

Discovery prospects for a light scalar in the NMSSM

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Supersymmetry and the Higgs mass

The hierarchy problem of the SM

In the SM, the Higgs mass receives radiative corrections proportional to a cut-off scale Λ^2 , which must be cancelled by a bare Higgs mass term. Due to this fact, the parameters must be set up to a precision of ~ 32 decimals or so to explain a light Higgs.

The SUSY solution

Supersymmetry offers a solution to the *hierarchy problem*: The Higgs mass is bounded at tree level and its radiative corrections are logarithmic. In the minimal SUSY extension of the SM (**MSSM**), the Higgs mass at tree level reads:

$$m_h \lesssim M_Z \cos 2\beta \xrightarrow{\tan \beta \gg 1} \sim 91 \text{ GeV}, \quad \text{where } \tan \beta = \frac{v_u}{v_d} \quad (1)$$

But $h \approx 125 \text{ GeV}$!

Need large radiative corrections (i.e. large stops masses) to reach this value
 \Rightarrow new fine-tuning problem !

The NMSSM

The NMSSM consists in MSSM + singlet (super)field S . The CP-even Higgs sector is therefore enlarged and is composed by 3 states (instead of 2 as in the MSSM): H (heavy), h (identified with h^{125}) and h_s (light or heavy...).

New contributions to the Higgs mass

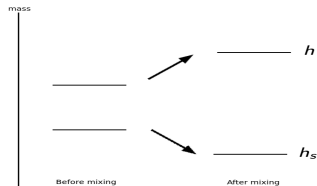
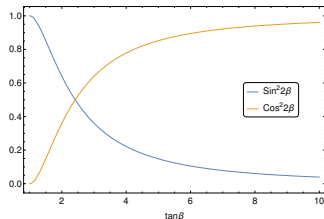
Due to the existence of the singlet, two mechanisms:

- 1 New tree level contribution to m_h ;

$$\mathcal{M}_{S,11}^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \quad (2)$$

where $\lambda \lesssim 0.8$ to avoid landau poles. This effect takes place mainly at small $\tan\beta$.

- 2 If $m_{h_s} < 125$ GeV \rightarrow **singlet-doublet mixing** can uplift m_h , up to 8 GeV beyond M_Z . This effect takes place mainly at large $\tan\beta$.



m_h uplift: Δ_{NMSSM}

Both effects are maximised in different regions of parameter space. We define a parameter, Δ_{NMSSM} in the following way:

$$\Delta_{\text{NMSSM}} = m_h^{\text{NMSSM}} - \max_{\tan \beta} m_h^{\text{MSSM}} \quad (3)$$

In this way, this parameter allows as to:

- ① Track how much we gain for m_h due to the existence of a singlet field S (i.e. w.r.t. the MSSM), due to mixing effects or the extra λ term.
- ② Assign a quantity to the "naturalness" of a point. The larger is Δ_{NMSSM} , the less radiative corrections one needs to reach 125 GeV.

Scanning the parameter space

Using NMSSMTools, we perform a scan in a vast region of parameter space.

The scan

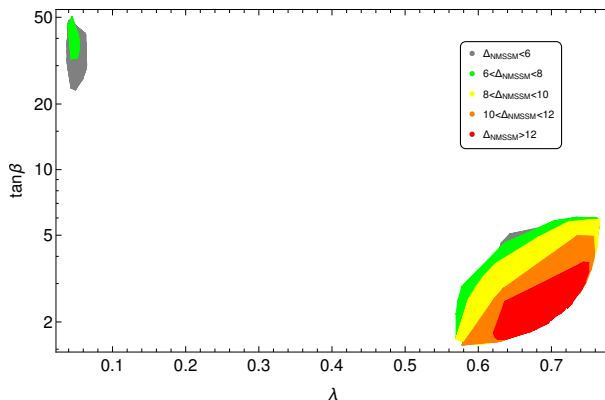
- ① We scan over $10^{-3} \leq \lambda \leq 0.8$ and $1 \leq \tan \beta \leq 40$, in order to cover all the regions where the two mass shifting effects can be enhanced.
- ② We require light stops, $500 \text{ GeV} \lesssim m_{\tilde{t}_{1,2}} \lesssim 1.1 \text{ TeV}$, and also a relatively small value for the stop mixing parameter, $-1 \text{ TeV} \leq A_t \leq 1 \text{ TeV}$, to avoid fine-tuned points.
- ③ We require one of the higgses, h , to resemble the one found at CERN, and the mostly singlet like Higgs, h_s , to be lighter than h , i.e. $h_s \leq 125 \text{ GeV}$.

