Institute of High Energy Physics
Chinese Academy of Sciences

ATLAS EXPERIMENT

CMS Compact Muon Solenoid

Resonant and non-resonant HH channel

SM@LHC

26 April 2021

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on behalf of the CMS and ATLAS Collaborations

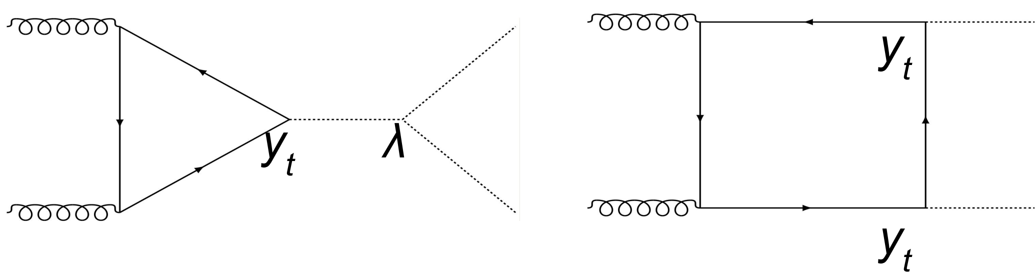
Outline

- Motivation for the HH searches
- Latest results from CMS and ATLAS experiments
- Outlook for Run 3 and HL-LHC

Non-resonant HH search

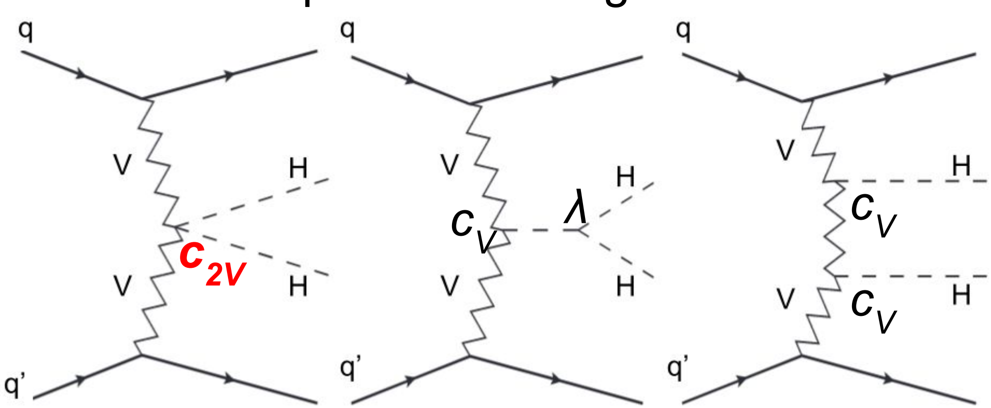
- HH production is sensitive to the Higgs trilinear coupling λ
- VBF HH is sensitive to c_{2V} coupling

ggF production (ggHH) diagrams at LO

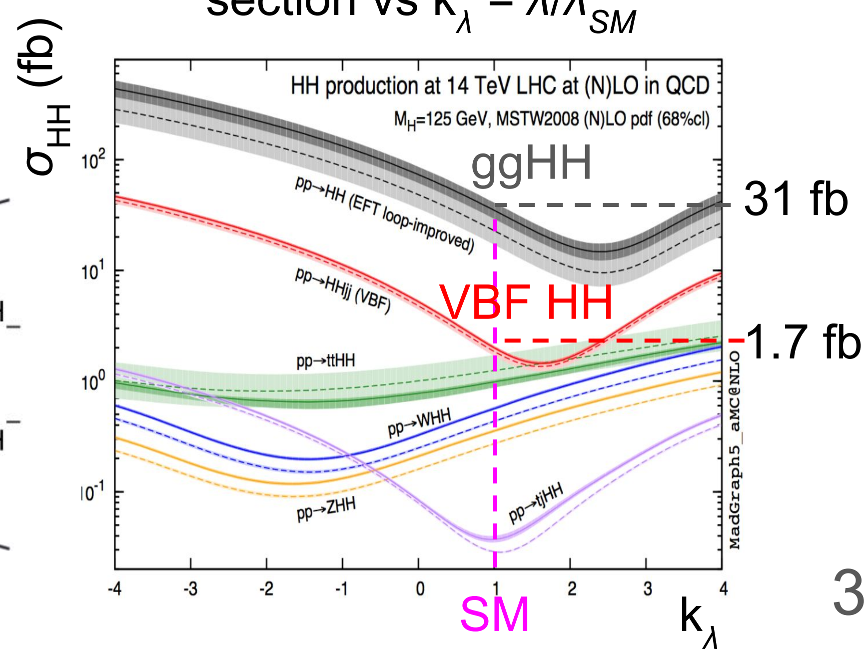


Sensitivity @LO to λ and c_{2V} parameters

VBF HH production diagrams at LO



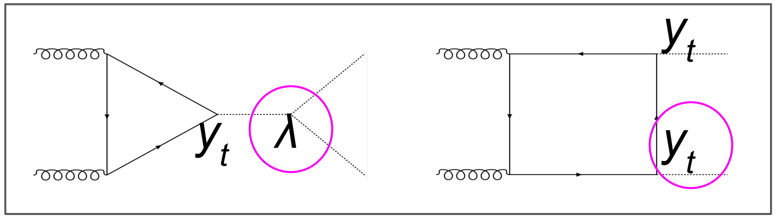
HH production cross section vs $k_\lambda = \lambda/\lambda_{SM}$



Sensitivity to effective field theory (EFT) couplings

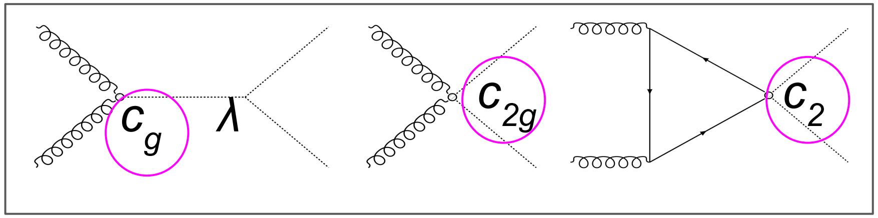
- ggHH production described by 5 diagrams:

