Mapping simplified models onto fundamental theories

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Introduction

Higgs pair production is an indirect tool for BSM searches:

- new physics can alter the trilinear Higgs coupling
- there could be new colored particles in the loop
- also the Higgs-top coupling could be altered, but this is constrained by the measured $ht\bar{t}$ production rate

If we see some deviation from the SM prediction, what can we learn from it? How can the created toolbox help in this?

This talk is based on ongoing work with Stefano Moretti, Luca Panizzi and Jörgen Sjölin. Some background can be found in [2302.03401].

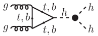
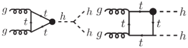
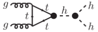
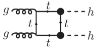
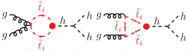
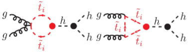
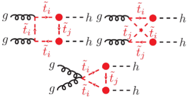
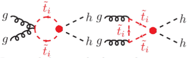
Assumptions for interpretation

- It seems unlikely that new colored particles would appear first as threshold effects in di-Higgs production
- We probably know that there is a new particle and have a reasonable idea of its mass
- We even might have an idea of the overall framework — supersymmetry, composite Higgs, extra dimensions
- The general idea is model-independent, but the detailed fit is model-dependent
- The concrete example is from supersymmetry, but a similar line of arguments holds for other scenarios as well

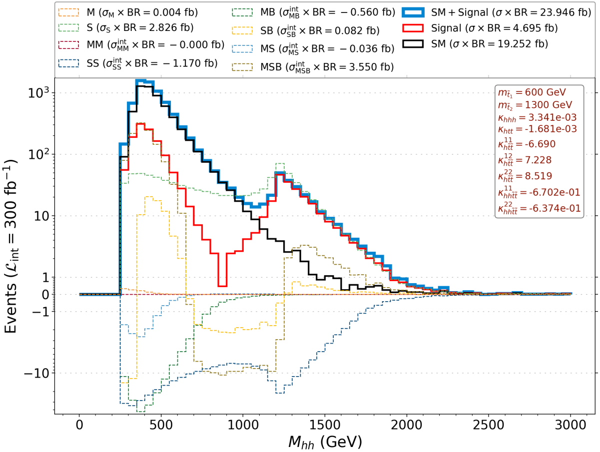
The distribution can be split into a coupling-dependent and coupling-independent part

- We write the top Yukawa coupling and the Higgs trilinear coupling with additive modifiers, $y_t = y_t^{SM} + \delta(y_t)$, $\lambda_{hhh} = \lambda_{hhh}^{SM} + \delta(\lambda_{hhh})$
- This allows us to write the amplitudes as a sum of the SM contribution and BSM modifications
- Hence for each class of diagrams, one gets a spesific coupling structure (that is model-dependent) and a kinematical part, which depends only on particle spins and masses (and we assume that at least one new colored particle mass is known)
- Once masses are known, all Passarino-Veltman integrals are calculable
- Then the full differential cross section can be computed by weighting the individual parts with the couplings

Diagrams can be classified according to their coupling structure

	Topology type	Feynman diagrams	Amplitude
1	**Modified Higgs trilinear coupling**		$\mathcal{A}_i \propto \kappa_{hhh}$
2	**One modified Yukawa coupling**		$\mathcal{A}_i \propto \kappa_{htt}$
3	**Modified Higgs trilinear coupling and modified Yukawa coupling**		$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{htt}$
4	**Two modified Yukawa couplings**		$\mathcal{A}_i \propto \kappa^2_{htt}$
5	**Bubble and triangle with $h\tilde{t}\tilde{t}$ couplings**		$\mathcal{A}_i \propto \kappa^{ii}_{h\tilde{t}\tilde{t}}$
	This class of topologies involves only diagonal couplings between the Higgs and the squarks, due to the absence of FCNCs in strong interactions and the presence of one $h\tilde{t}\tilde{t}$ coupling.		
6	**Modified Higgs trilinear coupling + Bubble and triangle with $h\tilde{t}\tilde{t}$ coupling**		$\mathcal{A}_i \propto \kappa_{hhh}\kappa^{ii}_{h\tilde{t}\tilde{t}}$
	Only diagonal couplings between the Higgs and the squarks due to the strong interaction.		
7	**Triangle and box with two $h\tilde{t}\tilde{t}$ couplings**		$\mathcal{A}_i \propto \lvert\kappa^{ij}_{h\tilde{t}\tilde{t}}\rvert^2$
8	**Bubble and triangle with $hh\tilde{t}\tilde{t}$ coupling**		$\mathcal{A}_i \propto \kappa^{ii}_{hh\tilde{t}\tilde{t}}$
	Only diagonal couplings between the Higgs and the squarks due to the strong interaction.		

Once masses are fixed, you get a set of contributions



- If couplings are known, the total distribution can be given in terms of individual contributions
- On the other hand, each distribution has an individual shape, so one could try to do a fit of couplings to data

The diagrammatic approach allows one to estimate the couplings

Now let's suppose we start getting data and eventually a distribution of di-Higgs events.

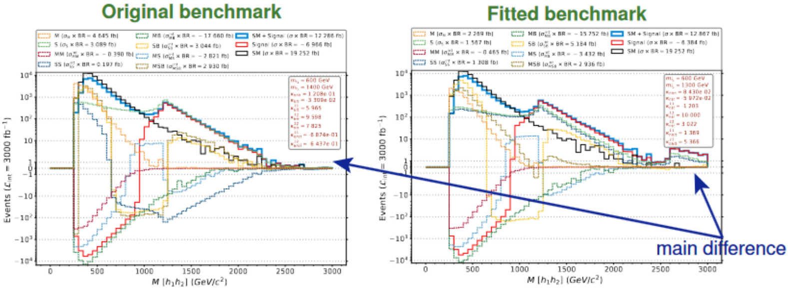
- One can look for an optimal combination of couplings by *e.g.* scanning over the parameter space in some reasonable range and comparing event rates bin-by-bin
- We did an exercise, where we made a distribution to one of us, who tried to infer the parameters
- In the SUSY case there was one degeneracy, which was due to $h\tilde{t}_i\tilde{t}_i$ $(i = 1, 2)$ being strongly correlated
- Once this piece of information was added in, the fit was reasonable — but so far only at the partonic level
- The inferred couplings were good, if they had a large impact on the distribution, but quartic Higgs-stop interactions cannot be inferred for SUSY, compositeness might have a better chance (=larger couplings)

Remarks and caveats

- While often the process converges to a good solution, it is not guaranteed that there would not be any other coupling combination, which would give an almost equally good fit
- In principle the fit has been tested on a M_{hh} spectrum throughout the range, in practice one needs to build this up from several experimental channels, some having significant backgrounds
- Reconstruction level was also tested without backgrounds, not completely bad, but of course larger uncertainties
- We tried this in the (N)MSSM with two squarks, the distributions are not particularly sensitive for the heavy squark mass, it can be off by 200–300 GeV and yet the fit of the lightest squark parameters gives reasonable results

Very different coupling sets can lead to similar distributions

Word of caution...



We made an error in submitting the parameters, hence point not a physical MSSM point — yet fit gives a reasonable resemblance, though decomposition is completely different

Summary

- The diagrammatic decomposition separates the dependence of couplings and masses
- Once masses are known, one can fit couplings from data
- Partonic fits have so far been reasonably good, but in real life one needs to reconstruct the data from several final states with different levels of background
- In such a large parameter space there is no guarantee that there would not be (nearly) degenerate solutions, which correspond to largely different coupling values