Combination of X→ *HH* searches in CMS with the RUN2 data

JRJC

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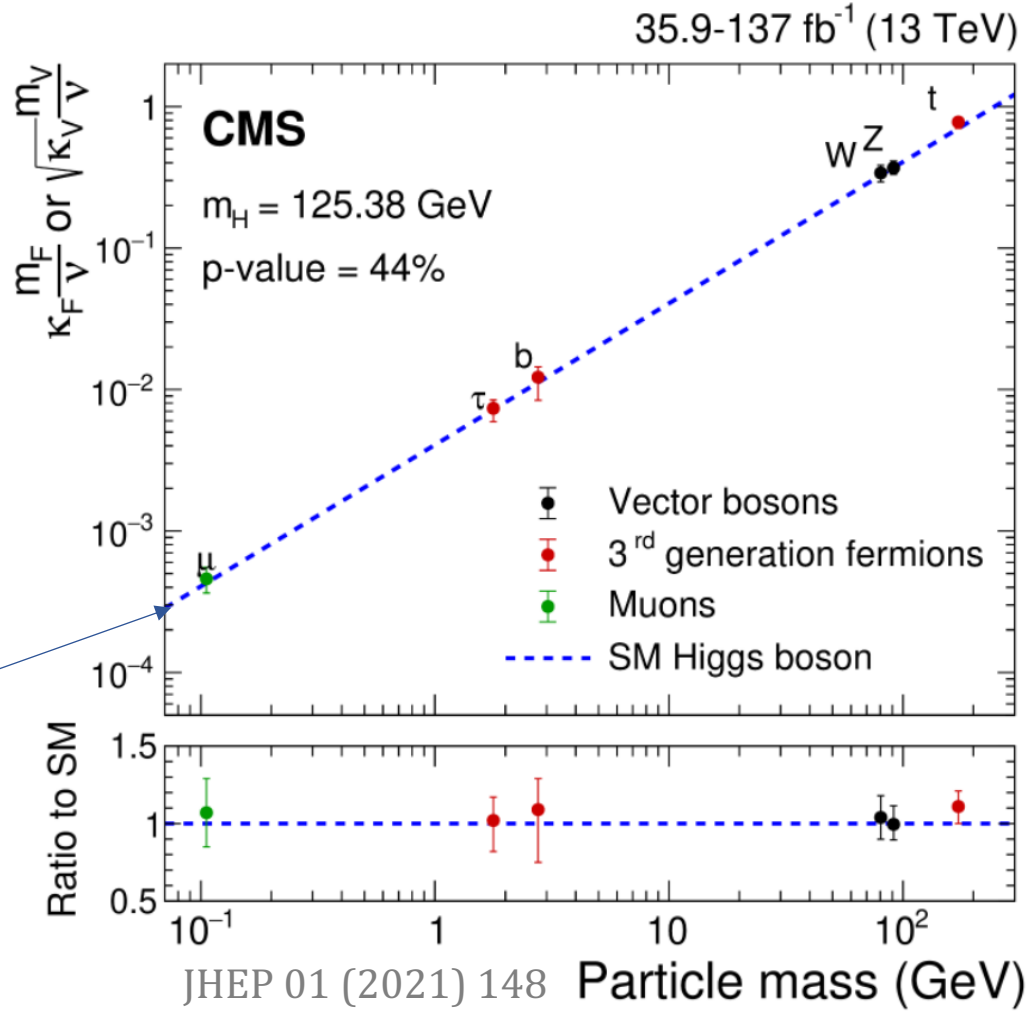
The Higgs boson

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 $\propto$ Interaction force with the Higgs field $\times$ Vacuum expectation value of the Higgs field (v)



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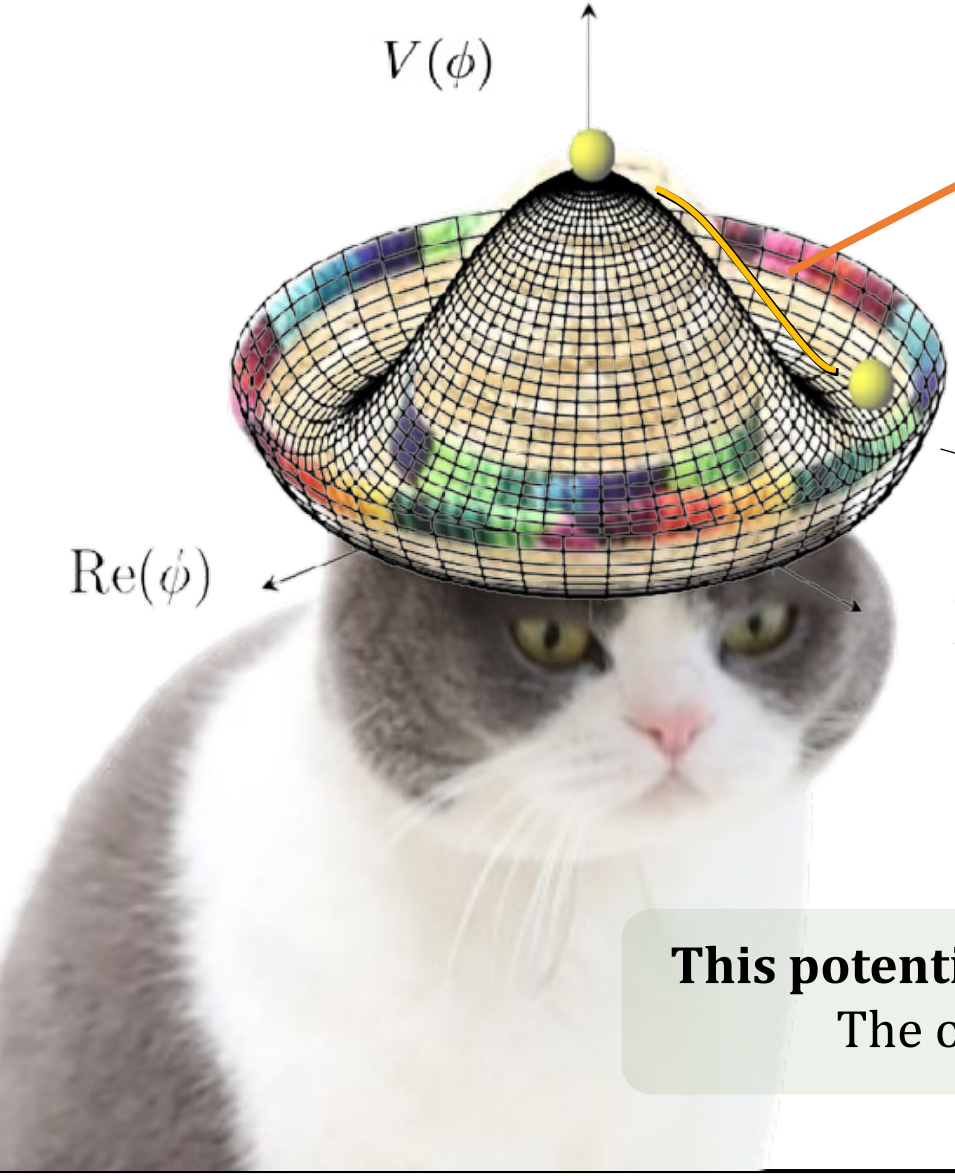
The BEH mechanism



Spontaneous symmetry breaking ⟹ **Mass gain**

The Standard Model postulates the simplest potential shape **:**

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

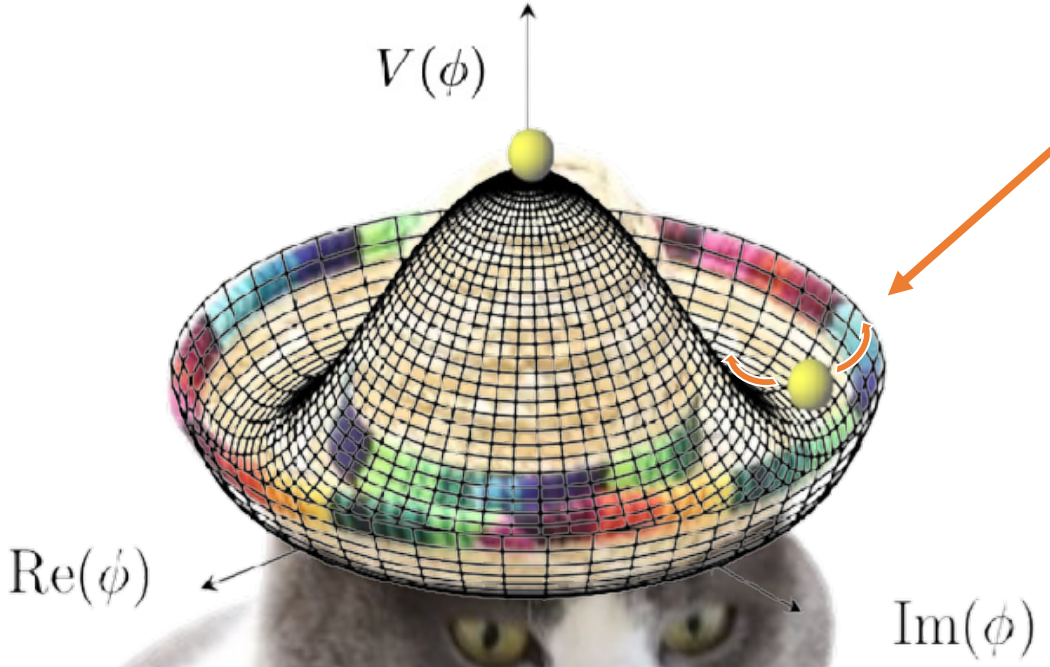
Higgs field

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

Vaccum exepectation value **Already measured**

This potential was never experimentally observed!
The only way is to do so is to measure λ

