Signatures from the Extended Higgs Sector in the NMSSM
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Recall the Extended Higgs Sector of the NMSSM

- Three scalars, most conveniently characterized as
  - a mostly SM-like H_{SM} with $M_{H_{SM}} \sim 125$ GeV
  - a mostly "MSSM"-like H_{MSSM} with $M_{H_{MSSM}} \gtrsim 300$ GeV (due to b-physics bounds on $M_{H^\pm}$)
  - a mostly singlet-like H_S with $0 < M_{H_S} < X$ TeV

- Two pseudoscalars, most conveniently characterized as
  - a mostly "MSSM"-like A_{MSSM} with $M_{A_{MSSM}} \gtrsim 300$ GeV (due to b-physics bounds on $M_{H^\pm}$)
  - a mostly singlet-like A_S with $0 < M_{A_S} < X$ TeV

- All singlet-doublet mixing angles, and hence all singlet-SM couplings, are proportional to a coupling λ which is responsible for the generation of the $\mu-$term $\mu_{eff} = \lambda \langle S \rangle$.

  Require running $\lambda < \infty$ below the GUT scale $\longrightarrow$ $0 < \lambda \lesssim 0.7$

Since $H_S - H_{SM}$ mixing reduces the couplings of H_{SM}, present measurements of the couplings of H_{SM} imply a small $H_S - H_{SM}$ mixing angle

$H_S - H_{MSSM}$ and $A_S - A_{MSSM}$ mixing angles are large only if the diagonal elements in the mass matrices happen to be close

$\longrightarrow$ The mixing angles are typically small

$\longrightarrow$ The couplings of H_S, A_S to SM particles are obtained by mixing (with the nearest SM/MSSM-like state)

$\longrightarrow$ This allows to estimate their branching fractions!
(Which final states are more or less promising...)

$\longrightarrow$ The production cross sections for H_S, A_S are typically small
(unless they are light with masses below ~ 125 GeV)

How to find them?

- If H_S, A_S are lighter than ~ 60 GeV: Via exotic decays of H_{SM}. The possible $BR(H_{SM} \to H_S + H_S)$ and $BR(H_{SM} \to A_S + A_S)$ are already limited, however, by the measured H_{SM} signal rates (notably into ZZ).

- If H_S, A_S are lighter than ~ 125 GeV: Via direct production in ggF, and decays into $\gamma\gamma$, bb, $\tau\tau$, $\mu\mu$ (or even $ggF \to H_S \to A_S + A_S$).
  Interesting results from ATLAS and CMS from run I are available which constrain corners of the NMSSM parameter space.
  Can these searches be improved at run II?
  (Not obvious due to larger background.)

- The production cross sections for H_{MSSM}, A_{MSSM} can be sizeable:
  Via associate production with b-quarks (if $\tan\beta$ is large),
  or associate production with t-quarks,
  or via ggF (if $\tan\beta$ is small, $\tan\beta \sim 1,5 \ldots 5$, preferred in the NMSSM)

  AND: In the NMSSM, the branching fractions $H_{MSSM} \to H_{SM} + H_S$ (and $A_{MSSM} \to H_S + Z$ and others) can be sizeable, even dominant!
  (May alleviate limits from searches for H_{MSSM}/A_{MSSM} in the $\tau\tau$ final state.)

The search for $X \to H_{SM} + H_S$ does not seem to be on the list of ATLAS/CMS search channels...

