Deconstruction approach to di-Higgs production

and application to NMSSM

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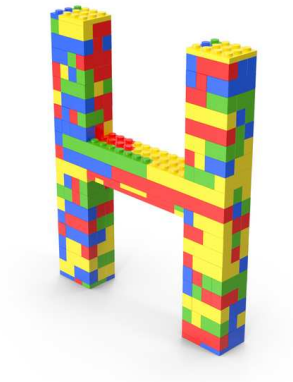
Higgs@Capri2025



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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Devise strategies to optimise and share resources

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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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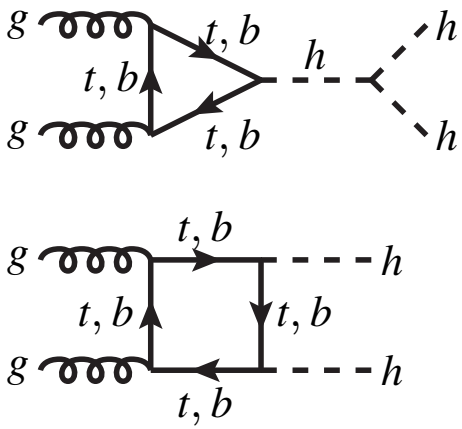
Using public simulated datasets

A possible way

Deconstruct new signals

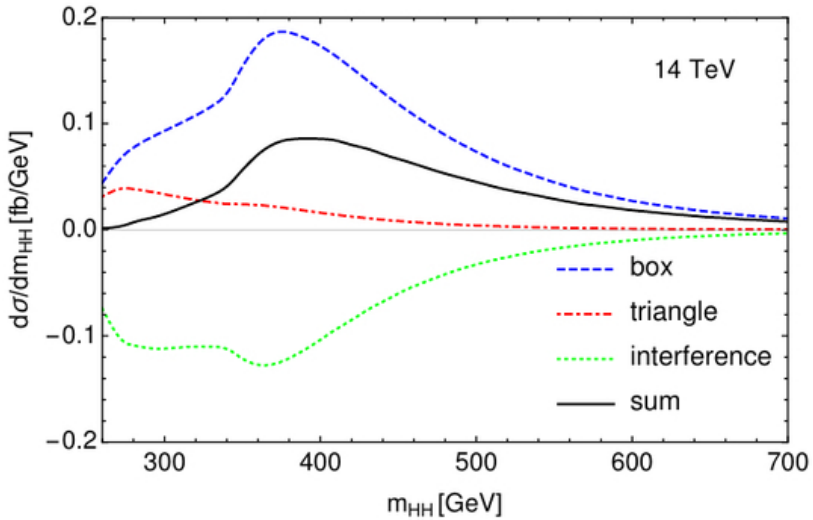
Looking for new physics at the LHC

the di-Higgs case



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

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



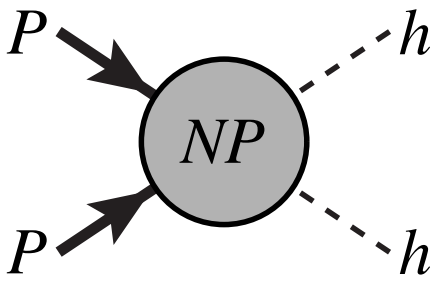
B. Di Micco *et al.* Rev. Phys. **5** (2020), 100045

- 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

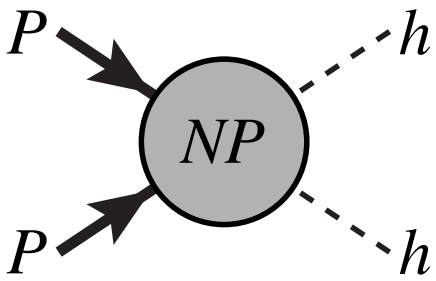
S. Moretti, **LP**, J. Sjölin, H. Waltari, Phys. Rev. D **107** (2023) no.11, 115010 (only non-resonant case)
S. Moretti, **LP**, J. Sjölin, H. Waltari, Phys. Rev. D **112** (2025) no.5, 055005 (adding resonant contributions)

Di-Higgs signal elements



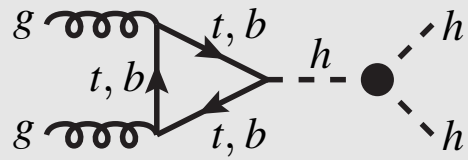
What can the signal be from a general perspective?

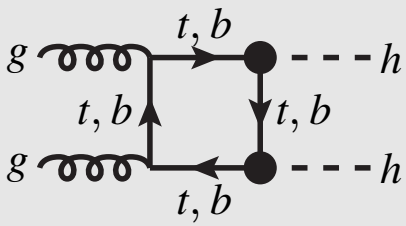
Di-Higgs signal elements

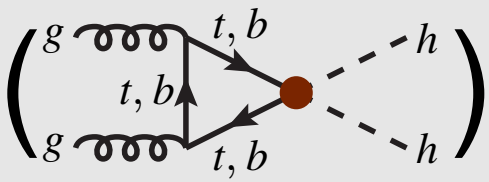


What can the signal be from a general perspective?

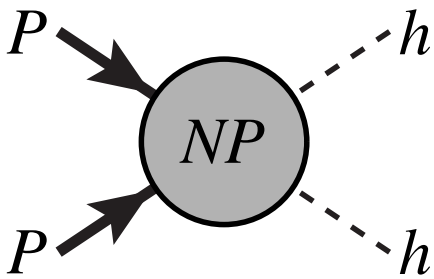
Modified SM







Di-Higgs signal elements



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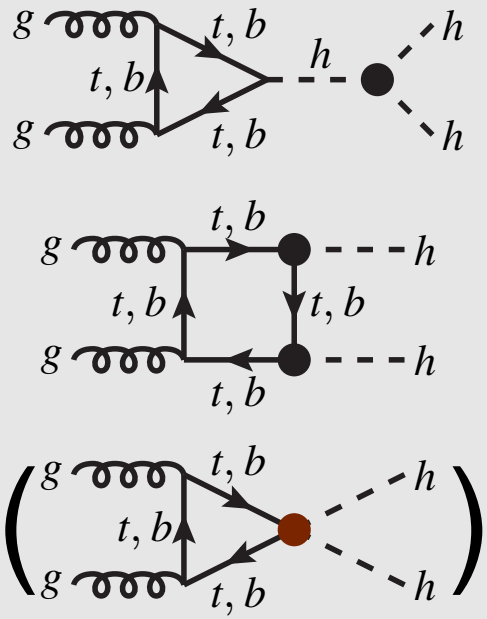
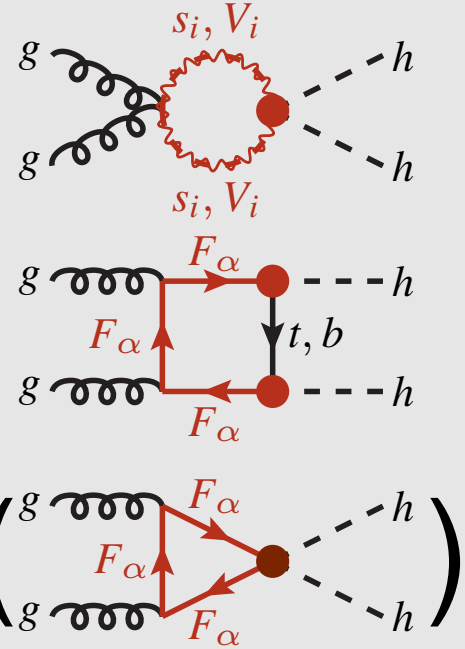
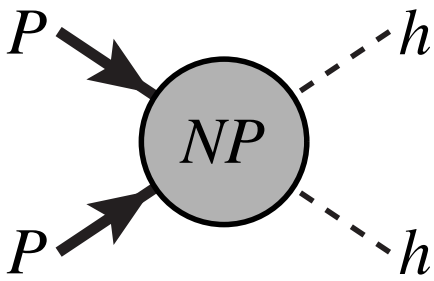


New coloured particles

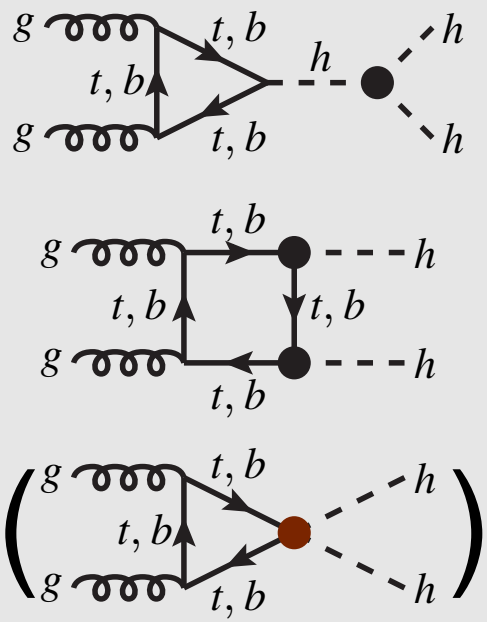


Di-Higgs signal elements



What can the signal be from a general perspective?

Modified SM



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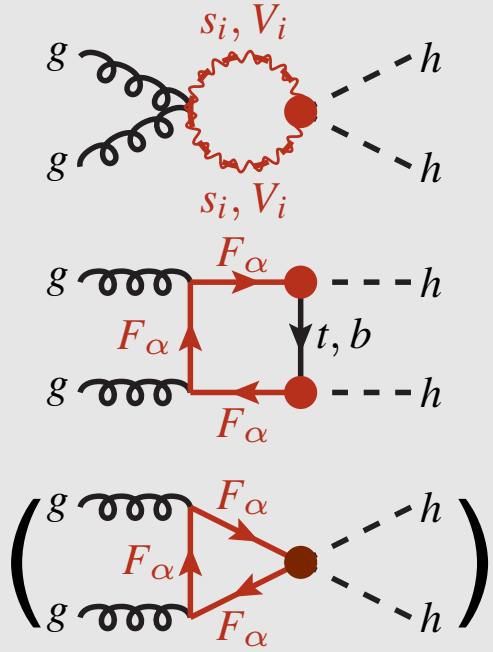
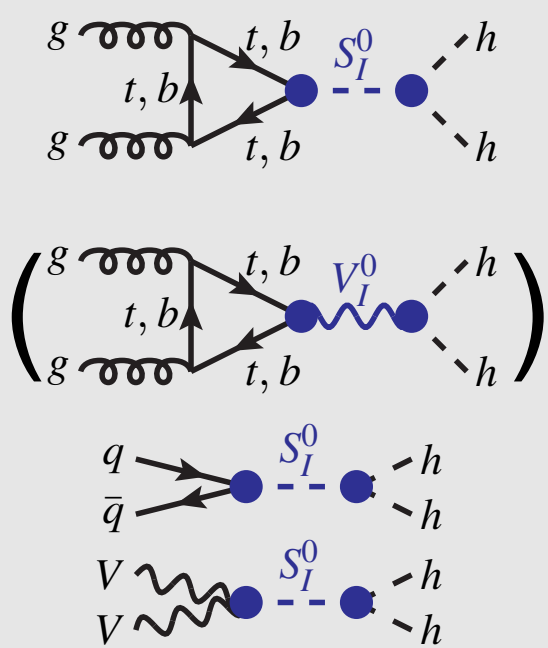


New neutral particles

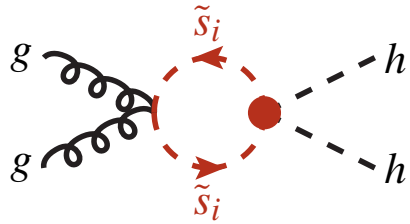


And combinations of these ingredients

The number of possibilities is limited!

