Deconstructing signals of new physics at collider

a case study with Higgs pair production and other applications

Luca Panizzi

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Looking for new physics at the LHC

general considerations

Problems

- Proliferation of 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

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Disk space and **computing time** are often very limited
Computations have an **environmental impact**

But not many efforts to address this issue within HEP (PH and TH)

arXiv > physics > arXiv:2203.12389

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Physics > Physics and Society

[Submitted on 23 Mar 2022 (v1), last revised 23 Aug 2022 (this version, v2)]

Climate impacts of particle physics

Kenneth Bloom, Veronique Boisvert, Daniel Britzger, Micah Buuck, Astrid Eichhorn, Michael Headley, Kristin Lohwasser, Petra Merkel

The pursuit of particle physics requires a stable and prosperous society. Today, our society is increasingly threatened by global climate change. Human-influenced climate change has already impacted weather patterns, and global warming will only increase unless deep reductions in emissions of CO_2 and other greenhouse gases are achieved. Current and future activities in particle physics need to be considered in this context, either on the moral ground that we have a responsibility to leave a habitable planet to future generations, or on the more practical ground that, because of their scale, particle physics projects and activities will be under scrutiny for their impact on the climate. In this white paper for the U.S. Particle Physics Community Planning Exercise ("Snowmass"), we examine several contexts in which the practice of particle physics has impacts on the climate. These include the construction of facilities, the design and operation of particle detectors, the use of large-scale computing, and the research activities of scientists. We offer recommendations on establishing climate-aware practices in particle physics, with the goal of reducing our impact on the climate. We invite members of the community to show their support for a sustainable particle physics field (this https URL).

Comments: contribution to Snowmass 2021
Subjects: **Physics and Society (physics.soc-ph)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2203.12389 **[physics.soc-ph]**
(or arXiv:2203.12389v2 **[physics.soc-ph]** for this version)
https://doi.org/10.48550/arXiv.2203.12389

arXiv:2203.12389

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Devise strategies to optimise and share resources

Goals

- **TH/PH:** improve recast possibilities
- **PH/EXP:** design new search strategies to explore new avenues
- **EXP:** improve signal modeling and data interpretation

Using public simulated datasets

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A possible way

The deconstruction framework

This has already been applied to di-Higgs production with squark propagation

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

arXiv > hep-ph > arXiv:2302.03401

Search...
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High Energy Physics - Phenomenology

[Submitted on 7 Feb 2023 (v1), last revised 19 May 2023 (this version, v2)]

Deconstructing squark contributions to di-Higgs production at the LHC

Stefano Moretti, Luca Panizzi, Jörgen Sjölin, Harri Waltari

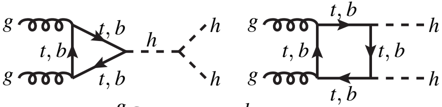
We present a novel approach to the study of di-Higgs production via gluon-gluon fusion at the LHC. The relevant Feynman diagrams involving two Standard Model-like Higgs bosons hh are computed within a simplified model approach that enables one to interpret possible signals of new physics in a model-independent way as well as to map these onto specific theories. This is possible thanks to a decomposition of such a signal process into all its squared amplitudes and their relative interferences, each of which has a well-defined coupling structure. We illustrate the power of this procedure for the case of both a minimal and next-to-minimal representation of Supersymmetry, for which the new physics effects are due to top squarks entering the loops of $gg \to hh$. The squarks yield both a change of the integrated cross section and peculiar kinematic features in its differential distributions with respect to the Standard Model. These effects can in turn be traced back to the relevant diagrammatic and coupling structures and allow for a detailed analysis of the process. In order to do so, we perform systematic scans of the parameter spaces of such new physics scenarios and identify benchmark points which exhibit potentially observable features during the current and upcoming runs of the LHC.

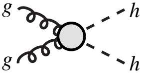
Comments: Version accepted by PRD. 18 pages, 11 figures, 4 tables
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2302.03401 **[hep-ph]**
(or arXiv:2302.03401v2 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.2302.03401

I'll use this process as illustrative example of the analysis strategy

The very same procedure can be applied to any other process

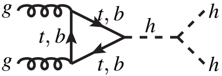
Signal elements

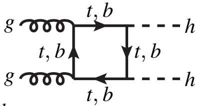
The Standard model topologies: 

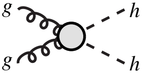
A new physics signal: 

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

Signal elements

The Standard model topologies: 



A new physics signal: 

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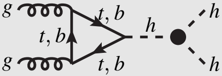
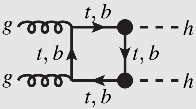
Modified SM couplings





