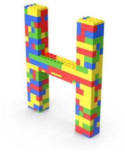
Deconstructing signals of new physics at colliders

a case study with Higgs pair production

Luca Panizzi

UNIVERSITÀ DELLA CALABRIA

IRN Terascale



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

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

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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

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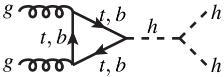
Using public simulated datasets

A possible way

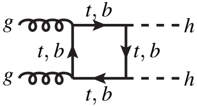
Deconstruct new signals

Looking for new physics at the LHC

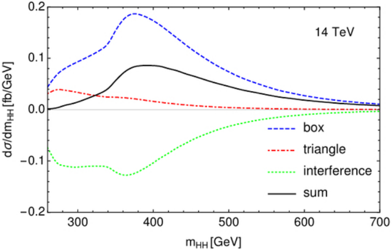
the di-Higgs case



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



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



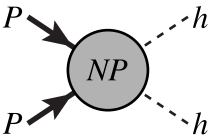
B. Di Micco *et al.* Rev. Phys. **5** (2020), 100045

- di-Higgs as a probe of Higgs self-interactions
- HL-LHC has the potential to discover Higgs pair production
- sizable deviations from the SM might be associated with light particles
  - → coupling modifiers do not catch all shape deviations
  - → the EFT approach might not be always applicable

Deconstruct di-Higgs and see what we can extract

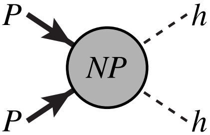
S. Moretti, **LP**, J. Sjölin, H. Waltari, Phys. Rev. D **107** (2023) no.11, 115010 (only non-resonant case)
S. Moretti, **LP**, J. Sjölin, H. Waltari, Phys. Rev. D **112** (2025) no.5, 055005 (adding resonant contributions)

Di-Higgs signal elements



What can the signal be from a general perspective?

Di-Higgs signal elements



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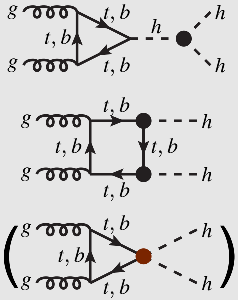
Modified SM



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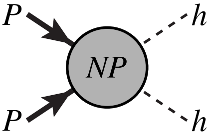

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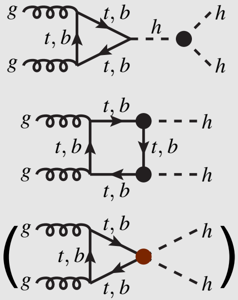
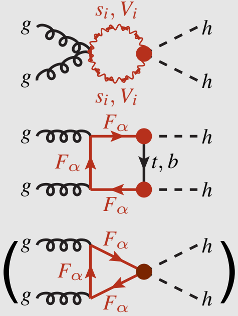
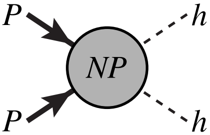


New coloured particles

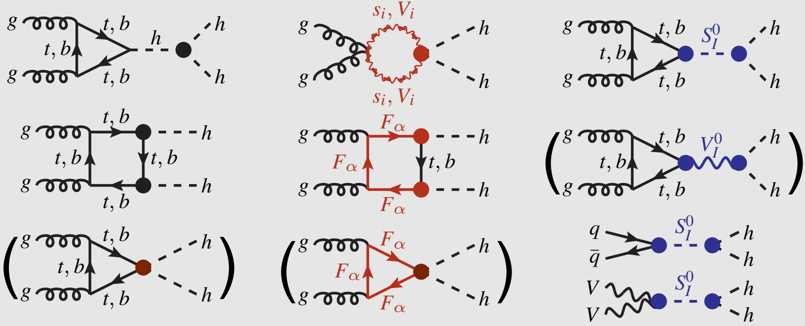


Di-Higgs signal elements



What can the signal be from a general perspective?

Modified SM	New coloured particles	New neutral particles

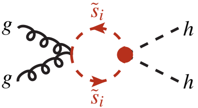


And combinations of these ingredients

The number of possibilities is limited!