Reduced cross-sections

Let's take one signal contribution:



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

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

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

Reduced cross-sections

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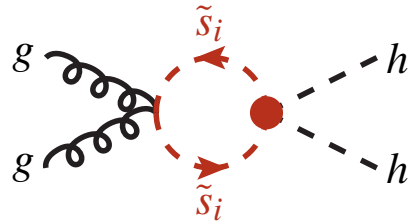

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- $\kappa_{hh\tilde{s}_i\tilde{s}_i}$: rescaling of the cross-section
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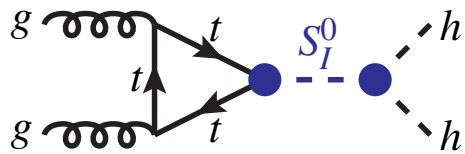
Let's add another contribution:



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

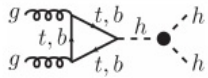
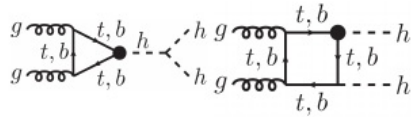
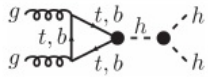
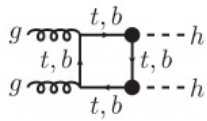
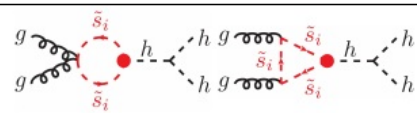
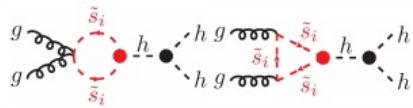
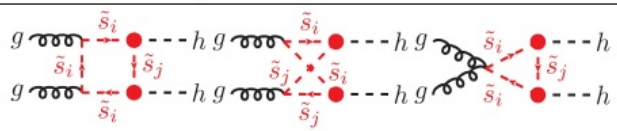
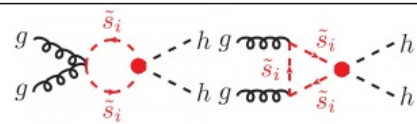
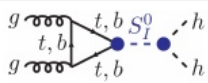
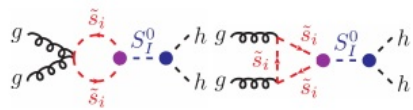
The recipe

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

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		$\mathcal{A}_i \propto \kappa^I_{Shh}\kappa^{Ii}_{S\tilde{s}\tilde{s}}$

10 kind of topologies

with NMSSM ingredients

1) Deconstruction

Cross-section

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

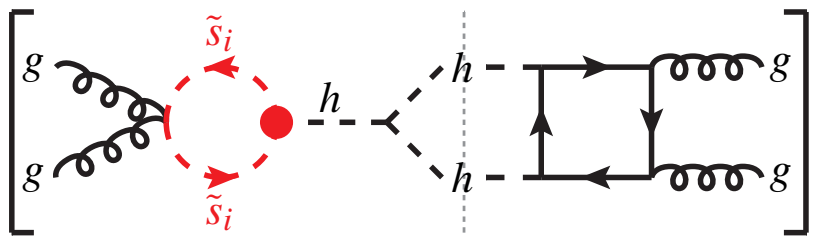
B: SM background, M: modified SM, s: squark propagation
S: neutral scalar propagation, Ss: neutral scalar+squark propagation

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

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

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

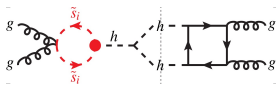
2) Database generation

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:

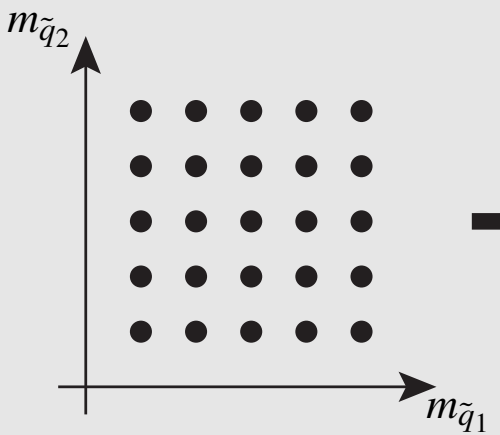
```
generate p p > h h [QCD] QCD^2==4 QED^2==4
```

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

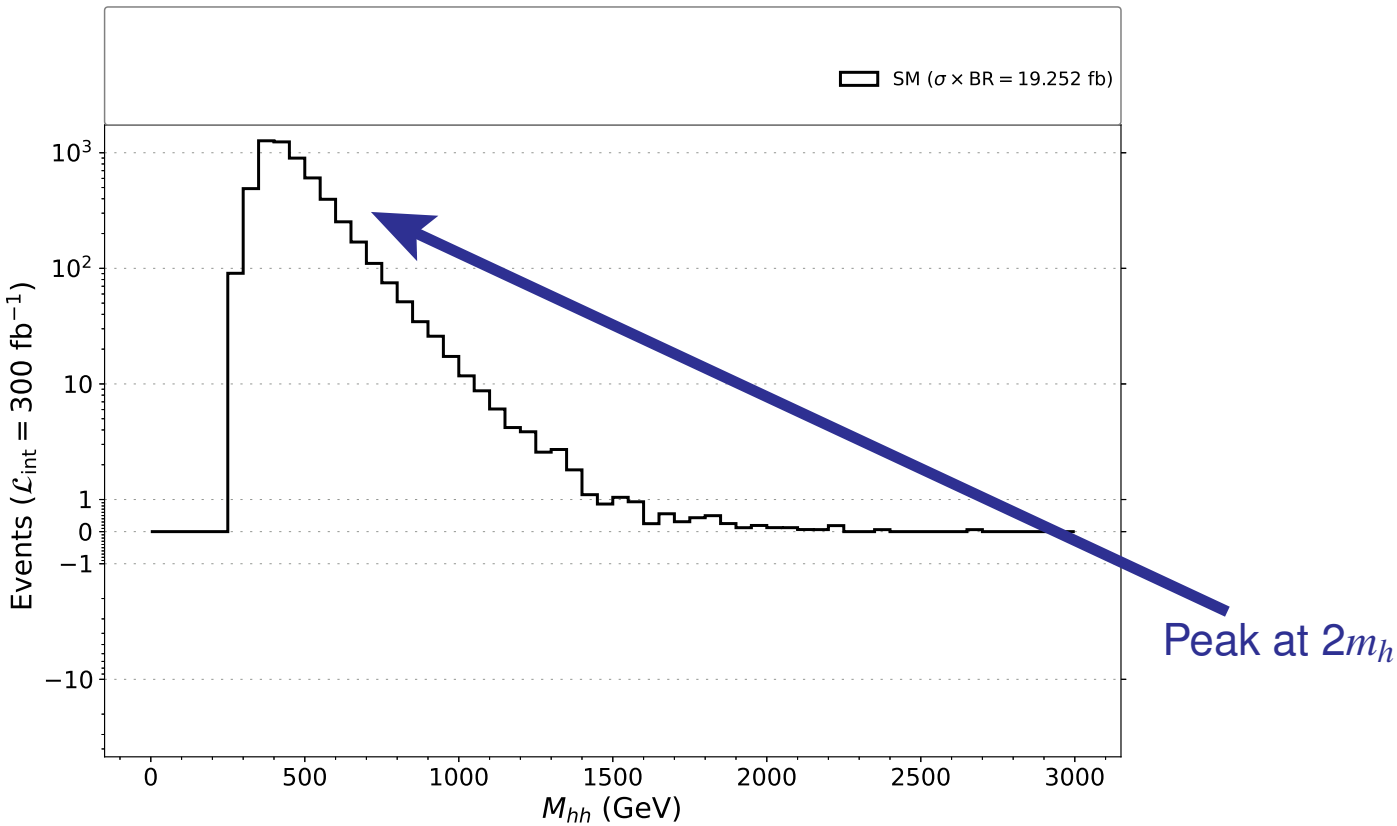


Database of samples
simulated once and for all

3) Recombination

invariant mass distribution m_{hh}

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



3) Recombination

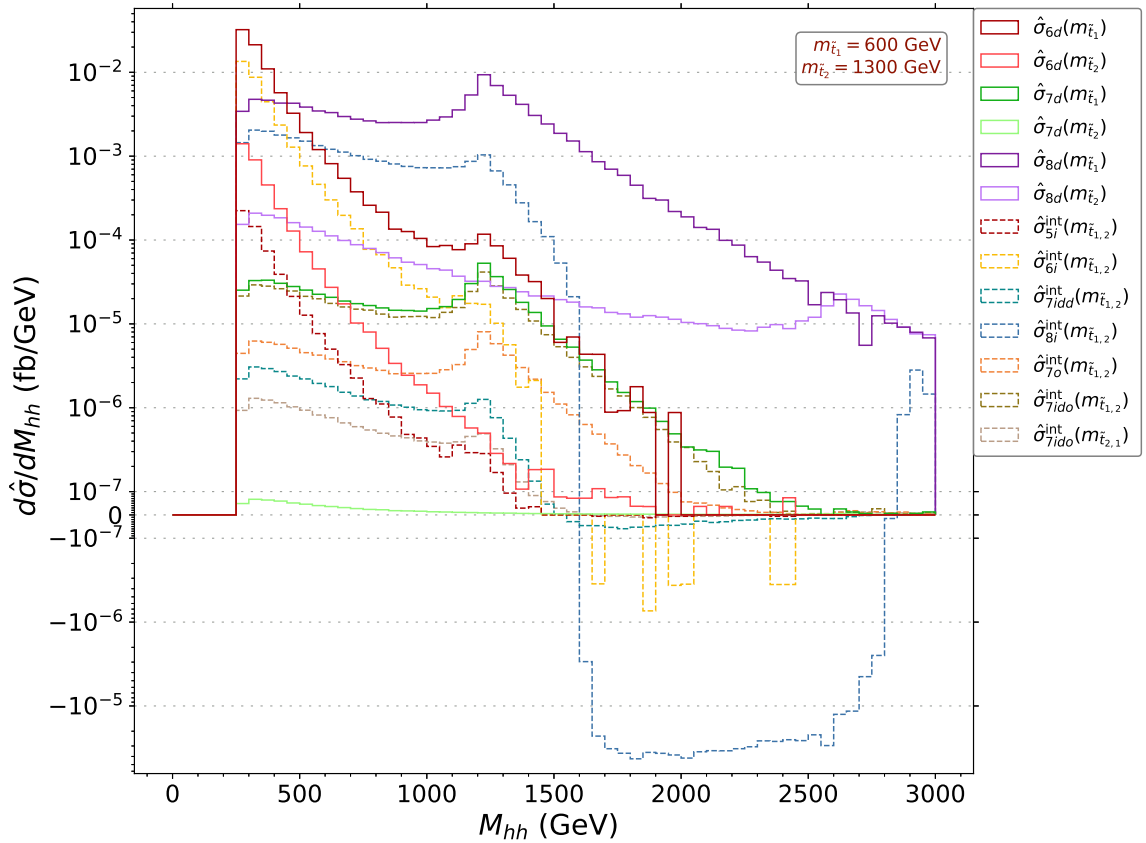
invariant mass distribution m_{hh}

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

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

3) Recombination

invariant mass distribution m_{hh}

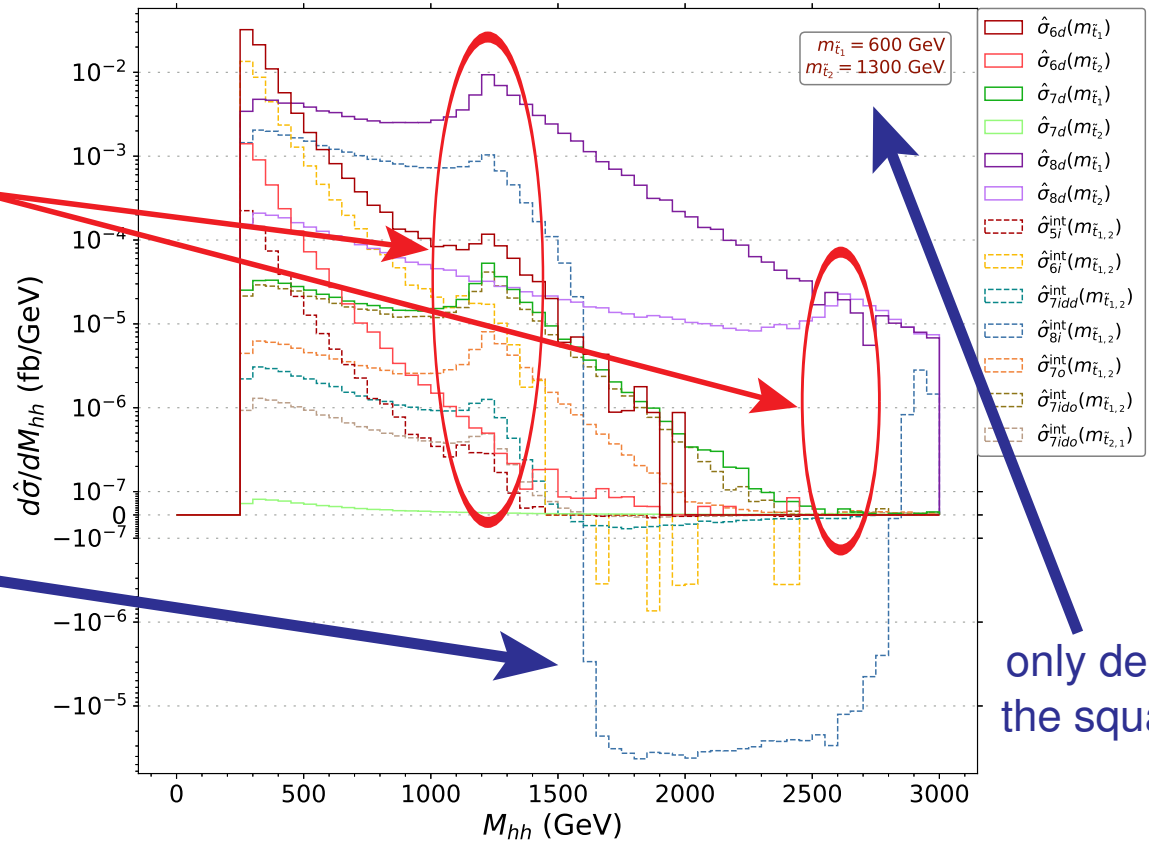
0) Background distribution (intrinsic background only: $pp \to hh$)

