Deconstructing signals of new physics at collider

a case study with Higgs pair production and other applications

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Beyond the Higgs boson

open problems

The Standard Model is complete
but are we happy with it?

Observations

Dark Matter | **Matter-antimatter asymmetry** | **Neutrino masses**

+ experimental anomalies: W mass, $(g-2)_\mu, \ldots$

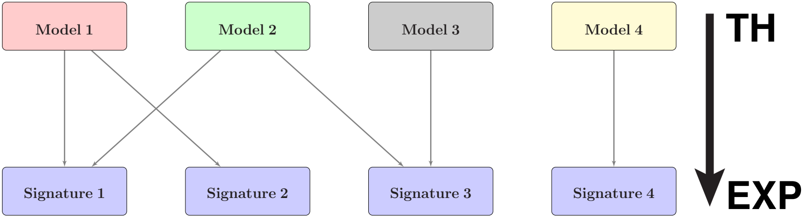
Theoretical issues

- Fermion mass hyerarchies
- Origin of flavour families
- Gauge coupling unification
- ...

There must be new physics
and most probably it's already in our reach!

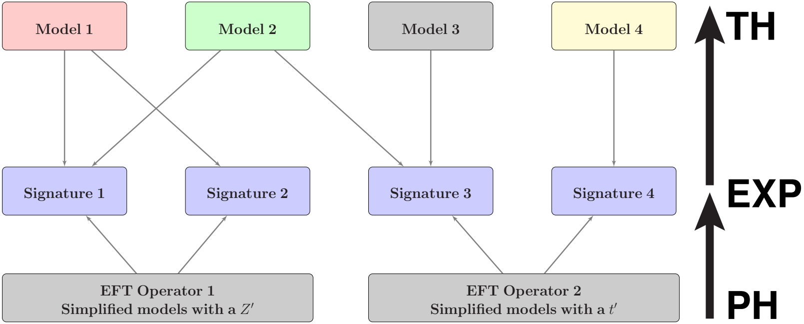
And if there's new physics we should be able to observe
new particles or modifications to SM predictions

Looking for new physics at the LHC



Designing searches or simulating signals to test specific models is a risky bet

Looking for new physics at the LHC



Designing searches or simulating signals to test specific models is a risky bet

Model-independent approach

EFTs: higher dimension operators where heavy d.o.f. are integrated out
Simplified models: minimal extensions of the SM with new states
Approximate description of classes of theoretical models

Looking for new physics at the LHC

Problems

- Proliferation of simplified models on the market
- Still many models have to be built "in-house" for specific problems
- Intensive (often redundant) MC simulations to achieve enough accuracy

Disk space and **computing time** are often very limited

Looking for new physics at the LHC

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Devise strategies to optimise and share resources

Looking for new physics at the LHC

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Goals

- **TH/PH:** recast public experimental data to constrain theoretical models
- **PH/EXP:** design new search strategies to explore new avenues
- **EXP:** optimise even more the interpretation of experimental data

Using public simulated datasets

Looking for new physics at the LHC

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Using public simulated datasets

A possible way

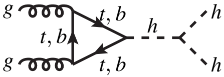
The deconstruction framework

A case study with Higgs pair production

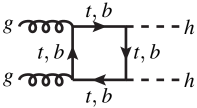
S. Moretti, **LP**, J. Sjölin, H. Waltari
"Deconstructing squark contributions to di-Higgs production at the LHC"
2302.03401 [hep-ph]

What happens in the SM

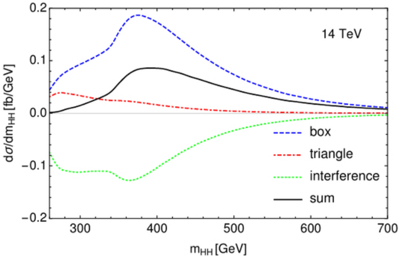
We only consider the gluon fusion process



$\mathcal{A} \propto y_t^{SM} \lambda^{SM} v$



$\mathcal{A} \propto (y_t^{SM})^2$



The leading-order is at one-loop, large destructive interference between the topologies.

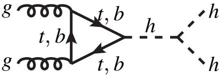
Wide literature treating the next-to-leading-order corrections

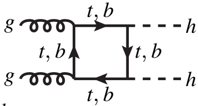
$\sqrt{s}$	13 TeV	14 TeV
ggF HH	$31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$	$36.69^{+2.1\%}_{-4.9\%} \pm 3.0\%$

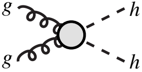
plot and table from B. Di Micco, M. Gouzevitch, J. Mazzitelli, C. Vernieri, J. Alison, K. Androsov, J. Baglio, E. Bagnaschi, S. Banerjee and P. Basler, *et al.* "Higgs boson potential at colliders: Status and perspectives," Rev. Phys. **5** (2020), 100045

Our analysis including BSM contributions is at LO

Signal elements

The Standard model topologies: 



A new physics signal: 

What can the signal be from a general perspective?
(limiting to gluon-fusion processes)

Signal elements

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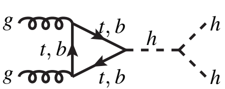

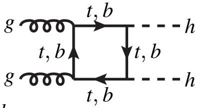

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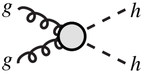

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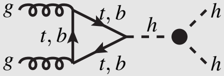
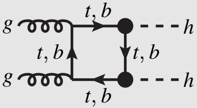
Modified SM couplings





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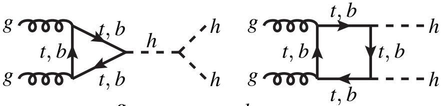

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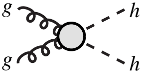

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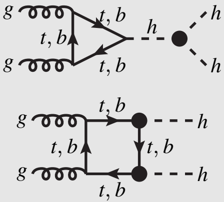
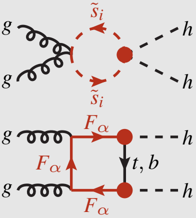


