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## X->HH searches in CMS

E. Jourd'Huy

► **To cite this version:**

E. Jourd'Huy. X->HH searches in CMS. Journées de Rencontre Jeunes Chercheurs 2023, Oct 2023, La Rivière in Saint-Jean-de-Monts, France. in2p3-04908107

**HAL Id: in2p3-04908107**

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Submitted on 23 Jan 2025

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# Combination of $X \rightarrow HH$ searches in CMS with the RUN2 data

JRJC

**Elise Jourd'huy**

*Supervised by Maxime Gouzevitch*

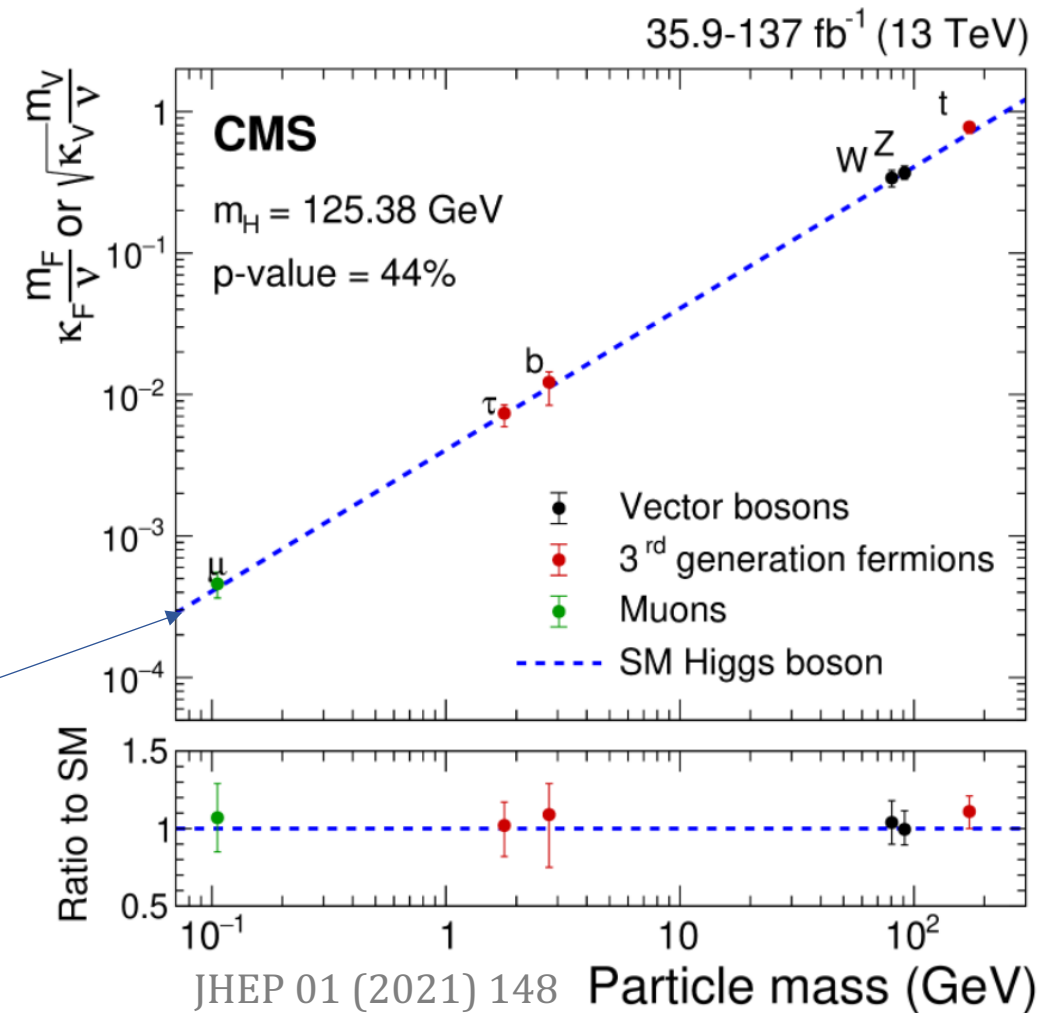
# The Higgs boson

**1964** : Higgs, Englert & Brout, Hagen & Guralnik & Kibble predicted a **field** (and its **boson**) **responsible for the masses of elementary particles.**

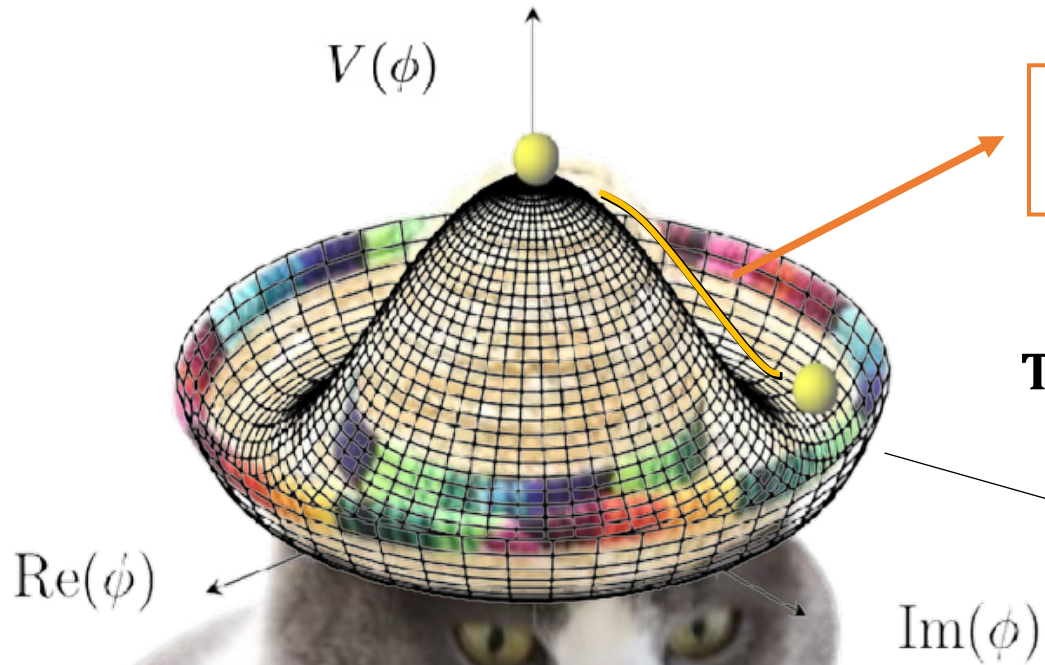
**2012** : Observation of a Higgs boson at CMS and ATLAS.

Mass  $\propto$

$$\begin{matrix} \text{Interaction force with the Higgs field} \\ \times \\ \text{Vacuum expectation value of the Higgs field } (v) \end{matrix}$$



# The BEH mechanism



The Standard Model postulates the simplest potential shape :

