The Hunt for Extra Higgs Bosons in the NMSSM

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The NMSSM: MSSM + an extra Singlet (Super-)Field $\widehat{S}$

- Solves the μ-problem of the MSSM:
  $\langle S \rangle$ generates the required higgsino mass term

- Alleviates the tension related to the SM-like Higgs mass:
  - In the MSSM the tree level quartic Higgs coupling is bounded by the electroweak gauge couplings $\rightarrow M_H \leq M_Z \rightarrow$ need large radiative corrections
  - The extra singlet in the NMSSM generates an extra quartic Higgs coupling $\sim \lambda^2 \rightarrow$ less radiative corrections required

- The "singlino" is a perfect dark matter candidate, good relic density compatible with its non-observation in direct and indirect searches

The Higgs Sector of the NMSSM:
("Higgs basis")

→ An essentially SM-like H_{125}, up to mixing with H_{MSSM}/H_S

→ H_{MSSM}, a heavy approximately degenerate SU(2) doublet:
neutral scalar + pseudoscalar + one charged state;
heavy due to lower bounds on $M_{H^\pm}$ amongst others from $b \to s + \gamma$

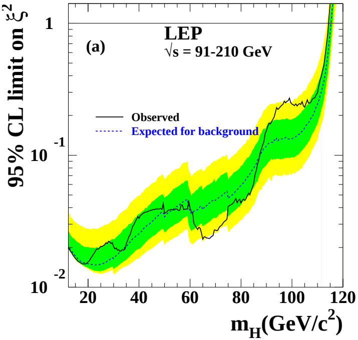
→ Essentially singlet-like scalar H_S and pseudoscalar A_S,
NOT degenerate in general, lighter or heavier than 125 GeV
depending on unknown parameters

How to Search for H_S/A_S: Direct Production:

Rely on mixing $\sim \xi$ of H_S with H_{125}: Induces couplings of H_S to SM particles
$\longrightarrow$ same production mechanisms but with smaller cross sections
Mixing reduces these couplings of $H_{125} \longrightarrow$ limited to $\xi^2 \lesssim 0.25$ (at present)

Summary of LEP search for a light scalar decaying into $b\bar{b}$ with reduced coupling ξ^2 to ZZ:

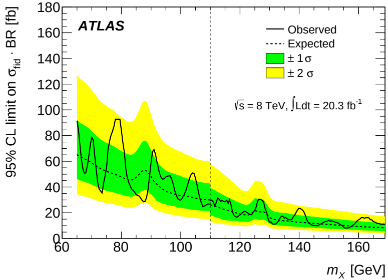
The region in the $\xi^2 - m_H$ plane below the black line is allowed
$\longrightarrow$ Weak bounds for $M_{H_S} \sim 90 - 100$ GeV

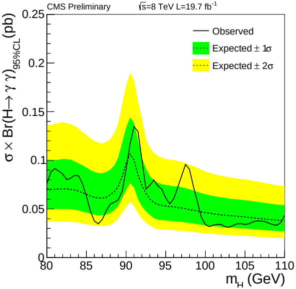


ATLAS and CMS searches for $ggF \to H_S \to \gamma\gamma$ at 8 TeV:

ATLAS, PRL 113 (2014) 17, 171801, 1407.6583

CMS-PAS-HIG-14-037



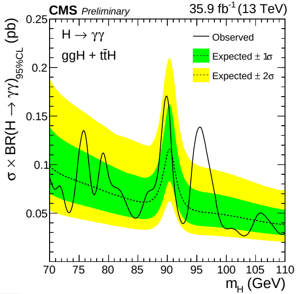


CMS search for $ggF \to H_S \to \gamma\gamma$ at 13 TeV:

(CMS PAS HIG-17-013)

