LCWS2015 Whistler Canada
4 Nobember 2015

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TEV SCALE MIRAGE MEDIATION IN NMSSM AND PRECISION HIGGS MEASUREMENT

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 superpartner (mq~ >1.5 TeV LHC7+8)
  - Higgs is too heavy → multi-TeV stop ?
  - Fine tuning <1%

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

Solution: “TeV scale mirage mediation in NMSSM !”

MIRAGE MEDIATION

Soft SUSY breaking terms= (Moduli + Anomaly) Mediation

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

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

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

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

$$m_i^2(M_G) = c_i |M_0|^2 + (\text{Anomaly Mediation})$$

$c_i = 0,\ 1/3,\ 1/2,\ 1$

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

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

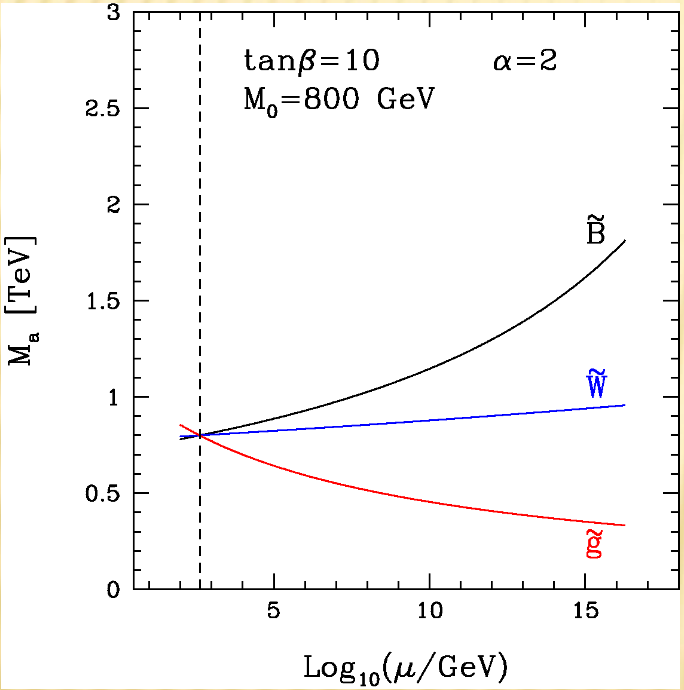
$c_i + c_j + c_k = 1$
for $Y_{ijk} = \mathcal{O}(1)$

TEV SCALE MIRAGE MEDIATION

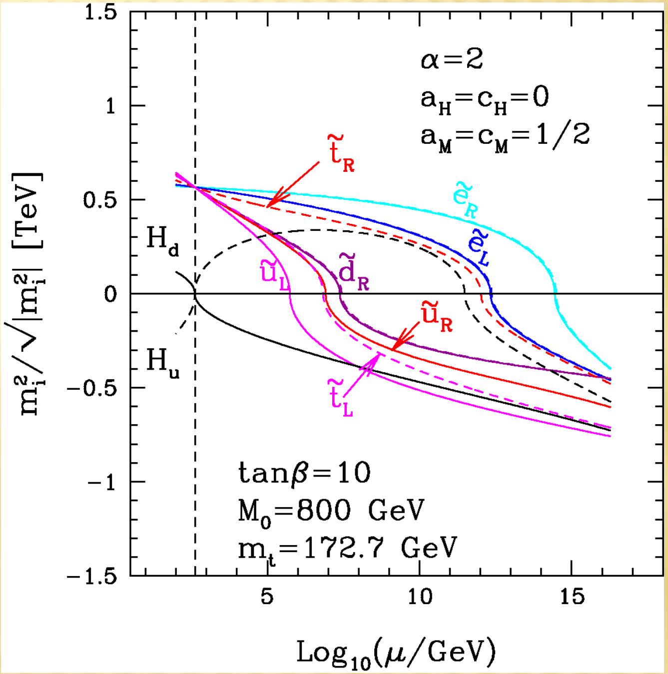
$$\boxed{M_{\rm mir} \simeq {\rm TeV}, \quad c_{H_u} = 0}$$

"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

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

- 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,

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

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

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

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

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

Small parameters, Uncontrollable 1-loop corrections

IMPROVED FINE-TUNING IN TEV SCALE MM

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

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

$$B_\mu = A_\lambda$$

$$\mathcal{M}_H^2 = \begin{array}{c|cc} & H_d & H_u \\ \hline H_d & M_0^2 + \mu^2 & M_0\,\mu \\ H_u & M_0\,\mu & \mu^2 \end{array}$$

$$\boxed{c_S = 0}$$

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

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

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 $\quad \mu \sim \sqrt{m_Z M_0}$

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 an approximate scale symmetry suppresses the mixing

