Search for extra Higgs bosons at the LHC

Matías Vázquez
with
Ulrich Ellwanger
LPT d'Orsay, Univ. Paris-Sud XI

based on 1512.04281 (JHEP 1602 (2016) 096)
and 1707.08522 (JHEP, to appear)

September 13th, 2017

Index

1. Introduction
2. The NMSSM
3. Present searches at the LHC
   - Direct searches
   - Indirect searches
4. A new search: $H \to hh_s$ / $A \to ha_s$
5. Results
6. Conclusions and outlook

Extended Higgs sectors

The Higgs sector of the SM

- In the SM, the EWSB mechanism is realized minimally. Only one Higgs doublet giving rise to one physical scalar after symmetry breaking.
- Some 'uncomfortable' facts of the SM: metastability of the Higgs potential, quadratically divergent contributions to the Higgs mass, hierarchy of Yukawa couplings...
- ... So far, h^{125} is (very) compatible with the SM predictions.

Extended Higgs sector

- Models featuring an extended scalar sector are well motivated (SUSY, extended symmetries, extra Higgs representations...).
- New physical states possibly within the reach of the LHC.
- Such models open the possibility for new Higgs-to-Higgs decays which can test the nature of EWSB.

The NMSSM Higgs sector

Higgs content of the NMSSM:

- Two SU(2) doublets H_u (couples to up-type fermions) and H_d (couples to down-type fermions) $\rightarrow$ 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:
  - $h \rightarrow M_h \sim 125$ GeV
  - $h_s \rightarrow$ mostly singlet-like
  - $H \rightarrow$ mostly MSSM-like, heavy, see below
- Two neutral pseudoscalars
  - $a_s \rightarrow$ mostly singlet-like
  - $A \rightarrow$ mostly MSSM-like, heavy, see below
- One charged Higgs $H^{\pm} \rightarrow$ MSSM-like, heavy, see below

Indirect constraints on the masses of the states beyond h

$H/A/H^{\pm}$

$H^{\pm}$ contributes to the $BR(b \to s + \gamma)$ which is in agreement with the SM
$\to M_{H^{\pm}} \gtrsim 350$ GeV
$\to H^{\pm}$, H and A form a nearly degenerate SU(2) multiplet with $M \gtrsim 350$ GeV

h_s/a_s

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

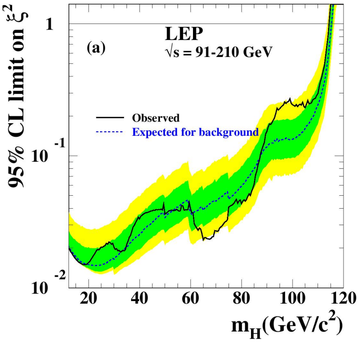
$\to M_{h_s} \sim 60 - 110$ GeV is natural, helps to explain $M_h \sim 125$ GeV (mixing effects) without inducing a too large $BR(h \to h_s h_s)$ which could reduce the SM-like branching fractions like $h \to Z^* Z$ below its measured values

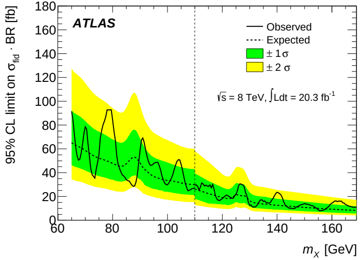
Particle:	$H/A/H^{\pm}$	h	h_s/a_s
Mass:	$\gtrsim 350$ GeV	125 GeV	$0 \ldots 1000$ GeV

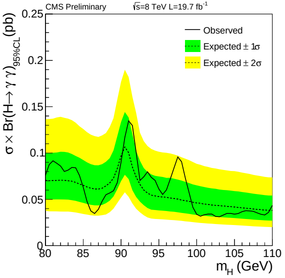
Searches for direct production of BSM Higgs bosons

- **Light states** : $\mathbf{h_s/a_s}$:
  - LEP search for a light scalar with reduced coupling ξ^2 to ZZ (recall: $\xi^2 \lesssim 0.29$ from hZZ 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:

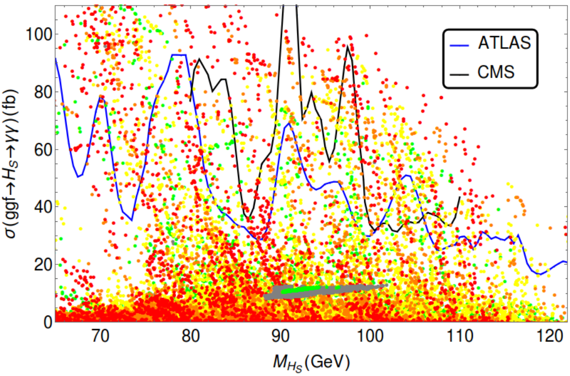






Searches for direct production of BSM Higgs bosons: h_s

Do the ATLAS/CMS searches touch possible values for $\sigma(ggF \to h_s \to \gamma\gamma)$ within the LEP-allowed NMSSM parameter space? (JHEP02(2016)096, U.Ellwanger, MRV):

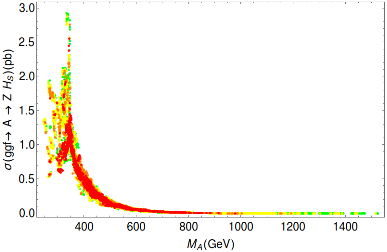


YES, but far from exclusion... even light h_s/a_s states may have too small direct production cross sections for discovery, even at 13 TeV

Indirect production of BSM Higgs states: $H/A \to Z(a_s/h_s)$

Searches for $H \to Za_s$ / $A \to Zh_s$ featuring **two unknown masses** have already been performed using Run I data (CMS-PAS-HIG-15-001, CMS-PAS-HIG-16-010);

$(ggF \to)A \to Zh_s$ COULD BE LARGE IN THE NMSSM: [JHEP02(2016)096, U.Ellwanger, MRV]



Strongest constraints: CMS-PAS-HIG-15-001

$A \to Zh_s \to llb\bar{b}$

(M_A, M_{h_s})	NMSSM (fb)	CMS limits (fb)
(500,60)	4.6	$\sim$ 10
(500,120)	2.7	$\sim$ 10
(350,60)	60	$\sim$ 60

$A \to Zh_s \to ll\tau\tau$

(M_A, M_{h_s})	NMSSM (fb)	CMS limits (fb)
(500,60)	0.5	$\sim$ 20
(500,120)	0.5	$\sim$ 6
(350,60)	6.6	$\sim$ 30

some current limits are close to the NMSSM allowed parameter space!

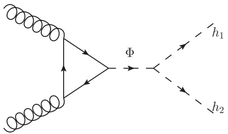
Indirect production of BSM Higgs states: Trilinear Higgs couplings

Typically $g_{Hhh} < \langle h \rangle$ (due to SU(2) symmetry). Searches for $H \rightarrow hh$ are not promising in the context of the (N)MSSM.
However, the doors are open for potentially large NMSSM-specific trilinear Higgs couplings:

$$g_{hh_sh_s},\ g_{ha_sa_s},\ g_{Hh_sh},\ g_{Aa_sh}$$

→ allow for decays

- $h \rightarrow h_s h_s$, $h \rightarrow a_s a_s$. Searches exist.(if kinematically allowed, i.e. $M_{h_s,a_s} \lesssim 60$ GeV)
- $H \rightarrow hh_s/A \rightarrow ha_s \Rightarrow$ **No searches!**



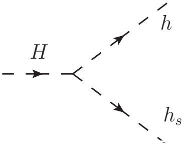
These searches are poorly constrained!

Exotic h decays reduce its SM-like branching ratios, and are limited by its SM-like signal rates $\Rightarrow m_{h_s,a_s} > 60$ GeV is favoured.

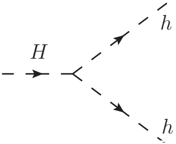
A new search: $H \to hh_s$ / $A \to ha_s$

Motivation

- g_{Hh_sh} can be large [JHEP02(2016)096, U.Ellwanger, MRV] (in contrast to g_{Hhh}, $g_{Hh_sh_s}$)
- The $BR(H \to h_s h)$ can be large ($\sim 50\%$, competing only with $H \to t\bar{t}$, reducing BR for the search into $\tau\tau$)
- Might be the main production channel for a singlet.
- **No experimental constraints until now!**