Phenomenological constraints applied

- All LEP constraints and LHC results in Higgs physics (by default in NMSSMTools)

Results: natural regions

For each point of the scan, its value of Δ_{NMSSM} has been computed.



- 1 Low λ /large $\tan \beta$: Δ_{NMSSM} from mixing.
- 2 Large λ /low $\tan \beta$: Δ_{NMSSM} from extra λ term.

Results: the diphoton channel

Present and future searches for h_s in the diphoton channel

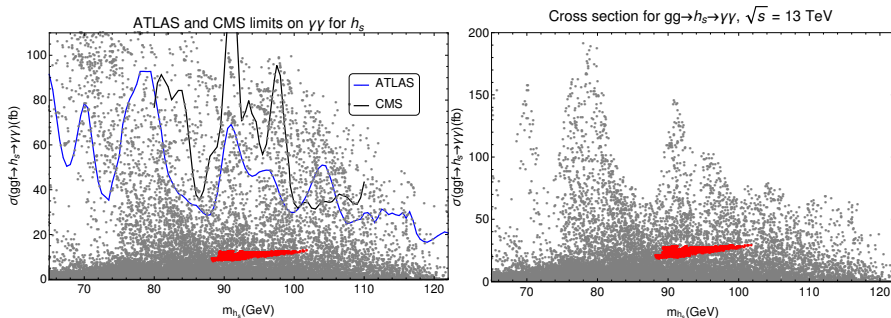


Figure : In red, the small λ island where the mixing effect is dominant for the uplift of h . In gray the large λ region, with $\Delta_{\text{NMSSM}} > 12$ practically everywhere, which is already being partially tested at the LHC. Left: current limits on $h_s \rightarrow \gamma\gamma$. Right: Expected values for the diphoton cross section at Run II (excluded points are removed).

- Large λ region: Already being tested (RUN I)!
- Small λ region: To be completely covered soon (RUN II)! Recall: Consistent with small excesses reported by LEP and CMS at 98 GeV.

Results: Correlations between h and h_s

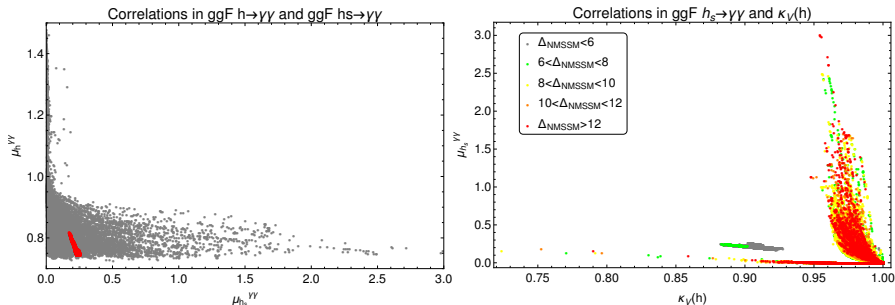


Figure : Left: Correlation in the diphoton signal strengths of the light scalars. Right: diphoton signal strength for h_s versus the coupling to vector bosons of the mostly SM boson.