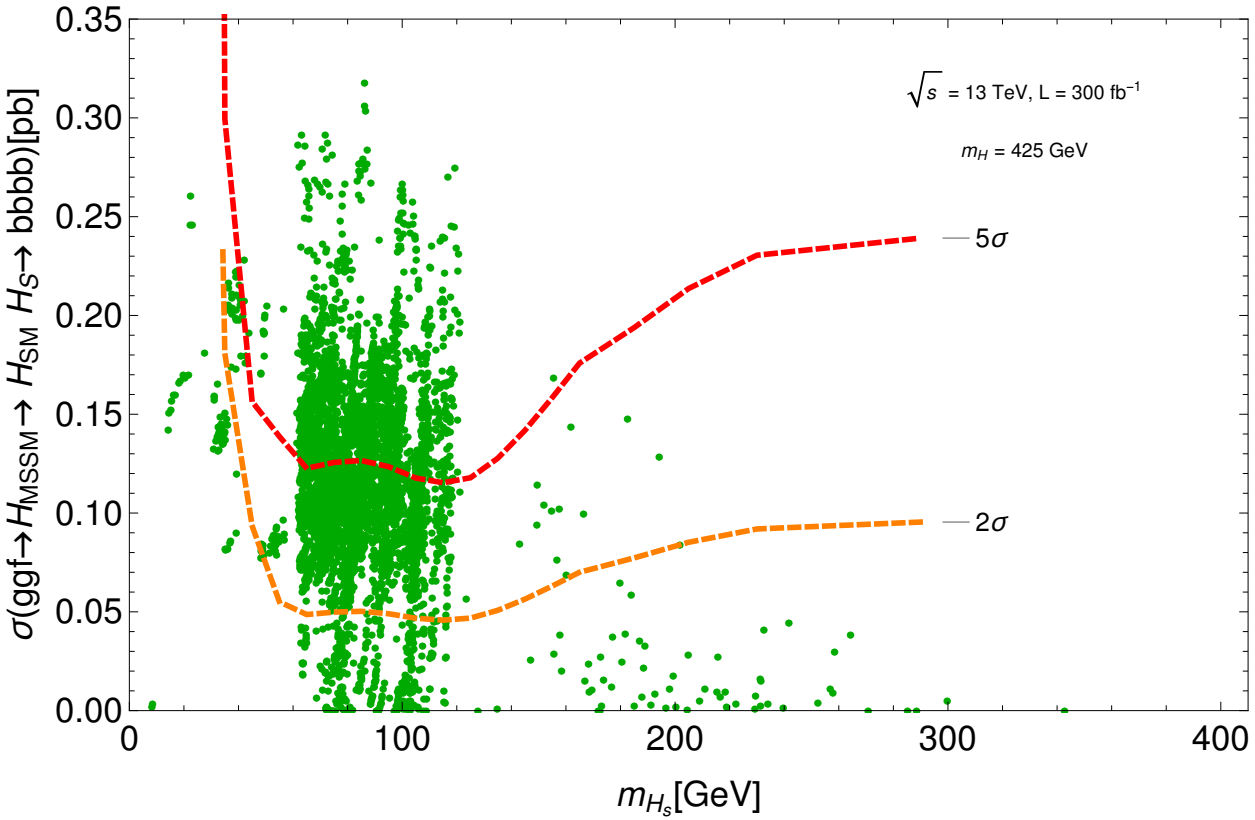
Admittedly tough in all $bbbb$, $bb\gamma\gamma$ and $bb\tau\tau$ final states:
Two unknown masses M_X and M_{H_S} (in contrast to searches for $X \to H_{SM} + H_{SM}$)

Studies by M. Rodríguez-Vázquez, to appear:

QCD bbbb backgrounds from Sherpa with NLO K-factor
tt background from MadGraph5_aMC@NLO with NNLO K-factor + Pythia 6.4
Detector simulation Delphes 3.3.3 with ATLAS p_T-dependent b-tagging and mistagging
FastJet v3.0.1 with anti-k_T jet clustering with $R = 0.4$
Backgrounds validated against ATLAS-CONF-2016-049, "Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state"

Signals with aMC_Sushi 2.3.3
Optimise event selection (pairing algorithm) and cuts (angles and p_T of b-jets) for each M_{H_S} search window; parametrize the background distribution (validated for $M_{H_S} \sim M_{H_{SM}}$); look for "bumps" in M_X for each M_{H_S} search window

Necessary Production Cross Sections × BRs to be visible above Background
bbbb Final State, Preliminary!

