Di-Higgs and New Physics

Stefano Moretti

Soton & Uppsala

Scalars 2025

UPPSALA UNIVERSITET

Outline

Where?

- Di-Higgs production at the LHC, key process for Run 3 and HL
- Higgs pair production sensitive to shape of Higgs potential: nature of EWSB, EW phase transition, etc.

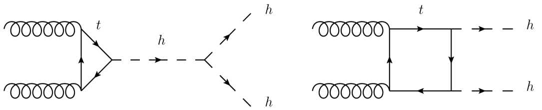
Why & how?

- $\Rightarrow$ One-loop process, BSM effects at same perturbative order
- $\Rightarrow$ New toolbox allows to extract model parameters (by Panizzi & Waltari)
- - Constructs differential distributions and analyse their origin by breaking down ME according to complete coupling (and mass) structure
  - Can map BSM parameter spaces without full MC simulation: includes tree-level BSM Higgses, ready for spin-0 loops (eg, squarks in MSSM & NMSSM), in progress for spin-1/2 (eg, VLQs in Compositeness)

Based on 2302.03401 (MSSM non-resonant case) and 2506.09006 (NMSSM resonant case) with Panizzi, Sjoelin & Waltari

Higgs pair production in the SM

Higgs pair hadro-production dominated by gluon fusion $gg \to hh$: SM process through two topologies (triangle and box of tops) interfering destructively:
- *BSM effects even more prominent*



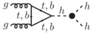
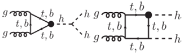
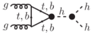
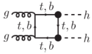
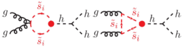
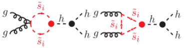
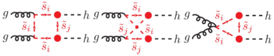
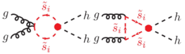
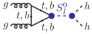
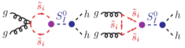
- Top box amplitude is largest in SM, hence difficult to exclude large upward deviations of $\lambda(hhh)$ (Run 2: $-1.5 < \lambda(hhh)/\lambda(\mathrm{SM}) < 6.7$)
- Destructive interference makes it very difficult to detect also at Run 3, HL-LHC should eventually discover it
- BSM effects can make it more visible, how to extract these in non-resonant production? (See my Scalars 2023 talk.) Easier in resonant production, yet interferences:
  - *Consider here this case*

BSM Higgs pair production

There can be BSM effects onto Higgs pair production, if

1. Top Yukawa coupling deviates from its SM value
   - somewhat constrained by tth(SM) production rate & h(SM) fits
   - 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, heavy Higgs propagator (resonant s-channel) and stops (loops) from SUSY models: use NMSSM as test case (it can have both a light BSM Higgs and light stops)*
   - *Approach is model independent: simplified model can be mapped on UV finite theory*

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		$\mathcal{A}_i \propto \kappa_{h\tilde{s}\tilde{s}}^{ii}$
6	Modified hhh coupling + Scalar bubble and triangle with $h\tilde{s}\tilde{s}$ coupling		$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{h\tilde{s}\tilde{s}}^{ii}$
7	Scalar triangle and box with two $h\tilde{s}\tilde{s}$ couplings		$\mathcal{A}_i \propto \lvert\kappa_{h\tilde{s}\tilde{s}}^{ij}\rvert^2$
8	Scalar bubble and triangle with $hh\tilde{s}\tilde{s}$ coupling		$\mathcal{A}_i \propto \kappa_{hh\tilde{s}\tilde{s}}^{ii}$
9	Neutral scalar		$\mathcal{A}_i \propto \kappa_{Shh}^{I}\kappa_{Sff}^{I}$
10	Neutral scalar + coloured scalar		$\mathcal{A}_i \propto \kappa_{Shh}^{I}\kappa_{S\tilde{s}\tilde{s}}^{Ii}$

We speed up simulations by recycling amplitudes

$$\mathcal{L}_M = -(\lambda^{\rm SM} + \kappa_{hhh}) v h^3 - \frac{1}{\sqrt{2}}(y_f^{\rm SM} + \kappa_{hff}) h \bar{f} f \,,$$

$$\mathcal{L}_{\tilde{s}} = \sum_i \kappa^{ii}_{h\tilde{s}\tilde{s}} v\, h \tilde{s}_i^* \tilde{s}_i + \kappa^{ii}_{hh\tilde{s}\tilde{s}}\, hh \tilde{s}_i^* \tilde{s}_i + \left(\sum_{i>j} \kappa^{ij}_{h\tilde{s}\tilde{s}} v\, h \tilde{s}_i^* \tilde{s}_j + h.c. \right)$$

$$\mathcal{L}_S = \sum_I \kappa^I_{Shh} v S_I^0 hh + \kappa^I_{Sff} S_I^0 \bar{f} f \,,$$

