Physics of Extended SUSY Higgs sector

Shinya KANEMURA (U. of TOYAMA)

S. K., T. Shindou, K. Yagyu: arXiv:1009.1836
M. Aoki, S. K., T. Shindou, K. Yagyu, work in progress

PPP2011, YITP Meeting, March. 7-10, 2011

ヒッグスセクターは未知

SMヒッグスの質量はフリーパラメータ

$$\boxed{V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4}$$

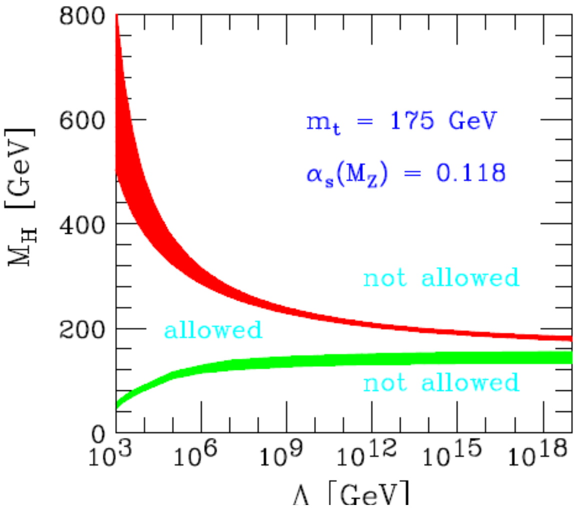
$$m_h{}^2 = 2\lambda v^2$$

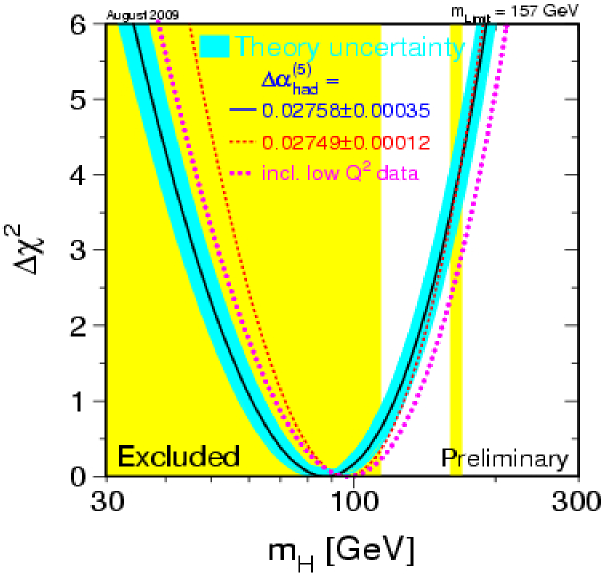
Relation to Λ (RGE)

- Light Higgs (weak： high Λ)
- Heavy Higgs (strong： low Λ）

Constraint from LEP, Tevatron

- $114\ \mathrm{GeV} < mh < 149\ \mathrm{GeV}$ allowed at 95%CL
- $158\ \mathrm{GeV} < mh < 175\ \mathrm{GeV}$ excluded (Tevatron)





理論と実験は軽いSMヒッグスを示唆

重いヒッグスは排除されたか？

No!

A heavy (SM-like) Higgs is not excluded, if there is new physics effect

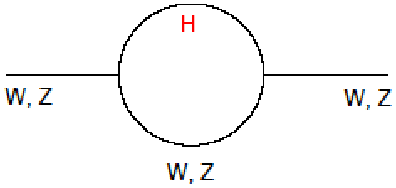
The upper bound comes from the loop effect of m_H.

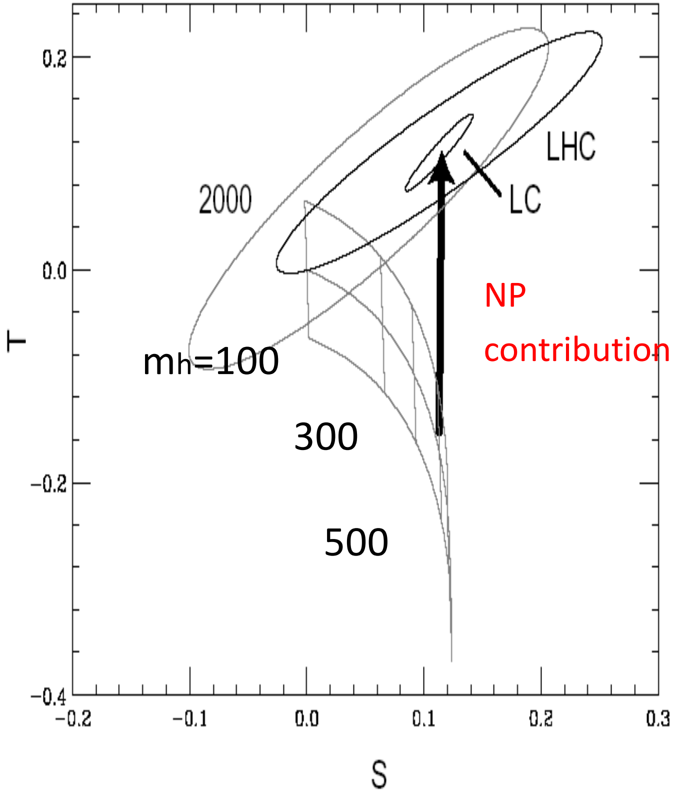
$$\Delta T_{\rm Higgs} \simeq -\ln \frac{m_H^2}{M_W^2} \quad (\sim 0)$$

A heavy Higgs is possible by additional new physics loop contributions to the T parameter

重いヒッグス＝新物理の証拠

Oblique Corrections





Prospect for Higgs searches at LHC

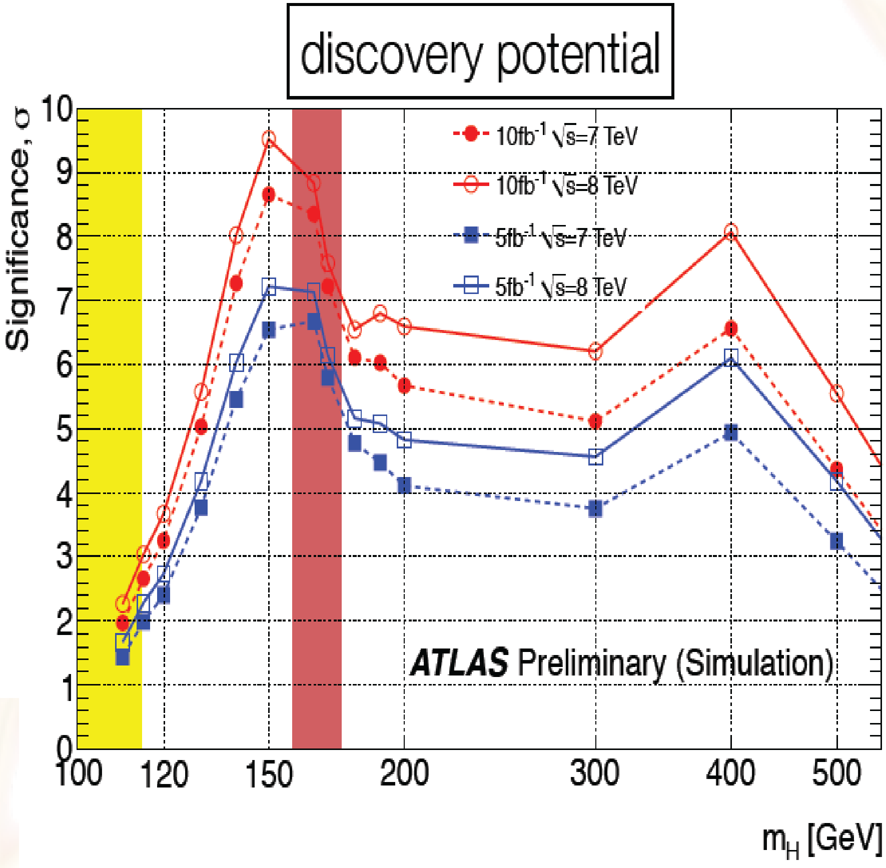
早ければ2年後（2012年末）SMのヒッグスは全ての質量領域で調べ尽くされる？

ヒッグスの質量がどこに出てくるかは新物理学模型を決定する上で極めて重要

SM Higgs ATLAS + CMS combined (non-optimized analyses):

