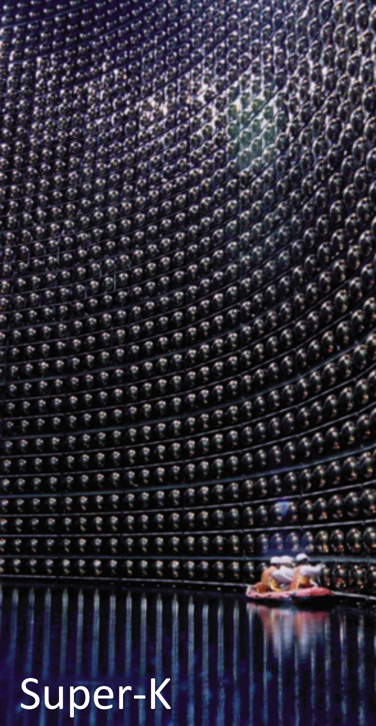


Extended Higgs sectors beyond 2HDM

Shinya Kanemura

Univ. of Toyama

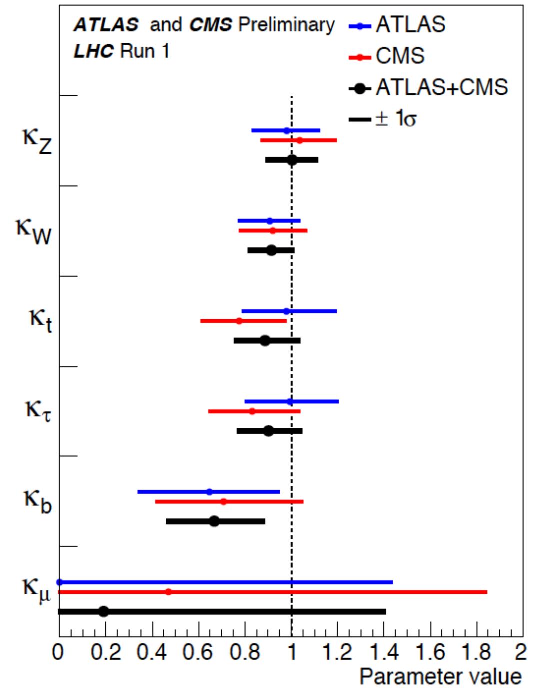
EXPERLHC16, April 19, 2016

Why extended Higgs sectors?

At LHC, *h*(125) was found, and its mass, quantum numbers and coupling constants have been measured, and the data are being improved at Run 2.

***h*(125) is SM-like, and no new particle has been found up to now.**

- ***hVV*** **Higgs mechanism**
- ***hFF*** **Origin of mass of matter**
- ***Hgg, hγγ*** **Dim-6 operator**
- ***hhh*** **Higgs potential (Dynamics of EWSB)**



SM might be enough, but

there are some anomalies

(h→μτ, diboson, diphoton, g-2, ….) [<5σ]

Why extended Higgs sectors

We know some established BSM phenomena

- Neutrino Oscillation
- Dark Matter
- Baryogenesis
- …

We wish to understand these phenomena by extension of the SM

Also, we do not know the origin of EWSB behind the Higgs sector (what is the origin of V(Φ)?)

- SUSY
- DSB
- pNGB in composite models
- Classical Scale Invariance with the CW mechanism
- …

Why extended Higgs sectors?

We might be able to solve the problems at TeV scale by introducing extend Higgs sectors

- **Type-2 Seesaw, Radiative seesaw models**
- **Electroweak Baryogenesis (CPV, strongly 1stOPT)**
- **Higgs portal dark matter scenarios**
- **…**

Apart from concrete scenario for BSM, we can think about the possibility of extended Higgs sectors and try to narrow down by experiments

Extended Higgs models

<u>Multiplet Structure (2nd simplest Higgs models)</u>

Φ_{SM}+Singlet, (NMSSM, B-L Higgs, …)

Φ_{SM}+Doublet (2HDM), (MSSM, EW Baryogenesis Radiative Neutrino mass…)

Φ_{SM}+Triplet, (Type II seesaw, LR models….)

…

<u>Additional Symmetry</u>

Global (such as Custodial symmetry)

Discrete or Continuous?

Exact, Softly broken or Spontaneously broken?

<u>Interaction</u>

Weakly coupled or Strongly Coupled ?

Decoupling or Non-decoupling?

Experimentally narrowing down the shape of the Higgs sector gives an important hint to New Physics BSM

Electroweak rho parameter

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

$Q = I_3 + Y$

$$\rho_{\rm tree} = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_j v_j^2 [T_j(T_j+1) - Y_j^2]}{\sum_i 2Y_i^2 v_i^2}$$

Ex) Higgs hunters guide

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

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

We solve the equation

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

(T_X, Y_X)	X
(0, 0)	Singlet
(1/2, 1/2)	Doublet
(3, 2)	Septet
(25/2, 15/2)	26-plet
....	....

Larger T_X (> 8) disfavored by unitarity (Logan et al, 2014)

2 Higgs Doublet Model (soft-broken Z_2)

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

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

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

↑ CPeven ↑ CPodd ↑charged

Diagonalization

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

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

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

Masses

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

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

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

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

M_{soft}: soft breaking scale

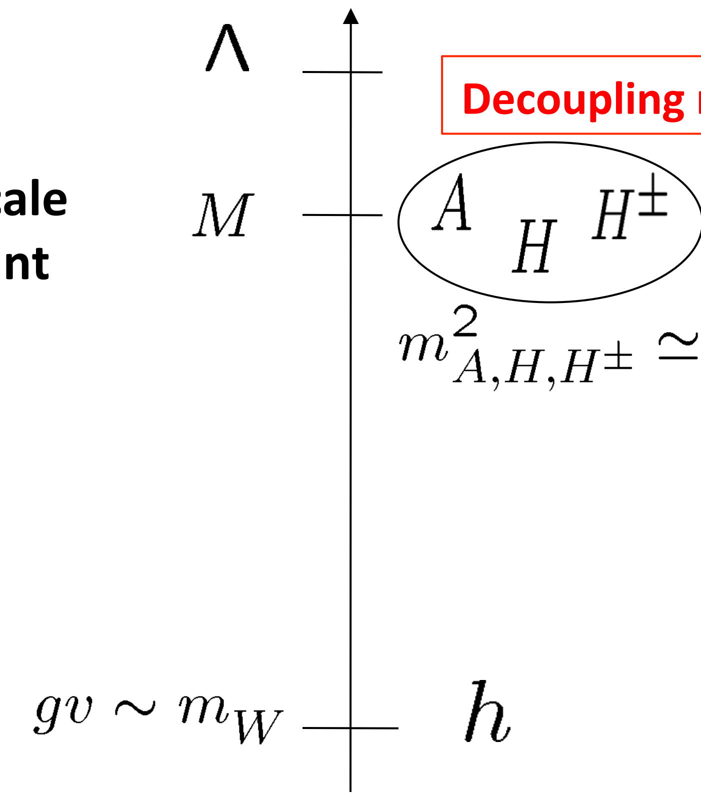
$M_{\mathrm{soft}} \ \left(= \frac{m_3}{\sqrt{\cos\beta\sin\beta}}\right)$:

soft-breaking scale
of the discrete symm.

Two SM-like situation

Λ: Cutoff

***M*: Mass scale irrelevant to VEV**

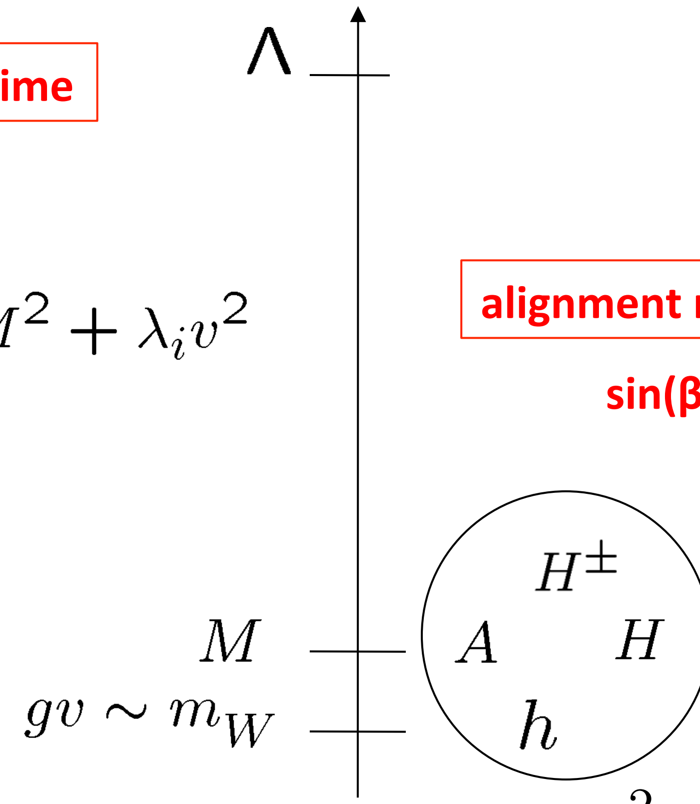


Decoupling regime

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

alignment regime

sin(β−α) ~ 1



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

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 effects

Models with triplets

$Q = I_3 + Y$

Minimal Triplet model with one triplet field

X with (I, Y)=(1, 0) or (1,1)

$\rho \neq 1 \rightarrow v_\eta, v_\Delta \ll v$

Real triplet

$$\rho = \frac{v_\varphi^2 + 4v_\eta^2}{v_\varphi^2} \qquad v^2 = (v_\varphi^2 + 4v_\eta^2),$$

Complex triplet

$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \qquad \rho = \frac{v_\varphi^2 + 2v_\Delta^2}{v_\varphi^2 + 4v_\Delta^2} \qquad v^2 = (v_\varphi^2 + 2v_\Delta^2),$$

Georgi-Machacek Model (1/2, 1/2)+(1,0)+(1,1)

Georgi, Machacek (1985); Chanowitz, Golden (1985)

vacuum alignment $v_\chi = v_\xi = v_\Delta$

$$\phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}$$

5-plet $H_5^{\pm\pm}, H_5^{\pm}, H_5^0$

3-plet $H_3^{\pm}, H_3^0$ — CP-odd

1-plet H_1^0

SM-like Higgs boson h — CP-even

$SU(2)_L \times SU(2)_R \times U(1)_Y$

$\rho = 1$ at tree

How these extended Higgs sectors can be tested at LHC

[1] Indirect test via coupling deviation of h(125)

S, T, U, m_W, hZZ, hWW, $h\gamma\gamma$, hgg, $hZ\gamma$, $h\tau\tau$, hbb, htt, hcc, hhh, …

In each non-SM model, they can deviate from SM values in a specific pattern, by which we may be able to fingerprint models

[2] Direct evidence of additional scalars at LHC

- ***H, A, H+, H++, …***
- **Charged Higgs as a probe of exotic Higgs sector**
  - ***H+W−Z*** **vertex**
  - **LFV Decays of H^+, H^{++} in neutrino mass models**

[3] The *hhh* coupling is sensitive to extended Higgs sectors in alignment regime. The prediction on the *hhh* coupling can be completely different from the SM

ATLAS-CONF-2015-044

Run 1
Best fit values for combination of ATLAS and CMS

Assumption,
absence of BSM particles in the loops and $BR_{BSM}=0$

$$\kappa_Z = 1.00^{+0.10}_{-0.11}$$

$$\kappa_W = 0.91^{+0.09}_{-0.09}$$

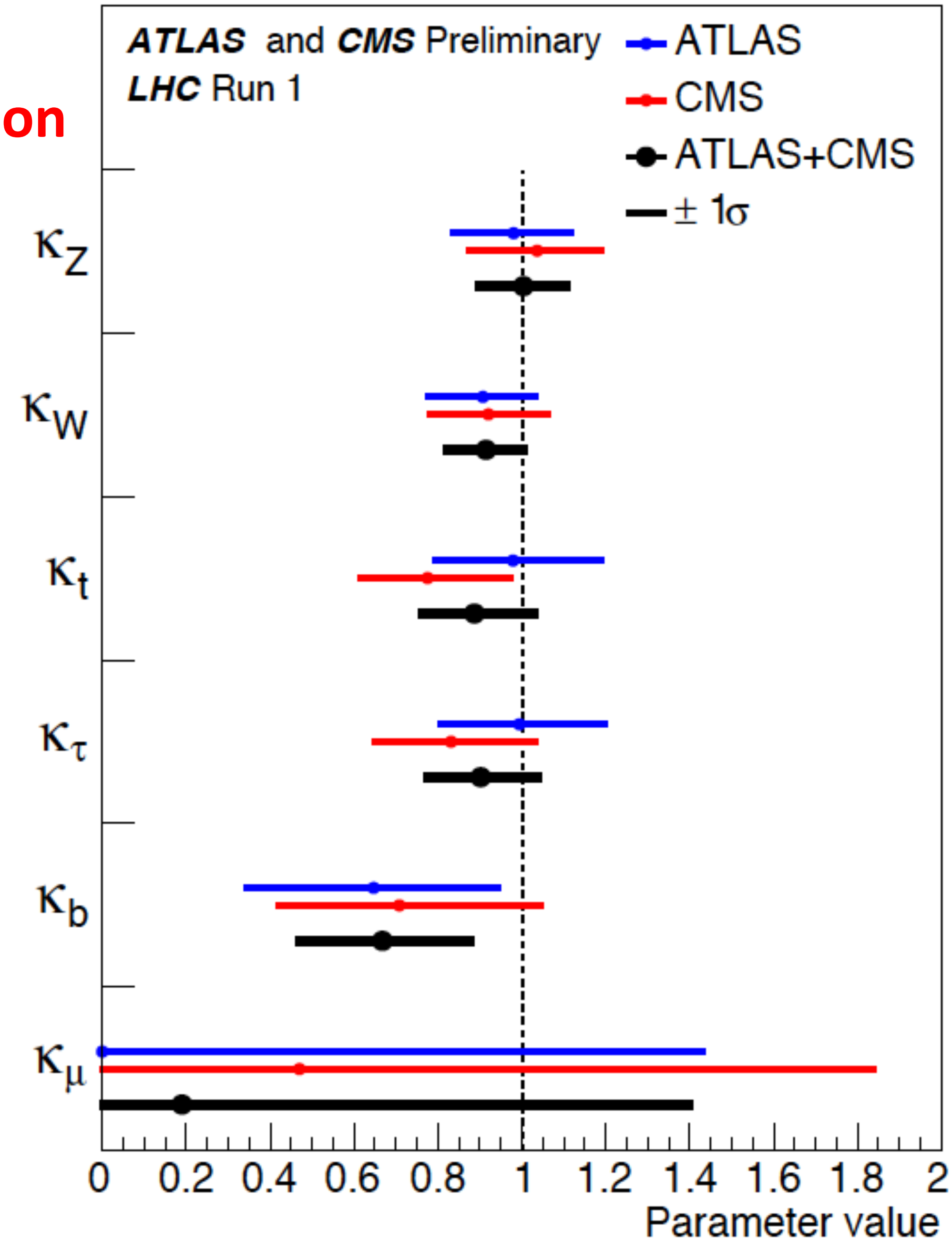
$$\kappa_t = 0.89^{+0.15}_{-0.13}$$

$$\kappa_\tau = 0.90^{+0.14}_{-0.13}$$

$$\kappa_b = 0.67^{+0.22}_{-0.20}$$

Extended Higgs sectors can deviate *h*-couplings with a specific pattern

$5\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV and $20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV



hVV coupling in the φ-X models
(X: second scalar)

