Search for non-resonant production of Higgs pair in CMS experiment at the LHC

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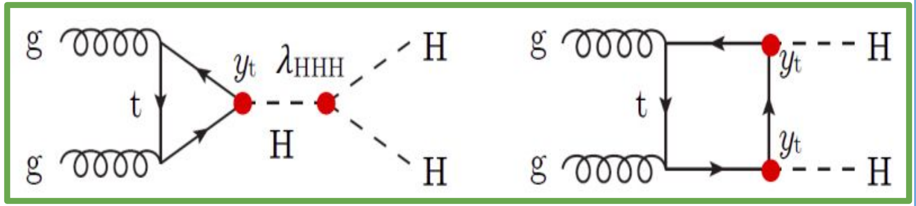
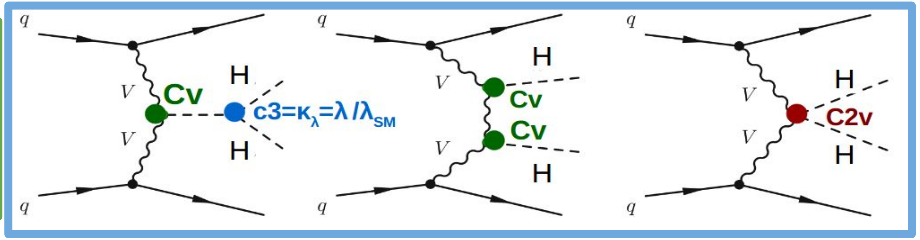
On behalf of the ***CMS*** *collaboration*

Higgs pair production in Standard Model

ggHH LO



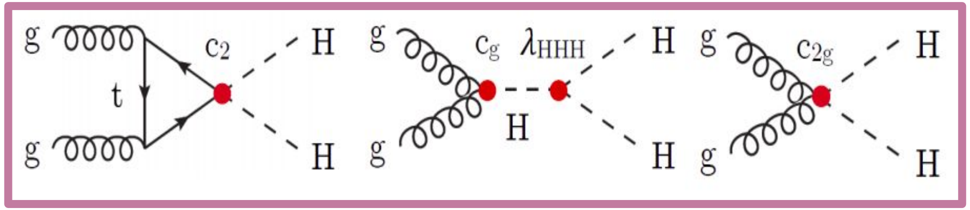
VBFHH LO



c_i / κ_i: modifier of SM coupling

- HH is the only process for the direct access of trilinear self Higgs coupling (λ_{HHH}) at the LHC, which dictates the shape of the Higgs potential.
- The standard model value of $\lambda_{HHH} = m_H^2/2v^2 \sim 0.13$
- **Gluon-gluon fusion (ggHH)** : the largest production mode of HH at the LHC, cross section with N^{2}LO QCD accuracy, σ_{ggHH} = 31.05 fb @13 TeV [1].
- **Vector Boson fusion (VBFHH)** : the sub-lead mode, at N^{3}LO, σ_{VBFHH} = 1.73 fb [2].
- VBFHH: **unique** process for accessing the coupling of Higgs pair with a pair of weak gauge bosons (VVHH, V = W/Z)

BSM scenario



- ❖ Typically probed via anomalous coupling parameters in terms of modifiers of SM values (c_i / κ_i).
  Anomalous values of the coupling modifiers enhance the cross section typically.

- ❖ EFT approach includes three new additional couplings for ggHH compared to SM.

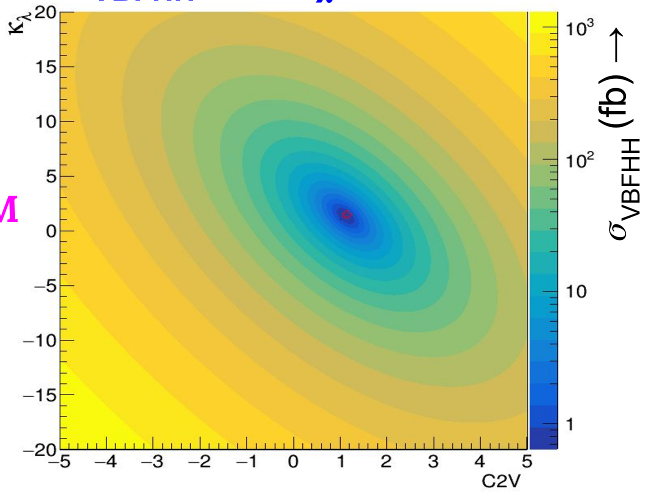
Parameters of interest: κ_λ, κ_t from SM + c_2, c_g, c_{2g} from BSM

- ❖ Hence, ggHH cross section and kinematics of final state particles depend on the above 5 coupling parameters.

- ❖ Similarly for VBFHH, relevant coupling modifiers C_V, C_{2V} **and κ_λ** dictate the kinematics & cross section.

- ❖ ***Recent analyses target VBFHH mode along with ggHH.***

σ_{VBFHH} (C_{2V}, κ_λ) for C_V = 1



HH search in CMS

- HH decay modes being explored using **full Run2 (137 fb^{-1})** data: HH→ 4b , bb$\tau\tau$, bb$\gamma\gamma$, bbWW, bbZZ, 4W, WW$\tau\tau$, 4τ, WW$\gamma\gamma$

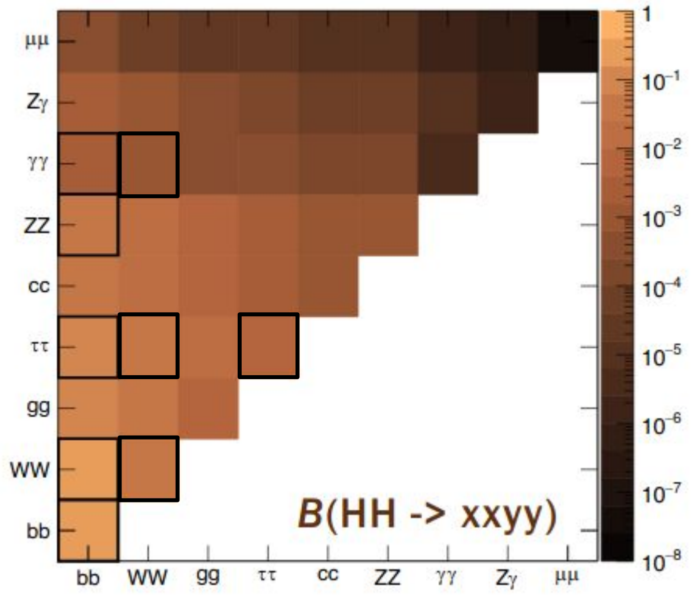
- Using **2016 (36 fb^{-1})** data other published results from CMS (atleast one H decays to bb)
  HH→ 4b
  HH→ bb$\tau\tau$
  HH→ bbVV (V = W/Z)
  HH→ bb$\gamma\gamma$