- $3\ \sigma$ over full mass range with ~ 4.5 fb^{-1}
- $5\ \sigma$ over full mass range with ~ 12 fb^{-1}

being able to close the SM Higgs chapter by end 2012 is very attractive



SUMIDA's talk at KEKPH2011

Higgs potential

電弱対称性の自発的破れの本質を知るうえで、ヒッグスポテンシャルの実験による再構成をする必要がある

＝　質量に次いでヒッグス3点相互作用も重要パラメータ

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

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

Renormalization Conditions

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

SM Case

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

Supersymmetry

新物理学のシナリオとして魅力的

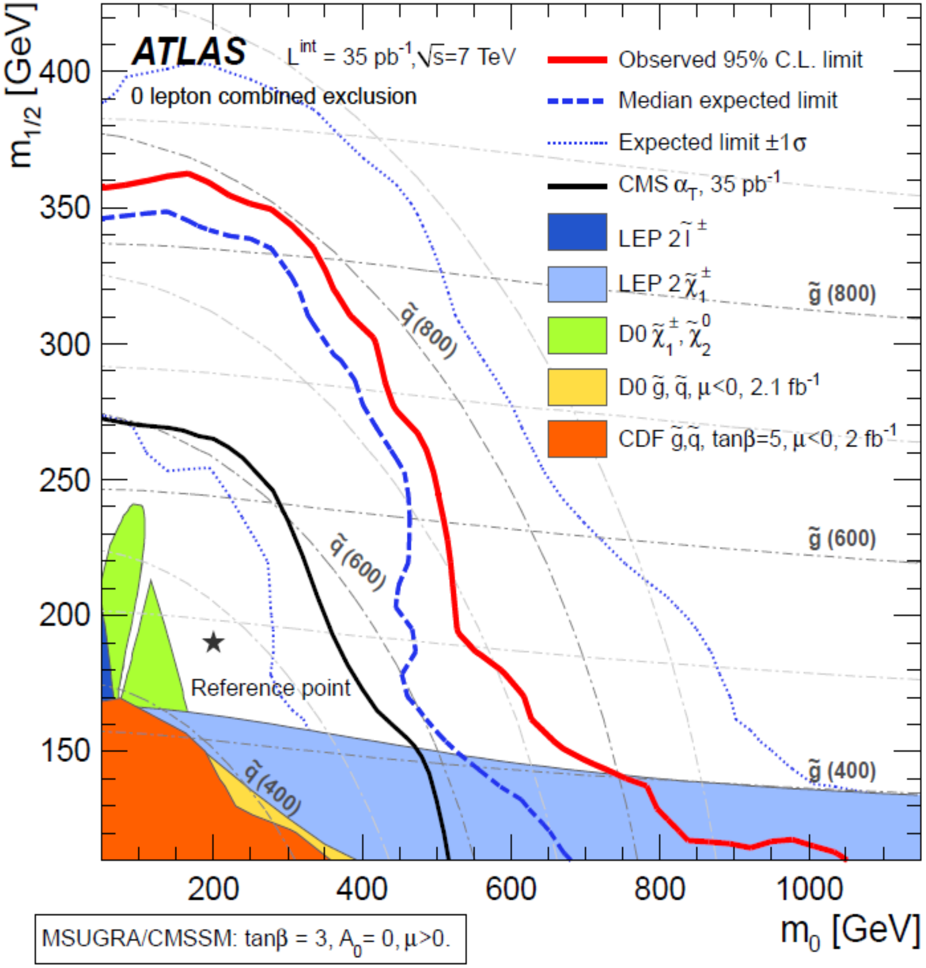
- 超対称パートナー粒子
- 2次発散が相殺
- R-parity ⇒ LSP はWIMP暗黒物質候補
- GUT, …

SUSY Searches at LHC

最近の成果（no signal）

M_{SUSY} は軽いところ（＜0.5TeV）にはない（かもしれない）

このような場合でもヒッグスについての情報がSUSY模型を検証するうえで重要になるはず



ATLAS Collaboration: arXiv:1102.5290

In this talk

TeV領域の様々な超対称模型のヒッグスセクター

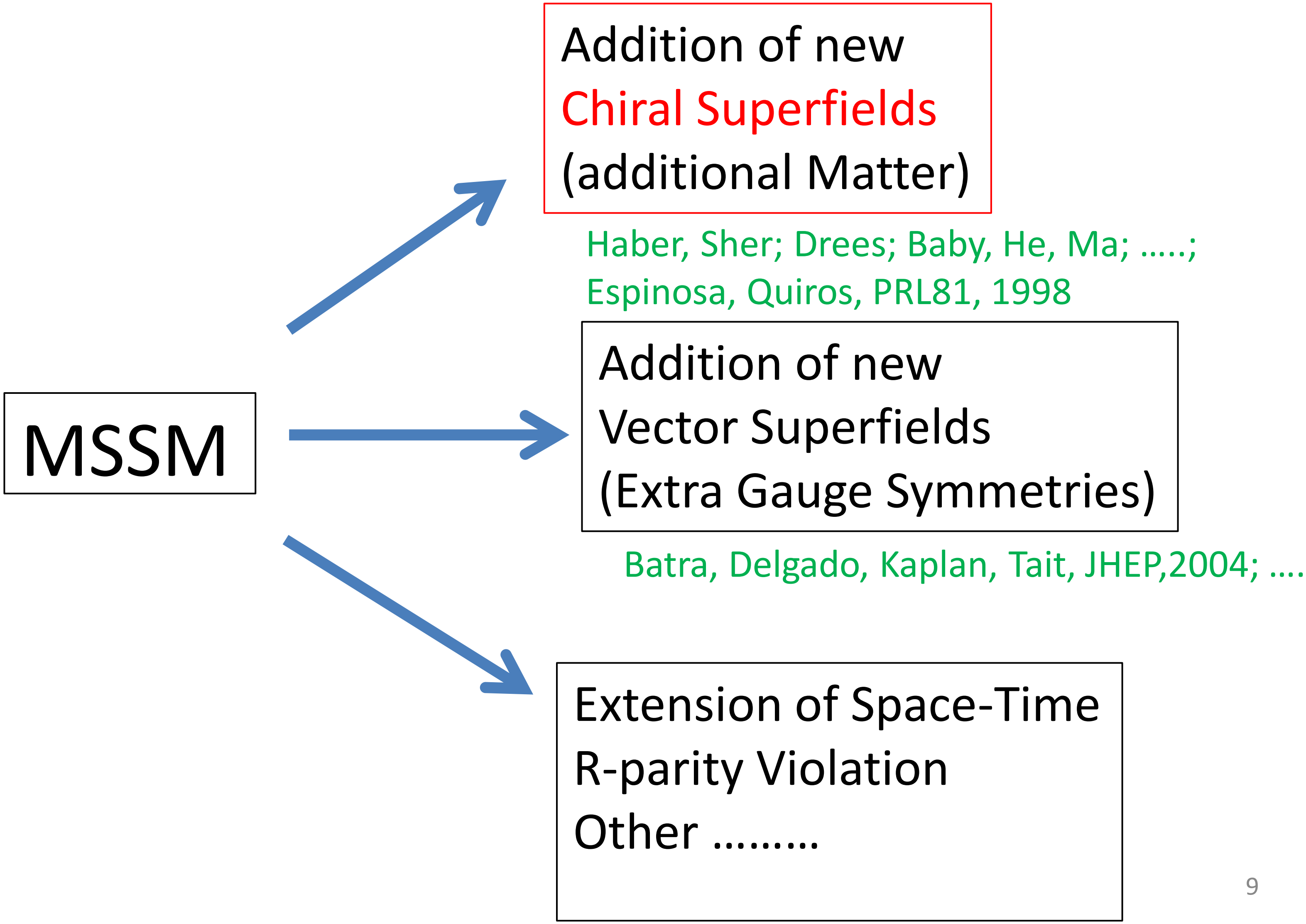
- MSSM (cMSSM, NUHM1, mSUGRA, ….)
- MSSM+(Singlets, +Doublets, +Triplets, …..)