New coloured particles



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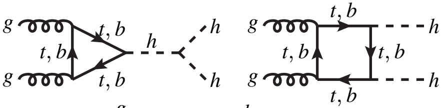

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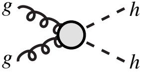

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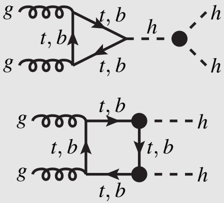

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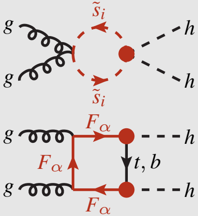
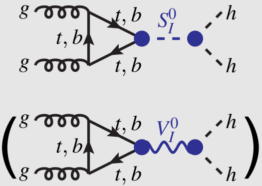


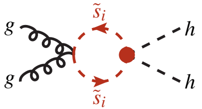
New neutral particles



And combinations of these ingredients

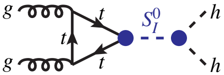
The number of possibilities is limited!

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**

Let's add another contribution:  with $\mathcal{L} = \kappa^I_{Shh} v\, S^0_I hh + \kappa^I_{Stt}\, S^0_I \bar{t}t$

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

- **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:** $-(\lambda^{\text{SM}} + \kappa_{hhh}) v h^3 - \frac{1}{\sqrt{2}} (y_t^{\text{SM}} + \kappa_{htt}) h \bar{t} t$
  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

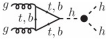
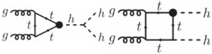
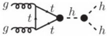
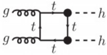
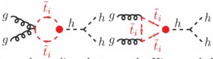
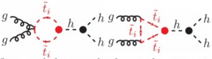
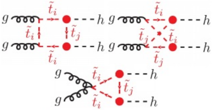
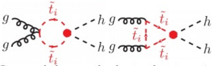
The recipe

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
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

Cross-section

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

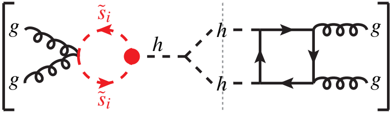
B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

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:

$\sigma^{\text{int}}_{5B}(m_{\tilde{q}_i}) = \Re$



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

Topology "5" SM topology

The interference term $6B$ is missing. . .

1) Deconstruction

Cross-section

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

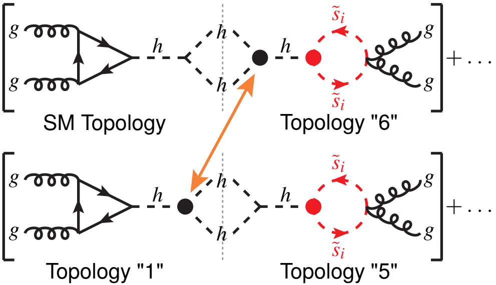
B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

It's in the mixed terms: $\sigma^{\text{int}}_{\text{MSB}} \supset \sum_{i=1,2} \kappa_{hhh} \kappa^{ii}_{h\tilde{t}\tilde{t}} \hat{\sigma}^{\text{int}}_{1,5-6B}(m_{\tilde{t}_i})$

The term $\sigma^{\text{int}}_{6B}(m_{\tilde{q}_i})$ shares the same coupling coefficient with the term $\sigma^{\text{int}}_{1,5}(m_{\tilde{t}_i})$:

$$\kappa_{hhh} \kappa^{ii}_{h\tilde{t}\tilde{t}} \hat{\sigma}^{\text{int}}_{6B}(m_{\tilde{q}_i}) = \Re \left[\ldots \right] + \ldots$$

$$\kappa_{hhh} \kappa^{ii}_{h\tilde{t}\tilde{t}} \hat{\sigma}^{\text{int}}_{1,5}(m_{\tilde{t}_i}) = \Re \left[\ldots \right] + \ldots$$



If the coupling coefficients are the same there is no way to separate the contributions

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:

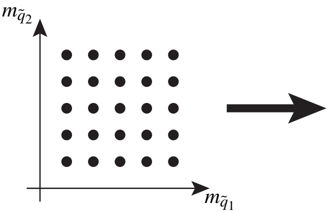
Background:

```
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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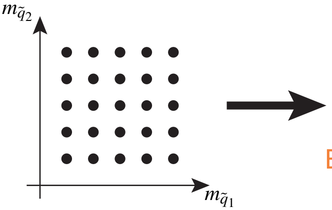

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But what is in the database?

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What is in the database?

Parton level

LHE from MG5_aMC

piping through PYTHIA 8 →

Reconstructed particles

LHE FastJet via MA5

ROOT from RIVET

→ **Recast**

Efficiency tables

$\sim$ 100Mb per 100k events

$\sim$ 80Mb LHE
$\sim$ 200Mb ROOT

$\mathcal{O}$(Kb)

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

3) Recombination

Here is where physics comes to play!

Now we have everything we need to address the initial 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 on the last two points

3) Recombination

defining a benchmark point

We considered the **MSSM** and scanned over parameters with the following rationale:

0) Maximise the signal by considering light propagators and large couplings

3) Recombination

defining a benchmark point

We considered the **MSSM** and scanned over parameters with the following rationale:

0) Maximise the signal by considering light propagators and large couplings
1) tree-level bound $m_h^2 \leq m_Z^2 \cos^2 2\beta$ ⟶ large loop corrections needed ⟶ how?
   Exploit the large coupling with the top/stops ⟶ large $\tan\beta$, heavy stops and large stop mixing (therefore large mass gap)

$$M_{\tilde{t}} = \begin{pmatrix} m^2_{\tilde{Q}_{33}} + m_t^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right) & m_t(\mu\cot\beta - A_t) \\ m_t(\mu\cot\beta - A_t) & m^2_{\tilde{U}_{33}} + m_t^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2\theta_W \end{pmatrix}$$

3) Recombination

defining a benchmark point

We considered the **MSSM** and scanned over parameters with the following rationale:

0) Maximise the signal by considering light propagators and large couplings
1) tree-level bound $m_h^2 \leq m_Z^2 \cos^2 2\beta$ ⟶ large loop corrections needed ⟶ how?
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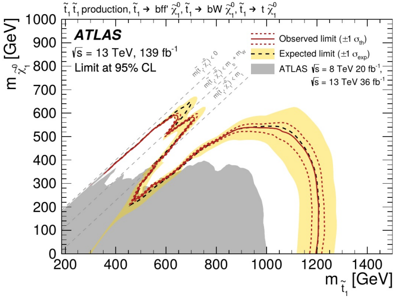
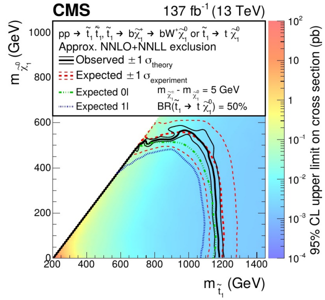
3) Experimental bounds on stop masses: $m_{\tilde{t}_1} \gtrsim 600$ GeV (if small mass gap with LSP) and $m_{\tilde{t}_2} \gtrsim 1250$ GeV





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Scan range

Parameter	minimum	maximum
$\tan\beta$	7	50
A_t (GeV)	1500	3500
$m^2_{\tilde{U}_{33}}$ (GeV^2)	1.35×10^6	2×10^6
$m^2_{\tilde{Q}_{33}}$ (GeV^2)	2.2×10^6	3.5×10^6

other parameters ⟶ small mass gap between $\tilde{t}_1$ and LSP, and decouple other particles

