NMSSM with a 125 GeV Higgs and enhanced $\gamma\gamma$ signal of a light singlet

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"Beyond the LHC" workshop, Nordita 26 July 2013

based on:

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

Foundation for Polish Science

National Science Centre

Outline

- Motivation
- 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
- 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

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

Good news for SUSY:
such Higgs mass is below the upper bound predicted in simple SUSY models

Not so good news for SUSY:
such Higgs mass is rather big for MSSM

Motivation

Higgs boson mass in MSSM and its extensions

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

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

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

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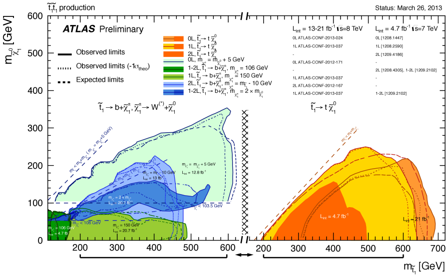
If non-MSSM contribution accounts for 10 (5) GeV of the Higgs mass:

- $M_{\rm SUSY} \gtrsim 2$ (3) TeV – for vanishing stop mixing $X_t^2 = 0$
- $M_{\rm SUSY} \gtrsim 300$ (400) GeV – for optimal stop mixing $X_t^2 \approx 6M_{\rm SUSY}^2$

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

LHC constraints on the stop mass

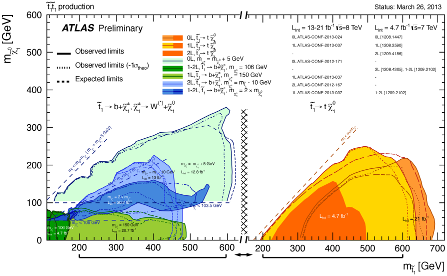


For typical SUSY spectra the stop masses below about $600 - 700$ GeV are ruled out by the LHC

One can try to:

1. hide light stops in some corners of SUSY parameter space $\Rightarrow$ EW fine-tuning may be small but different kind of fine-tuning (required to get SUSY spectrum avoiding the constraints) my pop up

LHC constraints on the stop mass



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One can try to:

1. hide light stops in some corners of SUSY parameter space $\Rightarrow$ EW fine-tuning may be small but different kind of fine-tuning (required to get SUSY spectrum avoiding the constraints) my pop up
2. accept some EW fine-tuning and hope that stop masses are just below 1 TeV

Taking the second approach:

- $\mathcal{O}(5)$ 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

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

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

Soft terms are usually assumed to be some subset of:

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

Various versions of NMSSM have different assumptions about which soft terms are present and what is the form of $f(S)$ e.g.:

The "scale-invariant" NMSSM:

- $f(S) = \kappa S^3/3$
- $m_3^2 = m_S'^2 = \xi_S = 0$

Higgs sector in NMSSM

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

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

The mass of the SM-like Higgs h:

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

NMSSM contributions:

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

Higgs sector in NMSSM

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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 $M_Z^2 \cos^2 2\beta$

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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

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

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

We concentrate on 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

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

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 $m_h = \hat{M}_{hh} + \Delta_{\rm mix}$

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

$\overline{g}_s$ is a coupling of s to Z bosons (normalized to the SM value)

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

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

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

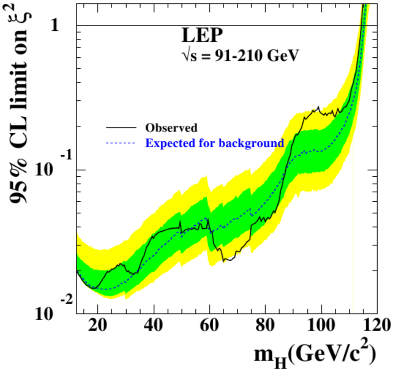
Light scalar with a substantial mixing with the SM-like Higgs would have been discovered by the LEP experiments