& combined

Emphasis of this talk

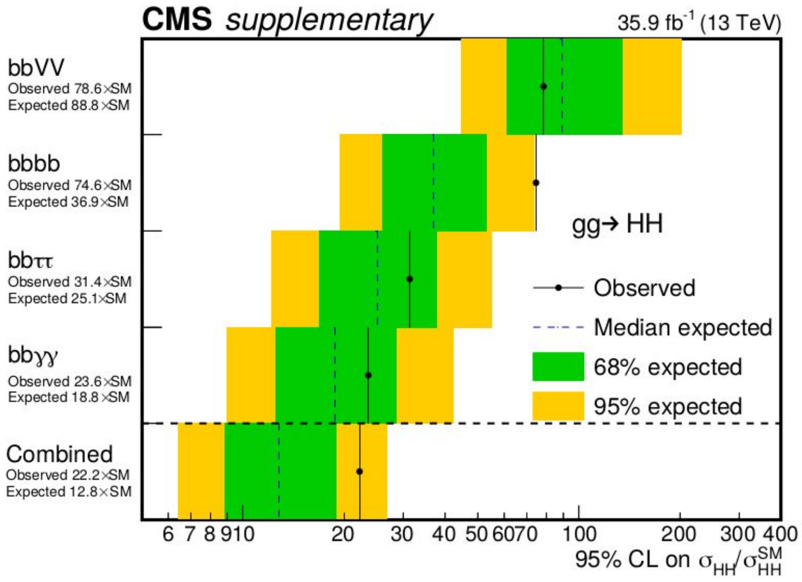
NEW

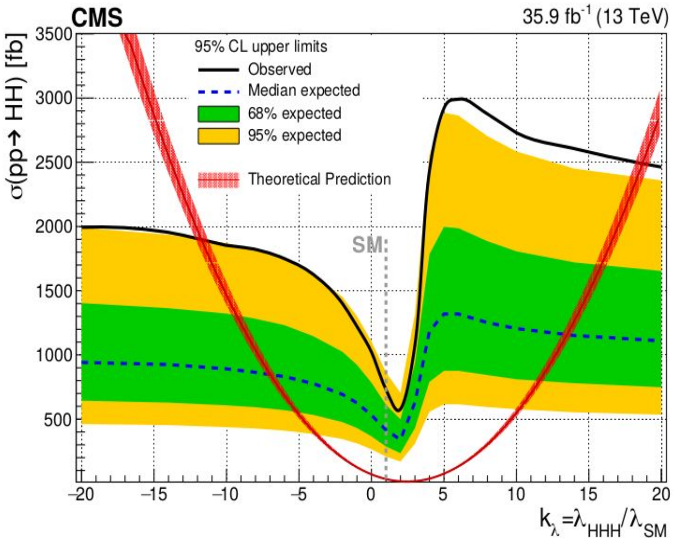
Using full RunII data recents results:
(i) bb$\gamma\gamma$ — CMS PAS-HIG-19-018
(ii) bbZZ*(4l) — CMS PAS-HIG-20-004



CMS combined HH result with 2016 data

PRL 122 (2019)





95% CL Upper Limit on (cross section*BR) :

Only ggHH (* SM)	
Observed	22.2
Expected	12.8

Allowed range @ 95% CL

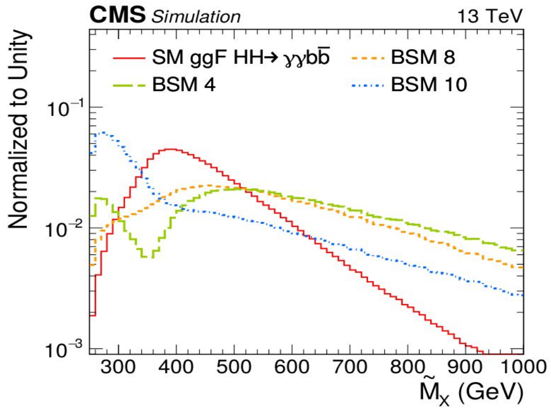
Observed: $-11.8 < \kappa_\lambda < 18.8$

Expected: $-7.1 < \kappa_\lambda < 13.6$

bbγγ : key features & analysis strategy

NEW

- Small branching ratio (0.26%) but highly sensitive
  - (i) excellent ECAL resolution for $H \rightarrow \gamma\gamma$ in CMS
  - (ii) large branching ratio for $H \rightarrow bb$

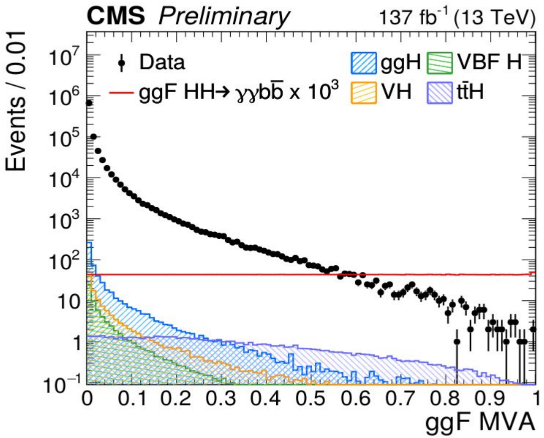


Strategy for recent analysis:

- **M_X (M_{HH}) = $M_{\gamma\gamma bb}$ - $M_{\gamma\gamma}$ - M_{bb} + 250 GeV:** sensitive for probing BSM
- BDT method to enhance signal vs. background discrimination

Selection: γ, b-jets, VBF jets → VBFHH → ggHH → ttH

- Total 14 categories based on MX & MVA
- Simultaneous 2D fit to $m_{\gamma\gamma}$ x m_{jj} distributions
- Assuming no $m_{\gamma\gamma}$ - m_{jj} correlation



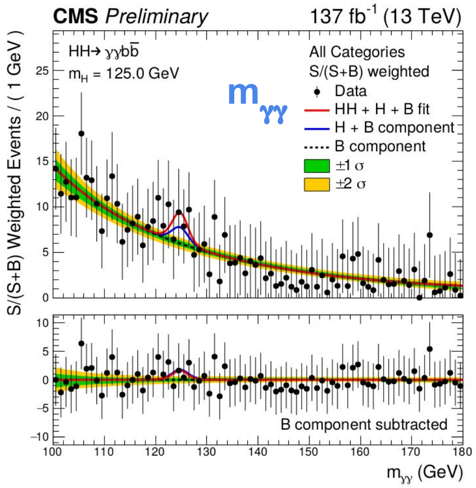
$bb\gamma\gamma$: signal & background modelling

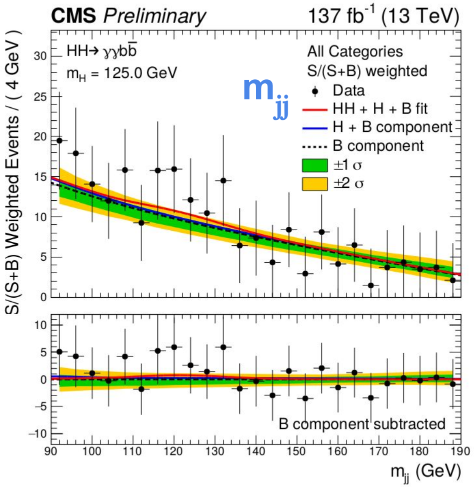
- Backgrounds:
  → QCD induced non-resonant $\gamma\gamma$ + jets, γ + jets
  → single Higgs production with $H \to \gamma\gamma$ (ttH most dominant)

- For each category, ggHH and VBFHH signal and single Higgs backgrounds modelling:
  - $m_{\gamma\gamma}$ → **multi-Gaussian**
  - m_{jj} → **Double-sided Crystal Ball**

- Shape of non-resonant background in each category determined directly from data using discrete profile method [3].

