Decoupling property of SUSY extended Higgs sectors

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S. K., T. Shindou, and K. Yagyu PLB699, 258 (2011)
M. Aoki, S.K., T. Shindou, K. Yagyu, arXiv: 1108.1356
S.K, E. Senaha, T. Shindou, in preparation

Higgs sector and New Physics

- SM has been successful
  - But, yet to be established
  - Higgs sector is unknown

Possibility of a non-minimal Higgs sector

- Physics BSM is necessary
  - Hierarchy problem
  - Dark Matter
  - Neutrino mass
  - Baryon Asymmetry of Universe

We expect new physics BSM at the TeV scale

Higgs sector is the key to new physics

Higgs as a probe of new physics

- In SM, the Higgs boson mass is a free parameter
  - Triviality gives upper bound as a function of Λ
- Data indicate a light SM-like Higgs : mh < 145 GeV
  - LEP precision data, Tevatron, LHC

- Among new physics models, MSSM predicts a light Higgs:
  - a special 2HDM: h, H, A, H^+, H^-
  - $m_h < m_Z$ (tree), m_h < 120-130 GeV (loop)
  - It can be milder in extended SUSY Higgs sectors (ex NMSSM)

- When a *h* is found in near future, its mass, couplings and spin are thoroughly measured at experiments.
- We may be able to discriminate models (SM, 2HDM, MSSM, NMSSM, ….) from these information, even if additional bosons are not found.

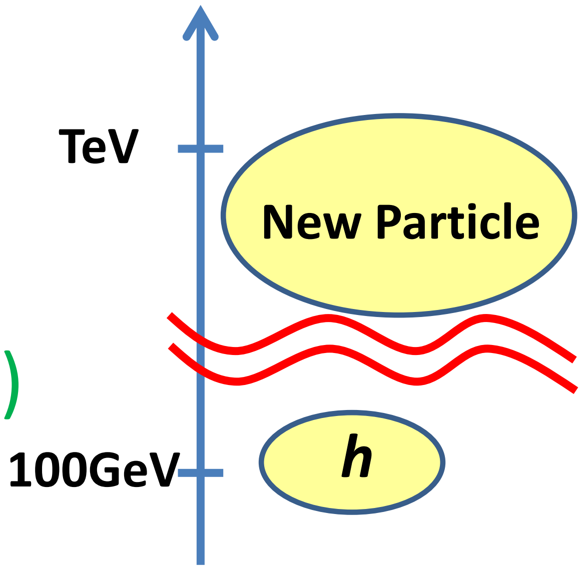
Decoupling/Non-decoupling

- Decoupling Theorem

  Appelquist-Carazzone 1975

  New phys. loop effect in observables

  $1/M^n \rightarrow 0$ (decouple for $M \rightarrow \infty$)



- Violation of the decoupling theorem
  - Chiral fermion loop (ex. Top, 4th gen.)

    $m_f = y_f v$

  - Boson loop (ex. H^+ in non-SUSY 2HDM)

    $m_\phi^2 = \lambda_i v^2 + M^2$ (when $\lambda v^2 > M^2$)

Non-decoupling effect

Higgs potential

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

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

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

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

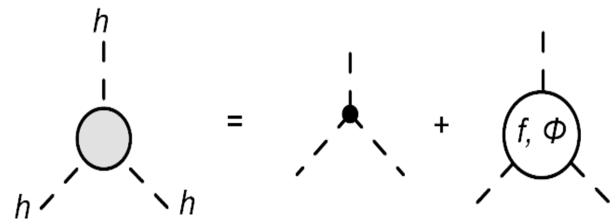
SM Case

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

Non-decoupling effect

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)

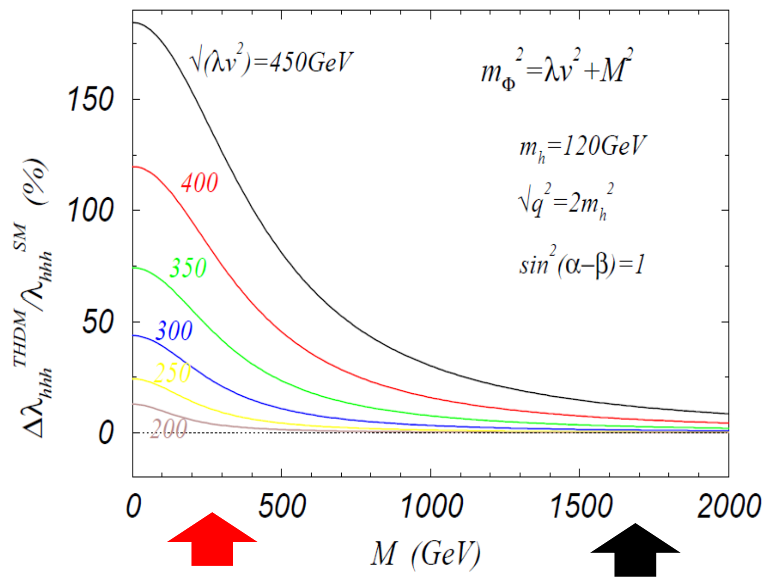
$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3-\frac{m_t^4}{\pi^2 v^2 m_h^2}\right]$$

Extra scalar loop **Top loop**

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

(Φ = *H, A, H*$^\pm$)