Signal elements

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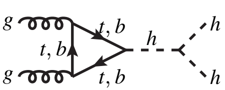
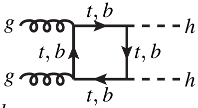
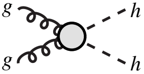




A new physics signal:



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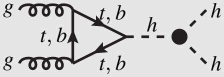
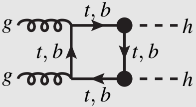
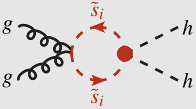
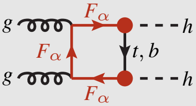




New coloured particles





Signal elements

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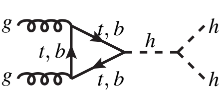
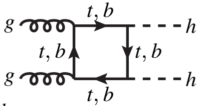
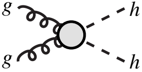




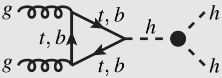
A new physics signal:

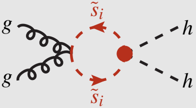


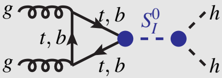
What can the signal be from a general perspective?

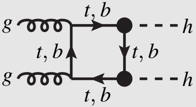
(limiting to gluon-fusion processes)

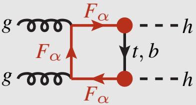
Modified SM couplings	New coloured particles	New neutral particles

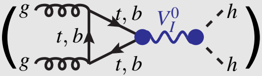








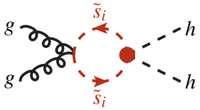




And combinations of these ingredients

The number of possibilities is limited!

Reduced cross-sections

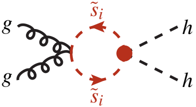
Let's take one signal contribution: 

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**

Reduced cross-sections

Let's take one signal contribution: 

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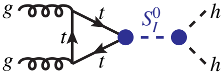
- $\hat{\sigma}(m_{\tilde{s}_i})$: kinematics of the process $\longrightarrow$ **reduced cross-section**

Let's add another contribution: 

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

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

- **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

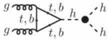
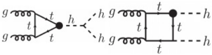
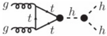
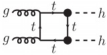
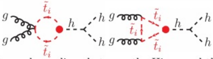
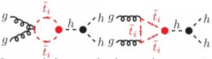
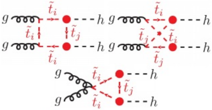
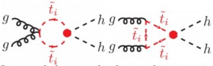
The recipe

1) Deconstruction
Identify all combinations proportional to unique couplings products

2) Database
Simulate individual MC event samples in a $\{m_{\tilde{q}_1}, m_{\tilde{q}_2}, \ldots\}$ 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.		

A simplified scenario
2 squarks and
modified SM couplings

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

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

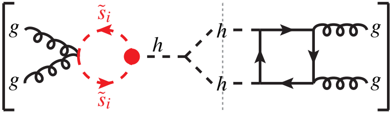
B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

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:

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



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

Topology "5" SM topology

2) Database generation

Need to perform separate MC simulations for each deconstructed term

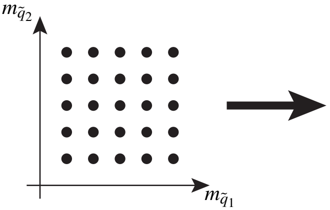
1) Use MG5_aMC with dedicated UFO models built in FeynRules
2) Associate individual coupling orders to each new coupling
3) Use specific simulation syntax for each process

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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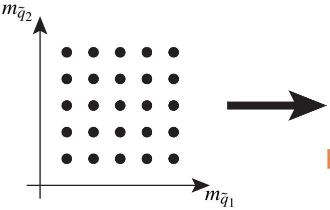

Database of samples
simulated once and for all

But what is in the database?

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database content

Parton level		Reconstructed particles	Recast
LHE from MG5_aMC	piping through Pythia 8 →	**LHE** FastJet via MA5 / **ROOT** from RIVET	→ **Efficiency tables**
∼ 100Mb per 100k events		∼ 80Mb LHE, ∼ 200Mb ROOT	$\mathcal{O}$(Kb)

