# DiHiggs searches in CMS

PhD days

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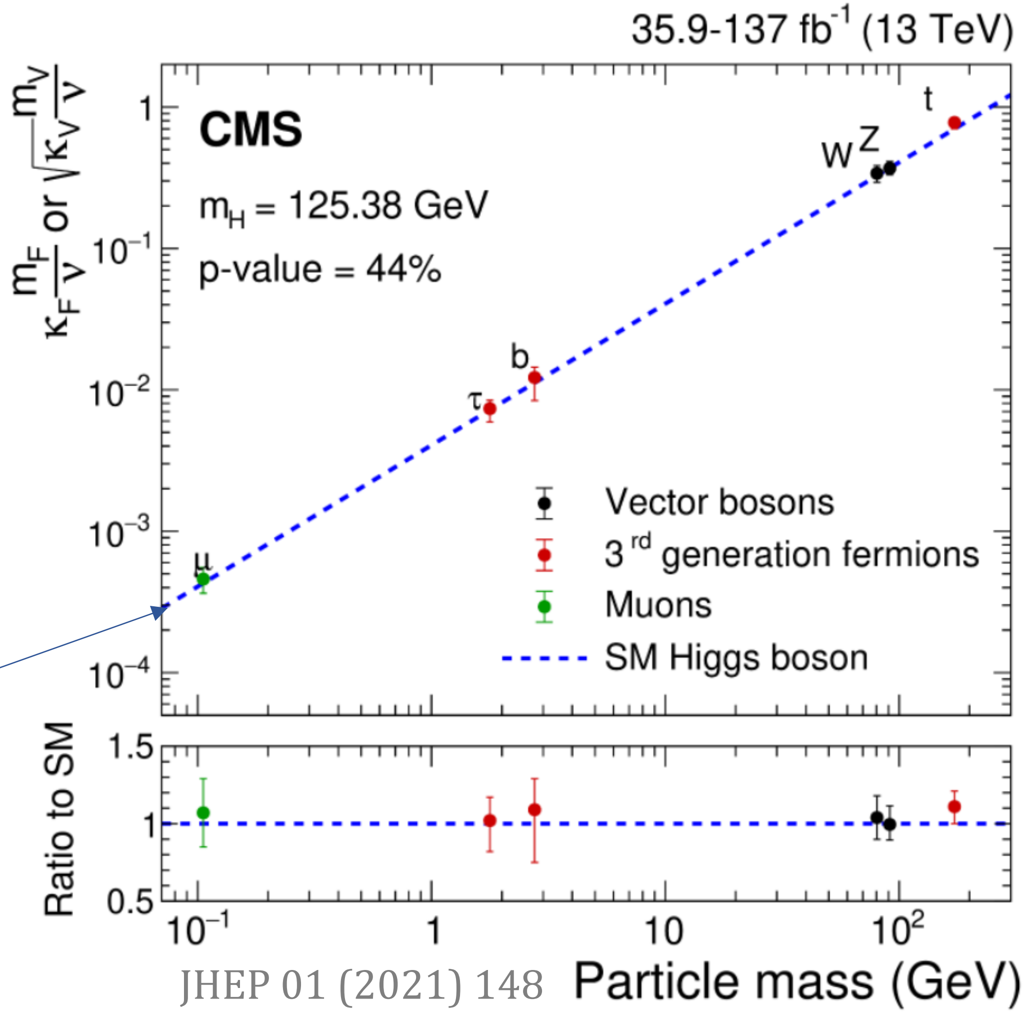
*Supervised by Maxime Gouzevitch*

# 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 ∝** Interaction force with the Higgs field × Vacuum expectation value of the Higgs field ($v$)



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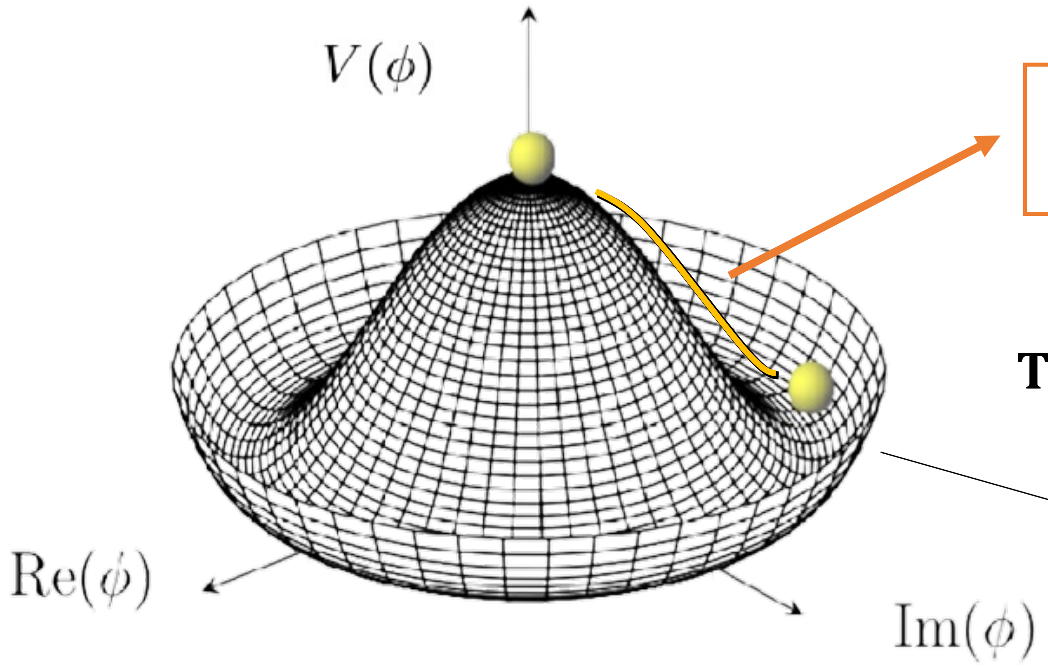
# The BEH mechanism




*Spontaneous* symmetry breaking ⇒ **Mass gain**

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

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

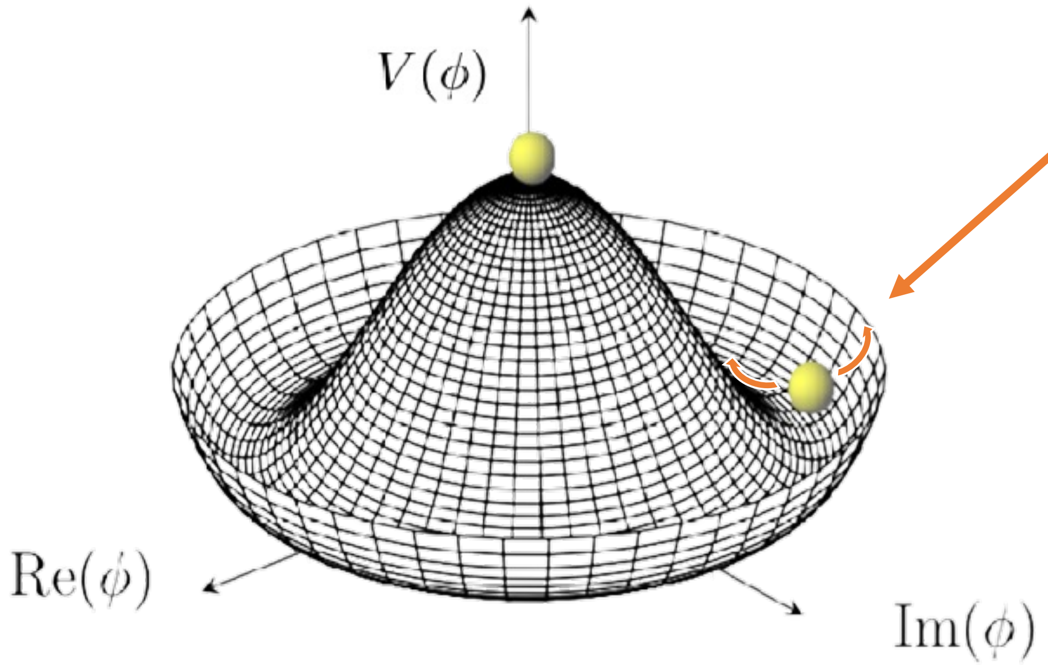
Higgs field

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

Vaccum exepectation value **Already measured**

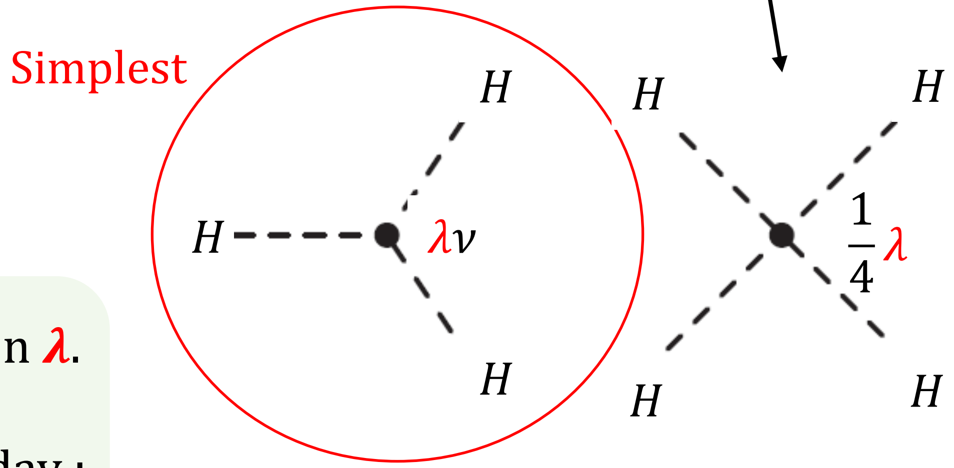
**This potential was never experimentally observed!**
The only way is to do so is to measure $\lambda$

# The self-coupling constant $\lambda$




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

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



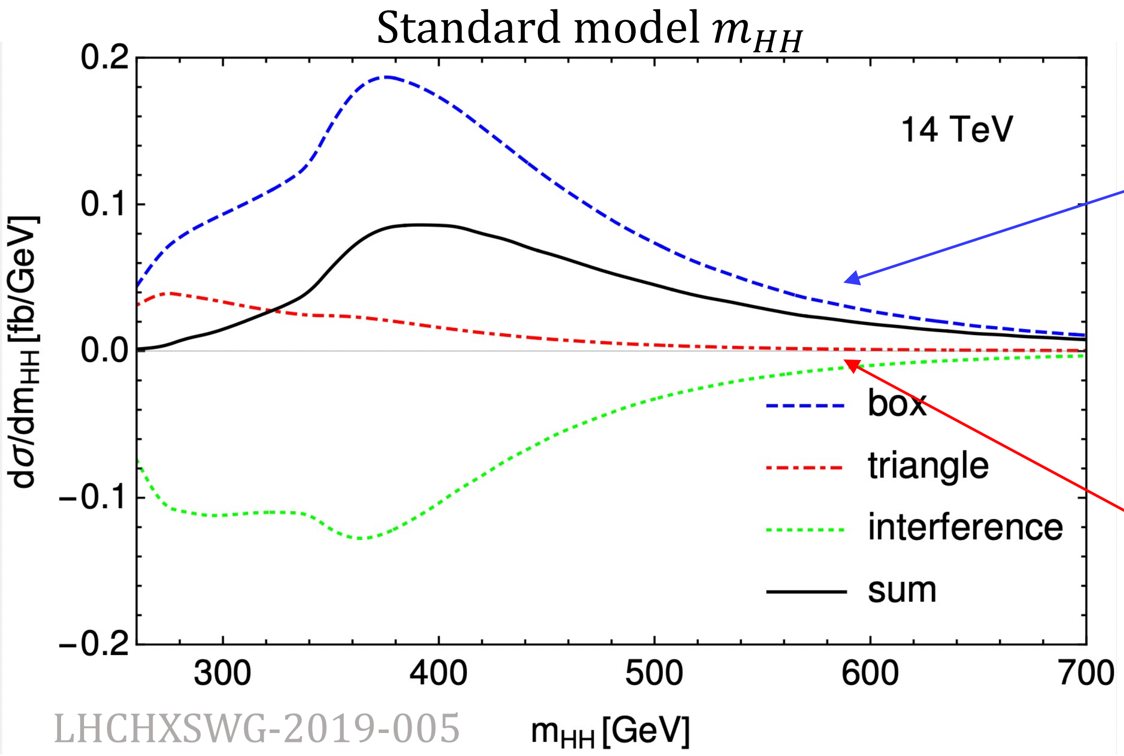

*Higgs boson self-interaction*

- 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

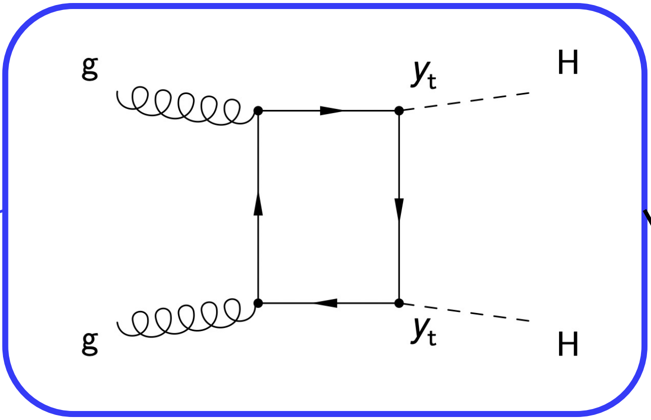
# HH spectrum in the SM

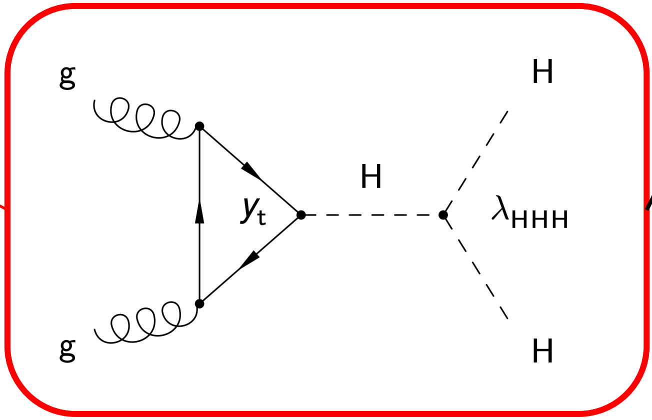
**The SM Higgs mechanism is minimal**

BEH potential different from the SM $\rightarrow$ **Deformation of Higgs pair invariant mass ($m_{HH}$)**




