Simultaneous Search for Extra Light and Heavy Higgs Bosons via Cascade Decays

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Motivation:

Higgs-to-Higgs decays the NMSSM:

Scale invariant Superpotential: $W = \lambda \hat{H}_u \hat{H}_d \hat{H}_S + \frac{\kappa}{3} \hat{H}_S^3 + \ldots$

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

Origin of trilinear Higgs couplings:

Mostly quartic (scale invariant) couplings $\sim \left(\lambda^2,\ \lambda\kappa,\ \kappa^2,\ g^2\right) \times H^4$, replace one H by $\langle H \rangle$

Exception: trilinear soft SUSY breaking term $\lambda A_\lambda H_u H_d H_S$
with λA_λ a few 100 GeV . . . O(TeV)

From H_u, H_d, H_S to mass eigenstates in two steps:

1) Rotate H_u, H_d by β with $\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$ into H'_{125}, H'_{MSSM} with

$$\langle H'_{125} \rangle = \langle H_{SM} \rangle,\ \langle H'_{MSSM} \rangle = 0 \text{ (``Higgs basis'')}$$

$\rightarrow$ H'_{125} is essentially SM-like, up to mixing with H_S

$\rightarrow$ H'_{MSSM} is essentially MSSM-like

A similar rotation in the CP-odd sector diagonalises the doublet sector
$\rightarrow$ Goldstone boson + A'_{MSSM} which is essentially MSSM-like

Now: trilinear coupling of CP-even scalars:

$$\frac{1}{\sqrt{2}}\lambda A_\lambda \left(\frac{\tan^2\beta - 1}{\tan^2\beta + 1} H'_{125} (H'_{MSSM} H_S + A'_{MSSM} A_S) + \ldots \right)$$

2) H'_{125}, H'_{MSSM}, A'_{MSSM} , H_S/A_S are nearly mass eigenstates in most of the parameter space, the remaining mixing angles are typically small
$\rightarrow$ omit the primes in the following

H_{MSSM}, A_{MSSM} are nearly degenerate with a charged Higgs $H^\pm$ with $M_{H^\pm} \gtrsim 350$ GeV to avoid too large contributions to the $BR(b \rightarrow s + \gamma)$

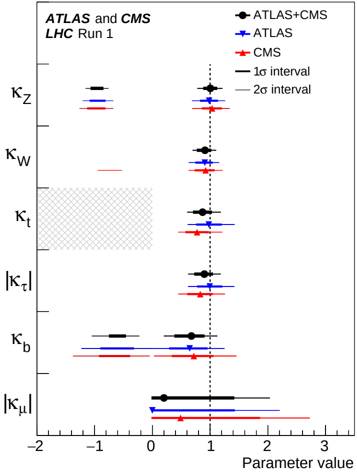
The masses of the mostly singlet-like scalars H_S/A_S depend on unknown parameters and can vary from 0 GeV…O(TeV); not degenerate!

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

How to detect H_S/A_S?

Their couplings to SM particles originate from mixing, but 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 $\kappa^2_{H_{SM}ZZ} \gtrsim 0.7$ (at $2\,\sigma$) and

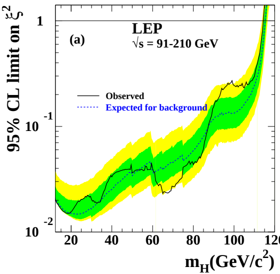
$\kappa^2_{H_{SM}ZZ} + \kappa^2_{H_S ZZ} \lesssim 1$

$\rightarrow$ The (relative) $H_S - ZZ/WW$ couplings squared can be at most ~ 0.3; valid for all H_S couplings (unless H_S mixes with H_{MSSM})

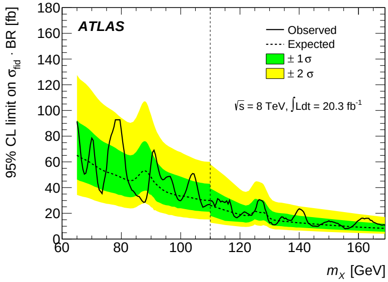
LEP search for a light scalar with reduced coupling ξ^2 to ZZ