$\to$ Excesses near 97 GeV

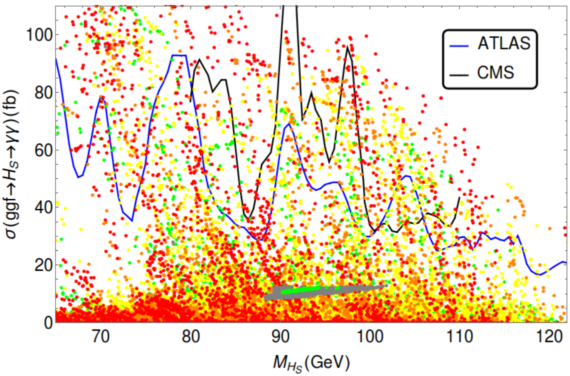
(not confirmed by ATLAS)



Do the 8 TeV ATLAS/CMS searches touch possible values for $\sigma(ggF \to H_S \to \gamma\gamma)$ within the LEP-allowed NMSSM parameter space?

(M. Rodríguez, U.E., JHEP 1602 (2016) 096):

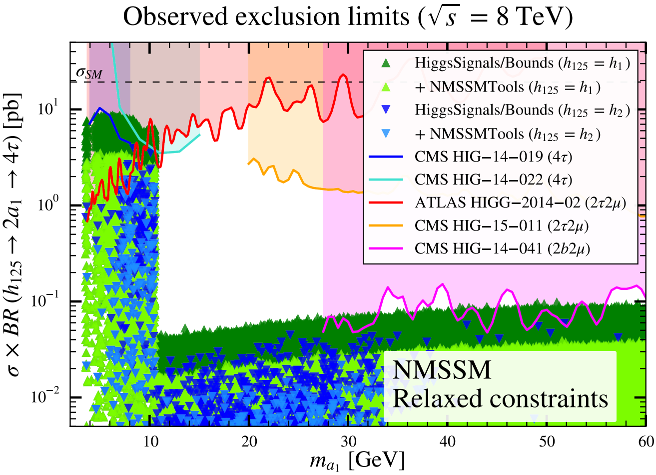
Red points: NMSSM-specific lift of $\Delta M_{H_{125}} > 12$ GeV



YES, the excess could be explained (if confirmed) ... but even light H_S states may have too small direct production cross sections for discovery, even at 13 TeV

Run I searches for $H_{125} \to A_S A_S (H_S H_S) \to 4$ leptons

(From R. Aggleton et al., JHEP 1702 (2017) 035, arXiv:1609.06089)



Light green/blue points: viable in the NMSSM after LEP/LHC constraints

$\to$ These searches for H_S/A_S have only scratched the NMSSM parameter space ...

... and are limited to $M_{H_S,A_S} \lesssim 60$ GeV; how to search for heavier H_S/A_S?

$\rightarrow$ Note: the trilinear couplings $H_{MSSM} H_S H_{125}$, $A_{MSSM} A_S H_{125}$ are SU(2) invariant and can be large (proportional to a parameter A_λ), in contrast to $H_{MSSM} H_{125} H_{125}$, $H_{MSSM} H_S H_S$, ... which must be proportional to a SU(2) breaking vev $\times$ couplings

$\rightarrow$ The $BRs(H_{MSSM}/A_{MSSM} \rightarrow H_{125} H_S/A_S)$ can be large $\sim 50\%$, competing only with $H/A_{MSSM} \rightarrow t\bar{t}$, and reducing the BR for the search into $\tau\tau$!

$ggF \rightarrow H_{MSSM} \rightarrow H_S H_{125}$ and $ggF \rightarrow A_{MSSM} \rightarrow A_S H_{125}$ look like resonant Higgs pair production, but with one SM Higgs replaced by H_S/A_S with unknown mass

A New Search: Look for $b\bar{b}b\bar{b}$ or $b\bar{b}\gamma\gamma$

with

- one $b\bar{b}$ or $\gamma\gamma$ pair: $M_{b\bar{b}/\gamma\gamma} \sim 125$ GeV,
- another $b\bar{b}$ or $\gamma\gamma$ pair: $M_{b\bar{b}/\gamma\gamma} \sim M_{H_S,A_S}$ (unknown),
- $M_{b\bar{b}b\bar{b}}$ or $M_{b\bar{b}\gamma\gamma} \sim M_{H/A_{MSSM}}$ (unknown)