$$V(\phi) = \lambda(\phi^2 - v^2)^2$$

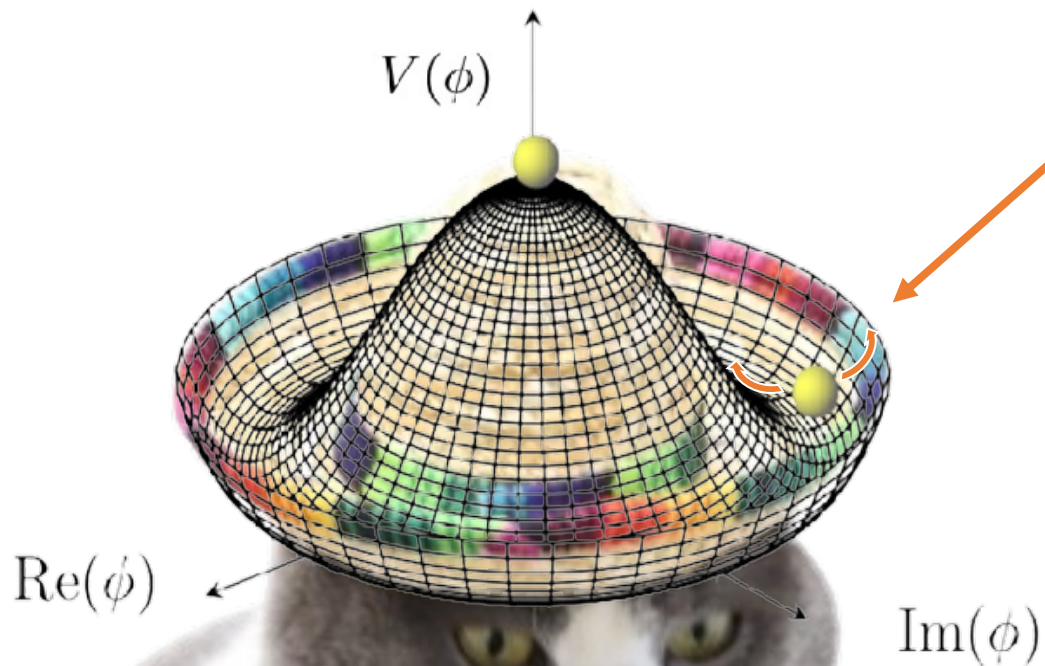
Higgs field

$$\lambda_{SM} \approx 0,13$$

Vacuum expectation value  
Already measured

**This potential was never experimentally observed!**  
The only way is to do so is to measure  $\lambda$

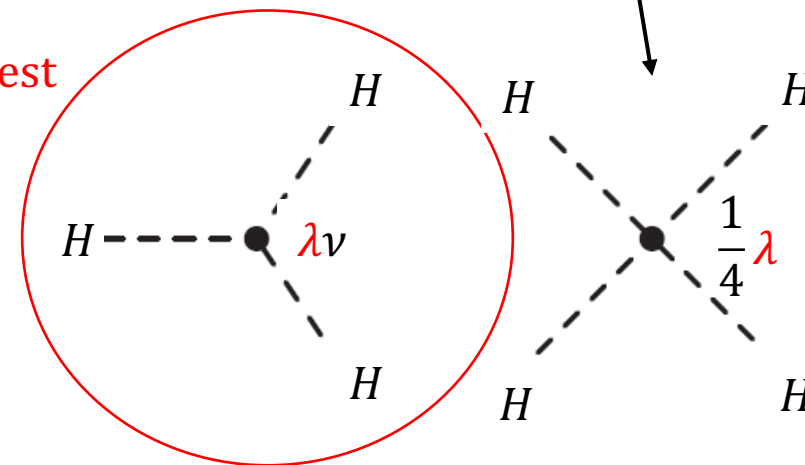
# The self-coupling constant $\lambda$



Fluctuations around  $v$  :  $\phi = (H + v)/\sqrt{2}$

$$V(H) = \frac{1}{4} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$

Simplest



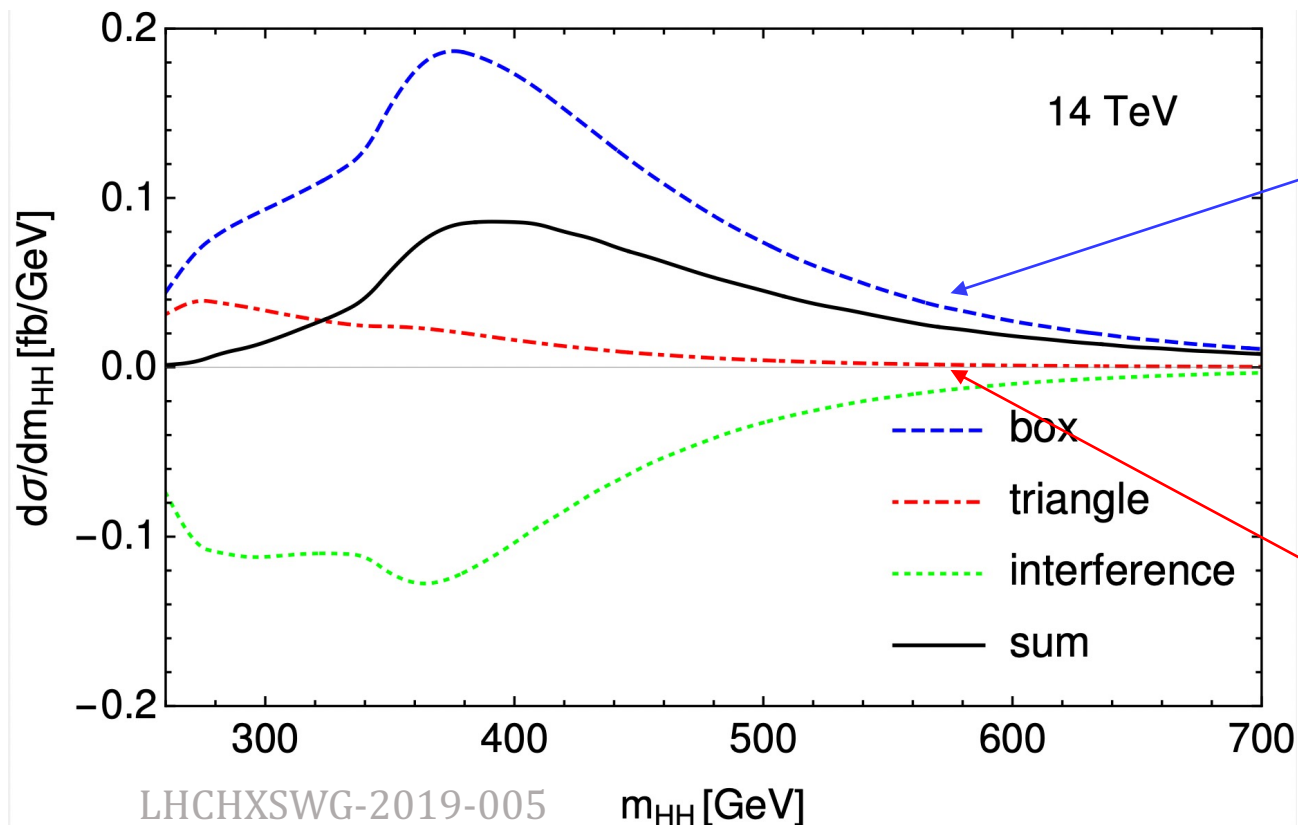
Higgs boson self-interaction

- The number of observed **Higgs boson pairs** events depends on  $\lambda$ .
- The Higgs boson pair production was **never observed** to this day :  $\approx 1000 \times$  **rarer** than a single Higgs production

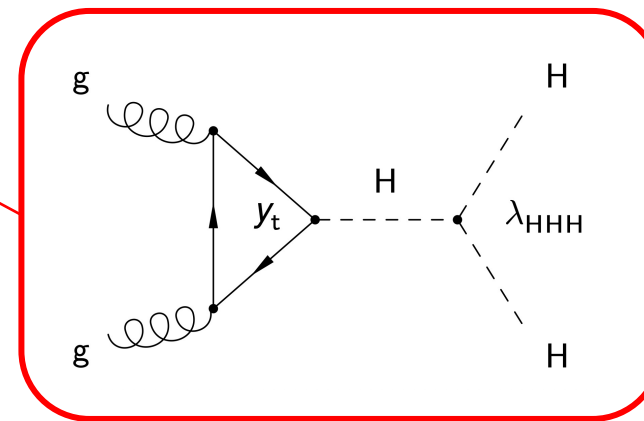
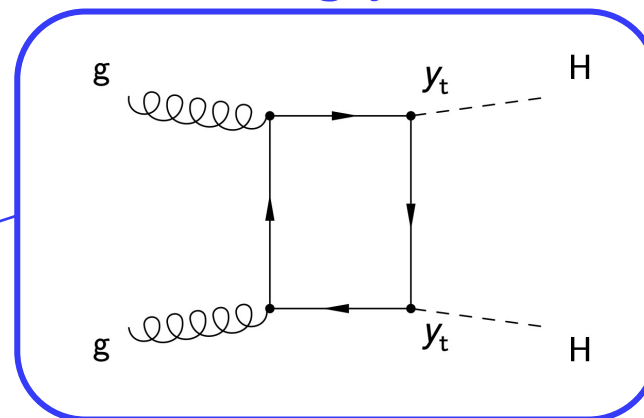
# HH spectrum in the SM

The Higgs pair invariant mass is the variable of interest in the BEH potential study.

