Institute of High Energy Physics
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HH→bbɣɣ search with the Run 2 dataset at CMS

CLHCP

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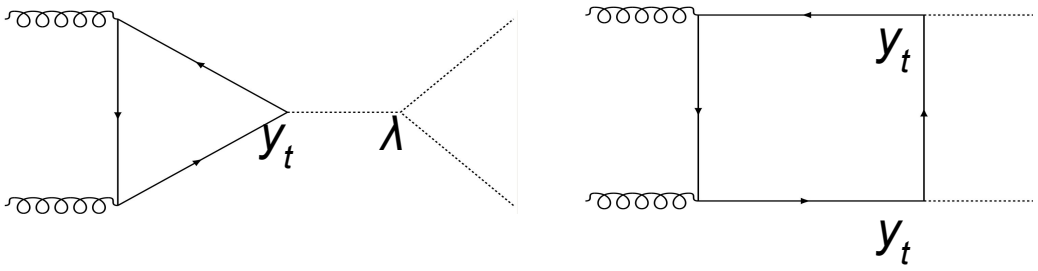
Outline

- Motivation for the HH search
- Analysis strategy
- Results

Sensitivity to double Higgs couplings

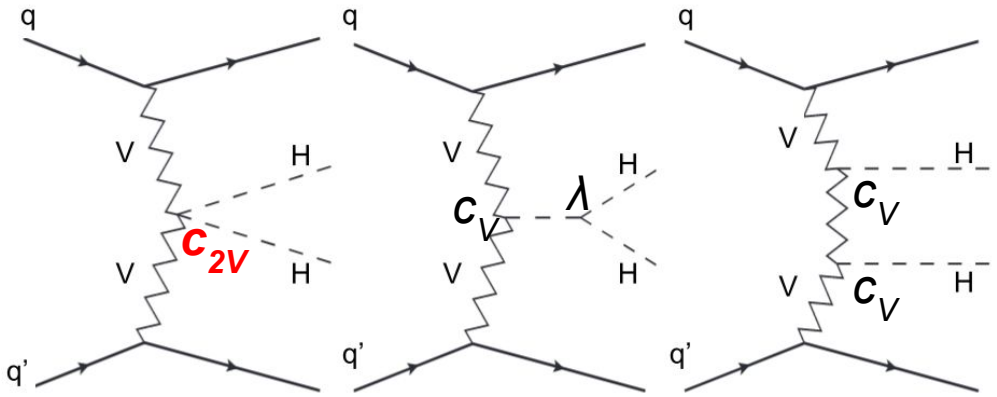
- HH production is sensitive to the Higgs trilinear coupling λ
- VBF HH is sensitive to HHVV coupling c_{2V}

ggF production (ggHH) diagrams at LO

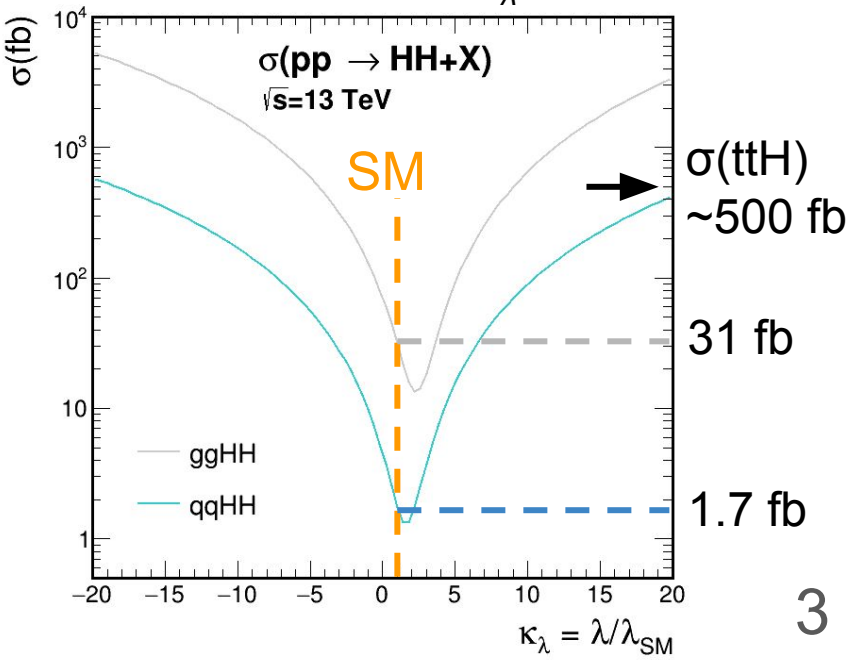


Fundamental tests of the SM symmetry breaking

VBF HH production diagrams at LO

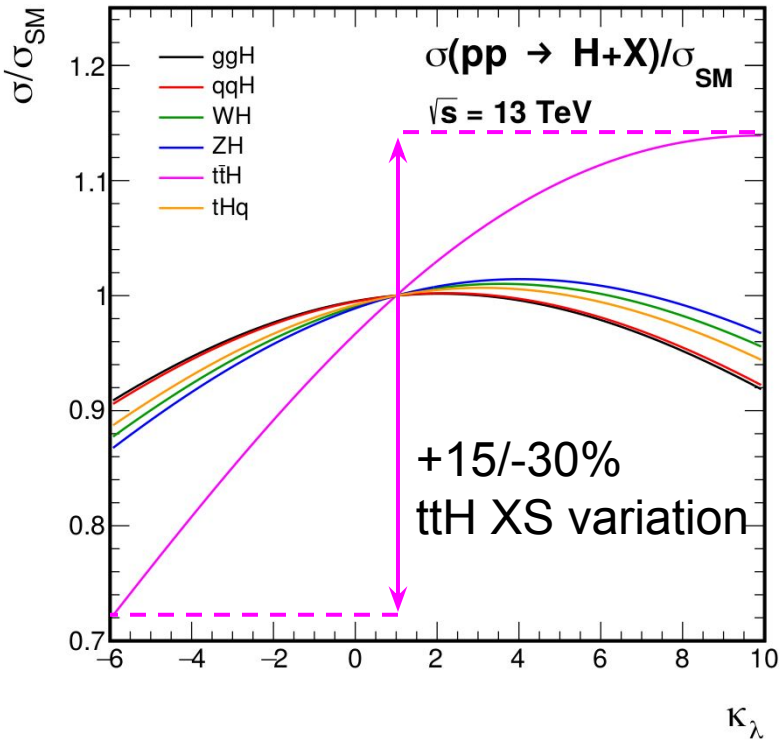


HH production cross section vs k_λ



Consistent model for a λ measurement

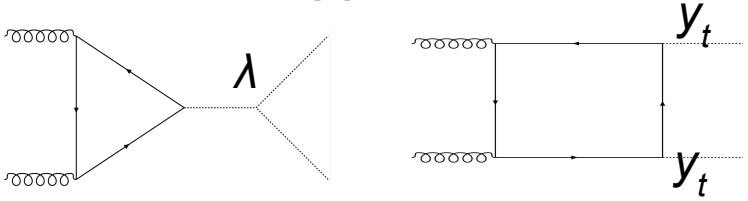
- λ-dependent NLO electroweak corrections to single-H XS
- Account for single-H contamination (ttH) in HH signal region



➢ Include ttH-enriched categories in the analysis

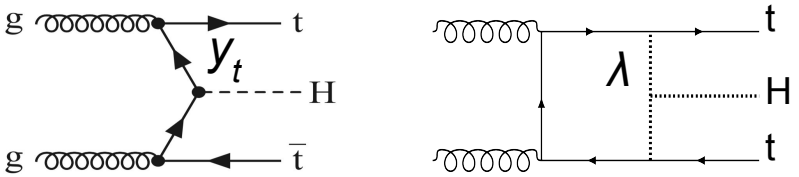
- Improve λ sensitivity
- Constrain ttH contamination in HH categories
- Simultaneous measurement of λ and y_t

