# CMS di-Higgs searches in final states with two photons

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# Introduction

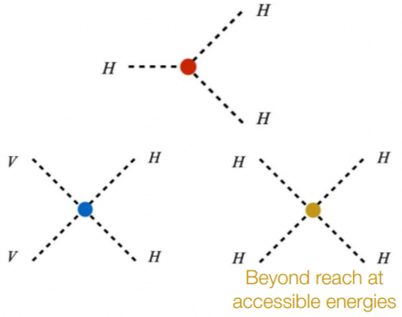
- The Higgs field potential:

$$V = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4 = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4$$

Mass-term | $\lambda_3$, trilinear self-coupling | $\lambda_4$, quartic self-coupling

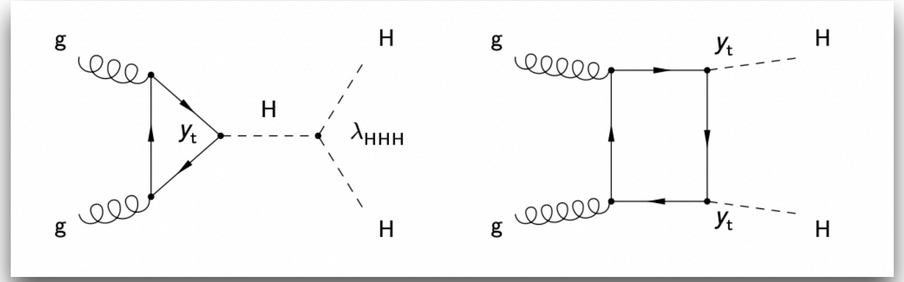
**plus** effect of cov. derivative on $\phi$ in $\mathcal{L}_H$

$C_{2V}$, VVHH coupling



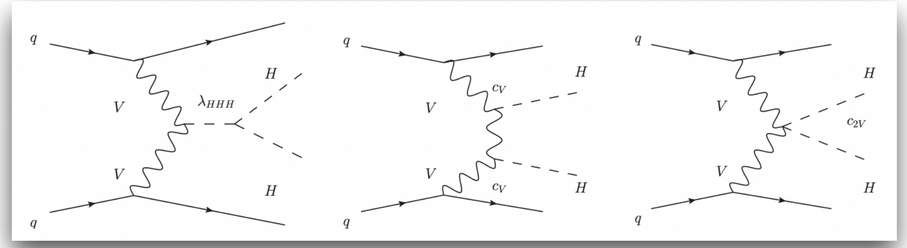

- Measurement of self-couplings $\lambda_3(\lambda_4)$ is crucial for understanding the field potential:
  - Mediates our understanding of how EWSB is realized.
- There are 2 production modes:

Gluon Gluon Fusion (~31 fb)




Could measure self-coupling of Higgs boson

Vector Boson Fusion (~1.7fb)




Could measure self-coupling of Higgs boson, and the coupling between 2 Higgs and 2 vector boson ($c_{2v}$)

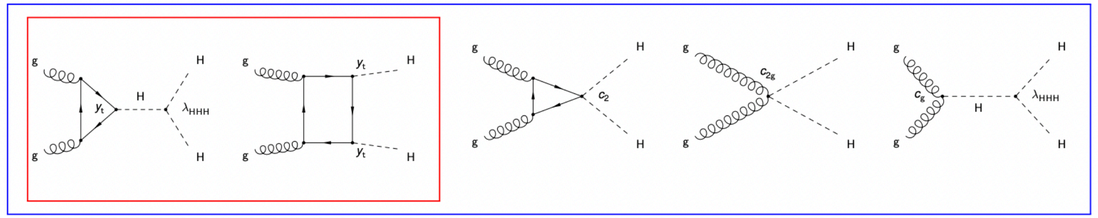
# Introduction

- Effective Field Theory Parameterised BSM Lagrangian:

$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v}(\kappa_t H + \frac{c_2}{v}H^2)(\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v}(c_g H - \frac{c_{2g}}{2v}H^2) G^a_{\mu\nu} G^{a,\mu\nu}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}},\ \lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2},\ \kappa_t = \frac{y_t}{y_t^{SM}},\ y_t^{SM} = \frac{\sqrt{2}m_t^2}{v}$$

**SM ($k_\lambda$=1, $k_t$=1, $c_{2g} = c_g = c_2$=0)** **BSM**



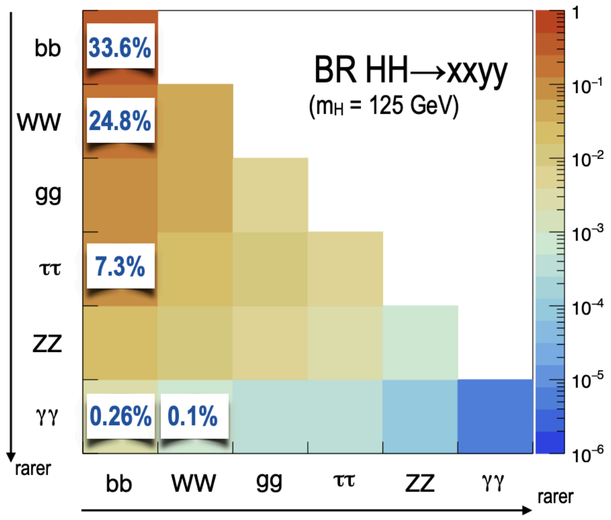

| Benchmark | $\kappa_\lambda$ | $\kappa_t$ | $c_2$ | $c_g$ | $c_{2g}$ |
|---|---|---|---|---|---|
| SM | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 |
| 1 | 7.5 | 1.0 | -1.0 | 0.0 | 0.0 |
| 2 | 1.0 | 1.0 | 0.5 | -0.8 | 0.6 |
| 3 | 1.0 | 1.0 | -1.5 | 0.0 | -0.8 |
| 4 | -3.5 | 1.5 | -3.0 | 0.0 | 0.0 |
| 5 | 1.0 | 1.0 | 0.0 | 0.8 | -1 |
| 6 | 2.4 | 1.0 | 0.0 | 0.2 | -0.2 |
| 7 | 5.0 | 1.0 | 0.0 | 0.2 | -0.2 |
| 8 | 15.0 | 1.0 | 0.0 | -1 | 1 |
| 9 | 1.0 | 1.0 | 1.0 | -0.6 | 0.6 |
| 10 | 10.0 | 1.5 | -1.0 | 0.0 | 0.0 |
| 11 | 2.4 | 1.0 | 0.0 | 1 | -1 |
| 12 | 15.0 | 1.0 | 1.0 | 0.0 | 0.0 |
| 8a | 1.0 | 1.0 | 0.5 | $\frac{0.8}{3}$ | 0.0 |
| 1b | 3.94 | 0.94 | $\frac{-1}{3}$ | 0.75 | -1 |
| 2b | 6.84 | 0.61 | $\frac{1}{3}$ | 0.0 | 1.0 |
| 3b | 2.21 | 1.05 | $\frac{-1}{3}$ | 0.75 | -1.5 |
| 4b | 2.79 | 0.61 | $\frac{1}{3}$ | -0.75 | -0.5 |
| 5b | 3.95 | 1.17 | $\frac{-1}{3}$ | 0.25 | 1.5 |
| 6b | 5.68 | 0.83 | $\frac{1}{3}$ | -0.75 | -1.0 |
| 7b | -0.10 | 0.94 | 1.0 | 0.25 | 0.5 |

An example of 20 EFT benchmarks

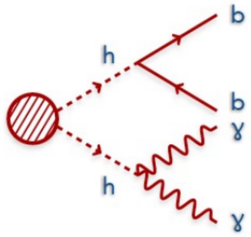
- There are 5 parameters in the Lagrangian : $\kappa_\lambda$, $\kappa_t$, $c_{2g}$, $c_2$, $c_g$.
- Points in the parameter phase space could be clustered in different benchmarks.