Correction can be huge ∼ 100%



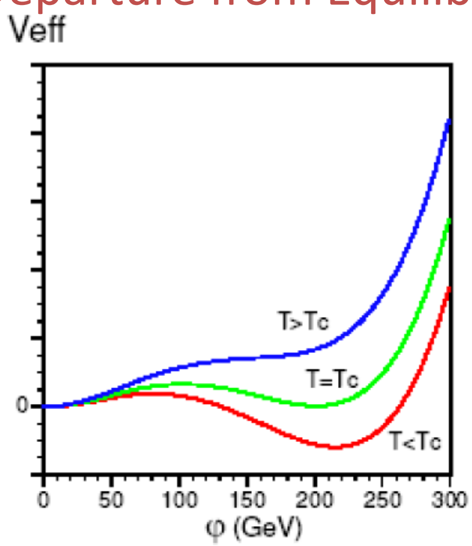
Non-decoupling effect

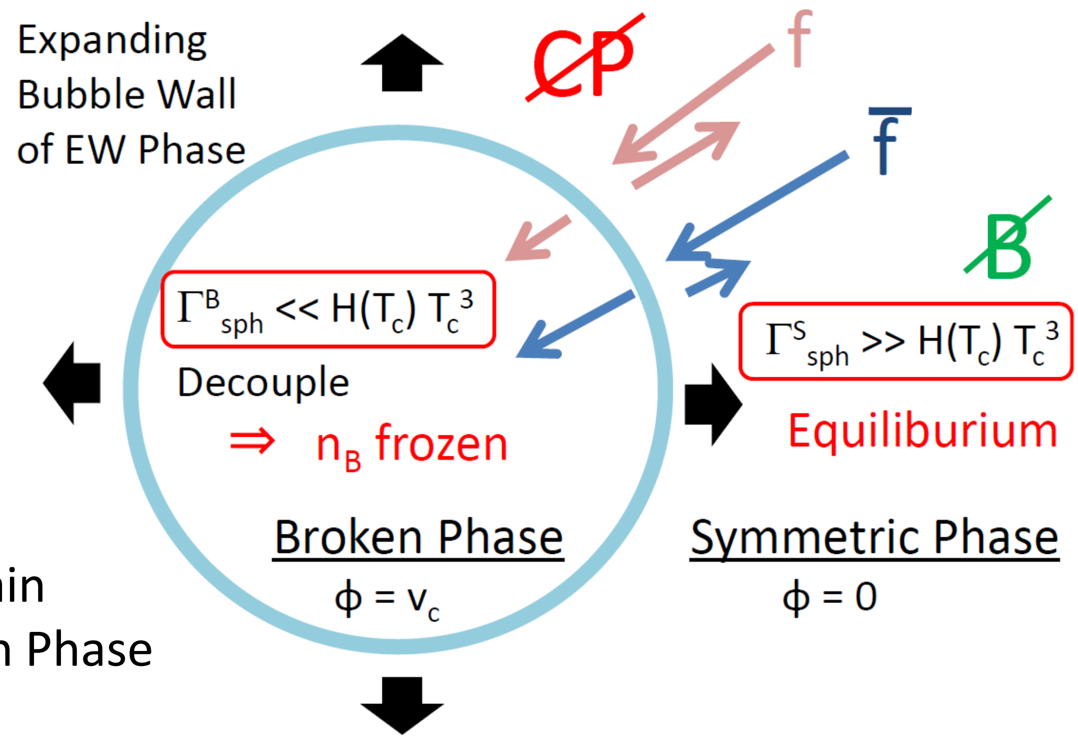
Decoupling

Large deviation in the *hhh* coupling:
= implication to EW Baryogenesis =

Sakharov's conditions:

- B Violation → Sphaleron transition at high *T*
- C and CP Violation → CP Phases in extended scalar sector
- Departure from Equilibrium → 1^{st} Order EW Phase Transition





Quick sphaleron decoupling to retain sufficient baryon number in Broken Phase

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

EW baryogenesis and the *hhh* coupling

Finite temperature potenital

$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots..$$

$$\phi_c/T_c = 2E/\lambda_{T_c}$$

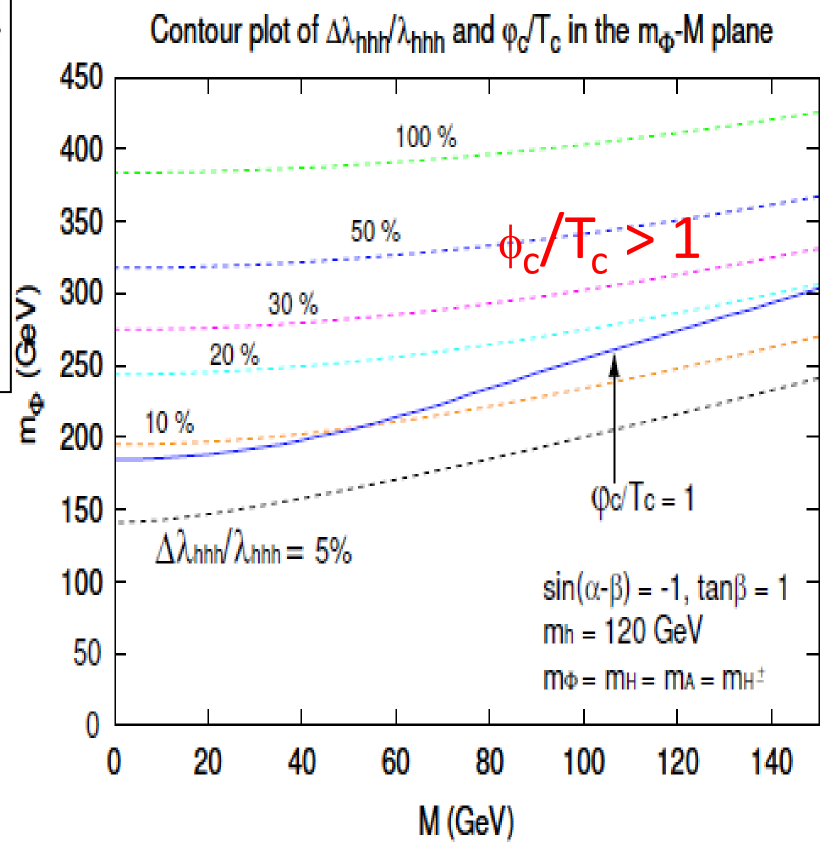
$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$ + New Phys. Effect

$$\lambda_T = m_h^2/2v^2 + \text{log corrections}$$

$$\boxed{\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1}$$

SM: $m_h < 60\text{GeV}$ Excluded by LEP

2HDM: $m_h = 120\text{GeV}$ Possible due to non-decoupling effect



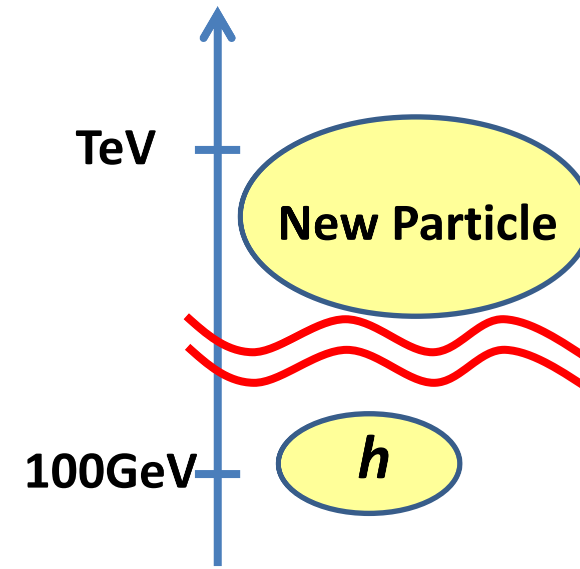
SK, Okada, Senaha (2005)

Strong 1st OPT ⇔ Large *hhh* coupling

In this talk

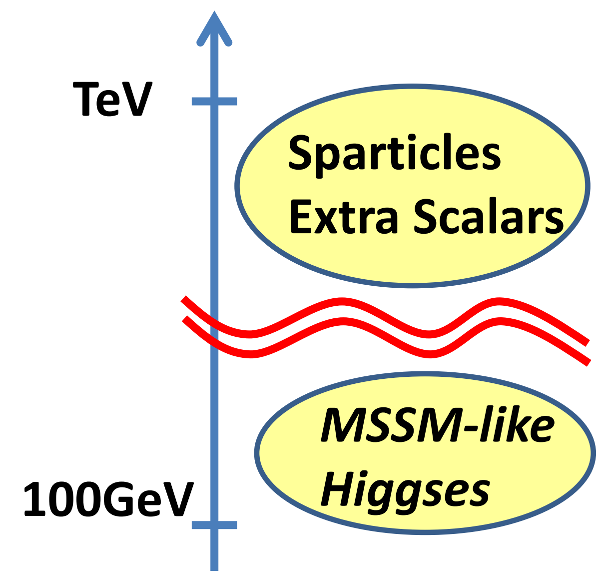
We discuss decoupling property of various extended SUSY Higgs sectors

MSSM
MSSM+singlet (NMSSM)
MSSM+triplets
4HDM
4HDM+charged singlets



Especially, we consider the situation where SUSY particles are heavy and decouple, and study the deviation from SM or MSSM predictions on

- The lightest Higgs boson mass m_h
- The hhh coupling
- Other MSSM observables such as m_{H+} and $\sin(\beta-\alpha)$.



What is the difference from MSSM in extended SUSY Higgs sectors?

