Resonant Multi-Higgs Production

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Higgs Pairs Mini-Workshop, 30.09.21

Lund University

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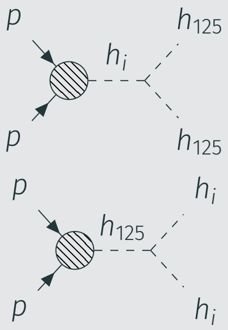
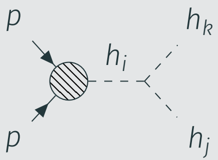
The Classics

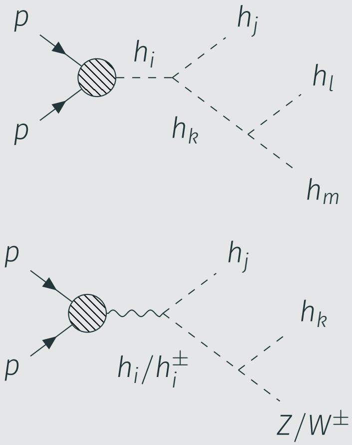


General Masses

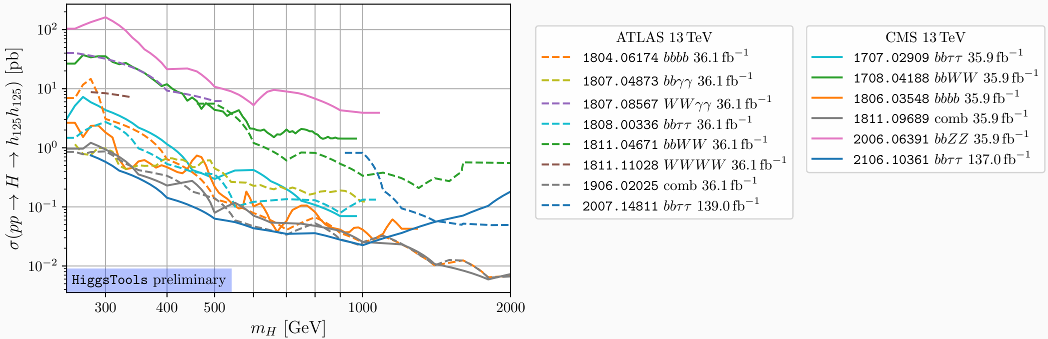


$h_{125} \in h_{i,j,k}$ or not.

Cascades

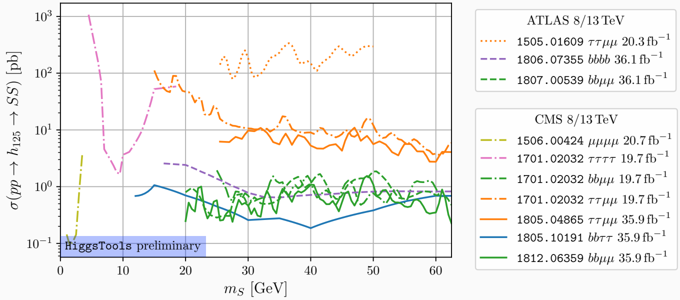


The Classics — Resonant h_{125}-Pair Production



- limits in may different final states constrain a wide variety of BSM models
- straightforward combinations since h_{125} is SM-like

The Classics — Decays of h_{125} into Higgs Pairs



Assumes SM-like BRs of S (e.g. in singlet extensions).
A similar alternative would be 2HDM A with $\tan\beta = 1$.

- good coverage of different final states
- h_{125} rate measurements often more constraining
- no generally applicable assumptions for S

Beyond the Classics — Finite Width Effects

When does $\sigma(gg \to h_i \to h_{125}h_{125})$ become large?

