Anatomy of di-Higgs production with light stops

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Fysikdagarna, Stockholm 15.6.2023

Outline

What?

- Light stop effects on Higgs pair production
- Toolbox to construct differential distributions and analyse their origin without full simulation

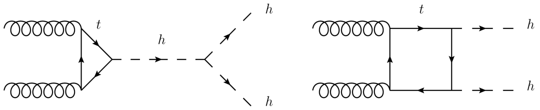
Why?

- Higgs pair production determines the shape of the Higgs potential $\Rightarrow$ nature of EW phase transition
- One-loop process, BSM effects enter at the same perturbative order
- Toolbox allows one to compare theory and experiment and understand the origins of deviations

This talk is based on 2302.03401 (PRD107, 115010) together with Stefano Moretti, Luca Panizzi and Jörgen Sjölin. We shall assume that we are in the alignment limit, meaning that the SM-like Higgs couplings to fermions are very near the SM values.

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: $-0.4 < \lambda_{hhh}/\lambda_{hhh,SM} < 6.3$)
- The destructive interference makes this process a very difficult one to detect, HL-LHC should eventually be able to discover it
- BSM effects can enter at the same perturbative order as the SM, but obviously not easy to distinguish between SM and BSM even with full HL-LHC data

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 of the leading diagram, 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 and Higgs bosons
   - our example today are stops in supersymmetric models, but other top partners can lead to similar effects

In the the MSSM self-coupling is SM-like

- At tree-level the MSSM Higgs self-coupling is a combination of gauge couplings and is always too small to give a 125 GeV Higgs
- Hence positive loop corrections are necessary and the most economical way is to use the largest coupling available, the top Yukawa
- To maximise the Higgs mass one needs to make sure that the SM-like state is mostly H_u^0, that the cancellation between top and stop loops is incomplete and to find the part of parameter space that maximizes the effect of loops
- This leads to a large value of $\tan\beta$, large stop masses and large stop mixing, respectively, the well-known recipe for a 125 GeV Higgs
- In this limit the only relevant term for Higgs mass generation is $\lambda_{eff}|H_u^0|^4$, like in the SM and hence $\lambda_{eff} \simeq \lambda_{SM}$ [Osland, Pandita, hep-ph/9806351, Djouadi et al. hep-ph/9903229, Hollik, Penaranda hep-ph/0108245...]

In the NMSSM the Higgs self-coupling can deviate

- In the NMSSM one adds a singlet chiral superfield to the model and a term $\lambda S H_u H_d$ to the superpotential, λ can be up to $\mathcal{O}(1)$
- Since this can be large coupling, it can be used to lift the Higgs mass via the scalar potential term $|\lambda|^2|H_u H_d|^2$, but it only can have an effect at low values of $\tan\beta$
- The impact of this term to the Higgs mass and self-coupling is misaligned, so it can cause a deviation from the SM value in the self-coupling
- If $\lambda > g, g'$ and $1 \lesssim \tan\beta \lesssim 3$, the Higgs self-coupling is larger than in the SM
- If $\lambda < g, g'$ and $\tan\beta$ is low, you can achieve a 125 GeV Higgs if the stops are heavy and you have a light ($\sim$ 100 GeV) singlet-like Higgs — in such a case you could have a Higgs self-coupling smaller than in the SM

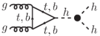
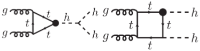
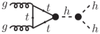
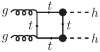
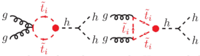
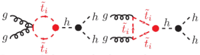
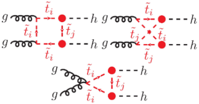
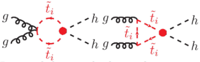
Stop masses in the MSSM

