Higgs boson mass in NMSSM with large $\tan\beta$

Marek Olechowski

Institute of Theoretical Physics, University of Warsaw

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based on:

M. Badziak, M.O. and S. Pokorski, in preparation

Outline

- Motivation
- Higgs boson mass in NMSSM with small $\tan\beta$
- Higgs boson mass in NMSSM with moderate or large $\tan\beta$
  - contribution from mixing with the singlet scalar
  - constraints on Δm_h from the LEP data
  - mixing with the heavy doublet scalar
- Numerical results
- Predictions for the branching ratios of the SM-like Higgs
- Conclusions

Motivation

Good news for SUSY:

a Higgs-like particle with the mass below the upper bound predicted in the simplest SUSY models has been apparently discovered at LHC

Not so good news for SUSY:

Higgs mass of 125-126 GeV is rather big for MSSM

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2} \right) + \frac{X_t^2}{M_{\rm SUSY}^2} - \frac{1}{12} \frac{X_t^4}{M_{\rm SUSY}^4} \right]$$

Ways to increase the Higgs boson mass

- Bigger values of $\tan\beta$
  - $\cos^2 2\beta > 0.96$ already for $\tan\beta = 10$
- Higher SUSY scale $M_{\rm SUSY}$
  - not very appealing from the phenomenological (prospects for SUSY discovery) and theoretical (hierarchy problem) points of view
- Stop mixing parameter X_t^2 close to the optimal value
  - in the above approximation the X_t^2-dependent contribution is maximized when $X_t^2/M_{\rm SUSY}^2 = 6$

Higgs boson mass in NMSSM with small $\tan\beta$

Mass of the SM-like Higgs:

$$m_h^2 = M_Z^2 \cos^2 2\beta + \Delta_{\rm rad} + \lambda^2 v^2 \sin^2 2\beta + \Delta_{\rm mix}$$

The tree level contribution **increases** with $\tan\beta$

The contribution proportional to the singlet-doublet-doublet coupling, $\lambda^2 v^2 \sin^2 2\beta$, **decreases** with $\tan\beta$

The most popular strategy to get big enough Higgs boson mass:

- λ as big as possible (or even bigger)
- $\tan\beta$ not much bigger than 1 (usually < 3)

Term $\Delta_{\rm mix}$ originates from (mainly) singlet-doublet mixing

It is positive (negative) when the singlet-dominated Higgs scalar is lighter (heavier) than the SM-like Higgs scalar

Higgs boson mass in NMSSM with small $\tan\beta$

Favored in many analyses (scans) of the NMSSM parameter space:

- $\tan\beta = \mathcal{O}(2)$
- SM-like Higgs is next-to-the-lightest Higgs scalar
  (the lightest Higgs is singlet-dominated)
- large values of λ ($W = \lambda S H_u H_d + \ldots$)

Are large/moderate values of $\tan\beta$ so strongly disfavored in NMSSM?

Moderate and large $\tan\beta$

$$m_h^2 = M_Z^2 \cos^2 2\beta + \Delta_{\rm rad} + \lambda^2 v^2 \sin^2 2\beta + \Delta_{\rm mix}$$

The tree level contribution is almost maximal (much bigger than for small $\tan\beta$)

For moderate or large $\tan\beta$ the term $\lambda^2 v^2 \sin^2 2\beta$ is (very) small.

The mixing contribution, $\Delta_{\rm mix}$, is necessary to have Higgs boson heavier than in the MSSM (with similar stop masses and mixing).

