Resonant di-Higgs production as a probe of the NMSSM

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Motivation

- Higgs pair production is our most direct probe of Higgs self-interactions
- HL-LHC should be able to discover di-Higgs production, but with somewhat large error bars
- Several types BSM effects can enter, so the usual coupling modifier framework is insufficient
- In fact, a clear deviation from SM predictions will require rather light BSM particles, so that also an EFT approach might be limited to the lower end of the m_{hh} distribution

Together with Stefano Moretti, Luca Panizzi, Jörgen Sjölin we have been developing ideas on how to interpret deviations from the SM. These results have been published in [2302.03401] and [2506.09006].

Outline

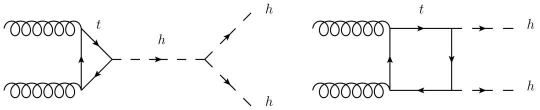
I'll breafly discuss some of the directions we are investigating

1. First a brief intro to di-Higgs in general
2. Deconstruction of BSM effects in terms of different diagrammatic contributions
3. Resonant di-Higgs — the significance of interferences and what they tell about the NMSSM?

Notice: We are working at one-loop (LO), we have not yet decided what to do for two-loop corrections (NLO). For SM diagrams differential K-factors available, but not for a generic BSM diagram. If you multiply everything with 1.8 you are reasonably close.

Higgs pair production in the SM

Higgs pair production is dominated by gluon fusion $gg \to hh$. In the SM the process arises (mainly) through two diagrams (triangle and box), which interfere destructively.



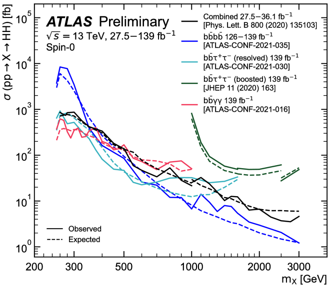
- The top box amplitude is larger, hence it is more difficult to exclude large upward deviations of λ_{hhh} (Run 2: $-1.5 < \lambda_{hhh}/\lambda_{hhh,SM} < 6.7$)
- The destructive interference makes this process a very difficult one to detect

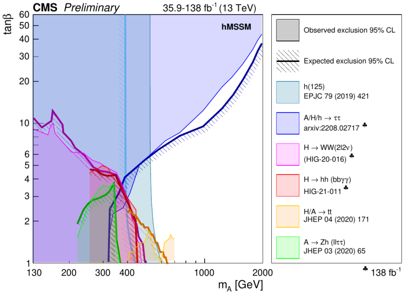
Higgs pair production beyond the SM

There can be deviations to Higgs pair production, if

1. the top Yukawa coupling deviates from its SM value
   - somewhat constrained by $t\bar{t}h$ production rate
   - enters quadratically to the amplitude, so small deviations can have a large impact
2. the trilinear Higgs self coupling deviated from its SM value
   - very mildly constrained by experiments
   - some models have intrinsic constraints that allow only small deviations, some others are more flexible
3. there are light BSM particles coupling strongly to gluons/tops and Higgs bosons
   - top partners (stops in SUSY, fermionic partners in composite models) in non-resonant production, new neutral scalars in resonant production

Experimental landscape





- Sensitivity driven by three channels $bb\gamma\gamma$ at low m_{hh}, $bb\tau\tau$ at intermediate m_{hh} and $bbbb$ at high m_{hh}
- For type-II 2HDM heavy Higgses excluded especially at high $\tan\beta$, mostly singlet Higgses can evade the limits

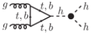
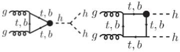
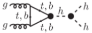
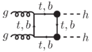
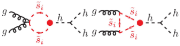
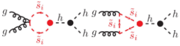
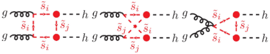
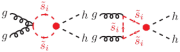
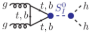
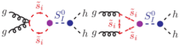
Model setup

Currently we have a SUSY-inspired model setup, in addition to the SM particle content we have

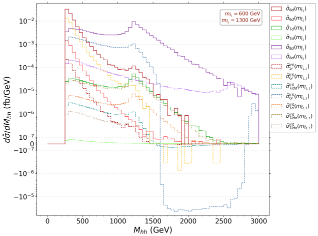
- additive coupling modifiers for the top Yukawa and the triple Higgs coupling
- up to four colored scalars in the fundamental representation (stops, sbottoms — but need not to have SUSY couplings)
- up to two additional CP-even scalars (heavy Higgses) for resonant di-Higgs (UFO model in Github)

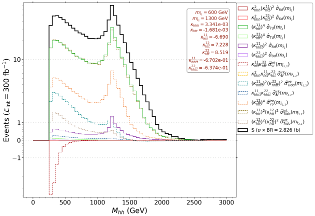
We use a private modification of SPheno to calculate the couplings and the spectra. Models for fermionic top partners not validated yet.

