Di-Higgs as a Probe of New Physics

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Outline

What?

- BSM physics in SM HH production: couplings & loops (eg, squarks)
- Toolbox to construct cross section distributions, analyse their origin without full MC simulation and also extract model parameters

Why?

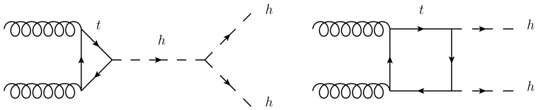
- Higgs pair production at the LHC can extract shape of the Higgs potential $\Rightarrow$ nature of EWSB, EWPTs, etc. (main target process for Run 3 & HL-LHC)
- One-loop process: BSM at same perturbative order as SM (& cancellations)
- Ambition to surpass current paradigms: HEFT/SMEFT (non-resonant) and explicit UV finite theories (resonant) => *simplified model approach*

To be quantitative, we shall assume (N)MSSM near alignment limit (without decoupling), ie, SM-like Higgs couplings to fermions/bosons are very near the SM values - but framework absolutely general

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?

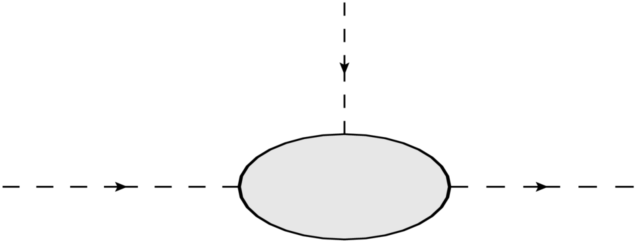
=> *Consider here non-resonant di-Higgs production (resonant production to come)*

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 $t\bar{t}h$ 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 BSM particles in loops coupling strongly to gluons and Higgs boson
   - here stops from supersymmetric models, but other top partners can lead to similar effects (see Egle's talk on VLTs in compositeness, C2HDM)

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 ($\sim$100 GeV) singlet-like Higgs— in such a case one could have a Higgs self-coupling smaller than in the SM

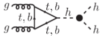
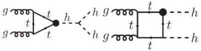
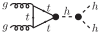
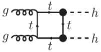
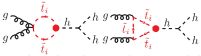
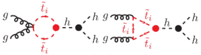
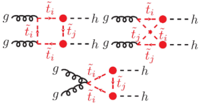
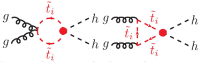
Stop masses in the (N)MSSM

Stop mass matrix is

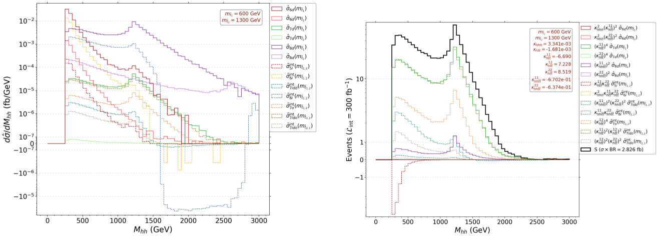
$$m^2_{\tilde{t}} = \begin{pmatrix} m_t^2 + m^2_{\tilde{t}_L} + m_Z^2 \cos 2\beta(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) & m_t(\mu \cot\beta - A_t) \\ m_t(\mu\cot\beta - A_t) & m_t^2 + m^2_{\tilde{t}_R} + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2\theta_W \end{pmatrix}$$

- 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. In NMSSM can have two light stops in theory (different cascades allows them).
- 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		$\mathcal{A}_i \propto \kappa_{h\tilde{t}\tilde{t}}^{ii}$
	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		$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{h\tilde{t}\tilde{t}}^{ii}$
	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		$\mathcal{A}_i \propto \lvert\kappa_{h\tilde{t}\tilde{t}}^{ij}\rvert^2$
8	Bubble and triangle with $hh\tilde{t}\tilde{t}$ coupling		$\mathcal{A}_i \propto \kappa_{hh\tilde{t}\tilde{t}}^{ii}$
	Only diagonal couplings between the Higgs and the squarks due to the strong interaction.		