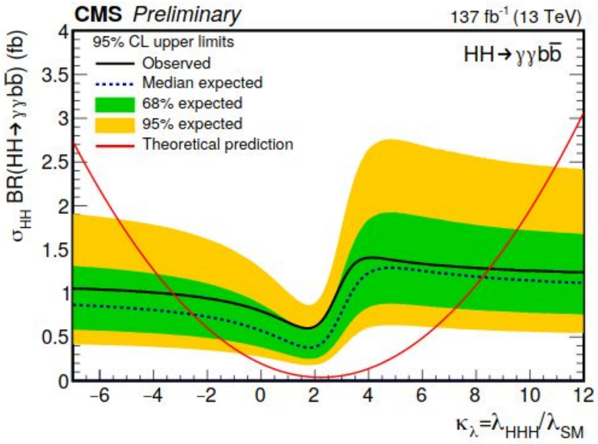
- **Final signal extraction** performed by simultaneous fit to all categories.

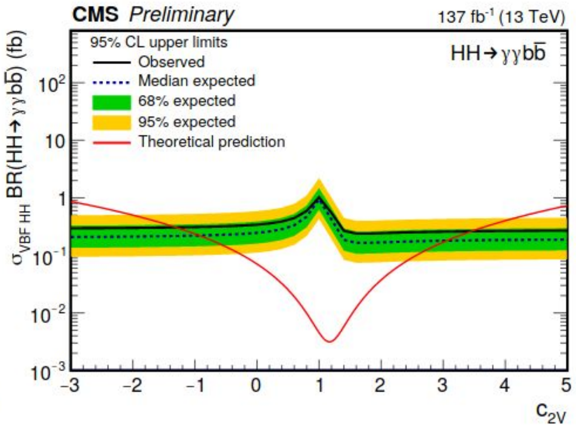




bbγγ (ggHH + VBFHH): results on σ * BR

NEW





Allowed range @ 95% CL

Observed: $-3.3 < \kappa_\lambda < 8.5$
Expected: $-2.5 < \kappa_\lambda < 8.2$

Observed: $-1.3 < C_{2V} < 3.5$
Expected: $-0.9 < C_{2V} < 3.0$

Best-to-date !

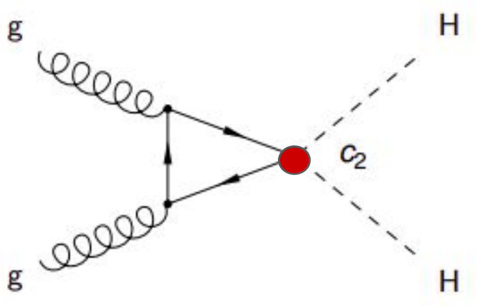
First from CMS

95% CL Upper Limit on (inclusive cross section*BR) :

Inclusive HH (* SM)	
Observed	7.7
Expected	5.2

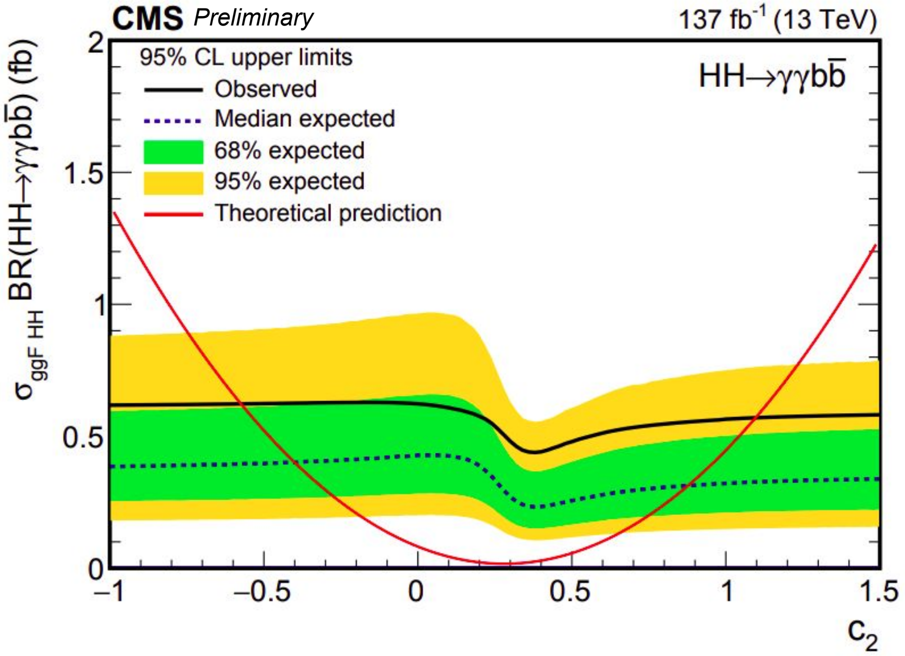
bb$\gamma\gamma$: constraining BSM, results for C_2

NEW



C_2 : ttHH coupling modifier

C_2 = 0 in SM



Allowed range @ 95% CL

Observed: -0.6 < C_2 < 1.0
Expected: -0.4 < C_2 < 0.9

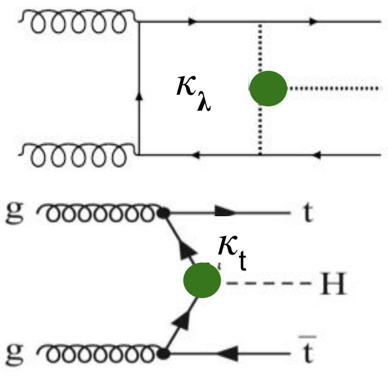
Constraints on 12 benchmark points are in backup

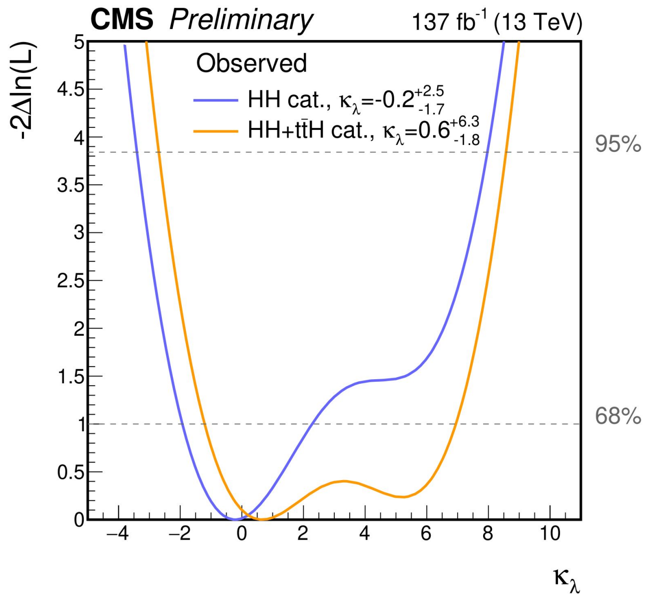
bbγγ: 1D Likelihood scans

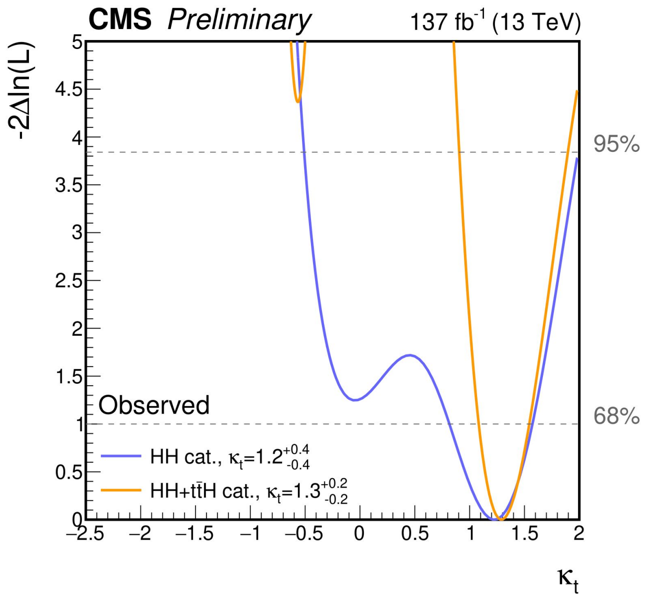
NEW

→ ttH process considered for better constraint on κ_λ and κ_t

→ ttH categories are mutually exclusive to the all HH categories [4]







