125 GeV Higgs in NMSSM with moderate or large $\tan\beta$

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Outline

- Motivation
- Higgs boson mass in NMSSM with moderate or large $\tan\beta$
  - contribution to m_h from mixing with the singlet scalar
  - modifications due to mixing with the heavy doublet scalar
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- Predictions for the branching ratios of the 125 GeV Higgs
- Prospects for discovery of singlet-dominated scalar at LHC
- Conclusions

Motivation

Higgs-like particle with the mass of about 125 GeV discovered by LHC experiments:

- Light enough to be not excluded in simple SUSY models
- Heavy enough to be rather difficult to obtain in MSSM
- 125 GeV Higgs allowed but not very natural in MSSM
- Can this be improved in simple extensions of MSSM?

Motivation

Higgs boson mass in MSSM and its extensions

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

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

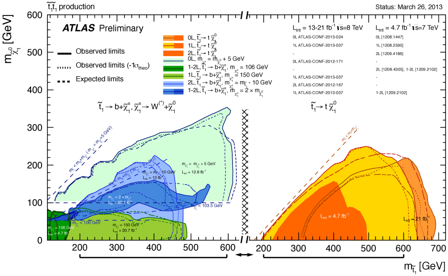
- $M_{\mathrm{SUSY}} \gtrsim$ 5 TeV – for vanishing stop mixing $X_t^2 = 0$
- $M_{\mathrm{SUSY}} \gtrsim 700$ GeV – for optimal stop mixing $X_t^2 \approx 6 M_{\mathrm{SUSY}}^2$

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

- $M_{\mathrm{SUSY}} \gtrsim$ 2 (3) TeV – for vanishing stop mixing
- $M_{\mathrm{SUSY}} \gtrsim 300$ (400) GeV – for optimal stop mixing

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

LHC constraints on the stop mass



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

Possibilities to avoid very heavy stops (large fine tuning):

- **light stops in some corners of SUSY parameter space (fine-tuning of the EW scale may be small but different kind of fine tuning may appear)**
- **stop masses just below 1 TeV giving moderate EW fine tuning**

In the second case:

- $\mathcal{O}(5)$ **GeV correction to the MSSM Higgs mass could be satisfactory**
  - **at least for moderate and large values of** $\tan\beta$ **for which the tree level MSSM term is close to its maximal value**

Higgs sector in NMSSM

Self-interacting singlet superfield S
is used to generate the effective μ-term

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

Soft terms in the Higgs sector:

$$\begin{aligned}-\mathcal{L}_{\text{soft}} \supset\, & m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 \\ & + (A_\lambda \lambda S H_u H_d + m_3^2 H_u H_d \\ & \quad + \frac{1}{3}\kappa A_\kappa S^3 + \frac{1}{2} m_S'^2 S^2 + \xi_S S + \text{h.c.})\end{aligned}$$

Conditions imposed on the above couplings define different versions of NMSSM

For example, the "$\mathbb{Z}_3$-invariant" NMSSM is defined by conditions

$$f(S) = \frac{\kappa}{3} S^3 \qquad\qquad m_3^2 = m_S'^2 = \xi_S = 0$$

Higgs sector in NMSSM

The Higgs squared mass matrix in the basis
$(\hat{h} = \cos\beta H_d + \sin\beta H_u, \hat{H} = \sin\beta H_d - \cos\beta H_u, \hat{s} = S)$
($\hat{h}$ has the same couplings as the SM Higgs)

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

$\hat{M}^2_{hh} = M_Z^2 \cos^2 2\beta + (\delta m_h^2)^{\rm rad} + \lambda^2 v^2 \sin^2 2\beta$
$\Lambda = A_\lambda + \langle \partial_S^2 f(S) \rangle$

The mass of the SM-like Higgs h (mass eigenstates: h, H, s):

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

NMSSM contributions:

- **tree-level contribution due to $\lambda S H_u H_d$ interaction**
- **contribution due to mixing among $\hat{h}$, $\hat{s}$, $\hat{H}$ states – mainly $\hat{h}$-$\hat{s}$**

Higgs sector in NMSSM

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

The most popular strategy to get big enough Higgs boson mass is to use the NMSSM tree-level contribution

