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Singlet-Doublet mixing in NMSSM and approximate scale symmetries

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In collaboration with T.Kobayashi, H.Makino, T.Shimomura, arXiv: 1509.05327

Intordunction

- LHC Run I tells “the SM-like Higgs boson + no light colored new particle”.
- If a light neutral scalar exists it may mix with the Higgs boson.
- This modifies the Higgs coupling and now subjects to rather strong constraints.
- We propose that approximate scale symmetries are useful to suppress such mixings e.g. in NMSSM.

SM like Higgs boson

Now we have 'the Higgs (BEH) boson' having properties predicted by the SM

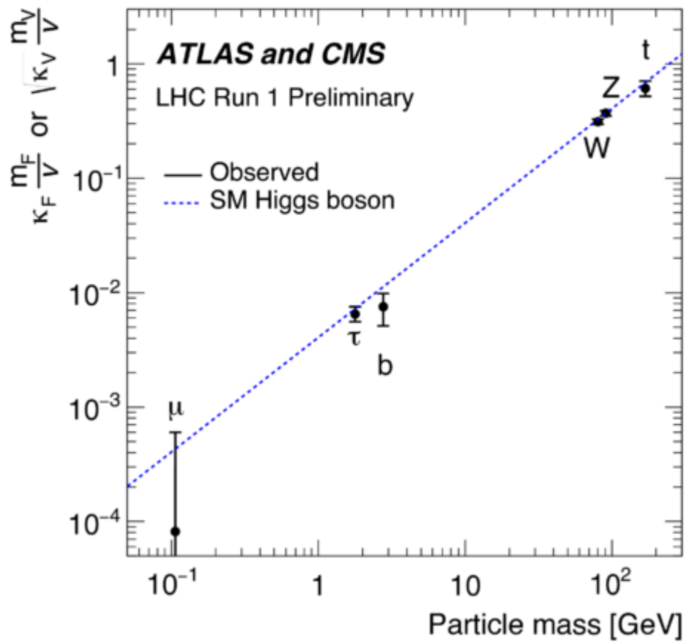
$$m_h = 125.09 \pm 0.21 \pm 0.11\mathrm{GeV}$$

$$\begin{aligned}\mathcal{L} &= \left[C_V \frac{\sqrt{2} m_W^2}{v} h W_\mu^+ W^{-\mu} + C_V \frac{m_Z^2}{\sqrt{2} v} h Z_\mu Z^\mu - \sum_{f=t,b,\tau} C_f \frac{m_f}{\sqrt{2} v} h \bar{f} f \right. \\ &\quad \left. + C_g \frac{\alpha_s}{12\sqrt{2}\pi v} h G^a_{\mu\nu} G^{a\,\mu\nu} + C_\gamma \frac{\alpha}{\sqrt{2}\pi v} h A_{\mu\nu} A^{\mu\nu} \right]\end{aligned}$$