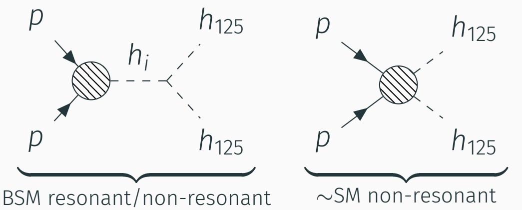
1. large $\sigma(gg \to h_i) \propto c^2(h_t t\bar{t}) \quad \Rightarrow \Gamma(h_i \to t\bar{t}) \propto c^2(h_i t\bar{t})$ is large
2. large $\mathrm{BR}(h_i \to h_{125}h_{125}) \quad \Rightarrow \Gamma(h_i \to h_{125}h_{125}) \propto c^2(h_i h_{125} h_{125}) \overset{!}{\gg} \Gamma(h_i \to t\bar{t})$

$\Rightarrow$ $\Gamma_{\mathrm{tot}}(h_i)$ typically large and possibly experimentally relevant

Width dependent limits, at least for $\Gamma_{\mathrm{tot}}(h_i)$ in $h_i \to h_{125}h_{125}$, would be important.

- Γ_{tot} of the decay products can be tiny as they don't need large SM-couplings.
- this assumes that interference effects remain negligible

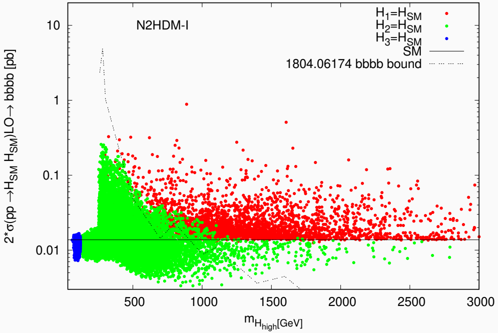
Beyond the Classics — Resonant and Non-Resonant Contributions



- all existing limits use purely (non-)resonant signal models
- often not a great approximation, interference possible [Basler et al. 1909.09987]

→ kinematics of the combined signal depend on model parameters (all masses and 3-Higgs couplings)

→ simply extending the signal model would introduce model-dependence



[Abouabid, Arhrib, Azevedo, Falaki, Ferreira, Mühlleitner, Santos preliminary]

- total cxn (non-resonant/resonant with interference) for h_{125} pair production
- all points comply with resonant limits in the individual channels

How to put limits on such scenarios?

→ Likelihood as a function of the sub-rates?

General Masses — Higgs-Pair Production in Non-Minimal Models

These *classic* cases cover:

- SM+singlet (*i.e.* RxSM),
- CP-conserving MSSM.

Even slightly larger models allow for more complex signatures:

- $pp \to h_i \to h_j h_j$ (2HDM)
- \+ $pp \to h_i \to h_j h_k$ with $h_{125} \in h_{i,j,k}$ (C2HDM, TRSM, CxSM, N2HDM)
- \+ $pp \to h_i \to h_j h_k$ (2HDMS, NMSSM, ...)

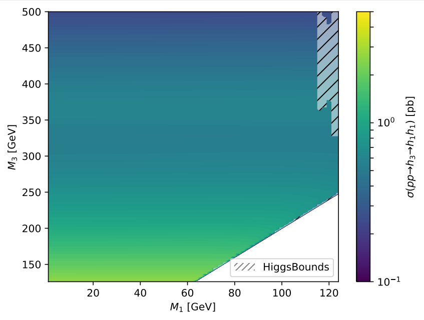
Goal: $pp \to h_i \to h_j h_k$ searches with all three masses varied.

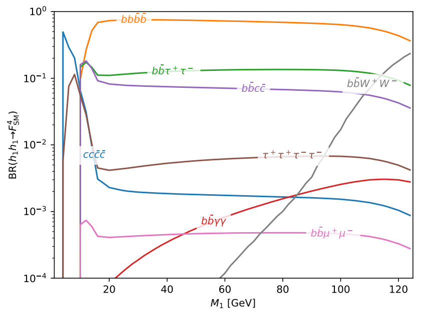
General Masses — $h_i \to h_j h_j$ in the TRSM

The TRSM extends the SM by two real singlets with softly broken Z_2 symmetries.

