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HIDDEN LIGHT SINGLET HIGGS BOSONS IN NMSSM WITH TEV SCALE MIRAGE MEDIATION

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Based on K.Hagimoto, T.Kobayashi, H. Makino, K.O., T.Shimomura
arXiv:1509.05327

Introduction

- Supersymmetry is attractive BSM candidate.
  - Big hierarchy + Unification
  - Light SM like Higgs (125 GeV): weak self-coupling
- Little hierarchy problem
  - Missing superpartners (mq~ >1.5 TeV LHC7+8)
  - Higgs is too heavy → multi-TeV stop ?
  - Fine tuning <1%

$$\frac{M_Z^2}{2} \simeq |m_{H_u}^2| - \mu^2 + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right)$$

"TeV scale mirage mediation in NMSSM" still fine !

⇒ light (~100 GeV) almost decoupled singlet

Mirage mediation

Soft SUSY breaking terms= (Moduli + Anomaly) Mediation

K.Choi A.Falkowski H.P.Niles M.Olechowski and S.Pokorski (2005)

$$-\mathcal{L}_{\rm Soft} = M_a \overline{\lambda_a} \lambda_a + m_i^2 |\phi_i|^2 + \left\{ + \frac{1}{3!} Y_{ijk} A_{ijk} \phi_i \phi_j \phi_k + \text{h.c.} \right\}$$

$$M_a(M_G) = M_0 + (\text{Anomaly Mediation})$$

$$A_{ijk}(M_G) = (c_i + c_j + c_k) M_0 + (\text{Anomaly Mediation})$$

$$m_i^2(M_G) = c_i |M_0|^2 + (\text{Anomaly Mediation}) \qquad c_i = 0,\ 1/3,\ 1/2,\ 1$$

RG corrections cancel with anomaly mediation at $M_{\rm mir}$.

$$M_{\rm mir} = \frac{M_G}{(M_{Pl}/m_{3/2})^{\alpha/2}} \qquad \alpha \equiv \frac{m_{3/2}}{M_0 \ln(M_{Pl}/m_{3/2})}$$

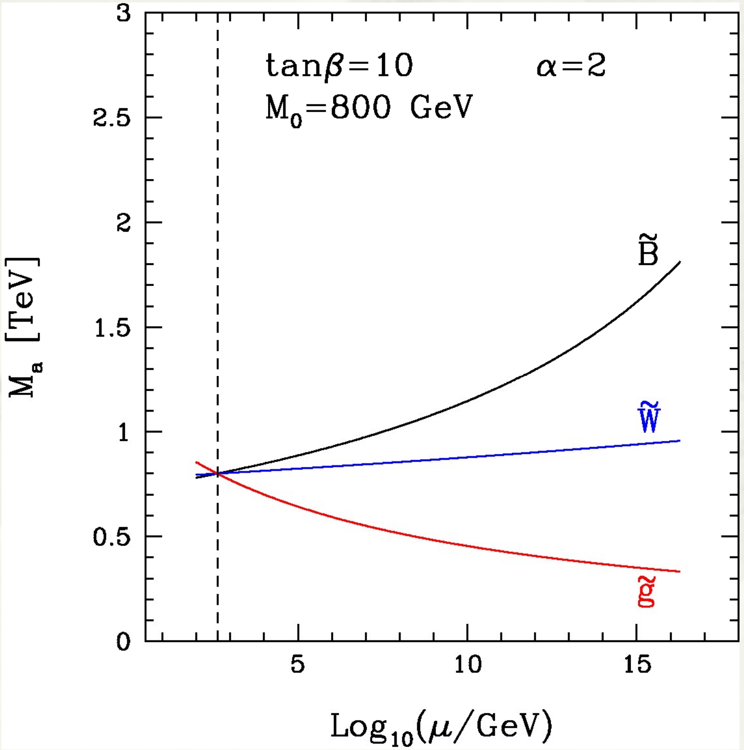
$c_i + c_j + c_k = 1$ for $Y_{ijk} = \mathcal{O}(1)$

TeV scale Mirage mediation

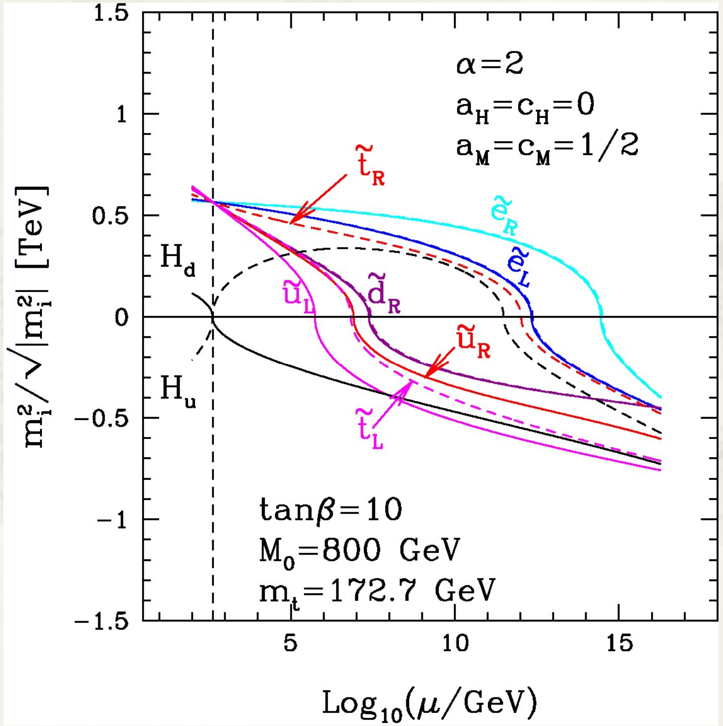
$$M_{\rm mir} \simeq {\rm TeV}, \quad c_{H_u} = 0$$

"Natural Little Hierarchy"

Gaugino Mass: M_a



Sfermion Mass: m_i^2



Two problems: $B \approx 8\pi^2 M_0$, m_h =125 GeV requires multi-TeV stop.