LHCHXSWG-2019-005



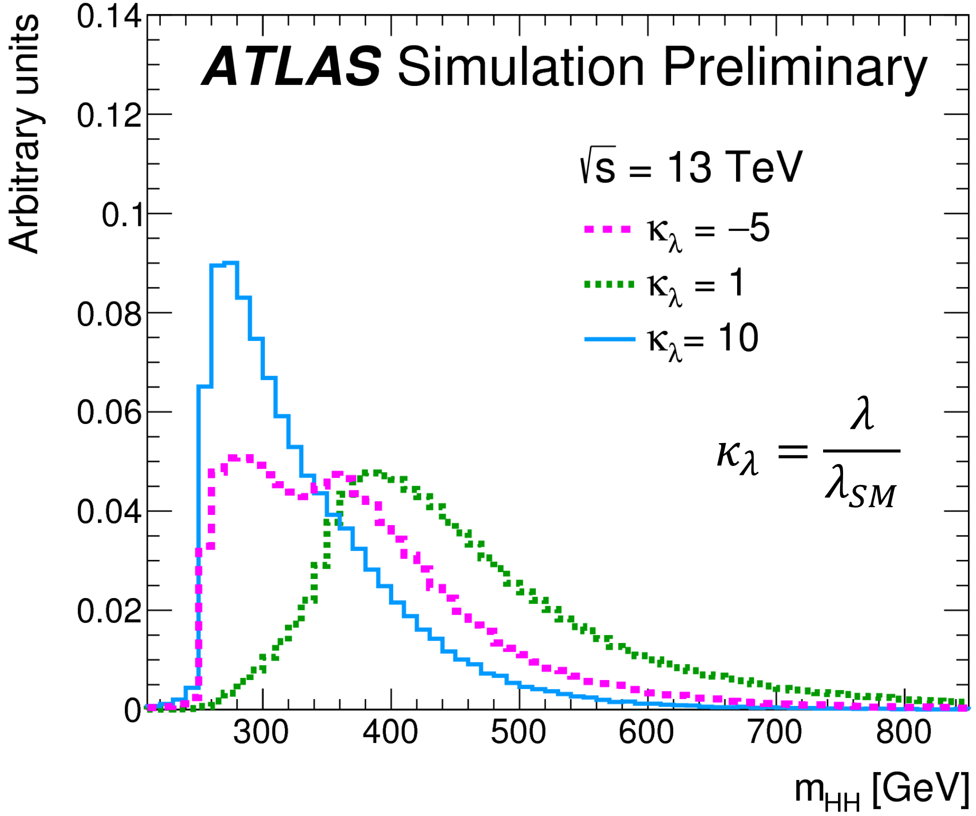




Major HH production processes

# HH spectrum

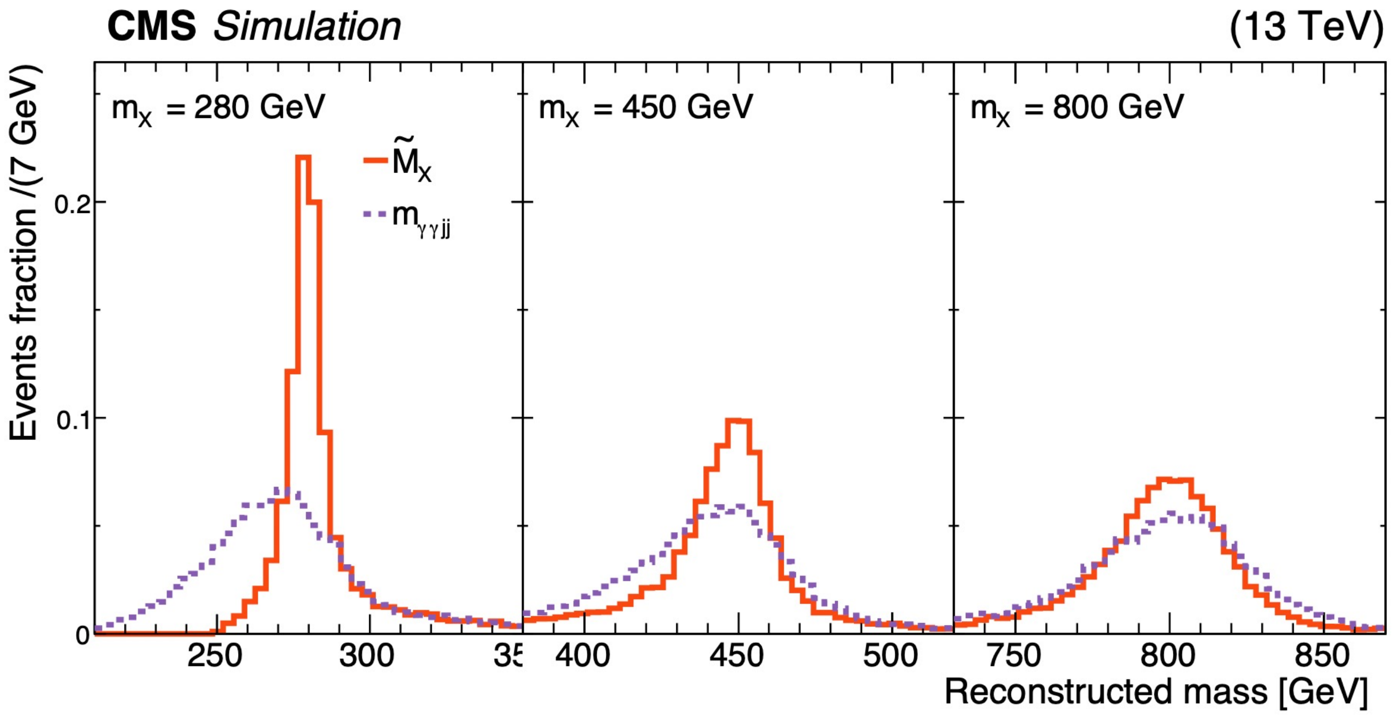
**Non-resonant :**

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




**Resonnant :**

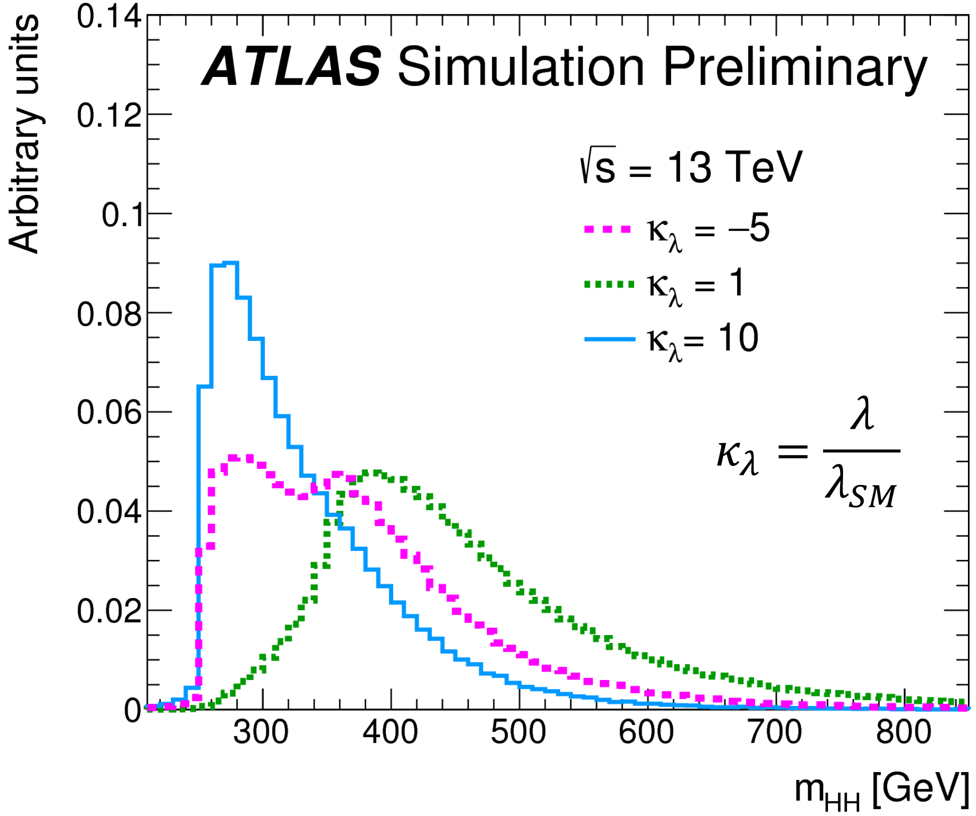
**Resonnance in the $m_{HH}$ spectrum**



# HH spectrum

**Non-resonant :**

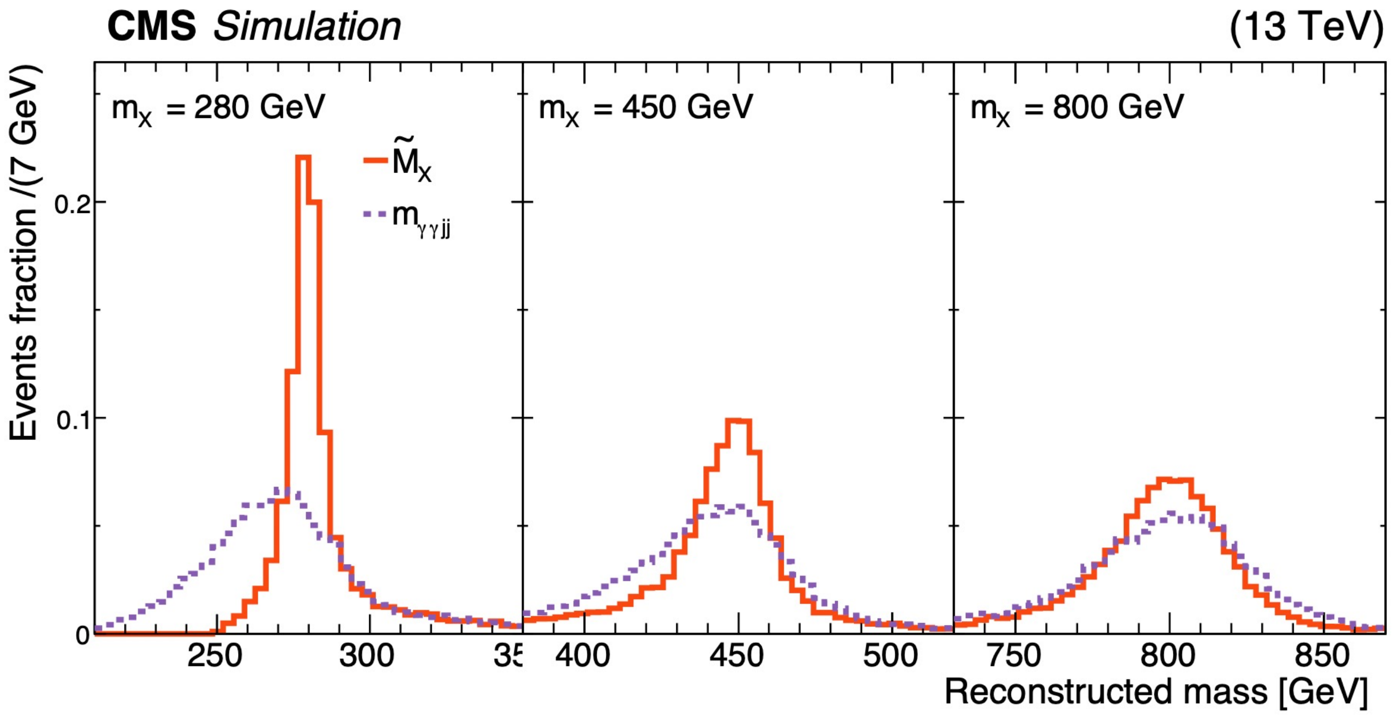
**Deformation of $m_{HH}$ spectrum**



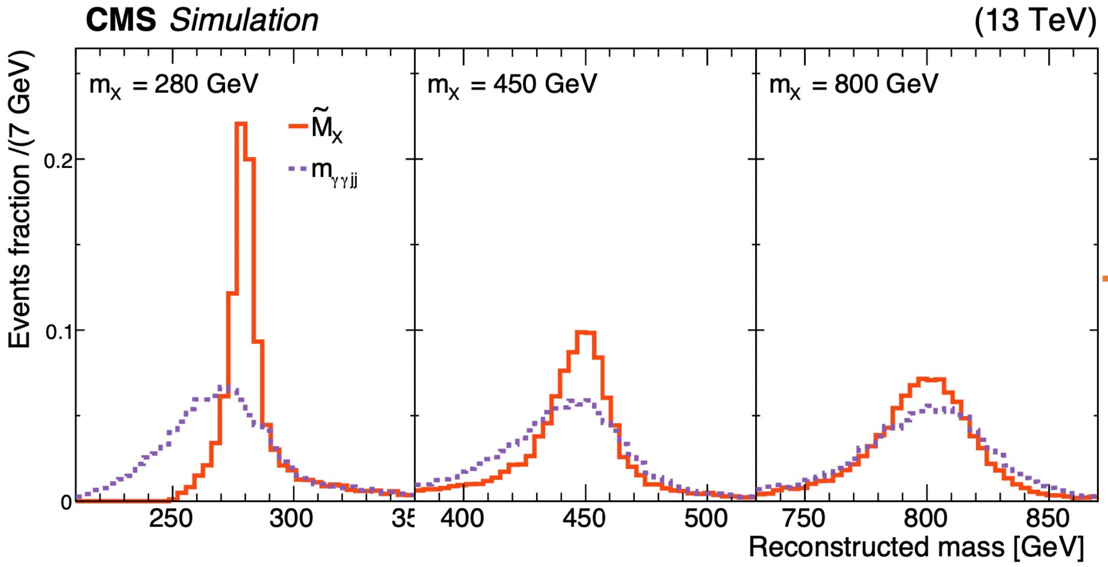

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

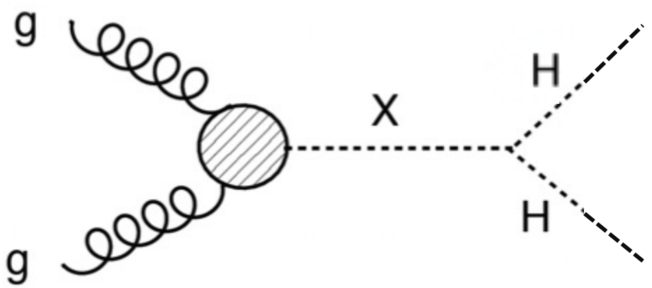
**Resonant :**

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



# $X \to HH$



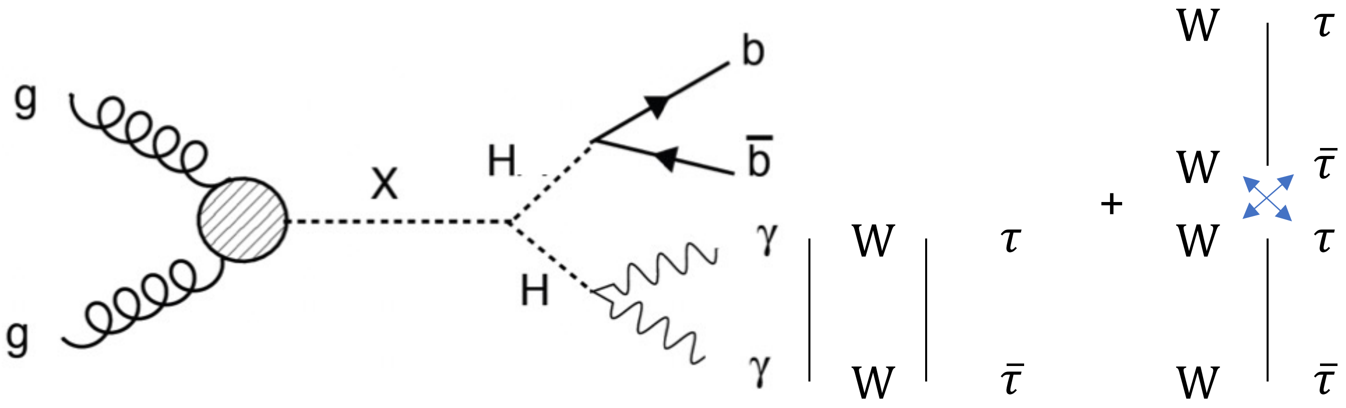




Some **BSM theories** predict additionnal particles
Like a **resonnance X decaying into a Higgs pair**