SCALE SYMMETRY IN NMSSM

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

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

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

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

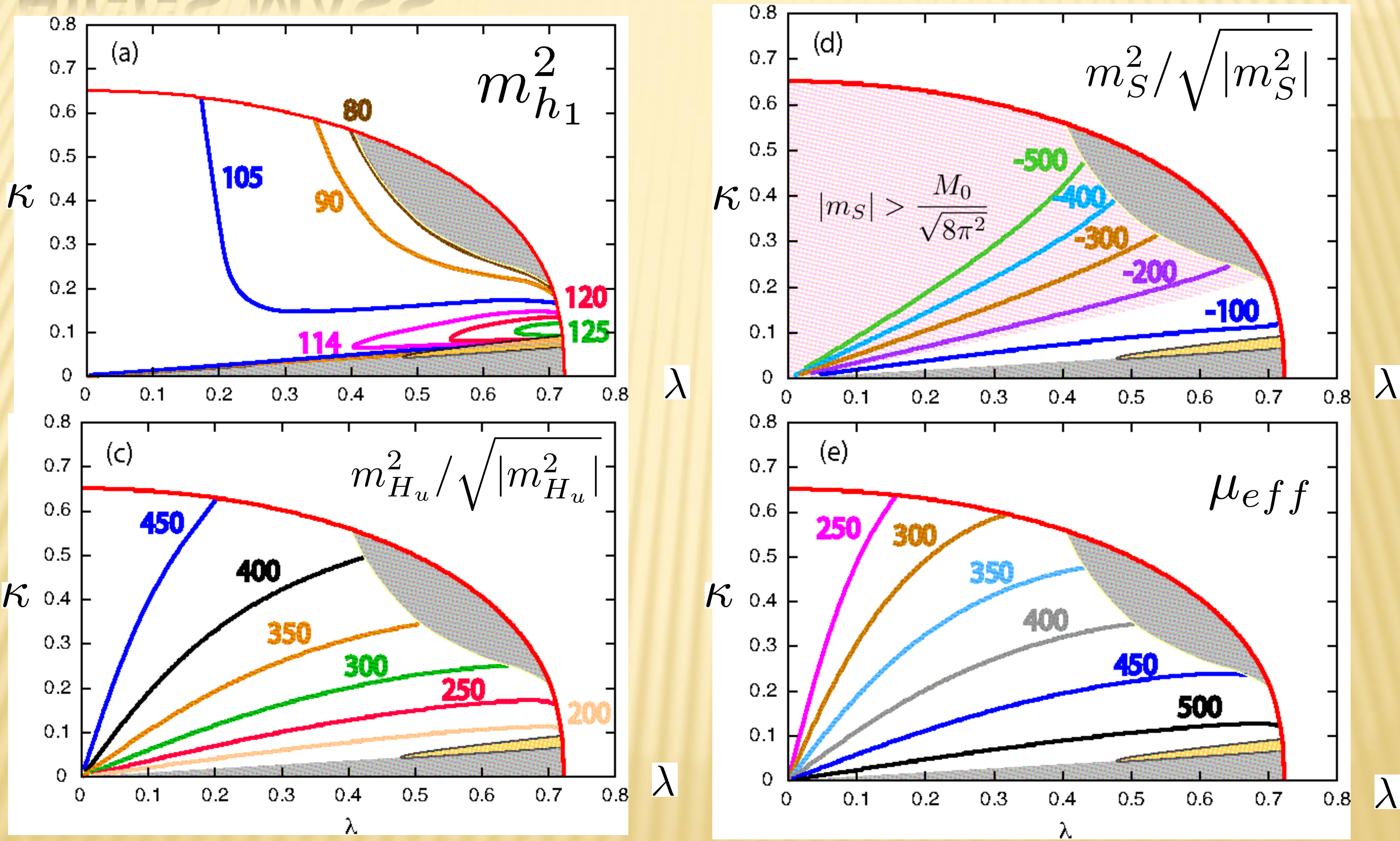
explicitly broken by $\mathcal{K}_S = S^\dagger S$ and D-term.

$H_{u,d}$ 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, $S \leftrightarrow H_u$

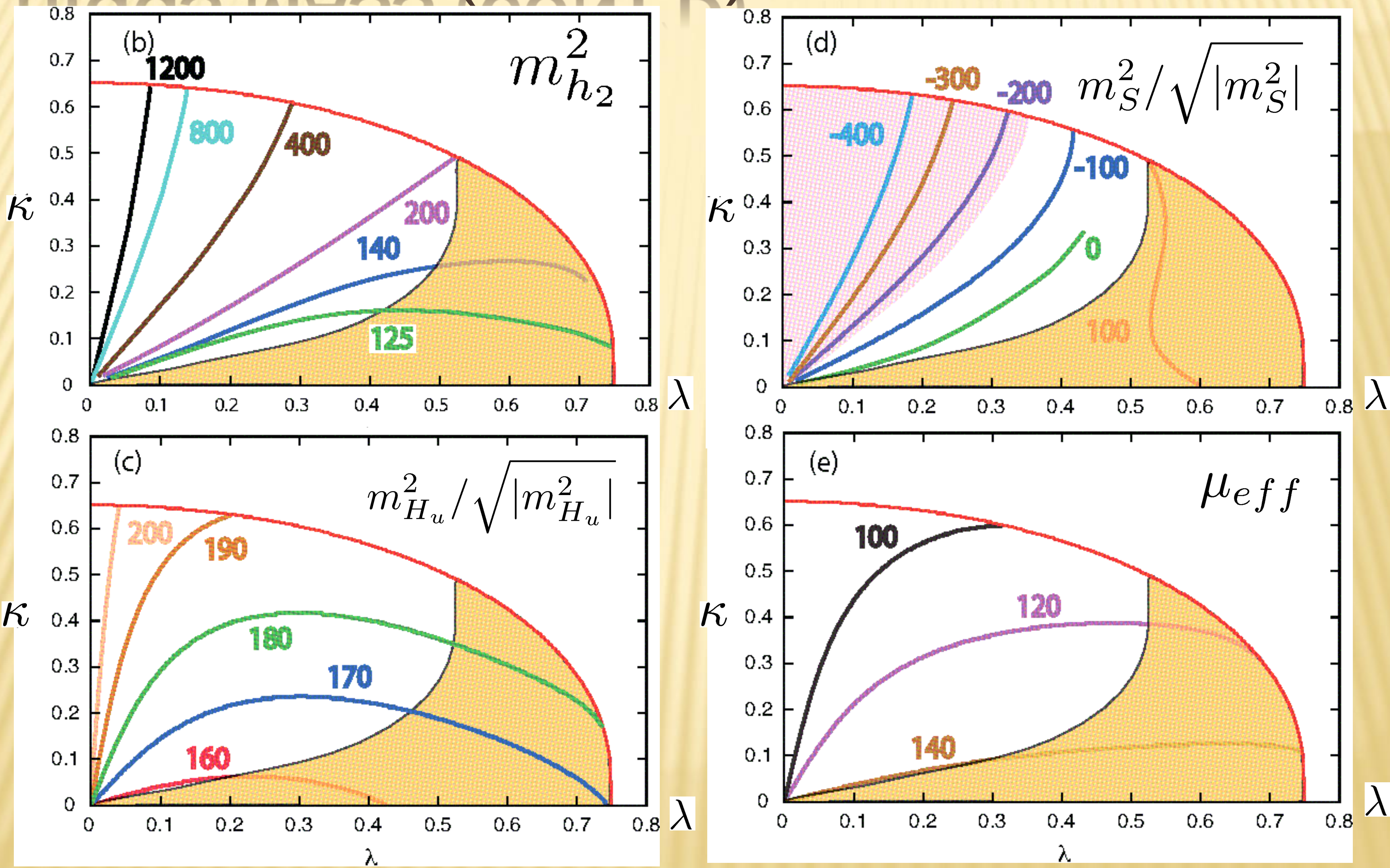
Singlet-like Higgs $(S + H_d) \rightarrow$ NG boson