NMSSM

$$W_H = -\lambda S H_u H_d + \frac{\kappa}{3} S^3 \quad (Z_3)$$

- New F-term potential → Tree-level Higgs mass $\Delta V_F = \lambda^2 |H_u H_d|^2$
  - Landau pole $\lambda \lesssim 0.6$
  - F-term ($\sin^2 2\beta$) max → D-term ($\cos^2 2\beta$) min
  - Mixing with S
- No gain in FT $\frac{M_Z^2}{2} \simeq |m_{H_u}^2| - \mu_{eff}^2 \quad \mu_{eff} = \lambda \langle S \rangle$
- Dimensionless → sol. of B_μ problem in MM

NMSSM in TeV scale mirage mediation

The soft SUSY breaking terms in Higgs sector are given by,

$$V_{\rm soft} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2$$
$$-\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 + h.c.$$

We chose the modular weights as $c_{H_d} = 1$, $c_{H_u} = 0$, $c_S = 0$, $c_{q,\ell} = \frac{1}{2}$

$M_a = M_0$ $\quad m_{H_d}^2 = M_0^2$ $\quad A_\lambda = M_0$ $\quad$ TeV scale

$m_{\tilde{q},\tilde{\ell}}^2 = \frac{1}{2} M_0^2$

$m_{H_u}^2 \approx 0$, $\; m_S^2 \approx 0$ $\quad A_\kappa \approx 0$ $\quad \Leftarrow \quad \sim \frac{M_0}{\sqrt{8\pi^2}}$ 100 GeV

Small parameters, Uncontrollable 1-loop corrections

Improved fine-tuning in TeV scale MM

$$c_{H_d} = 1,\ c_{H_u} = 0$$

K.Choi K.S.Jeong T.Kobayashi K.i.Okumura (2006)

$H_d \quad H_u$

$B_\mu = A_\lambda$

$$\mathcal{M}_H^2 = \begin{matrix} H_d \\ H_u \end{matrix} \begin{pmatrix} M_0^2 + \mu^2 & M_0\,\mu \\ M_0\,\mu & \mu^2 \end{pmatrix}$$

$$c_S = 0$$

$$\mathrm{Det}(\mathcal{M}_H^2) = M_H^2\, M_h^2 = (M_0^2 + \mu^2)\mu^2 - M_0^2\mu^2 = \mu^4$$

$$M_H \approx M_0 \to M_h \approx \mu \frac{\mu}{M_0} \quad !$$

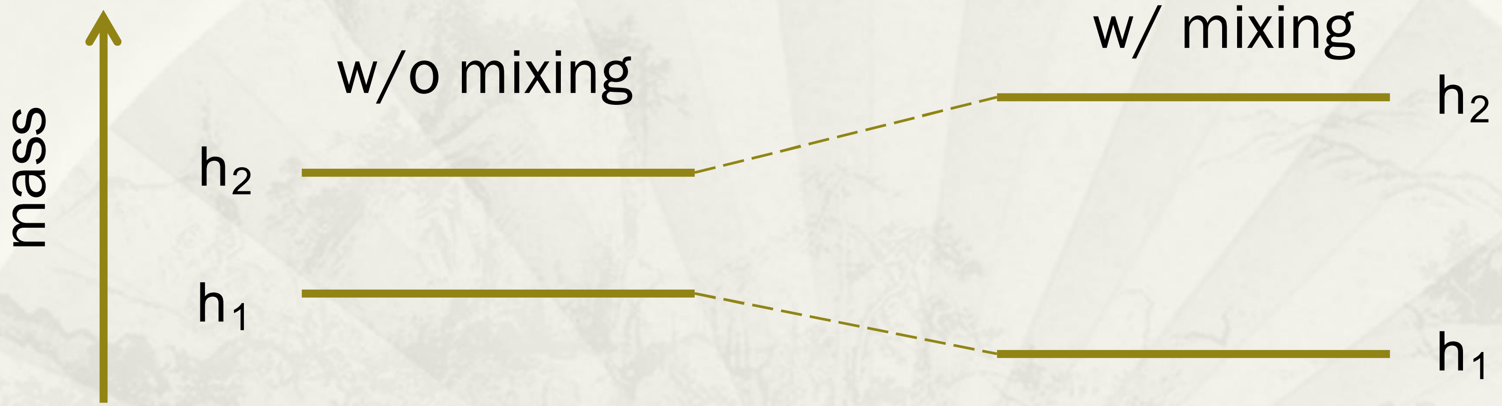
Pot. minimum chooses: $$\frac{M_Z^2}{2} \simeq |m_{H_u}^2| + \overbrace{\left(-\mu^2 + \frac{m_{H_d}^2}{\tan^2\beta}\right)}^{\text{Cancel}}$$

μ term can be large $$\mu \sim \sqrt{m_Z M_0}$$

Doublet-Singlet mixing

In NMSSM, mixing with the singlet may destroy the μ cancellation

In addition, if the doublet-singlet mixing in the mass matrix is large,



h_1: doublet-like ⟺ 125 GeV

h_1: singlet-like ⟺ LEP bound

We show approximate scale symmetries suppress the mixing

Scale symmetry IN NMSSM

In $\kappa = m_S^2 = 0$ limit, the scalar potential has an approximate scale symmetry,

$$\begin{aligned} H_u(x) &= e^{2\phi} H'_u(e^{\phi} x) \\ H_d(x) &= e^{2\phi} H'_d(e^{\phi} x) \\ S(x) &= S'(e^{\phi} x) \end{aligned}$$

$$W_H = -\lambda S H_u H_d$$

$$\begin{aligned} V_{\rm soft} &= m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 \\ &\quad -\lambda A_\lambda S H_u H_d + h.c. \end{aligned}$$

explicitly broken by $\mathcal{K}_S = S^\dagger S$ and D-term.

$H_{u,d}$ VEVs break the symmetry and the light doublet ($H_u/H_d = \tan\beta$) corresponds to the NG boson.

In $\kappa = m_{H_u}^2 = 0$ limit, there's another scale symmetry, $S \leftrightarrow H_u$

Singlet-like Higgs $(S + H_d) \to$ NG boson

Scale Symmetry in NMSSM (CONT'D)

$$\mathcal{S}\mathcal{M}_S^2\mathcal{S}^\dagger \approx \mathrm{diag}(m_Z^2\cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta, \quad A_\lambda^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta, \quad \lambda^2 v^2 \sin^2 2\beta)$$

$$\mathcal{S}^\dagger = \begin{matrix} \Delta H_d \\ \Delta H_u \\ \Delta S \end{matrix} \begin{pmatrix} \cos\beta & -\sin\beta & \lambda\frac{v}{A_\lambda}\sin\beta \\ \sin\beta & \cos\beta & \lambda\frac{v}{A_\lambda}\cos\beta \\ -\lambda\frac{v}{A_\lambda}\sin 2\beta & -\lambda\frac{v}{A_\lambda}\cos 2\beta & 1 \end{pmatrix} + \mathcal{O}\left(\frac{v}{A_\lambda}\right)^2,$$

