Higgs self-couplings for extended Higgs sectors

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Beyond the SM

SM is a good description of the nature around the EW scale, however ….

Problems

- **Gravity**
- **Unification**
- **Flavor**
- **No principle in the Higgs sector**
- **Beyond SM phenomena**
  - **Neutrino oscillation**
  - **Dark matter**
  - **Baryon asymmetry**
  - **…**

SM must be replaced by a more fundamental theory

Higgs sector is the key

Although the Higgs boson was found, the Higgs sector remains unknown

Elementary or composite?
Multiplet Structure?
Higgs potential (Dynamics of EWSB, EWPT, …)
Yukawa structure (Flavor Physics, CPV, …)

Higgs sector:
no principle

The SM Higgs sector can be modified

⇨ BSM phenomena may be explained

Tiny neutrino mass
Phase Transition (1st Order)
CPV sources for baryogenesis
DM candidates
…

Testable at future collider experiments

Higgs sector is an important probe of new physics

Extended Higgs sectors?

Multiplet Structure (with additional scalars)

Φ_{SM} + Isospin Singlet,

Φ_{SM} + Doublet (2HDM),

Φ_{SM} + Triplet,

…

Additional Symmetry

Discrete or Continuous?

Exact or Approximate or Softly broken?

Interaction

Weakly coupled or Strongly Coupled?

Hint for BSM models

Simple example: 2HDM (softly-broken Z_2)

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

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

Φ_1 and Φ_2 $\Rightarrow$ $\underbrace{h, \quad H,}_{\uparrow}$ $\quad A^0, \; H^\pm \oplus$ Goldstone bosons

$\uparrow$ CPeven $\quad \uparrow$ CPodd $\quad \uparrow$charged

Diagonalization

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

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

masses

$$m_h^2 = v^2 \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2} \sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$
$$m_H^2 = M_{\text{soft}}^2 + v^2 (\lambda_1 + \lambda_2 - 2\lambda) \sin^2\beta \cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$
$$m_{H^\pm}^2 = M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2} v^2,$$
$$m_A^2 = M_{\text{soft}}^2 - \lambda_5 v^2.$$

M_{soft}: soft breaking scale

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

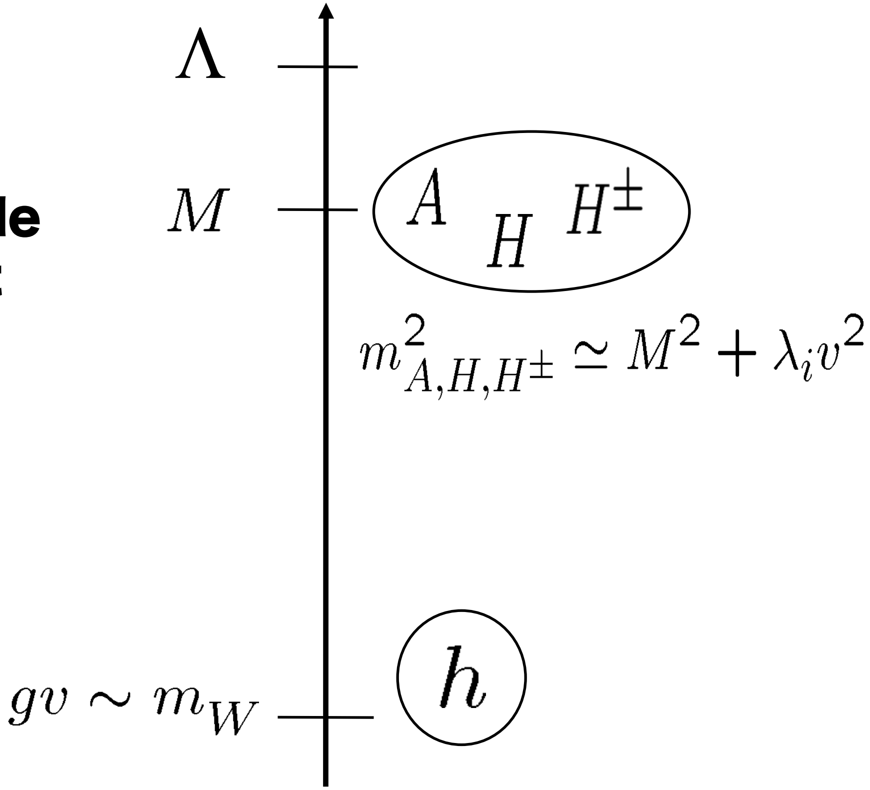
$$M_{\text{soft}} \;\left(= \frac{m_3}{\sqrt{\cos\beta \sin\beta}}\right):$$

soft-breaking scale
of the discrete symm.