Classification of topologies by coupling structure

	Topology type	Feynman diagrams	Amplitude
1	Modified hhh coupling		$\mathcal{A}_i \propto \kappa_{hhh}$
2	One modified hff coupling		$\mathcal{A}_i \propto \kappa_{hff}$
3	Modified hhh coupling and modified hff coupling		$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{hff}$
4	Two modified hff couplings		$\mathcal{A}_i \propto \kappa_{hff}^2$
5	Scalar bubble and triangle with $h\tilde{s}\tilde{s}$ couplings		$\mathcal{A}_i \propto \kappa^{ii}_{h\tilde{s}\tilde{s}}$
6	Modified hhh coupling + Scalar bubble and triangle with $h\tilde{s}\tilde{s}$ coupling		$\mathcal{A}_i \propto \kappa_{hhh}\kappa^{ii}_{h\tilde{s}\tilde{s}}$
7	Scalar triangle and box with two $h\tilde{s}\tilde{s}$ couplings		$\mathcal{A}_i \propto \lvert\kappa^{ij}_{h\tilde{s}\tilde{s}}\rvert^2$
8	Scalar bubble and triangle with $hh\tilde{s}\tilde{s}$ coupling		$\mathcal{A}_i \propto \kappa^{ii}_{hh\tilde{s}\tilde{s}}$
9	Neutral scalar		$\mathcal{A}_i \propto \kappa^{I}_{Shh}\kappa^{I}_{Sff}$
10	Neutral scalar + coloured scalar		$\mathcal{A}_i \propto \kappa^{I}_{Shh}\kappa^{Ii}_{S\tilde{s}\tilde{s}}$

We speed up differential simulations by reweighting

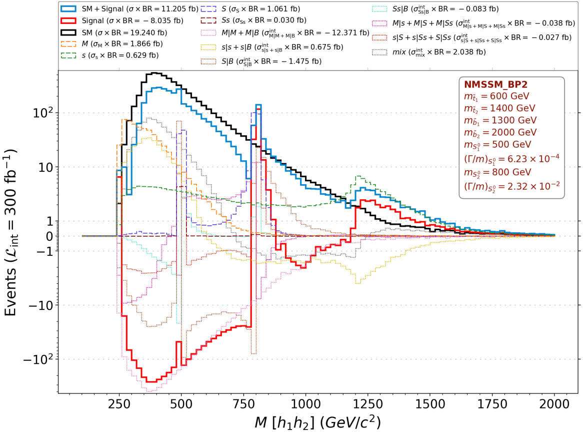




- The amplitude from a diagram depends on couplings, masses and Higgs decay widths
- We factorise out the coupling dependence and simulate the cross section per each coupling combination on a grid of mass values
- We can then quickly calculate the full cross section by weighting the results with the corresponding coupling values
- Contributions from individual diagrams and their intereferences can be easily extracted

Our approach allows to see individual contributions clearly

One of our benchmark points with various effects and interferences



Limitation: You can only have masses on the pre-simulated grid or need to simulate new samples

Triple Higgs couplings

In the alignment limit of the NMSSM the triple Higgs couplings needed for di-Higgs production are

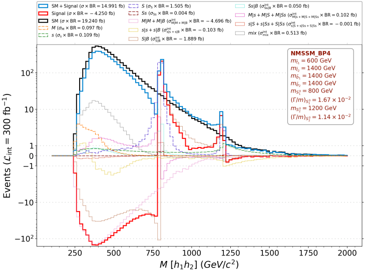
$$\begin{aligned}\lambda_{hhh} &= \left(\frac{g^2+g'^2\cos^2 2\beta}{8}+\frac{\lambda^2\sin^2 2\beta}{4}+4\delta\sin^4\beta\right)v\\ \lambda_{Hhh} &= \left(\frac{3(g^2+2\lambda^2)}{16}\sin 4\beta+12\delta\sin^3\beta\cos\beta\right)v\end{aligned}$$

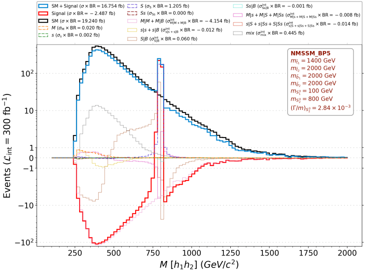
Here δ represents leading one-loop corrections to the Higgs potential.