singlet-doublet mixing is suppressed by $\frac{v}{A_\lambda}$ and $1/\tan\beta$

In $\kappa = m_S^2 = m_{H_u}^2 = \langle H_d \rangle = 0$ limit $\rightarrow$

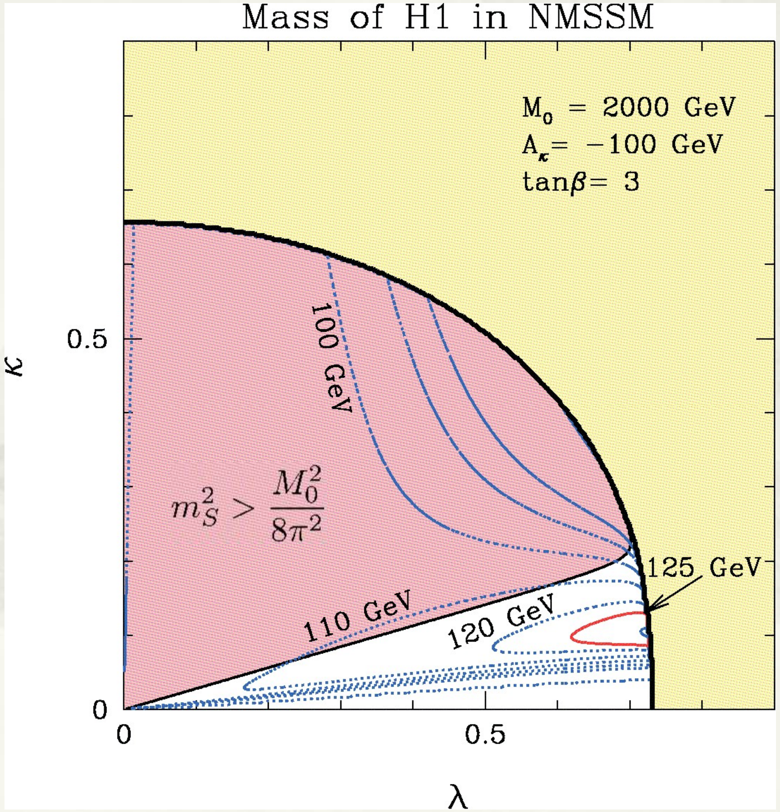
two NG bosons, H_u, S (mass eigenstates)

$\mathcal{S}_{31}^\dagger$ and $\mathcal{S}_{23}^\dagger$ must break the two symmetries and decouple with M_0.

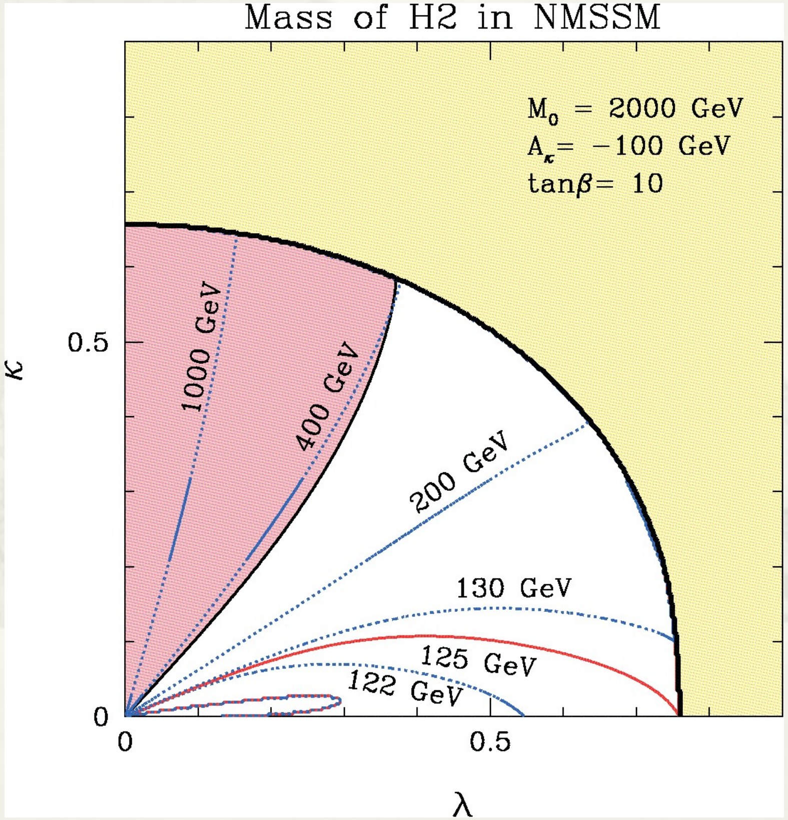
$$\kappa\frac{\langle S\rangle}{M_0}, \quad \frac{\langle H_d\rangle}{M_0}, \quad \frac{\langle H_u\rangle\langle S\rangle}{M_0^2}, \quad \frac{m_S^2\langle S\rangle}{M_0^3}, \quad \frac{m_{H_u}^2\langle H_u\rangle}{M_0^3}, \quad \frac{m_S^2 m_{H_u}^2}{M_0^4}$$

