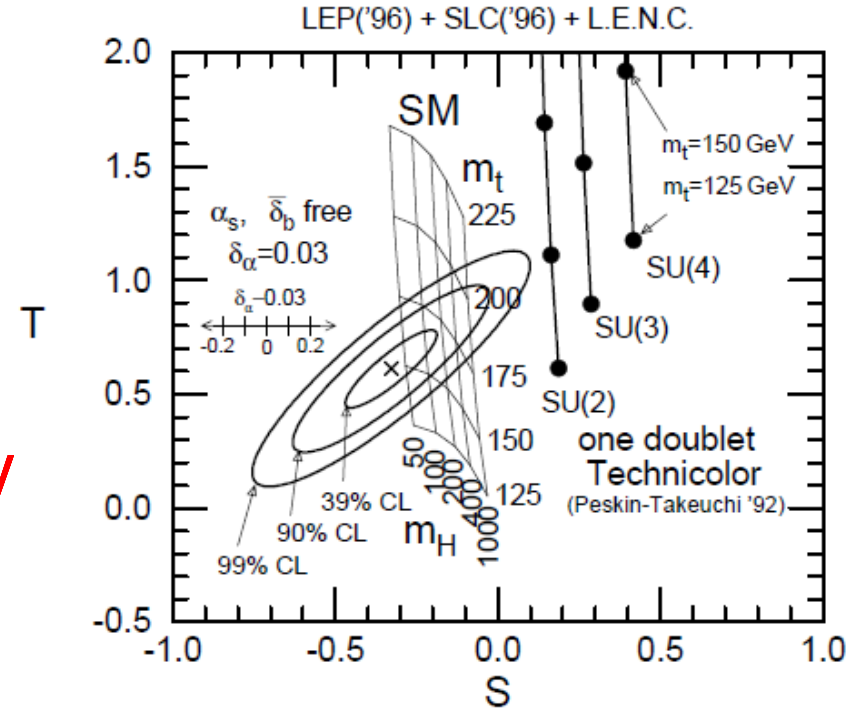
$$\Delta\rho \simeq \frac{3G_F}{8\sqrt{2}\pi^2}\left(m_t^2 - M_Z^2\sin^2\theta_W \ln\frac{m_H^2}{m_W^2}\right)$$

Quadratic **Logarithmic**

We knew the mass before discovery!

Case of the top quark

- Quadratic mass dep. in ρ parameter (T parameter)
- Forget about m_H because it is only logarismic
- LEP1 says m_t=150-200GeV
- Discovery at Tevatron（about 175GeV）



Hagiwara、et al

$$\Delta\rho \simeq \frac{3G_F}{8\sqrt{2}\pi^2}\left(m_t^2 - M_Z^2 \sin^2\theta_W \ln\frac{m_H^2}{m_W^2}\right)$$

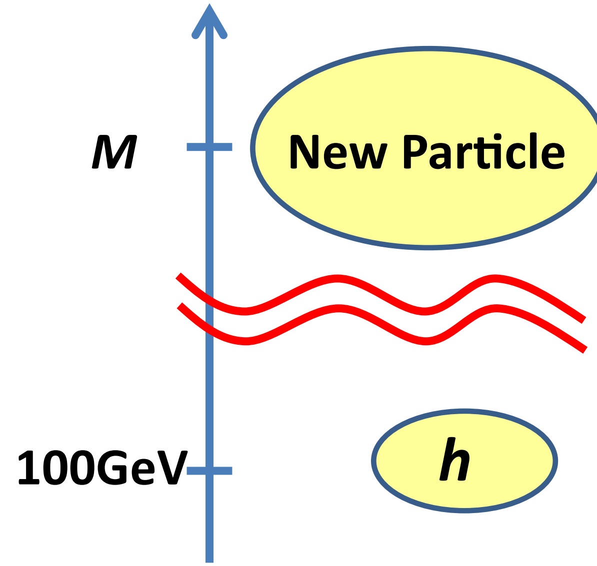
Decoupling Theorem and its breaking

Decoupling Theorem

Low energy observable O

Renormalized quantity O is a function of M via loop contributions, but it decouples in the large mass limit

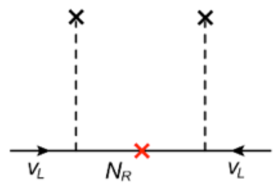
$$O(M) \sim \frac{1}{M^n}$$



Ex) GUT scale (10^{16} GeV) physics does not affect TeV scale physics

Ex) Seesaw Mechanism (Dim 5) at the tree-level

$$\mathcal{L} = \frac{c}{\Lambda}(\Phi^T \overline{\nu_L^c})(\nu_L \Phi)$$

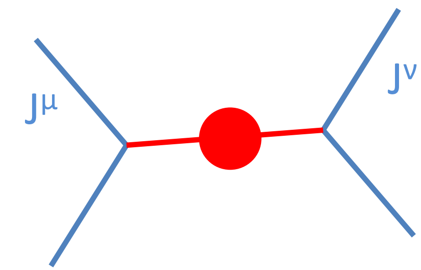


$$m_\nu \sim \frac{v^2}{M_{N_R}}$$

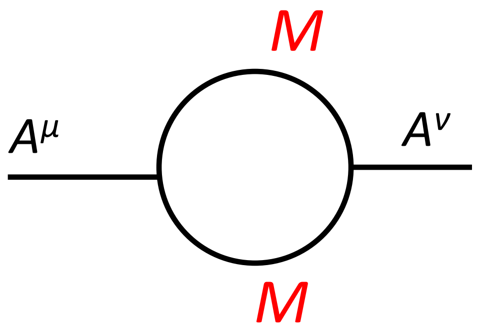
QED   Example of decoupling theorem

One-loop contributions to the two point functions

$$\mathcal{M}_{tree} \sim Qe\frac{1}{k^2}eQ' = \frac{QQ'}{\frac{1}{e^2}k^2}$$



$$\mathcal{M} \sim \frac{QQ'}{\frac{1}{e^2}k^2 - \Pi_{\rm new}(k^2)}$$



Self-Energy $\Pi_{new}(k^2)$ has dim. 2, so that it can have M^2 or $\ln M$ dependence from power counting (non-decoupling effects)

$$\Pi_{\rm new}(k^2) = \Pi_{\rm new}(0) + k^2\Pi'_{\rm new}(0) + \cdots$$

However from U(1) gauge symmetry $\Pi_{new}(0)=0$, and $\Pi'_{new}(0)$ is absorbed by renormalization

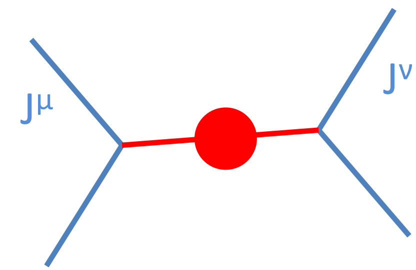
$$\mathcal{M} \sim \frac{QQ'}{\left(\frac{1}{e^2} - \Pi'(0)_{\rm New}\right)k^2 - \frac{(k^2)^2}{2}\Pi''_{\rm new}(k^2)} = \frac{QQ'}{\frac{1}{e_R^2}k^2 - \frac{(k^2)^2}{2}\Pi''_{\rm new}(0) + \cdots}$$

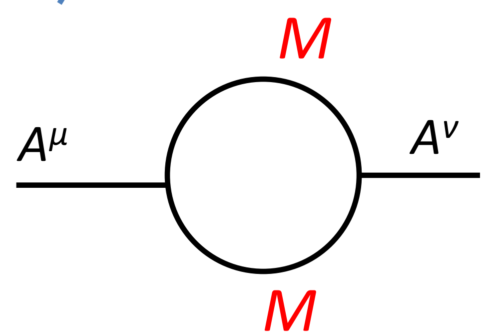
Remaining $\Pi''_{new}(0)$ is dim. −2, so that at most $1/M^2$ (Decouple!)

QED with spontaneously broken U(1)

$$\mathcal{M}_{tree} \sim Qe\frac{1}{k^2 - m_A^2}eQ' = \frac{QQ'}{\frac{1}{e^2}k^2 - v^2}$$

$$\mathcal{M} \sim \frac{QQ'}{\frac{1}{e^2}k^2 - v^2 - \Pi_{\text{new}}(k^2)}$$





Self-Energy $\Pi_{\text{new}}(k^2)$ has dim. 2, so that it can have M^2 or ln$M$ dependence from power counting (non-decoupling effects)

$$\Pi_{\text{new}}(k^2) = \Pi_{\text{new}}(0) + k^2\Pi'_{\text{new}}(0) + \cdots$$

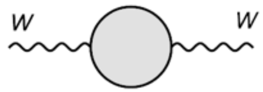
This time, U(1) is spontaneously broken, so that $\Pi_{\text{new}}(0)$ is non-zero.
But this time, $\Pi_{\text{new}}(0)$ and $\Pi'_{\text{new}}(0)$ are absorbed by v (or m_A) and e

$$\mathcal{M} \sim \frac{QQ'}{\left(\frac{1}{e^2} - \Pi'_{\text{new}}(0)\right)k^2 - (v^2 + \Pi_{\text{new}}(0)) - \frac{(k^2)^2}{2}\Pi''_{\text{new}}(0) + \cdots} = \frac{QQ'}{\frac{1}{e_R^2}k^2 - v_R^2 - \frac{(k^2)^2}{2}\Pi''_{\text{new}}(0) + \cdots}$$

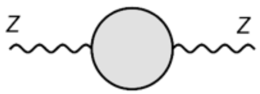
Remaining $\Pi''_{\text{new}}(0)$ is dim(-2), so that at most $1/M^2$ (Decouple!)

SM: Electroweak Theory with SSB

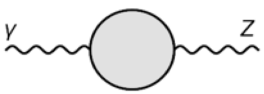
Two point functions 6 nondec. d.o.f.



