# New Regions in the NMSSM with a 125 GeV Higgs

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*SUSY 2013, ICTP Trieste 29 August 2013*

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

# Outline

- Motivation
- Higgs boson mass in NMSSM with moderate or large $\tan\beta$
  - contribution from mixing with the light singlet scalar
- Production and decays of the 125 GeV Higgs
- Signatures of the light singlet-like scalar at the LHC
  - strongly enhanced decays to $\gamma\gamma$
- 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 the LHC

Not so good news for SUSY:

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

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

Higher SUSY scale $M_{\rm SUSY}$ is not very appealing from the phenomenological (prospects for SUSY discovery) and theoretical (hierarchy problem) points of view

Perhaps, the LHC Higgs data tells us that SUSY is non-minimal...

# Higgs sector in NMSSM

NMSSM is MSSM extended by a singlet superfield $S$ that couples to $H_u$ and $H_d$ generating effective $\mu$-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 $\lambda$ and small $\tan\beta$

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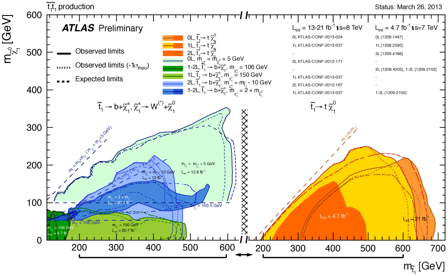
**Do we really need large correction to the MSSM Higgs mass?**

# 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 $\lambda$ is not necessary if the Higgs mixes with the light singlet and $\tan\beta$ is **not** small

In this talk: NMSSM with small $\lambda$ 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 $\hat{M}^2_{hh} = M_Z^2 \cos^2 2\beta + (\delta m_h^2)^{\mathrm{rad}}$

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

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

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

In order to obtain big positive $\Delta_{\mathrm{mix}}$ 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

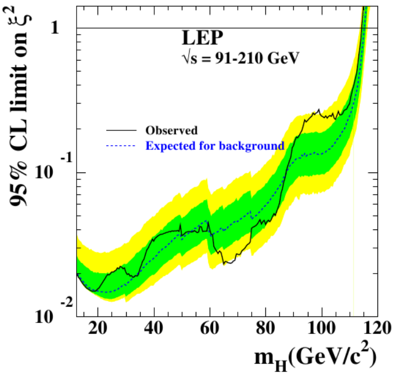
Light scalar with a substantial mixing with the SM-like Higgs would have been discovered by the LEP experiments

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

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

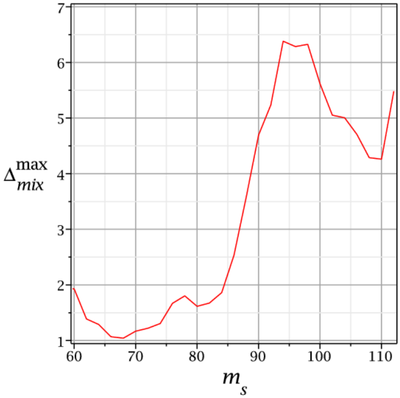
For $\hat{h} - \hat{s}$ mixing only: $\xi_{b\bar{b}}^2 = \bar{g}_s^2$

stronger LEP constraints on $\bar{g}_s^2$ 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 $\tau$ 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

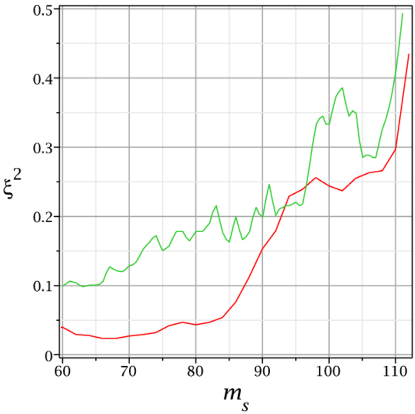
For large $\tan\beta$ and $\overline{g}_s \beta_s^{(H)} < 0$, $\overline{BR}(s \to b\bar{b})$ can be strongly suppressed