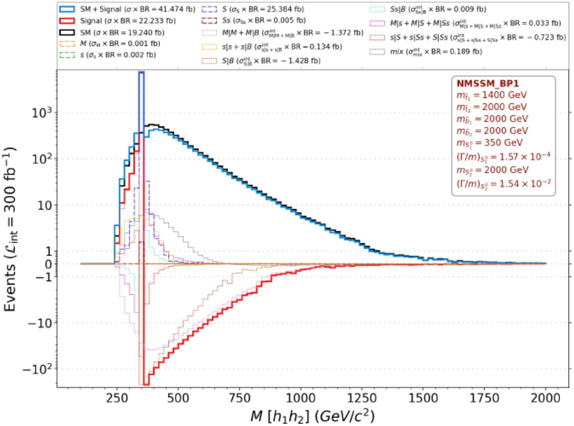
$$\mathcal{L}_{S\tilde{s}} = \sum_{I,i} \kappa^{Ii}_{S\tilde{s}\tilde{s}} v S_I^0 \tilde{s}_i^* \tilde{s}_i \,,$$

$$\sigma = \sigma_B + \sigma_M + \sigma_S + \sigma^{\rm int}_{MB} + \sigma^{\rm int}_{SB} + \sigma^{\rm int}_{MM} + \sigma^{\rm int}_{SS} + \sigma^{\rm int}_{MS} + \sigma^{\rm int}_{MSB}$$

Parameter	BP1	BP2	BP3	BP4	BP5
$\tan\beta$	30	1.38	2.5	2.31	7
λ	0.043	0.69	0.7	0.65	0.21
κ	0.04	0.43	0.54	0.68	0.16
A_λ (GeV)	150	−340	−345	220	−550
v_S (GeV)	13150	1250	1210	1280	943
m_H (GeV)	2000	800	1200	800	800
m_S (GeV)	350	500	800	1200	100
$m_{\tilde{t}_1}$ (GeV)	1600	600	600	600	1400

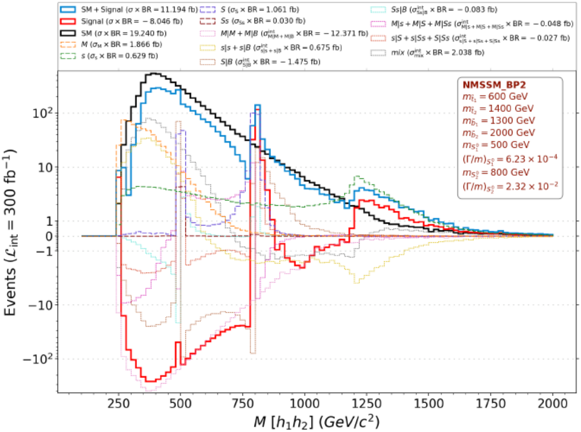
- The amplitude from a diagram depends on couplings and masses
- We factorise out the coupling dependence and simulate the individual amplitudes on a grid of mass values
- We can then quickly calculate the full cross section by weighting the amplitudes with the corresponding coupling values
- Contributions from individual diagrams and their *interferences* can be easily extracted (5 BPs, S & H are s-channel resonances of S_I^0 fields)

BP1: light singlet scalar



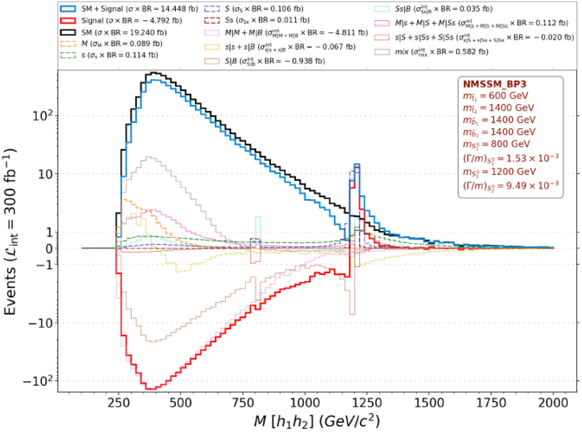
Our BP1 has a singlet Higgs with m_S =350 GeV.