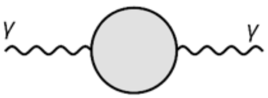
$$= M_{\rm New}^2 + p^2 \ln \frac{M_{\rm New}^2}{p^2} + \cdots$$



$$= M_{\rm New}^2 + p^2 \ln \frac{M_{\rm New}^2}{p^2} + \cdots$$



= ~~$M_{\rm New}^2$~~ $+ p^2 \ln \frac{M_{\rm New}^2}{p^2} + \cdots$



= ~~$M_{\rm New}^2$~~ $+ p^2 \ln \frac{M_{\rm New}^2}{p^2} + \cdots$

$$\Pi_T^{\gamma\gamma}(p^2) = e^2 \Pi_T^{QQ}(p^2),$$
$$\Pi_T^{\gamma Z}(p^2) = e g_Z [\Pi_T^{3Q}(p^2) - s_W^2 \Pi_T^{QQ}(p^2)],$$
$$\Pi_T^{ZZ}(p^2) = g_Z^2 [\Pi_T^{33}(p^2) - 2 s_W^2 \Pi_T^{3Q}(p^2) + s_W^4 \Pi_T^{QQ}(p^2)],$$
$$\Pi_T^{WW}(p^2) = g^2 \Pi_T^{11}(p^2).$$

WT identity: $\Pi_{QQ}(0)=\Pi_{3Q}(0)=0$

$$\alpha_*(0) = \alpha[1 + e^2 \Pi'_{QQ}(0)]$$
$$G_F = \frac{1}{\sqrt{2}v^2} - \frac{4}{\sqrt{2}v^4}\Pi_{11}(0)$$
$$m_Z^2 = \frac{e_0^2}{s_0^2 c_0^2}\frac{v^2}{4} + \frac{e_0^2}{s_0^2 c_0^2}(\Pi_{33} - 2 s_0^2 \Pi_{3Q} + s_0^4 \Pi_{QQ})|_{q^2=m_Z^2}$$

Input parameters（α, G_F, M_Z）can absorb 3 of 6 non-decoupling effects.

Still, there remain 3 non-vanishing non-decoupling effects

S, T, U (Peskin-Takeuchi)

$$S = 16\pi [\overline{\Pi}_T^{3Q\prime}(p^2=0) - \overline{\Pi}_T^{33\prime}(p^2=0)],$$
$$T = \frac{4\sqrt{2}G_F}{\alpha_{\rm EM}} [\overline{\Pi}_T^{33}(p^2=0) - \overline{\Pi}_T^{11}(p^2=0)],$$
$$U = 16\pi [\overline{\Pi}_T^{33\prime}(p^2=0) - \overline{\Pi}_T^{11\prime}(p^2=0)],$$

Non-decoupling effects

Non-decoupling effects on electroweak parameters

Γ_Z, $\sin\theta_w$, m_W , ρ , …

are all described by *S, T, U* (at the leading level)

$$S = 16\pi\left[\overline{\Pi}_T^{3Q\prime}(p^2=0) - \overline{\Pi}_T^{33\prime}(p^2=0)\right],$$

$$T = \frac{4\sqrt{2}G_F}{\alpha_{\rm EM}}\left[\overline{\Pi}_T^{33}(p^2=0) - \overline{\Pi}_T^{11}(p^2=0)\right],$$

$$U = 16\pi\left[\overline{\Pi}_T^{33\prime}(p^2=0) - \overline{\Pi}_T^{11\prime}(p^2=0)\right],$$

Ex)

$$\Delta\rho \equiv \rho - 1 = \alpha T$$

$$m_W^2 = m_W^2(\text{ref}) + \frac{\alpha c^2}{c^2 - s^2}\left(-\frac{1}{2}S + c^2 T + \frac{c^2 - s^2}{4s^2}U\right)$$

Non-decoupling effects

What kind of new physics can produce large non-decoupling effects?

- Chiral Fermion Loop

  $m_f = 0 \quad \rightarrow \quad m_f = y_f\, v$

- Higgs Loop

  $m_h^2 = 2\,\lambda\, v^2$

- Scalar Loop

  $m_S^2 = \lambda\, v^2 + M_{inv}^2$

SU(2) doublet (N,E), hypercharge Y, masses m_N, m_E

$$S = \frac{1}{6\pi}\left[1 - Y \ln\frac{m_N^2}{m_E^2}\right]$$

$$T = \frac{1}{16\pi s^2 c^2 m_Z^2}\left[m_N^2 + m_E^2 - \frac{2m_N^2 m_E^2}{m_N^2 - m_E^2}\ln\frac{m_N^2}{m_E^2}\right]$$

$$U = \frac{1}{6\pi}\left[-\frac{5m_N^4 - 22m_N^2 m_E^2 + 5m_E^4}{3(m_N^2 - m_E^2)^2} + \frac{m_N^6 - 3m_N^4 m_E^2 - 3m_N^2 m_E^4 + m_E^6}{(m_N^2 - m_E^2)^3}\ln\frac{m_N^2}{m_E^2}\right]$$

$\Delta m = |m_N - m_E| \ll m_N, m_E$

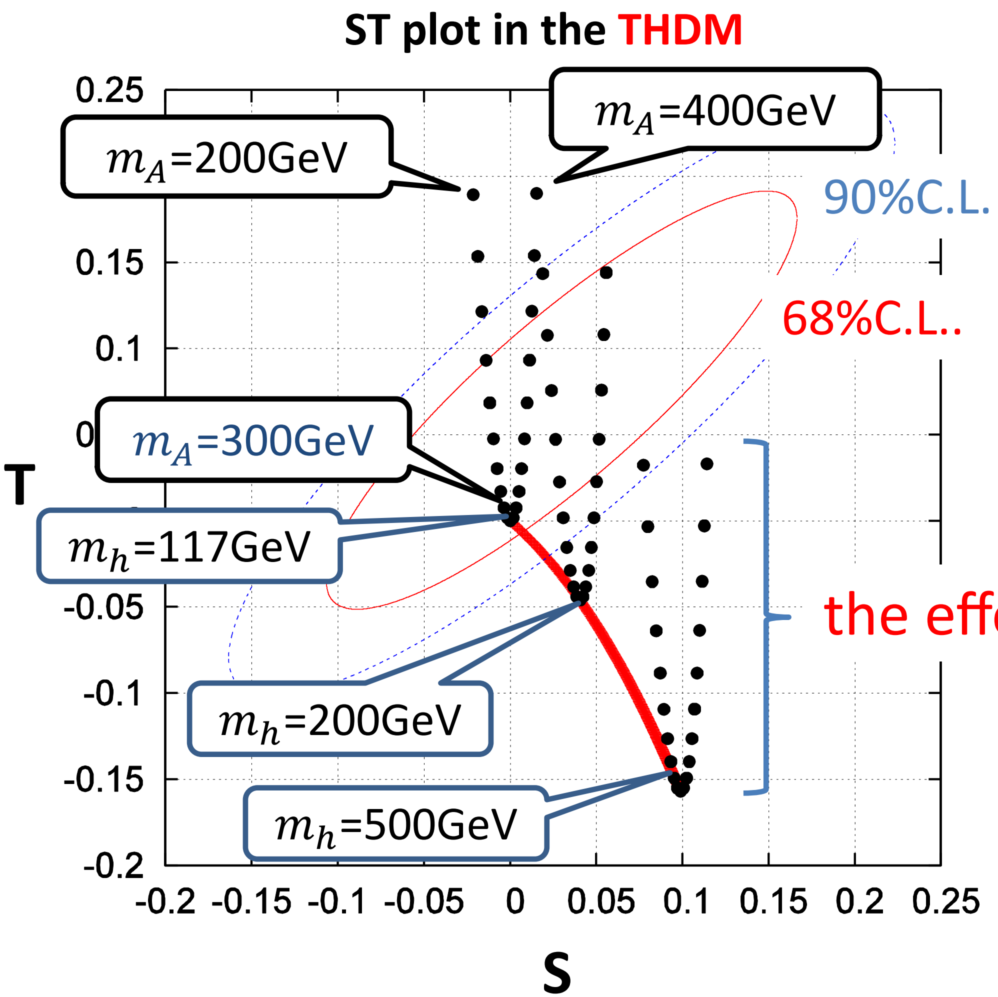
$$S = \frac{1}{6\pi}$$

$$T = \frac{1}{12\pi s^2 c^2}\frac{(\Delta m)^2}{m_Z^2}$$

$$U = \frac{2}{15\pi}\frac{(\Delta m)^2}{m_N^2}$$

$m_N = m_E$ → $T=U=0$ Custodial Symmetric O(4) ≒ $SU(2)_L \times SU(2)_R$

Effect of additional scalars in 2HDM



$$S_\Phi \approx -\frac{1}{12\pi}\ln\frac{m_{H^\pm}^2}{m_A^2},$$

$$T_\Phi \approx \frac{\sqrt{2}G_F}{12\pi^2\alpha_{EM}}\left(m_A - m_{H^\pm}\right)^2$$

$$m_H = m_A, \sin(\beta-\alpha) = 1$$

$$T = T_{SM} + T_\Phi$$

$m_{H^\pm}$=300GeV, m_A is varied from 200 to 400 GeV.

When $m_A = m_H = m_{H^\pm}$,
we obtain $S_\Phi = 0$ and $T_\Phi = 0$.

arXiv: 1108.3297

Radiative corrections to the Higgs boson couplings

All SM parameters are found

Next target is new physics!

