Monte Carlo event database for deconstructing signals of new physics at colliders

a case study with Higgs pair production
and other applications

Luca Panizzi

UNIVERSITÀ DELLA CALABRIA

Beyond the Higgs boson

open problems

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

Observations

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

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

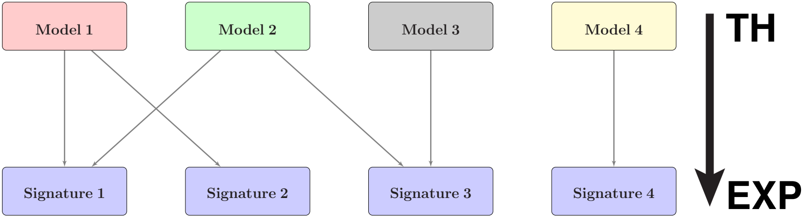
Theoretical issues

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

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

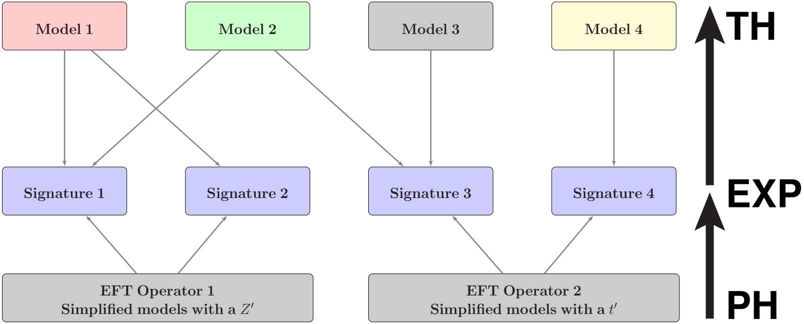
And if there's new physics we should be able to observe
new particles or modifications to SM predictions

Looking for new physics at the LHC



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

Looking for new physics at the LHC



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

Model-independent approach

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

Looking for new physics at the LHC

Problems

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

Looking for new physics at the LHC

Problems

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

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

But very few efforts to address this issue within HEP (PH and TH)

arXiv > physics > arXiv:2203.12389

Search...

Help | A

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

Looking for new physics at the LHC

Problems

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

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

Devise strategies to optimise and share resources

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

Problems

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

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

Devise strategies to optimise and share resources

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

A possible way

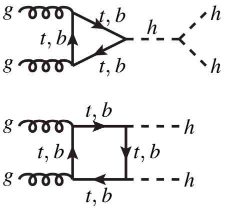
The deconstruction framework

A case study with Higgs pair production

S. Moretti, **LP**, J. Sjölin, H. Waltari
"Deconstructing squark contributions to di-Higgs production at the LHC"
Phys. Rev. D **107** (2023) no.11, 115010

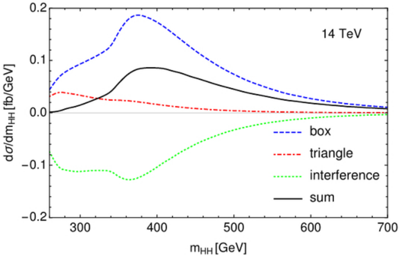
What happens in the SM

We only consider the gluon fusion process



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

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



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

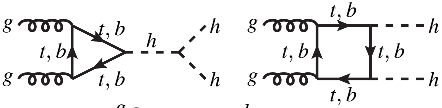
Wide literature treating the next-to-leading-order corrections

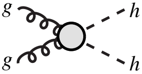
$\sqrt{s}$	13 TeV	14 TeV
ggF HH	$31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$	$36.69^{+2.1\%}_{-4.9\%} \pm 3.0\%$

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

Our analysis including BSM contributions is at LO

Signal elements

The Standard model topologies: 

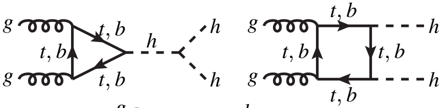
A new physics signal: 

What can the signal be from a general perspective?

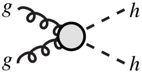
(limiting to gluon-fusion processes)

Signal elements

The Standard model topologies:



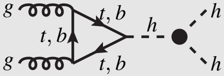
A new physics signal:

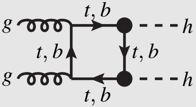


What can the signal be from a general perspective?

(limiting to gluon-fusion processes)

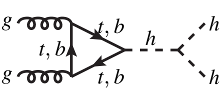
Modified SM couplings

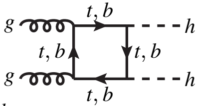




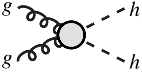
Signal elements

The Standard model topologies:





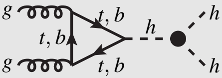
A new physics signal:

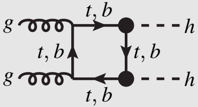


What can the signal be from a general perspective?

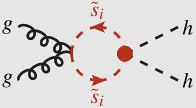
(limiting to gluon-fusion processes)

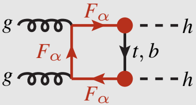
Modified SM couplings





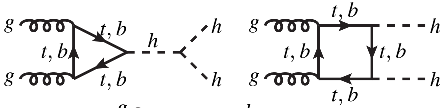
New coloured particles



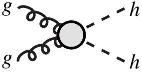


Signal elements

The Standard model topologies:



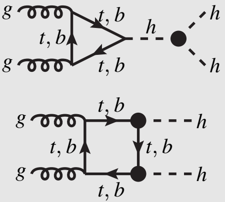
A new physics signal:



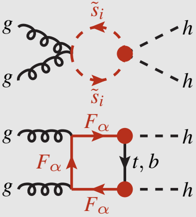
What can the signal be from a general perspective?

(limiting to gluon-fusion processes)

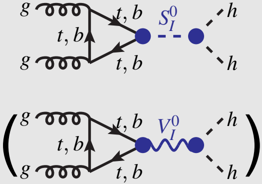
Modified SM couplings



New coloured particles



New neutral particles

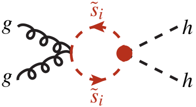


And combinations of these ingredients

The number of possibilities is limited!

