Enhanced $\gamma\gamma$ signal of a light singlet-like scalar in NMSSM

Marcin Badziak

Institute of Theoretical Physics, University of Warsaw

Rencontres de Moriond 2014

based on:

MB, M. Olechowski and S. Pokorski, JHEP **1306** (2013) 043 [arXiv:1304.5437]

Foundation for Polish Science

This project is co-funded by Foundation for Polish Science

Motivation

Good news for SUSY:

The Higgs mass of 125 GeV is below the upper bound predicted in the simplest SUSY models

Not so good news for SUSY:

The Higgs mass of 125 GeV is rather big for MSSM

$\Downarrow$

Rather heavy SUSY spectrum is required

$\Downarrow$

- Naturalness problem
- Bad prospects for SUSY discovery at the LHC

Motivation

Higgs boson mass in MSSM and its extensions

$$m_h^2 = M_Z^2 \cos^2 2\beta + (\delta m_h^2)^{\rm rad} + (\delta m_h^2)^{\rm non-MSSM}$$

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

- $M_{\rm SUSY} \gtrsim 4$ TeV – for vanishing stop mixing $X_t^2 = 0$
- $M_{\rm SUSY} \gtrsim 700$ GeV – for optimal stop mixing $X_t^2 \approx 6 M_{\rm SUSY}^2$

Motivation

Higgs boson mass in MSSM and its extensions

$$m_h^2 = M_Z^2 \cos^2 2\beta + (\delta m_h^2)^{\mathrm{rad}} + (\delta m_h^2)^{\mathrm{non-MSSM}}$$

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

- $M_{\mathrm{SUSY}} \gtrsim 4$ TeV – for vanishing stop mixing $X_t^2 = 0$
- $M_{\mathrm{SUSY}} \gtrsim 700$ GeV – for optimal stop mixing $X_t^2 \approx 6 M_{\mathrm{SUSY}}^2$

If non-MSSM contribution accounts for 10 (5) GeV of the Higgs mass:

- $M_{\mathrm{SUSY}} \gtrsim 1$ (1.5) TeV – for vanishing stop mixing $X_t^2 = 0$
- $M_{\mathrm{SUSY}} \gtrsim 300$ (400) GeV – for optimal stop mixing $X_t^2 \approx 6 M_{\mathrm{SUSY}}^2$

$5 \div 10$ GeV non-MSSM contribution to the Higgs mass
may allow for substantially lighter stops (less fine tuning)

Higgs sector in NMSSM

NMSSM is MSSM extended by a singlet superfield S that couples to H_u and H_d generating effective μ-term:

$$W_{\rm NMSSM} = \lambda S H_u H_d + f(S)$$

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

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

Mass of the SM-like Higgs:

$$m_h^2 = M_Z^2 \cos^2(2\beta) + (\delta m_h^2)^{\rm rad} + \lambda^2 v^2 \,\sin^2 2\beta + (\delta m_h^2)^{\rm mix}$$

The Higgs mass can be strongly enhanced with big λ and small $\tan\beta$

Higgs sector in NMSSM

NMSSM is MSSM extended by a singlet superfield S that couples to H_u and H_d generating effective μ-term:

$$W_{\rm NMSSM} = \lambda S H_u H_d + f(S)$$

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

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

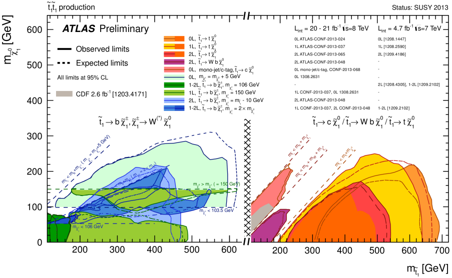
Mass of the SM-like Higgs:

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

The Higgs mass can be strongly enhanced with big λ and small $\tan\beta$

Do we really need large correction to the MSSM Higgs mass?

LHC constraints on the stop mass



For typical SUSY spectra the stop masses below about $600-700$ GeV are ruled out by the LHC

One is forced to accept some fine-tuning and hope that stop masses are just below 1 TeV. For such stop masses:

- $\mathcal{O}(5)$ GeV correction to the MSSM Higgs is enough to get 125 GeV $\Rightarrow$ big λ is not necessary if the Higgs mixes with the light singlet and $\tan\beta$ is **not** small