Two Possibilities satisfying current data

Λ : **Cutoff**

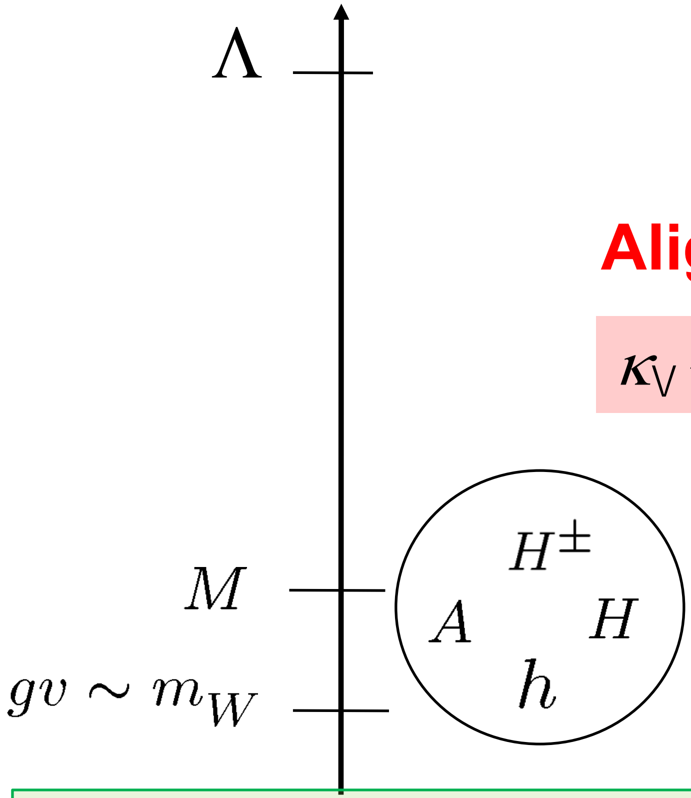
M : **Mass scale irrelevant to VEV**



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

Effective Theory is the SM

Decoupling



Alignment

$\kappa_V \sim 1$

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

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

Effective Theory is an extended Higgs sector

Alignment without decoupling

Small deviation ($\kappa_V \neq 1$) = New Scale

No-Lose Theorem Lee, Quigg, Thacker 1977

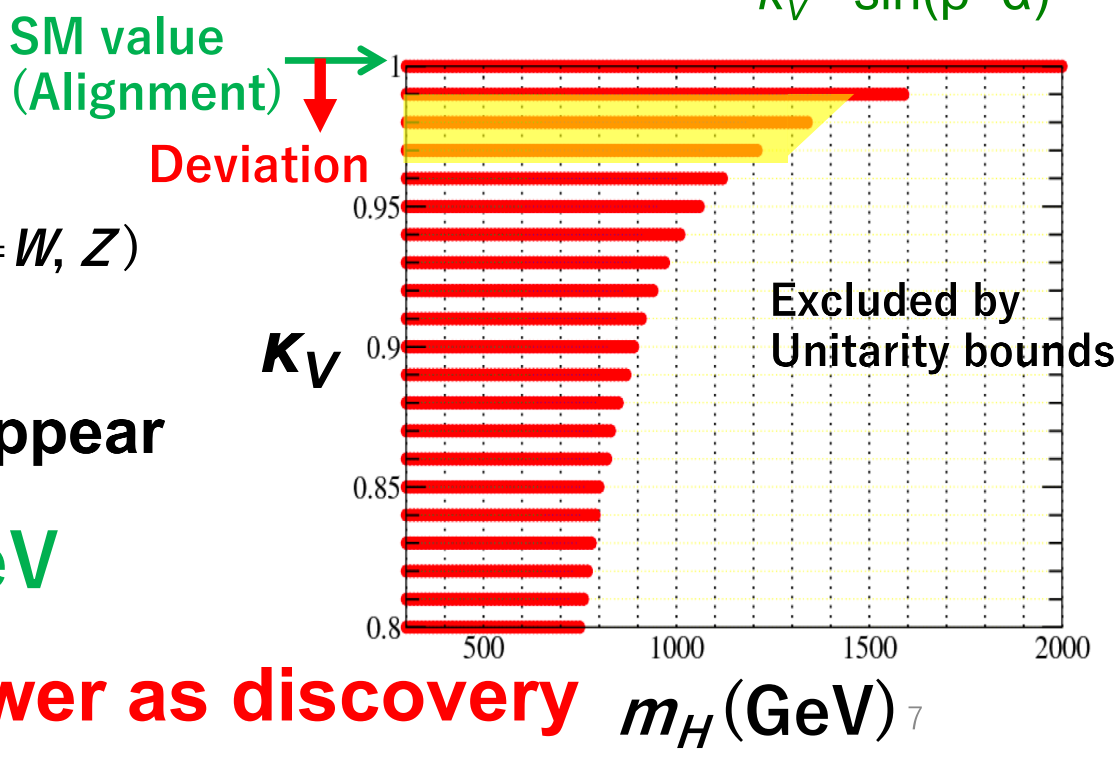
Unitarity: Higgs boson must appear below 1 TeV,
Otherwise, new physics must appear below 1TeV

Motivation to build SSC, LHC
Lead to Higgs discovery at LHC!
m_h=125 GeV

New No-Lose Theorem

hVV coupling ($V=W, Z$)

κ_V =sin(β−α)



Unitarity: If deviations in Higgs couplings,
the second Higgs *H* or new physics must appear