BP2: intermediate light scalars with light stops



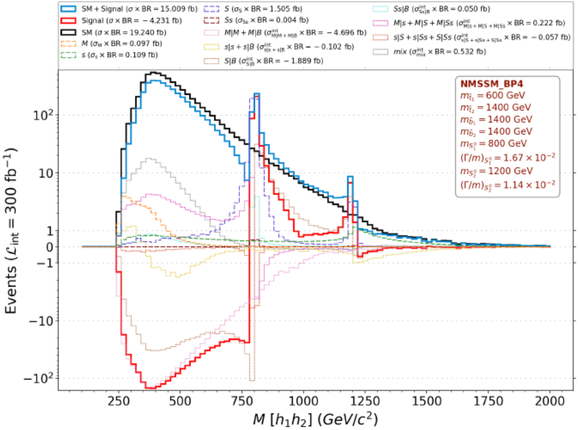
Our BP2 has a singlet Higgs with $m_S = 500$ GeV and a doublet Higgs with $m_H = 800$ GeV.

BP3: singlet and doublet scalar on stop threshold



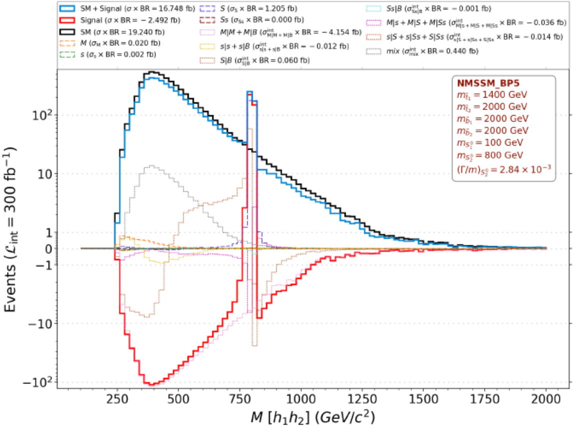
Our BP3 has a singlet Higgs with $m_S = 800$ GeV and a doublet Higgs with $m_H = 1200$ GeV.

BP4: doublet lighter than singlet



Our BP4 has a doublet Higgs with $m_H = 800$ GeV and a singlet Higgs with $m_S = 1200$ GeV.

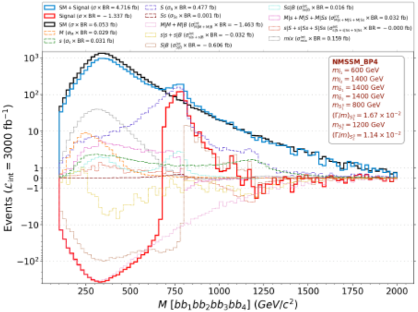
BP5: 100 GeV singlet & 800 GeV doublet

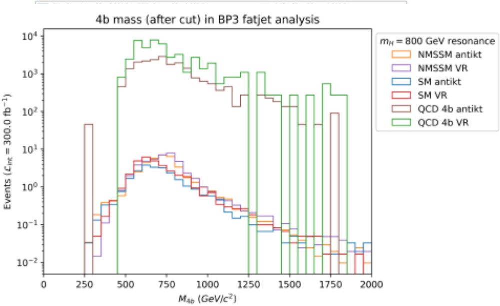


Our BP5 has a singlet Higgs state with $m_S = 100$ GeV and a doublet Higgs state with $m_H = 800$ GeV.

Experimental prospects

- Looked at $bb\gamma\gamma$, $bb\tau^+\tau^-$ and $bbbb$ with PS, hadronisation & detector
- Take $bbbb$ as example (same for other two channels)





Differences between SM plus heavy Higgs and full result persist
Large QCD noise requires ML (Transformer) analysis

Reverse engineering (i) - (aka interpretation)

(eg, MSSM non-resonant)

Reverse engineering

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

First try

Input parameters	Fitted parameters
$m_{\tilde{t}_1} = 600$ GeV	$m_{\tilde{t}_1} = 600$ GeV
$m_{\tilde{t}_2} = 1400$ GeV	$m_{\tilde{t}_2} = 1300$ GeV
$\kappa_{hhh} = 1.208\text{e-}01$	$\kappa_{hhh} = 8.430\text{e-}02$
$\kappa_{htt} = -3.309\text{e-}02$	$\kappa_{htt} = -5.972\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = 5.965$	$\kappa^{11}_{h\tilde{t}\tilde{t}} = -1.203$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 9.598$	$\kappa^{12}_{h\tilde{t}\tilde{t}} = 10.000$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 7.825$	$\kappa^{22}_{h\tilde{t}\tilde{t}} = 3.022$
$\kappa^{11}_{hh\tilde{t}\tilde{t}} = -6.874\text{e-}01$	$\kappa^{11}_{hh\tilde{t}\tilde{t}} = 1.369$
$\kappa^{22}_{hh\tilde{t}\tilde{t}} = -6.437\text{e-}01$	$\kappa^{22}_{hh\tilde{t}\tilde{t}} = 5.366$

But how wrong is this fit?