1. MSSM: only D term [+ (F-term top Yukawa at loop)] determines m_h, *hhh* etc.

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta m_{\rm loop}^2$$

2. General SUSY Higgs sector (F-term exists)

$V_{int} = |D|^2 + |F|^2 +$ Soft-breaking

F-term contributions: appear with additional singlets, triplets

$W = \lambda \quad H_u.H_d\, \varphi$

Large non-decoupling effects appear in MSSM observables via F-term

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + (\lambda_{HHS}^2 v^2/2) \sin^2 2\beta + \delta m_{\rm loop}^2$$

3. Model with only multi-doublets (MSSM + H_u', H_d', …)

No F-term (no trilinear *HHH* term in Superpotential) except for μ terms

These models can decouple to MSSM when Hu', Hd' are heavy

Only the D-term as well as Soft-breaking terms provide new effects

M. Aoki, S.K., T. Shindou, K. Yagyu, arXiv: 1108.1356

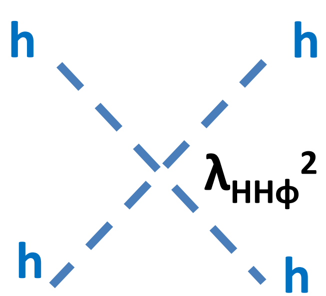
F-term contributions

NMSSM (MSSM+S), and MSSM+χ

Chiral Superfield: **S (singlet), χ (triplet)**
which generate F-term interaciton

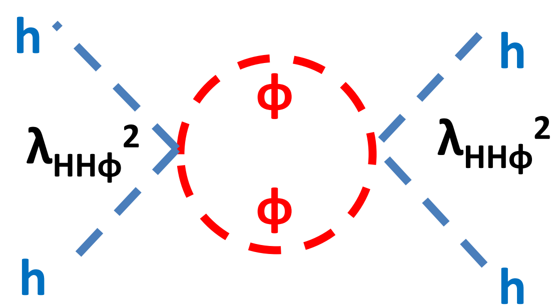
$$\boxed{W = \lambda_{HH\phi}\ H_u H_d\ \phi \qquad (\phi = S \text{ or } \chi\,)}$$

$$V_F = \lambda_{HH\phi}{}^2\ |H_u H_d|^2 + \lambda_{HH\phi}{}^2\ |H_u\, \phi|^2 + \lambda_{HH\phi}{}^2\ |H_d\, \phi|^2$$



Tree level
Contribution
To the mass

One-loop
Contribution to
The *hhh* coupling



Next-to-MSSM （NMSSM）

Two Higgs doublets H_u, H_d and a singlet S

$$\boxed{W = \lambda_{HHS} H_u . H_d S - \kappa S^3}$$

Mass of the lightest h in the NMSSM

$$m_h^2 \simeq \underbrace{m_Z^2 \cos^2 2\beta}_{\text{D-term}} + \underbrace{(\lambda_{HHS}^2 v^2/2) \sin^2 2\beta}_{\text{F-term}} + \delta m_{\rm loop}^2$$

Ellwanger;
Kane, Kolda, Wells
………

What is the size of λ_{HHS}?

RGE analysis with a cut-off scale Λ

Cut-off Λ : GUT scale	→ λ_{HHS} ~ 0.75	(m_h~ 140 GeV)
Cut-off Λ : TeV scale	→ λ_{HHS} ~ 2.5	(m_h~ 450 GeV)

Fat Higgs model

Harnik, Kribs, Larson, Murayama

Composite H_1, H_2, N

A UV complete theory

At low energy, a strong NMSSM

$$W = \lambda(NH_1H_2 - v_0^2)$$

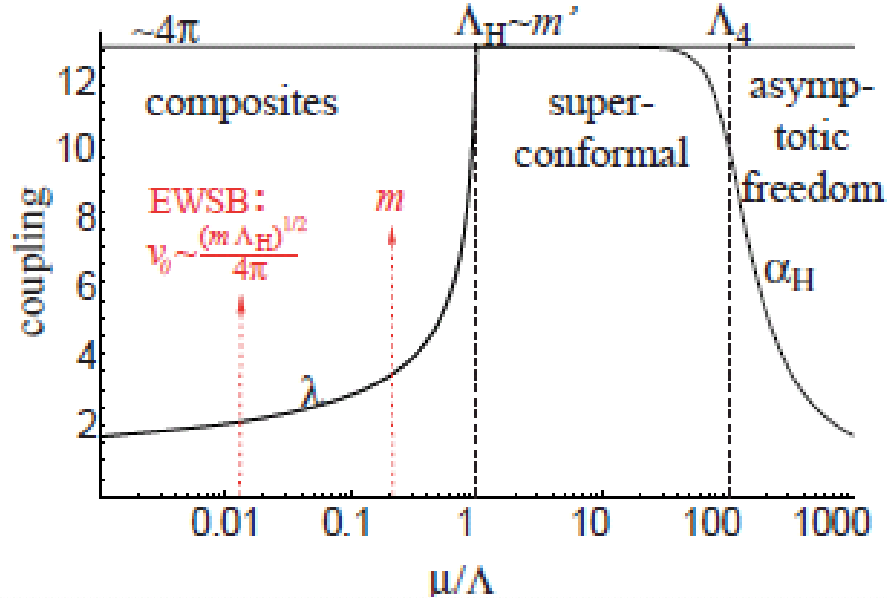
The SM-like Higgs can be heavy

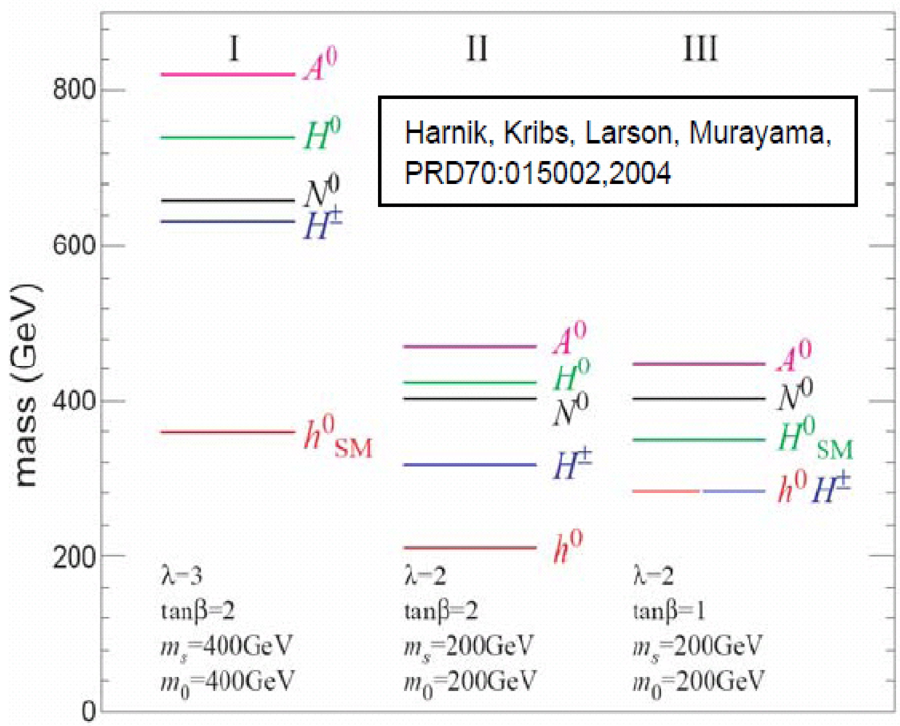
$$m_h^2 \simeq \lambda^2 v^2 + \mathcal{O}(m_Z^2)$$