BEH potential different from the SM → **Deformation of  $m_{HH}$**



**Bad guy ☹️**



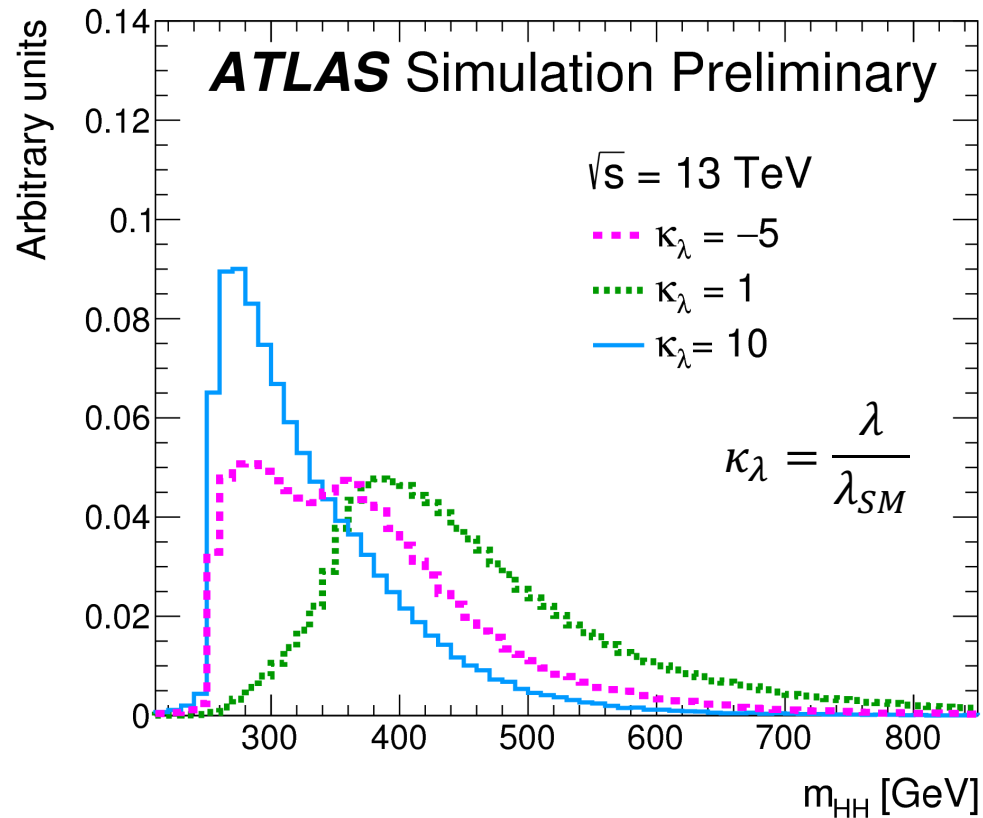
**Good guy ☺️**

Major HH production processes

# HH spectrum

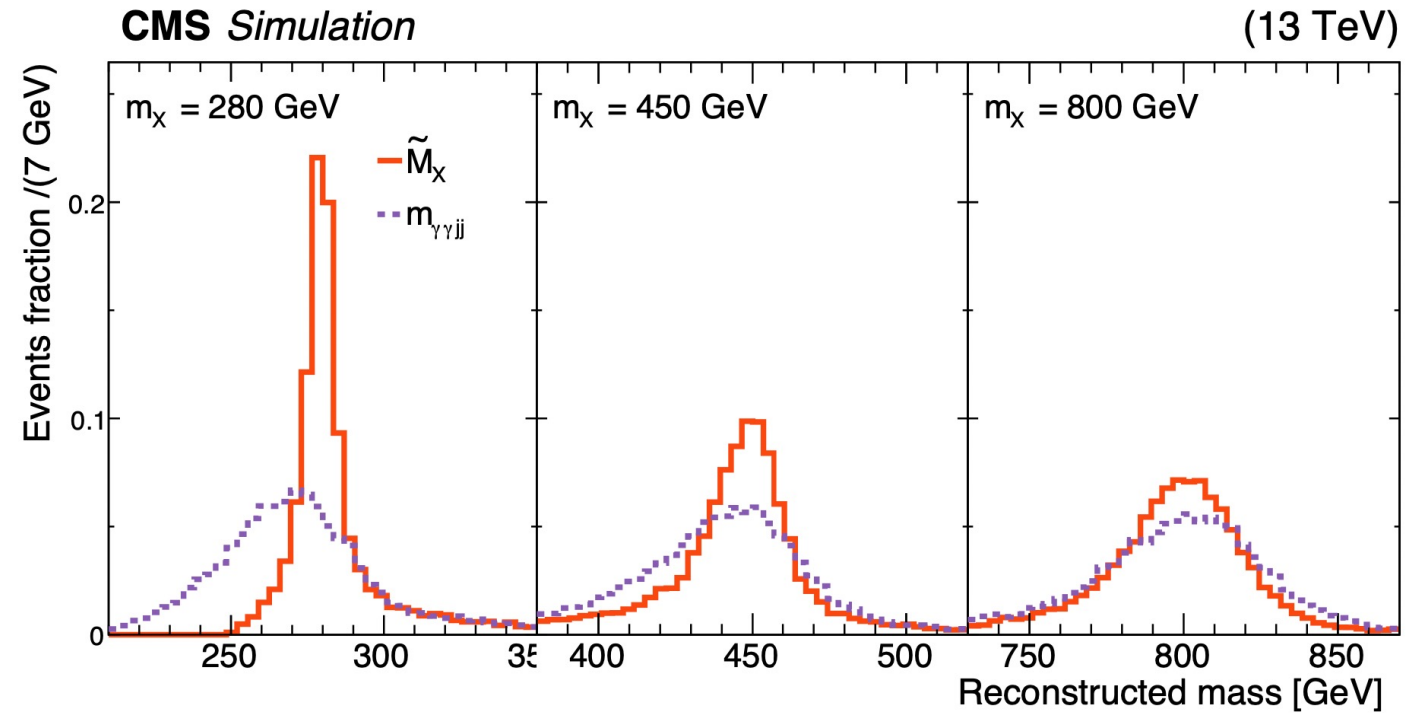
**Non-resonnant :**

**Deformation of  $m_{HH}$  spectrum**



**Resonnant :**

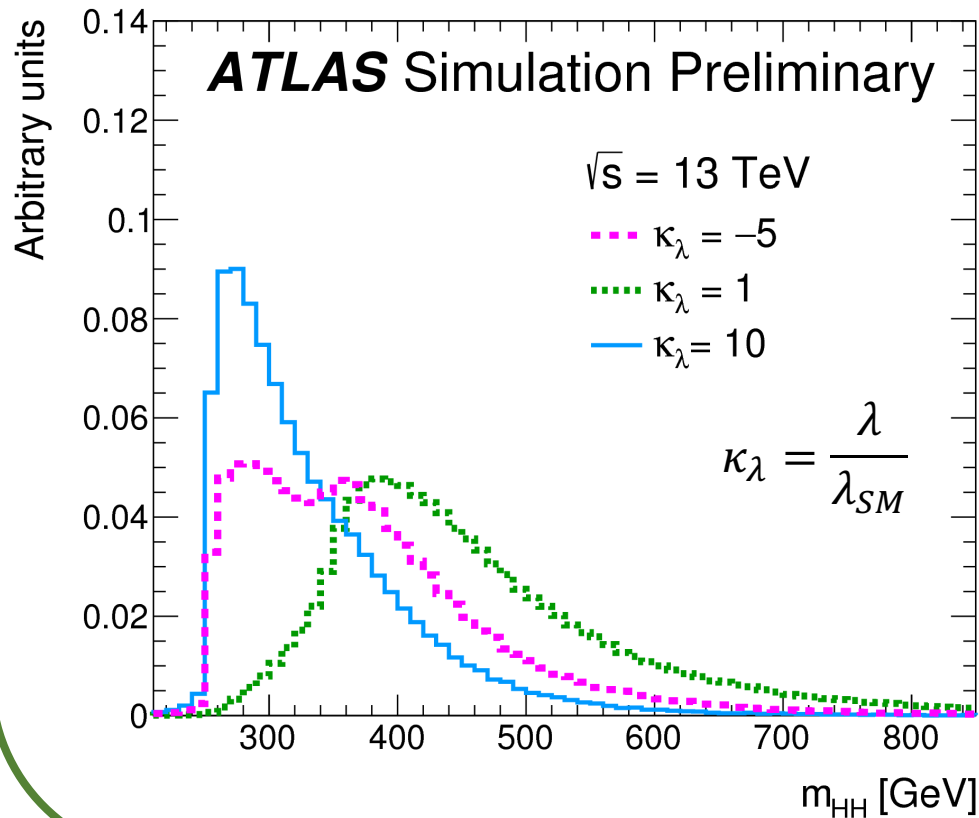
**Resonance in the  $m_{HH}$  spectrum**



