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Search for nonresonant Higgs boson pair production in the WW$\gamma\gamma$ channel in pp collisions at $\sqrt{s}$ =13 TeV

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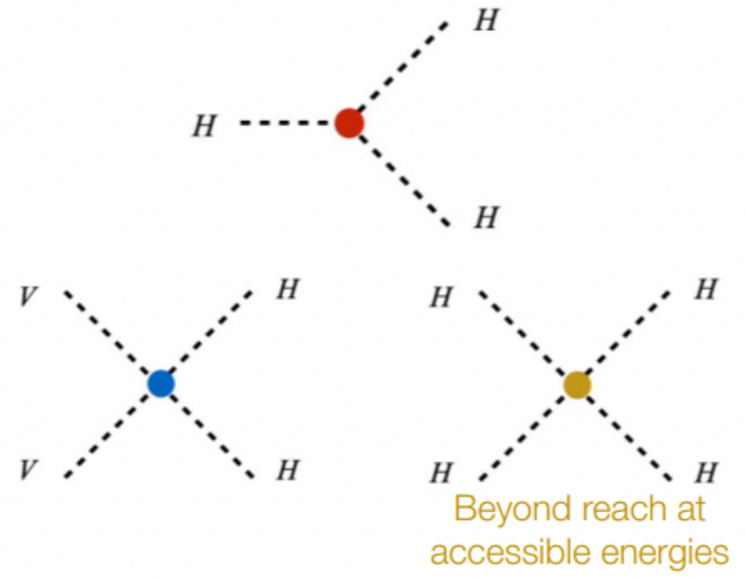
Introductions: HH productions

- The Higgs potential:

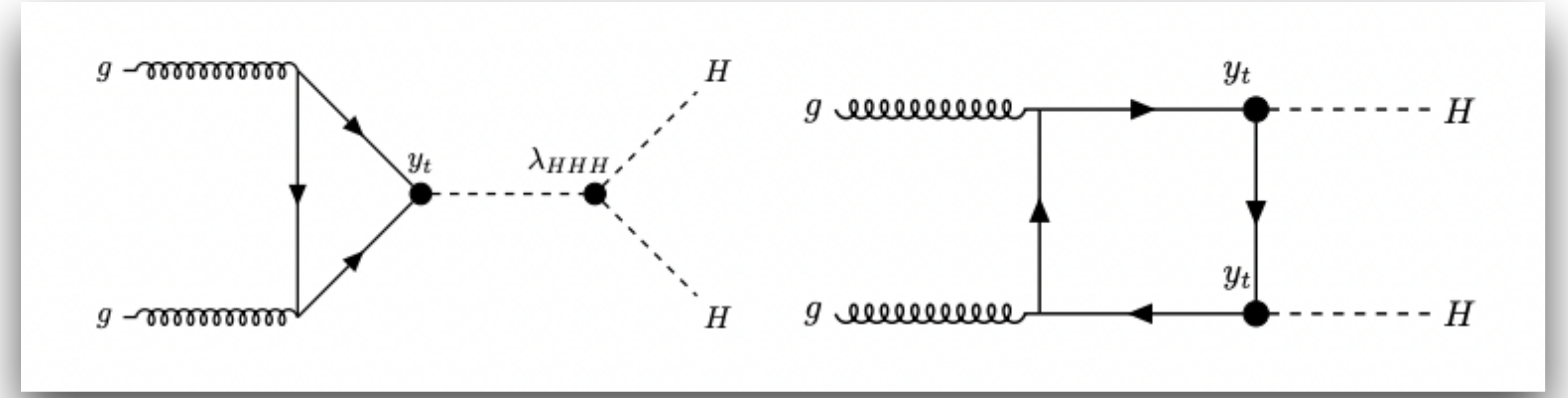
$$V = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4 = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4$$

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

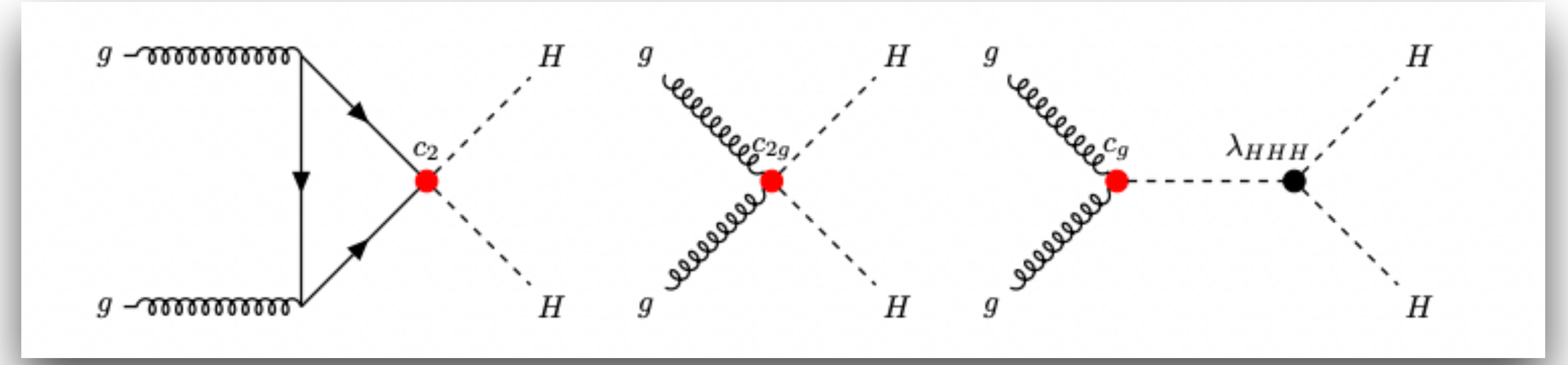
Mass-term | λ_3, trilinear self-coupling | λ_4, quartic self-coupling | C_{2V}, VVHH coupling



- Measurement of self-couplings is crucial for understanding the field potential



SM-like processes



BSM processes

- The ggHH production provide a window to measure the self-coupling.
- The ggHH is the main production mode of HH in LHC (~31fb).
  - In this analysis, VBF HH not included.
- The cross-section of ggHH is 1000X smaller than ggH.
- BSM processes can increase the HH cross-sections.