- **Importance of Radiative Correction calculation**
- **Future precision measurements**
  - ***S, T, U*** **(Giga Z, Mega W)**
  - **Top (e.g. ttZ) couplings**
  - **Couplings of the discovered Higgs**

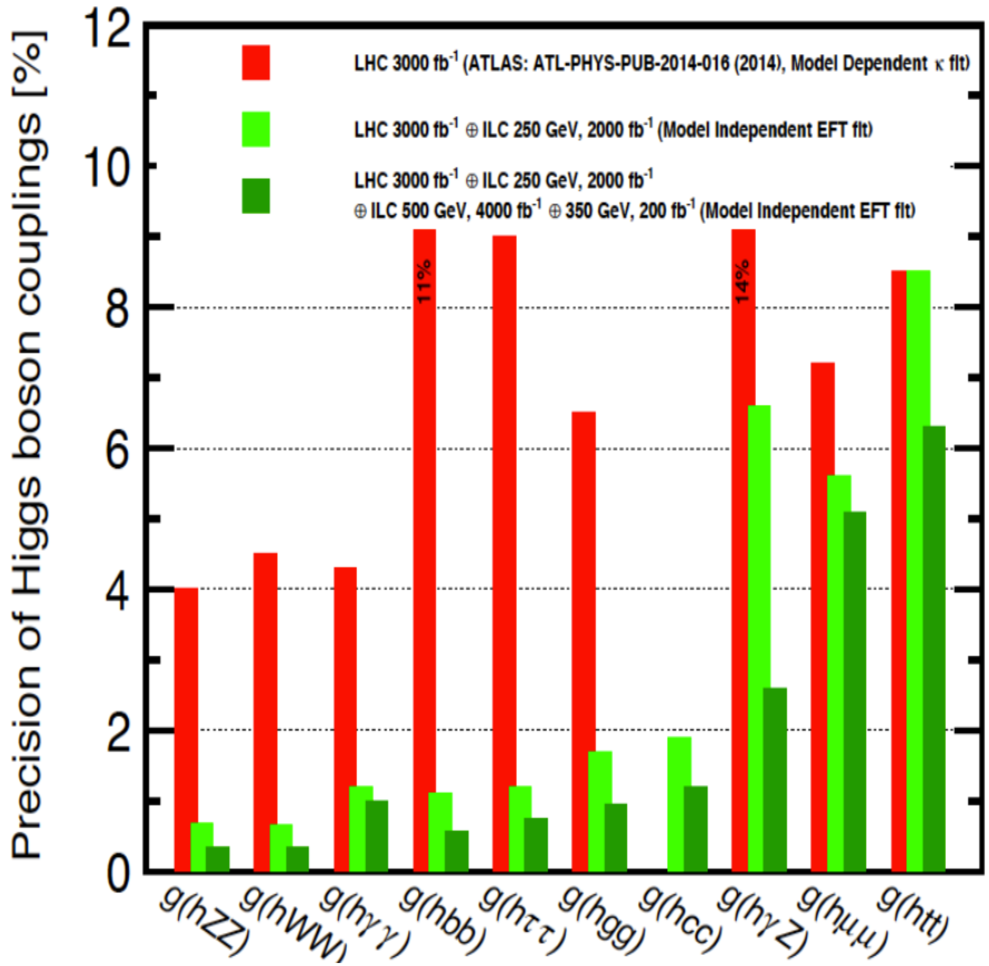
hgg, hγγ, hWW, hZZ, htt, hbb, hττ, hμμ, hcc, …, hhh

At ILC, we may be able to distinguish models by detecting a pattern of deviations in the *h(125)* couplings from the SM values!

Fingerprinting new physics models

Higgs Precision at HL-LHC, ILC250, …

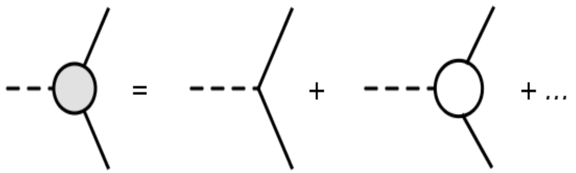
[K. Fujii, et al., arXiv:1710.07621]



Future lepton colliders ILC, CEPC, FCCee, CLIC, …

Radiative Corrections

Higgs couplings *hγγ, hgg, hWW, hZZ, hττ, hbb, htt, …*
will be measured thoroughly in the future
Analyses with radiative corrections are necessary



Accurate Theory Predictions × **Future Precision Measurements**

New Physics!

H-COUP Project *SK, Kikuchi, Sakurai, Yagyu (2017)*

Full set of Fortran codes to systematically calculate quantum corrections to Higgs couplings in various extended Higgs models

Program H-COUP ver. 1 completed and released
[Manual arXiv: 1710.04603]

Models

- **Additional Singlet**
- **2HDM (I)**
- **2HDM (II)**
- **2HDM (X)**
- **2HDM (Y)**
- **Inert doublet/singlet**
- **Triplet model,**
- **GM model**

Non-decoupling effect on the Higgs couplings

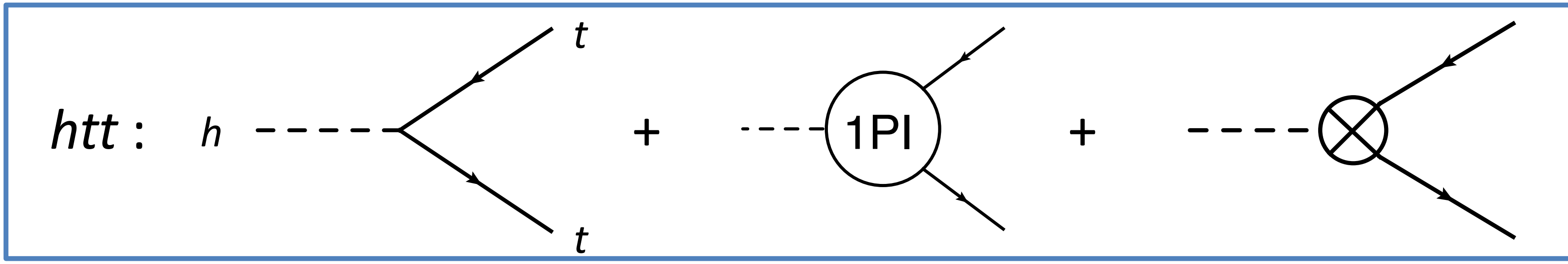
Top-loop contribution in the SM

$$g^R_{hWW} \sim \frac{2m_W^2}{v}\left(1 - \frac{5N_c}{96\pi^2}\frac{m_t^2}{v^2}\right)$$

$$y^R_{hff} \sim \frac{\sqrt{2}m_f}{v}\left(1 - \frac{N_c}{12\pi^2}\frac{m_t^2}{v^2}\right)$$

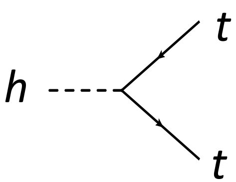
How about the new physics loop contributions?

For example: renormailzed *htt* coupling



tree level   1-loop level   counter term

tree level



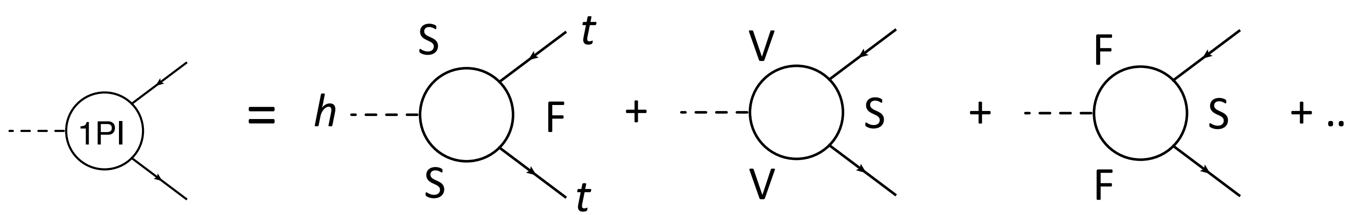
$$= -\frac{m_t}{v}\xi_h^u$$

$$\xi_h^u = \sin(\beta-\alpha) + cot\beta\cos(\beta-\alpha)$$

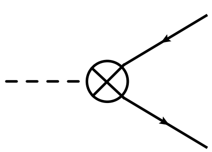
α : mixing angle for CP-even Higgs *H,h*

β : mixing angle for CP-odd Higgs *A,G⁰*

1-loop level



counter term



$$= -\frac{m_t}{v}\xi_h^u\left[\frac{\delta m_t}{m_t} - \frac{\delta v}{v} + \frac{1}{2}\delta Z_h + \delta Z_t + \frac{\delta\xi_h^u}{\xi_h^u} + \frac{\xi_H^u}{\xi_h^u}(\delta C_h + \delta\alpha)\right]$$

counter term parameters : $\delta m_t, \delta v, \delta\alpha, \delta\xi_h^u, \delta Z_h, \delta Z_t, \delta C_h$

these are determined by relevant renormalization conditions.

Scale Factors (1-loop level) in 2HDM

Mixing parameter x = cos(β−α) $\left[\sin(\beta-\alpha) = 1 - \frac{x^2}{2}\right]$ **SM-like x << 1**

Scale Factor of the *hVV* Couplings

$\Delta\kappa_X = \kappa_X - 1$

$$\Delta\hat{\kappa}_V \simeq -\frac{1}{2}x^2 - A(m_\Phi^2, M^2)$$

mixing loop

Loop Effect

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

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

$(\Phi = H^\pm, A, H)$

where

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

Decoupling $(M >> v)$

Non-decoupling $(M \sim v)$

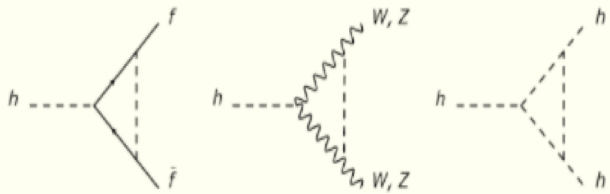
H-COUP

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

H-COUP

Website of H-COUP

You can download the program and the manual



H-COUP is a calculation tool composed of a set of Fortran codes to compute the renormalized Higgs boson couplings with radiative corrections in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. The impolved on-shell renormalization scheme is adopted, where the gauge depdence is eliminated.

Authors: Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu

The manual for H-COUP version 1.0 can be taken on arXiv:1710.04603 [hep-ph].

Downloads

- H-COUP version 1.0 : [HCOUP-1.0.zip] [The manual is here]

In order to run H-COUP version 1.0, you need to install LoopTools (www.feynarts.de/looptools/).