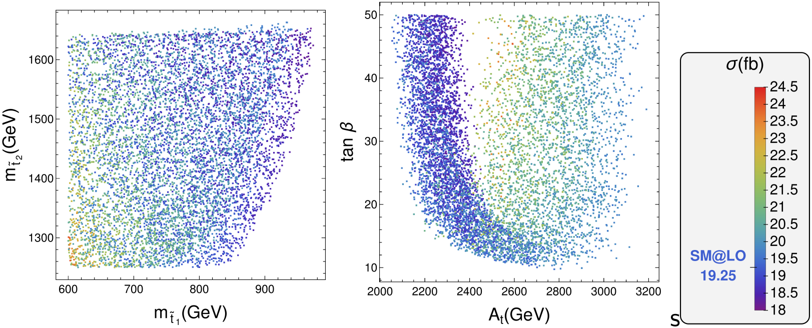
We speed up simulations by recycling amplitudes



- 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 interferences can be easily extracted (ie, unfolding known MSSM results here, eg, Huang, Joglekar, Li, Wagner, arXiv:1711.05743)

The overall cross section dependence is well known

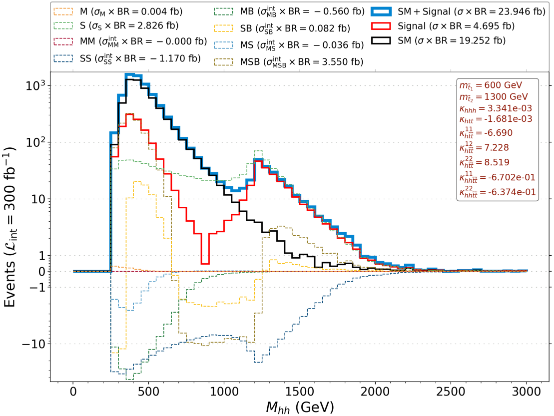
Previous studies have shown that light stops can produce sizable effects with large A_t and *tan* β *(MSSM)*



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

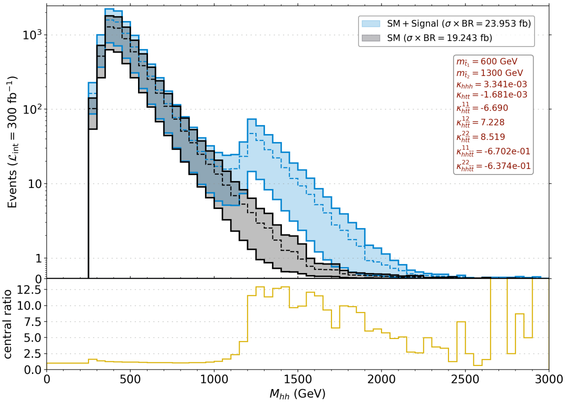
Our approach allows to see individual contributions clearly

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



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

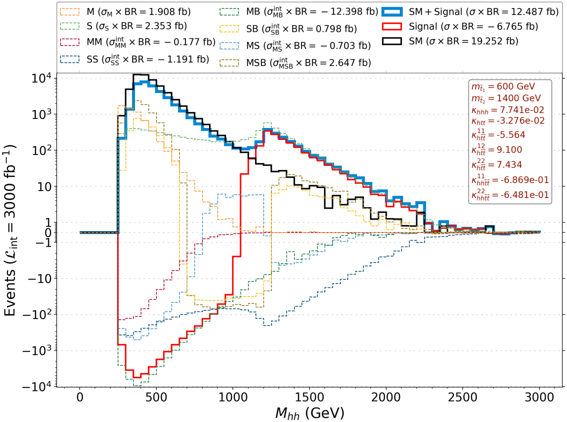
The excess is larger than PDF and scale uncertainties



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

NMSSM gives *different* features at low and high masses

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



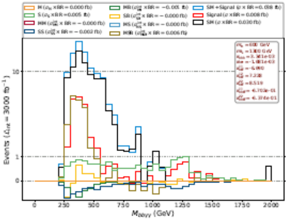
Depletion of -50% at *2m(top)* and *enhancement* (factor of 5) at *2m(stop)*

Experimental prospects

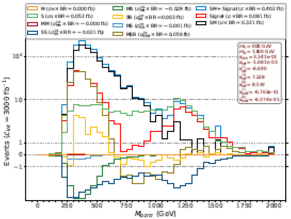
invariant mass at reconstruction level

Three final states after Higgs decay: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$