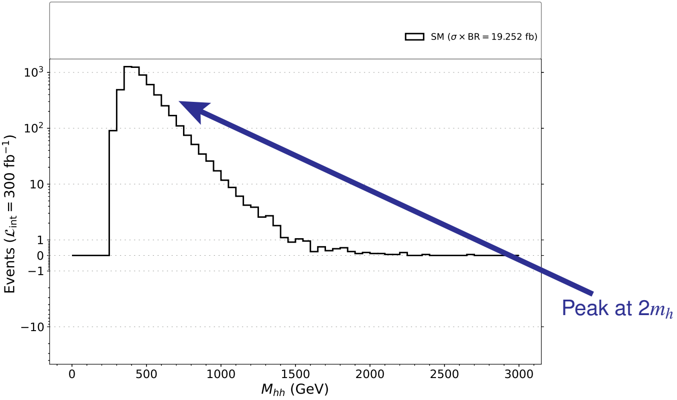
The grid doesn't need to be too dense ⟶ interpolation between points

Interrogate the database to select relevant samples

3) Recombination

invariant mass distribution m_{hh}

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



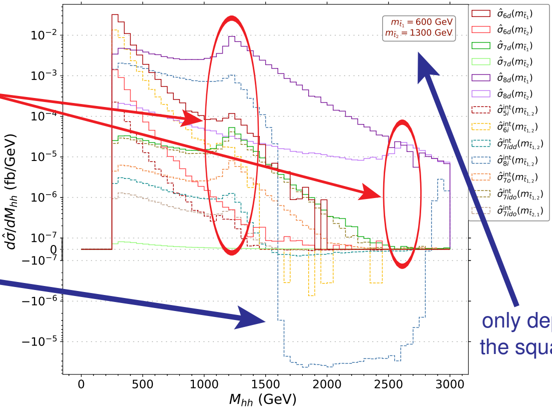
3) Recombination

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

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



Negative interference between topologies

only depending on the squark masses

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

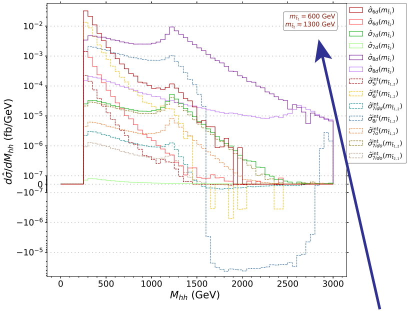
3) Recombination

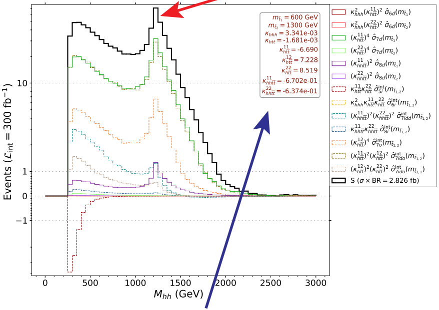
invariant mass distribution m_{hh}

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!**

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

3) Recombination

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)
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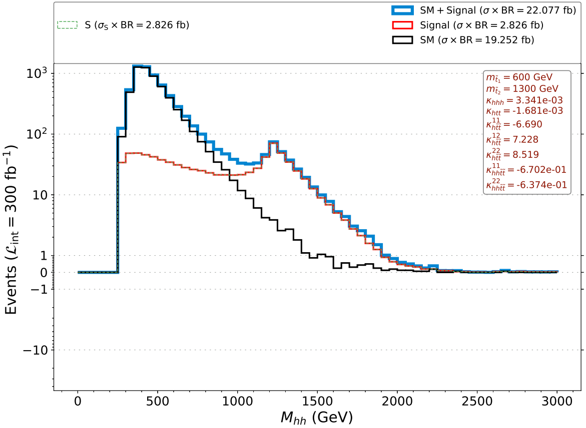

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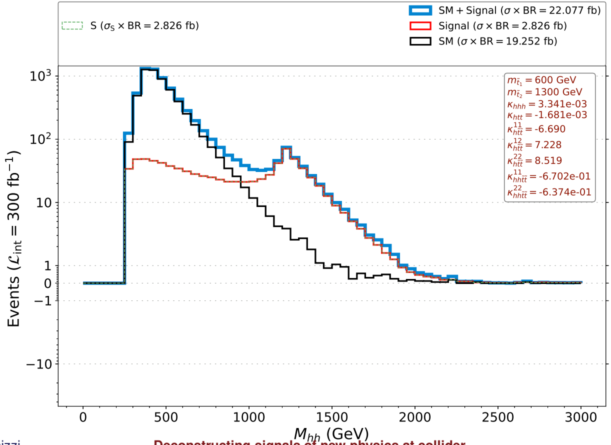