Higgs mass

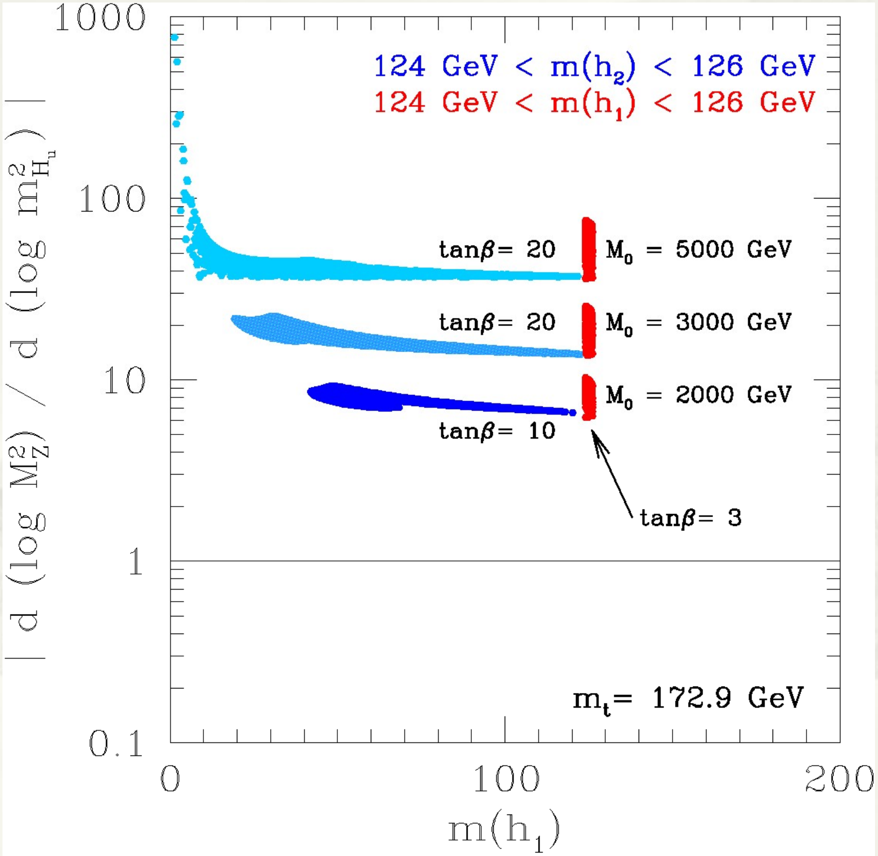
Small $\tan\beta$: H_1 = SM like

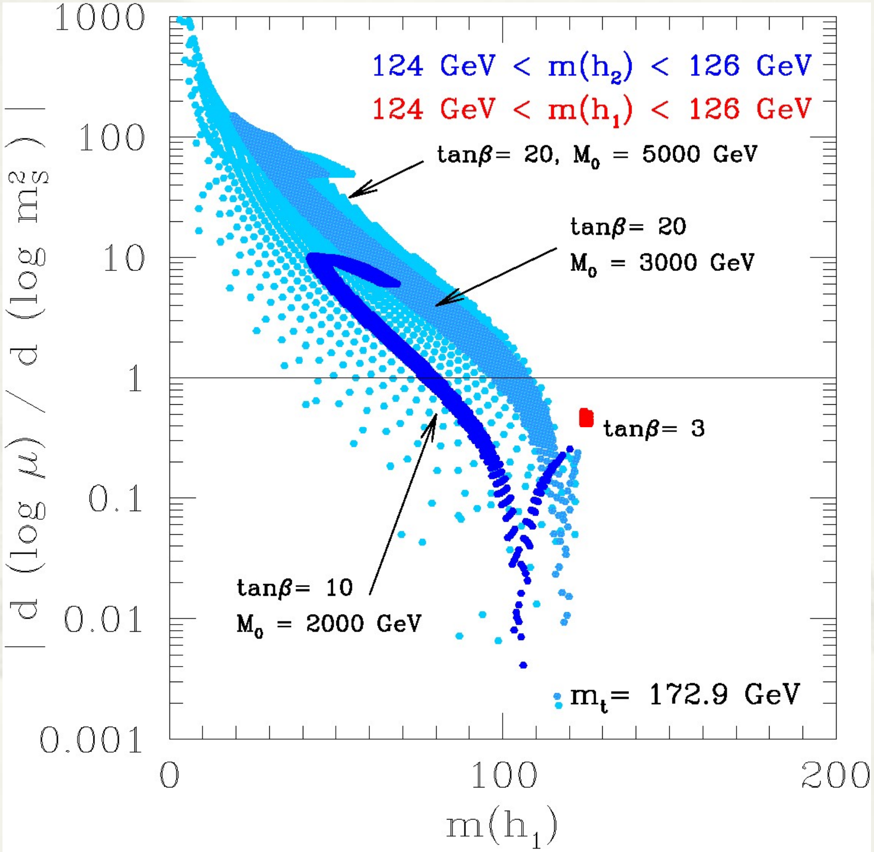


Large $\tan\beta$: H_2 = SM like



Fine-Tuning measures





$M_0 = 5$ TeV is acceptable in the standard of conventional 1 TeV models !

Higgs effective coupling constants

The effective coupling constants of CP-even Higgs bosons are defined as,

$$\mathcal{L} = \sum_{i=1}^{3}\Bigg[C_V^i \frac{\sqrt{2}m_W^2}{v} h_i W_\mu^+ W^{-\mu} + C_V^i \frac{m_Z^2}{\sqrt{2}v} h_i Z_\mu Z^\mu - \sum_f C_f^i \frac{m_f}{\sqrt{2}v} h_i \bar{f} f + C_g^i \frac{\alpha_s}{12\sqrt{2}\pi v} h_i G^a_{\mu\nu} G^{a\,\mu\nu} + C_\gamma^i \frac{\alpha}{\sqrt{2}\pi v} h_i A_{\mu\nu} A^{\mu\nu}\Bigg]$$

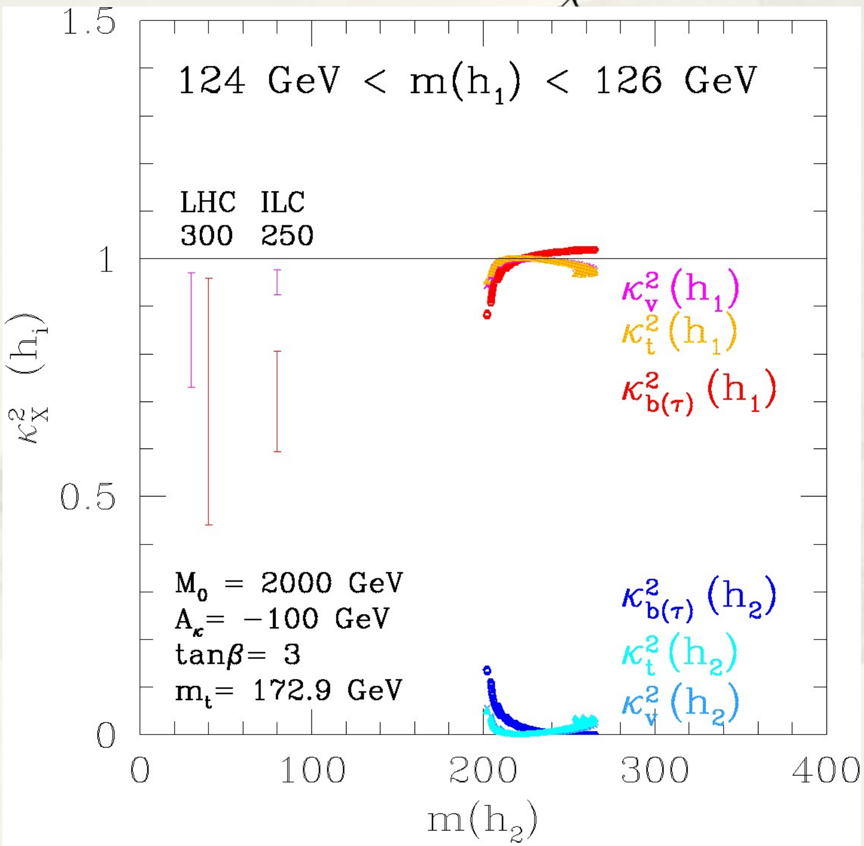
For the SM, $C_V^{SM} = C_f^{SM} = 1$, $C_g^{SM} \approx 1.03$, $C_\gamma^{SM} \approx -0.81$