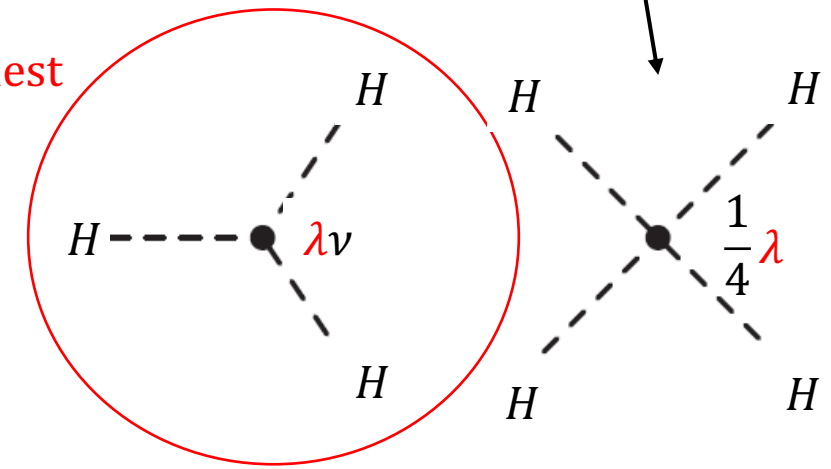
The self-coupling constant λ



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

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

Simplest



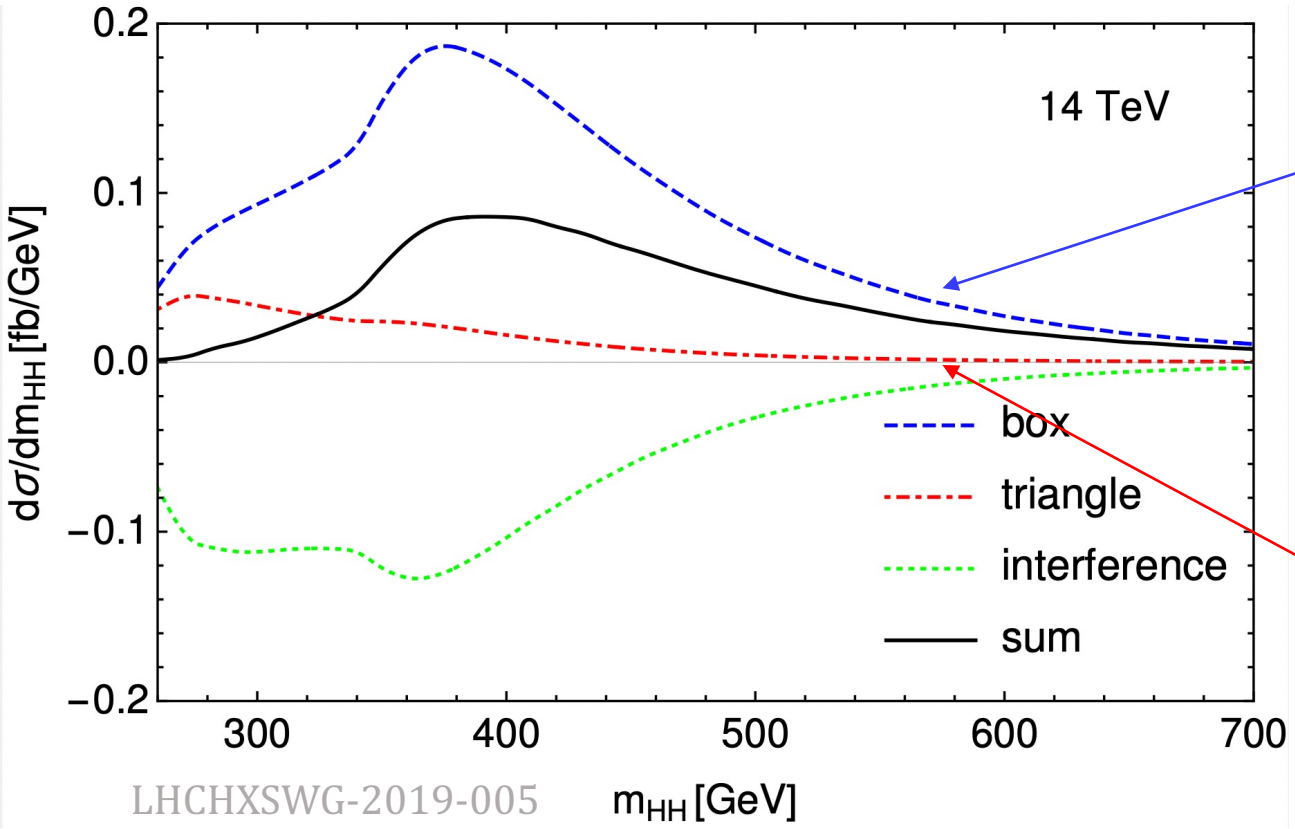
Higgs boson self-interaction

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

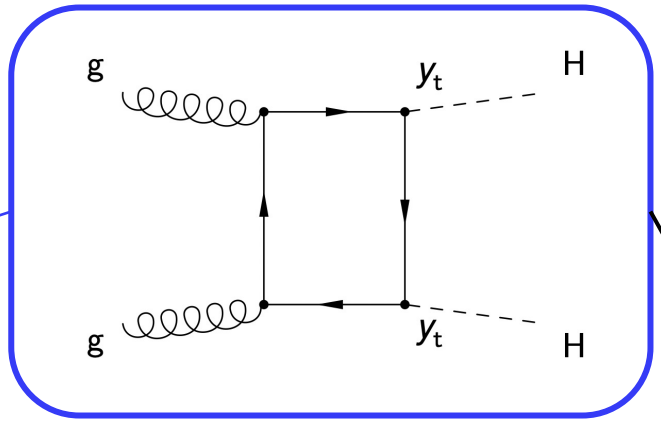
HH spectrum in the SM

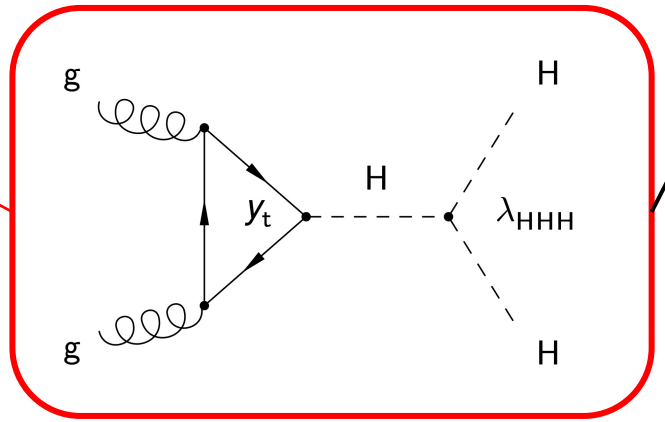
The Higgs pair invariant mass is the variable of interest in the BEH potential study.