を包括的に研究し、特にSUSY粒子がデカップルする領域において、ヒッグスセクターの重要な2つの量

- 最も軽いヒッグスボソンの質量
- hhh結合

に関する模型ごとの予言の違いを1ループレベルの計算に基づいて議論する

Extension of MSSM



MSSM

Addition of new
Chiral Superfields
(additional Matter)

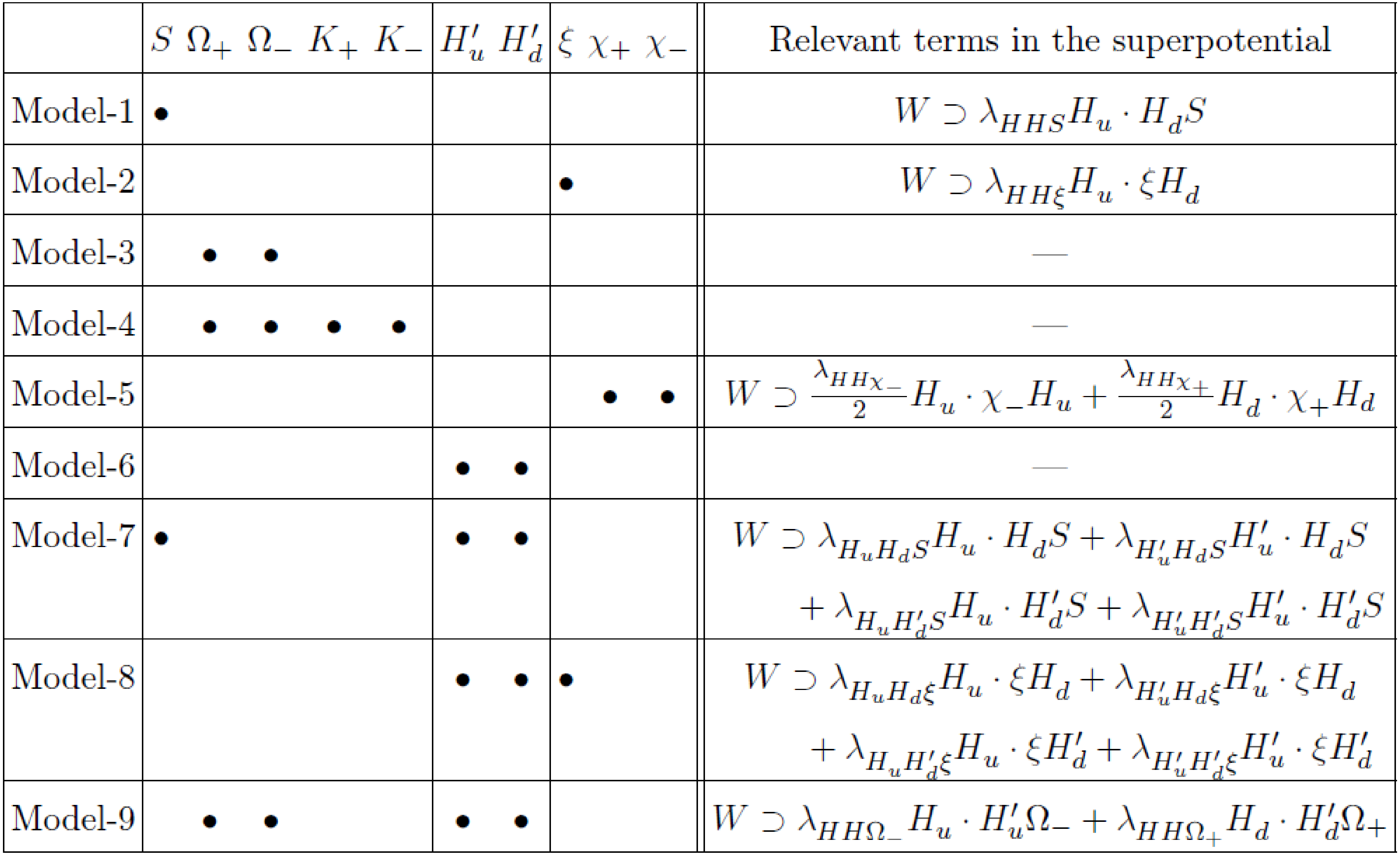
Haber, Sher; Drees; Baby, He, Ma; …..;
Espinosa, Quiros, PRL81, 1998

Addition of new
Vector Superfields
(Extra Gauge Symmetries)

Batra, Delgado, Kaplan, Tait, JHEP,2004; ….

Extension of Space-Time
R-parity Violation
Other ………

Models with additional superchiral fields



	S	Ω_+	Ω_-	K_+	K_-	H'_u	H'_d	ξ	χ_+	χ_-	Relevant terms in the superpotential
Model-1	●										$W \supset \lambda_{HHS} H_u \cdot H_d S$
Model-2								●			$W \supset \lambda_{HH\xi} H_u \cdot \xi H_d$
Model-3		●	●								—
Model-4		●	●	●	●						—
Model-5									●	●	$W \supset \frac{\lambda_{HH\chi_-}}{2} H_u \cdot \chi_- H_u + \frac{\lambda_{HH\chi_+}}{2} H_d \cdot \chi_+ H_d$
Model-6						●	●				—
Model-7	●					●	●				$W \supset \lambda_{H_u H_d S} H_u \cdot H_d S + \lambda_{H'_u H_d S} H'_u \cdot H_d S$ $+ \lambda_{H_u H'_d S} H_u \cdot H'_d S + \lambda_{H'_u H'_d S} H'_u \cdot H'_d S$
Model-8						●	●	●			$W \supset \lambda_{H_u H_d \xi} H_u \cdot \xi H_d + \lambda_{H'_u H_d \xi} H'_u \cdot \xi H_d$ $+ \lambda_{H_u H'_d \xi} H_u \cdot \xi H'_d + \lambda_{H'_u H'_d \xi} H'_u \cdot \xi H'_d$
Model-9		●	●			●	●				$W \supset \lambda_{HH\Omega_-} H_u \cdot H'_u \Omega_- + \lambda_{HH\Omega_+} H_d \cdot H'_d \Omega_+$

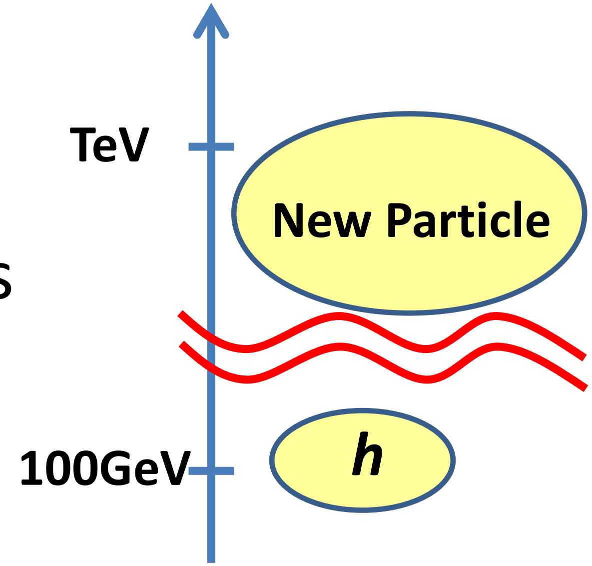
Decoupling/Non-decoupling

- Decoupling Theorem

  Appelquist-Carazzone 1975

  New phys. loop effect in observables

  $1/M^n \rightarrow 0$ (M→∞ : decouple)