Spectra calculated with SPHENO

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defining a benchmark point

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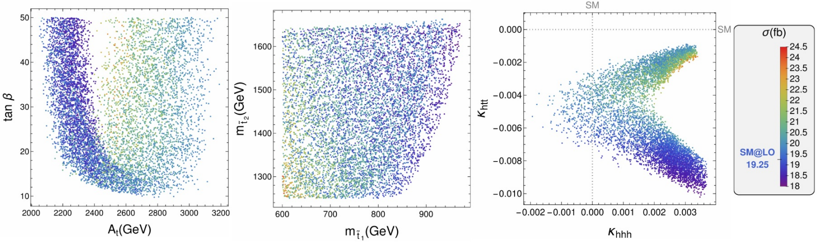
Scan results



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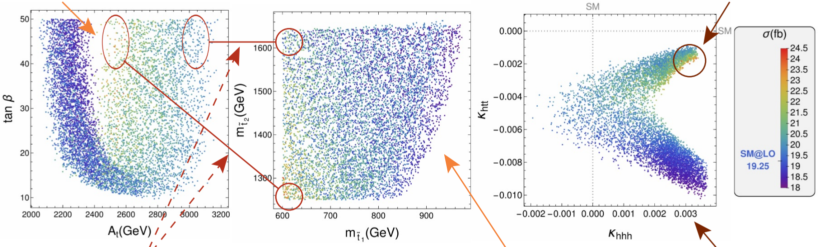
Here the Higgs is too heavy

Scan results

Highest increases for small Yukawa coupling



Larger A_t if larger average $\tilde{t}$ mass
For high $\tan\beta$, large σ for intermediate A_t

Smaller mass gap does not reconstruct m_h

Modified Higgs trilinear always small $\lesssim 3\%$

3) Recombination

defining a benchmark point

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An MSSM benchmark point with high cross-section

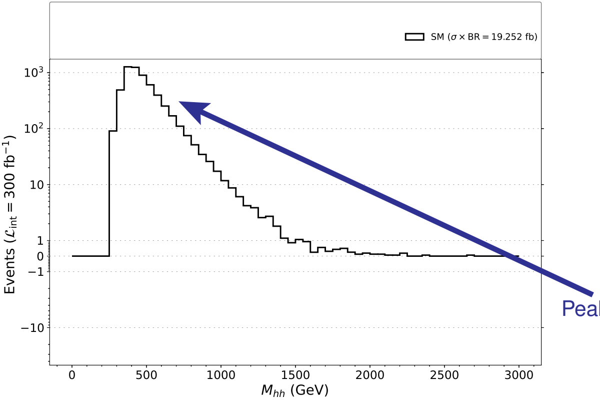
Masses and couplings	Value
$m_{\tilde{t}_1}$ (GeV)	600.6
$m_{\tilde{t}_2}$ (GeV)	1301.0
κ_{hhh}	3.34×10^{-3}
κ_{htt}	-1.68×10^{-3}

Masses and couplings	Value
$\begin{pmatrix} \kappa^{11}_{h\tilde{t}\tilde{t}} & \kappa^{12}_{h\tilde{t}\tilde{t}} \\ \cdot & \kappa^{22}_{h\tilde{t}\tilde{t}} \end{pmatrix}$	$\begin{pmatrix} -6.690 & 7.228 \\ \cdot & 8.519 \end{pmatrix}$
$\begin{pmatrix} \kappa^{11}_{hh\tilde{t}\tilde{t}} & \kappa^{12}_{hh\tilde{t}\tilde{t}} \\ \cdot & \kappa^{22}_{hh\tilde{t}\tilde{t}} \end{pmatrix}$	$\begin{pmatrix} -0.6702 & -0.0174 \\ \cdot & -0.6374 \end{pmatrix}$

3) Recombination

invariant mass distribution m_{hh}

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



Peak at $2m_h$

3) Recombination

invariant mass distribution m_{hh}

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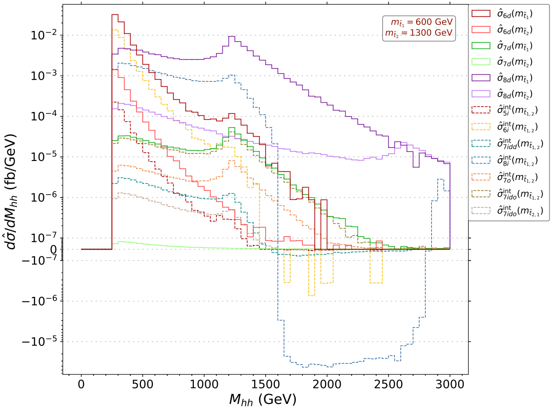
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)

Example with the σ_S elements



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

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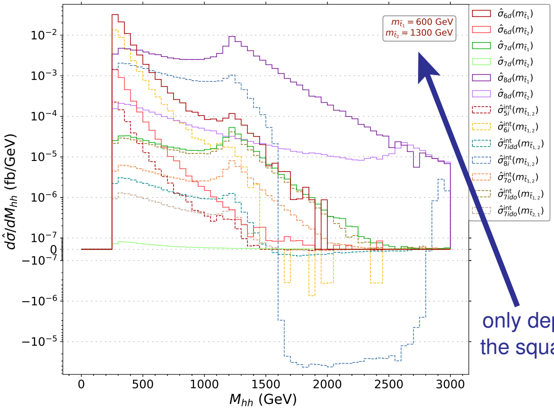

only depending on the squark masses

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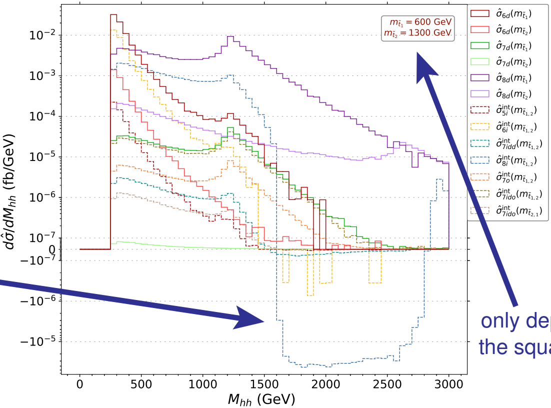

Negative interference between topologies

only depending on the squark masses

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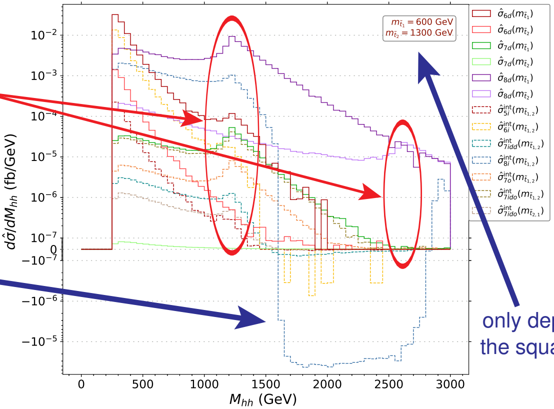
Example with the σ_S elements

Thresholds at $2m_{\tilde{t}_{1,2}}$



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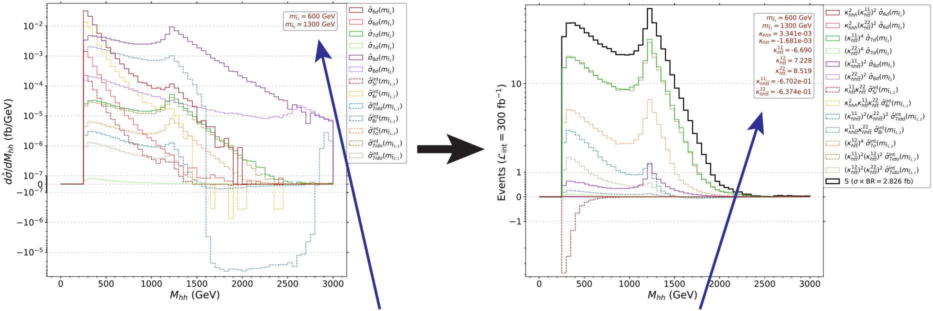
2) Weighting the distributions with the benchmark couplings **and recombine!**

Example with the σ_S elements



only depending on
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depending on
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The recombination is done bin-by-bin for each distribution