→ Inclusion of ttH makes positive κ_λ preferable

rules out negative κ_t at 95% CL

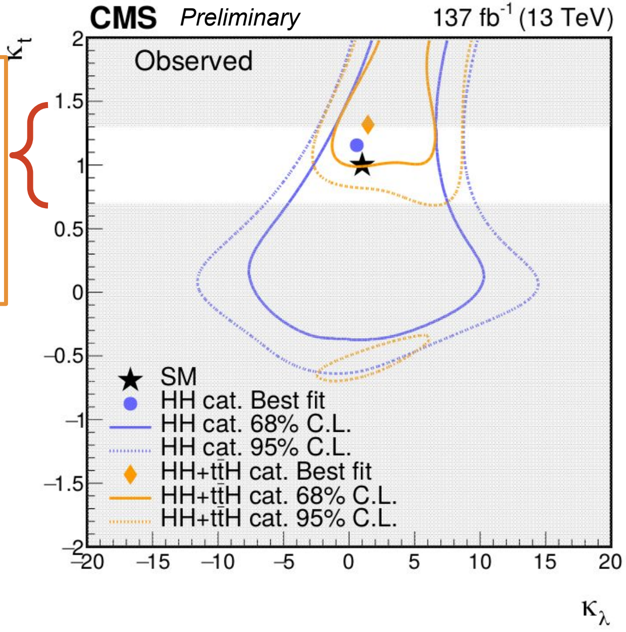
$bb\gamma\gamma$: 2D Likelihood scan for BSM search

NEW

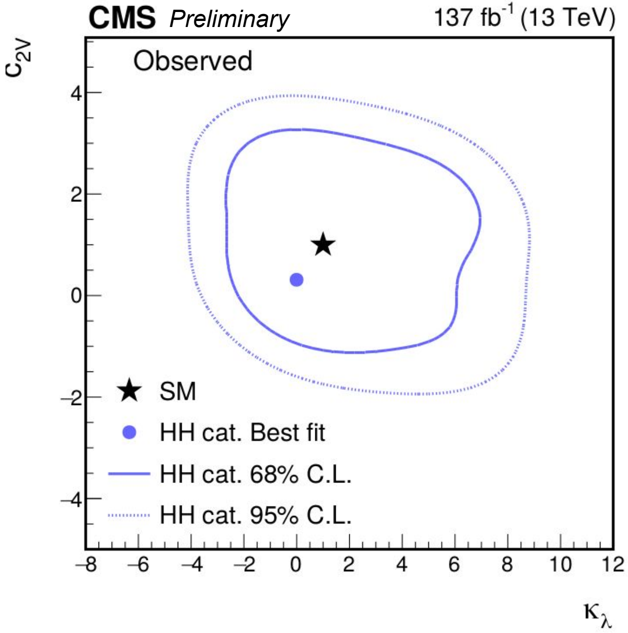
Validity region for using κ_t dependence of ttH at LO & κ_λ dependence at NLO [5]

VBFHH involves κ_λ and C_{2V} but not κ_t

κ_λ - κ_t



κ_λ - C_{2V}



bbZZ(4l) : analysis strategy

First from CMS

- Backgrounds:

  (i) Irreducible: determined from Monte Carlo

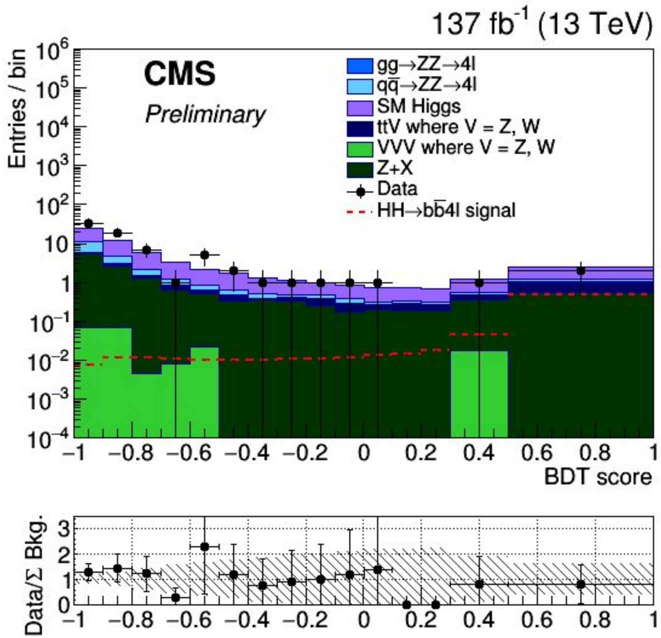
  (a) single Higgs production: ggH, VBFH, HW, HZ, ttH, bbH

  (b) QCD induced nonresonant production: qq→ZZ*, gg → ZZ*

  (c) ttW, ttZ

  (ii) Reducible: Z + X : where one or two leptons are fakes, mainly from heavy flavour decays, mis-reconstructed jets and converted γ

  → determined from data by measuring probability of *fake* **e**, μ in control regions



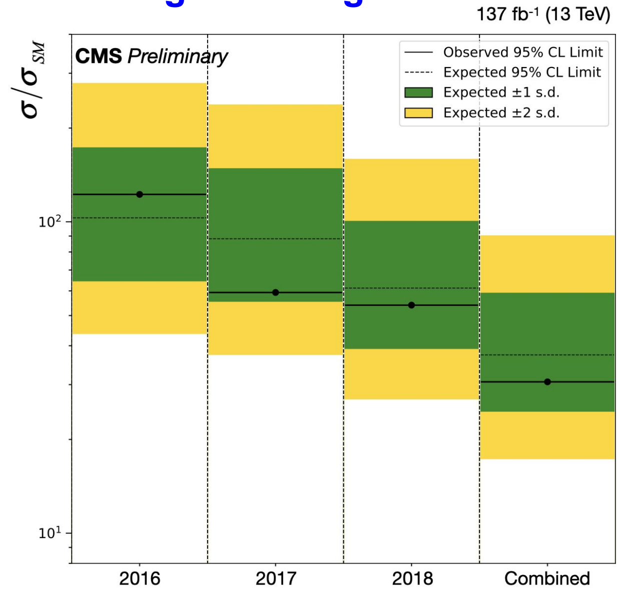
- Total 9 BDT trainings: 3 separate years (2016, 17, 18) & 3 channels (4e, 4μ and 2e2μ)

- Signal extracted using shape analysis: maximum likelihood fit to merged BDT output distribution of all years and all channels with proper weightage.