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

Example with the σ_s elements

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

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



Negative interference between topologies

only depending on the squark masses

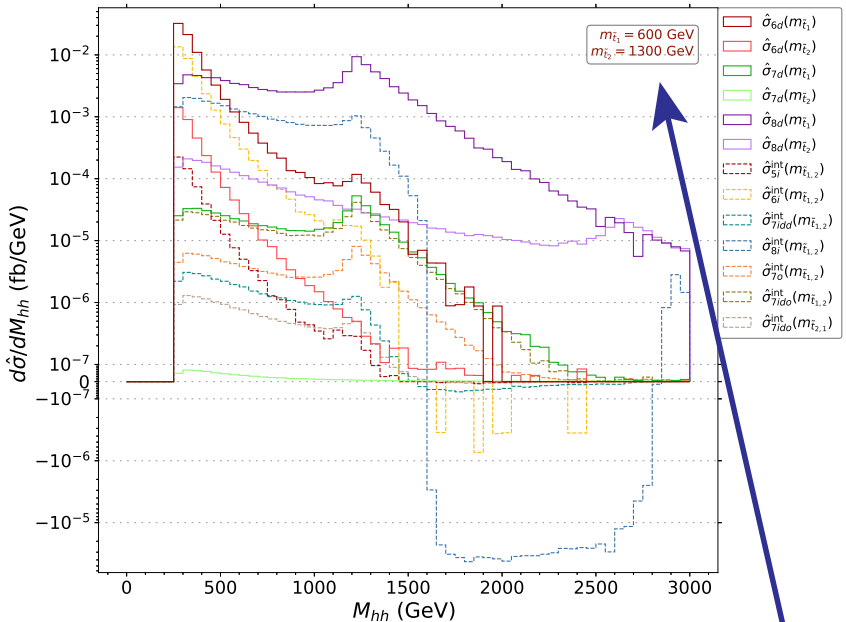
The deconstructed samples do not need to have the same number of MC events

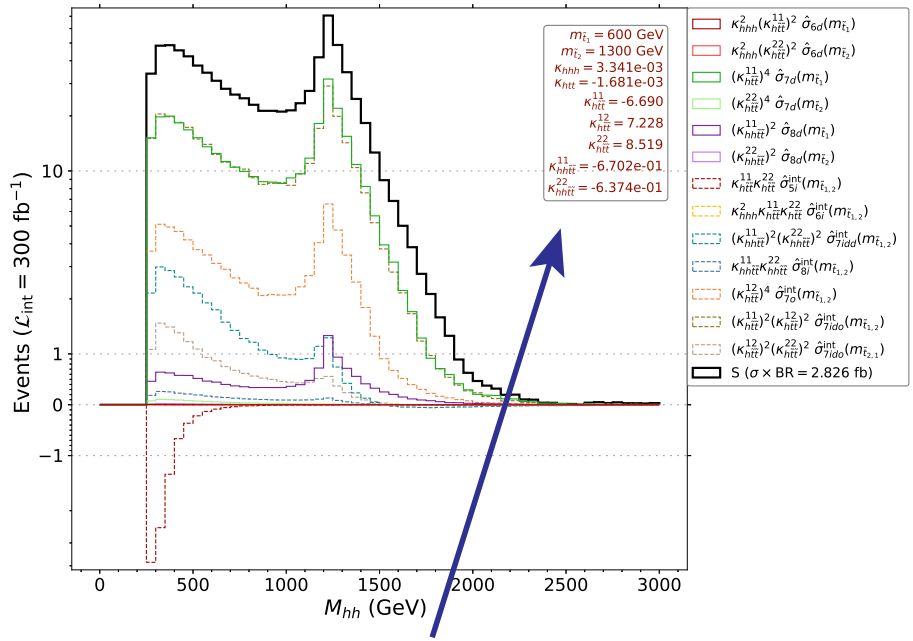
3) Recombination

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





only depending on
the squark masses

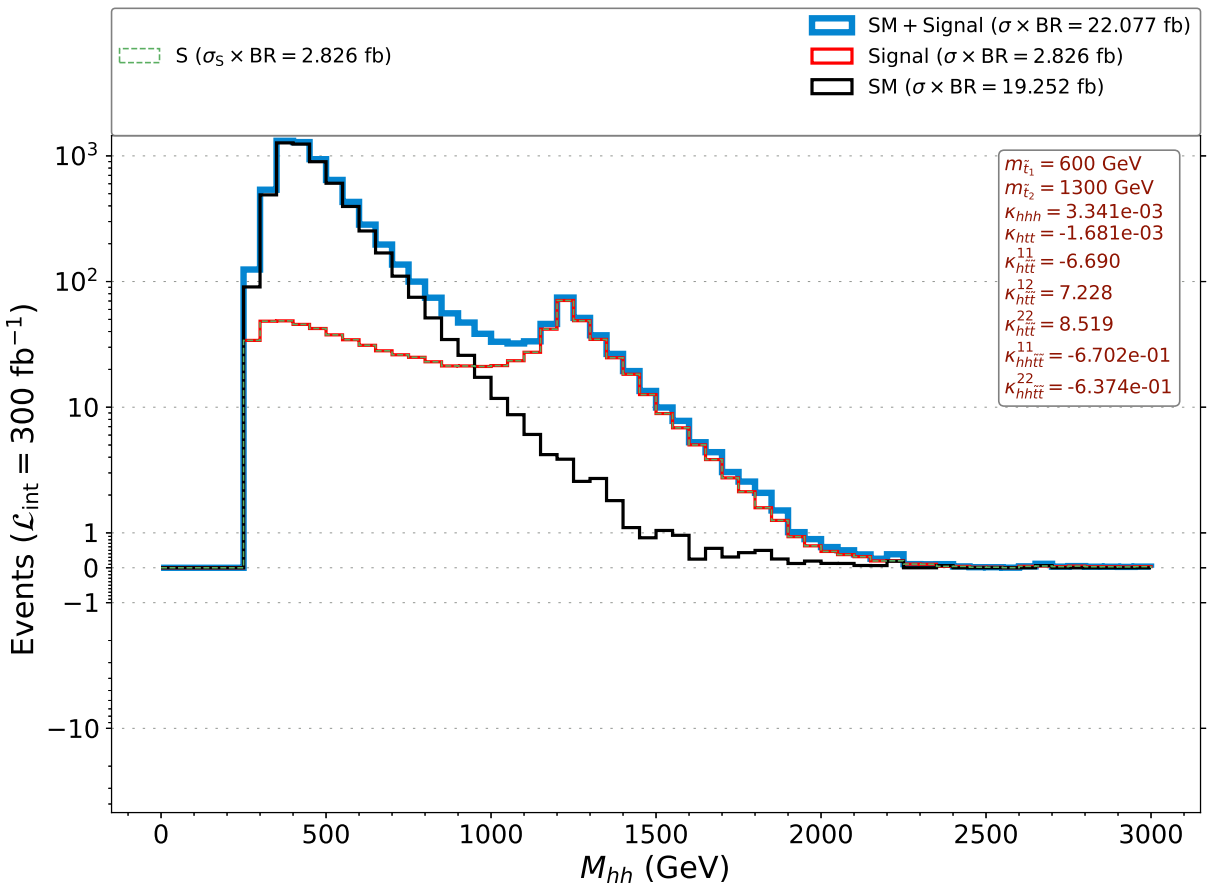
depending on
masses and coupling

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



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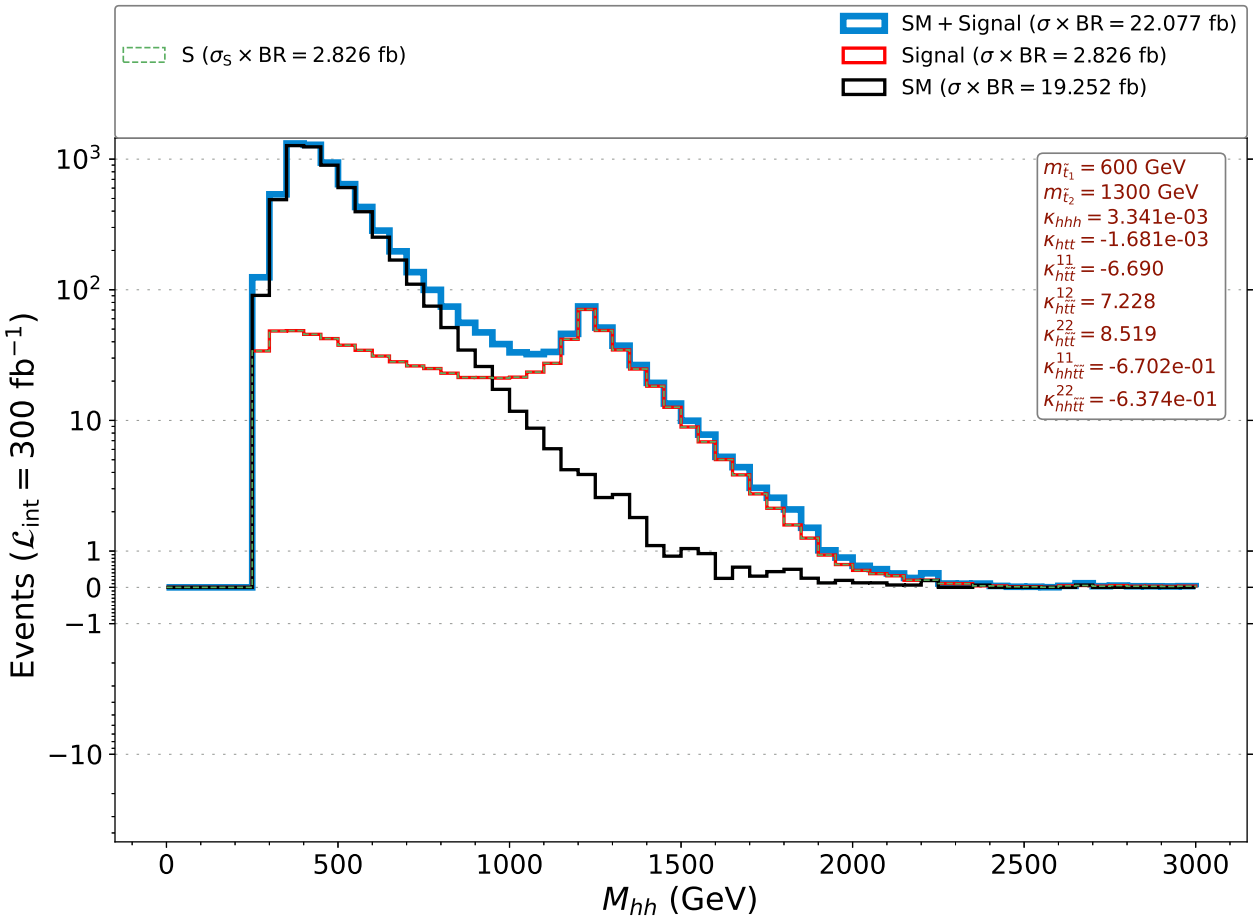

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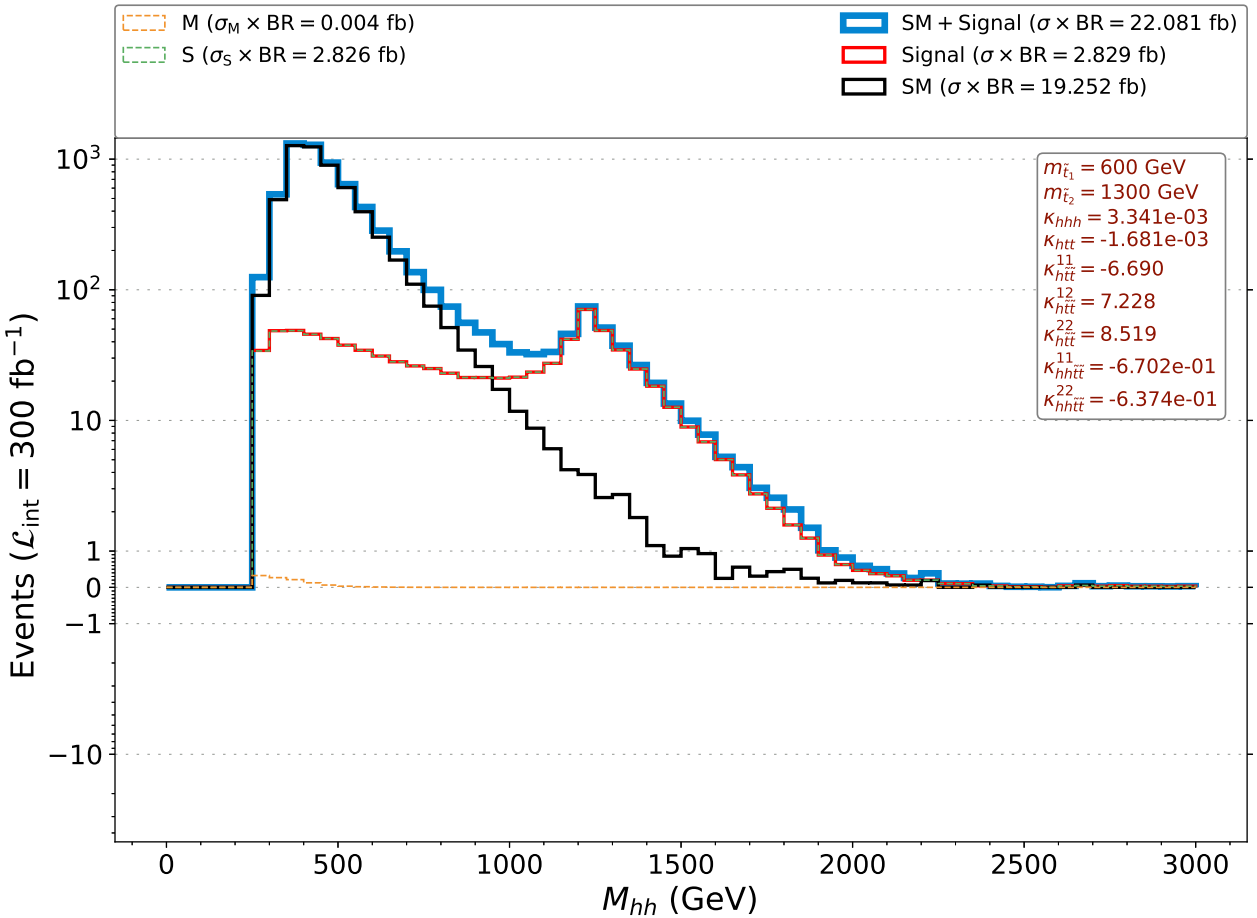