SM terms

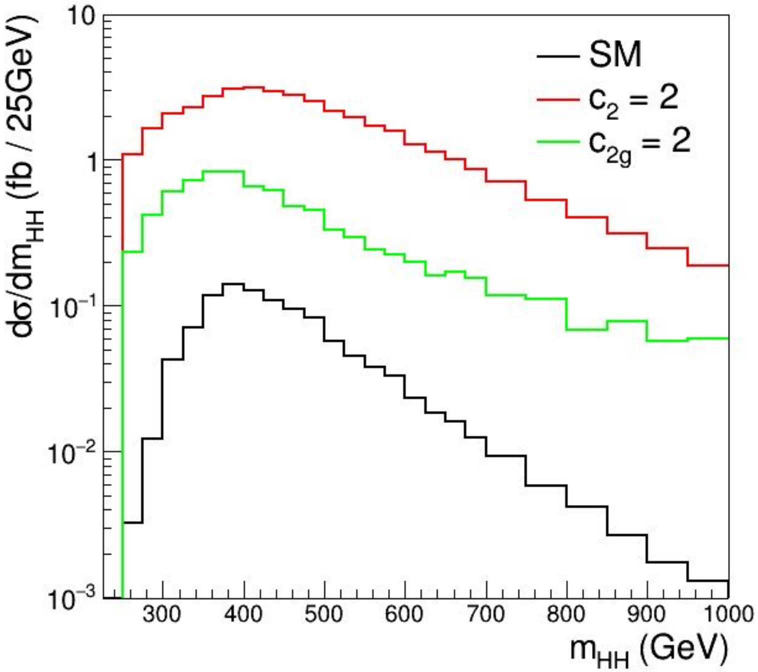


BSM terms

5 parameters



- Modification of total and differential XS

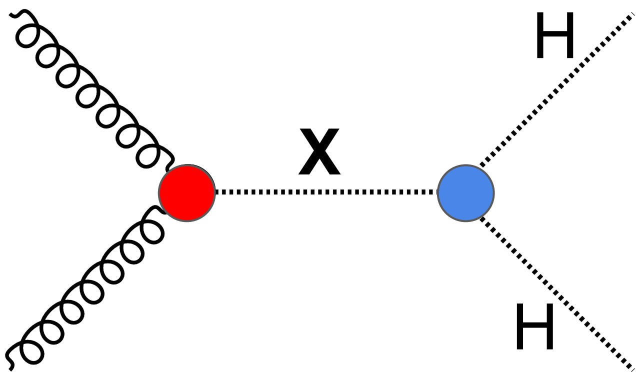


➢ Constraints on single couplings, e.g. c_2

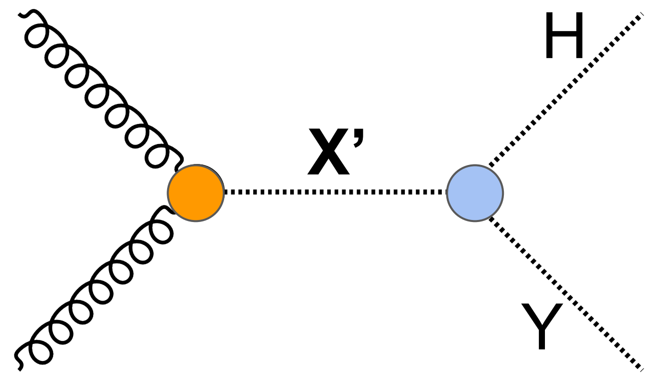
➢ Benchmarks in the 5D parameter space defined to explore the EFT sensitivity JHEP09(2018)057, JHEP03(2020)091

Resonant HH searches

X→HH



X’→YH



- Spin 0 resonances
  - Randall-Sundrum radion
  - 2 H doublets models (2HDM)
- Spin 2 resonances
  - Randall-Sundrum graviton

\+ VBF production mechanism

- Spin 0 resonances
  - Next-to-minimal supersimmetry models (NMSSM)

Non-resonant HH searches with 2016 data (~36 fb^{-1})

- No deviations from SM observed

Obs.(exp.) upper limit on σ(HH)