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

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

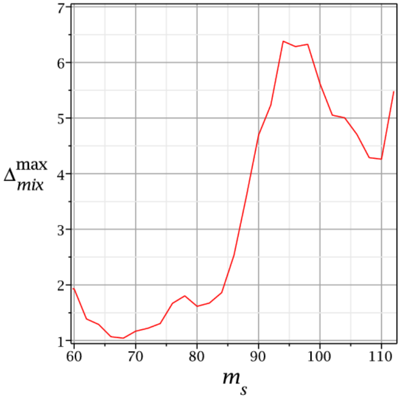
For $\hat{h} - \hat{s}$ mixing only: $\xi^2_{b\bar{b}} = \overline{g}^2_s$

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

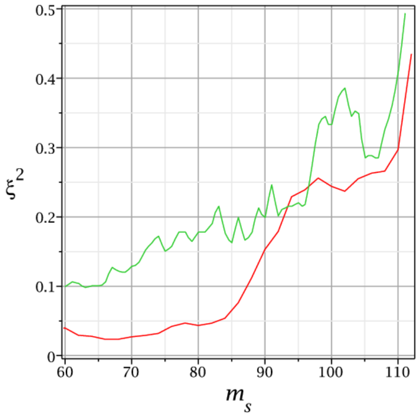
For large $\tan\beta$ and $\overline{g}_s \beta_s^{(H)} < 0$, $\overline{BR}(s \to b\bar{b})$ can be strongly suppressed

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



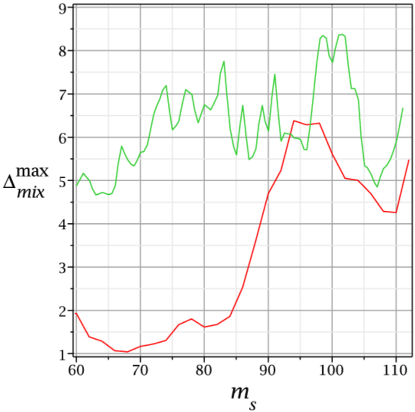
$\xi^2_{b\bar{b}} \equiv \overline{g}^2_s \cdot \overline{BR}(s \to b\bar{b})$

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

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 $\overline{g}^2_s$ 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



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

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

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

When does the $sb\bar{b}$ coupling suppression occur?

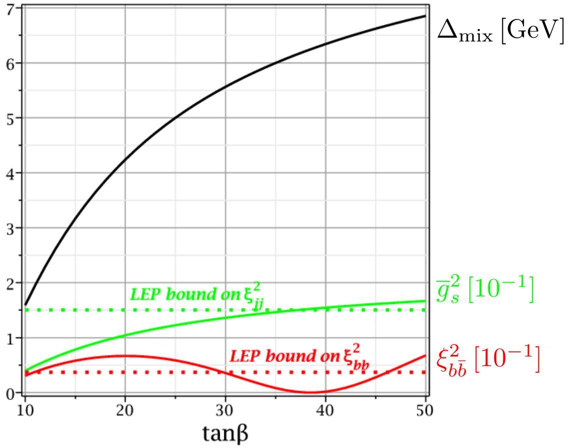
$\overline{BR}(s \to b\bar{b})$ of the light singlet-dominated scalar is a complicated function of $\tan\beta$

$\overline{BR}(s \to b\bar{b})$ is suppressed when:

$$\Lambda(\mu \tan\beta - \Lambda) \gtrsim 0 \qquad \Rightarrow \qquad \mu\Lambda > 0$$

- 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 ratio 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