# Introduction

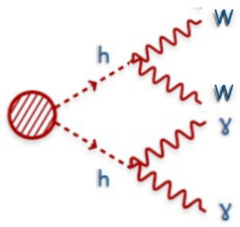
- The HH production has a very small cross-section in SM.
  - The cross-section of ggHH is 1000X smaller than ggH.
  - The cross-section of VBFHH is 2000X smaller than VBFH.
- It is a difficult work to distinguish HH signal from background.
  - The Higgs decays to two photons can provide help.
    - It has a clean final state in CMS, and a narrow di-photon mass spectrum.
    - The small branching ratio (~0.26%).
  - Combines higher rate of bb/WW with low backgrounds & excellent mass resolution of $\gamma\gamma$ would be a good choice.
- CMS has performed the search for non-resonant HH in the two decay channels with the top two largest branching ratios (bb$\gamma\gamma$ and WW$\gamma\gamma$).




Latest HH analyses in CMS



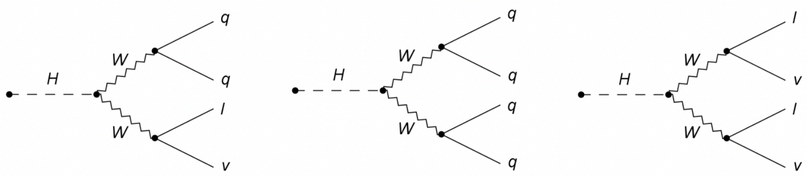

HH → $bb\gamma\gamma$




HH → $WW\gamma\gamma$

# HH → $WW\gamma\gamma$ search: Overview

- This analysis only investigated ggHH production.
- It used Full-RunII Data.
- There are 3 final states depending on the W bosons decays:
  - Fully-hadronic(FH) : 4q + $\gamma\gamma$
  - Semi-leptonic(SL) :2q + l + $\nu$ + $\gamma\gamma$
  - Fully-leptonic(FL) :2l + 2$\nu$ + $\gamma\gamma$

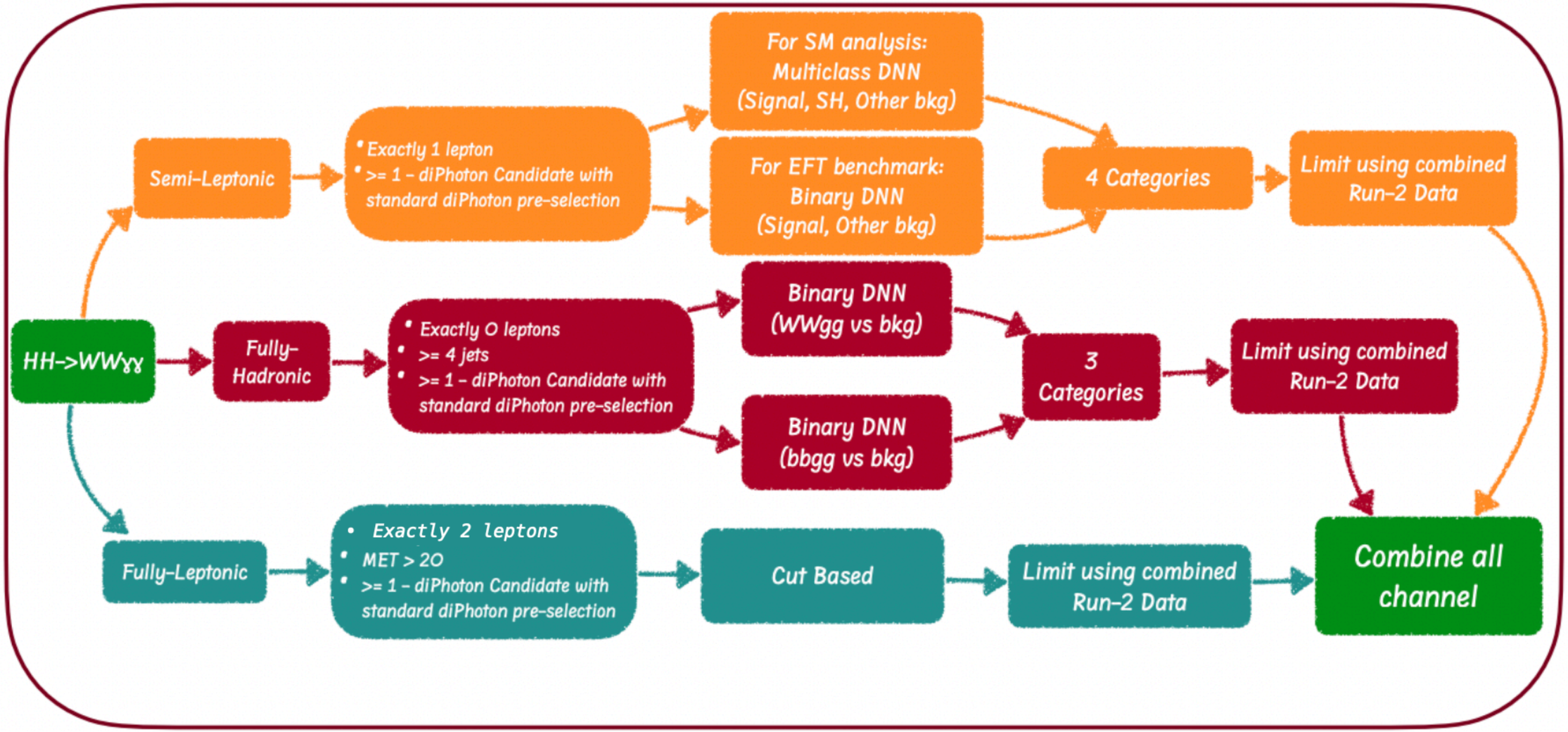



(a) Semi-Leptonic (b) Fully-Hadronic (c) Fully-Leptonic

The three decay modes of H→ WW.

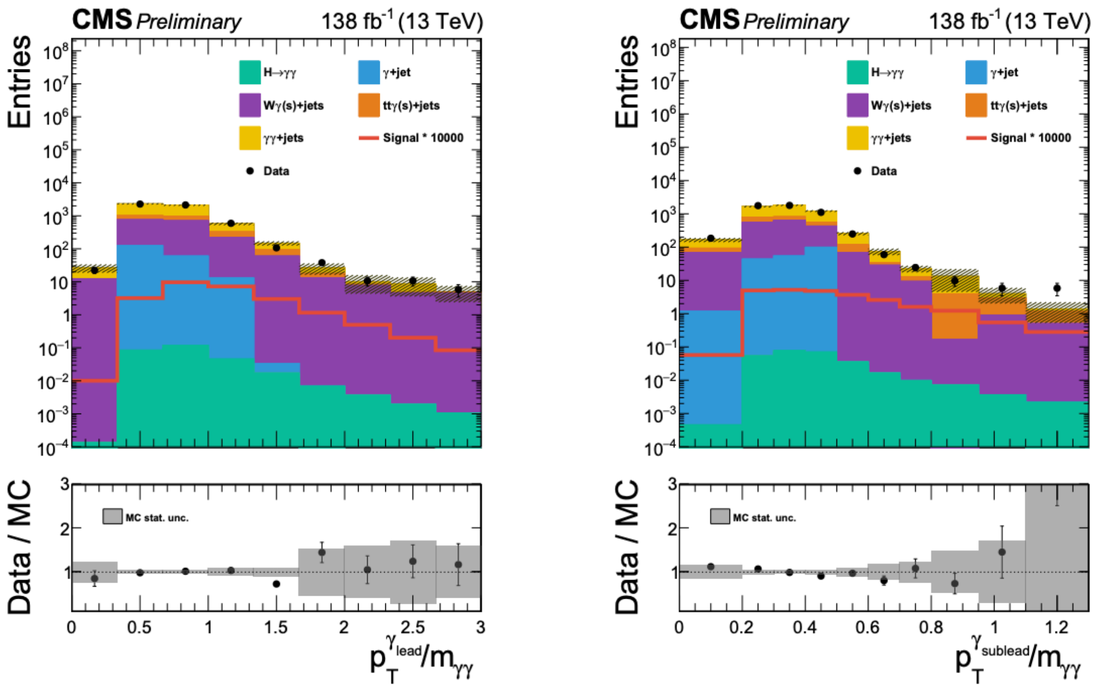
- For these 3 final states, chosen different strategies.
- 1D fit of $M_{\gamma\gamma}$ for signal extraction.
- This search (HIG-21-014) has been approved by CMS recently:
  - First time to be presented!