- Mixing angle α (φ and X)
- tanβ: Ratio of VEV between φ and X

$\tan\beta = v_\phi / (\eta\, v_X)$

where η is a factor

Doublet-Singlet Model (1/2,1/2) + (0,0)

$$\kappa_V = \cos\alpha$$

$\kappa_V < 1$

2HDM (1/2,1/2) + (1/2,1/2)

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

Doublet-Triplet Model (G-M Model) (1/2,1/2) + (1,1) + (1,0)

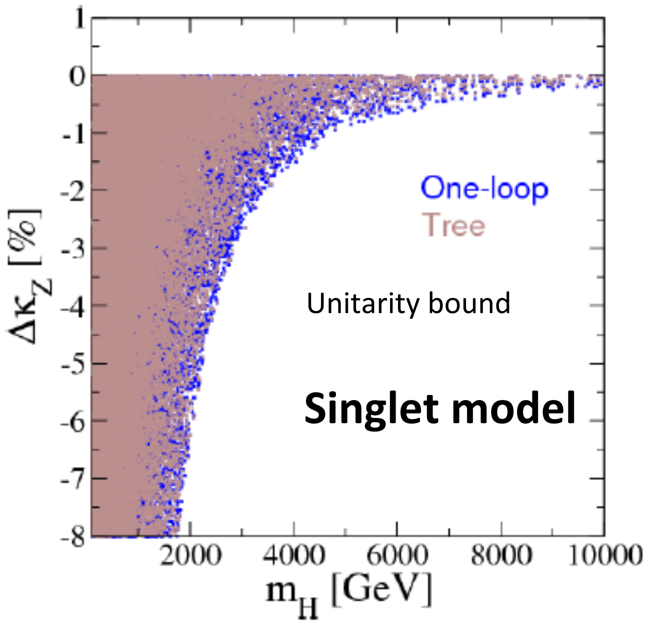
$$\kappa_V = \sin\beta\cos\alpha - 2\sqrt{2}\cos\beta\sin\alpha$$

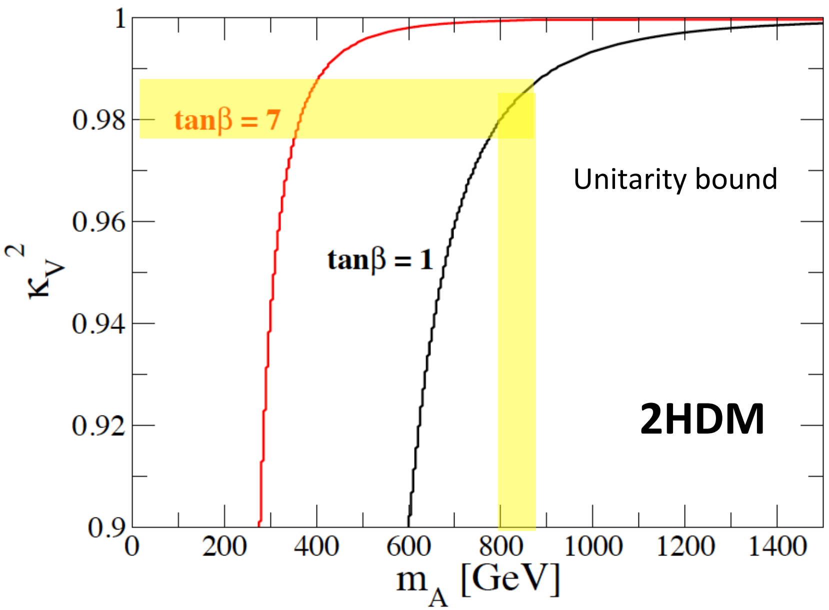
Doublet-Septet Model (1/2,1/2) + (3, 2)

$$\kappa_V = \sin\beta\cos\alpha - 4\cos\beta\sin\alpha$$

$\kappa_V > 1$ is possible

κ_Z and the scale of the second Higgs





$\kappa_V = \cos\alpha$

$\kappa_V^2 = \sin^2(\beta-\alpha)$

If κ_V is found to be less than 1, the upper bound on the mass of the second Higgs is obtained

2HDM with softly broken Z_2

$$\mathcal{L}^Y_{\mathrm{THDM}} = -\sum_{f=u,d,e} \frac{m_F}{v}\left(\xi^f_h \overline{f} f h + \xi^f_H \overline{f} f H - i\,\xi^f_A \overline{f}\gamma_5 f A\right)$$
$$+\left[\frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u\xi^u_A P_L + m_d\xi^d_A P_R\right) d\,H^+ + \frac{\sqrt{2}m_\ell\xi^e_A}{v}\overline{\nu}P_R e H^+ + \mathrm{h.c.}\right]$$

	ξ^u_h	ξ^d_h	ξ^ℓ_h	ξ^u_H	ξ^d_H	ξ^ℓ_H	ξ^u_A	ξ^d_A	ξ^ℓ_A
Type-I	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cot\beta$	$\tan\beta$	$-\cot\beta$

Fingerprinting the 2HDM (tree level)

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

x = cos(β−α) **SM-like: |x| <<1**

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

When a Fermion couples to Φ_1

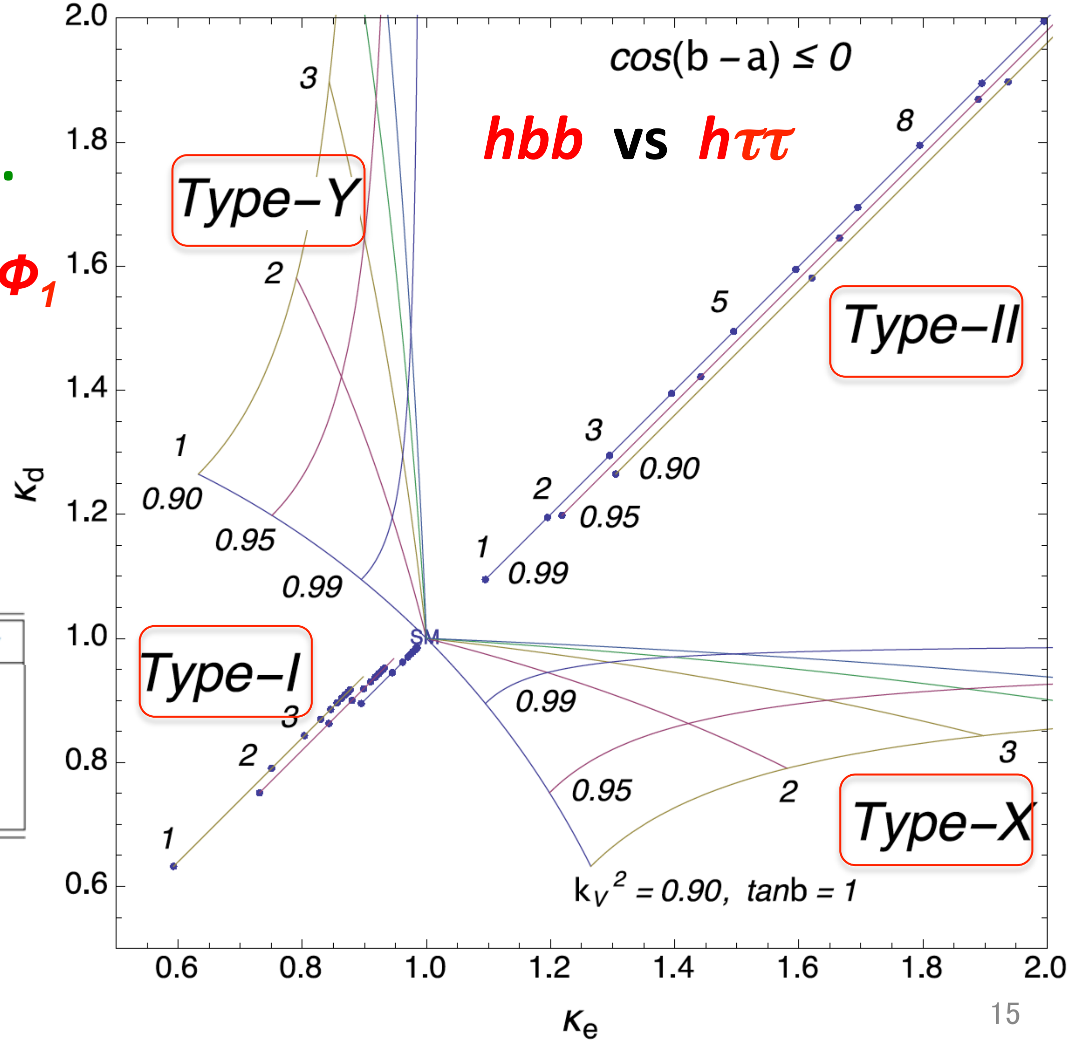
$$\kappa_f = 1 + \cot\beta\, x + \ldots$$

and if it couples to Φ_2

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

Model	μ	τ	b	c	t	g_V
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

SK, K. Tsumura, K. Yagyu, H. Yokoya 2014
ILC Higgs White Paper 2013



κ_f and κ_V in exotic Higgs models with ρ=1 at tree

	$\tan\beta$	κ_f	κ_V
Doublet-Singlet Model	—	$\cos\alpha$	$\cos\alpha$
Type-I THDM	v_0/v_{ext}	$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$
GM Model	$v_0/(2\sqrt{2}v_{\text{ext}})$	$\cos\alpha/\sin\beta$	$\sin\beta\cos\alpha - \frac{2\sqrt{6}}{3}\cos\beta\sin\alpha$
Doublet-Septet Model	$v_0/(4v_{\text{ext}})$	$\cos\alpha/\sin\beta$	$\sin\beta\cos\alpha - 4\cos\beta\sin\alpha$

κ_f is universal for all fermions

κ_V can be > 1

Fingerptinting the model (Exotics)

SK, K. Tsumura, K. Yagyu, H. Yokoya 2013

Universal Fermion Coupling (κ_F)