- Violation of the decoupling theorem
  - Chiral fermion loop (ex. top)

    $$m_f = y_f v$$

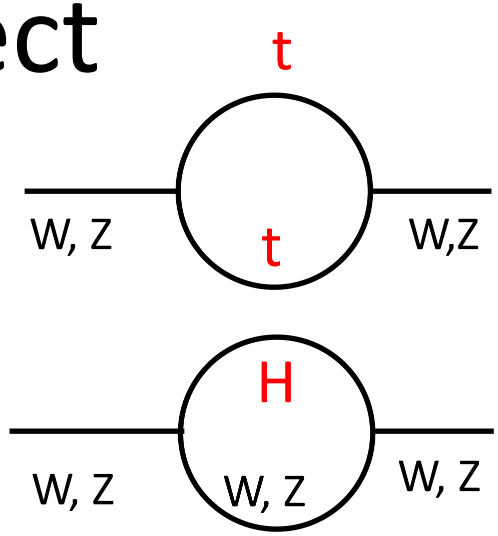
  - Boson loop (ex. H^+ in non-SUSY 2HDM)

    $$m_\phi^2 = \lambda v^2 + M^2$$ (only if $\lambda v^2 > M^2$)

Non-decoupling effect

Non-decoupling effect

Example (Electroweak *T* parameter)



$$\rho = \frac{m_W}{m_Z \cos\theta_W}, \quad \Delta\rho = \rho - 1 = \alpha T$$

Data |*T*| < 0.1

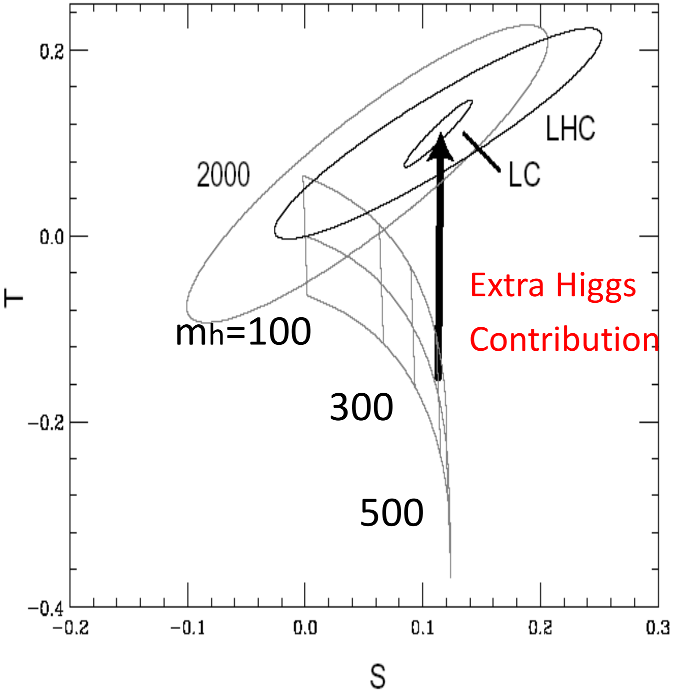
$$\Delta T_{\text{top}} \propto \frac{m_t^2}{M_W^2}$$

$$\Delta T_{\text{Higgs}} \simeq -\ln\frac{m_H^2}{M_W^2}$$ (SM)

$$\Delta T_{\text{Higgs}} \sim -\ln\frac{m_h^2}{M_W^2} + \frac{(m_A^2 - m_{H\pm}^2)^2}{M_W^2 m_A^2}$$

(2HDM)

Quadratic mass contribution (non-decoupling effect)



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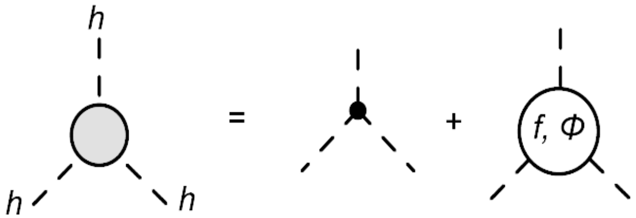
SM Case

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

Non-SUSY の 2HDM の場合

- 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 $M < v$）



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

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

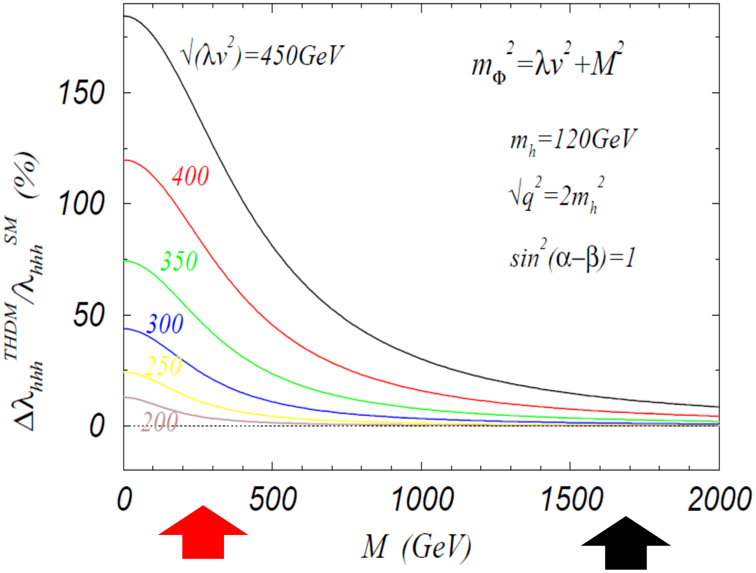
$$\boxed{\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\underline{\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3}-\underline{\frac{m_t^4}{\pi^2 v^2 m_h^2}}\right]}$$

Extra scalar loop

Top loop

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

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



Non-decoupling effect

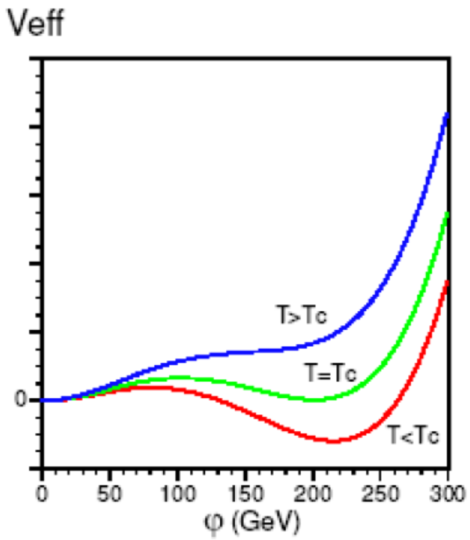
Decoupling

Correction can be huge　～ 100%

Electroweak Baryogenesis

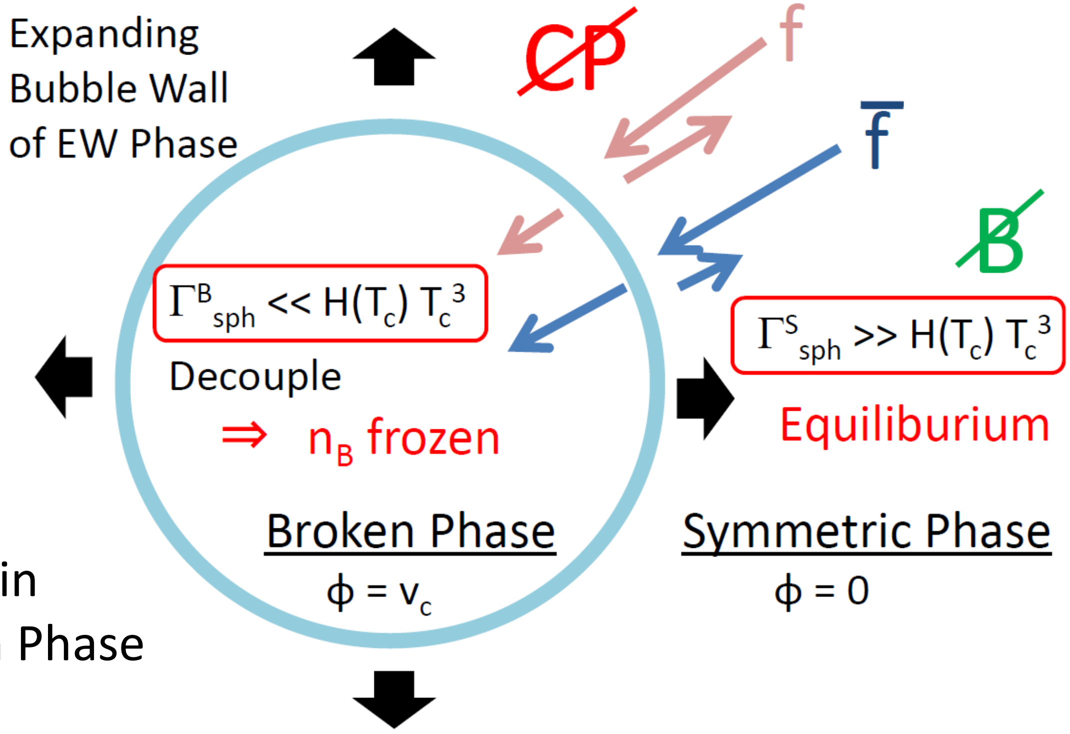
Sakharov's conditions:

- B Violation → Sphaleron transition at high *T*
- C and CP Violation → CP Phases in 2HDM
- Departure from Equilibrium → 1st Order EW Phase Transition



Quick sphaleron decoupling to retain sufficient baryon number in Broken Phase

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



Expanding Bubble Wall of EW Phase

$\cancel{CP}$

f

$\bar{f}$

$\cancel{B}$

$\boxed{\Gamma^B_{sph} << H(T_c)\, T_c^3}$

Decouple

⇒ n_B frozen

$\boxed{\Gamma^S_{sph} >> H(T_c)\, T_c^3}$

Equiliburium

Broken Phase

$\phi = v_c$

Symmetric Phase

$\phi = 0$

電弱バリオン数生成と *hhh* 結合

有限温度ポテンシャル（高温展開の式）

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

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

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

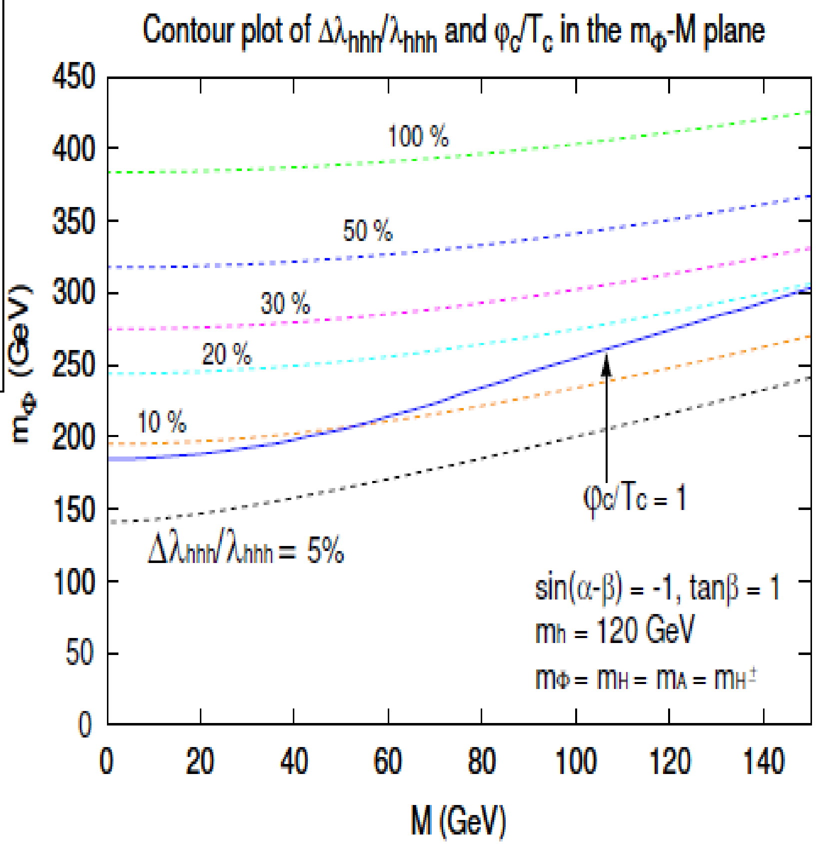
$$\lambda_T = m_h^2/2v^2 + \text{log corrections}$$

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

SM: $m_h < 60$GeV Excluded by LEP

2HDM: m_h =120GeV Possible due to non-decoupling effect

Strong 1st OPT ⇔ Large *hhh* coupling



SK, Okada, Senaha (2004)

Grojean, Wells, Servant, 2004

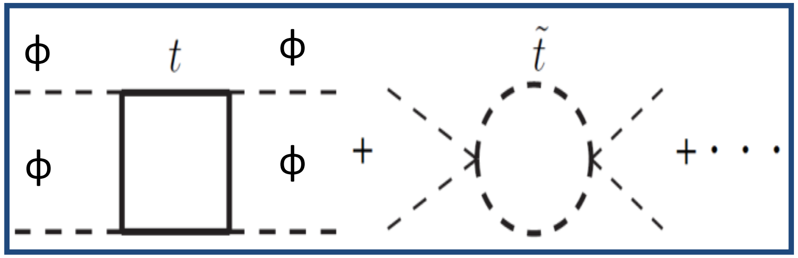
Mass of *h* in the MSSM

MSSM

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

↑

D-term



$$\delta m_{\text{loop}}^2 \simeq \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4} + \frac{3m_t^2 X_t^2 \sin^2\beta}{4\pi^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)} \ln \frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2}$$

m_h < 130GeV

Okada, Yamaguchi, Yanagida;
Ellis, Ridolfi,Zwirner;
Haber, Hempfing

LHCで 140 GeV 以下のヒッグスが見つからなければ？

- At the LHC, the Higgs search is underway.
- If no Higgs is found below 140 GeV, probably we must discard the MSSM.
  - *Q: Shall we abandon the low scale SUSY ?*
  - *A: Maybe No.*