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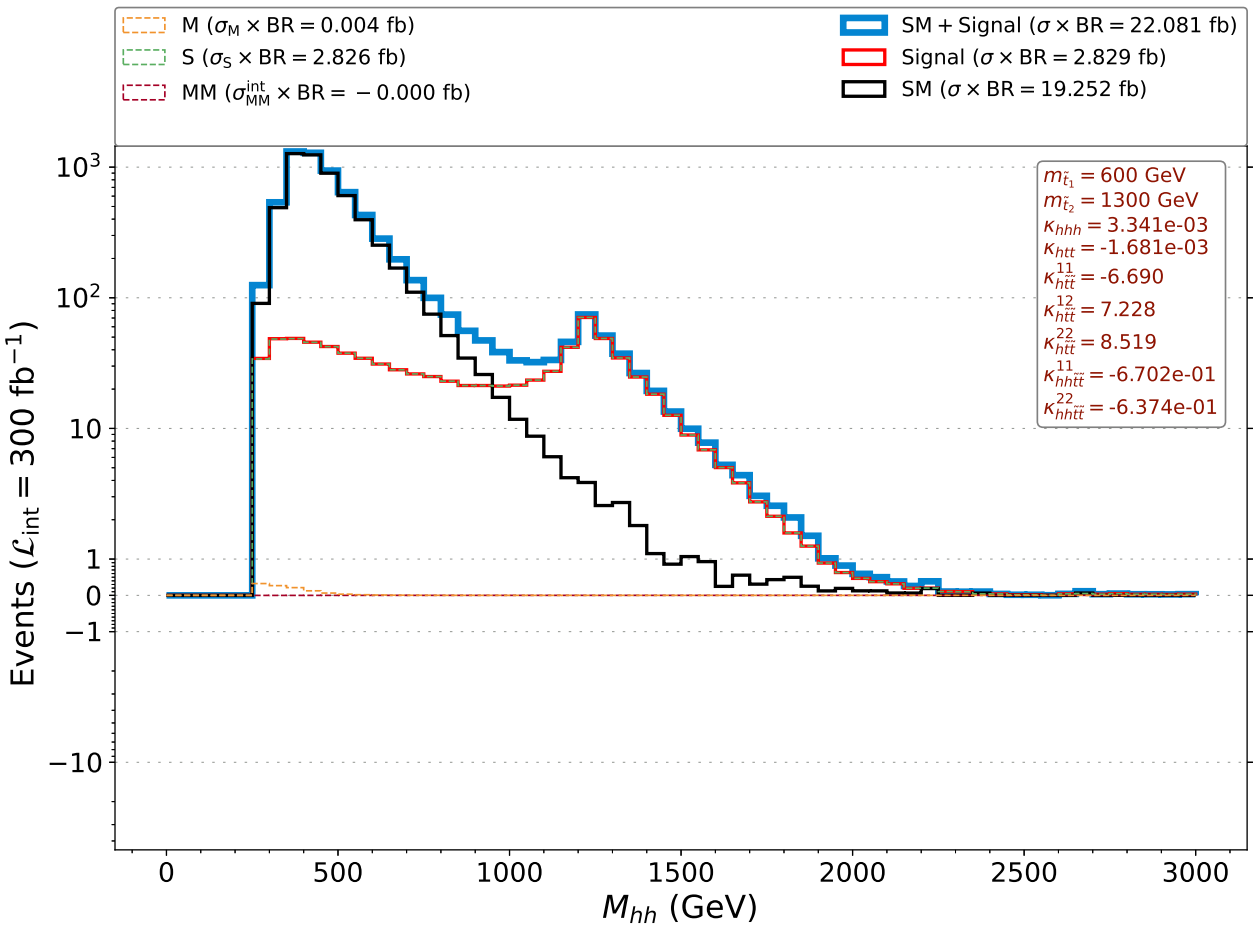

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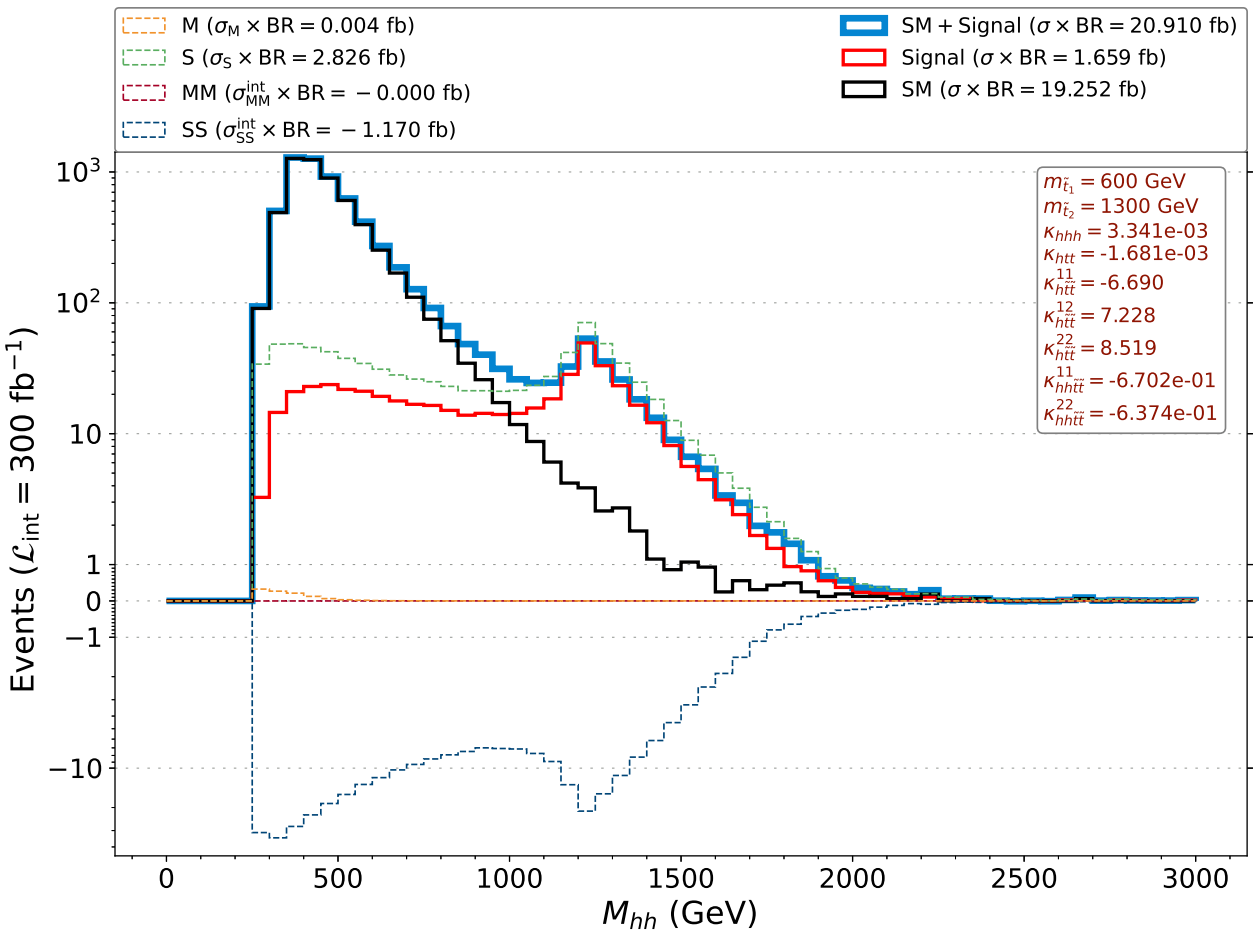

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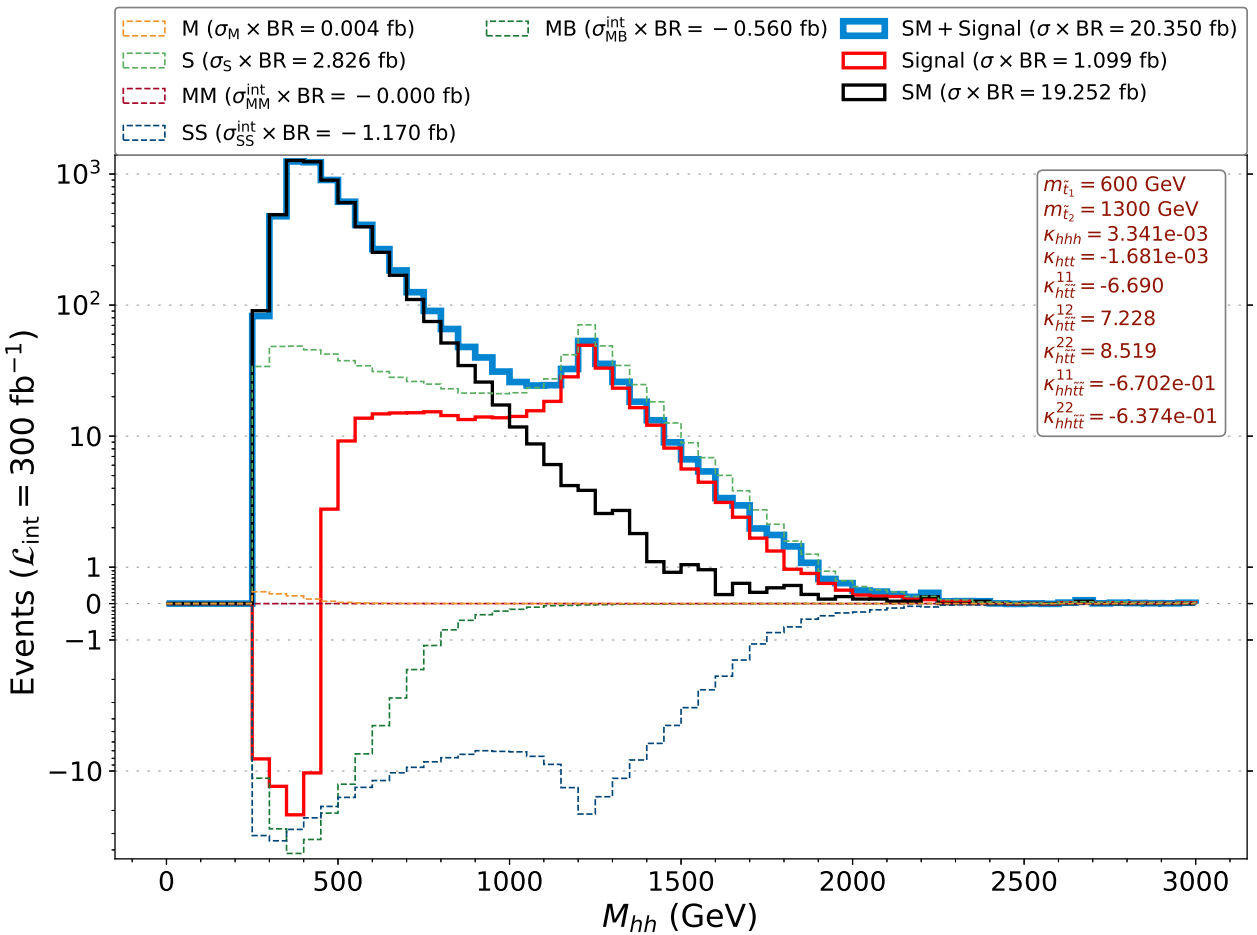