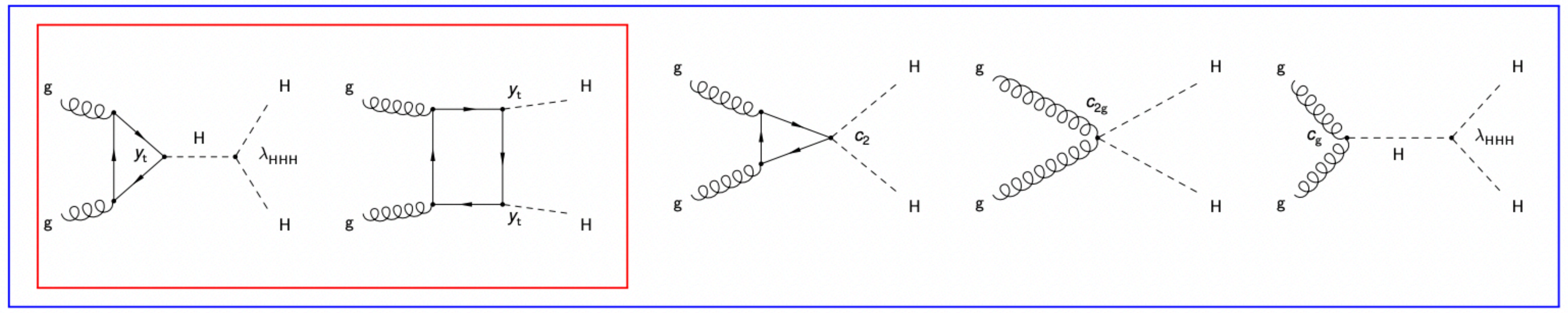
Introductions: EFT benchmarks

- Effective Field Theory Parameterised BSM Lagrangian

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

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

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

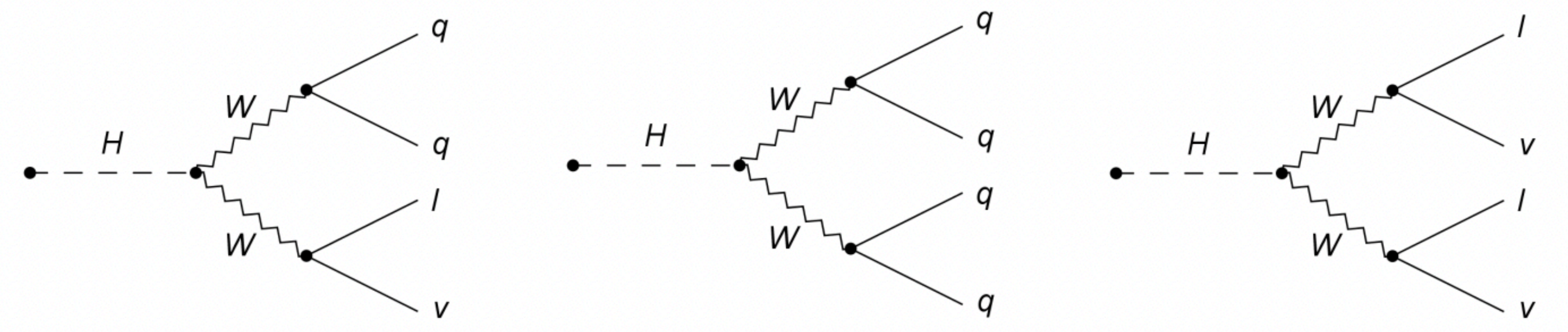


- There are 5 parameters in L_{BSM}: k_λ, k_t, c_{2g}, c_2, c_g
- Points in the parameter phase space could be clustered in 20 benchmarks
- EFT MC samples could be reweighted by NLO ggHH samples using the analytic formula derived in [link1][link2]

Benchmark	κ_λ	κ_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

20 EFT benchmarks

- The $WW\gamma\gamma$ channel:
  - H→γγ process which provides a distinguishable signature consisting of a narrow peak in DiPhoton Mass.
  - H→WW contributes a relatively large branching-ratio (~22%).
  - Three final states depending on the W bosons decays:
    - Fully-hadronic ($4q + \gamma\gamma$):
    - Semi-leptonic ($2q + l + \nu + \gamma\gamma$)
    - Fully-leptonic ($2l + 2\nu + \gamma\gamma$)



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

The three decay modes of H→ WW.

Data and MC samples

- Used Full-RunII Data (~138 fb^{-1})
- Signal samples:
  - HH samples generated at NLO with powerheg for each WW$\gamma\gamma$ final state:
    - MC samples for each of four kλ values: 0, 1(SM), 2.45, and 5
    - EFT benchmark samples obtained through reweighting of these NLO HH samples
  - HH samples also generated with madgraph at LO:
    - LO samples: 1-12 benchmarks + SM.
- Background MC samples:
  - Non-resonant backgrounds (Used to train DNN, not used to modeling background shape)
  - Single Higgs MC (Backgrounds for all final states in signal region)
  - HH backgrounds (bb$\gamma\gamma$ Samples)

Strategies: Overview

- 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

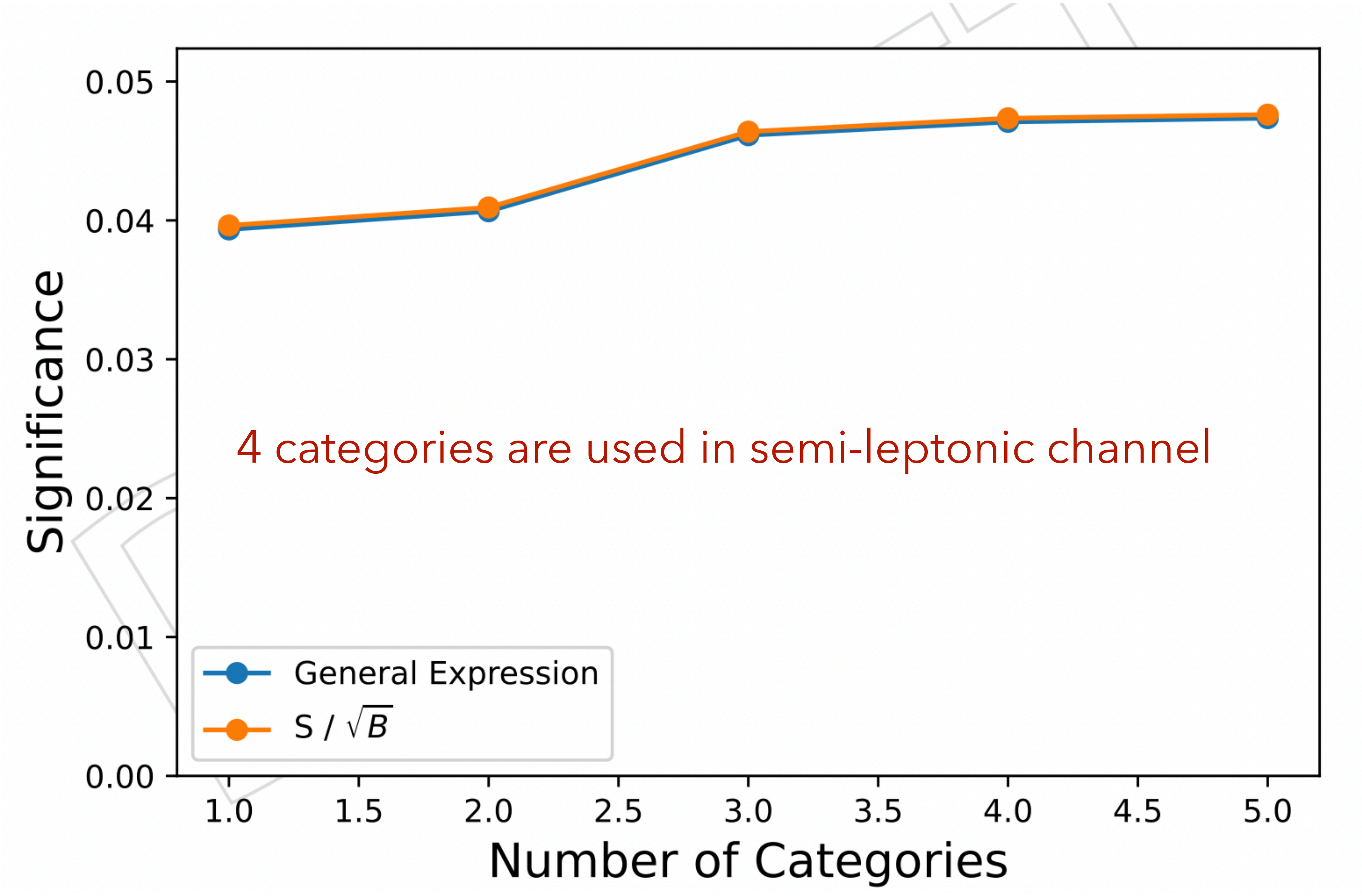
    -Because of the clean final state and low stats, we chosen cut-based method.
  - Fully-Hadronic: 2 Binary DNN (WW$\gamma\gamma$ DNN + bb$\gamma\gamma$ killer DNN)