$$M_{H^\pm}^2 = M_A^2 - \lambda^2 v^2$$

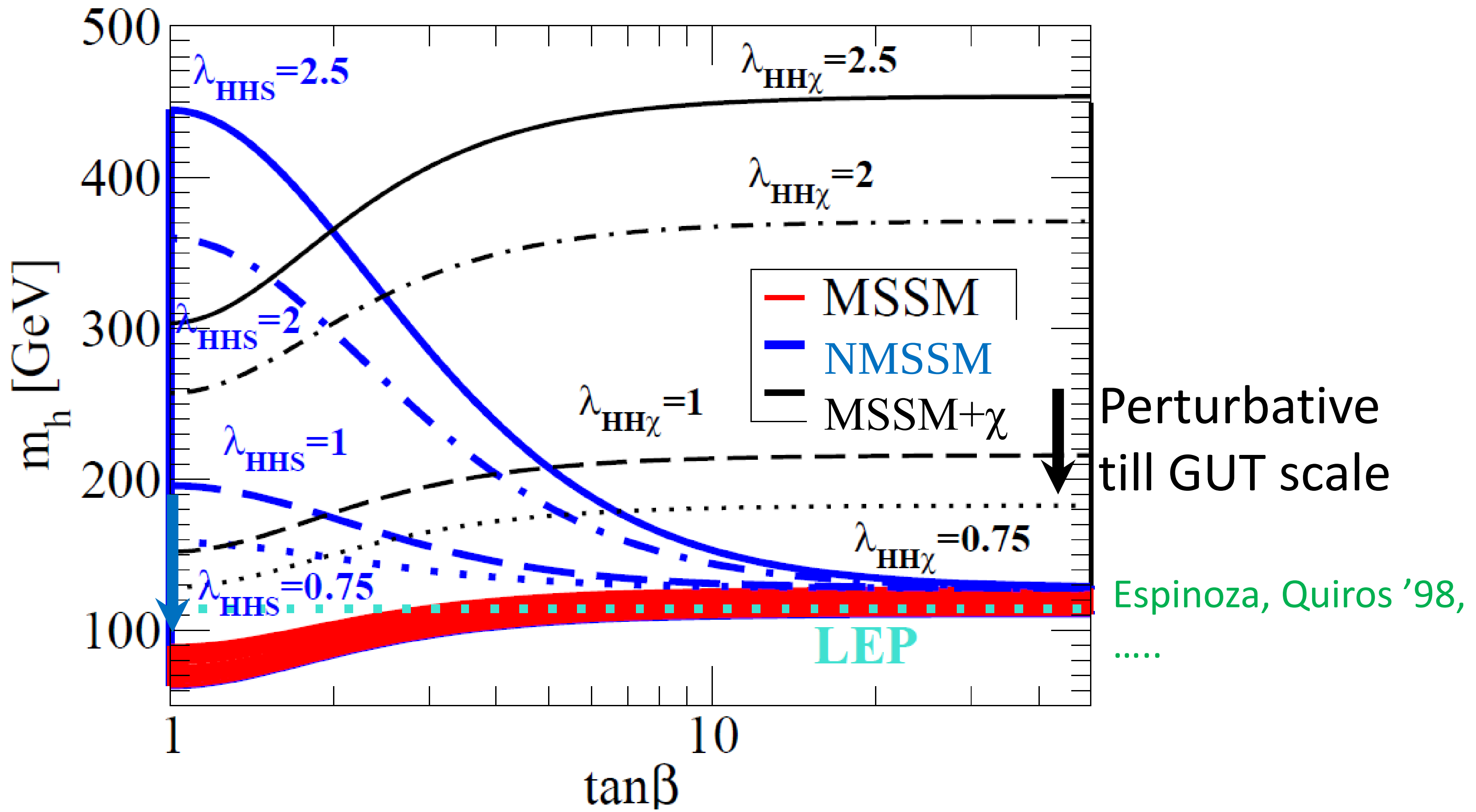
λ can be of O(1)

$\Leftrightarrow$ $m_h > 200$ GeV





Upper limit on m_h as a function of tanβ



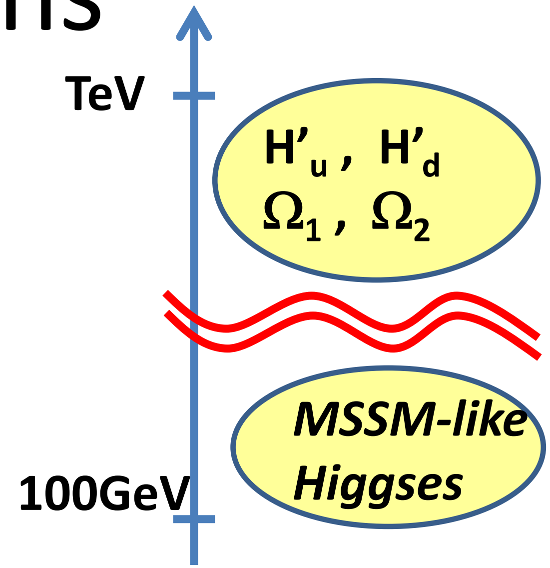
NMSSM (singlet)

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \delta_{\rm loop} + \frac{v^2}{2}\lambda_{HHS}^2 \sin^2 2\beta$$

MSSM+χ (triplet)

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \delta_{\rm loop} + \frac{v^2}{2}\lambda_{HH\chi}^2 (\sin^4 \beta + \cos^4 \beta)$$

F-term contributions



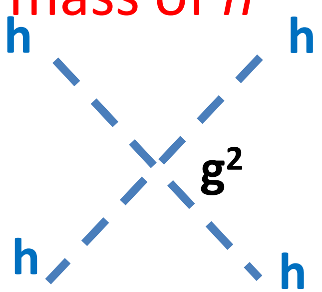
$\boxed{\text{4HDM} + \text{charged singlets } \Omega_{1,2}}$

$H'_{u,d}$: extra doublets, $\Omega_{1,2}$: charged singlets

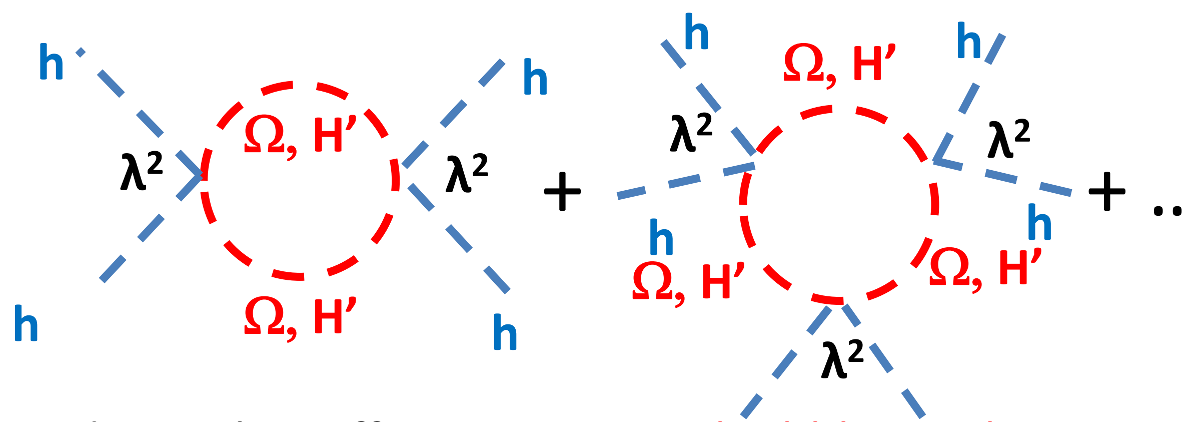
$$\boxed{W = \lambda_1 \; H_u H_u' \Omega_1 + \lambda_2 \; H_d H_d' \Omega_2}$$

$$V_F = \lambda_1{}^2 \; |H_u H_u'|^2 + \lambda_1{}^2 \; |H_u \Omega_1|^2 + \lambda_1^2 \; |H_u H_u'|^2$$
$$+\lambda_2{}^2 \; |H_d H_d'|^2 + \lambda_2{}^2 \; |H_d \Omega_2|^2 + \lambda_2{}^2 \; |H_d \; H_d'|^2$$

