Simplified models for di-Higgs studies

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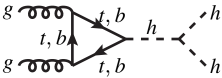
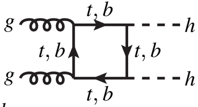
UNIVERSITÀ DELLA CALABRIA

S. Moretti, **LP**, J. Sjölin and H. Waltari, Phys. Rev. D **107** (2023), 2302.03401 [hep-ph]

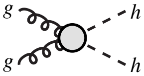
Signal elements

The Standard model topologies:





A new physics signal:



What can the signal be from a general perspective?

(limiting to gluon-fusion processes)

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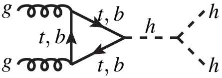
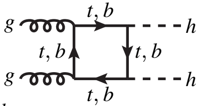
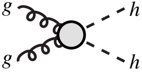
The Standard model topologies: 



A new physics signal: 

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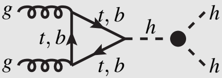
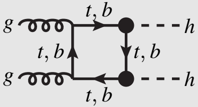
Modified SM couplings





Signal elements

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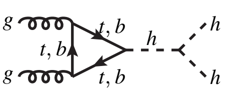

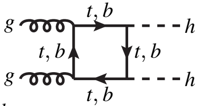

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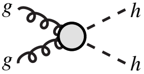

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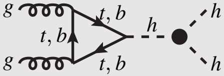
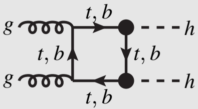
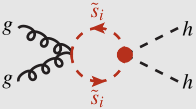
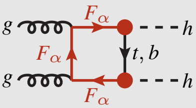




New coloured particles





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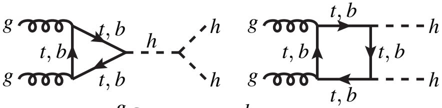

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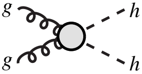

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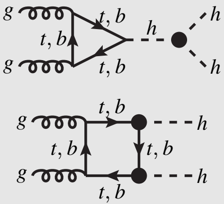

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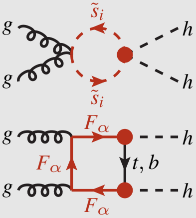
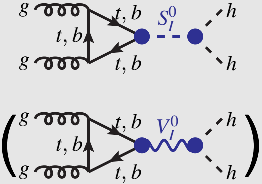


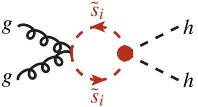
New neutral particles



And combinations of these ingredients

The number of possibilities is limited!

Reduced cross-sections

Let's take one signal contribution: 

with $\mathcal{L} = \kappa_{hh\tilde{s}_i\tilde{s}_i}\, hh\tilde{s}_i^*\tilde{s}_i$

$$\mathcal{A} \propto \kappa_{hh\tilde{s}_i\tilde{s}_i} \longrightarrow \sigma = {\kappa_{hh\tilde{s}_i\tilde{s}_i}}^2 \hat{\sigma}(m_{\tilde{s}_i})$$

- $\kappa_{hh\tilde{s}_i\tilde{s}_i}$: rescaling of the cross-section
- $\hat{\sigma}(m_{\tilde{s}_i})$: kinematics of the process $\longrightarrow$ **reduced cross-section**

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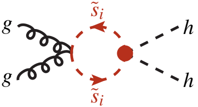

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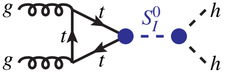
Let's add another contribution:



with $\mathcal{L} = \kappa^I_{Shh} v \, S_I^0 hh + \kappa^I_{Stt} \, S_I^0 \bar{t}t$

$$\sigma = {\kappa_{hh\tilde{s}_i\tilde{s}_i}}^2 \, \hat{\sigma}(m_{\tilde{s}_i}) + \left(\kappa^I_{Shh}\kappa^I_{Stt}\right)^2 \, \hat{\sigma}(m_{S_i}, \Gamma_{S_I}) + \kappa_{hh\tilde{s}_i\tilde{s}_i}\kappa^I_{Shh}\kappa^I_{Stt} \, \hat{\sigma}^{\text{int}}(m_{s_i}, m_{S_I}, \Gamma_{S_I})$$

- **couplings**: rescaling of the reduced cross-section
- **masses, total widths and Lorentz structures**: kinematics of the individual subprocess