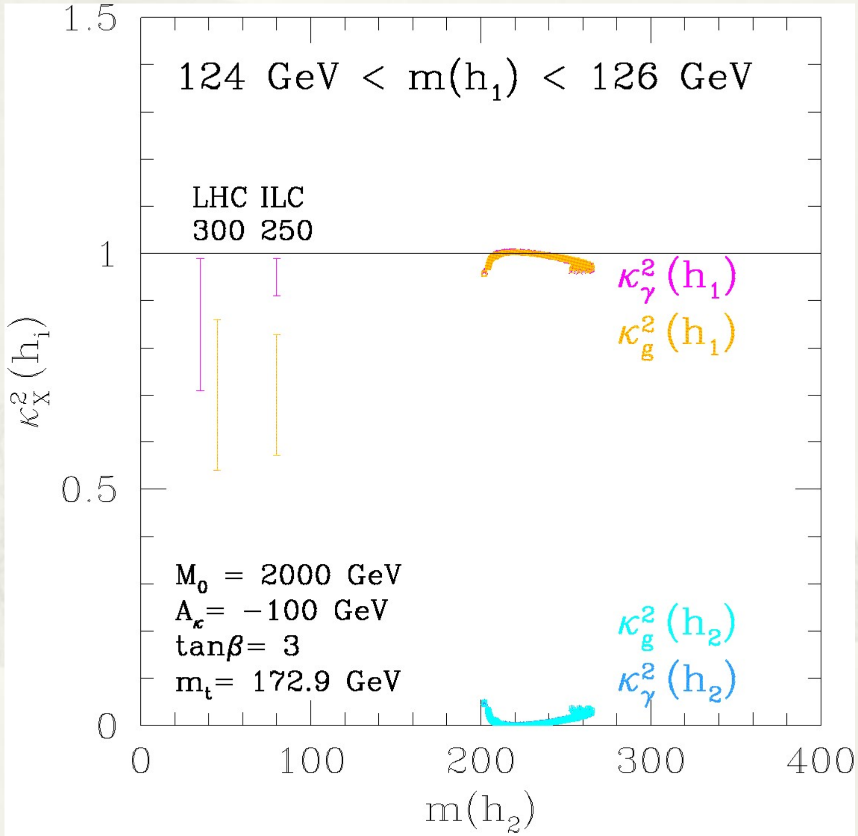
Their deviations from the SM value (or existence itself) encode information of new physics.

CP even Higgs

$\tan\beta = 3$ (Calculated by NMSSMTools)

Tree $\kappa_X^i = \dfrac{C_X^i}{C_X^{SM}}$ Loop

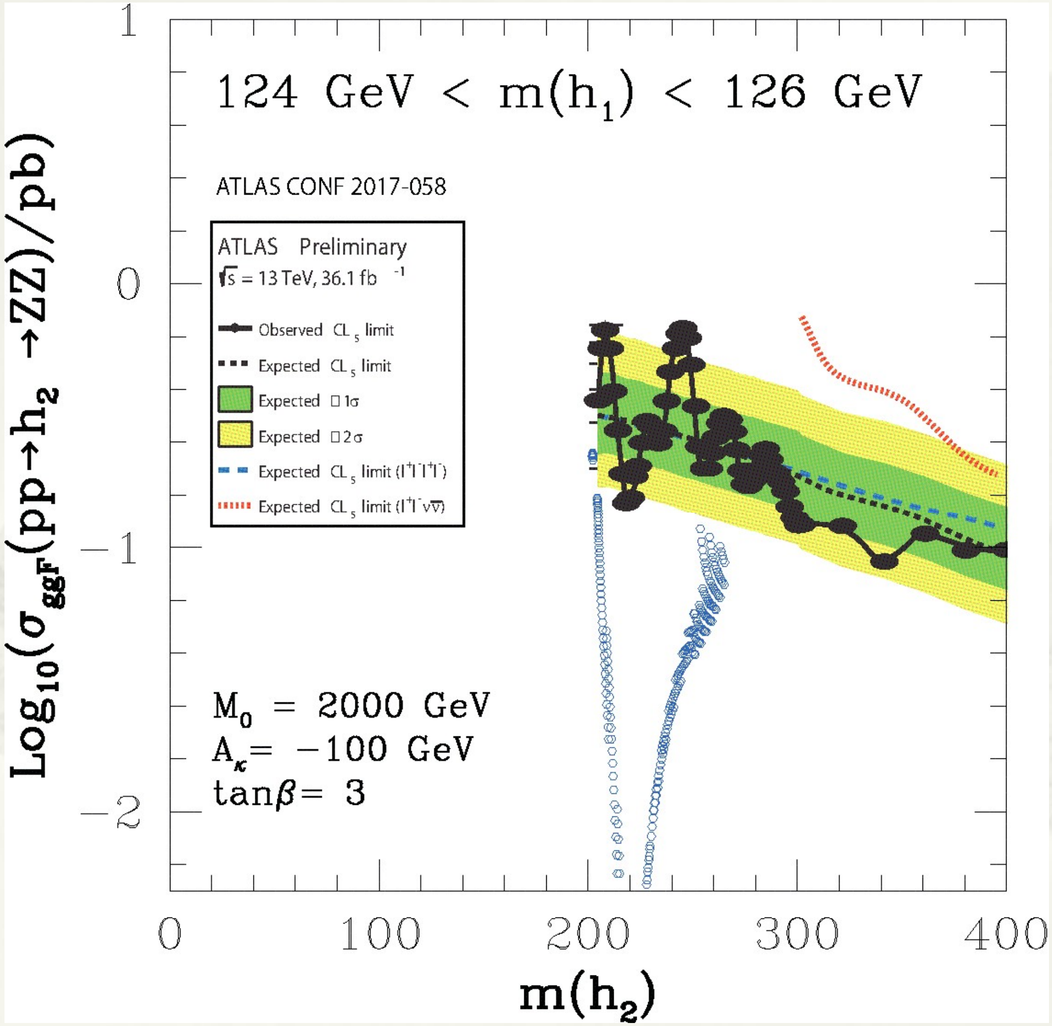




Sum rule $(\kappa^{h_1})^2 + (\kappa^{h_2})^2 = 1$ holds well except for $b(\tau)$.

~ 10 % deviation from the SM Higgs is possible for tree-level couplings.

CP even Higgs (cont'd)



H_1 = SM like

ILC250 can't reach

If we are lucky,
LHC will find the singlet

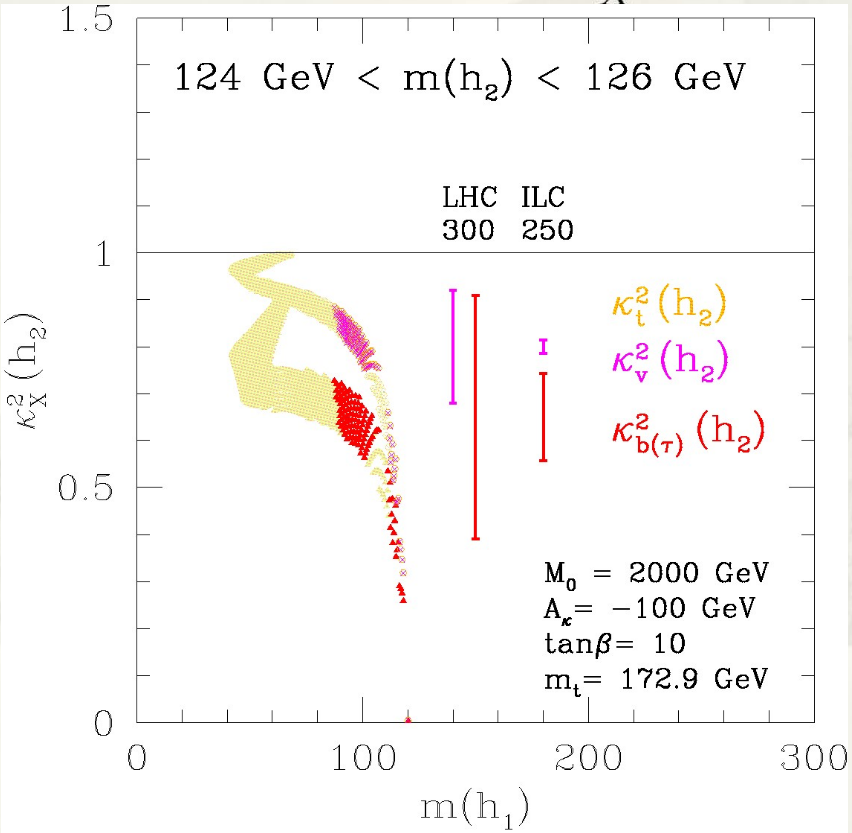
ILC can be upgraded
to measure it

CP even Higgs (cont'd)