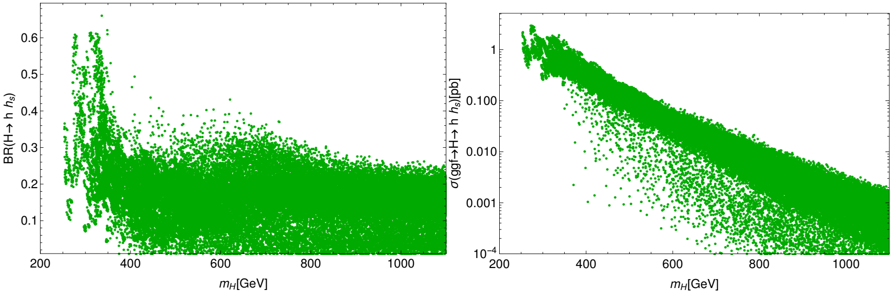
$\propto A_\lambda \sim 100GeV \ldots \mathcal{O}(TeV)$



$< \langle h \rangle \ll A_\lambda$

$\sigma(ggF \to H \to hh_s)$ from a scan of the param. space

Using NMSSMTools, we perform a scan in a large region of parameter space, including latest constraints from the experimental collaborations. ggF(H) xs computed at NNLO+NNLL using rescaled recommended values from the HXSWG [De Florian et al. arXiv:1610.07922]. Large signals are possible in $H \to hh_s$.



Questions

- Are these cross sections visible at the LHC?
- Which channels should we look for?

Objectives

- Design search strategies to study the discovery potential of the LHC in the processes $H \to hh_s$ (more generally, $\phi_1 \to h\phi_2$).
- Obtain expected sensitivities for these searches.

Approach

- Make signal-to-background studies by means of MC simulations of both the signals and backgrounds.
- Statistical analysis of the results.
- Explore the channels $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$.

Monte Carlo study

We performed a thorough signal-to-background study in three different channels, with $M_H = 350 \ldots 1000$ GeV, $M_{h_s} = 25 \ldots 400$ GeV.

The search strategy mimics resonant double SM Higgs searches, varying the mass of one of the Higgs bosons.

Simulations: `MadGraph5@NLO` + `Pythia` + `Delphes`, including *b*-tagging efficiencies as reported by the experimental collaborations for Run 2.

$b\bar{b}b\bar{b}$

- Resolved topologies
- Large QCD multijet background ($b\bar{b}b\bar{b}$, $b\bar{b}c\bar{c}$, $b\bar{b}jj$), but large branching ratios.

$b\bar{b}\tau\tau$ ($\tau\tau b\bar{b}$)

- 3 subchannels: $\tau_h\tau_h$, τ_h, e, τ_h, μ.
- Dominant background: $t\bar{t}$ and, to a less extent, Z+jets

$b\bar{b}\gamma\gamma$ ($\gamma\gamma b\bar{b}$)

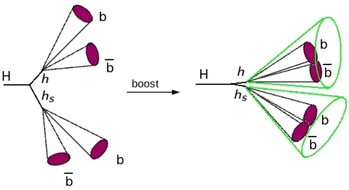
- Many different sources of background
- Cleaner than $b\bar{b}b\bar{b}$, but reduced cross sectios.
- Low statistics.

Goal: optimize search strategies, obtain realistic expected sensitivities for the process $ggF \to H/A \to h + h_s/a_s$.

$b\bar{b}b\bar{b}$ Analysis strategy

Complication: two unknown masses m_H and m_{h_s}. Focus on the **resolved region**, where the products of the heavy Higgs are not too boosted $\Rightarrow$ We consider $m_H < 1$ TeV. Heavier states feature very small xs.

Resolved analysis



Event reconstruction:

- b-tagging efficiencies $\epsilon(p_T)$ depending on p_T as reported by the experimental collaborations.
  ATL-PHYS-PUB-2015-022
- Jets clustered using `FastJet`, with $\Delta R = 0.4$.
- Require at least 4 b-jets with $p_T > 30$ GeV and $\eta < 2.5$.
- **Each analysis assumes a mass for the singlet,** $m_{h_s}^{\text{test}}$
- **Pairing algorithm:** Take the 4 leading-p_T b-tagged jets. Look for the pair that better reproduces the masses (m_h, m_{h_s}).