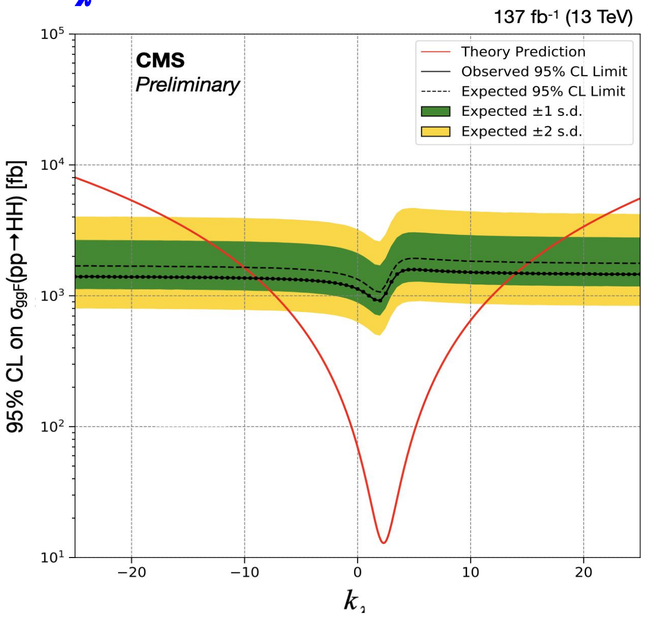
bbZZ(4l) : Results

First from CMS

Upper Limit on signal strength



κ_λ scan



95% CL Upper Limit on (cross section*BR)

Only ggHH (* SM)	
Observed	30
Expected	37

Allowed range @ 95% CL

Observed: $-9 < \kappa_\lambda < 14$

Expected: $-10.5 < \kappa_\lambda < 15.5$

Summary

1. Measurement of the Higgs boson self-coupling is of high priority in the CMS physics programme.
   Several analyses with different HH decay channels are being considered.

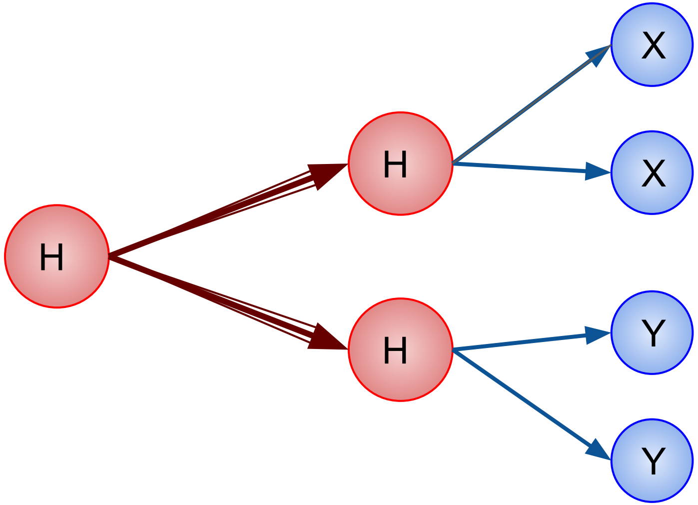
2. **Full Run2 analysis of HH→ bbγγ final state in CMS has been presented for the first time.**
   i) The VBFHH mode also been considered along with the ggHH mode to obtain the **first results on the VVHH coupling parameter (C_{2V})** in CMS.
   ii) 95% CL UL on (cross section * BR) improved by **60%** compared to analysis based on 2016 data only.

3. **HH→ bbZZ (4*l*) mode has been studied by CMS for the first time with full Run2 data.**

4. Other final state analyses with full Run2 data and final combined results are on the way.
   Stay tuned!

5. More interesting results are expected in Run3 and HL-LHC era.

Thank you very much for kind attention



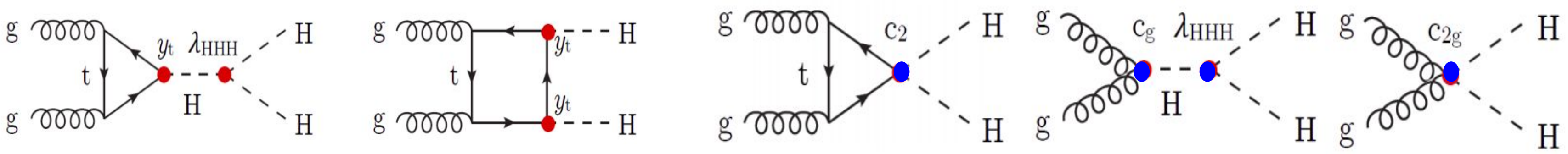
Backups and additional Materials

HH: EFT Lagrangian for ggHH process [6]

$$\mathcal{L}_{\mathrm{HH}} = \boxed{\kappa_\lambda} \lambda^{\mathrm{SM}}_{\mathrm{HHH}} v H^3 - \frac{m_t}{v}\left(\boxed{\kappa_t} H + \frac{\boxed{c_2}}{v} H^2\right)\left(\bar{t}_L t_R + \mathrm{h.c.}\right) + \frac{1}{4}\frac{\alpha_S}{3\pi v}\left(\boxed{c_g} H - \frac{\boxed{c_{2g}}}{2v} H^2\right) G^{\mu\nu} G_{\mu\nu}.$$

— SM couplings

— BSM couplings



HH: EFT BSM Benchmark [7]

- The different values of coupling parameters leads different kinematics and cross-sections
- In CMS HH analysis 12 benchmark points have been explored to get the EFT sensitivity
- Each benchmark points have been defined by a set of 5 coupling parameters
- The generator level m_{HH} distributions is hugely different in each benchmark scheme

Benchmark points:	1	2	3	4	5	6	7	8	9	10	11	12	SM
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.0
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	0.0
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0

ttH and single Higgs parametrization:

- The SM Higgs production and decay rates can be used to constrain on the k_λ
- Deviation from SM Higgs production and decay rate are parameterized by 3D model (k_λ, k_V, k_F)
- The production rates have been modified by this coupling parameter in terms of SM value

$$\mu_i(\kappa_V, \kappa_F, \kappa_\lambda) = Z_H^{BSM}(\kappa_\lambda)\left[S_i(\kappa_V, \kappa_F) + K_{BSM}(1-\kappa_\lambda)\right]$$

$$Z_H^{BSM}(\kappa_\lambda) = \left(1 - (\kappa_\lambda^2 - 1)\delta Z\right)^{-1}$$

K_{BSM} : Constants and process dependant
ttH has the largest value

References:

1. G. Degrassi, P. P. Giardino, F. Maltoni, and D. Pagani, *JHEP* 12 **(2016)** 080
2. F. Maltoni, D. Pagani, A. Shivaji, and X. Zhao, *Eur. Phys. J.* C 77 **(2017)**

$bb\gamma\gamma$: Event selection

Photon selection:

- Hgg MVA γ ID > -0.9
- Pixel-safe electron veto is applied
- $pT(\gamma 1)/M(\gamma\gamma) > 1/3$, $pT(\gamma 2)/M(\gamma\gamma) > 1/4$
- $100 < M(\gamma\gamma) < 180$ GeV

