

Phenomenology Symposium 2023 | 8-10 May 2023

Nonresonant di-Higgs searches in $bb\tau\tau$, $bb\gamma\gamma$, $bbZZ$, $bbWW$, $WW\gamma\gamma$, and multilepton final states at CMS

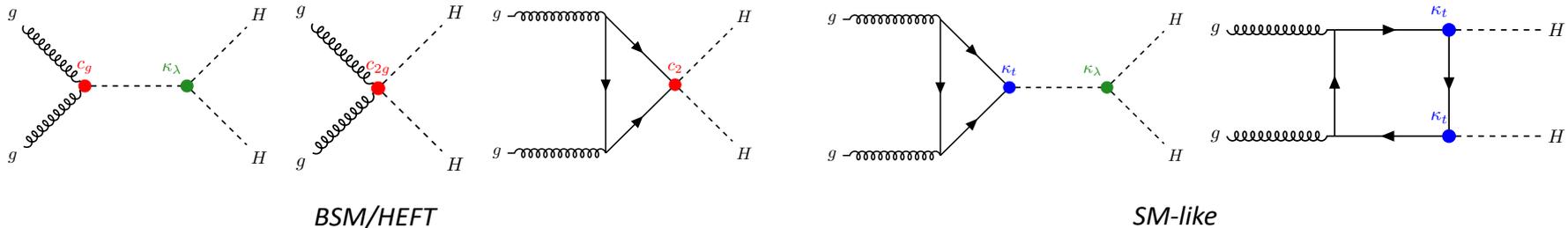
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on behalf of the CMS Collaboration

Searches for Higgs Boson Pair Production

The CMS Experiment performs searches for Nonresonant Higgs Pair Production in gluon fusion, vector boson fusion, and VHH production modes

Higgs pair production directly probes the Higgs self coupling and is sensitive to Beyond the Standard Model (BSM) effects such as: **modified SM couplings**, additional **couplings in Effective Field Theory** in which searches are performed in 20 EFT benchmark scenarios [1] [2]



The triangle and box diagrams are generalized in terms of a modified trilinear Higgs λ_{HHH} , κ_t , c_2 , c_{2g} , and c_g couplings

$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v} (\kappa_t H + \frac{c_2}{v} H^2) (\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v} (c_g H - \frac{c_{2g}}{2v} H^2) G_{\mu\nu}^a G^{a,\mu\nu}(4)$$

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

Searches for Higgs Boson Pair Production

- HH very rich phenomenologically, **combination of many channels** gives sensitivity to CMS Experiment's Run 2 (2016-2018) searches
- Today, covering results from **6 different channels**

$bb\tau\tau$ $bb\gamma\gamma$ $bbZZ$ $bbWW$ $WW\gamma\gamma$ multilepton

- Showing latest **CMS combined result** ^[3] which includes

$bb\tau\tau$ $bb\gamma\gamma$ $bbZZ$ multilepton $bbbb$

- For $bbbb$ final state, see later today's talk: *Non-resonant di-Higgs searches in four b final state at CMS by Chuyuan Liu*