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



Bad guy ☹





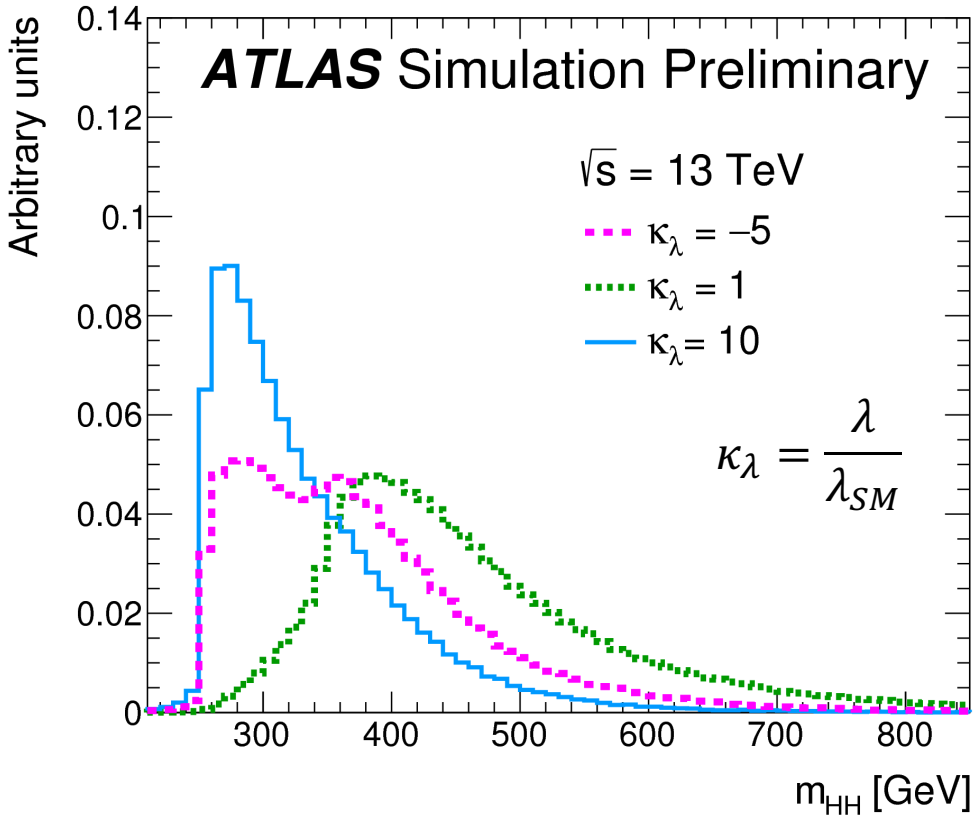
Good guy ☺

Major HH production processes

HH spectrum

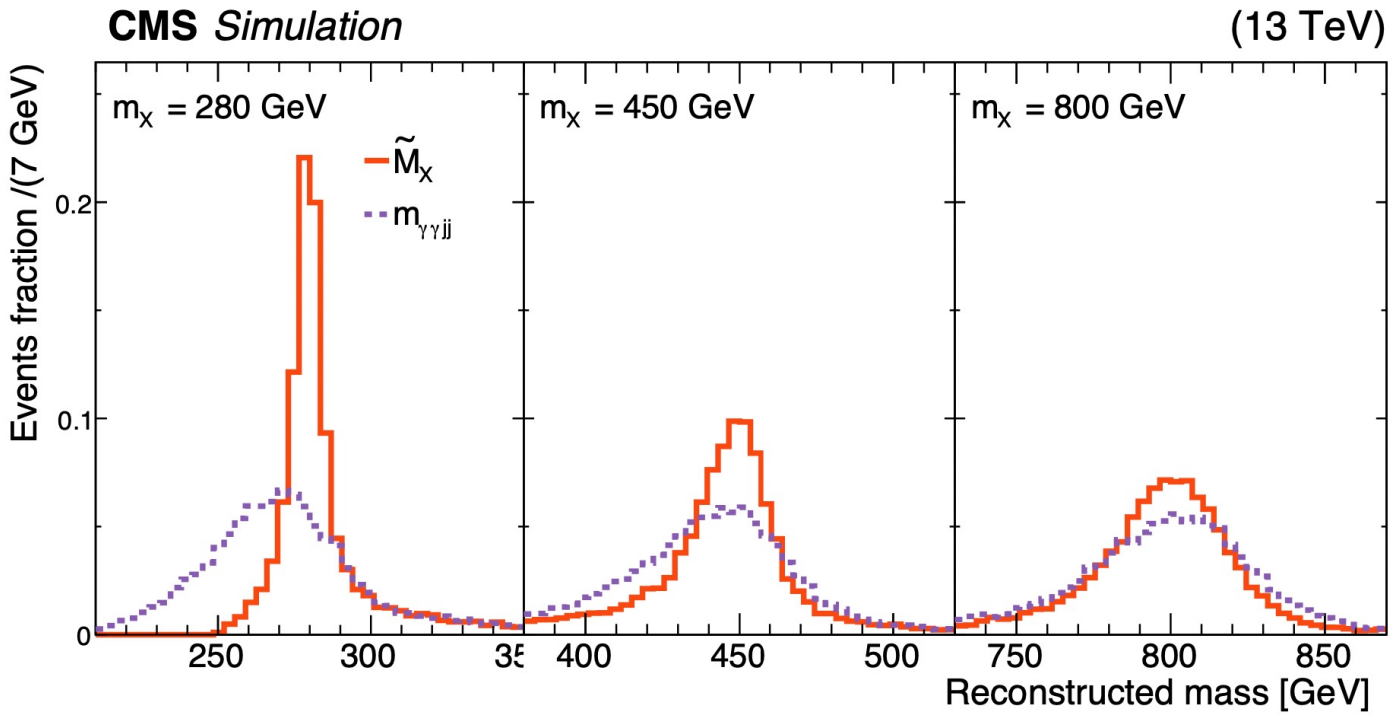
Non-resonnant :

Deformation of m_{HH} spectrum



Resonnant :

Resonnance in the m_{HH} spectrum



HH spectrum

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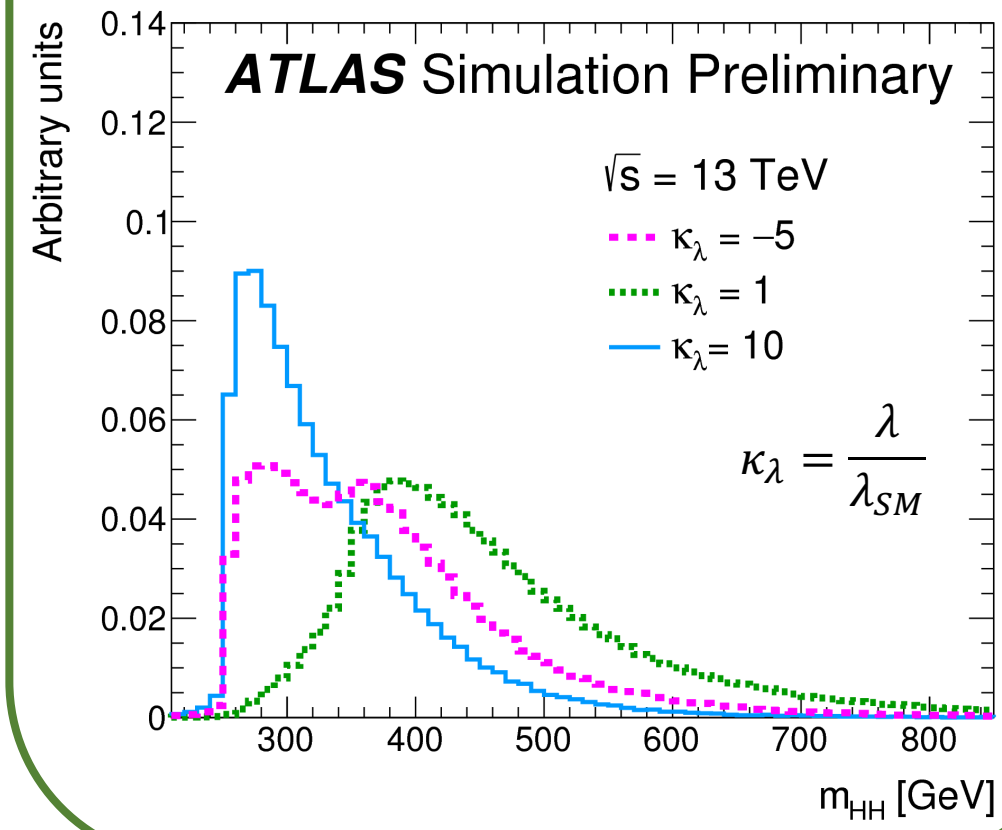

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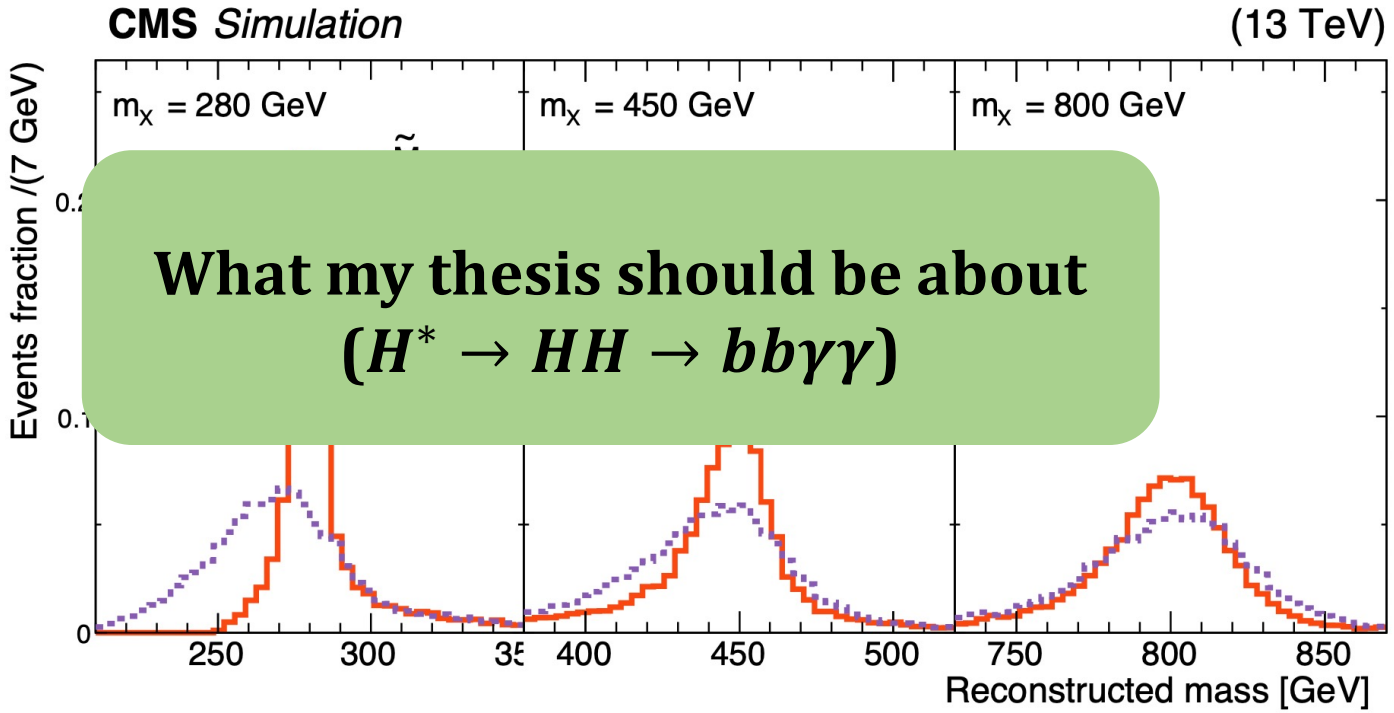
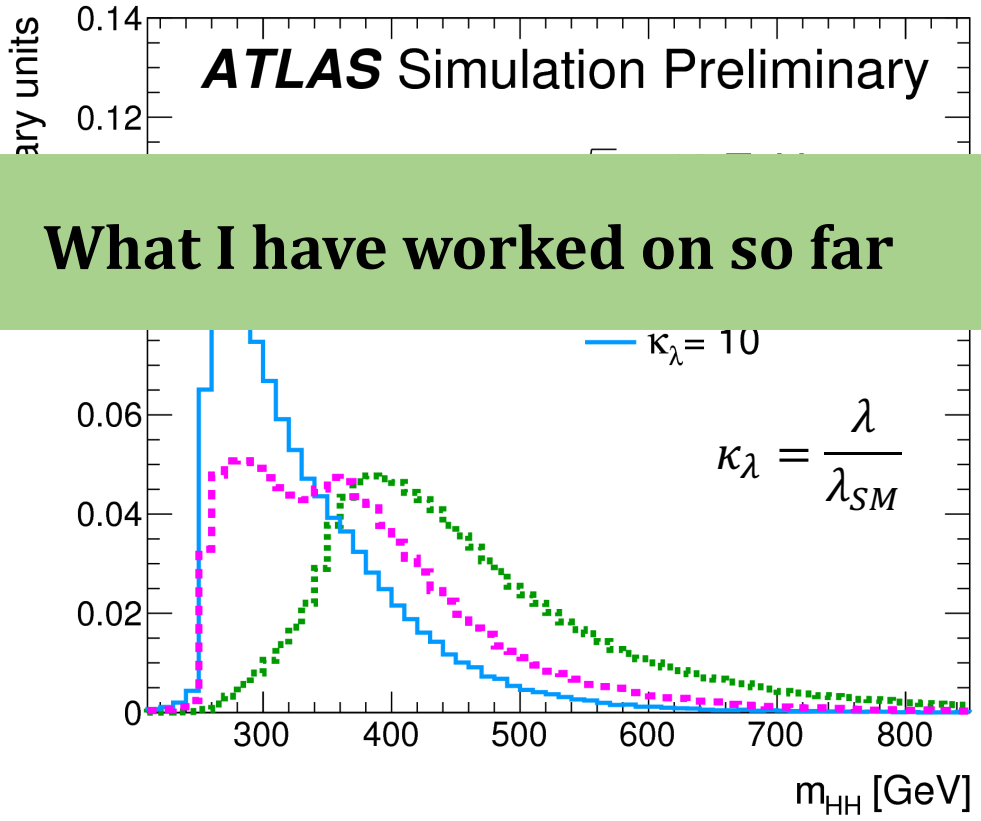