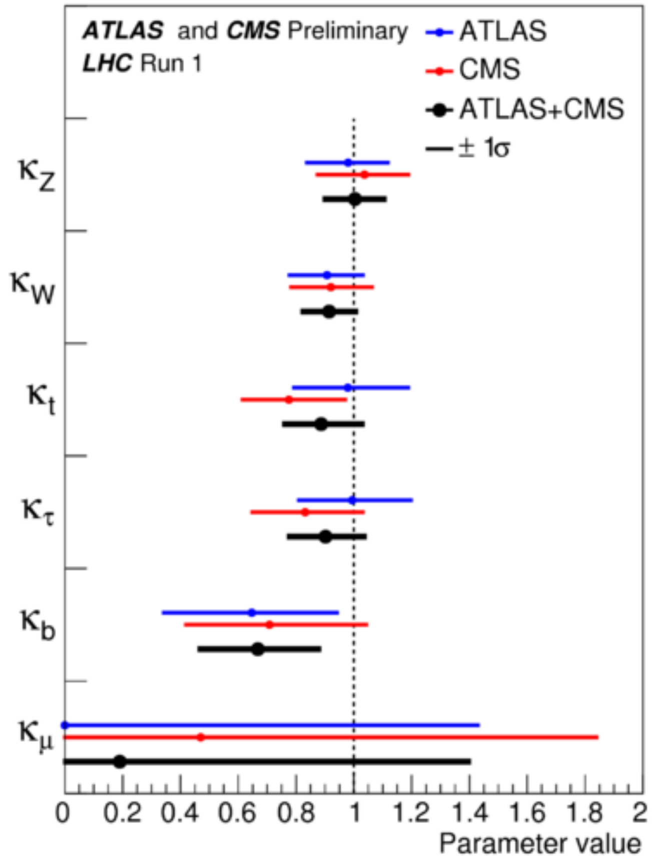
7 (5) parameter model

SM like Higgs boson

Any new physics model
must obey this new constraint



$$\kappa_X = C_X / C_X^{\mathrm{SM}}$$



ATLAS-CONF-2015-044

NMSSM

P.Fayet (1975) and many others…

MSSM + Singlet: S, sometime with Z_3 symmetry

$$\boxed{W_H = -\lambda S H_u H_d + \frac{\kappa}{3} S^3 \quad (Z_3) \qquad + \mathcal{L}_{\cancel{SUSY}}}$$

Solves the μ problem $\mu_{eff} = \lambda\langle S\rangle$ J.E.Kim, H.P.Nilles (1984)

New F-term potential pushes up the Higgs boson mass.

$$\Delta V_F = \lambda^2 |H_u H_d|^2$$

Landau pole, Low $\tan\beta$

Solution of the $B\mu$ problem (anomaly mediation)

Singlet-Doublet mixing in NMSSM

NMSSM has an extra CP-even (and odd) boson: h_S

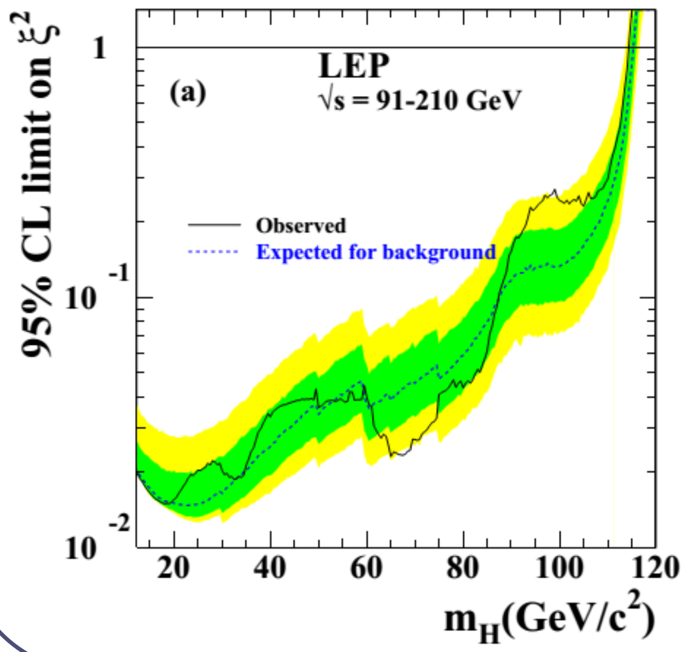
★ $m_{h_S} > m_h$

Mixing (off-diagonal mass) pushes down the SM-like Higgs mass

★ $m_{h_S} < m_h$

LEP Higgs boson search

$Z^* \to Z + h_S$



Singlet-Doublet mixing in NMSSM

$$\mathcal{M}_S^2 =$$

$$\left(\begin{array}{c|c|c} \begin{array}{l} g^2 v_d^2 \\ +\mu_{eff}(A_\lambda + \frac{\kappa}{\lambda}\mu_{eff})\tan\beta \end{array} & \begin{array}{l} (2\lambda^2 - g^2) v_d v_u \\ -\mu_{eff}(A_\lambda + \frac{\kappa}{\lambda}\mu_{eff}) \end{array} & \lambda\left\{2\mu_{eff} v_d - (A_\lambda + 2\frac{\kappa}{\lambda}\mu_{eff}) v_u\right\} \\ \hline & \begin{array}{l} g^2 v_u^2 \\ +\mu_{eff}(A_\lambda + \frac{\kappa}{\lambda}\mu_{eff})/\tan\beta \end{array} & \lambda\left\{2\mu_{eff} v_u - (A_\lambda + 2\frac{\kappa}{\lambda}\mu_{eff}) v_d\right\} \\ \hline & & \begin{array}{l} \lambda^2 A_\lambda v_u v_d/\mu_{eff} \\ +\frac{\kappa}{\lambda}\mu_{eff}(A_\kappa + 4\frac{\kappa}{\lambda}\mu_{eff}) \end{array} \end{array}\right)$$