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

Branching ratios of $HH \rightarrow xxyy$

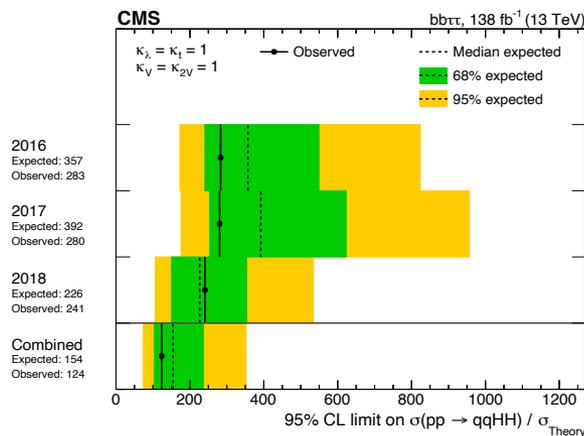
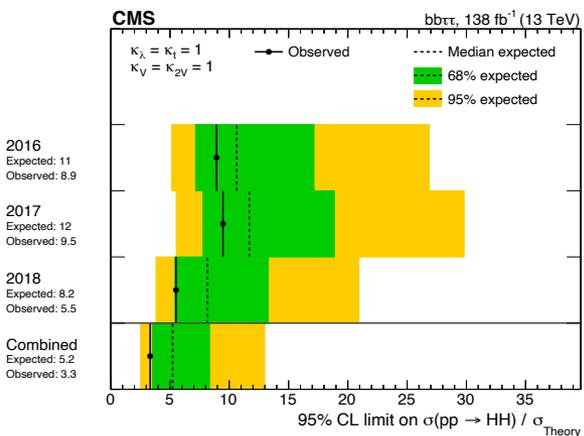
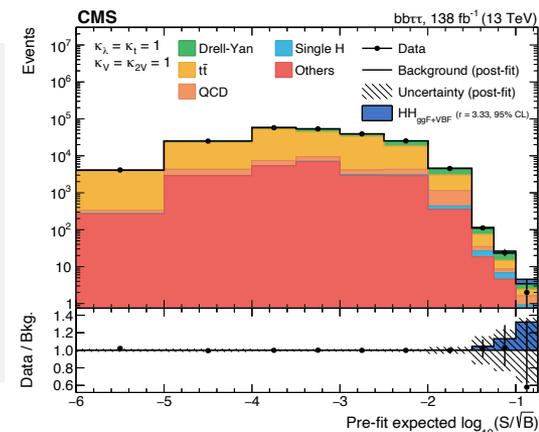
[3] "A Portrait of the Higgs boson by the CMS experiment ten years after the discovery", Nature

bbττ

Analysis Strategy

Three largest decay modes of ττ pair selected, one τ decays hadronically and the other leptonically/ hadronically

Different DNNs used to identify b jets, categorize events, and perform signal extraction



Observed (expected) limit on the nonresonant HH prediction at 95% CL

$$3.3 (5.2) \times \sigma_{HH}^{SM}$$

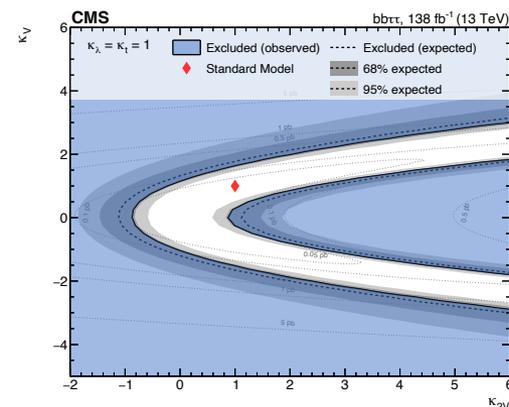
$$124 (154) \times \sigma_{qqHH}^{SM}$$

Results

Observed (expected) coupling constraints

$$-1.7 < \kappa_\lambda < 8.7 \quad (-2.9 < \kappa_\lambda < 9.8)$$

$$-0.4 < \kappa_{2V} < 2.6 \quad (-0.6 < \kappa_{2V} < 2.8)$$



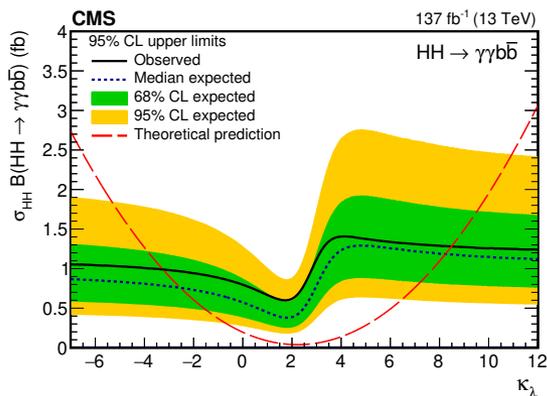
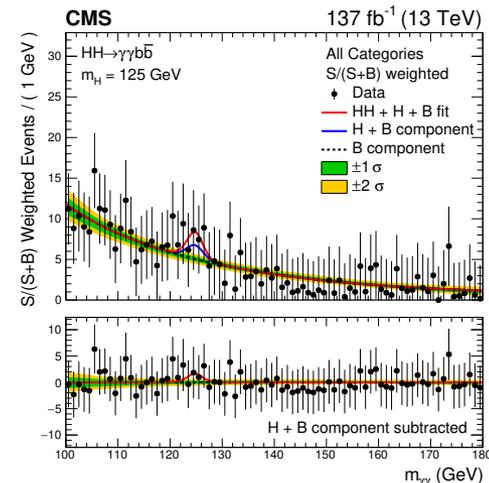
bbγγ