- λ_{hhh} always positive but λ_{Hhh} can be positive or negative depending on $\tan\beta$ and the relative sizes of λ and δ
- λ_{Hhh} tends towards zero at large $\tan\beta$
- λ_{Hhh} negative if λ is large and $\tan\beta \sim 2\ldots 3 \Rightarrow$ the conditions for tree-level enhancement of Higgs mass in the NMSSM

Interference effects lead to large peaks and dips

The interference of the resonant part with the non-resonant continuum creates a peak-dip structure as the propagator changes sign:

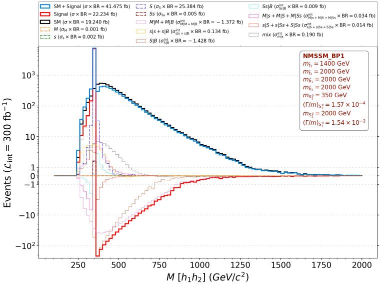


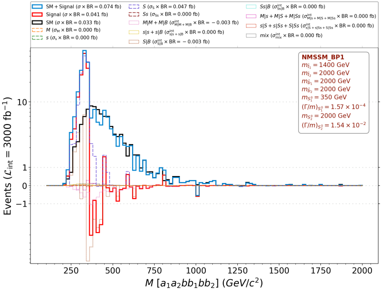


- on left a 800 GeV doublet Higgs and a 1200 GeV singlet, large λ
- on right a 800 GeV doublet Higgs (and a 100 GeV singlet), small λ
- notice the difference in interference patterns between the 800 GeV Higgses, dip before the peak if Higgs mass from tree-level, after if from top-stop loops

At decay level the features become somewhat smeared

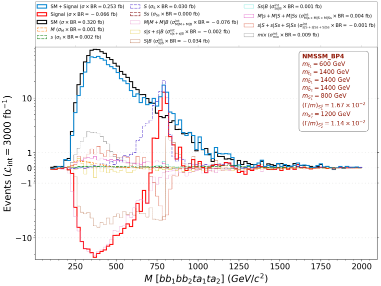
An example of a singlet Higgs at 350 GeV:

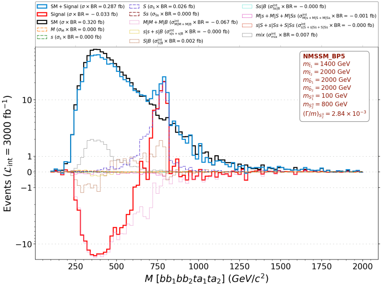




- peak very sharp at parton level, lot wider even in the $bb\gamma\gamma$ channel
- interference pattern hard to see experimentally, even though the dip above 350 GeV at parton level is $\sim 30\%$

It is easier to see, on which side the excess is





- here again the two benchmarks with 800 GeV Higgses, now in the $bb\tau\tau$ channel
- peak gets smeared out, but does not look like a Breit-Wigner distribution
- destructive interference gets washed out almost completely, constructive one survives better

Summary

- We have developed a framework, where one may compute differential distributions efficiently by reweighting the individual contributions
- This approach allows one to analyse processes at given benchmark points and to understand, which processess contribute to a given feature
- Interference effects in di-Higgs can be large in SUSY models and cannot be neglected
- The interference pattern in NMSSM tells us where the Higgs mass comes from — tree-level contributions or top-stop loops

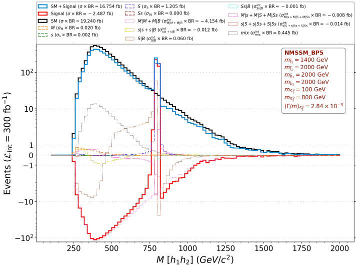
Future work:

- using the deconstructed data sets to extract couplings from (simulated) data and mapping it onto parameters of a fundamental theory
- investigating if one can interpolate between grid points somehow
- introduce fermionic particles in the loop, NLO corrections. . .

Details on the deconstruction

- In the UFO model each BSM coupling has its own coupling order, dimensionful couplings are divided by v to make them dimensionless
- For a given set of masses and Γ_H/m_H events are simulated in MadGraph5 setting all couplings to 0.01, simulations are run for all combinations of UFO coupling orders that exist in the differential cross sections
- For a given point this leads to $\sim$ 700 different unweighted contributions, which are then reweighted with the couplings fed into the code
- A script does the reweighting and then plots distributions (distributions are obtained from real events, one could make this faster by just stroring distributions, but one would be constrained to one binning choice)
- Some SPheno code examples can be obtained from the authors

Impact of a 95 GeV Higgs?



- one of the benchmarks contains a 100 GeV singlet Higgs and the intention was to see, what the impact would be
- no fit to the excesses was made, but the typical effects are not too dependent on the details
- the largest effect is the reduced top Yukawa, which reduces the overall cross section (mimics $\kappa_\lambda > 1$)
- the interference between the singlet diagram and the continuum is destructive, this is subleading and most visible at the lowest values of m_{hh}