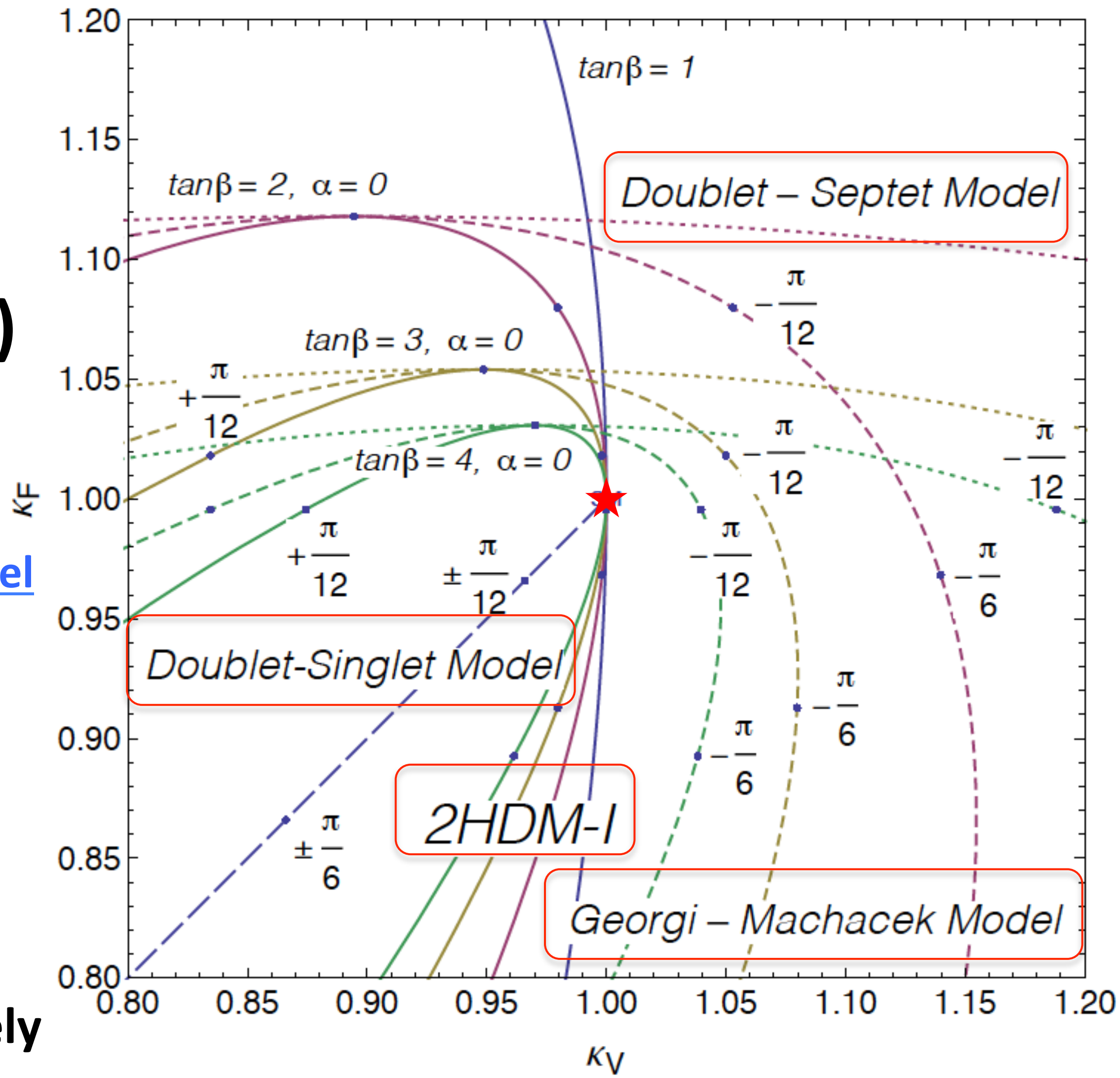
$\kappa_F = \kappa_d = \kappa_u$

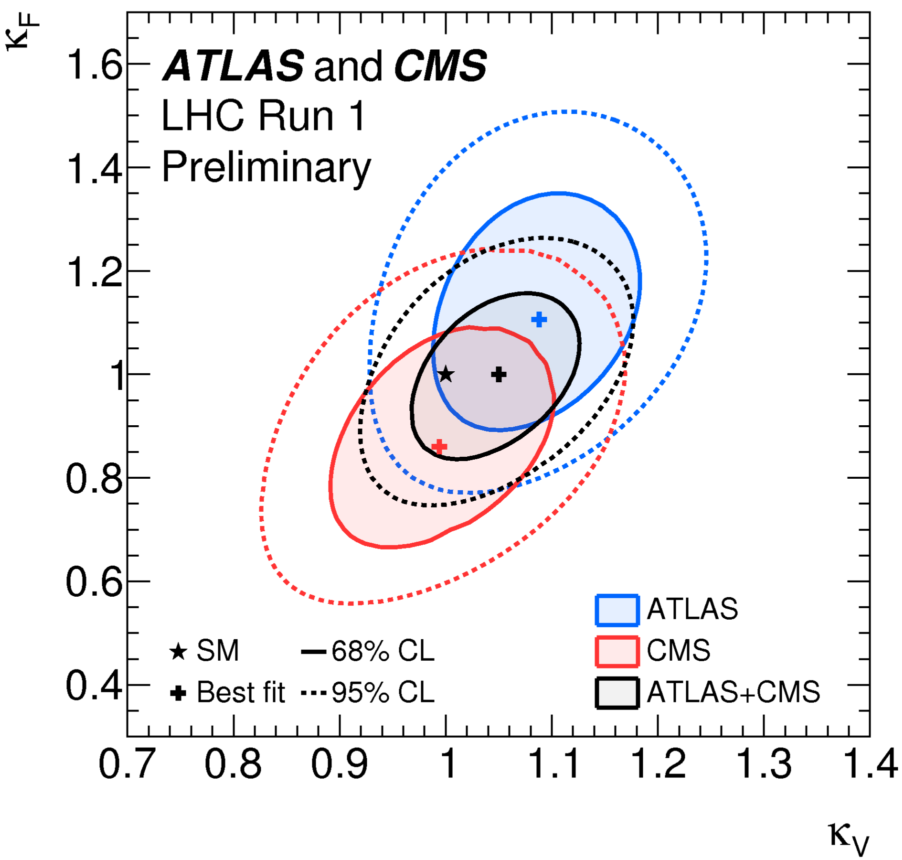
VS *hVV* coupling (κ_V)

- Singlet model
- 2HDM Type-I
- Georgi-Machacek model
- Septet model

Exotic models can predict $\kappa_V > 1$

The extended Higgs sector can be separated by measuring κ_V and κ_F acculately





Current data

Facility	LHC	HL-LHC
$\sqrt{s}$ (GeV)	14,000	14,000
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_ℓ	$6-8\%$	$2-5\%$
κ_d	$10-13\%$	$4-7\%$
κ_u	$14-15\%$	$7-10\%$

Snowmass White Paper

NLO(EW) corrections

SK, Kikuchi, Yagyu, 2015

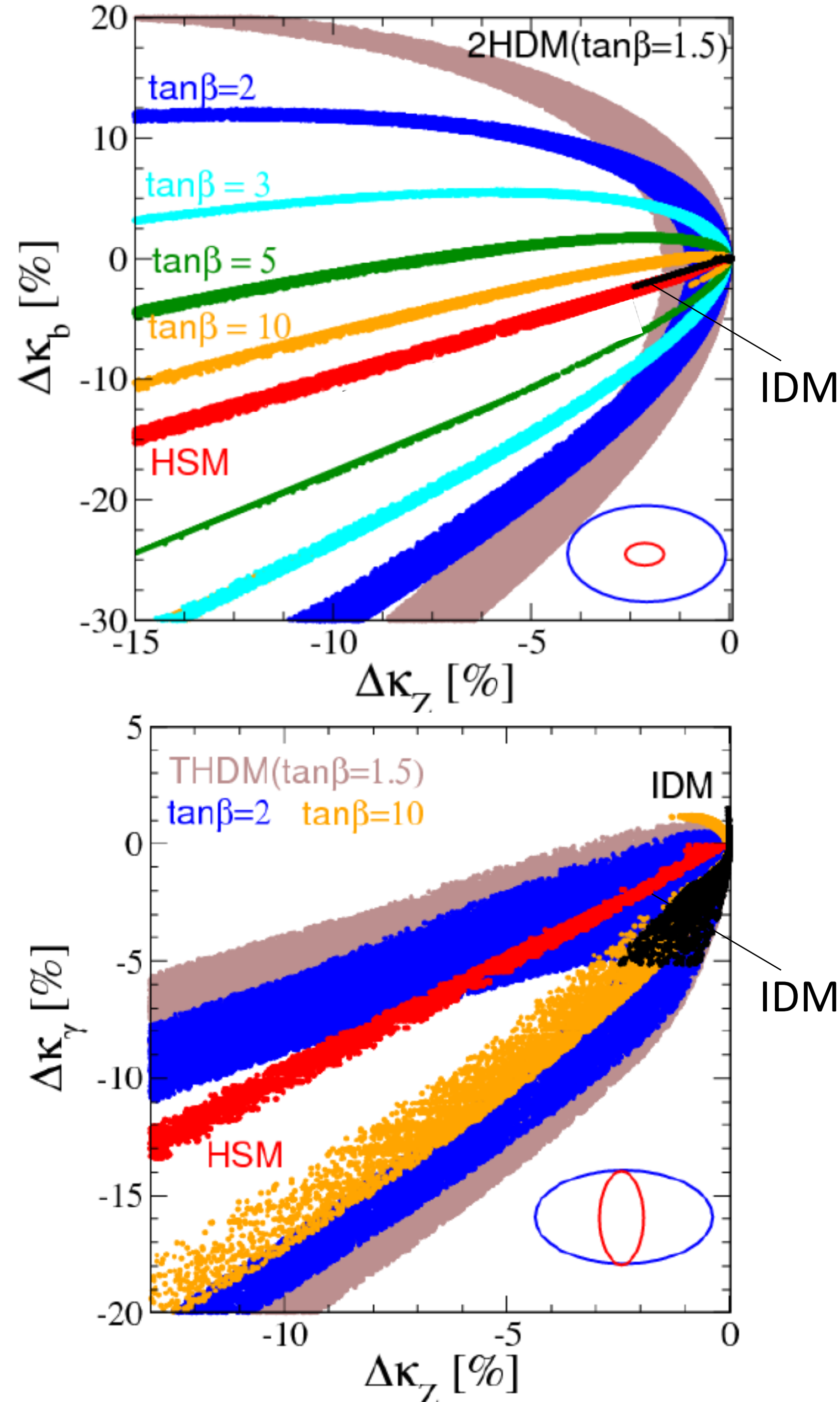
Comparison of

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
Wrong vacuum condition Cheng-Dawson-Levis 2014

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

Ellipse, ±1σ at LHC3000 and ILC500



H-COUP

S. K.
Mariko Kikuchi
Kei Yagyu

A full set of *Fortran Code* for evaluating one-loop corrected *h*(125) couplings in various 2nd simplest Higgs models

Doublet-Singlet model
SK, Kikuchi, Yagyu, 1511.06211, NPB to appear

Two Higgs doublet models (I, II, X, Y)
SK, Kikuchi, Yagyu, NPB896, 80 (2015)
SK, Kikuchi, Yagyu, PLB731, 27 (2014)

Doublet-Triplet model
Aoki, SK, Kikuchi, Yagyu, PRD87,015012(2013)

Inert Doublet/Singlet model
SK, Kikuchi, Sakurai, in preparation

All couplings of *h*(125)

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

Renormalization done in the *modified* on-shell scheme

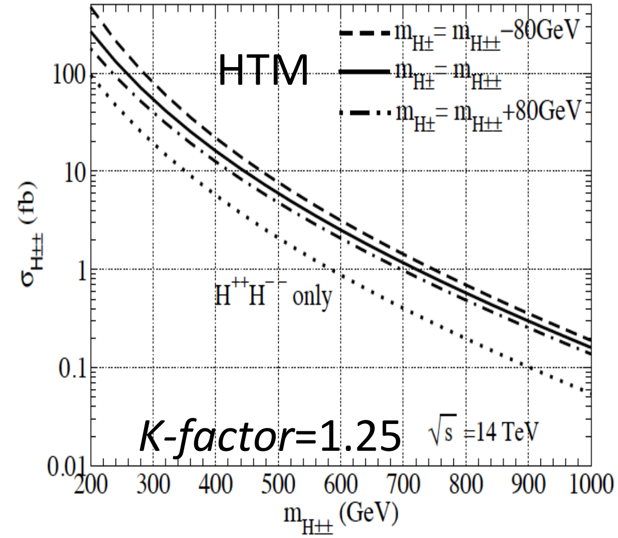
***H-COUP* (ver.1) is to be in public in mid 2016**

Doubly charged scalars (evidence of extended Higgs beyond 2HDM)

H^{++} appear in models with triplet or higher representations
A motivation is the type-II seesaw mechanism for neutrino mass

Doubly charged singlet k^{++} also appear
in various models for Loop induced neutrino mass

In the triplet model, H^{++} decay to same sign dilepton ($v_\Delta < 10^{-4}$ GeV) or diboson ($v_\Delta > 10^{-4}$ GeV)



A. Akeroyd, M. Aoki, 2005

Current data

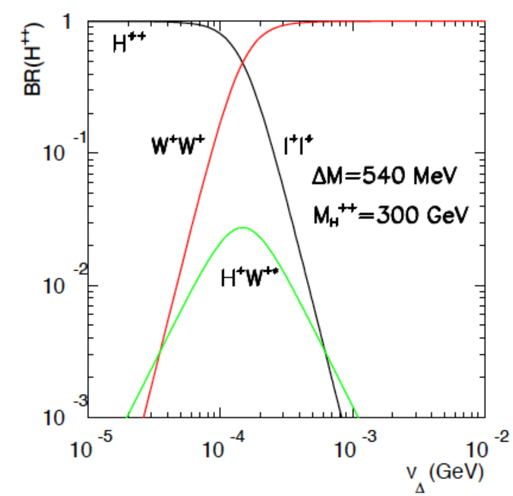
Dilepton

$m_{H++} >$ 551 GeV ($e_L e_L$ 100%, 95%CL) ATLAS, JHEP1503,041(2015)

$>$ 438 GeV ($\mu_R \mu_R$ 100%, 95%CL)

Diboson

$m_{H++} >$ 90 GeV ($\mu\mu$, 100% 95%CL)



P.F. Perez, T. Han, G. Huang, T. Li, K. Wang, 2008

Models with doublu charged Higgs

It would be related to neutrino physics

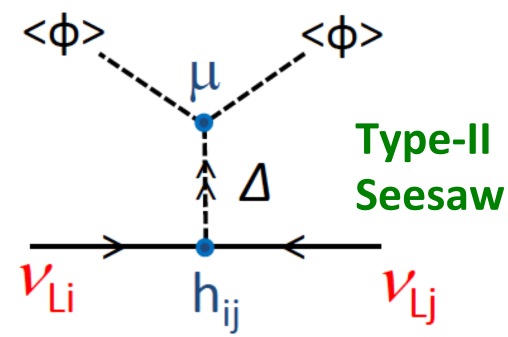
<u>Higgs Triplet Model (Type 2 Seesaw)</u>

$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}_\nu = h_{ij} \overline{L_L^{ic}} i\tau_2 \Delta L_L^j + \text{h.c.}.$$

$m_\nu^{ij} = h^{ij} v_\Delta = h_\Delta^{ij} \mu v^2 / M_\Delta^2$

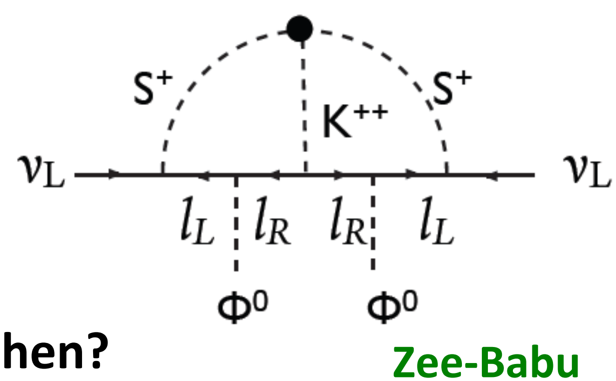
Δ^{++} decays to LH dilepton



<u>Doubly charged singlet (Zee-Babu model)</u>

$$\mathcal{L}_{\text{ZBM}} = -\overline{L^c} Y_a i\sigma_2 L k^+ - \overline{(\ell_R^-)^c} Y_s \ell_R^- k^{++} - \mu k^- k^- k^{++} + \text{H.c.}$$

k^{++} decays to RH dilepton

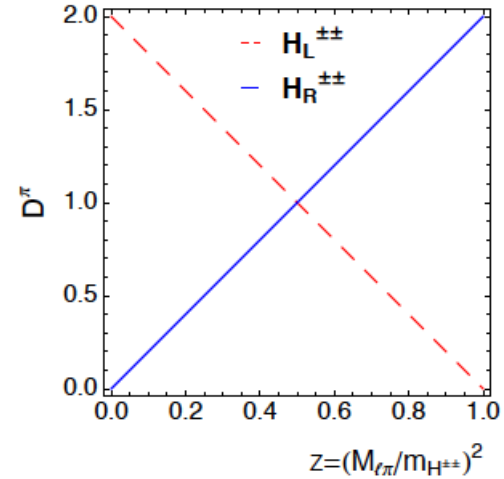


If dilepton decay is dominant, the mass of H^{++} (k^{++}) is limited by LHC **$m_{H++} >$ 450-550 GeV**

In Run II, Φ++ may be discovered by di-lepton modes, then?

Φ^{++} from which model?

Can we distinguish Singlet-like and triplet like Φ^{++} ?