$b\bar{b}b\bar{b}$ Analysis strategy

Selection:

- acceptances:

$$p_T(b) > 30 \text{ GeV}, \quad |\eta| < 2.5$$

- mass-dependent cuts to optimize signal-to-background significance:

$$p_T^h < 1.56 \text{ GeV} + 0.4m_X - 0.13m_{h_s} - 160m_{h_s}/m_X \text{ GeV}$$
$$p_T^{h_s} < 11.92 \text{ GeV} + 0.4m_X - 0.15m_{h_s} - 166.84m_{h_s}/m_X \text{ GeV}$$

- A **signal region** is defined as:

$$\chi^2_{hh_s} = \sqrt{\left(\frac{m_{2j}^h - 115GeV}{0.11m_{2j}^h}\right)^2 + \left(\frac{m_{2j}^{h_s} - 0.85m_{h_s}GeV}{0.11m_{2j}^{h_s}}\right)^2} < 2 \quad (1)$$

- Instead of the total invariant mass, we define a 4-body *corrected mass* m_X;

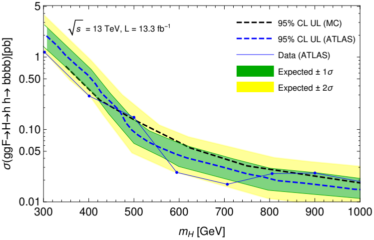
$$m_X = m_{4b} - m_{b\bar{b}}(h) + 125 \text{ GeV} - m_{b\bar{b}}(h_s) + m_{h_s} \quad (2)$$

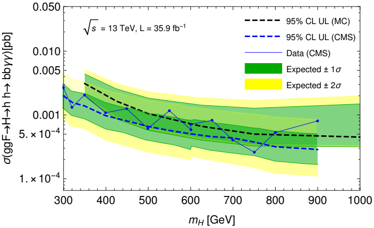
Improves the resolution! (already used by CMS in $bb\gamma\gamma$ [CMS-PAS-HIG-16-032])

m_X is the last discriminant in the search
$\Rightarrow$ Hunt for bumps in m_X!

Validation of the background simulation

$\longrightarrow$ Background shapes (for m_X) from MC are in **good agreement with data.**
$\longrightarrow$ We **rescaled** the samples using data from searches in $b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$ for double SM Higgs production [ATLAS-CONF-16-049, CMS-PAS-HIG-17-008, CMS-PAS-HIG-16-029] $\Rightarrow$ validation for the case $m_{h_s} = 125$ GeV.
$\longrightarrow$ The expected sensitivities from simulations reproduce well the ones from the experimental collaborations (data-driven).

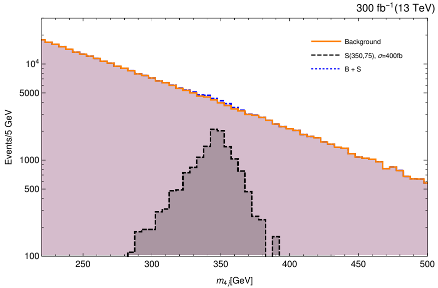


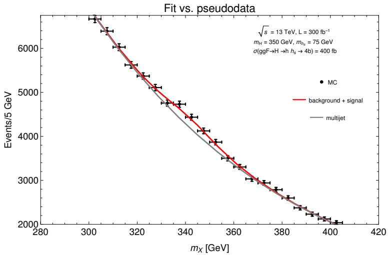


Results: Benchmark points

We take a bunch of phenomenologically allowed benchmark points. How would a bump in m_X look like?

P.1. $m_H = 350$ GeV, $m_{h_s} = 75$ GeV, $\sigma = 400$ fb

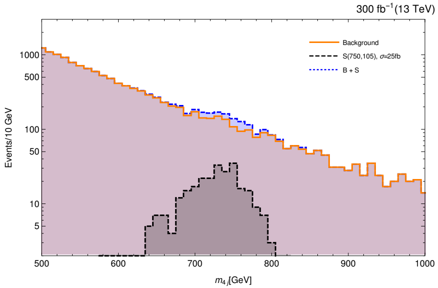


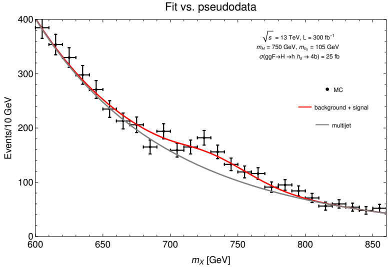


- Well behaved excesses sitting on an exponentially decaying background.