Analysis Strategy

Parametric fit to the invariant mass of the two Higgs boson candidates ($m_{\gamma\gamma}$ and m_{bb}), a “bump hunt”

MVA techniques used to distinguish GF and VBF signal from the background

ttH categories used to constrain κ_t



Results

Observed (expected) limit on the nonresonant HH prediction at 95% CL

$$7.7 (5.2) \times \sigma_{HH}^{SM}$$

$$225 (208) \times \sigma_{qqHH}^{SM}$$

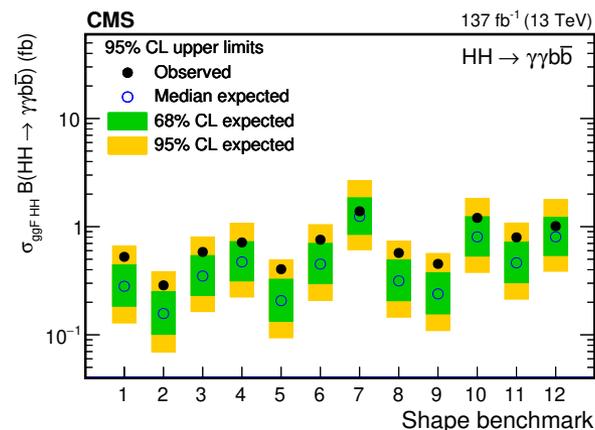
Observed (expected) limit on the nonresonant HH EFT benchmark models prediction at 95% CL and constraint on BSM coupling c_2

$$-0.6 < c_2 < 1.1 (-0.4 < c_2 < 1.1)$$

Observed (expected) coupling constraints

$$-3.3 < \kappa_\lambda < 8.5 (-2.5 < \kappa_\lambda < 8.2)$$

$$-1.3 < \kappa_{2V} < 3.9 (-0.9 < \kappa_{2V} < 3.1)$$



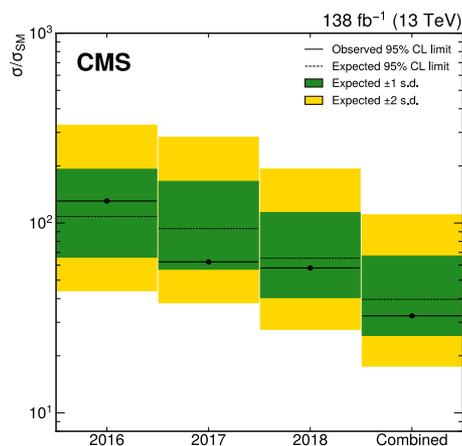
bbZZ

Analysis Strategy

Search in the fully leptonic decay of ZZ

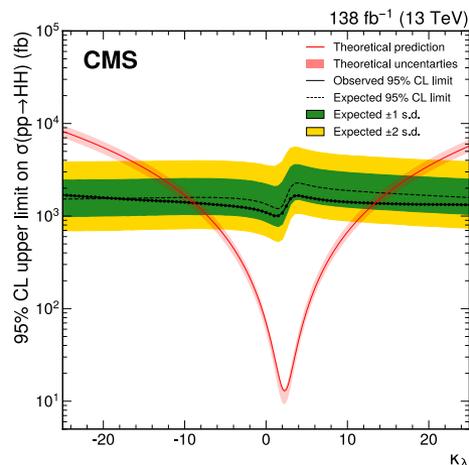
Z boson candidates chosen for $115 < m_{ZZ} < 135$ GeV