    -We trained a WW$\gamma\gamma$ DNN to separate HH from all backgrounds(H + continuum background)

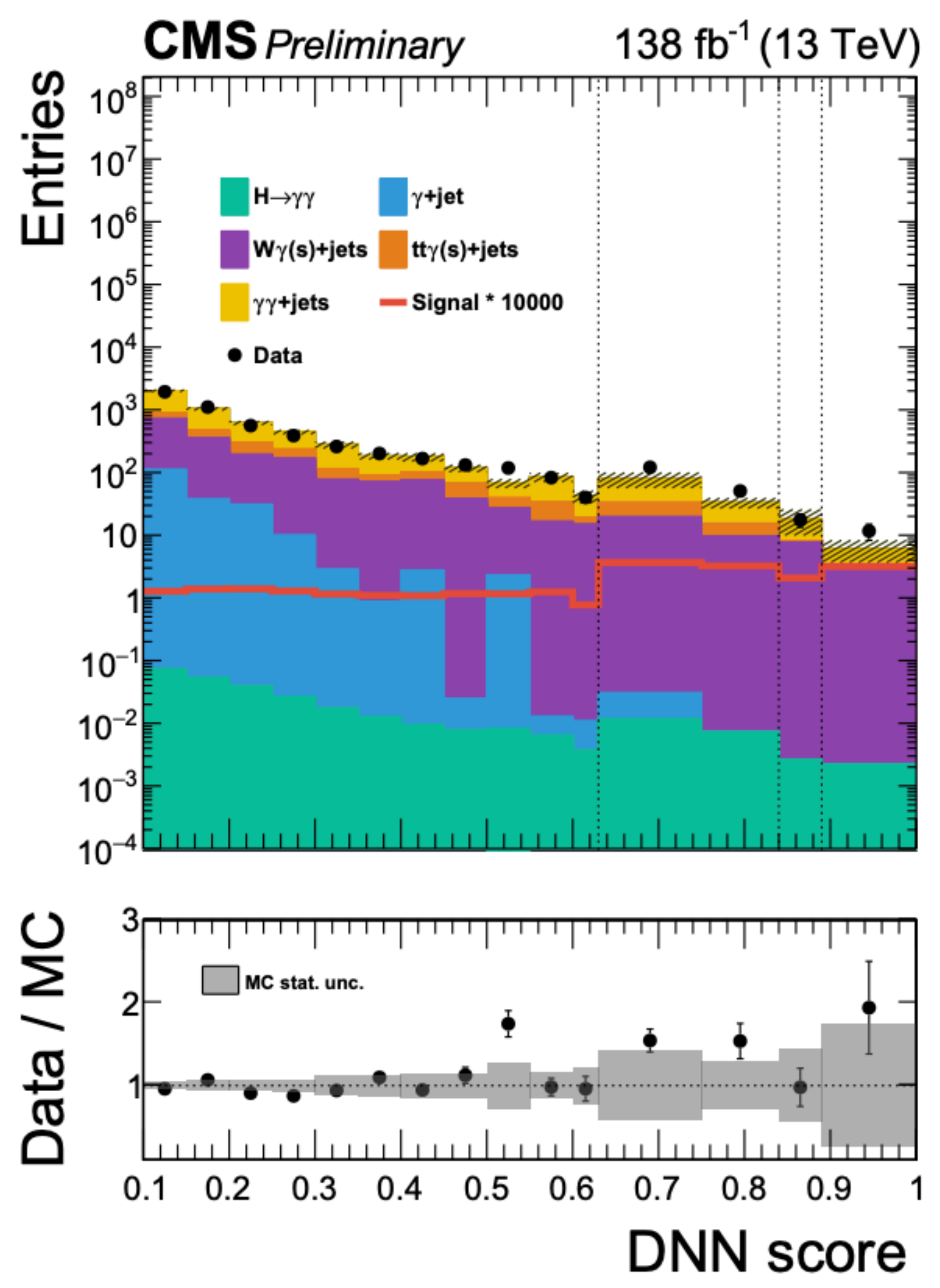
    -Then trained an additional bb$\gamma\gamma$ DNN to reject HH$\rightarrow$bb$\gamma\gamma$ events.