Results: Benchmark points

P.2. $m_H = 750$ GeV, $m_{h_s} = 105$ GeV, $\sigma = 25$ fb

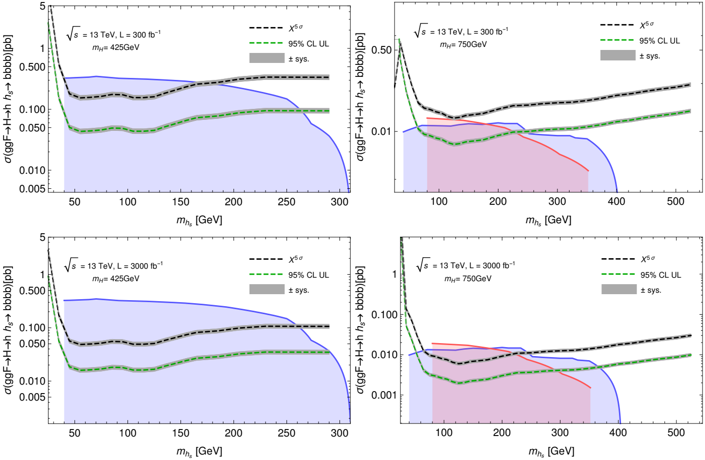




- satisfactory resolution in m_X even at large masses m_H.

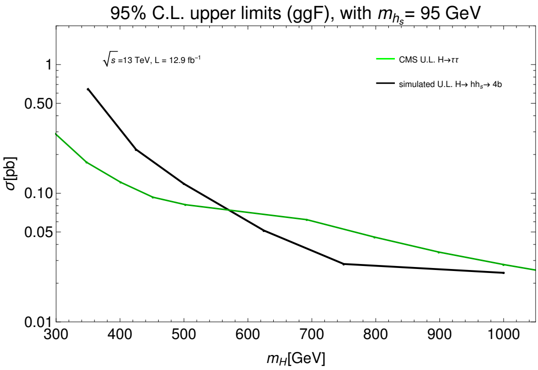
Results: Expected sensitivities $b\bar{b}b\bar{b}$

Upper left: $M_H = 425$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 300 fb^{-1}$
Upper right: $M_H = 750$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 300 fb^{-1}$
Lower left: $M_H = 425$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 3000 fb^{-1}$
Lower right: $M_H = 750$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 3000 fb^{-1}$
Blue and red: NMSSM allowed region for $H \to hh_s \to 4b$ and $A \to ha_s \to 4b$.



Results: Comparison with other H searches

Searches for heavy MSSM-like H bosons are carried out mainly in the $H \to \tau\tau$ final state. For a straight-forward comparison, we compare the existing upper limits on $H \to \tau\tau$ and the would-be upper limits for $H \to hh_s \to 4b$ for the same luminosity:

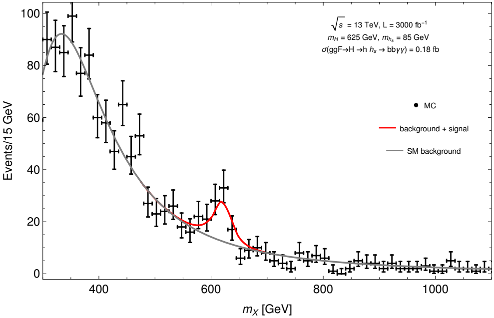


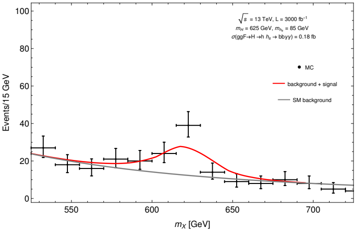
NOTE: $\frac{BR(H\to hh_s \to 4b)}{BR(H\to\tau\tau)} \sim 10 - 100 \Rightarrow H \to hh_s \to 4b$ **performs better!**

Results: Benchmark points

...proceeding in the same way for $b\bar{b}\gamma\gamma$:

$m_H = 625$ GeV, $m_{h_s} = 85$ GeV, $\sigma = 0.18$ fb





- Low statistics: we expect few events on top of a small background.

