Higgs Bosons in the NMSSM

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Higgs content of the NMSSM:

- Two SU(2) doublets H_u (couples to up-type quarks) and H_d (couples to down-type quarks and leptons) $\to$ like in the MSSM,
- A singlet S whose vev generates a Dirac mass term for higgsinos (replaces the μ term of the MSSM)

Mass eigenstates (– Goldstone boson):

- Three neutral scalars:
  - $H_{SM} \to M_{H_{SM}} \sim 125$ GeV
  - $H_S \to$ mostly singlet-like
  - $H \to$ mostly MSSM-like, heavy, see below
- Two neutral pseudoscalars
  - $A_S \to$ mostly singlet-like
  - $A \to$ mostly MSSM-like, heavy, see below
- One charged Higgs $H^{\pm} \to$ MSSM-like, heavy, see below

Indirect constraints on the masses of the states beyond H_{SM}:

$H^{\pm}$ contributes to the $BR(b \to s + \gamma)$ which is in agreement with the SM

$\to$ $M_{H^{\pm}} \gtrsim 350$ GeV $>$ scale of EW symmetry breaking

$\to$ $H^{\pm}$, H and A form a nearly degenerate SU(2) multiplet with $M \gtrsim 350$ GeV

BUT: The masses M_{H_S}, M_{A_S} of the mostly singlet-like (pseudo-)scalars depend on unknown parameters and can vary from $0 \dots 1000$ GeV (and are different);

$M_{H_S} \sim 60 - 110$ GeV is natural, helps to explain $M_{H_{SM}} \sim 125$ GeV without inducing a too large $BR(H_{SM} \to H_S H_S)$ which could reduce the SM-like branching fractions like $H_{SM} \to Z^* Z$ below its measured values

Couplings of the BSM Higgs states to SM particles (essential for searches!):

Use: $\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle} = 1 \dots 60$;

MSSM (typically): $\tan\beta \gtrsim 10$ for $M_{H_{SM}} \sim 125$ GeV,

NMSSM (typically): $\tan\beta \sim 2-4$ for NMSSM-specific contributions to $M_{H_{SM}}$

- H/A:
  - g_{Htt} suppressed by $1/\tan\beta$ (still dominant for $\tan\beta < 60$)
  - g_{Hbb}, $g_{H\tau\tau}$ enhanced by $\tan\beta$
  - g_{HWW}, g_{HZZ} strongly suppressed for $M_H \gg M_{H_{SM}}$ ("alignment")
- H_S: Mixes with H_{SM} and/or H
  - $M_{H_S} < 125$ GeV: most couplings like H_{SM} reduced by a common factor (mixing angle) $\rightarrow$ very similar branching fractions, except:
    Couplings of H_S to $\gamma\gamma$ can be considerably enhanced!
    (Due to a reduced coupling to $b\bar{b}$)
  - $M_{H_S} \gg 125$ GeV: most couplings like H reduced by a common factor $\rightarrow$ very similar branching fractions

Note: Mixing between H_S and H_{SM} reduces the couplings of "H_{SM}" to ZZ, WW below their SM values (corresponding to $\kappa = 1$);

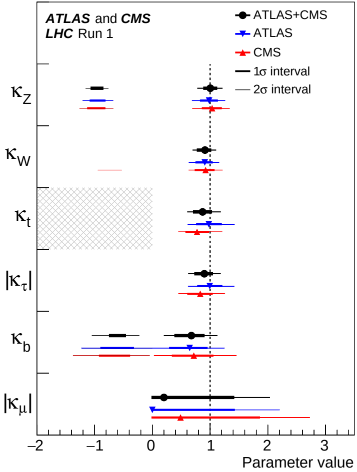
Run I ATLAS and CMS combination:

From $\kappa^2_{H_{SM}ZZ} + \kappa^2_{H_S ZZ} \lesssim 1$ and

$\kappa_{H_{SM}ZZ} > 0.84$ (at $2\,\sigma$):

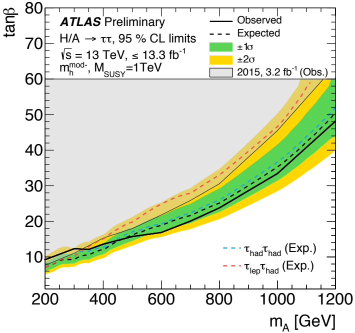
$\kappa_{H_S ZZ} (= \kappa_{H_S WW}) \lesssim 0.5$

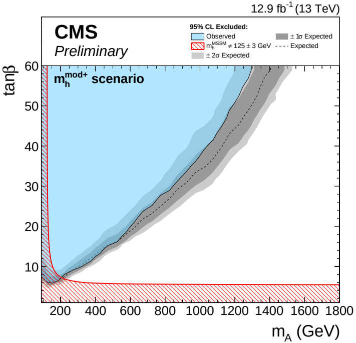
The (relative) $H_S - ZZ/WW$ couplings squared can be at most ~ 0.25



