SUSY Higgs sector with four doublets and its decoupling property

Tetsuo Shindou (Kogakuin University)

M. Aoki, S. Kanemura, T.S, and K. Yagyu, JHEP1111,038

24/04/2012 KILC12@Daegu, Korea

The SM and beyond

* SM is quite successful as an effective theory of elementary particles.

* There are several motivations for a new physics model
  - Neutrino mass
  - Dark matter
  - Elementary scalar?
  - Quadratic divergence
  - Baryogenesis
  - ...

* Most important part(Higgs sector) of the SM has not established yet   a sign at 125GeV?

Only one elementary scalar ? or more rich structure ?

Higgs sector — Strong connection — New physics

e.g. MSSM → Two Higgs bosons are required

Higgs sector is a window to New Physics!!

Supersymmetry

We focus on SUSY models as a candidate of NP in this talk

* No quadratic divergence
* Elementary scalar fields are naturally introduced
* If R-parity is conserved, LSP is a DM candidate
* Connection to a fundamental theory?
* Compatible with many neutrino mass generation mechanisms (seesaw, loop-induced, ...)
* Many CP and flavour sources (Baryogenesis, flavour experiments...)

Higgs sector of MSSM

$$W = \mu H_1 \cdot H_2$$

$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 + (m_3^2\Phi_1 \cdot \Phi_2 + \text{h.c.})$$
$$\frac{g^2+g'^2}{8}(|\Phi_1|^2 - |\Phi_2|^2)^2 + \frac{g^2}{2}|\Phi_1^\dagger\Phi_2|^2$$

The quartic couplings are determined by gauge couplings

$$\left\langle \frac{\partial V}{\partial \Phi^0_{1,2}} \right\rangle = 0$$ → Only one mass parameter is free

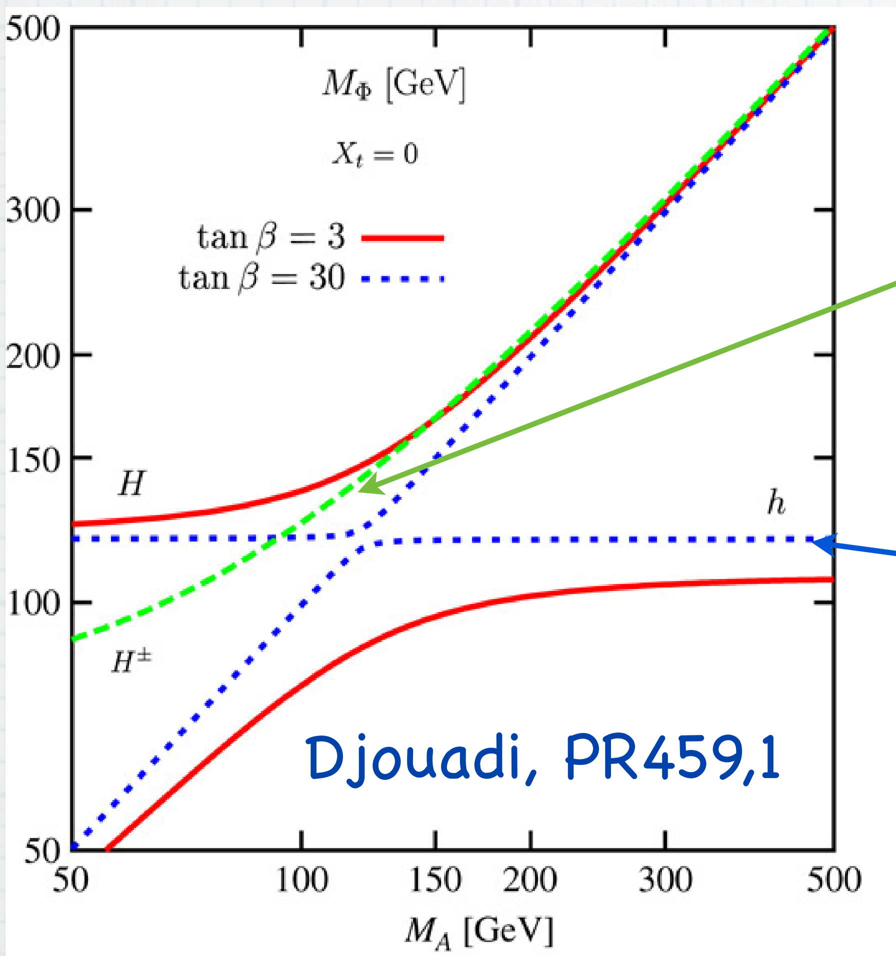
In the MSSM, the Higgs sector is parameterized by two parameters, $\tan\beta = v_2/v_1$ and m_A except for the radiative corrections

cf. In the SM, m_h controls the Higgs sector.

↑ free parameter in SM but it's not in the MSSM

Higgs sector in MSSM

There are specific features in the MSSM Higgs sector



$$m^2_{H^\pm} - m^2_A \simeq m^2_W$$

$$m_h^2 \lesssim m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{2\pi^2 v^2}\left[\ln\frac{M_S^2}{m_t^2} + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$

hhhh is only from D-term

$$x_t = \frac{A_t - \mu\cot\beta}{M_S}$$

$$M_S^2 = \frac{m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}}{2}$$

Okada&Yamaguchi&Yanagida,PTP85,1;Ellis&Ridolfi&Zwirner,PLB257,83

m_h=125GeV requires heavy m_A, large tanβ, heavy stops, and large stop mixing

Beyond the MSSM

Hierarchy problem and DM can be solved in the MSSM

On the other hand

Baryogenesis? ← They still remain → neutrino mass ?

SUSY seesaw model might be an attractive solution, but

- 😣 Thermal leptogenesis conflicts with gravitino problem
- 😣 The right-handed neutrino scale is too high to be tested by the experiments

It is interesting and important to consider the alternative testable solutions!!

↓

We try to solve these problems at TeV scale

e.g.

Electroweak Baryogenesis

Loop induced neutrino mass (radiative seesaw)

Beyond the MSSM

In many such models, R_p even extra scalars are introduced

↓

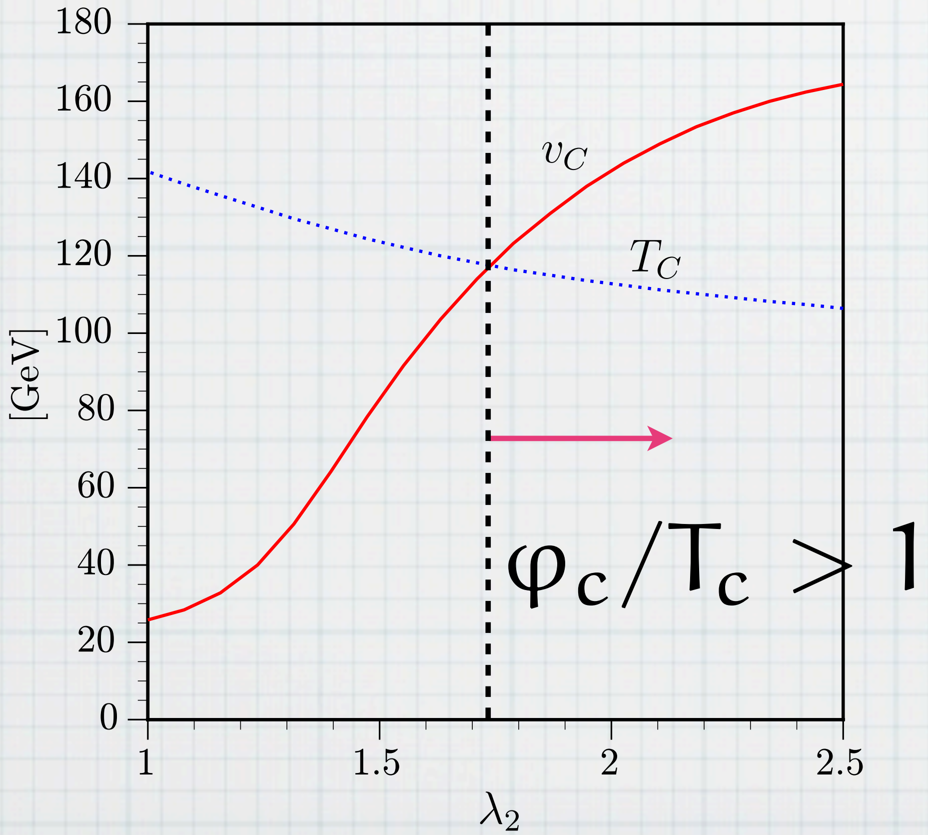
Extended SUSY Higgs models

electroweak baryogenesis

e.g. 4HDMΩ

a minimal framework for strong 1st order phase transition through F-term contribution

Kanemura, T.S, Senaha,PLB706,40



$$W = \lambda_1 \Omega_1 H_1 \cdot H_3 + \lambda_2 \Omega_2 H_2 \cdot H_4 - \mu H_1 \cdot H_2 - \mu' H_3 \cdot H_4 - \mu_\Omega \Omega_1 \Omega_2$$