# HH → $WW\gamma\gamma$ search: Strategy

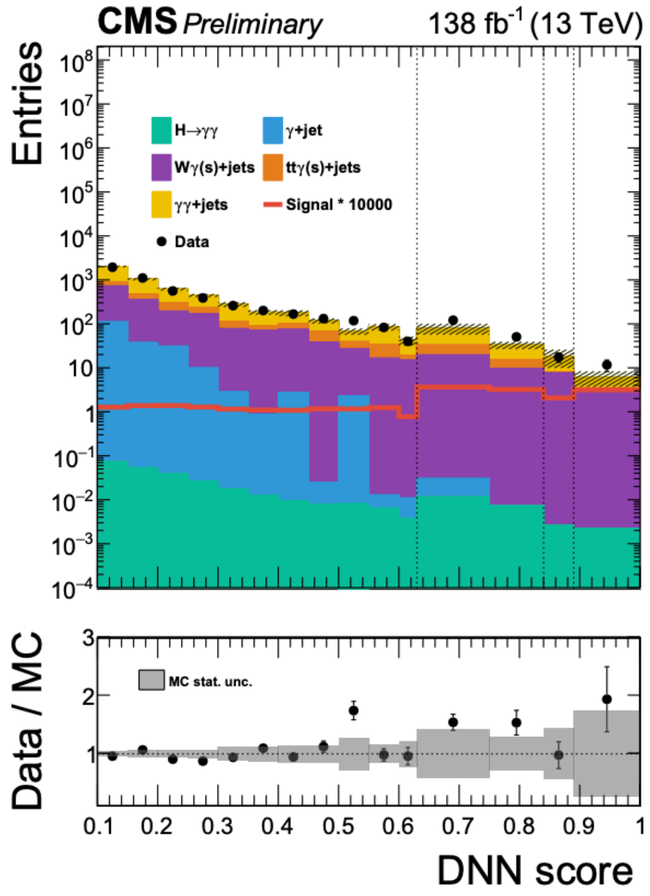


# HH → $WW\gamma\gamma$ search:Strategy

- Events categorisation in SL channel:
  - Trained multi-class DNN to separate HH, single-Higgs and backgrounds
  - Then used HH score to do the categorisation:
    - Simultaneous optimisation of number of categories and boundaries based on total significance




The leading 2 DNN input variables

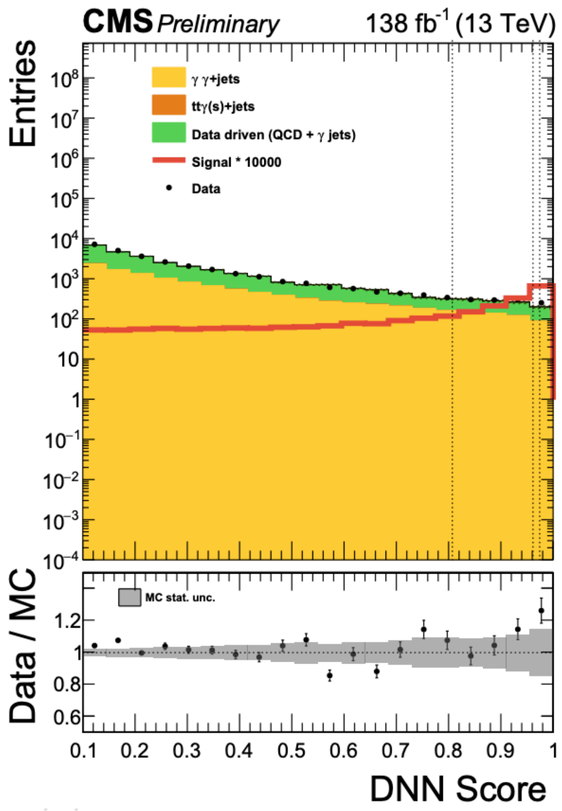



SL DNN score Data/MC distribution
The dashed lines indicate the DNN boundaries

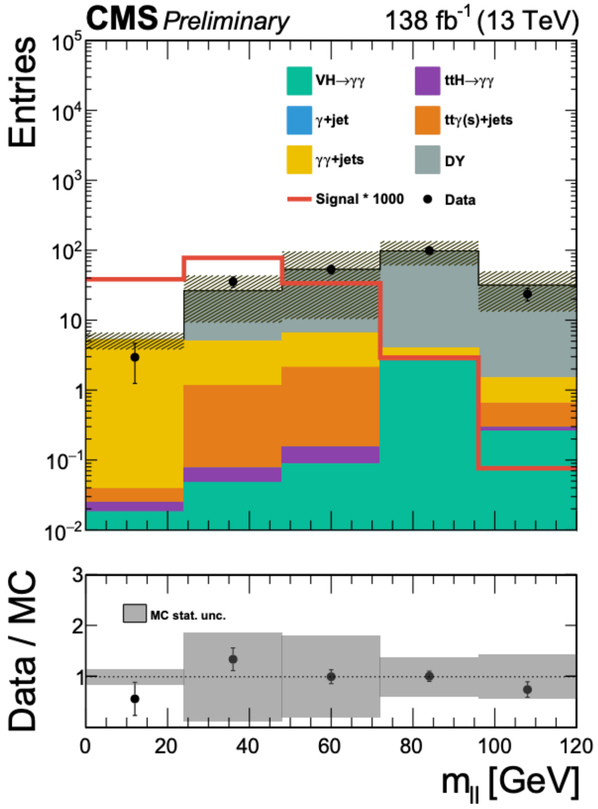
# HH → $WW\gamma\gamma$ search:Strategy

- Events categorisation in FH channel:
  - Trained binary DNN to separate HH from backgrounds
  - An dedicated bb$\gamma\gamma$ DNN was trained to reduce the overlaps.
  - Then used HH score to do the categorisation

- Events categorisation in FL channel:
  - The raw events of MC samples are not enough to train MVA.
  - Only cut based method was used in this channel.
  - Several optimised selections were used in this channel