In this talk: NMSSM with small λ and moderate or large $\tan\beta$

Mixing with the singlet only

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

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

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

$$\Delta_{\rm mix} = m_h - \sqrt{m_h^2 - \overline{g}_s^2\,(m_h^2 - m_s^2)} \approx \frac{\overline{g}_s^2}{2}\left(m_h - \frac{m_s^2}{m_h}\right) + \mathcal{O}(\overline{g}_s^4)$$

where $\overline{g}_s$ is a coupling of s to Z bosons

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

- large singlet-doublet mixing i.e. large $\overline{g}_s$
- $m_s \ll m_h$

Mixing with the singlet only

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

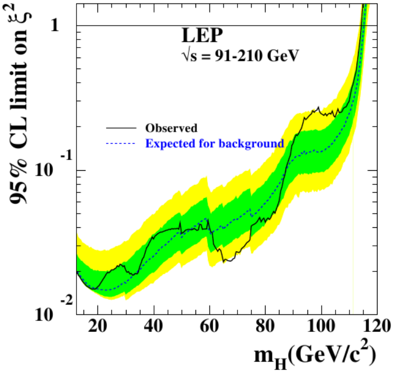
Light scalar with a substantial mixing with the SM-like Higgs would have been discovered by the LEP experiments

$$\overline{BR}(s \to b\bar{b}) \equiv \frac{\mathrm{BR}(s \to b\bar{b})}{\mathrm{BR}(h^{\mathrm{SM}} \to b\bar{b})}$$

$$\xi^2_{b\bar{b}} \equiv \overline{g}^2_s \times \overline{BR}(s \to b\bar{b})$$

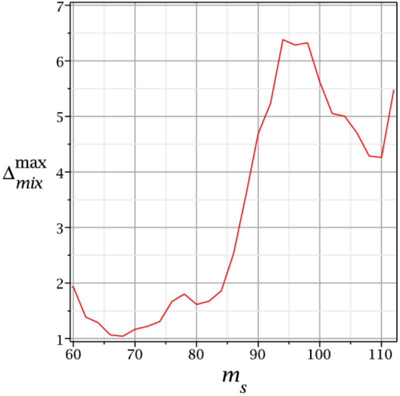
For $\hat{h} - \hat{s}$ mixing only: $\xi^2_{b\bar{b}} = \overline{g}^2_s$

stronger LEP constraints on $\overline{g}^2_s$ for lighter singlet-dominated scalars



Mixing with the singlet only

For a given m_s^2 we have upper bound on $\overline{g}_s^2$ $\Rightarrow$ upper bound on $\Delta_{\rm mix}$



- $\Delta_{\rm mix}$ up to 6 GeV in a few-GeV interval for m_s around 95 GeV
- $\Delta_{\rm mix}^{\rm max}$ drops down very rapidly for $m_s \lesssim 90$ GeV

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 s to b and τ if $\tan\beta$ is **not** small

$$C_{b_s} = C_{\tau_s} = \overline{g}_s + \beta_s^{(H)} \tan\beta$$

where $s = \overline{g}_s \hat{h} + \beta_s^{(H)} \hat{H} + \beta_s^{(s)} \hat{s}$ is the light scalar eigenvector

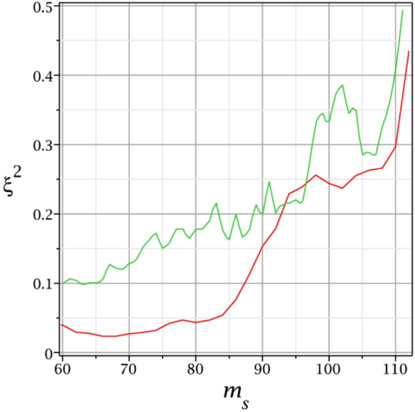
For large $\tan\beta$ and $\overline{g}_s \beta_s^{(H)} < 0$, $\overline{BR}(s \to b\bar{b})$ can be strongly suppressed

$\xi_{b\bar{b}}^2 \ll \overline{g}_s^2$ can be obtained relaxing the constraints from the b-tagged LEP searches!

LEP constraints on $s \to jj$

If $\overline{BR}(s \to b\bar{b})$ is suppressed the $s \to c\bar{c}$ and $s \to gg$ decays dominate

Flavour-independent LEP searches for $s \to jj$ provide the main constraint



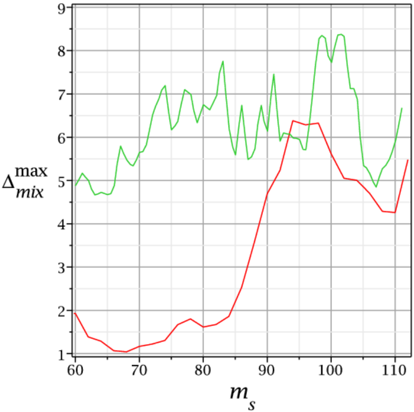
$$\xi^2_{b\bar{b}} \equiv \overline{g}_s^2 \cdot \overline{BR}(s \to b\bar{b})$$

$$\xi^2_{jj} \equiv \overline{g}_s^2 \cdot BR(s \to jj)$$

Constraints on ξ^2_{jj} are typically much weaker than on $\xi^2_{b\bar{b}}$, in particular for smaller m_s, so larger values of $\overline{g}_s^2$ are allowed