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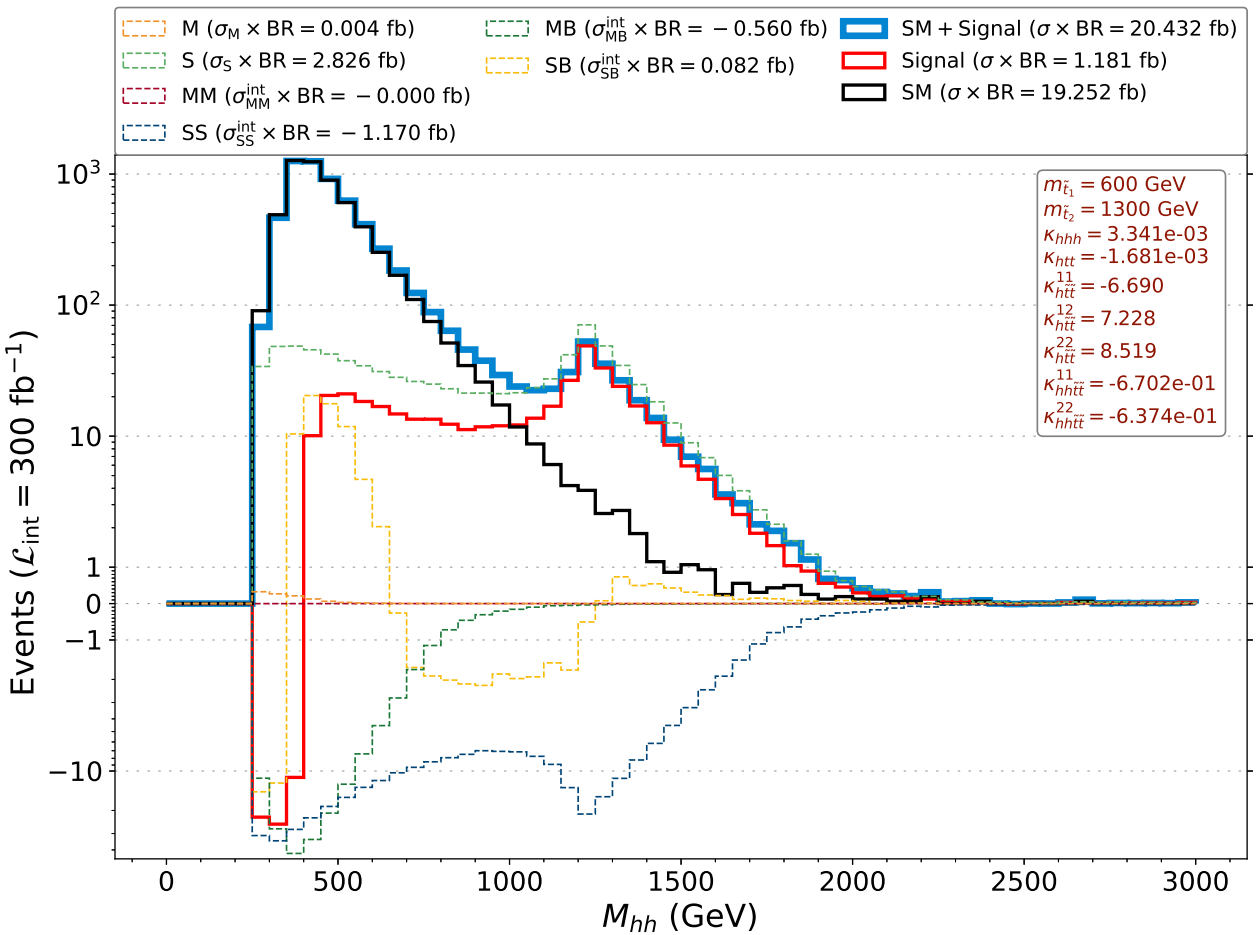

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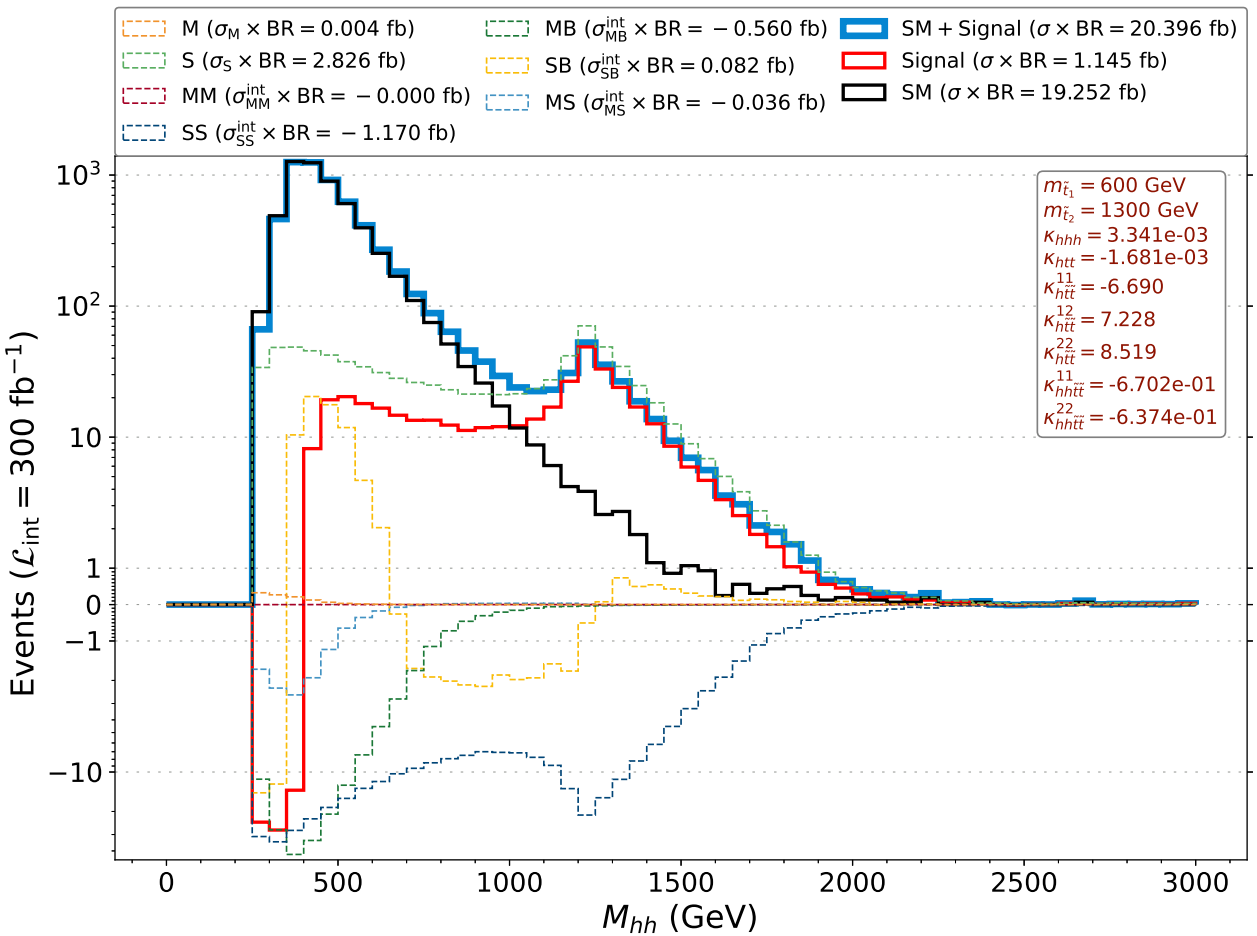

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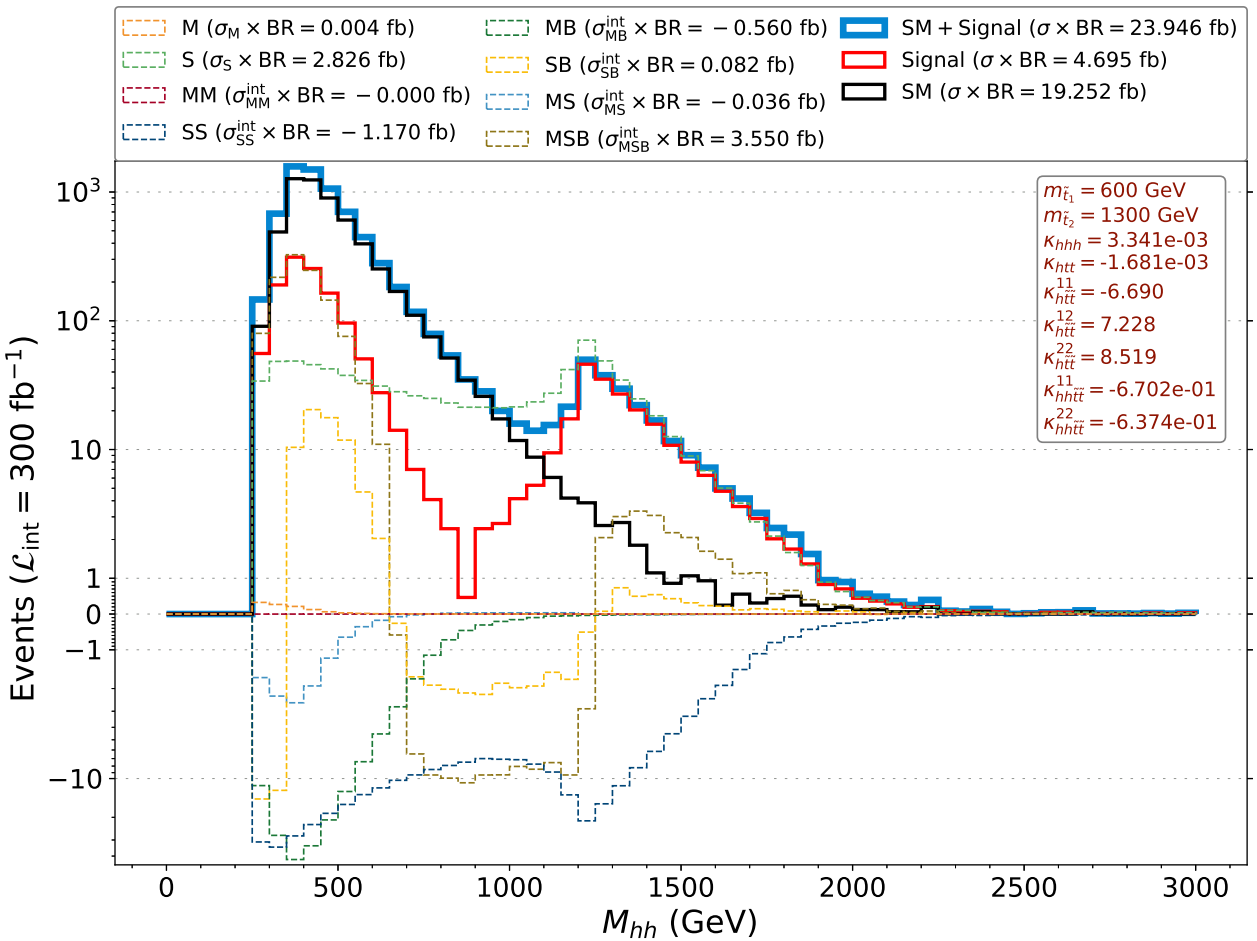
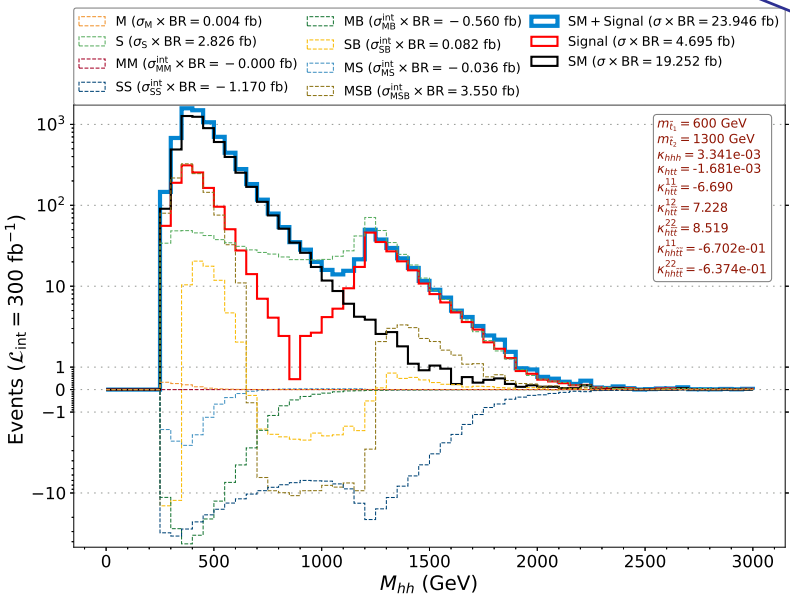
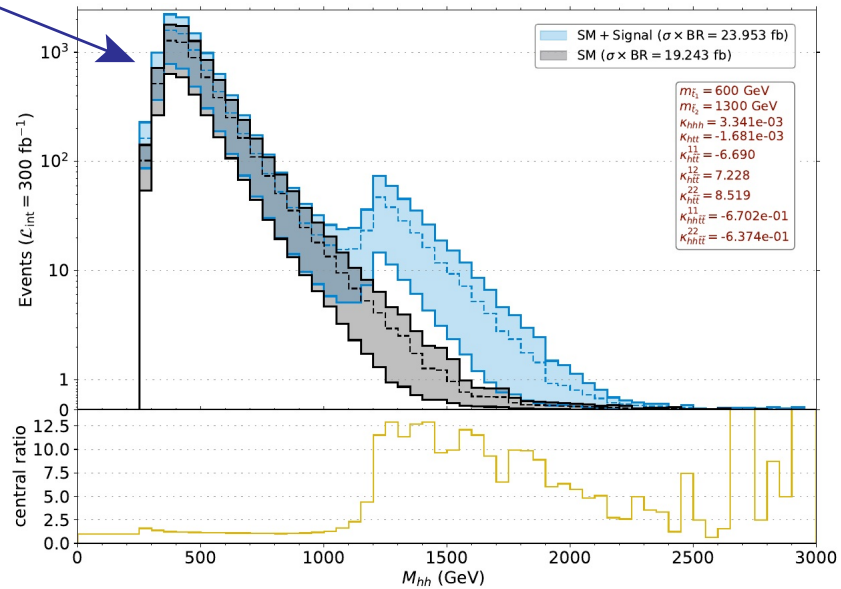


including systematics
independent simulation for cross-check

3) Recombination

invariant mass distribution m_{hh}





With the same database we can

- analyse the contribution of specific topologies to the total shape
- 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