Results: Expected sensitivities $b\bar{b}\gamma\gamma$

...proceeding in the same way for $b\bar{b}\gamma\gamma$: **Different region in param. space w.r.t. $b\bar{b}b\bar{b}$!**

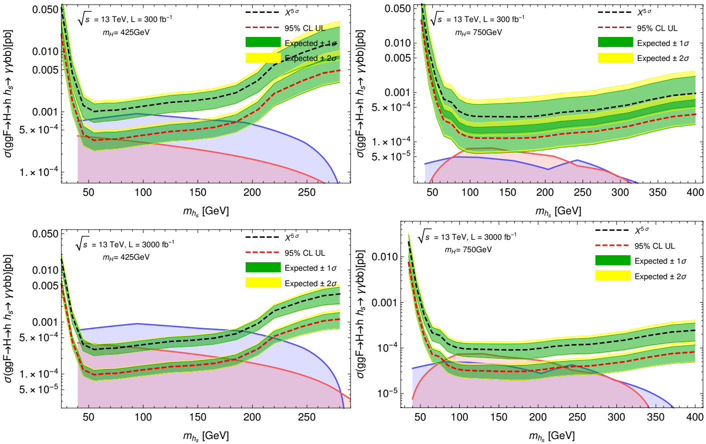
Upper left: $M_H = 425$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 300 fb^{-1}$

Upper right: $M_H = 750$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 300 fb^{-1}$

Lower left: $M_H = 425$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 3000 fb^{-1}$

Lower right: $M_H = 750$ GeV, 95% limits and $5\,\sigma$ discovery for $L = 3000 fb^{-1}$

Blue and red: NMSSM allowed region for $H \to hh_s \to \gamma\gamma b\bar{b}$ and $A \to ha_s \to \gamma\gamma b\bar{b}$.



Conclusions

- BSM Higgs bosons are poorly constrained by present searches $\Rightarrow$ Lot of room for new scalars, new searches are needed!
- Run I searches in the $ggF \to h_s \to \gamma\gamma$ channel are sensitive to a light h_s, motivated by naturalness.
- Searches for $H/A \to h + h_s/a_s$ can be sensitive to very singlet-like h_s/a_s! Excesses would discover simultaneously H/A and h_s/a_s!
- $H/A \to hh_s/a_s$ is a stronger search than the MSSM-like $H/A \to \tau\tau$ in the majority of the NMSSM parameter space.
- Regions featuring $m_{h_s} \lesssim m_h \Rightarrow BR(H \to hh_s) > 0$ will be largely covered for $m_H < 750$ GeV!
- $b\bar{b}\gamma\gamma$ and $b\bar{b}b\bar{b}$ test different regions of parameter space.
- These results could be easily reinterpreted in other models as $\phi_i \to h^{125}\phi_j$ (2HDM+S...).
- We encourage the experimental collaborations to carry out the $H \to hh_s$ search!

Thanks for your attention!

Conclusions

- BSM Higgs bosons are poorly constrained by present searches $\Rightarrow$ Lot of room for new scalars, new searches are needed!
- Run I searches in the $ggF \to h_s \to \gamma\gamma$ channel are sensitive to a light h_s, motivated by naturalness.
- Searches for $H/A \to h + h_s/a_s$ can be sensitive to very singlet-like h_s/a_s!
  Excesses would discover simultaneously H/A and h_s/a_s!
- $H/A \to hh_s/a_s$ is a stronger search than the MSSM-like $H/A \to \tau\tau$ in the majority of the NMSSM parameter space.
- Regions featuring $m_{h_s} \lesssim m_h \Rightarrow BR(H \to hh_s) > 0$ will be largely covered for $m_H < 750$ GeV!
- $b\bar{b}\gamma\gamma$ and $b\bar{b}b\bar{b}$ test different regions of parameter space.
- These results could be easily reinterpreted in other models as $\phi_i \to h^{125}\phi_j$ (2HDM+S...).
- We encourage the experimental collaborations to carry out the $H \to hh_s$ search!