$$Re\Delta H_d \qquad\qquad Re\Delta H_u \qquad\qquad Re\Delta S$$

Suppressing the singlet-doublet mixing: 2 well-known scenarios

(1) Heavy singlet: $(\mathcal{M}_S^2)_{33} \to \infty$

(2) Small couplings: Fixing, $\mu_{eff}, \ \dfrac{\kappa}{\lambda}$ $\qquad \lambda, \ \kappa \to 0$

Approximate scale symmetries

Approximate scale symmetries might be useful for suppressing the singlet-doublet mixing:

Consider the limit: $\kappa,\ g \to 0 \qquad m_S^2 \to 0$

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

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

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

explicitly broken by $\mathcal{K}_S = S^\dagger S$ and Kinetic-terms (θ).

Approximate scale symmetries

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

NG boson

$$\mathcal{M}_S^2 \equiv \frac{\partial^2 V}{\partial\phi_i \partial\phi_j}$$

$$= \begin{pmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & \boxed{0 \quad\quad 0} \\ 0 & A_\lambda^2 & -\lambda A_\lambda v \cos 2\beta \\ 0 & -\lambda A_\lambda v \cos 2\beta & \lambda^2 v^2 \end{pmatrix} \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$+ \begin{pmatrix} 0 & 2\lambda^2 v^2 \sin\beta\cos\beta & 0 \\ 2\lambda^2 v^2 \sin\beta\cos\beta & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$S^\dagger S$

No mixing with S or heavy H !
(up to breaking)

Approximate scale symmetries

Another limit: $\kappa,\ g \to 0 \qquad m_{H_u}^2 \to 0$

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

Broken by $H_u^\dagger H_u$

Now the singlet-like Higgs, $(S + H_d)$ becomes the NG boson

Mixing with H_u is suppressed.

Approximate scale symmetries

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

two NG bosons, H_u, S (mass eigenstates)

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

Breaking terms

$\mathcal{S}_{31}^\dagger$ and $\mathcal{S}_{23}^\dagger$ must break the both symmetries and decouple with $m_{H_d}^2$.

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

(Classical level)

TeV scale mirage mediation

K.Choi, K-S Jeong, KO, T Kobayashi (2005)

TeV scale mirage mediation gives an example of this class of model:

Modulus mediation + Anomaly mediation

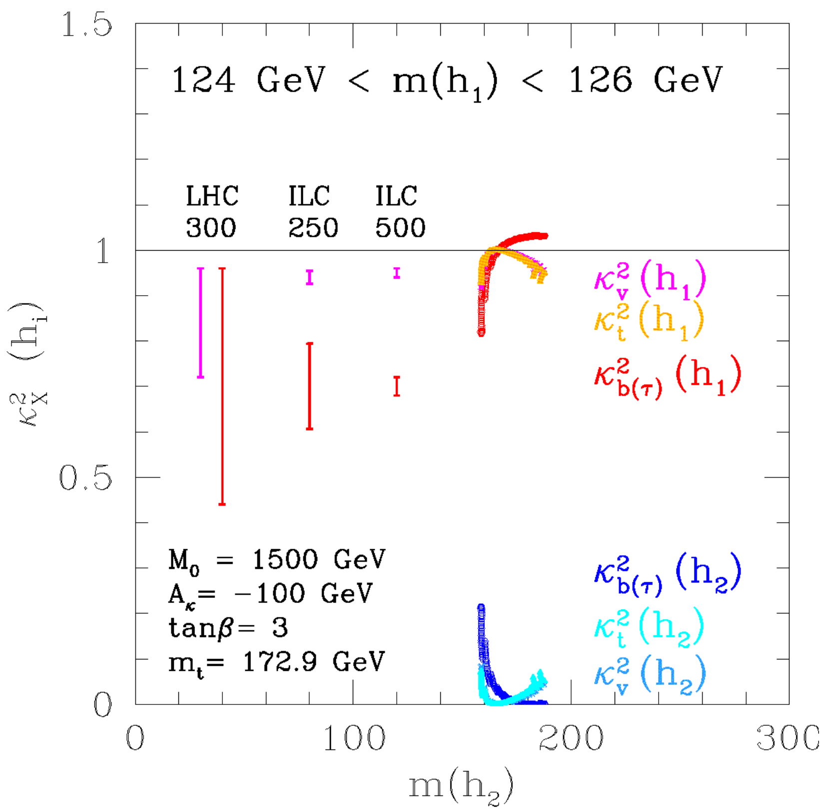
$$m_{\rm SUSY} \simeq M_0 \qquad \lambda = \mathcal{O}(1), \qquad \kappa << 1$$