The total cross-section is constructed by adding a complete set of elements

2 squarks and modified SM couplings

The simplified Lagrangian

- **Modified Higgs couplings:** $-(\lambda^{\rm SM} + \kappa_{hhh}) v h^3 - \frac{1}{\sqrt{2}} (y_t^{\rm SM} + \kappa_{htt}) h \bar{t} t$
  Additive terms, not multiplicative!
- **Trilinear squark-Higgs couplings:** $vh(\tilde{q}_1^* \ \tilde{q}_2^*) \begin{pmatrix} \kappa_{h\tilde{q}\tilde{q}}^{11} & \kappa_{h\tilde{q}\tilde{q}}^{12} \\ \cdot & \kappa_{h\tilde{q}\tilde{q}}^{22} \end{pmatrix} \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix}$
- **Quadrilinear squark-Higgs couplings:** $hh(\tilde{q}_1^* \ \tilde{q}_2^*) \begin{pmatrix} \kappa_{hh\tilde{q}\tilde{q}}^{11} & \kappa_{hh\tilde{q}\tilde{q}}^{12} \\ \cdot & \kappa_{hh\tilde{q}\tilde{q}}^{22} \end{pmatrix} \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix}$

All parameters are kept independent
(and real for simplicity)

⟶ $\kappa_{hh\tilde{q}\tilde{q}}^{12} = 0$ and we do not need to know the electric charge of $\tilde{q}_{1,2}$

What are we looking for?

- Analyse entire classes of scenarios (MSSM, NMSSM,...)
- Find parameter combinations which maximise signal visibility:
  ⟶ what can be observed at Run 3 or the high-luminosity upgrade of LHC?
- Identify distinct shape features to characterise different scenarios

All with one set of simulated samples

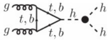
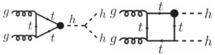
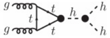
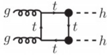
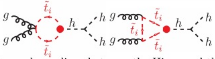
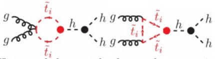
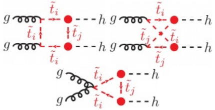
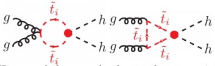
The recipe

1) Deconstruction
Identify all combinations proportional to unique couplings products

2) Database
Simulate individual samples in a $\{m_{\tilde{q}_1}, m_{\tilde{q}_2}\}$ grid and store the samples

3) Recombination/Analysis
Analyse the process for any choice of parameters (masses and couplings) by doing a weighted sum of the deconstructed samples

1) Deconstruction

	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.		

8 kind of topologies

1) Deconstruction

Cross-section

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

B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

1) Deconstruction

Cross-section

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

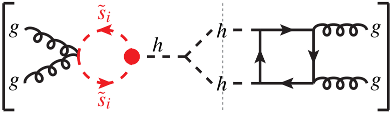
B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

One of these terms (interference between diagrams with squarks and the SM):

$$\sigma^{\text{int}}_{\text{SB}} = \sum_{i=1,2} \left[\kappa^{ii}_{h\tilde{q}\tilde{q}} \hat{\sigma}^{\text{int}}_{5B}(m_{\tilde{q}_i}) + \sum_{j>i} (\kappa^{ij}_{h\tilde{q}\tilde{q}})^2 \hat{\sigma}^{\text{int}}_{7oB}(m_{\tilde{q}_{i,j}}) + \kappa^{ii}_{hh\tilde{q}\tilde{q}} \hat{\sigma}^{\text{int}}_{8B}(m_{\tilde{q}_i}) \right]$$

The first element, graphically:

$$\sigma^{\text{int}}_{5B}(m_{\tilde{q}_i}) = \Re \left[\quad \right] + \cdots = \kappa^{ii}_{h\tilde{q}\tilde{q}} \hat{\sigma}^{\text{int}}_{5B}(m_{\tilde{q}_i})$$



Topology "5"   SM topology

2) Database generation

Need to perform separate MC simulations for each deconstructed term

1) Use MG5_aMC with dedicated UFO models built in FeynRules
2) Associate individual coupling orders to each new coupling
3) Use specific simulation syntax for each process

Examples:

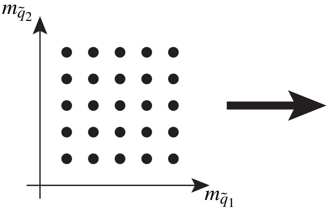
Background:

```
generate p p > h h [QCD] QCD^2==4 QED^2==4
```

5B:

```
generate p p > h h [QCD] QCD^2==4 QED^2==3 HSQ1SQ1^2==1
```

Remove any unwanted particle from propagation and set any other coupling order to 0



Database of samples
simulated once and for all

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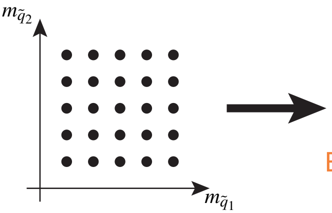

Database of samples
simulated once and for all

But what is in the database?