No tree level contribution to the mass of *h*



One-loop contribution

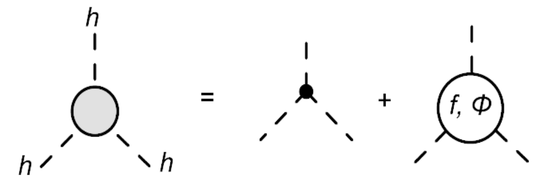


Nondecoupling effect appears in the hhh coupling after renormalization

The triple Higgs boson coupling

MSSM

Decouple!



$$\lambda_{hhh}^{\rm MSSM} \simeq \frac{3m_h^2}{v}\left[1-\frac{m_t^4}{\pi^2 v^2 m_h^2}\left\{1-\frac{m_t^2(m_{\tilde{t}_1}^2+m_{\tilde{t}_2}^2)}{2m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right\}\right]$$

NMSSM

Non-Decoupling effect!

$$m_{S_c}^2 \simeq M_{S_c}^2 + \frac{\lambda_{HHS}^2}{2}v^2$$

$$\boxed{\lambda_{hhh}^{\rm NMSSM} \simeq \frac{3m_h^2}{v}\left[1+\sum_{c=1}^{2}\frac{m_{S_c}^4}{12\pi^2 v^2 m_h^2}\left(1-\frac{M_{S_c}^2}{m_{S_c}^2}\right)^3\right]}$$

Non-decoupling when

$$M_{S_c}^2 \lesssim \frac{\lambda_{HHS}^2}{2}v^2$$

Large tanβ ⇒ Small m_h ⇒ Large hhh deviation

Small tanβ ⇒ Large m_h ⇒ Small hhh deviation

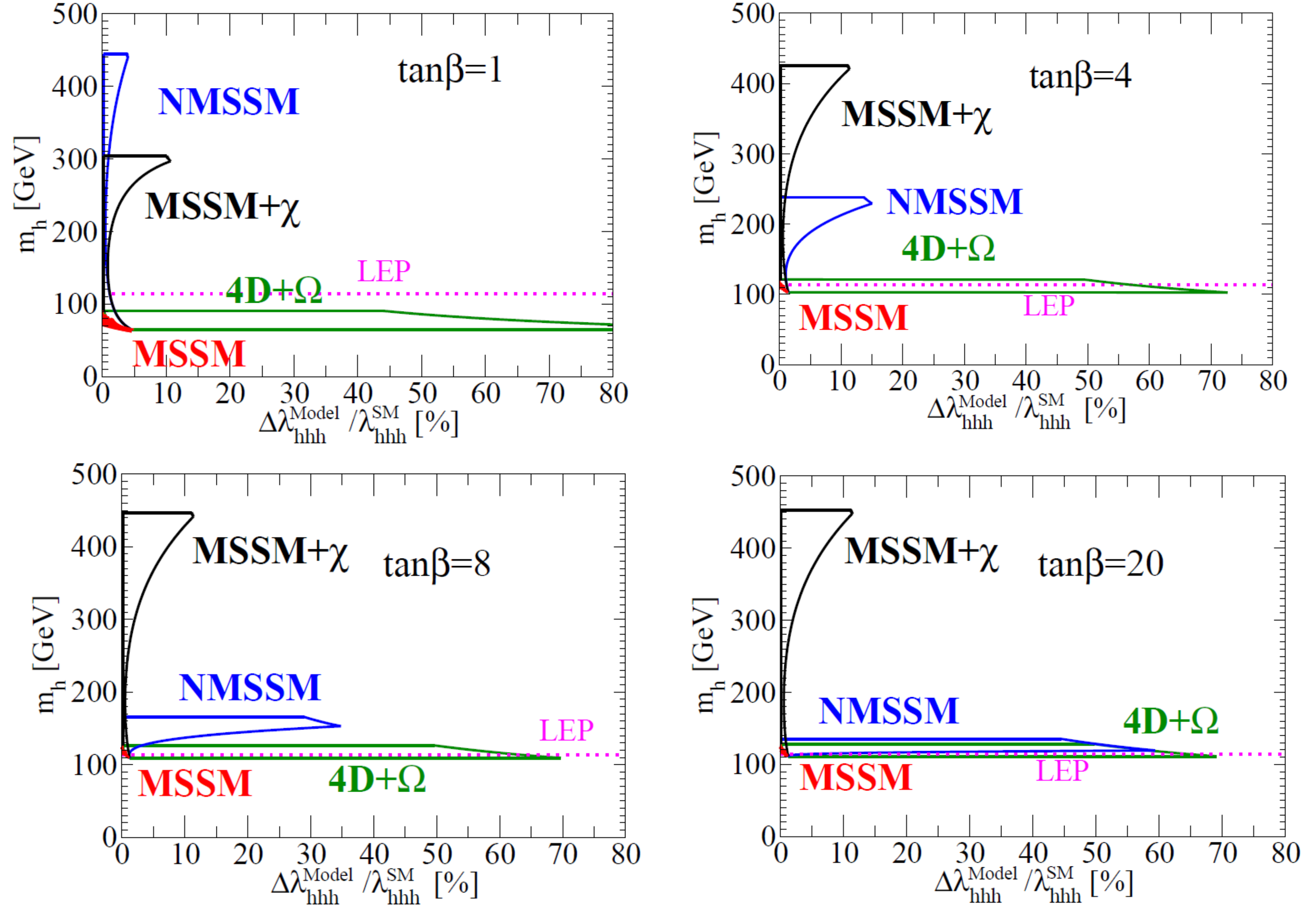
4HDM＋charged singlets

m_h determined by D-term

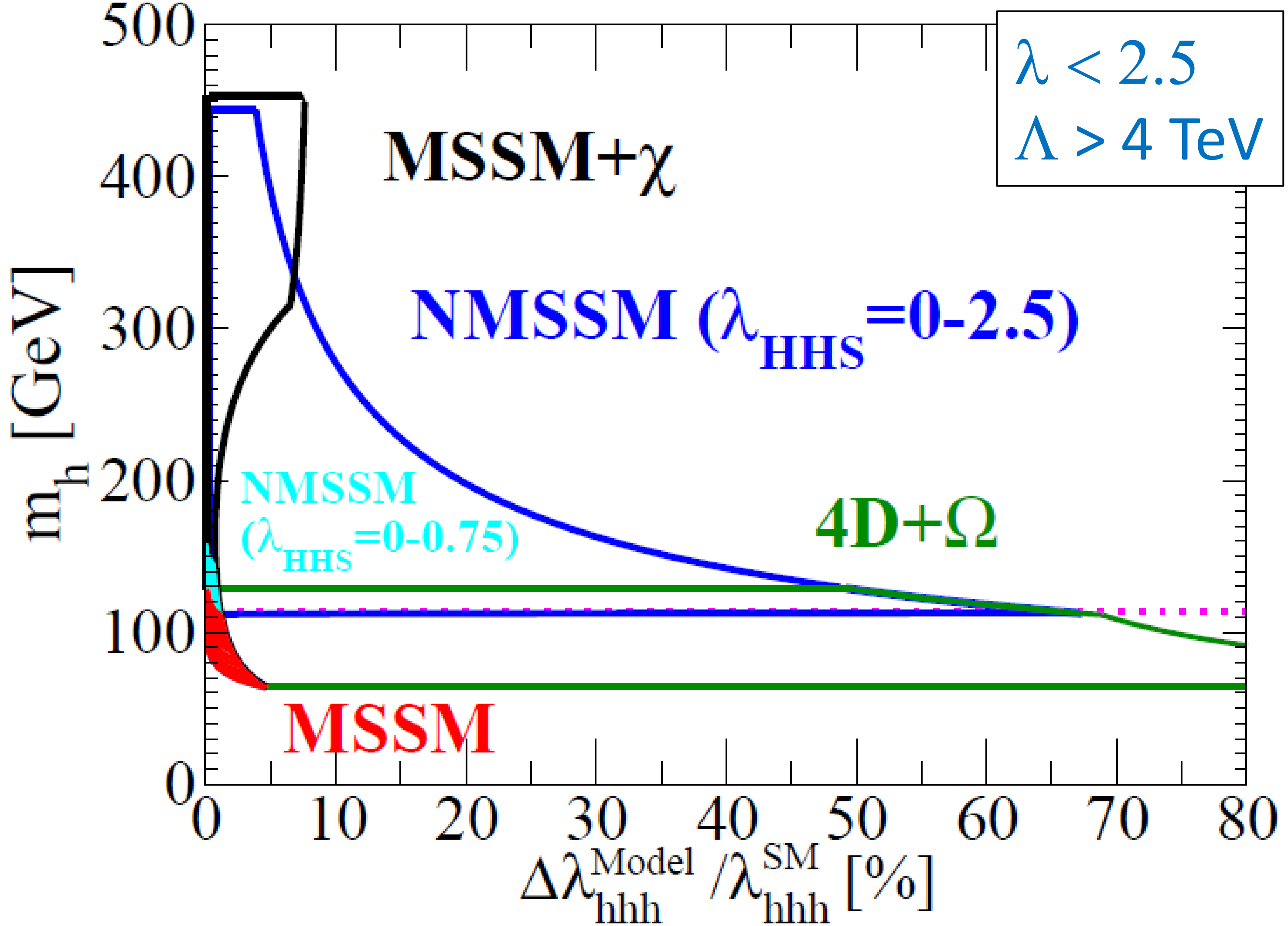
F-terms only contribute to hhh ⇒ Large hhh deviation