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We concentrate on models with

$$\frac{1}{2} m_h < m_s < m_h \ll m_H$$

The first inequality in order to avoid complications caused by the Higgs-to-Higgs decays

Mixing with the singlet

$$\hat{M}^2 = \begin{pmatrix} \hat{M}^2_{hh} & \hat{M}^2_{hs} \\ \hat{M}^2_{hs} & \hat{M}^2_{ss} \end{pmatrix}$$

where $\hat{M}^2_{hh}$ is the SM-like Higgs mass squared without mixing taken into account $\hat{M}^2_{hh} = M_Z^2 \cos^2 2\beta + \Delta_{\rm rad}$

With the mixing $\qquad m_h = \hat{M}_{hh} + \Delta_{\rm mix}$

$$\Delta^2_{\rm mix} = \frac{1}{2}\tan^2\theta \left(\left(\hat{M}^2_{hh} - \hat{M}^2_{ss} \right) + \sqrt{\left(\hat{M}^2_{hh} - \hat{M}^2_{ss} \right)^2 + 4 \left(\hat{M}^2_{hs} \right)^2} \right)$$

In order to obtain big $\Delta_{\rm mix}$ one prefers

- big doublet-singlet mixing angle θ
- big off-diagonal mass term $\hat{M}^2_{hs}$
- small diagonal singlet mass term $\hat{M}^2_{ss}$

These three parameters are not independent: $\tan 2\theta = \dfrac{2\hat{M}^2_{hs}}{\hat{M}^2_{hh} - \hat{M}^2_{ss}}$

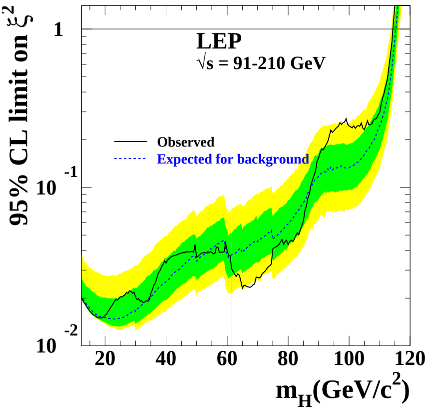
It is not possible to have simultaneously big mixing and light singlet

Light scalar with a substantial mixing with the SM-like Higgs would have been discovered by the LEP experiments

$$\xi^2 = \bar{g}^2 \cdot \overline{BR}(H \to b\bar{b})$$

$$\boldsymbol{\bar{g}^2 = \sin^2\theta}$$

stronger LEP constraints on the mixing angle for lighter singlet-dominated scalars



Mixing with the singlet

For a given m_s^2 we have upper bound on $\sin\theta \Rightarrow$ upper bound on $\Delta_{\rm mix}$

For $m_h = 125$ GeV we obtain:

$$m_s = 65 \text{ GeV} \qquad \Rightarrow \qquad \Delta_{\rm mix} \lesssim 1.0 \text{ GeV}$$

$$m_s = 75 \text{ GeV} \qquad \Rightarrow \qquad \Delta_{\rm mix} \lesssim 1.6 \text{ GeV}$$

$$m_s = 95 \text{ GeV} \qquad \Rightarrow \qquad \Delta_{\rm mix} \lesssim 5.7 \text{ GeV}$$

Mixing with the singlet and the heavy doublet

$$\hat{M}^2 = \begin{pmatrix} \hat{M}^2_{hh} & \frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta & \lambda v(2\mu - \Lambda \sin 2\beta) \\ \frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta & \hat{M}^2_{HH} & \lambda v \Lambda \cos 2\beta \\ \lambda v(2\mu - \Lambda \sin 2\beta) & \lambda v \Lambda \cos 2\beta & \hat{M}^2_{ss} \end{pmatrix}$$

$$\Lambda = A_\lambda + \left\langle \partial_S^2 W(S) \right\rangle$$

Mixing with the heavy doublet is usually neglected because

- $\sin 4\beta$ and $\cos 2\beta$ are small for small $\tan\beta$
- mixing with much heavier states is usually very small

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But:

- $\cos 2\beta \approx -1$ for moderate or large $\tan\beta$
- even small mixing between singlet and heavy doublet may be important

Mixing with the singlet and the heavy doublet

Mixing with (very) heavy doublet has little impact on the masses of two other scalars

However, even small admixture of the heavy doublet may change substantially the couplings of those light scalars to b and τ if $\tan\beta$ is **not** small

$$C_b = C_\tau = v_h + v_H \cdot \tan\beta$$

where $[v_h, v_H, v_s]^T$ is the light scalar eigenvector in the basis (h, H, s)