- $\sin 2\beta$ **can not be small** $\Rightarrow \tan\beta$ **close to 1 (usually** < 3**)**
- λ **must be big (may become non-perturbative below GUT scale) in order to overcompensate the decrease of the tree-level MSSM term** $M_Z^2 \cos^2 2\beta$
  - **mixing with** $\hat{H}$ **neglected**

Higgs sector in NMSSM

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Our proposal:
increase m_h by the mixing contribution

- moderate and large values of $\tan\beta$ especially interesting because they give big tree-level MSSM term $M_Z^2 \cos^2 2\beta$
- for moderate and large values of $\tan\beta$ we need the mixing contribution because the tree-level NMSSM one is very small
  - mixing with $\hat{H}$ important

Higgs sector in NMSSM

Mixing with $\hat{H}$ is usually neglected
but in general may be important

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

For small $\tan\beta$:

- $\tan\beta \to 1 \quad \Rightarrow \quad \sin 4\beta \to 0 \quad \cos 2\beta \to 0$
- **but:** $\tan\beta = 2 \quad \Rightarrow \quad \sin 4\beta = -0.96 \quad \cos 2\beta = -0.6$

while for large $\tan\beta$:

- $\tan\beta \to \infty \quad \Rightarrow \quad \sin 4\beta \to 0 \quad \cos 2\beta \to -1$

$\hat{H}$–$\hat{h}$ **mixing is small for (very!) small and large $\tan\beta$**
$\hat{H}$–$\hat{s}$ **mixing is small for small $\tan\beta$**
but may be non-negligible for large (or moderate) $\tan\beta$

Moderate and large $\tan\beta$

The mixing always "pushes away" the eigenvalues

- $\hat{h}$-$\hat{H}$ mixing decreases m_h
- $\hat{h}$-$\hat{s}$ mixing increases m_h only when $m_s < m_h$

$\Rightarrow$ we prefer

- $m_s < m_h$
- substantial $\hat{h}$-$\hat{s}$ mixing
- small $\hat{h}$-$\hat{H}$ mixing

$m_h < 2m_s$ to avoid problematic higgs-to-higgs decays

We consider models with: $\frac{1}{2}m_h < m_s < m_h \ll m_H$

First approximation: ignore mixing with $\hat{H}$

Mixing with the singlet only

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

SM-like Higgs mass squared without mixing taken into account:

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

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

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

$\overline{g}_s$ **is a coupling of** s **to** Z **bosons (relative to SM Higgs coupling)**

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

- **big** $\overline{g}_s$
- **small** m_s

Mixing with the singlet only

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

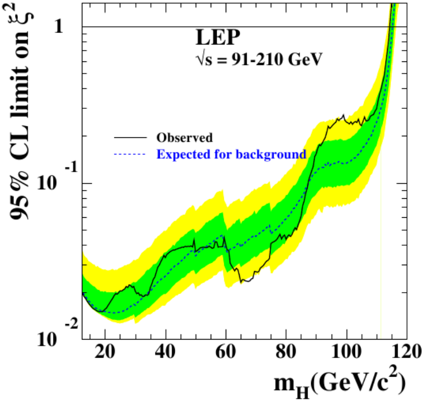
Light scalar with a substantial mixing with the SM-like Higgs would have been discovered by the LEP experiments

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

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

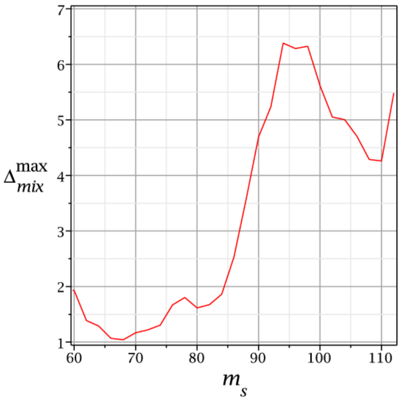
only $\hat{h}$-$\hat{s}$ **mixing** $\Rightarrow \xi^2_{b\bar{b}} \approx \bar{g}^2_s$

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



Mixing with the singlet only

For 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, $\hat{H}$, has little impact on the masses of two other scalars