BDT discriminates signal from background, such as pT of the 4 leptons, for 4e, 2e2 μ , and 4 μ



Observed (expected) limit on the nonresonant HH prediction at 95% CL

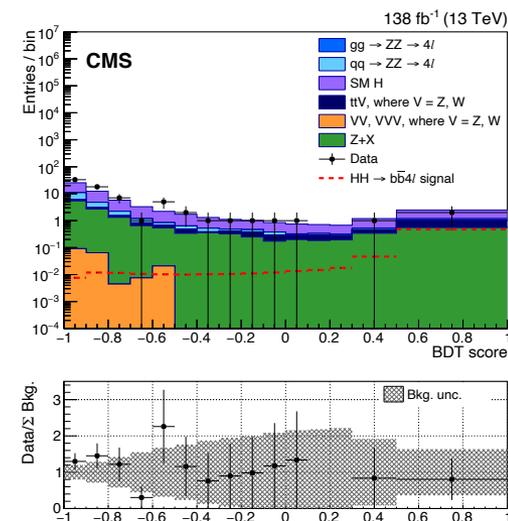
$$32.4 (39.6) \times \sigma_{HH}^{SM}$$



Results

Observed (expected) coupling constraints

$$-8.8 < \kappa_\lambda < 13.4 \quad (-9.8 < \kappa_\lambda < 15.0)$$



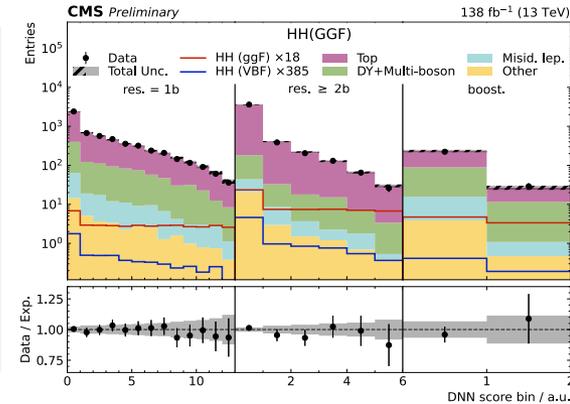
bbWW

Analysis Strategy

Categorized into Single Lepton and Dilepton channels

Fit performed on distribution of DNN score of signal and background

DNN and topology of H->bb candidate used to separate SL and DL categories into subcategories

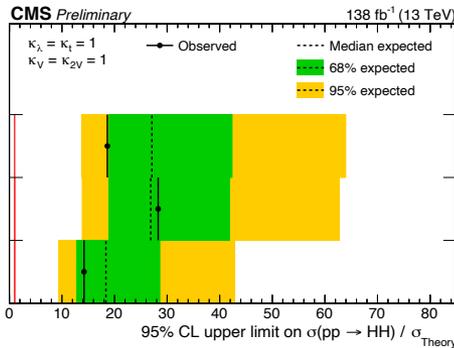


Results

Observed (expected) coupling constraints

$$-7.2 < \kappa_\lambda < 13.8 \quad (-8.7 < \kappa_\lambda < 15.2)$$

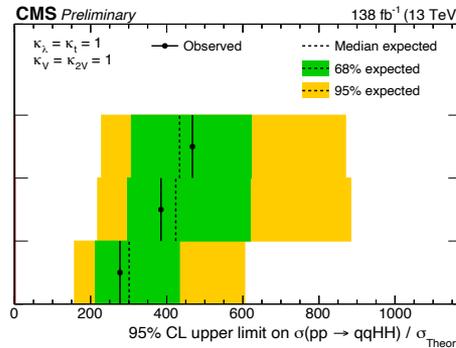
$$-1.1 < \kappa_{2V} < 3.2 \quad (-1.4 < \kappa_{2V} < 3.5)$$