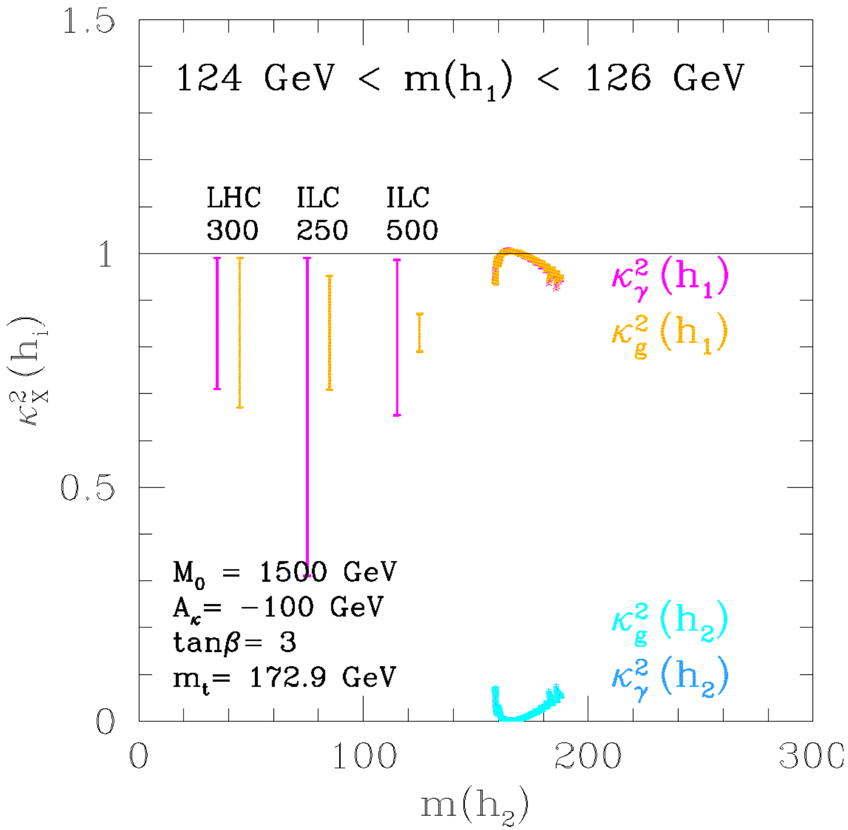
$$m_{H_d} = M_0^2, \qquad A_\lambda = M_0$$