History

Example for the application of H-COUP

H-COUP:
provides the EW (and Higgs) one-loop correction to the Higgs vertex functions in various extended Higgs sectors

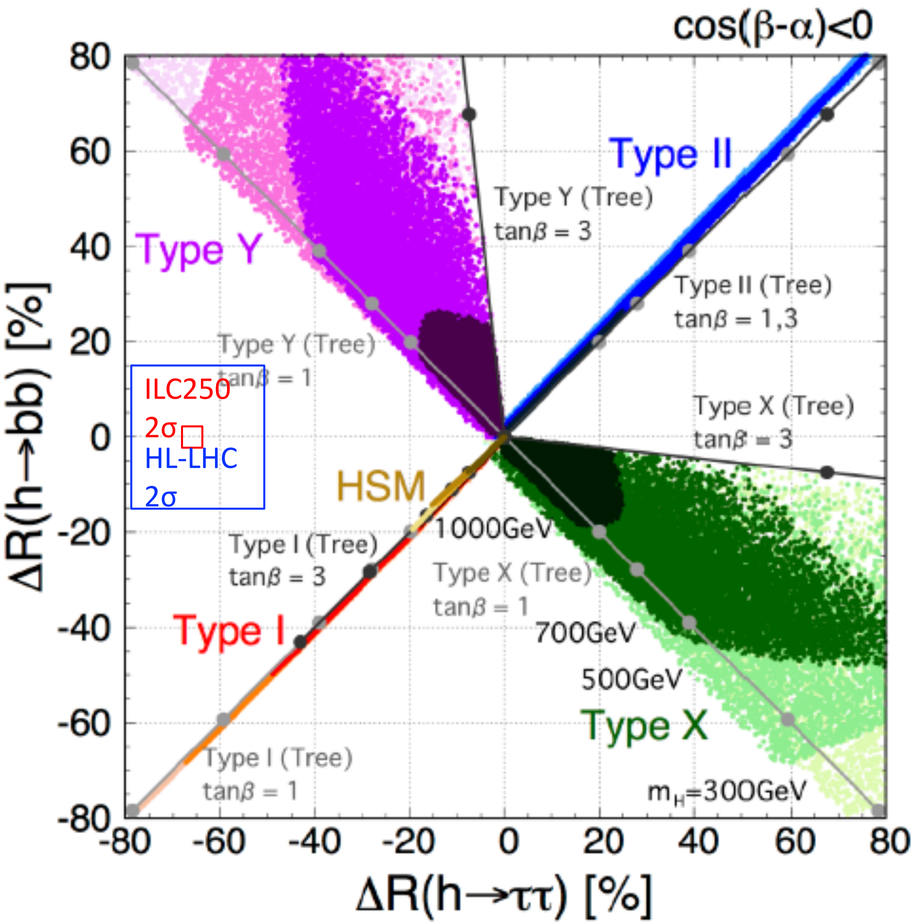
Using H-COUP,
the decay rates of the SM-like Higgs boson with EW (Higgs) and QCD corrections are Calculated in the HSM and 2HDM (type I, II, X, Y)

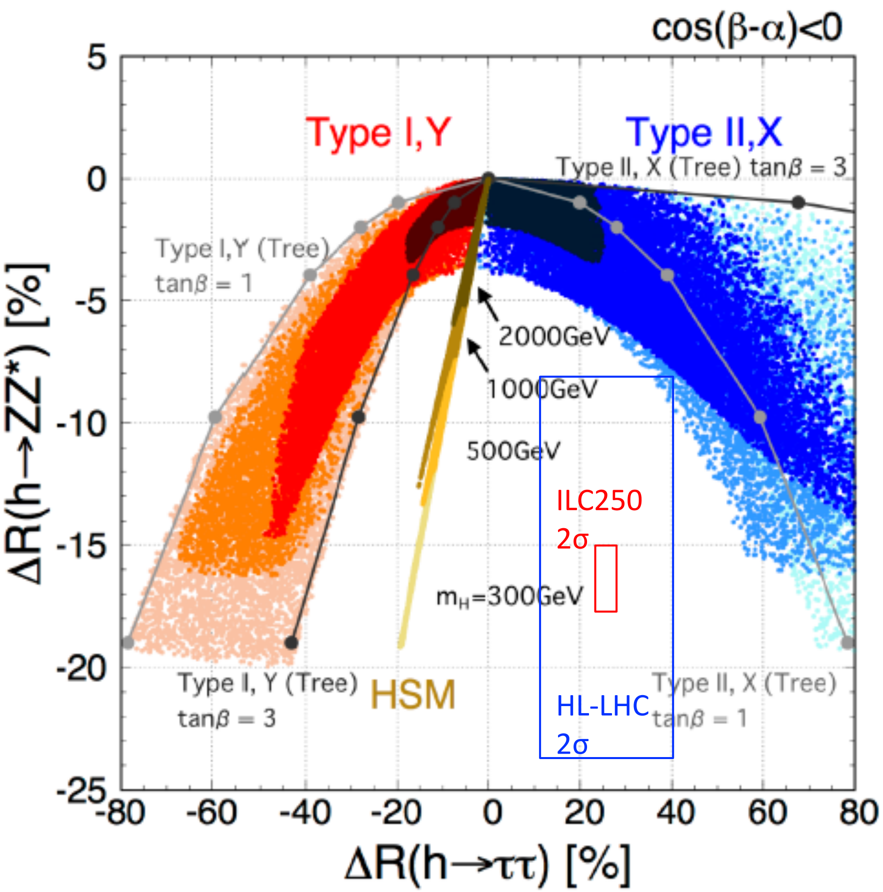
$$\Gamma(h \to f\bar{f}),\ \Gamma(h \to ZZ^* \to Zf\bar{f}),\ \Gamma(h \to \gamma\gamma),\ \Gamma(h \to Z\gamma),\ \Gamma(h \to gg)$$

$$\Delta R(h \to XX) = \frac{\Gamma_{NP}(h \to XX)}{\Gamma_{SM}(h \to XX)} - 1$$

H-COUP Project

SK, Kikuchi, Mawatari, Sakurai, Yagyu 2018

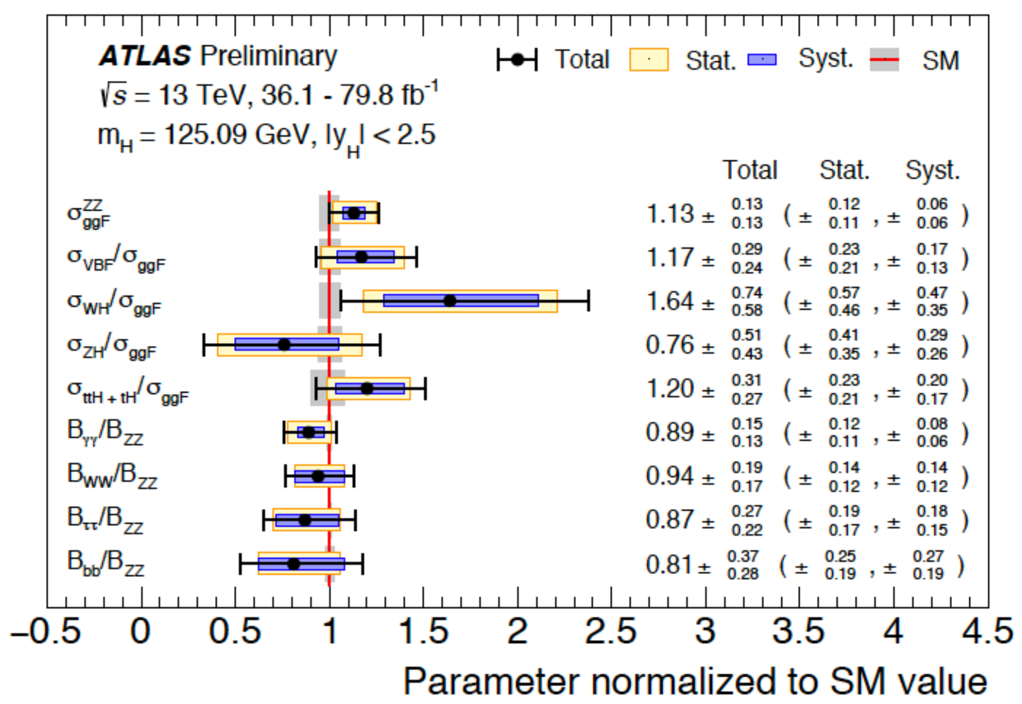


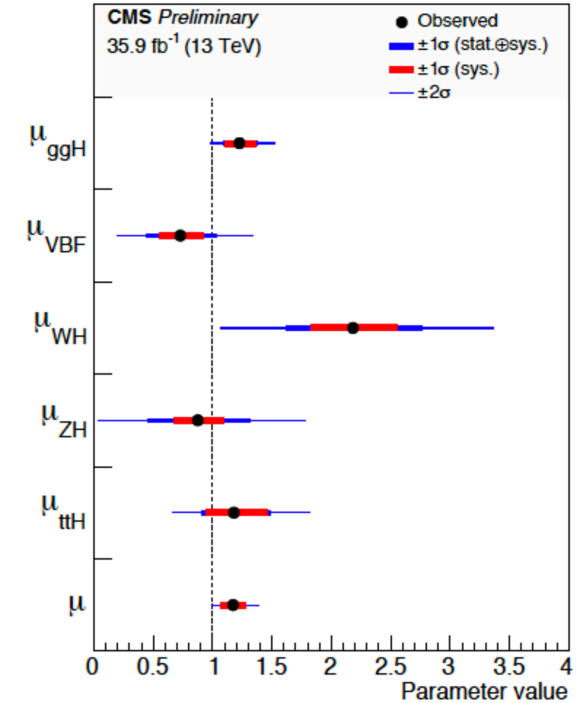


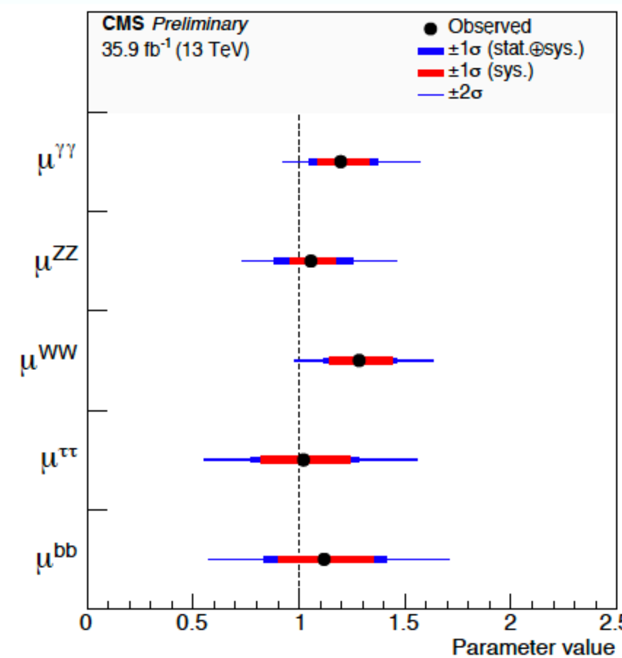
Full set of 1-loop corrections (EW + QCD + Higgs) to the decay rates in various Higgs sectors and future precision measurements at ILC250 make us possible to fingerprint models and also to get information of inner parameters such as mass of the second Higgs boson