Observed (expected) limit on the nonresonant HH prediction at 95% CL

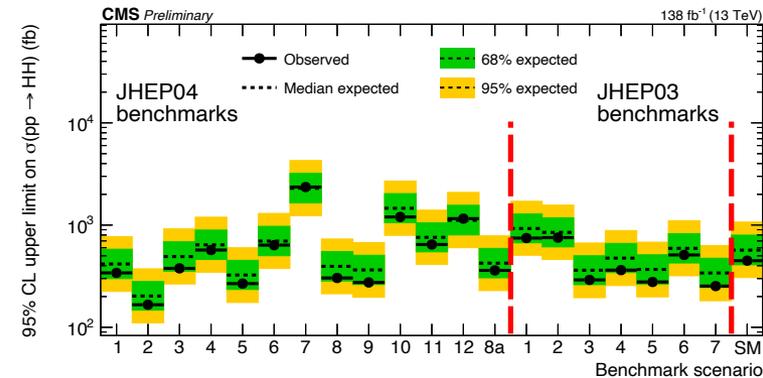
$$14 \text{ (18)} \times \sigma_{HH}^{SM}$$

$$277 \text{ (301)} \times \sigma_{qqHH}^{SM}$$



Observed (expected) limit on the nonresonant HH EFT benchmark models prediction at 95% CL and constraint on BSM coupling c_2

$$-0.8 < c_2 < 1.3 \quad (-1.0 < c_2 < 1.4)$$

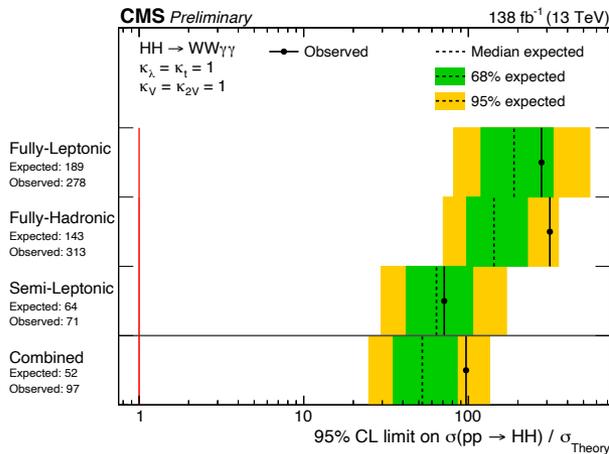
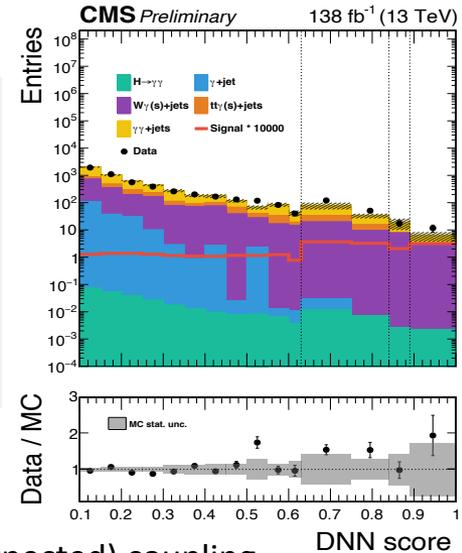


WWγγ

Analysis Strategy

Categories defined by 1) multiclassifier DNN in Single Lepton final state, 2) combination of two binary DNNs in the Fully Hadronic final state, 3) cut based selections in the Fully Leptonic final state

Parametric fit to the invariant diphoton mass, $100 < m_{\gamma\gamma} < 180$ GeV