Reduced cross-sections

Let's take one signal contribution:

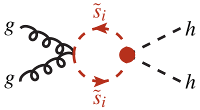


with $\mathcal{L} = \kappa_{hh\tilde{s}_i\tilde{s}_i}\, hh\tilde{s}_i^*\tilde{s}_i$

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

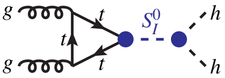
- $\kappa_{hh\tilde{s}_i\tilde{s}_i}$: rescaling of the cross-section
- $\hat{\sigma}(m_{\tilde{s}_i})$: kinematics of the process $\longrightarrow$ **reduced cross-section**

Reduced cross-sections

Let's take one signal contribution:  with $\mathcal{L} = \kappa_{hh\tilde{s}_i\tilde{s}_i}\; hh\tilde{s}_i^*\tilde{s}_i$

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

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

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

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

- **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

2 squarks and modified SM couplings

The simplified Lagrangian

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

All parameters are kept independent
(and real for simplicity)

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

What are we looking for?

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

All with one set of simulated samples

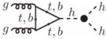
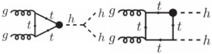
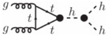
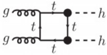
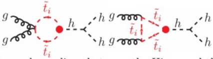
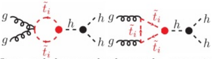
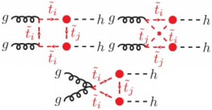
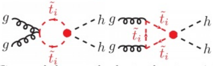
The recipe

1) Deconstruction
Identify all combinations proportional to unique couplings products

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

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

1) Deconstruction

	Topology type	Feynman diagrams	Amplitude
1	Modified Higgs trilinear coupling		$\mathcal{A}_i \propto \kappa_{hhh}$
2	One modified Yukawa coupling		$\mathcal{A}_i \propto \kappa_{htt}$
3	Modified Higgs trilinear coupling and modified Yukawa coupling		$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{htt}$
4	Two modified Yukawa couplings		$\mathcal{A}_i \propto \kappa_{htt}^2$
5	Bubble and triangle with $h\tilde{t}\tilde{t}$ couplings		$\mathcal{A}_i \propto \kappa_{h\tilde{t}\tilde{t}}^{ii}$
	This class of topologies involves only diagonal couplings between the Higgs and the squarks, due to the absence of FCNCs in strong interactions and the presence of one $h\tilde{t}\tilde{t}$ coupling.		
6	Modified Higgs trilinear coupling + Bubble and triangle with $h\tilde{t}\tilde{t}$ coupling		$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{h\tilde{t}\tilde{t}}^{ii}$
	Only diagonal couplings between the Higgs and the squarks due to the strong interaction.		
7	Triangle and box with two $h\tilde{t}\tilde{t}$ couplings		$\mathcal{A}_i \propto \lvert\kappa_{h\tilde{t}\tilde{t}}^{ij}\rvert^2$
8	Bubble and triangle with $hh\tilde{t}\tilde{t}$ coupling		$\mathcal{A}_i \propto \kappa_{hh\tilde{t}\tilde{t}}^{ii}$
	Only diagonal couplings between the Higgs and the squarks due to the strong interaction.		

8 kind of topologies

1) Deconstruction

Cross-section

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

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

1) Deconstruction

Cross-section

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

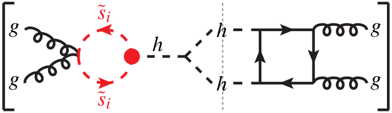
B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

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

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

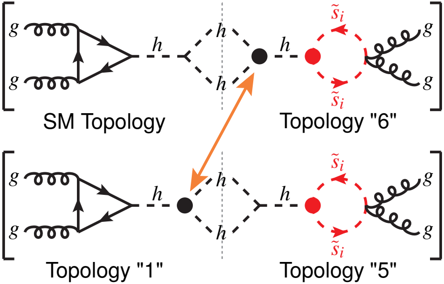
B: SM background, M: modified SM, S: squark propagation
MB, SB, MM, SS, MS, MSB: interference between these topologies

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

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

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



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

2) Database generation

Need to perform separate MC simulations for each deconstructed term

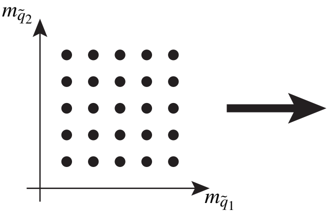
1) Use MG5_aMC with dedicated UFO models built in FeynRules
2) Associate individual coupling orders to each new coupling
3) Use specific simulation syntax for each process

Examples:

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

5B:
```
generate p p > h h [QCD] QCD^2==4 QED^2==3 HSQ1SQ1^2==1
```

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



Database of samples
simulated once and for all

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:

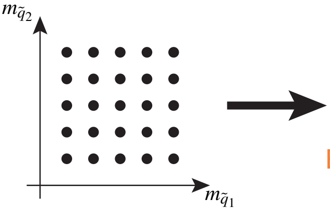
Background:

```
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

But what is in the database?

2) Database generation

Need to perform separate MC simulations for each deconstructed term

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

What is in the database?

Parton level

LHE
from MG5_aMC

piping through
Pythia 8

Reconstructed particles

LHE
FastJet via MA5

ROOT
from RIVET

Recast

Efficiency tables

$\sim$ 100Mb
per 100k events

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

$\mathcal{O}$(Kb)

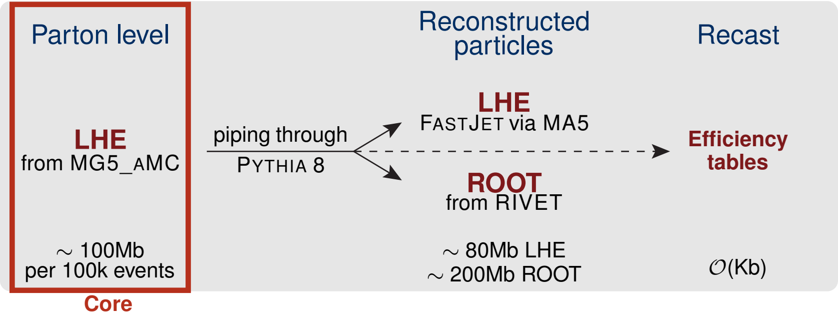
The grid doesn't need to be too dense → interpolation between points

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

What is in the database?



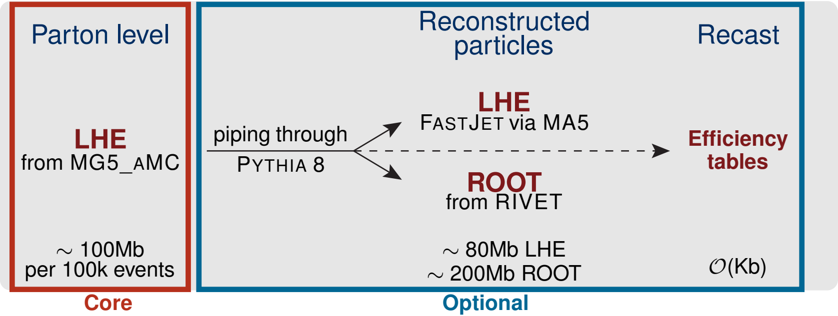
The grid doesn't need to be too dense → interpolation between points

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

What is in the database?



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

3) Recombination/Analysis

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/Analysis

defining a benchmark point

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

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

An MSSM benchmark point with high cross-section

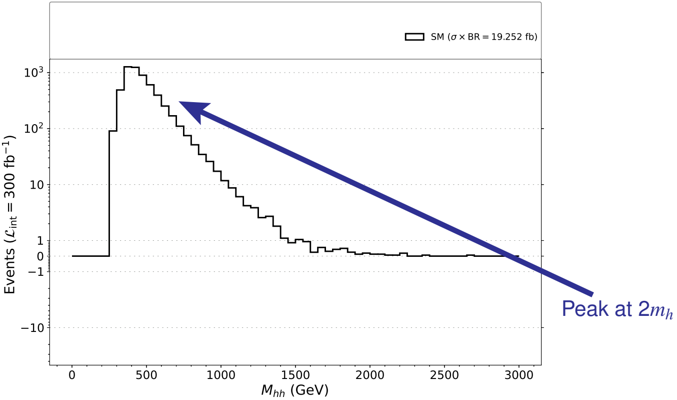
Masses and couplings	Value
$m_{\tilde{t}_1}$ (GeV)	600.6
$m_{\tilde{t}_2}$ (GeV)	1301.0
κ_{hhh}	3.34×10^{-3}
κ_{htt}	-1.68×10^{-3}

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

3) Recombination/Analysis

invariant mass distribution m_{hh}

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



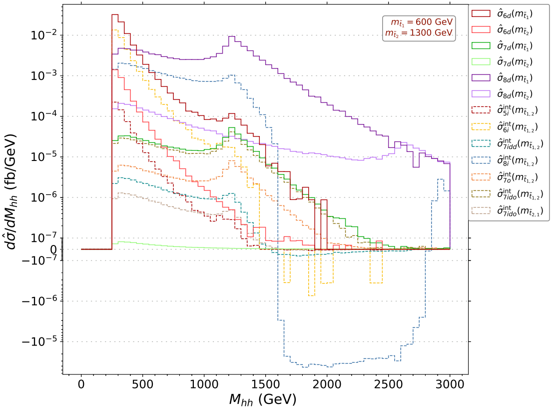
3) Recombination/Analysis

invariant mass distribution m_{hh}

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

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

Example with the σ_S elements



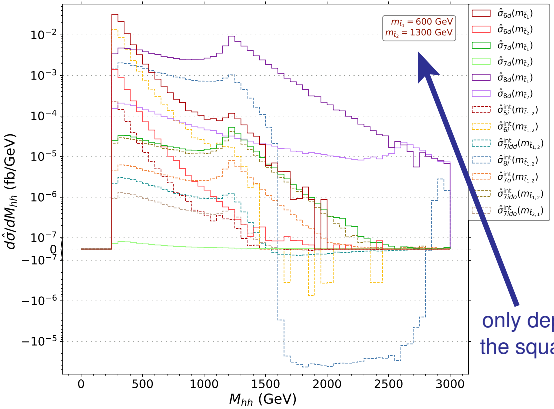
The deconstructed samples do not need to have the same number of MC events

3) Recombination/Analysis

invariant mass distribution m_{hh}

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 depending on the squark masses

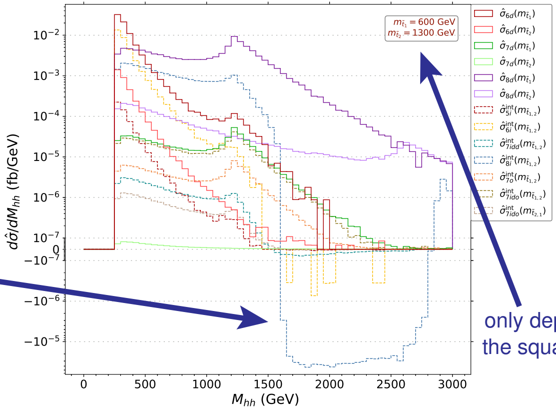
The deconstructed samples do not need to have the same number of MC events

3) Recombination/Analysis

invariant mass distribution m_{hh}

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

Example with the σ_S elements



Negative interference between topologies

only depending on the squark masses

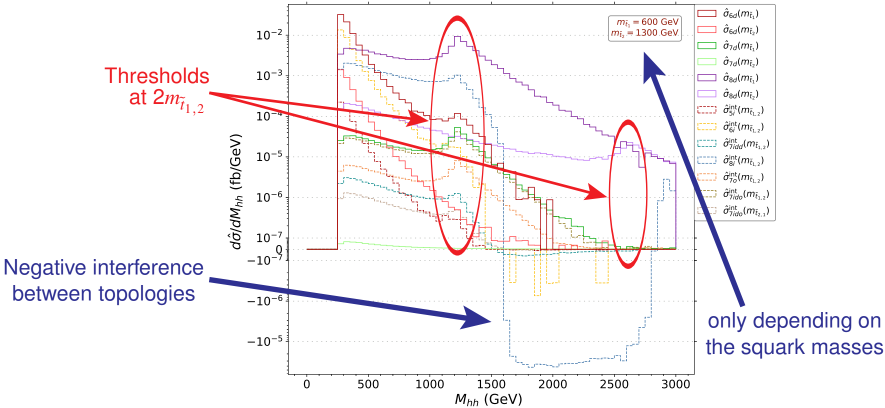
The deconstructed samples do not need to have the same number of MC events

3) Recombination/Analysis