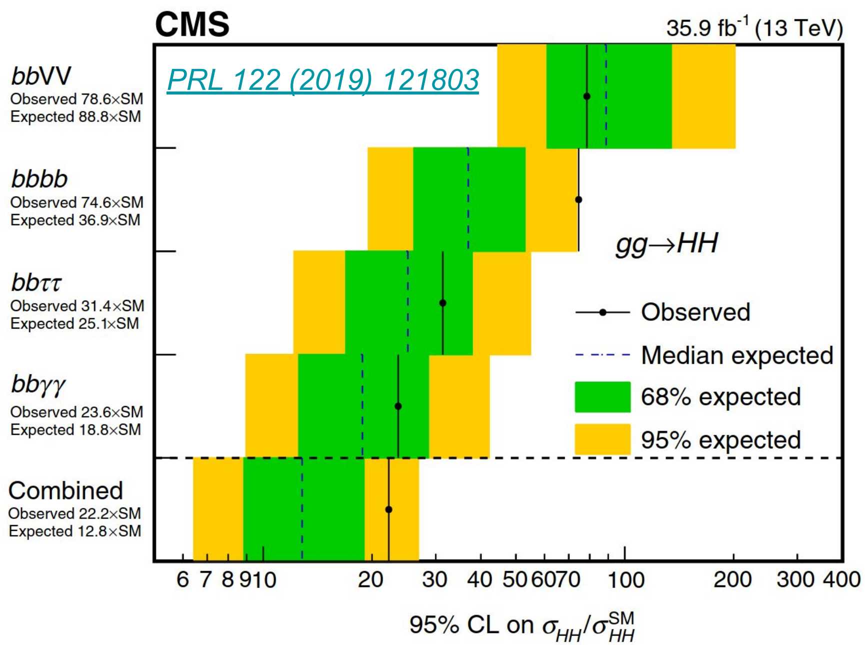
22.2(12.8)×SM from CMS

6.9(10)×SM from ATLAS

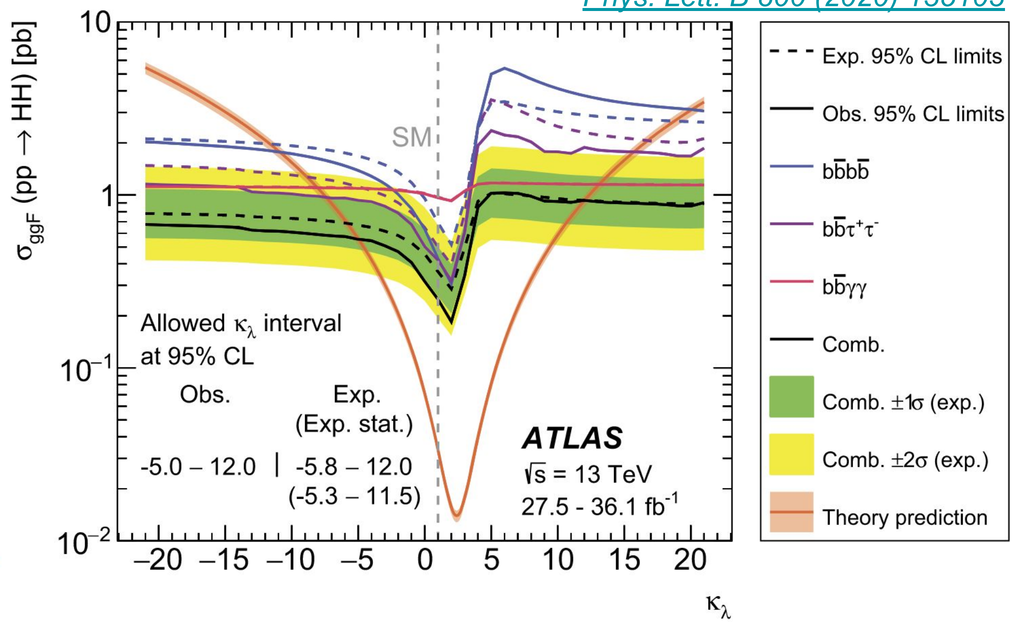
Obs. k_λ exclusion

$-11 < k_\lambda < 17$ @ 95% C.L. from CMS

$-5 < k_\lambda < 12$ @ 95% C.L. from ATLAS



Phys. Lett. B 800 (2020) 135103

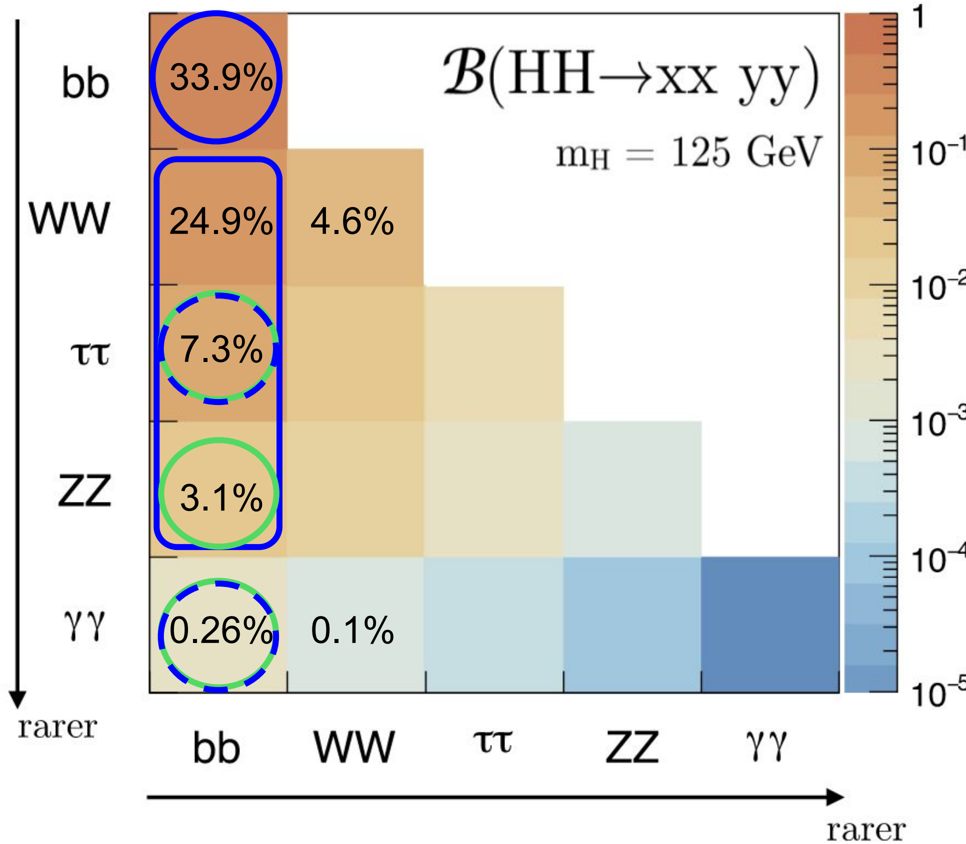


New results with Run 2 dataset (~140 fb^{-1}) in this presentation

Explored final states

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

Available Run 2 results by **CMS** & **ATLAS**



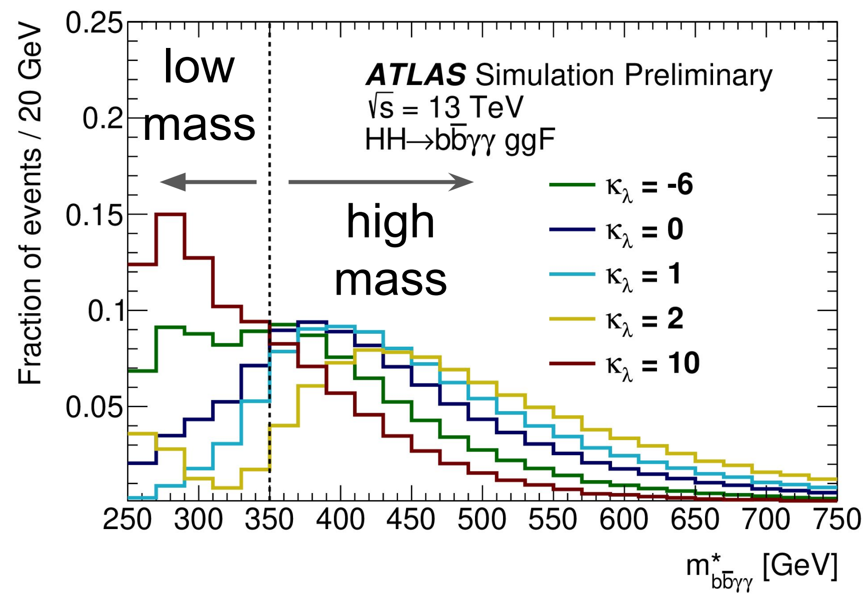
➢ Analyses ongoing to cover more channels

➢ No HH golden channel
  - Channel sensitivity dependent on the SM/BSM interpretation