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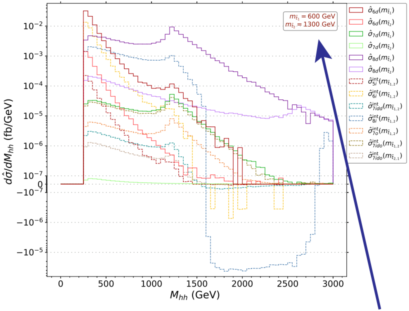
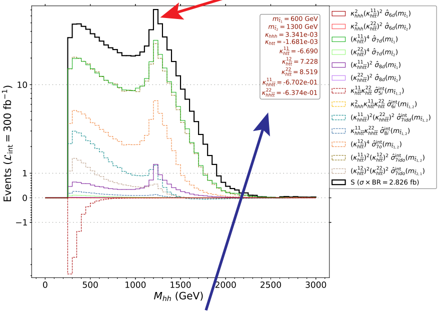
Example with the σ_S elements

Sum of the contributions





only depending on the squark masses

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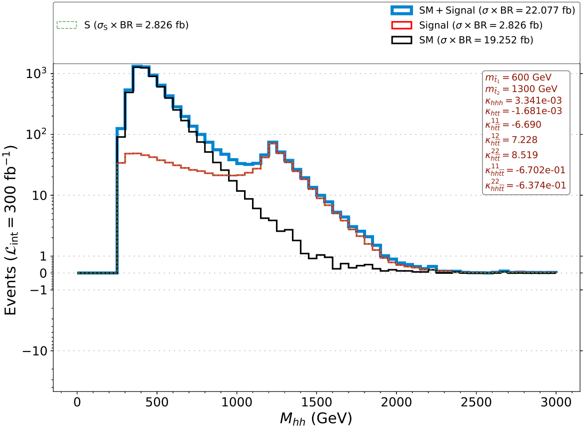

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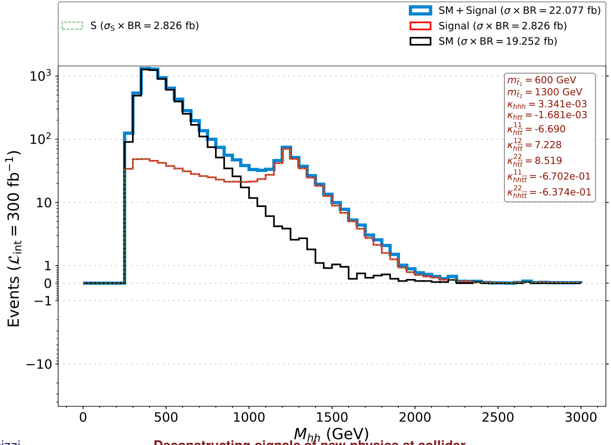
3) Repeat for all deconstructed elements



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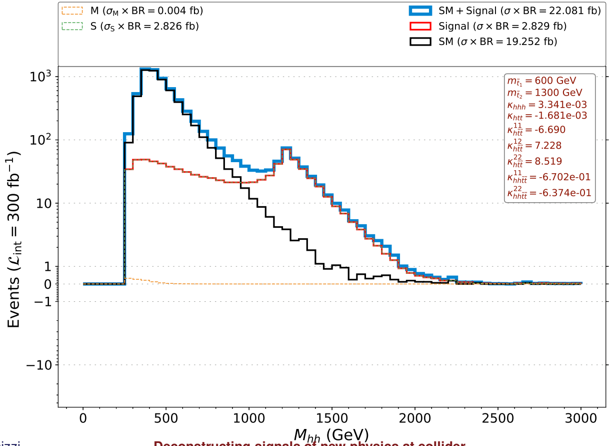

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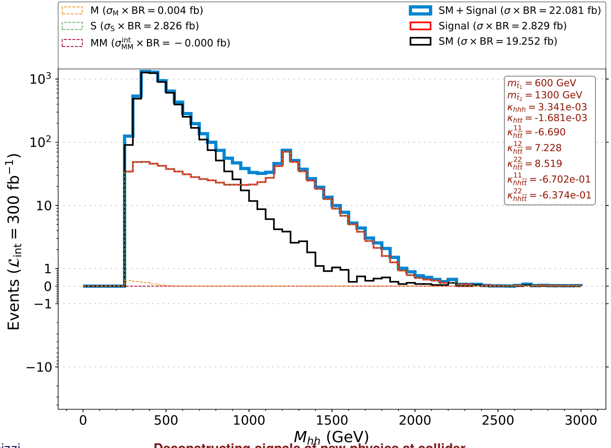

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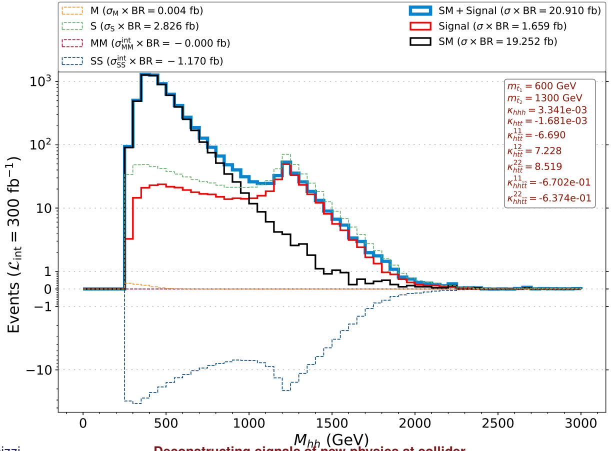

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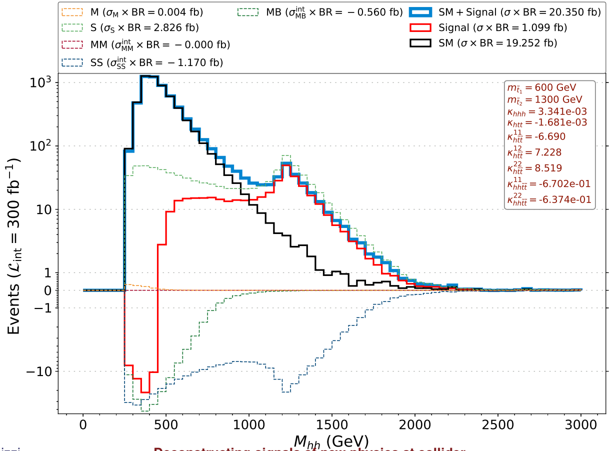

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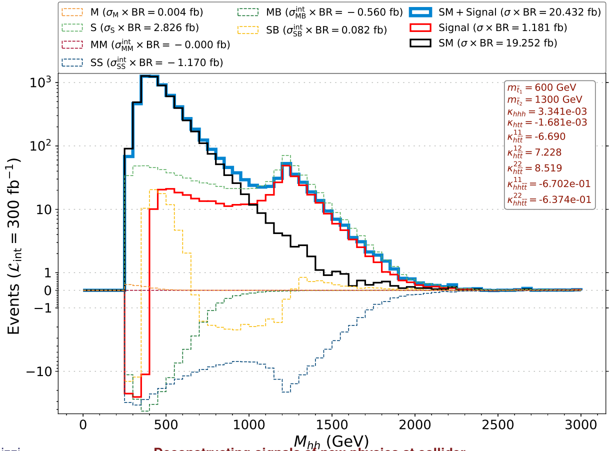

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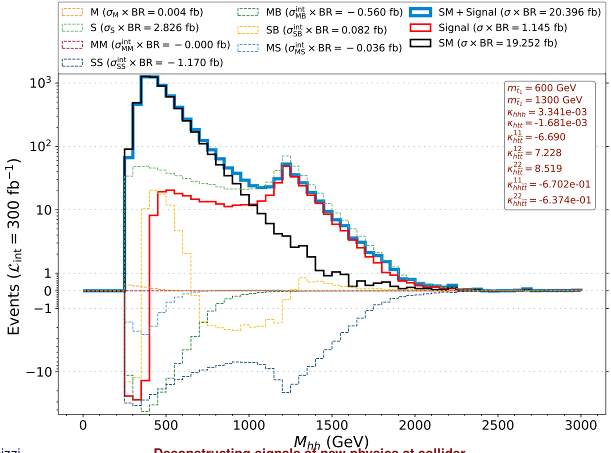

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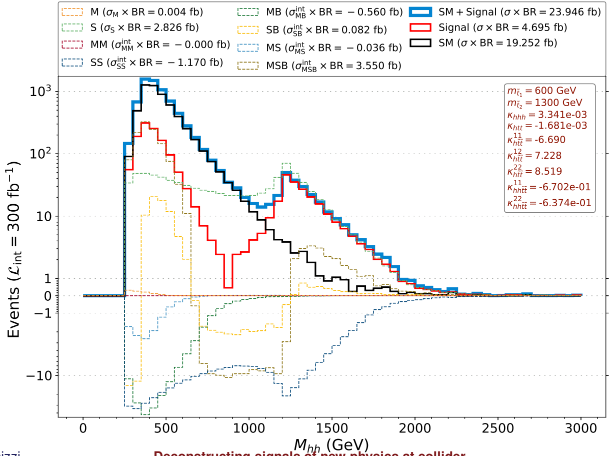
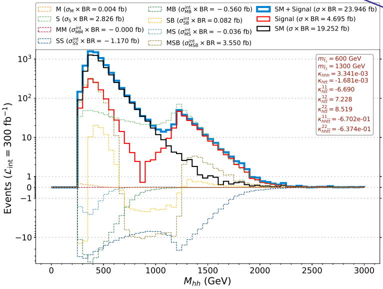


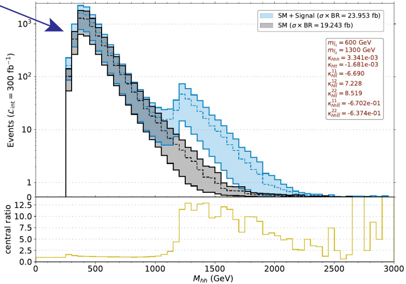
including systematics

independent simulation for cross-check

3) Recombination

invariant mass distribution m_{hh}





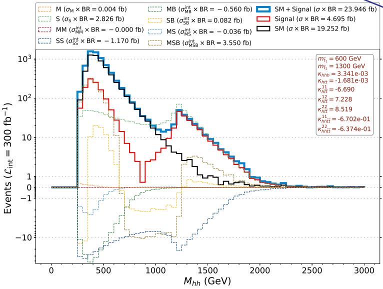
With the same database we can

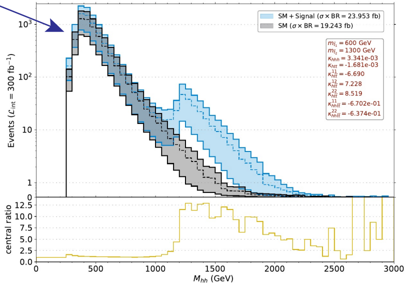
- analyse the contribution of specific topologies to the total shape
- use a semi-analytic approach to find parameters which maximise key features
  ⟶ excesses, deficits, threshold effects,. . .
- find predictions for any other theoretical scenario with same particle content
  ⟶ more on this in a bit

including systematics
independent simulation for cross-check

3) Recombination

invariant mass distribution m_{hh}





All good so far at parton level, but what happens in real life?

Basic content of the database

MG5 LHE files with SM particles in the final state (+ dark matter candidates if needed)

Next steps

1. Use the recombined samples and perform your analysis
2. Use the stored reconstructed samples (LHE or ROOT)

3) Recombination

invariant mass at reconstruction level

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

basic selection cuts

$bb\gamma\gamma$	$bb\tau\tau$	$bbbb$
$N(b) > 1$	$N(b) > 1$	$N(b) > 3$
$N(\gamma) > 1$	$N(\tau) > 1$	–
$p_T(b) > 45$ (20) GeV	$p_T(b) > 45$ (20) GeV	$p_T(b) > 40$ GeV
$\|\eta(b)\| < 2.5$	$\|\eta(b)\| < 2.5$	$\|\eta(b)\| < 2.5$
$\|\eta(\gamma)\| < 2.5$	$\|\eta(\tau)\| < 2.5$	–