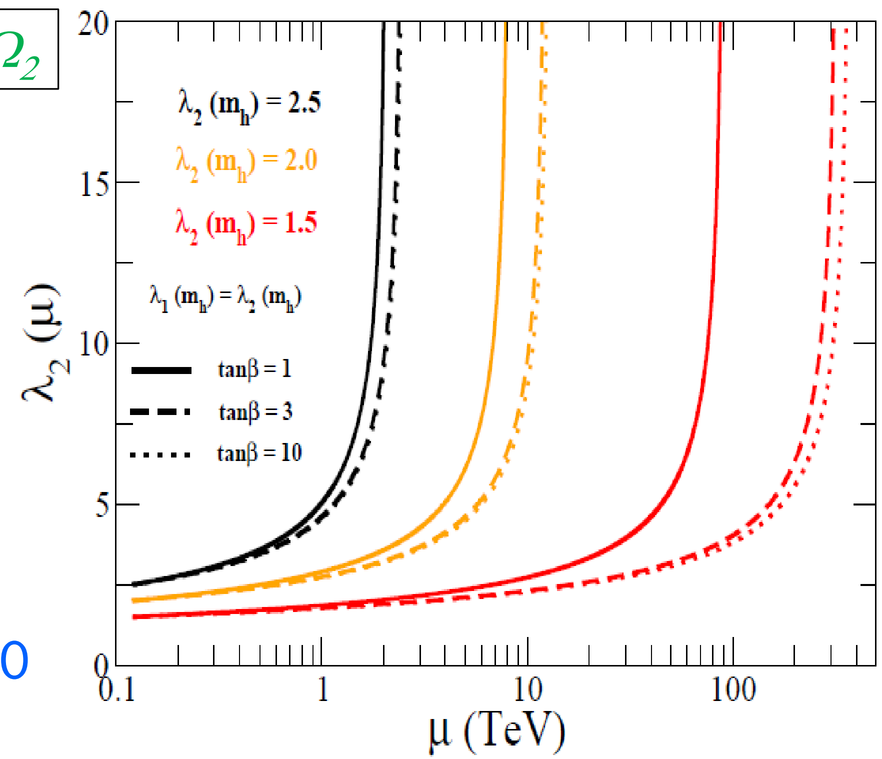
Talk by E. Senaha on 25th 14:00

Model with strong coupling

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

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

Kanemura, T.S, Yagyu, 2010



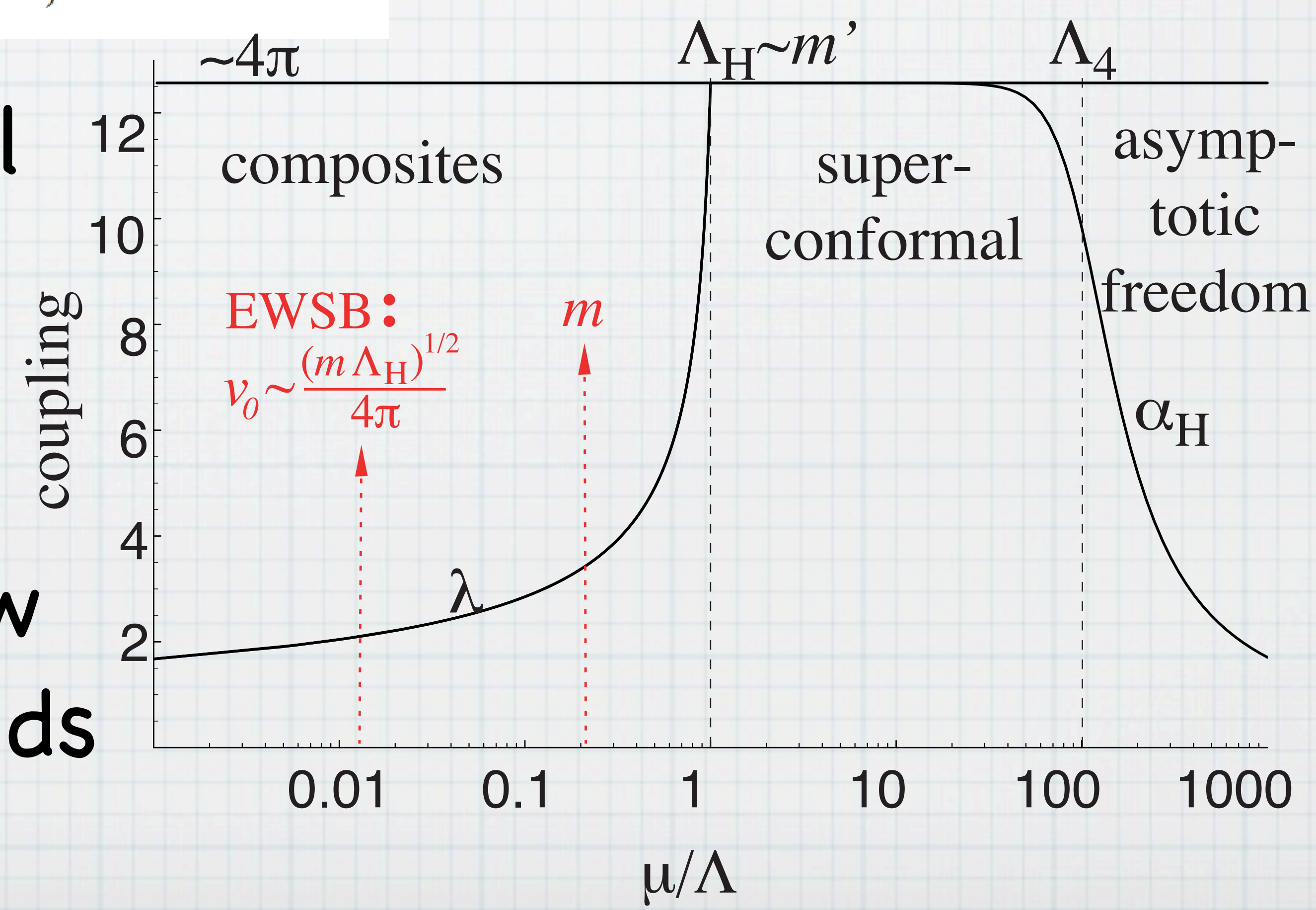
The cutoff scale should be at multi-TeV

not grand desert but fertile fields

e.g. SUSY fat Higgs model

Harnik et al.,PRD70,015002

Higgs bosons appear below the cutoff as composite fields

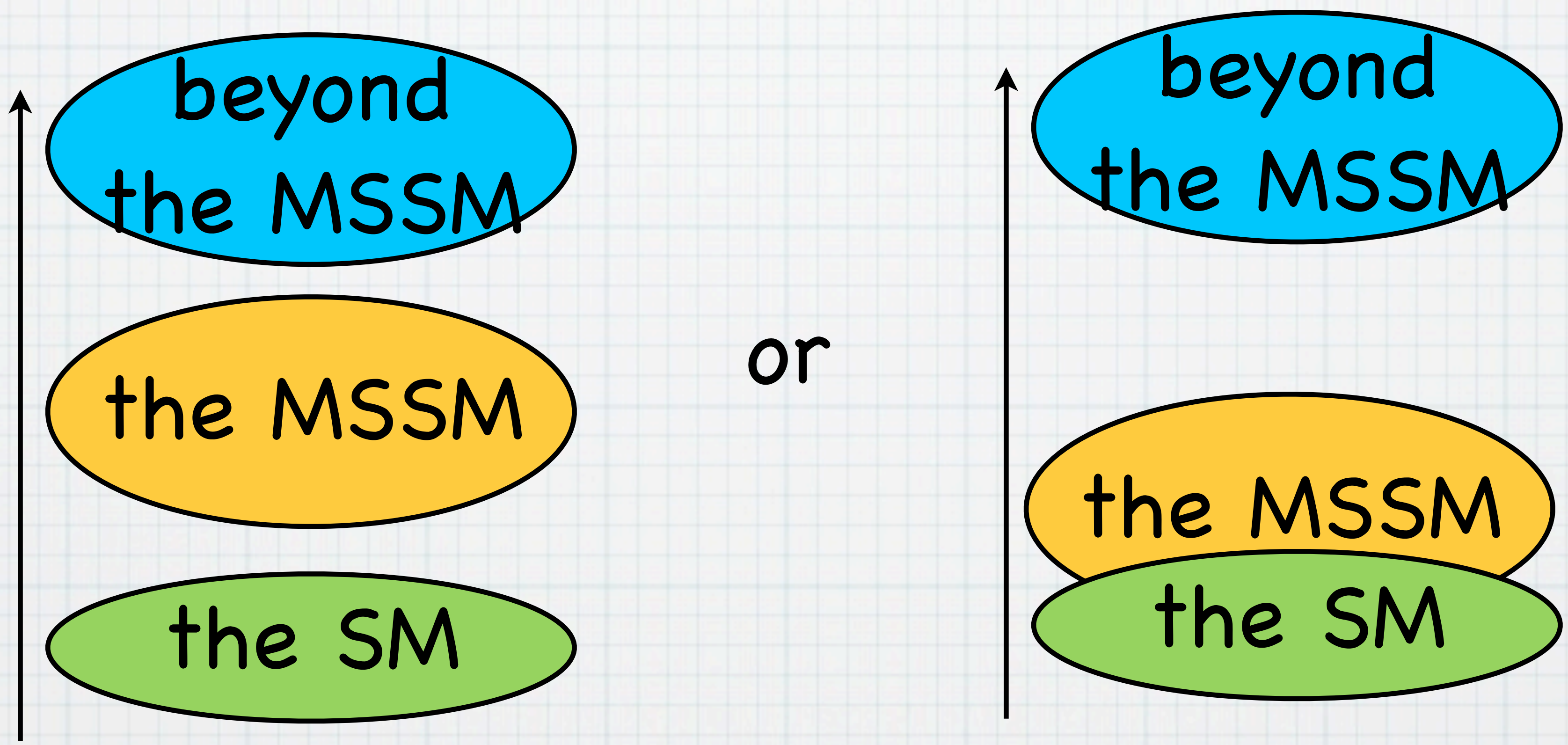


Question

Can we distinguish the MSSM and models beyond the MSSM?

If extra fields are directly found, we can easily do it

If not, we should find some non-decoupling effects



No new particles are found

Only MSSM particles are found

We will discuss non-decoupling effects in SUSY models

F-term contribution

General SUSY models:

$$V = |F|^2 + |D|^2 + \text{soft-terms}$$ + loop correction with Yukawa couplings

Can be a strong source of non-decoupling effects

e.g. $W = \lambda H_1 H_2 S \rightarrow |\lambda|^2 \left(\Phi_1^\dagger \Phi_1 |\Phi_S|^2 + \Phi_2^\dagger \Phi_2 |\Phi_S|^2 + |\Phi_1 \Phi_2|^2 \right)$

$$M_{\Phi_S}^2 = M_0^2 + \lambda^2 v^2$$

m_h=125GeV ⟷ large tree level contribution to m_h

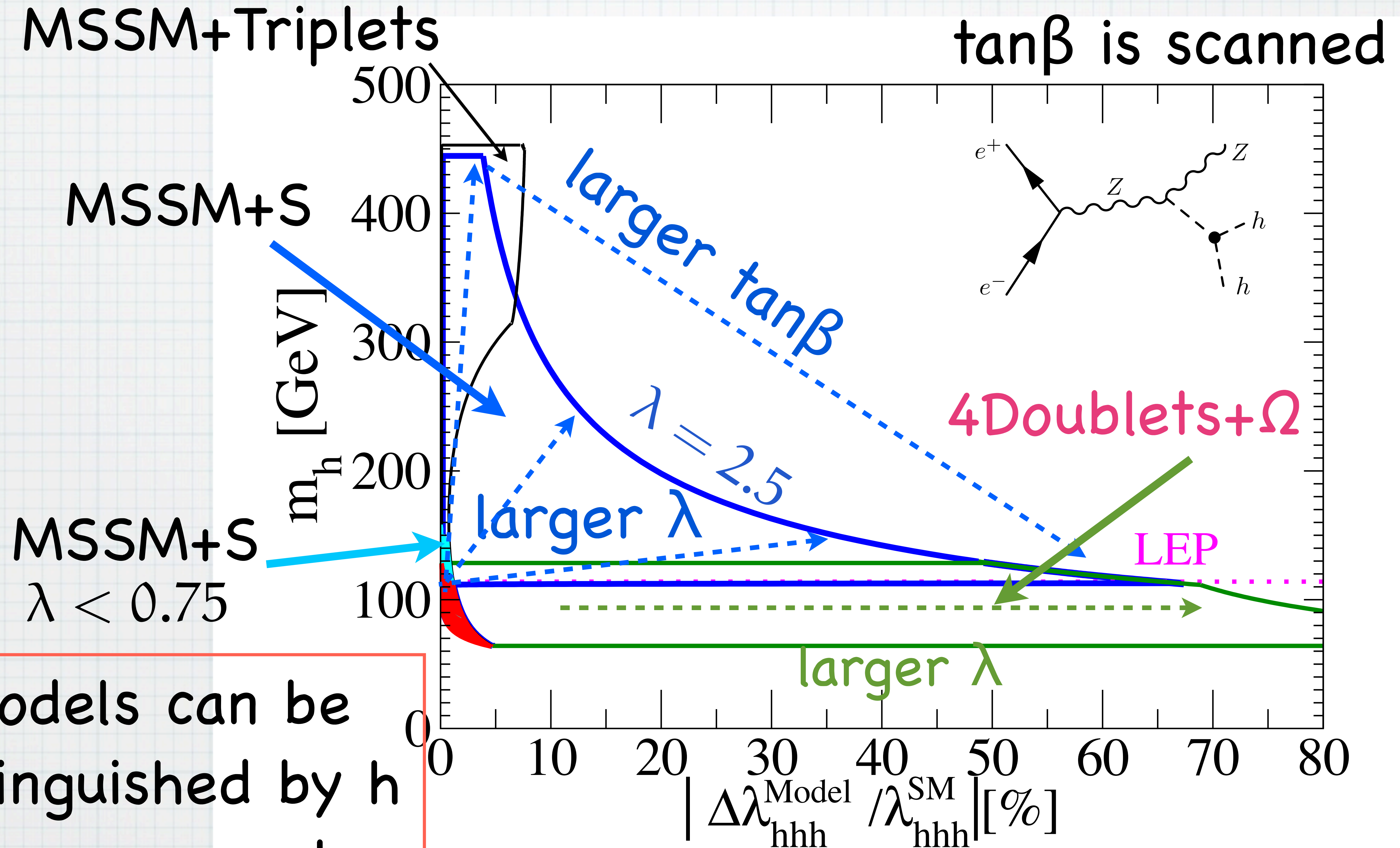
The additional scalar can give a significant non-decoupling effect when vev dominates its mass

The structure of contribution depends on which extra fields are introduced

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v}\left[1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \frac{m_{\Phi_S}^4}{12\pi^2 m_h^2}\left(1 - \frac{M_0^2}{m_{\Phi_S}^2}\right)^3\right]$$

m_h and λ_{hhh}

4Doublets+Ω is a simplest example of $W = \lambda \Phi_{u,d} \Phi'_1 \Phi'_2$



Models can be distinguished by h measurement

S.Kanemura, T.S., K. Yagyu, PLB699.258

Quasi non-decoupling

Strong F-term coupling can cause large non-decoupling effect such as $\Delta\lambda_{hhh}$

because $m_\varphi^2 = M^2 + \lambda^2 v^2$ contribution from vev can be significantly large

Extra scalar mass

If F-term coupling is not strong, no large vev contribution to the extra scalar mass