Chirality of dilepton is different between

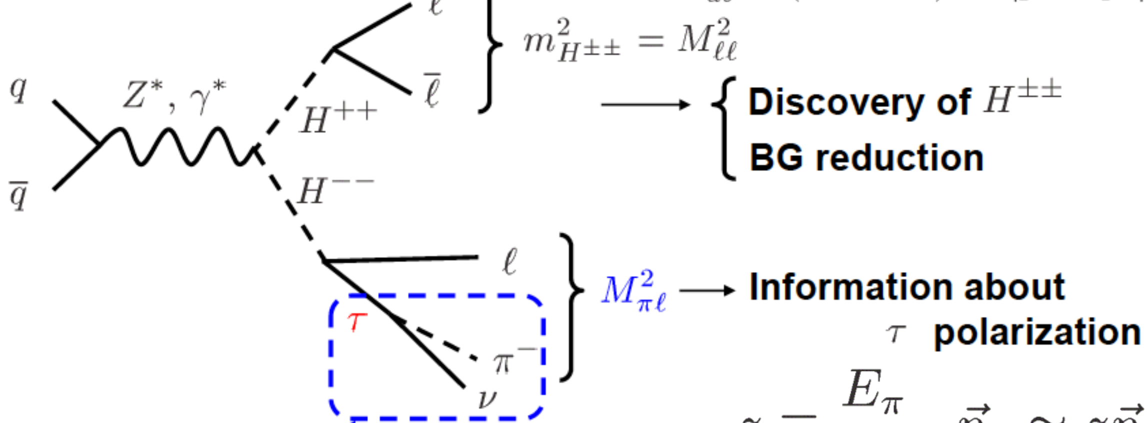
Triplet $H^{++} \to l_L^+\ l_L^+$ (HTM)

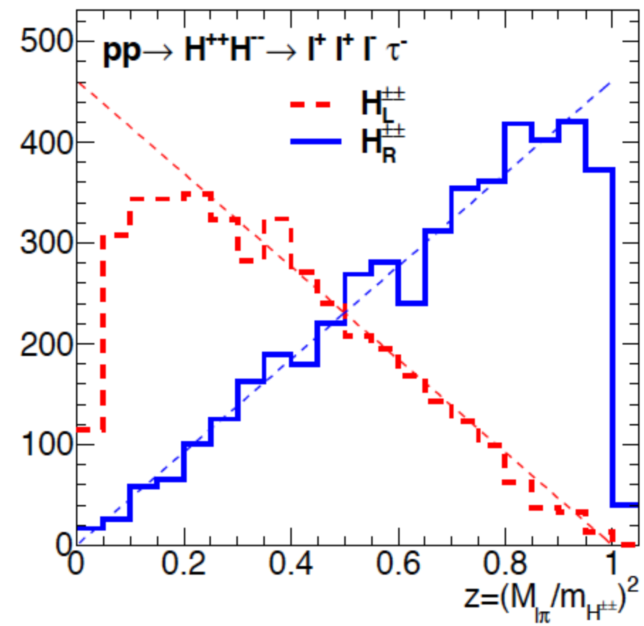
Singlet $k^{++} \to l_R^+\ l_R^+$ (Zee-Babu model)

$$\tau^+ \to \pi^+ \nu_L \quad \text{(branching 10\%)}$$

Produced pion from RH (LH) tau is hard (soft)

$$M_{ab}^2 \equiv (E_a + E_b)^2 - |\vec{p}_a + \vec{p}_b|^2$$





$$z \equiv \frac{E_\pi}{E_\tau}, \quad \vec{p}_\pi \simeq z\vec{p}_\tau$$

$\sigma(H^{++}H^{--})$ ~ O(1) fb for m_{H++}=500 GeV

H. Sugiyama, K. Tsumura, H. Yokoya, 2012

Testable? $N = 300\text{fb}^{-1} \times 1\text{fb} \times Br(H^{++} \to l^+\tau^+) \times B(H^{--} \to l^- l^-) \times B(\tau^+ \to \pi^+\nu)$ ~ 2-3!

1/6 1/2 1/10

Distribution after event selection

Initial # of sample of *llττ* = 30,000

By using more decay modes of taus, we may be able to distinguish H_L^{++} and H_R^{--}

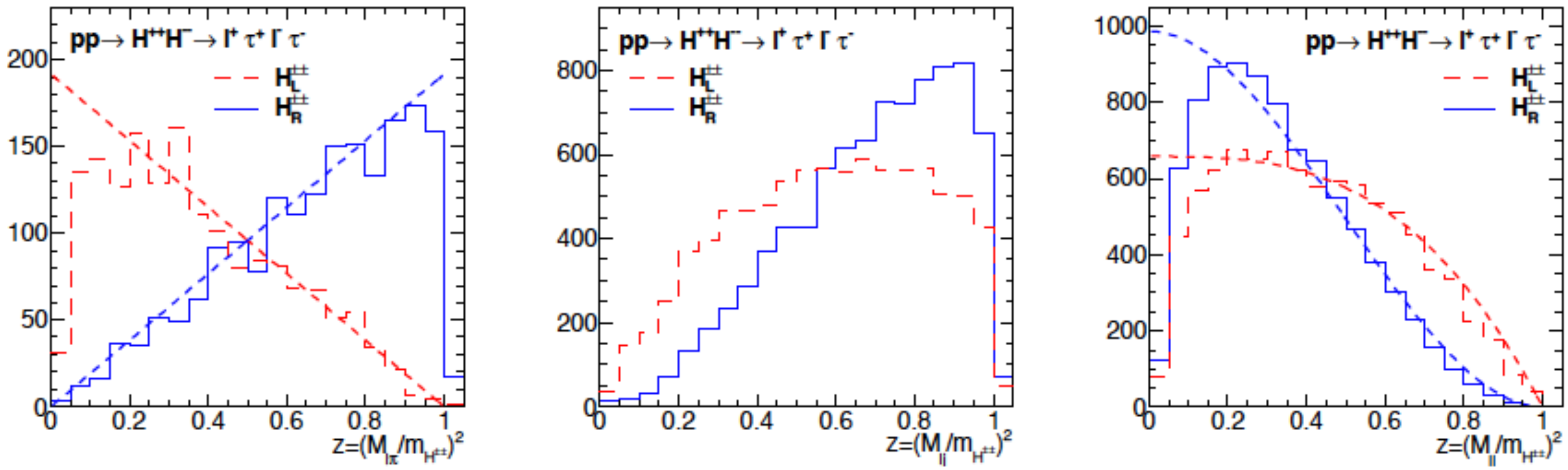


FIG. 5: Invariant-mass distributions of $\ell\pi_\tau$ (left), ℓj_τ (middle) and $\ell\ell_\tau$ (right) in the $pp \to H^{++}H^{--} \to \ell^+\tau^+\ell^-\tau^-$ process followed by one leptonic and one hadronic decays of τ's after the requirement of the proper momentum reconstruction by using the collinear approximation method. Dashed (Solid) histograms are for $H_L^{\pm\pm}$ ($H_R^{\pm\pm}$). Smooth lines in the left and right panels are theoretical expectations by using Eqs. (4) and Eqs. (5), respectively, with some normalization.

H. Sugiyama, K. Tsumura, H. Yokoya, 2012

Event Selection

e **and** μ **:**

$p_T > 15\,\mathrm{GeV}$ $\quad |\eta| < 2.5$

τ **jet (two methods) :**

$p_T > 25\,\mathrm{GeV}$ $\quad |\eta| < 2.5$ $\quad R = 0.4$

i) $\pi^{\pm}$ **jet from** τ **decay :**

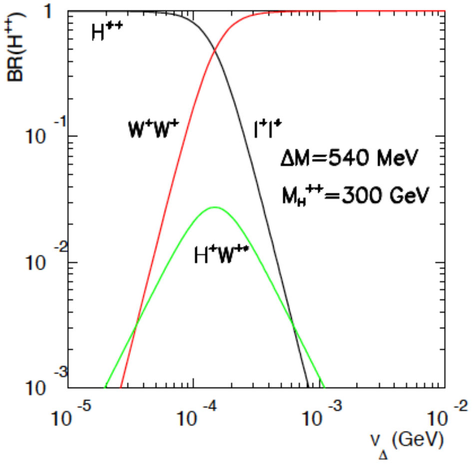
A jet which has only 1 charged hadron whose energy is more than 0.95 of the jet energy

ii) General jet from τ **decay :**

A jet which has 1 or 3 charged hadrons in $R = 0.15$ **in which more than 0.95 of the jet energy is included**

H. Sugiyama, K. Tsumura, H. Yokoya, 2012

Diboson decay

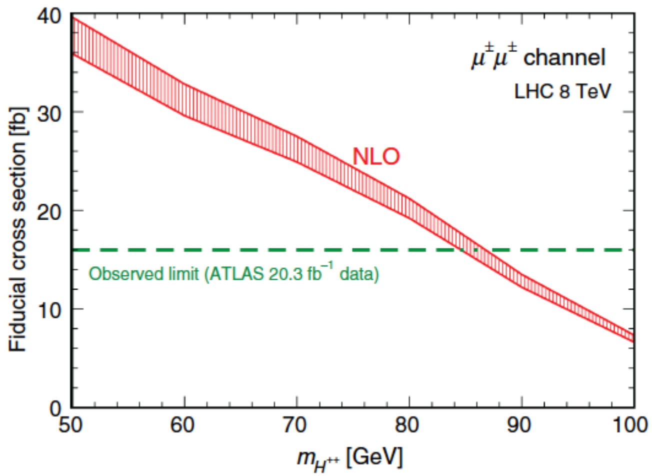


In the HTM, if v_Δ >>10^{-4} GeV $H^{++} \rightarrow W^+W^+$ is dominant. $h^{ij} < g^2 v_\Delta$

The v_Δ is limited by the ρ parameter

(v_Δ < a few GeV)

$H^{++} \rightarrow W^+W^+ \rightarrow l^+l^+\nu\nu$



Current bound at LHC 8TeV, 20.3 fb^{-1} **m <87GeV**

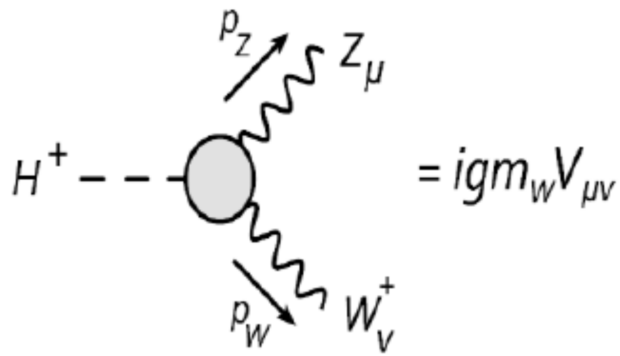
($H^{++} \rightarrow W^+W^+ \rightarrow \mu^+\mu^+\nu\nu$) 1412.7603

Fig. 1. The fiducial cross section for the $\mu^\pm\mu^\pm$ channel at the LHC 8 TeV collision as a function of $m_{H^{\pm\pm}}$. The green dashed horizontal line shows the 95% CL upper limit from the ATLAS data of the integrated luminosity to be 20.3 fb^{-1} [1]. The red shaded band shows the NLO prediction with 5% uncertainty. Details can be found in Table 1.

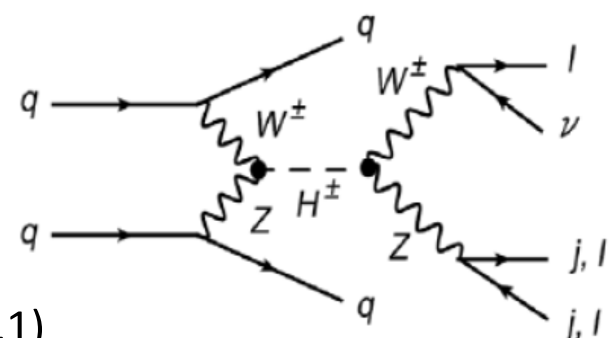
H^+W^-Z vertex

$$\mathcal{L}_{\rm eff} = g_Z m_W F H^+ W^-_\mu Z^\mu + \text{h.c.}$$

$$|F|^2 = \frac{2g^2}{m_W^2} \sum_i Y_i^2 [T_i(T_i+1) - Y_i^2] v_i^2 - \frac{1}{\rho^2_{\rm tree}}$$



$\lvert F\rvert^2 =$	$\frac{4v^2 v_\eta^2}{\cos^2\theta_W (v^2+4v_\eta^2)^2}$	$\frac{2v^2 v_\Delta^2}{\cos^2\theta_W (v^2+2v_\Delta^2)^2}$	$\frac{4v_\Delta^2}{\cos^2\theta_W (v^2+4v_\Delta^2)}$
	Real Triplet (Y=0)	Composite Triplet (Y=1)	Georgi-Machacek Model (1/2,1/2)+(1,0)+(1,1)



Small because of ρ parameter restricts v_η, v_Δ << a few GeV

ρ=1, so V_Δ ~ 50 GeV is possible
→ cause large coupling

2HDM: $|F|^2 = 0$ at tree, but appears at one-loop level and can be significant according to breakdown of custodial symmetry for the particles in the loop

H^+W^-Z is a probe of exotic Higgs sectors

The *hhh* coupling

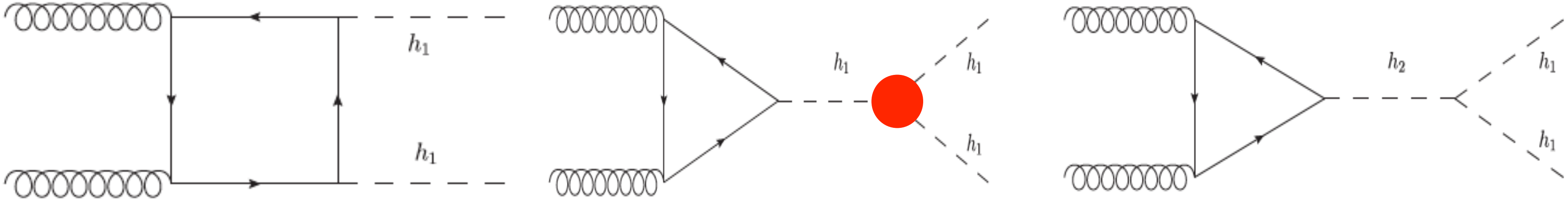
It was considered to be challenging to measure the hhh coupling at LHC.
At the ILC, we can expect that it is measured with O(10)% accuracy.

In the scenario of electroweak baryogenesis, the requirement of strongly 1^{st} OPT leads to a large deviation in triple Higgs coupling

In the case of renormalizable extended Higgs sectors, the large deviations are caused either

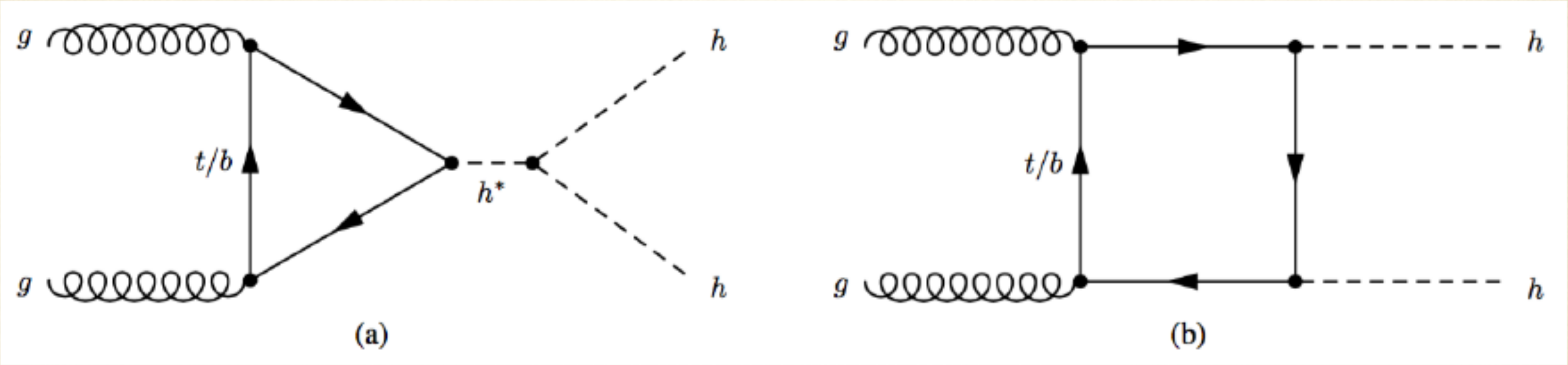
Tree level mixing effect (H-S mixing) or
Quantum correction (Non-decoupling loop effect)

Can we measure λ_{hhh} in such scenarios at LHC?