What my thesis should be about
($H^* \rightarrow HH \rightarrow bb\gamma\gamma$)

HH spectrum

Non-resonnant :

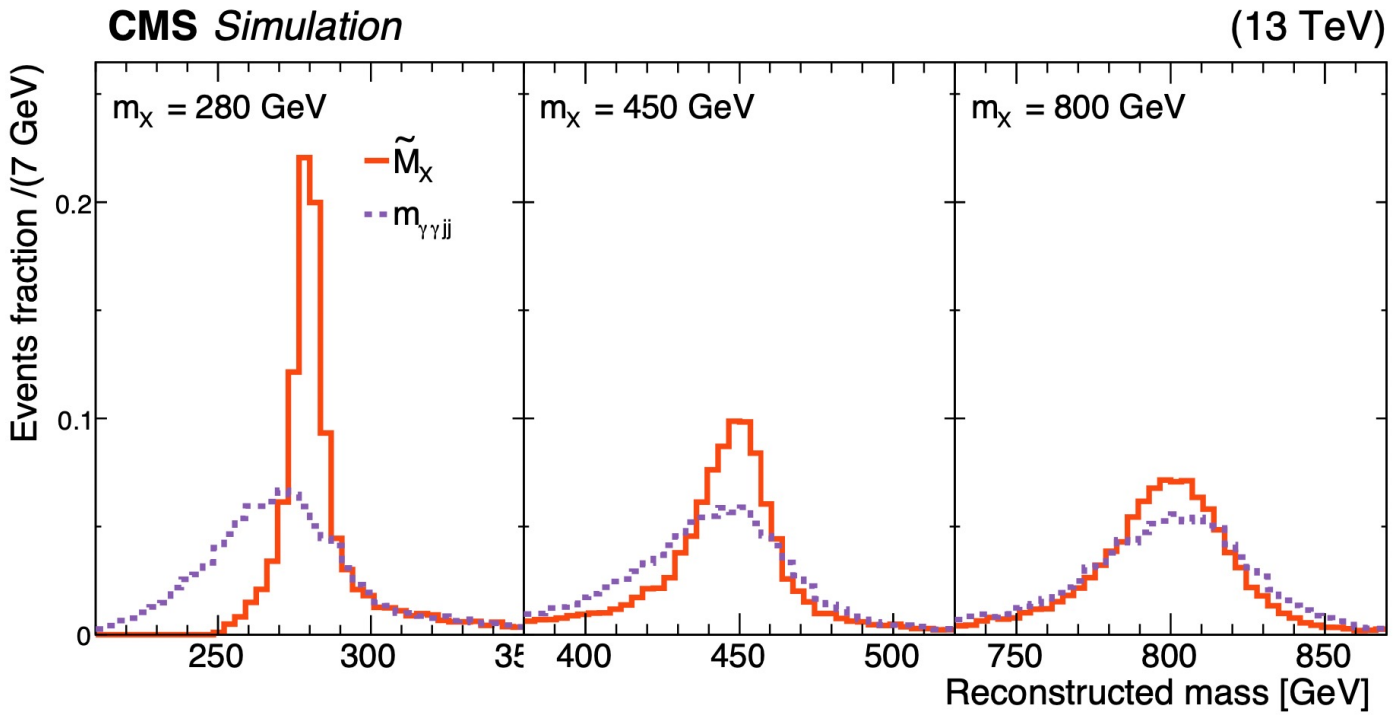
Deformation of m_{HH} spectrum



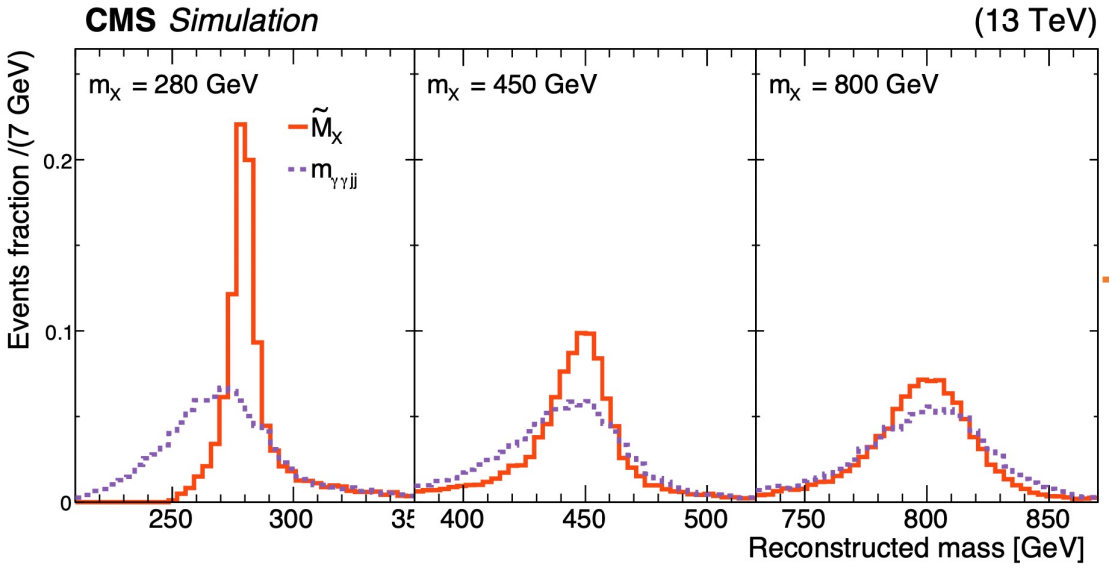
What I have worked on so far

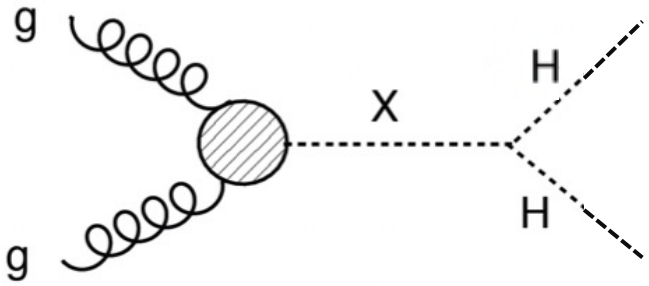
Resonnant :