$b\bar{b}\tau\tau$ final states are slightly less promising;

Best Strategy (M. Rodríguez, U.E., JHEP_072P_0817)

Borrowed from ATLAS/CMS searches for resonant SM Higgs pair production:

Do not just look for simultaneous bumps in $M_{b\bar{b}}$ (corresponding to M_{H_S}) and in $M_{b\bar{b}b\bar{b}}$ (corresponding to $M_{H_{MSSM}}$), but:

Use a "test" mass M_{H_S}; for given M_{H_S} (or M_{A_S}):

- Optimize the cuts on p_T and the pairing of 4 b-tagged jets into 2×2 b-tagged jets:
  cut on bb masses arond 115 GeV and $M_{H_S} - 10$ GeV
  (allow for "losses" outside the $R = 0.4$ – jets)
- Only if M_{H_S} was chosen correctly, one observes a "bump" in $M_{b\bar{b}b\bar{b}}$ near $M_{H_{MSSM}}$ whose significance can be computed as function of M_{H_S}, $M_{H_{MSSM}}$ and notably the $\sigma(ggF \to H_{MSSM} \to H_{125} + H_S \to b\bar{b}b\bar{b})$

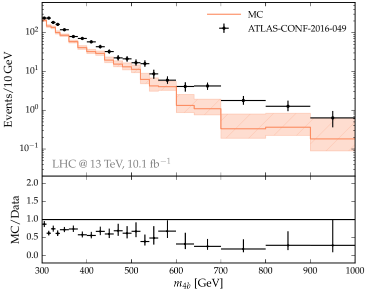
Background

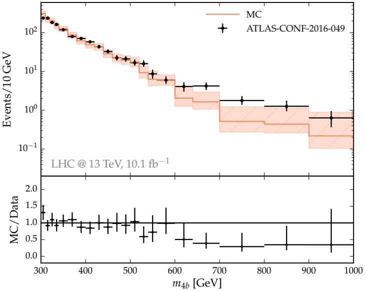
The dominant QCD backgrounds are multijets $b\bar{b}b\bar{b}$, $b\bar{b}c\bar{c}$ (mistagged), and a few % $t\bar{t}$.

Simulations are insufficient; the absolute scale should be obtained from sidebands as done by ATLAS/CMS in their search for Higgs pair production in ATL-CONF-2016-049, CMS-PAS-HIG-16-002

Here: Take $M_{H_s} \sim 125$ GeV, simulate multijets ($+\ t\bar{t}$), apply ATLAS cuts, compare our simulated M_{4b} distribution to ATLAS data in their search for Higgs pair production, used as "sideband"

$\rightarrow$ Rescale the simulated M_{4b} distribution from multijets by a factor 1.55 ± 0.27 (beyond a NLO K-factor 1.7): Approximately M_{4b} independent!





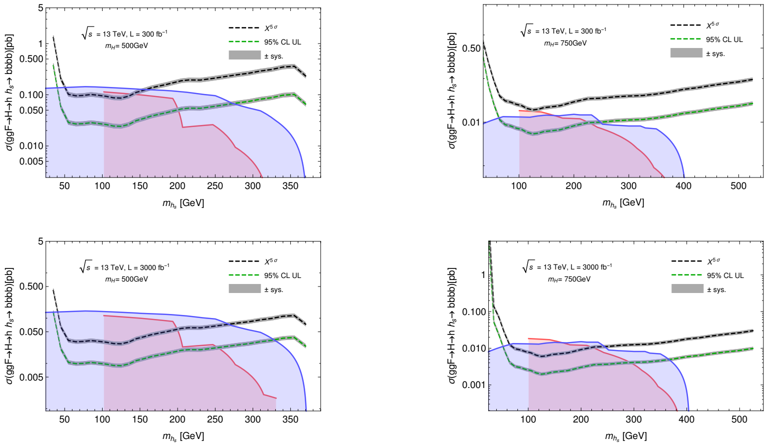
L.h.s.: M_{4b} distribution from MC vs. ATL-CONF-2016-049.