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

$$m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250\text{ GeV}$$

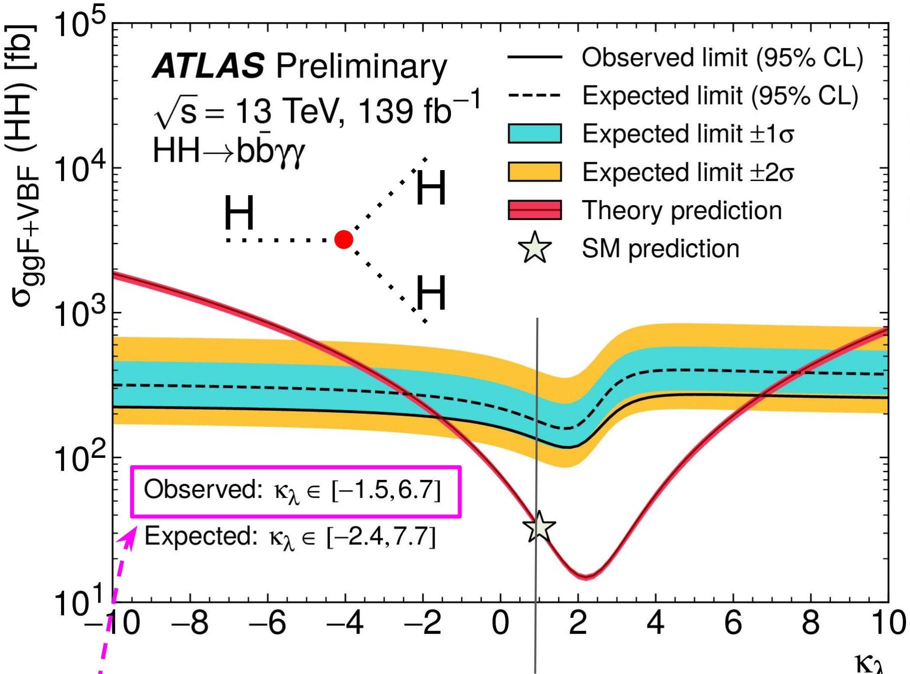


ATLAS-CONF-2021-016

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

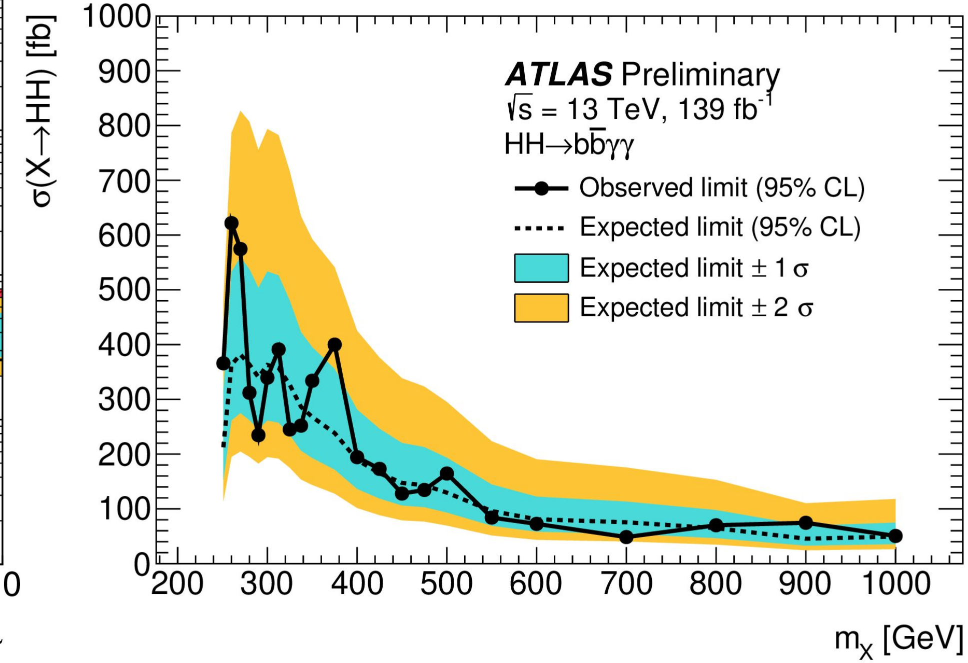
- No deviations from SM observed

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



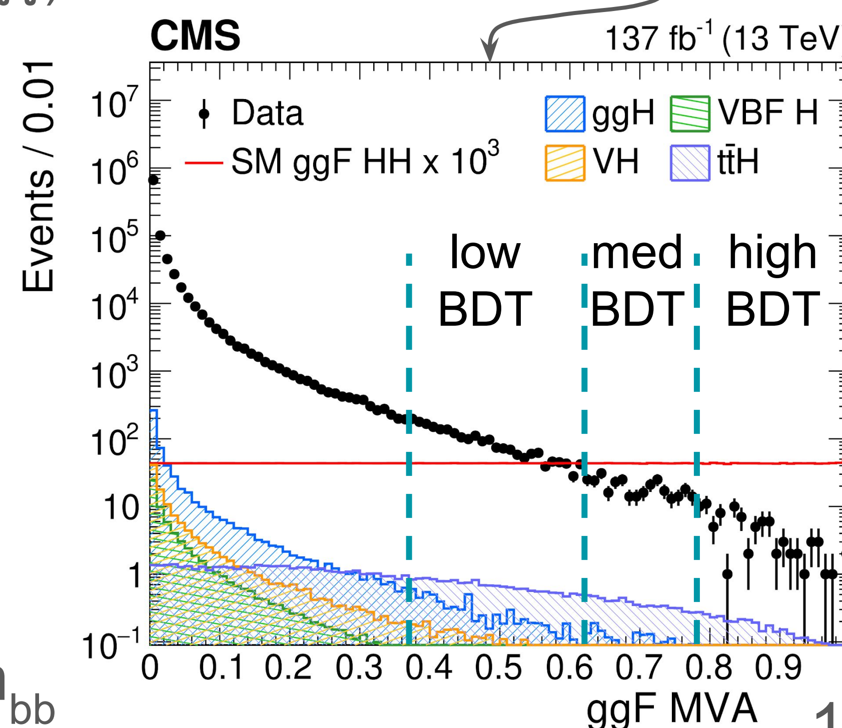
Obs. limit between 620 and 50 fb for $m_X \in$ [251, 1000] GeV

Best HH results to date

JHEP03(2021)257

HH→bbγγ at CMS with 137 fb^{-1} - overview

- Non-resonant HH search
- Selections similar to ATLAS bbγγ
- MVA strategy to optimize signal-bkg separation
  - BDT to separate ggF or VBF HH from γ(γ)+jets events
  - DNN to separate HH from $t\bar{t}H(\gamma\gamma)$ events
- Optimize sensitivity to SM, anomalous k_λ, and c_{2V}
  - 3 BDT × 4 $m^*_{bb\gamma\gamma}$ categories targeting ggHH
  - 2 $m^*_{bb\gamma\gamma}$ categories targeting VBF HH
- Signal extraction from simultaneous fit of $m_{\gamma\gamma}$ and m_{bb}