# And what do I do ?

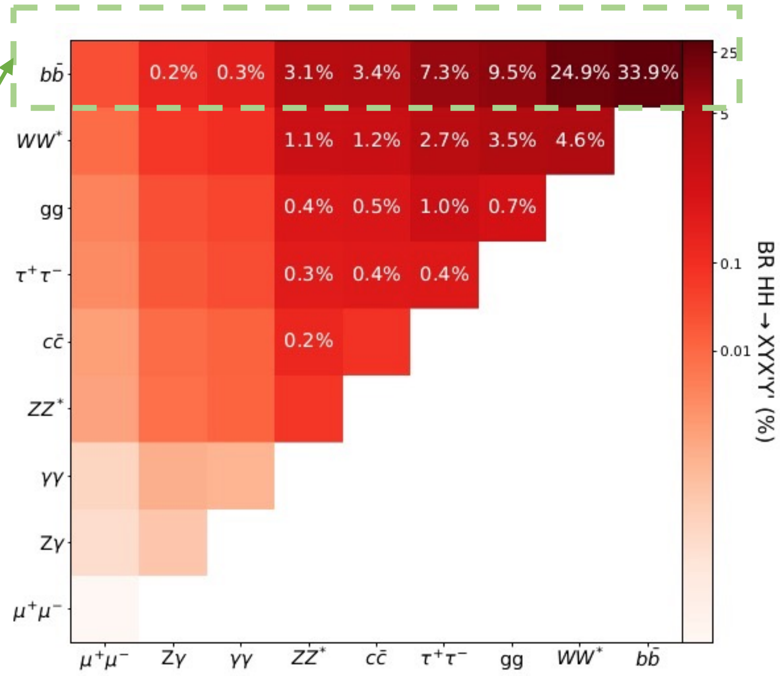
I worked on the **Run 2 (2015-2018) statistical combination** of the **X→ HH** searches

Channels considered : $bb\gamma\gamma, bbVV$ *(resolved and boosted)*, *bbbb boosted* , $bb\tau\tau$ , *multilepton*




Combining different analyses will result in a **more senstive** « final result »

Reviews in Physics (2020) 100045




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

# Combination recipe

- **Check the compatibility of input analyses**
  - ✓ Overlaps : 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**

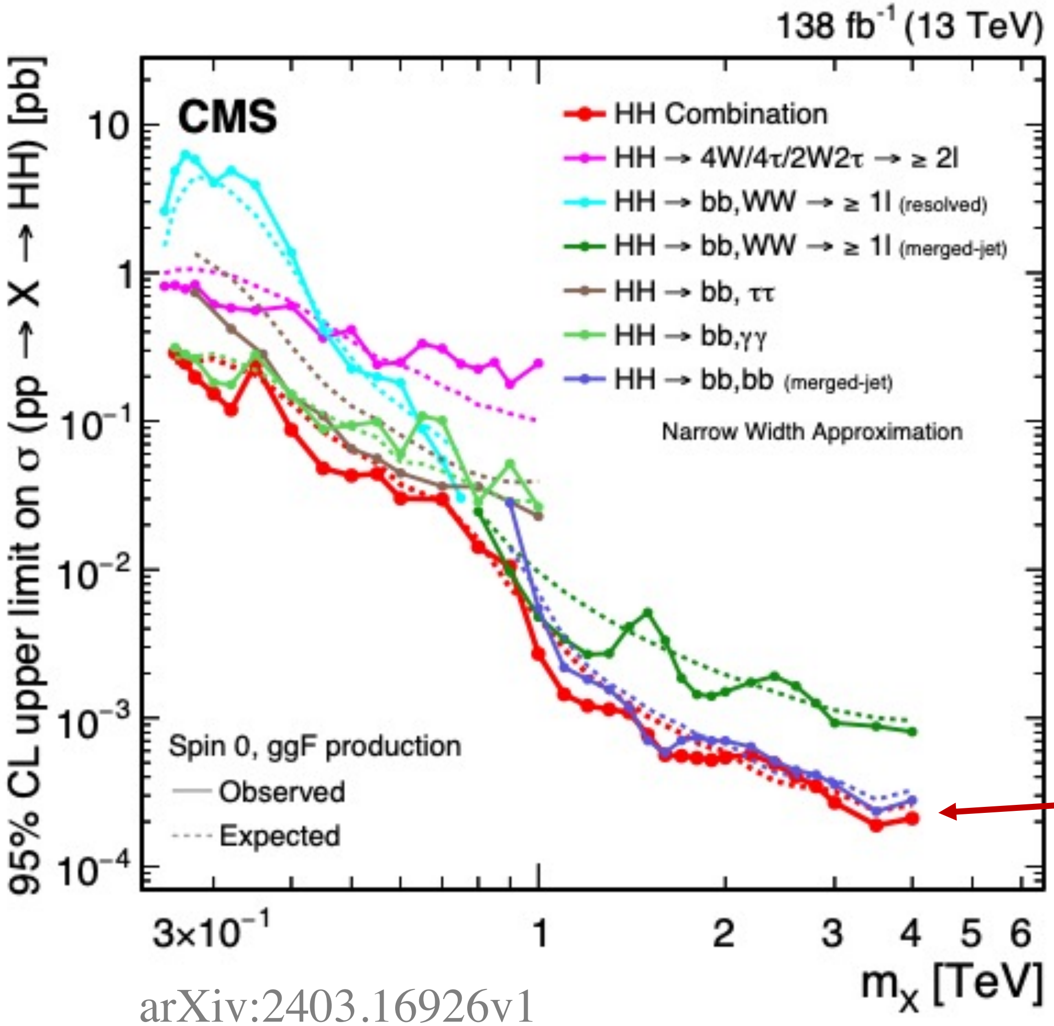
✓ **Correlation between parameters :**

Systematic uncertainties ⟹ Nuisance parameters in the fit : some of them are correlated across analyses

*The combination counts over 1000 nuisance parameters !*

✓ **Same normalization for all analysis**

# " Perform your combination "




arXiv:2403.16926v1

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

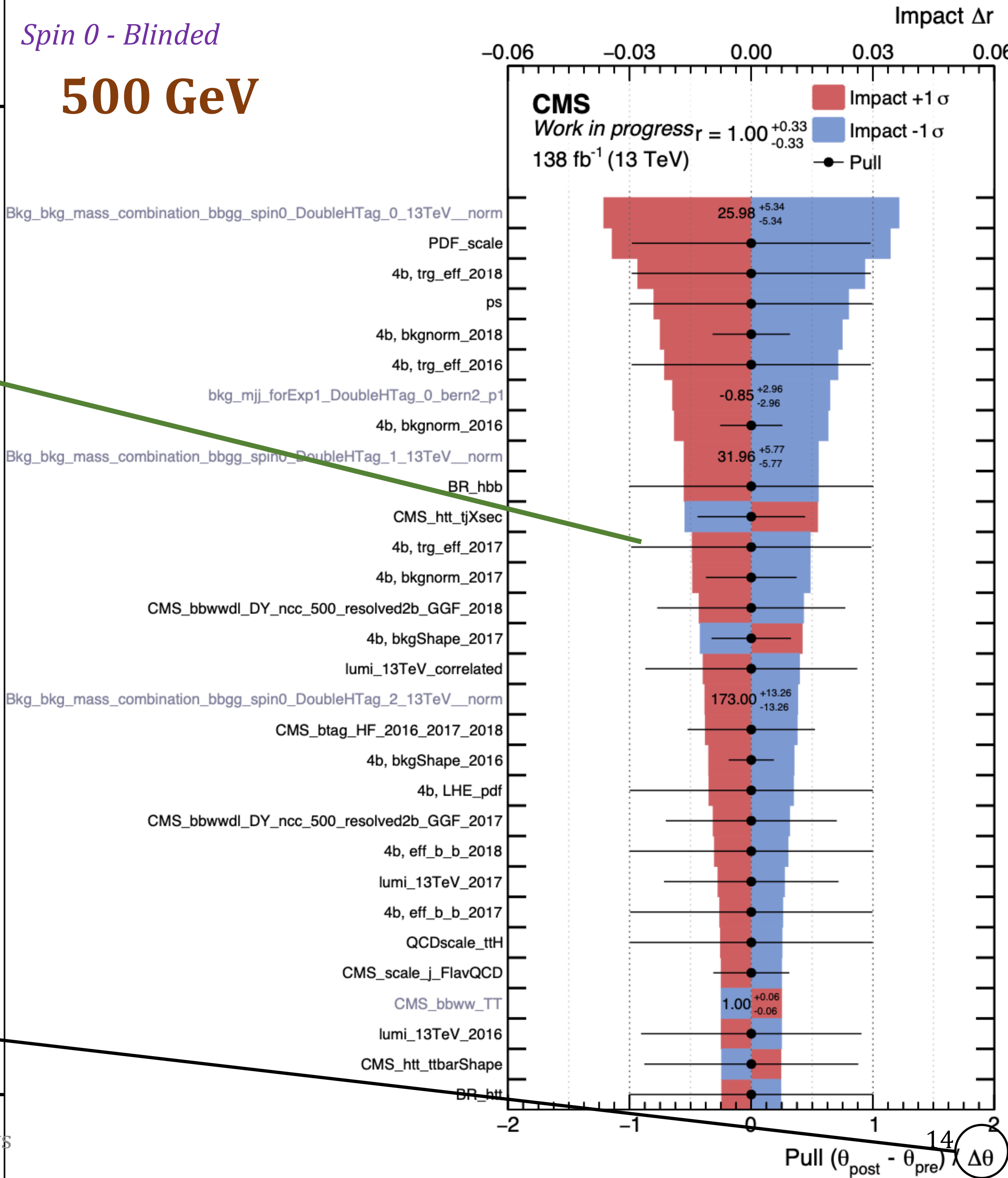
If $\boldsymbol{pulls} < \mathbf{1}$ : The uncertainty was **over-estimated**

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

pre-fit uncertainty

*Spin 0 - Blinded*

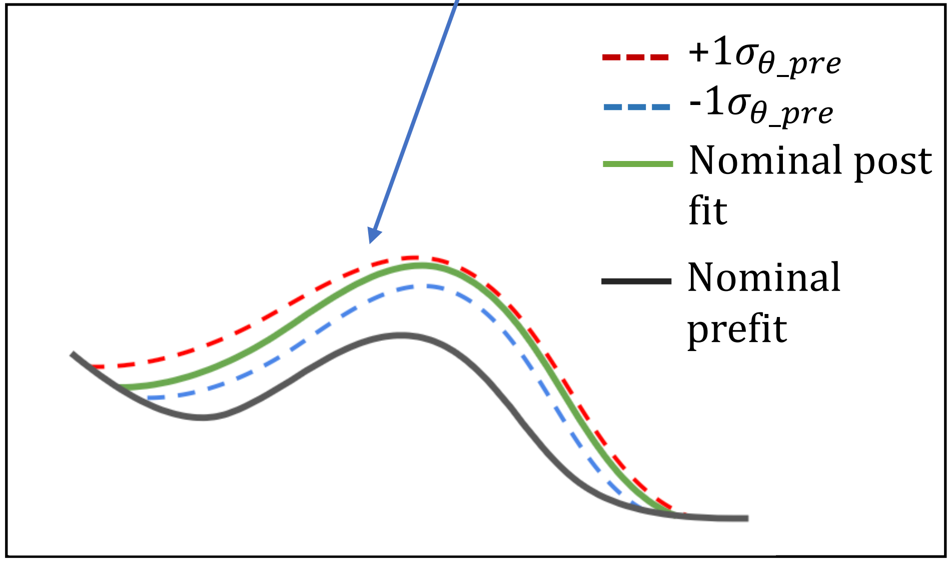
**500 GeV**



# Impacts

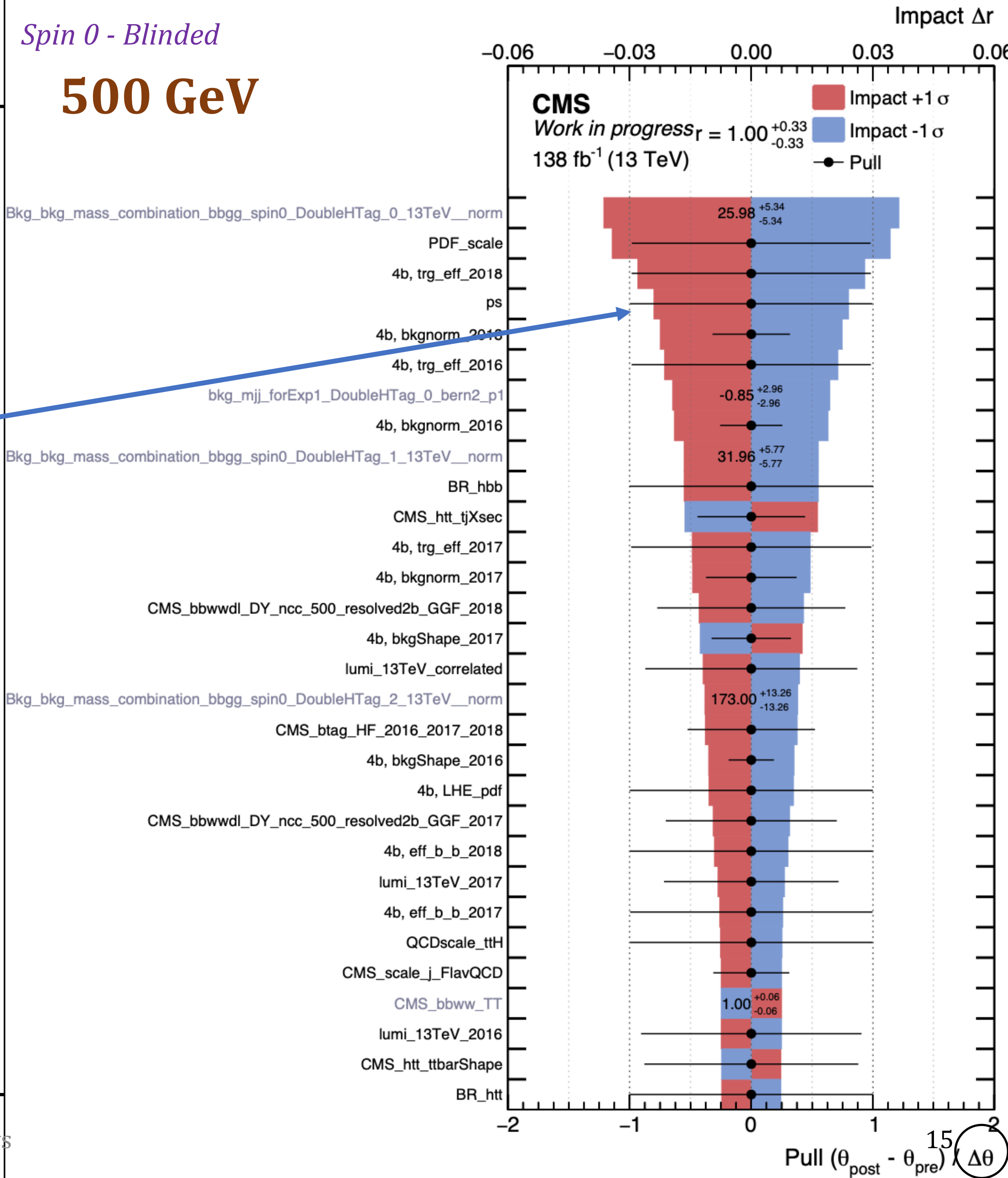
**Impacts** : impacts of the uncertainty of the signal