However, even small admixture of the heavy doublet may change substantially the couplings of singlet-dominated scalar to b and τ if $\tan\beta$ is not small

$$C_b^{(s)} = C_\tau^{(s)} = \overline{g}_s + \rho_s \tan\beta$$

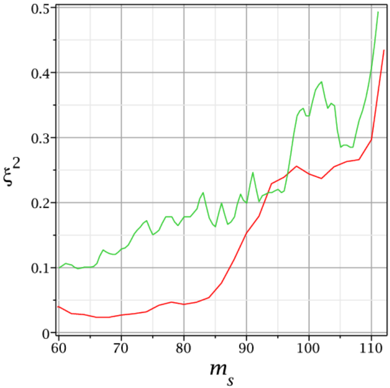
$s = \overline{g}_s \hat{h} + \rho_s \hat{H} + \sigma_s \hat{s}$ **is the singlet-dominated mass eigenstate**

- $\xi_{b\bar{b}}^2 \ll \overline{g}_s^2$ **is possible**
  $\Rightarrow$ **constraints from the b-tagged LEP searches may be relaxed**

Mixing with the singlet and the heavy doublet

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

Main constraint from flavor-independent LEP searches for $s \to jj$

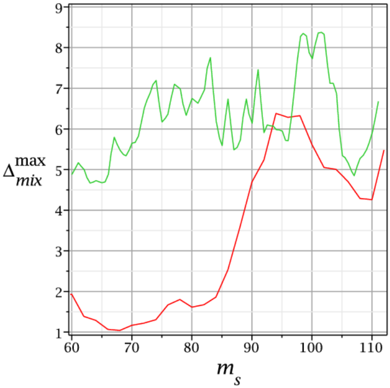


$$\xi^2_{b\bar{b}} \equiv \bar{g}^2_s \cdot \overline{\mathrm{BR}}(s \to b\bar{b})$$

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

LEP constraints on ξ^2_{jj} are typically much weaker than on $\xi^2_{b\bar{b}}$ especially for smaller m_s

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



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

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

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

Mixing with the singlet and the heavy doublet

Do we need fine tuning to suppress $\overline{\mathrm{BR}}(s \to b\bar{b})$?

$$C_b^{(s)} = C_\tau^{(s)} = \bar{g}_s + \rho_s \tan\beta$$

$\overline{\mathrm{BR}}(s \to b\bar{b})$ is suppressed when: $\mu\Lambda > 0$

$\overline{\mathrm{BR}}(s \to b\bar{b})$ is a complicated function of $\tan\beta$

- One of the regions with strongly suppressed $\xi^2_{b\bar{b}}$ occurs close to $\tan\beta_1 \sim \mathcal{O}(\Lambda/\mu)$
- The other region with strongly suppressed $\xi^2_{b\bar{b}}$ 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 Λ/μ
- When Λ/μ is big enough two regions of strongly suppressed $\xi^2_{b\bar{b}}$ may merge to produce one large region in $\tan\beta$ compatible with the LEP results

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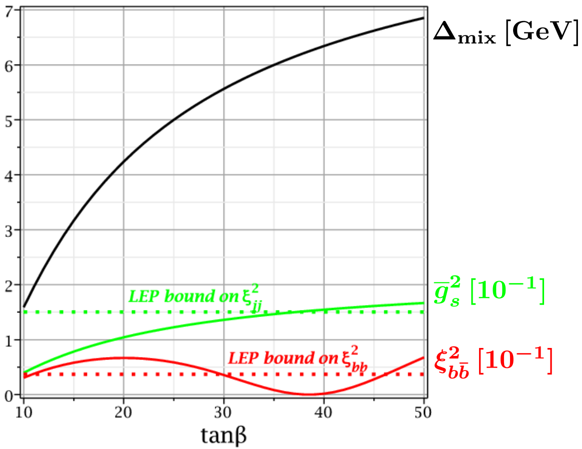
No new fine tuning is necessary