# HH spectrum

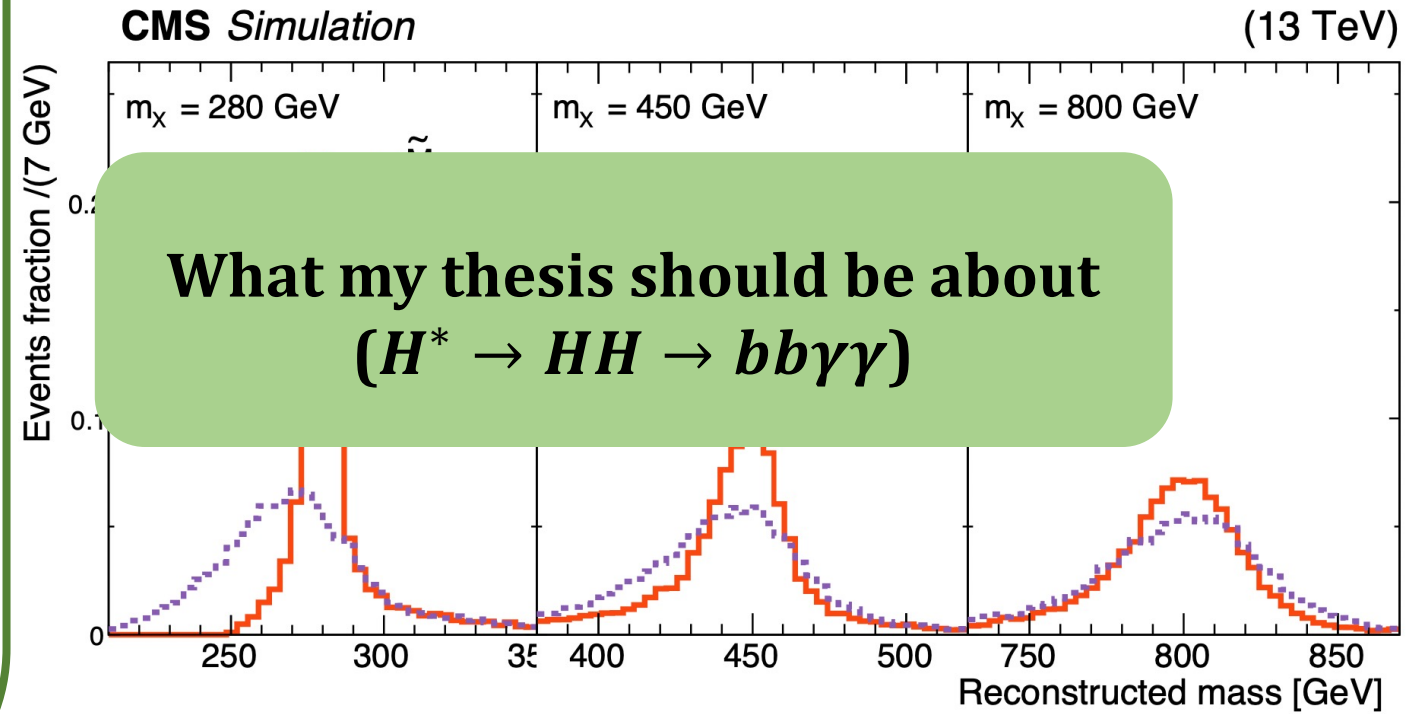
**Non-resonnant :**

**Deformation of  $m_{HH}$  spectrum**



**Resonnant :**

**Resonance in the  $m_{HH}$  spectrum**

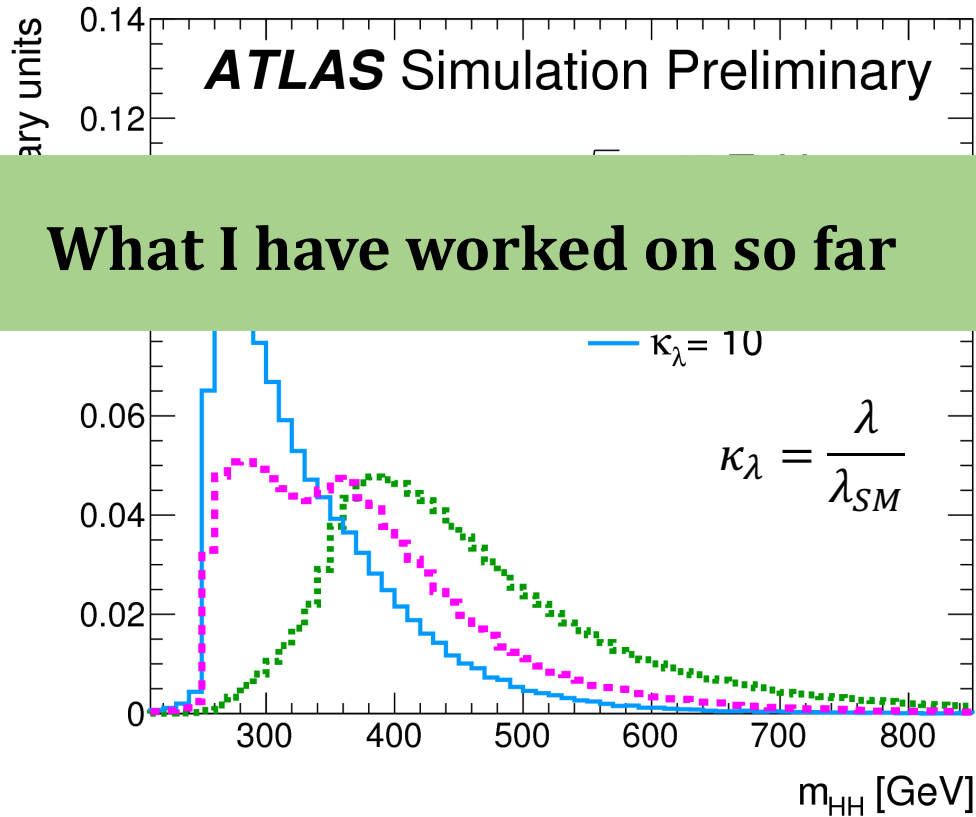




# HH spectrum

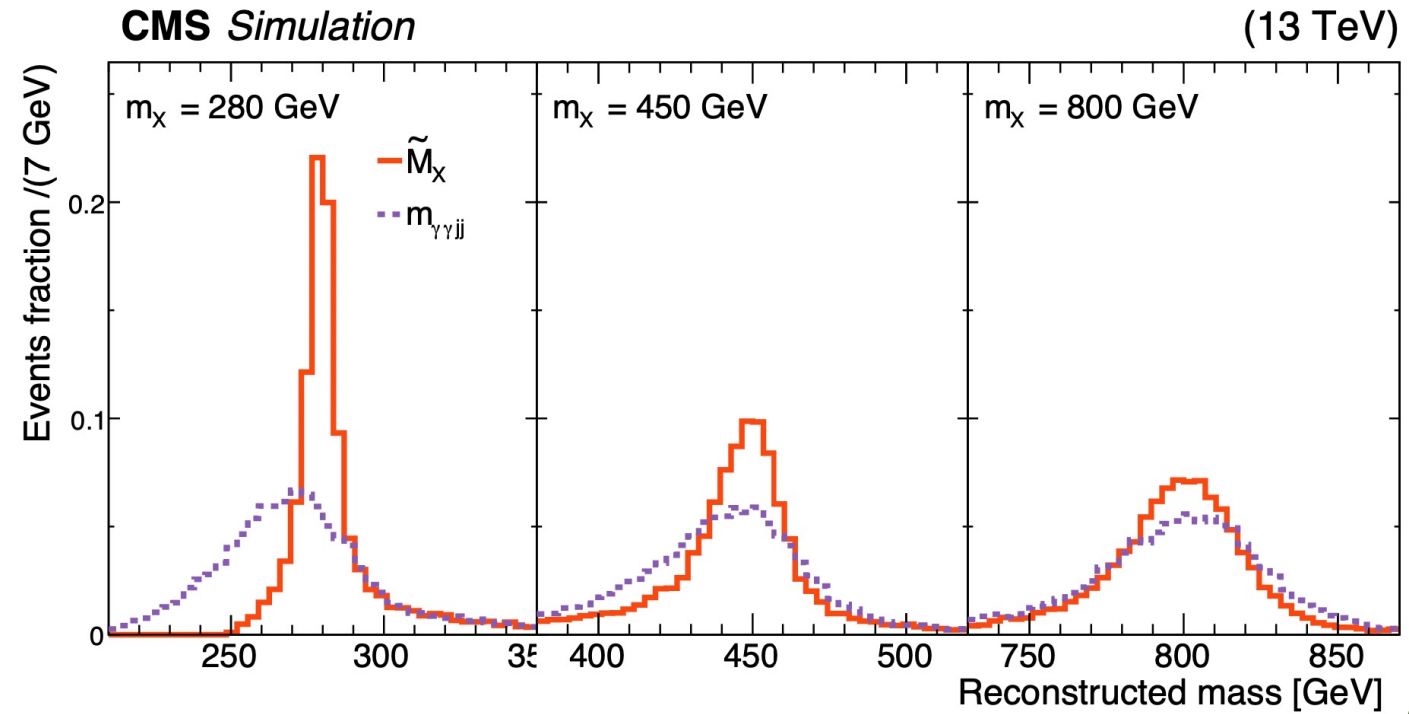
Non-resonnant :

Deformation of  $m_{HH}$  spectrum

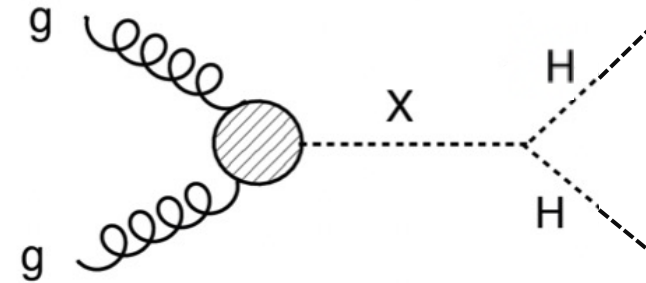
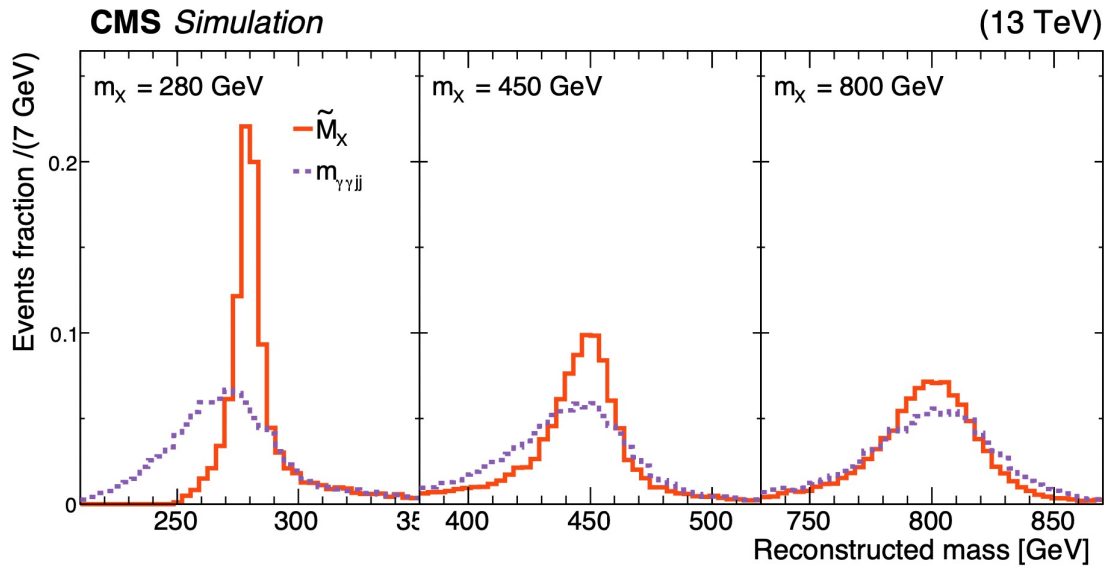
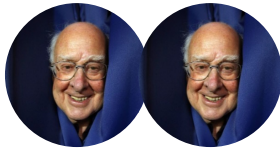


Resonnant :

Resonance in the  $m_{HH}$  spectrum

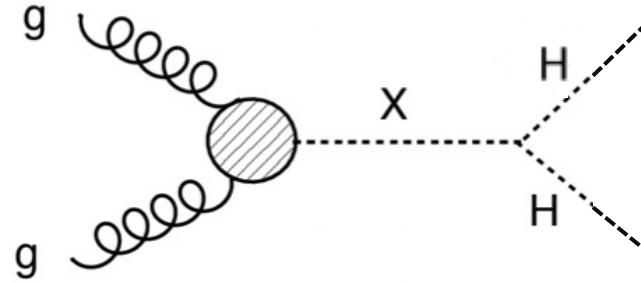


$X \rightarrow$



**Some BSM theories predict the presence of a resonance X decaying into a Higgs pair**

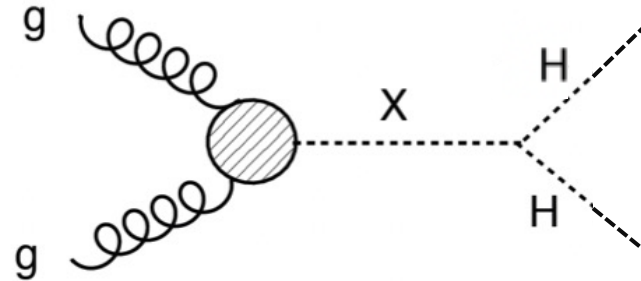
# For those who like theory



- **Extended Higgs sector** : The SM complex Higgs doublet can be extended with additional singlet or doublet
  - Additional SM-like Higgs boson
  - Depending on the precise theory, it can tackle some of the BIG QUESTIONS ( matter-antimatter asymetry, dark matter, naturalness and hierarchy problem ...)

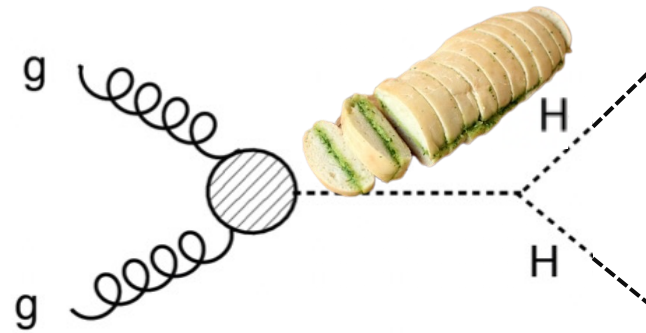
**The SM Higgs mechanism is minimal → Other models predict additionnal particles**

# For those who like theory



- **Extended Higgs sector** : The SM complex Higgs doublet can be extended with additional singlet or doublet
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  - Depending on the precise theory, it can tackle some of the BIG QUESTIONS ( matter-antimatter asymmetry, dark matter, naturalness and hierarchy problem ...)
- **Warped Extra Dimensions** : postulates the existence of one extra dimension
  - New particles decaying into  $HH$  such as a Spin-0 radion and the spin2 Kaluza-Klein excitation of the Graviton.