↓ Decoupling theorem

The extra field contributions are decoupled in SM limit

Even in such a case, non-decoupling effects can remain in the MSSM limit

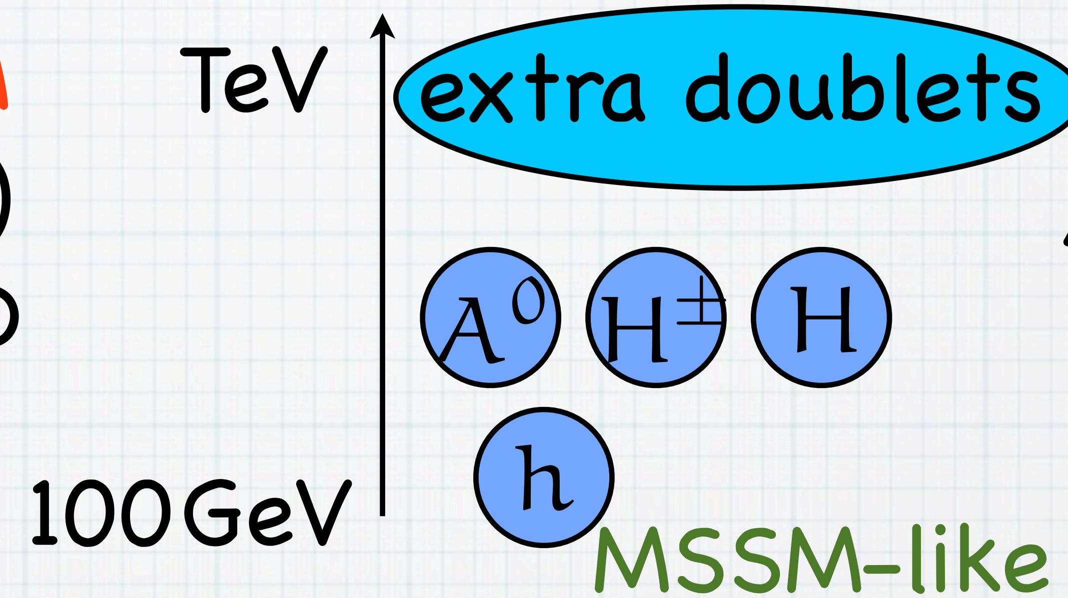
Quasi non-decoupling

No deviation in λ_{hhh}, but deviations in the MSSM prediction on Higgs sector e.g. $m_{H^\pm}^2 \simeq m_A^2 + m_W^2$

4HDSSM

Gupta&Wells,PRD81,055012;Marshall&Sher, PRD83,015005;
Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038;...

We consider a SUSY-SM with 4doublets(4HDSSM) in order to see how QND effects appear



4 CP even&
3 CP odd&
3 charged

Extra doublets model is quite interesting

4HDSSM+Ω ⟶ strong 1st order EWPT is easily realized

In loop induced neutrino mass model, extra doublets are sometimes introduced.

If strong λ in $W = \lambda\Phi_{u,d}\Phi'_{u,d}\Omega^{\mp}$ ⟶ significant deviation in λ_{hhh}

Even if λ is weak/no λ,

quasi non-decoupling effect can appear in the MSSM limit

Yukawa Types in 4HDSSM

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038

To suppress FCNC , Z_2 symmetry is often introduced.

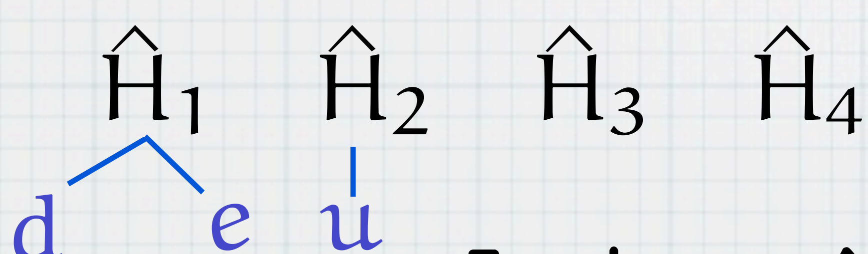
In the 4HDSSM, there are two types.

If right-handed neutrino is considered,

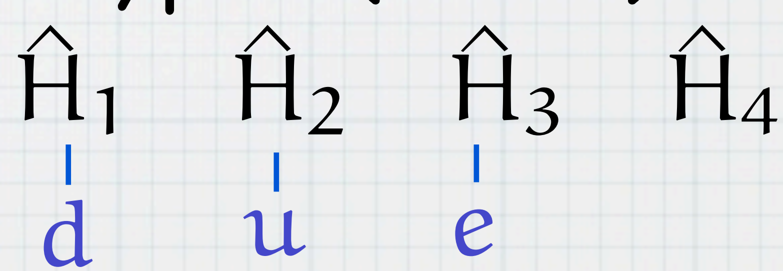
the number of types is doubled

	$\hat{H}_1$	$\hat{H}_2$	$\hat{H}_3$	$\hat{H}_4$	U^c_R	D^c_R	E^c_R	Q_L	L_L	N^c_R
Type A	+	+	−	−	+	+	+	+	+	+
Type B	+	+	−	−	+	+	−	+	+	+
Type C	+	+	−	−	+	+	+	+	+	−
Type D	+	+	−	−	+	+	−	+	+	−

type A(and C)



type B(and D)



In type A and C, Z_2 can be exact

In this talk, we focus on the scalar sector

Lagrangian (Higgs sector)

Superpotential

$$W = -\mu_{12} H_1 \cdot H_2 - \mu_{14} H_1 \cdot H_4 - \mu_{32} H_3 \cdot H_2 - \mu_{34} H_3 \cdot H_4$$

SUSY breaking terms

$$\mathcal{L}_{\rm soft} = \begin{pmatrix} \hat{\Phi}_1^\dagger & \hat{\Phi}_3^\dagger \end{pmatrix} \tilde{\mathbf{M}}_-^2 \begin{pmatrix} \hat{\Phi}_1 \\ \hat{\Phi}_3 \end{pmatrix} + \begin{pmatrix} \hat{\Phi}_2^\dagger & \hat{\Phi}_4^\dagger \end{pmatrix} \tilde{\mathbf{M}}_+^2 \begin{pmatrix} \hat{\Phi}_2 \\ \hat{\Phi}_4 \end{pmatrix}$$

$$- \Big(B_{12}\mu_{12} \hat{\Phi}_1 \cdot \hat{\Phi}_2 + B_{12}\mu_{34} \hat{\Phi}_3 \cdot \hat{\Phi}_4 + B_{12}\mu_{14} \hat{\Phi}_1 \cdot \hat{\Phi}_4 + B_{12}\mu_{32} \hat{\Phi}_3 \cdot \hat{\Phi}_2 + \text{h.c.} \Big)$$

We retake the basis as:

$$\begin{pmatrix} \Phi_1 \\ \Phi_1' \end{pmatrix} = U_- \begin{pmatrix} \hat{\Phi}_1 \\ \hat{\Phi}_3 \end{pmatrix} \quad \begin{pmatrix} \Phi_2 \\ \Phi_2' \end{pmatrix} = U_+ \begin{pmatrix} \hat{\Phi}_2 \\ \hat{\Phi}_4 \end{pmatrix}$$

Only Φ_1 and Φ_2 get the vev

$$\langle \Phi_1 \rangle = \frac{v}{\sqrt{2}} c_\beta \quad \langle \Phi_2 \rangle = \frac{v}{\sqrt{2}} s_\beta$$

Decoupling case

Scalar potential is

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038

$$V = \begin{pmatrix}\Phi_1^\dagger & \Phi_1'^\dagger\end{pmatrix} \mathbf{M_1^2} \begin{pmatrix}\Phi_1 \\ \Phi_1'\end{pmatrix} + \begin{pmatrix}\Phi_2^\dagger & \Phi_2'^\dagger\end{pmatrix} \mathbf{M_2^2} \begin{pmatrix}\Phi_2 \\ \Phi_2'\end{pmatrix}$$

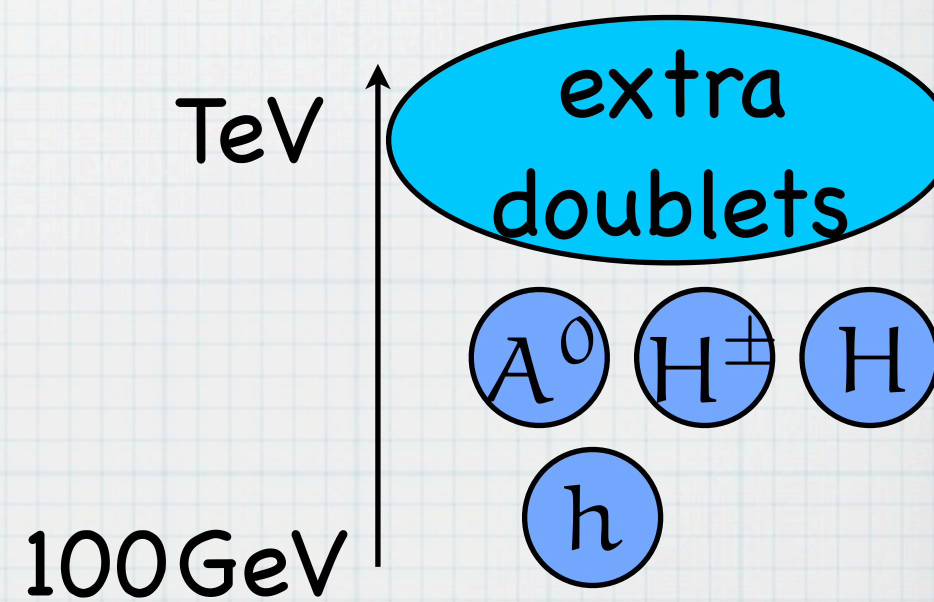
$$- \left(\begin{pmatrix}\Phi_1 & \Phi_1'\end{pmatrix} \mathbf{M_3^2} \cdot \begin{pmatrix}\Phi_2 \\ \Phi_2'\end{pmatrix} + \text{h.c.} \right) + \text{D-terms}$$

$$\hat{M}_A^2 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 2(M_3^2)_{11}/s_{2\beta} & k' M^2 & k M^2 \\ 0 & k' M^2 & M^2 & 0 \\ 0 & k M^2 & 0 & r M^2 \end{pmatrix}$$

Φ' are mixed with angle $\bar{\theta}$

MSSM-like sector

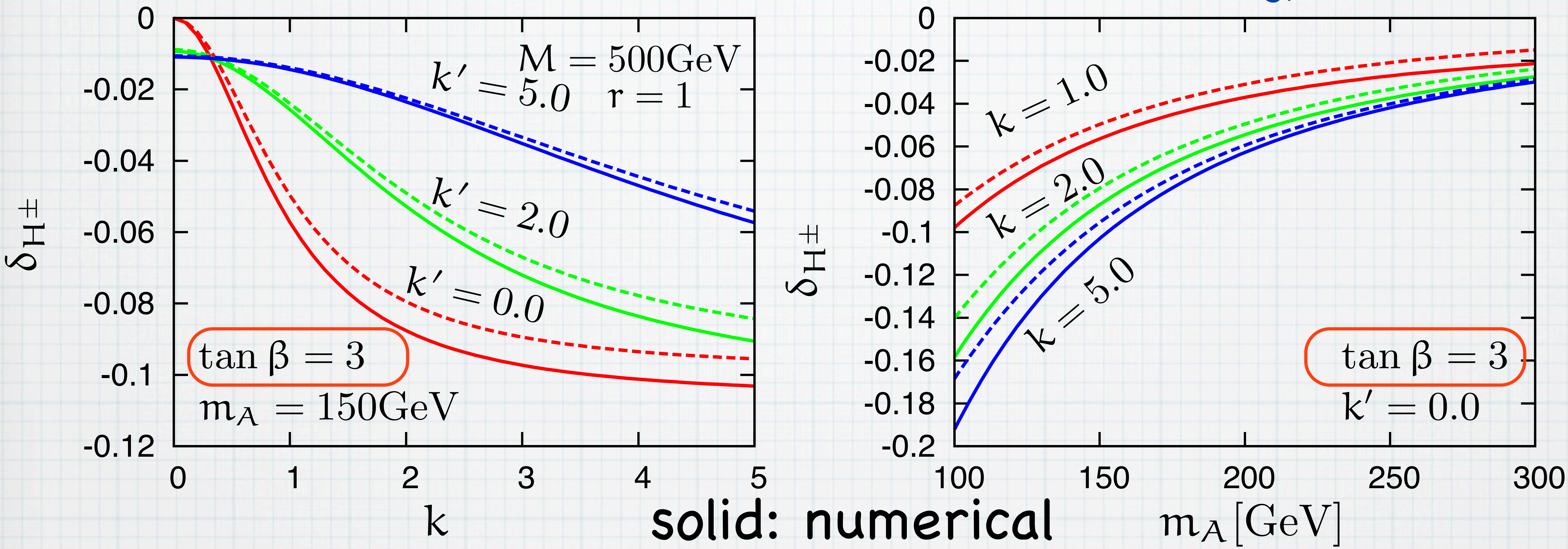
is obtained by further base rotation.