Numerical example: $m_s = 75$ GeV



$m_s = 75$ GeV

$m_h = 125$ GeV

$m_H = 1000$ GeV

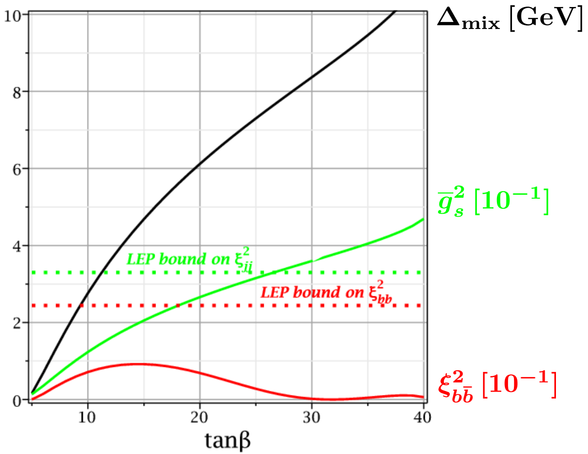
$\mu = 150$ GeV

$\Lambda = 800$ GeV

$\lambda = 0.08$

- the LEP bounds satisfied for $30 \lesssim \tan\beta \lesssim 40$
- 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

Numerical example: $m_s = 100$ GeV



$m_s = 100$ GeV

$m_h = 125$ GeV

$m_H = 500$ GeV

$\mu = 150$ GeV

$\Lambda = 600$ GeV

$\lambda = 0.06$

- the LEP bounds satisfied for $\tan\beta \lesssim 27$
- $\Delta_{\rm mix}$ up to about 8 GeV
  - $\tan\beta \lesssim 18$, $\Delta_{\rm mix} \lesssim 5$ GeV if mixing with H is neglected

Why λ is small?

Mixing term between singlet and SM-like doublet:

$$\hat{M}^2_{hs} = \lambda v (2\mu - \Lambda \sin 2\beta)$$

For moderate and large values of $\tan\beta$

$$\hat{M}^2_{hs} \approx 2\lambda v \mu$$

$v \simeq 174$ **GeV,** $\mu \gtrsim 100$ **GeV**
$\Rightarrow$ m_s^2 **becomes negative for λ bigger than $\mathcal{O}(0.1)$**

For small values of $\tan\beta$ and $\lambda = \mathcal{O}(1)$
$\Rightarrow$ **some tuning of terms in $(2\mu - \Lambda \sin 2\beta)$ is necessary**

Predictions for the branching ratios of the 125 GeV Higgs

Mixing changes also the properties of the SM-like Higgs

Couplings of the 125 GeV Higgs to up-type quarks and gauge bosons are reduced with respect to the SM:

$$C_g^{(h)} \approx C_t^{(h)} \approx C_V^{(h)} = \sqrt{1-\bar{g}_s^2} \quad \Rightarrow \quad \frac{\sigma(pp \to h)}{\sigma^{\rm SM}(pp \to h)} \approx 1-\bar{g}_s^2$$

Branching ratios of h and s are anti-correlated:

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

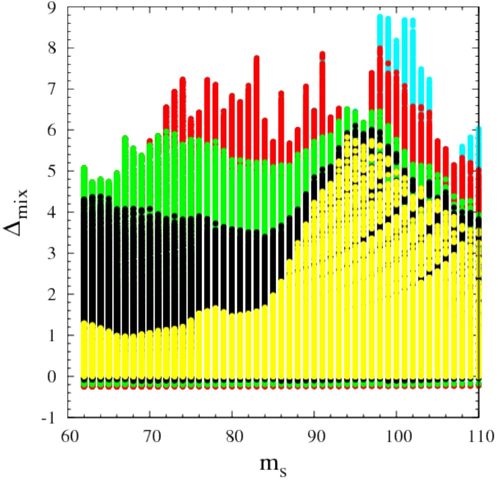
$\Downarrow$

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

$\mathrm{BR}^{\rm SM}(h \to b\bar{b}) \approx 60\% \Rightarrow$ **change of** $\mathrm{BR}(h \to b\bar{b})$ **affects all channels**