HIGGS MASS



$$\tan\beta = 3, \qquad M_0 = 1500\,GeV, \qquad m_t = 172.9\,GeV$$

HIGGS MASS (CONT'D)



$\tan\beta = 10, \qquad M_0 = 1500\,GeV, \qquad m_t = 172.9\,GeV$

FINE-TUNING MEASURES

We define the fine-tuning measure as:

$$\Delta_x^y = \frac{\partial \ln(y)}{\partial \ln(x)}$$

x: input parameter
y: output parameter

Natural choice is, $y = v_i = \{\langle H_u \rangle, \langle H_d \rangle, \langle S \rangle\}$

Instead we choose, $y = \{M_Z^2, \tan\beta, \mu\}$.

$$\tan\beta \approx \frac{\mu}{M_0}$$

We examine their sensitivity to λ, κ and the *small* parameters:

$$x = \{\lambda, \kappa, m_{H_u}, m_S, A_\kappa\}$$

Master Formula:

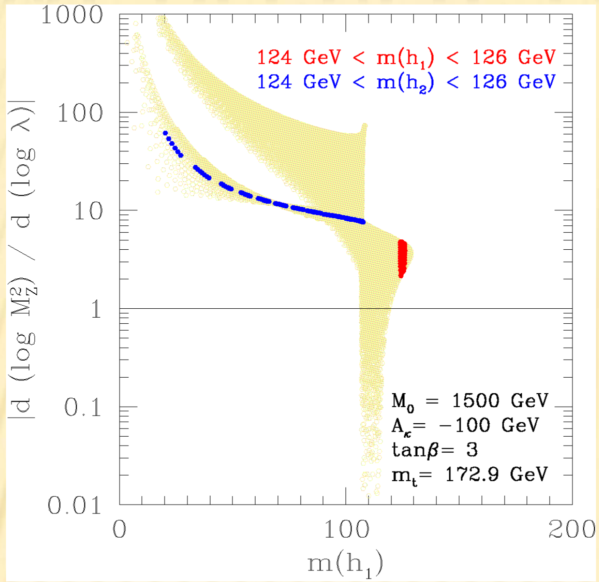
$$\frac{\partial v_i}{\partial \ln x_a} = -\frac{1}{\sqrt{2}} \sum_k (\mathcal{M}_S^2)^{-1}_{ik} \frac{\partial^2 V}{\partial \phi_k \partial \ln x_a}$$

