

Di-Higgs production in BSM models

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I give a short overview on di-Higgs production in models that extend the Standard Model of particle physics by additional fields and particle content, including EFT prescriptions.

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1. Introduction

After the discovery of a scalar boson that complies with the properties of the Standard Model (SM) Higgs boson [1, 2], particle physics has entered an exciting era. The confirmation that the scalar sector realized by nature indeed corresponds to the one predicted by the SM also requires an accurate knowledge of triple and quartic scalar couplings. Projections for the accuracy with which these couplings can be determined at future colliders are currently in the % range, from roughly 50% accuracy at the HL-LHC up to projected 2 – 3% at future high-energy lepton colliders (see e.g. [3–6]).

In this context, it is also interesting to investigate the modification of $h_{125}h_{125}$ rates by the presence of new states, either directly via a heavy resonance e.g. in the s-channel or via modified couplings in an effective field theory (EFT) approach, where the additional possible new heavy resonances have been integrated out. For reference, the current value for di-Higgs production in the SM at a 13 TeV LHC is given by 31.05 fb (see [7, 8] for details and uncertainties).

2. Resonance-enhanced di-scalar production

A simple example is the enhancement of the di-Higgs final state by mediation of an s-channel resonance, where the resonance corresponds to a second CP-even neutral scalar that mixes with the 125 GeV particle. Imposing an additional symmetry on this model, the number of additional free parameters can be constrained to 3, which are typically chosen to be the second scalar mass m_2 , a mixing angle $\sin \alpha$, and the ratio of the vacuum expectation values $\tan \beta$. This model has e.g. been discussed at length in [9–12]. In figure 1, I show the resonance enhanced rates for di-Higgs production in that model, taking current theoretical as well as experimental constraints into account. This figure includes the experimental constraints from ATLAS run I combination [13] as well as dedicated searches with full run II data [14–16]¹, and corresponds to an update of figure 1 in [12].

Apart from enhancement stemming from a relatively simple model, one can also consider di-Higgs rates that can be achieved in models with larger scalar sector extensions. Some examples in this direction have been presented in [17]. In figure 2, I show two examples for the N2HDM, a two Higgs doublet model with an additional singlet. In this model 3 CP-even neutral scalar states exist. One of these has to comply with the current measurements of the 125 GeV resonance at the LHC, while the others can take other mass values and couplings granted that all other theoretical and experimental constraints are fulfilled. We see that in this model, the di-Higgs rate can be enhanced by roughly an order of magnitude with respect to the current SM prediction of around 30 fb.

3. EFT approach

In effective field theory approaches, coupling modifiers are introduced that either multiply couplings already existing on the SM or introduce new coupling structures that do not exist in the SM. All corresponding production mechanisms can then contribute and also interfere. This leads to a very distinct behaviour in differential distributions, that depend on the specific values

¹I thank D. Azevedo for providing exclusion limits for $b\bar{b}\tau^+\tau^-$ [16] in a digitized format, as used in [17].

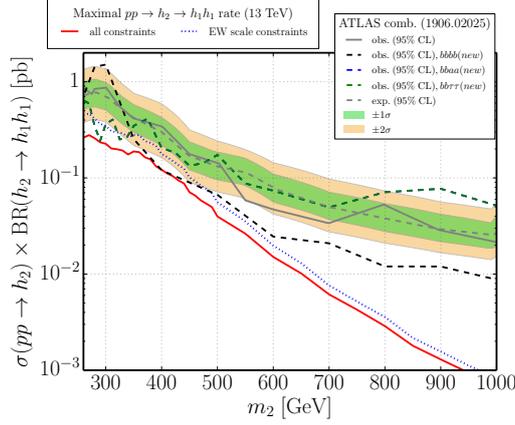


Figure 1: Possible maximal bounds as well as current constraints for resonance-enhanced di-Higgs production in the \mathbb{Z}_2 -symmetric singlet extension. Updated from [12]. Experimental constraints from [13–16].

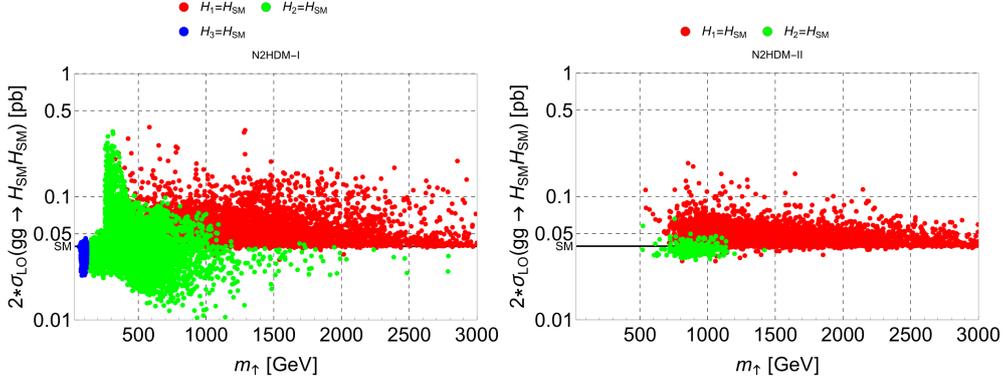


Figure 2: Rates for di-Higgs production in various scalar extended models. *Top:* Real 2HDM, *Bottom:* 2HDM+singlet. *Left:* Type I. *Right:* Type II. The model features 3 CP-even neutral scalars; rates are shown as a function of the heaviest additional scalar. Taken from [17].

of these coupling modifiers. A prominent approach is then to define clusters in the corresponding parameter space that display similar behaviour. I here show an example of such clusters taken from [18]². Leading and next-to-leading order (NLO) production cross sections at the LHC can reach the pb range and are given in [19, 20], respectively. In [21], an alternative set of clusters has been proposed based on NLO predictions.