invariant mass distribution m_{hh}

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

Example with the σ_S elements



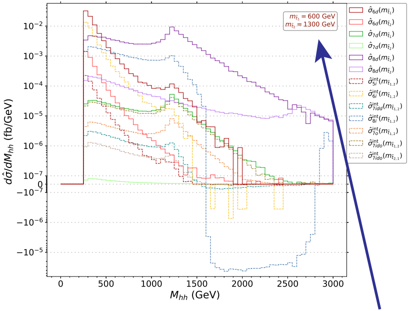
The deconstructed samples do not need to have the same number of MC events

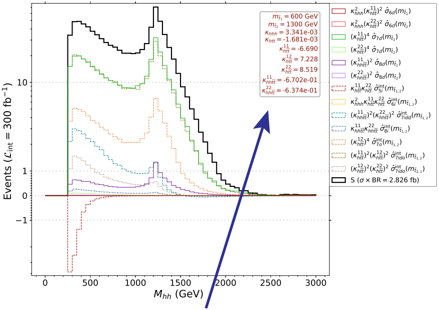
3) Recombination/Analysis

invariant mass distribution m_{hh}

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 depending on the squark masses

depending on masses and coupling

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

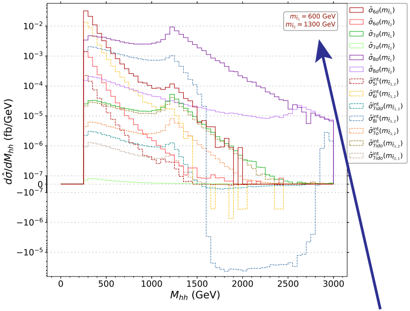
3) Recombination/Analysis

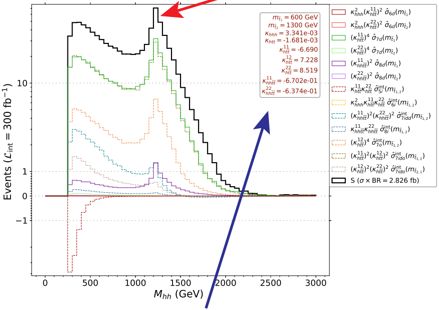
invariant mass distribution m_{hh}

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

Example with the σ_S elements

Sum of the contributions





only depending on the squark masses

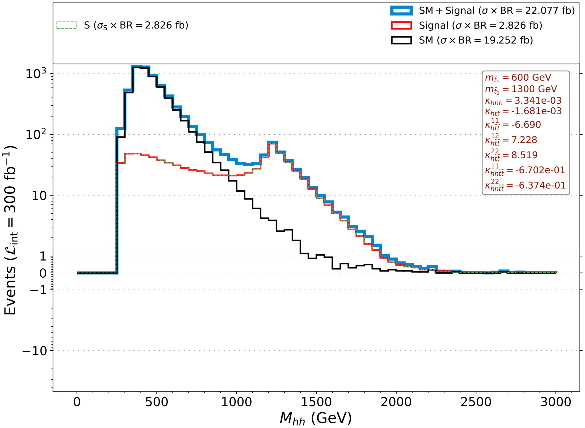
depending on masses and coupling

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

3) Recombination/Analysis

invariant mass distribution m_{hh}

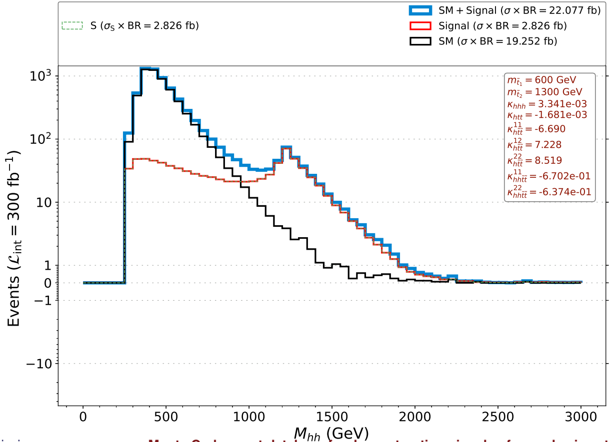
0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**



3) Recombination/Analysis

invariant mass distribution m_{hh}

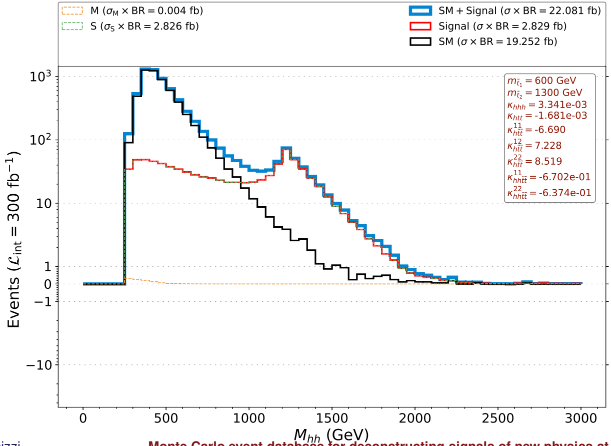
0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**
3) Repeat for all deconstructed elements



3) Recombination/Analysis

invariant mass distribution m_{hh}

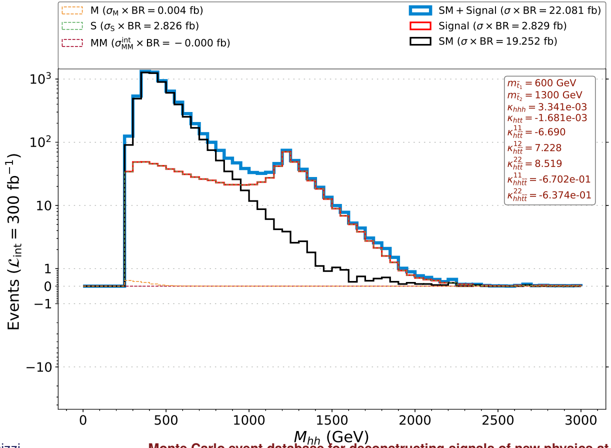
0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**
3) Repeat for all deconstructed elements



3) Recombination/Analysis

invariant mass distribution m_{hh}

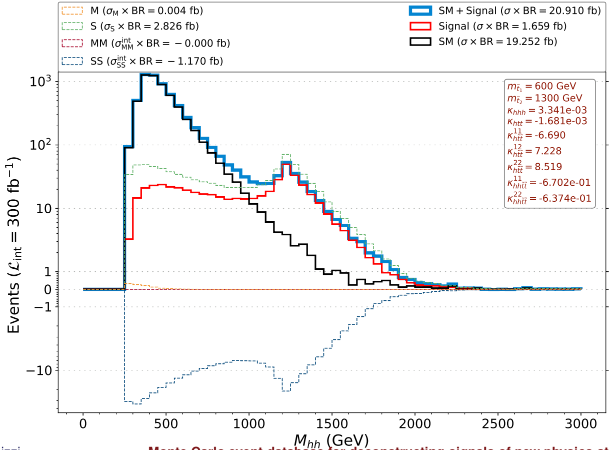
0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**
3) Repeat for all deconstructed elements



3) Recombination/Analysis

invariant mass distribution m_{hh}

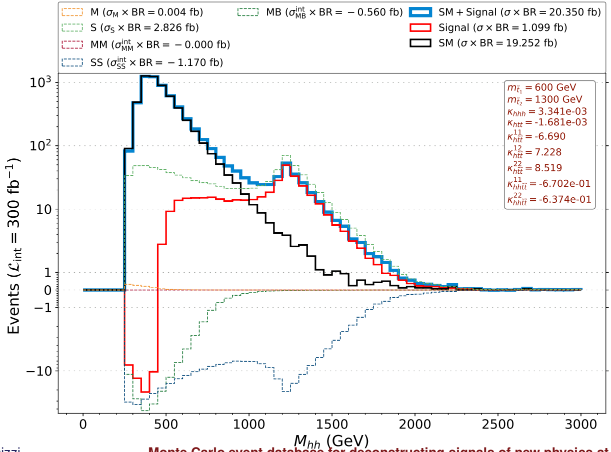
0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**
3) Repeat for all deconstructed elements



3) Recombination/Analysis

invariant mass distribution m_{hh}

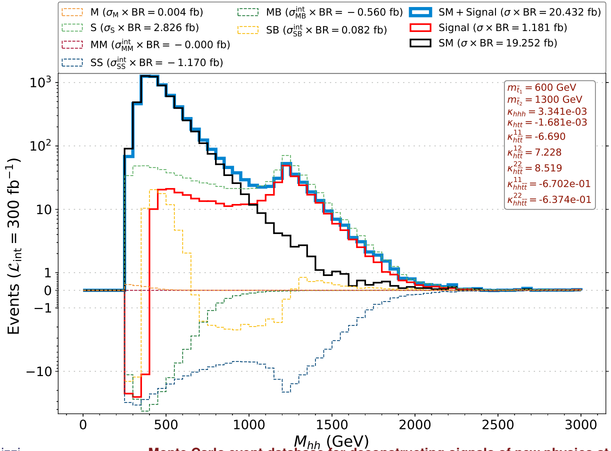
0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**
3) Repeat for all deconstructed elements



3) Recombination/Analysis

invariant mass distribution m_{hh}

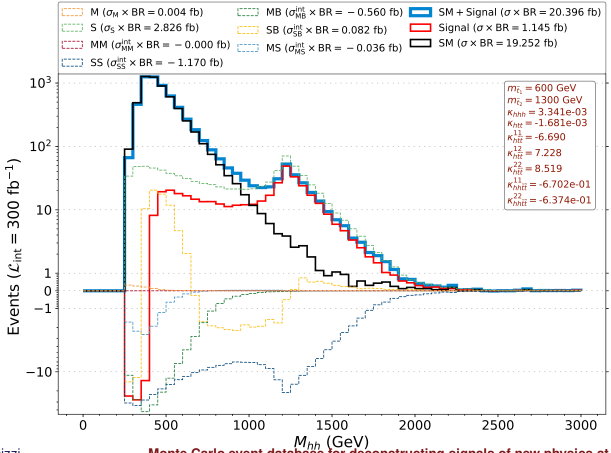
0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**
3) Repeat for all deconstructed elements



3) Recombination/Analysis

invariant mass distribution m_{hh}

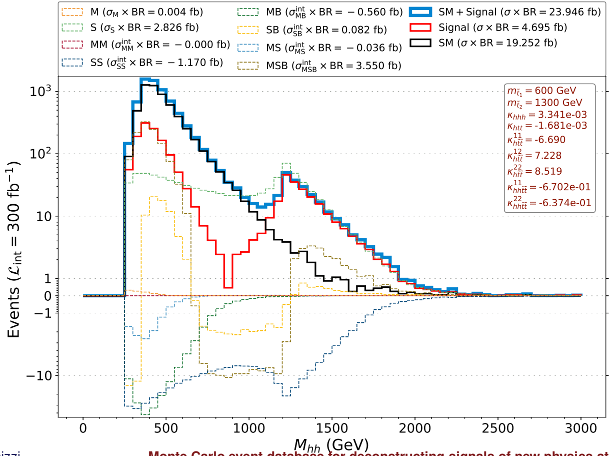
0) Background distribution (intrinsic background only: $pp \to hh$)
1) Distributions from deconstructed elements (*i.e.* with couplings factorised away)
2) Weighting the distributions with the benchmark couplings **and recombine!**