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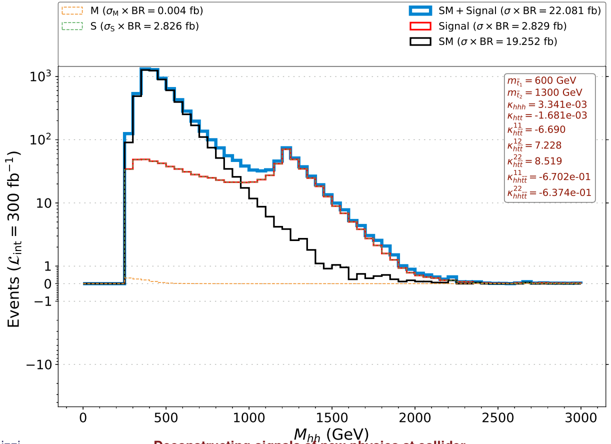

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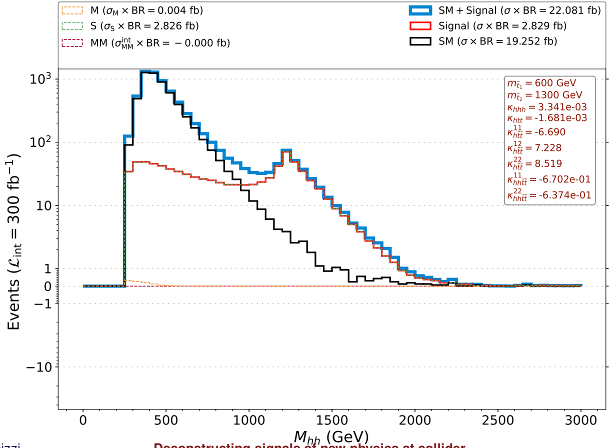

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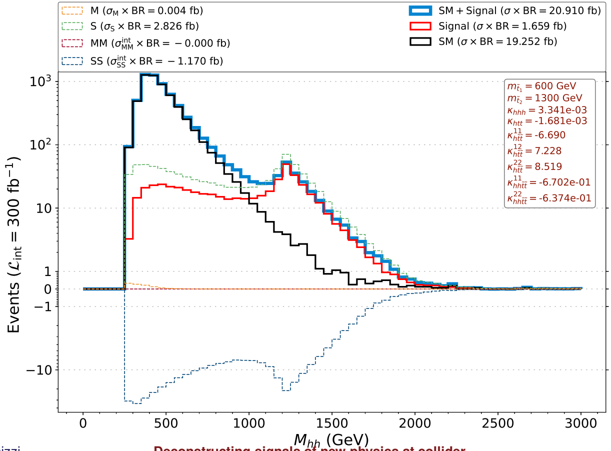

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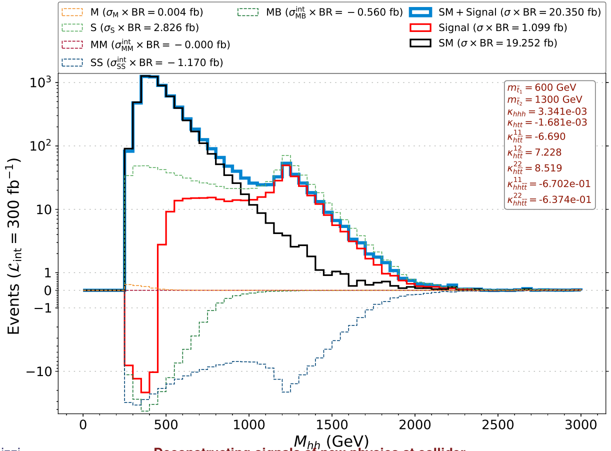

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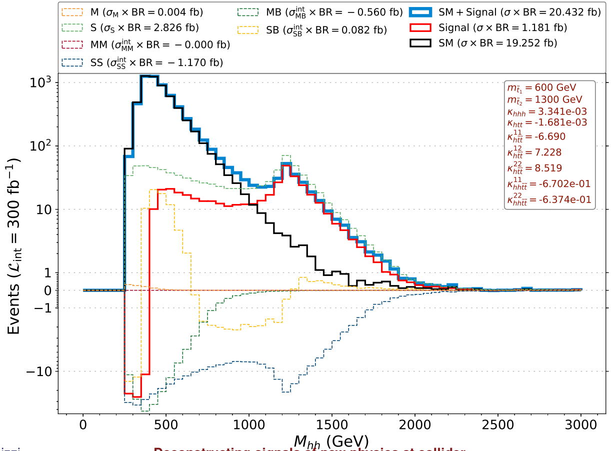