We assume MSSM-like Higgs bosons are light and the extra ones are too heavy to be directly observed.

Charged Higgs mass

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038



solid: numerical

dashed: approximate

$$\delta_{H^\pm} \equiv \frac{m_{H^\pm}}{m_{(H^\pm)^{MSSM}}} - 1$$

$$(m^2_{H^\pm})^{MSSM}_{tree} = m_A^2 + m_W^2$$

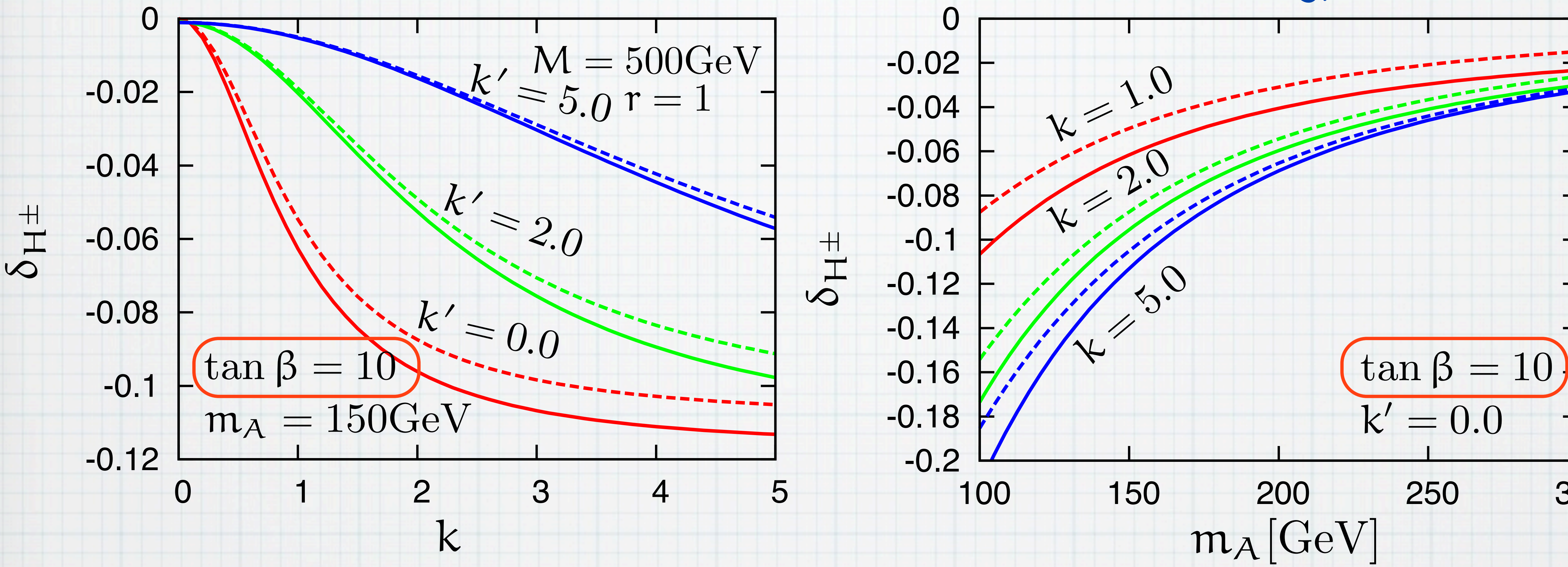
For $k' = \bar{\theta} = 0$

$$\delta_{H^\pm} = -\frac{m_W^2}{2(m_A^2+m_W^2)}\frac{k^2 s_\beta^2}{(r^2+k^2)} + \mathcal{O}\left(\frac{m_A^2}{M^2}\right)$$

nondecoupling(QND) for $M \to \infty$

Charged Higgs mass

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038



$$\delta_{H^\pm} \equiv \frac{m_{H^\pm}}{m_{(H^\pm)^{MSSM}}} - 1$$

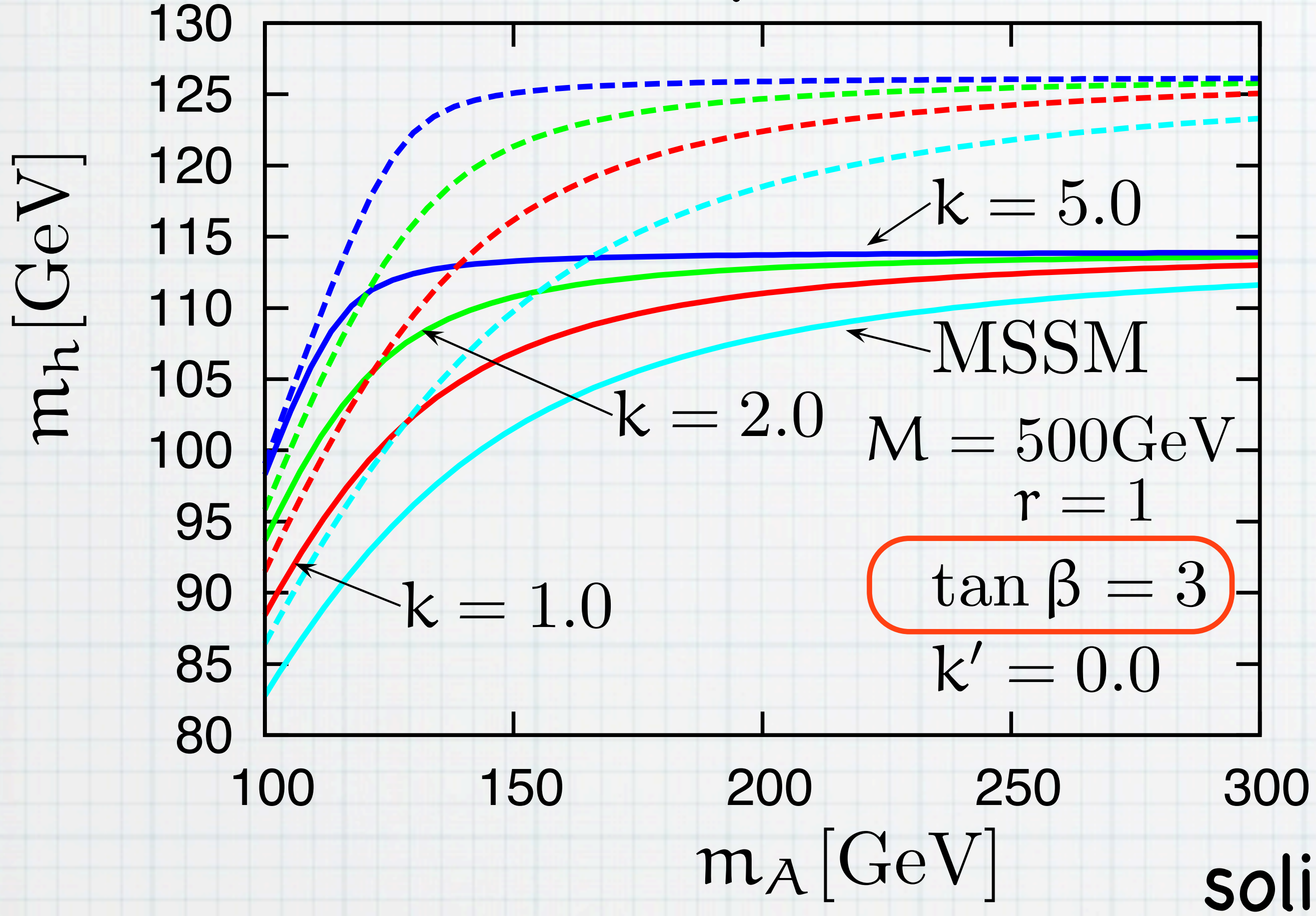
$$(m^2_{H^\pm})^{MSSM}_{tree} = m_A^2 + m_W^2$$