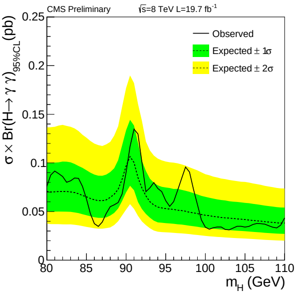
(recall: $\xi^2 \lesssim 0.3$ from $H_{SM}ZZ$ coupling):

The region in the $\xi^2 - m_H$ plane below the black line and below 0.3 is allowed

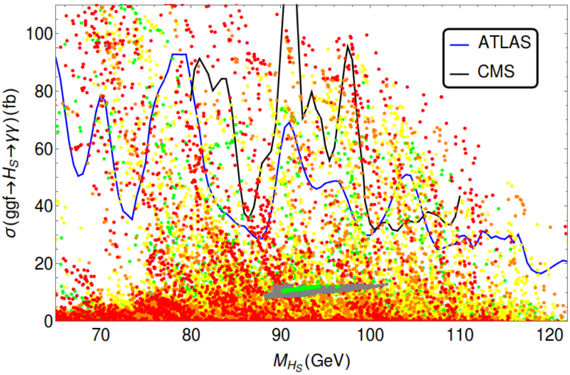


ATLAS/CMS searches for $ggF \to H_S \to \gamma\gamma$ at 8 TeV:





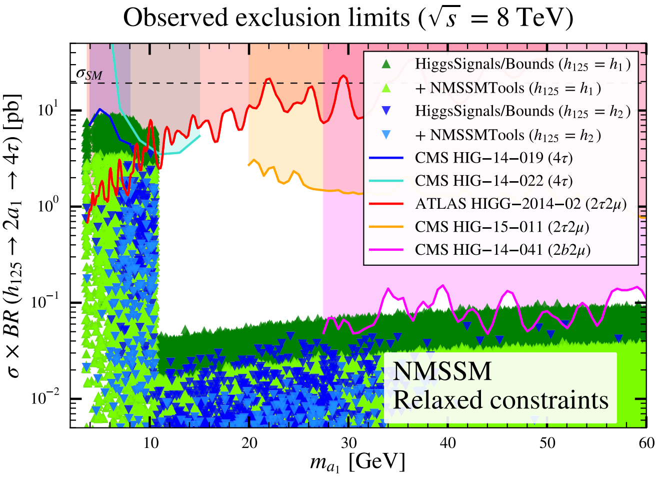
Do the ATLAS/CMS searches touch possible values for $\sigma(ggF \to H_S \to \gamma\gamma)$ within the LEP-allowed NMSSM parameter space? (M. Rodríguez, U.E.):



YES, but far from exclusion... 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?

$\rightarrow$ Recall: the couplings $H_{MSSM} H_S H_{125}$, $A_{MSSM} A_S H_{125}$ can be large (in contrast to $H_{MSSM} H_{125} H_{125}$, $H_{MSSM} H_S H_S$, $\ldots$)

$\rightarrow$ The $BRs(H_{MSSM}/A_{MSSM} \rightarrow H_{125} H_S/A_S)$ can be large $\sim 50\%$, (competing only with $H/A_{MSSM} \rightarrow t\bar{t}$, 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

$\rightarrow$ 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: $M_{b\bar{b}} \sim M_{H_S,A_S}$ (unknown),
- $M_{b\bar{b}b\bar{b}} \sim M_{H/A_{MSSM}}$ (unknown)

($b\bar{b}\tau\tau$ final states are slightly less promising;
$b\bar{b}\gamma\gamma$ final states possibly promising for $M_{H/A} \lesssim 500$ GeV)

Best Strategy (M. Rodríguez)

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

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

- Optimize the cuts on p_T,
- 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_{4b} from the 4 b-tagged jets (after correcting both $M_{b\bar{b}}$ to 125 GeV/M_{H_S})
- 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 $\sigma(ggF \to H_{MSSM} \to H_{125} + H_S \to b\overline{b}b\overline{b})$
- Expected 95% CL exclusion limits and $5\,\sigma$ discovery limits can be obtained
- These are model independent (assuming just a width $\lesssim$ a few GeV)