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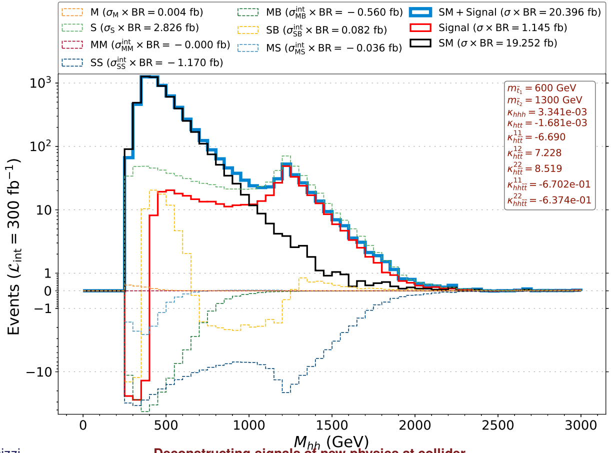

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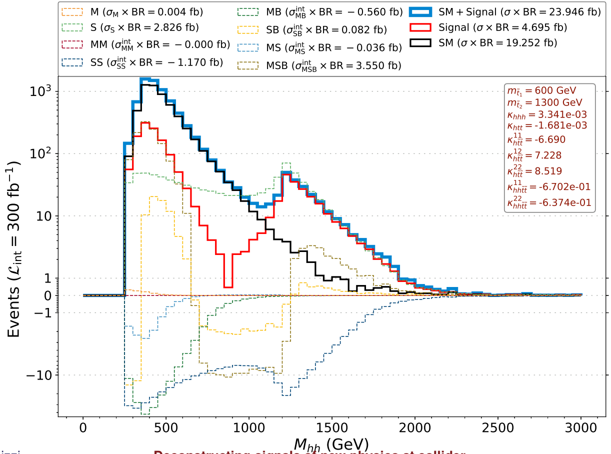
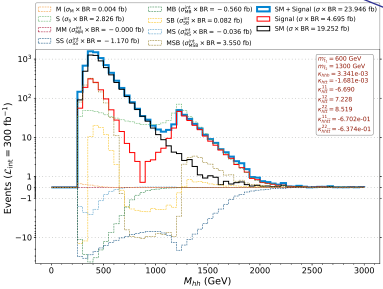


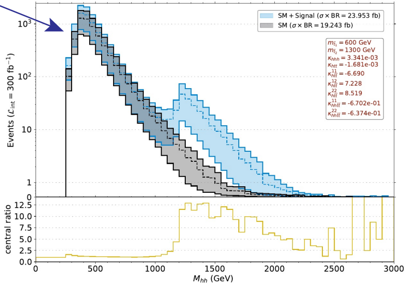
including systematics

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
- 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,...

Reverse engineering

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

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$m_{\tilde{t}_1} = 600$ GeV		$m_{\tilde{t}_1} = 600$ GeV
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$\kappa_{hhh} = 1.208\text{e-}01$		$\kappa_{hhh} = 8.430\text{e-}02$
$\kappa_{htt} = -3.309\text{e-}02$		$\kappa_{htt} = -5.972\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = 5.965$		$\kappa^{11}_{h\tilde{t}\tilde{t}} = -1.203$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 9.598$		$\kappa^{12}_{h\tilde{t}\tilde{t}} = 10.000$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 7.825$		$\kappa^{22}_{h\tilde{t}\tilde{t}} = 3.022$
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Caveats:

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- MSSM relations between couplings were assumed, but the point was random

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But how wrong is this fit?

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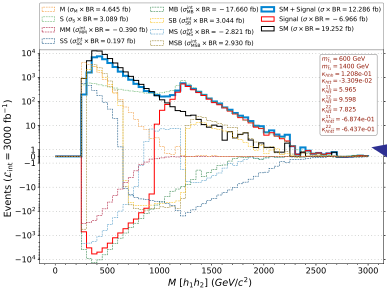
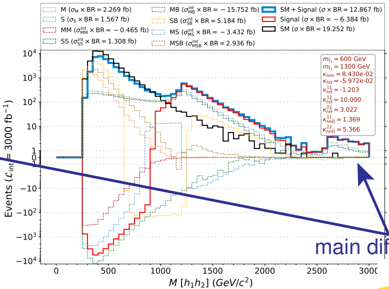
Original benchmark



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?