120 GeV $< M(\gamma\gamma) <$ 130 GeV	–	–

3) Recombination

invariant mass at reconstruction level

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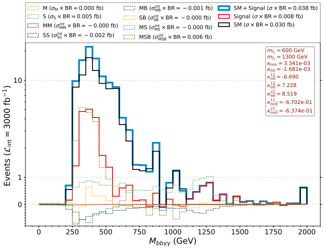
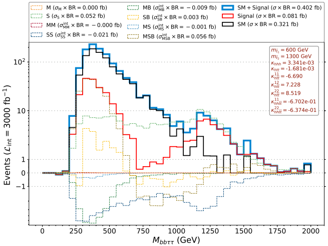
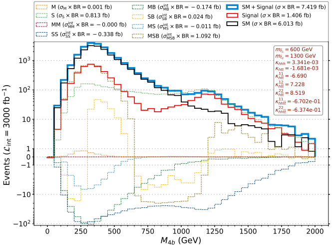
$b\bar{b}\gamma\gamma$



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



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



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

Discriminating models

The **MSSM** is constrained: $\begin{cases} \text{Large difference between squarks masses to obtain } m_h \\ \text{SM modified couplings } (\lambda \text{ and } y_t) \text{ are close to the SM values} \end{cases}$

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In the **NMSSM**: $\begin{cases} \text{New scalar allows to obtain } m_h\text{=125 GeV at tree level} \\ \text{Both stops can be light } (\sim 600 \text{ GeV from exp bounds}) \\ \lambda \text{ can be large, } y_t \text{ is constrained by } t\bar{t}h \text{ at LHC} \end{cases}$

Discriminating models

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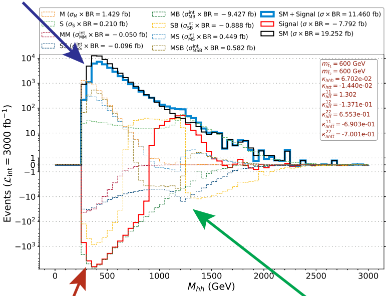
Both stops can be light ($\sim$ 600 GeV from exp bounds)
λ can be large, y_t is constrained by $t\bar{t}h$ at LHC

deficit at low m_{hh}

$m_{\tilde{t}_{1,2}}$ ~600 GeV and $\lambda \simeq 1.5\lambda^{SM}$



large negative MB interference

Large peak cancellation despite 2 light stops

Discriminating models

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- Large difference between squarks masses to obtain m_h
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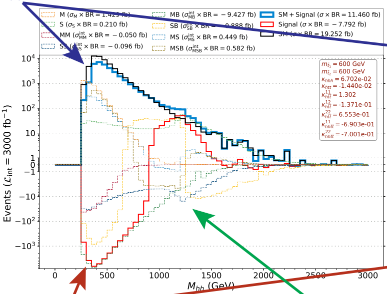
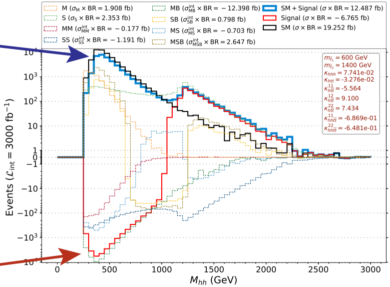


MSSM-like masses but $\lambda \simeq 1.6\lambda^{SM}$



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Reverse engineering

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

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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

Reverse engineering

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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

Reverse engineering

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A testing with our MC sets:

1) We generated a benchmark
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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
$\kappa_{hhh} = 1.208\text{e-}01$		$\kappa_{hhh} = 8.430\text{e-}02$
$\kappa_{htt} = -3.309\text{e-}02$		$\kappa_{htt} = -5.972\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = 5.965$		$\kappa^{11}_{h\tilde{t}\tilde{t}} = -1.203$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 9.598$		$\kappa^{12}_{h\tilde{t}\tilde{t}} = 10.000$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 7.825$		$\kappa^{22}_{h\tilde{t}\tilde{t}} = 3.022$