拡張されたSUSYヒッグスセクターの可能性

Next-to-MSSM （NMSSM）

Two Higgs doublets H_u, H_d and a singlet S

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

μ problem
may be solved

Mass of the lightest h in the NMSSM

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

Moroi, Okada;
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

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

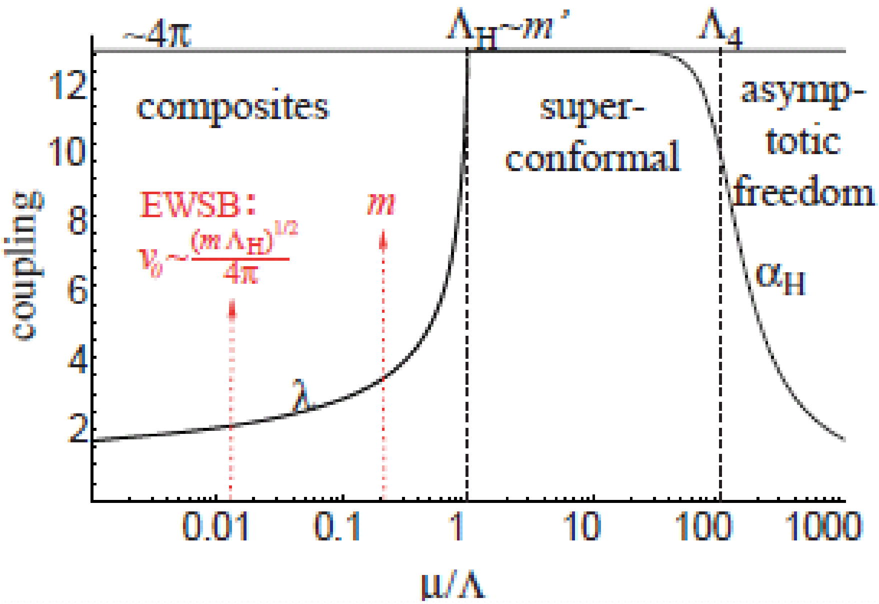
The SM-like Higgs can be heavy

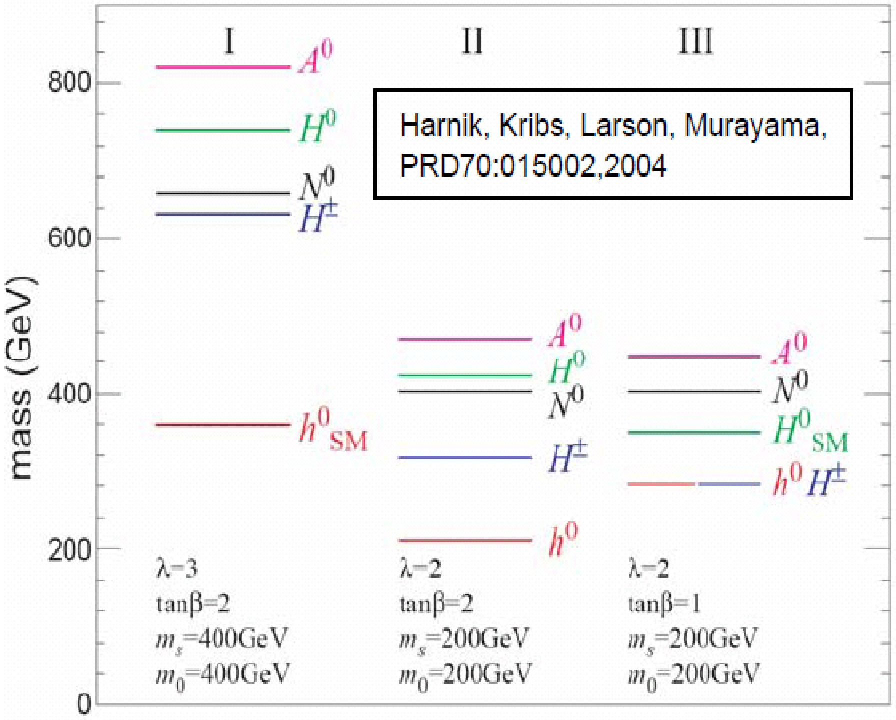
$$m_h^2 \simeq \lambda^2 v^2 + \mathcal{O}(m_Z^2)$$

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

λ can be of O(1)

⇔ $m_h > 200$ GeV





Harnik, Kribs, Larson, Murayama, PRD70:015002,2004

Variation of SUSY Higgs sectors

- The mass of the lightest Higgs boson *h* is a good tool to discriminate the SM, MSSM, NMSSM.
- The *hhh* coupling can also be important
- How about the other possibility of extended SUSY Higgs sectors?
  - MSSM+χ (χ : triplet) [Left-Right, Type-II Seesaw]
  - 4HDM+Ω (Ω: charged singlet) [Super Zee-Model]
- See prediction on m_h and λ_{hhh}

(*h*: Lightest Higgs (SM-like))

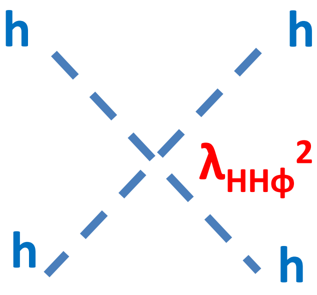
F-term contributions to m_h and hh$\phi\phi$

F-term: $$V_F = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2$$

(ϕ_i: Scalar component
of a chiral superfield)

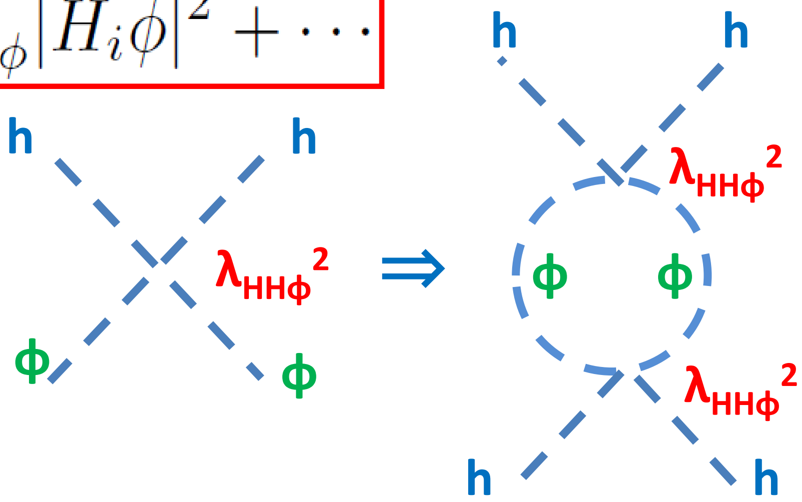
ϕ: Chiral Superfield **S, $\Omega_\pm$, $\chi_\pm$** which generates F-term

$$W \supset \lambda_{H_iH_j\phi} H_i H_j \phi, \quad i,j = u,d$$
$$\rightarrow V_F = \lambda^2_{H_iH_j\phi}|H_iH_j|^2 + \lambda^2_{H_iH_j\phi}|H_i\phi|^2 + \cdots$$