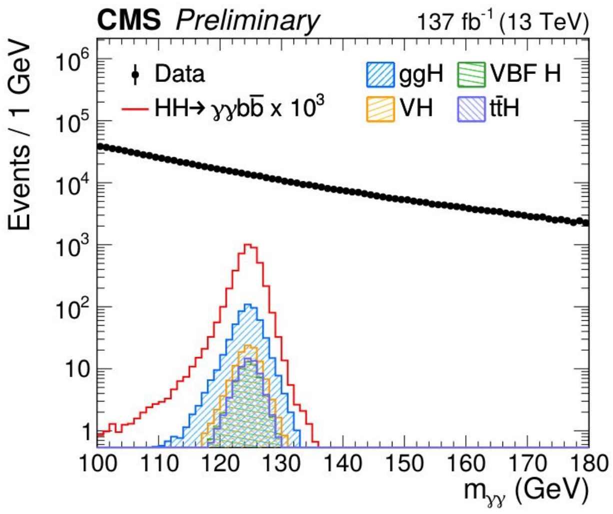
b-jet selection:

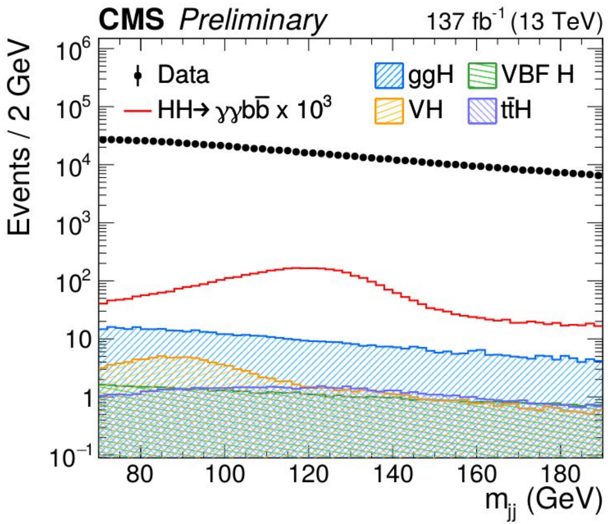
- b jets are chosen with the highest sum of DeepJet score
- pT(jets) > 25 GeV, $|\eta| < 2.4$ (2016) & $|\eta| < 2.5$ (2017/2018)
- $70 < M_{bb} < 190$ GeV

VBF Jet selection:

- **Tight PU** jet ID for jet $p_T < 50$ GeV for all η
- $\Delta R < 0.4$ applied between one jet and one photons and one jet and one selected b-jet
- Identify pair of jets with $|\eta| < 4.7$, lead jet $p_T > 40$ GeV & sublead jet $p_T > 30$ GeV
- VBF jets: pair of highest invariant mass (M_{jj}).

bb$\gamma\gamma$: Invariant mass distributions in ggHH

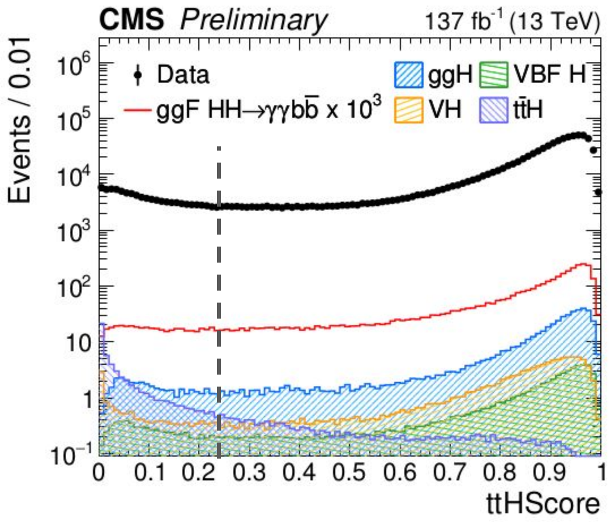




bb$\gamma\gamma$: ttHScore (An MVA to separate HH Vs ttH)

- **A DNN based classifier**
- **Signal:** SM ggHH + 12 BSM Benchmark samples
  Background: ttH

- **Input variables:**
  (i) Low level information of individual particle flow (PF) objects
  (ii) High level event kinematics
  - Angular variables: $\cos\theta^{*}_{CS}$, $\cos\theta_{bb}$, $\cos\theta_{\gamma\gamma}$
  - Variables for the leptonic decays of W from top
    $\Delta R_{MET,\,b1}$, $\Delta R_{MET,\,b2}$, four vector of Leptons $p_T > 0$
  - Variables for the hadronic decays of W boson



- Hyper parameters are optimized by Bayesian optimization

- Good signal to background separation.
- Optimization for threshold value is chosen by taking 90% of signal efficiency.

$bb\gamma\gamma$:List of input variables used for training

Common variables with ggHH analysis

1. Leading & subleading DeepJet score
2. $\cos(\theta^*_{CS})$, $\cos(\theta_{\gamma\gamma})$ and $\cos(\theta_{bb})$ - Helicity angles
3. $p_T^{\gamma\gamma}/ M_{HH}$, p_T^{bb}/ M_{HH}
4. Leading & subleading photon ID MVA
5. $p_T^{\gamma}/ m_{\gamma\gamma}$ → lead and sublead photon
6. p_T^{b}/ m_{bb} → lead and sublead b-jet
7. min $\Delta R_{\gamma b}$ and other $\Delta R_{\gamma b}$
8. p_T^{HH}
9. MX
10. Leading and subleading photon resolution, σ_E/E
11. Diphoton mass resolution, $\sigma_m/ m_{\gamma\gamma}$
12. Leading ans subleading b-jet resolution σ_E/E
13. Di-bjet mass resolution, σ_m/ m_{bb}
14. Median energy density in an event (ρ)

VBF jet related variables

1. Leading and subleading VBF jet p_T/ M_{jj}^{VBF}
2. Leading and subleading VBF jet η
3. Product of VBF jet η
4. Difference of VBF jet η
5. Quark Gluon Likelihood(QGL) of two VBF jets
6. Minimum angular distance between one VBF jet and one photon & one VBF jet and one b-jet

   → min $\Delta R_{j\gamma}$ and min ΔR_{jb}

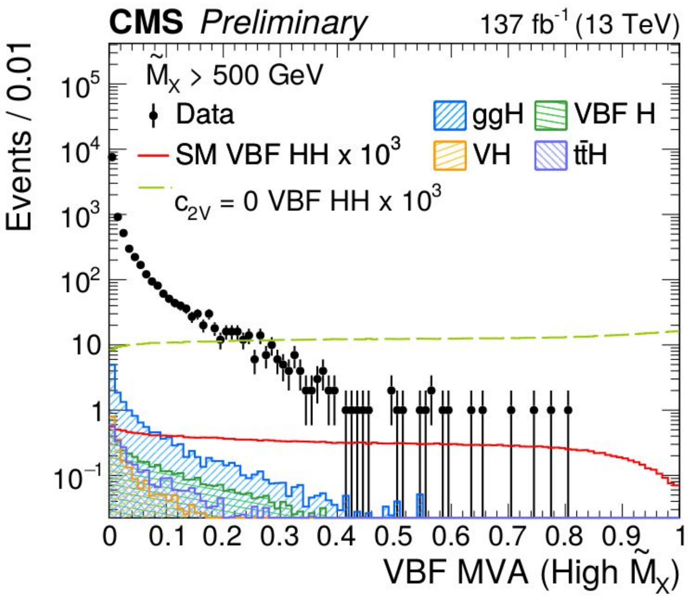
7. Centrality variables between diphoton and di-bjet system with respect two the two VBF jets, $C_{\gamma\gamma}$, C_{bb}