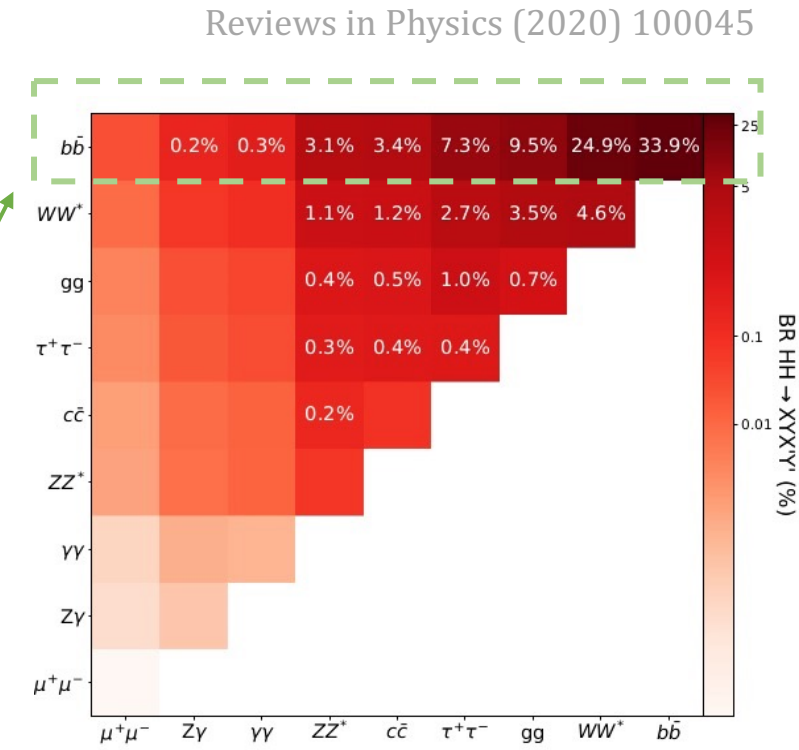
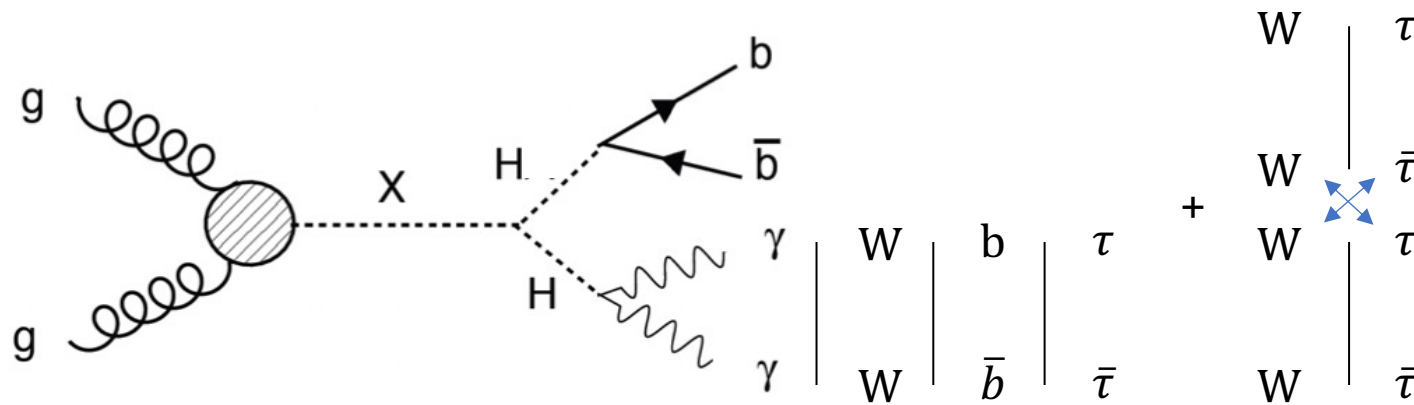
# For those who like theory



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- **Warped Extra Dimensions** : postulates the existence of one extra dimension
  - New particles decaying into HH such as a Spin-0 radion and the spin2 Kaluza-Klein excitation of the Graviton.
- **The Vendée theory** : Theory created by Mr. Charrette while visiting the Puy du fou, postulating the existence of a **Prefou** that could decay into a Higgs pair.
  - *Would solve everything*

# And what do I do ?

I worked on the **statistical combination** of the  $X \rightarrow HH$  searches :  
*bbγγ, bbVV (resolved and boosted), bbbb (resolved and boosted), bbττ, multilepton*



Most channels take advantage of the high b-quark Branching ratio



# Combination recipe



- Check the compatibility of input analyses
  - ✓ An event can not appear in two different analyses
  - ✓ Parameters should be correctly correlated among analyses
  - ✓ Same normalisation
- Perform your combination
- Check the sanity of your combination with statistical tests
  - ✓ Impacts and pulls of the parameters
  - ✓ Injection tests
  - ✓ ...

# “Compatibility of the analyses”

✓ One event cannot appear in two different analyses

✓ Correlation between parameters :

Profile likelihood ratio test statistic :

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\vec{\theta}}(\vec{\alpha}))}{L(\vec{\alpha}, \hat{\vec{\theta}})}$$

Nuisance parameters

Parameter of interest (POI)

Systematic uncertainties  $\Rightarrow$  Nuisance parameters in the fit : some of them are correlated across analyses

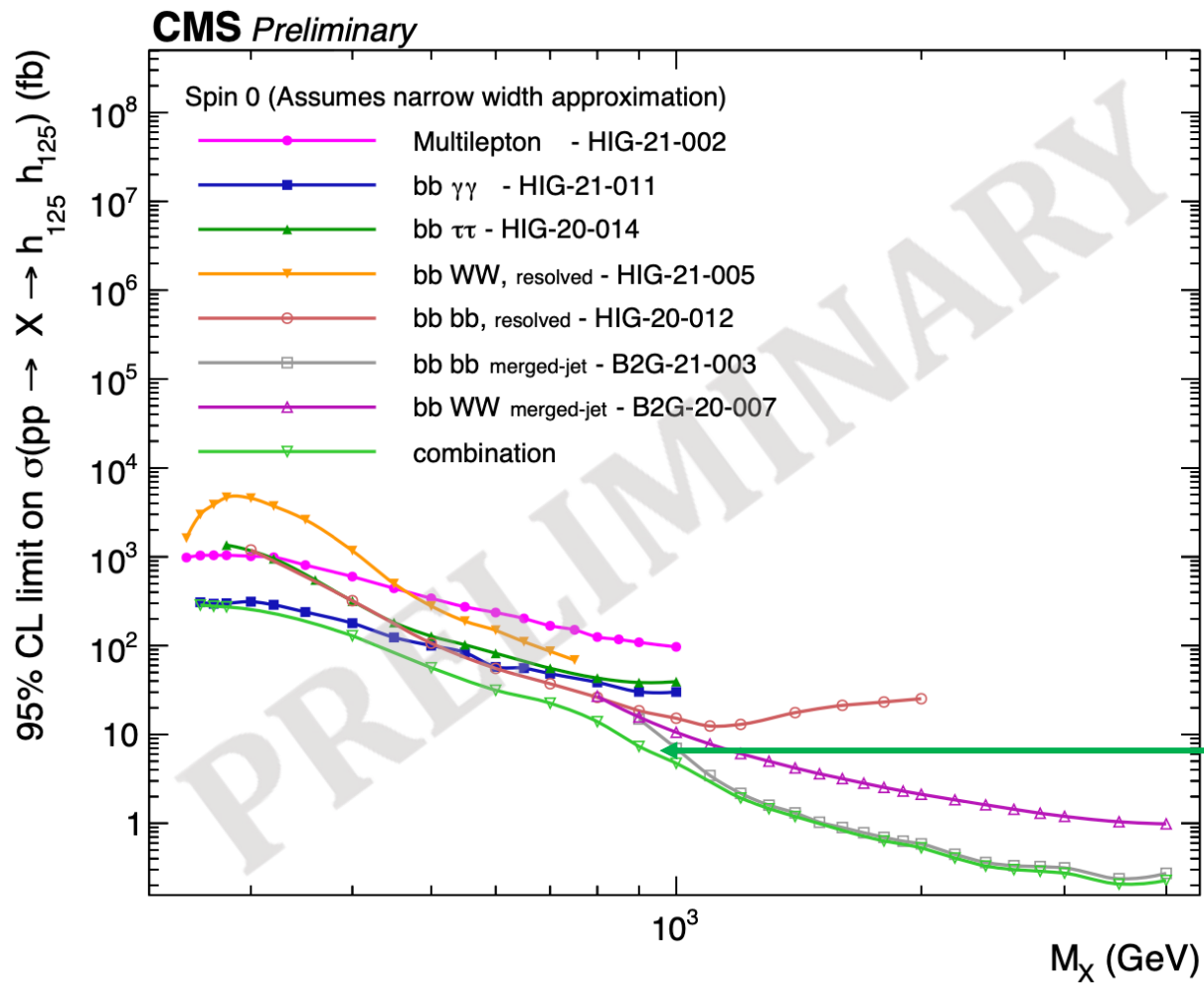
Example : The *luminosity* has an uncertainty, which is fully correlated across analyses. Only **one** nuisance parameter should appear, and not one for each analysis.