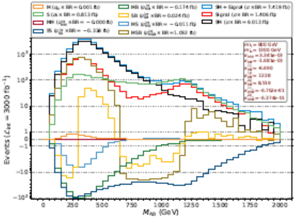
$b\bar{b}\gamma\gamma$



$b\bar{b}\tau^+\tau^-$



$b\bar{b}b\bar{b}$



- $b\bar{b}\gamma\gamma$ sensitive to low m_{hh}
  $b\bar{b}b\bar{b}$ to high m_{hh}
  $b\bar{b}\tau^+\tau^-$ is intermediate
- No hope at Run 3
  possibly at HL-LHC (shown in this slide)
- Proper background study necessary

But searches are not optimised
(no correlations in line-shape used)

Future developments: Framework

Presently

=> *We developed new numerical approach through simplified model library*

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 (can do di-Higgs + jets, other BSM probe)
- 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 (supersymmetry, compositeness, etc.)*

Future developments: Physics

Presently

=> *Library applied to supersymmetry ((N)MSSM) & compositeness (C2HDM)*

Plans to

- use the framework to study a larger class of realistic models
- use the framework to revert the collider problem: if some excess were seen, can we extract the couplings and model parameters (and even understand which model to choose)? It (kind of) works with blind MSSM points.
- study cosmology (EWPTs) of non-SM Higgs potentials pegged to LHC data

=> *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*

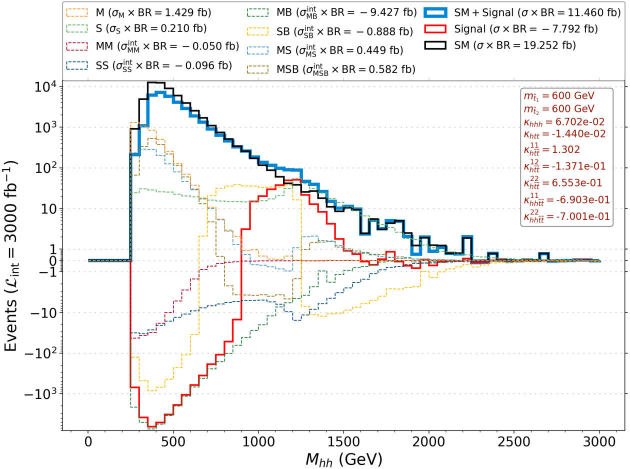
Summary

- New simplified model-independent framework for di-Higgs studies, MC efficient 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 (Sjoelin, ATLAS)
- Example: light stops produce very significant deviations at high invariant masses and sizeable ones at low invariant masses
- Coupling modifier/EFT framework incorrect if light BSM particles are present (consider hybrid EFT), full theories cumbersome to test
- UFO model at https://hepmdb.soton.ac.uk/hepmdb:0223.0337 with instructions for supersymmetry (compositeness case available soon)

=> *Gone beyond current phenomenology paradigms for di-Higgs production*

PS: Many thanks to Panizzi & Waltari for template 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

Given an experimental dataset, is it possible to fit the parameters?

A testing with our MC sets:

1) We generated a benchmark
2) "Blinded" the parameters and asked our ATLAS colleague to do the parametric fit

Input parameters

$m_{\tilde{t}_1} = 600$ GeV
$m_{\tilde{t}_2} = 1400$ GeV
$\kappa_{hhh} = 1.208\text{e-}01$
$\kappa_{htt} = -3.309\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = 5.965$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 9.598$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 7.825$
$\kappa^{11}_{hh\tilde{t}\tilde{t}} = -6.874\text{e-}01$
$\kappa^{22}_{hh\tilde{t}\tilde{t}} = -6.437\text{e-}01$

→

Fitted parameters

$m_{\tilde{t}_1} = 600$ GeV
$m_{\tilde{t}_2} = 1300$ GeV
$\kappa_{hhh} = 8.430\text{e-}02$
$\kappa_{htt} = -5.972\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = -1.203$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 10.000$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 3.022$
$\kappa^{11}_{hh\tilde{t}\tilde{t}} = 1.369$
$\kappa^{22}_{hh\tilde{t}\tilde{t}} = 5.366$

Caveats:

- Only couplings were fitted, stop masses were assumed
- MSSM relations between couplings were assumed, but the point was random

But how wrong is this fit?