Reduced cross-sections

Let's take one signal contribution:

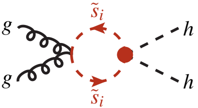


with $\mathcal{L} = \kappa_{hh\tilde{s}_i\tilde{s}_i}\, hh\tilde{s}_i^*\tilde{s}_i$

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

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

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- $\kappa_{hh\tilde{s}_i\tilde{s}_i}$: rescaling of the cross-section
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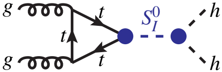
Let's add another contribution:  with $\mathcal{L} = \kappa^I_{Shh} v\ S^0_I hh + \kappa^I_{Stt}\ S^0_I \bar{t}t$

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

- **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

The recipe

For a given process, broadly defined as "initial state $\rightarrow$ final state" at parton level

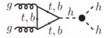
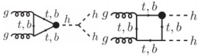
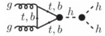
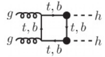
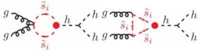
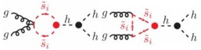
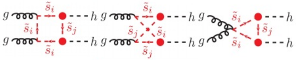
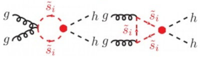
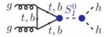
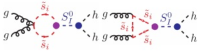
1) Deconstruction
Identify all combinations proportional to **unique couplings products**

2) Database building
Simulate individual samples in a multidimensional grid of **parameters which affect kinematics** and store the samples

3) Recombination
Analyse the process for any choice of theory parameters (masses, couplings, BRs. . .) by doing a **weighted sum** of the deconstructed samples

Samples are recycled if there are more particles with same relevant parameters
masses, widths. . .

1) Deconstruction

	Topology type	Feynman diagrams	Amplitude
1	Modified hhh coupling		$\mathcal{A}_i \propto \kappa_{hhh}$
2	One modified hff coupling		$\mathcal{A}_i \propto \kappa_{hff}$
3	Modified hhh coupling and modified hff coupling		$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{hff}$
4	Two modified hff couplings		$\mathcal{A}_i \propto \kappa^2_{hff}$
5	Scalar bubble and triangle with $h\tilde{s}\tilde{s}$ couplings		$\mathcal{A}_i \propto \kappa^{ii}_{h\tilde{s}\tilde{s}}$
6	Modified hhh coupling + Scalar bubble and triangle with $h\tilde{s}\tilde{s}$ coupling		$\mathcal{A}_i \propto \kappa_{hhh}\kappa^{ii}_{h\tilde{s}\tilde{s}}$
7	Scalar triangle and box with two $h\tilde{s}\tilde{s}$ couplings		$\mathcal{A}_i \propto \lvert\kappa^{ij}_{h\tilde{s}\tilde{s}}\rvert^2$
8	Scalar bubble and triangle with $hh\tilde{s}\tilde{s}$ coupling		$\mathcal{A}_i \propto \kappa^{ii}_{hh\tilde{s}\tilde{s}}$
9	Neutral scalar		$\mathcal{A}_i \propto \kappa^{I}_{Shh}\kappa^{I}_{Sff}$
10	Neutral scalar + coloured scalar		$\mathcal{A}_i \propto \kappa^{I}_{Shh}\kappa^{Ii}_{S\tilde{s}\tilde{s}}$

di-Higgs
in the NMSSM

10 kind of topologies

Minimal deconstruction ingredients

- modified SM couplings
- 4 coloured scalars (of any charge)
- 2 neutral scalars

1) Deconstruction

Cross-section

$$\sigma = \sigma_B + \sigma_M + \sigma_s + \sigma_S + \sigma_{Ss} + \sum_{i=M,s,S,Ss} \sigma^{int}_{i|B} + \sum_{i,j=M,s,S,Ss} \sigma^{int}_{i|j}$$

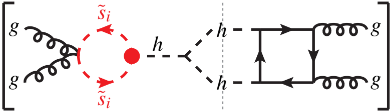
B: SM background, M: modified SM, s: squark propagation
S: neutral scalar propagation, Ss: neutral scalar+squark propagation

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

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

The first element, graphically:

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



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

Topology "5" SM topology

Each term is not physical *per se*, only the total sum is physical!