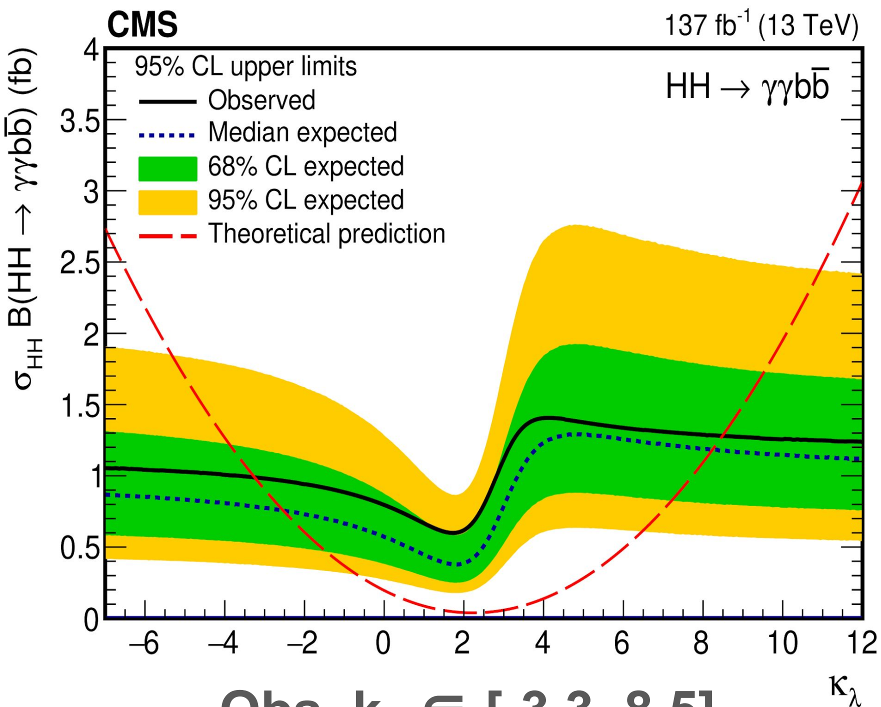


JHEP03(2021)257

HH→bbɣɣ at CMS with 137 fb^{-1} - results

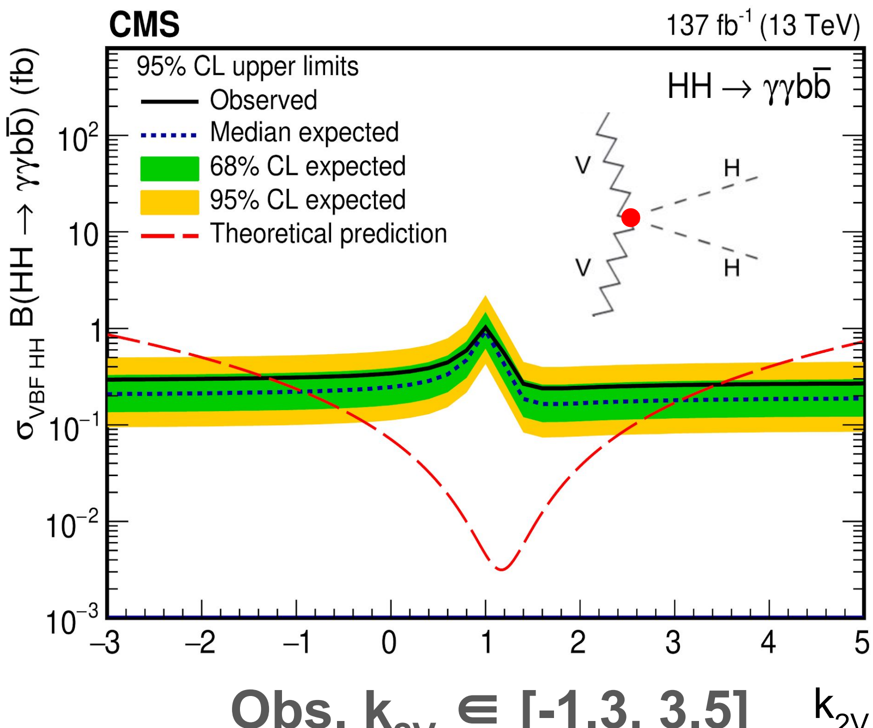
- No deviations from SM observed
- **Obs.**(exp.) upper limit on HH signal strength **7.7**(5.2)×SM

Limit on HH XS×BR vs k_λ



Obs. k_λ ∈ [-3.3, 8.5]
Exp. k_λ ∈ [-2.5, 8.2]

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



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

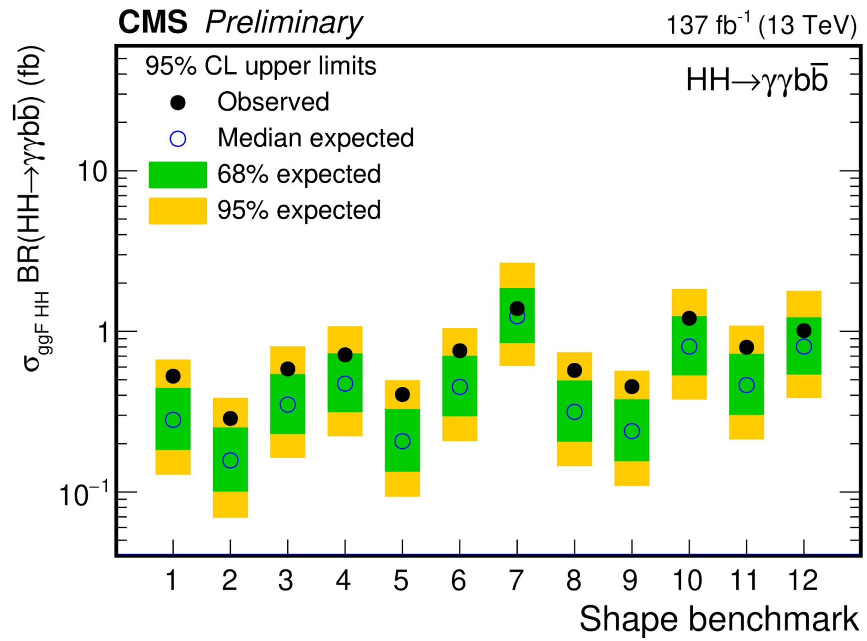
➢ Expected sensitivity close to ATLAS bbɣɣ