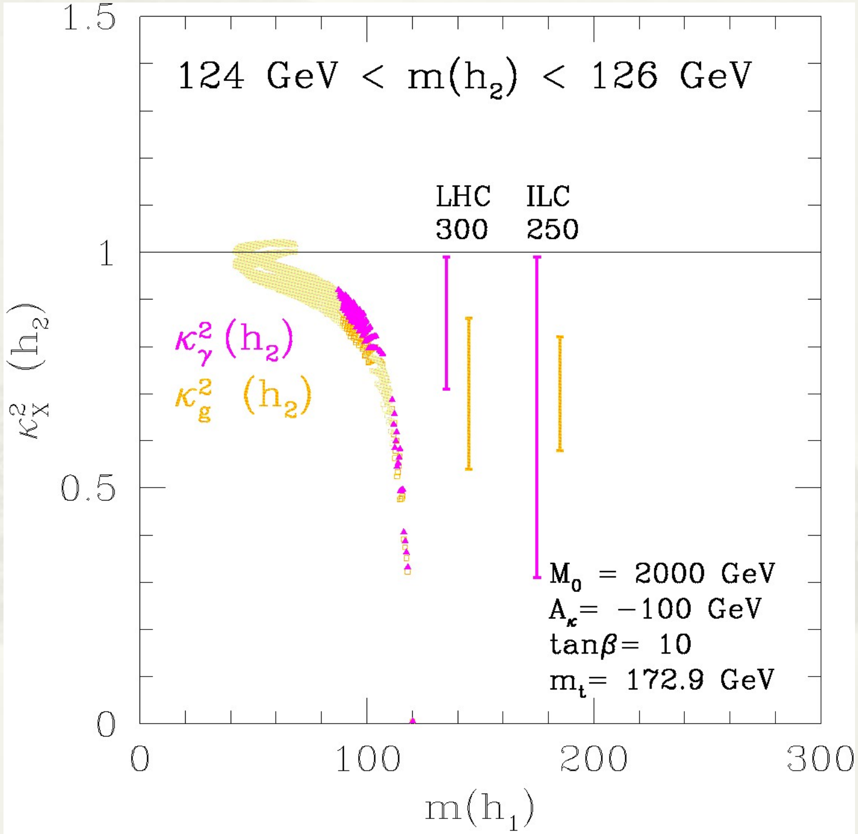
$\tan\beta = 10$

$$\kappa_X^i = \frac{C_X^i}{C_X^{SM}}$$

Tree



Loop



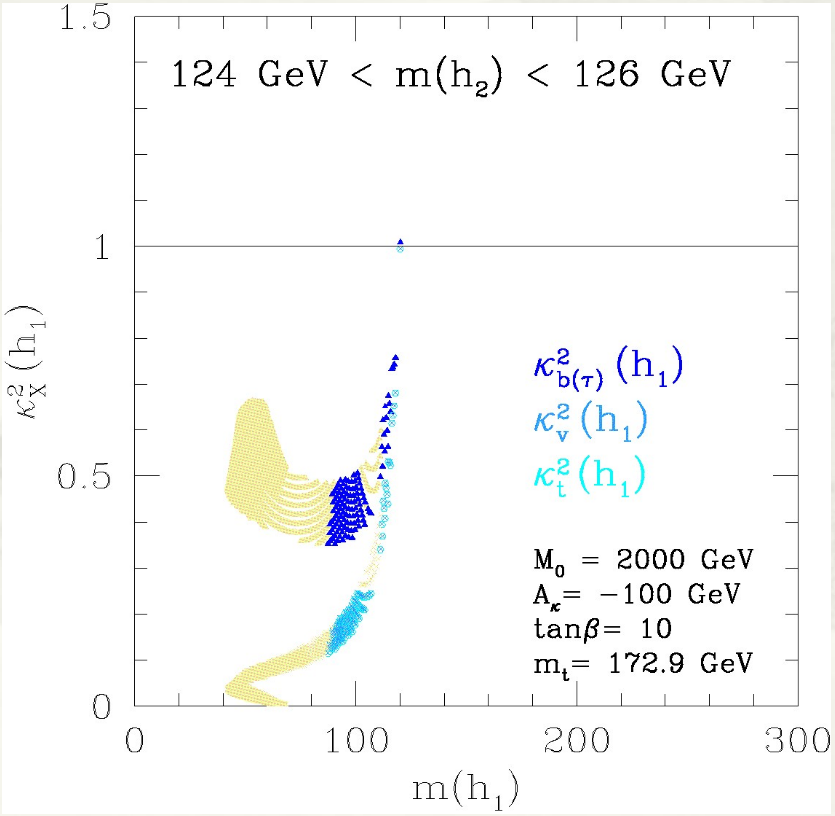
Singlet-doublet mixing is required by $m_{h_2} = 125$ GeV.

~ 40 % deviation is possible for κ_b (mixing with $\tan\beta$ enhanced H coupling).

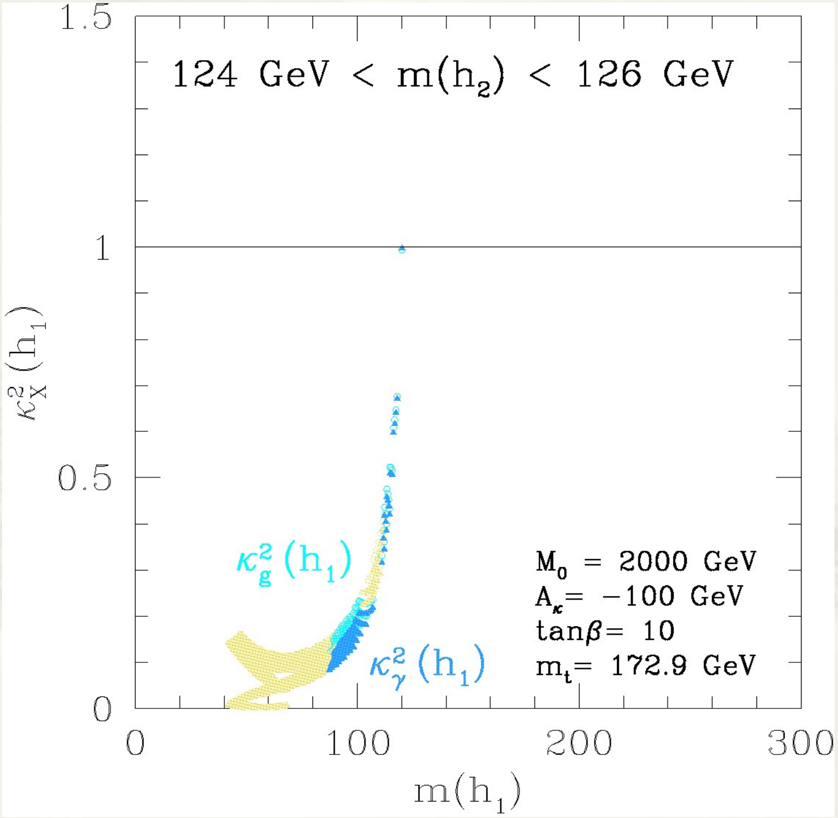
CP even Higgs (cont'd)