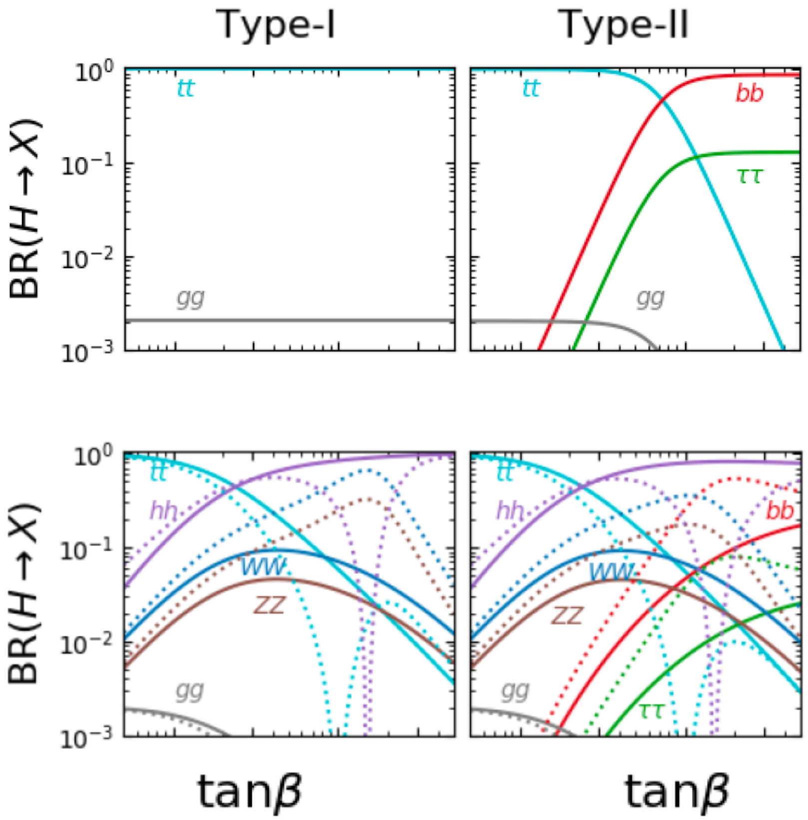
$$\Delta\kappa_V = 2\,\% \quad \rightleftarrows \quad m_H < 1.4\text{ TeV}$$

Higgs precision test has the same power as discovery

Regions of alignment without decoupling

HL-LHC and the Higgs Factory (CEPC) can explore cases of $\kappa \neq 1$ but not the case of $\kappa = 1$

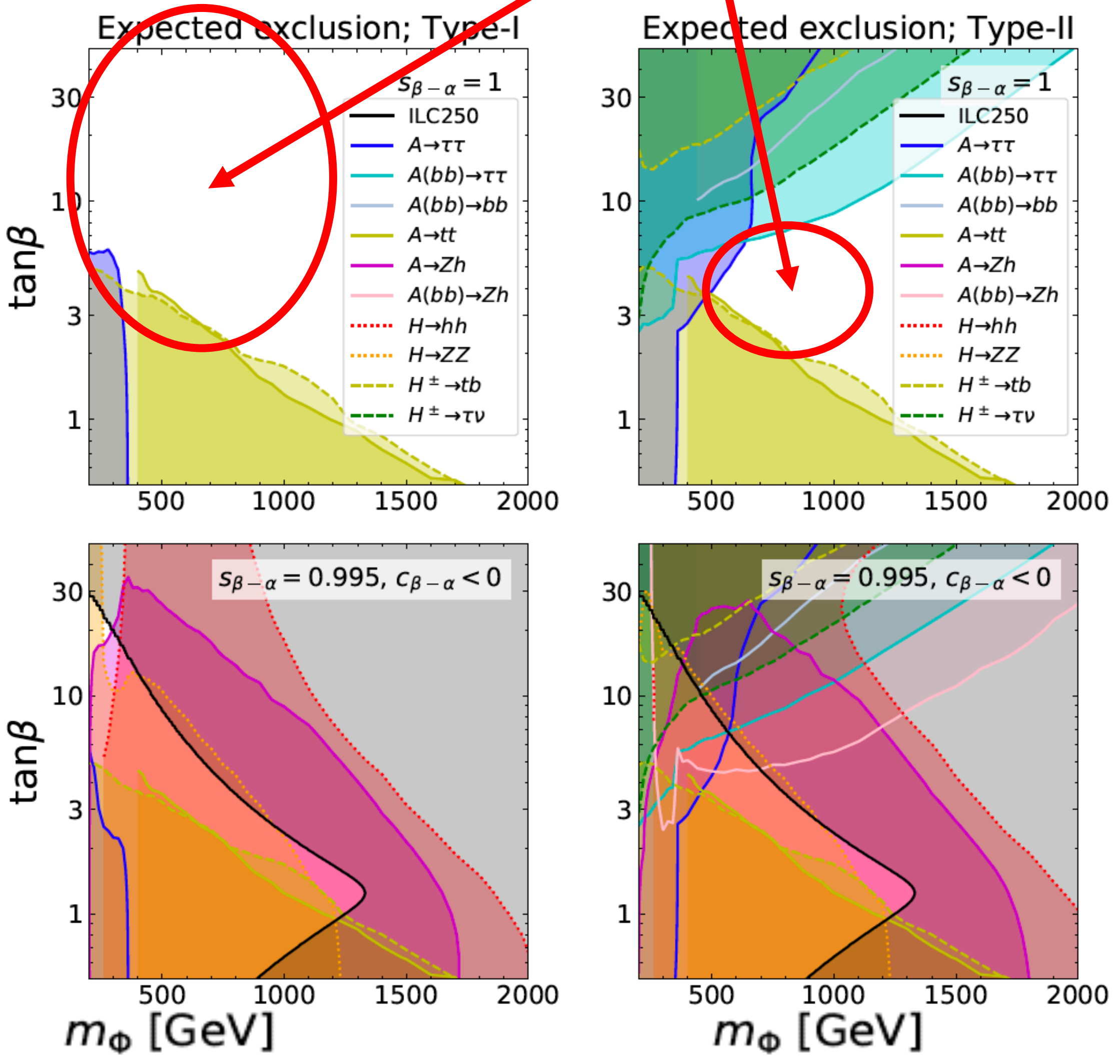
Near and exact are drastically different