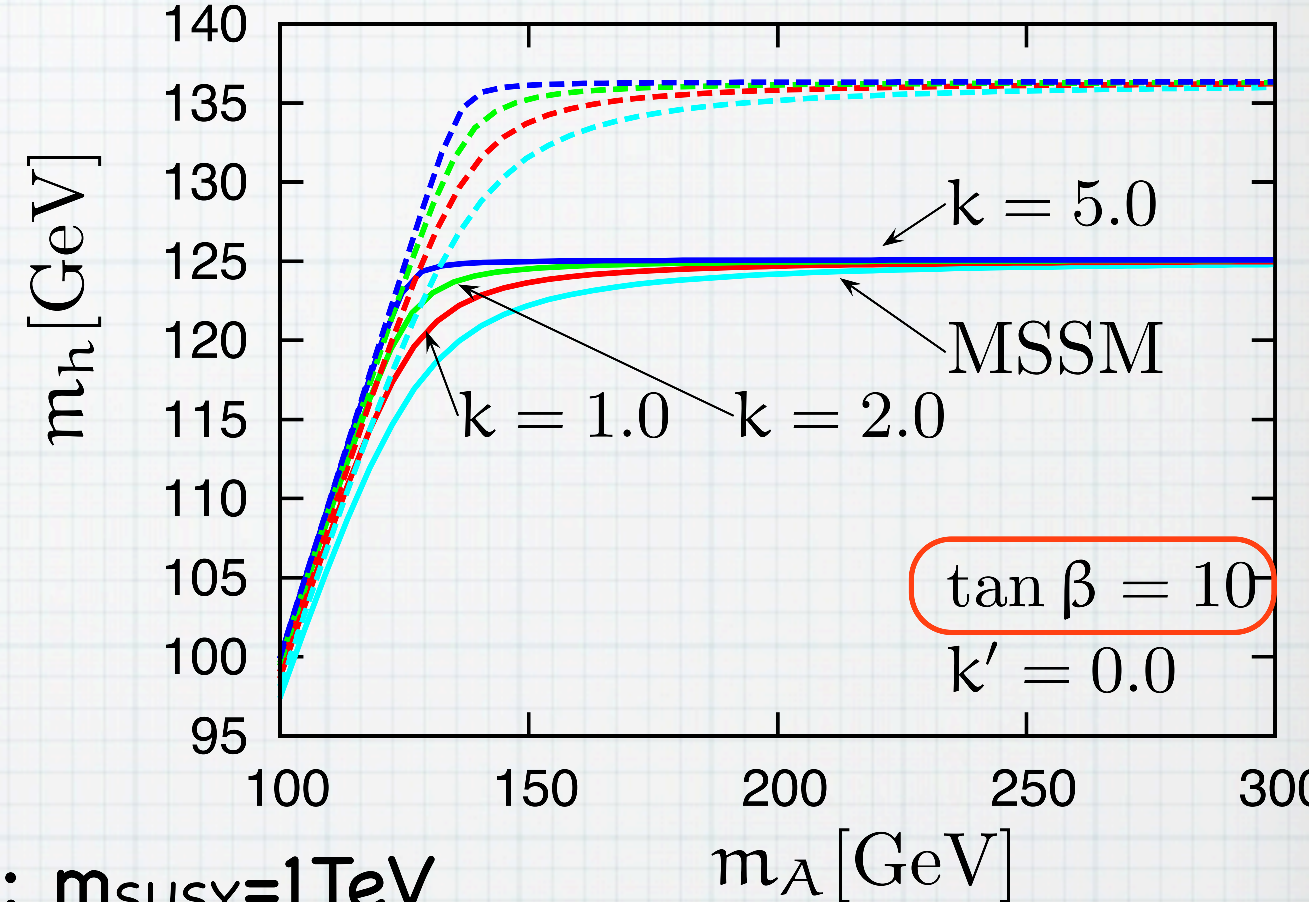
tanβ dependence is small

The lightest Higgs mass

m_h @ 1-loop

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038





solid: m_{SUSY}=1TeV

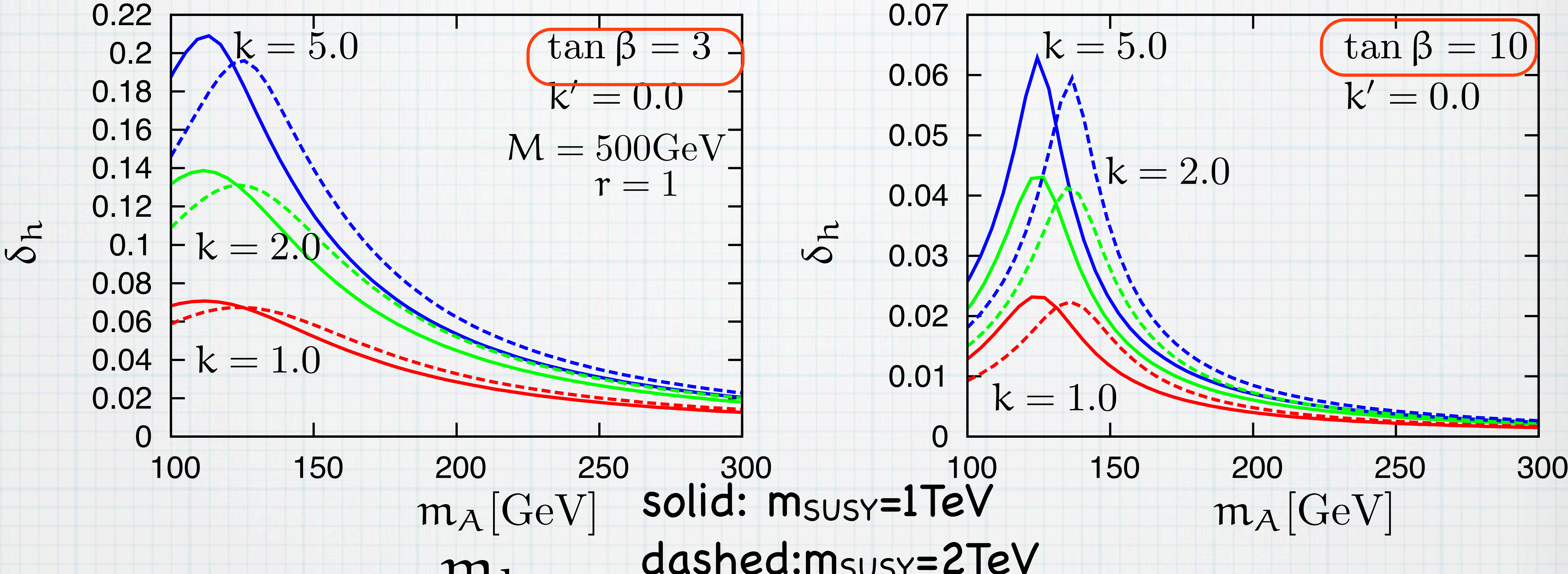
dashed:m_{SUSY}=2TeV

The upper bound is the same as the MSSM one.

However, m_h can reach the upper bound for smaller m_A and tanβ !!

The lightest Higgs mass

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038



$$\delta_h = \frac{m_h}{m_h^{\rm MSSM}} - 1$$

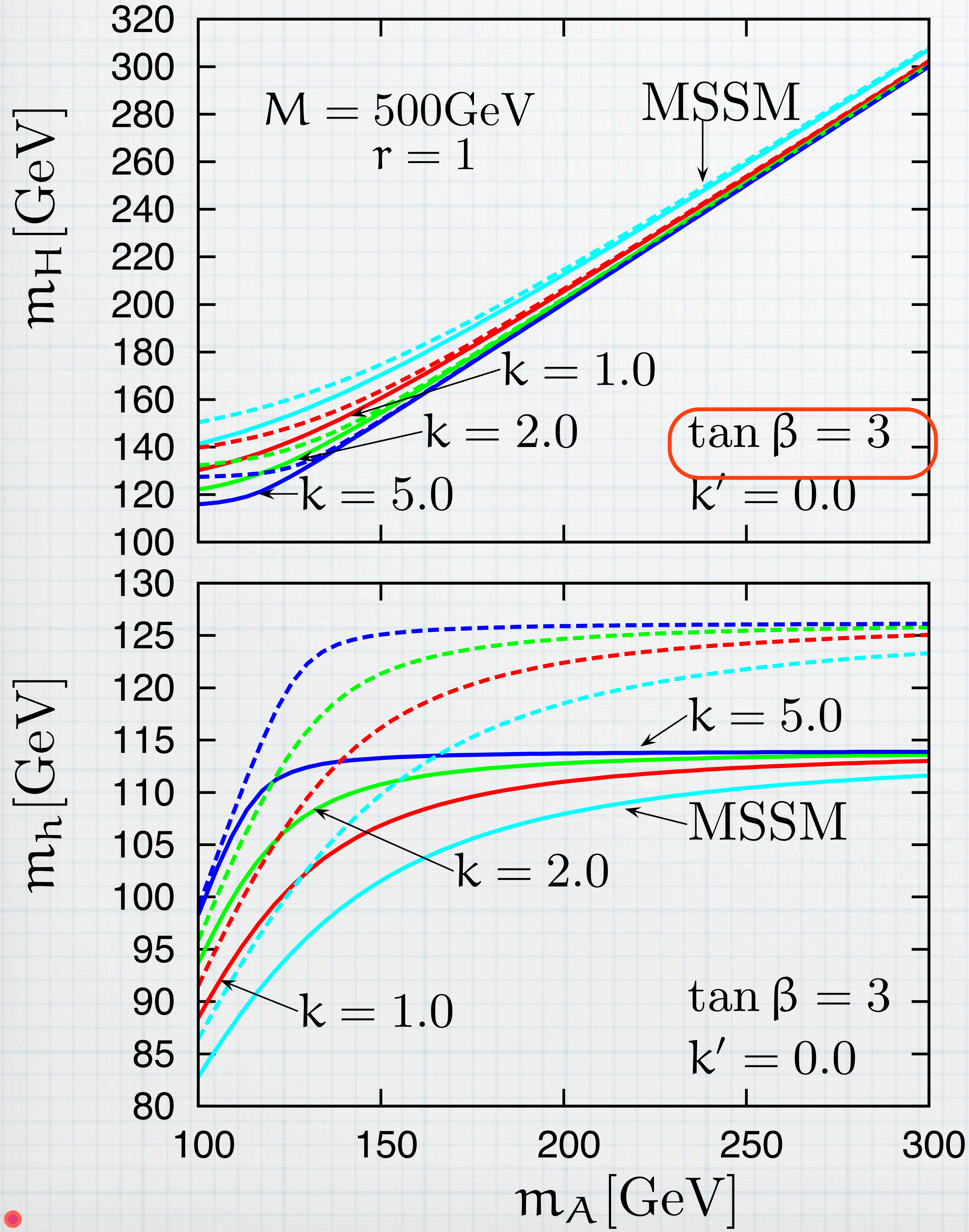
The effect is larger for smaller tanβ

10% deviation is possible for m_A=150GeV(tanβ=3)

The lightest Higgs mass is pushed up!

Heavy Higgs mass

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038



solid: m_{SUSY}=1TeV

dashed: m_{SUSY}=2TeV

m_h: larger

m_H: smaller

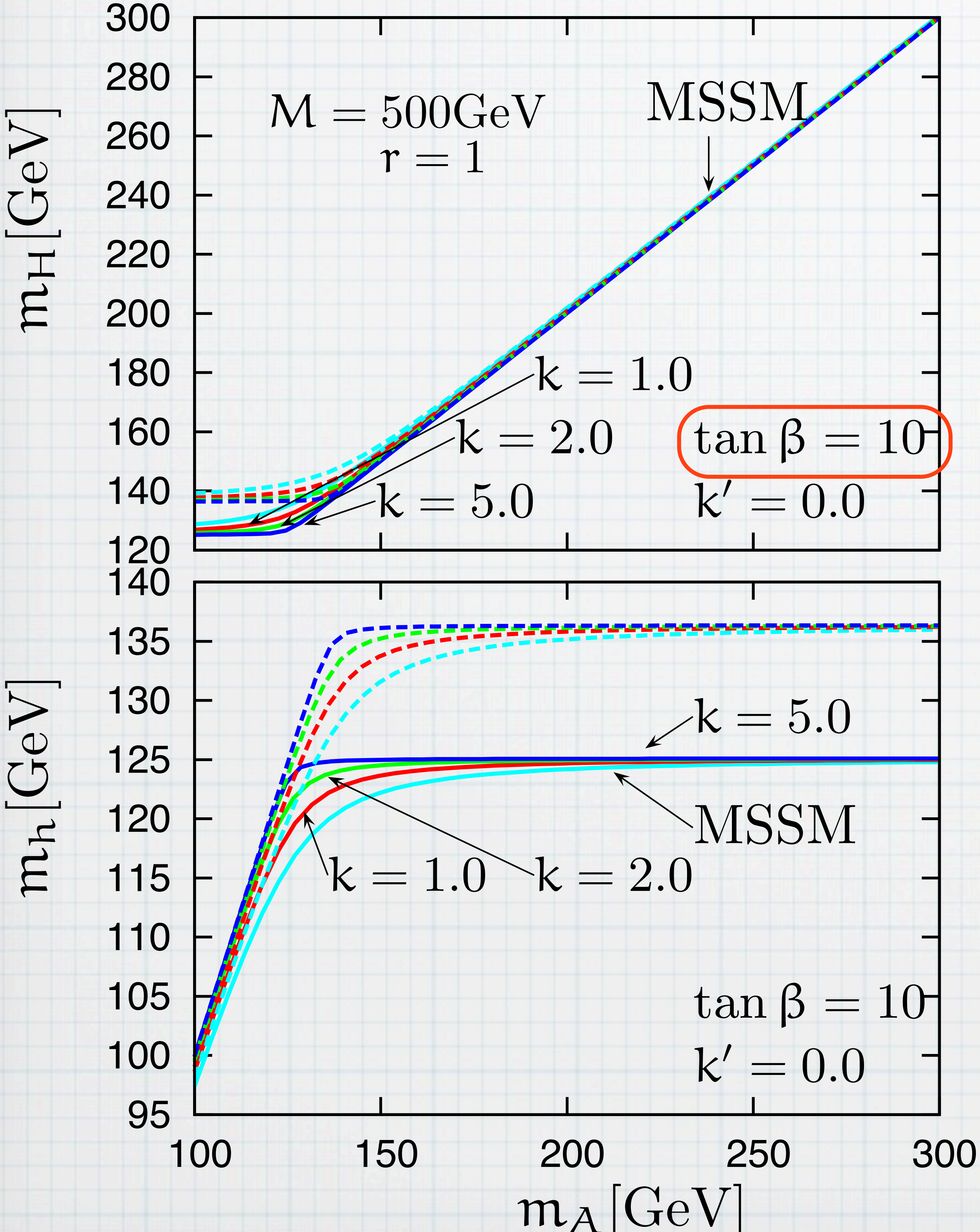
h-H crossing effect becomes strong

The crossing point shifts

k and k′ accelerate the decoupling of m_A

Heavy Higgs mass

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038



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m_h: larger

m_H: smaller

h-H crossing effect becomes strong

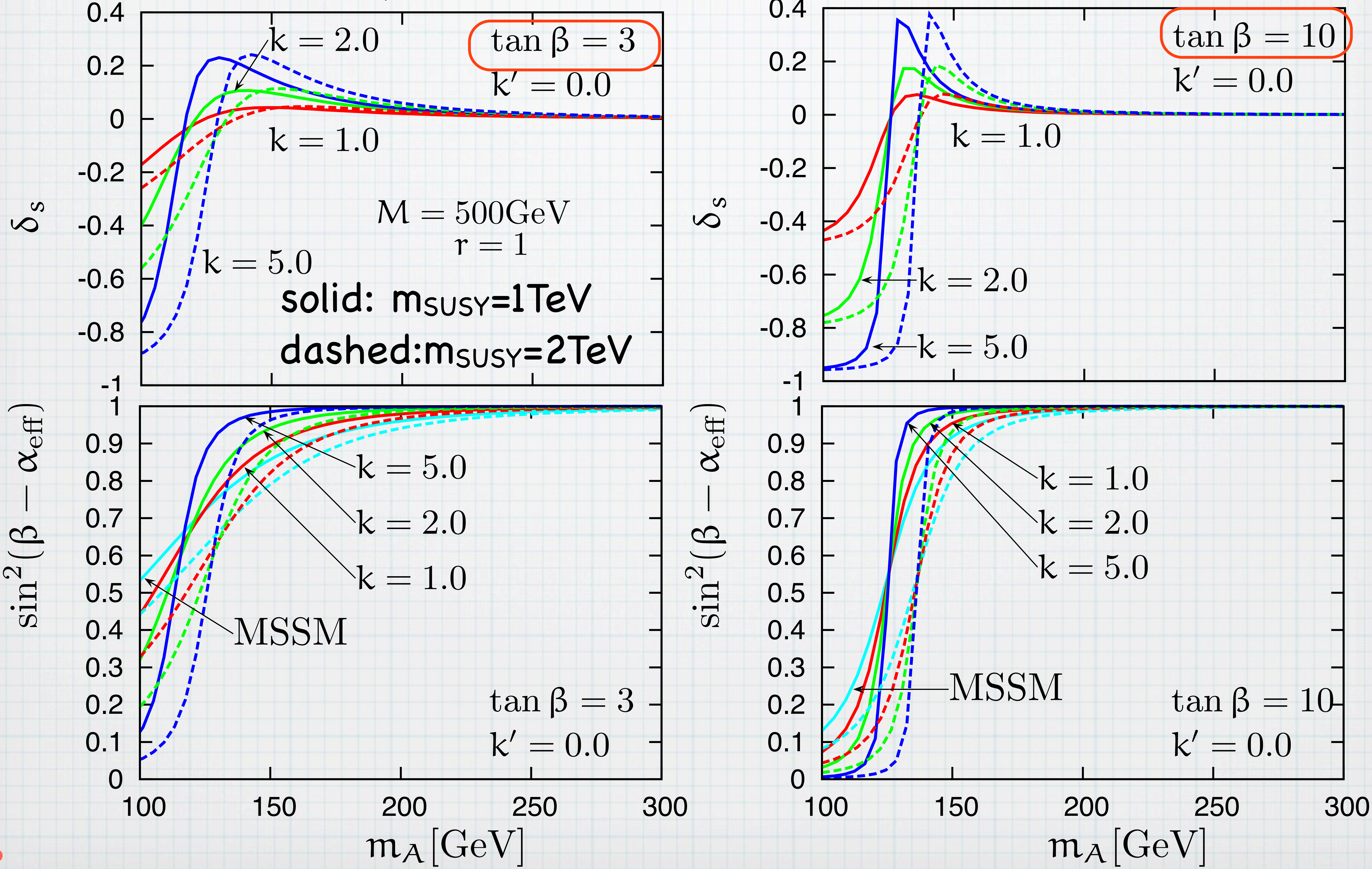
The crossing point shifts

k and k′ accelerate the decoupling of m_A

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

$$\sin(\beta - \alpha_{\rm eff}) \equiv \frac{v}{m_V^2}\Gamma_{VVh} \quad V = W, Z$$