m_h-$\Delta\lambda_{hhh}$ plot for each $\tan\beta$

$\lambda < 2.5$
$\Lambda > 4$ TeV



m_h-$\Delta\lambda_{hhh}$ plot (tanβ = 1-50)



EW Phase Transition in 4HDM+Ω

S.K., E. Senaha, T. Shindou in preparation

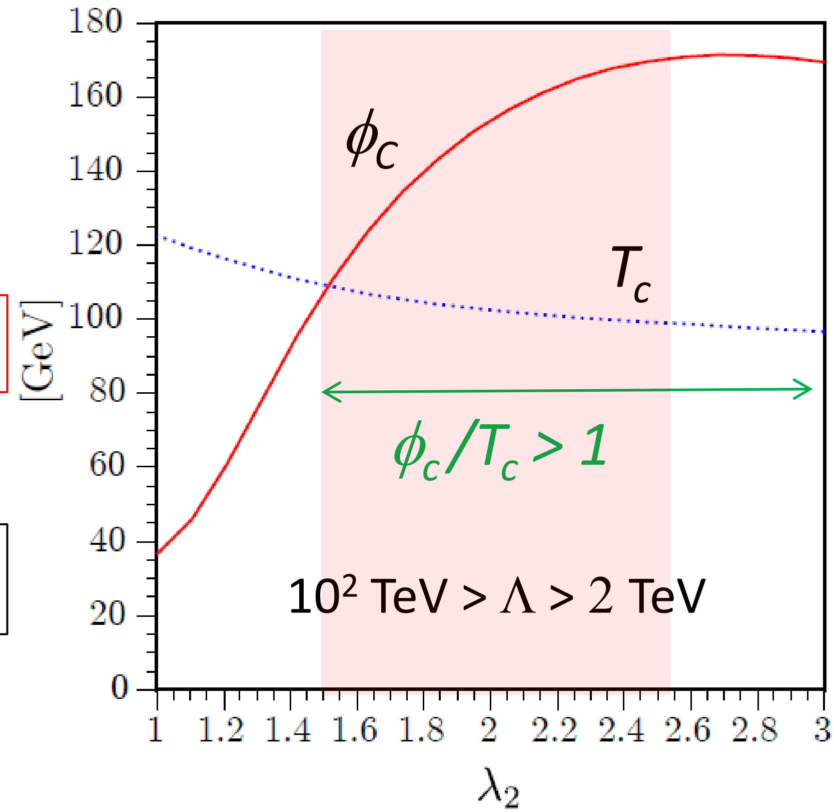
EW baryogenesis in SUSY models

MSSM, MSSM+U(1), NMSSM,..

Large *hhh* coupling ⇔ Strong 1st OPT

3) 4HDM+Ω NEW!

$$W = \lambda_1 \; H_u H_u' \Omega_1 + \lambda_2 \; H_d H_d' \Omega_2$$



4HDM+Ω is a new viable model which can give the strong 1st OPT easily.

(2 TeV < Λ_{cutoff} < 10^2 TeV)

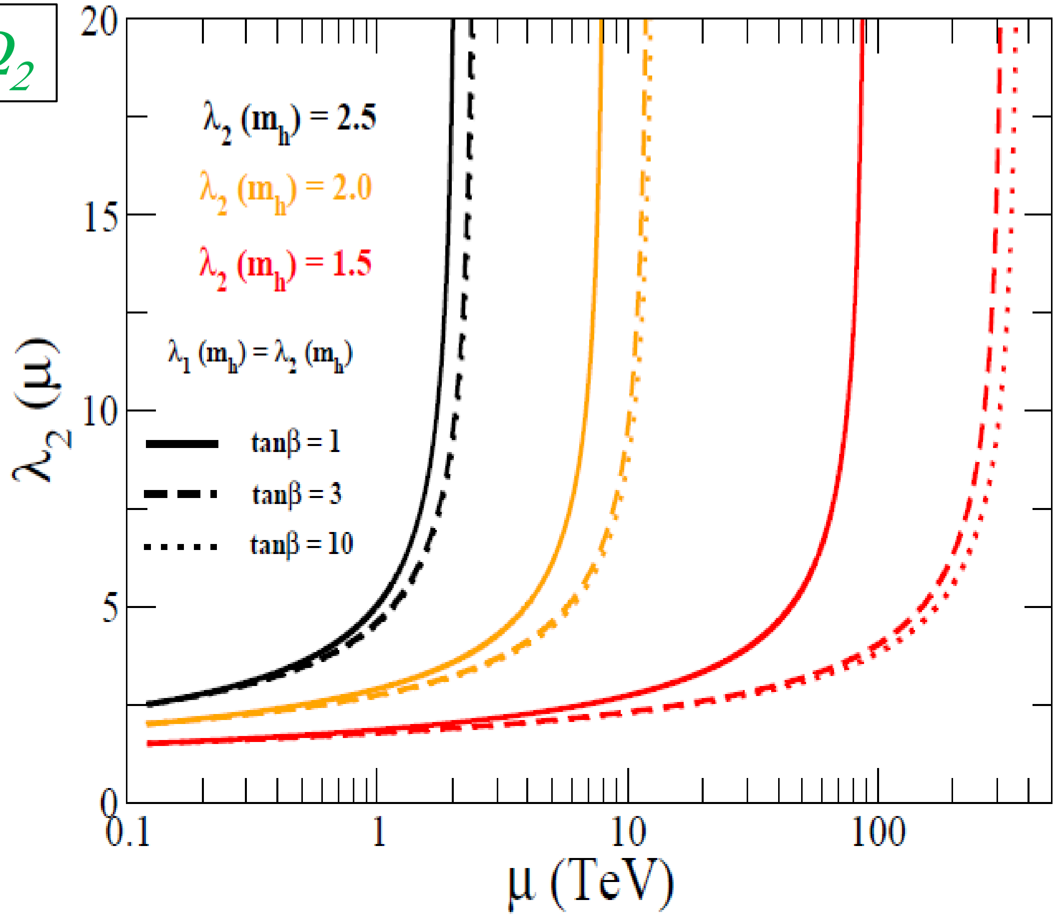
hhh deviation= 15% - 70 %

Testable at ILC !