*The combination counts over 1000 nuisance parameters !*

✓ Same normalization for all analysis



# “ Perform your combination ”



Results for **expected limits** on  $\sigma(X \rightarrow HH)$



**Gain in sensitivity**

# Statistical tests

The statistical tests are performed for 3 representative X masses :  $M_X = 280, 500, 1000 \text{ GeV}$

*They are done to check if our fit worked correctly, that the nuisances parameters are well defined (and well correlated)*

# Pulls

$$pulls = \frac{\theta_{post} - \theta_{pre}}{\Delta\theta}$$

If  $pulls = 1 \Rightarrow \theta_{post} - \theta_{pre} = \Delta\theta$   
 the uncertainty of the nuisance was well estimated : **perfection**

If  $pulls < 1$  : The uncertainty was **over-estimated**

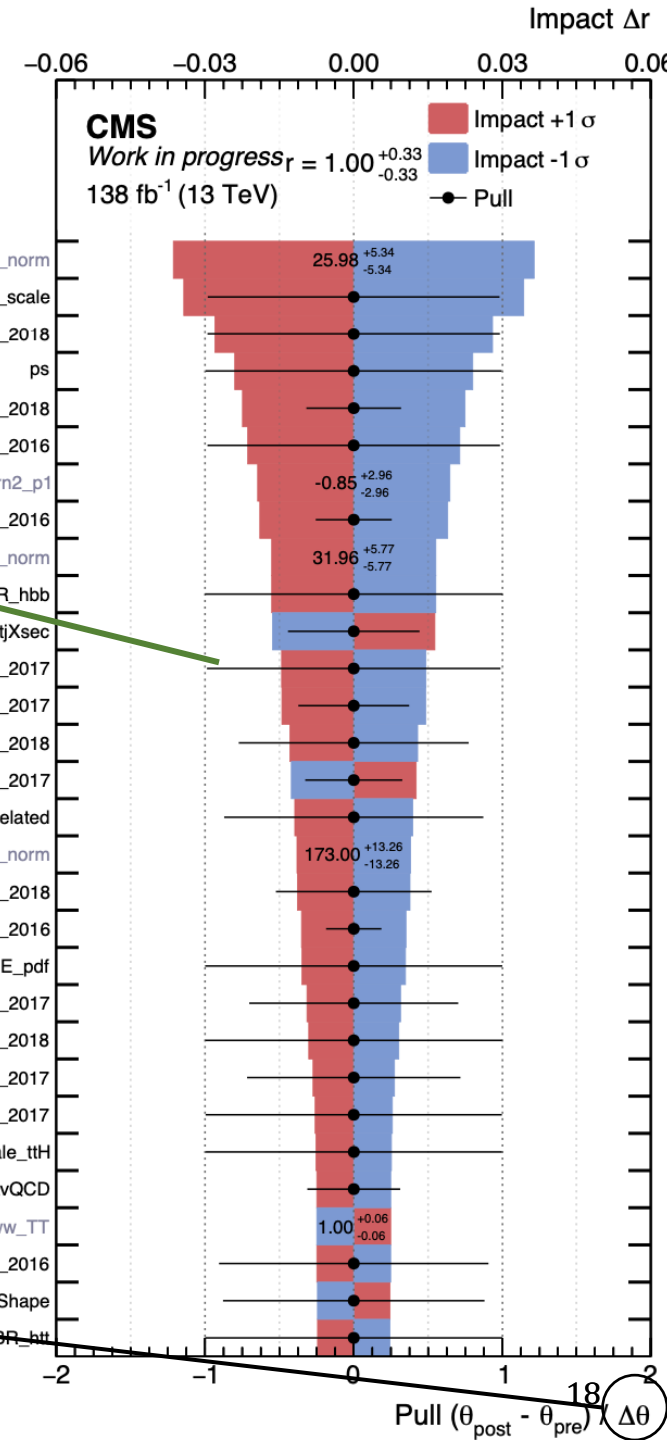
If  $pulls < 1$  : The uncertainty was **under-estimated**

pre-fit uncertainty

## 500 GeV

*bbyy* [ ]  
*bbττ* [ ]  
*bbbb res* [ ]  
*bbww* [ ]

- Bkg\_bkg\_mass\_combination\_bbgg\_spin0\_DoubleHTag\_0\_13TeV\_\_norm
- PDF\_scale
- 4b, trg\_eff\_2018
- ps
- 4b, bkgnorm\_2018
- 4b, trg\_eff\_2016
- bkg\_mjj\_forExp1\_DoubleHTag\_0\_bern2\_p1
- 4b, bkgnorm\_2016
- Bkg\_bkg\_mass\_combination\_bbgg\_spin0\_DoubleHTag\_1\_13TeV\_\_norm
- BR\_hbb
- CMS\_htt\_tjXsec
- 4b, trg\_eff\_2017
- 4b, bkgnorm\_2017
- CMS\_bbwwdl\_DY\_ncc\_500\_resolved2b\_GGF\_2018
- 4b, bkgShape\_2017
- lumi\_13TeV\_correlated
- Bkg\_bkg\_mass\_combination\_bbgg\_spin0\_DoubleHTag\_2\_13TeV\_\_norm
- CMS\_btag\_HF\_2016\_2017\_2018
- 4b, bkgShape\_2016
- 4b, LHE\_pdf
- CMS\_bbwwdl\_DY\_ncc\_500\_resolved2b\_GGF\_2017
- 4b, eff\_b\_b\_2018
- lumi\_13TeV\_2017
- 4b, eff\_b\_b\_2017
- QCDscale\_tth
- CMS\_scale\_j\_FlavQCD
- CMS\_bbww\_TT
- lumi\_13TeV\_2016
- CMS\_htt\_ttbarShape
- BR\_htt

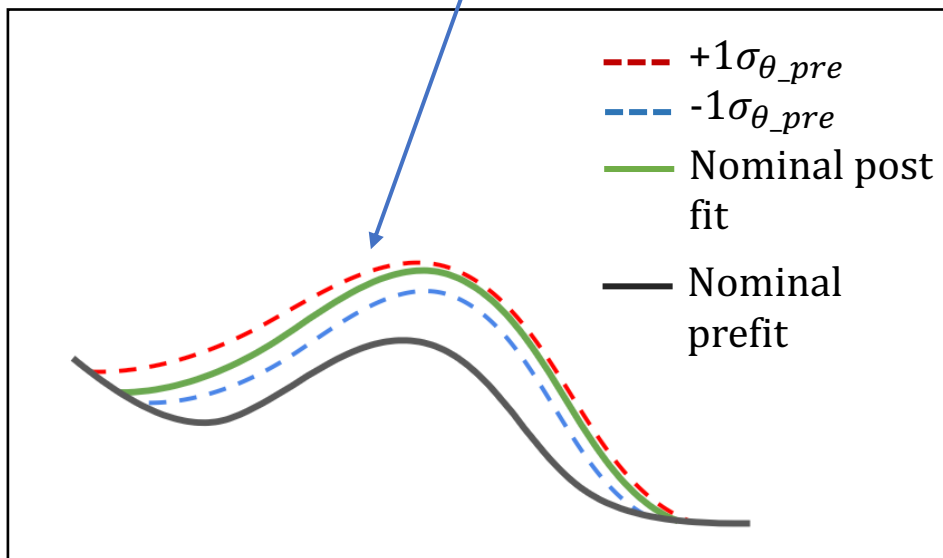


# Impacts

**Impacts** : impacts of the uncertainty of the signal

$\theta = \text{nuisance}$

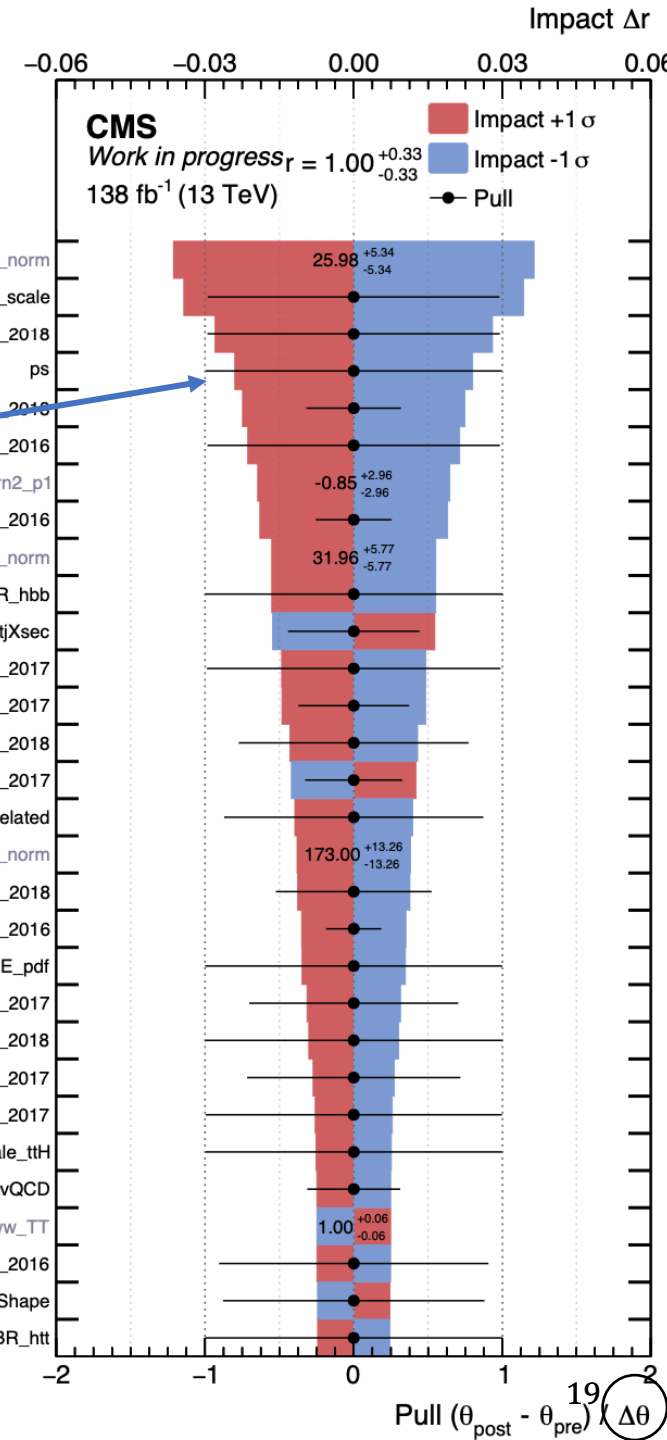
- - -  $+1\sigma_{\theta\_pre}$
- - -  $-1\sigma_{\theta\_pre}$
- Nominal post fit
- Nominal prefit