Junping Tian

measurement of Higgs self-coupling @ LHC



LHC Run1: pp—>hh @ ATLAS   95% C.L. upper limit: $\sigma / \sigma_{SM} < 70$ (48)

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
		Upper limit on the cross section [pb]			
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
		Upper limit on the cross section relative to the SM prediction			
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

arXiv:1509.0467

Snowmass Higgs working group: $\delta\lambda_{HHH} / \lambda \sim 50\%$ @ 14 TeV, 3000 fb^{-1}

(arXiv: 1310.8361)

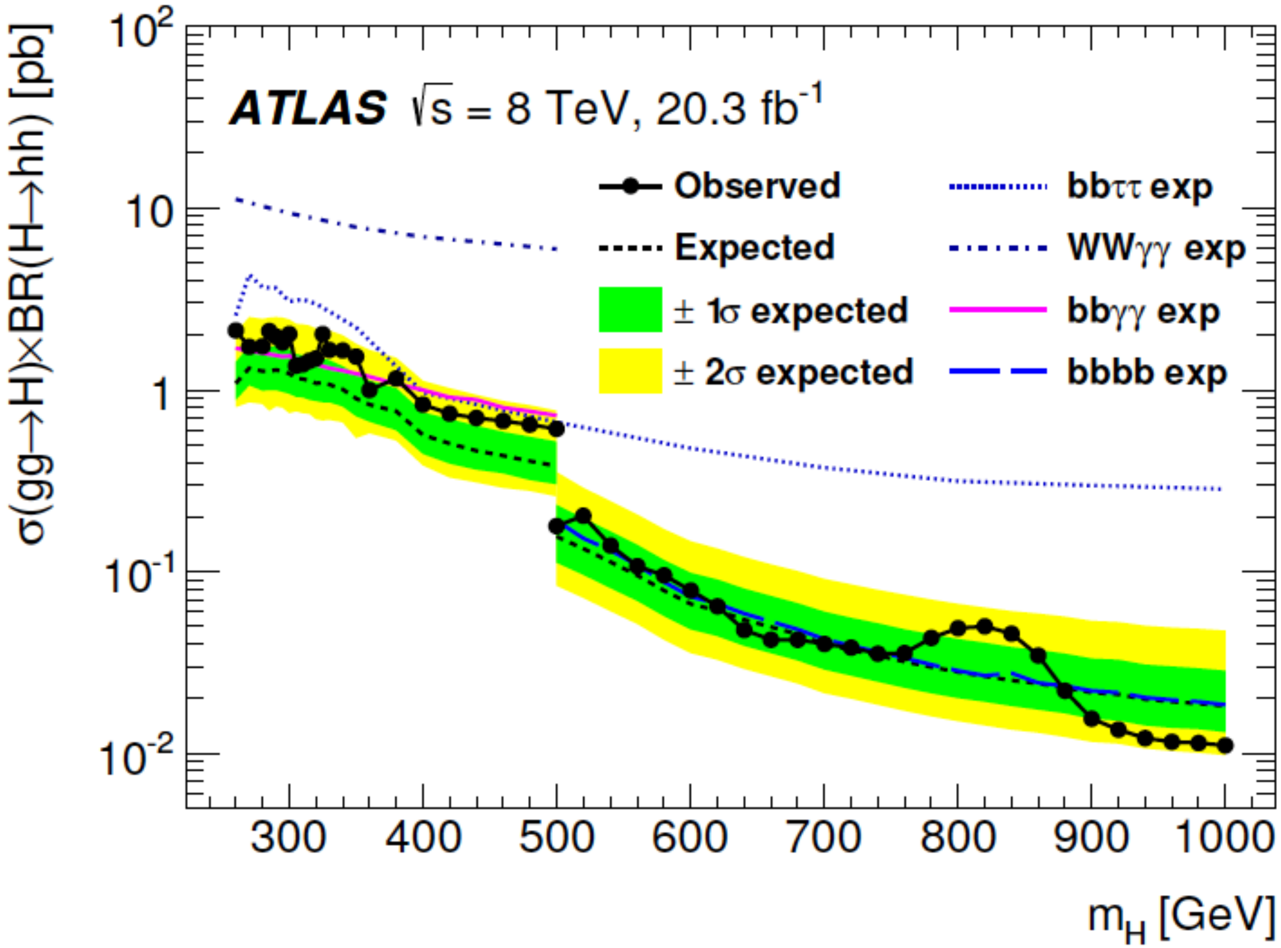
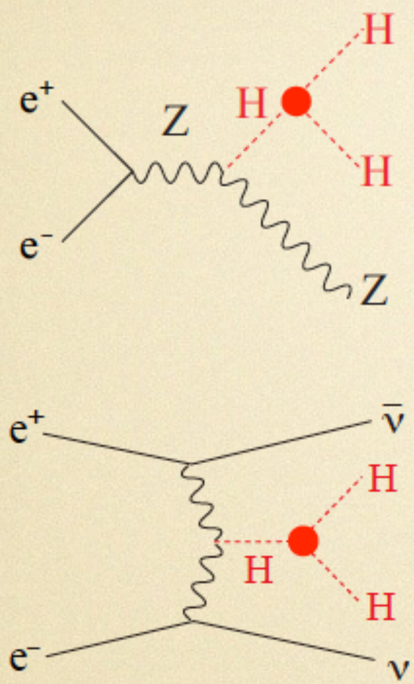
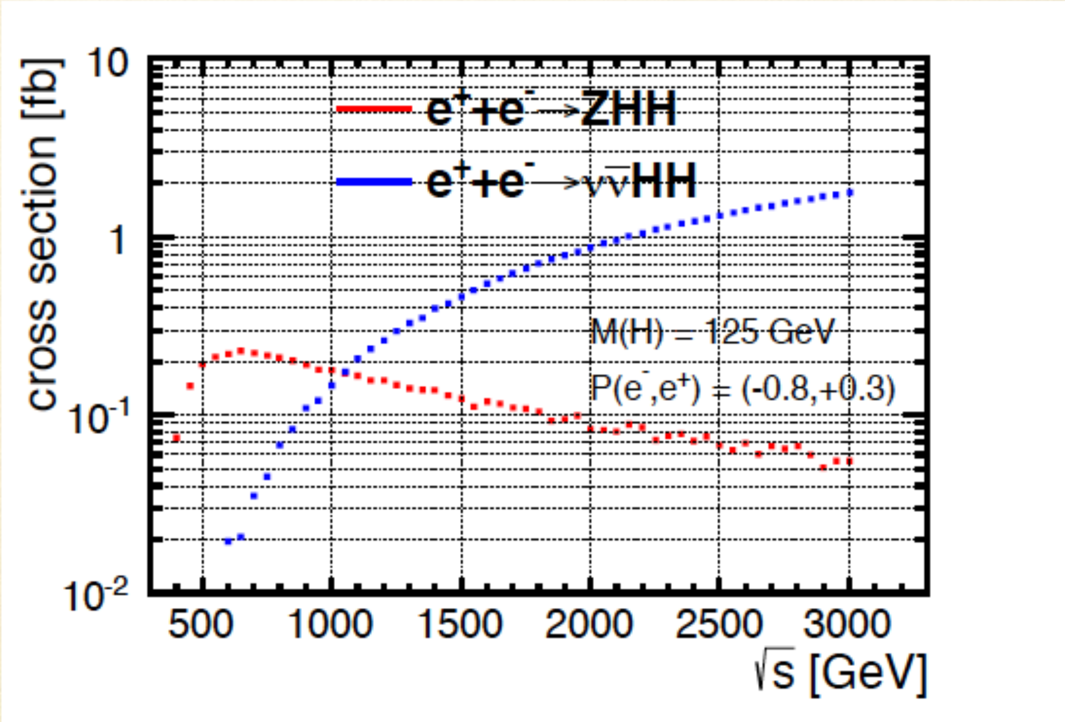


Figure 6: The observed and expected 95% CL upper limits on $\sigma(gg \to H) \times \mathrm{BR}(H \to hh)$ at $\sqrt{s} = 8$ TeV as functions of the heavy Higgs boson mass m_H, combining resonant searches in $hh \to \gamma\gamma bb$, $bbbb$, $bb\tau\tau$ and $\gamma\gamma WW^*$ final states. The expected limits from individual analyses are also shown. The combination assumes SM values for the decay branching ratios of the lighter Higgs boson h. The green and yellow bands represent $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty ranges of the expected combined limits. The improvement above $m_H = 500$ GeV is due to the sensitivity of the $hh \to bbbb$ analysis. The more finely spaced mass points of the combination reflect the better mass resolutions of the $hh \to \gamma\gamma bb$ and $hh \to bbbb$ analyses than those of the $hh \to bb\tau\tau$ and $hh \to \gamma\gamma WW^*$ analyses.

Junping Tian

prospects of Higgs self-coupling @ linear colliders





prospects from full simulation studies:

ILC

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Snowmass	46%	13%
H20	29%	10%

(ref. H20 arXiv: 1506.07870)

CLIC

1.4 TeV	+3 TeV
21%	10%

(arXiv: 1307.5288)

J. Tian, LC-REP-2013-003 C. Dürig @ ALCW15 M. Kurata, LC-REP-2014-025

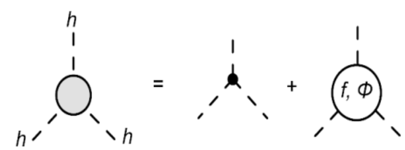
The *hhh* coupling in extended Higgs models

To understand the essence of EWSB, we must know the self-coupling in addition to the mass independently

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

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

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



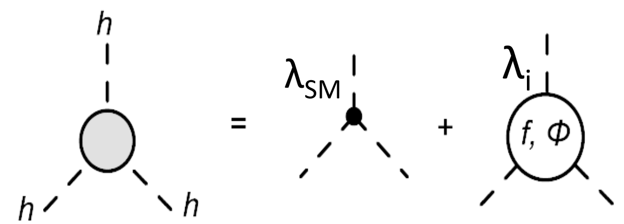
SM Case

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

Non-decoupling effect

Case of extended Higgs sectors

- 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 $3m_h^2/2$
- At 1-loop, non-decoupling effect $\propto m_\Phi^4$ appears (If *M* < *v*)



Φ = H, A, H±, ...

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

Extra scalar loop

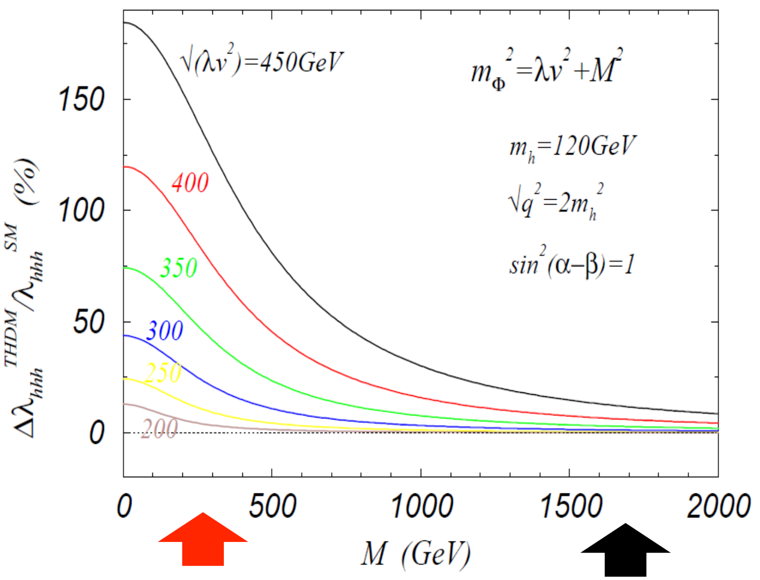
Top loop

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

(Φ = *H, A, H±*)

Correction can be huge ∼ 100%

SK, Kiyoura, Okada, Senaha, Yuan, 2003



Non-decoupling effect

Decoupling regime

Similar enhancement can happen all extended Higgs sectors

Strongly 1st OPT

High Temperature Expansion (just for sketch)

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

Condition of Strongly 1st OPT

$$\frac{\varphi_C}{T_C} \simeq \frac{2E}{\lambda_{T_C}} > 1$$

However, the SM cannot realize the strongly 1st OPT

$$E \simeq \frac{1}{12\pi v^3}\left(6m_W^3 + 3m_Z^3 + \cdots\right) \quad \lambda_{T_C} \sim \frac{m_h^2}{2v^2} + \cdots$$

$$\frac{\varphi_C}{T_C} \simeq \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1$$

For m_h = 125 GeV

We need a mechanism to enlarge *E* to realize strongly 1st OPT

Strongly 1st OPT and the *hhh* coupling

High Temperature Expansion (just for sketch)

$$V_{\rm eff}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

Condition of Strongly 1st OPT

$$\frac{\varphi_C}{T_C} \simeq \frac{2E}{\lambda_{T_C}} > 1$$

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

The condition can be satisfied by thermal loop effects of additional scalar bosons Φ (Φ = *H, A, H^+, H^{++}* …)

$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \sum_\Phi m_\Phi^3\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\left(1 + \frac{3M^2}{2m_\Phi^2}\right)\right\} > 1$$

In this case, large quantum effects also appear in the *hhh* coupling

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v^2}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \sum_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\right\} > \lambda_{hhh}^{SM}$$

Strong 1st OPT and the *hhh* coupling

Strongly 1st OPT (Φc/Tc>1)
⇔ Non-decoupling quantum effect
⇔ large deviation in *hhh* at loop

Electroweak Baryogenesis can be tested by measuring the *hhh* coupling !