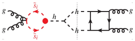
2) Database generation

Perform separate MC simulations for each deconstructed term

Example with MG5_aMC:
1) Associate individual coupling orders to each new coupling
2) Use specific simulation syntax for each process

Background:

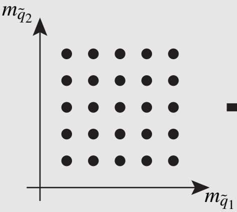
```
generate p p > h h [QCD] QCD^2==4 QED^2==4
```

5|B: 

```
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

Scan over relevant kinematic parameters for each contribution



Database of samples
simulated once and for all

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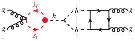
5|B: 

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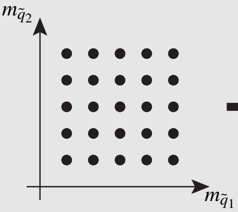

Database of samples
simulated once and for all

But what is in the database?

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Example with MG5_AMC:
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2) Use specific simulation syntax for each process

database content

Parton level		Reconstructed particles	Recast
LHE from MG5_AMC	piping through PYTHIA 8	**LHE** FASTJET via MA5 / **ROOT** from RIVET	**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

2) Database generation

Perform separate MC simulations for each deconstructed term

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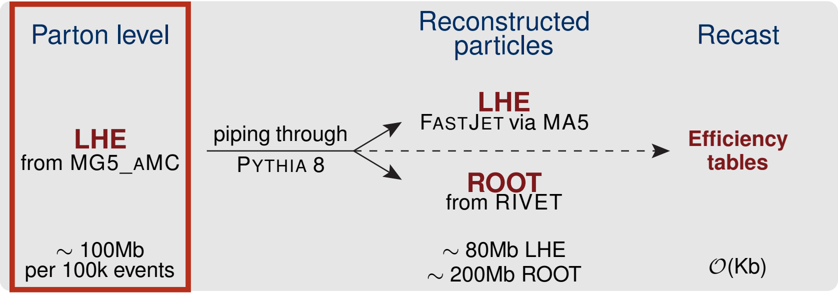

Core

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