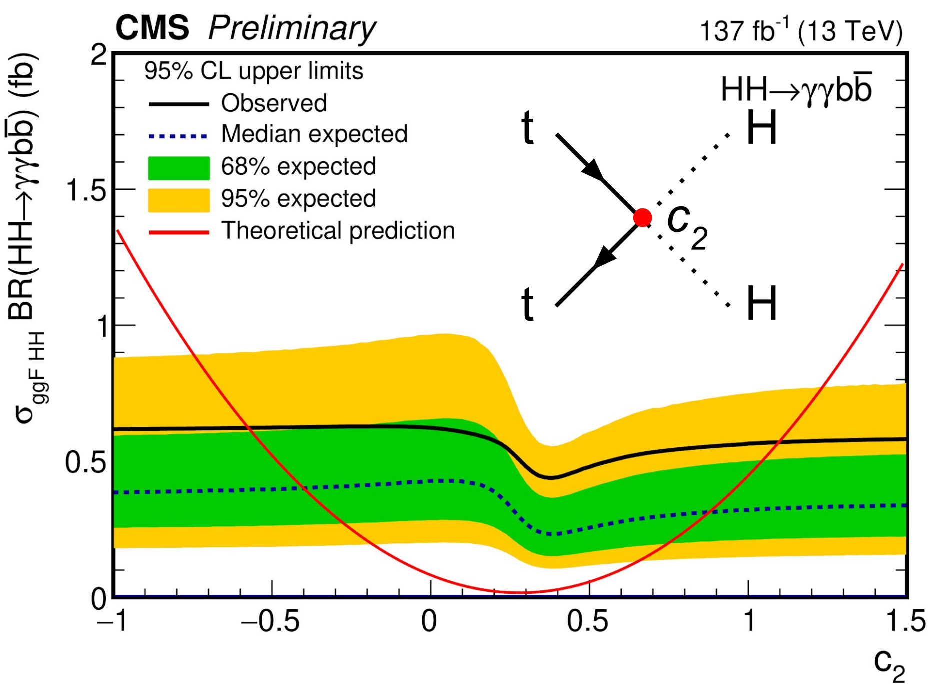
JHEP03(2021)257

HH→bbγγ at CMS with 137 fb^{-1} - EFT results

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

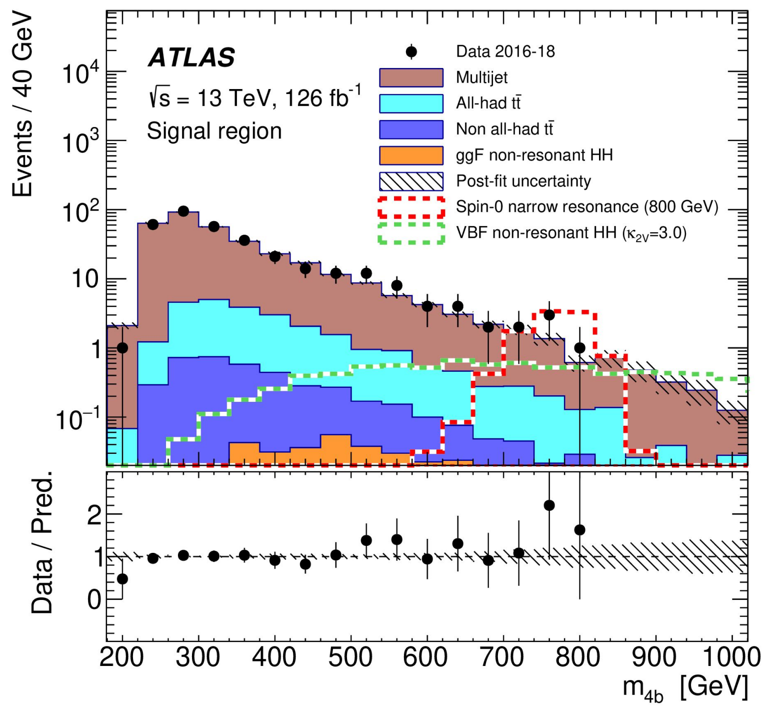
- Special role of H and t in several BSM theories
- HHtt effective coupling

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

JHEP07(2020)108

VBF HH→bbbb at ATLAS with 127 fb^{-1} - overview

- Resonant + non-resonant VBF HH searches
- Signal featuring 4 b-jets + forward-backward jet pair
- Main background from QCD events
  - requirement on b-jet ID & m_{bb} masses & event kinematics
  - data-driven bkg estimation
- b-jet energy regression to improve ~25% m_{bb} mass resolution
- Signal extracted from fit to four-body mass m_{4b}