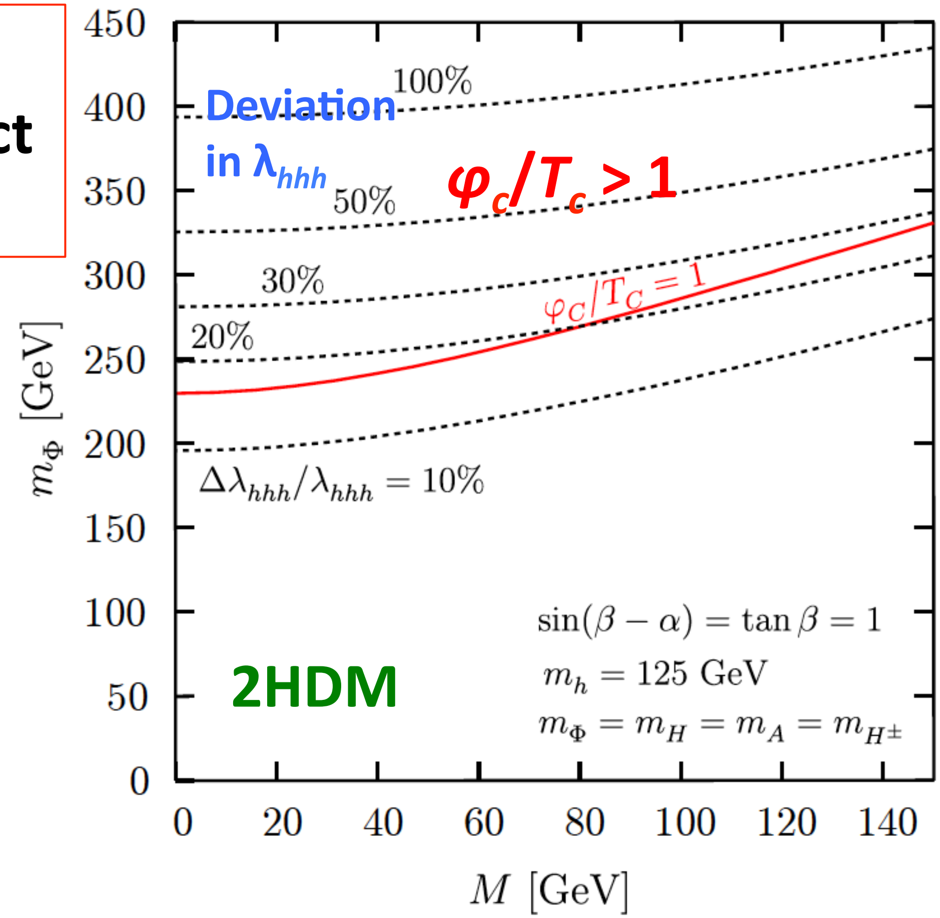
Grojean et al (effective theory)

It is considered that at LHC challenging to measure λ_{hhh}

ILC (1 TeV) can measure λ_{hhh} by O(10) %

K. Fujii et al., arXiv:1506.05992 [hep-ex]

S.K., Y. Okada, E. Senaha (2005)



Singlet, Inert Doublet
Triplet, GM models, …

Case of a singlet extension

$$V_0 = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$
$$+\mu_{HS} H^\dagger H S + \frac{\lambda_{HS}}{2} H^\dagger H S^2$$
$$+\mu_S^3 S + \frac{m_S^2}{2} S^2 + \frac{\mu'_S}{3} S^3 + \frac{\lambda_S}{4} S^4$$

HHS and HHSS terms change the property of EW phase transition to of strongly 1st order

At the same time, it also enhance the hhh coupling

Additional singlet also causes 1st OPT at tree by mixing between Φ and S

Higgs singlet model (and NMSSM)

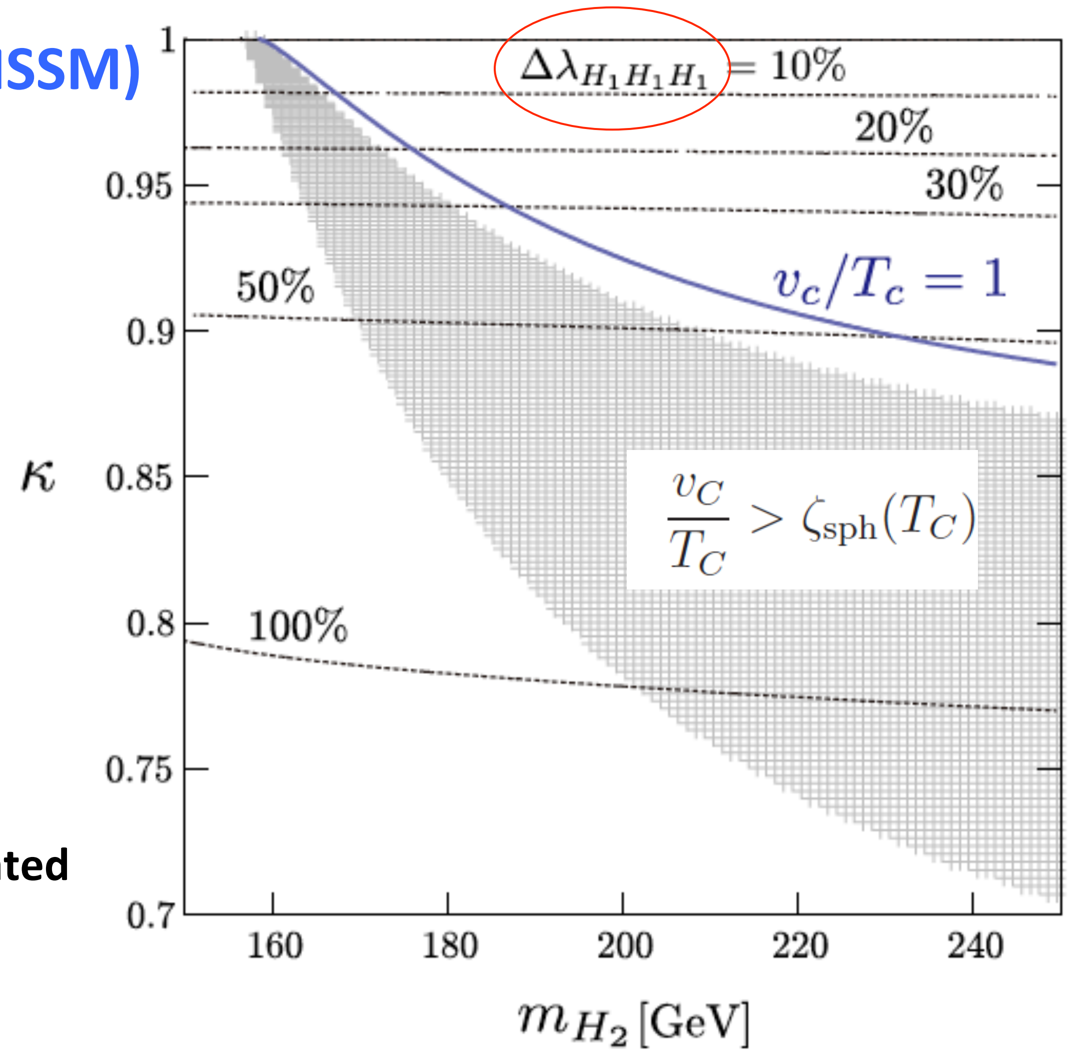
$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

$$-\pi/4 \le \alpha \le \pi/4$$

$$\kappa_V = \frac{g_{H_1VV}}{g^{SM}_{hVV}} = \cos\alpha$$

$$\kappa_F = \frac{g_{H_1ff}}{g^{SM}_{hVV}} = \cos\alpha$$

$$\kappa \equiv \kappa_V = \kappa_F$$



K. Fuyuto and E. Senaha, 2014

K, λ_{hhh} and the mass of H are correlated

The scenario can be tested by mesuring κ and the hhh coupling

What if quantum correction is taken into account?

Theoretical conditions for constraining the parameter spaces

Vacuum Stability

$$\lambda_1 > 0. \quad \lambda_2 > 0, \quad \sqrt{\lambda_1\lambda_2} + \lambda_3 + \mathrm{MIN}(0, \lambda_4 + \lambda_5, \lambda_4 - \lambda_5) > 0$$

Unitarity

$$|x_i^{\pm}| \leq \frac{1}{2}$$

$$x_1^{\pm} = \frac{1}{32\pi}\left[3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2 + 4(2\lambda_3+\lambda_4)^2}\right]$$

$$x_2^{\pm} = \frac{1}{32\pi}\left[(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2}\right],$$

$$x_3^{\pm} = \frac{1}{32\pi}\left[(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2}\right],$$

$$x_4^{\pm} = \frac{1}{16\pi}(\lambda_3 + 2\lambda_4 \pm 3\lambda_5),$$

$$x_5^{\pm} = \frac{1}{16\pi}(\lambda_3 \pm \lambda_4),$$

$$x_6^{\pm} = \frac{1}{16\pi}(\lambda_3 \pm \lambda_5).$$

Eigen channel
in the Higgs singlet model

EW vacuum $(v, v_S) = (v_{EW}, 0)$

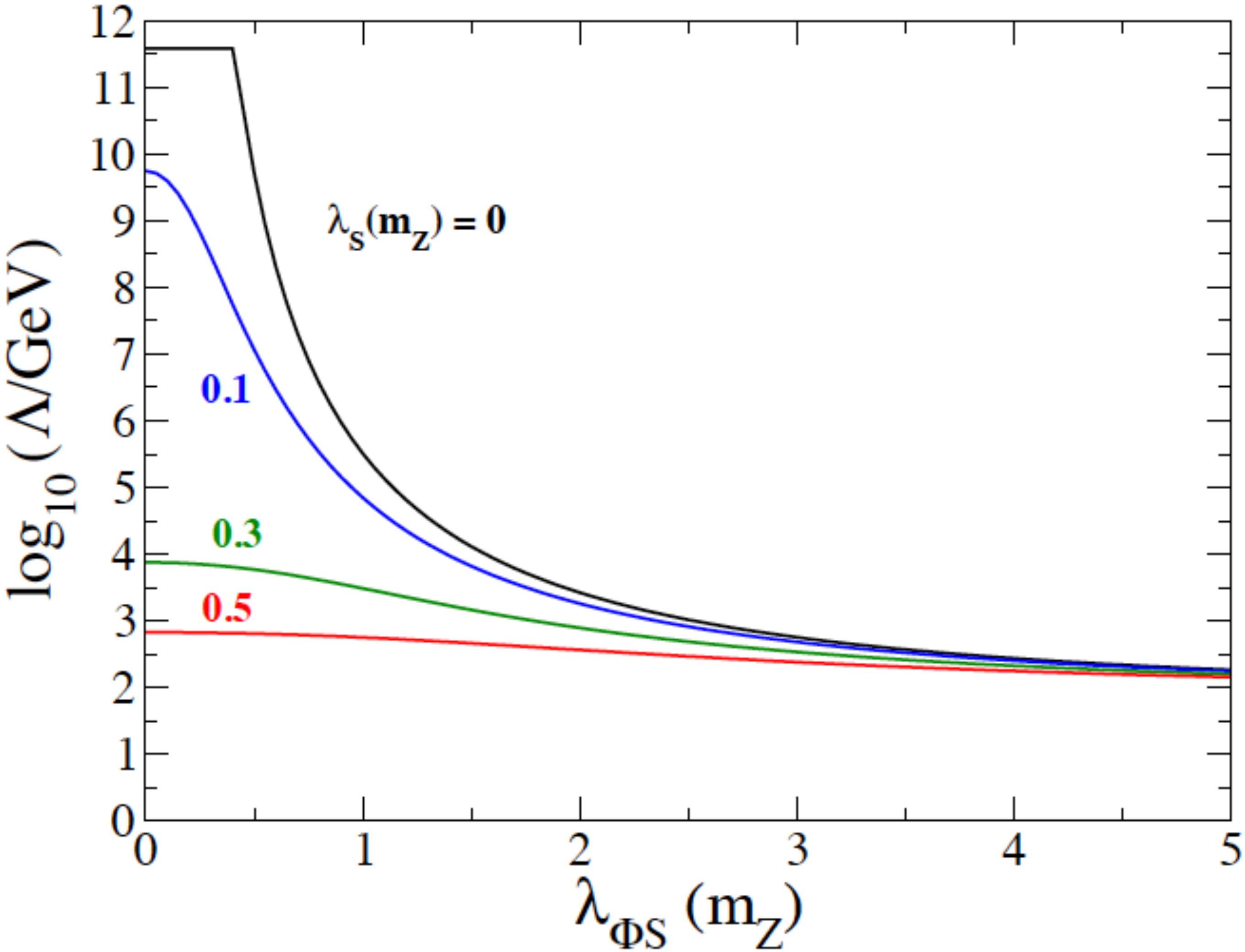
Other extrema (Wrong vacuum) $(v', v'_S) = (v_+, x_+),\ (v_-, x_-),\ (0, x_1^0),\ (0, x_2^0),\ (0, x_3^0)$