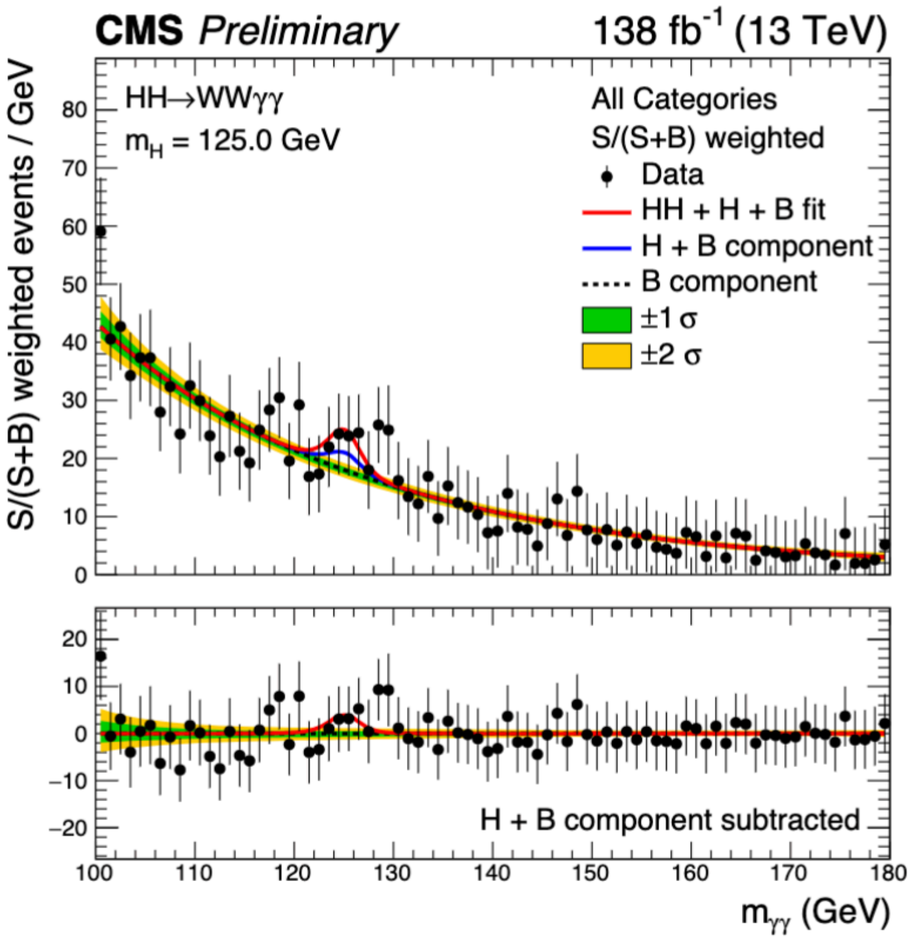

FH DNN score Data/MC distribution
The dashed lines indicate the DNN boundaries




FL Data/MC comparison of dilepton invariant mass.
The main NR background is DY, the main resonant background is VH.

# HH → $WW\gamma\gamma$ search: Results

- Inclusive S+B Fitting:



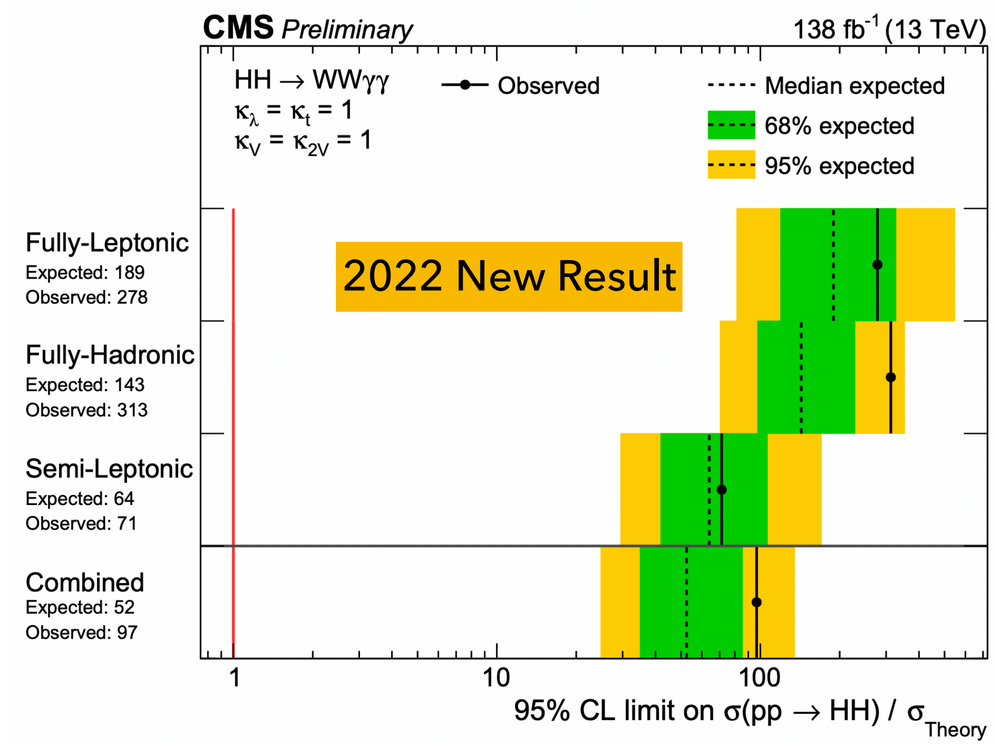

**The observed diphoton mass distributions:**

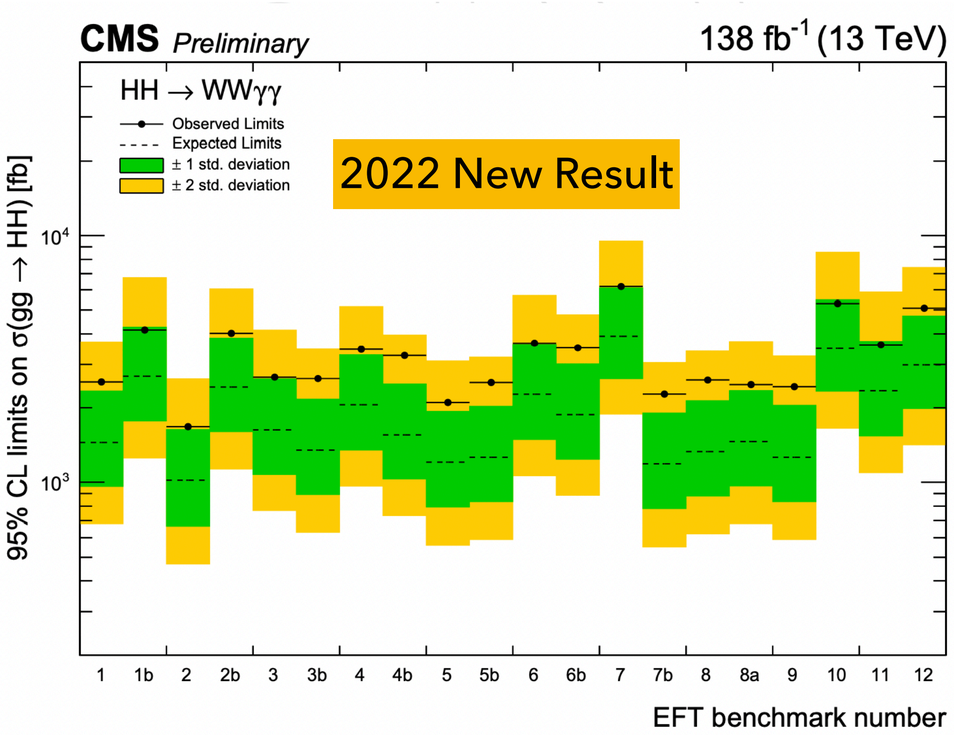
- The signal plus background fit (red)
- The Single-Higgs + continuum background fit (blue)
- Continuum background (black dashed line), with bands covering the ±1σ and ±2σ uncertainties
- All analysis categories are combined and weighted by S over S+B

Inclusive S+B fits for full-run2 data, all categories summed.

# HH → $WW\gamma\gamma$ search: Results

- Obs.(exp.) upper limit on HH signal strength: 97(52)×SM at 95% C.L.
  - No deviations from SM observed.