$\theta = nuisance$




*Spin 0 - Blinded*

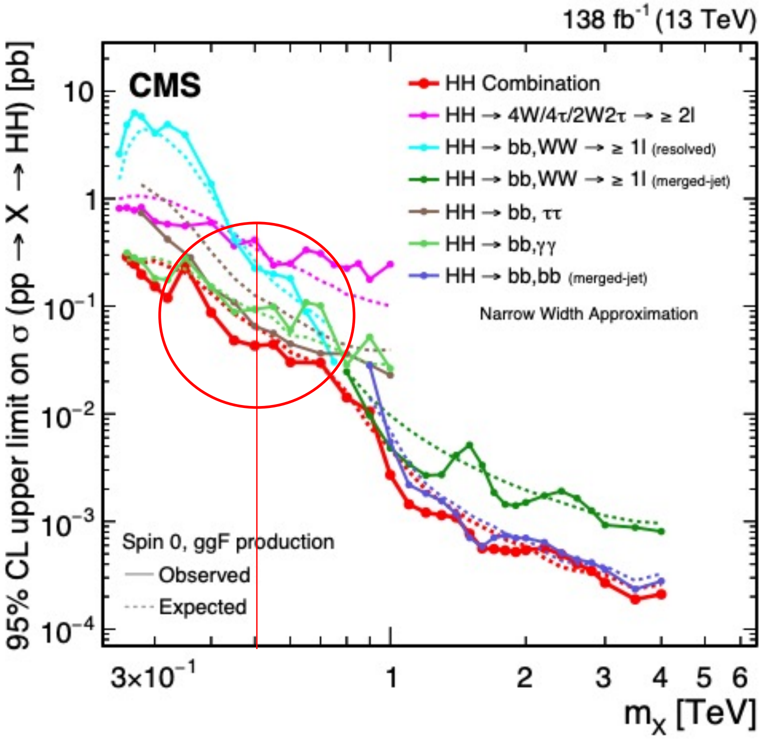
## 500 GeV



# Impacts

**Impacts consistent** :

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



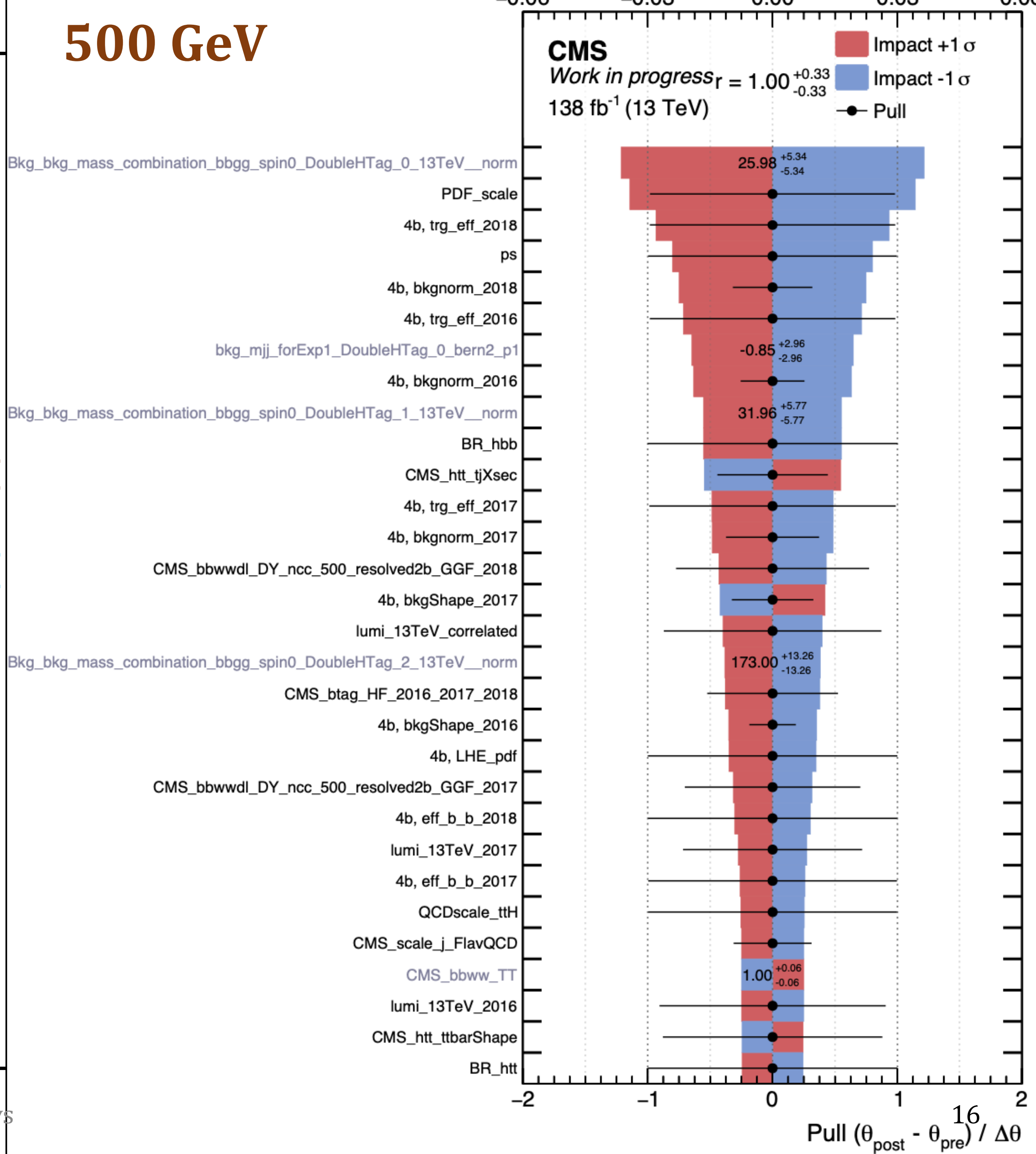

$bb\gamma\gamma$

$bb\tau\tau$

$bbww$

*Spin 0 - Blinded*

**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*

*How ?*

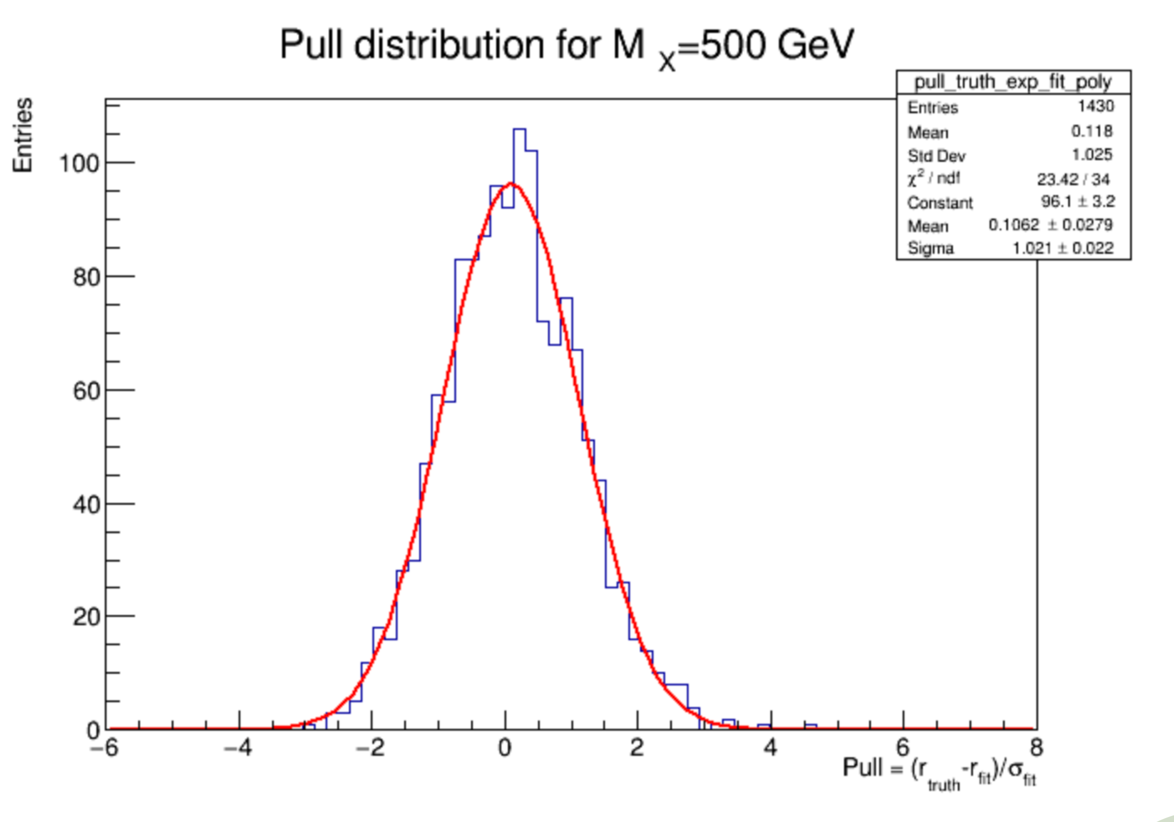
***1500 répétitions***

BCKG Toy generation → Injection of a $3/4\sigma$ signal

*fit* ↓

Extraction of the post-fit signal

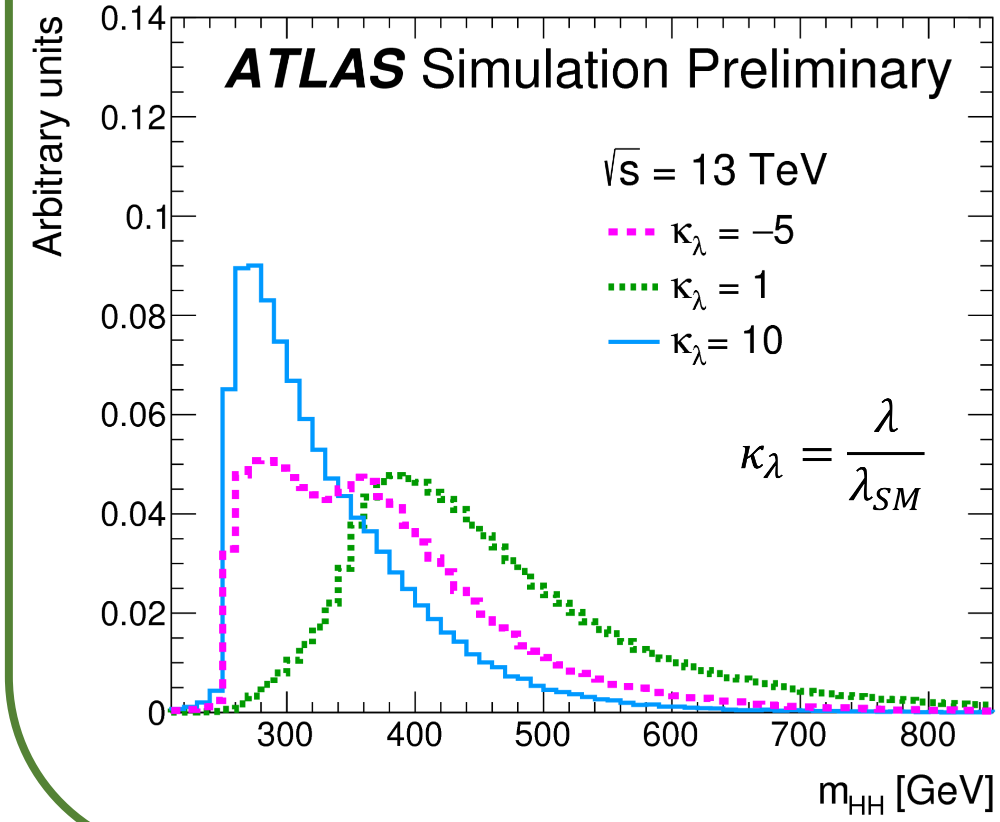
If no bias is introduced, we should get a $\mathcal{N}(0,1)$