$K_V = 1$
Alignment

$K_V = 0.995$
Near alignment

Higgs to Higgs decays become important



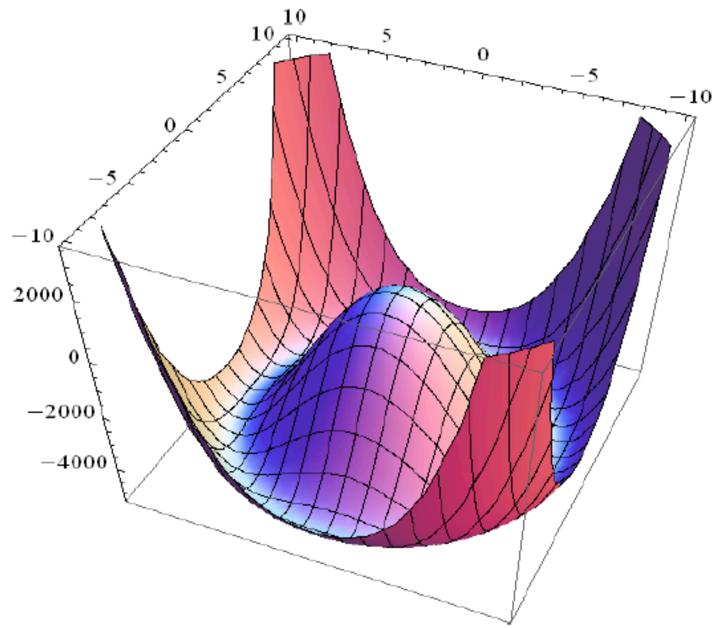
Region of alignment without decoupling can be explored by higher energy e+e- collisions, and also by the *hhh* measurement

For near alighment cases, all the parameter regions are excluded by 95%CL

Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu, 2020

Higgs Potential

Dynamics of EWSB $SU(2)_I \times U(1)_Y \rightarrow U(1)_{\rm em}$

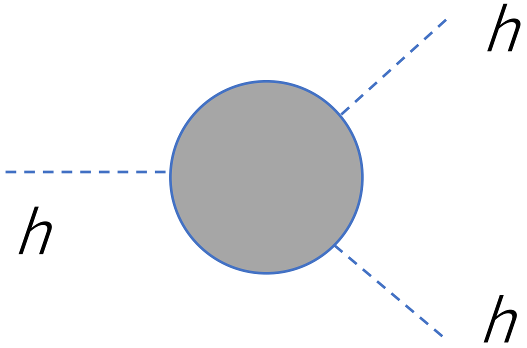


It is very important to know the *hhh* coupling to reconstruct the Higgs potential

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

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

Top loop effect in the SM



Non-decoupling effect

EWSB by Coleman Weinberg Mechanism： ~ 70%

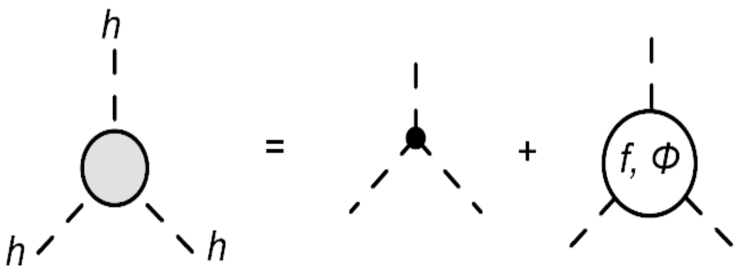
EW Baryogenesis (1st Order Phase Trasition)： > 22% 2HDM

> 60% EFT (dim6)

Sensitive to the new physics scenario! **The *hhh* measurement is crucial**

The hhh coupling in extended Higgs sectors

$$\lambda_{hhh}^{2\mathrm{HDM}} \simeq \frac{3m_h^2}{v}\left[1+\underbrace{\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3}_{\text{Extra scalar loop}}-\underbrace{\frac{m_t^4}{\pi^2 v^2 m_h^2}}_{\text{Top loop}}\right]$$