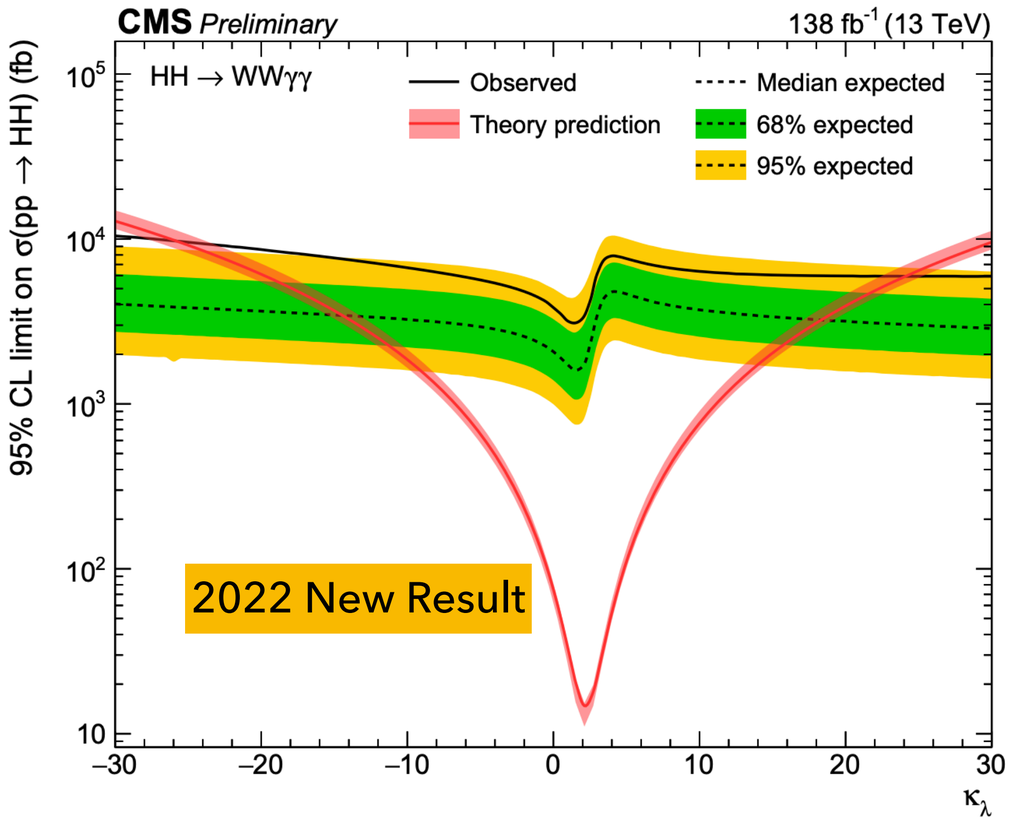


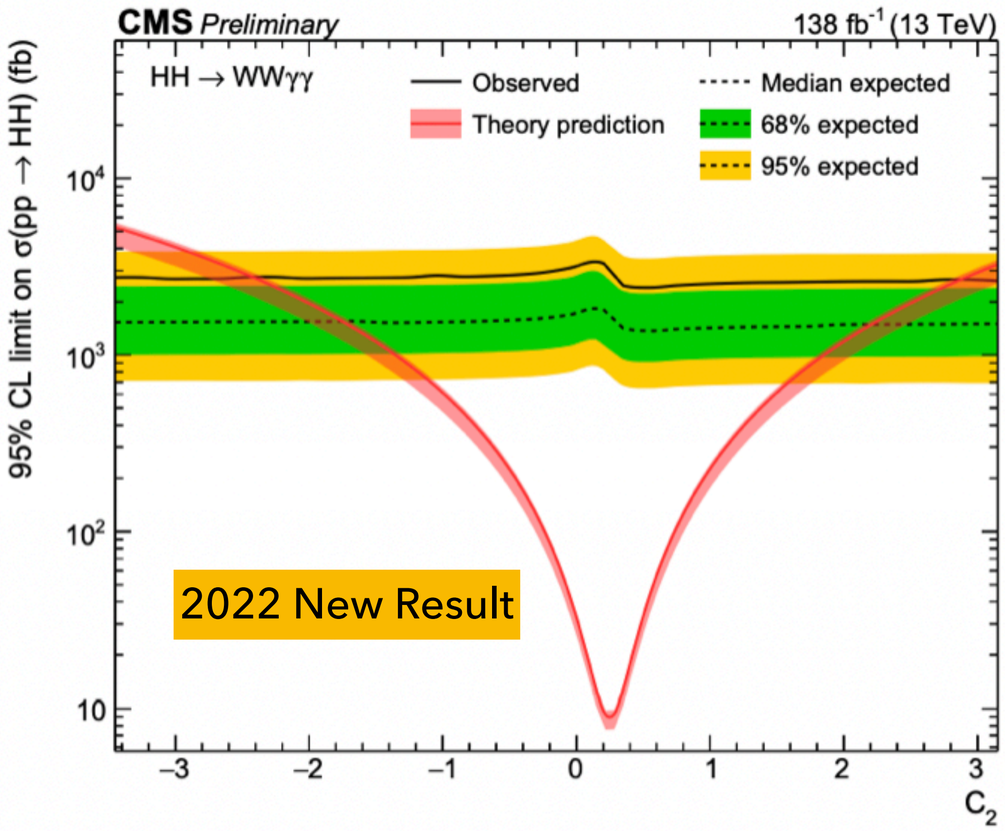

- Obs.(exp.) upper limit on HH signal for 20 EFT benchmarks:
  - 1.7 - 6.2 (1.0 - 3.9) pb.

# HH → $WW\gamma\gamma$ search: Results

- $\kappa_\lambda$ (Higgs self-coupling) and $C_2$ (coupling of 2 top and 2 Higgs) scan:




Obs. (Exp.) $\kappa_\lambda \in$ [-25.8 (-14.4) , 24.1 (18.3)]



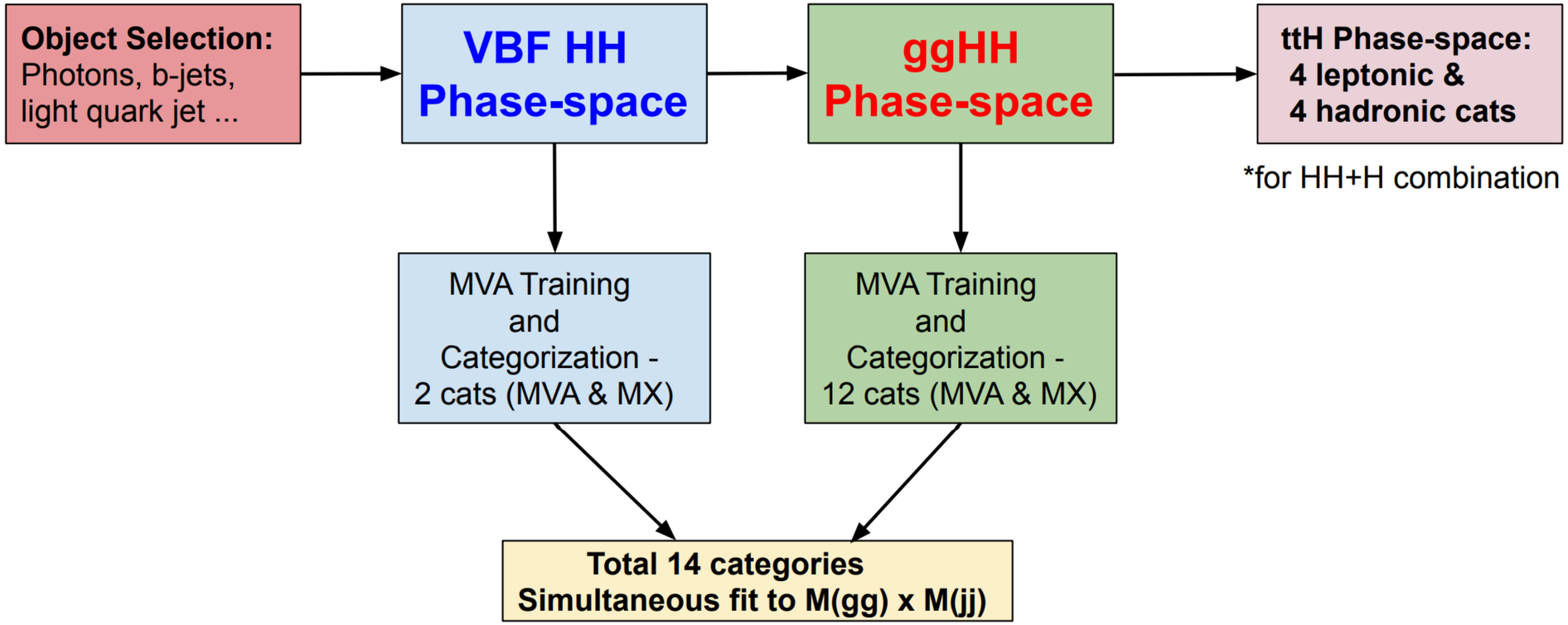

Obs. (Exp.) $C_2 \in$ [-2.4 (-1.7) , 2.9 (2.2)]

# HH → $bb\gamma\gamma$ search: Overview

- This analysis investigated both ggHH and VBFHH productions.
- It used Full-RunII Data.
- The main backgrounds:
  - Non-resonant (NR) backgrounds primarily from QCD
  - Secondary, peaking background from SM single Higgs (Mainly ttH).
- MVA strategy used to separate signal and backgrounds.
  - BDT was used in ggF and VBF to separate HH from $\gamma(\gamma)$ + Jets events.
  - Dedicated DNN was used to reject ttH(H $\rightarrow \gamma\gamma$) events.
- Simultaneous fit of $m_{\gamma\gamma}$ and $m_{bb}$ was performed for signal extraction
- Results has been published in JHEP03(2021)257.