Results

Observed (expected) limit on the nonresonant HH prediction at 95% CL

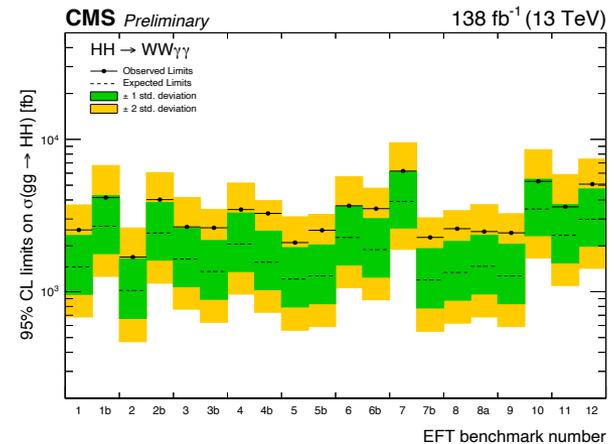
$$97 (53) \times \sigma_{HH}^{SM}$$

Observed (expected) coupling constraints

$$-25.8 < \kappa_\lambda < 24.1 \quad (-14.4 < \kappa_\lambda < 18.3)$$

Observed (expected) limit on the nonresonant HH EFT benchmark models prediction at 95% CL and constraint on BSM coupling c_2

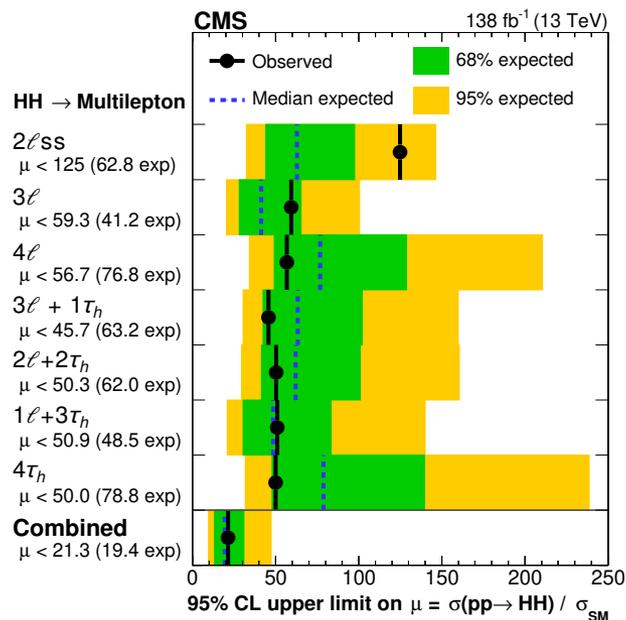
$$-2.4 < c_2 < 2.9 \quad (-1.7 < c_2 < 2.2)$$



multilepton

Analysis Strategy

Search in 7 channels, analyzed events with two, three, or four leptons including electrons, muons, and hadronically decaying taus



Results

Observed (expected) limit on the nonresonant HH prediction at 95% CL

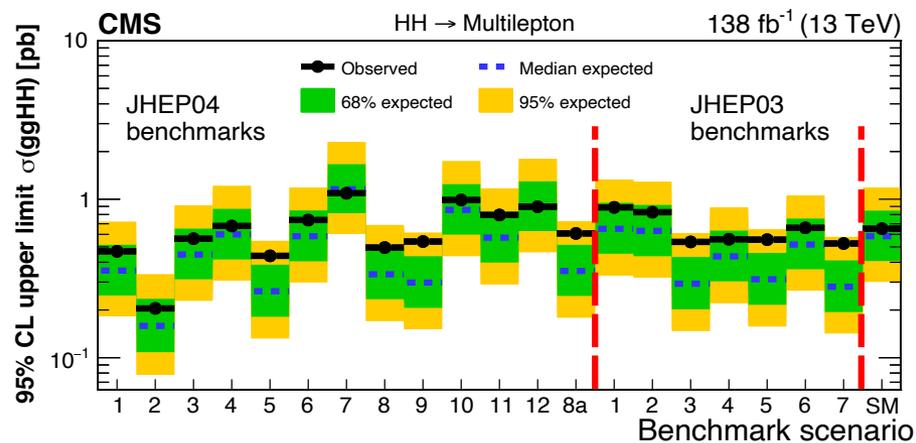
$$21.3 \text{ (19.4)} \times \sigma_{\text{HH}}^{\text{SM}}$$