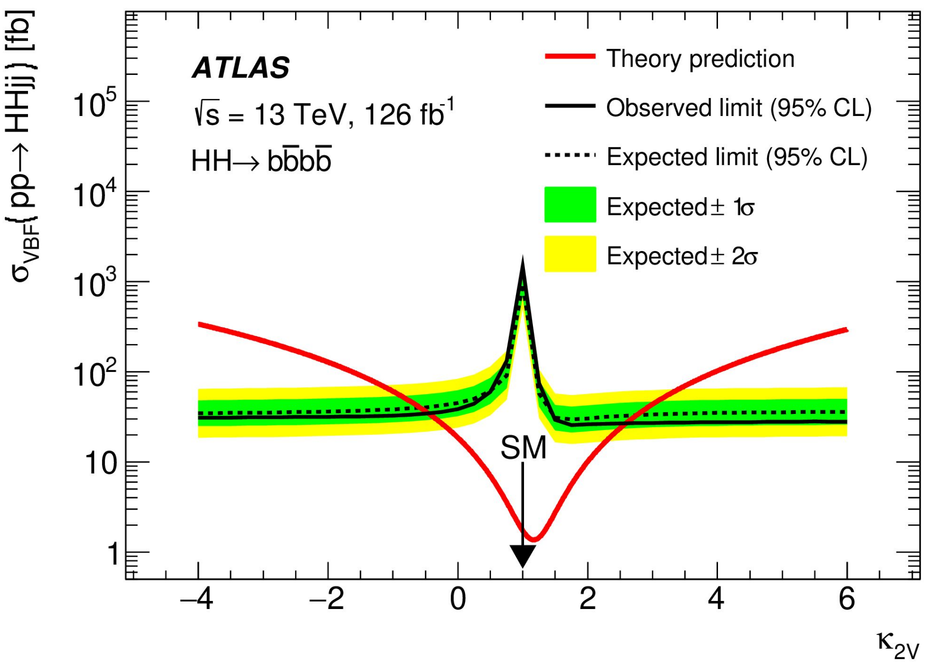


JHEP07(2020)108

VBF HH→bbbb at ATLAS with 127 fb^{-1} - results

- No deviations from SM observed

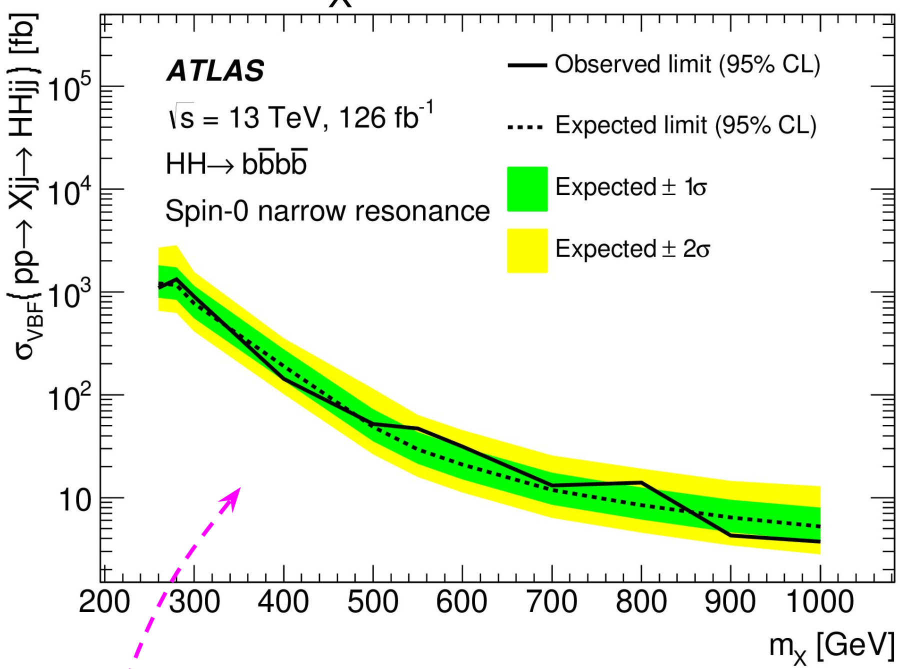
Limit on VBF HH XS vs k_{2V}



Obs. k_{2V} ∈ [-0.43, 2.56]
Exp. k_{2V} ∈ [-0.55, 2.72]

Best result to date

Limit on spin 0 resonance with mass m_X and narrow width



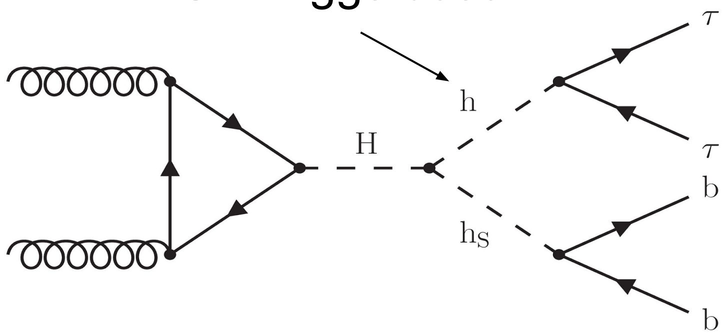
Obs. limit between 10^3 and 4 fb for m_X ∈ [260, 1000] GeV

First result for VBF production mechanism

CMS-PAS-HIG-20-014

$H \to h_S h \to bb\tau\tau$ at CMS with 137 fb^{-1} - overview

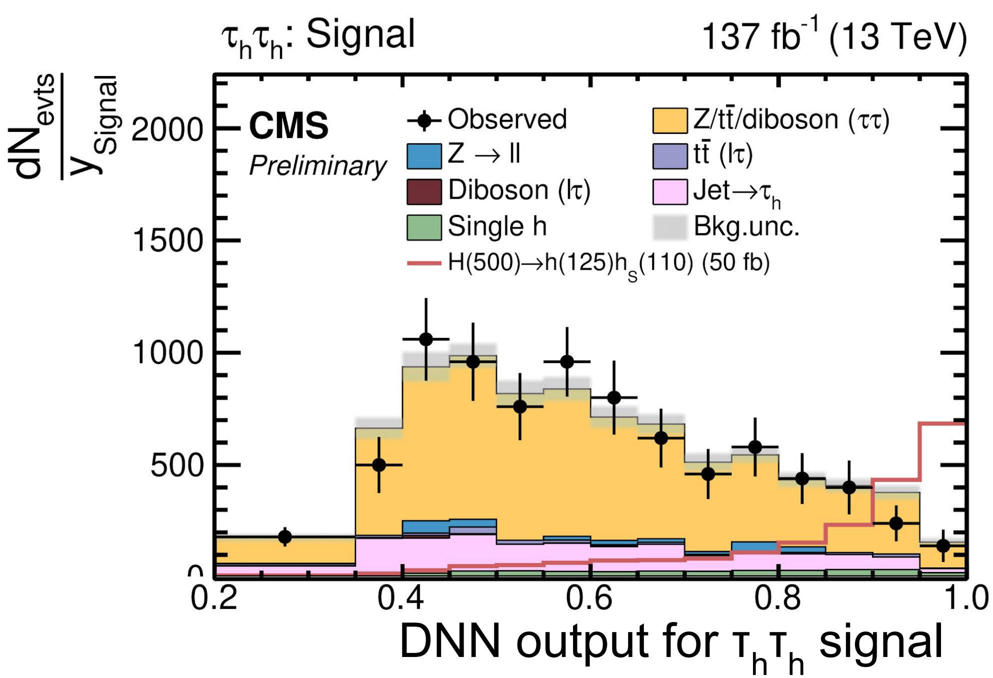
SM Higgs boson



Online+offline selections targeting $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$

Require ID of exactly 1 or 2 b-jets

- Signature predicted by NMSSM
- Main backgrounds from QCD, $t\bar{t}$, and Z+jets



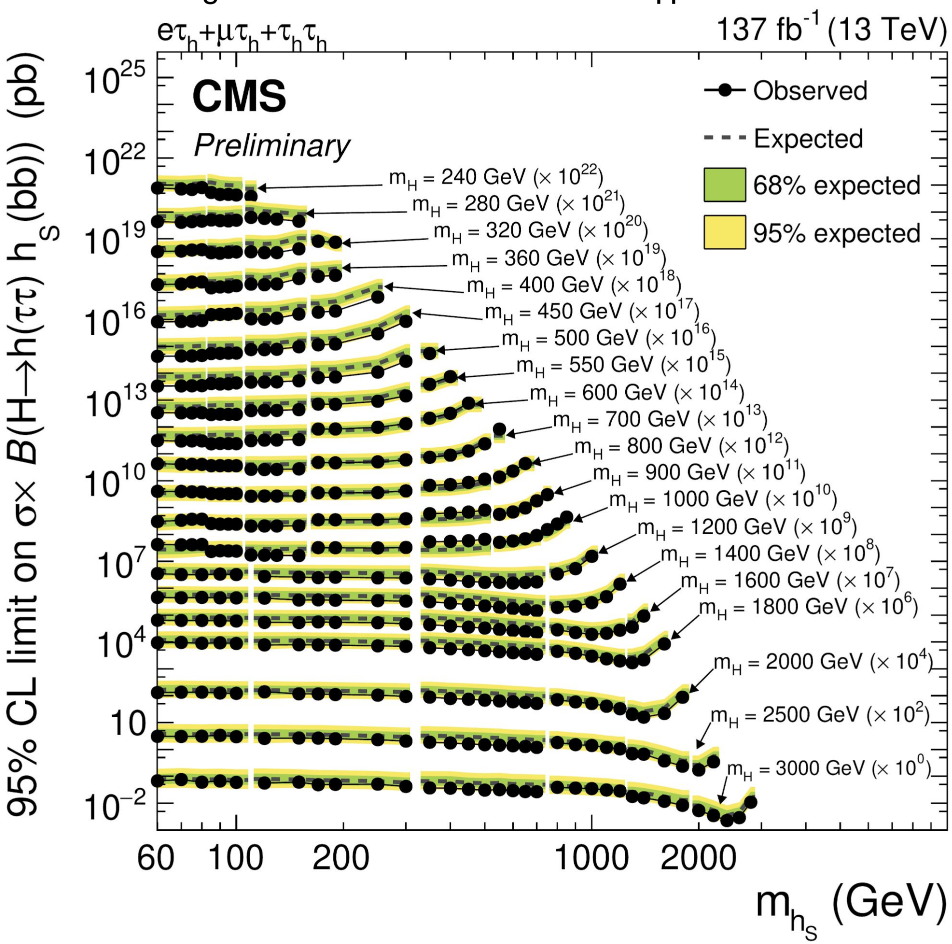
➢ Optimize signal vs bkgs separation with NN multiclassifier
  - Signal region dominated by events with genuine τ_h