# HH → $bb\gamma\gamma$ search:Strategy

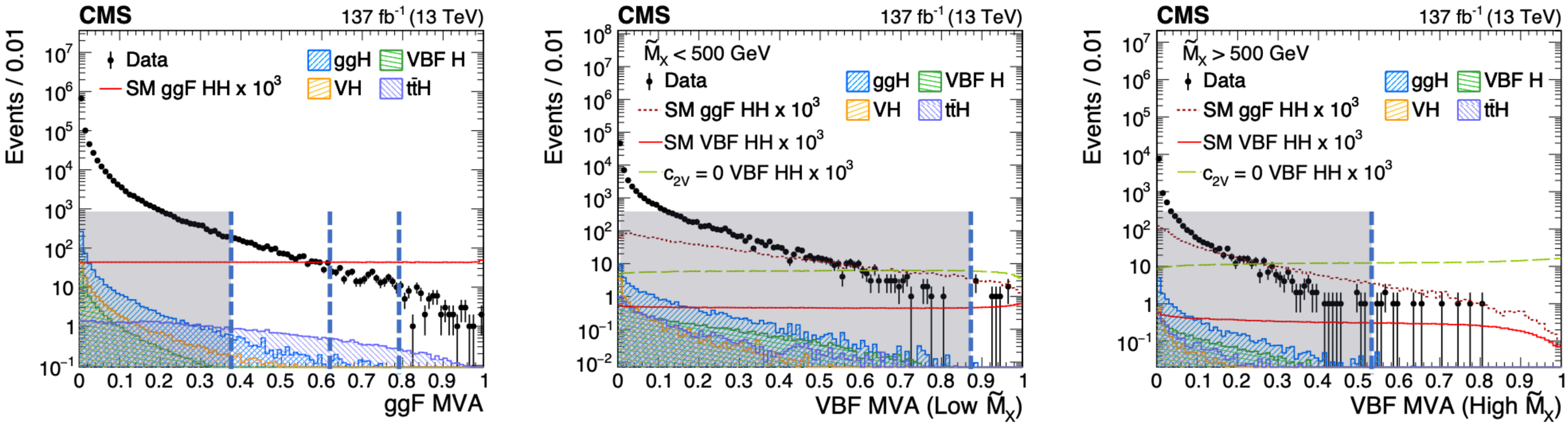
- Analysis strategy




- $MX = M_{\gamma\gamma jj} - M_{jj} - M_{\gamma\gamma} + 250$, Effective 4-body invariant mass of bb$\gamma\gamma$.

# HH → $bb\gamma\gamma$ search:Strategy

- Event categorisation based on MVA score & $\tilde{M}_X$

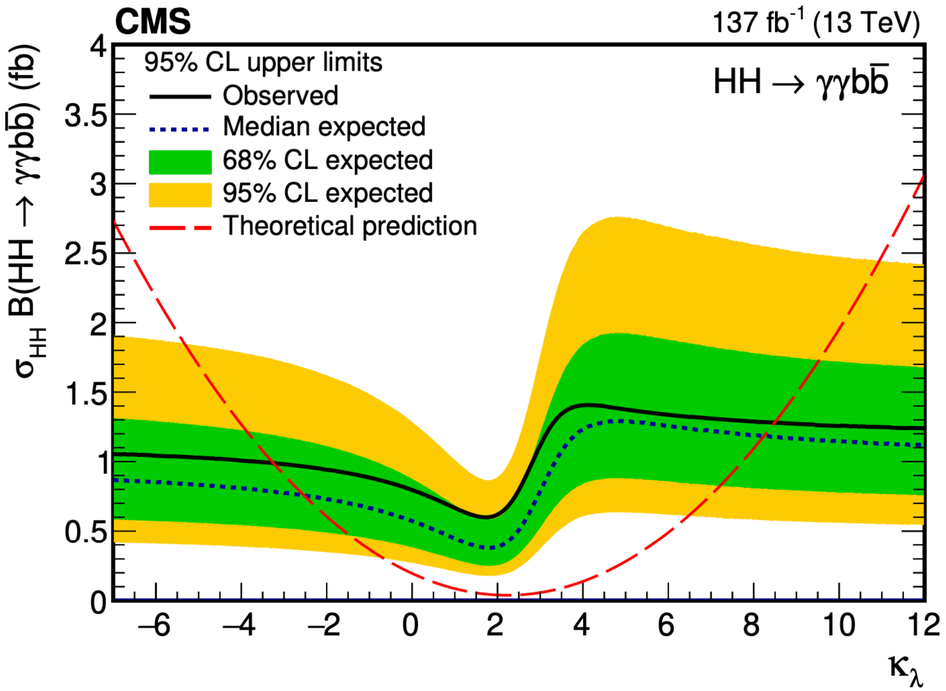



MVA score distributions, the grey regions are removed, the blue dashed lines indicate the boundaries.

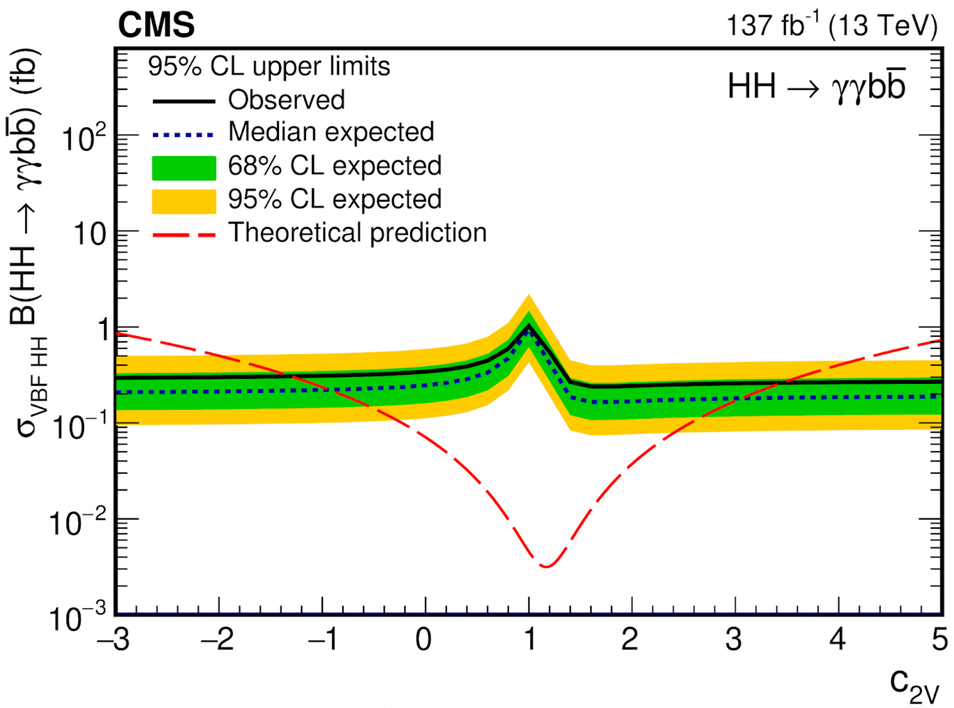
- In final, there are 3 MVA categories x 4 $\tilde{M}_X$ categories in ggF mode.
- And 2 MVA categories for low and high $\tilde{M}_X$ categories in VBF mode.

