Di-HPNP - Deconstructing squark contributions to di-Higgs production at the LHC

Stefano Moretti

Soton & Uppsala

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UPPSALA UNIVERSITET

Outline

What?

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

Why?

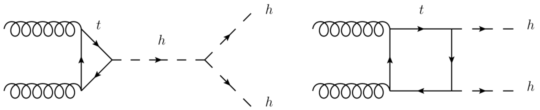
- Higgs pair production determines shape of the Higgs potential $\Rightarrow$ nature of EWSB, EW phase transition, etc.
- One-loop process, BSM effects enter at the same perturbative order
- Toolbox allows one to compare theory and experiment and also extract model parameters (by Panizzi & Waltari)

We shall assume alignment limit (without decoupling), meaning that the SM-like Higgs couplings to fermions are very near the SM values

Based on 2302.03401 (now in PRD) with Panizzi, Sjoelin & Waltari.

Higgs pair production in the SM

Higgs pair production dominated by gluon fusion $gg \to hh$: SM process arises through two topologies (triangle and box of top quarks), which interfere destructively



- Top box amplitude is largest in SM, hence difficult to exclude large upward deviations of λ_{hhh} (Run 2: $-1.5 < \lambda_{hhh}/\lambda_{hhh,SM} < 6.7$)
- Destructive interference makes it very difficult to detect also at Run 3, HL-LHC should eventually discover it
- BSM effects hence more visible, how to extract these?

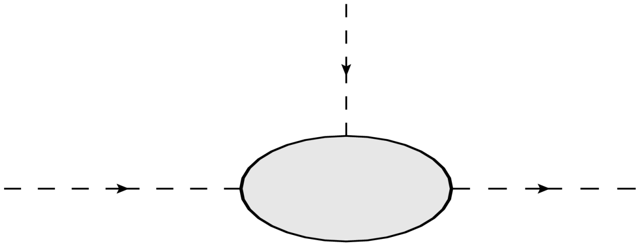
=> *Consider here non-resonant di-Higgs production (resonant production to come)*

Higgs pair production beyond the SM

There can be BSM effects onto Higgs pair production, if

1. top Yukawa coupling deviates from its SM value
   - somewhat constrained by $tt\bar{h}$ production rate
   - enters quadratically to the amplitude, so small deviations can have a large impact
2. trilinear Higgs self coupling deviates from SM value
   - very mildly constrained by experiments
   - some models have intrinsic constraints that allow only small deviations, some others are more flexible
3. new light BSM particles coupling strongly to gluons and Higgs bosons
   - here stops from supersymmetric models, but other top partners can lead to similar effects (see De Curtis' talk)

Higgs self-coupling is related to mass



- Higgs self-couplings are related to its mass as above diagrams are corrections to the mass (at zero incoming momentum) if the additional legs are replaced with the VEV
- Lot of the possibilities to deviate from the SM self-coupling are related to how Higgs mass is generated
- You need misalignment between mass and self-coupling

In the the MSSM self-coupling is SM-like

- At tree-level MSSM Higgs self-coupling is combination of gauge couplings and is always too small to give a 125 GeV Higgs
- Hence positive loop corrections are necessary and most economical way is to use largest coupling available, the top Yukawa
- To maximise Higgs mass one needs to make sure that the SM-like Higgs state is mostly H_u^0 so that the cancellation between top and stop loops is incomplete and to find part of parameter space that maximises the effect of loops
- This leads to a large *tan* β, large stop masses and large stop mixing, respectively, the well-known recipe for a 125 GeV Higgs
- In this limit, 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 *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 small, you can achieve a 125 GeV Higgs if the stops are heavy and you have a light (∼100 GeV) singlet-like Higgs— in such a case one could have a Higgs self-coupling smaller than in the SM

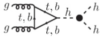
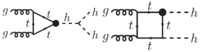
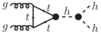
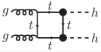
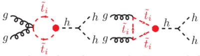
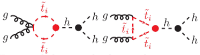
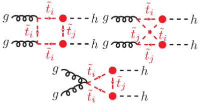
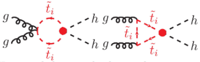
Stop masses in the MSSM