Observed (expected) constraints

$$-6.9 < \kappa_\lambda < 11.1 \text{ (-6.9 < } \kappa_\lambda < 11.7 \text{)}$$

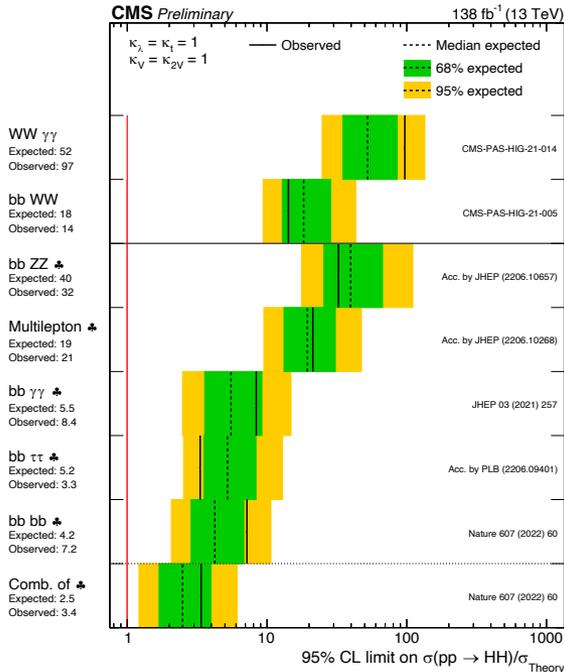
Observed (expected) limit on the nonresonant HH EFT benchmark models prediction at 95% CL and constraint on BSM coupling c_2

$$-1.05 < c_2 < 1.48 \text{ (-0.96 < } c_2 < 1.37 \text{)}$$



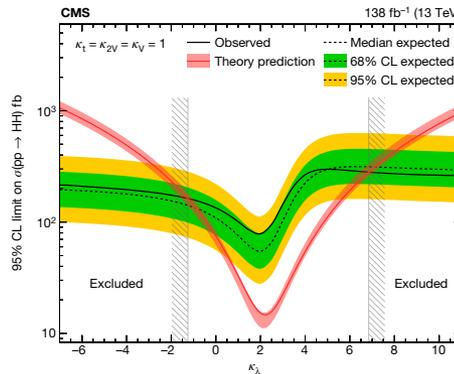
CMS Run 2 Combination

Latest Run 2 Combination of HH channels



CMS results constrain the Higgs boson self-interaction coupling modifier κ_λ

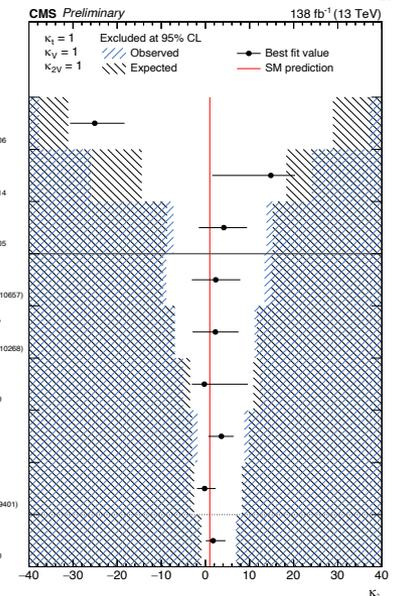
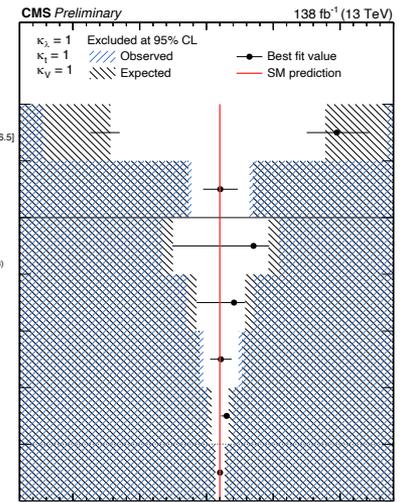
$$-1.24 < \kappa_\lambda < 6.49$$



CMS results constrain the coupling modifier κ_{2V} with other parameters fixed to the SM values