- Projected 1σ sensitivities on $\mu_{h_{125}}^{\gamma\gamma}$ for RUN II, $\Delta\mu_{h_{125}}^{\gamma\gamma} (300 \text{ fb}^{-1}) \sim 0.13$, $\Delta\mu_{h_{125}}^{\gamma\gamma} (3000 \text{ fb}^{-1}) \sim 0.09 \Rightarrow$ precise measurements of $\mu_h^{\gamma\gamma}$ could exclude the small λ region.
- Any excess in $\mu_h^{\gamma\gamma}$ makes h_s practically invisible in $\gamma\gamma$.
- Projected 1σ sensitivities: $\Delta\kappa_V(h)(300 \text{ fb}^{-1}) \sim 0.059$, $\Delta\kappa_V(h)(3000 \text{ fb}^{-1}) \sim 0.037$

Results: Production through heavy Higgs decays

The large lambda region opens the door for sizeable $H \rightarrow H_{SM} H_S$ and $A \rightarrow Z H_S$

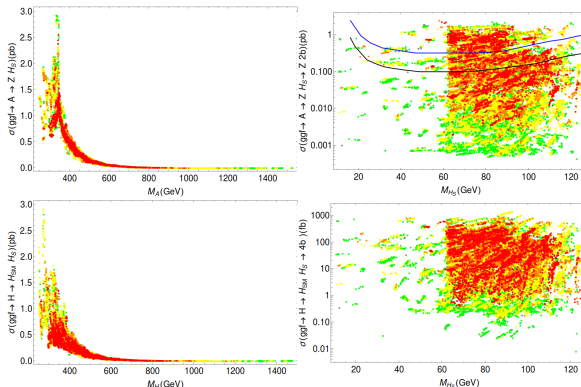


Figure : Cross sections for ggF produced Heavy MSSM-like Higgses producing $H_S + X$

- Expected sensitivity (**300 fb⁻¹** and **3000 fb⁻¹**) for $A \rightarrow Z H_S$ [Bomark *et al.*, 1409.8393] at Run II will cover a part of the large lambda region.
- Sizeable $\sigma(H \rightarrow H_{SM} H_S) \Rightarrow$ search strategies including background studies needed!

Conclusions

- Run II will be sensitive to the NMSSM natural regions featuring a lighter singlet-like state.
- Measurements of signal strengths and couplings of h^{125} together with direct searches for the additional lighter singlet-like state h_s in the diphoton channel can test substantial regions of the natural NMSSM parameter space.
- Large mixing effects as responsible for $m_h = 125$ GeV will be covered IF
 - $\kappa_V(h^{125}) \lesssim 0.93$ can be excluded, or
 - $\mu_{h_s}^{\gamma\gamma} \gtrsim 0.85$ can be excluded .

\Rightarrow *complementarity!*
- H_5 production through heavy Higgs decays, particularly $A \rightarrow Z H_5$, are important search strategies for covering part of the natural large lambda region featuring a light singlet.

Thanks for your attention!

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Thanks for your attention!

BACKUP

CP-even Higgs mass matrix

The mass matrix $\mathcal{M}_S'^2$ in the basis (h', H', S_r) reads:

$$\mathcal{M}_{S,11}'^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \sin^2 \beta \Delta_{\text{rad}} \quad (4)$$

$$\mathcal{M}_{S,12}'^2 = \frac{1}{2} \sin 2\beta \cos 2\beta (M_Z^2 - \lambda^2 M_Z^2) - \frac{\sin 2\beta}{2} \Delta_{\text{rad}}, \quad (5)$$

$$\mathcal{M}_{S,13}'^2 = \lambda v (2\mu - \Lambda \sin 2\beta) \quad (6)$$

$$\mathcal{M}_{S,22}'^2 = M_A^2 + (M_Z^2 - \lambda^2 v^2) \sin^2(2\beta) + \cos^2 \beta \Delta_{\text{rad}} \quad (7)$$

$$\mathcal{M}_{S,23}'^2 = \lambda v \Lambda \cos 2\beta \quad (8)$$

$$\mathcal{M}_{S,33}'^2 = \lambda^2 v^2 \sin 2\beta \left(\frac{M_A^2 \sin 2\beta}{4\mu^2} - \frac{\kappa}{2\lambda} \right) + \frac{\kappa \mu A_\kappa}{\lambda} + \frac{4\kappa^2 \mu^2}{\lambda^2} \quad (9)$$

where we have defined $\Lambda = A_\lambda + 2\kappa S$.

Production and BRs of the singlet