質量にツリーで寄与

hhhにループで寄与

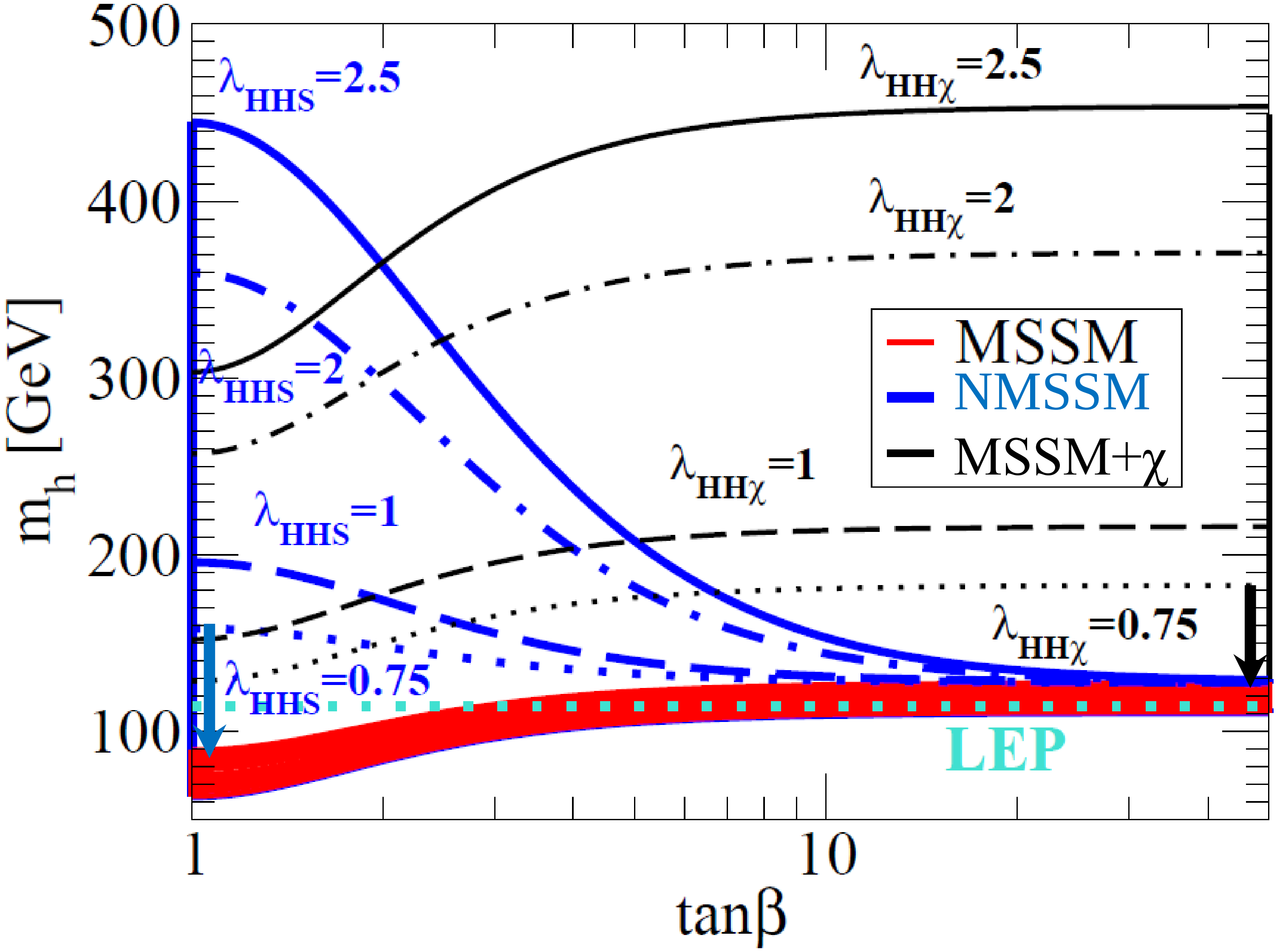


4HDM＋charged singlet Ω の模型について

Super Potential: H_u・$H_{u'}$ Ω+ ⇒ No effect on the mass

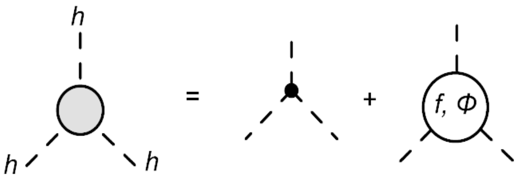
(4 doublets needed, because of H_u・H_u = 0)

Upper limit on m_h as a function of tanβ



Perturbative till GUT scale

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!

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

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

Non-decoupling when

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

Large tanβ ⇒ Small m_h ⇒ Large hhh deviation

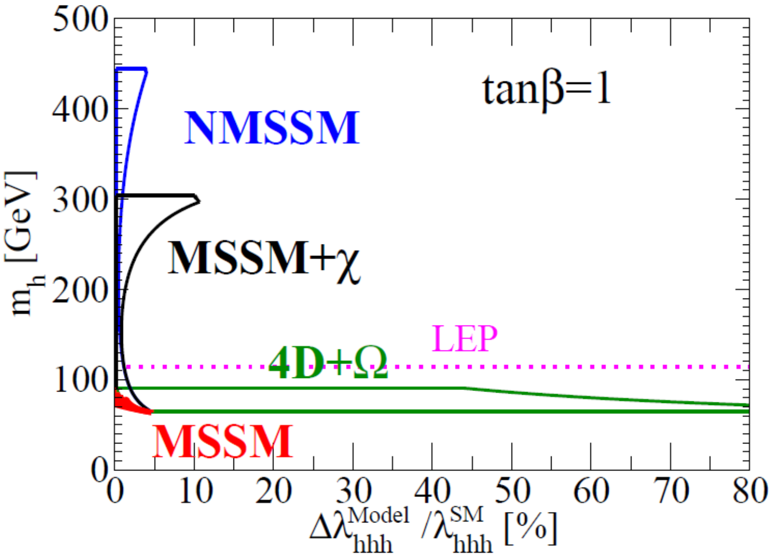
Small tanβ ⇒ Large m_h ⇒ Small hhh deviation

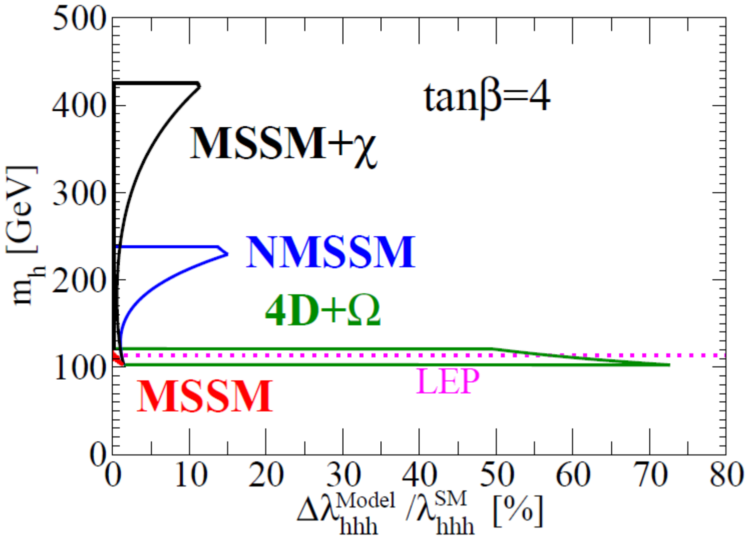
4HDM＋charged singlet の模型

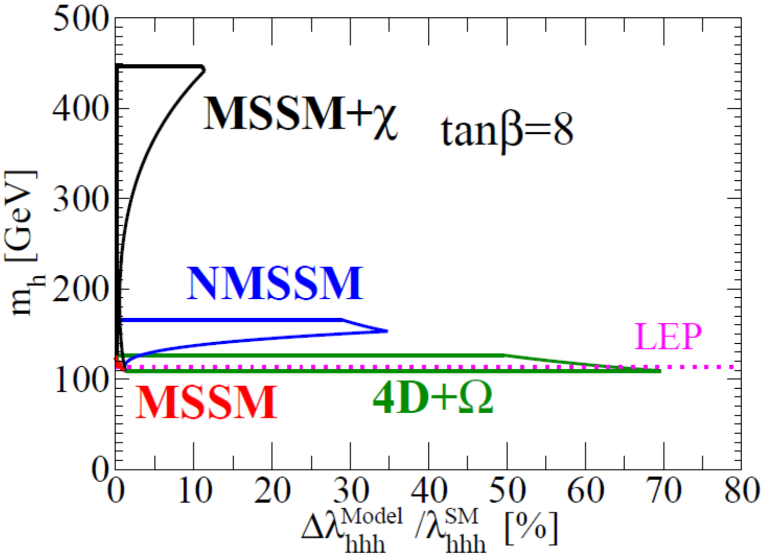
m_h determined by D-term

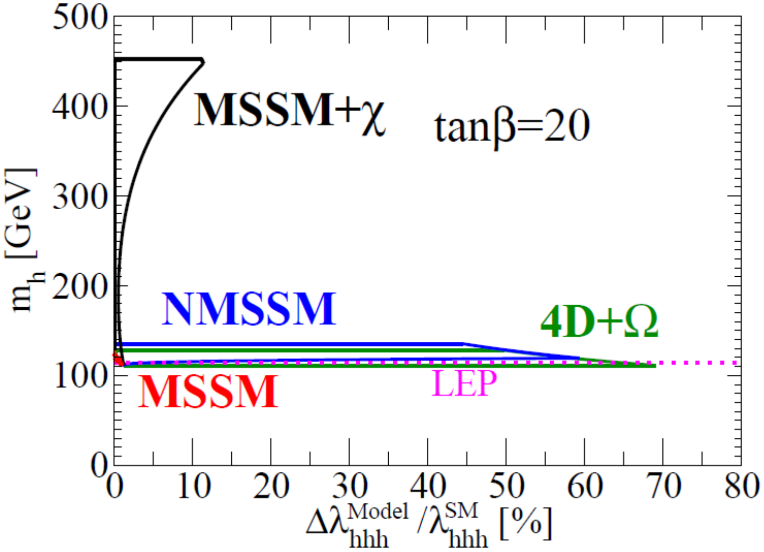
F-terms only contribute to hhh ⇒ Large hhh deviation