DNN categorisation:

- There are 3 DNN outputs (HH score, H score, continuum background score)
- Used HH score to do the categorisation.
- Simultaneous optimisation of number of categories and boundaries based on total significance



$$\text{significance}=\sqrt{2((S+B)ln(1+\frac{S}{B})-S)}$$



HH DNN score distributions, the dashed lines indicates the DNN boundaries

CMS-PAS-HIG-21-014

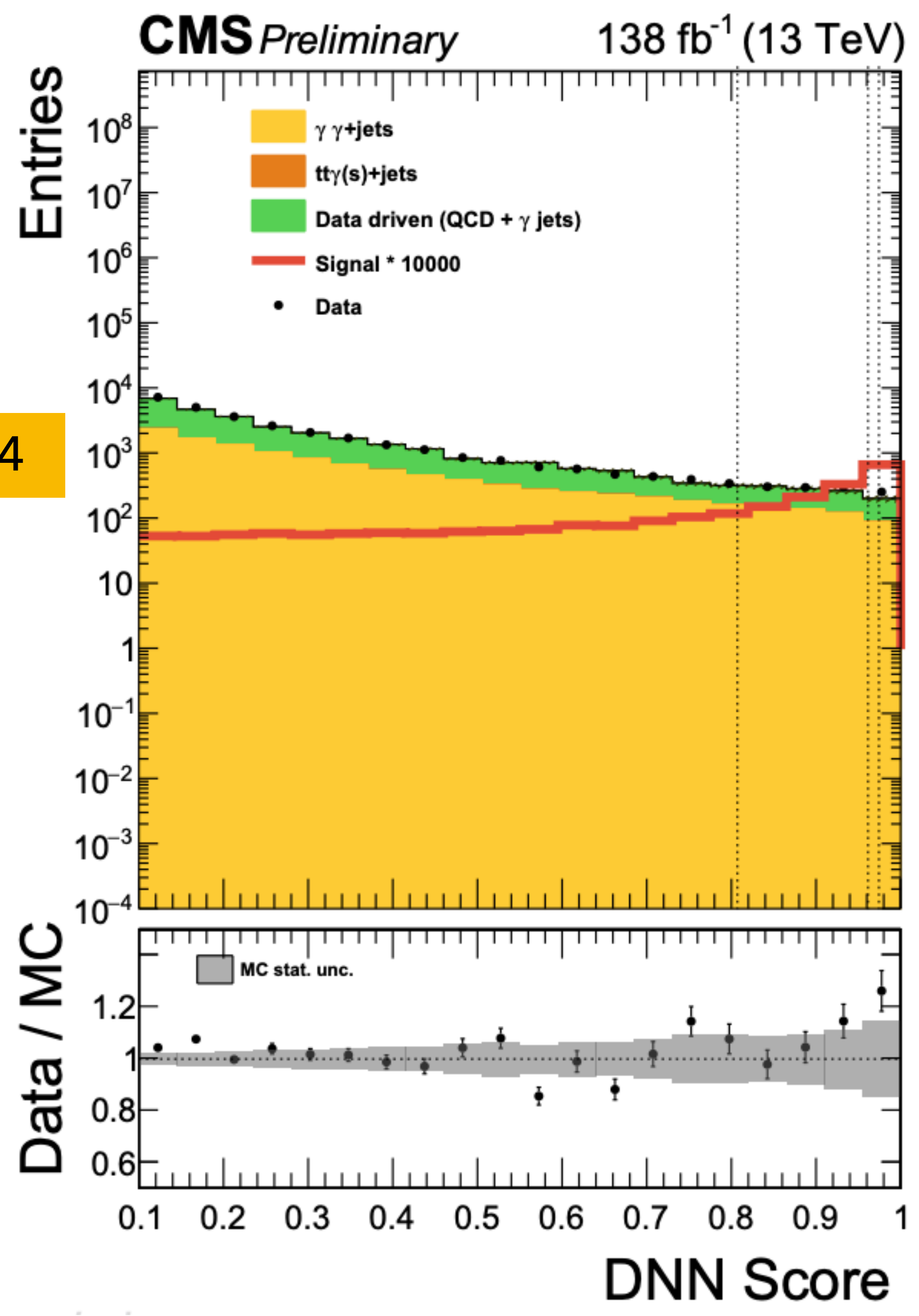
Analysis Strategy: Fully-Hadronic

- Fully-Hadronic channel:Events fall into the FH channel if they contain a diphoton candidate, >= 4 AK4 jets and exactly 0 lepton.
  - In this channel, background dominated by QCD, γ + jets and $\gamma\gamma$ + jets.
  - In the perspective of the HH combination, need to minimise the overlap of HH→bb$\gamma\gamma$ signal with HIG-19-018.
  - Two dedicated binary DNN classifiers:
    - WW$\gamma\gamma$ DNN:
      - The WW$\gamma\gamma$ DNN could be used to separate HH signal from the backgrounds.
    - bb$\gamma\gamma$ killer DNN:
      - bb$\gamma\gamma$ killer DNN was used to suppress bb$\gamma\gamma$ contamination.
      - The final contamination <3%.
  - Data-driven modeling of QCD and g+jets used in the DNNs trainings.

Analysis Strategy: Fully-Hadronic

- Category optimisation:
  - Before optimise the WW$\gamma\gamma$ DNN boundaries, we applied $bb\gamma\gamma$ score > 0.6.
  - The events with $WW\gamma\gamma$ score < 0.1 are rejected.