Caveats:

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

Reverse engineering (ii)

Reverse engineering

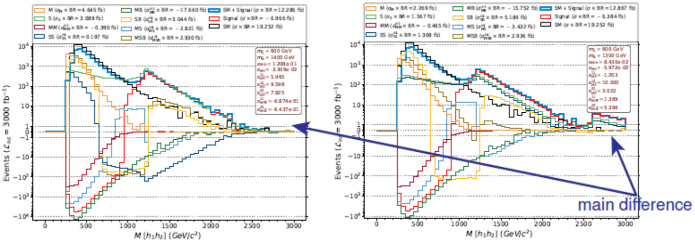
Given an experimental dataset, is it possible to fit the parameters?

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

First try

Original benchmark | **Fitted benchmark**



Different parameter sets lead to very similar distributions

Improve by injecting *h*(SM) coupling information (to tops)

Reverse engineering (iii)

Reverse engineering

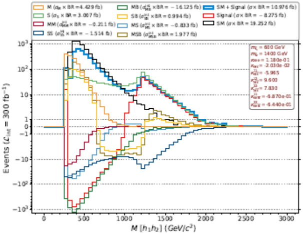
Given an experimental dataset, is it possible to fit the parameters?

A testing with our MC sets:

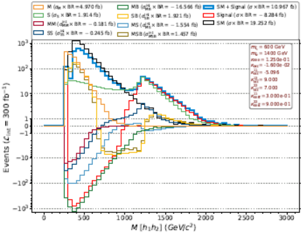
1) We generated a benchmark
2) "Blinded" the parameters and asked our ATLAS colleague to do the parametric fit

Second try

Original benchmark



Fitted benchmark



perfect fit with very close numerical values of relevant parameters!

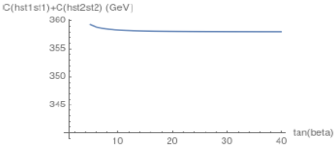
Backup: mapping onto SUSY parameters (eg, MSSM)

- Fit gives y_t and take g and g' to be known.
- $$C_{h\tilde{t}_1\tilde{t}_1} = y_t^2 v \sin^2\beta - \sqrt{2} y_t \mu \cos\beta \sin 2\theta_{\tilde{t}} + \sqrt{2} A_t \sin\beta \sin 2\theta_{\tilde{t}} + \frac{g^2 v}{8} \cos 2\beta \sin^2\theta_{\tilde{t}} - \frac{g'^2 v}{4} \cos 2\beta \left(\frac{1}{6} \sin^2\theta_{\tilde{t}} - \frac{2}{3} \cos^2\theta_{\tilde{t}} \right), \quad (1)$$
  $$C_{h\tilde{t}_2\tilde{t}_2} = y_t^2 v \sin^2\beta + \sqrt{2} y_t \mu \cos\beta \sin 2\theta_{\tilde{t}} - \sqrt{2} A_t \sin\beta \sin 2\theta_{\tilde{t}} + \frac{g^2 v}{8} \cos 2\beta \cos^2\theta_{\tilde{t}} - \frac{g'^2 v}{4} \cos 2\beta \left(\frac{1}{6} \cos^2\theta_{\tilde{t}} - \frac{2}{3} \sin^2\theta_{\tilde{t}} \right), \quad (2)$$
  $$C_{h\tilde{t}_1\tilde{t}_2} = -\frac{y_t \mu}{\sqrt{2}} \cos\beta \cos 2\theta_{\tilde{t}} + \frac{1}{\sqrt{2}} A_t \sin\beta \cos 2\theta_{\tilde{t}} - \frac{g^2 v}{8} \cos 2\beta \sin 2\theta_{\tilde{t}} + \frac{5 g'^2 v}{48} \cos 2\beta \sin 2\theta_{\tilde{t}}. \quad (3)$$
- Construct: $C_{h\tilde{t}_1\tilde{t}_1} + C_{h\tilde{t}_2\tilde{t}_2} = 2 y_t^2 v \sin^2\beta + \frac{(g^2 + g'^2) v}{8} \cos 2\beta$ and (4)