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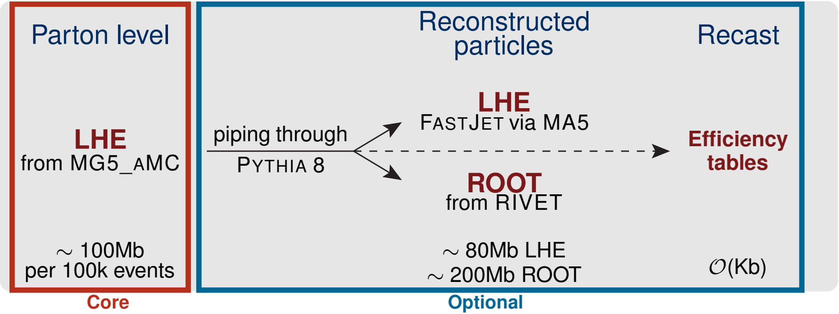
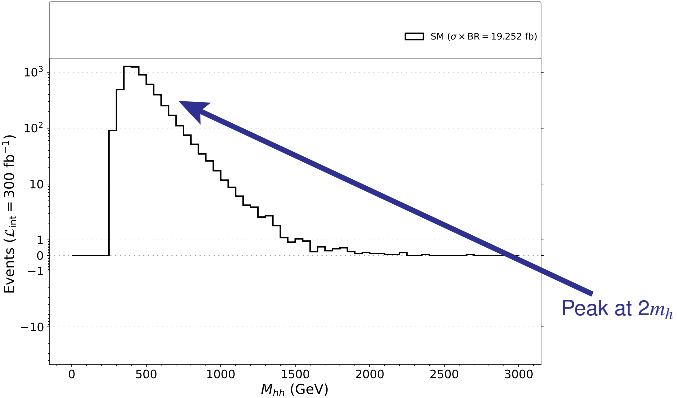


The grid doesn't need to be too dense ⟶ interpolation between points

3) Recombination

invariant mass distribution m_{hh}

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



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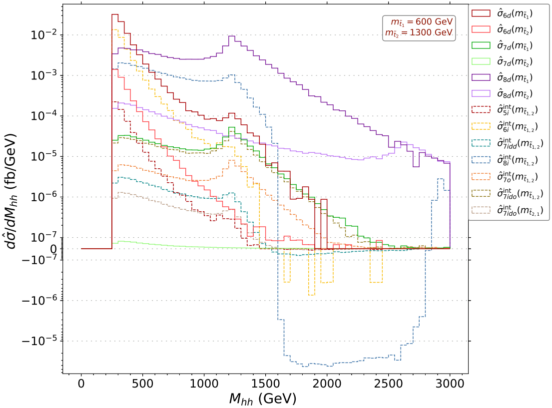
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)

Example with the σ_s elements

only squarks for the next few slides $\to$ **non-resonant case**



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

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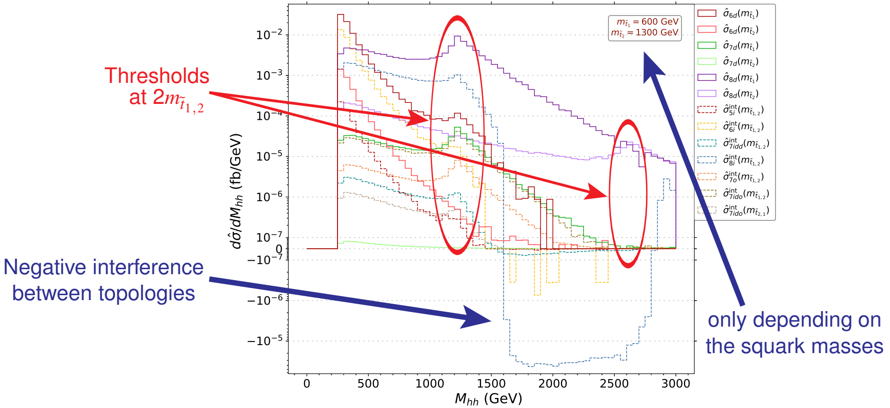

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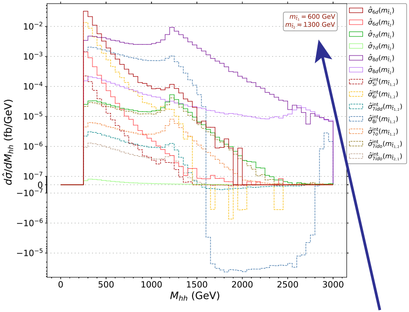

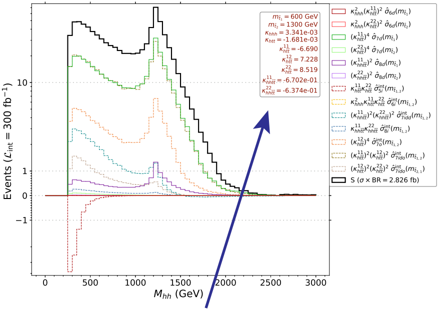

only depending on the squark masses

depending on masses and coupling

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

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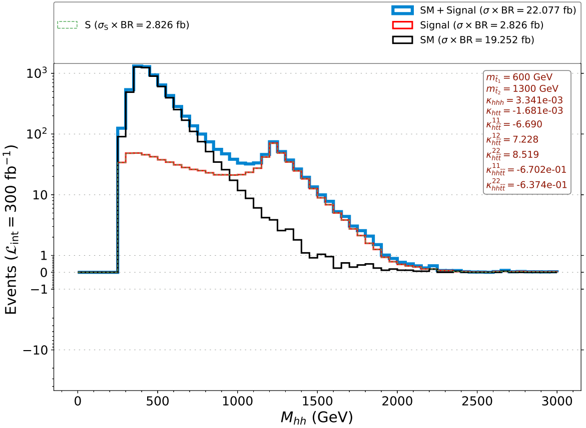

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invariant mass distribution m_{hh}

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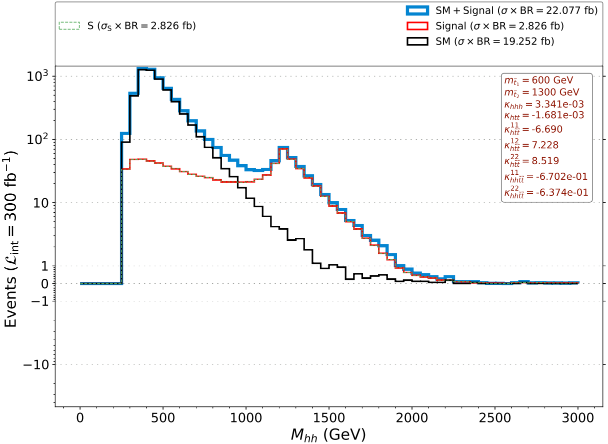
3) Repeat for all deconstructed elements



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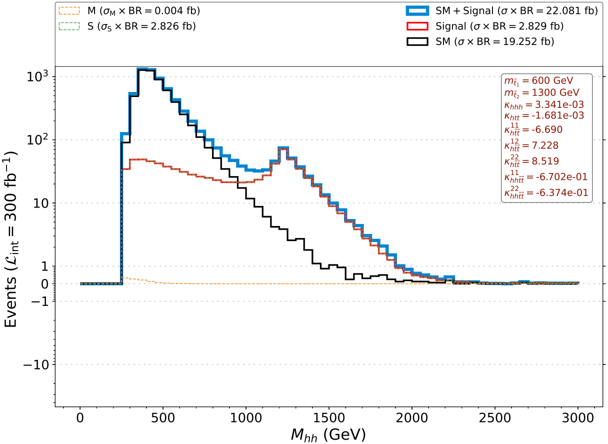