Upper bound on $\Delta_{\rm mix}$

For suppressed $\overline{BR}(s \to b\bar{b})$ larger corrections to the Higgs mass from mixing are consistent with the LEP data



$\xi_{b\bar{b}}^2 = \overline{g}_s^2$

$\xi_{jj}^2 = \overline{g}_s^2$

- $\Delta_{\rm mix} \gtrsim 5$ GeV for m_s between 60 and 110 GeV
- $\Delta_{\rm mix} \gtrsim 8$ GeV for m_s around 100 GeV

Predictions for the branching ratios of the SM-like Higgs

Mixing with $\hat{H}$ changes also the properties of the SM-like Higgs

Production and decays of the 125 GeV Higgs

$$R_i^{(h)} \equiv \frac{\sigma(pp \to h) \times \mathrm{BR}(h \to i)}{\sigma^{\mathrm{SM}}(pp \to h) \times \mathrm{BR}^{\mathrm{SM}}(h \to i)}$$

Mixing with the singlet reduces production cross-section of the 125 GeV Higgs:

$$\frac{\sigma(pp \to h)}{\sigma^{\mathrm{SM}}(pp \to h)} \approx 1 - \bar{g}_s^2$$

Anti-correlation between the branching ratios of h and s:

$\overline{BR}(s \to b\bar{b})$ suppressed (enhanced)

$\Downarrow$

$\overline{BR}(h \to b\bar{b})$ enhanced (suppressed)

For the SM 125 GeV Higgs: BR$(h^{\mathrm{SM}} \to b\bar{b}) \approx 60\%$

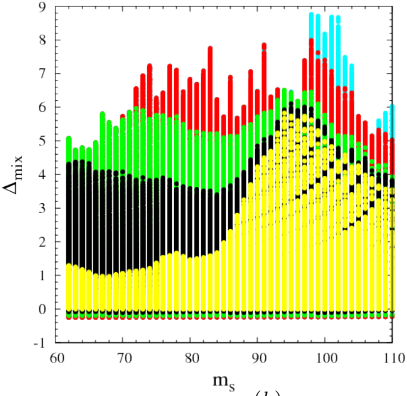
$\Downarrow$

modification of $\overline{BR}(h \to b\bar{b})$ affects all channels:

$\overline{\mathbf{BR}}(\mathbf{s} \to \mathbf{b\bar{b}})$ suppressed $\Rightarrow \mathbf{R}_{\gamma\gamma}^{(\mathbf{h})} \approx \mathbf{R}_{\mathbf{VV}}^{(\mathbf{h})} < \mathbf{1} - \bar{\mathbf{g}}_{\mathbf{s}}^{\mathbf{2}}$

Numerical scan

	m_H [GeV]	λ	Λ [GeV]	$\tan\beta$
Minimal value	250	0.05	100	10
Maximal value	2000	0.15	3000	60
Step size	250	0.01	100	5



$R_{\gamma\gamma}^{(h)} \approx R_{VV}^{(h)} < 0.5$

$R_{\gamma\gamma}^{(h)} \approx R_{VV}^{(h)} \in (0.5, 0.7)$

$R_{\gamma\gamma}^{(h)} \approx R_{VV}^{(h)} \in (0.7, 0.8)$

$R_{\gamma\gamma}^{(h)} \approx R_{VV}^{(h)} \in (0.8, 1)$

$\boldsymbol{R_{\gamma\gamma}^{(h)} \approx R_{VV}^{(h)} > 1}$

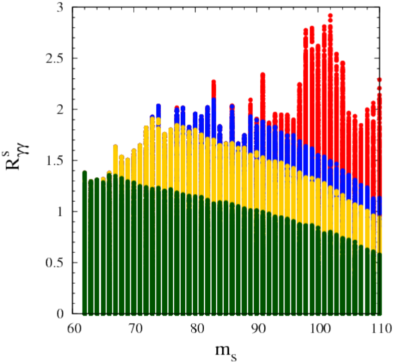
$\Delta_{\rm mix} \gtrsim 5-6$ GeV with $R_{VV}^{(h)} > 0.7$ for wide range of $m_s \in (60, 105)$ GeV

$\boldsymbol{R_{VV}^{(h)} > 1}$ $\Rightarrow$ $\Delta_{\rm mix}$ up to 6 GeV but only for m_s around 95 GeV

Enhanced $s \to \gamma\gamma$

In the region with suppressed $sb\bar{b}$ coupling the branching ratios to up-type fermions and gauge bosons are enhanced by a factor that may exceed 10.