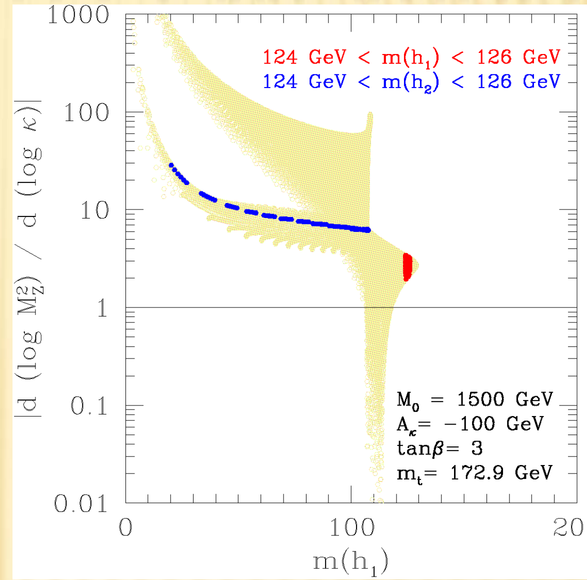
NUMERICAL RESULTS FOR FT MEAURES

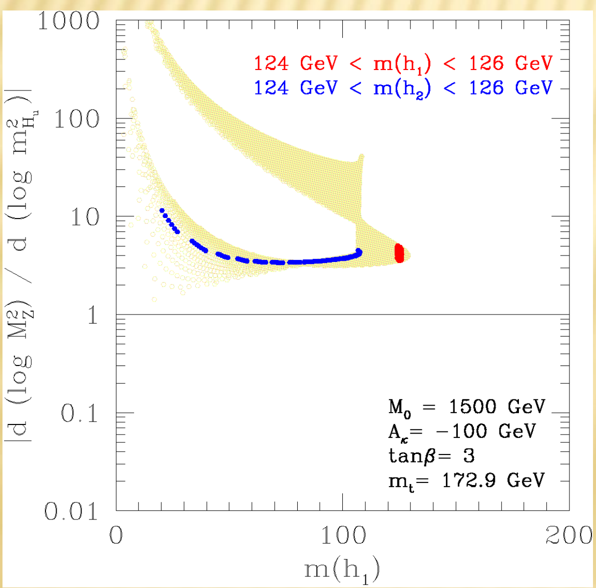
$$\Delta_x^{M_Z^2}$$

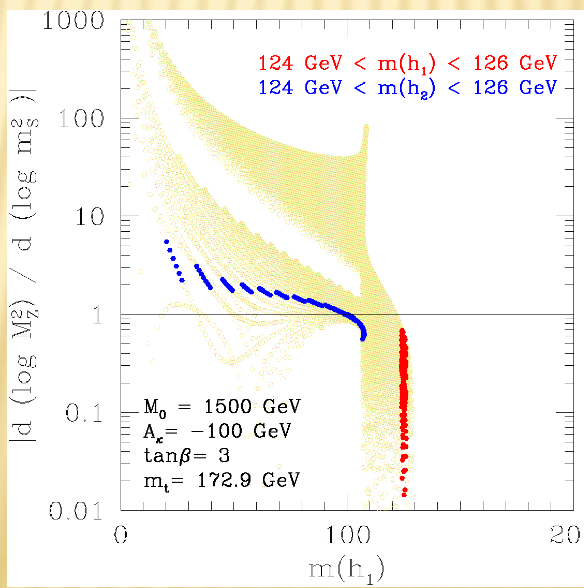
$$\tan\beta = 3$$

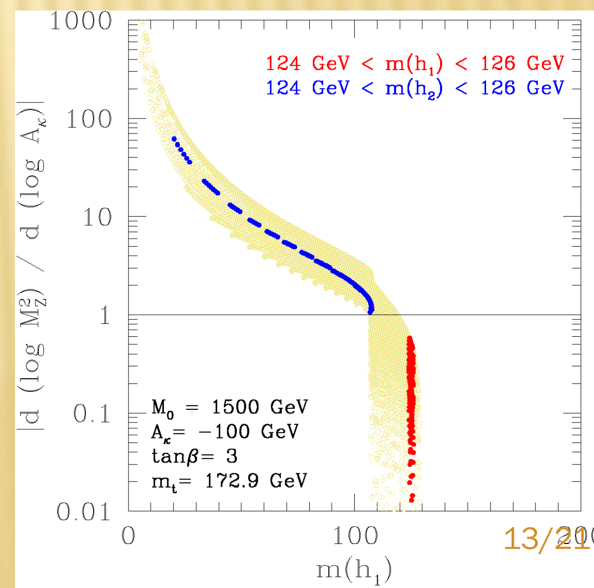
$$M_0 = 1500\,\text{GeV}$$









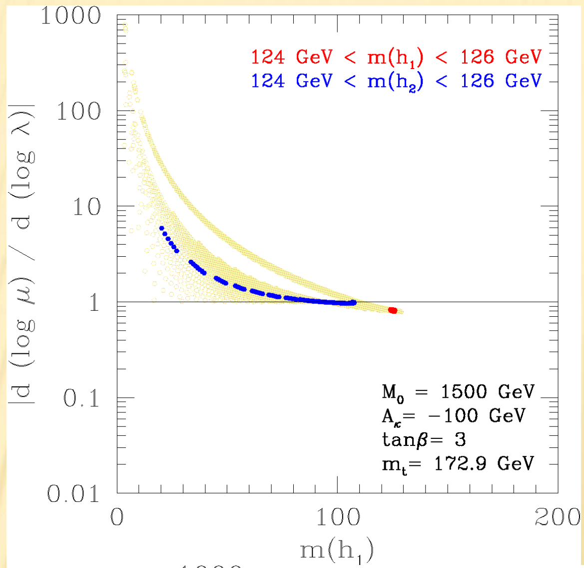


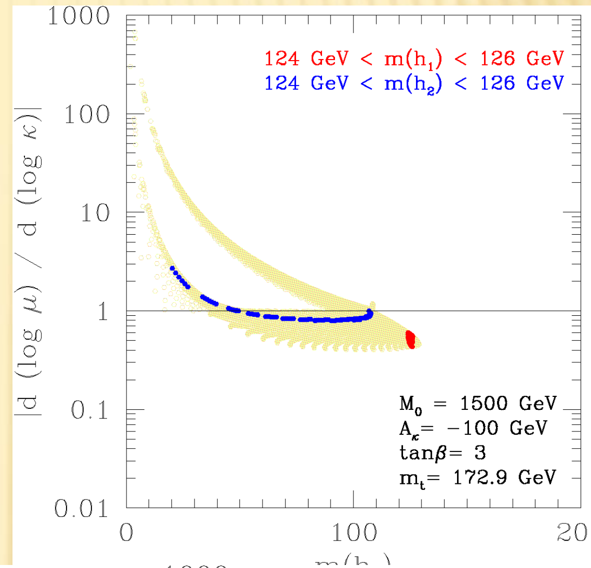
NUMERICAL RESULTS FOR FTS (CONT'D)