ggHH



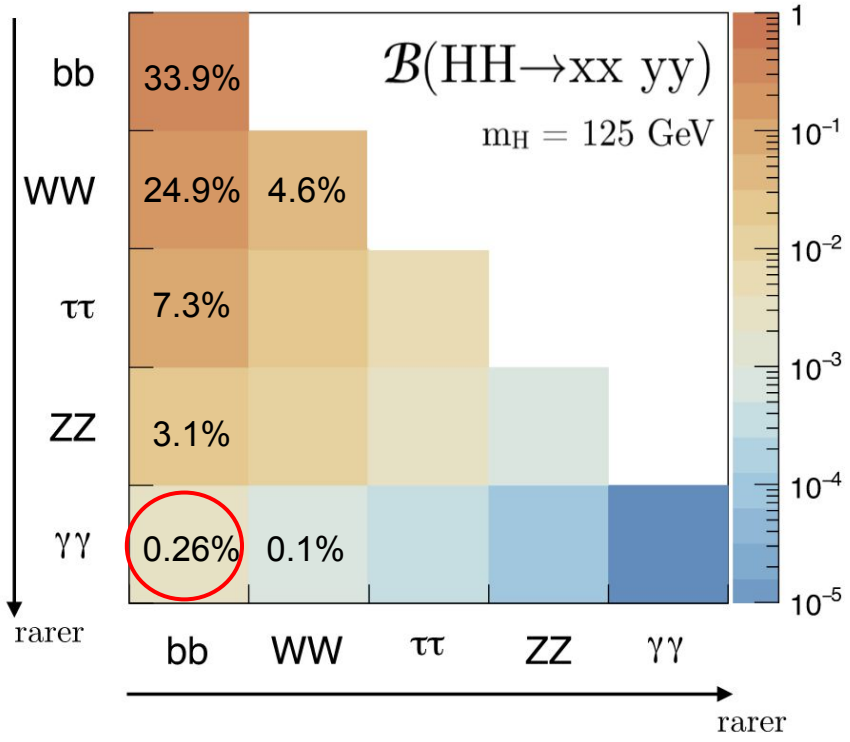
ttH

NLO EW correction

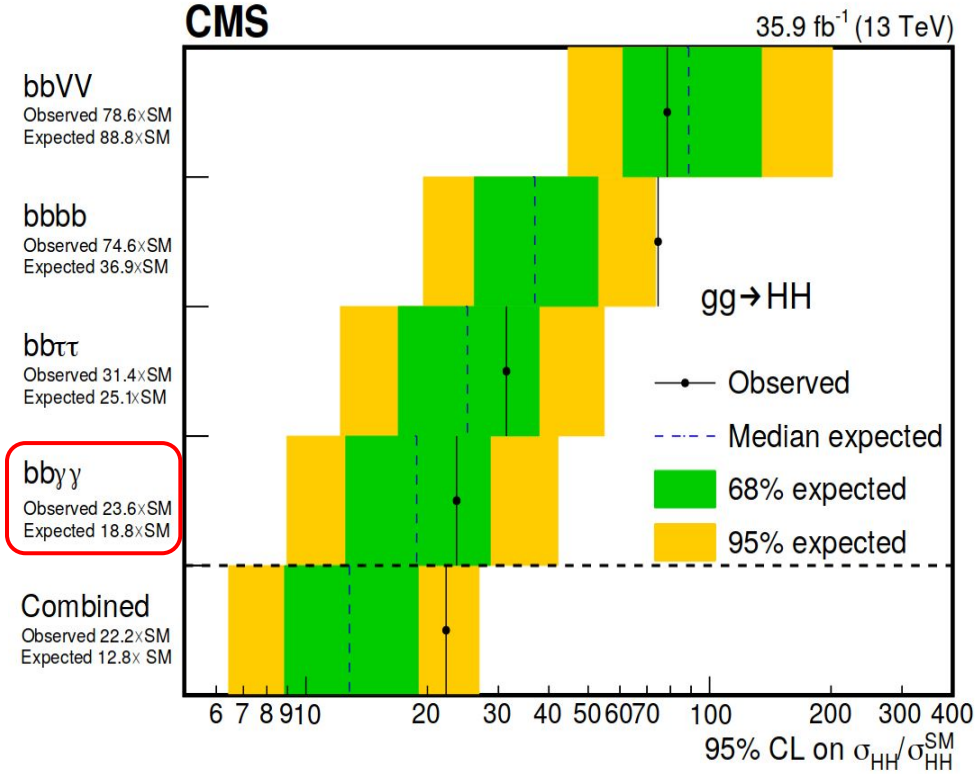


Explored HH final states

- H→bb: large BR & bkg rejection from heavy-flavour jet ID
- H final states with leptons, γ, or τ_h: efficient bkg rejection



Limit on σ/σ^{SM}
Combination using 2016 data



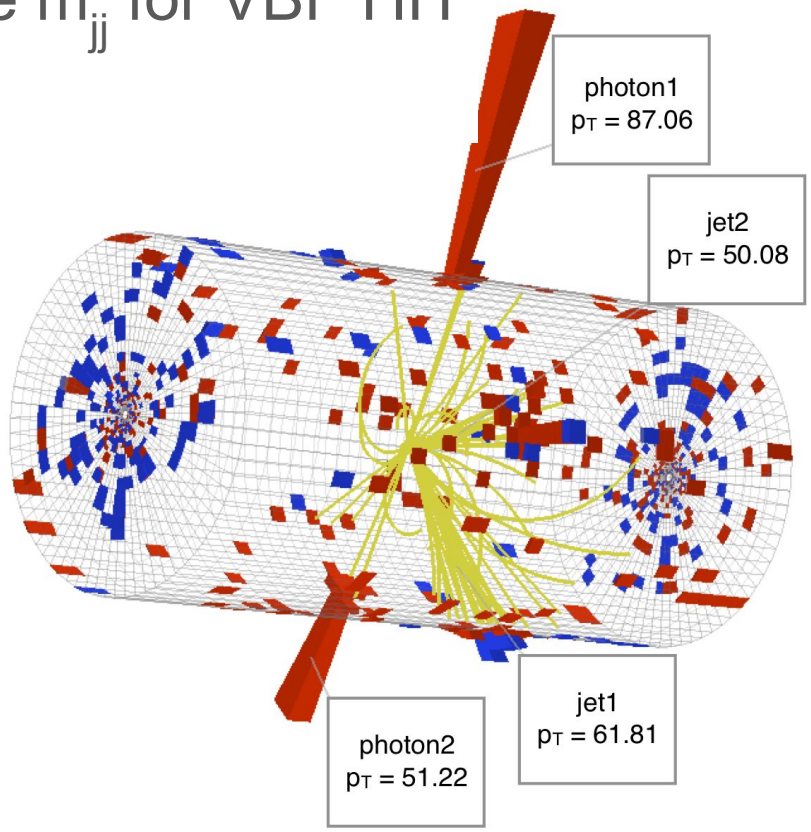
bbγγ among the most sensitive channels

Experimental signature and main bkg

- 2 high-energy photons resonant on m_H = 125 GeV
- 2 b-jets resonant on m_H
- \+ fwd-backward jet pair with large m_{jj} for VBF HH

- Continuum background
  - **γγ+(b)jets** and **γ+(b)jets** with one jet misidentified as a γ
  - ttγγ and t(t)γ+jets with one jet/electron misidentified as a γ

- Single H(γγ) background
  - resonant on m_H
  - **ttH(γγ)** has similar final state



Analysis strategy

- Use full Run 2 dataset (~138 fb^{-1} of data)

Maximize sensitivity through production-enriched categories

- Online selections
- Photons and jets selections
- H→γγ candidate selection

HH categories

- H→bb candidate selection
- DNN classifier to reduce ttH contamination

- Requirements on VBF jets
- BDT multi-class. to distinguish VBF HH, from ggHH and γ(γ)+jets

→ VBF HH categories

fail VBF HH selections

- BDT class. to distinguish ggHH from its bkg

→ ggHH categories

sig. extraction from 2D fit of ($m_{\gamma\gamma}$, m_{bb})

fail HH selections

- BDT to distinguish ttH from its bkg

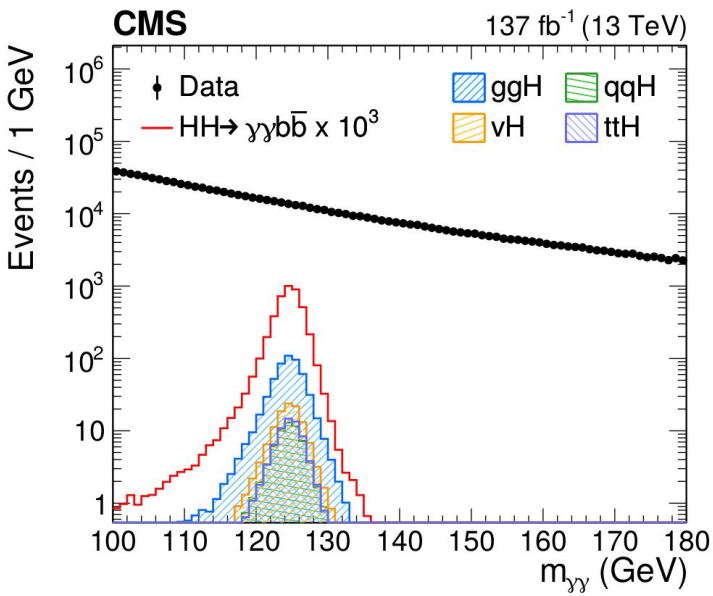
→ ttH categories

1D fit of $m_{\gamma\gamma}$

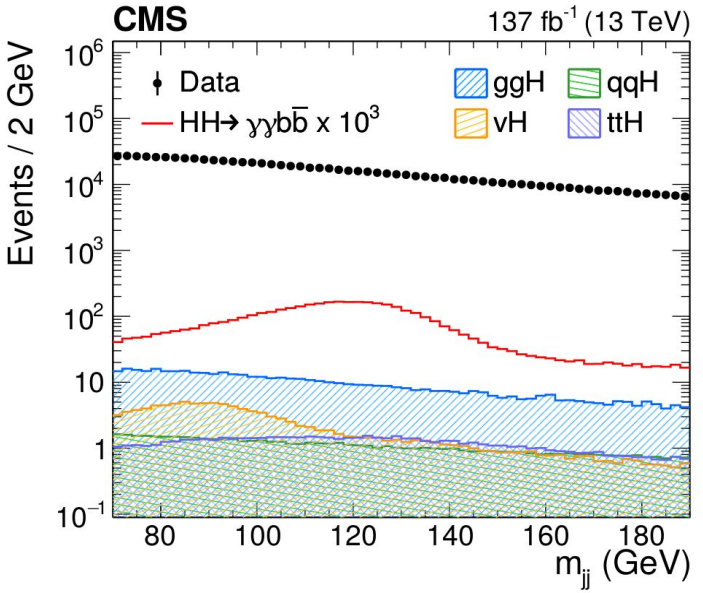
Photon & jet selections

- γ selections optimized for CMS H→γγ measurements
- Consider *anti-kT* jets with *R*=0.4
- H→bb jets
  - p_T(jets) > 25 GeV
  - |η(jets)| < 2.5
  - Two jets with highest b-tag score
  - 70 < m_{jj} < 190 GeV
- VBF HH extra-jets
  - |η| < 4.7 and p_T > 30 GeV
  - Jet pair with highest m_{jj}