By Production and Decay

- Several possible choices for model parameters allowed to account for SM deviations in combinations
- Ratios of cross sections and branching ratios cancel out some uncertainties







Another example of non-decoupling effects

Higgs potential

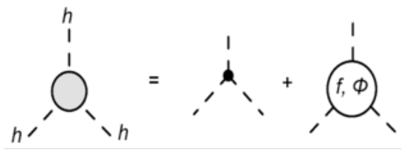
Self-Coupling Constant

It is very important to know *hhh* coupling to reconstruct the Higgs potential

$$V_{\rm Higgs} = \frac{1}{2}\underline{m_h^2} h^2 + \frac{1}{3!}\underline{\lambda_{hhh}} h^3 + \frac{1}{4!}\lambda_{hhhh} h^4 + \cdots$$

Effective Potential $$V_{\rm eff}(\varphi) = -\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{4}\varphi^4 + \sum_f \frac{(-1)^{2s_f} N_{C_f} N_{S_f}}{64\pi^2} m_f(\varphi)^4 \left[\ln\frac{m_f(\varphi)^2}{Q^2} - \frac{3}{2}\right]$$

Renoramalization $$\left.\frac{\partial V_{\rm eff}}{\partial\varphi}\right|_{\varphi=v} = 0, \quad \left.\frac{\partial^2 V_{\rm eff}}{\partial\varphi^2}\right|_{\varphi=v} = m_h^2, \quad \left.\frac{\partial^3 V_{\rm eff}}{\partial\varphi^3}\right|_{\varphi=v} = \lambda_{hhh}$$



Top loop Effect in the SM

$$\lambda_{hhh}^{\rm SMloop} \sim \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)$$

Non-decoupling effect

Tree level coupling $\lambda_{hhh} = \frac{3m_h^2}{v_0}$

Effective Potential

$$V_{\rm eff}(\varphi) = V_{\rm tree}(\varphi) + \frac{1}{64\pi^2} N_{c_i} N_{s_i} (-1)^{2s_i} (M_i(\varphi))^4 \left[\ln \left(\frac{(M_i(\varphi))^2}{Q^2} - \frac{3}{2} \right) \right]$$

Top quark effect $M_\varphi = \frac{y_t \varphi}{\sqrt{2}}$

Expand the $V_{\rm eff}$ by *h* $\varphi = v_0 + h$

$$V_{\rm eff} = -\frac{\mu^2}{2}(v_0 + h) + \frac{1}{4}\tilde{\lambda}(v_0 + h)^4 - \frac{N_c}{16\pi^2}\frac{y_t^4}{2} v_0^4 \left(\frac{h}{v_0} + \frac{7}{2}\frac{h^2}{v_0^2} + \frac{13}{3}\frac{h^3}{v_0^3} + \cdots \right)$$

$$\tilde{\lambda} = \lambda - \frac{N_c}{16\pi^2} y_t^4 \left(\ln \frac{y_t^2 v_0^2}{2Q^2} - \frac{3}{2} \right)$$

Renormalization conditions

$$\left.\frac{\partial V}{\partial \varphi}\right|_{\varphi=v} = 0, \qquad \left.\frac{\partial^2 V}{\partial h^2}\right|_{\varphi=v} = m_h^2, \qquad \left.\frac{\partial^3 V}{\partial h^3}\right|_{\varphi=v} = \lambda_{hhh}^R$$

$$\frac{\partial V_{\text{eff}}}{\partial h} = -\mu^2 v_0 + \tilde{\lambda} v_0^3 - \frac{1}{2} A v_0^3 = 0,$$

$$\frac{\partial^2 V_{\text{eff}}}{\partial^2 h} = -\mu^2 + 3\tilde{\lambda} v_0^2 - \frac{7}{2} A v_0^2 = m_h^2, \qquad A = \frac{N_c y_t^4}{16\pi^2}$$

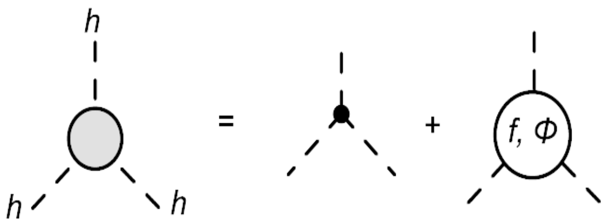
$$\frac{\partial^3 V_{\text{eff}}}{\partial^3 h} = 6\tilde{\lambda} v_0 - 13 A v_0 = \lambda_{hhh}^R,$$

Eliminating μ^2 and $\tilde{\lambda}$, and using $y_t = \frac{\sqrt{2} m_t}{v_0}$

$$\lambda_{hhh}^R = \frac{3 m_h^2}{v_0} \left(1 - \frac{N_c}{3\pi^2} \frac{m_t^4}{v_0^2 m_h^2} \right)$$

Case of Non-SUSY 2HDM

- Consider when the lightest *h* is SM-like [sin(β–α)=1]
- At tree, the *hhh* coupling takes the same form as in the SM
- At 1-loop, non-decoupling effect $m_\Phi{}^4$ (If *M* < *v*)



Φ = *H*, *A*, $H^\pm$

SK, Kiyoura, Okada, Senaha, Yuan, PLB558 (2003)

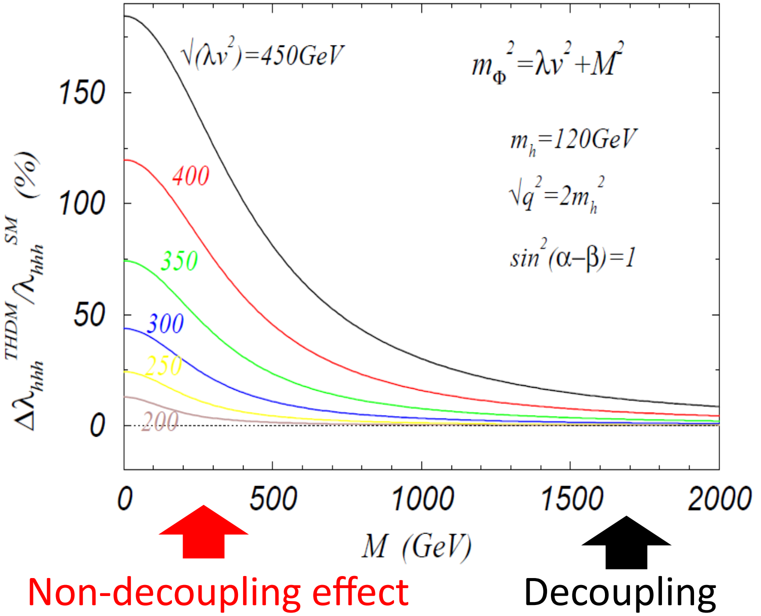
$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3-\frac{m_t^4}{\pi^2 v^2 m_h^2}\right]$$

Extra scalar loop — Top loop

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

(Φ = *H*, *A*, $H^\pm$)

Correction can be huge ～ 100%



Part II Summary

- A Higgs boson was found, but the Higgs sector remains unknown
- Possibility of Extended Higgs sectors
- Direct Searches at LHC
- Indirect test of the Higgs sector via precision measurements for couplings of h(125) at future lepton colliders (ILC, CEPC, FCCee, CLIC, …)
- Study with radiative corrections is important

Slide by K. Sakurai

Numerical calculations

We discuss a possibility of discrimination among various extended Higgs models with the deviations from the SM in the decay width.

- Model

  HSM, THDM Type-I, THDM Type-II, THDM Type-X, THDM Type-Y

- Scan region of input parameter in the THDMs

  $0.9 < \sin(\beta - \alpha) < 1, \quad 1 < tan\beta < 3,$

  $m_\Phi = 300, 500, 700, 1000$ GeV, $\quad 0 < M^2 < m_\Phi,$ $\quad m_H = m_A = m_{H^+}$