- When the mixing with the heavy doublet is neglected the LEP bounds on ξ^2 simply translate to bounds on $\Delta_{\rm mix}$ because in such case $\xi^2 = \bar{g}^2 \cdot \overline{BR}(h_s \to b\bar{b}) \approx \bar{g}^2$

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- Mixing with the heavy doublet changes $\overline{BR}(h_s \to b\bar{b})$ of the singlet-dominated scalar
    - substantially if $\tan\beta$ is big enough (but not too big)

Mixing with the singlet and the heavy doublet

$\overline{BR}(h_s \to b\bar{b})$ of the light siglet-dominated scalar is a complicated function of $\tan\beta$

In the limit of large mass of H and large $\tan\beta$
$\overline{BR}(h_s \to b\bar{b})$ vanishes for two values of $\tan\beta$:

$$\tan\beta_1 \approx \mathcal{O}\left(\frac{\Lambda}{\mu}\right) \qquad\qquad \tan\beta_2 \approx \mathcal{O}\left(\frac{\mu}{\Lambda}\,\frac{m_H^2}{m_h^2}\right)$$

For these values of $\tan\beta$ the lightest Higgs boson was invisible for LEP experiments (independent of its mass) because it decays mainly to c quarks

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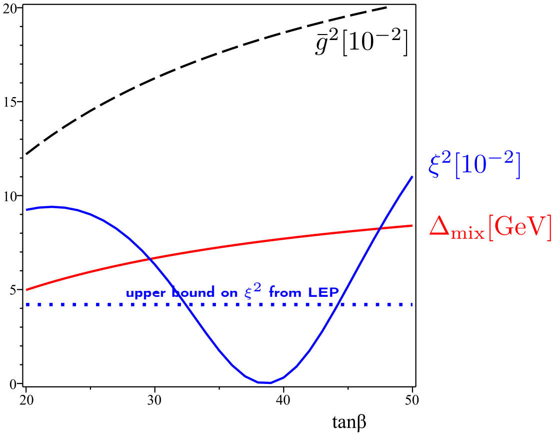
Important questions:

- How big are regions around $\tan\beta_1$ and $\tan\beta_2$ for which the suppression of $\overline{BR}(h_s \to b\bar{b})$ is substantial?
- How much does this effect change the upper bound on Δ_{mix}?

Numerical results



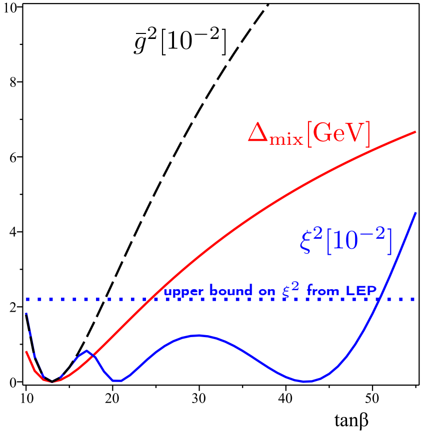
$m_s = 75$ GeV
$m_h = 125$ GeV
$m_H = 1000$ GeV
$\mu = 100$ GeV
$\Lambda = 550$ GeV
$\lambda = 0.13$

- ξ^2 is below the LEP upper bound for $32 \lesssim \tan\beta \lesssim 44$
  - It is about 4 times too large if mixing with H is neglected
- Correction to the SM-like Higgs mass is $\Delta_{\rm mix} \approx 7 \div 8$ GeV

Numerical results

- One of the regions with strongly suppressed ξ^2 occurs close to $\tan\beta_1 \sim \mathcal{O}(\Lambda/\mu)$
- The other region with strongly suppressed ξ^2 occurs close to $\tan\beta_2 \sim \mathcal{O}\left((\mu/\Lambda)(m_H^2/m_h^2)\right)$
- $\tan\beta_1$ increases while $\tan\beta_2$ decreases with increasing ratio Λ/μ
- When Λ/μ is big enough two regions of strongly suppressed ξ^2 may merge to produce one large region in $\tan\beta$ compatible with the LEP results