Resonnance in the m_{HH} spectrum



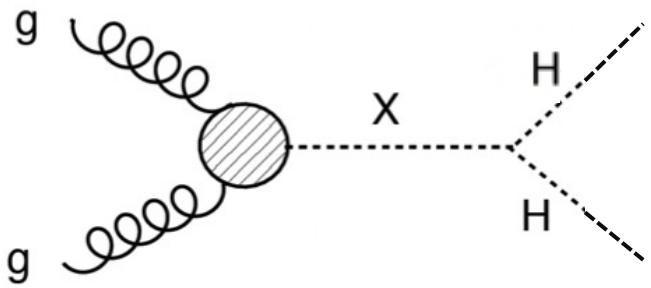
$X \rightarrow$ 





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

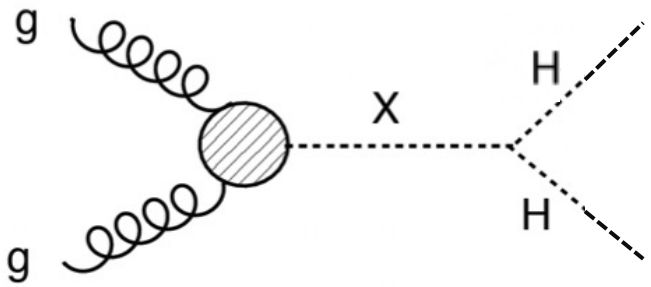
For those who like theory



- **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



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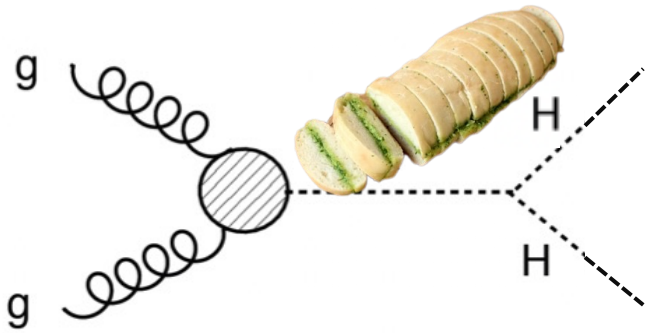
- **Warped Extra Dimensions** : postulates the existence of one extra dimension
  - New particles decaying into HH such as a Spin-0 radion and the spin2 Kaluza-Klein excitation of the Graviton.

For those who like theory



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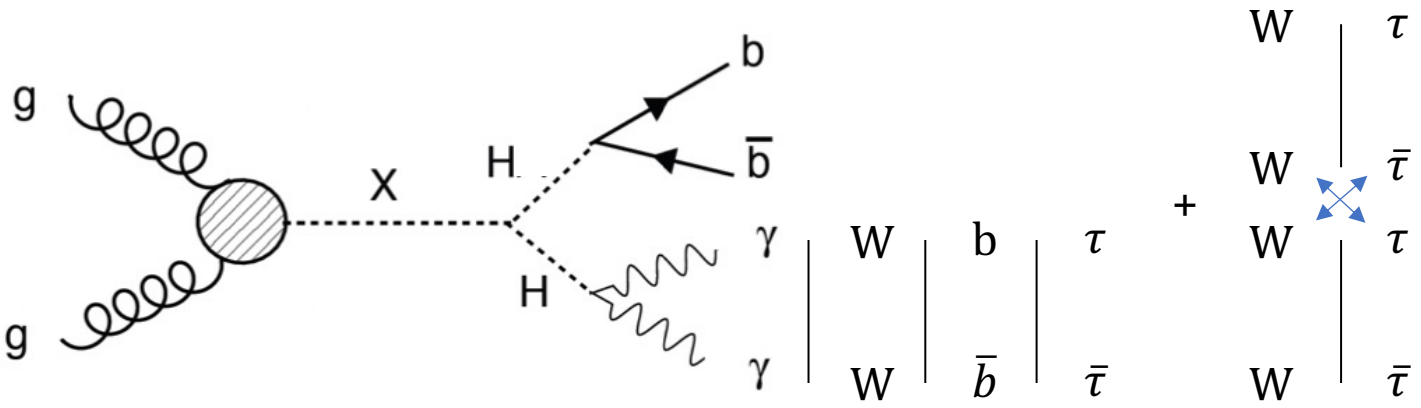
- **The Vendée theory** : Theory created by Mr. Charrette while visiting the Puy du fou, postulating the existence of a **Prefou** that could decay into a Higgs pair.
  - ***Would solve everything***

And what do I do ?

I worked on the **statistical combination** of the **X→ HH** searches :

bbγγ, *bbVV* (*resolved and boosted*), *bbbb* (*resolved and boosted*), bb*ττ*, *multilepton*



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

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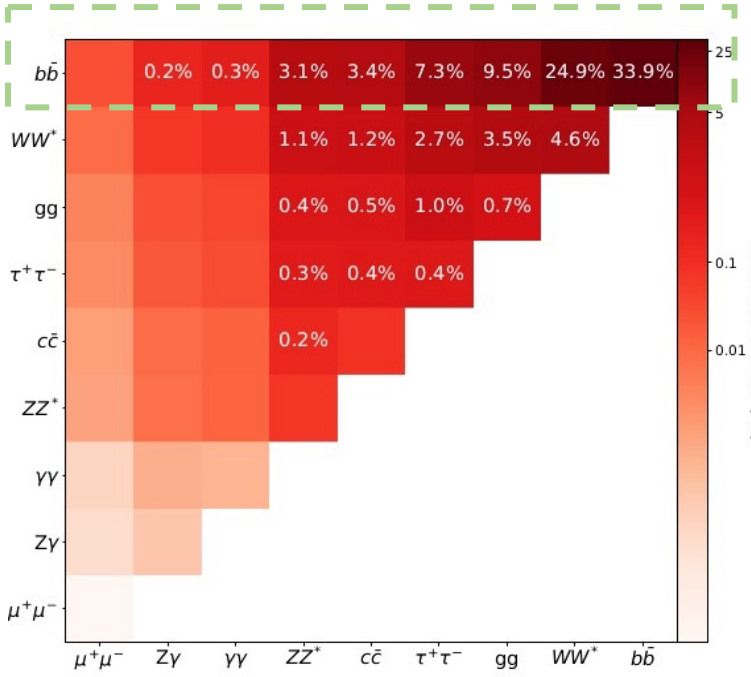


Combination recipe

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

Nuisance parameters

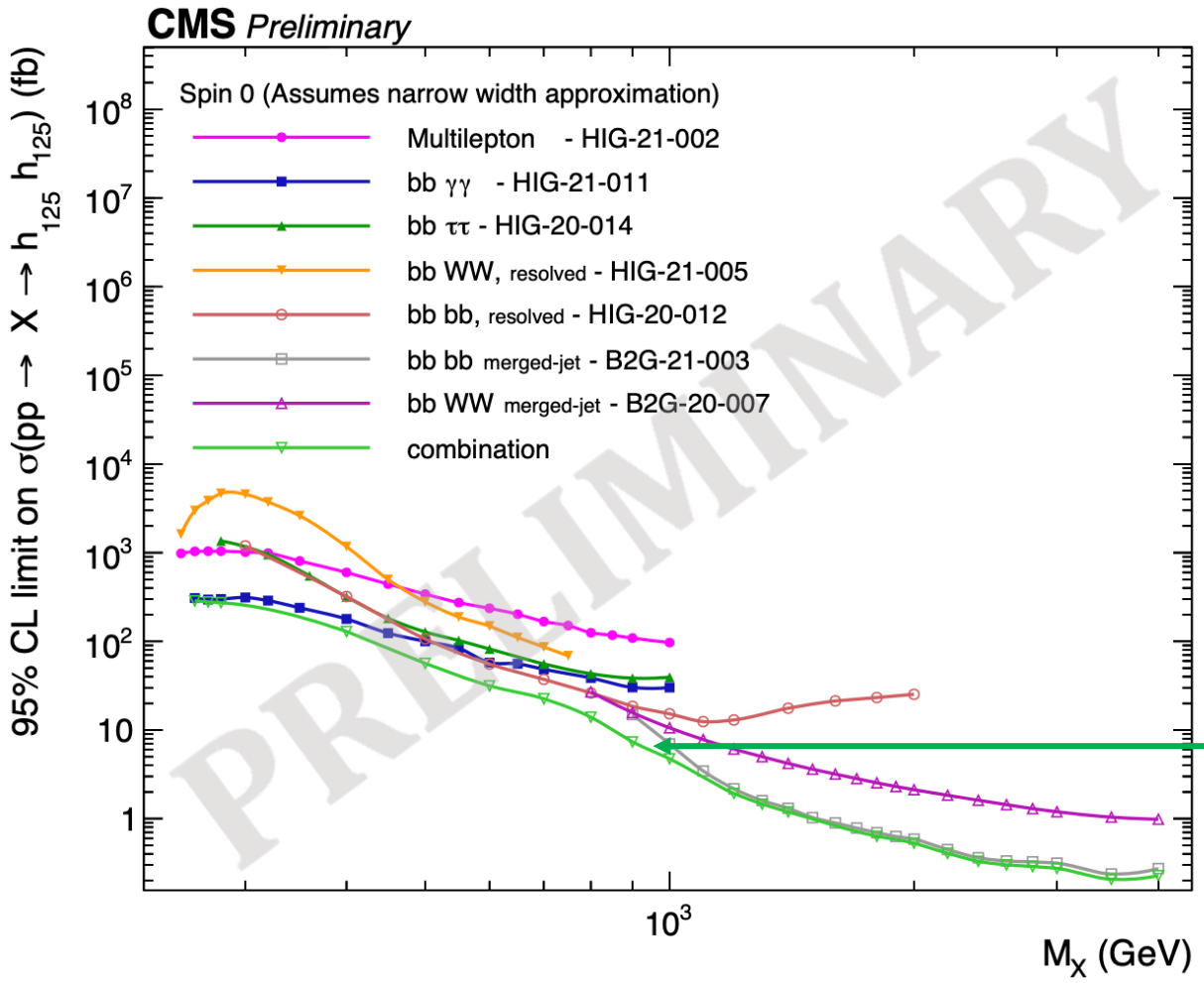
Parameter of interest (POI)