Avoiding wrong vacuum

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

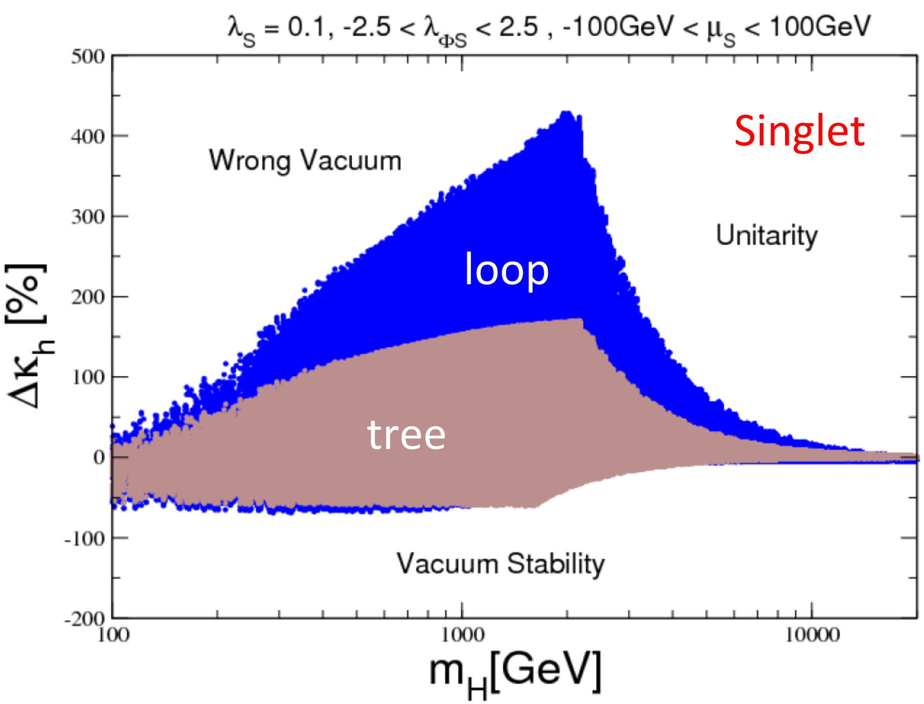
$$V_{nor}(v_{EW}, 0) = 0$$

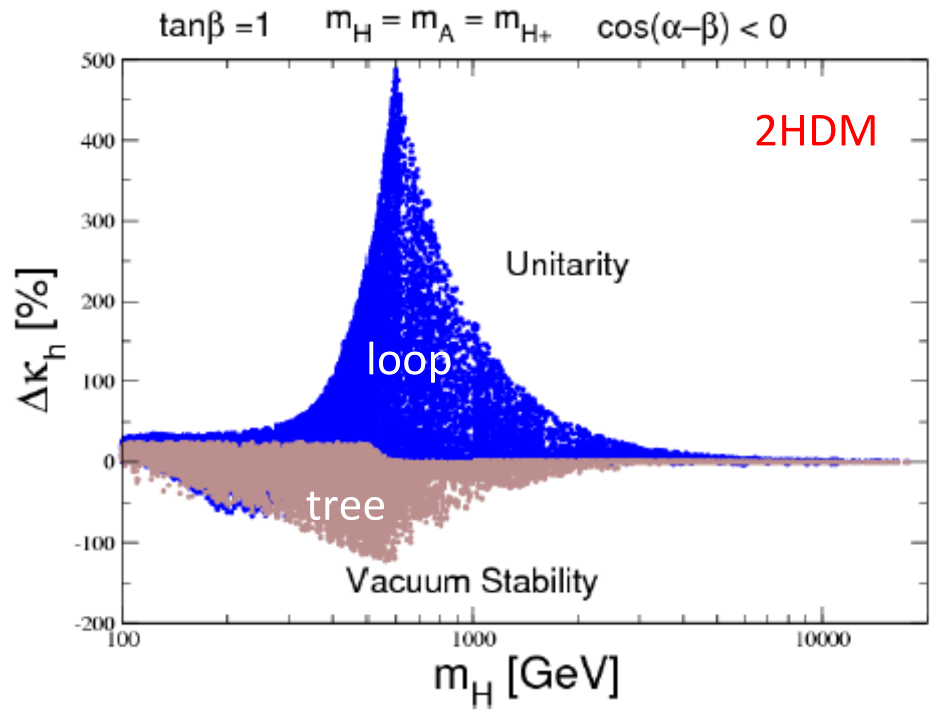
Landau pole $\lambda(\Lambda)=4\pi$



Quantum correction can drastically change λ_{hhh} coupling in extended Higgs models.

SK, Kikuchi, Yagyu, preliminary





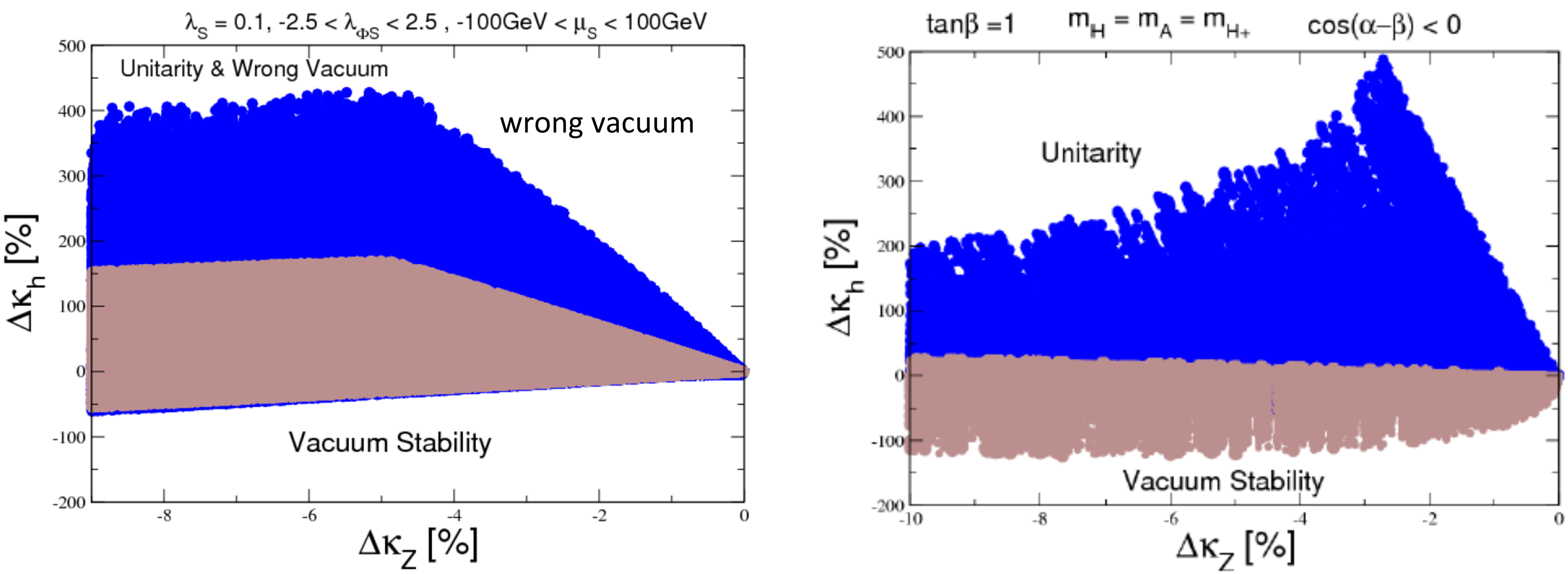
Singlet model without Z_2

Tree level analysis is not really sufficient for the analysis including λ_{hhh}

2HDM
Singlet with unbroken Z_2
Singlet with spontaneous broken Z_2
Inert Doublet
Triplet Model
GM model

Correlation between λ_{hhh} and κ_Z

SK, Kikuchi, Yagyu, preliminary

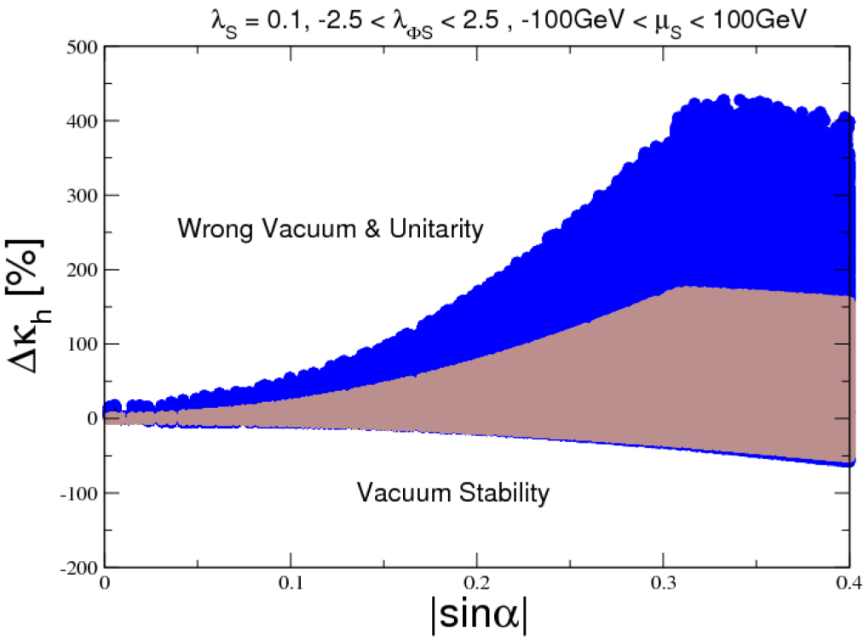


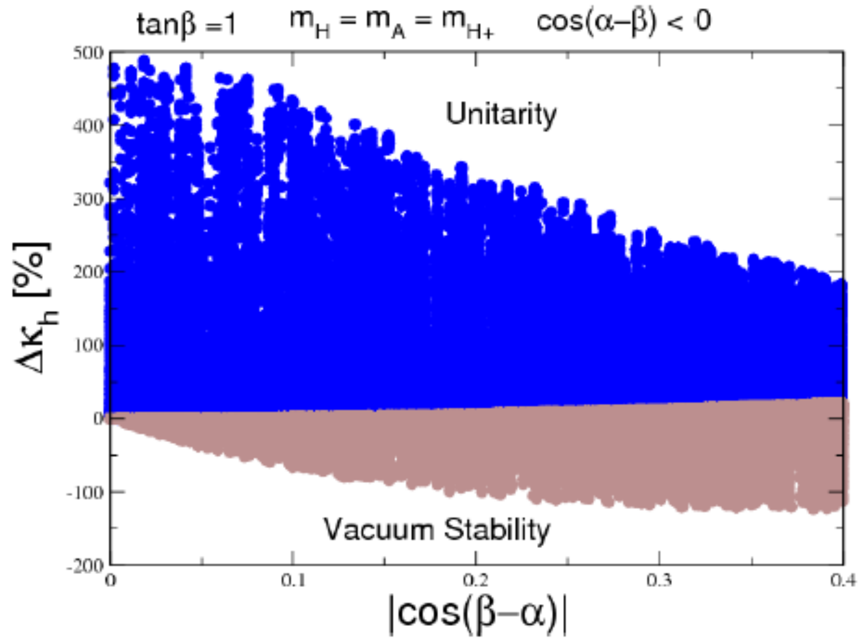
$$\Delta\kappa_V = \frac{\hat{\Gamma}_{hVV}}{\hat{\Gamma}^{\rm SM}_{hVV}} - 1 \simeq -\frac{\alpha^2}{2} - \frac{1}{16\pi^2}\frac{v^2}{6m_H^2}\lambda_{\Phi S}^2 \simeq \Delta\kappa_f,$$

$$\Delta\kappa_h = \frac{\hat{\Gamma}_{hhh}}{\hat{\Gamma}^{\rm SM}_{hhh}} - 1 \simeq \frac{\alpha^2}{2}\left(\frac{4v^2}{m_h^2}\lambda_{\Phi S} - 3\right) + \frac{1}{16\pi^2}\frac{v^4}{m_H^2 m_h^2}\left[\frac{4}{3} + 3\alpha^2(25 - 4\sqrt{3}\pi)\right]\lambda_{\Phi S}^3$$

Even if $|\Delta\kappa_Z|$ is smaller than 5 %, $\Delta\kappa_h$ can be400-500%.

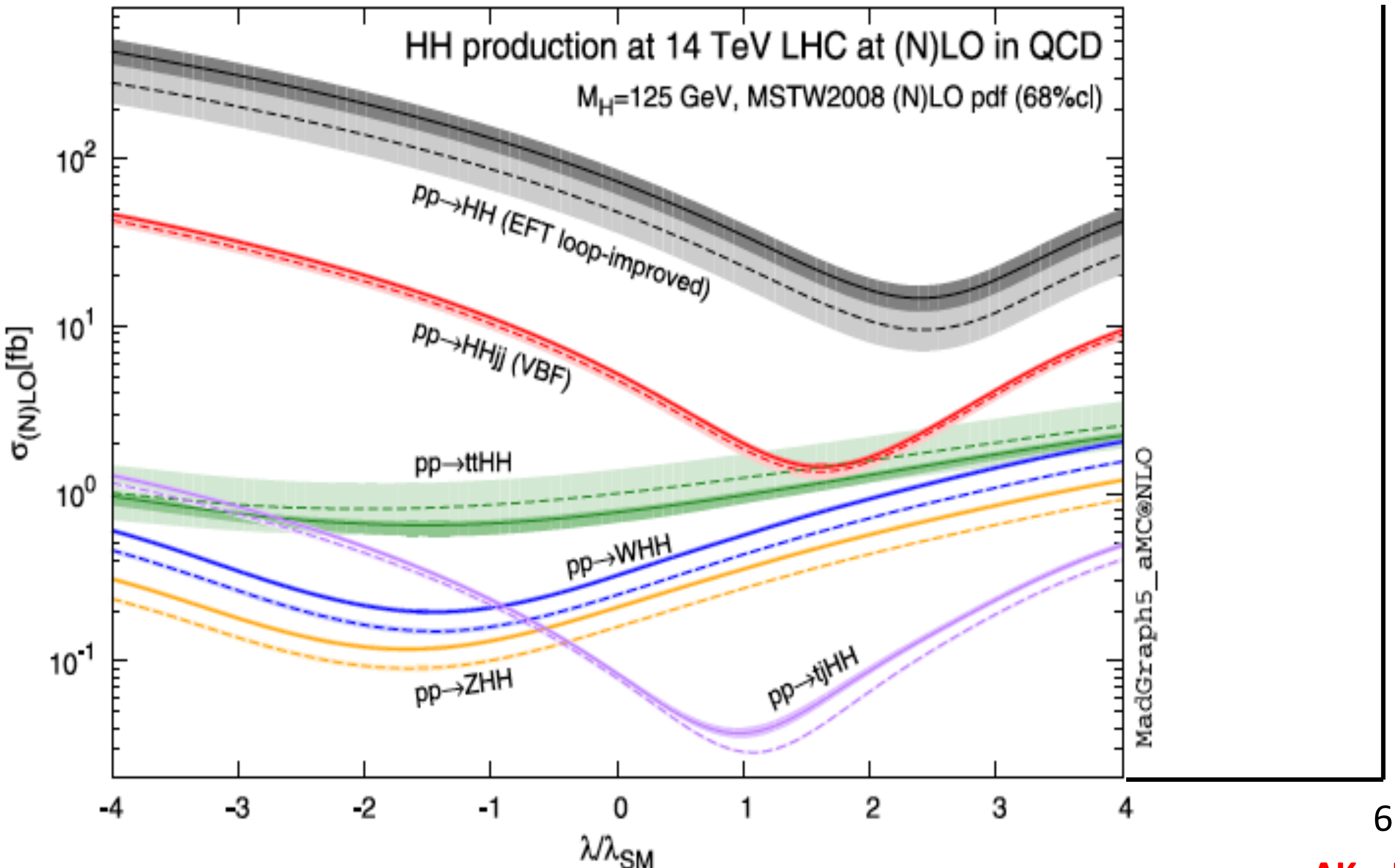
SK, Kikuchi, Yagyu, preliminary





Enhancement due to large λ_{hhh} deviations?