Numerical example: $m_s = 75$ GeV



$m_s = 75$ GeV

$m_h = 125$ GeV

$m_H = 1000$ GeV

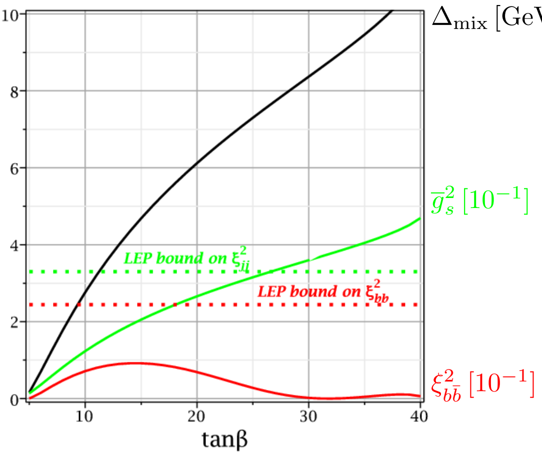
$\mu = 150$ GeV

$\Lambda = 800$ 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

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 $\tan\beta \lesssim 25$
- $\Delta_{\rm mix}$ up to about 8 GeV
  - $\tan\beta \lesssim 18$, $\Delta_{\rm mix} \lesssim 2.5$ 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
$\Rightarrow \quad m_s^2$ becomes negative for λ bigger than $\mathcal{O}(0.1)$

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

Production and decays of the 125 GeV Higgs

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

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

$$C_g \approx C_\gamma \approx C_{t_h} \approx C_{V_h} = \sqrt{1-\bar{g}_s^2} \qquad \Rightarrow \qquad \frac{\sigma(pp \to h)}{\sigma^{\mathrm{SM}}(pp \to h)} \approx 1-\bar{g}_s^2$$

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

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

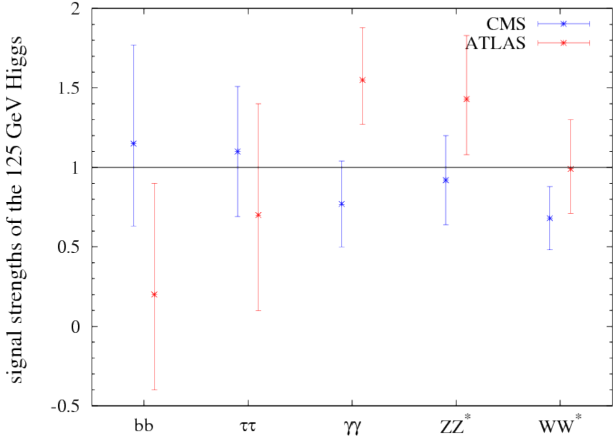
For the SM 125 GeV Higgs: $\mathrm{BR}(h^{\mathrm{SM}} \to b\bar{b}) \approx 60\%$

$$\Downarrow$$

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

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

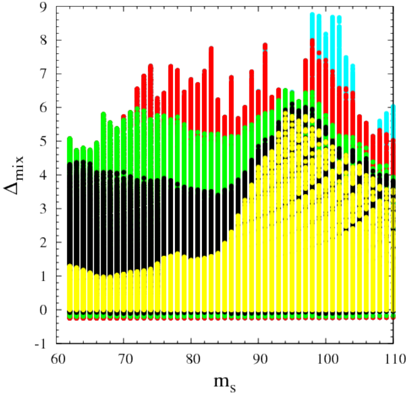
Signal strengths of the 125 GeV Higgs



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

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



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

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

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

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

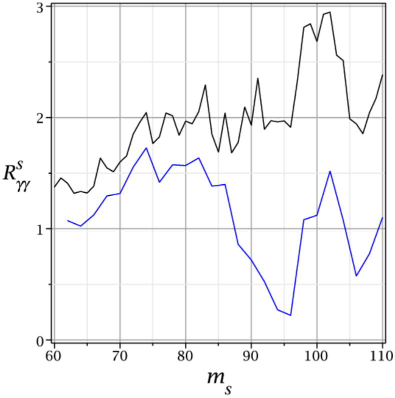
$\boldsymbol{R^{(h)}_{\gamma\gamma} \approx R^{(h)}_{VV} > 1}$

- $\Delta_{\rm mix}$ up to 8 GeV with $R^{(h)}_{VV} > 0.5$
- $\Delta_{\rm mix} \gtrsim 5$ GeV with $R^{(h)}_{VV} > 0.7$ possible for wide range of m_s
- $R^{(h)}_{VV}$ **> 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