$m_{\gamma\gamma}$ of H→γγ candidates



m_{jj} of H→bb candidates

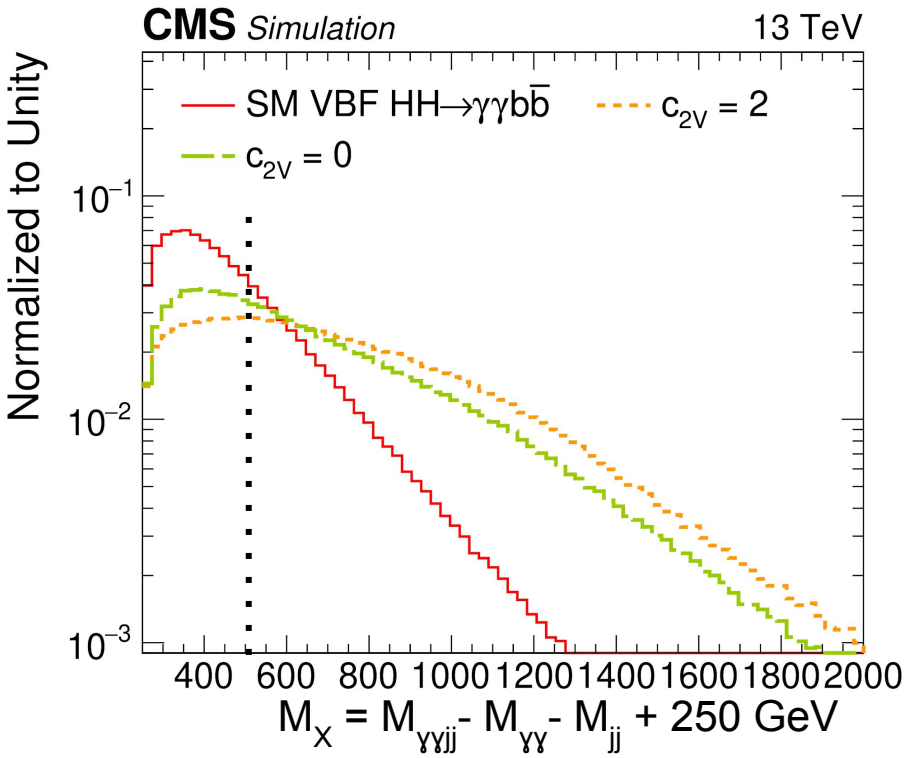


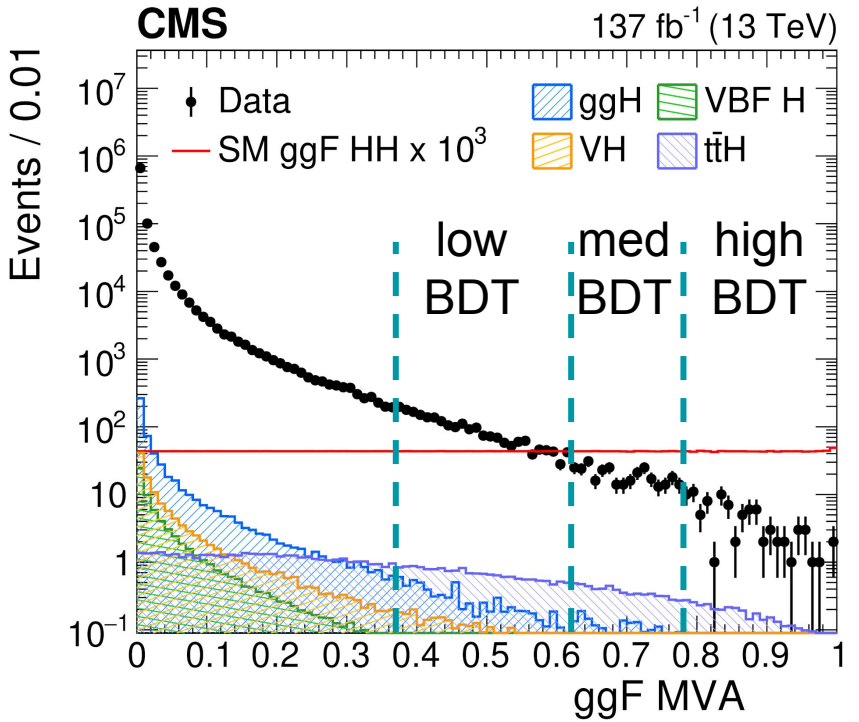
Event categorization

- Optimize sensitivity to SM, anomalous k_λ and c_{2V}
  - 2 four-body mass (M_X) categories targeting VBF HH
  - 3 BDT × 4 M_X categories targeting ggHH
  - 8 ttH categories as in PRL125.061801 [ttH(γγ) CMS measurement]

See H. Mei talk for details

M_X improves sensitivity to BSM

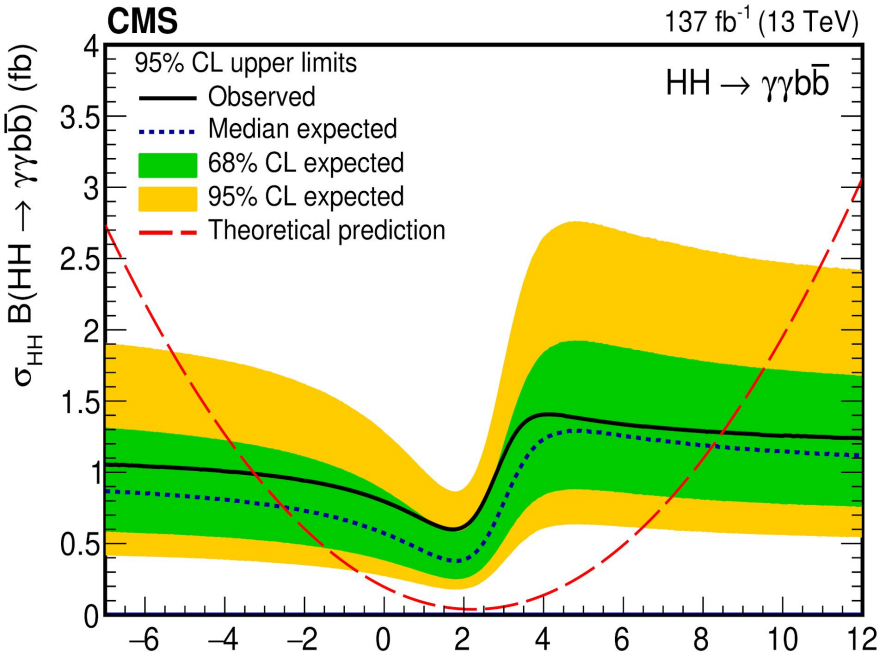




Results

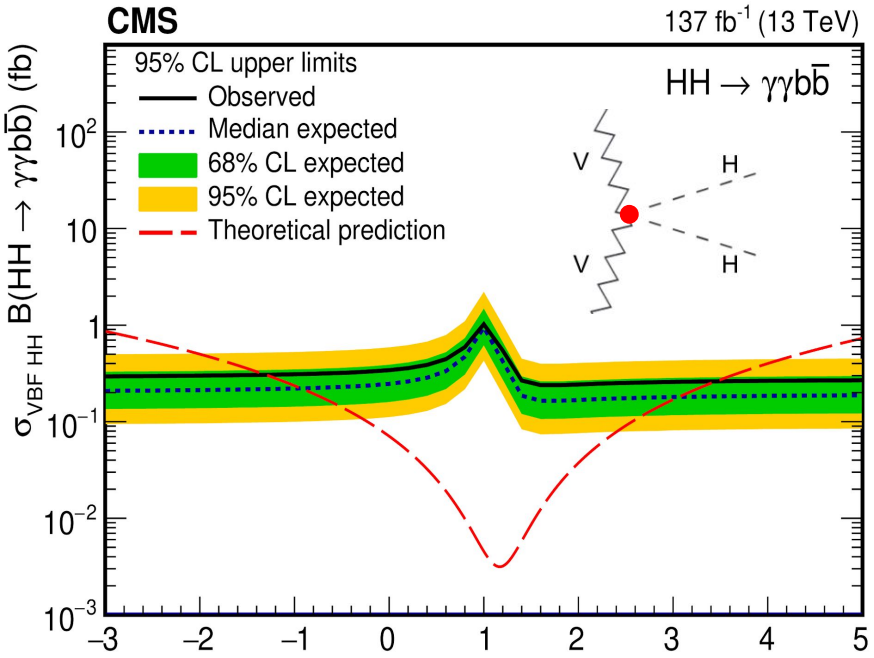
- No deviations from SM observed
- **Obs.**(exp.) upper limit on HH signal strength **7.7**(5.2)×SM