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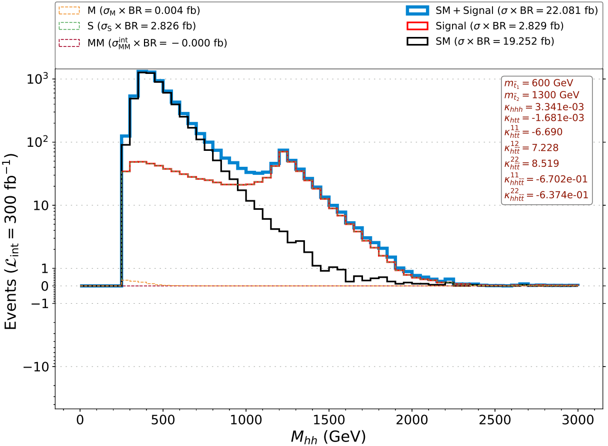

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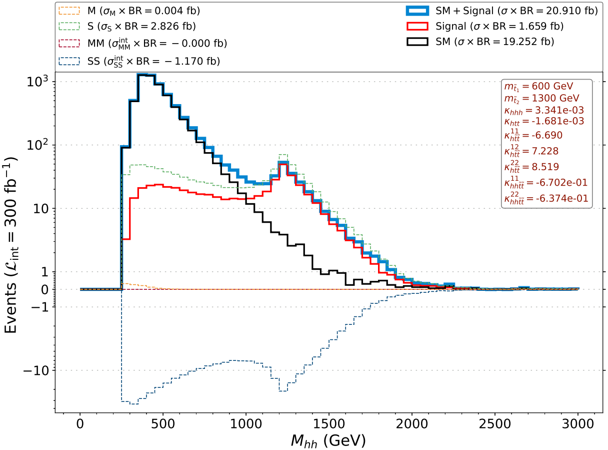

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invariant mass distribution m_{hh}

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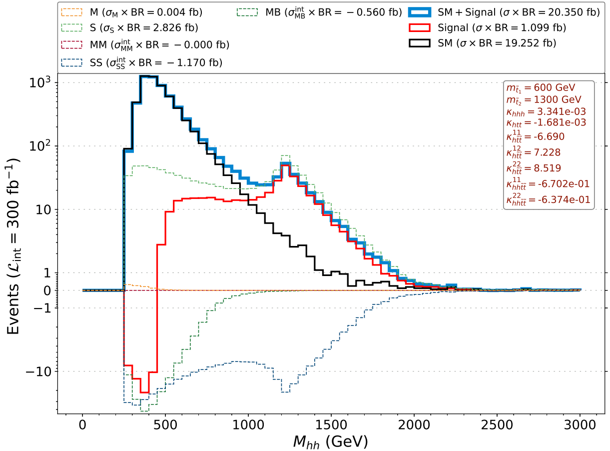

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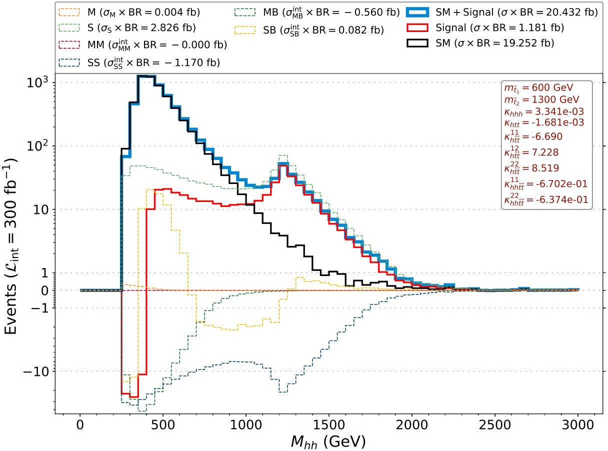

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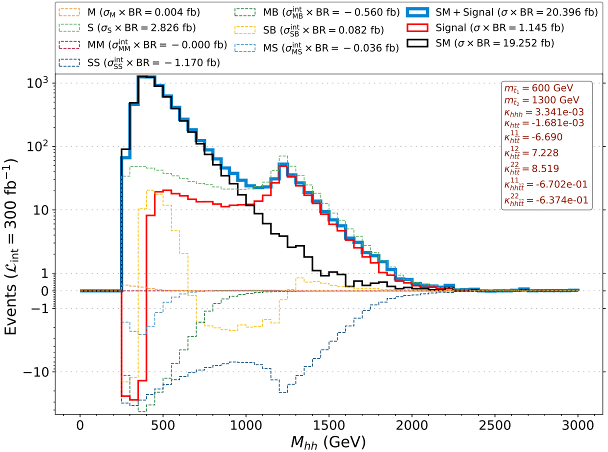

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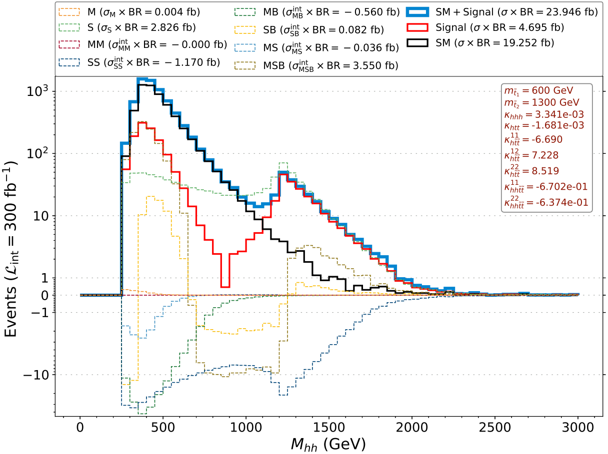
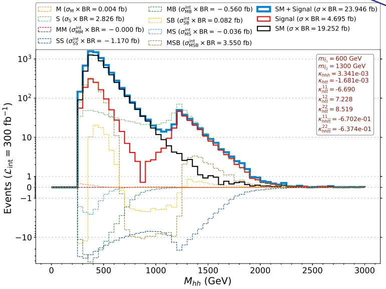


including systematics

independent simulation for cross-check



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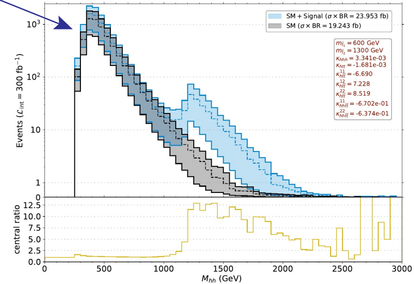


With the same database we can

- 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

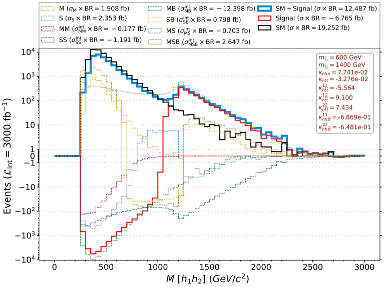
Adding resonances and all squarks

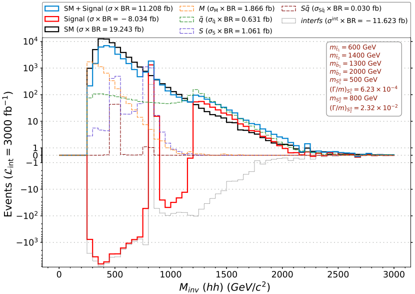
i.e. going full NMSSM

2 stops (one light)
2 sbottoms

A 500 GeV scalar singlet

A 800 GeV scalar doublet





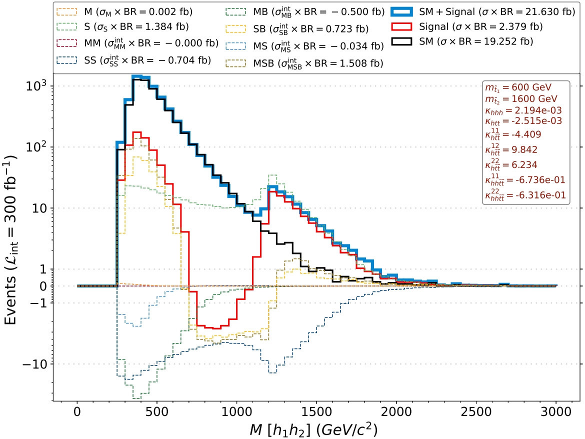
- Stronger **negative interference in the squark sector** above the threshold
- Stronger **event depletion at low** m_{hh}
- **Singlet scalar** nearly **invisible** (very small couplings to SM quarks)