2) Database generation

Need to perform separate MC simulations for each deconstructed term

1) Use MG5_aMC with dedicated UFO models built in FeynRules
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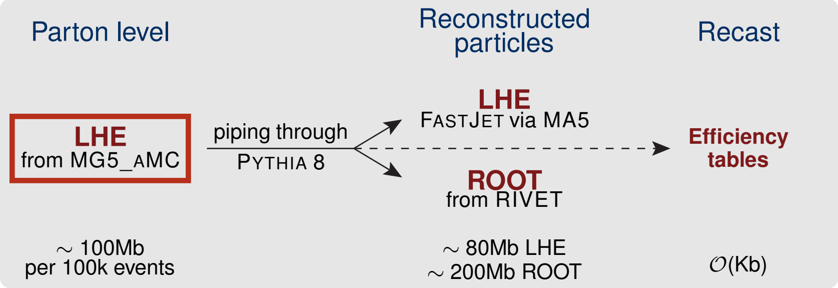
database content



The grid doesn't need to be too dense ⟶ interpolation between points

Interrogate the database to select relevant samples

3) Recombination/Analysis

Here is where THEORY comes to play!
so far it was about organising signals according to kinematic features

Now we have everything we need to address multiple goals:

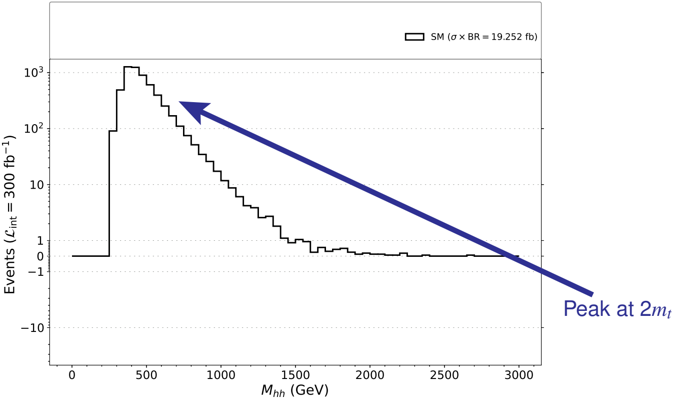
1. **TH/PH:** map theory parameters in the simplified Lagrangian and recast bounds
2. **PH/EXP:** global analysis of the parameter space to design new search strategies
3. **EXP:** use observed distributions to find the best fit parameters

I'll focus mostly on the second points (Harri will discuss the first)

3) Recombination/Analysis

invariant mass distribution m_{hh}

0) Background distribution (intrinsic background only: $pp \to hh$)

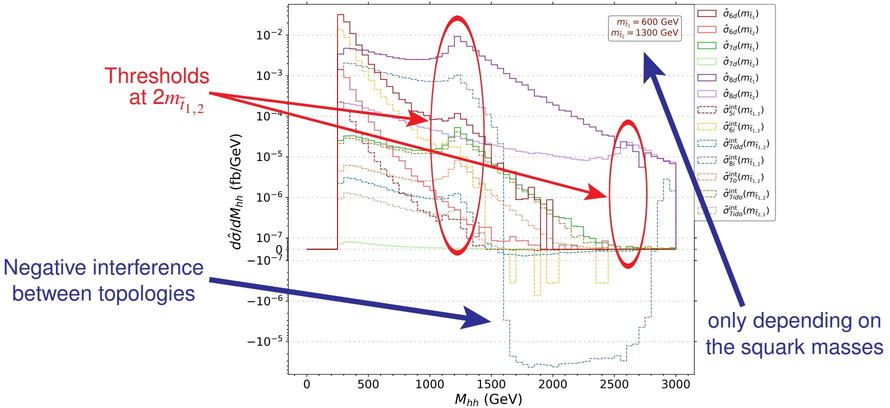


3) Recombination/Analysis

invariant mass distribution m_{hh}

0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)