Limit on HH XS×BR vs k_λ



Obs. $k_\lambda \in$ [-3.3, 8.5]
Exp. $k_\lambda \in$ [-2.5, 8.2]

Limit on VBF HH XS×BR vs $k_{2V} = c_{2V} / c_{2V}^{SM}$



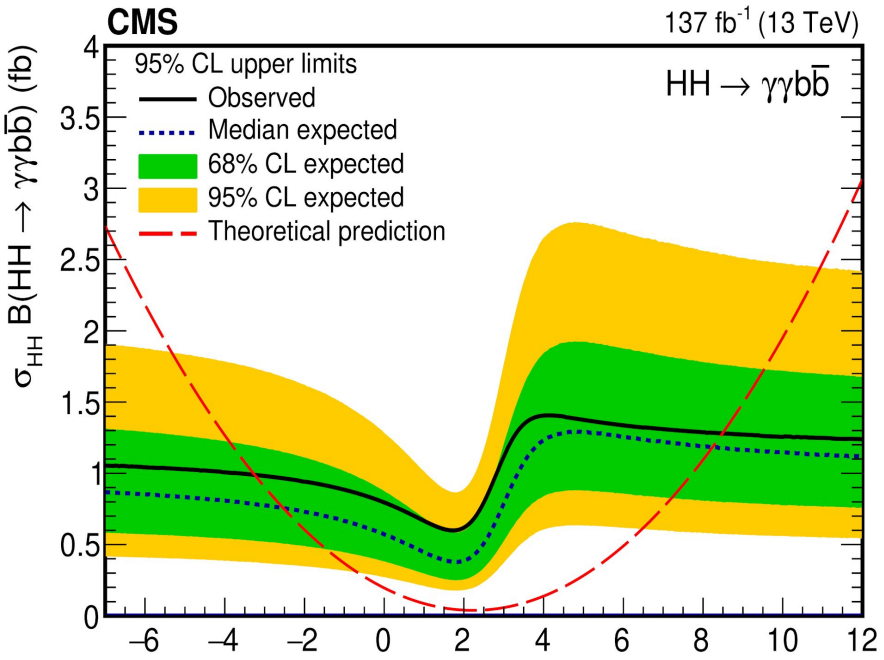
Obs. $k_{2V} \in$ [-1.3, 3.5]
Exp. $k_{2V} \in$ [-0.9, 3.0]

Results

➢ Expected sensitivity close to ATLAS bbγγ

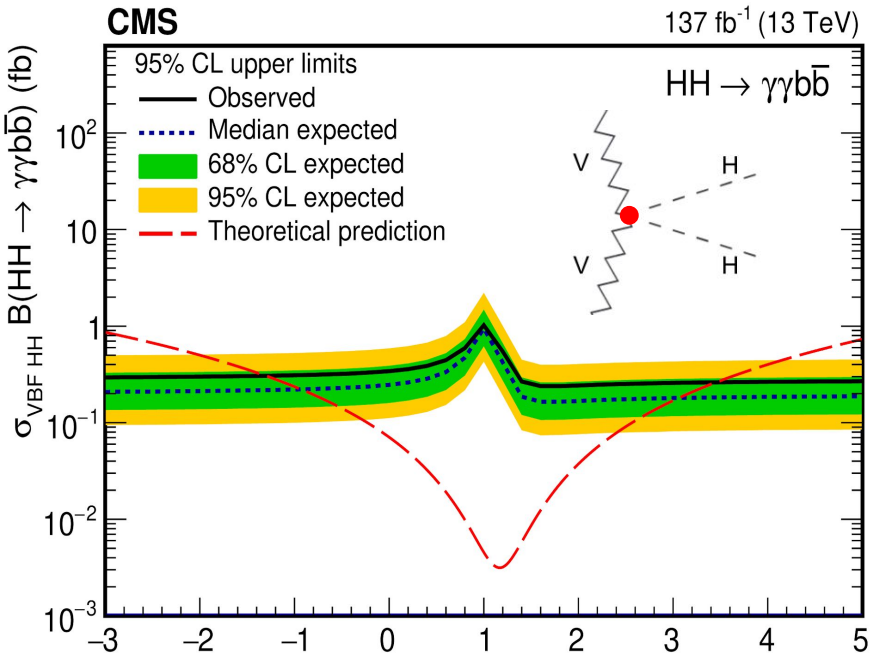
- No deviations from SM observed — **4.1**(5.5)×SM
- **Obs.**(exp.) upper limit on HH signal strength **7.7**(5.2)×SM

Limit on HH XS×BR vs k_λ



Obs. $k_\lambda \in$ [-3.3, 8.5]
Exp. $k_\lambda \in$ [-2.5, 8.2]

Limit on VBF HH XS×BR vs $k_{2V} = c_{2V} / c_{2V}^{SM}$

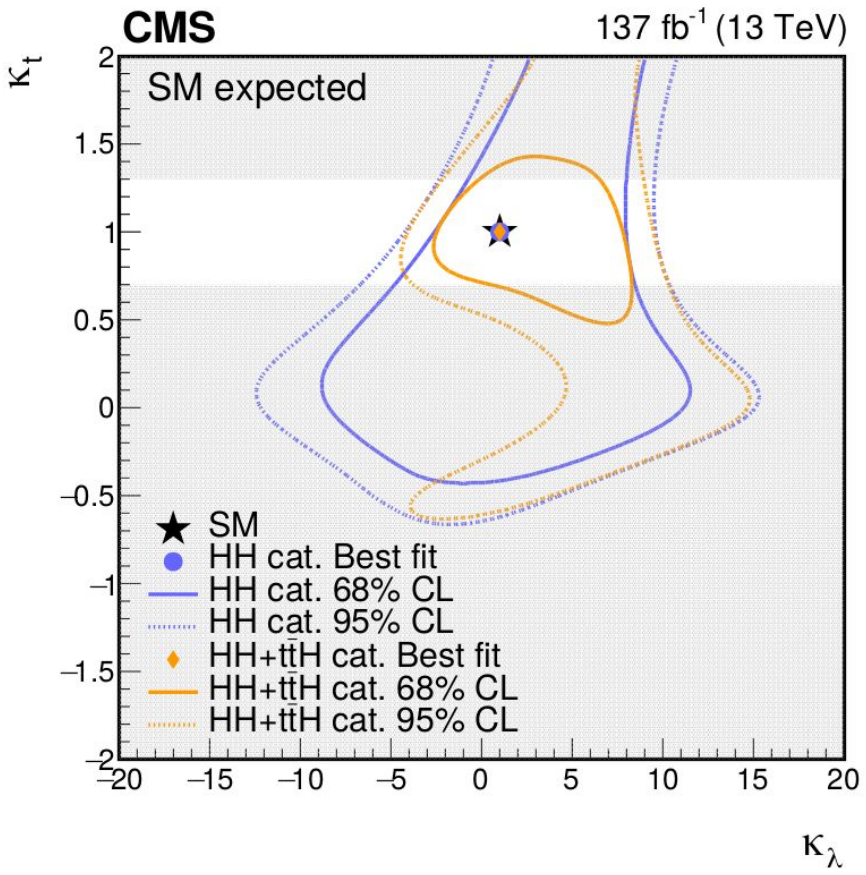


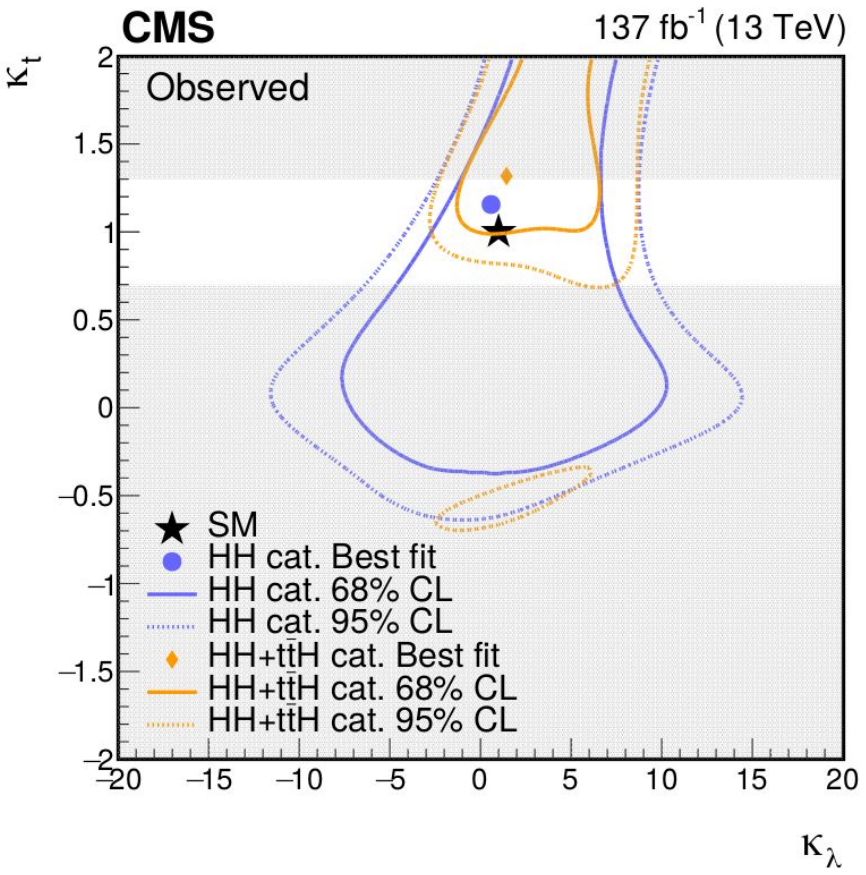
Obs. $k_{2V} \in$ [-1.3, 3.5]
Exp. $k_{2V} \in$ [-0.9, 3.0]