- **Visible peak** from the **doublet resonance**

But this analysis has further scope

The EFT limit

gradually increasing $m_{\tilde{t}_1}$

$m_{\tilde{t}_1} = 600$ GeV, $m_{\tilde{t}_2} = 1600$ GeV



Smooth exploration of the interface between low scale and EFT limit

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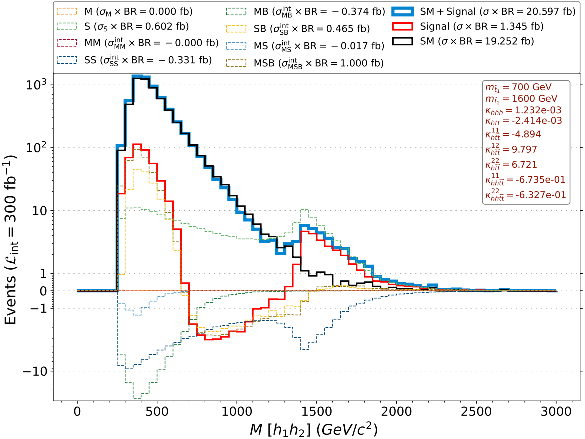

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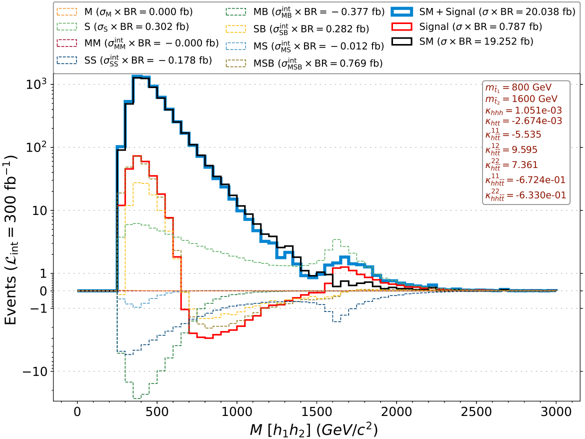

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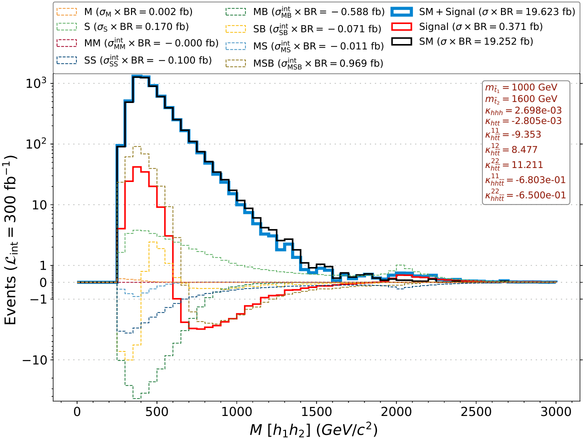

Smooth exploration of the interface between low scale and EFT limit

This approach contains and goes beyond EFT

It can be used to assess the validity range of EFT descriptions

Reverse engineering

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

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A testing with our MC sets:

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Input parameters	Fitted parameters
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$\kappa_{htt} = -3.309\text{e-}02$	$\kappa_{htt} = -5.972\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = 5.965$	$\kappa^{11}_{h\tilde{t}\tilde{t}} = -1.203$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 9.598$	$\kappa^{12}_{h\tilde{t}\tilde{t}} = 10.000$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 7.825$	$\kappa^{22}_{h\tilde{t}\tilde{t}} = 3.022$