Example with the σ_S elements



The deconstructed samples do not need to have the same number of MC events

3) Recombination/Analysis

invariant mass distribution m_{hh}

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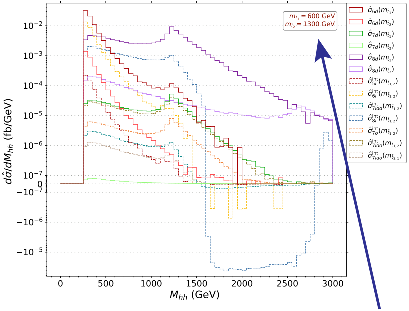
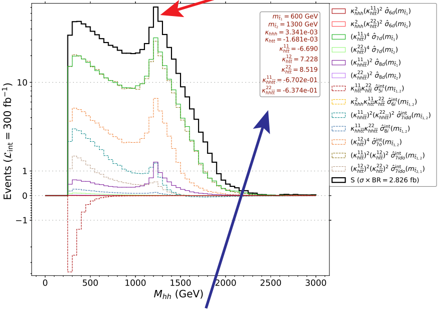
2) Weighting the distributions with the benchmark couplings **and recombine!**

Example with the σ_S elements

Sum of the contributions





only depending on the squark masses

depending on masses and coupling

The recombination is done bin-by-bin for each distribution

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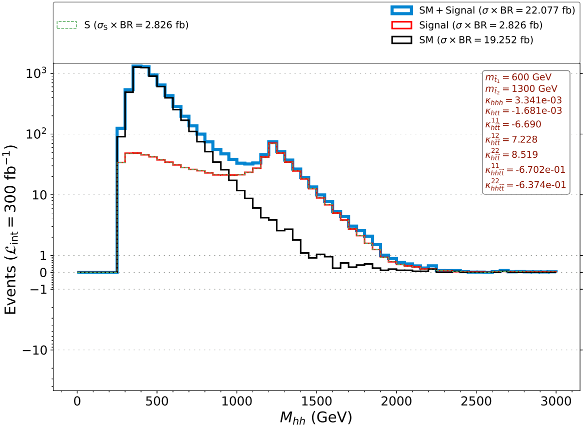

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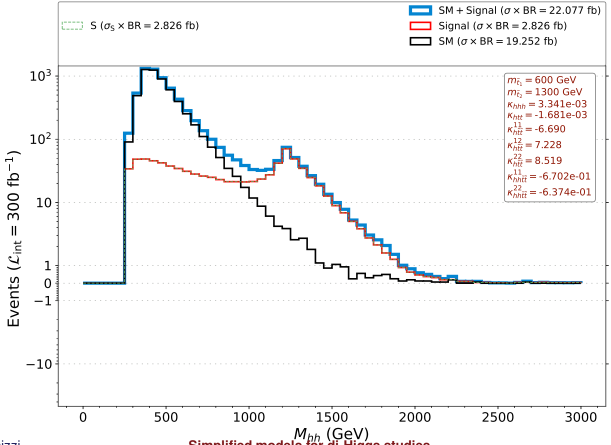
3) Repeat for all deconstructed elements



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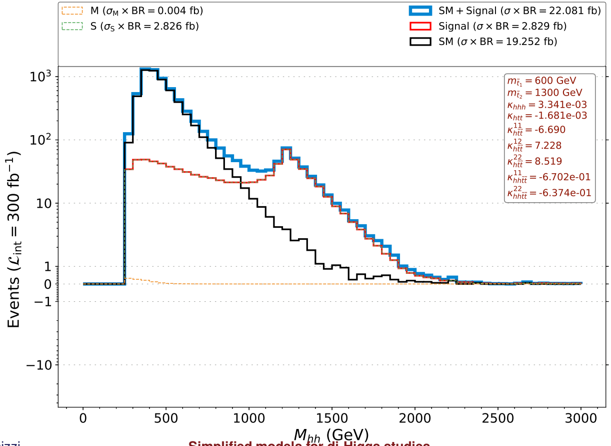

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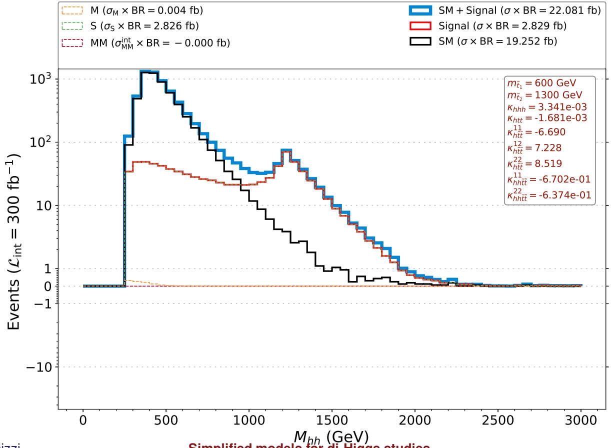