Systematic uncertainties ⟹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 : $\boldsymbol{M_X = 280,\ 500,\ 1000\ GeV}$

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

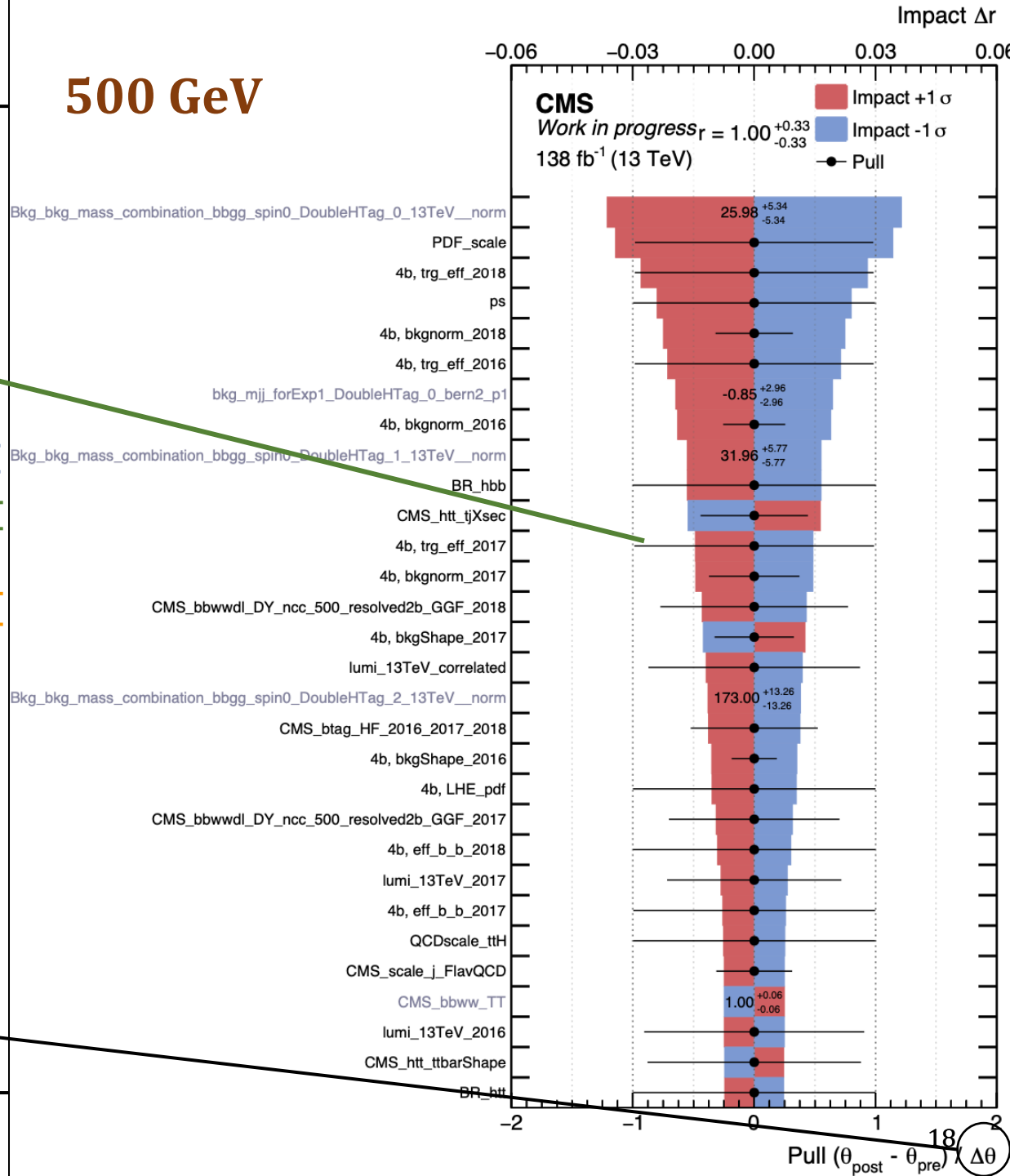
If $\boldsymbol{pulls < 1}$: The uncertainty was **over-estimated**

If $\boldsymbol{pulls < 1}$: The uncertainty was **under-estimated**

$bb\gamma\gamma$
$bb\tau\tau$
$bbbb\ res$
$bbww$

pre-fit uncertainty

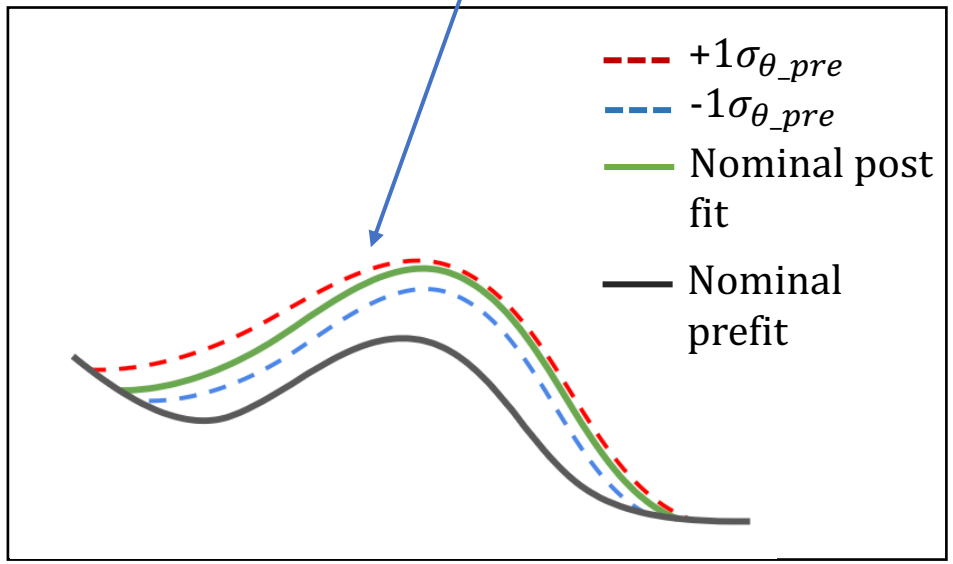
500 GeV



Impacts

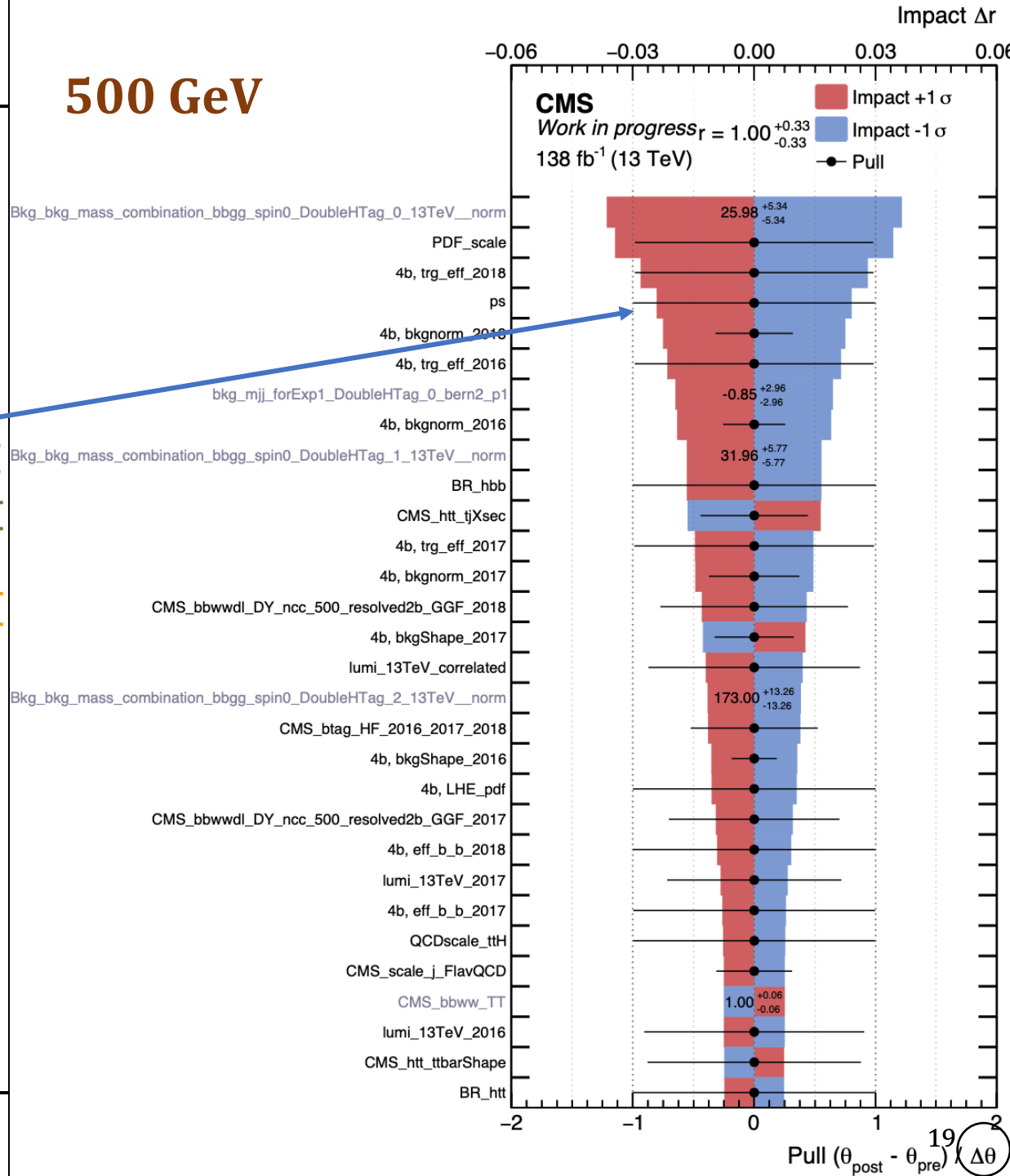
Impacts : impacts of the uncertainty of the signal