$$C_{h\tilde{t}_1\tilde{t}_1} - C_{h\tilde{t}_2\tilde{t}_2} = 2\sqrt{2} (A_t \sin\beta - y_t \mu \cos\beta) \sin 2\theta_{\tilde{t}} - \frac{(g^2 + g'^2) v}{8} \cos 2\beta \cos 2\theta_{\tilde{t}} \quad (5)$$

- Can extract A_t and $\tan\beta$ since $A_t \gg y_t \mu$ and $|\sin\theta_{\tilde{t}}| \simeq |\cos\theta_{\tilde{t}}| \simeq 1/\sqrt{2}$ plus:

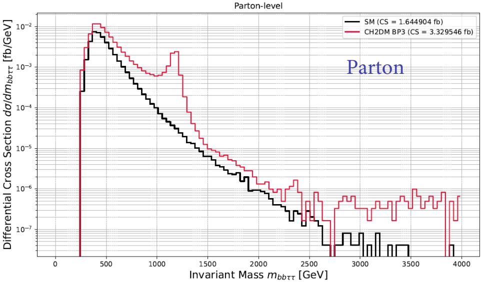
- Can finally extract λ(hhh)

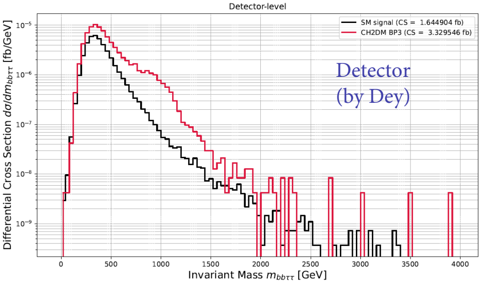


Other models

- Reverse engineering: can fit distributions to underlying BSM parameters
- Mapping onto fundamental theories SUSY done, Compositeness coming:

  - Composite 2HDM (2HDM) by De Curtis, Delle Rose, SM & Yagyu (1810.06465)
  - Di-Higgs in C2HDM in De Curtis, Delle Rose, Egle, SM & Mühlleitner (2310.10471)





- Again looked at $bb\gamma\gamma$, $bb\tau^+\tau^-$ and $bbbb$ with PS, hadronisation & detector
- Take $bb\tau^+\tau^-$ as example (very wide resonant case, requires HL-LHC)

Summary

- Di-Higgs production at the LHC as hallmark process for Run 3 and HL
- Gives access to Higgs potential via trilinear Higgs coupling:

  - Resonant case approaches exploit NWA or BW, missing interference effects
- Accurate modelling of the latter required to ascertain BSM effects
- Using NMSSM: distortion to peaks driven by both SM and stops diagrams
- Significant computational effort required to include these:

  -Deployed library adopting simplified model approach exploiting coupling decomposition:
  https://github.com/FeynRules/Models/tree/main/DiHiggs-BSM-Simplified

  -Efficient as it recycles kinematical structure over mass grid (can interpolate widths)

  -Decomposition can be used to track full ME behaviour

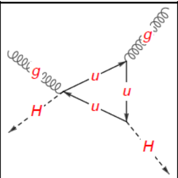
Outlook

- \- Other UV finite theories too can be captured through our simplified model approach
- \- Decoupled spectrum via SMEFT+ (low energy limit is SM + light stops/VLTs & modified Wilson coefficients) with Enberg, Camargo-Molina, Waltari & Yao

  \- Use QGRAPH combined with FeynArts, FormCalc & LoopTools ⟹

  \- Matchings required

  \- NLO QCD in progress

67		$\frac{1}{\Lambda^2}$	{[g,H,u,U] → cpv cuG QED^2, [g,u,U] → cpv cuG QED SM, [H,u,U] → cHbox cHDD cHl3 cll cpv cuH QED SM} (180 diagrams through D=6)

- Case proven for both non-resonant and resonant di-Higgs production

  \- ATLAS (UU) and CMS (RAL) now deploying new analyses

  \- Surpass both prevalent paradigms: 1) SMEFT/HEFT approaches in non-resonant searches
  2) NWA/BW approaches in resonant searches