Discovery prospects for a light scalar in the NMSSM

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NMSSMTools

NMSSMTools is a Fortran code for NMSSM calculations. It takes as input a set of parameters given at the SUSY breaking or GUT or GMSB scale.

Computes

- Masses of the Higgs bosons and all sparticles.
- Couplings and decay widths of all Higgs bosons.
- Possible to connect with MicrOmegas for the computation of dark matter relic density as well as direct and indirect DM detection cross section.

Several NMSSM-like models

- General NMSSM.
- $\mathbb{Z}_3$-invariant NMSSM.
- SUSY-breaking scenarios: minimal supergravity and gauge mediated SUSY breaking.
- CP-violating NMSSM: under construction.

NMSSMTools

Precision

- Fully diagrammatic calculation of Higgs masses at one-loop level + 2-loop corrections of $\mathcal{O}(\alpha_s(h_b^2 + h_t^2))$ at zero external momentum.
- Also, MSSM-like 2-loop corrections at $\mathcal{O}(h_b^2 + h_t^2)^2$.
- Computation of the whole SUSY spectrum and BR at 1-loop level.

Phenomenological constraints

- B-physics observables (arXiv:0710.3714).
- Muon anomalous magnetic moment (arXiv:0806.0733).
- Bounds on the Higgs sector by LEP (arXiv:hep-ex/0602042).
- Measured values on the SM-like Higgs couplings reported by the experimental collaborations at LHC (arXiv:1306.2941, arXiv:1409.1588).

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:

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

But $h \approx 125$ 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

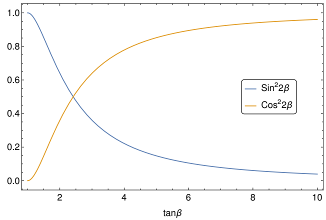
Due to the existence of the singlet, two mechanisms:

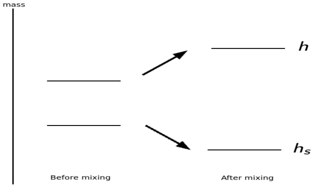
1. **New tree level contribution** to m_h;

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

   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:

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

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

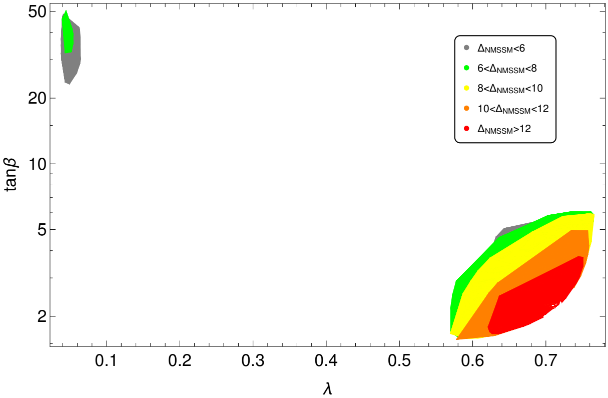
1. We scan over $10^{-3} \leq \lambda \leq 0.8$ and $1 \leq \tan\beta \leq 40$, in order to cover all the regions where the two mass shifting effects can be enhanced.
2. We require light stops, 500 GeV $\lesssim m_{\tilde{t}_{1,2}} \lesssim 1.1$ TeV, and also a relatively small value for the stop mixing parameter, -1 TeV $\leq A_t \leq 1$ 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. $h_s \leq 125$ 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

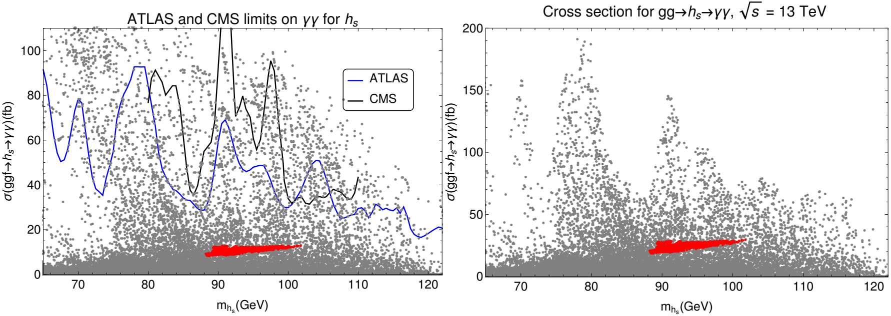


Figure : In red, the small λ island where the mixing effect is dominant for the uplift of h. In gray the large λ region, with $\Delta_{\rm NMSSM} > 12$ practically everywhere, which is already being partially tested at the LHC. Left: current limits on $h_s \to \gamma\gamma$. Right: Expected values for 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

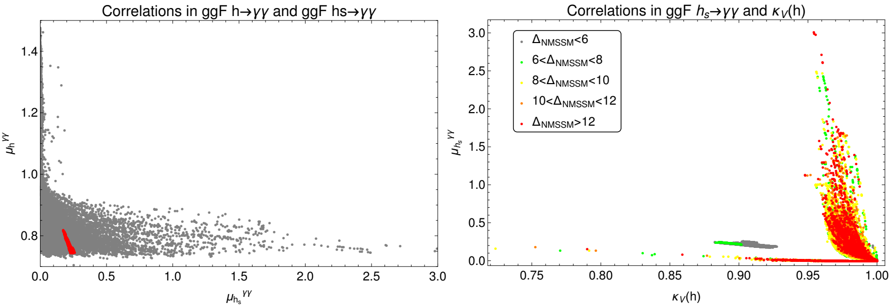


Figure : Left: Correlation in the diphoton signal strengths of the light scalars. Right: diphoton signal strength for h_s versus the coupling to vector bosons of the mostly SM boson.

- Projected 1σ sensitivities on $\mu_{h125}^{\gamma\gamma}$ for RUN II ,$\Delta\mu_{h125}^{\gamma\gamma}$ $\left(300\ \text{fb}^{-1}\right) \sim 0.13$, $\Delta\mu_{h125}^{\gamma\gamma}$ $\left(3000\ \text{fb}^{-1}\right) \sim 0.09 \Rightarrow$ 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: $\Delta\kappa_V(h)(300\ \text{fb}^{-1}) \sim 0.059$, $\Delta\kappa_V(h)(3000\ \text{fb}^{-1}) \sim 0.037$

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!*

Thanks for your attention!

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Thanks for your attention!

Backup

CP-even Higgs mass matrix

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

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

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

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

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

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

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

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

Production and BRs of the singlet