	SM
pp→HH	35 fb
pp→HHjj(VBF)	2 fb

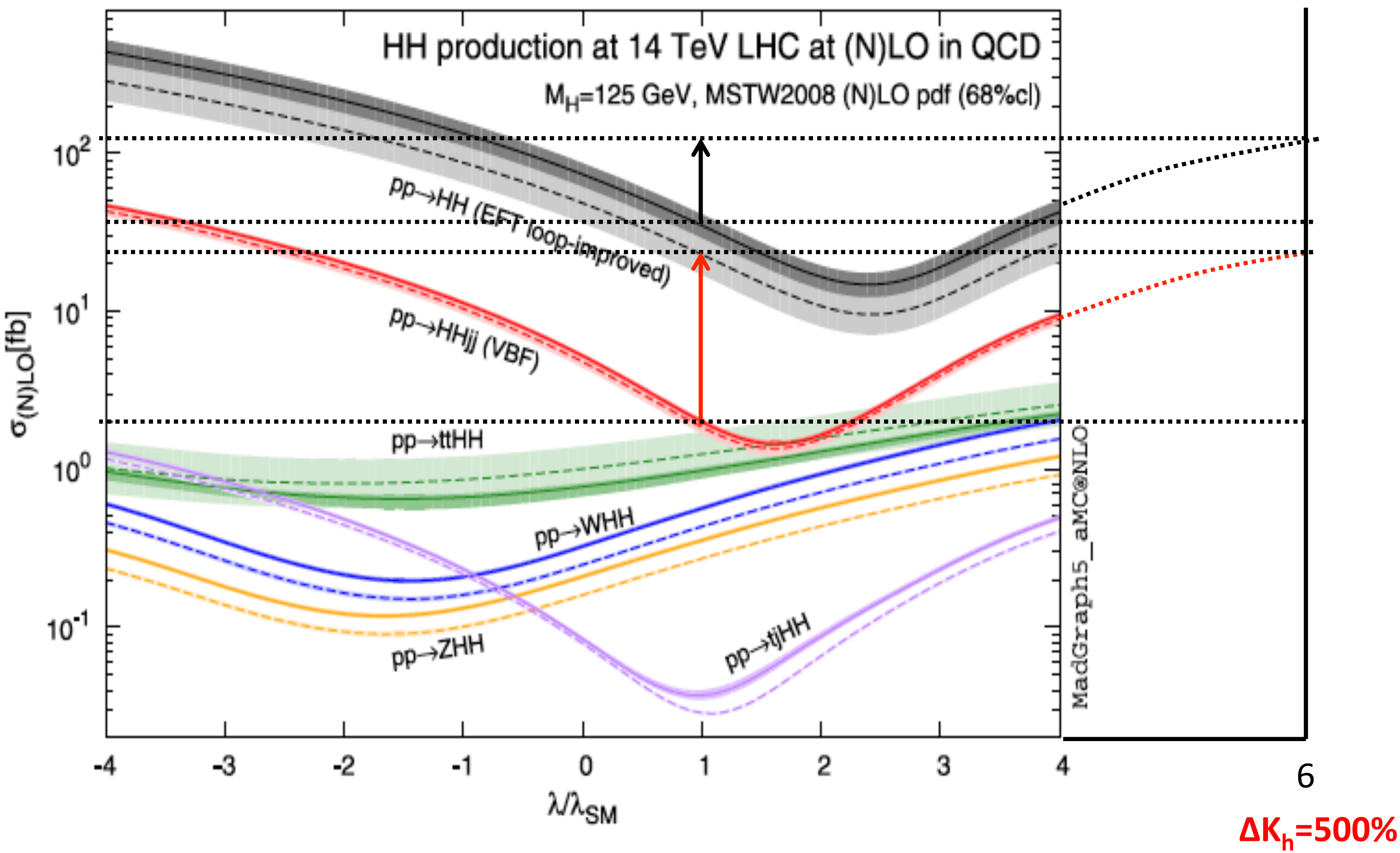


ΔK_h=500%

R. Flederix, et. al, PLB732, 142 (2014).

Enhancement due to large λ_{hhh} deviations?

	SM	
pp→HH	35 fb →	110 fb
pp→HHjj(VBF)	2 fb →	22fb



R. Flederix, et. al, PLB732, 142 (2014).

Conclusion

Various extended Higgs sectors are possible

Testing them at LHC

- **Fingerprinting extended Higgs sectors**
- **Direct search of additional scalars**
- **Importance of study with (EW, scalar) quantum corrections to the Higgs potential**

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, SM-like Higgs boson

H Extra Higgs boson

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

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

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

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

- **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**

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

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

Georgi-Machacek model

◆ヒッグスセクター (二重項場(Φ)+複素三重項(χ)+実三重項場(ξ))

$$\phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0} \end{pmatrix}$$

$SU(2)_L \times SU(2)_R \times U(1)_Y$

field	T	Y
Φ	$\frac{1}{2}$	$\frac{1}{2}$
ξ	1	0
χ	1	1

◆ヒッグスポテンシャル

$$\begin{aligned} V &= m_1^2 Tr(\Phi^\dagger\Phi) + m_2^2 Tr(\Delta^\dagger\Delta) + \lambda_1 Tr[\Phi^\dagger\Phi]^2 \\ &+ \lambda_2 Tr[\Delta^\dagger\Delta]^2 + \lambda_3 Tr[\Phi^\dagger\Phi]Tr[\Delta^\dagger\Delta] + \lambda_4 Tr[(\Delta^\dagger\Delta)^2] \\ &+ \lambda_5 Tr[\Phi^\dagger \frac{\tau^i}{2}\Phi\frac{\tau^j}{2}]Tr[\Delta^i T_i \Delta T_j] + \mu_1 Tr[\Phi^\dagger\frac{\tau_i}{2}\Phi\frac{\tau_j}{2}]\Delta_p^{ij} + \mu_2 Tr[\Delta^\dagger T_i \Delta T_j]\Delta_p^{ij} \end{aligned}$$

◆質量固有状態

5-plet $H_5^{\pm\pm}$, $H_5^{\pm}$, H_5^{0}

3-plet $H_3^{\pm}$, H_3^{0} — CP-odd

1-plet H_1^{0}

SM-ライクヒッグス h

(1-plet, SM-ライクヒッグス, H_5^0: CP-even)

$$\Delta_p = P^\dagger \Delta P, \quad P = \begin{pmatrix} -\frac{1}{\sqrt{2}} & i\frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 1 \\ \frac{1}{\sqrt{2}} & i\frac{1}{\sqrt{2}} & 0 \end{pmatrix}$$

◆タイプIIのシーソー機構によりニュートリノ質量説明できる

Model with septet field

field	T	Y
Φ	$\frac{1}{2}$	$\frac{1}{2}$
Σ	3	2

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi \end{pmatrix}, \quad \varphi_7 = \begin{pmatrix} \varphi^{5+} \\ \varphi^{4+} \\ \varphi^{3+} \\ \varphi^{2+} \\ \varphi^{+} \\ \varphi \\ \tilde{\varphi}^{-} \end{pmatrix}$$

$$\phi = \frac{1}{\sqrt{2}}(\phi^0 + iz + v_\phi), \quad \varphi = \frac{1}{\sqrt{2}}(\varphi^0 + i\eta + v_7).$$

◆ヒッグスポテンシャル

$$V(\phi, \varphi_7) = m^2|\phi|^2 + m_7^2|\varphi_7|^2 + \lambda|\phi|^4 + \lambda_1(|\varphi_7|^4)_1 + \lambda_2(|\varphi_7|^4)_2 + \lambda_3(|\varphi_7|^4)_3 + \lambda_4(|\varphi_7|^4)_4 + \kappa_1(|\phi|^2|\varphi_7|^2)_1 + \kappa_2(|\phi|^2|\varphi_7|^2)_2,$$

SU(2)L×U(1)対称性のほかに、accidentalな大局的U(1)対称性をもつ。

◆ 質量固有状態

$$\begin{pmatrix} \mathrm{Re}\Phi^0 \\ \mathrm{Re}\varphi_7^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

$$\begin{pmatrix} \mathrm{Im}\Phi^0 \\ \mathrm{Im}\varphi_7^0 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

$$\begin{pmatrix} \Phi^+ \\ \varphi_7^+ \\ \bar{\varphi}_7^+ \end{pmatrix} = \begin{pmatrix} c_\beta & -\sqrt{\frac{5}{5+3c_\beta^2}}s_\beta & -\sqrt{\frac{3}{5+3c_\beta^2}}s_\beta c_\beta \\ \sqrt{\frac{5}{8}}s_\beta & \sqrt{\frac{8}{5+3c_\beta^2}}c_\beta & -\sqrt{\frac{15}{8(5+3c_\beta^2)}}s_\beta^2 \\ -\sqrt{\frac{3}{8}}s_\beta & 0 & -\sqrt{\frac{5+3c_\beta^2}{8}} \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \\ H'^+ \end{pmatrix}$$

Large momentum dependences on *hhh* for the case of SM

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

Effective potential method

~ – 12% (m_h=120GeV)

Diagrammatic method (q^2-dependence)

$$h^* \rightarrow hh$$

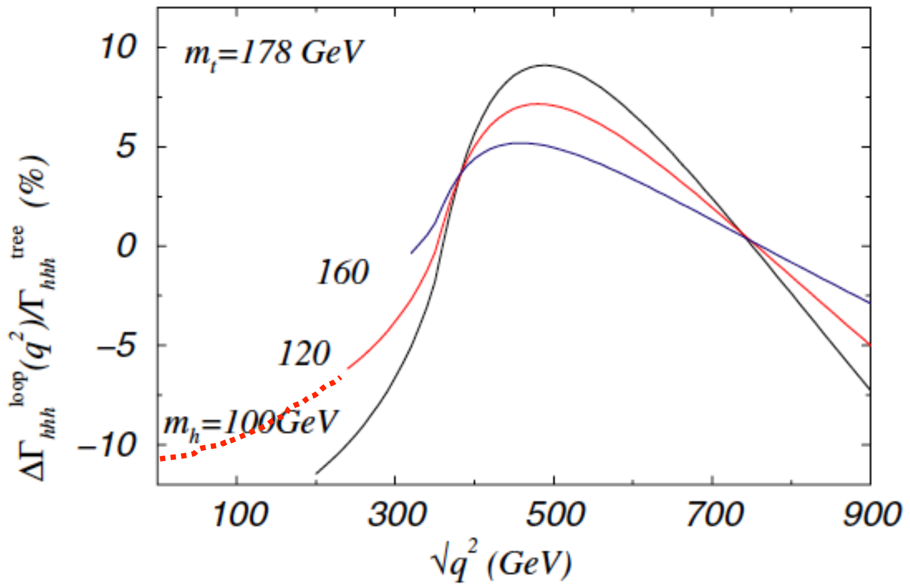


FIG. 1 (color online). The one-loop contribution of the top quark to the effective hhh coupling as a function of $\sqrt{q^2}$, where q^μ is the momentum of the off-shell h boson in $h^* \rightarrow hh$. $\Delta\Gamma_{hhh}^{\mathrm{loop}}(q^2)$ is defined by $\Gamma_{hhh}(q^2) - \Gamma_{hhh}^{\mathrm{tree}}$ in the SM.

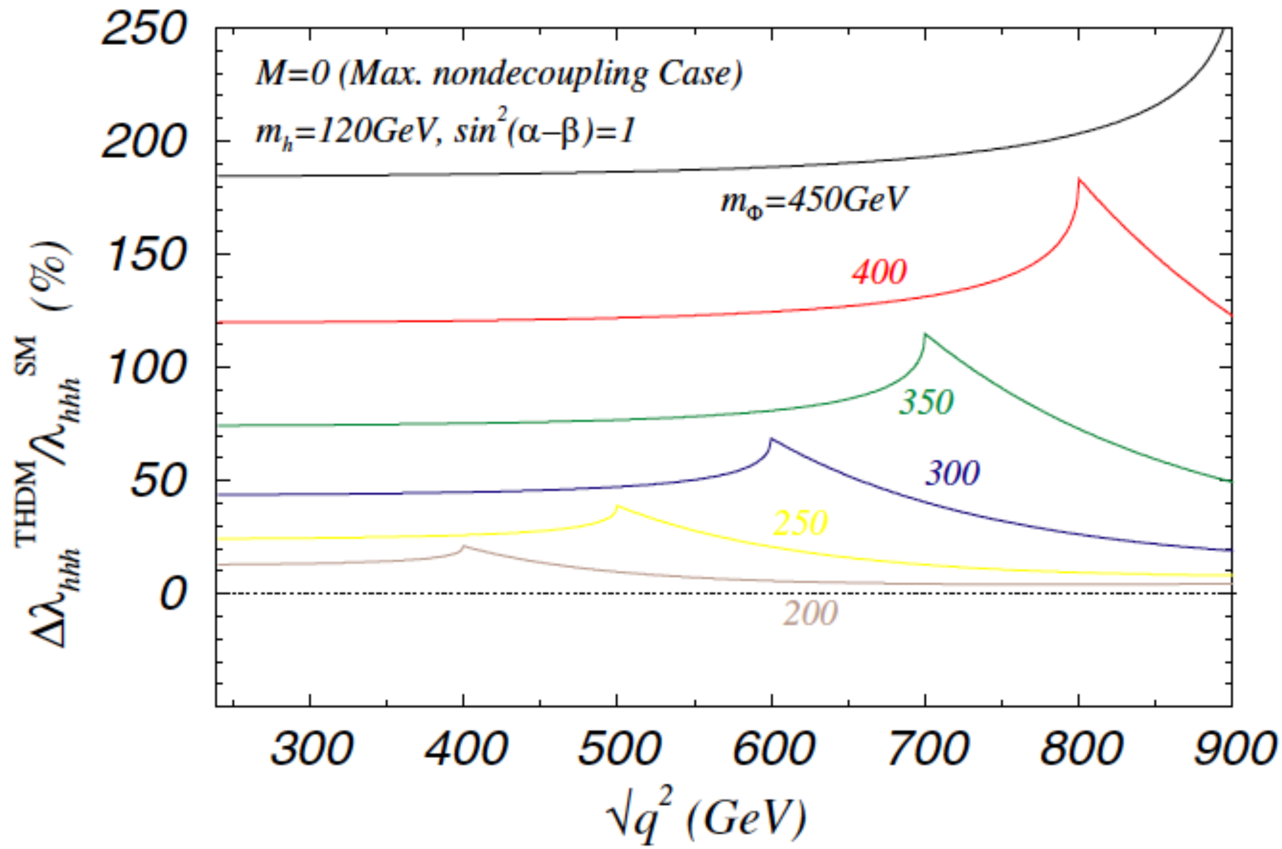


FIG. 4 (color online). The momentum dependence of $(\Delta\lambda_{hhh}^{\rm THDM}/\lambda_{hhh}^{\rm SM})$ is shown, where $\sqrt{q^2}$ is the invariant mass of h^* in $h^* \to hh$, for each value of m_Φ ($\equiv m_H = m_A = m_{H^\pm}$) when $m_h = 120$ GeV, $\sin(\alpha - \beta) = -1$, and $M = 0$.