$\theta = nuisance$



$bb\gamma\gamma$
$bb\tau\tau$
$bbbb\ res$
$bbww$

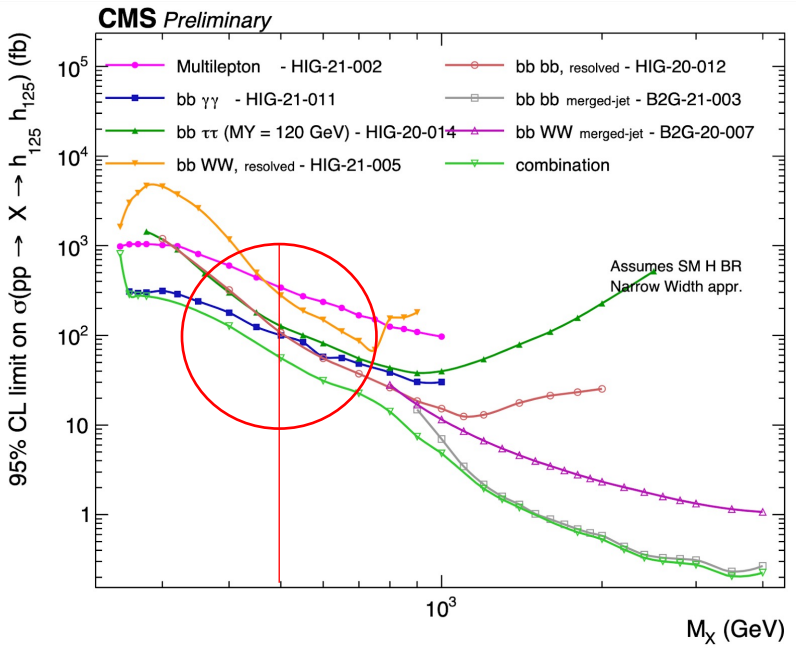
500 GeV



Impacts

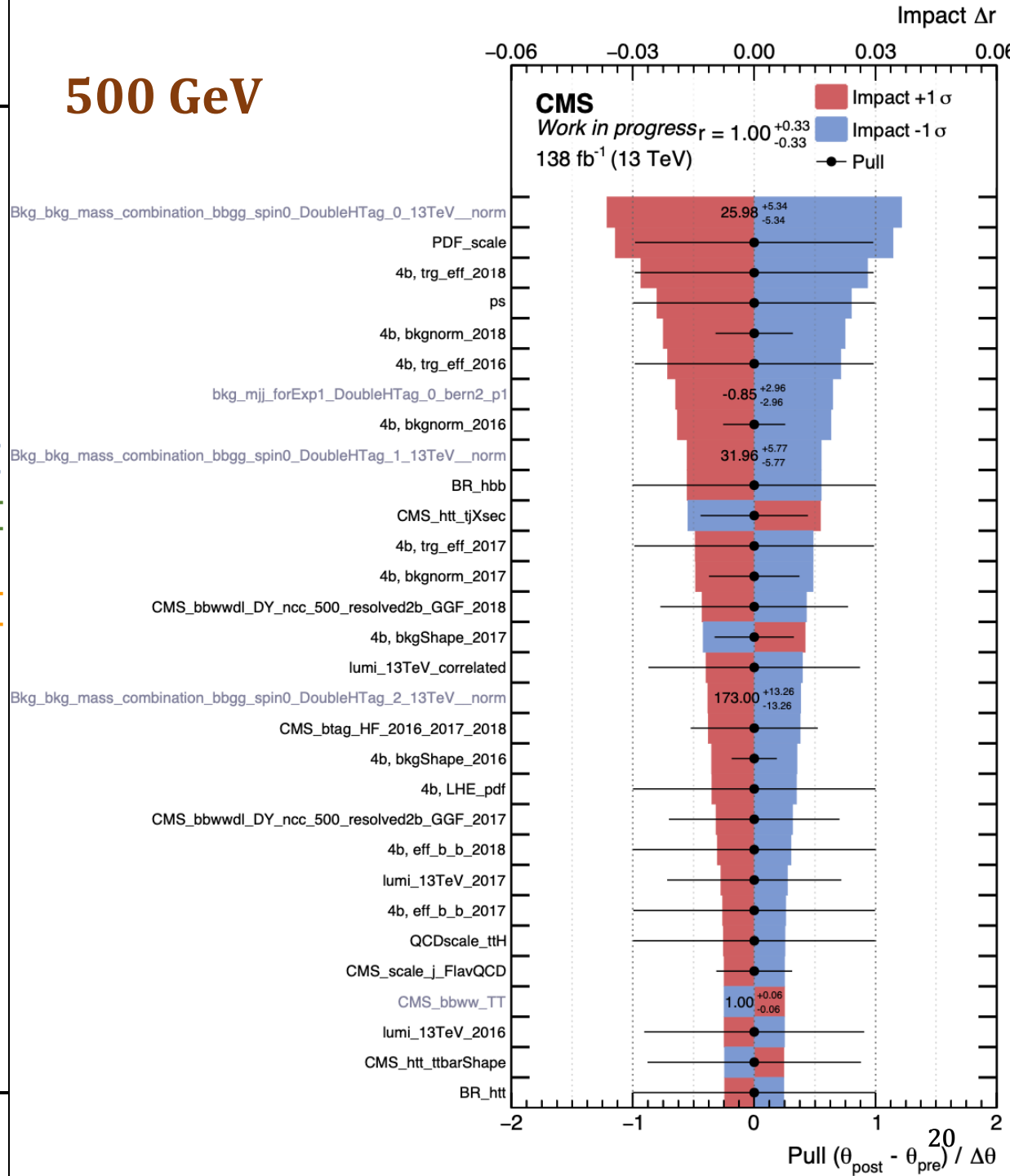
Impacts consistent :

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



$bb\gamma\gamma$
$bb\tau\tau$
$bbbb\ res$
$bbww$

500 GeV



Injection test

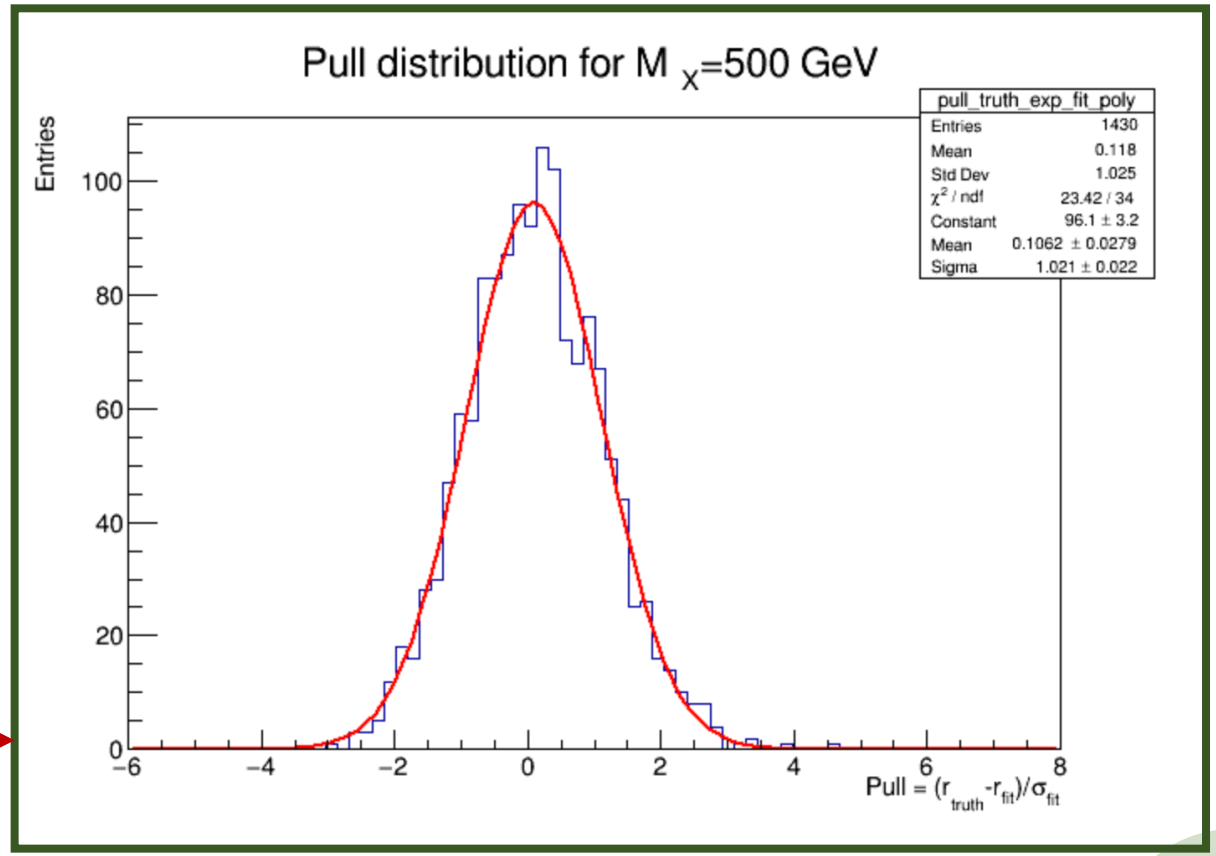
We need to check if no bias is introduced by our analysis →If a signal is injected, we should ge it back as it is, *not much more, not much less*

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

How ?