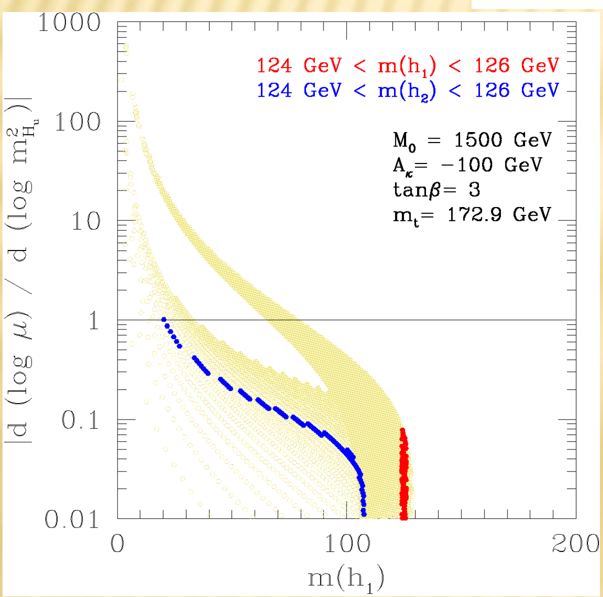
$$\Delta_x^\mu$$

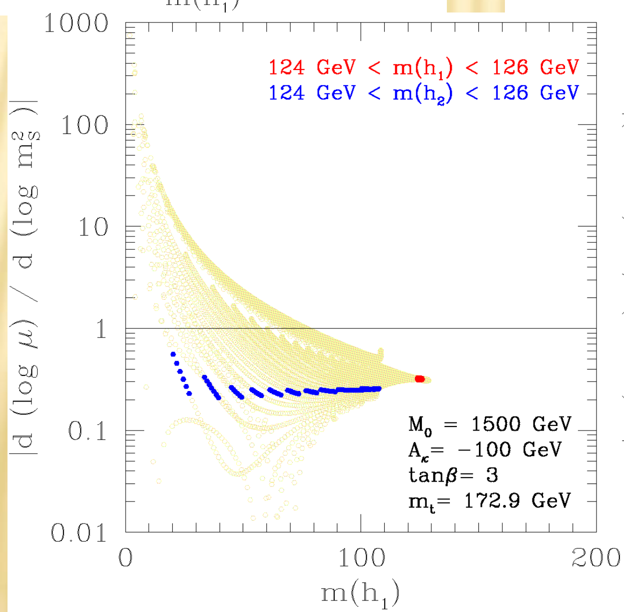
$$\tan\beta = 3$$

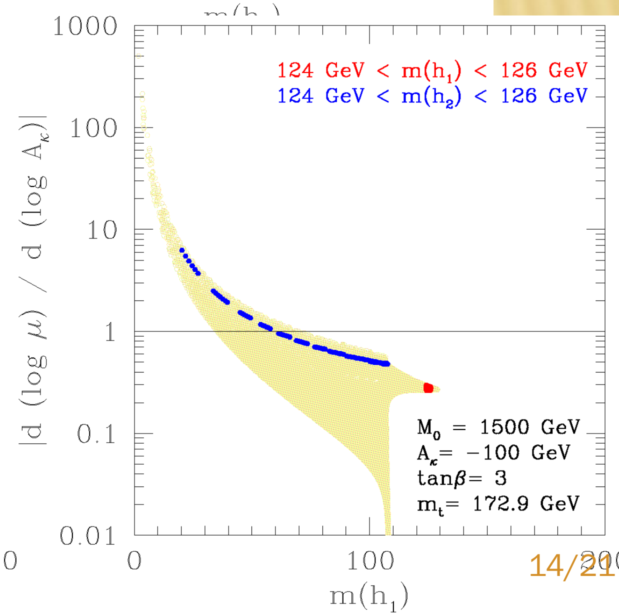
$$M_0 = 1500\,\mathrm{GeV}$$







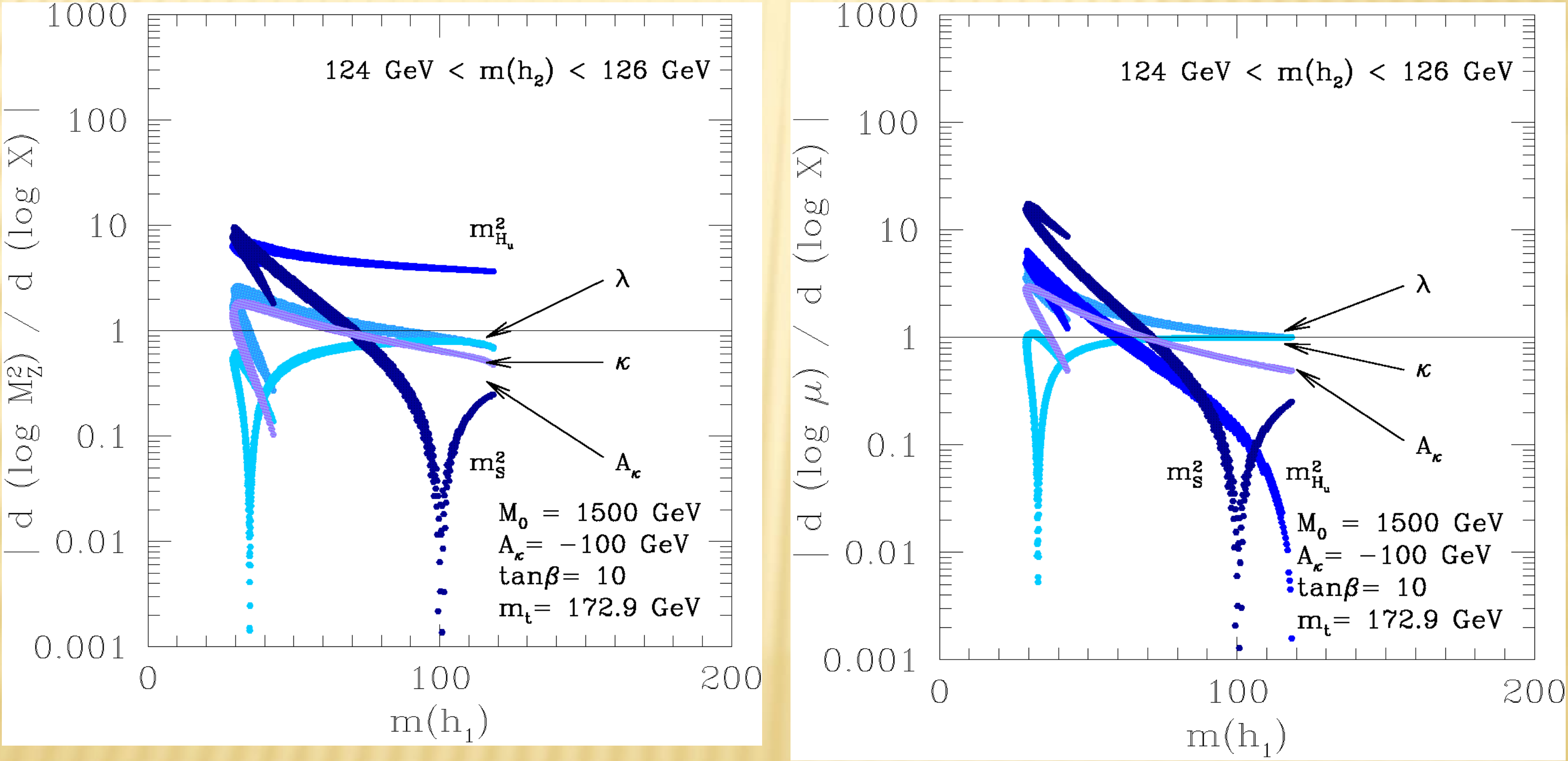




NUMERICAL RESULTS FOR FTS (CONT'D)

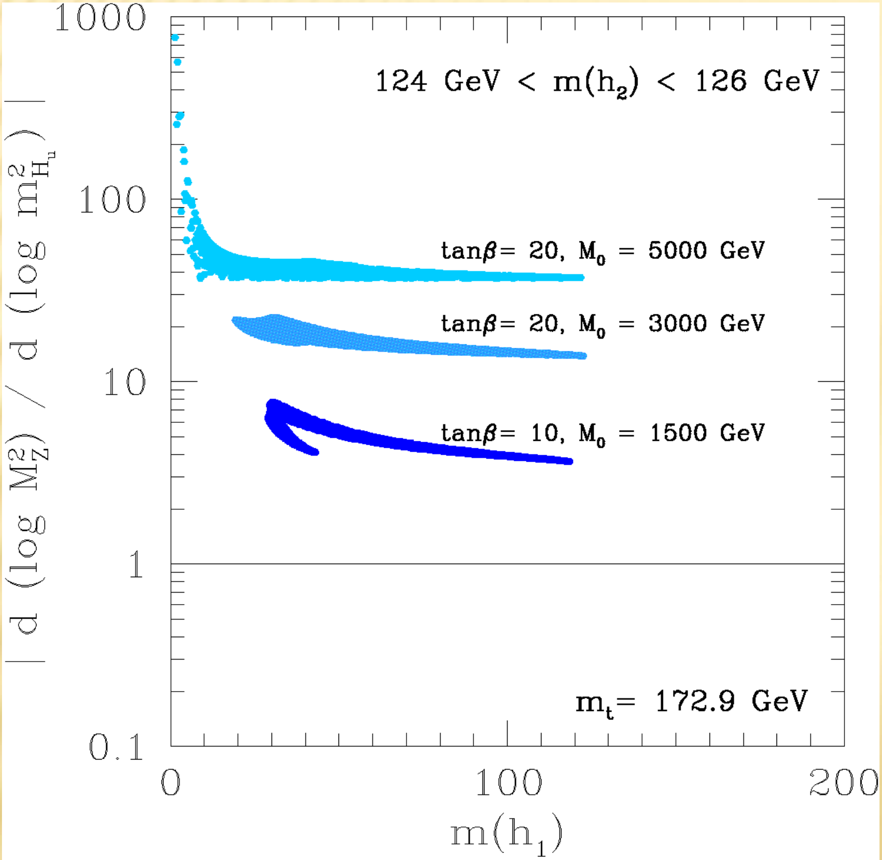
$\tan\beta = 10 \qquad M_0 = 1500\,\mathrm{GeV}$