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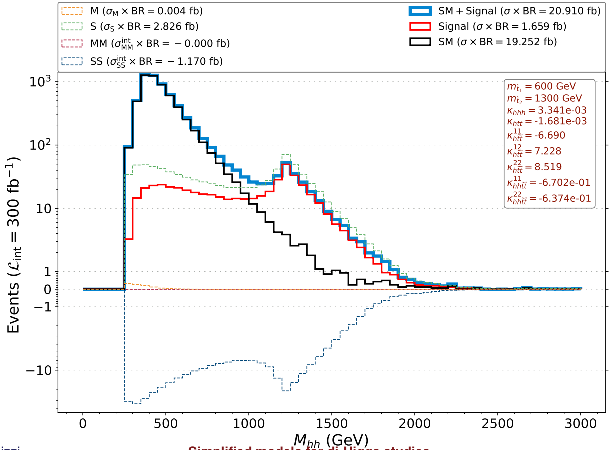
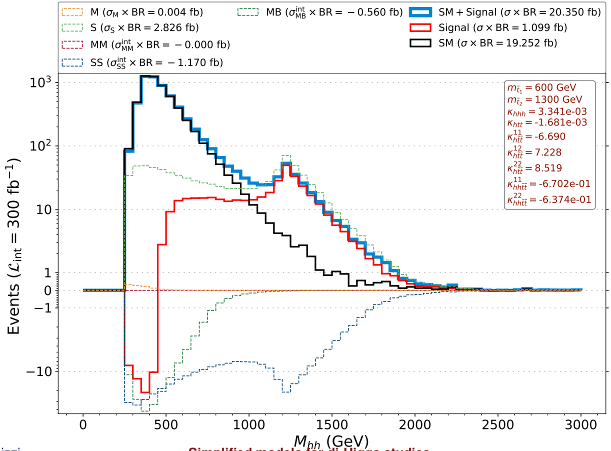


3) Recombination/Analysis

invariant mass distribution m_{hh}

0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**
3) Repeat for all deconstructed elements



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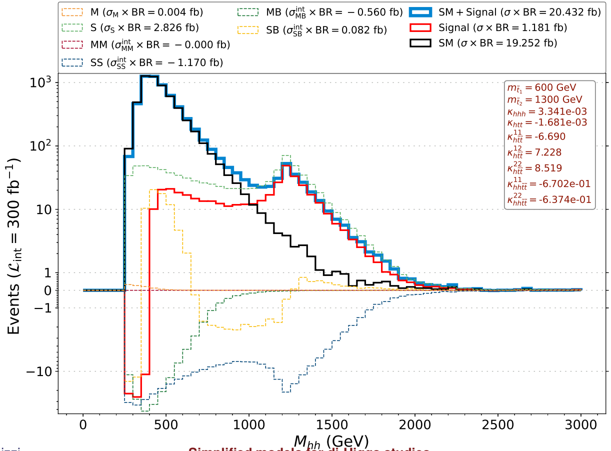

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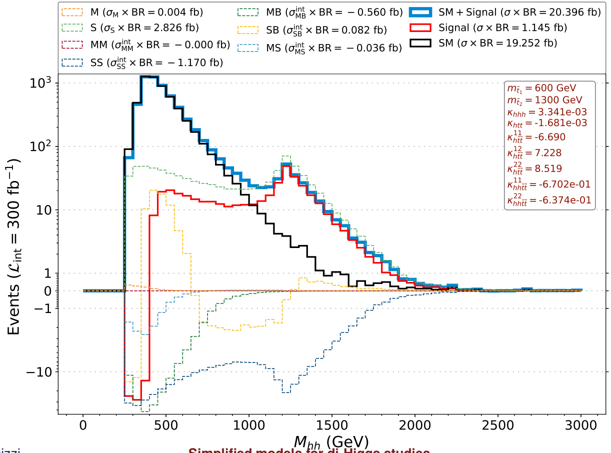