# HH spectrum

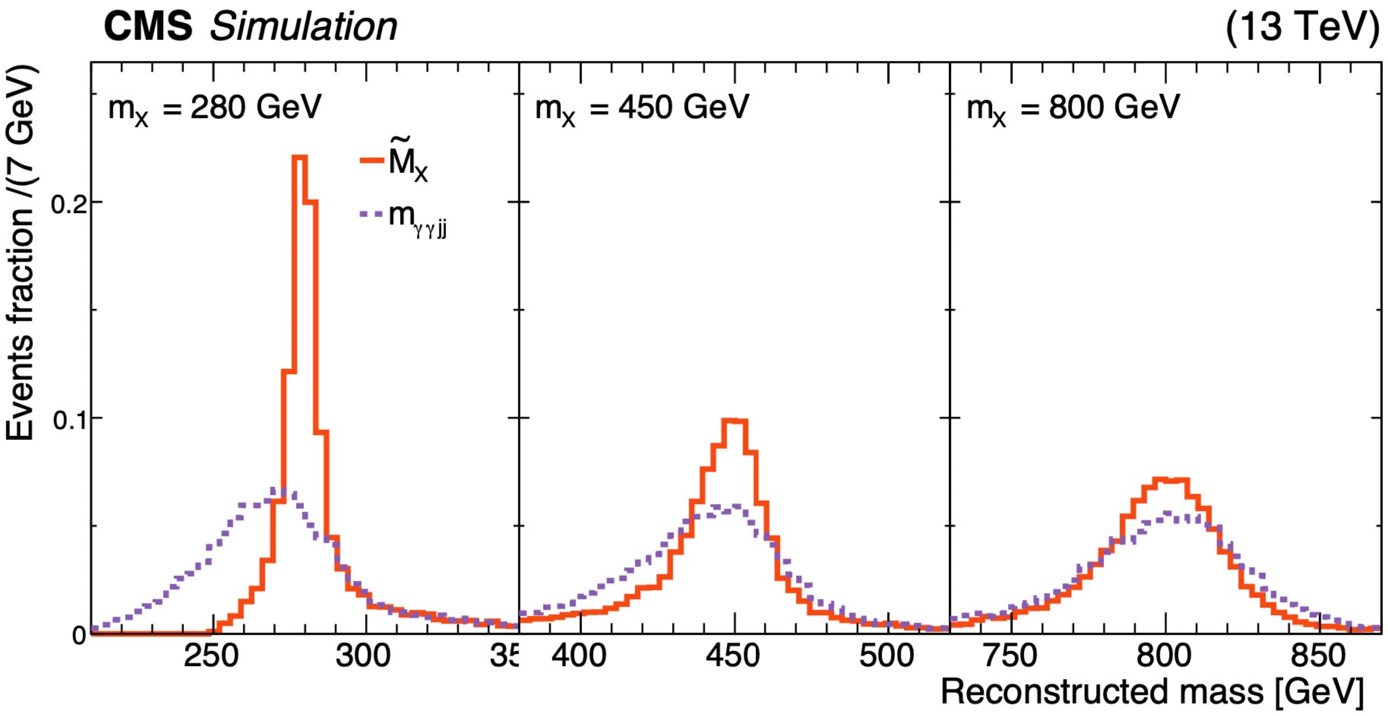
**Non-resonant :**

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

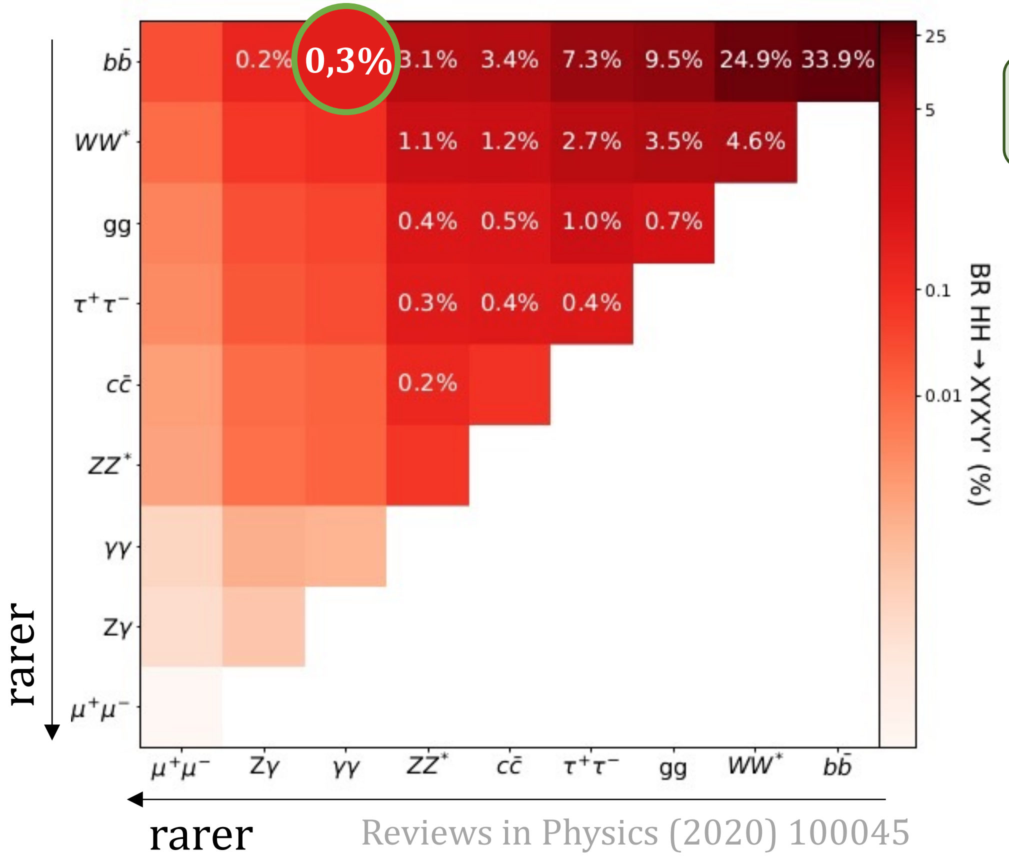



**Resonant :**

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



# $HH \rightarrow b\bar{b}\gamma\gamma$

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**$HH \rightarrow b\bar{b}\gamma\gamma$ is the most sensitive channel**

## b quarks

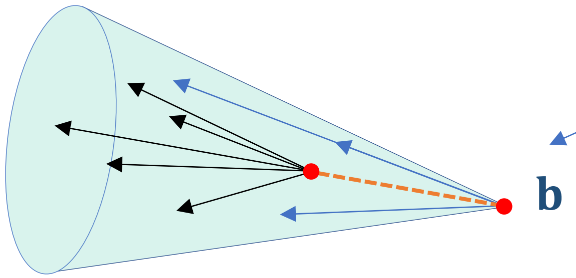
**Strong interaction** with the Higgs boson

## Photons

**Good selection** of the event

Compromise

*Color confinement* $\Longrightarrow$ b quarks cannot be isolated. They materialize as **particle jets** in the detector.




➢ **Room for improvement in the reconstruction of b jets**

# Analysis strategy for Run 2

Experiment → Object reconstruction & selection : Photons, jets, … → MVA training and categorization

↓

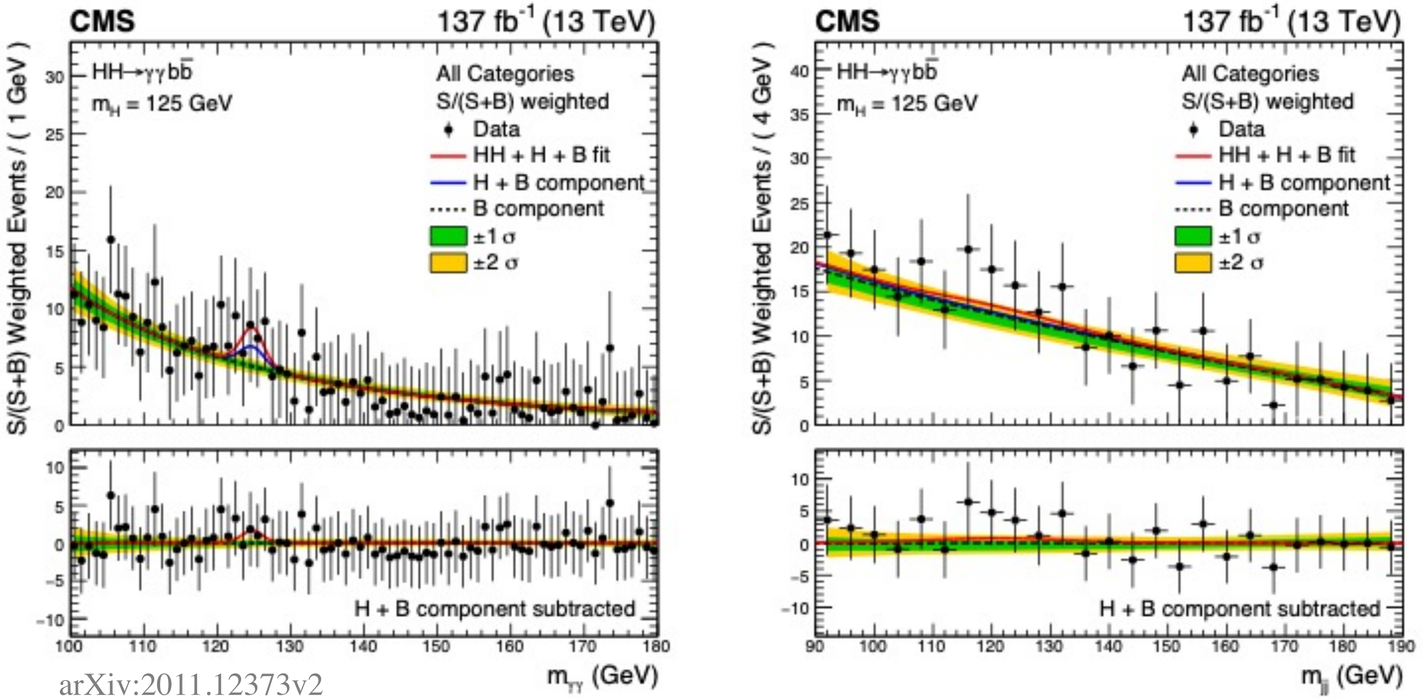
Simultaneous fit on $M_{\gamma\gamma}$ and $M_{jj}$

↓

Limits on $\sigma(HH \to bb\gamma\gamma)$

↓

Limits on $\boldsymbol{\kappa_\lambda} = \frac{\lambda}{\lambda_{SM}} \in [\mathbf{-3.3}\ ,\ \mathbf{8.5}]$




arXiv:2011.12373v2

# Aim for Run 3 (2022-2025)

Experiment → Object reconstruction & selection : Photons, jets, … → MVA training and categorization

↓

Simultaneous fit on $M_{\gamma\gamma}$ and $M_{jj}$

↓

Limits on $\sigma(HH \rightarrow bb\gamma\gamma)$

↓

Limits on $\boldsymbol{\kappa_\lambda} = \frac{\lambda}{\lambda_{SM}} \in [\mathbf{-3.3}\ ,\ \mathbf{8.5}]$

**Improving the limits on $\boldsymbol{\sigma(HH \rightarrow bb\gamma\gamma)}$**

↓

**Improving the limits on the self coupling constant $\boldsymbol{\lambda}$**

# My work

## Early Run 3 $HH \rightarrow bb\gamma\gamma$

Experiment → Object reconstruction & selection : Photons, jets, … → MVA training and categorization

*Work in progress…*

**Selecting as much $HH \rightarrow bb\gamma\gamma$ events as possible while rejecting as much background as possible**

# Main Backgrounds

- Resonant : single Higgs production
  - ggF $H \rightarrow \gamma\gamma$
  - VBF $H \rightarrow \gamma\gamma$
  - tt$(H \rightarrow \gamma\gamma)$
  - V$(H \rightarrow \gamma\gamma)$

- Non resonant
  - $\gamma\gamma$ + jets
  - $\gamma$ + jets

# Main Backgrounds

- Resonant : single Higgs production
  - ggF $H \rightarrow \gamma\gamma$
  - VBF $H \rightarrow \gamma\gamma$
  - tt$(H \rightarrow \gamma\gamma)$
  - V$(H \rightarrow \gamma\gamma)$

- Non resonant
  - $\gamma\gamma$ + jets
  - $\gamma$ + jets

→ Largest background

# Object Selection

Construction of a workflow analyzing, selecting events and applying systematics and corrections

## Selection of the photon pair

Same as the $H \to \gamma\gamma$ analysis :

- Identification : Conditions on the photon identification score (photon ID MVA)
- Highest $p_T^{\gamma\gamma}$
- $p_T^{\gamma 1}$> 35 GeV, $p_T^{\gamma 2}$>25 GeV

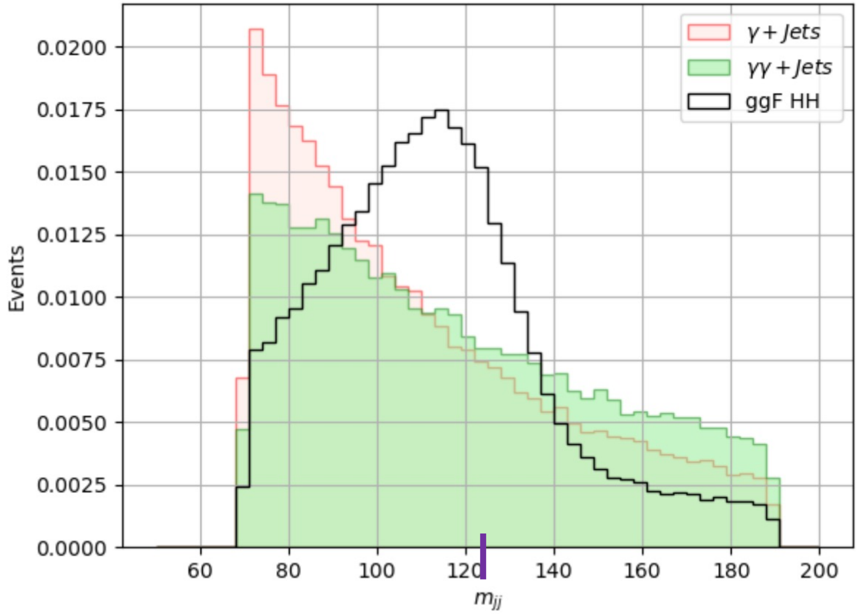
## Selection of the jet pair

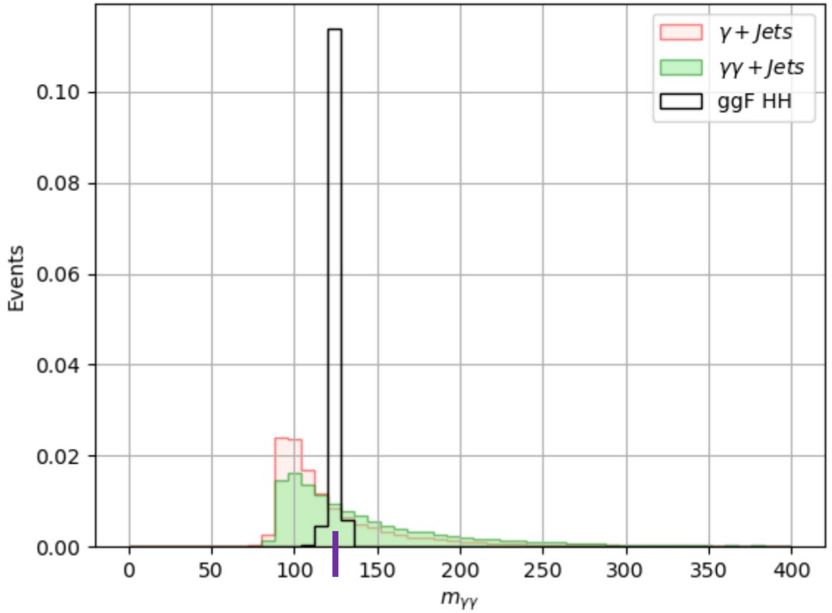
- Identification : ParticleNet b-tagging score > 0
- The 2 b-jets are selected as the highest sum of PNet scores (≈ more likely to be b-jets )
  *(same as Run2 for now)*
- $p_T^j > 20\ GeV$

*These selections are not detailed because not relevant yet (they are taken as loose or as the same as Run 2 to developpe the analysis tool and waiting for further investigation)*

# Run 3 kinematic distributions

Kinematic properties help to differentiate signal from backgrounds → Use of Monte Carlo simulations

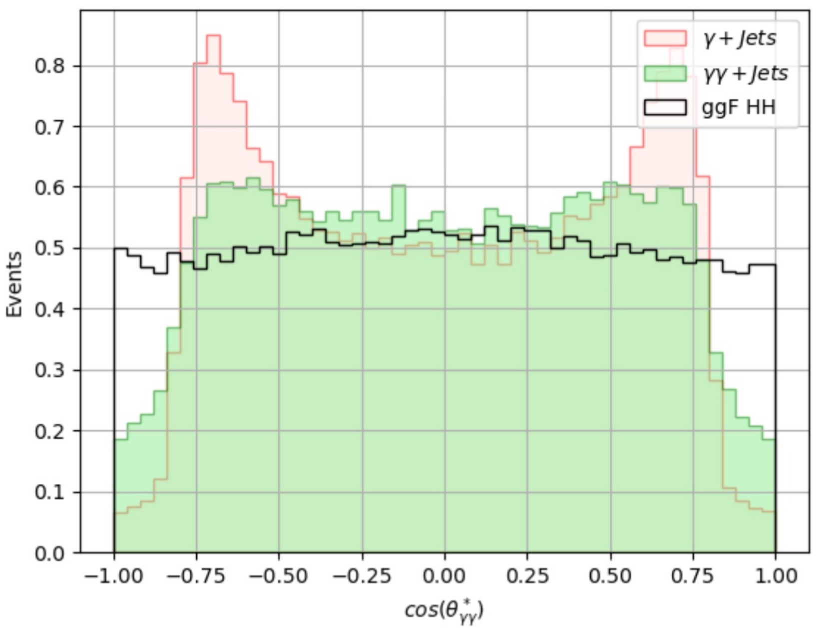


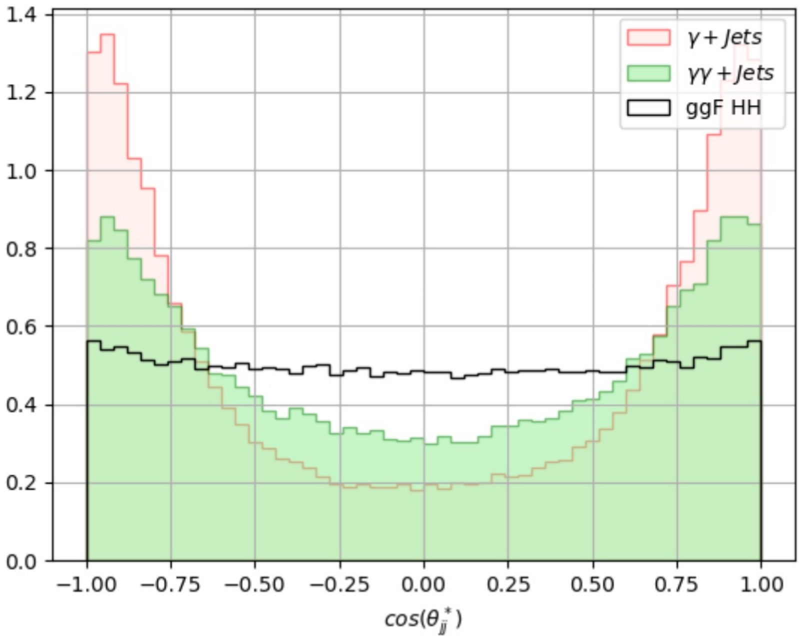



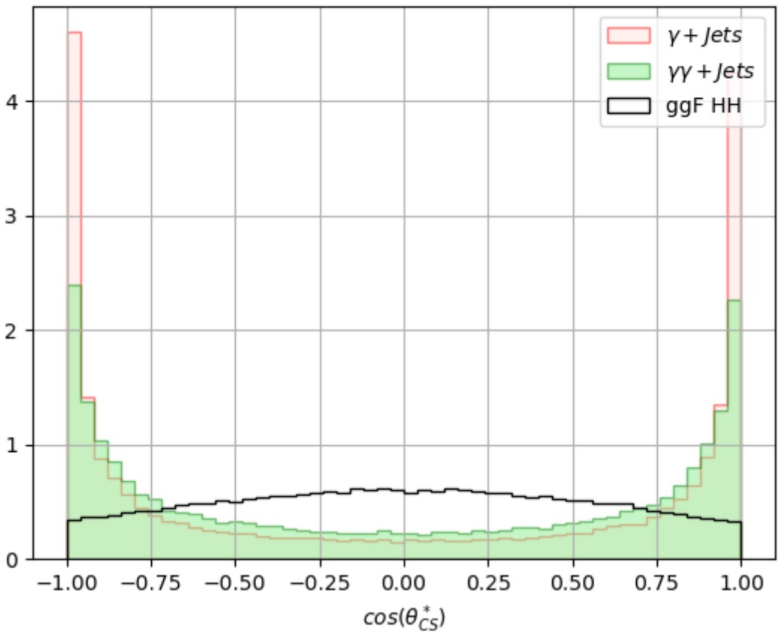

The invariant mass of the two jets and two photons selected should be close the $m_H = 125\ GeV$