$$m_{H_u}^2,\ m_S^2 \simeq \frac{M_0^2}{8\pi^2}$$

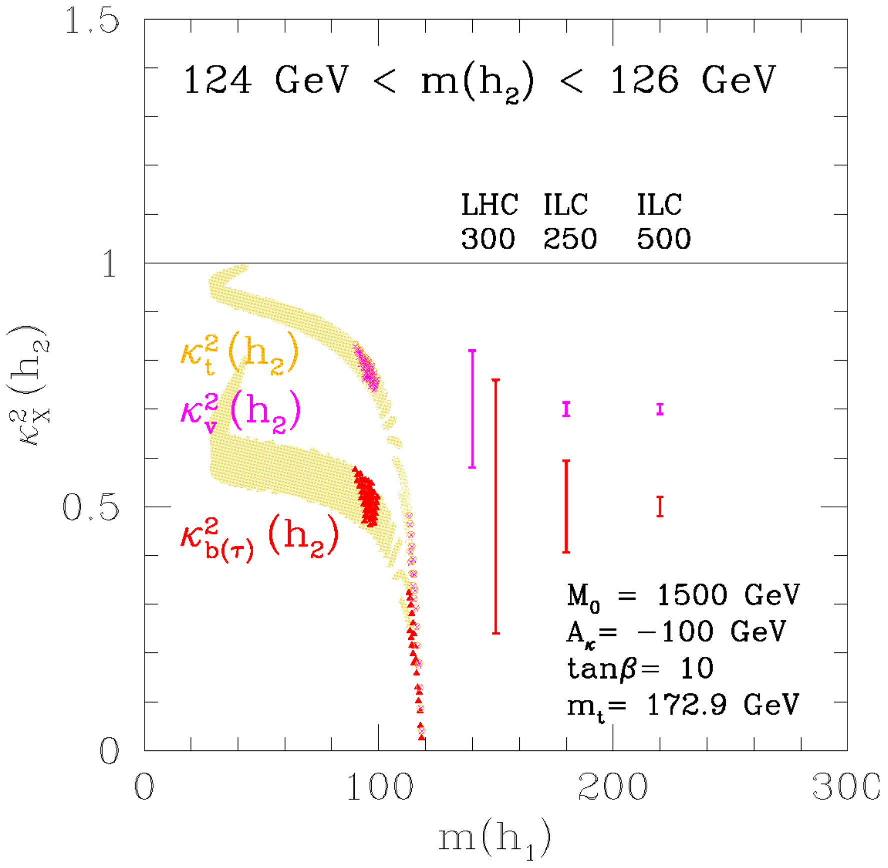
@ TeV scale

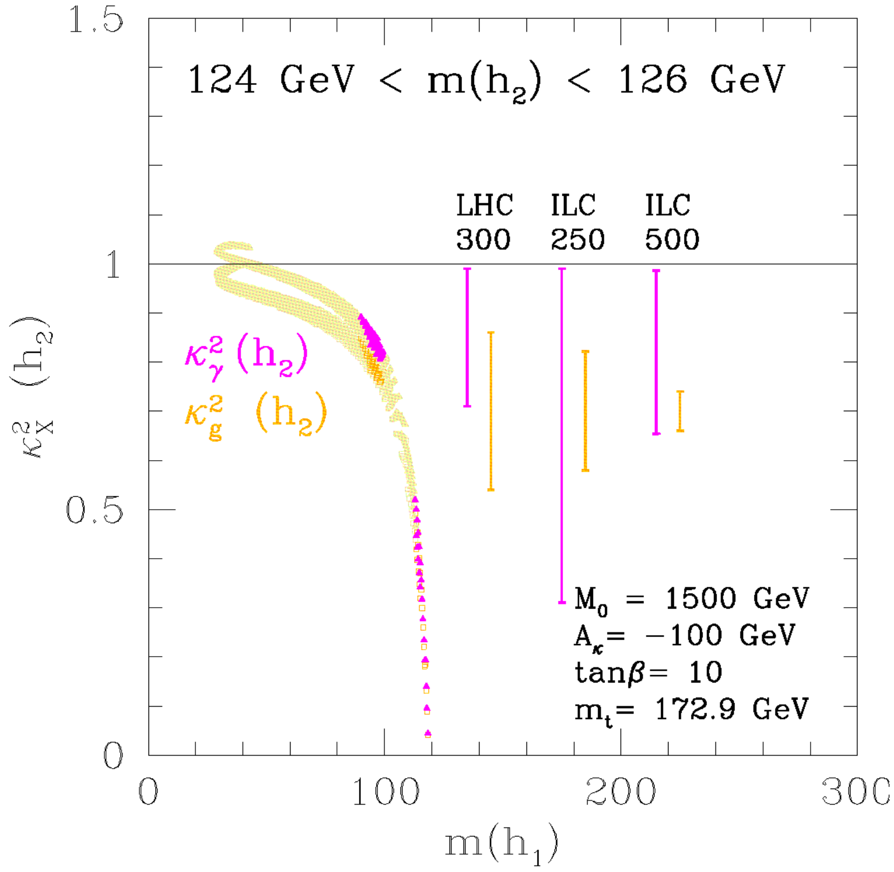
Higgs couplings



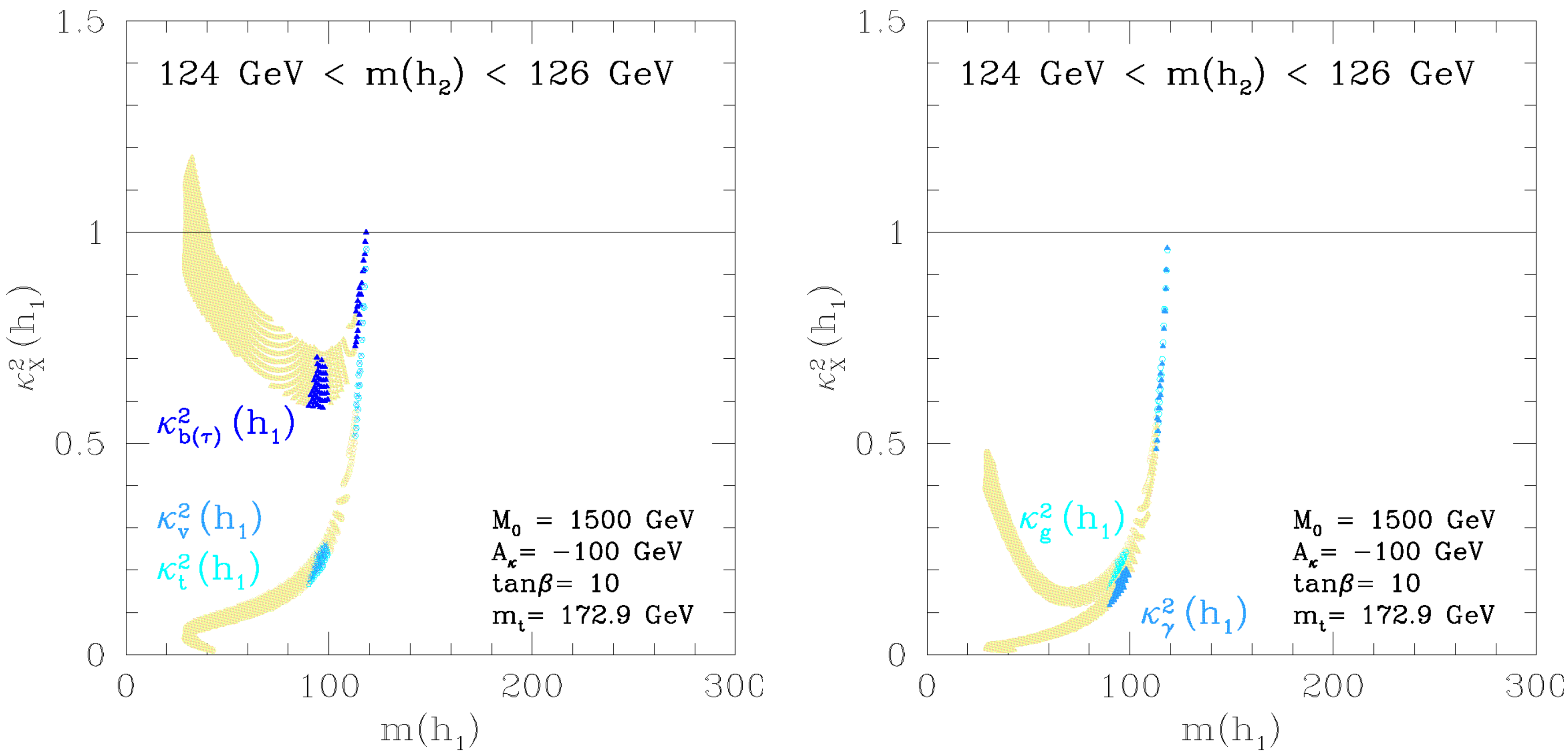