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

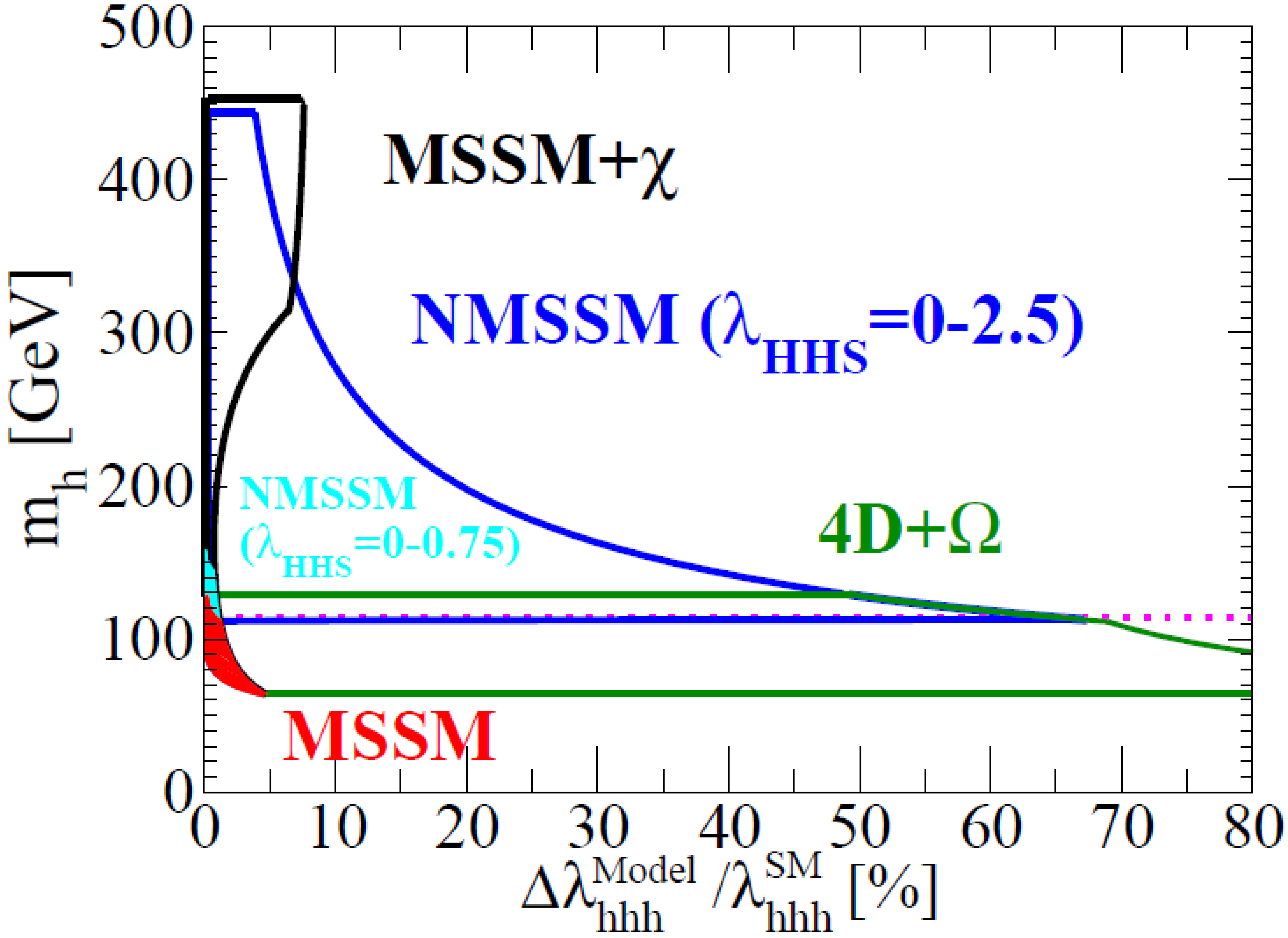








m_h-$\Delta\lambda_{hhh}$ plot (tanβ = 1-50)

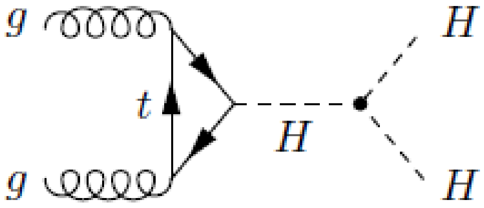


HHH measurement at LHC and ILC

LHC

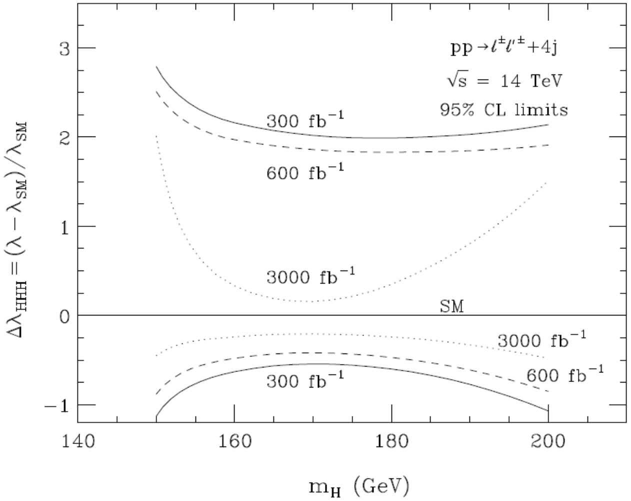
LHC, SLHC (3000fb^{-1})

Hopeless for mH < 140GeV

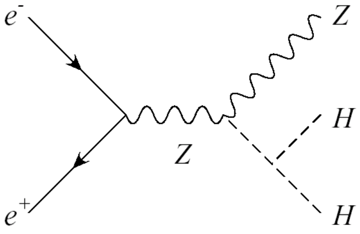


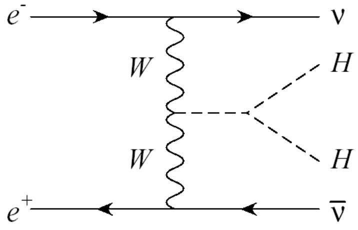
$pp\rightarrow HH\rightarrow W^+W^-W^+W^-\rightarrow l^+l^-\ 4\ j$

Bauer, Plehn, Rainwater 2003



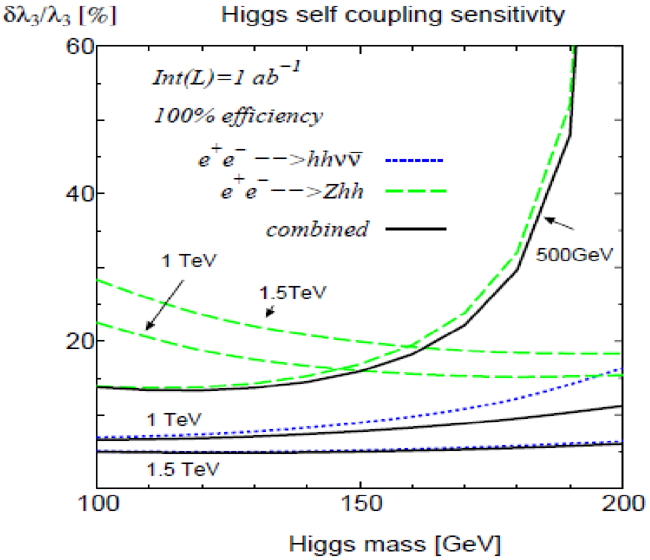
ILC





10-30 % may be expected. Simulation underway

Precision measurement of the *hhh* coupling is business of the ILC.



Summary

- ヒッグスは未知であり様々な可能性がある
- 超対称ヒッグスセクターのバリエーションを考えた
  - MSSM
  - MSSM＋1重項
  - MSSM＋3重項
  - 4HDM＋荷電1重項
- エキストラなカイラル超場φとのHHφ項の結合が強結合　(Λ =O(1) TeV)なら、m_hとhhhの予言に大きな違いが出る

NMSSM(small tanb), MSSM+triplet では

$m_h < 200\text{-}400\mathrm{GeV}$,　hhh結合のずれは小さい

NMSSM(large tanb), 4HDM+Ωでは

m_h＜120－130GeV,　hhh結合のずれは大きい（～50%）

- たとえエキストラな場がある程度重くても、最も軽いヒッグス場 h の性質からLHC, ILCで模型を区別できるかもしれない