$\kappa^{11}_{hh\tilde{t}\tilde{t}} = -6.874\text{e-}01$	$\kappa^{11}_{hh\tilde{t}\tilde{t}} = 1.369$
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Caveats:

- Only couplings were fitted, stop masses were assumed
- 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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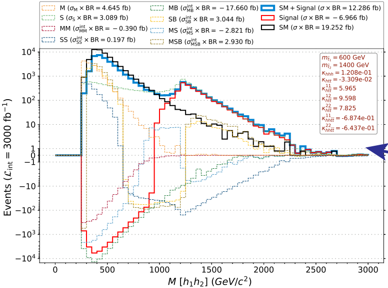
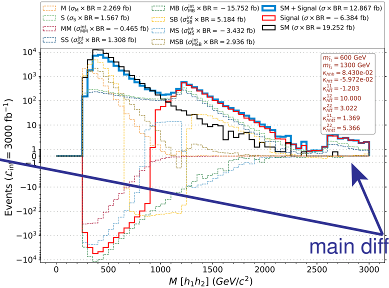


Fitted benchmark



main difference

Different parameter sets lead to very similar distributions

Reverse engineering

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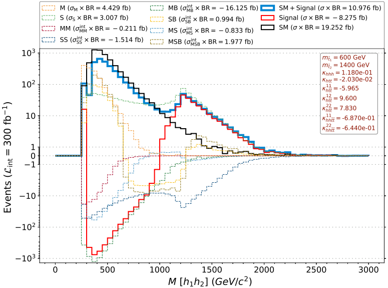
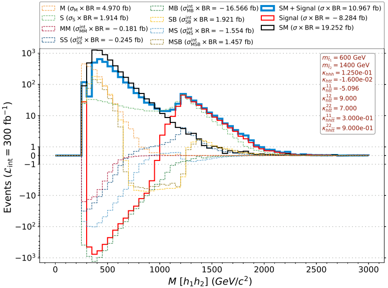
Second try

Original benchmark



Fitted benchmark



perfect fit with very close numerical values of relevant parameters!

Relative contributions are different **but fitted result is indistinguishable from original**

Classes of solutions can fit possible excesses

The technical part

Deconstructing di-Higgs with coloured and neutral scalars

Database grids

Coloured scalars masses (GeV):	600, 800, 1000, 1200, 1400
	2000 (EFT limit)
	700, 1300 $\longrightarrow$ points for validating interpolation
Neutral scalars masses (GeV):	300, 500, 800, 1200, 1300
	100 (below m_H), 250 ($2m_H$), 350 ($2m_t$) $\longrightarrow$ the thresholds
	2000 (EFT limit)
Neutral scalars Γ/M ratios:	0.001, 0.01 both NWA, but different to quantify interference effects

Around 33k simulations with 100k MC events each