Aoki&Kanemura&T.S.&Yagyu, JHEP1111,038



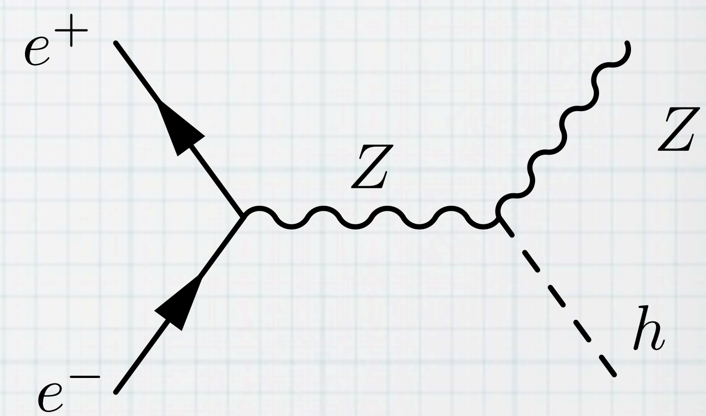
Summary

If the excess at 125 GeV is a real signal

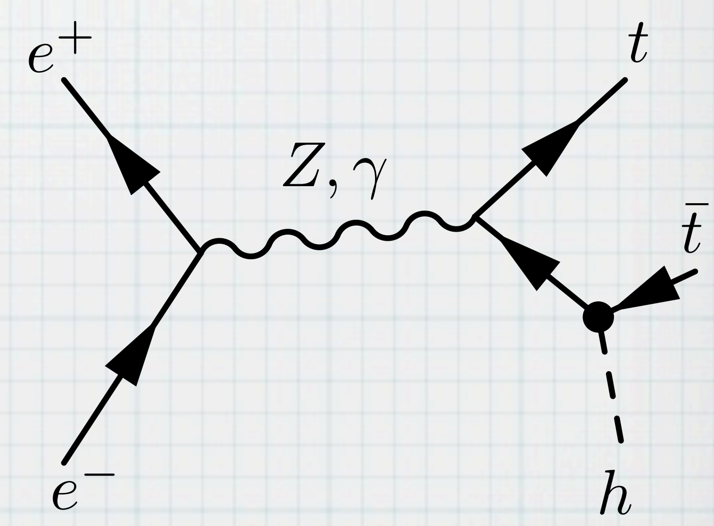
Is it really Higgs ? ← It will be tested by Measuring the couplings ZZh, hff ...

If it seems SM Higgs

Is it the SM Higgs?
or
SM-like Higgs in extended Higgs sector ?



In addition, if extra scalars (e.g. A, H, $H^\pm$, SUSY particles) are discovered



- Non-SUSY extended Higgs sector?
- MSSM Higgs sector?
- Extended SUSY Higgs sector?

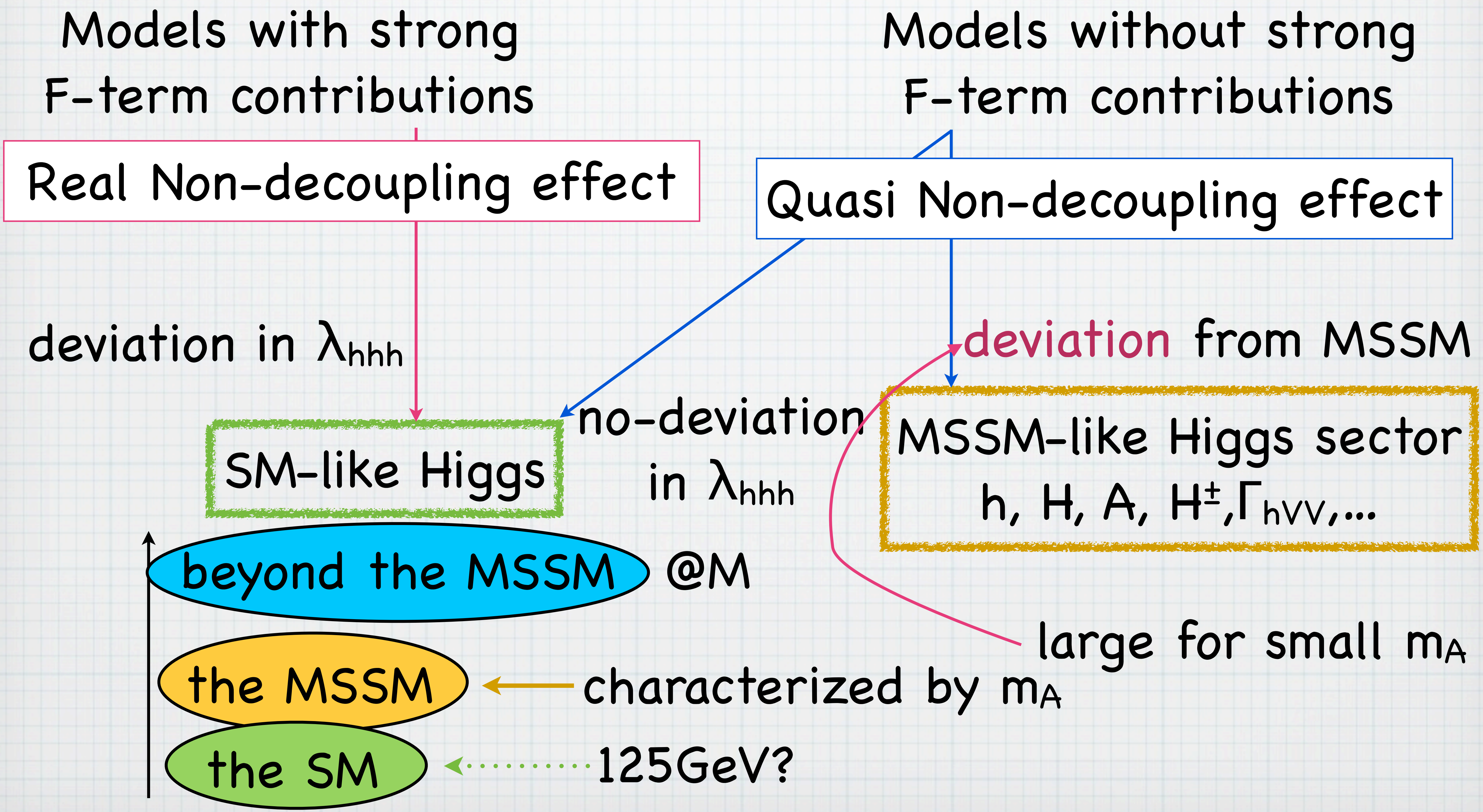
Summary

- Precision exploration on Higgs sector is very important
  - Structure of the Higgs sector decides the direction of more fundamental theory

    GUT with grand desert? or strong dynamics at TeV?
- SUSY model has two types of non-decoupling effects
  - Real non-decoupling through strong F-term coupling
    - Precise measurement on hhh coupling can detect it
  - Quasi non-decoupling effects — typically O(10%)
    - Precise test of MSSM relations is sensitive to them
- ILC is a powerful tool to take a great step toward the fundamental picture of the elementary particle theory

Summary

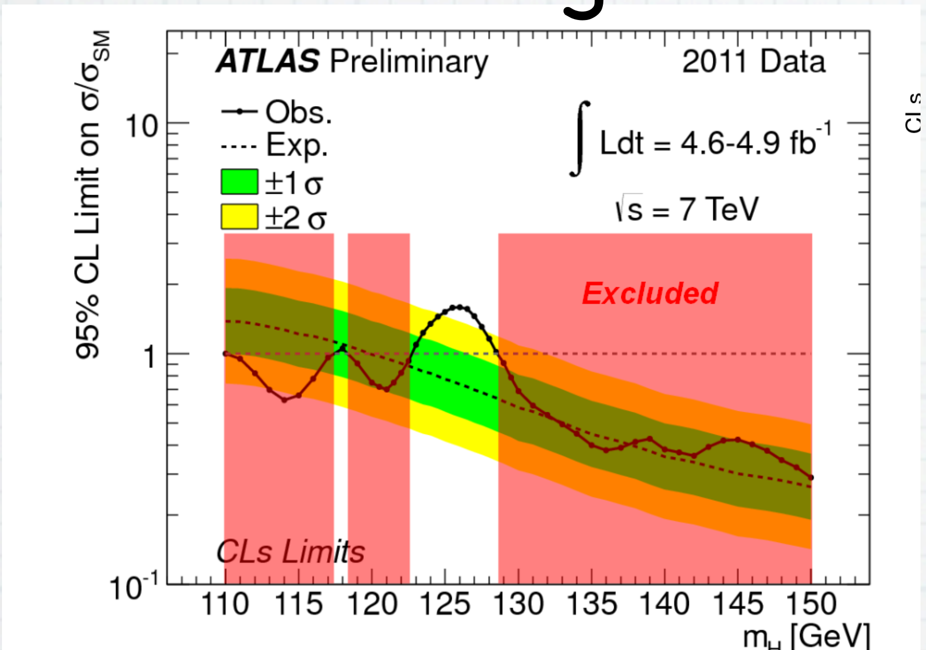
Two types of non-decoupling effects are possible in the extended SUSY Higgs sectors with m_h=125GeV



BACKUP

Higgs mass of 125GeV?

The wide region of the Higgs mass has already excluded !!