Extending the di-Higgs analysis

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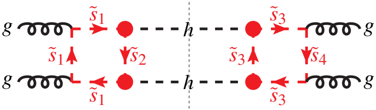
New particles

- **Coloured scalars:** $\begin{cases} \text{Charge is not important} \\ \text{At most 4 particles} \end{cases}$



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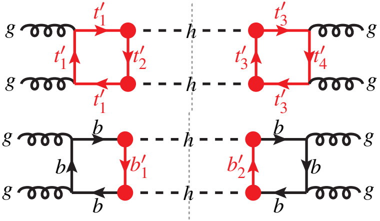

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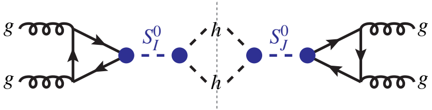

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factorisation of color coefficients in the deconstruction

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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

vector-like quark and dark matter studies

Papers using preliminary deconstruction techniques

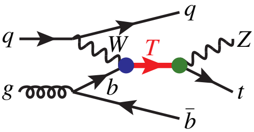
A. Carvalho, S. Moretti, D. O'Brien, **LP** and H. Prager, Phys. Rev. D **98** (2018) no.1, 015029

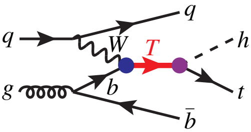
A. Deandrea, T. Flacke, B. Fuks, **LP** and H. S. Shao, JHEP **08** (2021), 107

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

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

When the width is large (compared to the mass)

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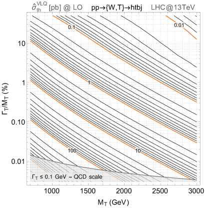
\end{aligned}$$

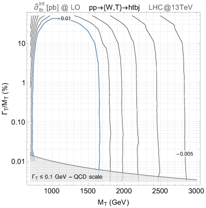
- κ_W, κ_Z **and** κ_h **couplings**: partial widths and rescaling of cross-section
- **Mass and total width**: kinematics of the process

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

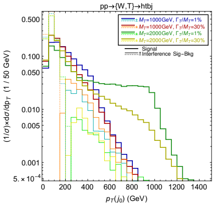
The large width regime

Mass vs total width reduced cross-sections



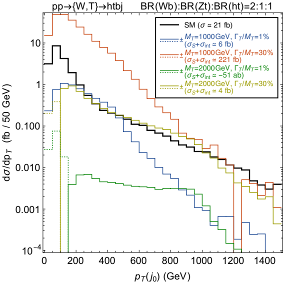


Differential distributions



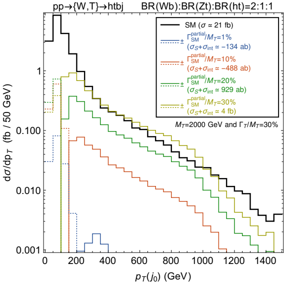
Physical scenario 1

different masses and total widths
100% SM interactions



Physical scenario 2

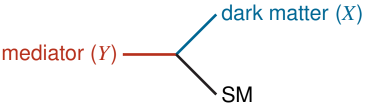
same mass and total width
but $\leq$100% SM interactions

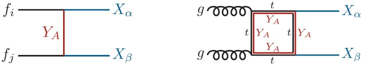
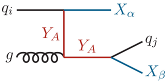
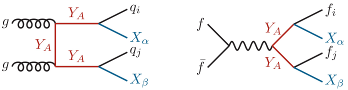
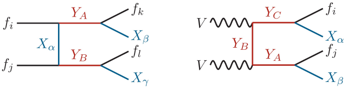


Dark matter

t-channel scenarios

Study of scenarios based on the schematic interaction:



process	Representative topologies
XX	
XY	
YY (QCD/DY)	
YY (t-channel/VBF)	

Relatively small number of possibilities can cover a large number of theoretical scenarios

Work in progress in the LHCDMWG

Deconstruction framework

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

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Further developments

- Develop a **public portal**
- Include **further final states**

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Challenges

- Design **simulation grids** which minimize computing resources
- Requires a tight **organizing principle**, to allow for expansions
- Implement fast and reliable **interpolation methods** → Work in progress

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Limitations

- Relatively simple final states
- Storage space ($\lesssim$350 GB for HH with all coloured and neutral scalars)
- 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

Backup

1) Deconstruction

Cross-section

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

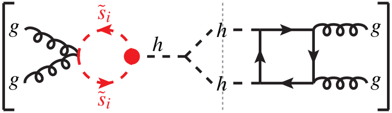
B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

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

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

The first element, graphically:

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



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

Topology "5" SM topology

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

1) Deconstruction

Cross-section

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

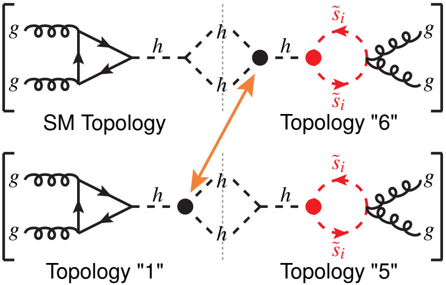
B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