$\Rightarrow$ 3 CP-even scalars $h_{1,2,3}$ one of which is h_{125}. [Robens et al. 1908.08554]

BP5: $pp \to h_3 \to h_1 h_1$ with $h_{125} \equiv h_2$

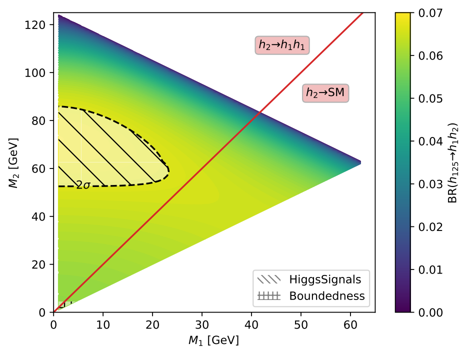




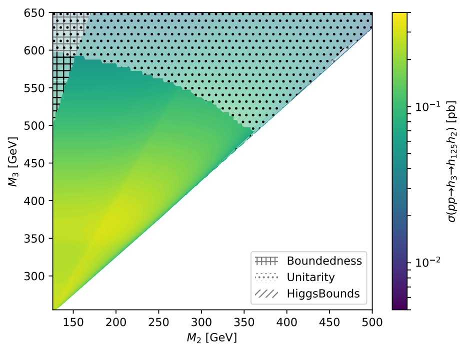
Similar benchmark planes for $h_2 \to h_1 h_1$ (BP4) and $h_3 \to h_2 h_2$ (BP6).

General Masses — $h_i \to h_j h_{125}$ in the TRSM

BP1: $pp \to h_{125} \to h_1 h_2$



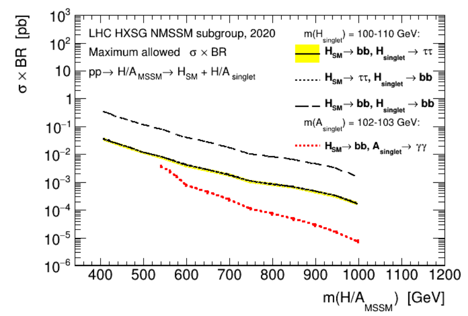
BP3: $pp \to h_3 \to h_{125} h_2$



The remaining $h_3 \to h_1 h_{125}$ case is covered by BP2. [Robens et al. 1908.08554]

General Masses — $h_i \to h_j h_{125}$ in the NMSSM

NMSSM: $pp \to H/A \to h_{125} H_S/A_S$



LHC Higgs WG NMSSM Benchmark

More benchmarks:

- NMSSM and 2HDMS [Baum and Shah `1904.10810`]
- NMSSM and C2HDM [Basler et al. `1812.03542`]

Different (spin-0) signal models only differ in their predicted cross section, as long as non-resonant contributions are truly negligible.

General Masses — Experimental Status of $h_i \to h_j h_k$

Experimental work on general di-Higgs signatures is slowly picking up.

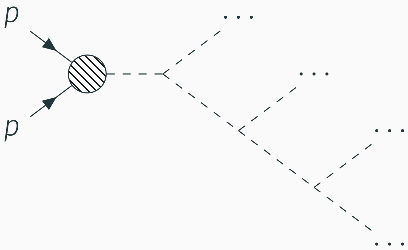
$h_i \to h_j h_j$

- LEP $bbbb$ and $\tau\tau\tau\tau$ [ALEPH, DELPHI, L3, OPAL, LEP Working Group for Higgs Boson Searches **hep-ex/0602042**]
- CMS 8 TeV $\mu\mu\mu\mu$ [CMS **1506.00424**]
- ATLAS 13 TeV $\gamma\gamma\gamma\gamma$ [ATLAS **1808.10515**]
- ATLAS 13 TeV $WWWW$ [ATLAS **1811.11028**]
- CMS 13 TeV $\mu\mu\tau\tau$ [CMS **2005.08694**]

$h_i \to h_j h_{125}$

- CMS 13 TeV $bb\tau\tau$ [CMS **2106.10361**]

Cascades — Higgs-to-Higgs Decay Chains

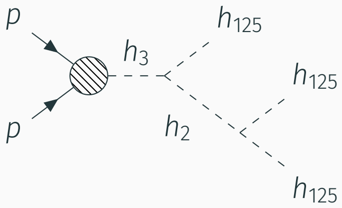


- n-Higgs cascade final state involves up to $2n-1$ distinct particles
  - 3-Higgs final state can already involve 5 distinct BSM particles
- number of chained decays is limited by CM energy and the mass differences in the spectrum:

$$m_{h_{i+1}} = 2m_{h_i} \quad \Rightarrow \quad pp \to h_{2\,\mathrm{TeV}} \to \ldots \to 16h_{125}$$