Database size

LHE samples (parton level):	**around 4.4 TB**
LHE samples (reconstructed objets):	around 3.5 TB

The core database could even fit in commercial USB keys

The di-Higgs case study

- Low-energy resonant peaks vs threshold effects can be **very relevant**
  - → **interplay between interferences and width effects**
  - → **NMSSM as a playground** to explore different regimes and combinations
- Characterise a signal can be **challenging**
  - → Difficult even at HL-LHC at differential level unless NP is light

But it is possible to treat NP contributions in a general way!

modular, collaborative, flexible and resource-friendly

Deconstruction

- Comprehensive description of NP effects while **minimizing computing resources**
- Complete description of **interferences** and **non-trivial shapes**
- Smooth connection with **EFT description** (going beyond EFT actually)
- Limited on grids but **interpolation methods**
- **Reverse engineering** of experimental results
- Requires **person-power** for extending the framework

} → Work in progress

The deconstruction approach as been applied also in:

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

A. Banerjee, E. Bergeaas Kuutmann, V. Ellajosyula, R. Enberg, G. Ferretti and **LP**, SciPost Phys. Core **7** (2024), 079

C. Arina, B. Fuks, **LP**, *et al.* Eur. Phys. J. C **85** (2025), 975

S. Moretti, **LP** and L. Shang, JHEP **06** (2025), 132