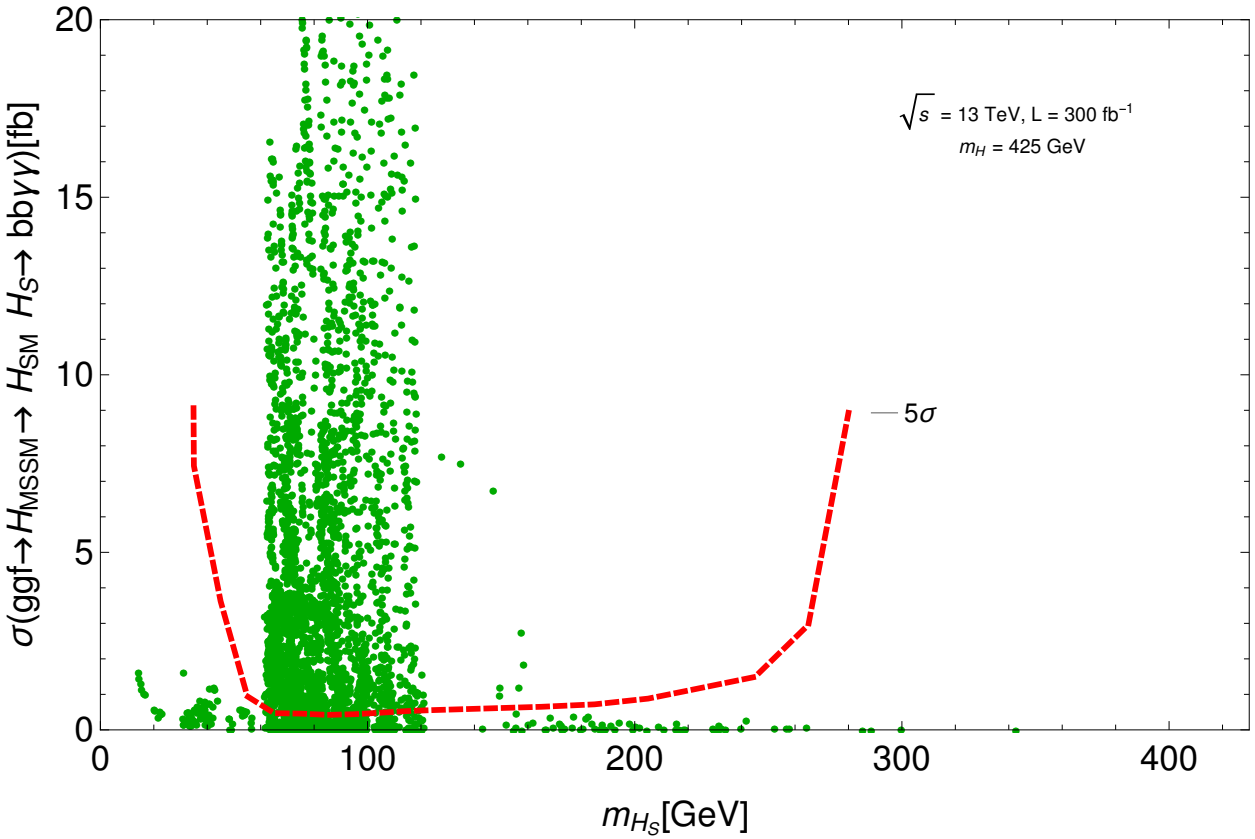


Green: NMSSM points from a scan focussing on $M_{H_S} < 125$ GeV

For $M_{H_S} \lesssim 50$ GeV the $b\bar{b}$ jets from H_S merge into a single one $\rightarrow$ reduced eff.

For $M_{H_S} \gtrsim 200$ GeV the $b\bar{b}$ jets from H_S become back-to-back $\rightarrow$ reduced eff.

Necessary Production Cross Sections × BRs to be visible above Background
$bb\gamma\gamma$ Final State, Preliminary!



Green: NMSSM points from a scan focussing on $M_{H_S} < 125$ GeV

These channels look promising!
Benchmark planes e.g. (Production Cross Sections $\times$ BRs) in the plane $M_{H_{MSSM}} - M_{H_S}$ can easily be provided for $bbbb$, $bb\gamma\gamma$ and $bb\tau\tau$ final states

Of course there are (many) more channels and scenarios to look at, see Yellow Report 4, NMSSM:

- Longer decay chains
- CP violation ($\rightarrow$ scalar-pseudoscalar Mixing)
- NMSSM Higgs production in sparticle decays (e.g. stops)

General Remarks

The absence of an excess of events in a given channel/final state and combinations thereof should be interpreted in the form of constraints on parameters (combinations of masses/couplings) within a given model (here: the NMSSM).

This is important information for the future!

But these are laborious tasks!

And depend, of course, on the considered channels, including the ones dedicated to general 2HD model or MSSM searches. Typically:

Channels which are "likely" in the NMSSM (frequent in parameter space) and "simple" (no long decay cascades) simplify this task; e.g. $ggF \to H_S \to \gamma\gamma$.