Cascades — $pp \to h_3 \to h_1 h_2 \to h_1 h_1 h_1$

Start with the simplest case:

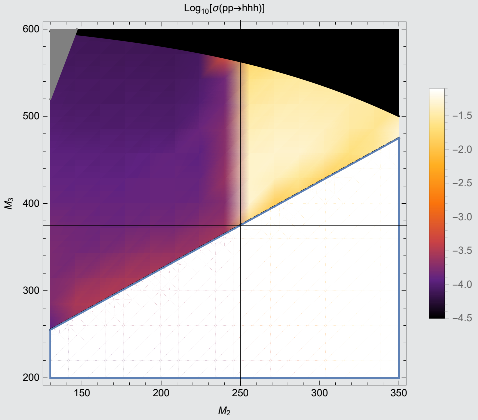


- SM non-resonant cxn is negligible at the LHC

$\to$ up to 50 fb (full cxn)

- also in the N2HDM/C2HDM

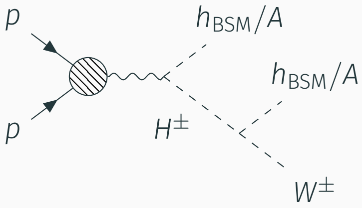
TRSM: BP3



[Papaefstathiou et al. `2101.00037`]

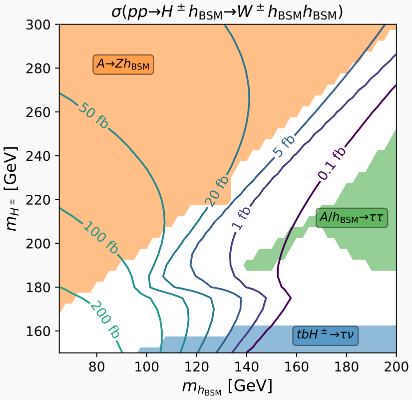
Alignment in the CP-conserving 2HDM:

$$c^2(h_{125}VV) \to 1 \Rightarrow \begin{cases} c^2(h_{\rm BSM}VV) \to 0 \\ g^2(H^\pm W^\mp h_{125}) \to 0 \\ g^2(H^\pm W^\mp h_{\rm BSM}) \to g^2(H^\pm W^\mp A) = \frac{g^2}{4} \end{cases}$$



- distinct kinematics, half-resonant
- very important $H^\pm$ search channel
- negligible $pp \to Wh_{\rm BSM}, h_{\rm BSM} \to AA$

[Bahl et al. 2103.07484]



[Bahl et al. 2103.07484]

Existing searches

- $A \to Zh_{\text{BSM}}$ [ATLAS 1804.01126, 1712.06518; CMS 1903.00941]
- $A/h_{\text{BSM}} \to \tau\tau$ [ATLAS 2002.12223]
- $tbH^{\pm} \to \tau\nu$ [ATLAS 1807.07915]

Model dependent complementarity to neutral Higgs searches.

$\text{BR}_{h_{\text{BSM}} \to bb} \gtrsim 80\%$ $\text{BR}_{h_{\text{BSM}} \to \tau\tau} \approx 8\%$

$\text{BR}_{h_{\text{BSM}} \to \gamma\gamma} \approx \mathcal{O}(0.1\%)$ $\text{BR}_{h_{\text{BSM}} \to c\bar{c}/gg} = \text{rest}$

Summary

- the classic channels $h_i \to h_{125}h_{125}$ and $h_{125} \to h_ih_i$ are being explored in many different final states and put stringent limit on BSM models
- s-channel Higgs typically has a large Γ_{tot} that may be experimentally relevant
- in many scenarios both resonant and non-resonant contributions to $h_{125}h_{125}$ production are relevant, potentially with interference
  - $\to$ challenging to probe experimentally in a model-independent fashion
- the next step is dropping the h_{125} assumptions and going to $h_i \to h_jh_k$
  - ready to use benchmark scenarios in many different BSM models
  - experimental investigations are starting, for now only with 2 masses varied
- Higgs-to-Higgs cascades can lead to hhh or hhV signatures with large cxns