3) Repeat for all deconstructed elements



3) Recombination/Analysis

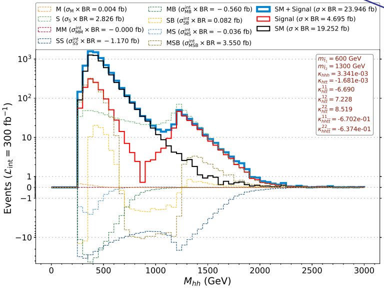
invariant mass distribution m_{hh}

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

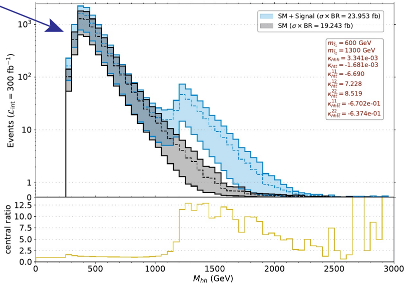


3) Recombination/Analysis

including systematics
independent simulation for cross-check



invariant mass distribution m_{hh}



With the same database we can

- analyse the contribution of specific topologies to the total shape
- use a semi-analytic approach to find parameters which maximise key features
  → excesses, deficits, threshold effects,. . .
- perform a “real life” analysis including reconstruction and applying selection and kinematical cuts to the signal
- find predictions for any other theoretical scenario with same particle content

Discriminating models

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

Discriminating models

The **MSSM** is constrained:
- Large difference between squarks masses to obtain m_h
- SM modified couplings (λ and y_t) are close to the SM values

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

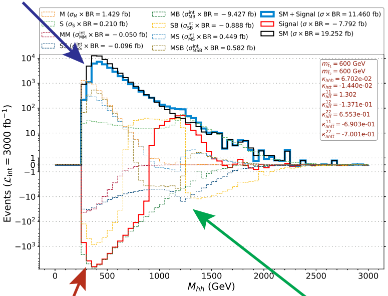
Discriminating models

The **MSSM** is constrained: { Large difference between squarks masses to obtain m_h; SM modified couplings (λ and y_t) are close to the SM values

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

deficit at low m_{hh}

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



large negative MB interference

Large peak cancellation despite 2 light stops

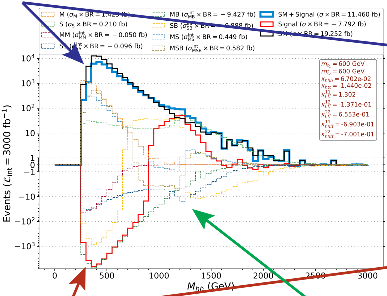
Discriminating models

The **MSSM** is constrained:
- Large difference between squarks masses to obtain m_h
- SM modified couplings (λ and y_t) are close to the SM values

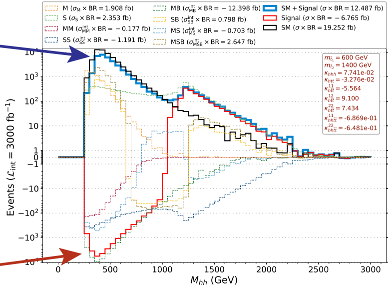
In the **NMSSM**:
- New scalar allows to obtain m_h=125 GeV at tree level
- Both stops can be light ($\sim$ 600 GeV from exp bounds)
- λ can be large, y_t is constrained by $t\bar{t}h$ at LHC

deficit at low m_{hh}

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



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



large negative MB interference

Large peak cancellation despite 2 light stops

Reverse engineering

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

Reverse engineering

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

A testing with our MC sets:

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

Reverse engineering

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

A testing with our MC sets:

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

First try

Input parameters

$m_{\tilde{t}_1} = 600$ GeV