# HH → $bb\gamma\gamma$ search: Results

- Obs.(exp.) upper limit on HH signal strength: 7.7(5.2)×SM at 95% C.L.
  - No deviations from SM observed.
- $\kappa_\lambda$ (Higgs self-coupling) and $C_{2v}$ (coupling of 2 Vector boson and 2 Higgs) scan:



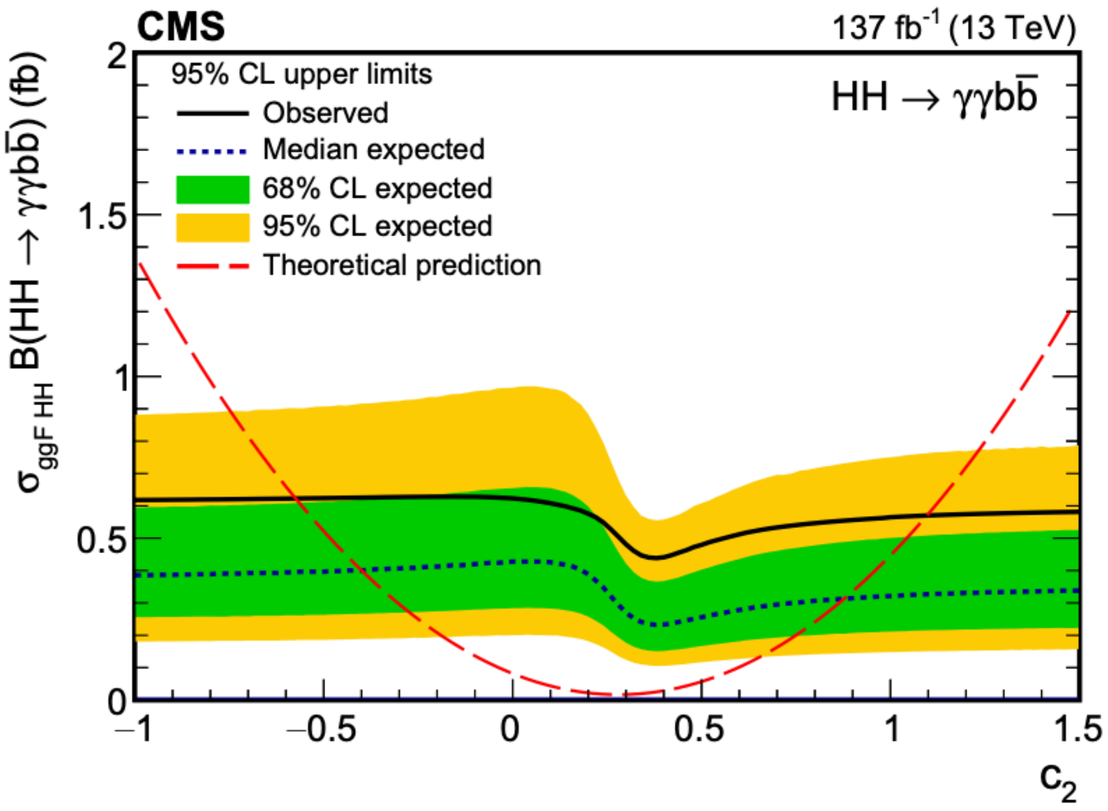

Obs. (Exp.) $\kappa_\lambda \in$ [-3.3 (-2.5) , 8.5 (8.2)]



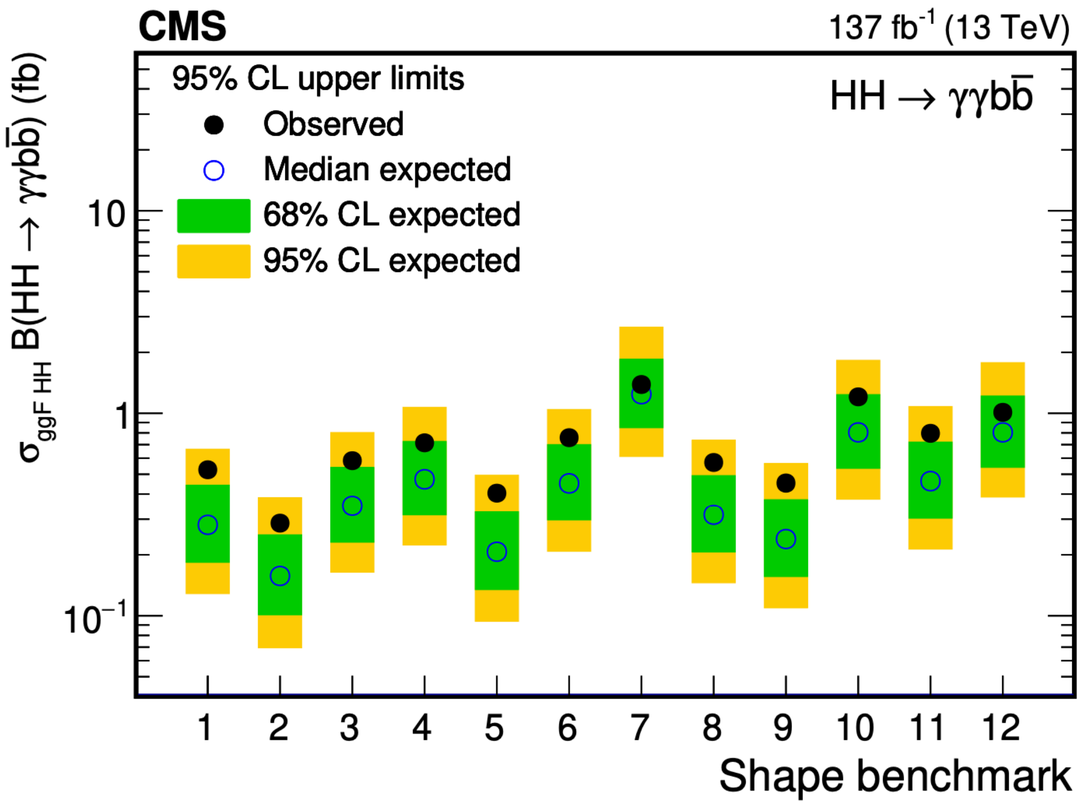

Obs. (Exp.) $C_{2v} \in$ [-1.3 (-0.9) , 3.5 (3.1)]

# HH → $bb\gamma\gamma$ search: Results

- $C_2$ (coupling of 2 top and 2 Higgs ) scan and limits for 12 EFT benchmarks




Obs. (Exp.) $C_2 \in$ [-0.6 (-0.4) , 1.1 (0.9)]




Obs. (Exp.) limits for 12 benchmarks: 0.3-1.0 (0.2 - 1.0)fb

# Summary

- The Di-Photon final state has special features in HH analyses.
  - Presented HH analyses with one Higgs decays to two photons and the other Higgs decays to the final states with the top 2 largest branching ratio (bb/WW).
  - HH $\rightarrow WW\gamma\gamma$ 2022 new results:
    - This is the first HH $\rightarrow WW\gamma\gamma$ search with full RunII dataset in LHC!
    - Obs.(Exp.) SM limit:97(52)×SM
    - Obs.(Exp.) coupling constraints:
      - $\kappa_\lambda \in$ [-25.8 (-14.4) , 24.1 (18.3)], $C_2 \in$ [-2.4 (-1.7) , 2.9 (2.2)]
    - Obs.(Exp.) EFT limits on HH: 1.7 - 6.2 (1.0 - 3.9) pb.
  - HH $\rightarrow bb\gamma\gamma$ results:
    - Obs.(Exp.) SM limit:7.7(5.2)×SM
    - Obs.(Exp.) coupling constraints:
      - $\kappa_\lambda \in$ [-3.3 (-2.5) , 8.5 (8.2)], $C_2 \in$ [-0.6 (-0.4) , 1.1 (0.9)], $C_{2v} \in$ [-1.3 (-0.9) , 3.5 (3.1)]
    - Obs.(Exp.) EFT limits on HH $\rightarrow bb\gamma\gamma$: 0.3-1.0 (0.2 - 1.0)fb