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

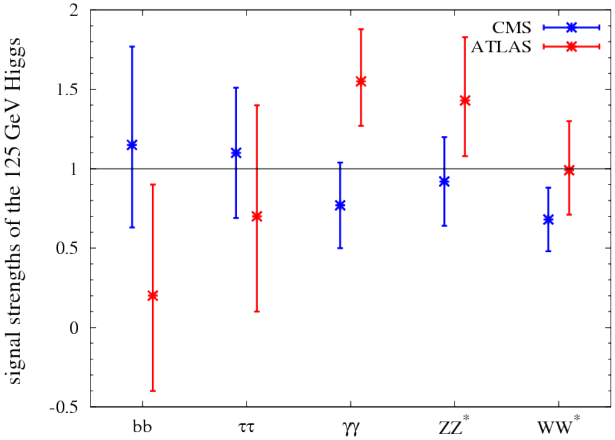
Numerical scan



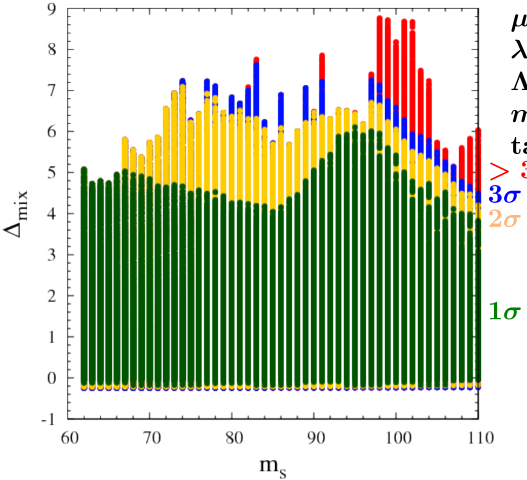
$\mu = 150$ GeV
$\lambda = 0.05 \div 0.15$
$\Lambda = 100 \div 3000$ GeV
$m_H = 250 \div 2000$ GeV
$\tan\beta = 10 \div 60$

$R_{\gamma\gamma}^{(h)} \approx R_{VV}^{(h)}$:
- < 0.5
- $\in (0.5, 0.7)$
- $\in (0.7, 0.8)$
- $\in (0.8, 1)$
- > 1

- $\Delta_{\rm mix}$ up to 8 GeV with $R_{VV}^{(h)} > 0.5$
- $\Delta_{\rm mix} > 5$ GeV with $R_{VV}^{(h)} > 0.7$ possible for wide range of m_s
- $R_{VV}^{(h)} > 1 \Rightarrow \Delta_{\rm mix}$ up to 6 GeV but only for $m_s \sim 95$ GeV



Properties of the 125 GeV Higgs have not been measured with a good precision



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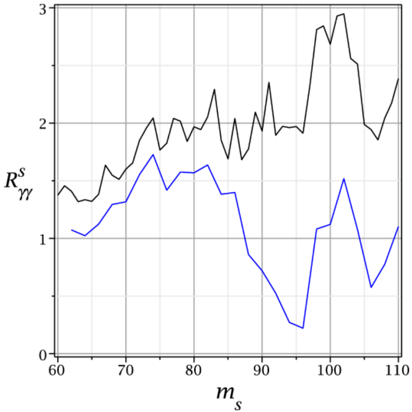
- $\Delta_{\rm mix} > 6$ GeV at 2σ possible for 72 GeV $\lesssim m_s \lesssim$ 100 GeV
- $\Delta_{\rm mix} > 5$ GeV at 2σ possible for 67 GeV $\lesssim m_s \lesssim$ 105 GeV
- $\Delta_{\rm mix} > 4$ GeV at 1σ possible for all values of m_s

Prospects for discovery of s at the LHC

In regions with suppressed $sb\bar{b}$ coupling the branching ratios of s to up-type fermions and gauge bosons are quite large

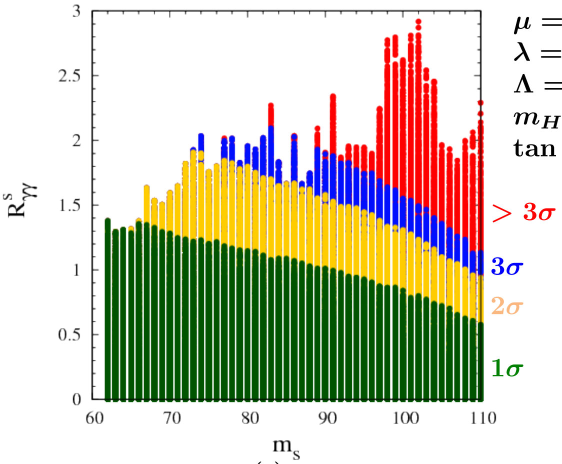
The $s \to \gamma\gamma$ channel is very promising for the s discovery at LHC



$$C_b^{(s)} = 0$$

$C_b^{(s)}$ **suppressed only by the amount required to satisfy LEP constraints on $\xi^2_{b\bar{b}}$**

