Searches for extra light and heavy Higgs bosons via cascade decays

Matías R. Vázquez
LPT d’Orsay, Univ. Paris Saclay
with Ulrich Ellwanger

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Why Higgs-to-Higgs decays are interesting?

- Extended Higgs sectors are a common framework in BSM (SUSY, 2HDM, cxSM...).
- Measure the parameters of the scalar potential: allow us to test how EWSB is realised.
- So far, searches for resonant double SM Higgs production $\Phi \rightarrow hh$ (with $m_h = 125$ GeV) have been done. However, decays involving more scalars can be more promising...
Trilinear couplings

Terms in the lagrangian responsible for Higgs-to-Higgs decays.

What do we expect?

- $\Phi hh$ with $\Phi$ a $SU(2)_L$ doublet. This trilinear coupling \textbf{is not gauge invariant} $\Rightarrow$ bounded by $M_Z$. Moreover, in the \textit{alignment limit} (i.e. $h$ has SM couplings), it is suppressed.
- However, $\Phi$ better be a doublet to have sizeable production through ggF or bbH (Excepting radions!).
- $\Phi hS$ with $S$ a SM singlet. This term is gauge invariant, hence not bounded $\Rightarrow$ \textbf{Potentially large coupling}!
- If singlets exist at all, Higgs cascades may be their only sizeable production mode.

Realistic scenarios where this process takes place?
This scenario can be realised in the NMSSM!

Higgs content of the NMSSM:

- Two SU(2) doublets $H_u$ (couples to up-type fermions) and $H_d$ (couples to down-type fermions) → like in the MSSM,
- A singlet $S$ whose vev generates a Dirac mass term for higgsinos (replaces the $\mu$ 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
The NMSSM: $H \rightarrow hh_s/A \rightarrow ha_s$

Recall:

- $H, A, H^\pm$ are MSSM like, nearly degenerate in mass, with $M_A > 350$ GeV (to avoid $BR(b \rightarrow s + \gamma)$ too large).

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

- The trilinear couplings $Hhh_s/Aha_s$ are proportional to a soft-SUSY breaking term, $A_\lambda$. It can be large in natural regions of the parameter space [M.Carena et al.; U.Ellwanger, MRV], whereas $Hhh \rightarrow 0$ as $h \rightarrow h^{SM}$. 

\[ H \xrightarrow{\lambda} h \xrightarrow{A} h_s \propto A_\lambda \sim 100\text{GeV} \ldots \mathcal{O}(\text{TeV}) \]
\(\sigma(ggF \to H \to hh_s)\) 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. Large signals are possible in \(ggF \to H \to hh_s\):

Are these cross sections visible at the LHC? Which channels should we look for?
Monte Carlo study

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

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.

\[ b\bar{b}bb \]
- Resolved topologies
- Large QCD multijet background (\( b\bar{b}bb, b\bar{b}cc, b\bar{b}jj \)), but large branching ratios.

\[ b\bar{b}\tau\tau (\tau\tau b\bar{b}) \]
- 3 subchannels: \( \tau_h\tau_h, \tau_h, e, \tau_h, \mu. \)
- Dominant background: \( t\bar{t} \) and, to a less extent, \( Z+\text{jets} \)

\[ b\bar{b}\gamma\gamma (\gamma\gamma b\bar{b}) \]
- Many different sources of background
- Cleaner than \( b\bar{b}bb \), but reduced cross sections.
- Low statistics.

**Goal:** optimize search strategies, obtain realistic expected sensitivities for the process \( ggF \to H/A \to h + h_s/a_s. \)
Validation of the MC

→ Background shapes from MC are in good agreement with data.
→ We rescaled the samples using data at $m_{h_s} = 125$ GeV, i.e. from double SM Higgs production [ATLAS-CONF-16-049, CMS-PAS-HIG-17-008, CMS-PAS-HIG-16-029].
→ The expected sensitivities from simulations reproduce well the ones from the experimental collaborations (data-driven).
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: NMSSM allowed region.
Results: Expected sensitivities $\bar{b}b\gamma\gamma$

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: NMSSM allowed region.

$\sqrt{s} = 13$ TeV, $L = 300 fb^{-1}$
$m_h = 425$ GeV

$\sqrt{s} = 13$ TeV, $L = 300 fb^{-1}$
$m_h = 750$ GeV

$\sqrt{s} = 13$ TeV, $L = 3000 fb^{-1}$
$m_h = 425$ GeV

$\sqrt{s} = 13$ TeV, $L = 3000 fb^{-1}$
$m_h = 750$ GeV
Conclusions

- Searches for $H/A \rightarrow h + h_s/a_s$ can be sensitive to very singlet-like $h_s/a_s$!
Excesses would discover simultaneously $H/A$ and $h_s/a_s$!
- ‘Pure’ singlets detectable although direct production cross section vanish.
- Regions featuring $m_{h_s} \lesssim m_h \Rightarrow BR(H \rightarrow hh_s) > 0$ will be largely covered for $m_H < 750$ GeV!
- Complementarity between $b\bar{b}\gamma\gamma$ and $b\bar{b}b\bar{b}$.
- These results could be easily reinterpreted in other models as $\Phi \rightarrow h^{125}h'$ ($2\text{HDM+S}$, $\text{C2HDM}$ ...).
- We encourage the experimental collaborations to carry out the $H/A \rightarrow h + h_s/a_s$ search!

Thanks for your attention!
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