# Run 3 kinematic distributions

Kinematic properties help to differentiate signal from backgrounds → Use of Monte Carlo simulations



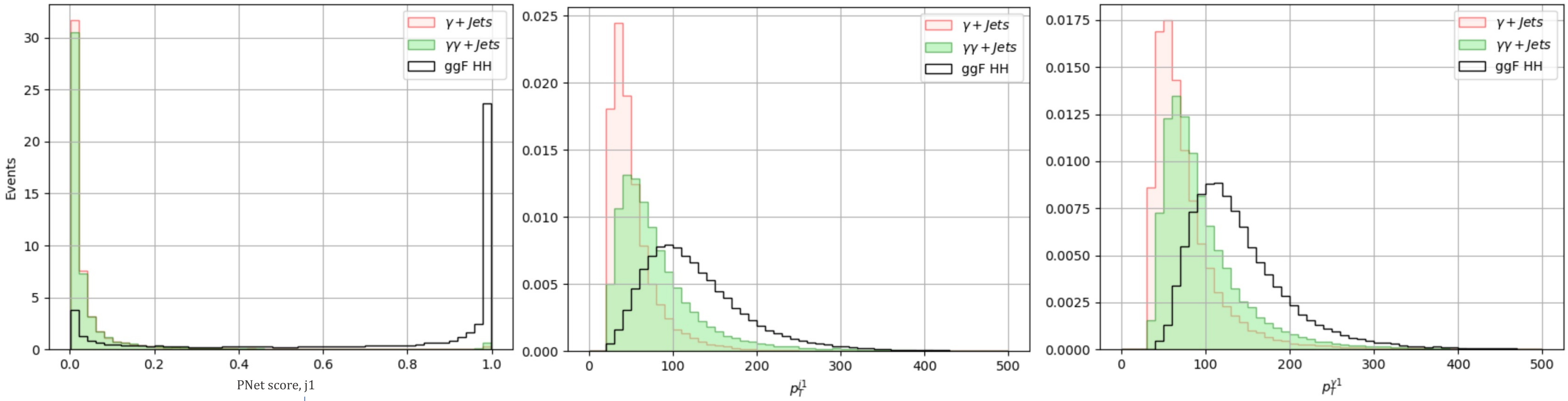




**Angular variables** : The Higgs boson has a spin of 0 , and its decay is **isotropic**

# Run 3 kinematic distributions

Kinematic properties help to differentiate signal from backgrounds → Use of Monte Carlo simulations

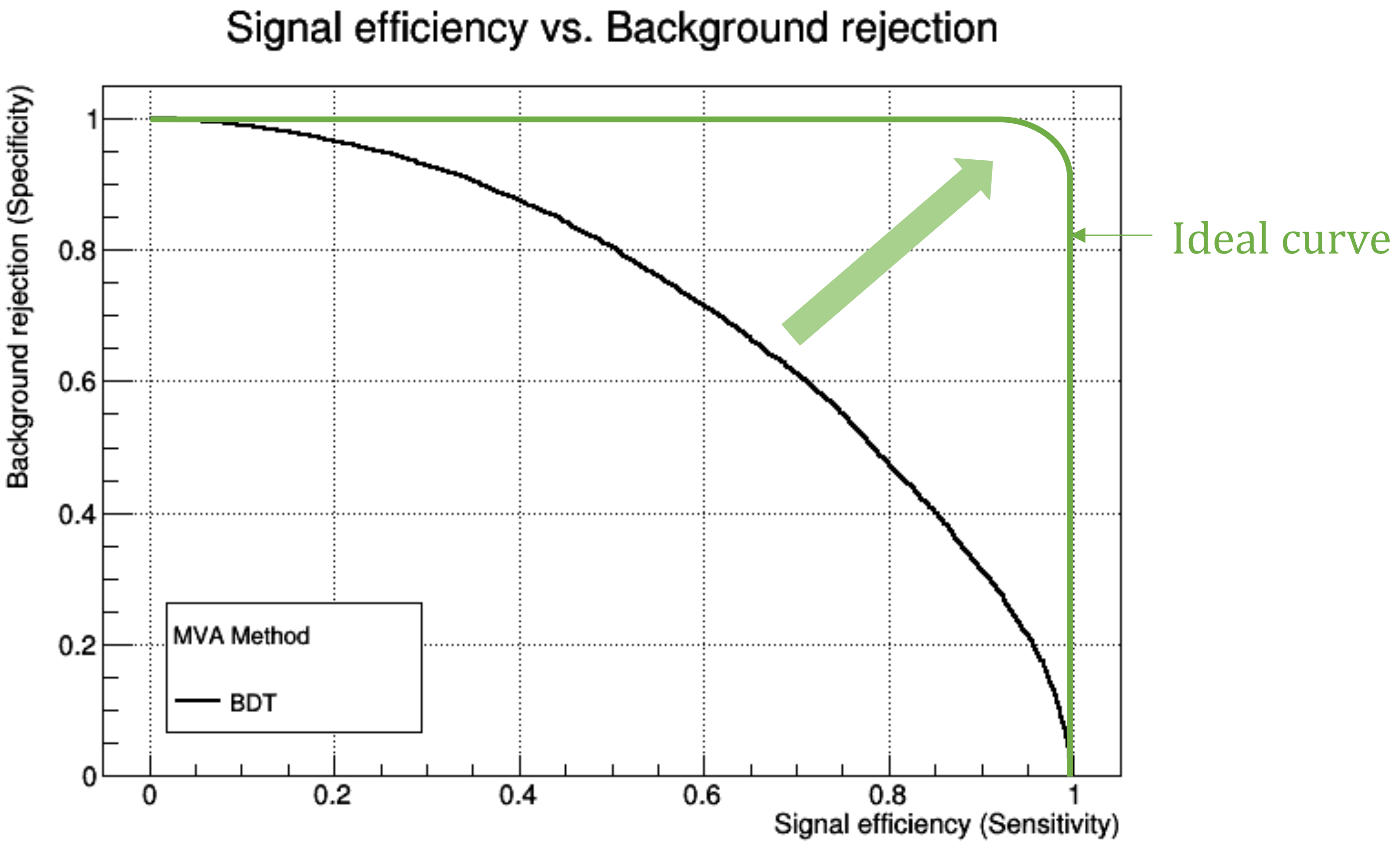



Score of the ParticleNet b-tagging algorithm

*Non exhaustive plots …*

# Background rejection

- These discriminating variables are used for **cuts** and as inputs to train **machine learning** algorithms



# Summary

✓ **Work on Run 2 statistical combination of X→ $HH$ searches finished**

- The nuisances correlations, overlap removals and stastical tests also apply to spin 2 $X \rightarrow HH$ and $X \rightarrow YH$

**Run 3 non-resonant $HH \rightarrow bb\gamma\gamma$ analysis ongoing**

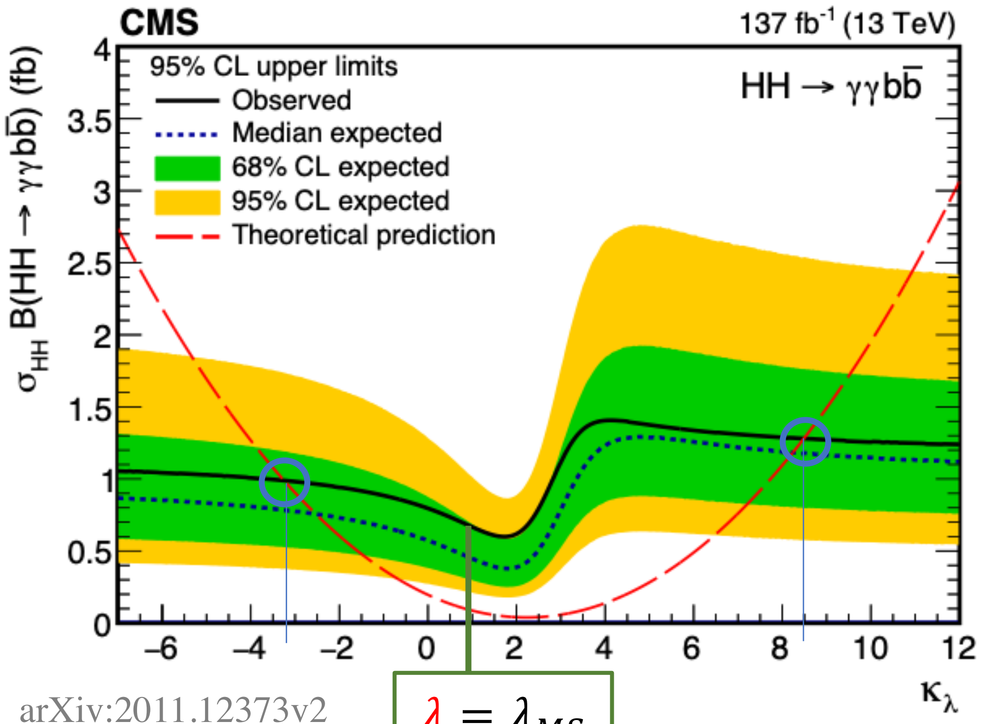
- Construction of a workflow analyzing the events
  - ❑ Applying all needed corrections, systematics, and fixing the cuts
- Improvement of the background rejection and signal efficiency with machine learning
  - ❑ Adding more discriminating variables and testing of different architectures
- ❑ Statistical analysis (fit and Preliminary limits on $\sigma(HH \rightarrow bb\gamma\gamma)$ and $\lambda$ )

# Thank you !

# Backup

# Analysis strategy for Run 2

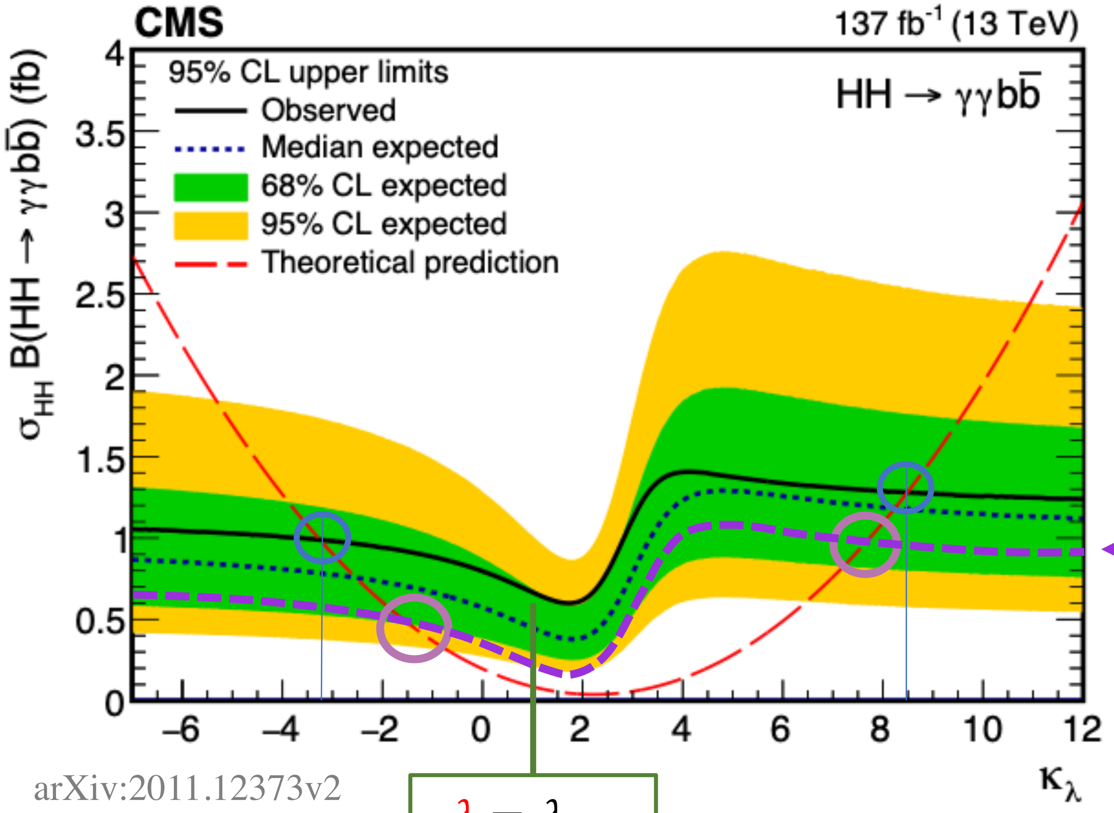
Experiment → Object reconstruction & selection : Photons, jets, … → MVA training and categorization → Simultaneous fit on $M_{\gamma\gamma}$ and $M_{jj}$ → Limits on $\boldsymbol{\kappa_\lambda} = \frac{\boldsymbol{\lambda}}{\boldsymbol{\lambda_{SM}}} \in [\mathbf{-3.3}\ ,\ \mathbf{8.5}]$




arXiv:2011.12373v2

$\lambda = \lambda_{MS}$

# Aim for Run 3 (2022-2025)




arXiv:2011.12373v2

$\lambda = \lambda_{MS}$

Improving the limits on $\sigma(HH \rightarrow bb\gamma\gamma)$

↓

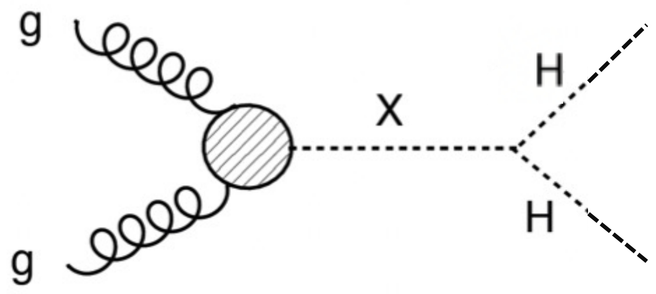
Improving the limits on the self coupling constant $\lambda$