$m_{\tilde{t}_2} = 1400$ GeV
$\kappa_{hhh} = 1.208\text{e-}01$
$\kappa_{htt} = -3.309\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = 5.965$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 9.598$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 7.825$
$\kappa^{11}_{hh\tilde{t}\tilde{t}} = -6.874\text{e-}01$
$\kappa^{22}_{hh\tilde{t}\tilde{t}} = -6.437\text{e-}01$

Fitted parameters

$m_{\tilde{t}_1} = 600$ GeV
$m_{\tilde{t}_2} = 1300$ GeV
$\kappa_{hhh} = 8.430\text{e-}02$
$\kappa_{htt} = -5.972\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = -1.203$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 10.000$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 3.022$
$\kappa^{11}_{hh\tilde{t}\tilde{t}} = 1.369$
$\kappa^{22}_{hh\tilde{t}\tilde{t}} = 5.366$

Caveats:

- Only couplings were fitted, stop masses were assumed
- MSSM relations between couplings were assumed, but the point was random

Reverse engineering

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

A testing with our MC sets:

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

First try

Input parameters	→	Fitted parameters
$m_{\tilde{t}_1} = 600$ GeV		$m_{\tilde{t}_1} = 600$ GeV
$m_{\tilde{t}_2} = 1400$ GeV		$m_{\tilde{t}_2} = 1300$ GeV
$\kappa_{hhh} = 1.208\text{e-}01$		$\kappa_{hhh} = 8.430\text{e-}02$
$\kappa_{htt} = -3.309\text{e-}02$		$\kappa_{htt} = -5.972\text{e-}02$
$\kappa^{11}_{h\tilde{t}\tilde{t}} = 5.965$		$\kappa^{11}_{h\tilde{t}\tilde{t}} = -1.203$
$\kappa^{12}_{h\tilde{t}\tilde{t}} = 9.598$		$\kappa^{12}_{h\tilde{t}\tilde{t}} = 10.000$
$\kappa^{22}_{h\tilde{t}\tilde{t}} = 7.825$		$\kappa^{22}_{h\tilde{t}\tilde{t}} = 3.022$
$\kappa^{11}_{hh\tilde{t}\tilde{t}} = -6.874\text{e-}01$		$\kappa^{11}_{hh\tilde{t}\tilde{t}} = 1.369$
$\kappa^{22}_{hh\tilde{t}\tilde{t}} = -6.437\text{e-}01$		$\kappa^{22}_{hh\tilde{t}\tilde{t}} = 5.366$

But how wrong is this fit?

Caveats:

- Only couplings were fitted, stop masses were assumed
- MSSM relations between couplings were assumed, but the point was random

Reverse engineering

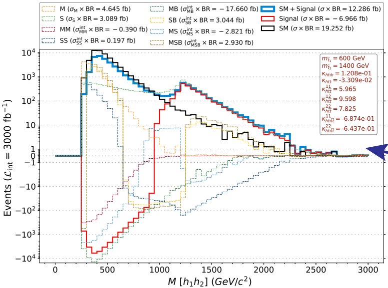
Given an experimental dataset, is it possible to fit the parameters?

A testing with our MC sets:

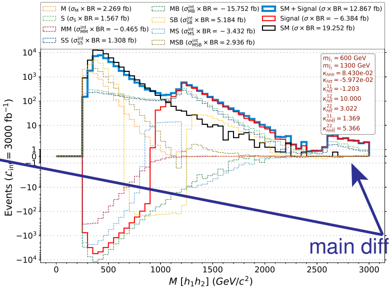
1) We generated a benchmark
2) "Blinded" the parameters and asked our ATLAS colleague to do the parametric fit

First try

Original benchmark



Fitted benchmark



main difference

Different parameter sets lead to very similar distributions

Reverse engineering

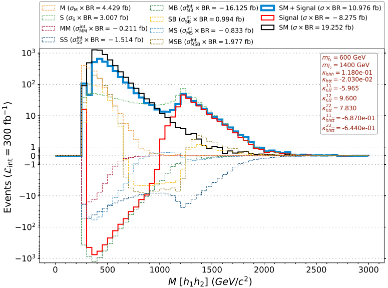
Given an experimental dataset, is it possible to fit the parameters?

A testing with our MC sets:

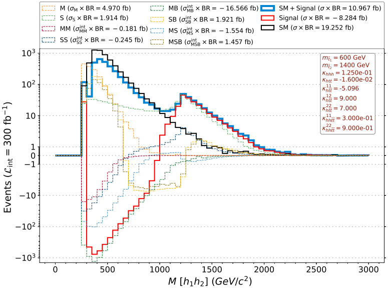
1) We generated a benchmark
2) "Blinded" the parameters and asked our ATLAS colleague to do the parametric fit

Second try

Original benchmark



Fitted benchmark



perfect fit with very close numerical values of relevant parameters!

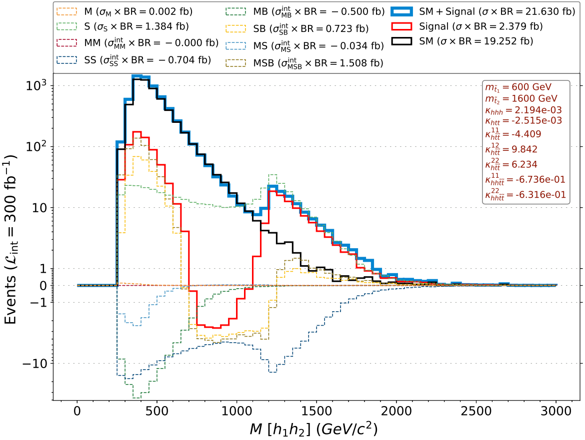
Relative contributions are different **but fitted result is indistinguishable from original**

Classes of solutions can fit possible excesses

The EFT limit

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

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

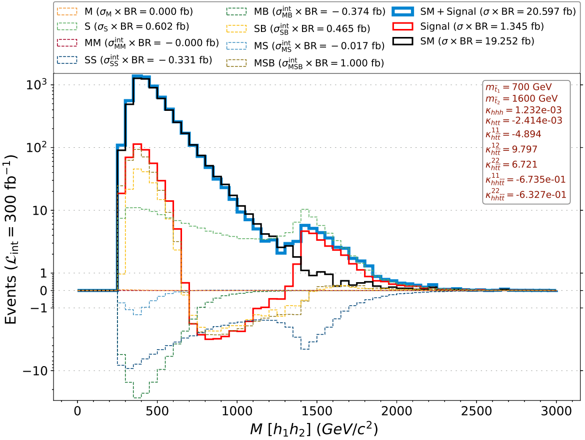


Smooth exploration of the interface between low scale and EFT limit

The EFT limit

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

$m_{\tilde{t}_1} = 700$ GeV, $m_{\tilde{t}_2} = 1600$ GeV

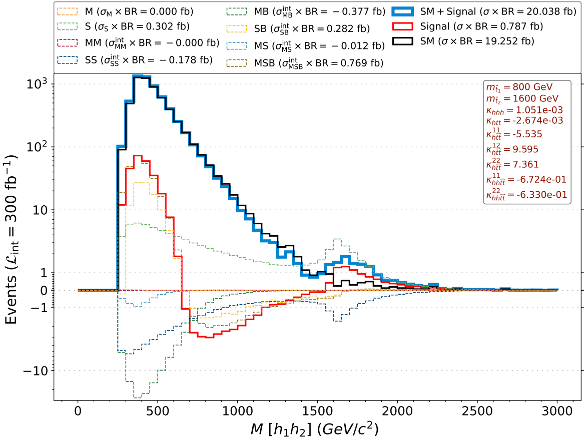


Smooth exploration of the interface between low scale and EFT limit

The EFT limit

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

$m_{\tilde{t}_1} = 800$ GeV, $m_{\tilde{t}_2} = 1600$ GeV

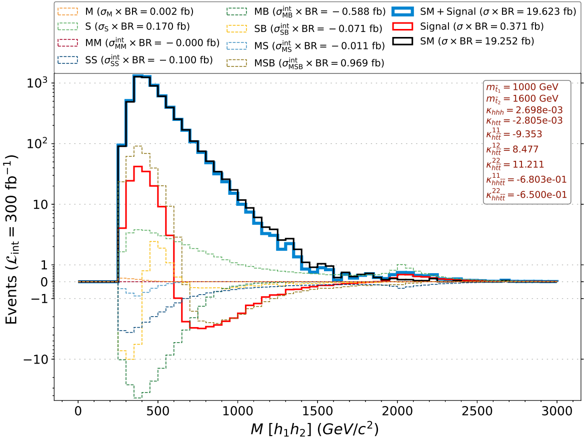


Smooth exploration of the interface between low scale and EFT limit

The EFT limit

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

$m_{\tilde{t}_1} = 1000$ GeV, $m_{\tilde{t}_2} = 1600$ GeV



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

Other applications

vector-like quark and dark matter studies

Papers using deconstruction techniques

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

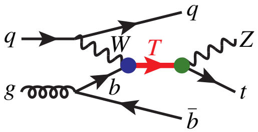
A. Deandrea, T. Flacke, B. Fuks, **LP** and H. S. Shao, JHEP **08** (2021), 107

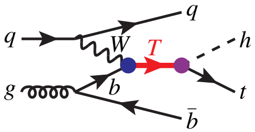
C. Arina, B. Fuks, J. Heisig, M. Krämer, L. Mantani and **LP**, Phys. Rev. D **108** (2023) no.11, 115007

A. Banerjee, E. Bergeaas Kuutmann, V. Ellajosyula, R. Enberg, G. Ferretti and **LP**
arXiv:2406.09193 [hep-ph].

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)

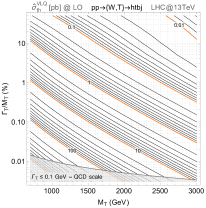
$$\begin{aligned}
\sigma_\mathrm{tot}(pp\to Wbbj) &= \sigma_{Wb}^\mathrm{SM} + \kappa_W^4\ \hat{\sigma}_{Wb}^\mathrm{VLQ}(M_T,\Gamma_T) + \kappa_W^2\ \hat{\sigma}_{Wb}^\mathrm{int}(M_T,\Gamma_T)\ ,\\
\sigma_\mathrm{tot}(pp\to Ztbj) &= \sigma_{Zt}^\mathrm{SM} + \kappa_W^2\kappa_Z^2\ \hat{\sigma}_{Zt}^\mathrm{VLQ}(M_T,\Gamma_T)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

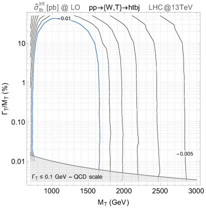
- **κ_W, κ_Z and κ_h couplings**: partial widths and rescaling of cross-section
- **Mass and total width**: kinematics of the process

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

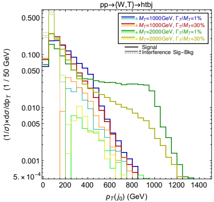