- bbyy [ ]
- bbtt [ ]
- bbbb res [ ]
- bbww [ ]

## 500 GeV

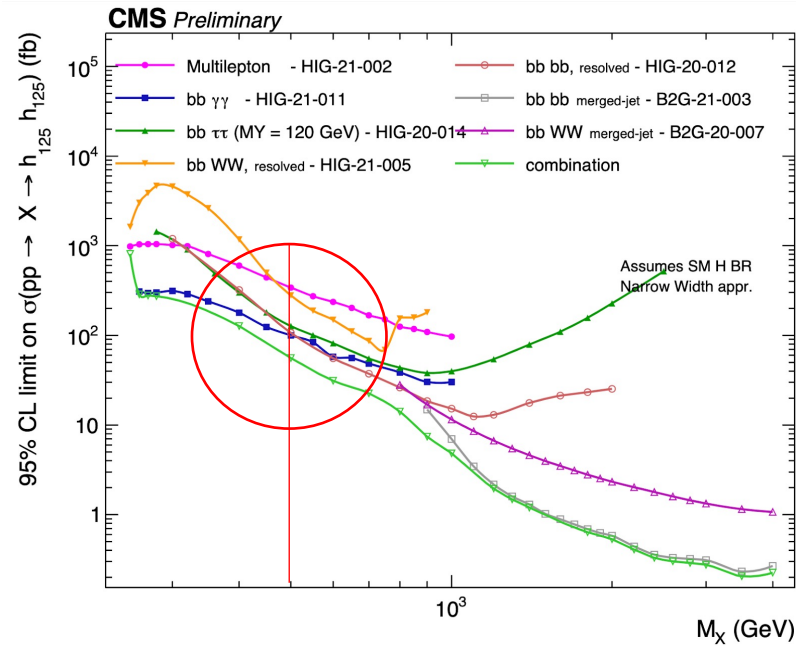
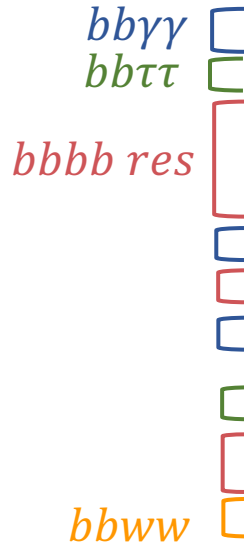
- Bkg\_bkg\_mass\_combination\_bbgg\_spin0\_DoubleHTag\_0\_13TeV\_\_norm
- PDF\_scale
- 4b, trg\_eff\_2018
- ps
- 4b, bkgnorm\_2018
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- bkg\_mjj\_forExp1\_DoubleHTag\_0\_bern2\_p1
- 4b, bkgnorm\_2016
- Bkg\_bkg\_mass\_combination\_bbgg\_spin0\_DoubleHTag\_1\_13TeV\_\_norm
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- lumi\_13TeV\_2016
- CMS\_htt\_ttbarShape
- BR\_htt



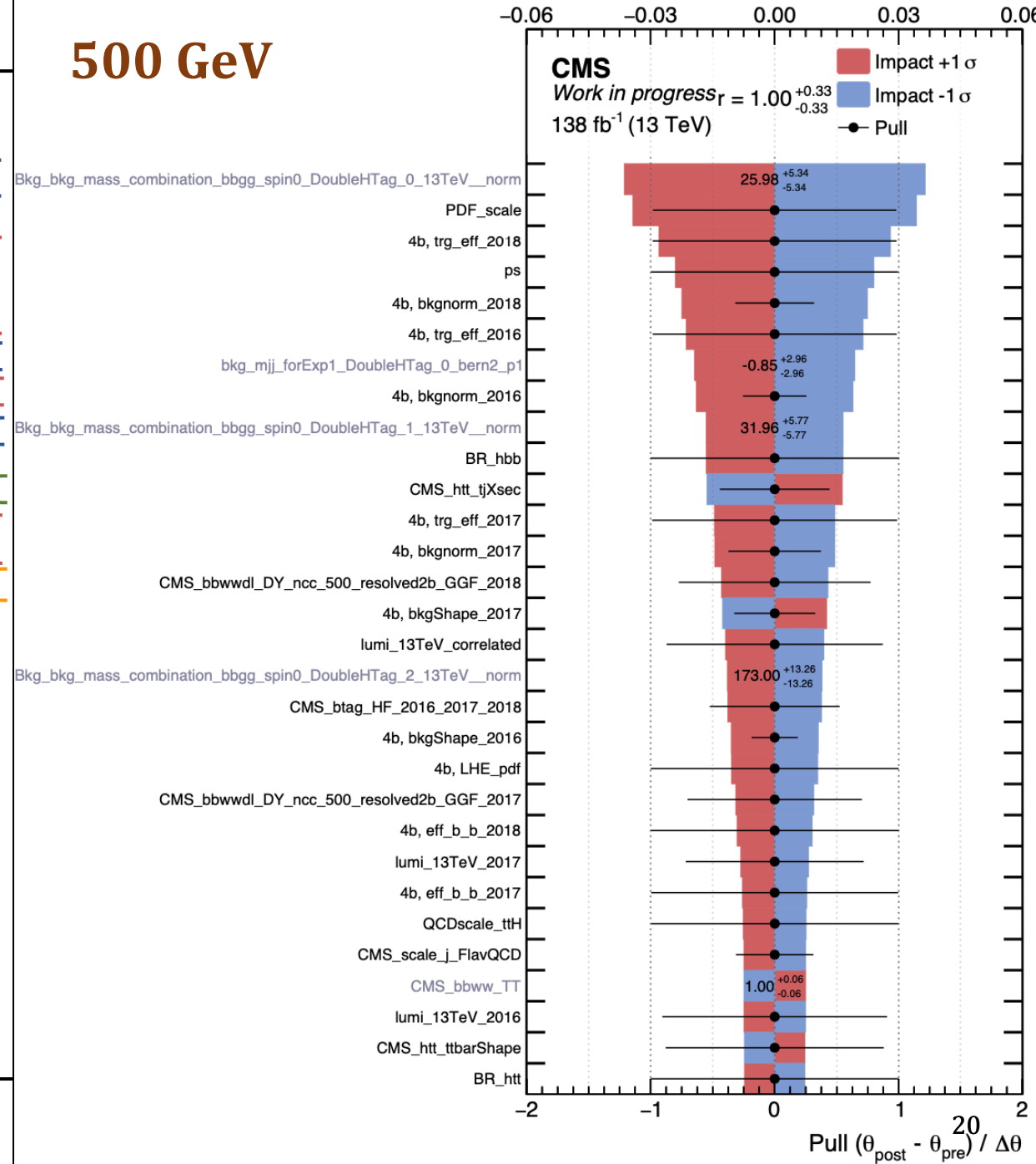
# Impacts

Impacts consistent :

- $bb\gamma\gamma$  has the largest impacts
- $bb\tau\tau$  second
- $bbbb\ res$  third



## 500 GeV



# Injection test

We need to check if no bias is introduced by our analysis → If a signal is injected, we should get it back as it is, *not much more, not much less*

How ?

1500 répétitions

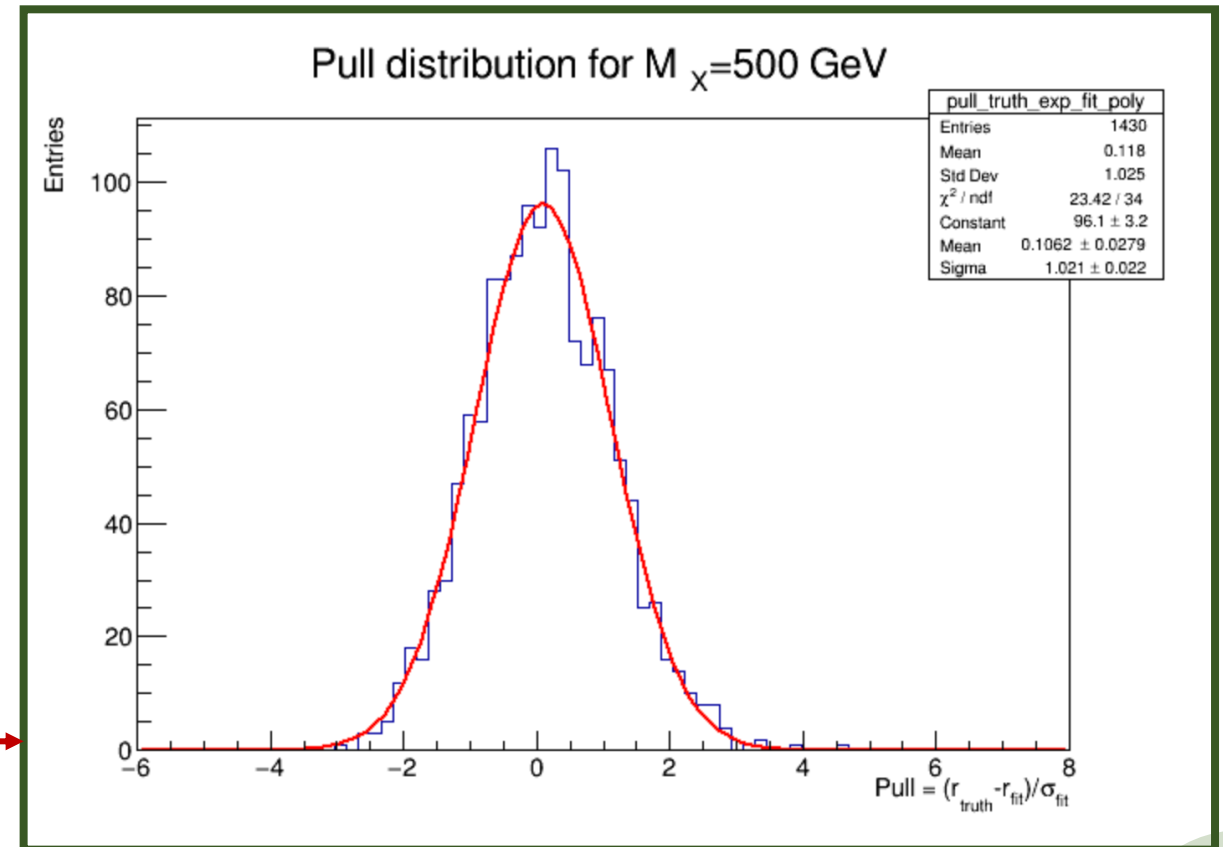
BCKG Toy generation

Injection of a  $3/4\sigma$  signal

fit

Extraction of the post-fit signal

If no bias is introduced, we should get a  $\mathcal{N}(0,1)$



# What is next ?

- You can do other statistic tests (Goodness Of Fit tests )
- The work done for  $X \rightarrow HH$  can be used with  $X \rightarrow YH$  searches ( $X \rightarrow SH$  see Maxime's Talk)
- Only the **blinded** combination was done here, so the **unblinding** is still to be done.