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

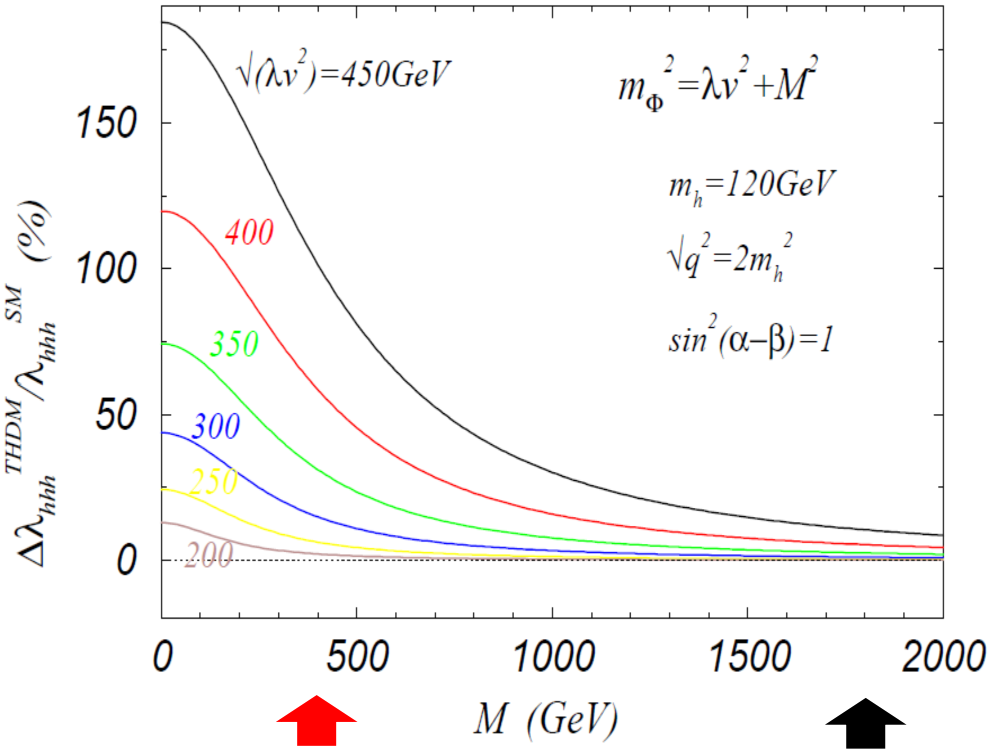
Mass of extra Higgs bosons

$$m_\Phi^2 = M^2 + \lambda_i v^2 \quad (\Phi = H, A, H^\pm)$$

- Consider the case: *h* is SM-like
- At 1-loop, powerlike effect m_Φ^4

Deviation can be very large
～ 100% (NLO)
under constraint from unitarity bounds etc