The $s \to \gamma\gamma$ channel is very promising for the s discovery at the LHC



Constraints from the 125 GeV Higgs data:

excluded at 3σ

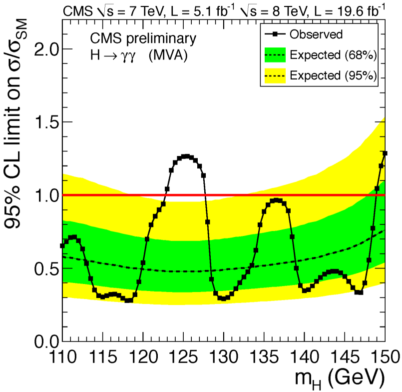
consistent within 3σ

consistent within 2σ

consistent within 1σ

- Maximal $\Delta_{\rm mix}$ predicts $R^s_{\gamma\gamma} > 1$ for (almost) all values of m_s
- The signal in $\gamma\gamma$ channel 2 times stronger than in the SM is viable!

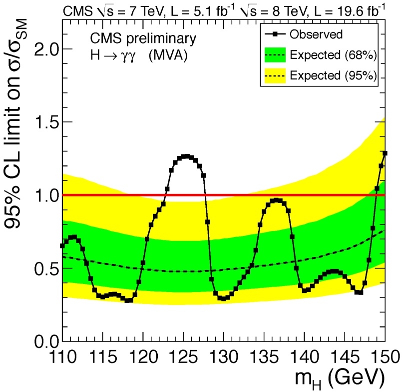
LHC constraints on $s \to \gamma\gamma$



For $m_s = 110$ GeV:

- CMS upper bound $R^s_{\gamma\gamma} \lesssim 0.6$
- $\Delta^{\max}_{\text{mix}}$ more constrained by the LHC than the LEP $s \to jj$ searches

LHC constraints on $s \to \gamma\gamma$



For $m_s = 110$ GeV:

- CMS upper bound $R^s_{\gamma\gamma} \lesssim 0.6$
- $\Delta^{\max}_{\mathrm{mix}}$ more constrained by the LHC than the LEP $s \to jj$ searches

s could have already been discovered at the LHC if the already collected data were analysed for $m_s < 110$ GeV

Conclusions

125 GeV Higgs mass may be much more natural in NMSSM with large $\tan\beta$ due to mixing in the Higgs sector leading to interesting (testable) phenomenology:

Correction from mixing $\Delta_{\rm mix}$ up to $5-7$ GeV for $m_s \in (60, 110)$ GeV $\Rightarrow$ the predicted stop masses brought down below 1 TeV

The signal for s in the $\gamma\gamma$ decay channel (in all production channels) is typically stronger than for the SM Higgs, even by a factor of 2.

Conclusions

125 GeV Higgs mass may be much more natural in NMSSM with large $\tan\beta$ due to mixing in the Higgs sector leading to interesting (testable) phenomenology:

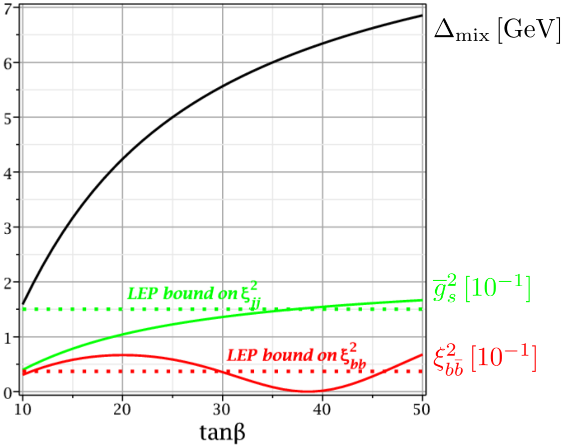
Correction from mixing $\Delta_{\rm mix}$ up to $5-7$ GeV for $m_s \in (60, 110)$ GeV $\Rightarrow$ the predicted stop masses brought down below 1 TeV

The signal for s in the $\gamma\gamma$ decay channel (in all production channels) is typically stronger than for the SM Higgs, even by a factor of 2.

It is worth to extend the Higgs searches in the $\gamma\gamma$ channel to masses below 110 GeV, down to 60 GeV

Backup slides

Numerical example: $m_s = 75$ GeV



$m_s = 75$ GeV

$m_h = 125$ GeV

$m_H = 1000$ GeV

$\mu = 150$ GeV

$\Lambda = 800$ GeV

$\lambda = 0.08$

- the LEP bounds satisfied for $30 \lesssim \tan\beta \lesssim 40 \Rightarrow$ no new fine-tuning needed
- Correction to the SM-like Higgs mass is $\Delta_{\mathrm{mix}} \sim 6$ GeV
  - It would be below 2 GeV if mixing with H was neglected