CMS-PAS-HIG-21-014



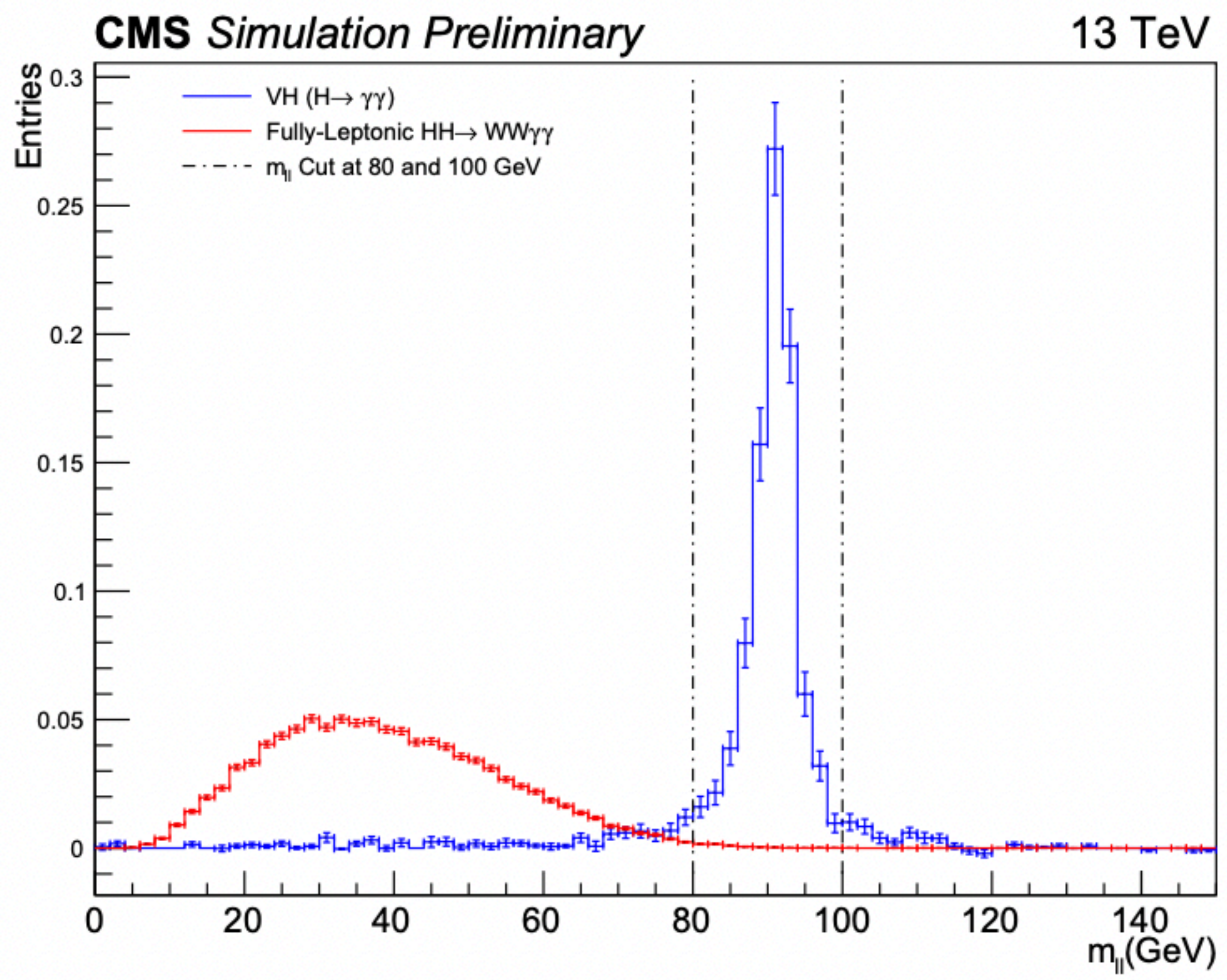
WW$\gamma\gamma$ DNN score

- By using similar optimise strategy in SL channel.
- By comparing the total significance of different number of categories.
- The last category has been removed, because the contamination
- Finally, we choose 3 categories for FH channel.

Analysis Strategy: Fully-Leptonic

- Selections in FL channel:
  - After the FL pre-selections applied, the dominant backgrounds:
    - Drell-Yan process (Non-resonant backgrounds)
    - VH($H \rightarrow \gamma\gamma$) process (Resonant backgrounds)