S. Kortner, talk at Moriond

117.5-118.5GeV, 122.5-128.5GeV

or

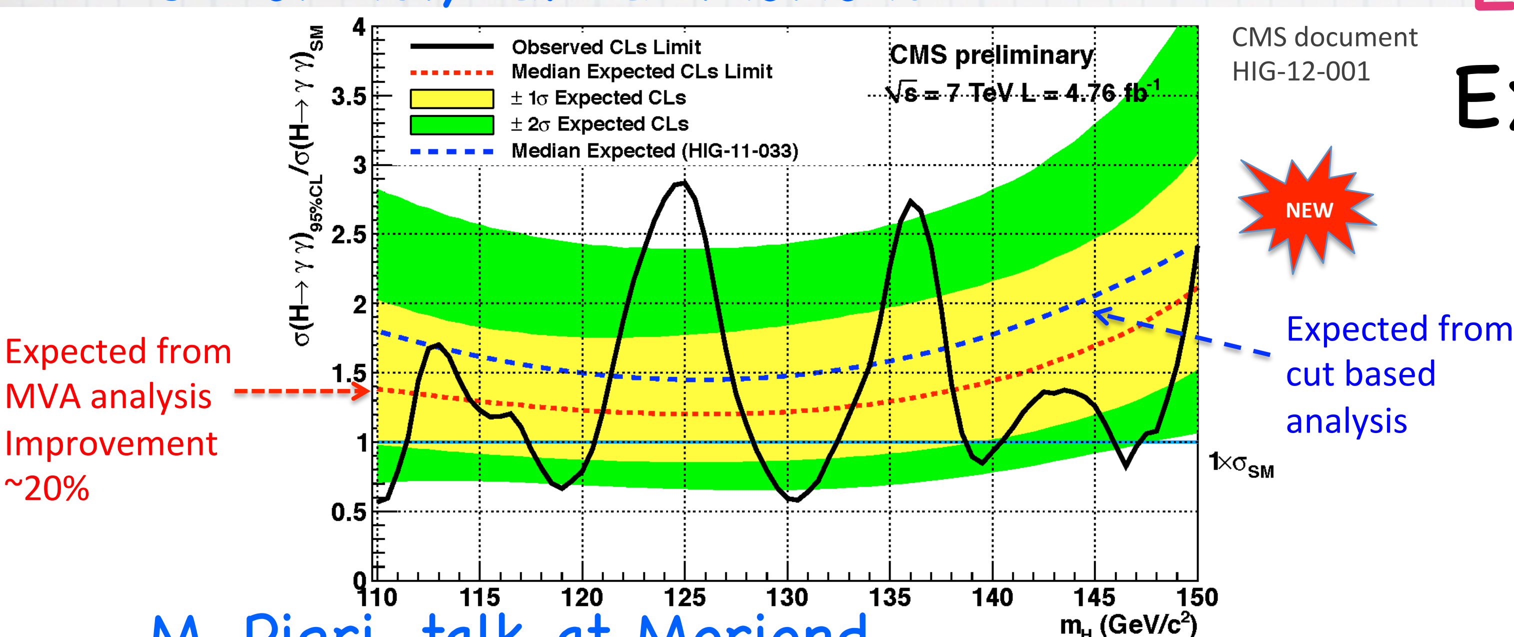
Heavier than 539GeV

are allowed.

Light Higgs is suggested

Excess of events is observed at ~125GeV

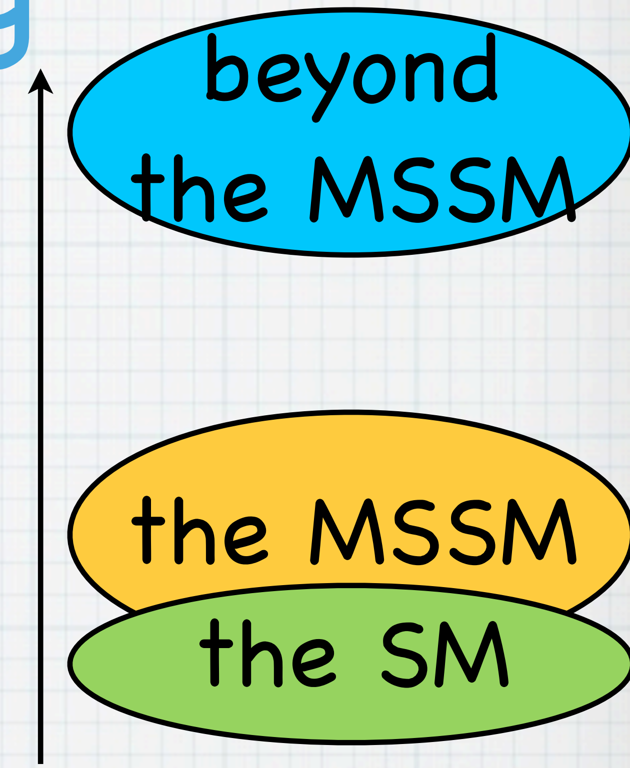
Is it real signature or statistical fluctuations?



M. Pieri ,talk at Moriond

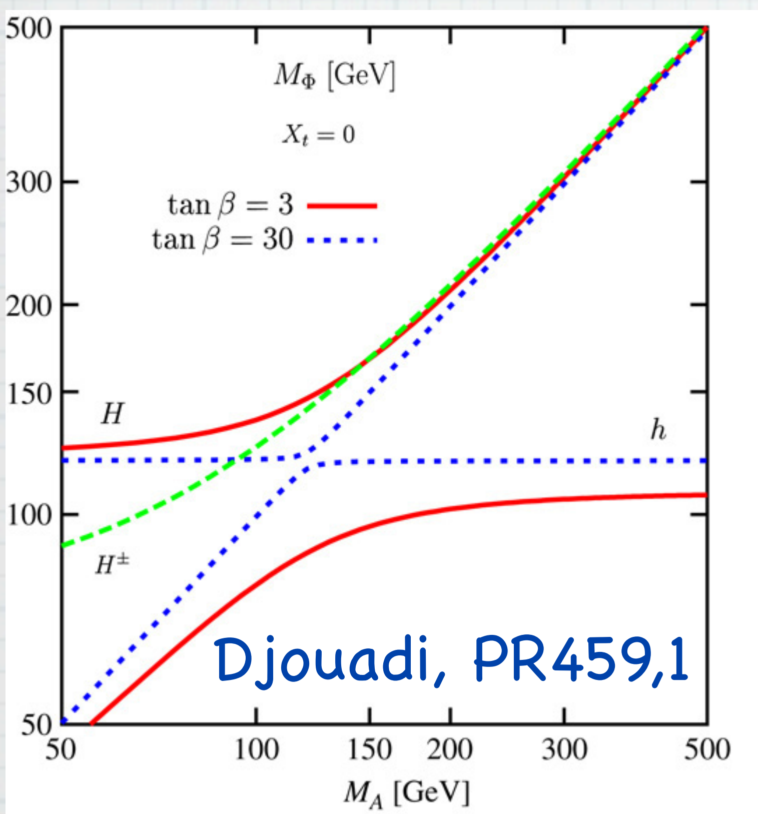
If 125GeV Higgs is realized in nature, it will be discovered in a year.

Quasi non-decoupling



Even when the extra field mass is not dominated by the vev, contributions to the MSSM observables remains

MSSM Higgs sector can be characterized by only two parameters, m_A and $\tan\beta$



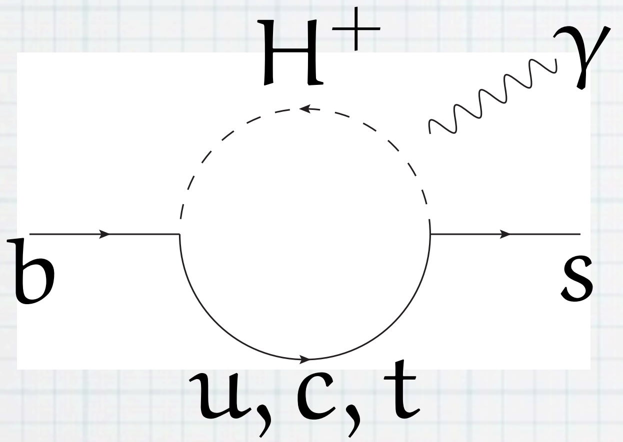
Mixing between MSSM sector and heavy extra scalars significantly affect such predictions.

In the SM limit, such effects are decoupling!!

(No deviations in the SM prediction e.g. on the hhh coupling)

Flavour problem

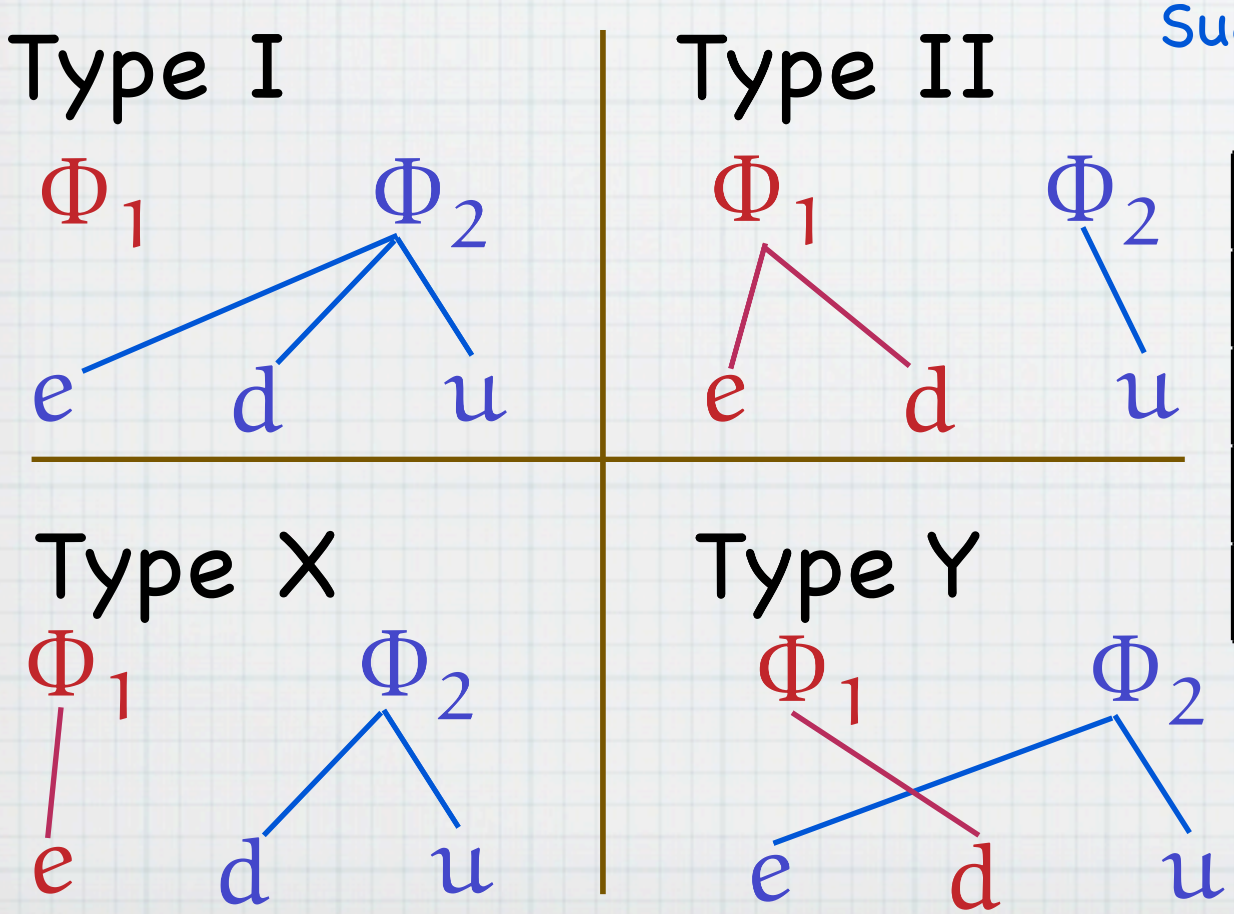
FCNC is very serious in the multi doublets model



In order to suppress it , discrete symmetry (e.g. Z_2) is often introduced.

non-SUSY 2HDM: 4 Types of Yukawa couplings

Barger et al.,PRD41; Grossman, NPB426;Aoki et al.,PRD80; Su&Thomas,PRd79;Logan&MacLennan,PRD79