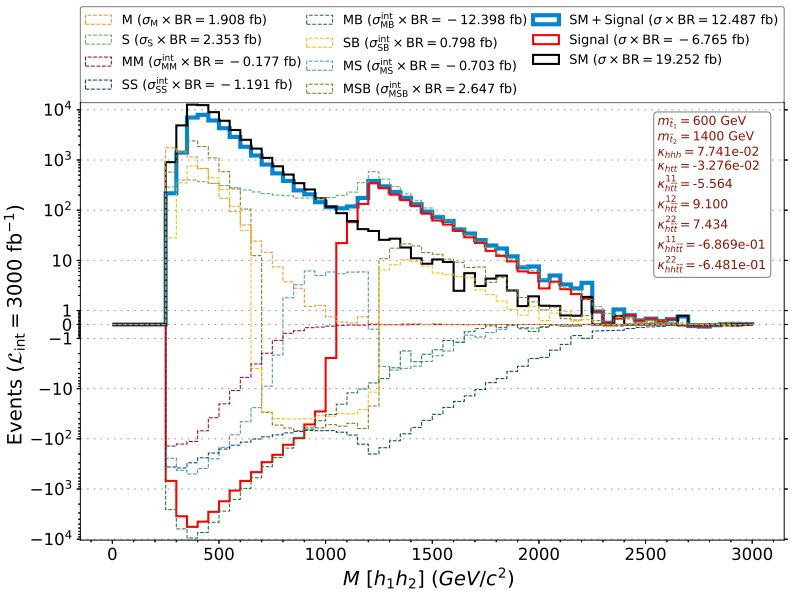
Adding resonances and all squarks

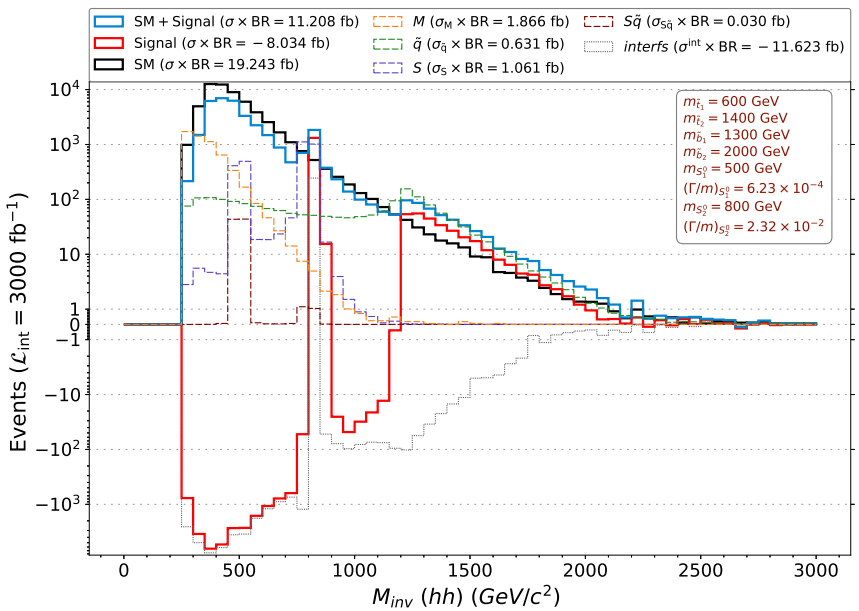
i.e. going full NMSSM

2 stops (one light)
2 sbottoms

A 500 GeV scalar singlet

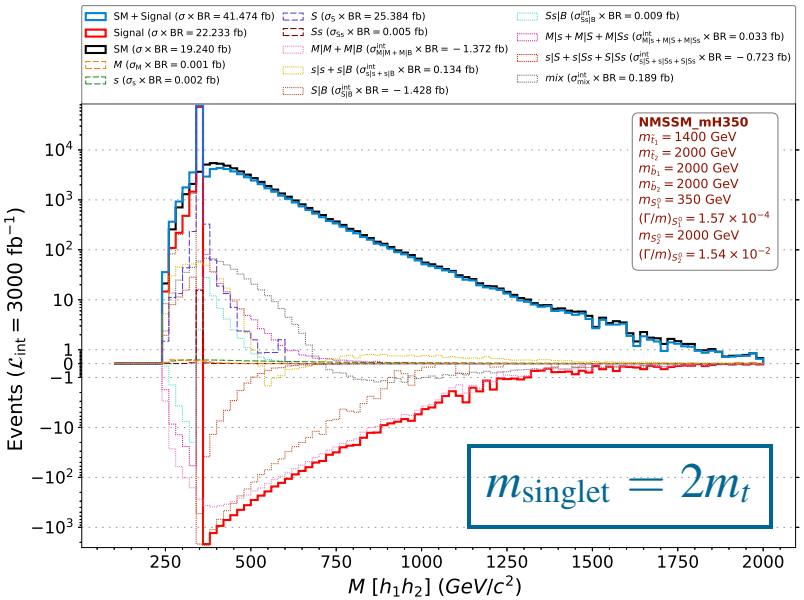
A 800 GeV scalar doublet

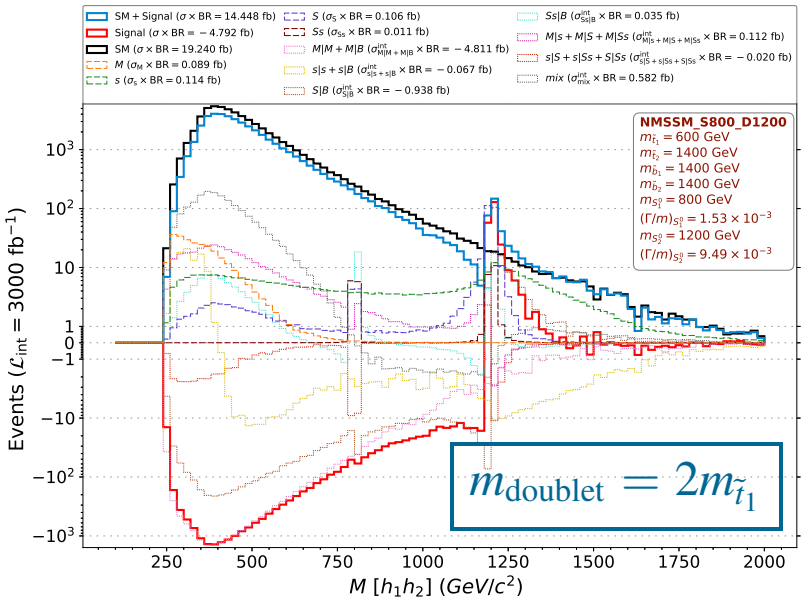


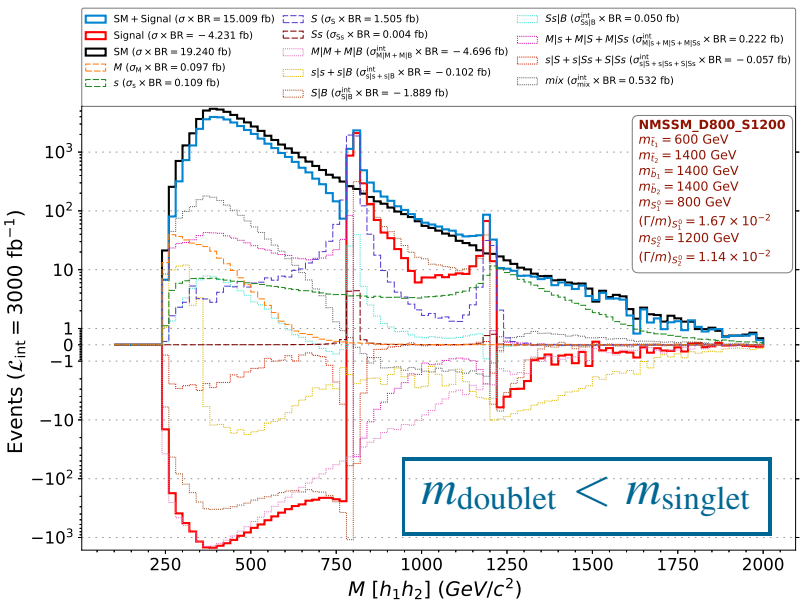


- Stronger **negative interference in the squark sector** above the threshold
- Stronger **event depletion at low** m_{hh}
- **Singlet scalar** nearly **invisible** (very small couplings to SM quarks)
- **Visible peak** from the **doublet resonance**

Varying the scenarios





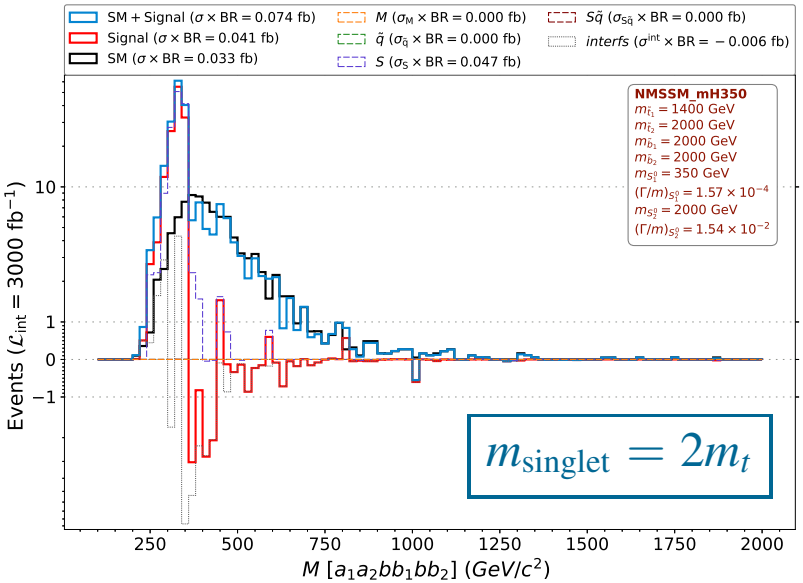


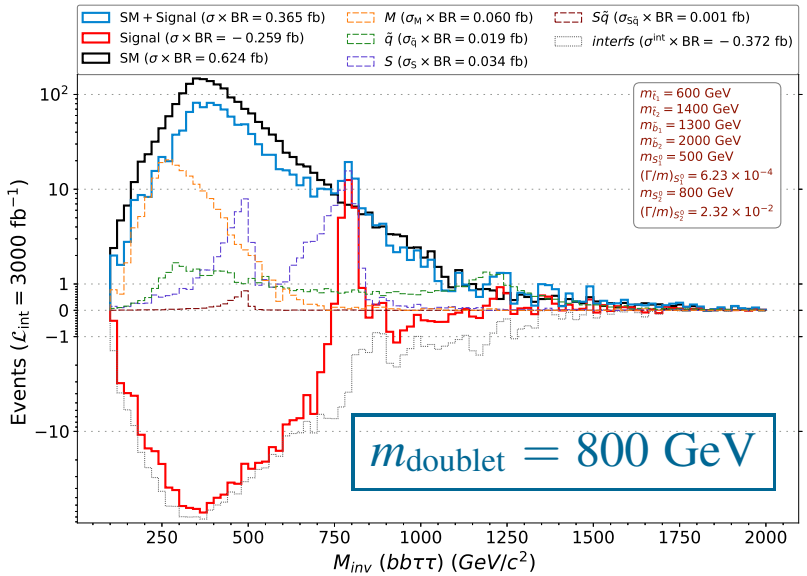
Large range of possibilities with potentially visible effects

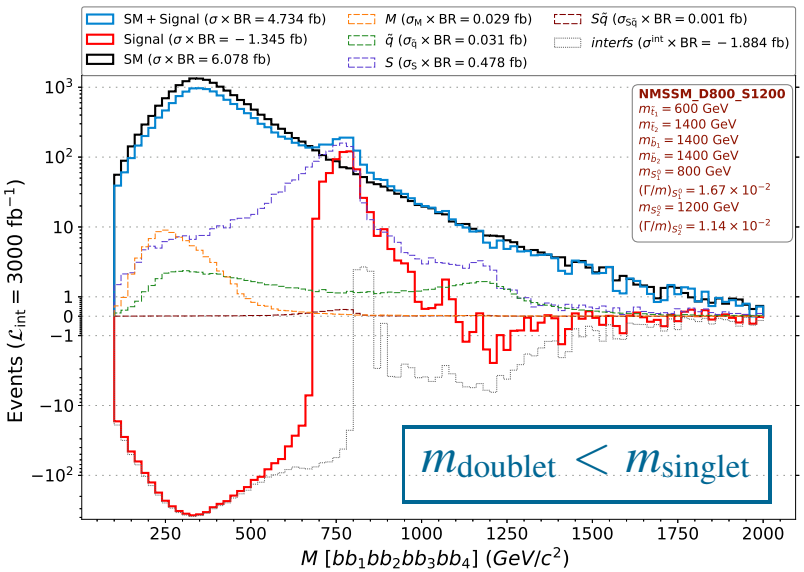
or is it?