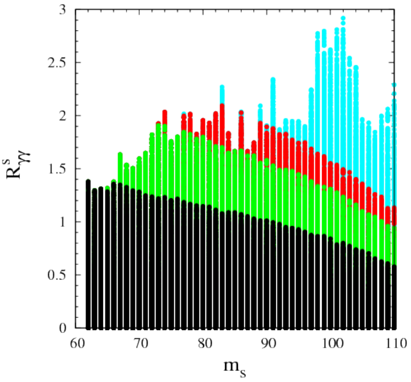


$C_{b_s} = C_{\tau_s} = 0$

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 up to 3 times stronger than in the SM!
- Maximal $\Delta_{\rm mix}$ predicts $R^s_{\gamma\gamma} > 1$ for (almost) all values of m_s

Constraints on $R^s_{\gamma\gamma}$ from the 125 GeV Higgs data



excluded at 3σ

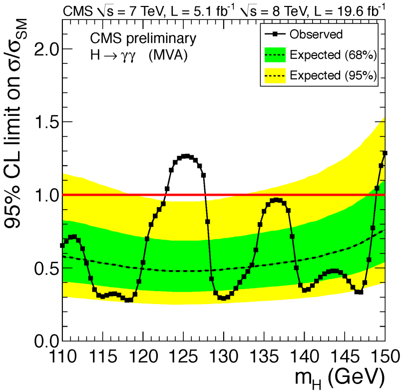
consistent within 3σ

consistent within 2σ

consistent within 1σ

Significant enhancement of $R^s_{\gamma\gamma}$ allowed by the 125 GeV Higgs properties measurements!

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

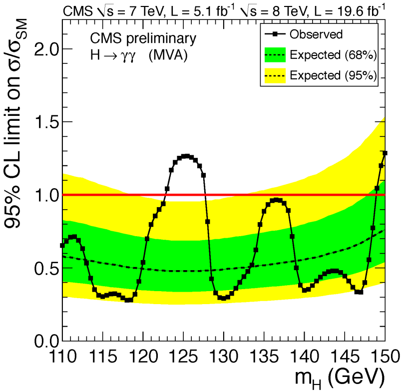


For $m_s = 110$ GeV:

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

The sensitivity of the search in the $\gamma\gamma$ channel gets worse quite slowly with decreasing m_s

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



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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:

- Mixing contribution to the SM-like Higgs mass, $\Delta_{\rm mix}$, with neglected heavy doublet scalar is:
  - up to 6 GeV only if $m_s \sim 95$ GeV
  - less than about 2 GeV for smaller m_s
- Mixing with heavy doublet has important consequences if $\tan\beta$ is large or moderate:
  - $BR(s \to b\bar{b})$ may be substantially reduced due to mixing
  - LEP $s \to b\bar{b}$ constraints easily fulfilled for large ranges of $\tan\beta$ values
  - $\Delta_{\rm mix}$ up to $5-8$ GeV for $m_s \in (60, 110)$ GeV
- Decays of s and 125 GeV Higgs are anti-correlated
  - Typically $R_{VV}^{(h)} < 1$ when $\Delta_{\rm mix}$ is large
  - e.g. $\Delta_{\rm mix}^{\rm max} \approx 6$ GeV if $R_{VV}^{(h)} > 0.7$
  - For $\Delta_{\rm mix} \sim 5$ GeV, $R_{\gamma\gamma}^{(h)}$ may be enhanced only if $m_s \sim 95$ GeV

Large $\Delta_{\rm mix}$ typically implies $R_{\gamma\gamma}^{(s)} > 1$ ($R_{\gamma\gamma}^{(s)}$ up to about 2 consistently with the 125 GeV Higgs data)

The Higgs searches in the $\gamma\gamma$ channel need to be extended below 110 GeV, down to 60 GeV.