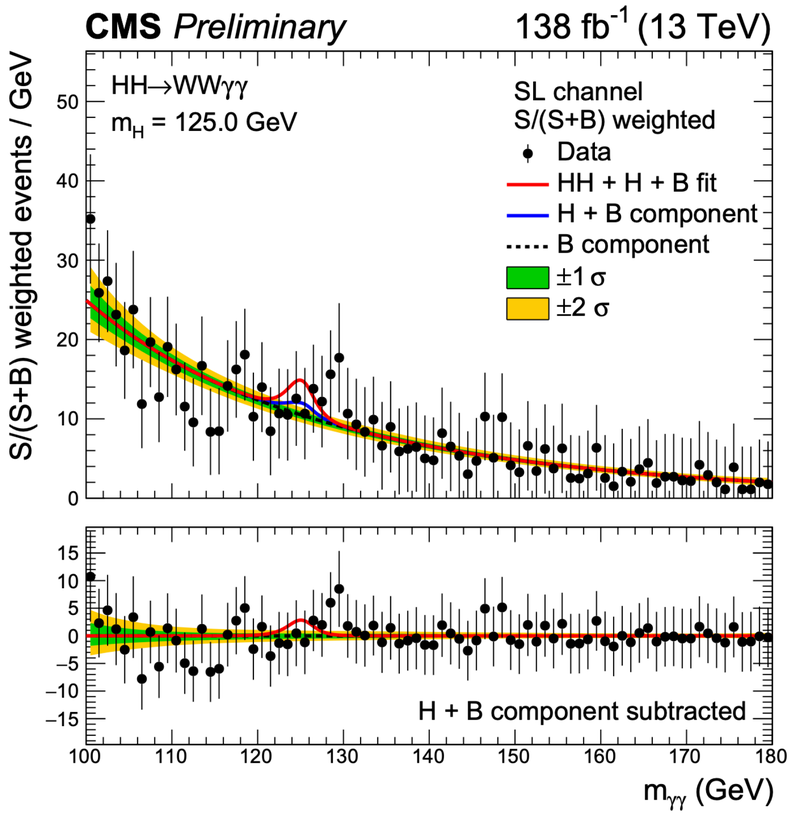
# Thanks for your attention！

# Backup

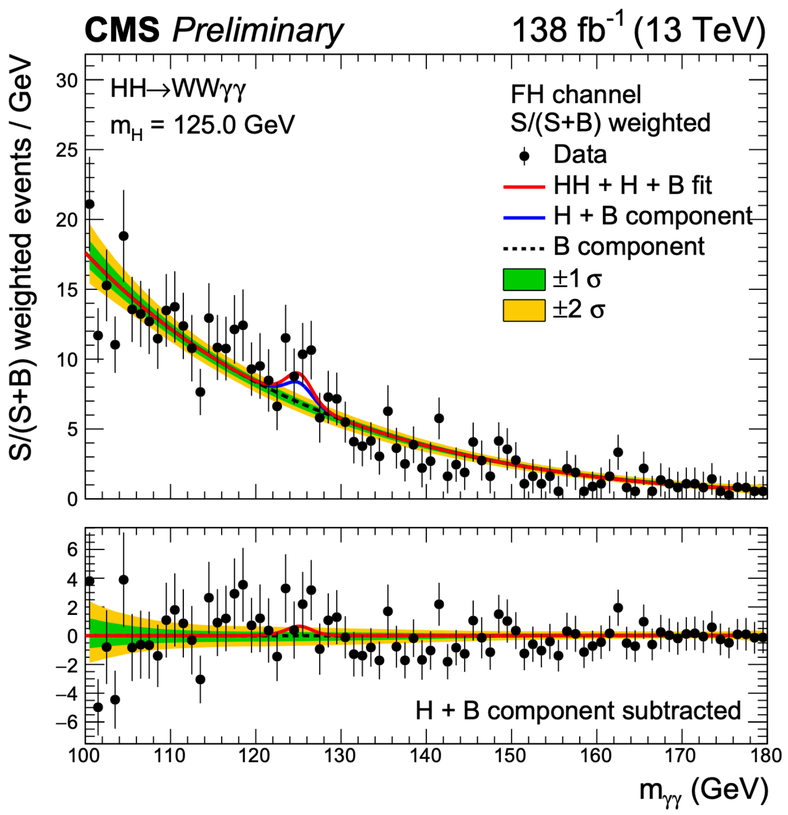
# HH → $WW\gamma\gamma$ search: Strategy

- Event classification in exclusive categories based on the number of good leptons:
  - Semi-Leptonic: Exactly 1 lepton
  - Fully-Leptonic: Exactly 2 leptons
  - Fully-Hadronic: Exactly 0 lepton
- Because of the different statistics and characteristics in different channels, we chosen different strategies for 3 final states
  - Semi-Leptonic: Multi-Class DNN
    -Trained a multi-classed DNN to separate HH , H and continuum background.
  - Fully-Leptonic: Cut-based
    -Because of the clean final state and low stats, we chosen cut-based method.
  - Fully-Hadronic: 2 Binary DNN ($WW\gamma\gamma$ DNN + $bb\gamma\gamma$ killer DNN )
    -We trained a $WW\gamma\gamma$ DNN to separate HH from all backgrounds(H + continuum background)
    -Then trained an additional $bb\gamma\gamma$ DNN to reject HH→$bb\gamma\gamma$ events

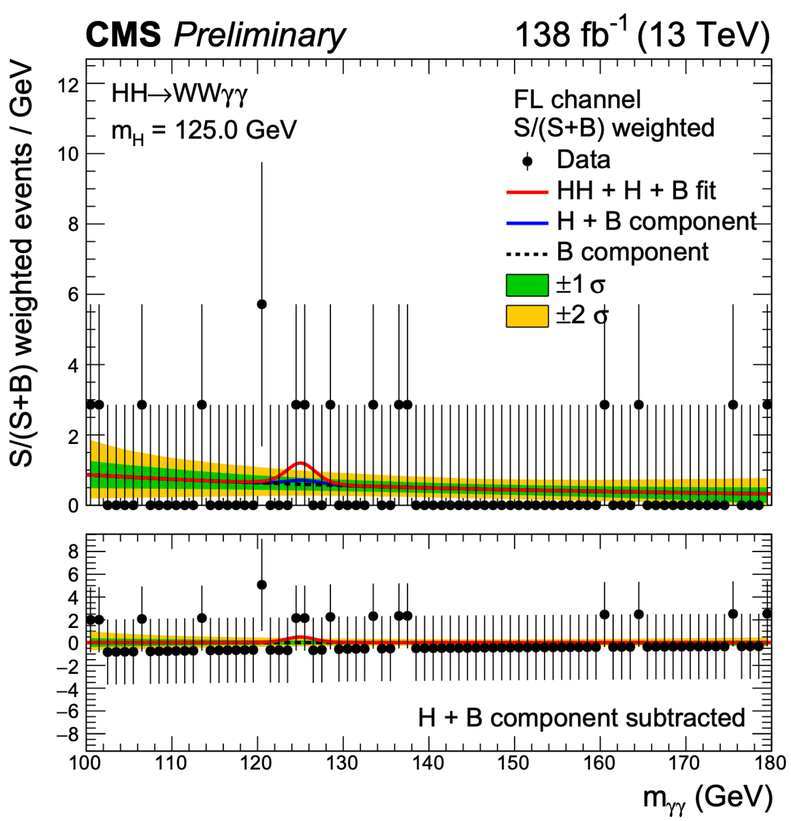
# HH → $WW\gamma\gamma$ per-channels fit




SL channel




FH channel




FL channel