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 $\sigma^{\text{int}}_{1,5}(m_{\tilde{t}_i})$:

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

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



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

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

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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)

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

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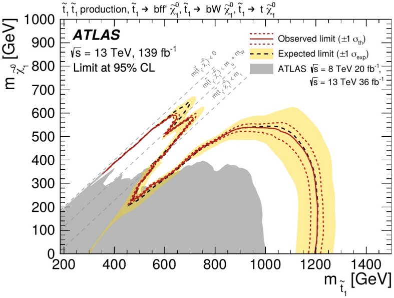
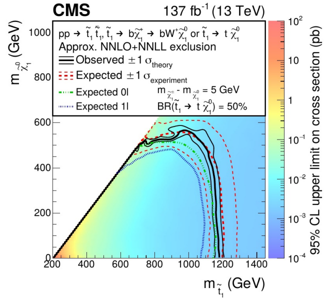
3) Experimental bounds on stop masses: $m_{\tilde{t}_1} \gtrsim 600$ GeV (if small mass gap with LSP) and $m_{\tilde{t}_2} \gtrsim 1250$ GeV





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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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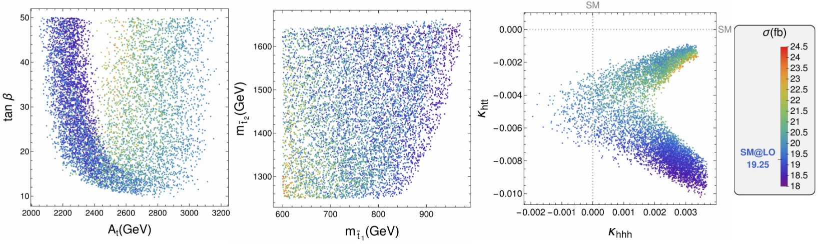
Scan results



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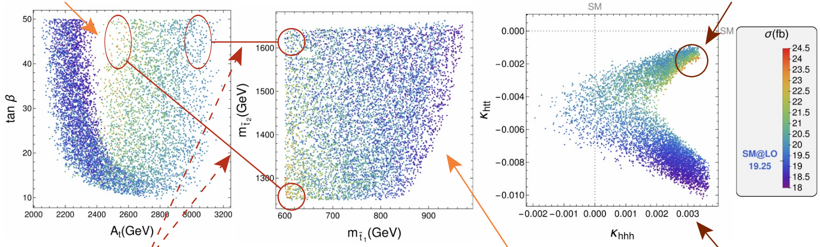
Here the Higgs is too heavy

Highest increases for small Yukawa coupling

Scan results



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

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An MSSM benchmark point with high cross-section

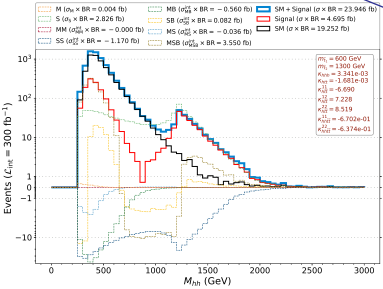
Masses and couplings	Value
$m_{\tilde{t}_1}$ (GeV)	600.6
$m_{\tilde{t}_2}$ (GeV)	1301.0
κ_{hhh}	3.34×10^{-3}
κ_{htt}	-1.68×10^{-3}

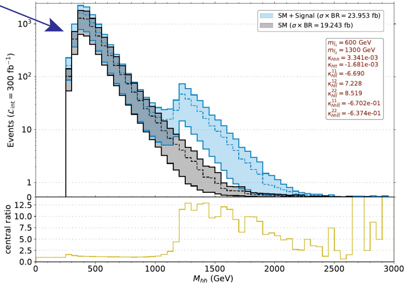
Masses and couplings	Value
$\begin{pmatrix} \kappa^{11}_{h\tilde{t}\tilde{t}} & \kappa^{12}_{h\tilde{t}\tilde{t}} \\ \cdot & \kappa^{22}_{h\tilde{t}\tilde{t}} \end{pmatrix}$	$\begin{pmatrix} -6.690 & 7.228 \\ \cdot & 8.519 \end{pmatrix}$
$\begin{pmatrix} \kappa^{11}_{hh\tilde{t}\tilde{t}} & \kappa^{12}_{hh\tilde{t}\tilde{t}}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