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:

$$\mathcal{M}'^2_{S,11} = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \sin^2 \beta \Delta_{\text{rad}} \quad (3)$$

$$\mathcal{M}'^2_{S,12} = \frac{1}{2} \sin 2\beta \cos 2\beta \left(M_Z^2 - \lambda^2 M_Z^2\right) - \frac{\sin 2\beta}{2} \Delta_{\text{rad}}, \quad (4)$$

$$\mathcal{M}'^2_{S,13} = \lambda v \left(2\mu - \Lambda \sin 2\beta\right) \quad (5)$$

$$\mathcal{M}'^2_{S,22} = M_A^2 + \left(M_Z^2 - \lambda^2 v^2\right) \sin^2(2\beta) + \cos^2 \beta \Delta_{\text{rad}} \quad (6)$$

$$\mathcal{M}'^2_{S,23} = \lambda v \Lambda \cos 2\beta \quad (7)$$

$$\mathcal{M}'^2_{S,33} = \lambda^2 v^2 \sin 2\beta \left(\frac{M_A^2 \sin 2\beta}{4\mu^2} - \frac{\kappa}{2\lambda} \right) + \frac{\kappa \mu A_\kappa}{\lambda} + \frac{4\kappa^2 \mu^2}{\lambda^2} \quad (8)$$

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

Analysis: statistical treatment

Profile likelihood ratio

The corrected mass of the 4 jets m_X is the last discriminant. Although for the singlet Higgs candidate we cut in mass with $\chi^2_{hh_s}$, we make a shaped-based analysis in the final m_x histogram by means of a profile likelihood ratio as a test statistics for constructing the expected sensitivities [G.Cowan, K.Cranmer, E.Gross, O.Vitells arXiv:1007.1727]:

$$L(\mu) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j} e^{-(\mu s_j + b_j)}, \qquad \lambda(\mu) = \frac{L(\mu)}{L(0)}, \qquad q_\mu = -2 \ln \lambda(\mu) \tag{9}$$

(i.e. *we are asking: which signal μ would reject the background-only hypothesis at a given C.L.?*) Using asymptotic formulas, we can compute the significance for a signal μ:

$$Z_\mu = \sqrt{q_\mu}. \tag{10}$$

This shape-based analysis gives as a 20-30% better sensitivity than a cut-and-count analysis in this search.

The $b\bar{b}\gamma\gamma$ channel

...we repeat the procedure...

1. **Study of the background:** simulation (we consider the main sources: $b\bar{b}\gamma\gamma(+\text{ jet})$, $c\bar{c}\gamma\gamma(+\text{ jet})$), fitting. Validation is tricky due to low statistics in current data [CMS-PAS-HIG-16-032, ATLAS-CONF-2016-004]. **Good agreement between MC and DATA**
2. **Optimization** of the search (cuts, photon isolation, define m_X ...).
3. Statistical treatment of the (pseudo)data. We obtain the **expected discovery sensitivities**. Interpretation in the NMSSM

$\Rightarrow$ Results for $b\bar{b}\gamma\gamma$. $\gamma\gamma b\bar{b} \Rightarrow$ work in progress!.

CUTS:

$$\Delta R(b,\gamma) > 0.4, \qquad p_T(b) > 40 \text{ GeV}$$
$$E_T^{\gamma lead}/m^{\gamma\gamma} > 0.35, \qquad E_T^{\gamma sub}/m^{\gamma\gamma} > 0.25$$
$$p_T^{b\bar{b}} > 16.91 \text{ GeV} + 0.18 m_X, \qquad E_T(\gamma\gamma) > 68.32 \text{ GeV} + 0.25 m_X$$

$$100 \text{ GeV} \leq m_{b\bar{b}} \leq 150 \text{ GeV} \tag{11}$$
$$|m_{h_s} - m_{\gamma\gamma}| \leq 2\sigma_{m_{\gamma\gamma}} = 4.61 + 0.02 m_X \Rightarrow 95\% \text{ of signal events} \tag{12}$$

Signal generation (all channels)

Production through ggF

- Signal events for a heavy Higgs of $m_H = \{350...1000\}$ GeV, produced in ggF, have been simulated at NLO QCD using `aMCSusHi v2.3.3` (`MadGraph5_aMC@NLO v2.3.3` with amplitudes given by `SusHi`) [H.Mentler, M.Wiesemann arXiv:1504.06625].
- The decays $H \to hh_s$ and $hh_s \to b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ computed via `Pythia6`, together with the showering and hadronization of the decay products.
- For each simulation of H with a mass m_H, we generate different samples for m_{h_s} ranging from $\{25 \ldots (m_H - 125)\}$ GeV.
- 150k events have been simulated for each pair (m_H, m_{h_s}) (more than the HL-LHC!).