Obs. $k_\lambda \in$ [-1.5, 6.7]
Exp. $k_\lambda \in$ [-2.4, 7.7]

See HH→bbγγ @ ATLAS talk for details

2D likelihood-scan of (k_λ, k_t)



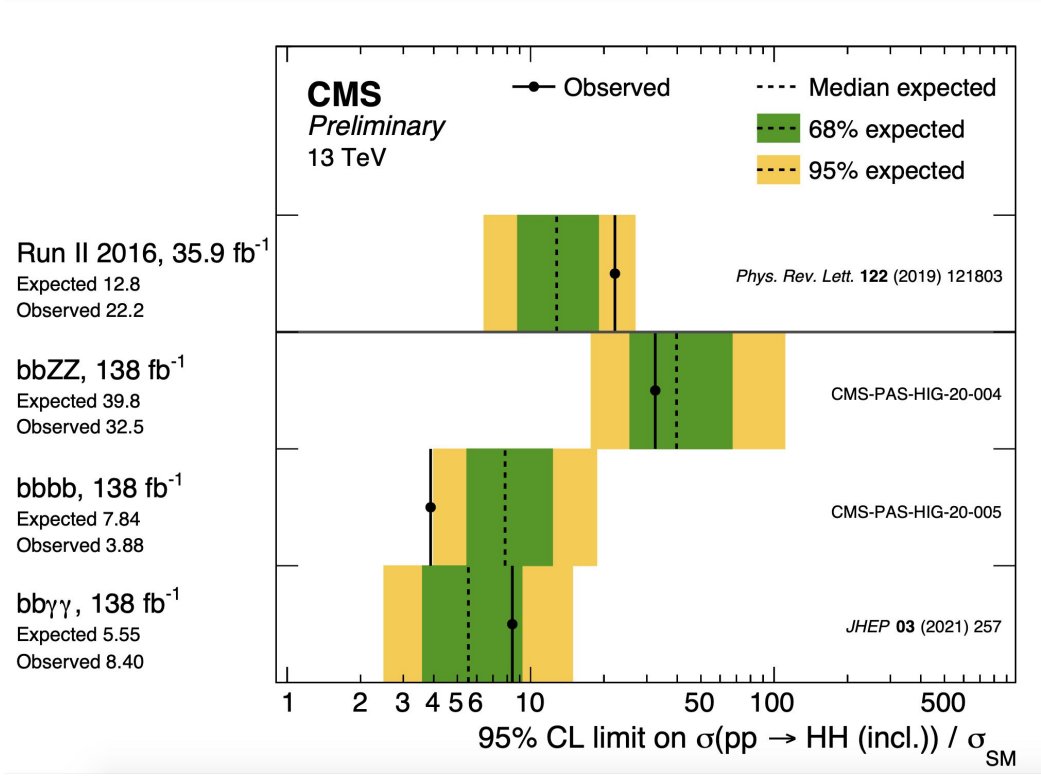


- k_t sensitivity improved through inclusion of ttH categories

Summary

- HH physics offers broad physics program at LHC
  - HHVV, tri-H couplings
- HH→bbɣɣ among the most sensitive channels
- Non-resonant HH→bbɣɣ search with Run 2 data @CMS
  - Results consistent with SM predictions
  - $\sigma(HH \rightarrow bb\gamma\gamma) < 7.7 \times SM$ and $k_\lambda \in [-3.3, 8.5]$ @ 95% C.L.
- Combination of ttH and HH enriched categories
  - Results consistent with SM predictions

Status of non-resonant HH searches with Run 2 data



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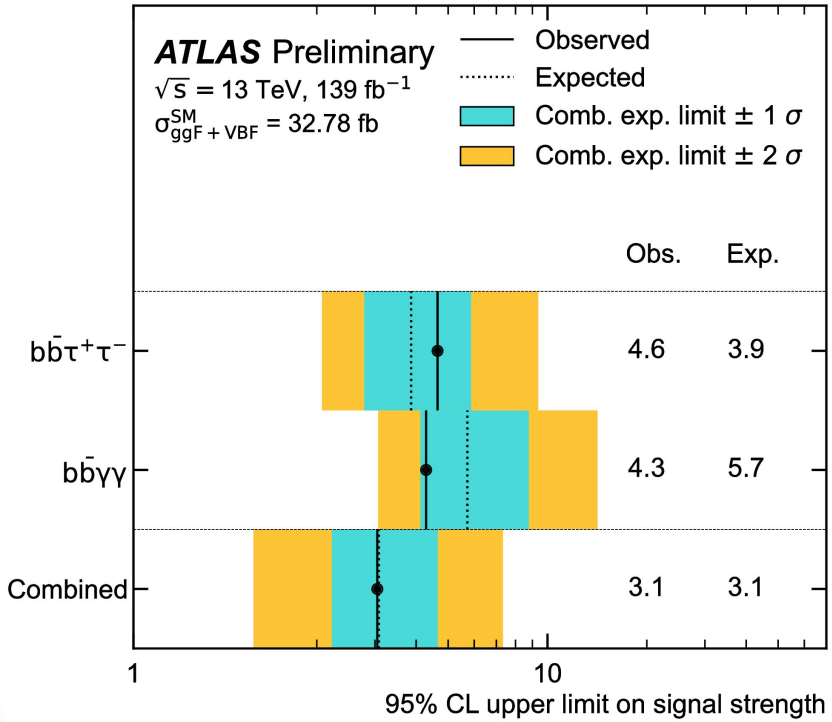


Approaching to sensitivity for SM HH

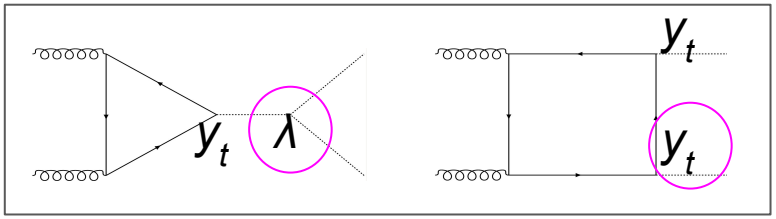
Exciting time ahead!!

BACKUP

Sensitivity to effective field theory (EFT) couplings

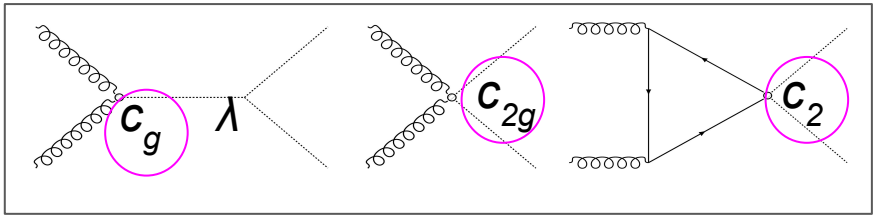
- ggHH production described by 5 diagrams:

SM terms

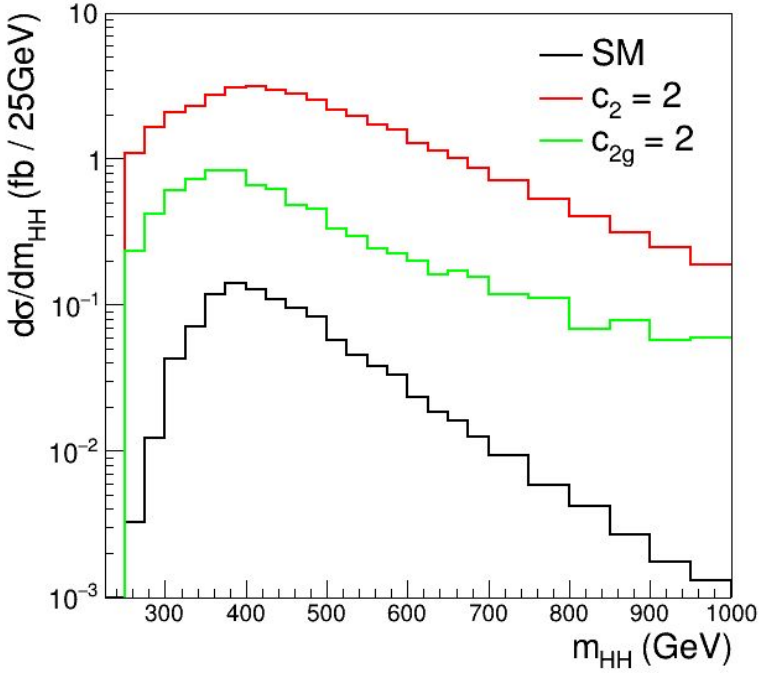


BSM terms

5 parameters



- Modification of total and differential XS



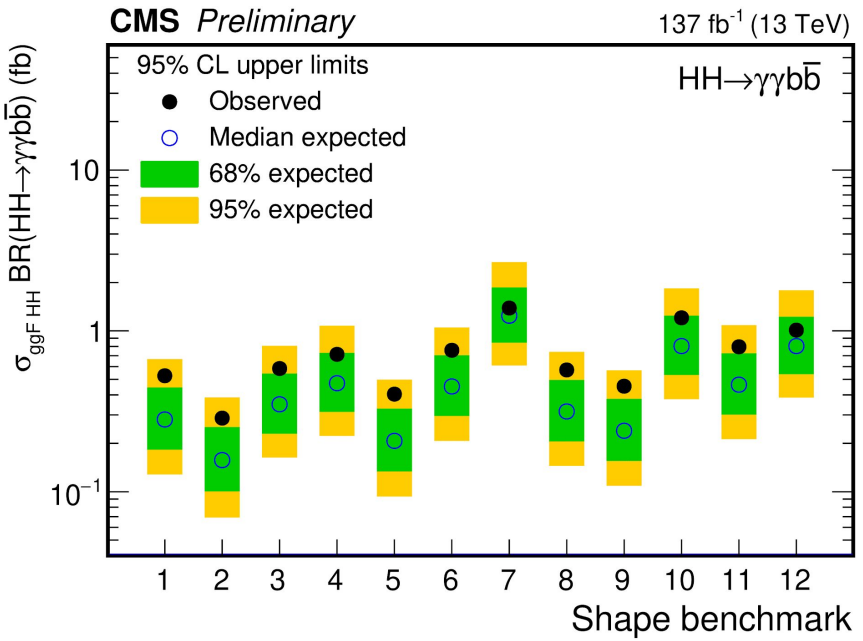
➢ Constraints on single couplings, e.g. c_2

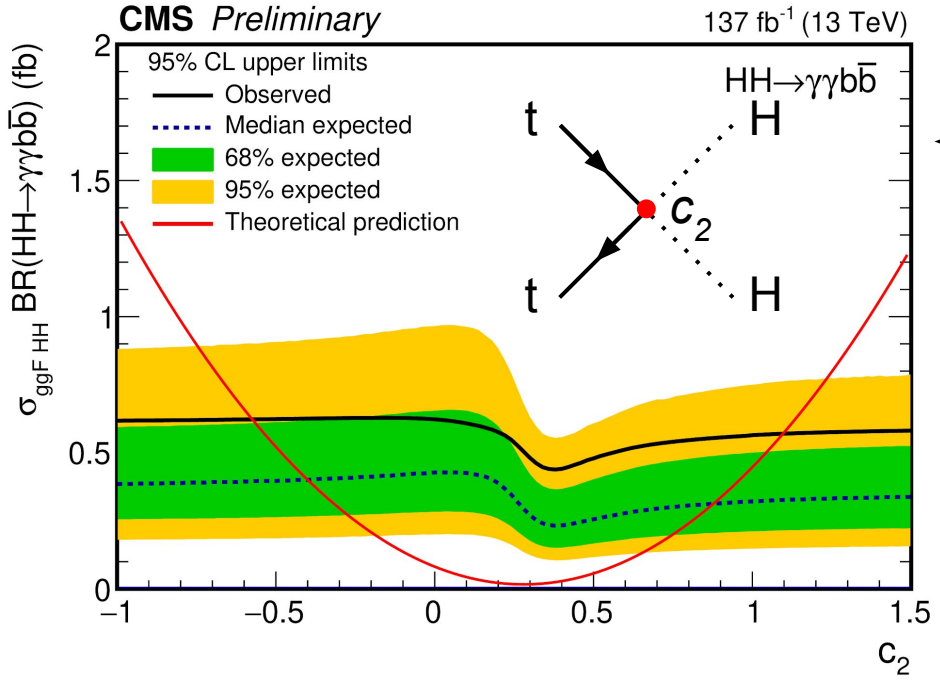
➢ Benchmarks in the 5D parameter space defined to explore the EFT sensitivity JHEP09(2018)057, JHEP03(2020)091

EFT interpretation

Limit on ggHH XS×BR for benchmarks of JHEP04(2016)126

- Obs. limits ranging from 0.3 to 1 fb
- Kinematics variations between benchmarks → different upp. limit





← Limit on ggHH XS×BR vs c_2

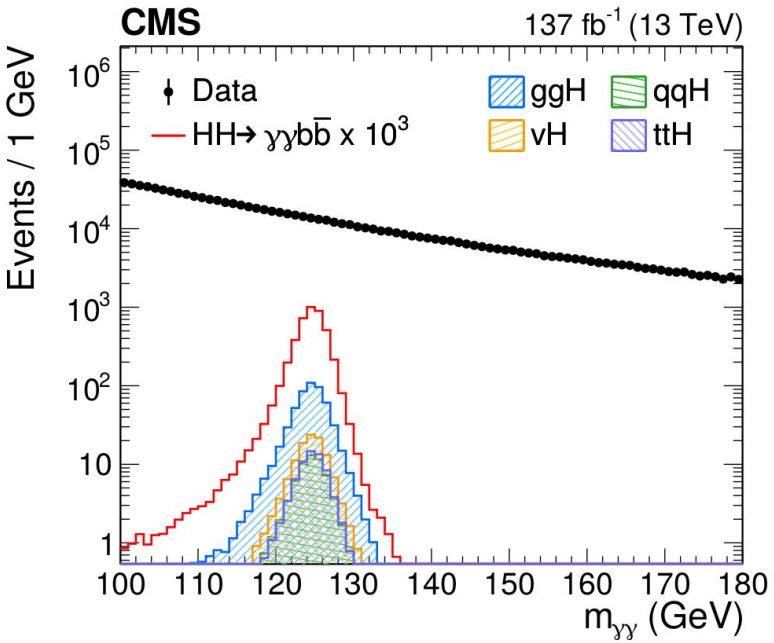
- Special role of H and t in several BSM theories
- HHtt effective coupling

Obs. $c_2 \in$ [-0.6, 1.1]
Exp. $c_2 \in$ [-0.4, 0.9]

Online requirement and photon selections

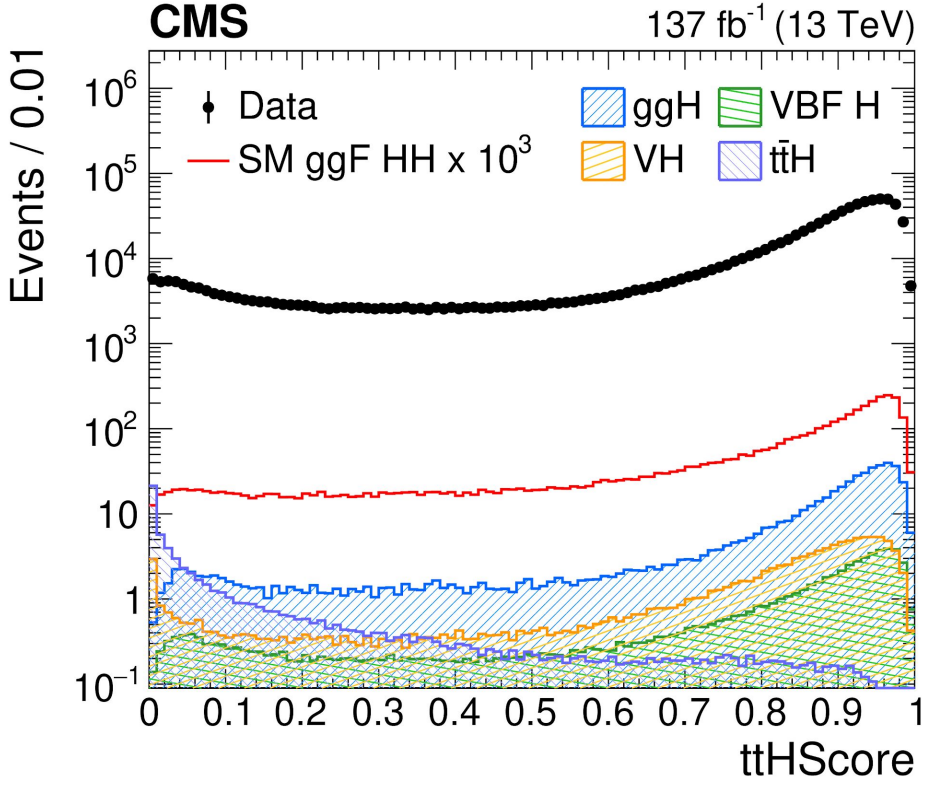
- Select online events with two high-energy photons
  - Shower shape, isolation, and $m_{\gamma\gamma}$
- MVA-based ID requirement offline
  - ~99% efficiency on photons from primary interaction vertex
  - ~50% rejection on other photons
- Electron veto
- $H \rightarrow \gamma\gamma$ candidate using lead and sublead γ's
  - $p_T(\gamma_{LEAD})/m_{\gamma\gamma} > 1/3$ and $p_T(\gamma_{SUBLEAD})/m_{\gamma\gamma} > 1/4$
  - $100 < m_{\gamma\gamma} < 180$ GeV