RGE analysis in 4HDM+Ω

$W = \lambda_1 \; H_u H_u'\Omega_1 + \lambda_2 \; H_d H_d'\Omega_2$

λ_2	Λ_{cutoff}
2.5	2 TeV
2.0	10 TeV
1.5	100 TeV



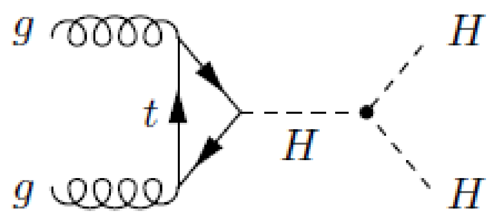
S.K., T. Shindou, K. Yagyu, 2010

HHH measurement at LHC and ILC

LHC

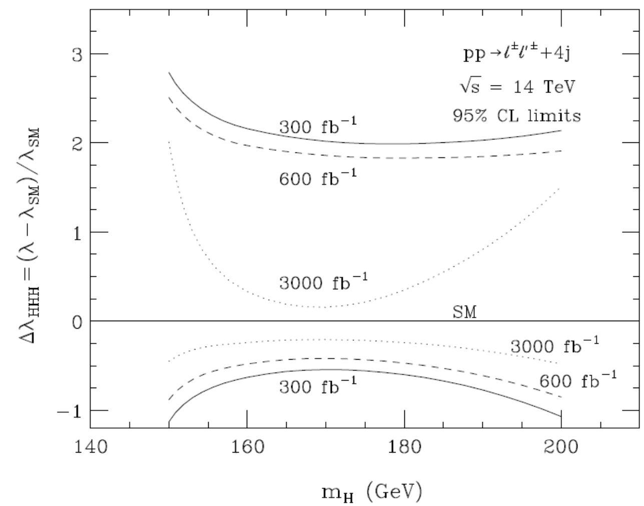
LHC, SLHC (3000fb^{-1})

Hopeless for mH < 140GeV

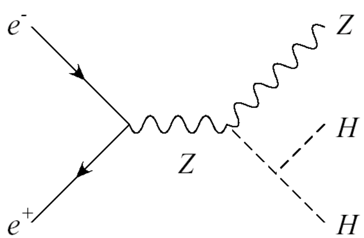


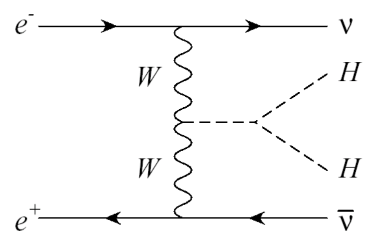
$pp \to HH \to W^+W^-W^+W^- \to l^+l^-\ 4\ j$

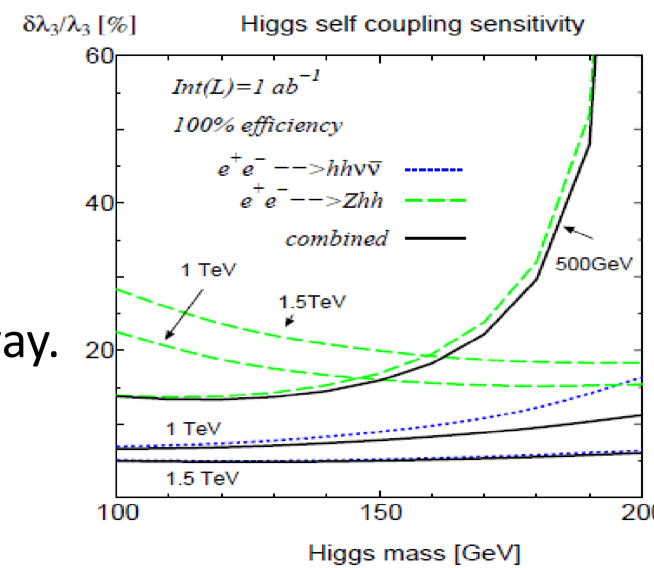
Bauer, Plehn, Rainwater   2003



ILC







10-30 % may be expected. Simulation underway.

Precision measurement of the *hhh* coupling is expected at the ILC.

Summary

- Decoupling property of variant SUSY models

  F-term (nondecoupling effect)

  1) Large effect on mh

  NMSSM (low tanβ) , MSSM with Triplets

  2) Large effect on the *hhh* coupling

  4HDM+Ω (charged singlets)

  NMSSM (high tanβ)

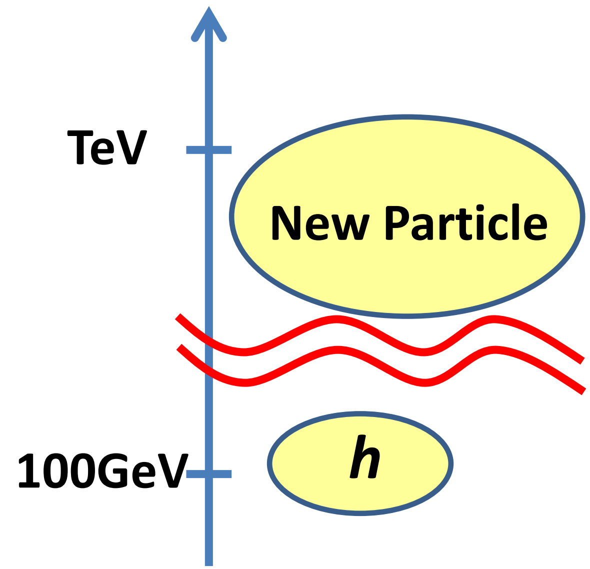
  These models can be a new viable model for EW baryogenesis

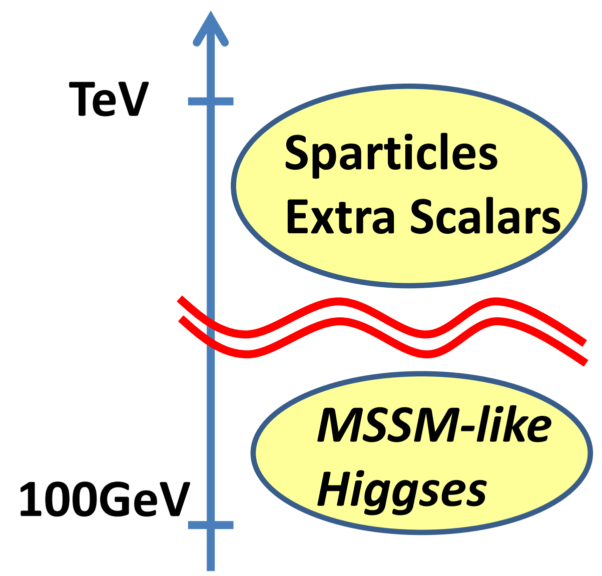
  Soft-term Mixing (quasi-nondecoupling effect)

  3) Large effect on *mh, mH+, mH, sin(b-a)*

  4HDM

- By precision measurements of the light Higgs properties, we can distinguish the various extended SUSY models.