Limite visée pour le Run III :

$$\sigma_{exclue}^{III+II} = \frac{\sigma_{exclue}^{II}}{\sqrt{2} \times 1.2}$$

Doublement des données

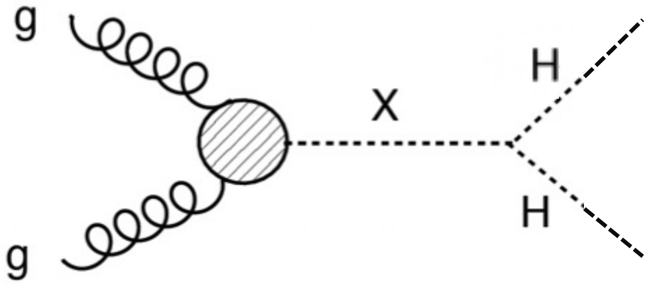
# For those who like theory




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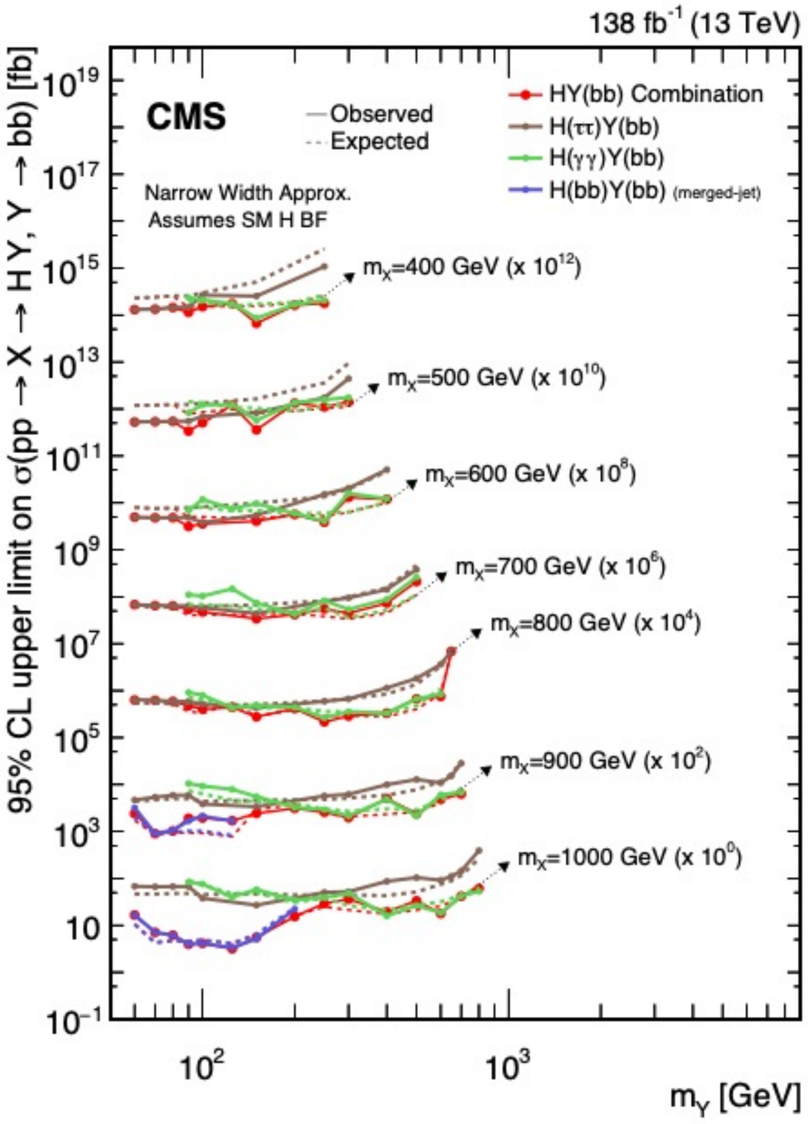
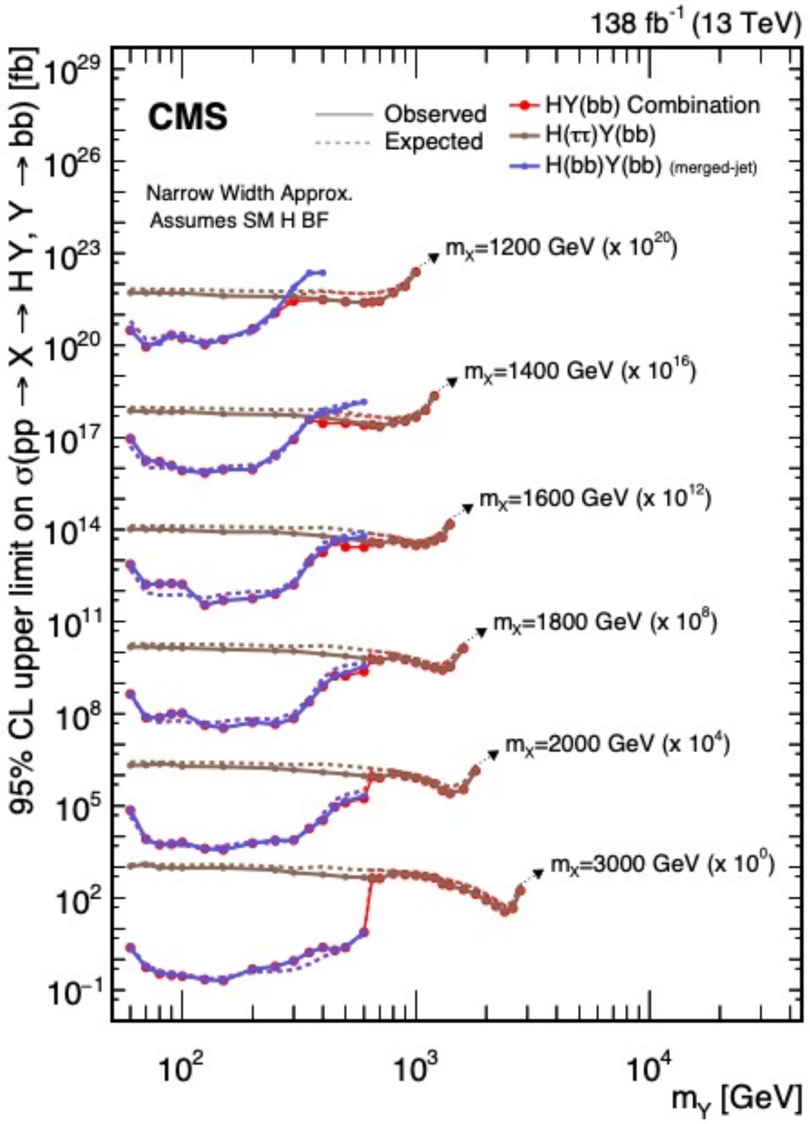
- **Warped Extra Dimensions** : postulates the existence of one extra dimension
  - New particles decaying into HH such as a Spin-0 radion and the spin2 Kaluza-Klein excitation of the Graviton.

# X→HY

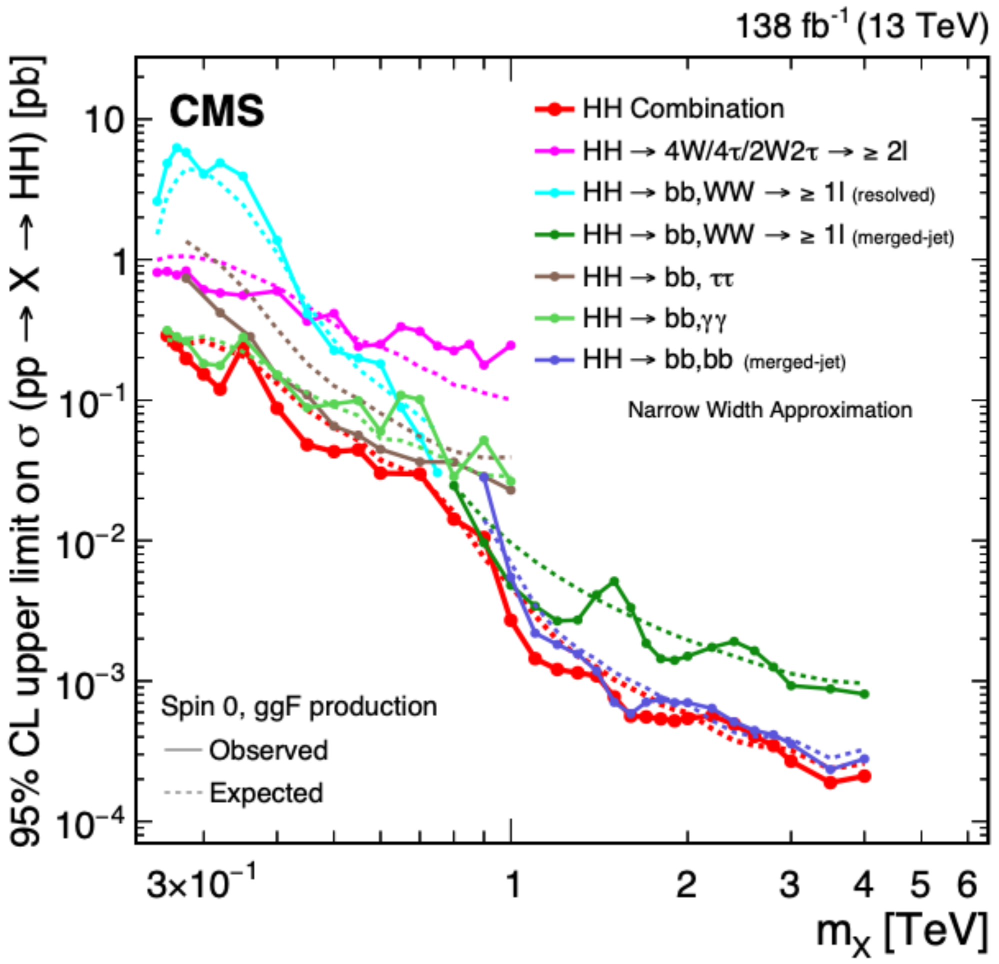


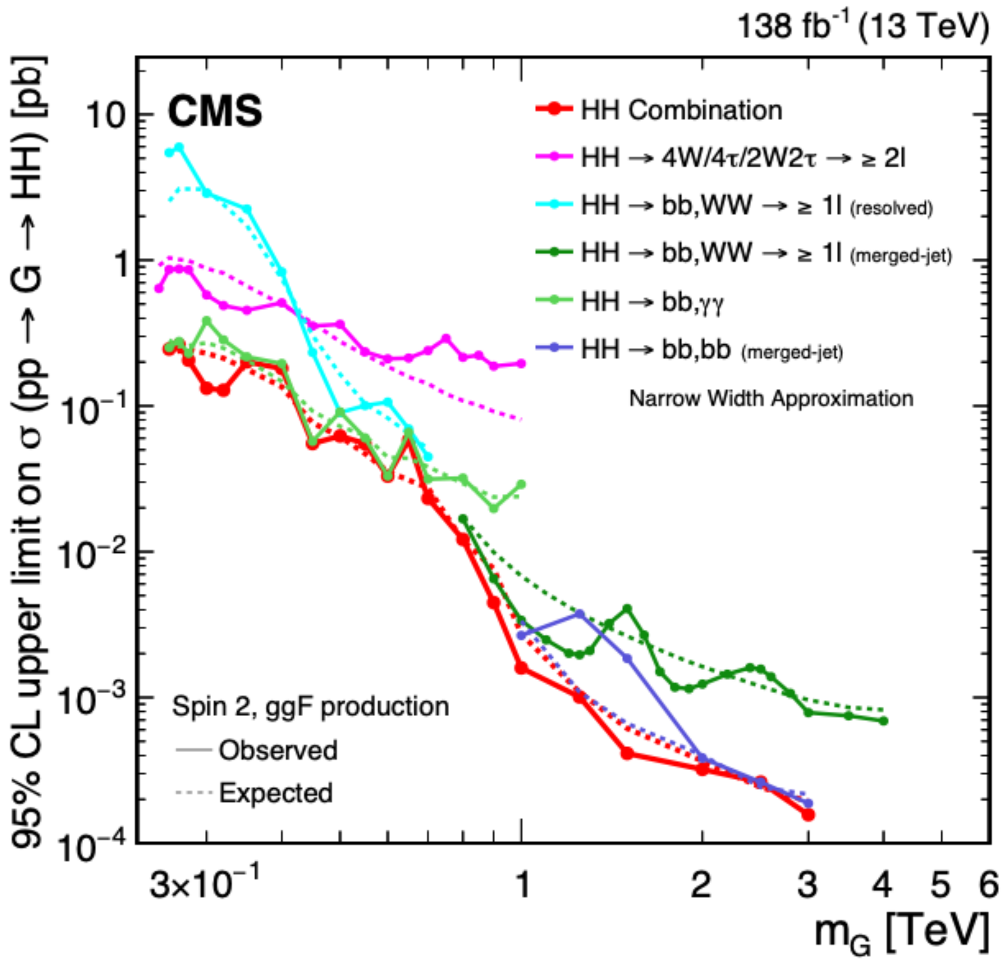
138 fb$^{-1}$ (13 TeV)
CMS
Observed
Expected
HY(bb) Combination
H(ττ)Y(bb)
H(γγ)Y(bb)
H(bb)Y(bb) (merged-jet)
Narrow Width Approx.
Assumes SM H BF
m$_X$=400 GeV (x 10$^{12}$)
m$_X$=500 GeV (x 10$^{10}$)
m$_X$=600 GeV (x 10$^{8}$)
m$_X$=700 GeV (x 10$^{6}$)
m$_X$=800 GeV (x 10$^{4}$)
m$_X$=900 GeV (x 10$^{2}$)
m$_X$=1000 GeV (x 10$^{0}$)
95% CL upper limit on σ(pp → X → H Y, Y → bb) [fb]
m$_Y$ [GeV]