$m_{\gamma\gamma}$ of HH candidates from data and MC events



Separate ttH(γγ) from HH selections

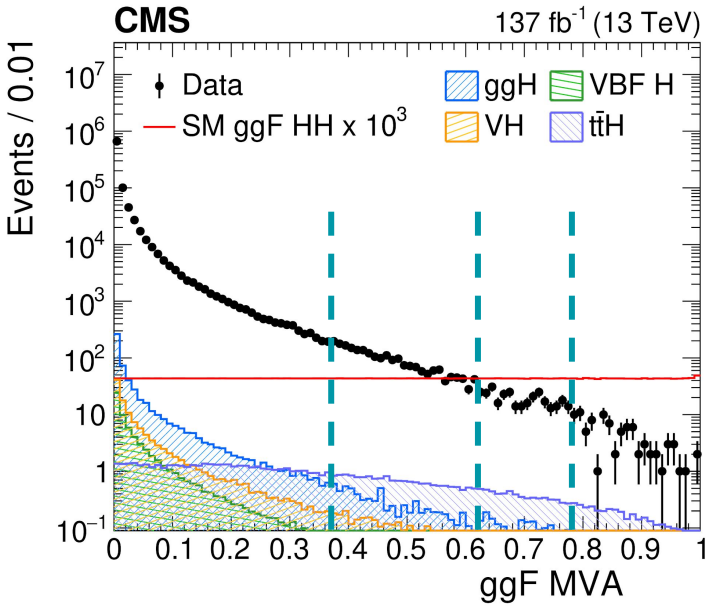
- Important and resonant bkg contribution
  - Maximise separation between HH and ttH events
- low-level information from individual objects
- high-level information from event kinematics
- DNN trained with MC events
  - Signal: SM ggHH + BSM benchmarks
  - Background: ttH(γγ)
- Simultaneous optimization of ttH-score cut and MVA boundaries



Reject continuum background from ggHH selections

- BDT multi-classifier with 3 classes:
  - Signal: SM ggHH + all benchmarks
  - Bkg1: γγ+jets and Bkg2: γ+jets
- 19 training variables
  - Kinematic
  - Object ID
  - Object resolution
- Optimize categories to maximize $S/\sqrt{B}$ in 2 steps:

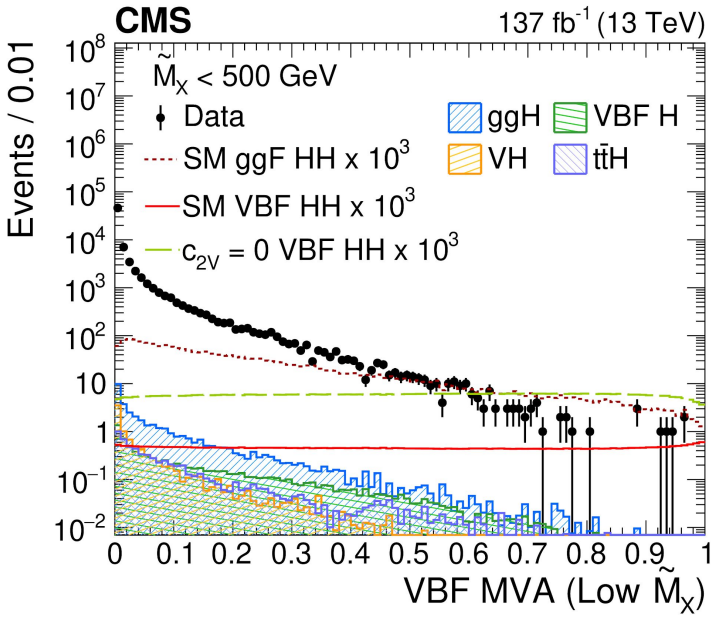
1. Optimize 3 BDT-score categories together with the ttH score cut
2. Optimize 4 M_X categories × 3

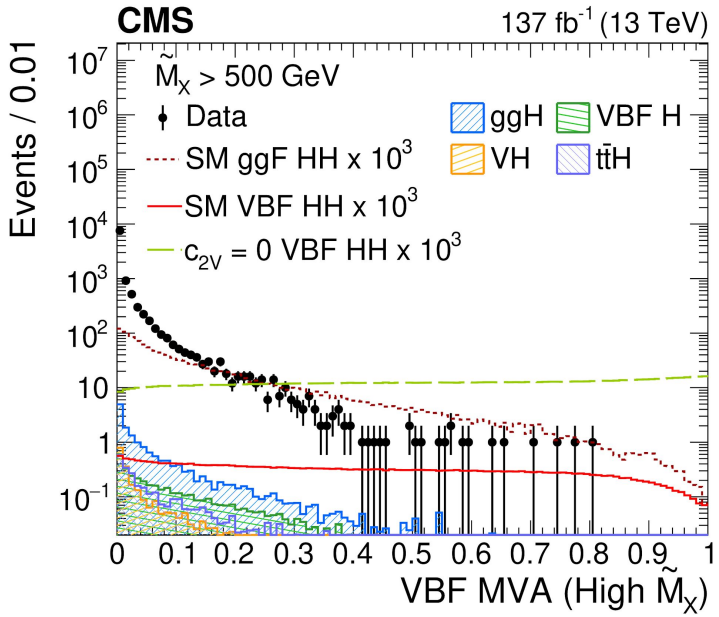


Category	MVA	$\widetilde{M}_X$ (GeV)
VBF CAT 0	0.52–1.00	>500
VBF CAT 1	0.86–1.00	250–500
ggF CAT 0	0.78–1.00	>600
ggF CAT 1		510–600
ggF CAT 2		385–510
ggF CAT 3		250–385
ggF CAT 4	0.62–0.78	>540
ggF CAT 5		360–540
ggF CAT 6		330–360
ggF CAT 7		250–330
ggF CAT 8	0.37–0.62	>585
ggF CAT 9		375–585
ggF CAT 10		330–375
ggF CAT 11		250–330

VBF HH selections

- Sensitivity to SM VBF HH and $c_{2V}= 0$
- BDT multi-classifier with 3 classes:
  - signal: SM + $c_{2V} = 0$ VBF HH samples
  - bkg1: ggHH, bkg2: ɣ(ɣ)+jets
- Re-use ggHH-BDT variables + additional variables exploiting VBF kinematics
- Separate BDT trainings for $M_X \gtrless 500$ GeV





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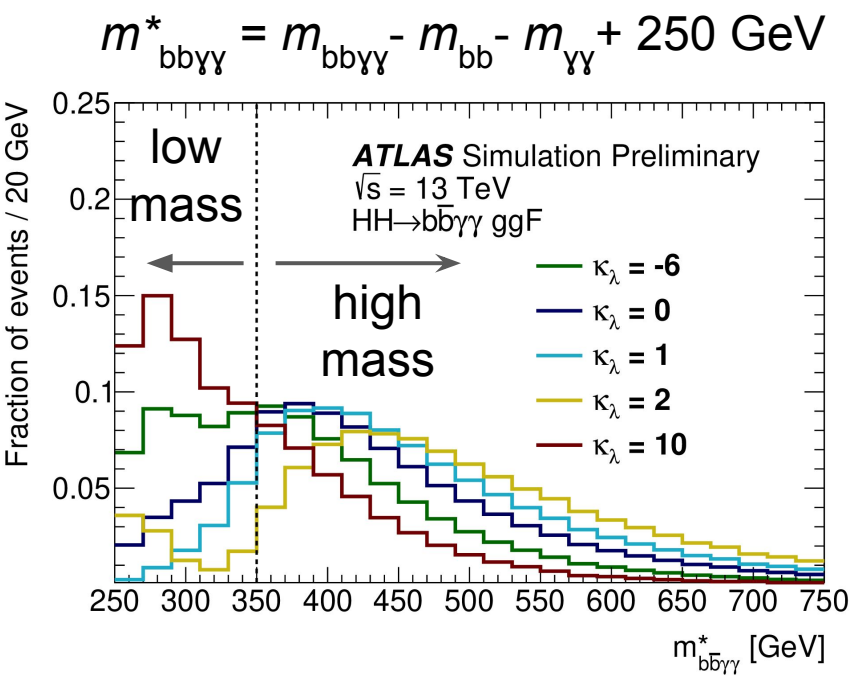
HH→bbγγ at ATLAS with 139 fb^{-1} - overview