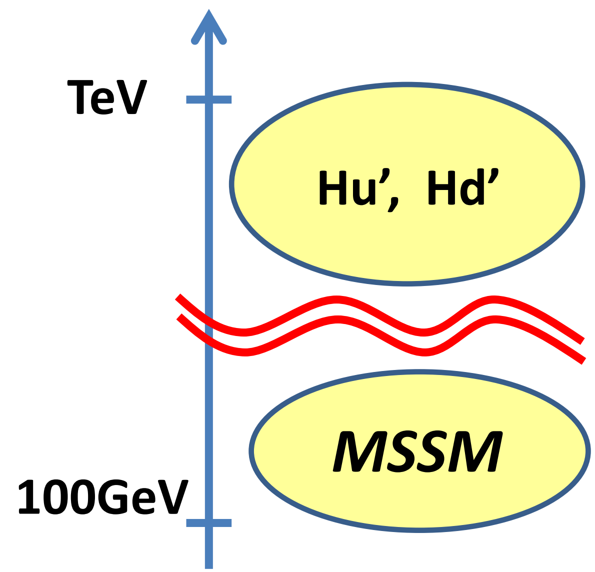
Multi-Higgs doublets

M. Aoki, S.K., T. Shindou, K. Yagyu, arXiv: 1108.1356

- Additional doublets H_u', H_d' (4HDM)
- No tri-linear *HHH* term in Superpotential
- No F-term contriubtion to the potential at tree
- The model can reduce to the MSSM for heavy H_u', H_d'.
- But possible non-decoupling effects from B-term with mixing between H_u, H_d and H_u', H_d'.

When h, H, H^+, A are found to be somehow MSSM like, we will thoroughly examine whether they are really of the MSSM or not. We then constrain the possibility of more than two doublets...

4HDM (Hu, Hd, Hu’, Hd’)



MSSM-like limit

(h, H^+, A, H) + (extra doublets)

B-term mixing effect

$$L_{soft} = -B_{14}\mu_{14} H_u . H_d' - B_{23}\mu_{23} H_u' . H_d + \ldots$$

$$\bar{M}_A^2 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{2(M_3^2)_{11}}{s_{2\beta}} & \frac{m'M}{c_\beta} & \frac{mM}{s_\beta} \\ 0 & \frac{m'M}{c_\beta} & M^2 + \frac{m_Z^2}{2}c_{2\beta} & 0 \\ 0 & \frac{mM}{s_\beta} & 0 & M^2 - \frac{m_Z^2}{2}c_{2\beta} \end{pmatrix}$$

Bterm-Mixing

4HDM

$$R = \frac{1}{\sqrt{1 + \frac{k^2}{r^2} + k'^2}}$$

$k = m/M$, $k' = m'/M$
$r = O(1)$

Mass of *h*

$$\boxed{m_h^2 = \frac{1}{2}\left(m_A^2 + m_Z^2\left(1 - (1 - R^2)s_{2\beta}^2\right) - \sqrt{\left(m_A^2 - m_Z^2\left(1 - (1 - R^2)s_{2\beta}^2\right)\right)^2 + 4 m_A^2 m_Z^2 s_{2\beta}^2 R^2 + m_A^2 \mathcal{O}\left(\frac{m_A^2}{M^2}\right)}\right)}$$

Mass of *H*$^+$

$$\boxed{m_{H^\pm} = \sqrt{m_A^2 + m_W^2}(1 + \delta)}$$

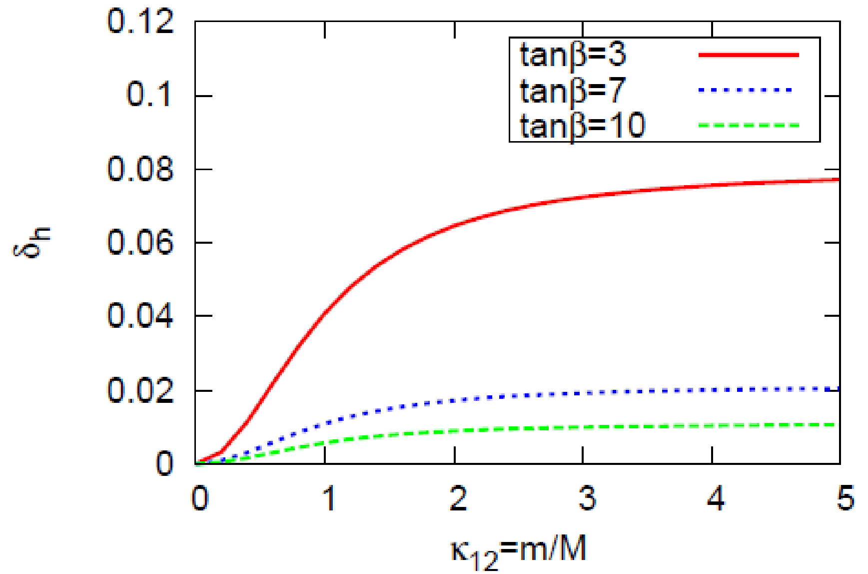
$$\delta = -\frac{1}{2}\frac{m_W^2}{m_A^2 + m_W^2}\frac{k^2 + k'^2 r^2 - c_{2\beta}\left\{(k^2 - k'^2 r^2)c_{2\bar\theta} + 2kk' r s_{2\bar\theta}\right\}}{2(k^2 + (1 + k'^2)r^2)} + \mathcal{O}\left(\frac{m_A^2}{M^2}\right)$$

4HDM

Mass of *h*

- Effect of extra doublet via *B*-term mixing

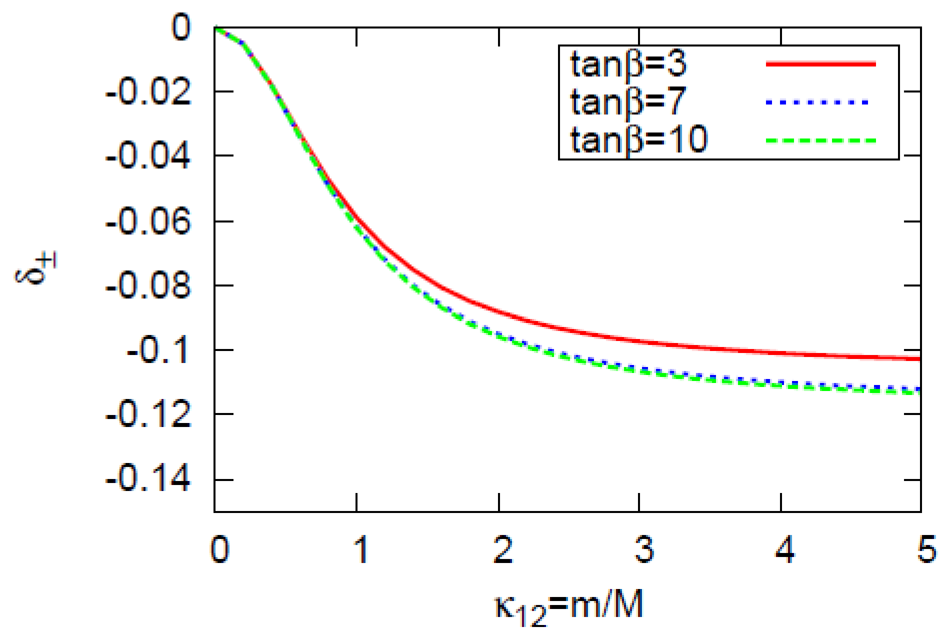
$$\delta_h \equiv \frac{m_h}{m_h^{MSSM}} - 1$$



- Positive correction by a few % (Sensitive to tanβ)
- Comparable or less than MSSM one-loop $(A_t/M)^2$ effects

Mass of H^+

$$\delta_\pm \equiv \frac{m_{H^\pm}}{\sqrt{m_A^2 + m_W^2}} - 1$$



- Deviation from MSSM predictio[n] Negative 5-10%

  (Insensitive to tanβ)
- Comparable or greater than MSSM radiative correction