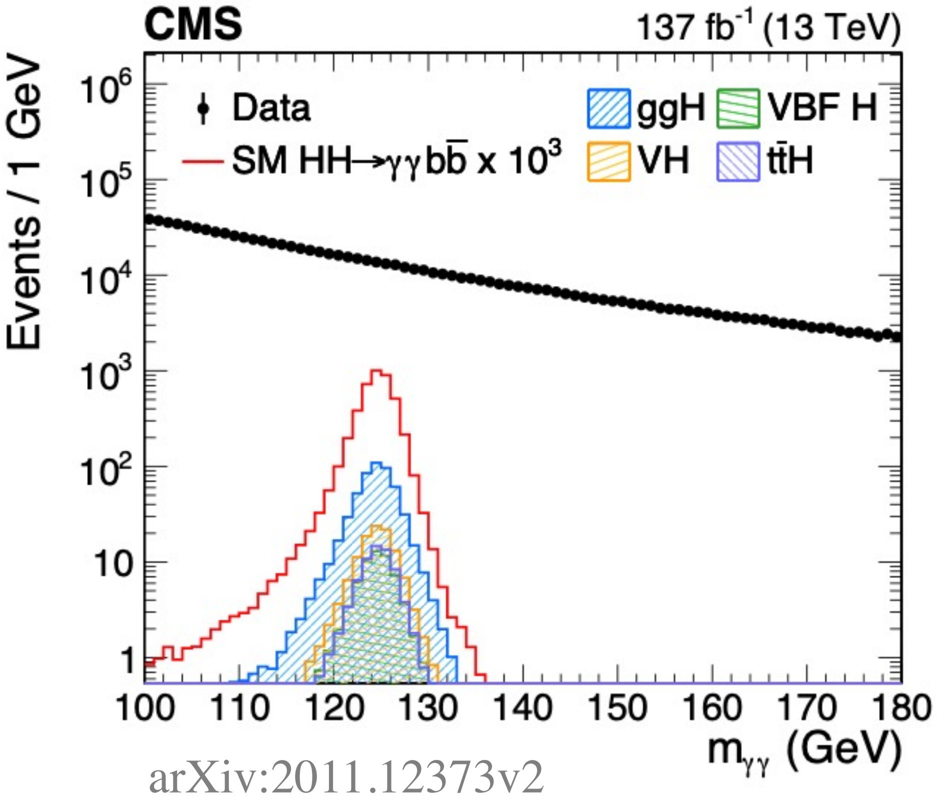
138 fb$^{-1}$ (13 TeV)
CMS
Observed
Expected
HY(bb) Combination
H(ττ)Y(bb)
H(bb)Y(bb) (merged-jet)
Narrow Width Approx.
Assumes SM H BF
m$_X$=1200 GeV (x 10$^{20}$)
m$_X$=1400 GeV (x 10$^{16}$)
m$_X$=1600 GeV (x 10$^{12}$)
m$_X$=1800 GeV (x 10$^{8}$)
m$_X$=2000 GeV (x 10$^{4}$)
m$_X$=3000 GeV (x 10$^{0}$)
95% CL upper limit on σ(pp → X → H Y, Y → bb) [fb]
m$_Y$ [GeV]

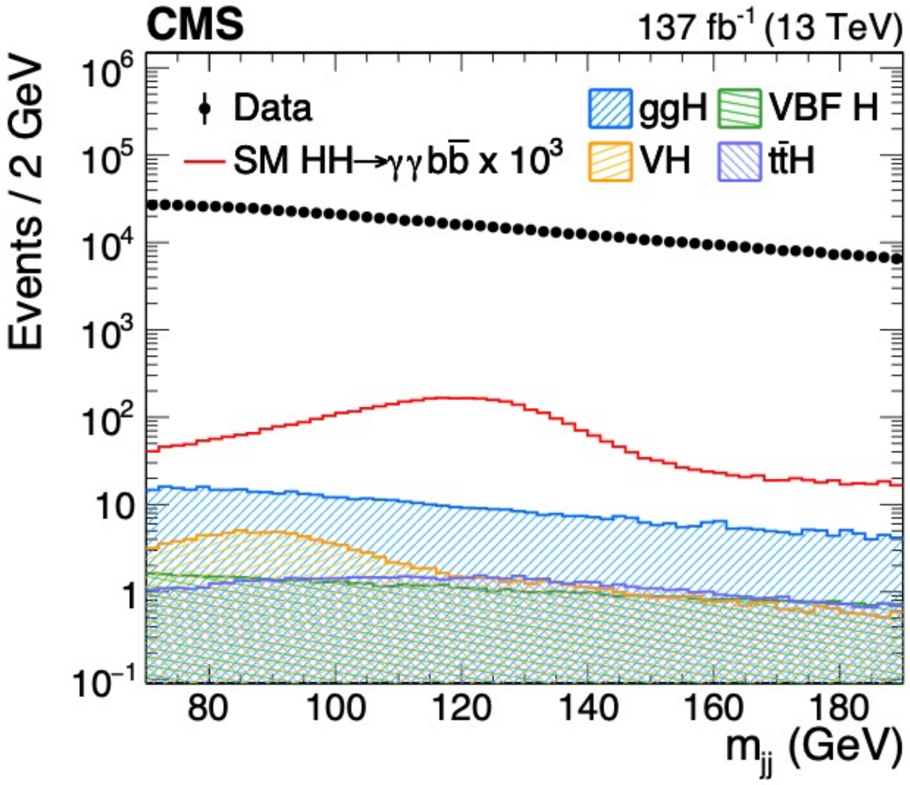
# $X \rightarrow HH$ spin 2



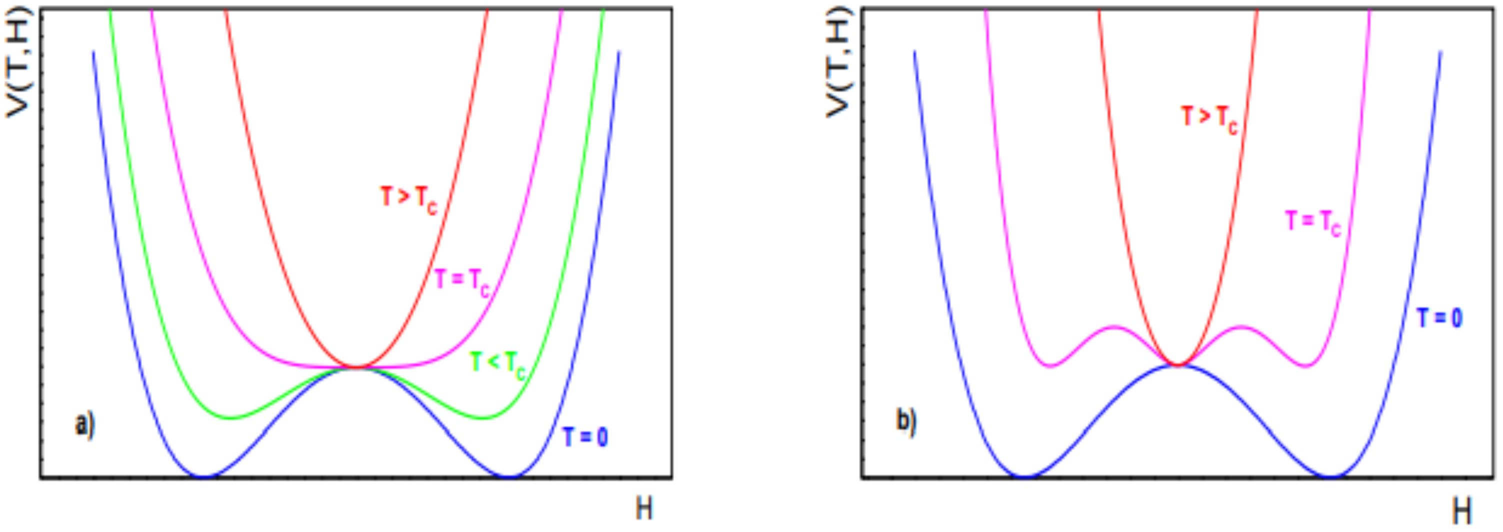
# Background composition




arXiv:2011.12373v2

# Electroweak phase transition




Modèle standard

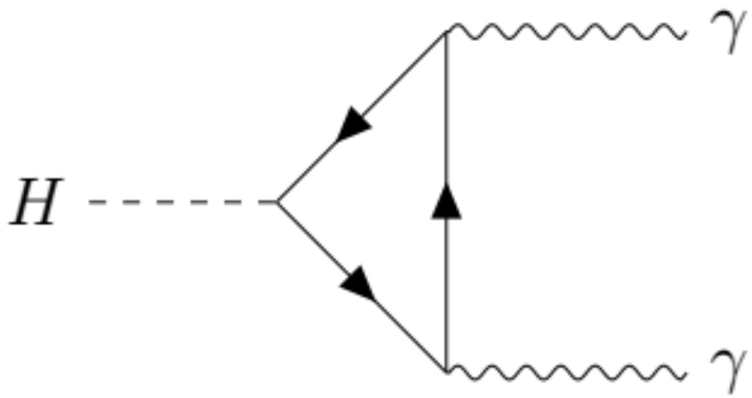
•*Eur.J.Phys.* 38 (2017) 6, 065404

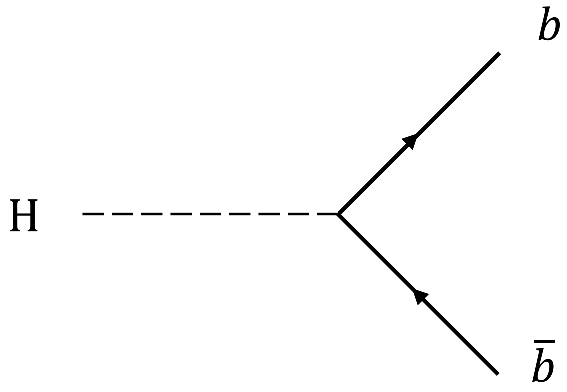
# $HH \rightarrow b\bar{b}\gamma\gamma$

**Table 17.1** The predicted branching ratios of the Higgs boson for $m_H = 125$ GeV.

| Decay mode | Branching ratio |
|---|---|
| $H \rightarrow b\bar{b}$ | 57.8% |
| $H \rightarrow WW^*$ | 21.6% |
| $H \rightarrow \tau^+\tau^-$ | 6.4% |
| $H \rightarrow gg$ | 8.6% |
| $H \rightarrow c\bar{c}$ | 2.9% |
| $H \rightarrow ZZ^*$ | 2.7% |
| $H \rightarrow \gamma\gamma$ | 0.2% |

Thomson, M. (2013).
*Modern Particle Physics*



# Sections efficaces (1)

| $\sqrt{s}$ | 13 TeV | 14 TeV | 27 TeV | 100 TeV |
|---|---|---|---|---|
| ggF $HH$ | $31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$ | $36.69^{+2.1\%}_{-4.9\%} \pm 3.0\%$ | $139.9^{+1.3\%}_{-3.9\%} \pm 2.5\%$ | $1224^{+0.9\%}_{-3.2\%} \pm 2.4\%$ |
| VBF $HH$ | $1.73^{+0.03\%}_{-0.04\%} \pm 2.1\%$ | $2.05^{+0.03\%}_{-0.04\%} \pm 2.1\%$ | $8.40^{+0.11\%}_{-0.04\%} \pm 2.1\%$ | $82.8^{+0.13\%}_{-0.04\%} \pm 2.1\%$ |
| $ZHH$ | $0.363^{+3.4\%}_{-2.7\%} \pm 1.9\%$ | $0.415^{+3.5\%}_{-2.7\%} \pm 1.8\%$ | $1.23^{+4.1\%}_{-3.3\%} \pm 1.5\%$ | $8.23^{+5.9\%}_{-4.6\%} \pm 1.7\%$ |
| $W^+HH$ | $0.329^{+0.32\%}_{-0.41\%} \pm 2.2\%$ | $0.369^{+0.33\%}_{-0.39\%} \pm 2.1\%$ | $0.941^{+0.52\%}_{-0.53\%} \pm 1.8\%$ | $4.70^{+0.90\%}_{-0.96\%} \pm 1.8\%$ |
| $W^-HH$ | $0.173^{+1.2\%}_{-1.3\%} \pm 2.8\%$ | $0.198^{+1.2\%}_{-1.3\%} \pm 2.7\%$ | $0.568^{+1.9\%}_{-2.0\%} \pm 2.1\%$ | $3.30^{+3.5\%}_{-4.3\%} \pm 1.9\%$ |
| $t\bar{t}HH$ | $0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$ | $0.949^{+1.7\%}_{-4.5\%} \pm 3.1\%$ | $5.24^{+2.9\%}_{-6.4\%} \pm 2.5\%$ | $82.1^{+7.9\%}_{-7.4\%} \pm 1.6\%$ |
| $tjHH$ | $0.0289^{+5.5\%}_{-3.6\%} \pm 4.7\%$ | $0.0367^{+4.2\%}_{-1.8\%} \pm 4.6\%$ | $0.254^{+3.8\%}_{-2.8\%} \pm 3.6\%$ | $4.44^{+2.2\%}_{-2.8\%} \pm 2.4\%$ |

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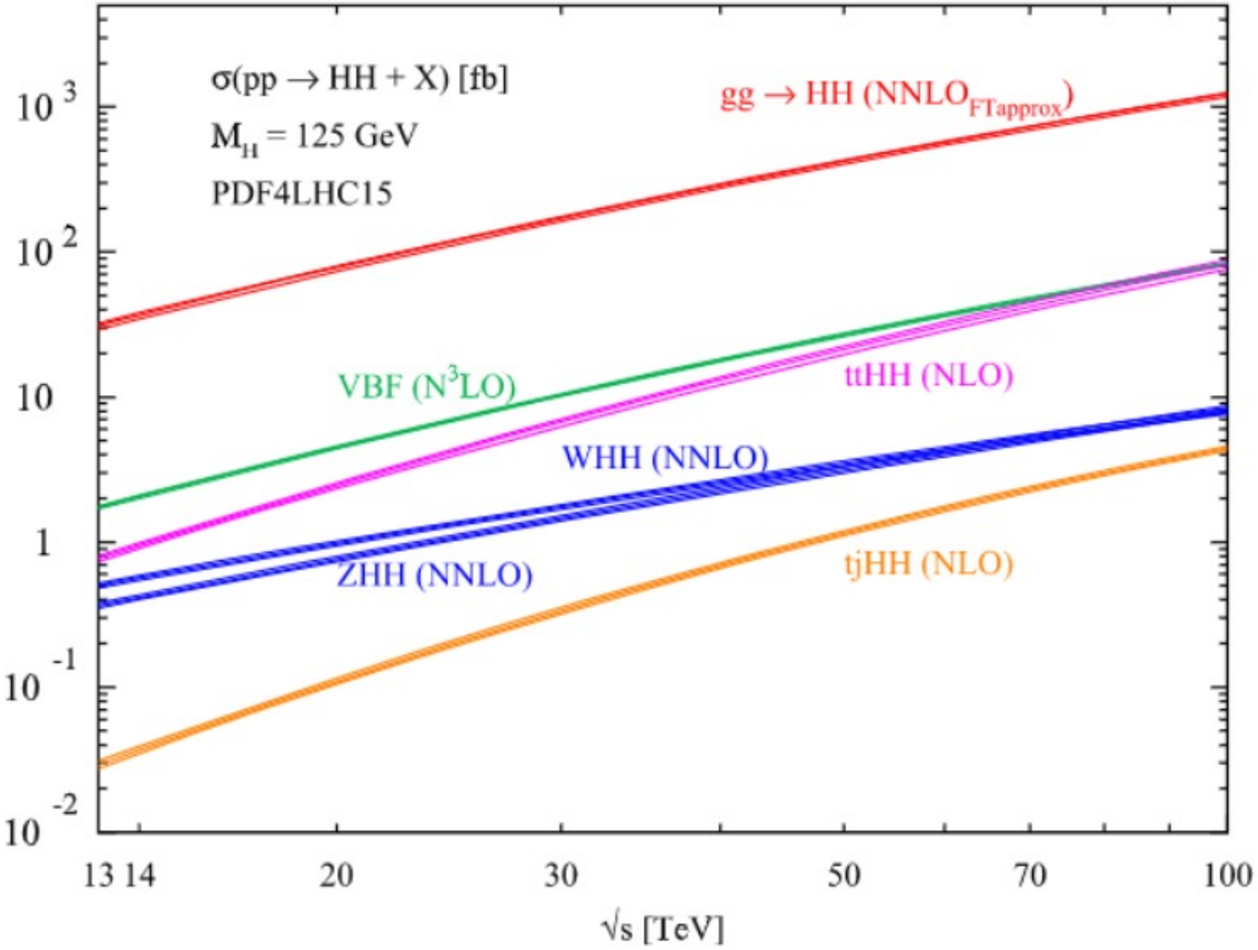
# Sections efficaces (2)

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