# *Congratulations*

You reached the end of the combination recipe got a **Prefou** ! Now admire the result





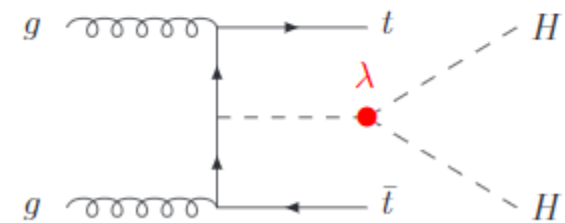
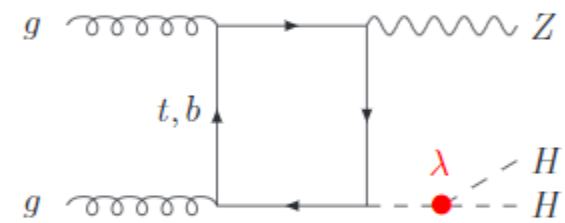
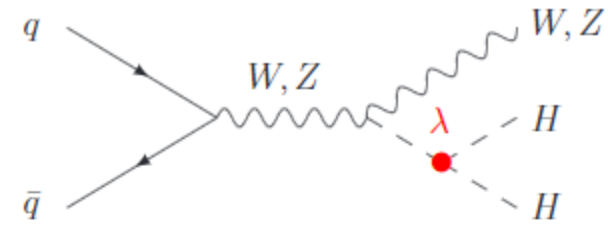
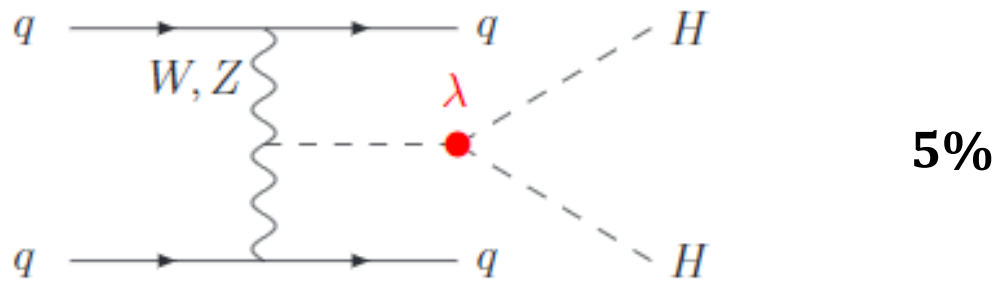
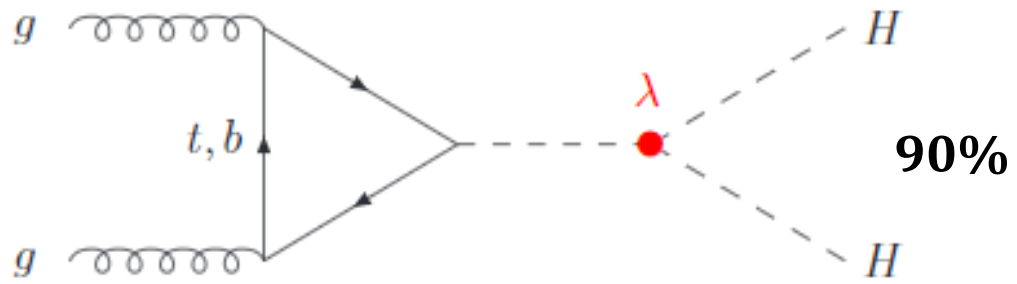
# ~~Congratulations~~

Oops you failed.



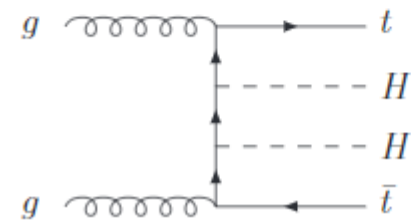
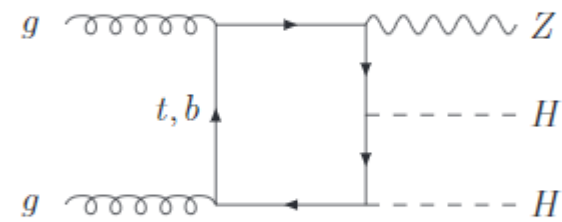
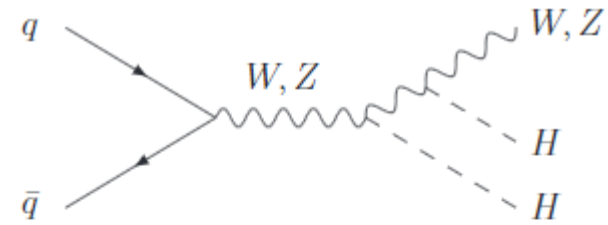
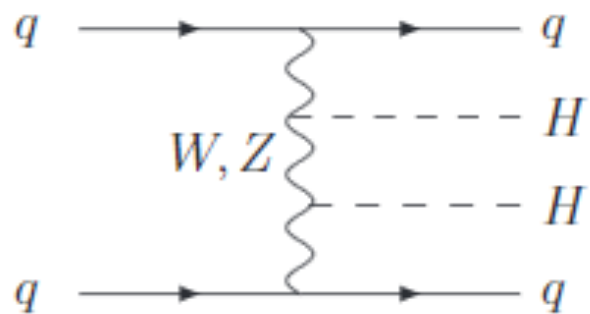
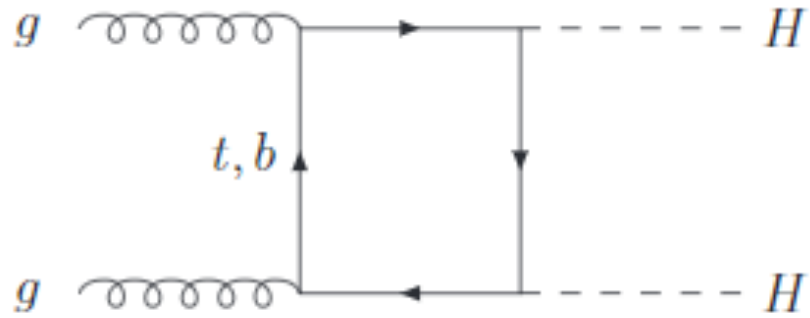
# Backup

# HH Production at CMS (1)

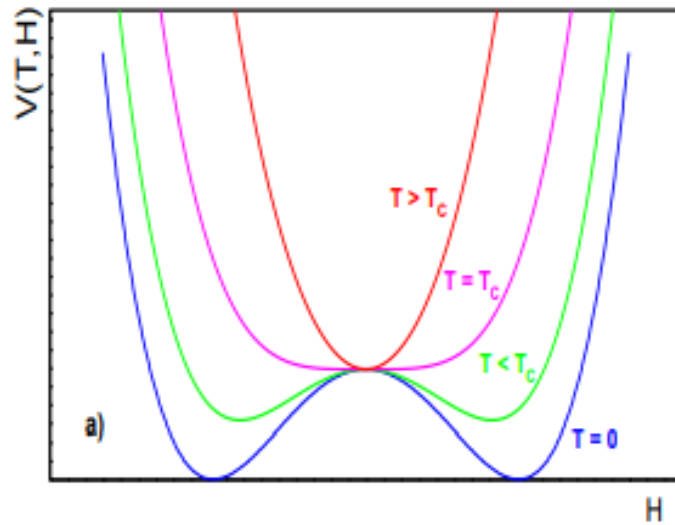


% restants

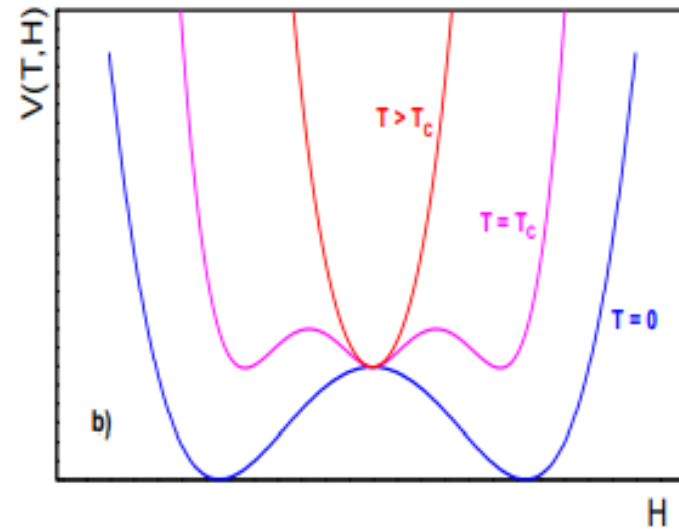
# HH Production at CMS (2)



# Electroweak phase transition



Modèle standard



•*Eur.J.Phys.* 38 (2017) 6, 065404