$\tan\beta = 10$ $\qquad \kappa_X^i = \frac{C_X^i}{C_X^{SM}}$

Tree



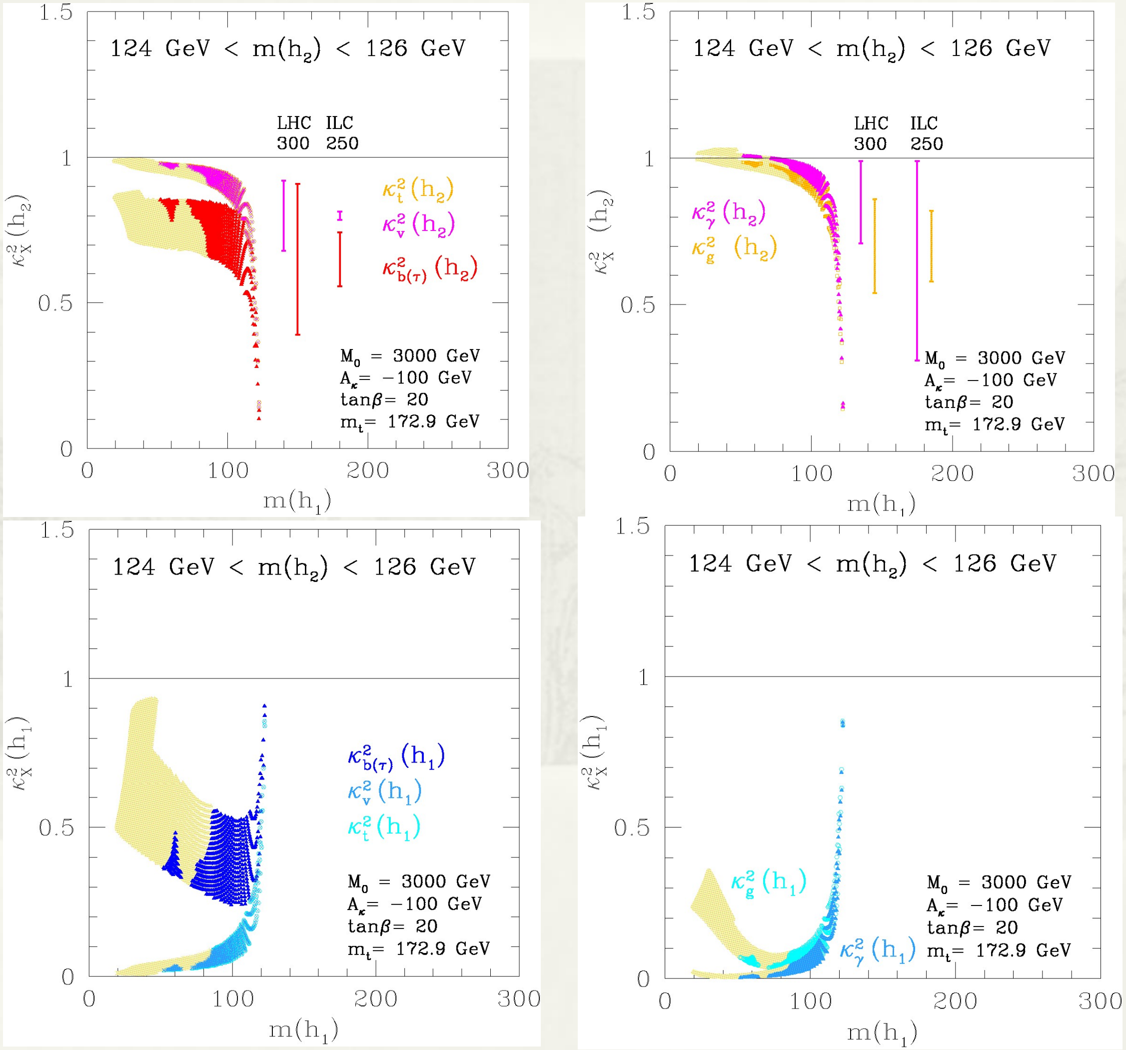
Loop



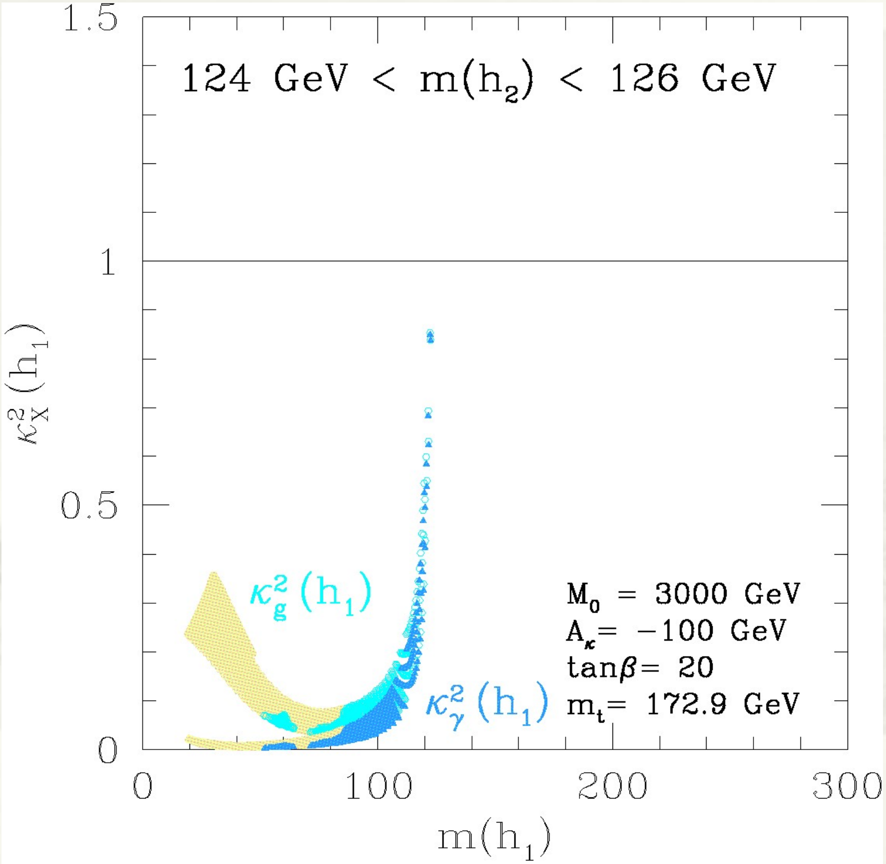
$\kappa_{t,V}$ comes from singlet-doublet mixing.