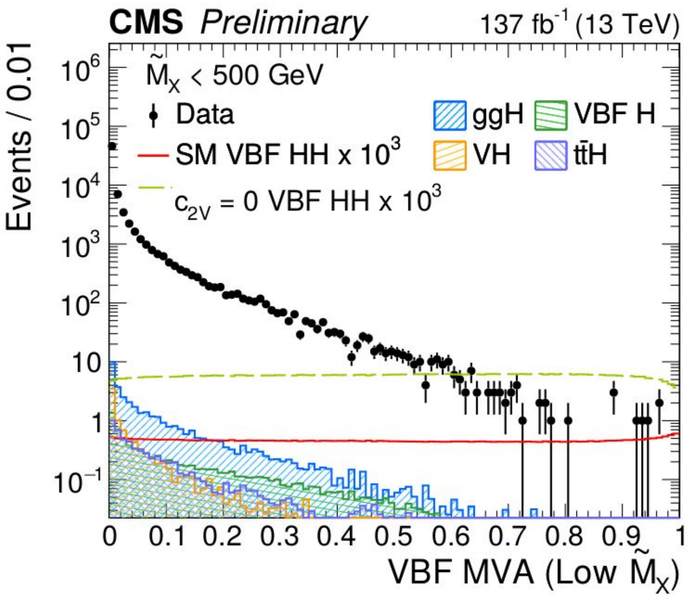
$$C_{xx} = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_{xx}-\frac{\eta_1+\eta_2}{2}\right)^2\right]$$

where x= γ or b

QGL: CMS DP -2016/070

bbγγ: MVA distributions for VBFHH





bb$\gamma\gamma$: Systematic uncertainties

-- Statistically dominated analysis
-- Total impact of systematics on signal strengths is around 2% on

Experimental:

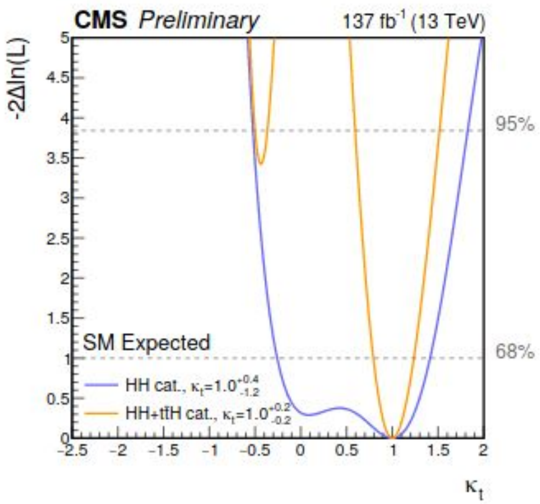
- ➢ Luminosity
- ➢ Preselection SF
- ➢ Triggers
- ➢ Photons ID MVA
- ➢ Photon resolution
- ➢ Electron Veto SF
- ➢ Jet energy scale & resolution
- ➢ b-tagging SF
- ➢ Pile up jet Id
- ➢ Prefiring Issue
- ➢ HEM (HCAL Minus)

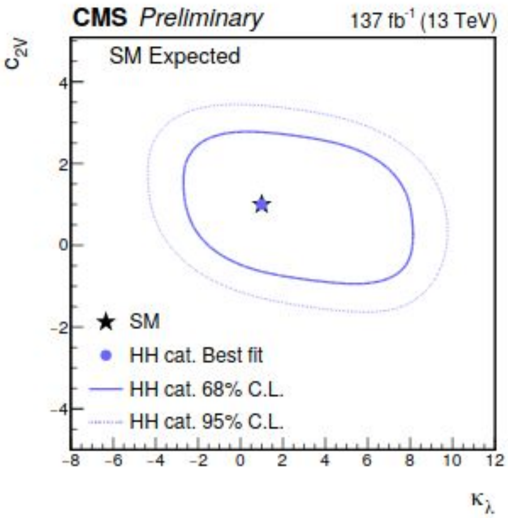
Theoretical:

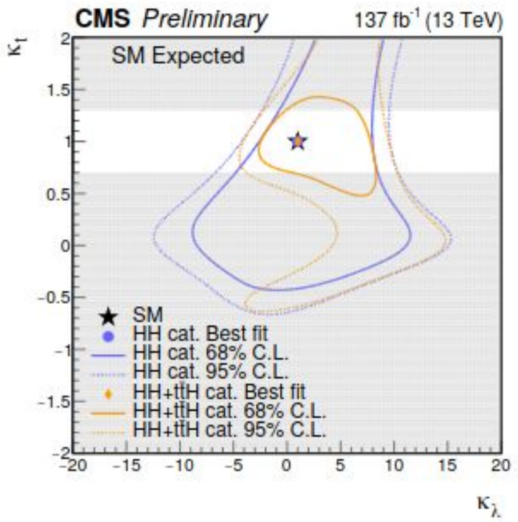
- ➢ Background Modelling
- ➢ QCD scale
- ➢ PDF systematics
- ➢ PS scheme

bb$\gamma\gamma$: Expected likelihood scans

NEW







bb$\gamma\gamma$: Benchmark points [5]