- **The signal in $\gamma\gamma$ channel 2 times stronger than in SM possible**
- **Maximal Δ_{mix} predicts $R^{(s)}_{\gamma\gamma} > 1$ for (almost) all values of m_s**

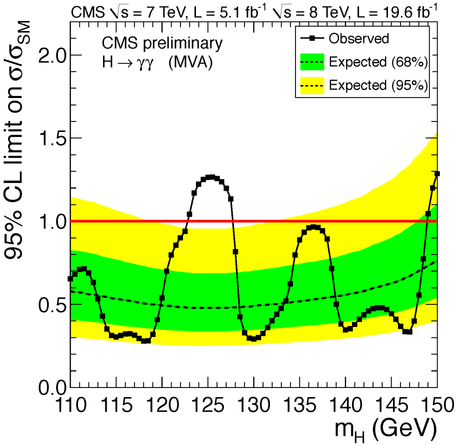


$\mu = 150$ GeV
$\lambda = 0.05 \div 0.15$
$\Lambda = 100 \div 3000$ GeV
$m_H = 250 \div 2000$ GeV
$\tan\beta = 10 \div 60$

At the 2σ level:

- $R^{(s)}_{\gamma\gamma}$ up to 1.9 possible (for $m_s \approx 74$ GeV)
- $R^{(s)}_{\gamma\gamma} > 1.0$ possible for all values of m_s
- $R^{(s)}_{\gamma\gamma}$ up to 1.0 for $m_s = 110$ GeV

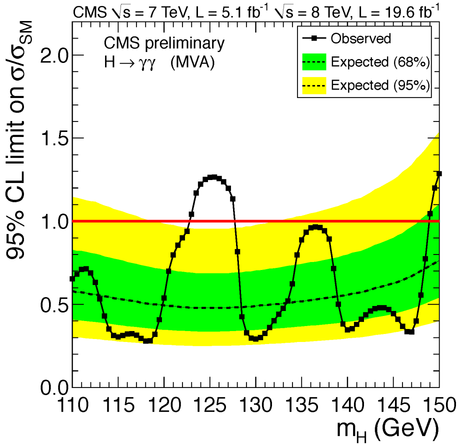
Prospects for discovery of s at the LHC



For $m_s = 110$ GeV:

- **CMS upper bound $R^{(s)}_{\gamma\gamma} \lesssim 0.65$**
- **$\Delta^{\max}_{\mathrm{mix}}$ more constrained by the fit the the LHC data than by the LEP $s \to jj$ searches**
- **$\Delta^{\max}_{\mathrm{mix}}$ even more constrained by the direct CMS search**

Prospects for discovery of s at the LHC



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LHC data for $m < 110$ GeV should be analysed

Maybe the singlet-dominated scalar is already there!

Conclusions

- Region of moderate/large $\tan\beta$ and small λ in NMSSM is interesting for obtaining 125 GeV Higgs mass
- About 2 times smaller stop masses are allowed if SM-like Higgs mass is pushed up by $\mathcal{O}(5)$ GeV due to h-s mixing (when $m_s < m_h$)
- Mixing contribution to the SM-like Higgs mass, $\Delta_{\rm mix}$, with neglected heavy doublet scalar (e.g. at small $\tan\beta$) is:
  - up to 6 GeV only if $m_s \sim 95$ GeV
  - less than 2 GeV for smaller m_s
- Mixing with heavy doublet has important consequences in the region of moderate/large $\tan\beta$ and small λ:
  - $\mathrm{BR}(s \to b\bar{b})$ may be substantially reduced due to mixing
  - LEP constraints easily fulfilled for large ranges of $\tan\beta$ values
  - $\Delta_{\rm mix}$ up to $5 \div 7$ GeV compatible with LHC data at 2σ level for $m_h/2 \lesssim m_s \lesssim 110$ GeV
- Decay branching ratios of s and h are correlated with $\Delta_{\rm mix}$
  - typically $R^{(h)}_{\gamma\gamma} < 1$ when $\Delta_{\rm mix}$ is large
  - typically $R^{(s)}_{\gamma\gamma} > 1$ ($R^{(s)}_{\gamma\gamma}$ up to almost 2 for m_s ~75 GeV)
- LHC data for $m_s < 110$ GeV should be analysed