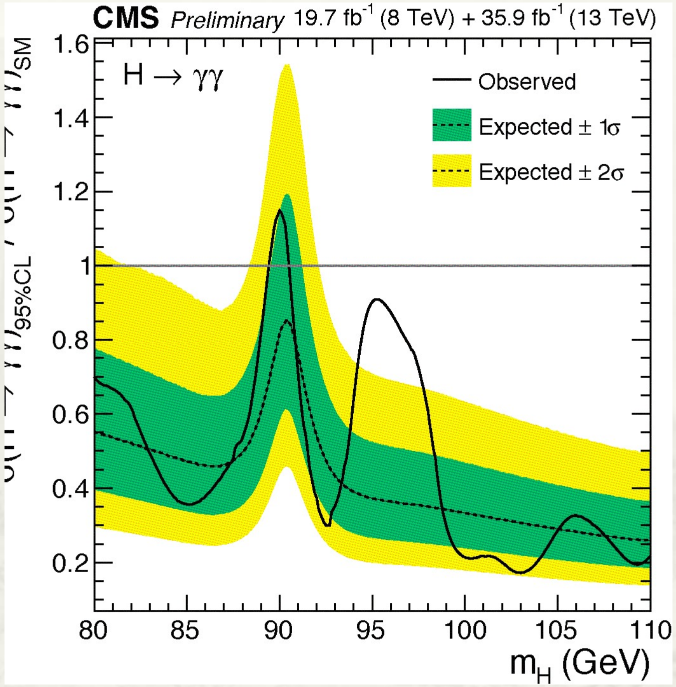
κ_b is enhanced by $\tan\beta$.

CP even Higgs (cont'd)



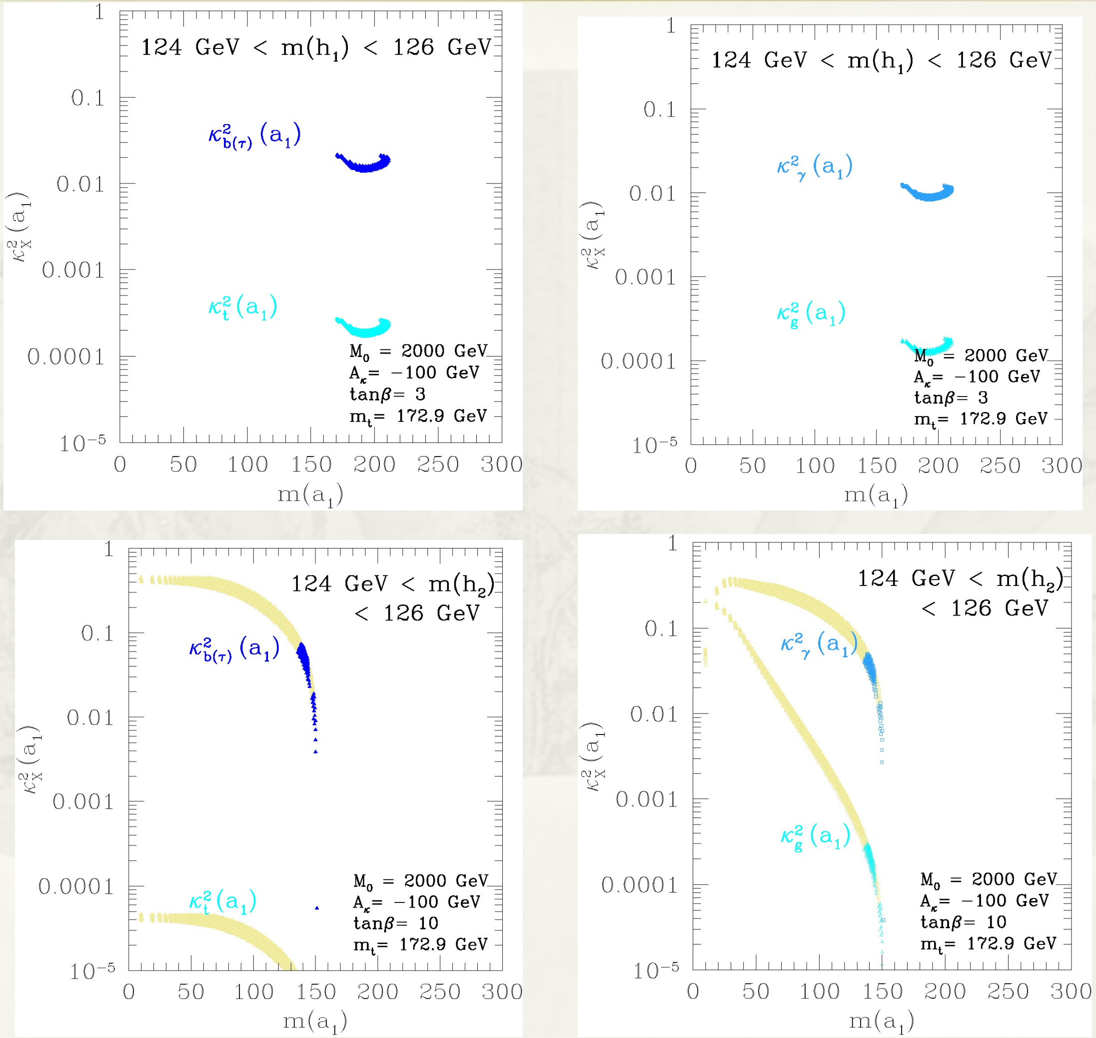
CP even Higgs (cont'd)





It is important to find a signal LEP has missed

CP odd Higgs



124 GeV < m(h_1) < 126 GeV
κ²_b(τ) (a_1)
κ²_t (a_1)
M_0 = 2000 GeV
A_κ = −100 GeV
tanβ = 3
m_t = 172.9 GeV
κ²_X (a_1)
m(a_1)
κ²_γ (a_1)
κ²_g (a_1)
124 GeV < m(h_2) < 126 GeV
tanβ = 10

Conclusion

* TeV scale mirage mediation in NMSSM is an attractive model.
* 125 GeV Higgs can be accommodated.
* Fine-tuning is better than 10% with 1.5 TeV stop while μ can be as heavy as 700 GeV.
* Singlet-doublet mixing is suppressed due to accidental scale symmetries.
* 10% deviation is expected in SM-like Higgs coupling. 40% deviation is possible for b (τ).
* Hidden light singlets are characteristic and interesting targets for future colliders