Numerical results



$m_s = 65$ GeV
$m_h = 125$ GeV
$m_H = 2000$ GeV
$\mu = 100$ GeV
$\Lambda = 1300$ GeV
$\lambda = 0.15$

- ξ^2 is below the LEP upper bound for $10 \lesssim \tan\beta \lesssim 50$
- $\Delta_{\rm mix}$ up to about 6 GeV
    - $\tan\beta \lesssim 18$, $\Delta_{\rm mix} \lesssim 1$ GeV if mixing with H is neglected
- Mixing with H not important for $\tan\beta \lesssim 16$

Numerical results

- Neglecting mixing with the heavy doublet one gets maximal correction to the SM-like Higgs for rather heavy singlet-dominated scalar

$$\Delta_{\rm mix} \lesssim 5.7 \text{ GeV} \qquad \text{for} \qquad m_s \approx 95 \text{ GeV}$$

while

$$\Delta_{\rm mix} < 2 \text{ GeV} \qquad \text{for} \qquad m_s < 80 \text{ GeV}$$

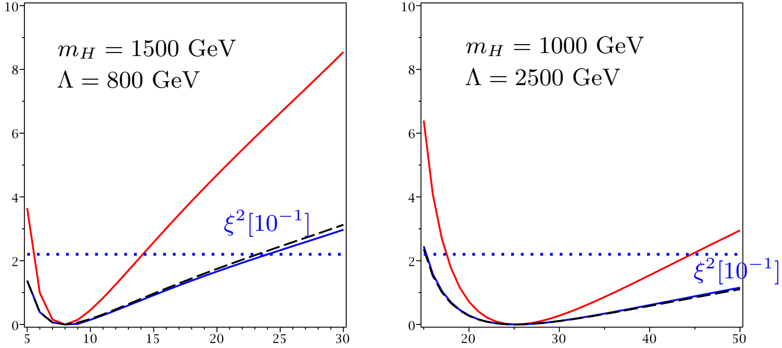
- Including effects of mixing with H one can get

$$\Delta_{\rm mix} = \mathcal{O}(10 \text{ GeV}) \qquad \text{for} \qquad m_s \approx 65 \div 75 \text{ GeV}$$

- Is mixing with H also so important for singlet with mass $m_s \approx 95$ GeV?

Numerical results

$$m_h = 125 \text{ GeV} \qquad m_s = 95 \text{ GeV} \qquad \lambda = 0.12$$

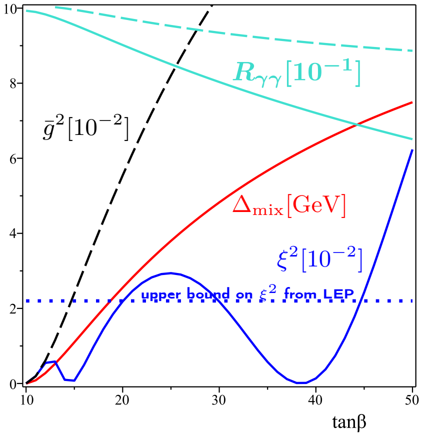


- Very small effect of mixing with H
- Δ_{mix} up to ~ 6 GeV for moderate or large $\tan\beta$ depending on the parameters

Predictions for the branching ratios of the SM-like Higgs

- Mixing with H may change the properties of the lightest singlet-dominated Higgs in an important way
- How mixing with H changes the properties of the SM-like Higgs?