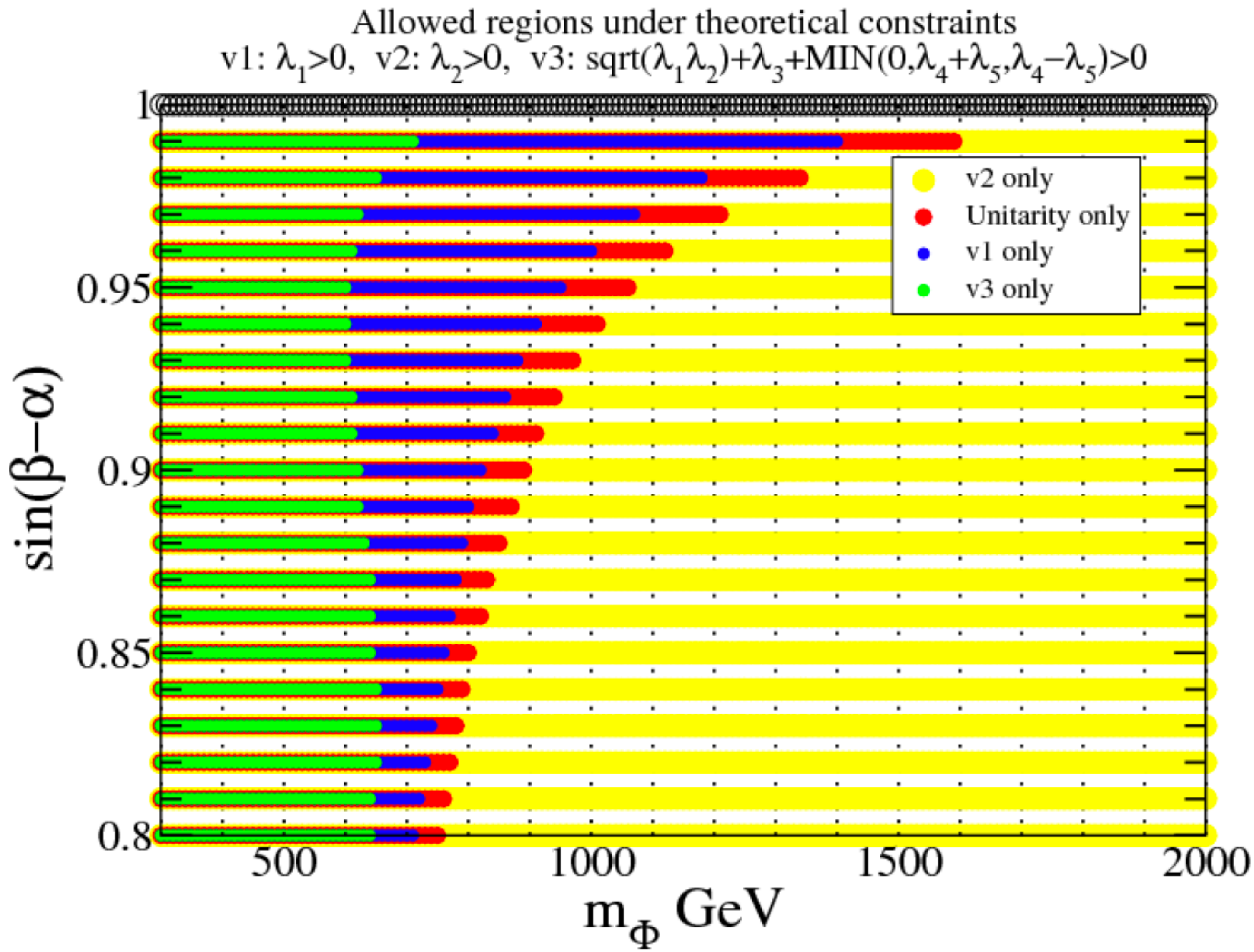
  $(\Phi = H, A, H^\pm)$

- Constraint

  Pertabative unitarity, Vacuum stability,

  Wrong vacuum condition (for HSM),

  S, T parameters

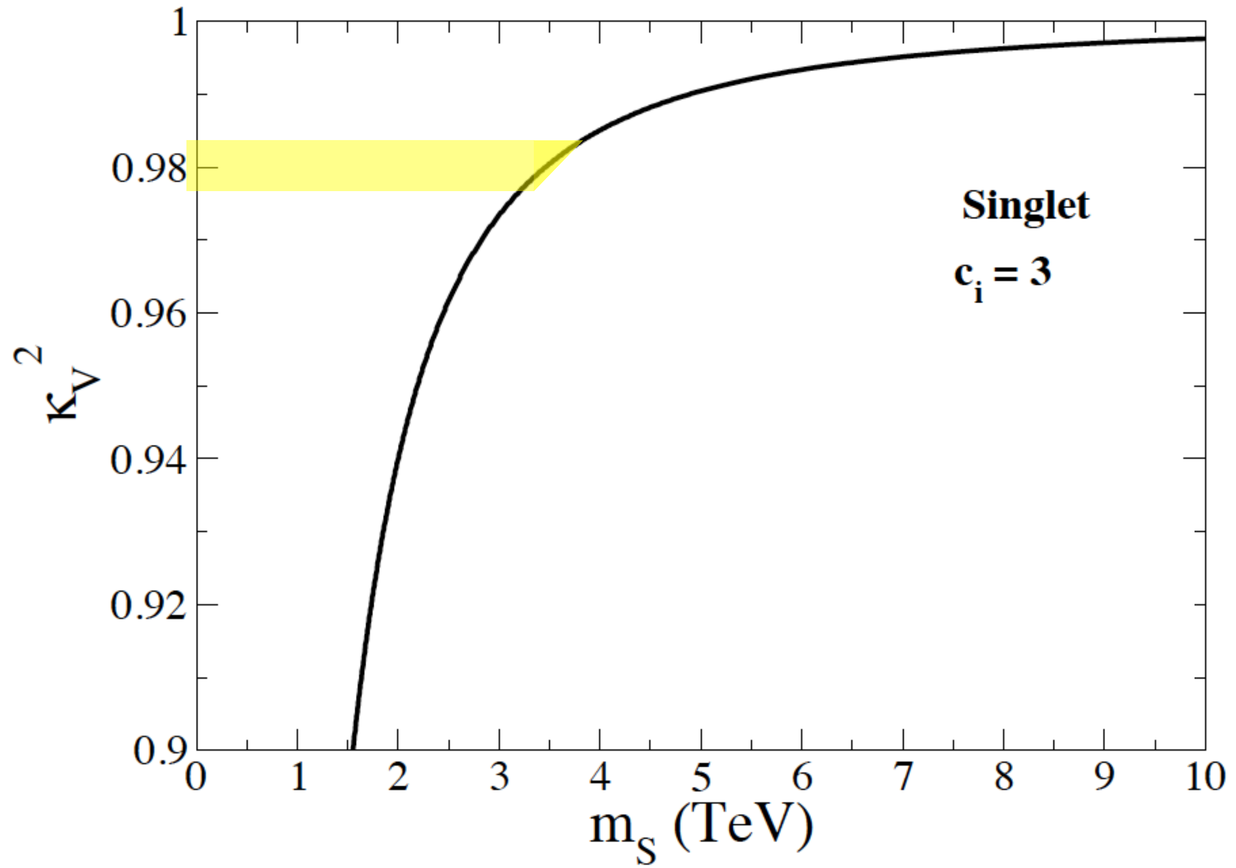


Allowed regions under theoretical constraints
v1: λ1>0, v2: λ2>0, v3: sqrt(λ1λ2)+λ3+MIN(0,λ4+λ5,λ4−λ5)>0
v2 only
Unitarity only
v1 only
v3 only
sin(β−α)
1
0.95
0.9
0.85
0.8
500
1000
1500
2000
mΦ GeV

Unitarity in Non-SUSY 2HDM

In Higgs Singlet model (Φ+S)

$\kappa_V^2 = \cos^2\theta$



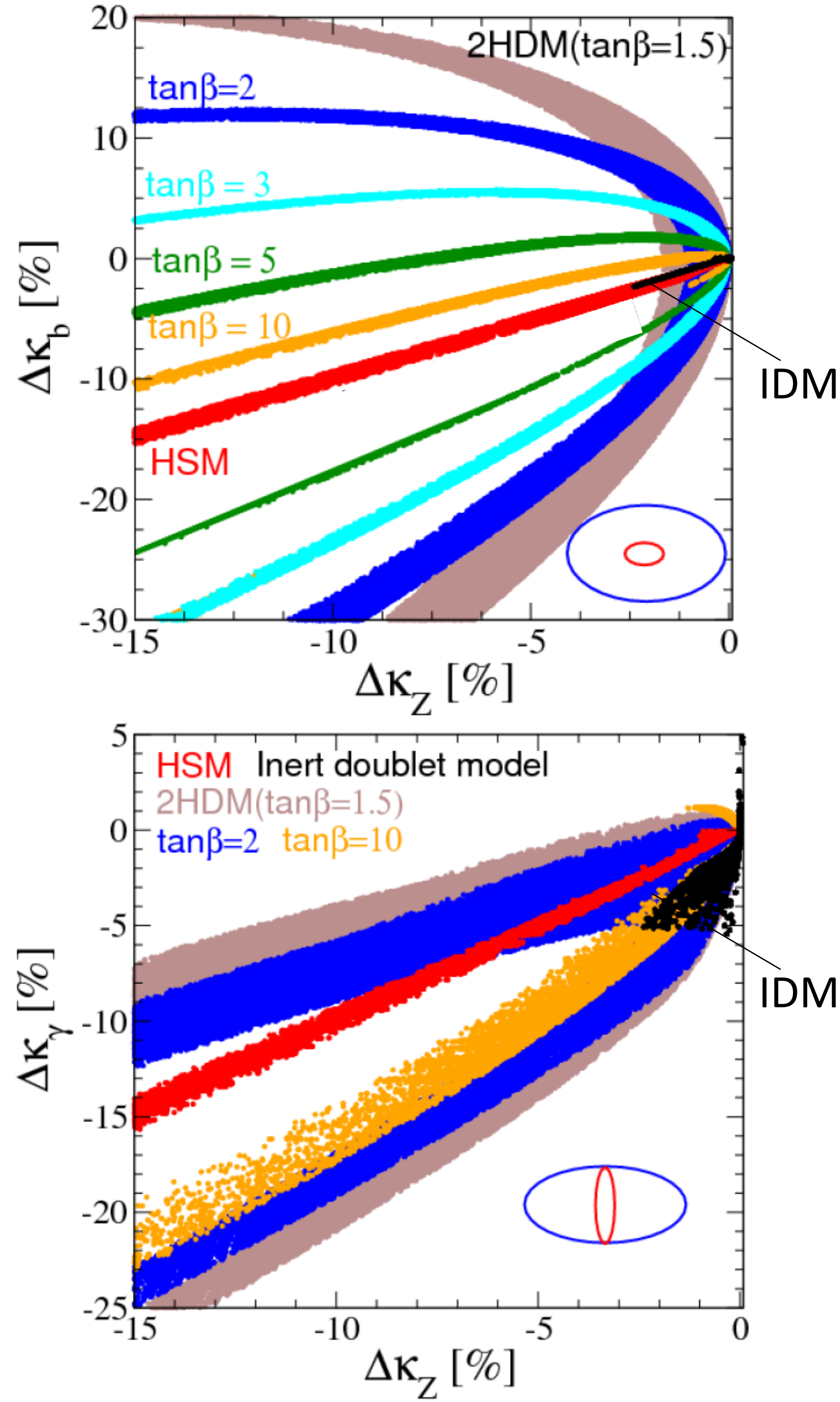
Comparison of

1. 2HDM-I
2. Doublet-Singlet Model (HSM)
3. Inert Doublet Model (IDM)

Scan of inner parameters (mass, mixing angles) under the theoretical conditions of
Perturbative unitarity
Vacuum stability
Condition for avoiding wrong vacuum (HSM)