Can we actually see these features?

i.e. going to object reconstruction







Short answer: **some hope at HL-LHC**

$2b2\gamma$: clean but low BR, possibly good for light resonances and to probe negative interferences in low m_{hh}

$2b2\tau$: larger BR, low QCD background, better for features in intermediate m_{hh} range

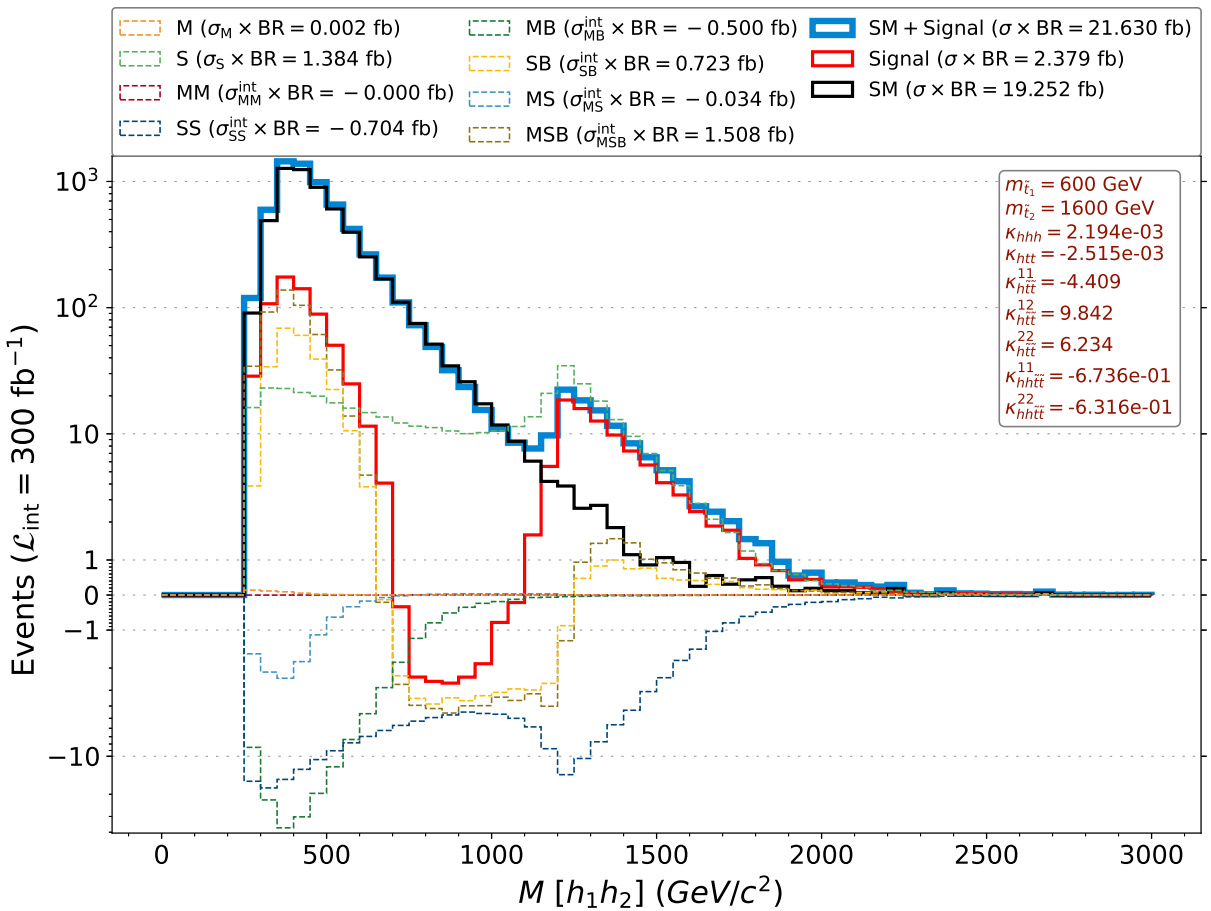
$4b$: largest BR, better for high m_{hh} but poor resolution of heavy resonances

But this analysis has further scope

The EFT limit

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

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



Smooth exploration of the interface between low scale and EFT limit

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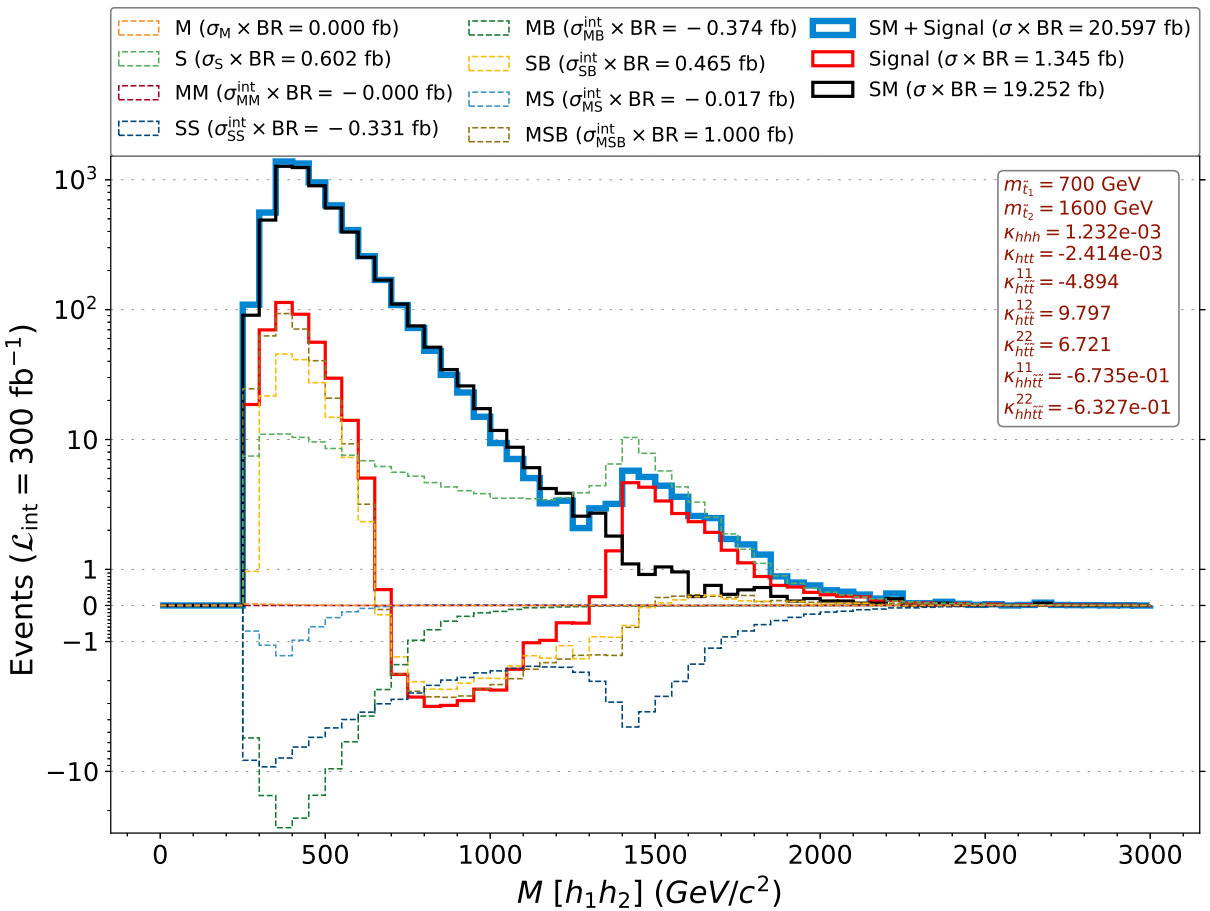

Smooth exploration of the interface between low scale and EFT limit

The EFT limit

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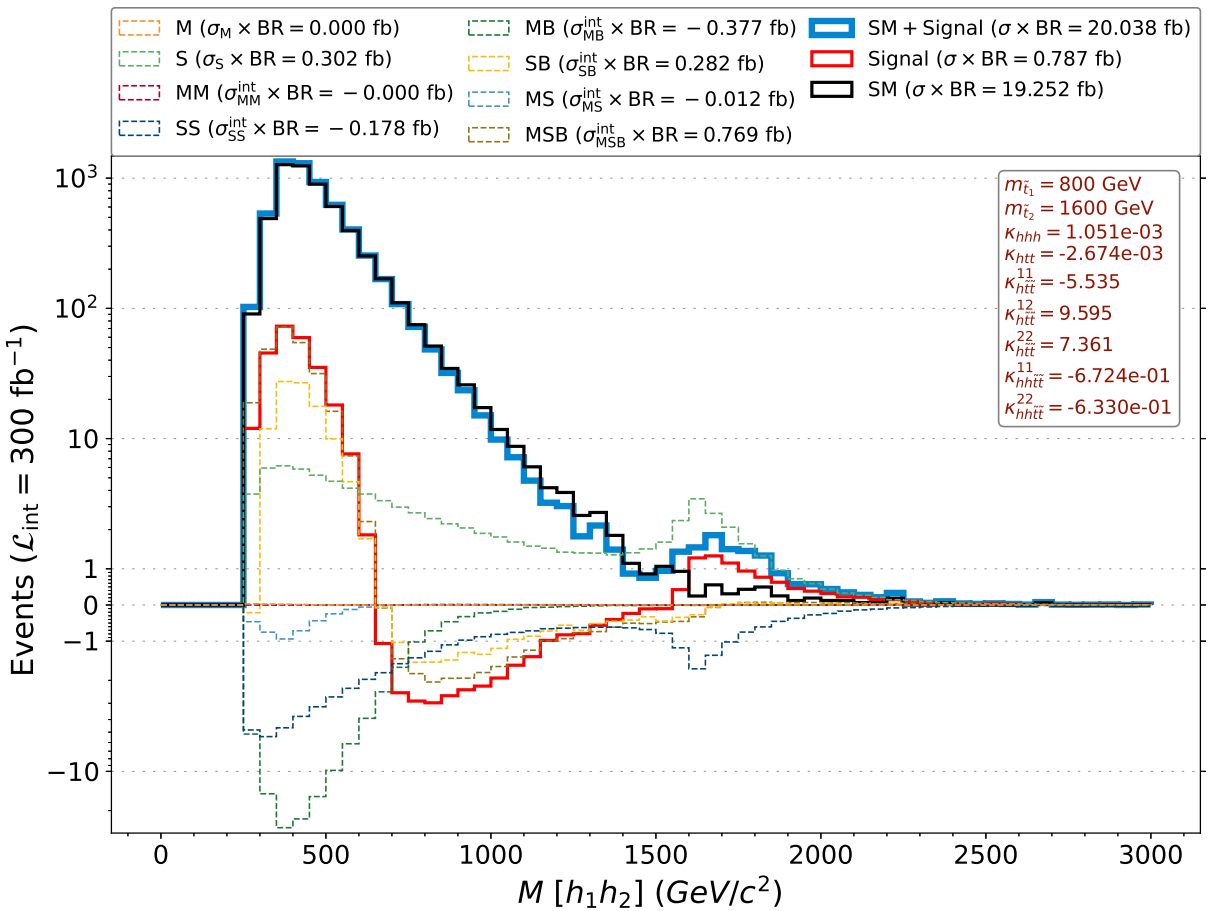