Possible direct production of the BSM Higgs states:

- H/A:
  - ggF: dominant, but large QCD background to $H \to tt$, $H \to bb$
  - Ass. production with b quarks:
    enhanced for large $\tan\beta$ where also the BRs into bb, $\tau\tau$ become larger;
    bb + resonant $\tau\tau$ final state: background under control, but: no excess
    $\to$ constraints in the plane $\tan\beta - M_A$ ($\simeq M_H, M_{H^\pm}$)
    (from ATLAS-CONF-2016-085/CMS-PAS-HIG-16-037):

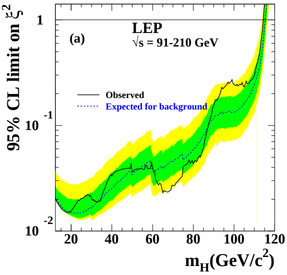




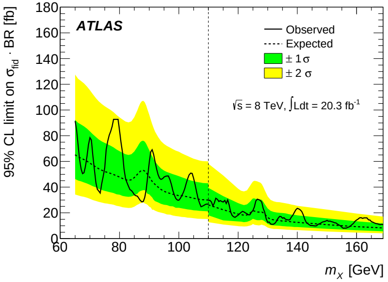
- H_S/A_S:

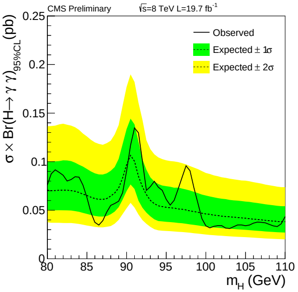
LEP search for a light scalar with reduced coupling ξ^2 to ZZ (recall: $\xi^2 \lesssim 0.25$ from $H_{SM}ZZ$ coupling):

The region in the $\xi^2 - m_H$ plane below the black line is allowed

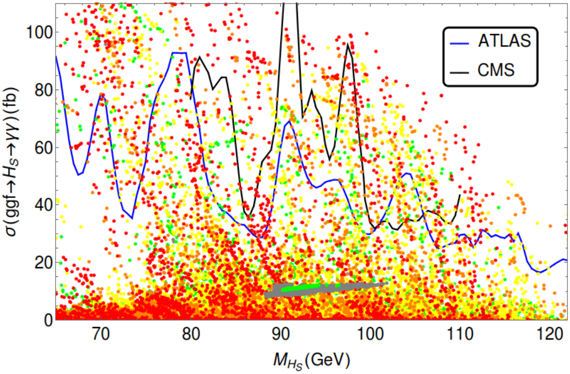


ATLAS/CMS searches for $ggF \to H_S \to \gamma\gamma$ at 8 TeV:





Do the ATLAS/CMS searches touch possible values for $\sigma(ggF \to H_S \to \gamma\gamma)$ within the LEP-allowed NMSSM parameter space? (M. R.-Vázquez, U.E.):



YES, but far from exclusion... even light H_S/A_S states may have too small direct production cross sections for discovery, even at 13 TeV

Possible indirect production of the BSM Higgs states:

Potentially (relatively) large NMSSM-specific trilinear Higgs couplings:

$$g_{H_{SM}H_S H_S},\ g_{H_{SM}A_S A_S},\ g_{HH_S H_{SM}}$$

$\rightarrow$ allow for decays

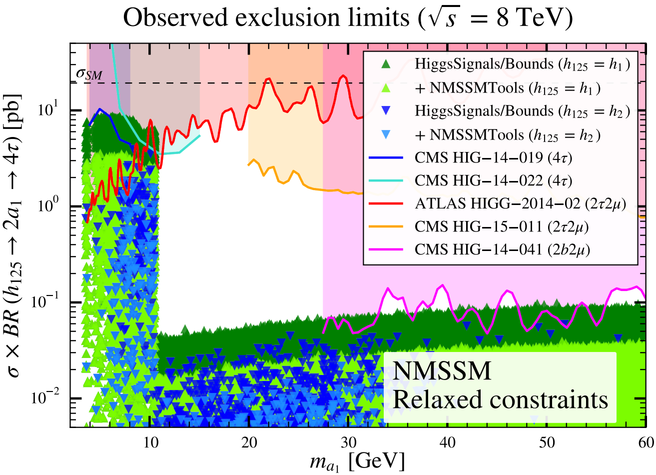
- $H_{SM} \rightarrow H_S H_S$, $H_{SM} \rightarrow A_S A_S$
  (if kinematically allowed, i.e. $M_{H_s,A_s} \lesssim 60$ GeV)
- $H \rightarrow H_{SM} H_S$

Exotic H_{SM} decays reduce its SM-like branching ratios, and are limited by its SM-like signal rates (see above); still ...