1500 répétitions

BCKG Toy generation → Injection of a $3/4\sigma$ signal → *fit* → Extraction of the post-fit signal



What is next ?

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

Summary

Congratulations

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

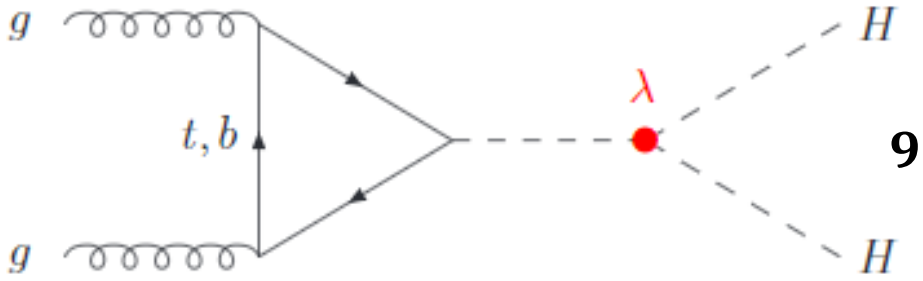
Summary

~~Congratulations~~

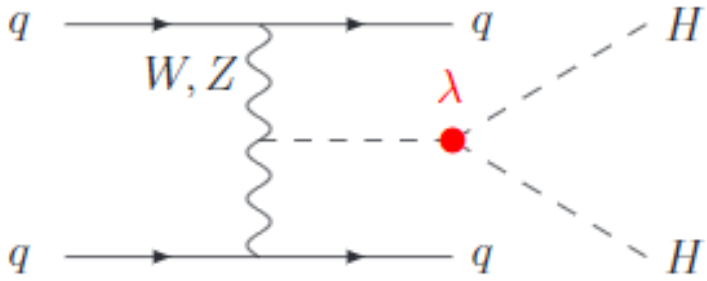
Oops you failed.

Backup

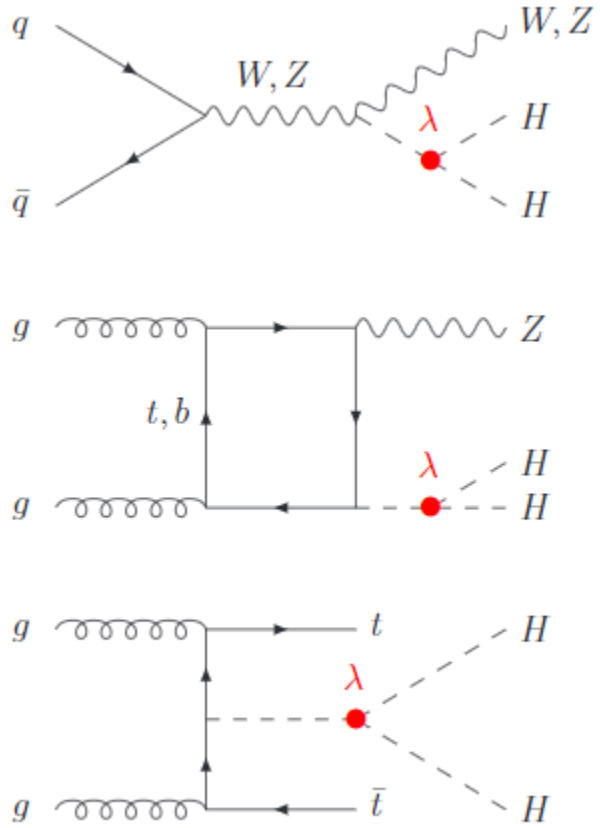
HH Production at CMS (1)



90%



5%



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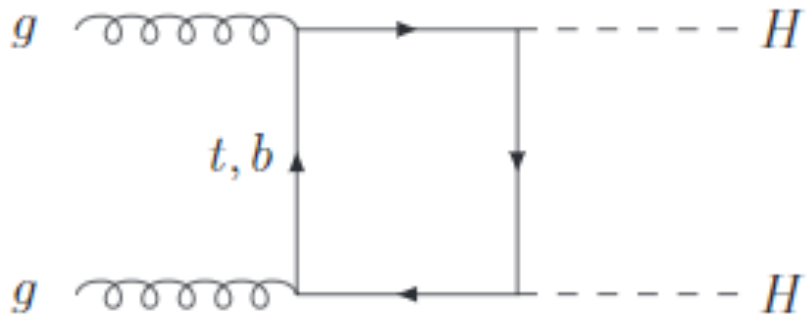
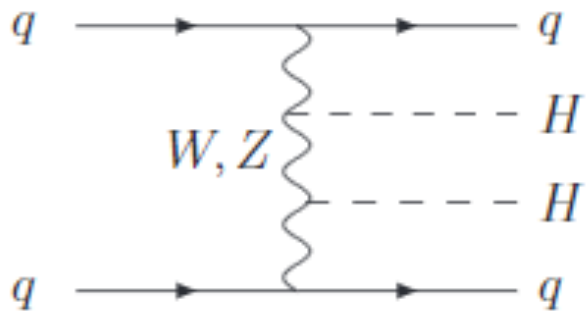
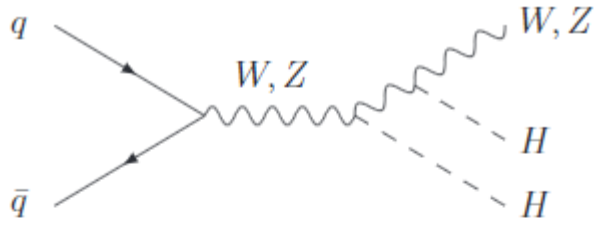
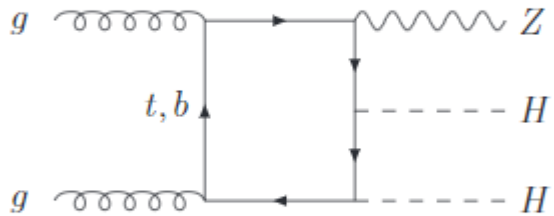
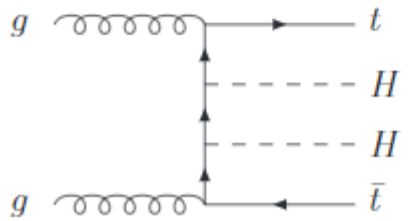
HH Production at CMS (2)



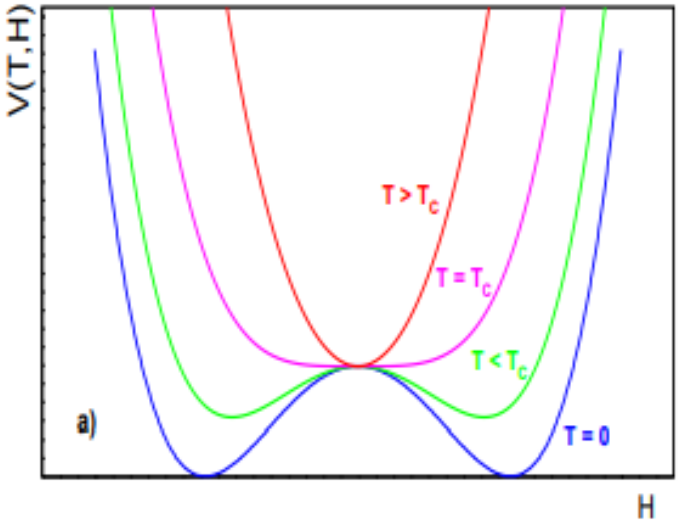


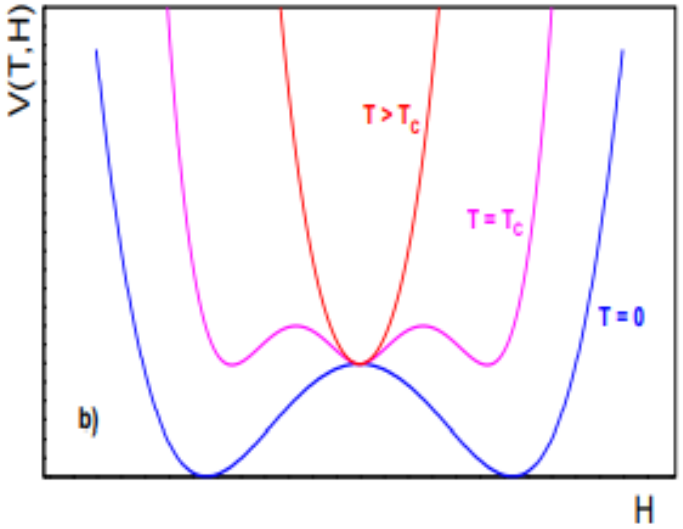






Electroweak phase transition





Modèle standard

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