$\kappa^{11}_{hh\tilde{t}\tilde{t}} = -6.874\text{e-}01$		$\kappa^{11}_{hh\tilde{t}\tilde{t}} = 1.369$
$\kappa^{22}_{hh\tilde{t}\tilde{t}} = -6.437\text{e-}01$		$\kappa^{22}_{hh\tilde{t}\tilde{t}} = 5.366$

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?

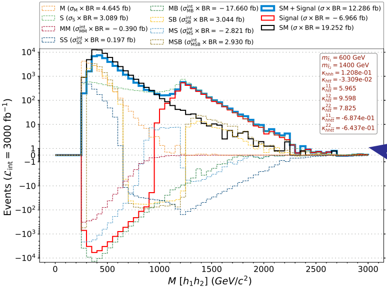
Reverse engineering

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

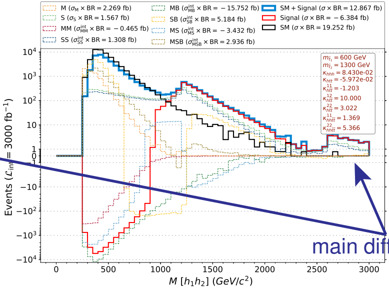
A testing with our MC sets:

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

Original benchmark



Fitted benchmark



main difference

Different parameter sets lead to very similar distributions

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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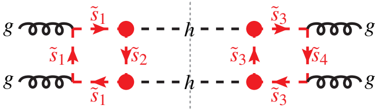
New particles

- **Coloured scalars:** { Charge is not important; At most 4 particles }



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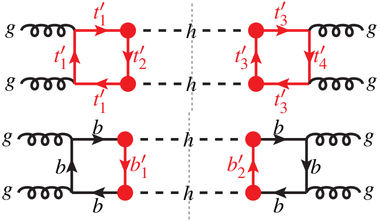

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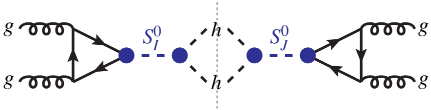

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$SU(3)$ representation is not important for MC simulations
factorisation of color coefficients in the deconstruction

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$SU(3)$ representation is not important for MC simulations
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New couplings

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

Other applications
studies of vector-like quarks

Papers using preliminary deconstruction techniques

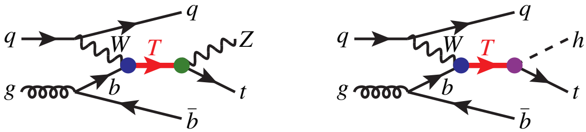
A. Carvalho, S. Moretti, D. O'Brien, **LP** and H. Prager, Phys. Rev. D **98** (2018) no.1, 015029

A. Deandrea, T. Flacke, B. Fuks, **LP** and H. S. Shao, JHEP **08** (2021), 107

G. Corcella, A. Costantini, M. Ghezzi, **LP**, G. M. Pruna and J. Šalko, JHEP **10** (2021), 108

The large width regime

example for W-mediated production



In the narrow-width approximation - no interference with the SM background

$$\sigma(\kappa_W, \kappa_Z \text{ or } \kappa_h, m_T, \Gamma_T) = \sigma_P(\kappa, m_T) BR_{T\to\text{decay channel}} = \kappa_W^2 \hat{\sigma}_{NWA}(m_T) BR_{T\to\text{decay channel}}$$

When the width is large (compared to the mass)

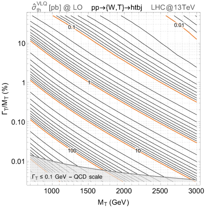
$$\begin{aligned}
\sigma_{\text{tot}}(pp \to Wbbj) &= \sigma^{\text{SM}}_{Wb} + \kappa_W^4\, \hat{\sigma}^{\text{VLQ}}_{Wb}(M_T, \Gamma_T) + \kappa_W^2\, \hat{\sigma}^{\text{int}}_{Wb}(M_T, \Gamma_T)\,, \\