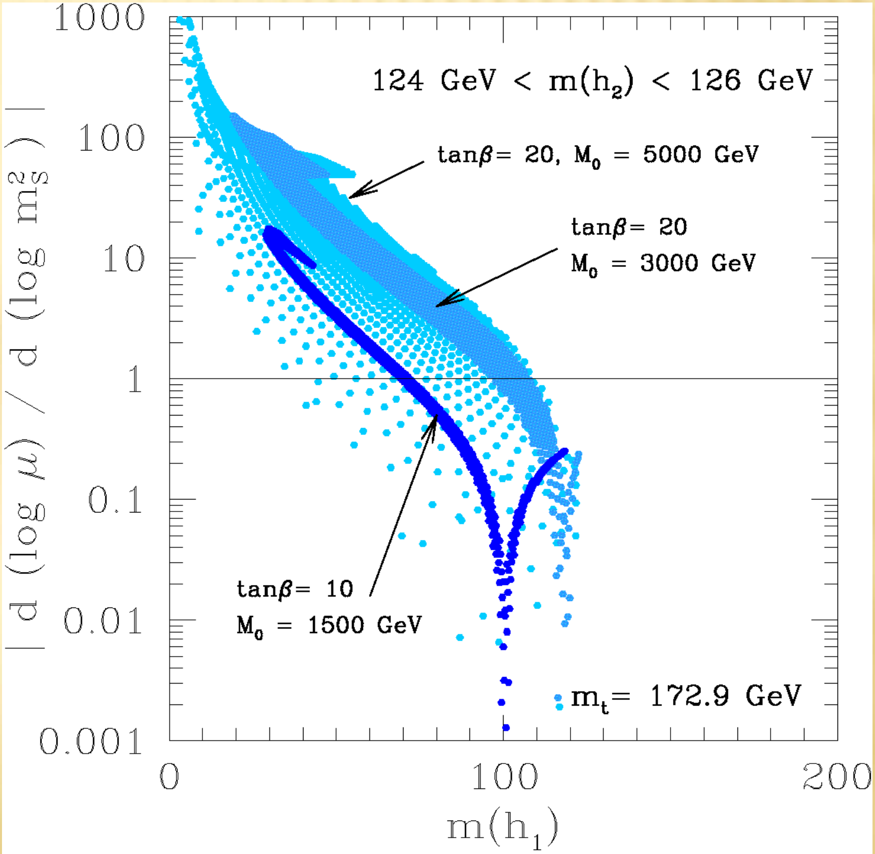
$\Delta_x^{M_z^2}$ Δ_x^{μ}



FT is minimized around $m_{h_1} \simeq 100$ GeV.

NUMERICAL RESULTS FOR FTS (CONT'D)





$M_0 = 5$ 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,

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

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.