- We applied few additional selections to remove them and improve the significance.
  - $|M_{\gamma e} - M_Z|$>5GeV to reject Z to ll events
  - $p_T(\gamma_1)/M(\gamma\gamma) > 1/3$, $p_T(\gamma_2)/M(\gamma\gamma) > 1/4$
  - $M_{ll} > 100$GeV or $M_{ll} < 80$GeV to suppress DY and VH events
  - $p_T(\gamma\gamma) > 91$ GeV optimized to have better significance while keep enough statistics in mass sideband for background modeling



DiLepton Mass distributions

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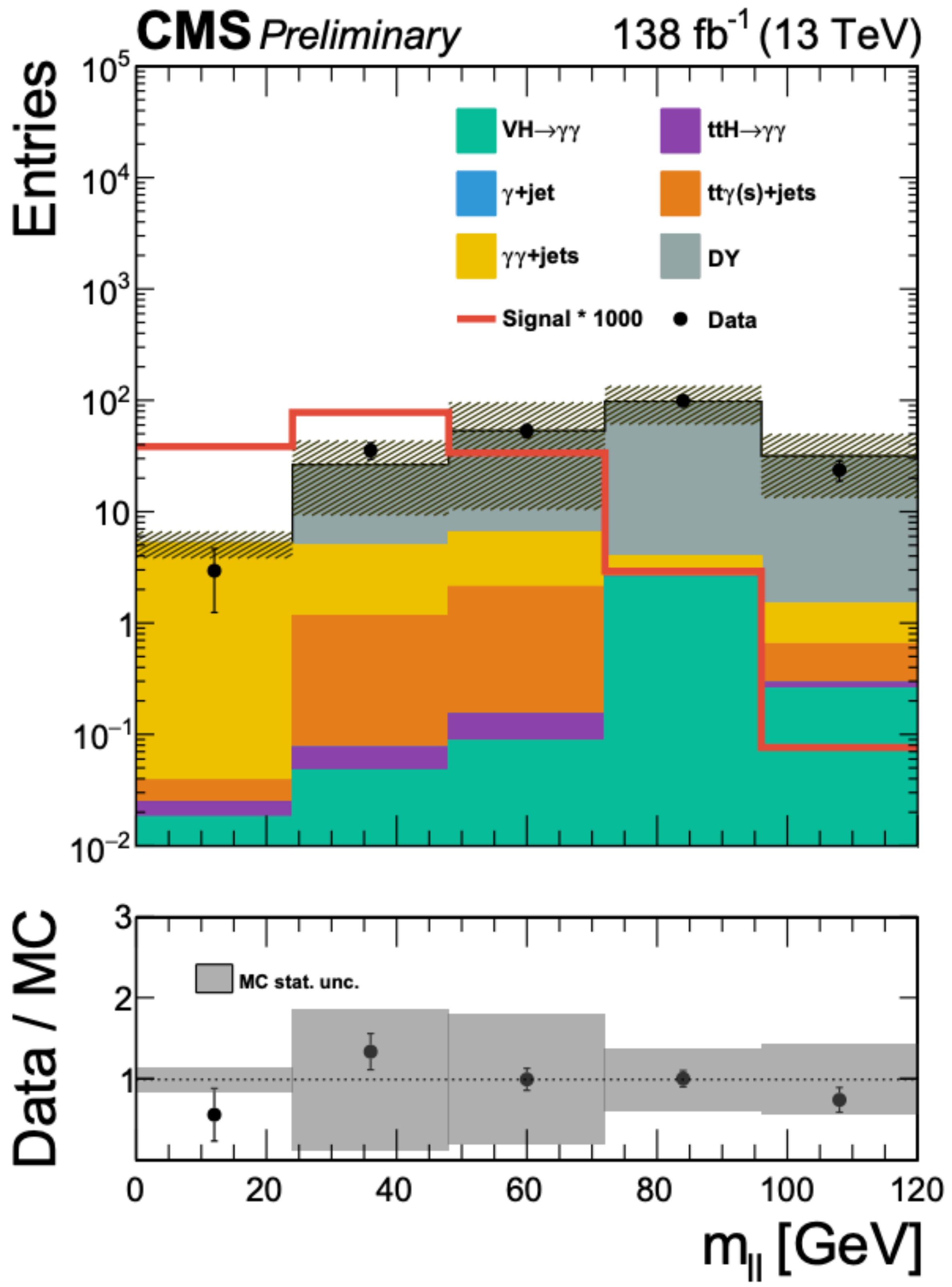
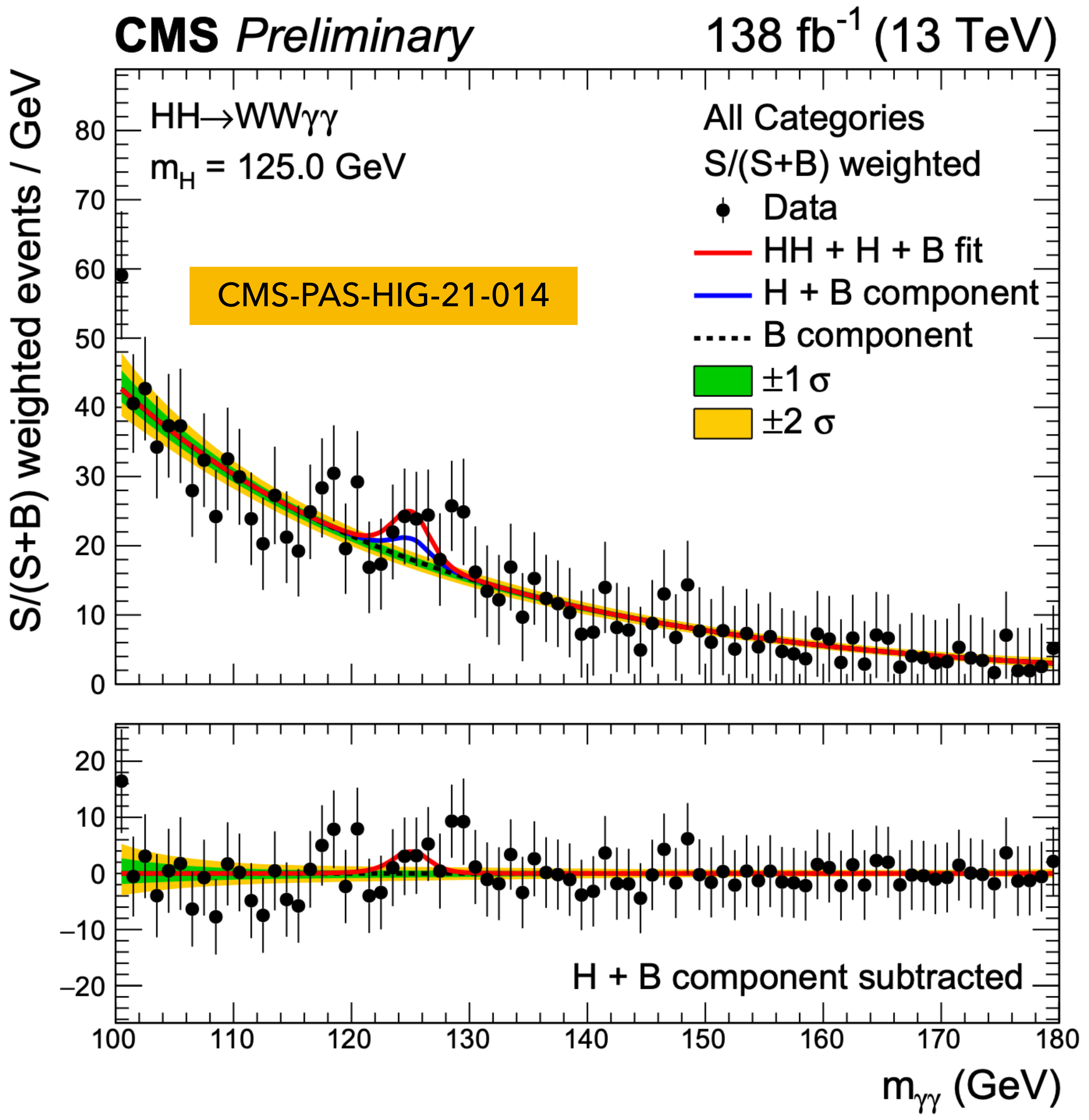