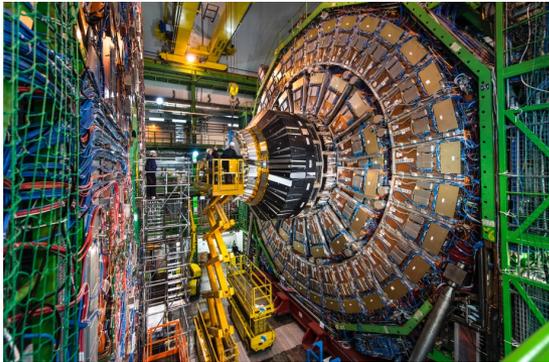
$$0.67 < \kappa_{2V} < 1.38$$

Excluding $\kappa_{2V} = 0$ at 6.6 σ

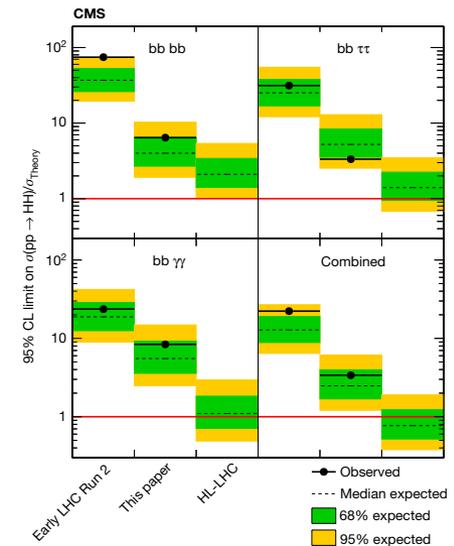


Summary

- At CMS, searches for Higgs Pair Production using Run 2 (2016-2018) data set a combined limit for nonresonant production at 3.4 (2.5) $\times \sigma_{HH}^{SM}$ and $-1.24 < \kappa_\lambda < 6.49$
- These physics searches also covered coupling modifiers and EFT benchmark scenarios
- $\kappa_{2V} = 0$ **excluded** at 6.6σ with the combined channels
- Resonant searches also performed (not covered today)
- HL-LHC will provide a window into the Higgs mechanism and Higgs potential via Higgs Pair Production as we approach SM HH sensitivity



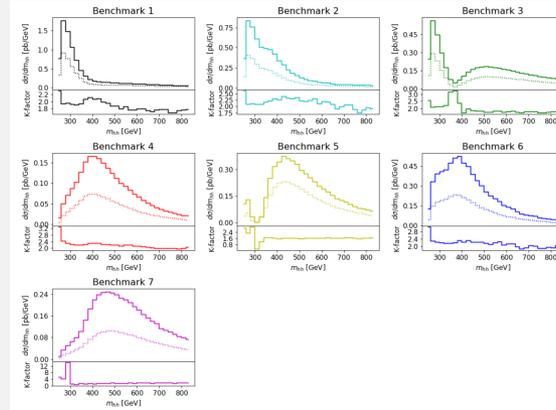
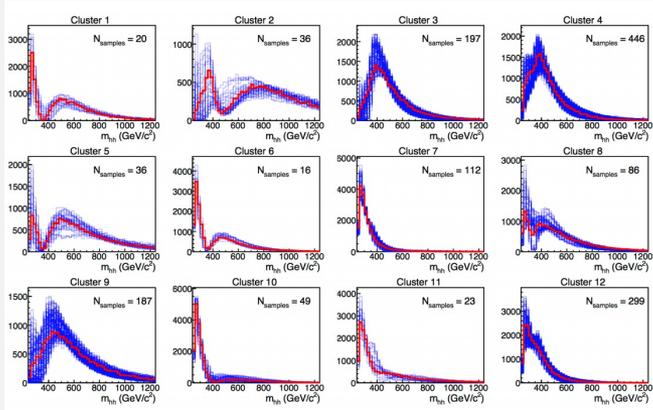
HL-LHC projections for HH:



Backup

EFT Benchmark Scenarios

- EFT benchmark scenarios chosen using cluster analysis, labeled as:
SM, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 8a, 1b, 2b, 3b, 4b, 5b, 6b, 7b



m_{hh} for 19 gluon fusion EFT benchmarks [5], [6], [7]

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	-1.0
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	-1.0	1.0
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	1.0	-1.0
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	-1.0
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