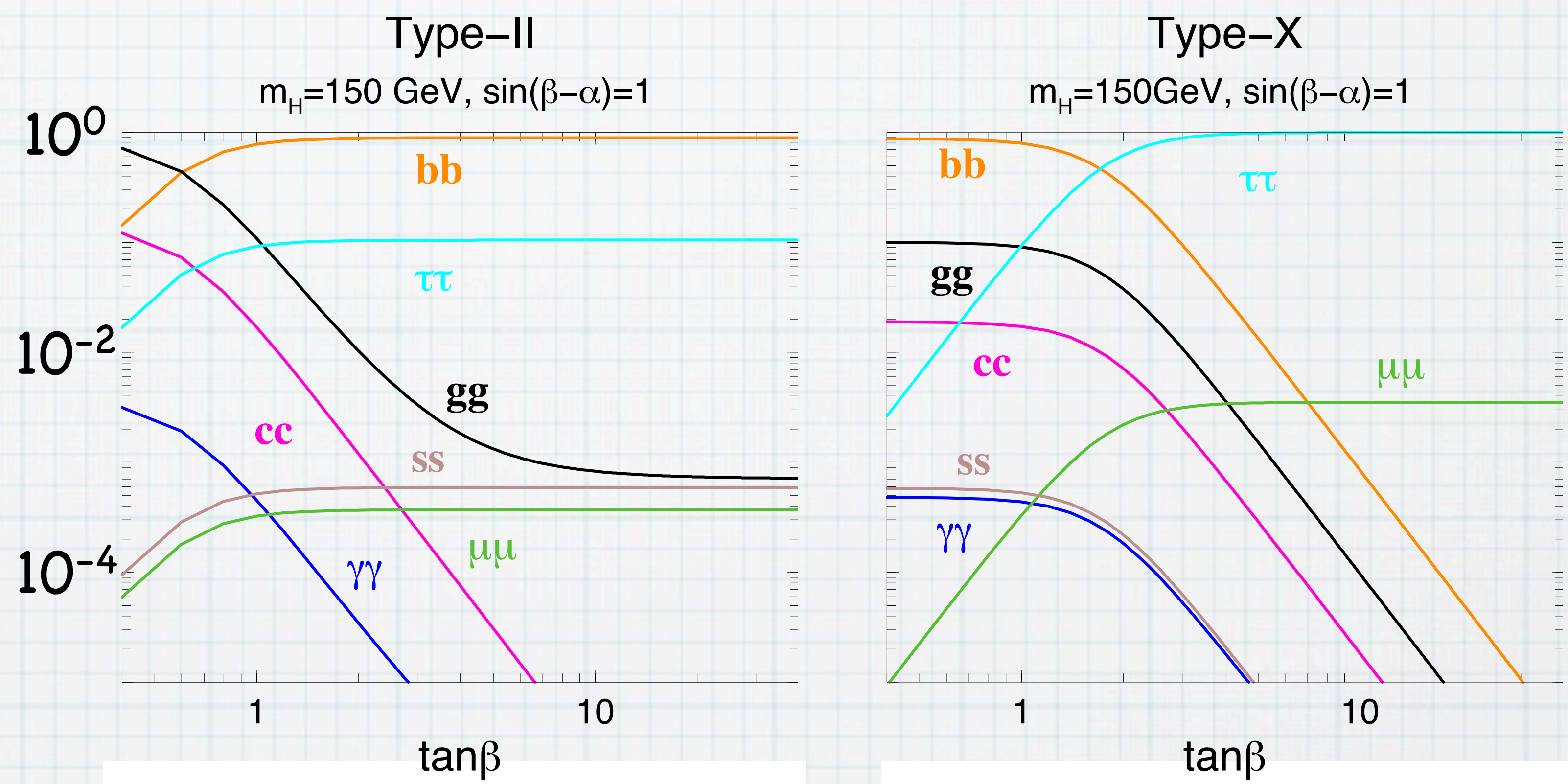
Type	Φ_1	Φ_2	u_R	d_R	e_R	q_L, ℓ_L
I	+	−	−	−	−	+
II	+	−	−	+	+	+
X	+	−	−	−	+	+
Y	+	−	−	+	−	+

Types of non-SUSY 2HDM

Difference in collider/flavour phenomenology

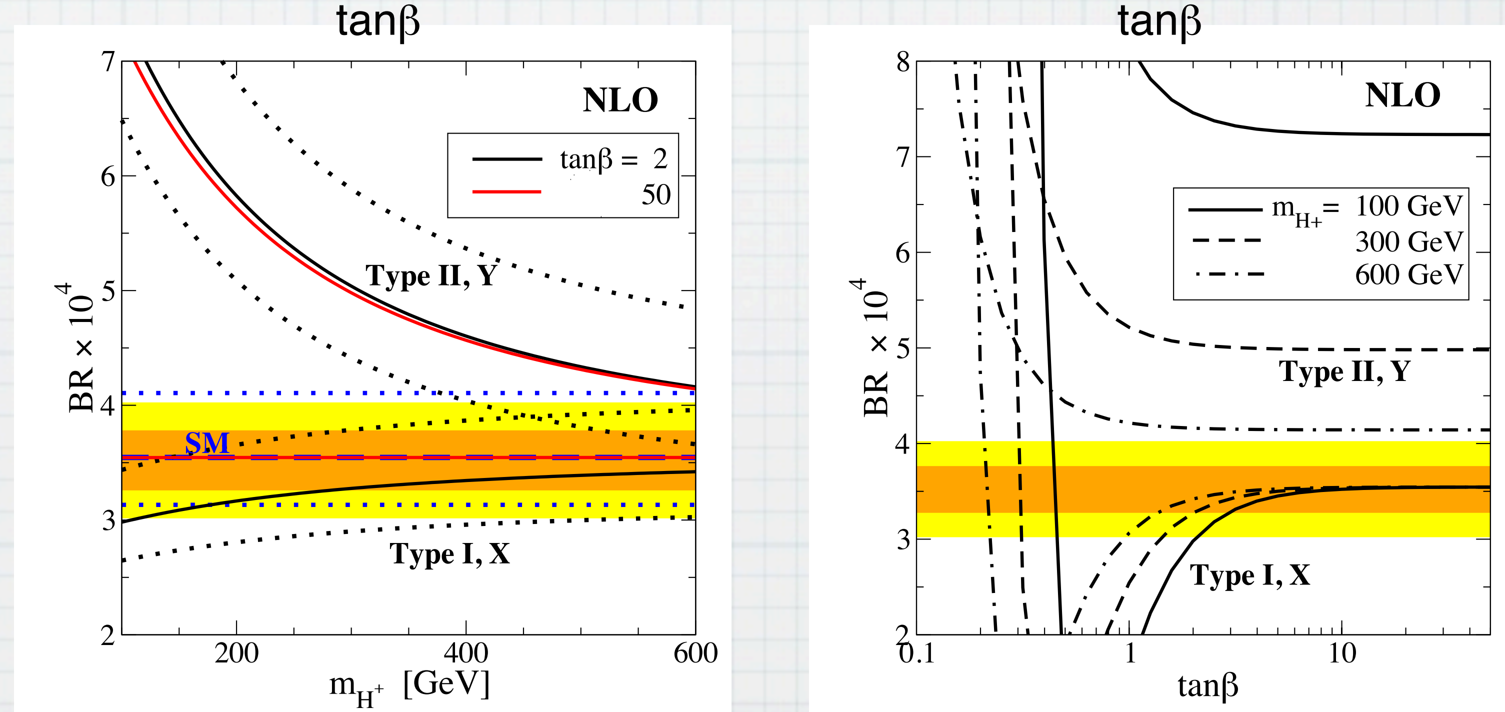
Decay branching ratio of Heavy Higgs

$H \to \tau\tau$ is specific in type X



Branching ratio of $b \to s\gamma$

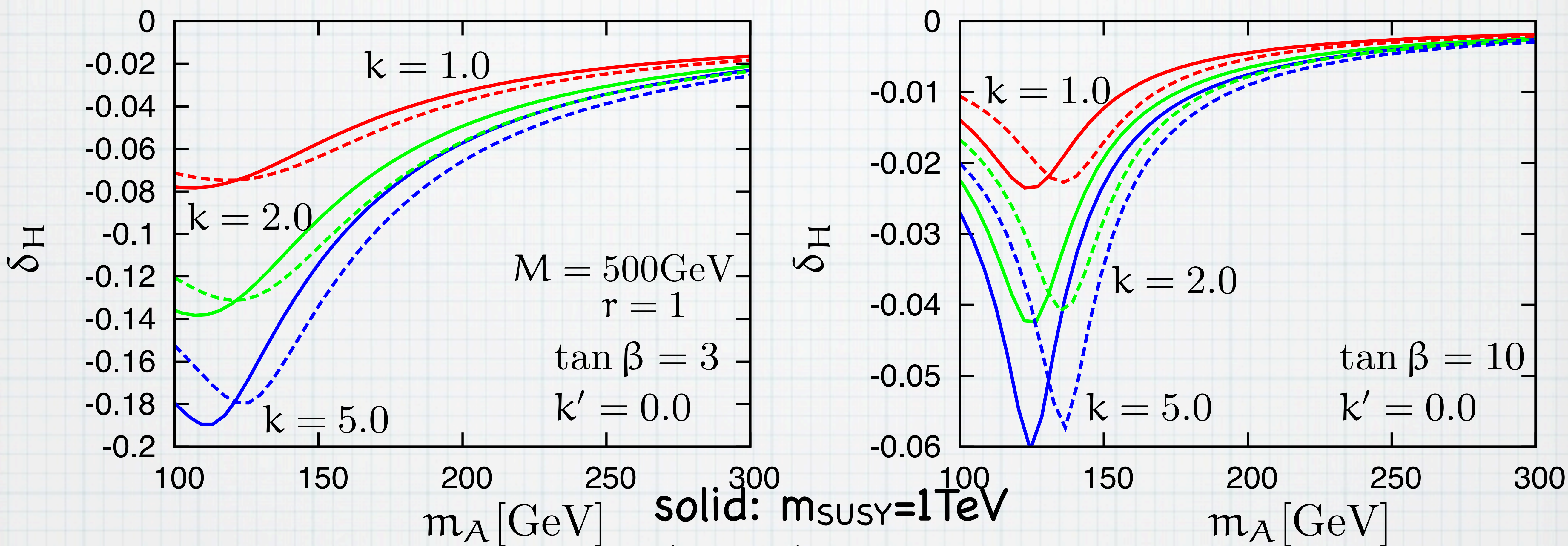
I,X and II, Y are quite different



M.Aoki, S.Kanemura, K.Tsumura,K.Yagyu,PRD80,015017

Heavy Higgs mass

Aoki&Kanemura&T.S.&Yagyu, arXiv:1108.1356



solid: m_{SUSY}=1TeV

dashed:m_{SUSY}=2TeV

Heavy Higgs mass get a negative correction

The effect is larger for smaller tanβ

10% deviation is possible for m_A=150GeV(tanβ=3)

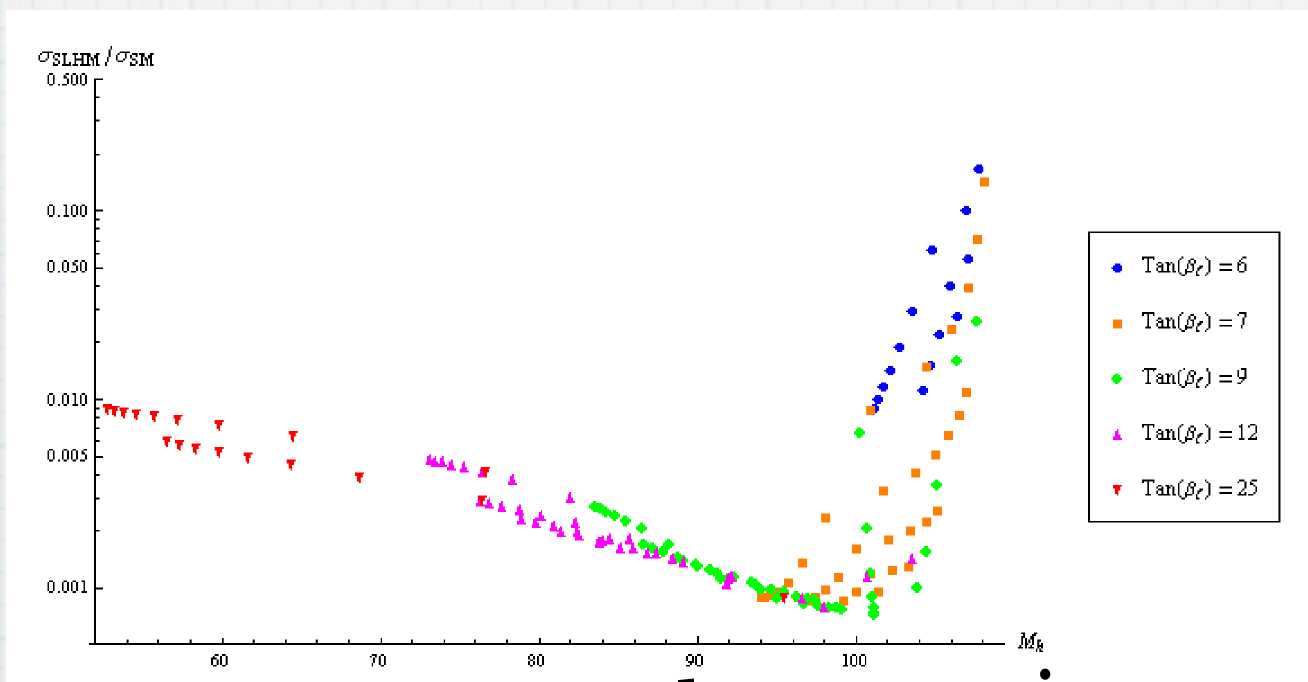
Lepton specific 4DSSM

Marshall&Sher, PRD83, 015005

Lepton specific case (Type-B) is interesting scenario.

Especially if non-MSSM-like doublets are rather light, the situation is drastically changed from the MSSM

Very light Higgs is possible (LEP bound is relaxed) owing to mixing effect



$h \rightarrow \tau\tau$ is a main decay mode

FIG. 6: Logplot of the ratio of the production cross section of the lightest neutral scalar by gluon fusion in the SLHM to the Standard Model.