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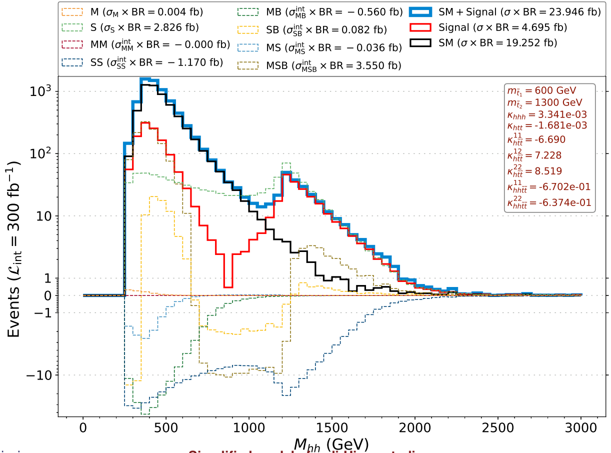
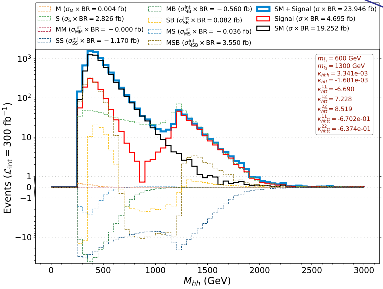


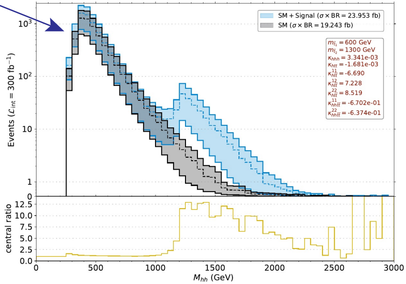
3) Recombination/Analysis

including systematics

independent simulation for cross-check

invariant mass distribution m_{hh}





With the same database we can

- analyse the contribution of specific topologies to the total shape
- fully treat any interference effect
- find predictions for any other theoretical scenario with same particle content
- explore the interface between NP effects at low energy and in the EFT limit
- use a semi-analytic approach to find parameters which maximise key features
  → excesses, deficits, threshold effects,. . .

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

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$\kappa_{htt} = -3.309\text{e-}02$		$\kappa_{htt} = -5.972\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = 5.965$		$\kappa^{11}_{h\tilde{t}\tilde{t}} = -1.203$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 9.598$		$\kappa^{12}_{h\tilde{t}\tilde{t}} = 10.000$
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But how wrong is this fit?

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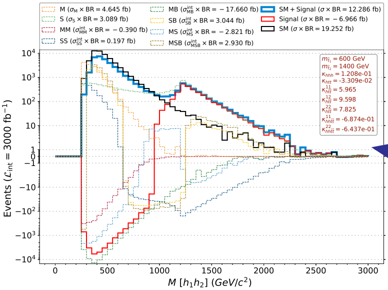
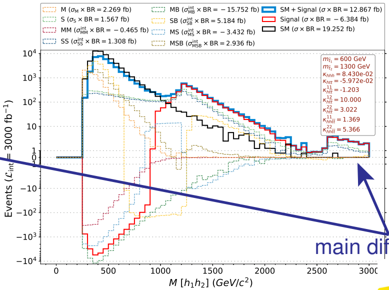
Original benchmark



Fitted benchmark



main difference

Different parameter sets lead to very similar distributions

It's not unexpected!

Use combination of observables and machine learning

Extending the di-Higgs analysis

What is the minimal parameter set to study this process?

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New particles

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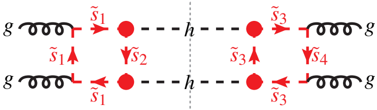

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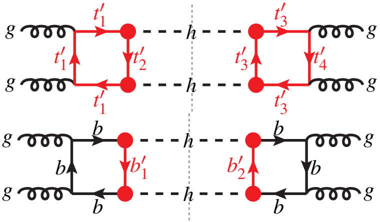

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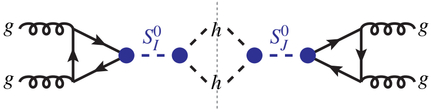

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factorisation of color coefficients in the deconstruction

New couplings

- **Modified SM couplings:** only hhh and $ht\bar{t}$
- **Coloured particles:** { Between themselves; With the Higgs boson; With Higgs and top or bottom (only fermions); With the neutral bosons
- **Neutral bosons:** { With the Higgs boson; With top or bottom; Total widths are free parameters too!

Conclusions

- **Deconstruction with simplified models** is powerful for catching NP effects at different energy scales (from low energy to EFT)
- **It is not restricted to di-Higgs**: it is applicable also to process of production of Higgs with another BSM scalar for example