Smooth exploration of the interface between low scale and EFT limit

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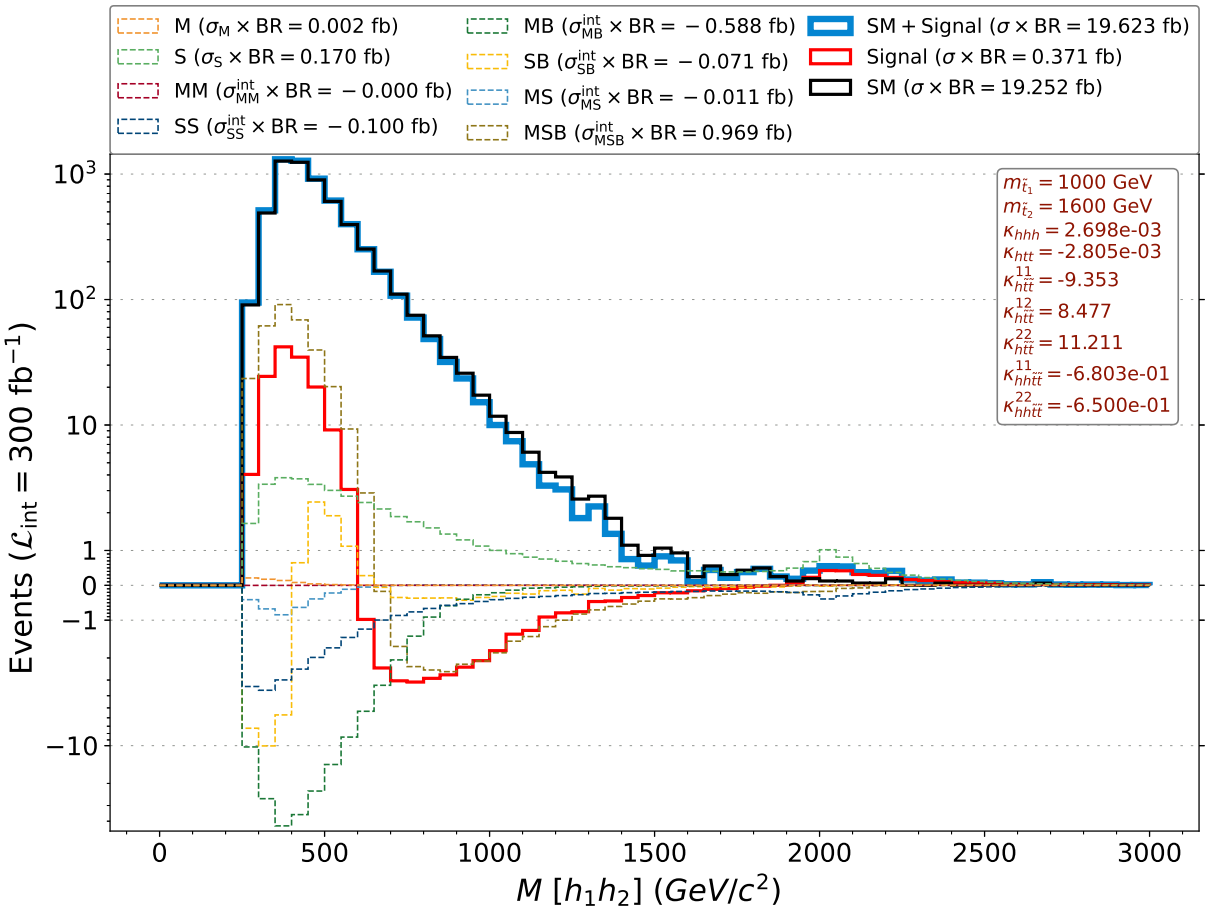

Smooth exploration of the interface between low scale and EFT limit

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:

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

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First try

Input parameters

$m_{\tilde{t}_1} = 600$ GeV
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$\kappa_{hhh} = 1.208\text{e-}01$
$\kappa_{htt} = -3.309\text{e-}02$
$\kappa_{h\tilde{t}\tilde{t}}^{11} = 5.965$
$\kappa_{h\tilde{t}\tilde{t}}^{12} = 9.598$
$\kappa_{h\tilde{t}\tilde{t}}^{22} = 7.825$
$\kappa_{hh\tilde{t}\tilde{t}}^{11} = -6.874\text{e-}01$
$\kappa_{hh\tilde{t}\tilde{t}}^{22} = -6.437\text{e-}01$

Fitted parameters

$m_{\tilde{t}_1} = 600$ GeV
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$\kappa_{hhh} = 8.430\text{e-}02$
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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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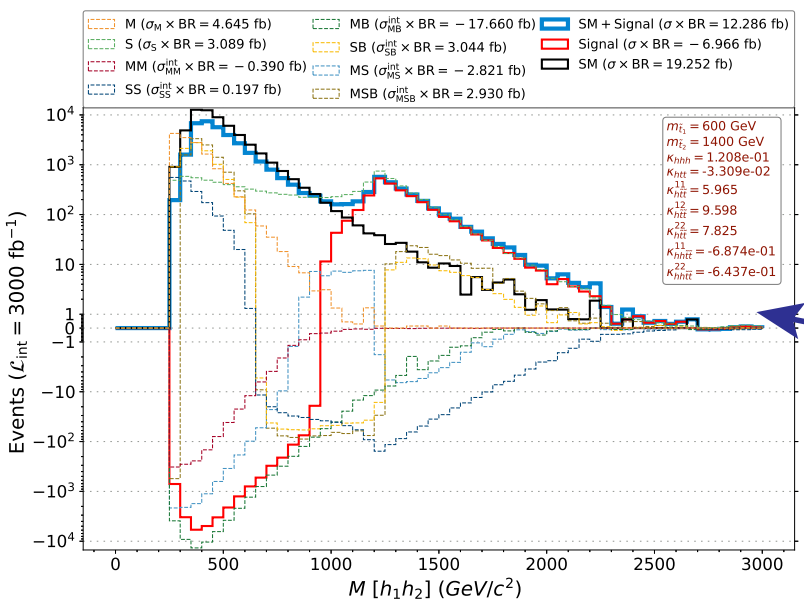
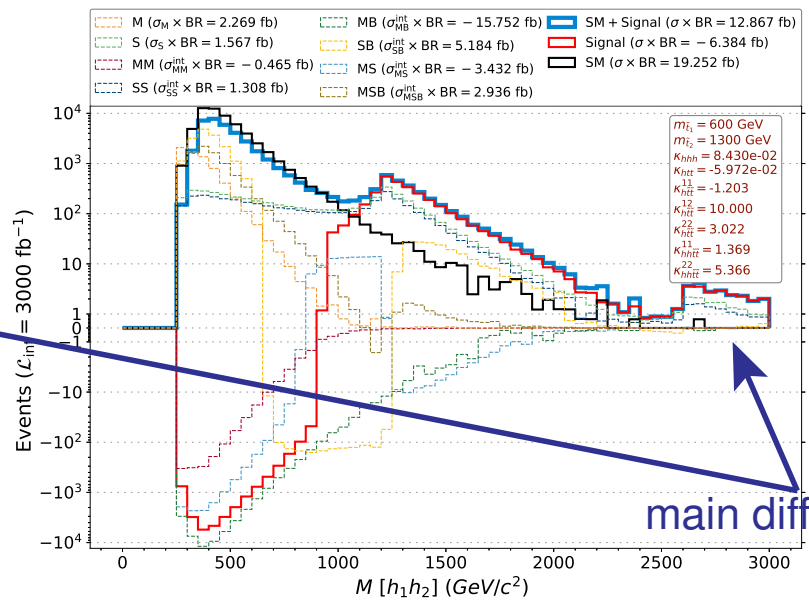


Fitted benchmark



main difference

Different parameter sets lead to very similar distributions

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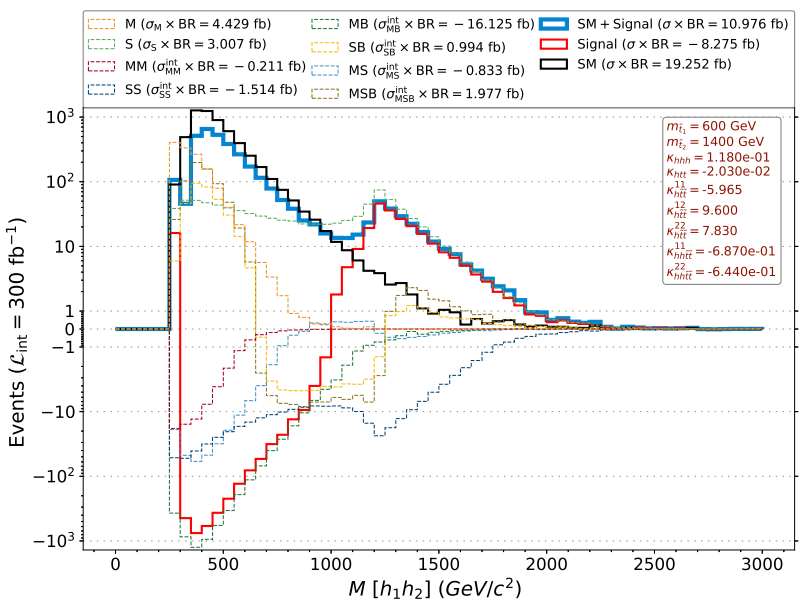
Second try

Original benchmark



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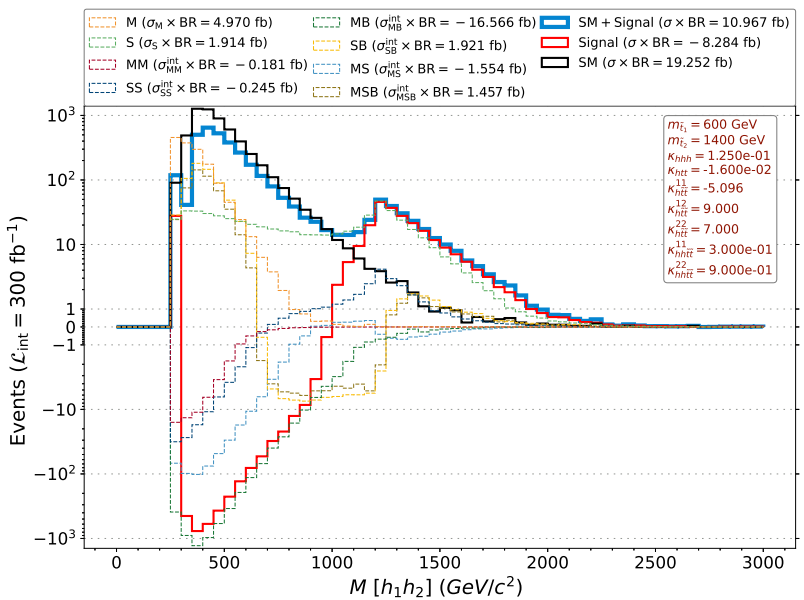


perfect fit with very close numerical values of relevant parameters!

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

Classes of solutions can fit possible excesses

Deconstructing Di-Higgs

New physics in di-Higgs

- Difficult even at HL-LHC at differential level unless NP is light
- Low-energy resonant peaks vs threshold effects
  - → NMSSM allows to explore different regimes and combinations
- Characterise a signal can be challenging

Deconstruction

- Comprehensive description of NP effects while **minimizing computing resources**
- Useful to assess the relevance of **interferences and interplay between different contributions**
- Smooth connection with **EFT description**
- Limited on grids but **interpolation methods**
- **Reverse engineering** of experimental results
- **Add fermion contributions** motivated by composite Higgs

} → Work in progress

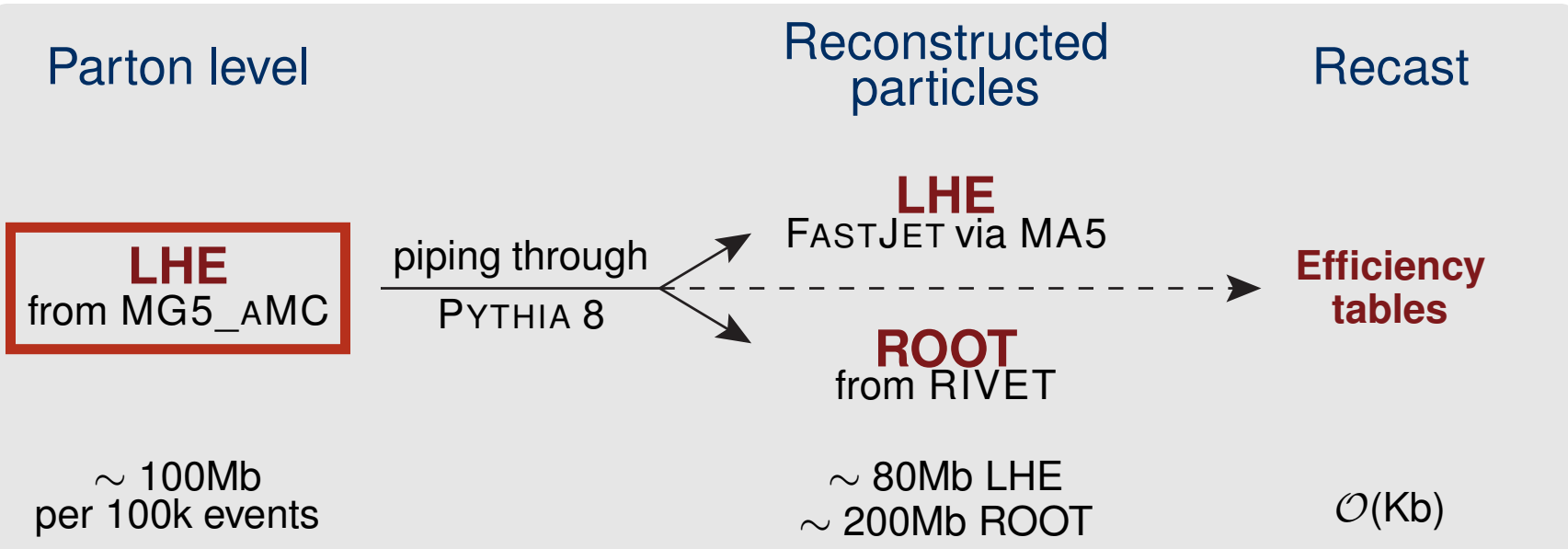
Backup

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

database content



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