R.h.s.: M_{4b} distribution from MC vs. ATL-CONF-2016-049 after rescaling

Subsequently: Rescale M_{4b} distributions from MC by 1.55 ± 0.27 for all M_{H_s}

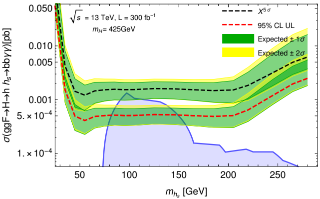
Exp. sensitiv. to $\sigma(ggF \to H/A \to H_{SM} + H_S/A_S \to b\bar{b}b\bar{b})$ as function of M_{H_S}:

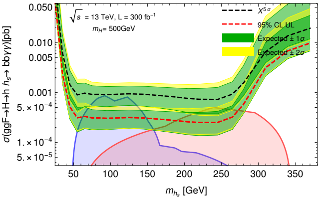
Upper left: $M_{H_{MSSM}} = 500$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 300 fb^{-1}$
Upper right: $M_{H_{MSSM}} = 750$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 300 fb^{-1}$
Lower left: $M_{H_{MSSM}} = 500$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 3000 fb^{-1}$
Lower right: $M_{H_{MSSM}} = 750$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 3000 fb^{-1}$
Blue: NMSSM points for H_S, Orange: NMSSM points for A_S

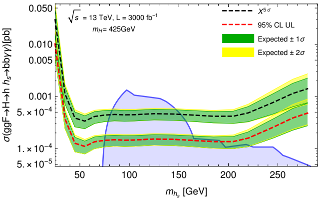


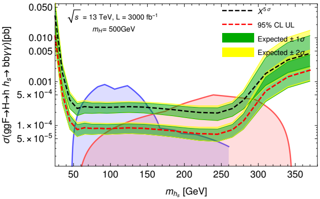
Exp. sensitiv. to $\sigma(ggF \to H/A \to H_{SM} + H_S/A_S \to b\bar{b}\gamma\gamma)$ as function of M_{H_S}:

Upper left: $M_{H_{MSSM}} = 425$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 300 fb^{-1}$
Upper right: $M_{H_{MSSM}} = 500$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 300 fb^{-1}$
Lower left: $M_{H_{MSSM}} = 425$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 3000 fb^{-1}$
Lower right: $M_{H_{MSSM}} = 500$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 3000 fb^{-1}$
Blue: NMSSM points for H_S, Orange: NMSSM points for A_S









Conclusions

- The NMSSM contains a rich BSM Higgs sector which is hardly tested
- Mostly singlet-like scalars H_S (or A_S) are difficult to detect:
- If lighter than 60 GeV possibly via H_{125} decays;
  indirect constraints from SM-like signal rates of H_{125} notably $H_{125} \to Z^* Z$,
  many ongoing ATLAS/CMS studies on exotic Higgs decays
- If heavier than 60 GeV: $ggF \to H_S/A_S \to \gamma\gamma$ cross sections may be large enough if H_S/A_S mix considerably with H_{125}, H_{MSSM}/A_{MSSM};
  excesses near $M_{H_S} \sim 97$ GeV remain to be confirmed
- Searches for $H_{MSSM}/A_{MSSM} \to H_{125} + H_S/A_S$ in $bbbb$ or $bb\gamma\gamma$ can even be sensitive to pure singlet-like H_S/A_S!
- Such decays would also reduce the branching ratio of H_{MSSM}/A_{MSSM} into the usually employed $\tau\tau$ channel $\to$ alleviated limits!
- The proposed strategy allows to discover simultaneously H/A and H_S/A_S in any Two Higgs Doublet + Singlet model