The large width regime

Mass vs total width reduced cross-sections





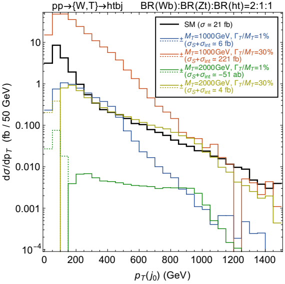
Differential distributions



Physical scenario 1

different masses and total widths

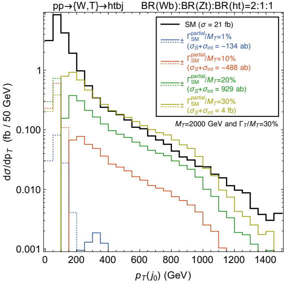
100% SM interactions



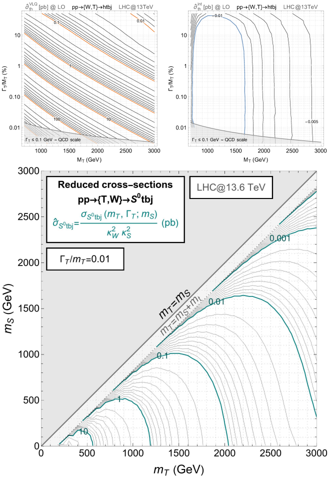
Physical scenario 2

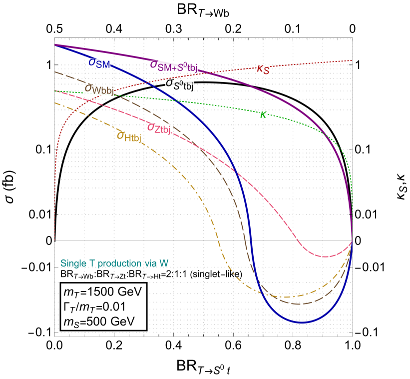
same mass and total width

but $\leq$100% SM interactions



Adding exotic decays





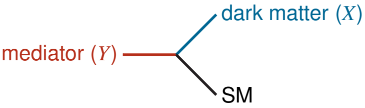
Combining SM and exotic final states
to understand when single production is observable and in which final states

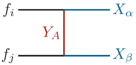
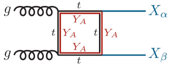
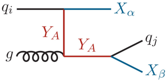
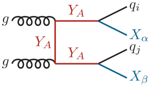
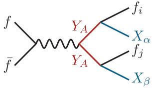
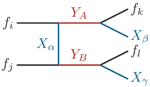
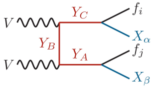
Ongoing discussions with ATLAS about implementing this approach

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)		

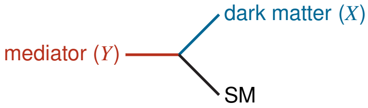
Relatively small number of possibilities can cover a large number of theoretical scenarios

Work in progress in the LHCDMWG

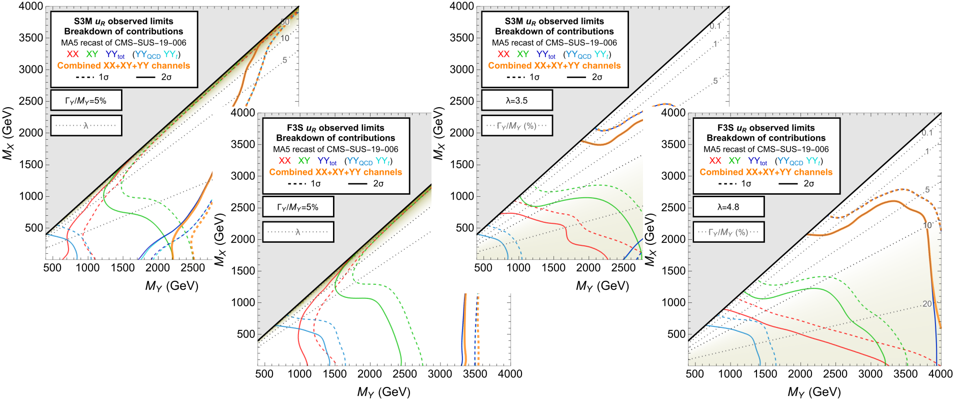
Dark matter

t-channel scenarios

Study of scenarios based on the schematic interaction:



Study of different benchmarks with the same dataset



Deconstruction framework

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

Deconstruction framework

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

Further developments

- Develop a **public portal**
- Include **further final states** and interface with **EFT studies**

Deconstruction framework

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

Further developments

- Develop a **public portal**
- Include **further final states** and interface with **EFT studies**

Challenges

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

Deconstruction framework

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

Further developments

- Develop a **public portal**
- Include **further final states** and interface with **EFT studies**

Challenges

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

Limitations

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

Deconstruction framework

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

Further developments

- Develop a **public portal**
- Include **further final states** and interface with **EFT studies**

Challenges

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

Limitations

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

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