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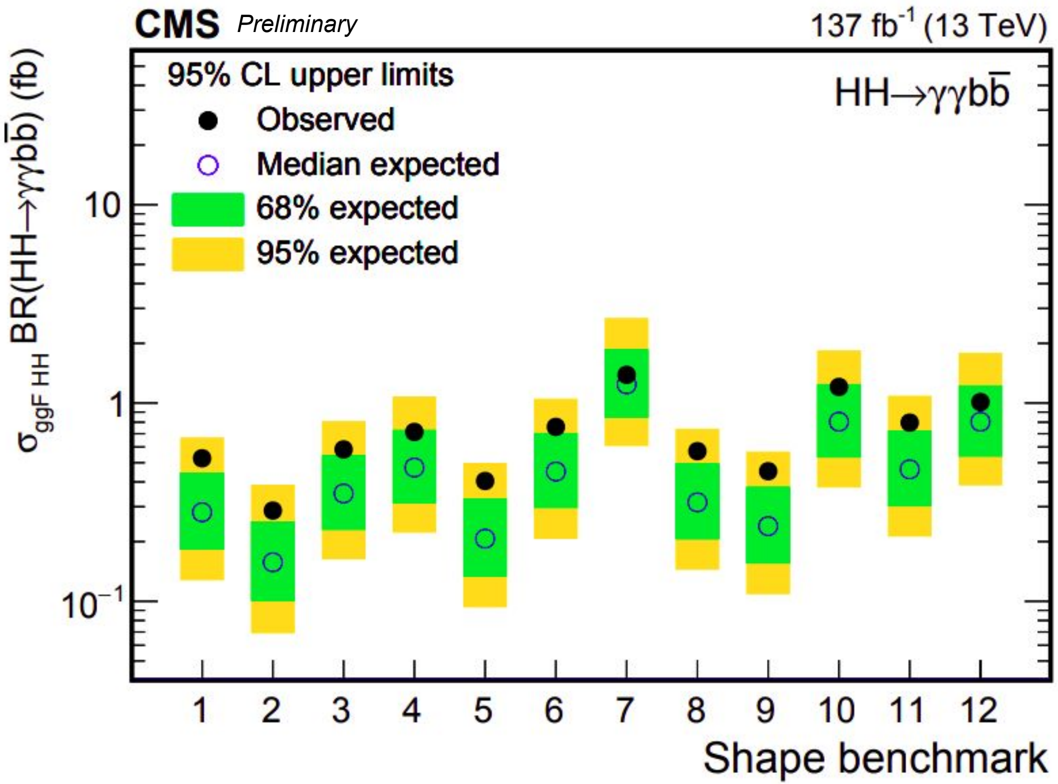
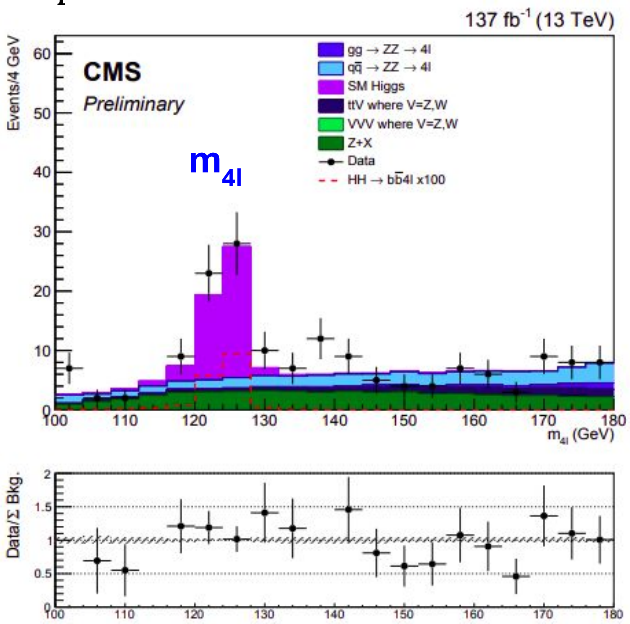
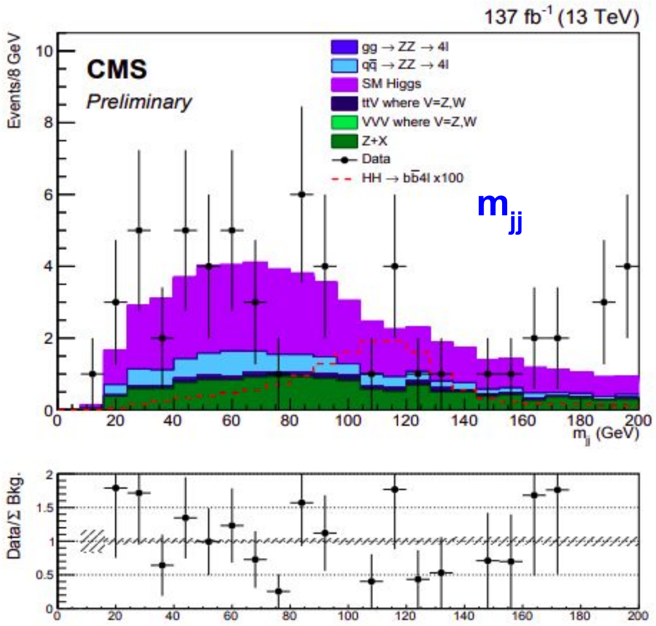


bbZZ(4l) : key features

- **(i) Clear signature from 4l (ii) Large BR. H→ bb**
- Targets only ggHH production





- Full reconstruction of $H \rightarrow ZZ^*$ final states.
- H(bb) reconstructed from jets with highest b tag score.

bbZZ(4l): Event selection

H→ ZZ

4 leptons → Z candidates → ZZ candidates

Lepton pairs:
- Opposite charge
- Same flavour
- 12<$m_{ll(\gamma)}$<120 GeV

Non overlapping Z cand pairs:
- m_{Z1}>40 GeV (Z1 is Zcand with closest mass to nominal Z mass)
- $\mathrm{p_T(l1)} > 20$ GeV, $\mathrm{p_T(l2)} > 10$ GeV
- $\Delta R > 0.02$ for each of the 4leptons
- $\mathrm{m_{ll}} > 4$ GeV for the opposite charge lepton pairs
- $4e$ and 4μ candidated discarded if the alternative combination $Z_a Z_b$ satisfies $|m(Z_a) - m(Z)| < |m(Z_1) - m(Z)|$ and $m(Z_b) < 12$ GeV
- $m_{4l} > 70$ GeV
- If more than one ZZ candidate survives the selection, the one with the highest value of the scalar sum of transverse momentum of leptons is chosen

Events in signal region:
$115 \leq \mathrm{m4l} \leq 135$ GeV

H→ bb

- If <2 jets, events are not considered
- If only 2 jets, the bb candidate is built with the 2 jets
- If ≥2 jets, bb candidate is built from the **2 highest b tagger score jets** in the event

bbZZ(4l): Systematic uncertainties

Theory uncertainties	
PDF and α_s	
PDF set and α_s HH	3.0%
m_{top} unc HH	2.6%
PDF set ggH	1.8%
α_s ggH	2.59 – 2.62%
PDF set and α_s VBFH	2.1%
PDF set and α_s ZH	1.6%
PDF set and α_s WH	1.3%
PDF set and α_s bbH	3.2%
PDF set and α_s ttH	3.6%
PDF set and α_s qqZZ	3.1 – 3.4%
PDF set and α_s ttW	25 – 37.5%
PDF set and α_s ttZ	7 – 14%
PDF set and α_s VVV	2 – 17%
PDF set and α_s ggZZ	3.2%
QCD scale	
HH	2.2 – 5%
ggH	4.27 – 6.49%
VBFH	0.3 – 0.4%
ZH	2.7 – 3.5%
WH	0.5%
bbH	4.6 – 6.7%
ttH	6.0 – 9.2%
qqZZ	3.2 – 4.2%
ttW	3 – 4%
ttZ	2 – 3%
VVV	3%
ggZZ	4.6 – 6.7%
Electroweak corrections	
qqZZ	0.1%
ggZZ	10.0%

Experimental uncertainties			
source	2016	2017	2018
Luminosity	2.6%	2.3%	2.5%
Leptons ID and reco eff	1.6 – 15.5%	1.1 – 12.1%	1.0 – 11%
b tagging SF	shape	shape	shape
JEC	shape	shape	shape
JER	shape	shape	shape
Z+X uncertainties	30 – 41%	30 – 38%	30 – 37%

bbZZ(4l): BDT Variables

- p_T of the four leptons
- ΔR between two reconstructed H
- B-tag score of two b-jets
- p_T and invariant mass of the two jets
- The highest value of the b-tagging score.

CMS HH analyses results with 2016 data (36 fb^{-1})

Channels	95% CL UL on cross section*BR (* SM)	Constraints on κ_λ
HH→ $bb\gamma\gamma$ PLB 778 (2019) 7	Obs.: 9 Exp.: 24	Obs.: $-11 < \kappa_\lambda < 17$ Exp.: $-8 < \kappa_\lambda < 14$
HH→ $bb\tau\tau$ PLB 778 (2018) 101	Obs.: 30 Exp.: 25	Obs.: $-18 < \kappa_\lambda < 26$ Exp.: $-14 < \kappa_\lambda < 22$
HH→ bbbb JHEP 04 (2019) 112	Obs.: 75 Exp.: 37	Obs.: $-23 < \kappa_\lambda < 30$ Exp.: $-15 < \kappa_\lambda < 23$
HH→ bbVV (V = W/Z) JHEP 01 (2018) 054	Obs.: 79 Exp.: 89	Obs.: $-11 < \kappa_\lambda < 17$ Exp.: $-8 < \kappa_\lambda < 14$

All consider only ggHH production mode