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



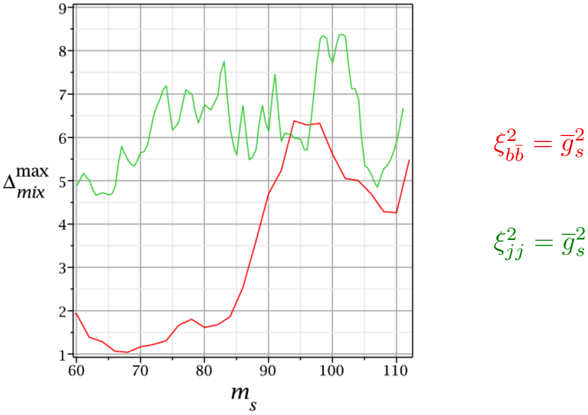

$$\xi^2_{b\bar{b}} \equiv \bar{g}^2_s \cdot \overline{BR}(s \to b\bar{b})$$

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

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

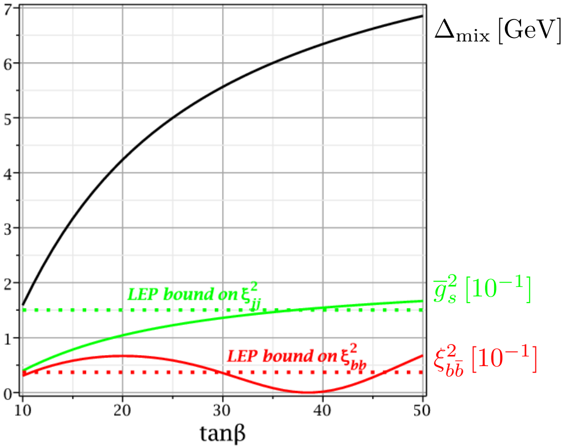
# Upper bound on $\Delta_{\rm mix}$

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




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

# 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 $\Delta_{\rm mix} \sim 6$ GeV
  - It would be below 2 GeV if mixing with $H$ was neglected

# 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$(h^{\mathrm{SM}} \to b\bar{b}) \approx 60\%$

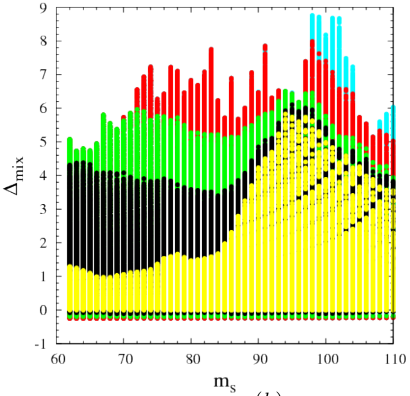
$\Downarrow$

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] | $\lambda$ | $\Lambda$ [GeV] | $\tan\beta$ |
|---|---|---|---|---|
| Minimal value | 250 | 0.05 | 100 | 10 |
| Maximal value | 2000 | 0.15 | 3000 | 60 |
| Step size | 250 | 0.01 | 100 | 5 |




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

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

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

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

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

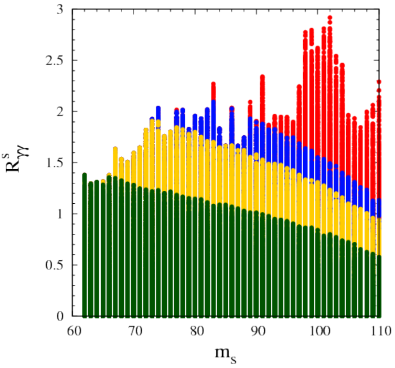
$\Delta_{\rm mix} \gtrsim 5-6$ GeV with $R^{(h)}_{VV} > 0.7$ for wide range of $m_s \in (60, 105)$ GeV

$\boldsymbol{R^{(h)}_{VV} > 1}$ $\Rightarrow$ $\Delta_{\rm mix}$ 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 $3\sigma$

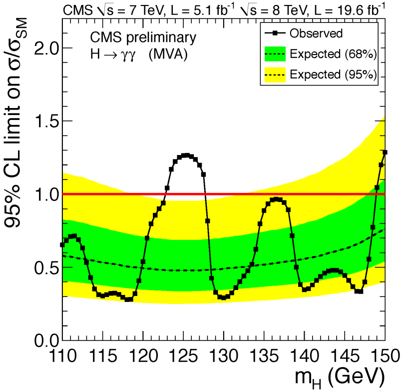
consistent within $3\sigma$

consistent within $2\sigma$

consistent within $1\sigma$

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

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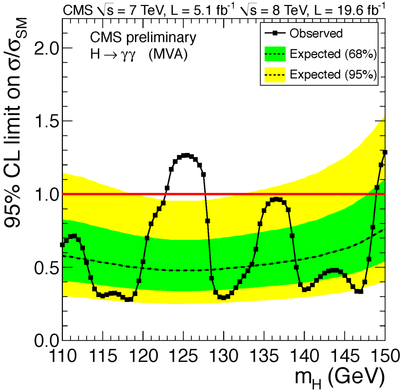


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- CMS upper bound $R^s_{\gamma\gamma} \lesssim 0.6$
- $\Delta^{\max}_{\text{mix}}$ more constrained by the LHC than the LEP $s \to jj$ searches

**$s$ 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 easier to obtain in NMSSM with large $\tan\beta$ due to mixing in the Higgs sector:

Correction from mixing $\Delta_{\mathrm{mix}}$ up to $5-8$ GeV for $m_s \in (60, 110)$ GeV

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

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

Message to the CMS and ATLAS collaborations:

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