Higgs couplings





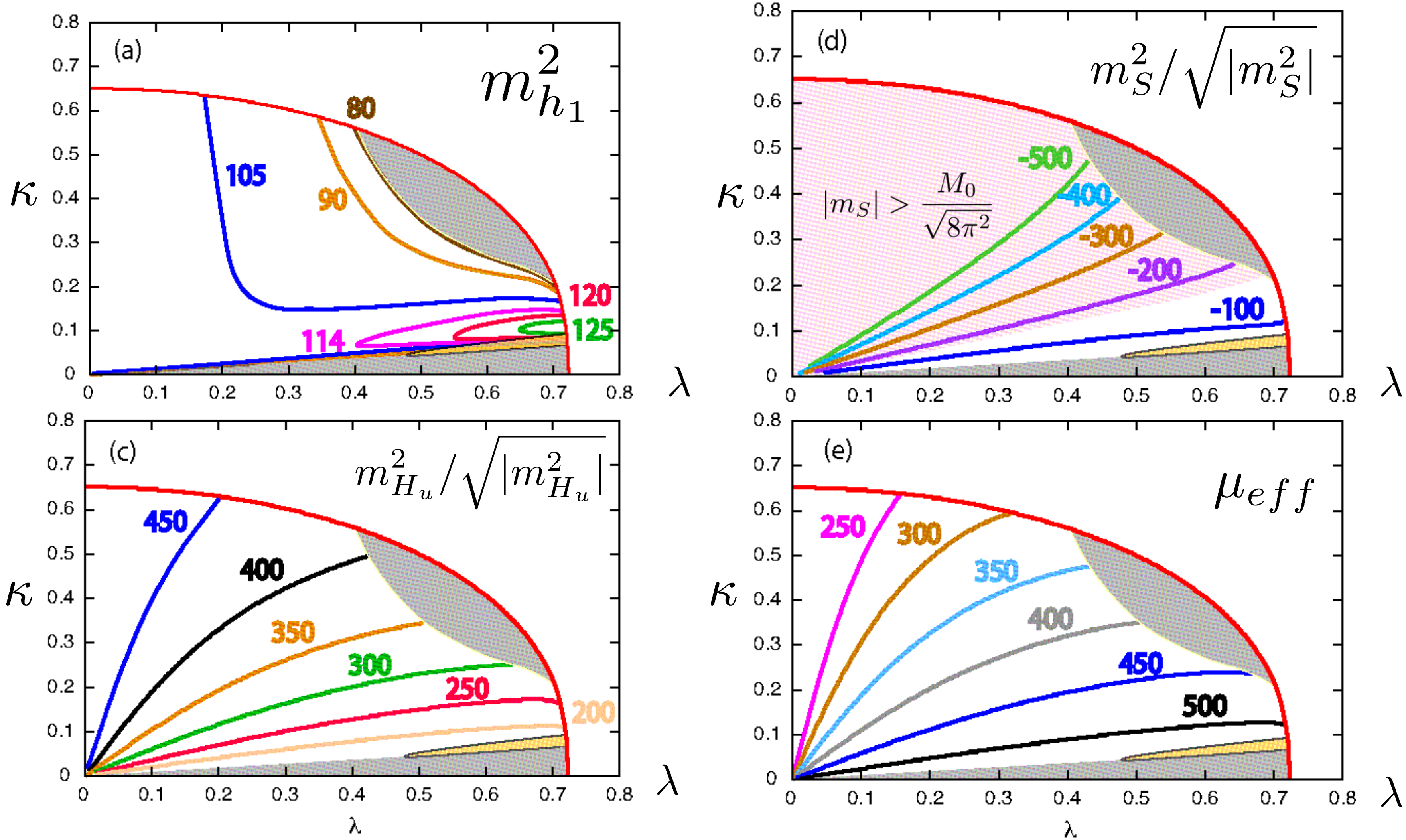
Higgs couplings



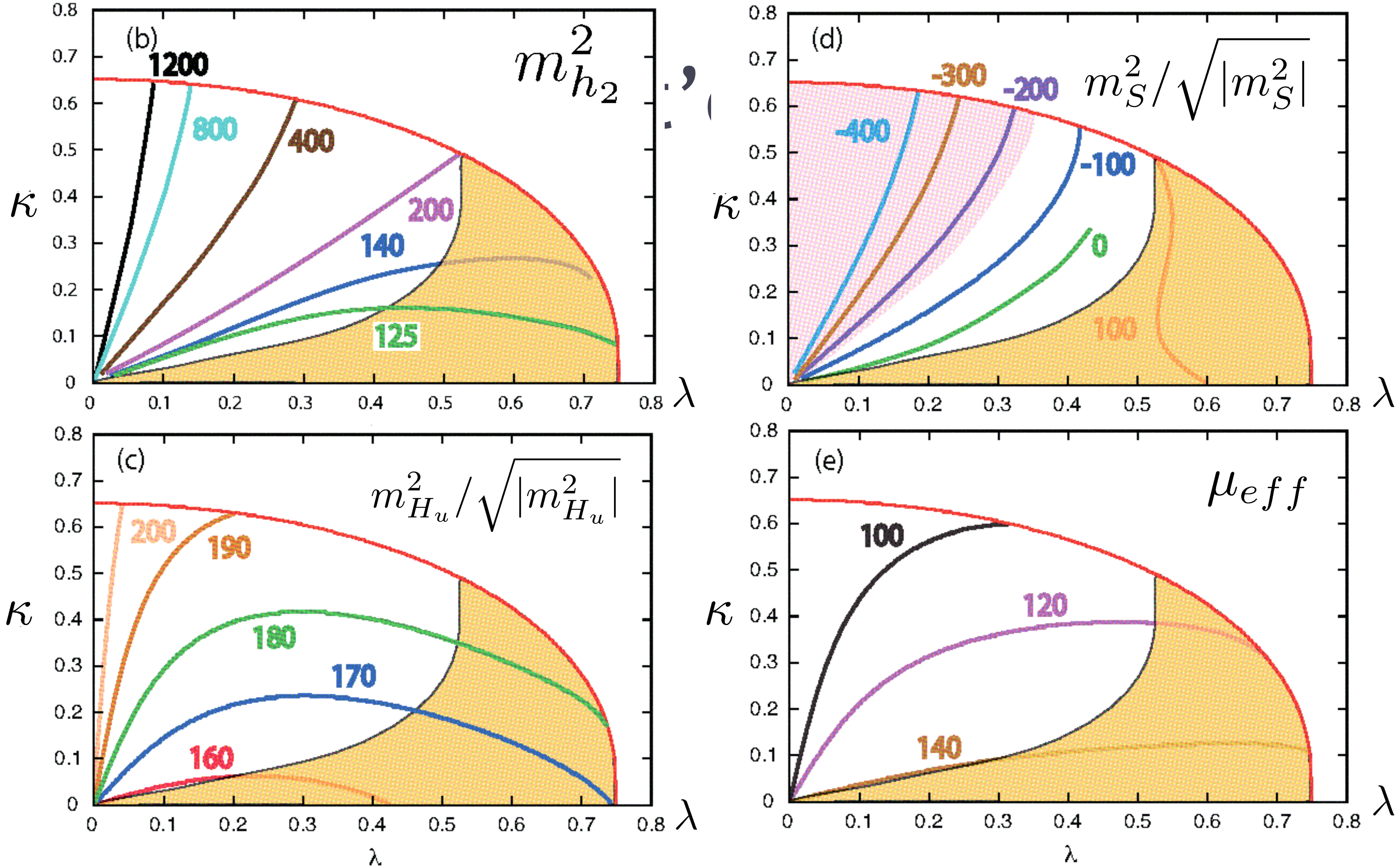
Conclusion

- LHC Run I requires the Higgs boson is SM-like
- Mixing with a new singlet must be suppressed
- In NMSSM, we observed that approximate scale symmetries are useful to suppress the singlet-doublet mixing up to the breaking effects.
- Application of this kind of scale symmetries to more general models might be interesting.

Back Up



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



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