\sigma_{\text{tot}}(pp \to Ztbj) &= \sigma^{\text{SM}}_{Zt} + \kappa_W^2 \kappa_Z^2\, \hat{\sigma}^{\text{VLQ}}_{Zt}(M_T, \Gamma_T) + \kappa_W \kappa_Z\, \hat{\sigma}^{\text{int}}_{Zt}(M_T, \Gamma_T)\,, \\
\sigma_{\text{tot}}(pp \to htbj) &= \sigma^{\text{SM}}_{ht} + \kappa_W^2 \kappa_h^2\, \hat{\sigma}^{\text{VLQ}}_{ht}(M_T, \Gamma_T) + \kappa \kappa_h\, \hat{\sigma}^{\text{int}}_{ht}(M_T, \Gamma_T)
\end{aligned}$$

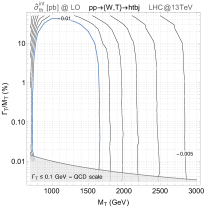
- κ_W, κ_Z **and** κ_h **couplings**: partial widths and rescaling of cross-section
- **Mass and total width**: kinematics of the process

Consistency relation: $\Gamma_T^{\text{partial}}(\kappa_W) + \Gamma_T^{\text{partial}}(\kappa_Z \text{ or } \kappa_h) \leq \Gamma_T$

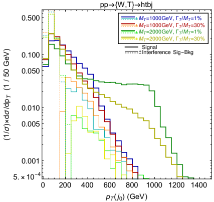
The large width regime

Mass vs total width reduced cross-sections





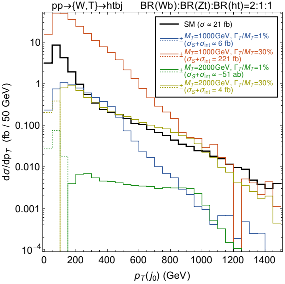
Differential distributions



Physical scenario 1

different masses and total widths

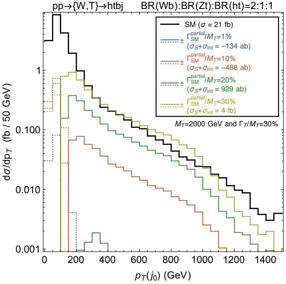
100% SM interactions



Physical scenario 2

same mass and total width

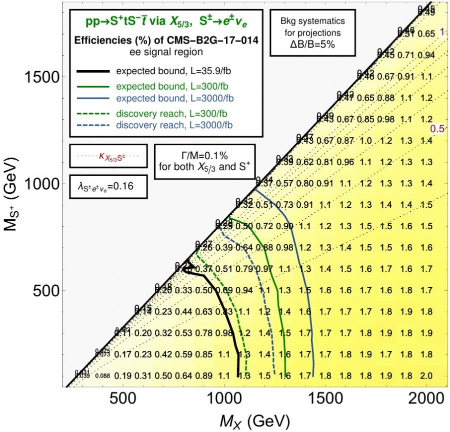
but $\leq$100% SM interactions



Exotic decays

efficiency tables for pair production of $X_{5/3}$ VLQ

The deconstructed samples can be processed through recasting tools



- 3 particles: $X_{5/3}$, S^+ and S^{++}
- Chain decay:
  $$\begin{cases} X_{5/3} \to S^+ t \to l^+ \nu_l t \\ X_{5/3} \to S^{++} b \to l^+ l^+ b \end{cases}$$
- Efficiencies in the mass-mass plane

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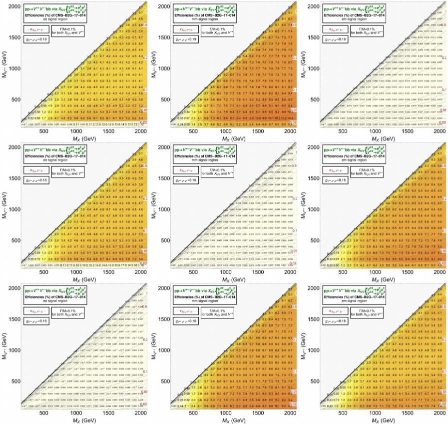

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- Efficiencies in the mass-mass plane
- Compute for each final state (including unphysical combinations)
- Use the efficiencies as further weights for the recombination

Deconstruction framework

modular **collaborative** **flexible** **resource-friendly**

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Further developments

- Develop a **public portal**
- Include **further final states** and **EFT operators**

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- Requires a tight **organizing principle**, to allow for expansions
- Implement fast and reliable **interpolation methods**

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- Storage space
- Person-power to develop all the above (only me on the software part so far...)

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Multidisciplinary aspects

- The idea can be extended to **other domains in physics and not only**
- Develop tools to address **completely different problems** as long as they can be deconstructed