 Background 

The dominant QCD backgrounds are multijets $b\bar{b}b\bar{b}$, $b\bar{b}c\bar{c}$ (with mistagging), and a few % $t\bar{t}$. Simulations are insufficient; the absolute scale should be obtained from sidebands as done by ATLAS/CMS:

Search for Higgs pair production in ATL-CONF-2016-049, CMS-PAS-HIG-16-002:

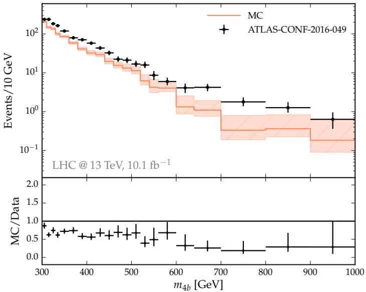
— Simulate multijets ($+\ t\bar{t}$)

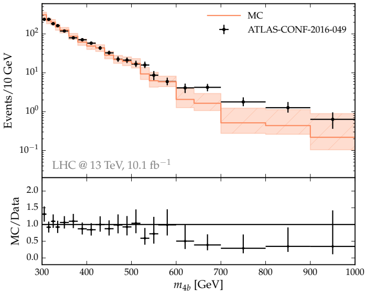
— Compare to data in sidebands (2 b-tags only)

— Rescale the simulated M_{4b} distribution into the signal region (4 b-tags)

— Compare to data

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 used as "sideband"
$\longrightarrow$ 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!



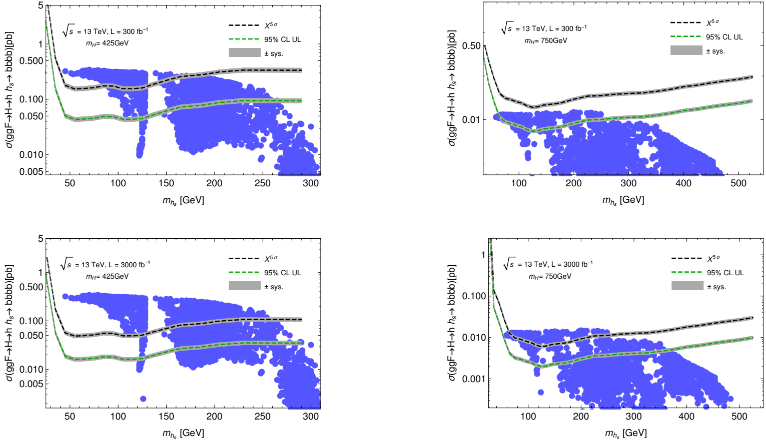


L.h.s.: M_{4b} distribution from MC vs. ATL-CONF-2016-049.
R.h.s.: M_{4b} distribution from MC vs. ATL-CONF-2016-049 after rescaling

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

Expected sensitivities to $\sigma(ggF \to H \to H_{SM} + H_S \to b\bar{b}b\bar{b})$ 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: $M_{H_{MSSM}} = 750$ 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: $M_{H_{MSSM}} = 750$ GeV, 95% limits and $5\,\sigma$ discovery 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 (or A_S) are difficult to detect:
- If lighter than 60 GeV possibly via H_{125} decays;
  many ongoing ATLAS/CMS studies on exotic Higgs decays,
  indirect constraints from SM-like signal rates of H_{125} notably $H_{125} \to Z^* Z$
- Direct production $H_S/A_S \to \gamma\gamma$ cross sections may be large enough only if H_S/A_S happen to mix strongly with $H_{125},\ H_{MSSM}/A_{MSSM}$
- Present result: Searches for $H_{MSSM}/A_{MSSM} \to H_{125} + H_S/A_S$ can be sensitive to very singlet-like H_S/A_S!
  Excesses would descover simultaneously H_{MSSM}/A_{MSSM} and 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!)