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

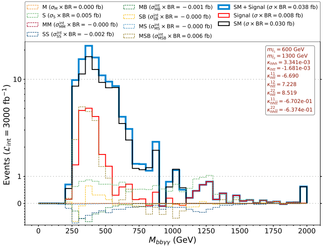
$bb\gamma\gamma$	$bb\tau\tau$	$bbbb$
$N(b) > 1$	$N(b) > 1$	$N(b) > 3$
$N(\gamma) > 1$	$N(\tau) > 1$	–
$p_T(b) > 45$ (20) GeV	$p_T(b) > 45$ (20) GeV	$p_T(b) > 40$ GeV
$\|\eta(b)\| < 2.5$	$\|\eta(b)\| < 2.5$	$\|\eta(b)\| < 2.5$
$\|\eta(\gamma)\| < 2.5$	$\|\eta(\tau)\| < 2.5$	–
120 GeV $< M(\gamma\gamma)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

3) Recombination

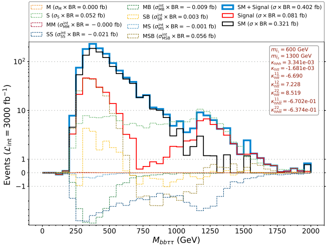
invariant mass at reconstruction level

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

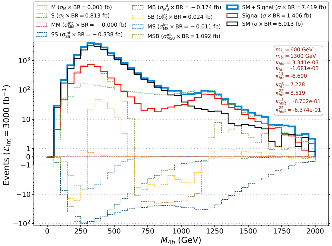
$b\bar{b}\gamma\gamma$



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



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



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

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**:
- New scalar allows to obtain m_h=125 GeV at tree level
- 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

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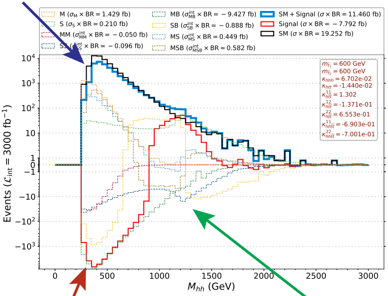
deficit
at low m_{hh}

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



large negative
MB interference

Large peak cancellation
despite 2 light stops

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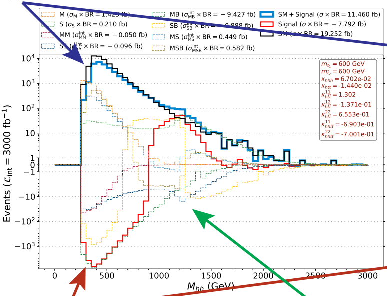
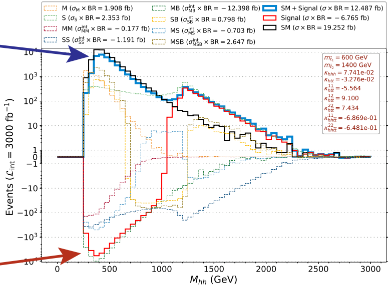


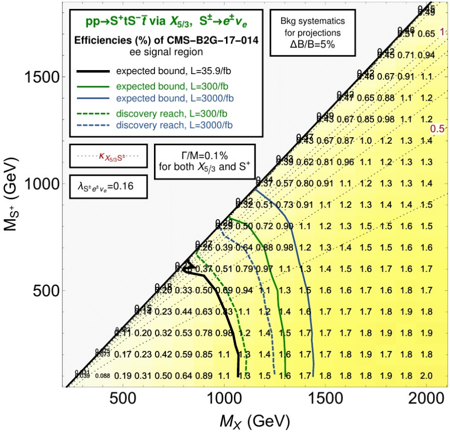
MSSM-like masses but $\lambda \simeq 1.6\lambda^{\rm SM}$



large negative MB interference

Large peak cancellation despite 2 light stops

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

Exotic decays

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

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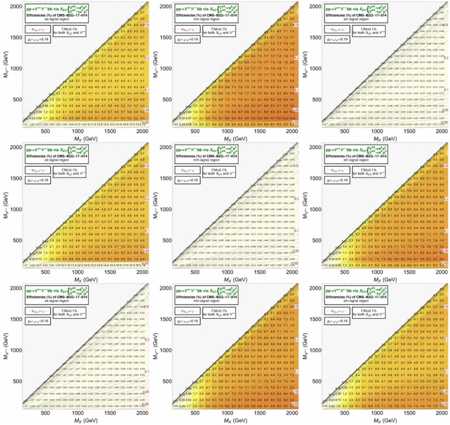

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$$\begin{cases} X_{5/3} \to S^+ t \to l^+ \nu_l t \\ X_{5/3} \to S^{++} b \to l^+ l^+ b \end{cases}$$
- Efficiencies in the mass-mass plane
- Compute for each final state (including unphysical combinations)
- Use the efficiencies as further weights for the recombination