- Non-resonant + resonant (spin 0) HH search
- Clean but rare final state:
  - bkg from jets(+γγ) → γ and b-jet ID requirements
  - bkg from $t\bar{t}H(\gamma\gamma)$ & $t\bar{t}\gamma\gamma$ → veto events with e, μ, or ≥6 jets
- BDT classifiers to separate HH signal from main bkgs
- Four-body mass $m^*_{bb\gamma\gamma}$ to improve BSM sensitivity
  - 2 $m^*_{bb\gamma\gamma}$ × 2 BDT score cat's for non-resonant
  - $m^*_{bb\gamma\gamma}$ selection around resonance mass for X→HH
- Fit $m_{\gamma\gamma}$ for signal extraction

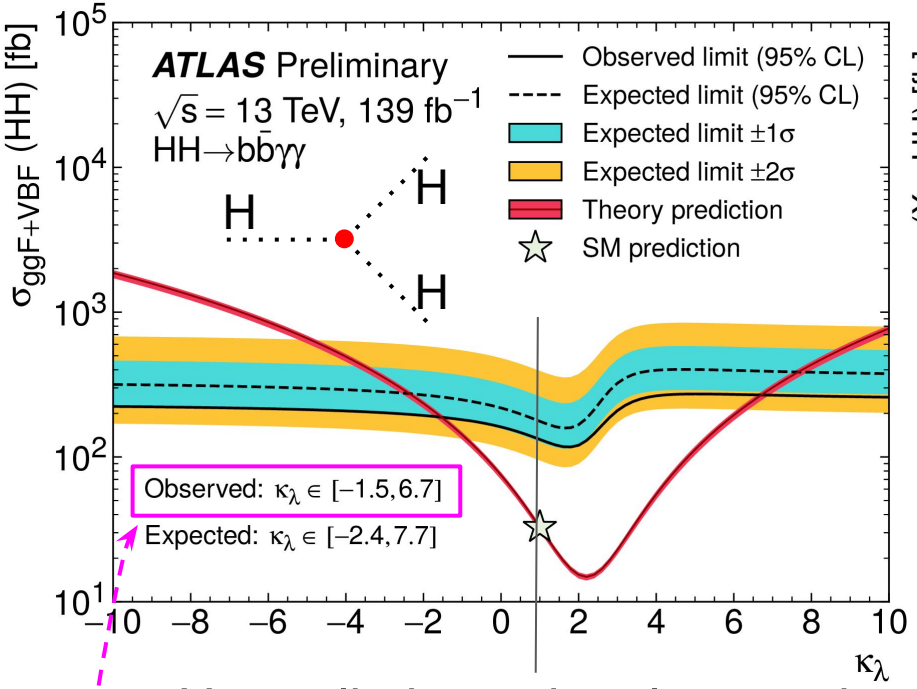


ATLAS-CONF-2021-016

HH→bbγγ at ATLAS with 139 fb^{-1} - results

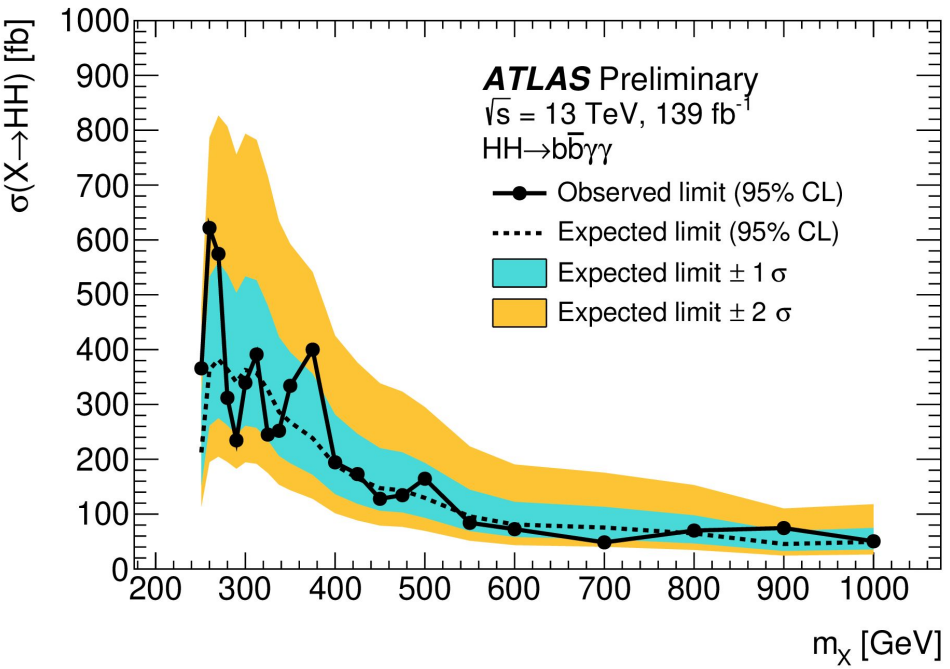
- No deviations from SM observed

Limit on HH XS vs k_λ



Upper limit on signal strength
obs.(exp.) = **4.1**(5.5)×SM

Limit on spin 0 resonance with mass m_X and narrow width



Obs. limit between 620 and 50 fb for $m_X \in [251, 1000]$ GeV

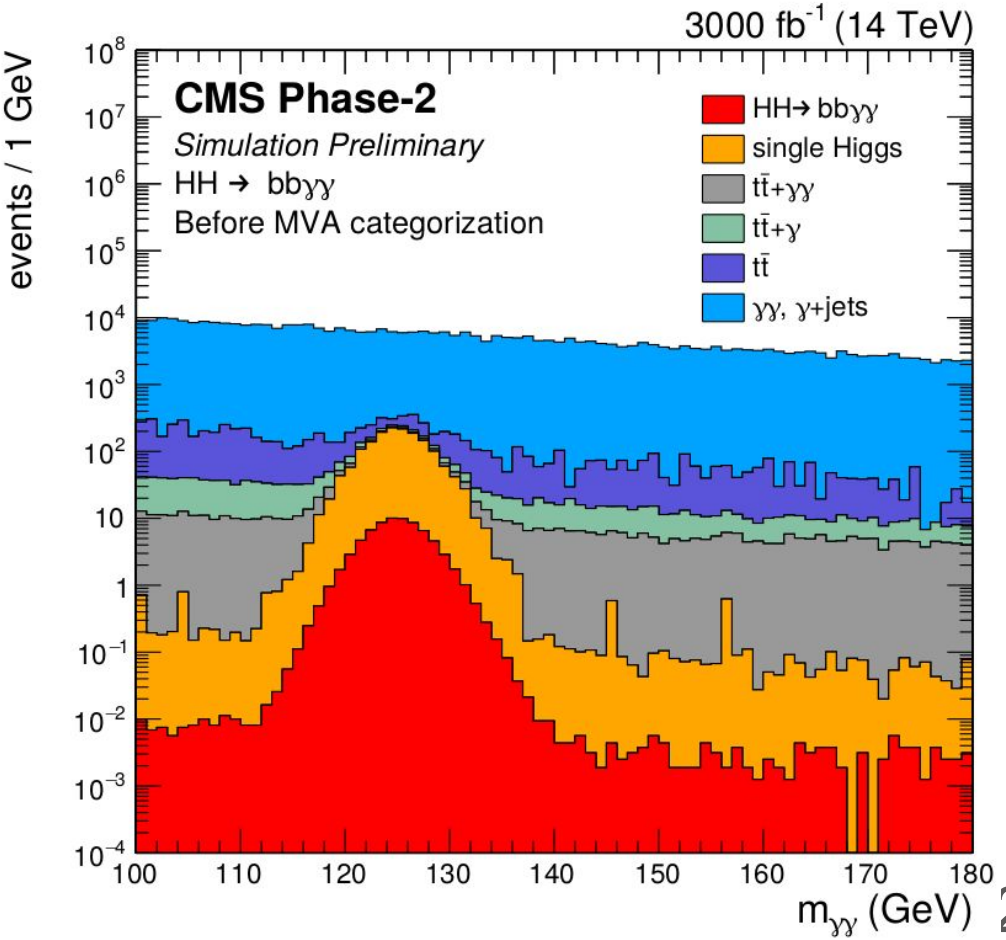
Best HH results to date

Projection for 3000 fb^{-1}

- Huge number of MC events required
  - use Delphes fast-simulation for particle-detector interaction
- Pre-select events compatible with *HH→bbγγ*

Main backgrounds

- *γγ+jets*
- *γ+jets* with one jet misidentified as a photon
- single-Higgs background, in particular *ttH*



Projections for SM analysis @14TeV and 3000 fb^{-1}

- $HH \to bb\gamma\gamma$ is the most sensitive channel with 1.8σ significance
- Combining all the channels 2.6σ significance

Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
$bbbb$	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(l\nu l\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	**1.8**	**1.8**	**1.1**	**1.1**
$bbZZ(llll)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

Projections for di-Higgs anomalous couplings

- Most stringent constraint from *HH→bbγγ* channel
  - The mass categorization removes the degeneracy between the two minima

HH combination

Only bbγγ channel splitted in mass categories