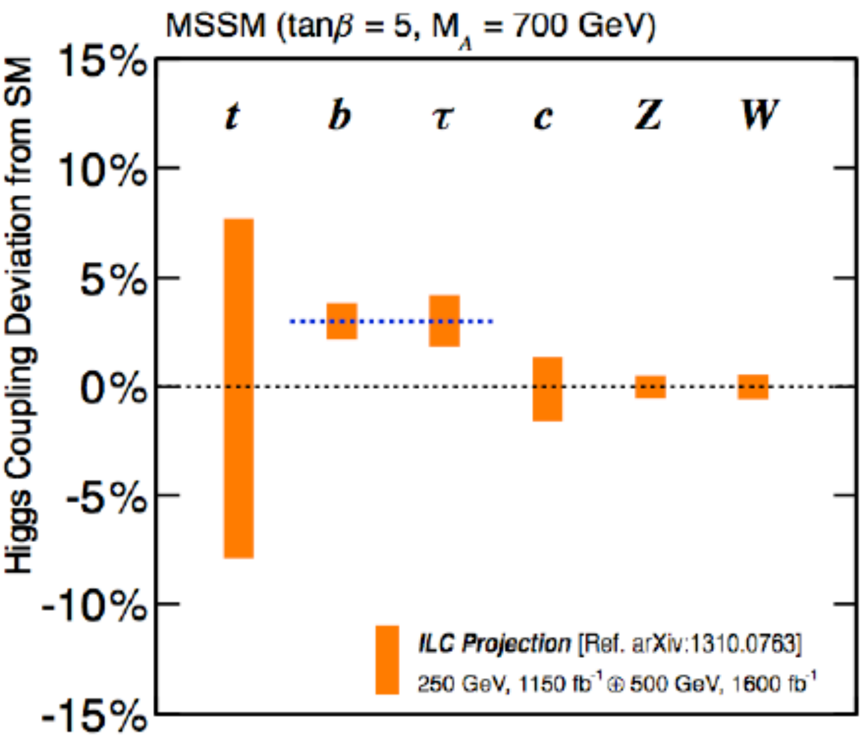
These models may be distinguished, as long as a deviation in κ_Z is detected