The stop mass matrix is

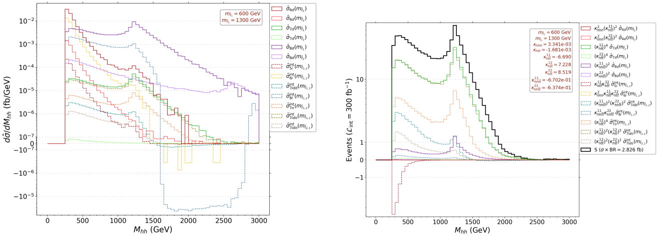
$$m_{\tilde{t}}^2 = \begin{pmatrix} m_t^2 + m_{\tilde{t}_L}^2 + m_Z^2 \cos 2\beta(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) & m_t(\mu\cot\beta - A_t) \\ m_t(\mu\cot\beta - A_t) & m_t^2 + m_{\tilde{t}_R}^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2\theta_W \end{pmatrix}$$

- Here A_t is the SUSY breaking trilinear coupling between H_u, $\tilde{t}_L$ and $\tilde{t}_R$, $m_{\tilde{t}_{L,R}}$ are the soft SUSY breaking masses
- In general one needs large values of A_t, typically somewhere between 2–3 TeV, to reach a 125 GeV Higgs
- This leads to a large mixing between the stops and a large mass splitting between them ($>$ 200 GeV) — experimentally $m(\tilde{t}_1) \geq 600$ GeV (requires compressed spectrum), $m(\tilde{t}_2) \geq 1250$ GeV
- Large stop mixing and large trilinear couplings mean large Higgs-stop-stop interactions, so stop diagrams including these couplings will have a large impact

Classification of topologies by 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**		$\mathcal{A}_i \propto \kappa_{htt}^2$
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.		

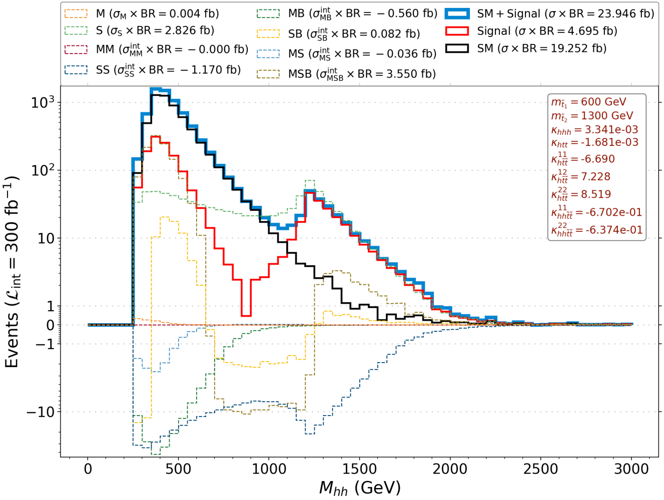
We speed up differential simulations by recycling amplitudes



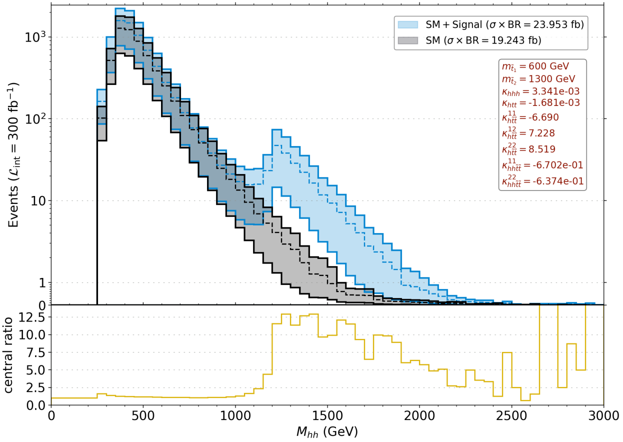
- The amplitude from a diagram depends on couplings and masses
- We factorise out the coupling dependence and simulate the individual amplitudes (their squares and interferences) on a grid of mass values
- We can then quickly calculate the full cross section by weighting the distributions with the corresponding coupling values