Data/MC comparison of M_{ll} after FL pre-selections applied

Results

Inclusive S+B Fitting:



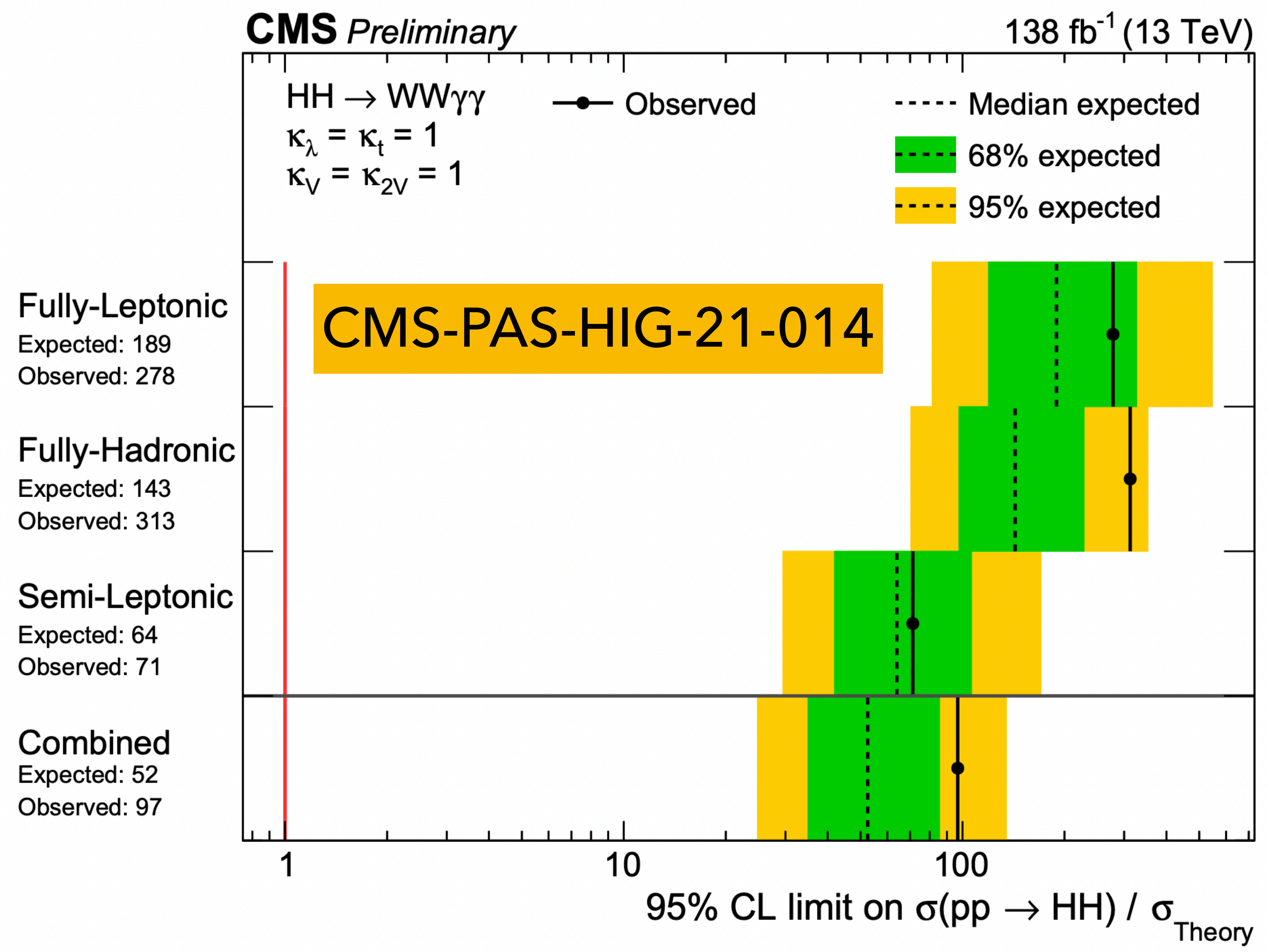
Inclusive S+B fits for full-run2 data

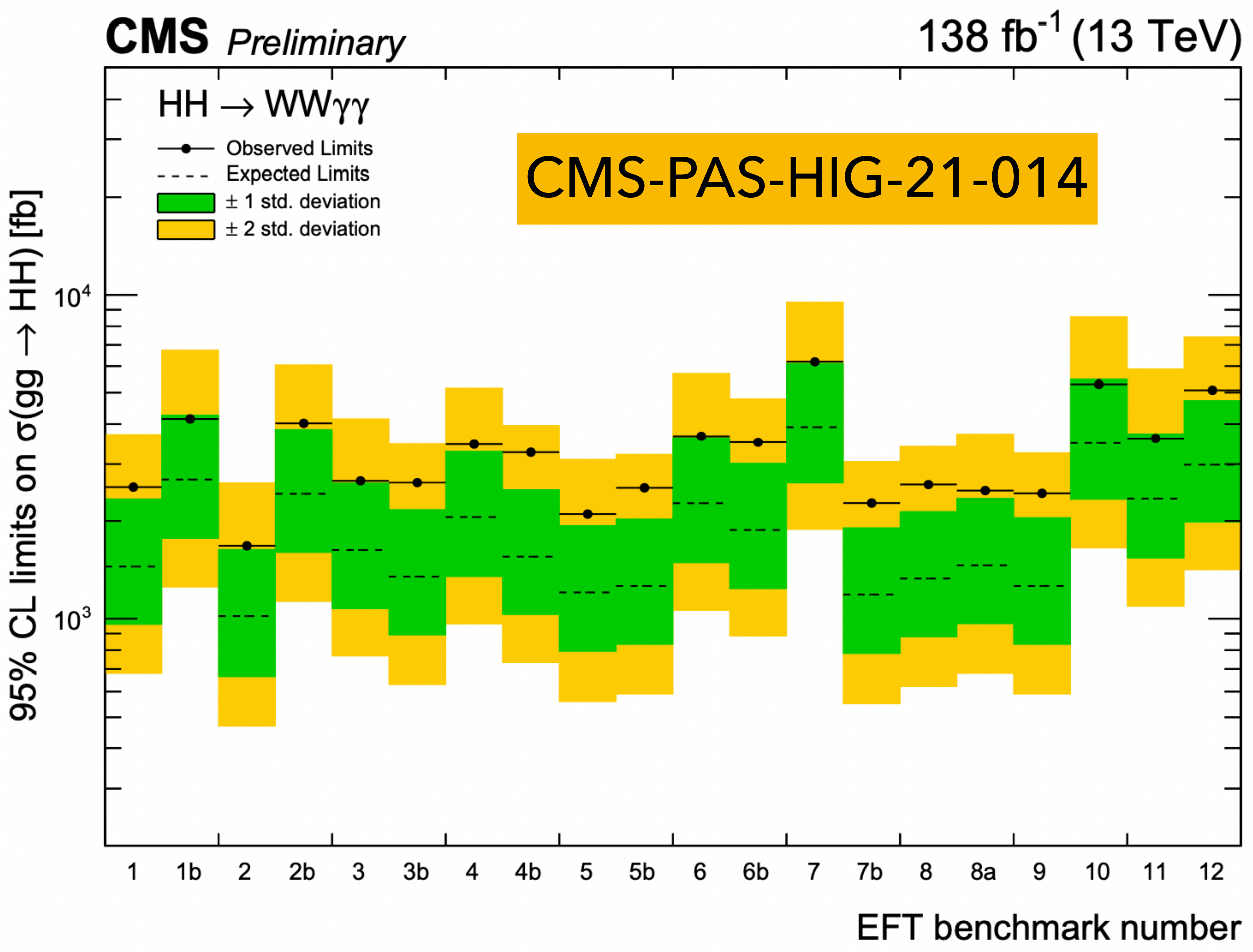
The observed diphoton mass distribution:

- 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

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.