SK, Kiyoura, Okada, Senaha, Yuan, 2003



Non-decoupling effect

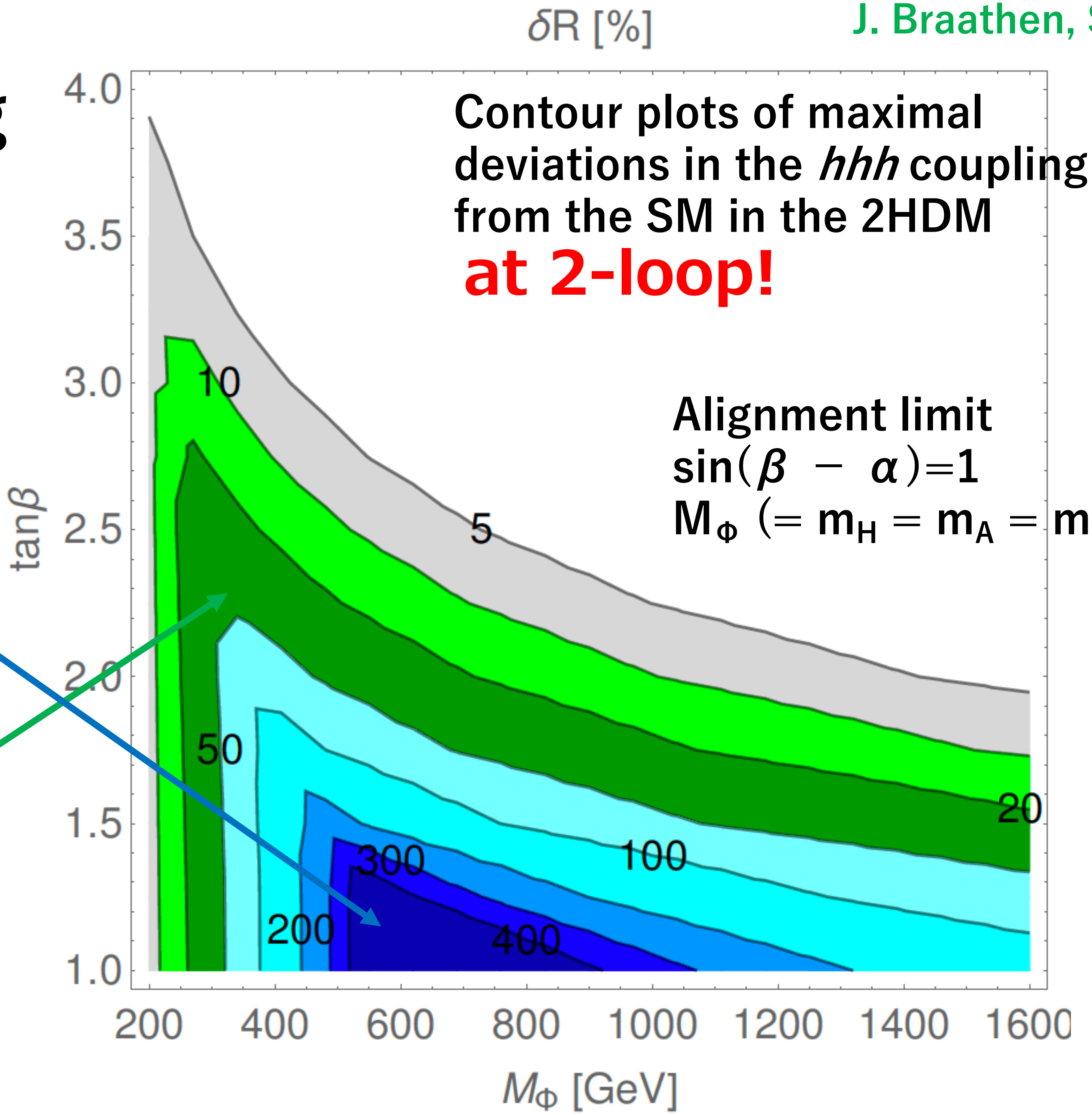
Decoupling

Possible deviation in the *hhh* coupling

J. Braathen, SK (2019)

HL-LHC can test?

ILC1TeV CLIC, HE-LHC, … can test?



Contour plots of maximal deviations in the *hhh* coupling from the SM in the 2HDM **at 2-loop!**

Alignment limit
$\sin(\beta - \alpha)=1$
$M_\Phi\ (= m_H = m_A = m_{H^+})$

1st Order Phase Transition

Electroweak Baryogenesis

Sakharov 3rd condition

Departure from Thermal Equilibrium

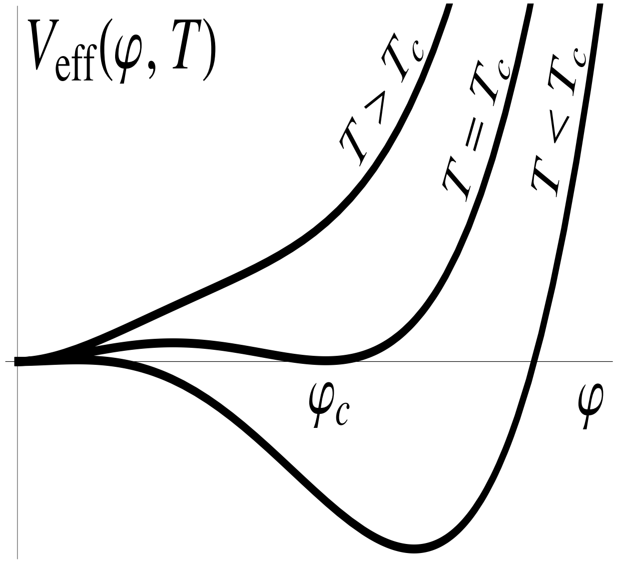
Sphaleron Decoupling condition

$$\boxed{\Gamma_{sph} < H(T_c)}$$

$$\Gamma_{sph} \sim e^{-E_{sph}/T_c} \sim e^{-\alpha' \varphi_c/T_c}$$

$$\Rightarrow \boxed{\frac{\varphi_c}{T_c} \gtrsim 1} \Rightarrow$$

Strong 1st Order Phase Transition



High Temp Exp.