Our approach allows to see individual contributions clearly

We took a MSSM benchmark point that gives a large cross section

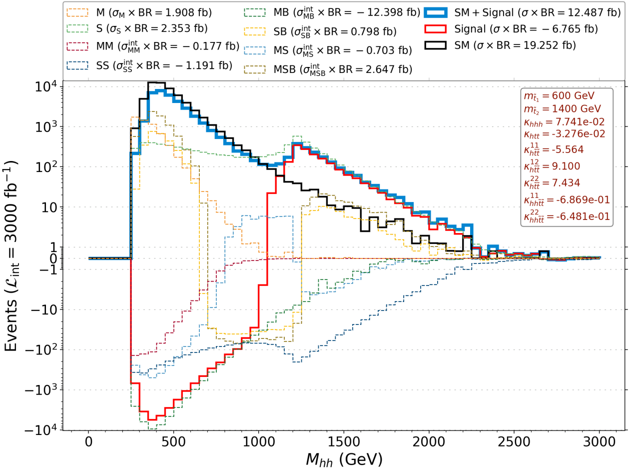


The excess is clearly larger than PDF and scale uncertainties



Note: We used LO PDFs, obviously with a NLO implementation and NLO PDFs these uncertainties will be smaller.

NMSSM can give features at low and high masses



Experimental prospects

- Experimentally the most sensitive channels are $b\bar{b}\gamma\gamma$ at low M_{hh}, $b\bar{b}\tau^+\tau^-$ at intermediate M_{hh} and $b\bar{b}b\bar{b}$ at high M_{hh} (SU/UU involved)
- For $b\bar{b}\gamma\gamma$ there are two main effects: modification of SM couplings (+intereference with SM) and interference of squark contributions with SM
- For $b\bar{b}\tau^+\tau^-$ the sensitivity to BSM is limited as interference effects cancel largely in the best M_{hh} region
- $b\bar{b}b\bar{b}$ has the best sensitivity to squark effects, though backgrounds are larger than in the two other channels
- A coupling modifier approach is not sufficient to capture all physics effects even below the squark threshold, a full EFT approach is needed (see Christina Dimitriadi's talk)

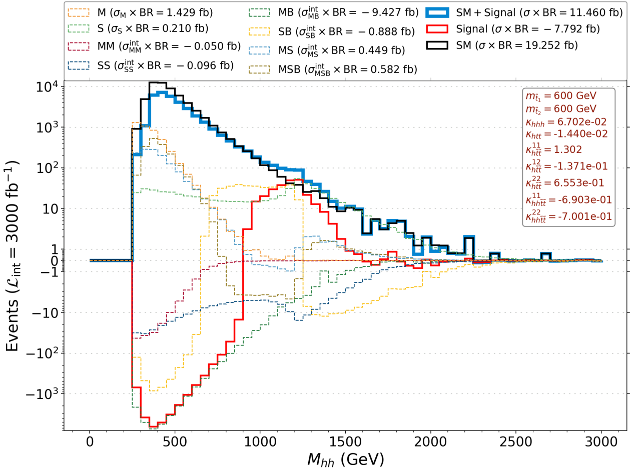
Summary

- 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
- Light stops can produce significant deviations at high invariant masses and moderate ones at low invariant masses
- A coupling modifier framework can be insufficient if light BSM particles are present even below their mass scale
- UFO model available at https://hepmdb.soton.ac.uk/hepmdb:0223.0337, instructions in the appendix of our paper

Future prospects

- revert the problem: From experimental distribution to model parameters
- add further models (more than one scalar, other spins/SU(3) representations)
- incorporate NLO corrections
- publish the library for public use

NMSSM with two light stops has no clear excess



- clear deficit at low M_{hh} due to modified couplings
- no excess at $2m_{\tilde{t}}$ due to small trilinear couplings

Mass dependence of squark excess