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)

Observed exclusion limits ($\sqrt{s} = 8$ TeV)



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

$\to$ These searches for A_S/H_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?

$\rightarrow$ Recall: $g_{HH_SH_{SM}}$ can be large (in contrast to $g_{HH_{SM}H_{SM}}$, $g_{HH_SH_S}$)

$\rightarrow$ The $BR(H \rightarrow H_S H_{SM})$ can be large ($\sim 30\%$, competing only with $H \rightarrow t\bar{t}$, reducing BR for the search into $\tau\tau$)

$\rightarrow$ Looks like resonant Higgs pair production, but with one SM Higgs replaced by H_S with unknown mass in the range up to $M_H - 125$ GeV

$\rightarrow$ Look for $b\bar{b}b\bar{b}$ (4 b-tagged jets) with

- one $b\bar{b}$ pair: $M_{b\bar{b}} \sim 125$ GeV,
- another $b\bar{b}$ pair: $M_{b\bar{b}} \sim M_{H_S}$ (unknown),
- $M_{b\bar{b}b\bar{b}} \sim M_H$ (unknown)

($b\bar{b}\tau\tau$ final states are slightly less promising;
$b\bar{b}\gamma\gamma$ final states possibly promising for $M_H \lesssim 500$ GeV, under study)

Best Strategy (M. R.-Vázquez)

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

Use "test" mass $M_{b\bar{b}} \sim M_{H_S}$; for given M_{H_S}: Optimise 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)

Study the distribution of $M_{b\bar{b}b\bar{b}}$ from the 4 b-tagged jets (after correcting $M_{b\bar{b}}$ near 115 GeV to 125 GeV)

→ The (by far) dominant 4b QCD background is a smoothly decreasing function of $M_{b\bar{b}b\bar{b}}$, obtained from SHERPA (during a secondment in Durham)

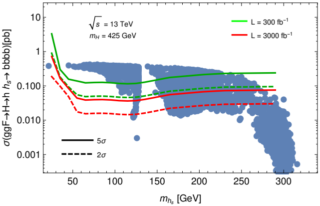
→ If M_{H_S} was chosen correctly, one observes a "bump" in $M_{b\bar{b}b\bar{b}}$ near M_H whose significance can be computed as function of M_{H_S}, M_H and notably the $\sigma(ggF \to H \to H_{SM} + H_S \to b\bar{b}b\bar{b})$

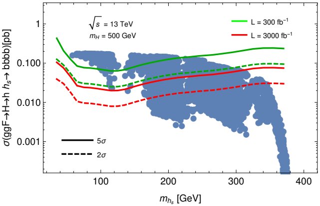
→ Expected $2\,\sigma$ exclusion limits and $5\,\sigma$ discovery limits can be obtained

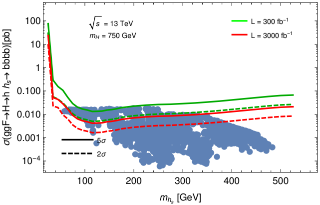
→ These are model independent (assuming just a width not larger than a few GeV), but can be compared to possible values for $\sigma(ggF \to H \to H_{SM} + H_S \to b\bar{b}b\bar{b})$ in the NMSSM:

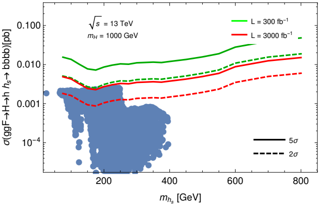
Expected sensitivities to $\sigma(ggF \to H \to H_{SM} + H_S \to b\bar{b}b\bar{b})$ as function of M_{HS}:

Upper left: assuming $M_H = 425$ GeV, upper right: assuming $M_H = 500$ GeV
Lower left: assuming $M_H = 750$ GeV, lower right: assuming $M_H = 1000$ GeV
Full/dotted green: $5/2\sigma$ excess for $L = 300 fb^{-1}$
Full/dotted red: $5/2\sigma$ excess for $L = 3000 fb^{-1}$; Blue: NMSSM points









Conclusions

- The NMSSM contains a rich BSM Higgs sector which is hardly tested
- Mostly singlet-like scalars H_S/pseudoscalars A_S (light <125 GeV, or heavy >125 GeV) are far from being excluded; their direct production is detectable only in some regions of the NMSSM parameter space
- If lighter than 60 GeV they may be detectable via H_{SM} decays (many ongoing ATLAS/CMS studies on exotic Higgs decays)
- Otherwise they may be detectable via
  $H \to Z + A_S$ (ongoing ATLAS/CMS studies) or
  $H \to H_{SM} + H_S$ decays (see above, no LHC studies yet)

  (These decays, if taken into account, reduce the sensitivities to MSSM-like H/A states in the standard $b\bar{b}\tau\tau$ channel!)