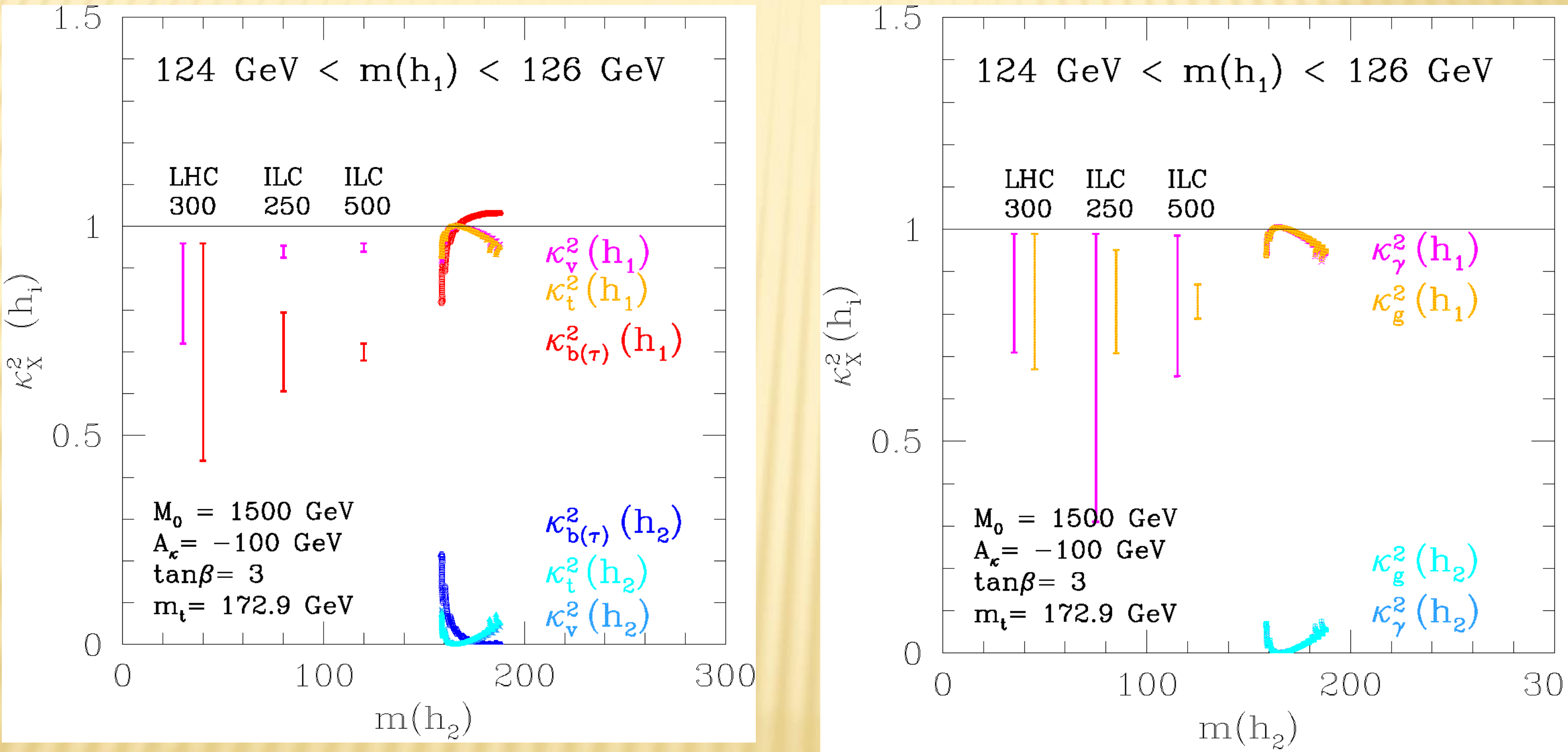
NUMERICAL RESULTS FOR CP EVEN HIGGS

(Calculated by NMSSMTools)

$\tan\beta = 3$

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

Tree　　　　Loop



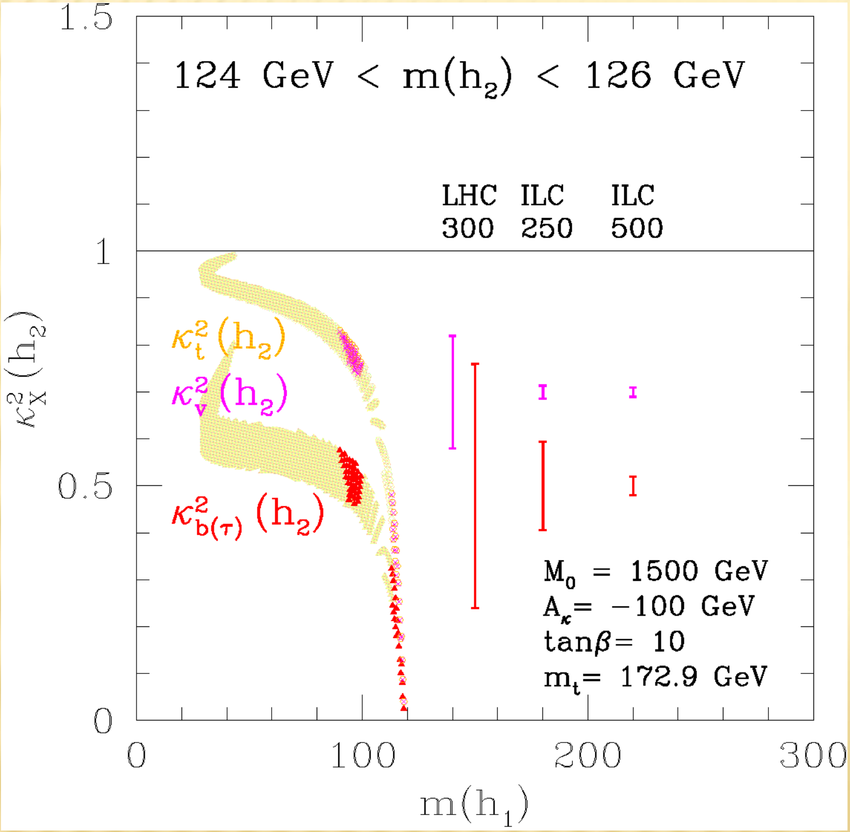
Sum rule $(\kappa^{h_1})^2 + (\kappa^{h_2})^2 = 1$ holds well except for $b(\tau)$.

~ 20 % deviation from the SM Higgs is possible for tree-level couplings.

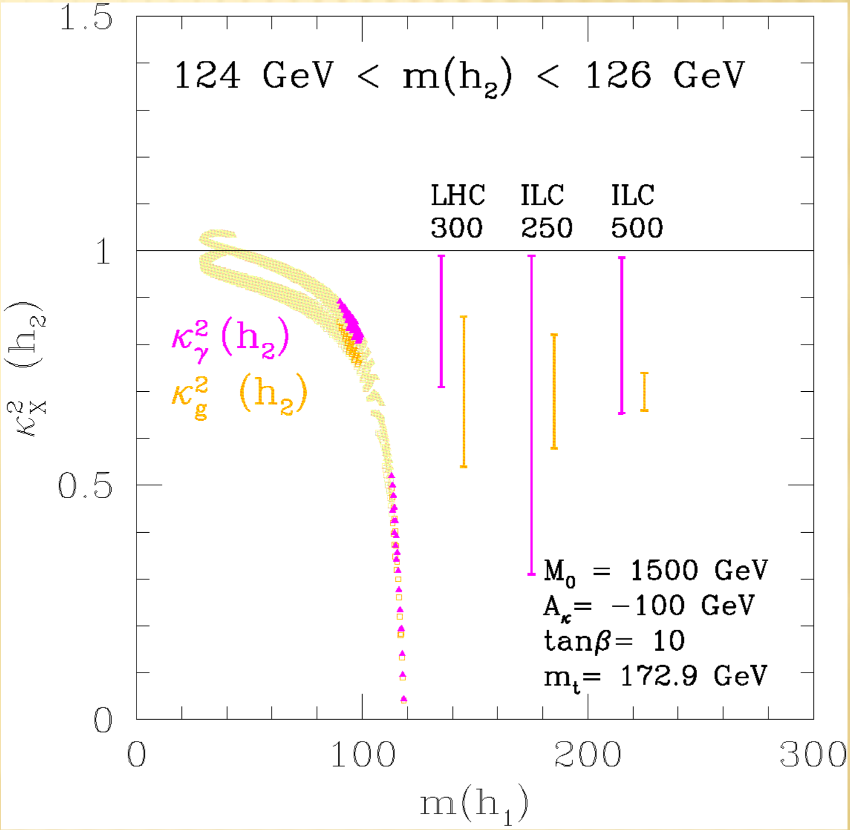
NUMERICAL RESULTS FOR CP EVEN HIGGS (CONT'D)