Stop mass matrix is

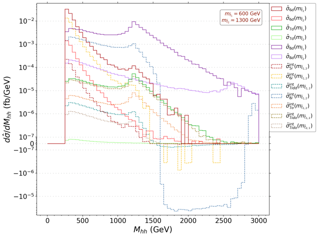
$$m_{\tilde{t}}^2 = \begin{pmatrix} m_t^2 + m_{\tilde{t}_L}^2 + m_Z^2 \cos 2\beta(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) & m_t(\mu \cot\beta - A_t) \\ m_t(\mu \cot\beta - A_t) & m_t^2 + m_{\tilde{t}_R}^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2\theta_W \end{pmatrix}$$

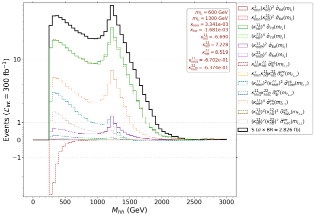
- A_t is SUSY breaking trilinear coupling between H_u, $\tilde{t}_L$ and $\tilde{t}_R$, $m_{\tilde{t}_{L,R}}$ are soft SUSY breaking masses
- In general one needs large values of A_t, between 2–3 TeV, to reach a 125 GeV SM-like Higgs mass
- This leads to large mixing between stops and large mass splitting between them (> 200 GeV) — numerically $m(\tilde{t}_1) \geq 600$ GeV (requires compressed spectrum, so presently escapes LHC limits) & $m(\tilde{t}_2) \geq 1250$ GeV
- Large stop mixing and large trilinear couplings mean large Higgs-stop-stop interactions, so stop diagrams including these couplings will have strong 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 simulations by recycling amplitudes

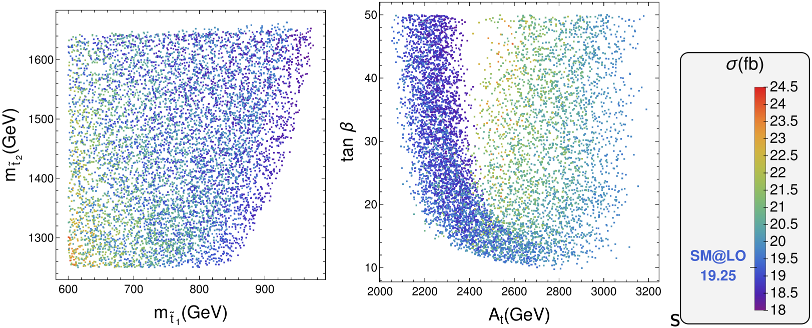




- The amplitude from a diagram depends on couplings and masses
- We factorise out the coupling dependence and simulate the individual amplitudes on a grid of mass values
- We can then quickly calculate the full cross section by weighting the amplitudes with the corresponding coupling values
- Contributions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

The overall cross section dependence is well known

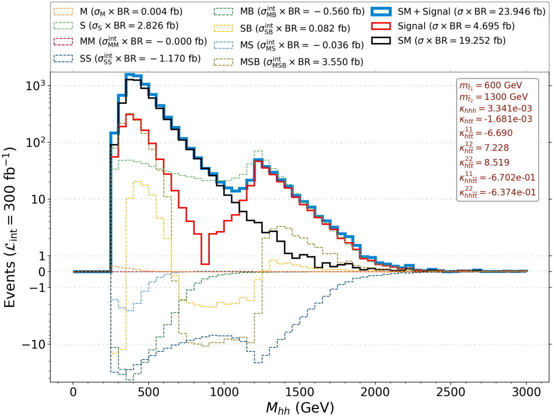
Previous studies (e.g., Huang at al. [1711.05743]) have shown that light stops can produce sizable effects with large A_t and $\tan\beta$



Use (N)MSSM spectrum from SPheno, HB/HS for experimental constraints, direct stop searches, MG5_aMC engine, NNPDF3.0 LO PDFs

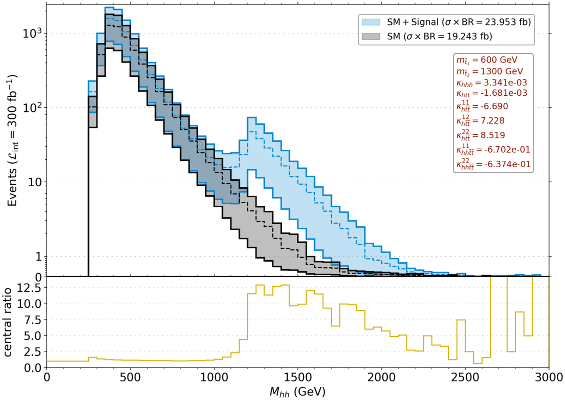
Our approach allows to see individual contributions clearly

Take a MSSM benchmark point that gives a largish cross section (23 fb)