Ellipse, ±1σ at LHC3000 and ILC500

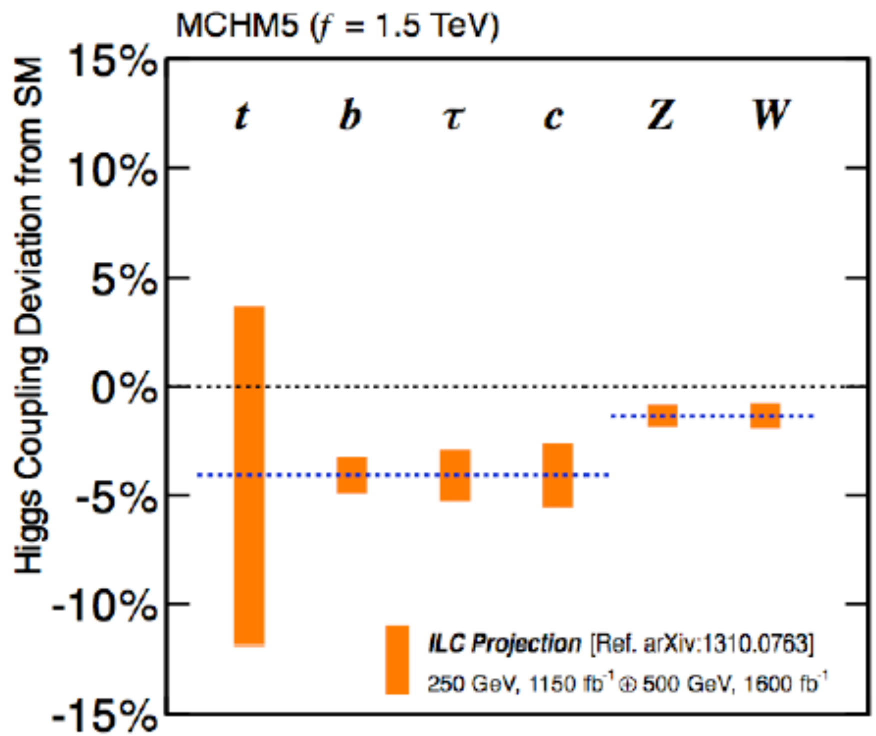


Fingerprinting SUSY model and Composite Higgs models

SUSY



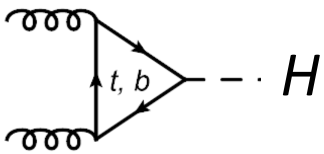
Composite Higgs

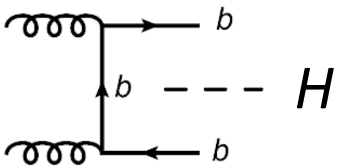


Fingerprinting models by precision study at ILC

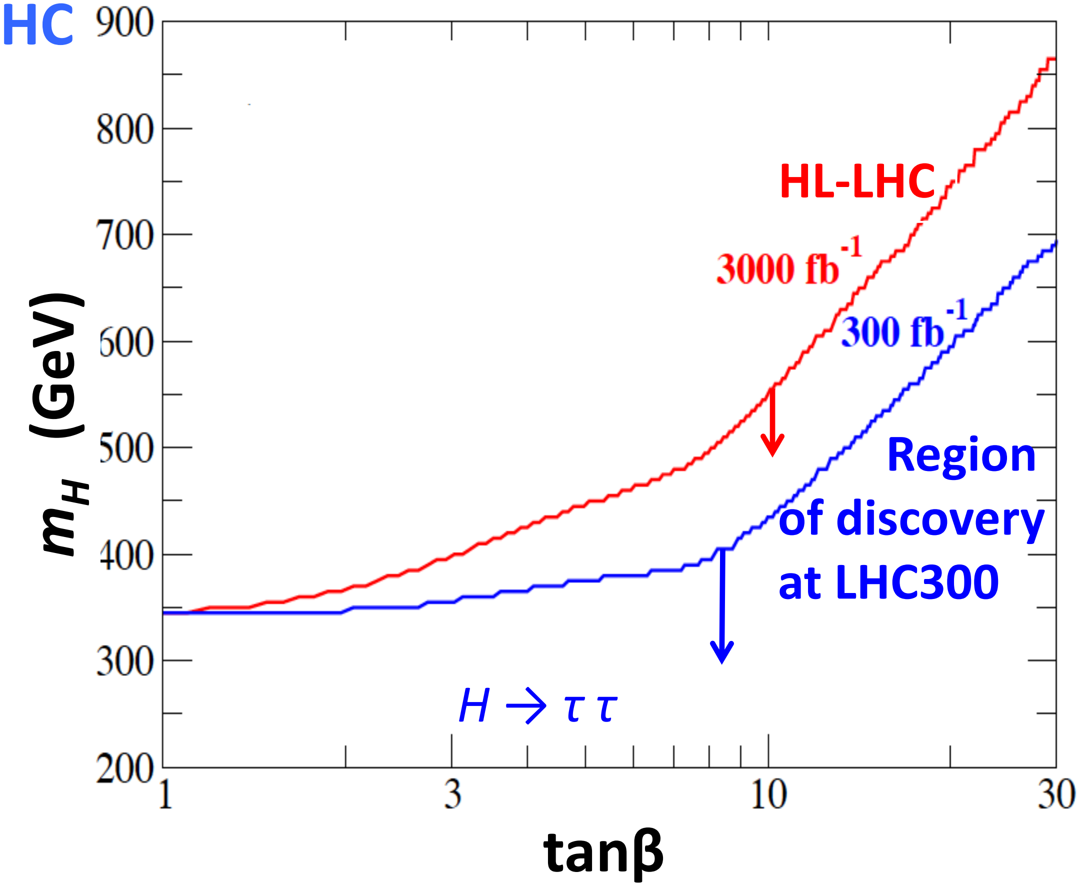
Complementarity

Direct detection of the heavier Higgs boson *H* at LHC





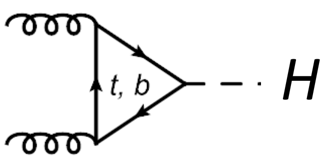
Type-II 2HDM

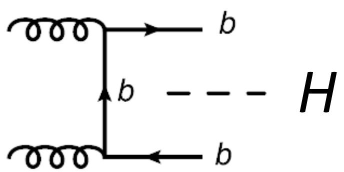


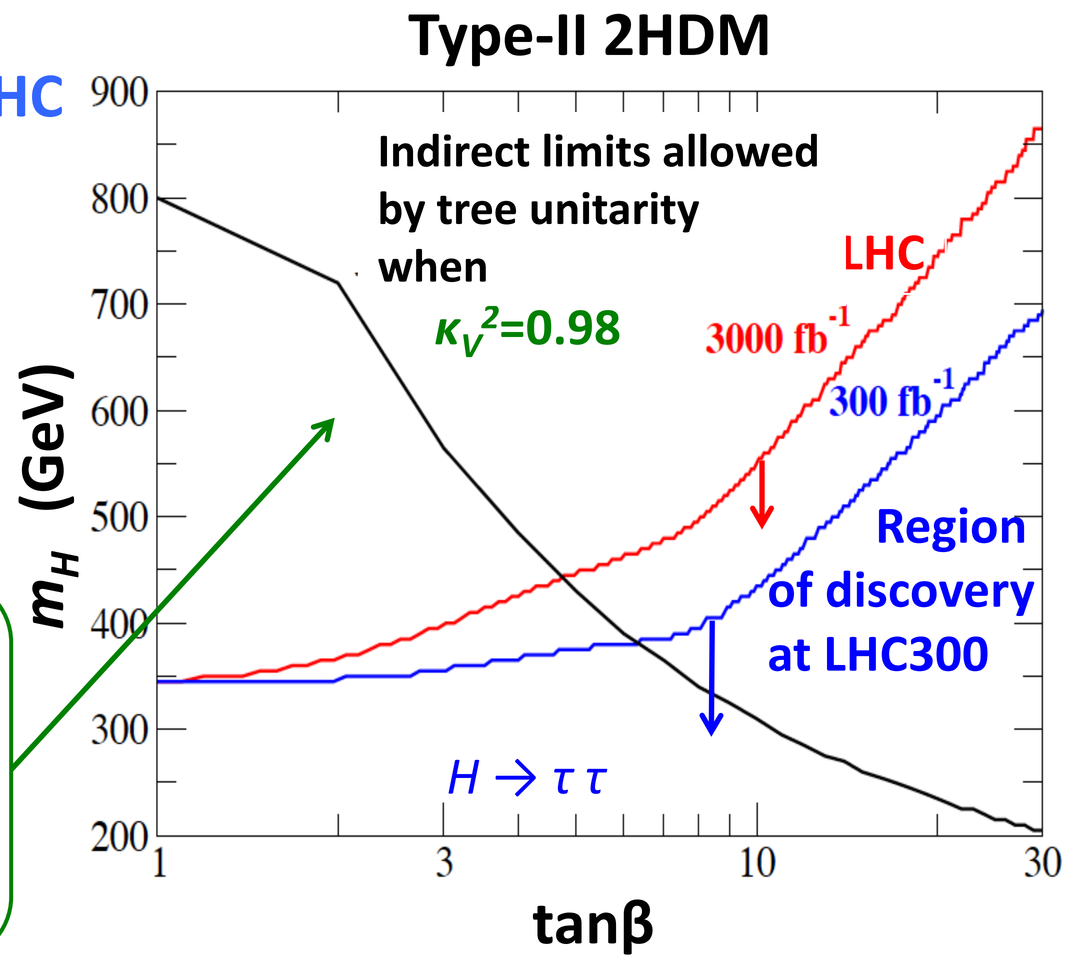
SK, Tsumura, Yagyu, Yokoya, 2014

Complementarity

Direct detection of the heavier Higgs boson *H* at LHC







Indirectly, new physics can be surbeyed by detecting deviations even out of the direct search regions

SK, Tsumura, Yagyu, Yokoya, 2014

Fingerptinting the model (Exotics)

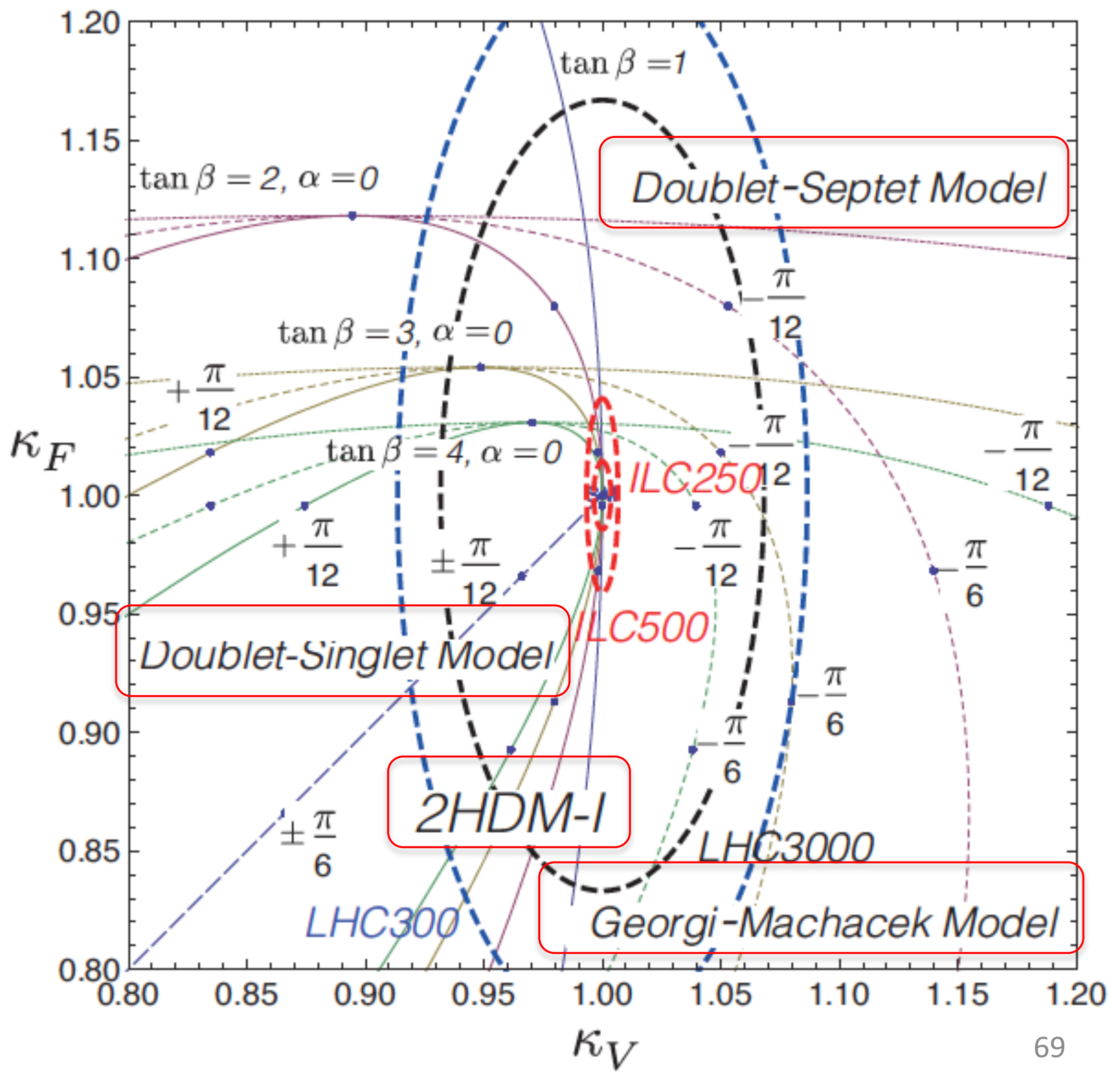
SK, K. Tsumura, K. Yagyu, H. Yokoya 2014

Universal Fermion Coupling (κ_F)
VS
***hVV* coupling (κ_V)**

Exotic models predict $\kappa_V > 1$

We can discriminate Exotic models

Ellipse = 68.27% CL

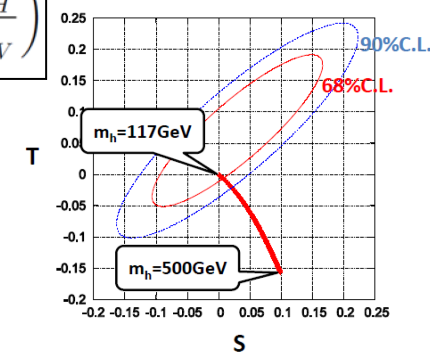


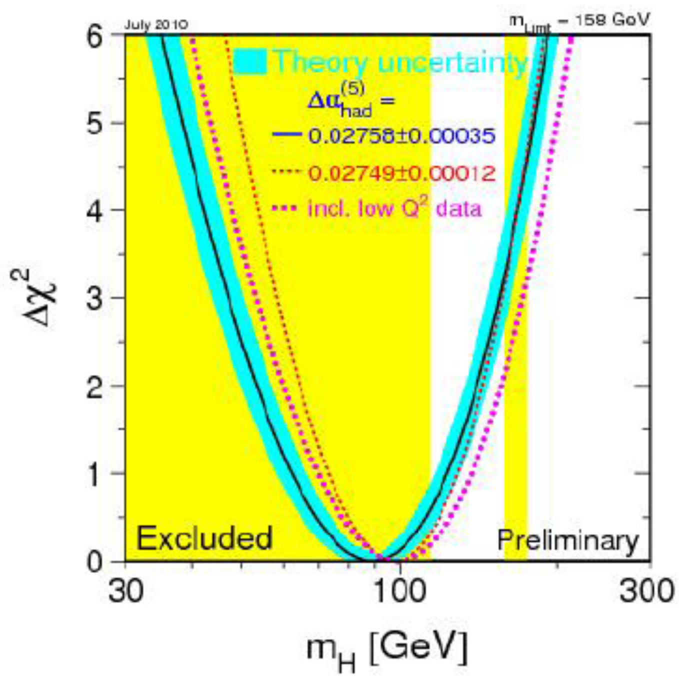
It was repeated for Higgs at LEP2

$$\Delta\rho \simeq \frac{3G_F}{8\sqrt{2}\pi^2}\left(m_t^2 - M_Z^2 \sin^2\theta_W \ln\frac{m_H^2}{m_W^2}\right)$$

Case of Higgs boson

- Now we know top mass
- Rho is a funcution of only m_H
- Precision measurement at LEP2
- 114GeV< mH <150 GeV!
- LHC found new boson at 126GeV（Higgs boson!）





LEP Electroweak Working Group 2010

Victory of precision measurements and theory calculations

（VIVA! SM）

Deviation in *hff*

If $\Delta\kappa_V = 1\,\%$

Singlet, Exotics,

$\Delta\kappa_u = -(1/2)\,x^2$, $\Delta\kappa_d = -(1/2)\,x^2$, $\Delta\kappa_\tau = -(1/2)\,x^2$ O(1) %

Type I 2HDM

$\Delta\kappa_u = -\cot\beta\,|x|$, $\Delta\kappa_d = -\cot\beta\,|x|$, $\Delta\kappa_\tau = -\cot\beta\,|x|$ O(10) %

Type X (Lepton Specific) 2HDM

$\Delta\kappa_u = -\cot\beta\,|x|$, $\Delta\kappa_d = -\cot\beta\,|x|$, $\Delta\kappa_\tau = +\tan\beta\,|x|$ O(10) %

MSSM (Type II 2HDM)

$\Delta\kappa_u = +\cot\beta\,|x|$, $\Delta\kappa_d = -\tan\beta\,|x|$, $\Delta\kappa_\tau = -\tan\beta\,|x|$ O(10) %

MCHM4

$\Delta\kappa_u = -(1/2)\,x^2$, $\Delta\kappa_d = -(1/2)\,x^2$, $\Delta\kappa_\tau = -(1/2)\,x^2$ O(1) %

MCHM5

$\Delta\kappa_u = -(3/2)\,x^2$, $\Delta\kappa_d = -(3/2)\,x^2$, $\Delta\kappa_\tau = -(3/2)\,x^2$ O(1) %