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

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

SM with m_h=125GeV,
1st OPT not realized

1^{st} Order Phase Transition

Extended Higgs: Strongly 1^{st} OPT possible

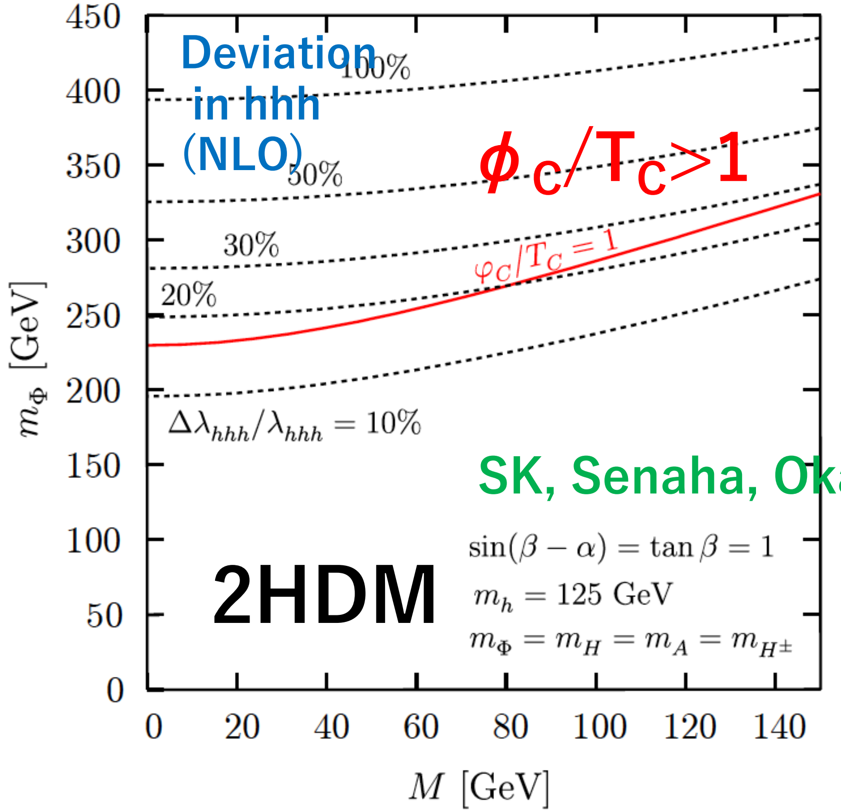
Quantum effect of additional Scalar field Φ (= *H, A, H*$^+$, ⋯)

Realized by Quantum Effect by Φ (= *H, A, H*$^+$, ⋯)

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

Large deviation in the *hhh* coupling

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



SK, Senaha, Okada 2007

The sphaleron decoupling condition can be satisfied when $\Delta\lambda_{hhh} > 22\%$

SK, Tanaka (2020)

ILC can test 1^{st} OPT by measuring the *hhh* coupling

Improvement for the Sphaleron Decoupling Condition

Sphaleron decoupling condition

$$\boxed{v_c/T_c > \zeta_{sph}(T_c)}$$

can be determined

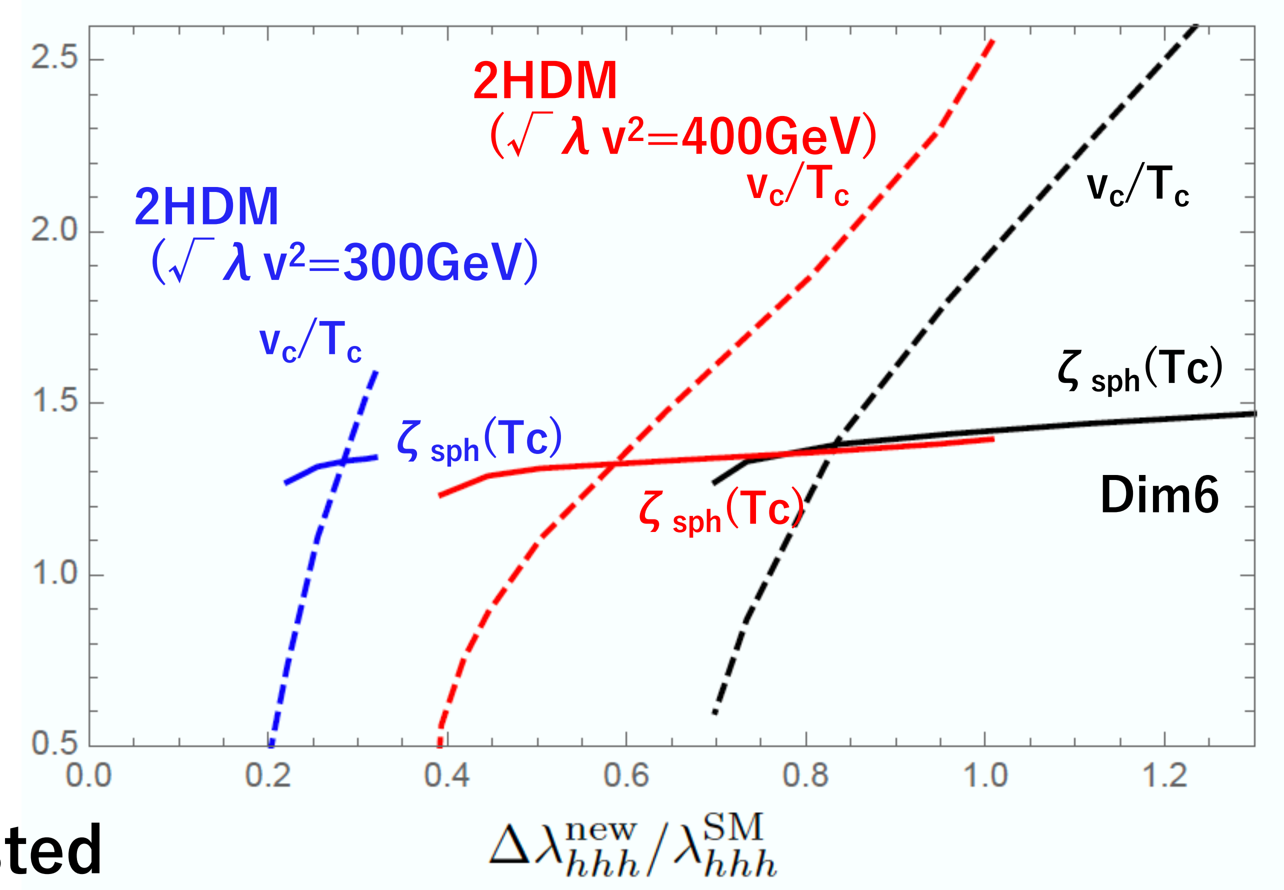
$\Delta\lambda_{hhh} \Rightarrow E_{sph}(0) \Rightarrow E_{sph}(Tc) \Rightarrow \zeta_{sph}(Tc)$