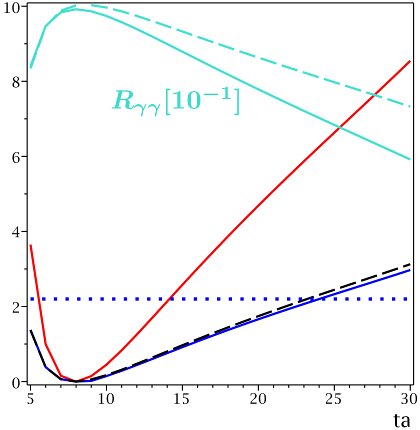
Predictions for the branching ratios of the SM-like Higgs



$m_s = 65$ GeV
$m_h = 125$ GeV
$m_H = 1500$ GeV
$\mu = 100$ GeV
$\Lambda = 1000$ GeV
$\lambda = 0.15$

- $R_{\gamma\gamma}$ is anti-correlated with $\Delta_{\rm mix}$
- $R_{\gamma\gamma}$ drops to about 0.7 for $\Delta_{\rm mix} \approx 7$ GeV
  - Neglecting mixing with H: $R_{\gamma\gamma} \approx 1$ for maximal $\Delta_{\rm mix} \approx 1$ GeV
- Mixing with S and with H have similar impact on $R_{\gamma\gamma}$

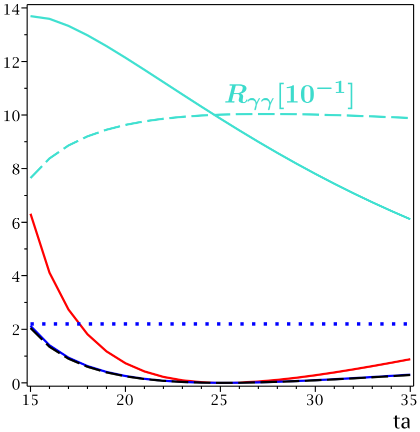
Predictions for the branching ratios of the SM-like Higgs



$m_s = 95$ GeV
$m_h = 125$ GeV
$m_H = 1500$ GeV
$\mu = 100$ GeV
$\Lambda = 800$ GeV
$\lambda = 0.12$

- $R_{\gamma\gamma}$ is anti-correlated with $\Delta_{\rm mix}$
- $R_{\gamma\gamma}$ drops to about 0.7 for $\Delta_{\rm mix} \approx 6$ GeV
  - Neglecting mixing with H: $R_{\gamma\gamma}$ drops to about 0.8 for $\Delta_{\rm mix} \approx 6$ GeV
- stronger tuning at small $\tan\beta$

Predictions for the branching ratios of the SM-like Higgs



$m_s = 95$ GeV
$m_h = 125$ GeV
$m_H = 1000$ GeV
$\mu = 100$ GeV
$\Lambda = 2500$ GeV
$\lambda = 0.13$

- $R_{\gamma\gamma}$ may be bigger than 1 for moderate values of $\tan\beta$
- Neglecting mixing with H:
  - $R_{\gamma\gamma}$ drops to about 0.8 for $\Delta_{\rm mix} \approx 6$ GeV
  - is close to 1 for small $\Delta_{\rm mix}$

Conclusions

- Positive contribution to the Higgs mass in NMSSM due to mixing with the singlet scalar if $m_s < m_h$
- Calculations neglecting mixing with the heavy doublet scalar give the following contribution to the SM-like Higgs mass
  - up to $5 \div 6$ GeV only if $m_s \sim 95$ GeV
  - less then about 2 GeV for smaller m_s
  - $\Delta_{\rm mix}$ simply and strongly correlated with the LEP bounds
- Mixing with heavy doublet has important consequences if $\tan\beta$ is large or moderate:
  - $BR(h_s \to b\bar{b})$ may be substantially reduced due to mixing
  - LEP constraints easily fulfilled for quite large ranges of $\tan\beta$ values
  - $\Delta_{\rm mix}$ may be even ~ 10 GeV for $m_s \lesssim 80$ GeV
- $\Delta_{\rm mix}$ is correlated with the SM-like branching ratios
  - $R_{\gamma\gamma}$ decreases with increasing $\Delta_{\rm mix}$ in most cases with large $\tan\beta$
  - e.g. $\Delta_{\rm mix} \lesssim 7$ GeV if $R_{\gamma\gamma} > 0.7$
  - $R_{\gamma\gamma}$ may be substantially enhanced for moderate $\tan\beta$
- 125 GeV Higgs mass may be much easier to obtain in NMSSM with large $\tan\beta$ due to mixing in the Higgs sector