$\tan\beta = 10$ $\kappa^i_X = \frac{C^i_X}{C^{SM}_X}$

Tree



Loop



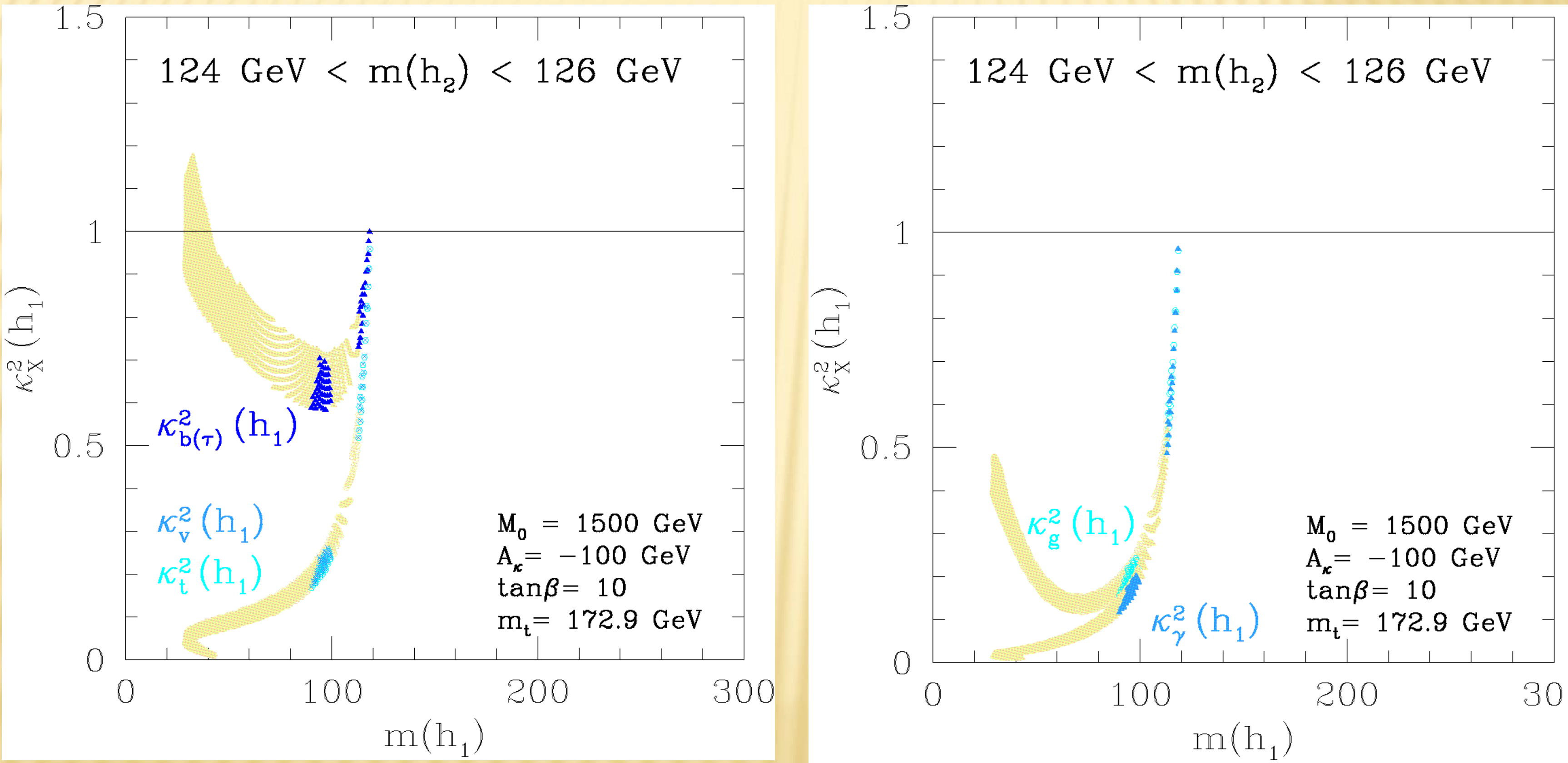
Singlet-doublet mixing is required by $m_{h_2} = 125$ GeV.

~ 50 % deviation is possible for κ_b (mixing with $\tan\beta$ enhanced H coupling).

NUMERICAL RESULTS FOR CP EVEN HIGGS (CONT'D)

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

Tree $\qquad\qquad$ Loop



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

κ_b is enhanced by $\tan\beta$.

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 TeV stop while μ can be as heavy as 500 GeV.
- Singlet-doublet mixing is suppressed due to accidental scale symmetries.
- 10-20% deviation is expected in SM-like Higgs coupling. O(1) deviation is possible for b (τ).
- Light hidden singlet is characteristic and an interesting target for future colliders

BACKUP

SCALE SYMMETRY IN MSSM (CONT'D)

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

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

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.

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

EFFECTIVE COUPLINGS IN NMSSM

In the NMSSM, the effective couplings for V and f are given by,

$$C_V^i = S_{2i}^\dagger \sin\beta + S_{1i}^\dagger \cos\beta, \qquad \Big(\sum_i (C_V^i)^2 = 1\Big)$$

$$C_f^i = \begin{cases} S_{1i}^\dagger \dfrac{1}{\cos\beta} & (f = e, \mu, \tau, d, s, b) \\ S_{2i}^\dagger \dfrac{1}{\sin\beta} & (f = u, c, t) \end{cases},$$

S: unitary matrix for mass diagonalization

In the $\kappa = m_S^2 = 0$ limit, they are summarized as:

	h	H	h_S
$m_{h_i}^2$	$m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$	$A_\lambda^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta$	$\lambda^2 v^2 \sin^2 2\beta$
C_V^i	1	0	$\lambda \frac{v}{A_\lambda} \sin 2\beta$
$C_{d,e}^i$	1	$-\tan\beta$	$\lambda \frac{v}{A_\lambda} \tan\beta$
C_u^i	1	$\cot\beta$	$\lambda \frac{v}{A_\lambda} \cot\beta$

$C_{d,e}^h$ is sensitive to the mixing with H due to $\tan\beta$ enhancement.