Enhancement of 40% at *2m(top)* and factor of 10 at *2m(stop)*

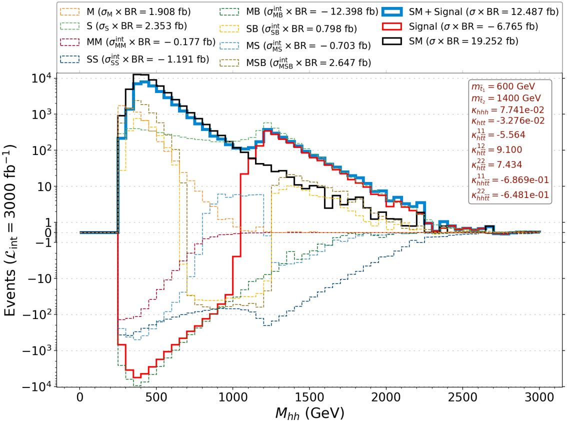
The excess is larger than PDF and scale uncertainties



Cinderella shoe plots: high mass enhancement separates from SM background (ME@NLO analysis in progress) while low mass effect needs better systematics

NMSSM can give features at low and high masses

Take a NMSSM benchmark point that gives a largish cross section (12 fb)



Depletion of -50% at *2m(top)* and enhancement (factor of 5) at *2m(stop)*

Experimental prospects

- Experimentally the most sensitive channels: i) $b\bar{b}\gamma\gamma$ at low M_{hh}, ii) $b\bar{b}\tau^+\tau^-$ at intermediate M_{hh}, iii) $b\bar{b}b\bar{b}$ at high M_{hh}
- For $b\bar{b}\gamma\gamma$ there are two main effects: modification of SM couplings (+interference 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 recent Alasfar et al. [2304.01968])

=> *We propose alternative approach through simplified model library*

Future developments: Framework

Plans to

- generalise the framework to other representations of SU(3) and to spin 1/2 so that $gg \to hh$ could be simulated easily within a large class of models
- make a public database of unweighted amplitudes for the community to use
- include two-loop corrections
- investigate if one could deform the distributions so that one is not limited to the grid values for masses

=> *Final mapping onto EFT frameworks (SMEFT, HEFT, etc.) and UV finite theories (eg, supersymmetry, compositeness, etc.)*

Future developments: Physics

Plans to:

- use the framework to study a larger class of models
- use the framework to revert the collider problem: if some excess was seen, can we extract the couplings and model parameters (and even understand which model to choose)? It works with blind MSSM point.
- study the cosmological implications of non-standard Higgs potentials

=> *If excess is seen, simplified model library allows extraction of masses and couplings, then mapping onto EFT (including hybrid EFT) and UV finite theories and as well as inform cosmology dynamics*

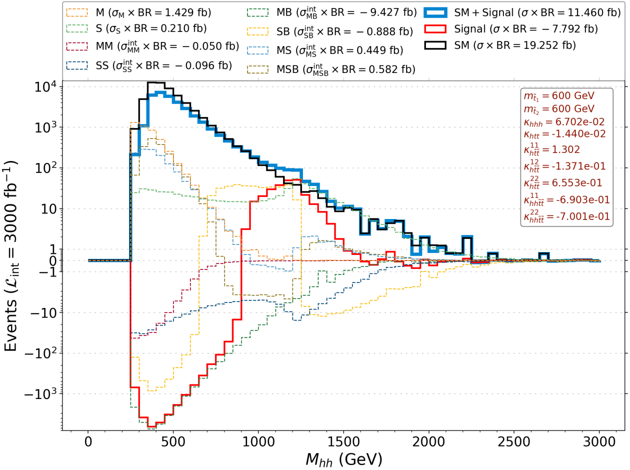
Summary

- New simplified model framework to compute di-Higgs cross sections efficiently by reweighting individual contributions (Panizzi & Waltari)
- Approach allows one to analyse processes at given benchmark points and to understand which topologies contribute to a given feature (including reverse engineering possible deviations, by Joergen)
- Example: light stops can produce significant deviations at high invariant masses and sizeable ones at low invariant masses
- A coupling modifier or EFT framework will be insufficient if light BSM particles are present (could consider hybrid EFT)
- UFO model at https://hepmdb.soton.ac.uk/hepmdb:0223.0337 with instructions in appendix (compositeness case available soon)

=> *New (numerically efficient) framework for di-Higgs production*

PS: Many thanks to Harri for most of the slides!

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