4. Di-scalar states with masses $\neq 125$ GeV

I now present predictions for a model that features 3 CP-even neutral scalar states. The model extends the SM scalar sector by two real gauge singlet scalar fields and applies an additional $\mathbb{Z}_2 \otimes \mathbb{Z}'_2$ symmetry [22, 23]. Figure 4 shows benchmark planes in this model for decays with of either

²One of the clusters presented in [18] has been modified in [19], where in addition higher-order corrections have been taken into account. I thank G. Heinrich for useful conversation regarding this point.

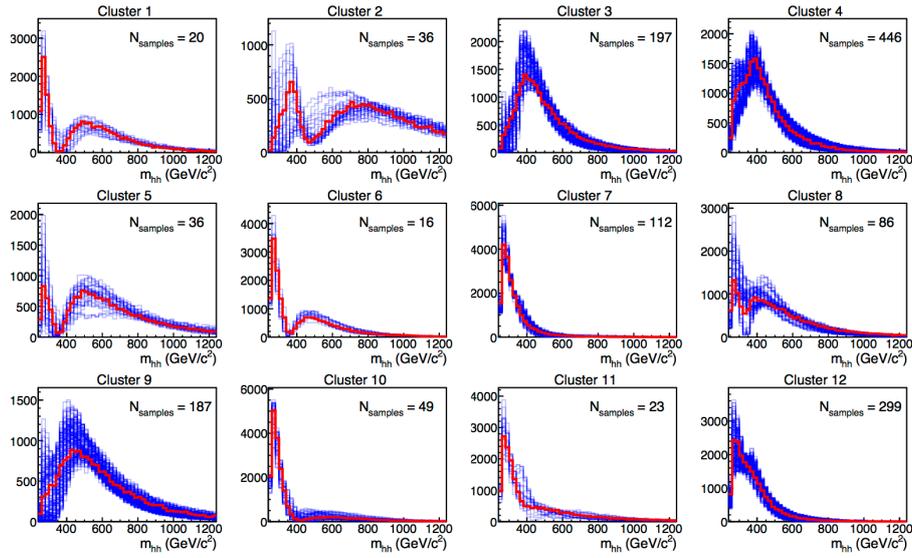


Figure 3: Di-Higgs invariant mass distributions for specific clusters characterizing typical modifications if coupling parameters are altered from their SM values. More details in and figure from [18].

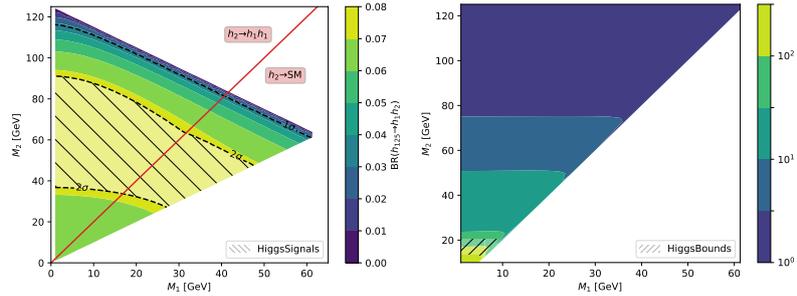


Figure 4: Benchmark plane examples for cases where one or two masses differ from h_{125} . *Left:* BP1, with $m_1, m_2 \leq 125$ GeV. Shown is the branching ratio $h_{125} \rightarrow h_1 h_2$. *Right:* BP4, with the same mass ranges. Shown is the factorized production time decay rate for $h_1 h_1$ final states via h_2 mediation. Taken from [22].

the SM like scalar decaying into two lighter states with different masses (BP1, *left*) or a light scalar decaying into two light scalars with the same mass (BP 4, *right*), with cross sections ranging around 3.5 pb and 60 pb at a 13 TeV LHC, respectively. In BP1, a $h_1 h_1 h_1$ final state is predominant if kinematically allowed. The light scalars decay mostly into $b\bar{b}$ in both scenarios, leading to $b\bar{b}b\bar{b}(b\bar{b})$ final states. Both scenarios are currently not yet explored by the LHC experiments.

5. Discussion and outlook

In this proceeding, I have discussed various new physics scenarios that allow to modify or enhance the SM prediction for di-Higgs final state rates. I have given a couple of examples, both for UV-complete models as well as in an EFT approach, and listed the corresponding references for further reading.

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