N=4 Scalar Model (2HDM)

The decoupling condition can be satisfied when $\Delta\lambda_{hhh} > 22\%$

SK, M. Tanaka (2020)

Sphaleron decoupling condition at Tc and the hhh coupling at T=0



Consistency of the model can be tested

Future measurement of the hhh coupling

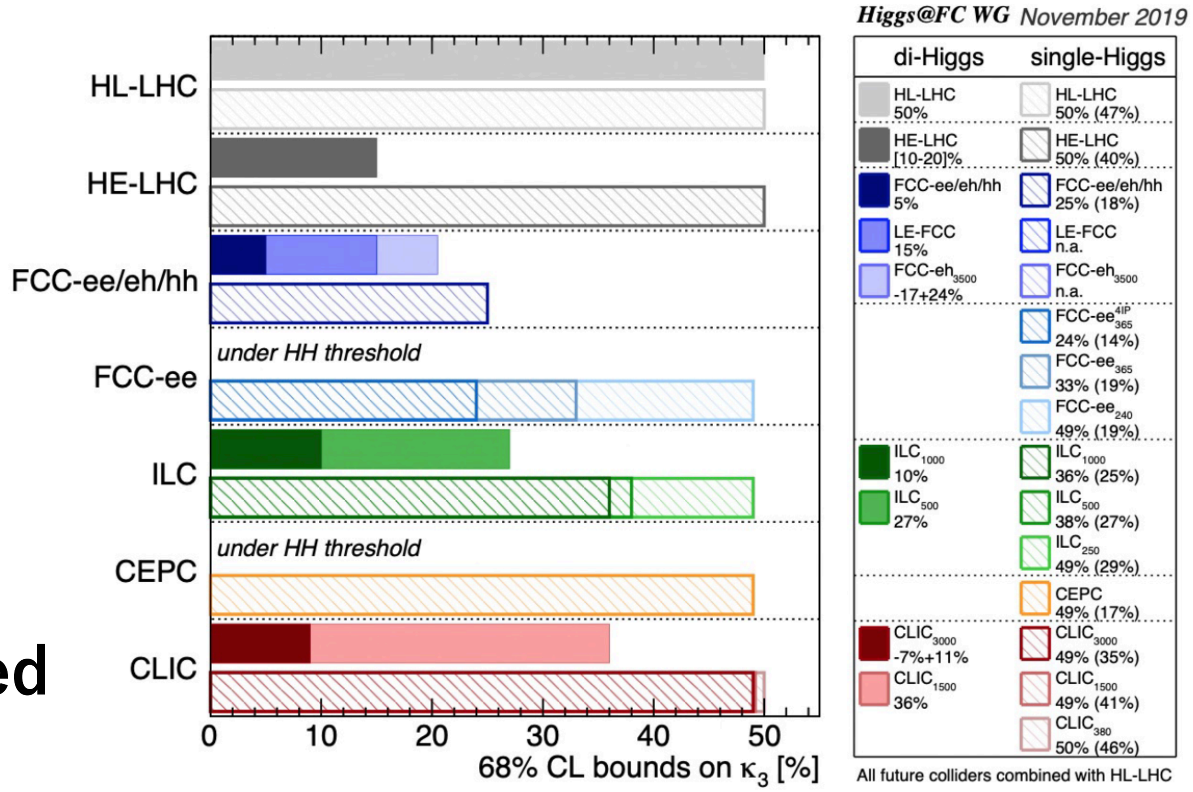
HE-LHC, FCC$_{hh}$, …

$$pp \to hhX$$

ILC500, ILC1000, CLIC, …

$$e^+e^- \to Zhh$$
$$e^+e^- \to \nu\bar{\nu}hh$$

The triple Higgs coupling is expected to be measured with 10% at ILC1000, CLIC3000, FCC$_{hh}$, …



arXiv: 1905.03764

We do not miss to test the 1st order phase transition for EW baryogenesis

Summary

- Higgs sector is a probe of new physics
- Possibilities of Extended Higgs (1^{st} OPT, CPV, SUSY, DM, …)
- HL-LHC and future Higgs factories (ILC250, CEPC, FCCee) can explore cases with near alignment almost completely
- Just decoupling? Or alignment without decoupling? ($\kappa = 1$)
- This is explored by measuring the *hhh* coupling
- Scenarios of the alignment without decoupling (for EW baryogenesis) can be tested by looking whether a large deviation $\Delta\lambda_{hhh}$ is detected or not at FCC_{hh}, ILC1000, CLIC, …

Thank you for your attention!