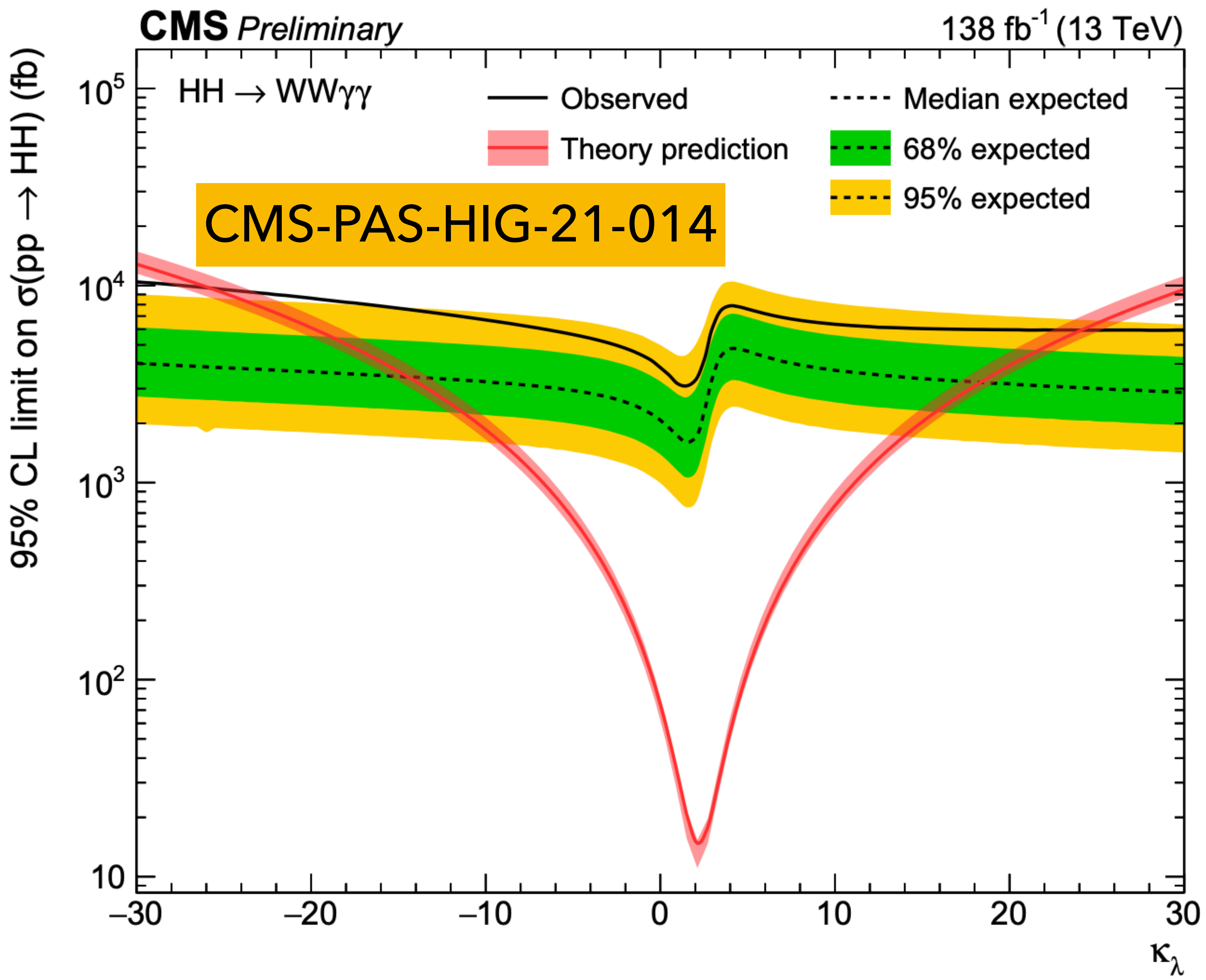




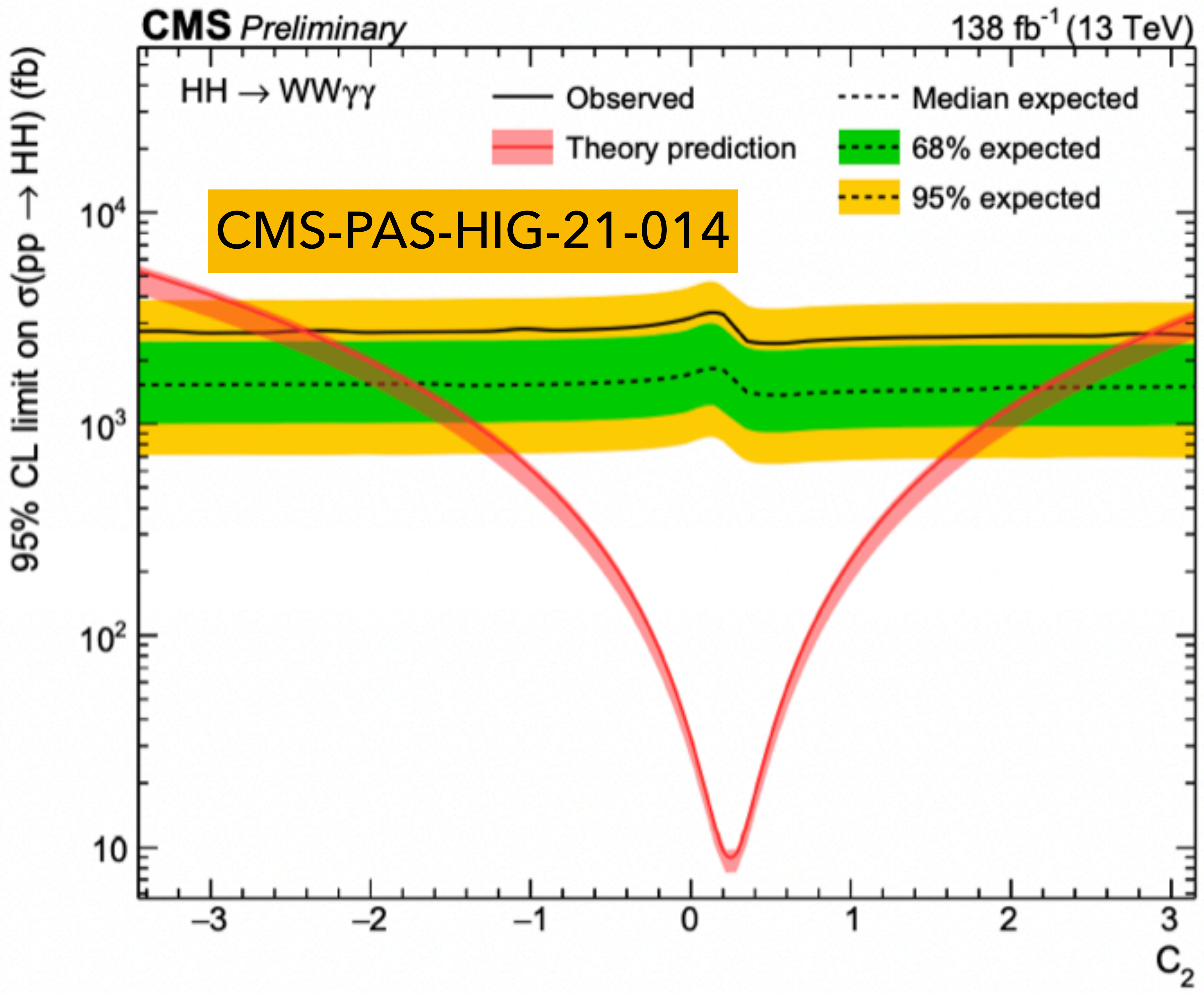
- Obs.(exp.) upper limit on HH signal for 20 EFT benchmarks:
  - 1.7 - 6.2 (1.0 - 3.9) pb.

HH → $WW\gamma\gamma$ search: Results

- κ_λ (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)]

Summary

- Search for HH production in $WW\gamma\gamma$ channel (CMS-PAS-21-014):
  - This is the first $HH \rightarrow WW\gamma\gamma$ search with full RunII dataset in LHC!
  - No deviations from SM observed for SM signal and BSM benchmark signals.
  - Observed (expected) results:
    - SM: 96.8 (52.5) x SM (31.05 fb)
    - kλ scan: −25.8 (−14.4) to 24.1 (18.3)
    - C2 scan: −2.4 (−1.7) to 2.9 (2.2)
    - EFT benchmarks: 1.7 – 6.2 (1.0 – 3.9) pb
- Plan to join in HH combination.

Thanks for your attention !