CMS-PAS-HIG-20-014

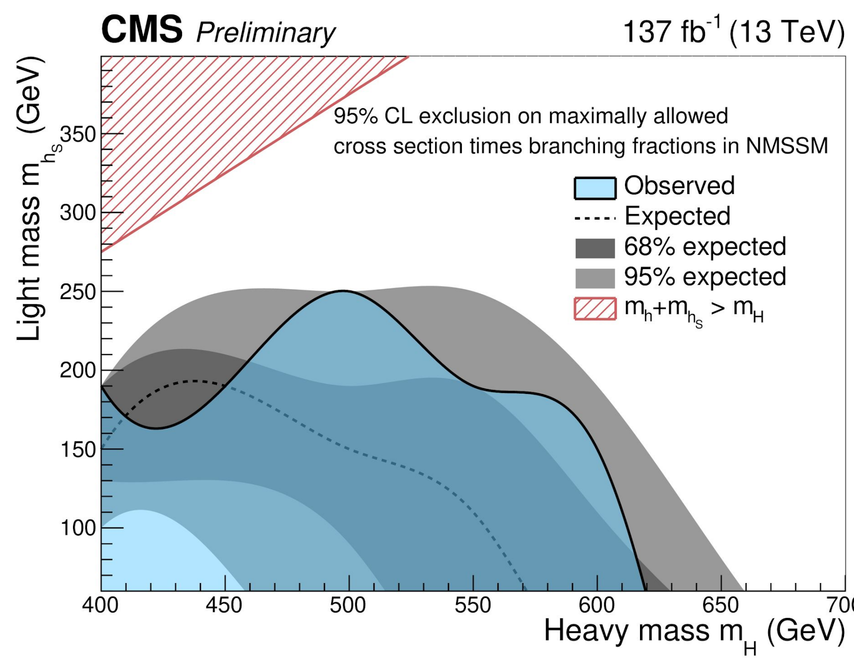
$H \to h_S h \to bb\tau\tau$ at CMS with 137 fb^{-1} - results

- No deviations from SM observed
  - Upper limits from 125 fb (m_H = 240 GeV) to 2.7 fb (m_H = 3 TeV)

model-independent limit on $H \to hh_s$ XS vs h_s mass for different m_H hypotheses



NMSSM interpretation



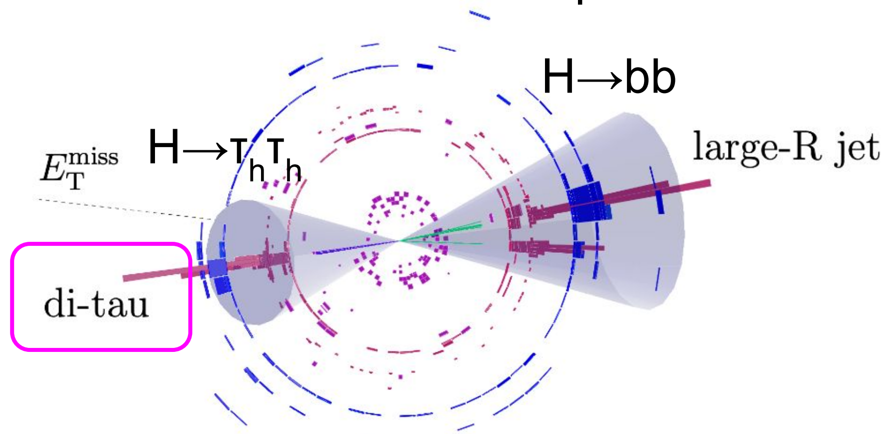
- ➢ Exclude m_H up to ~620 GeV
- ➢ Exclude m_{hs} up to ~250 GeV

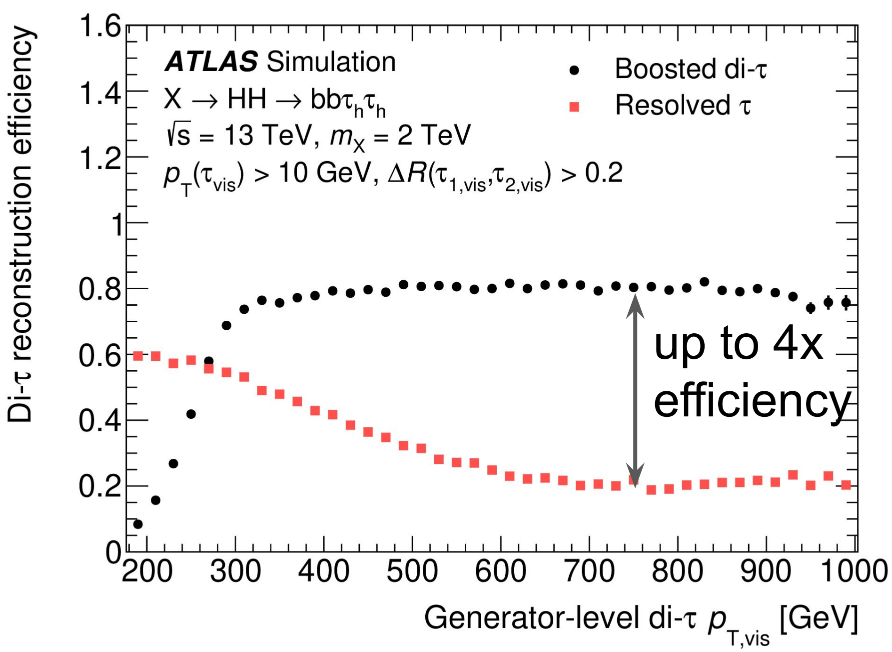
JHEP11(2020)163

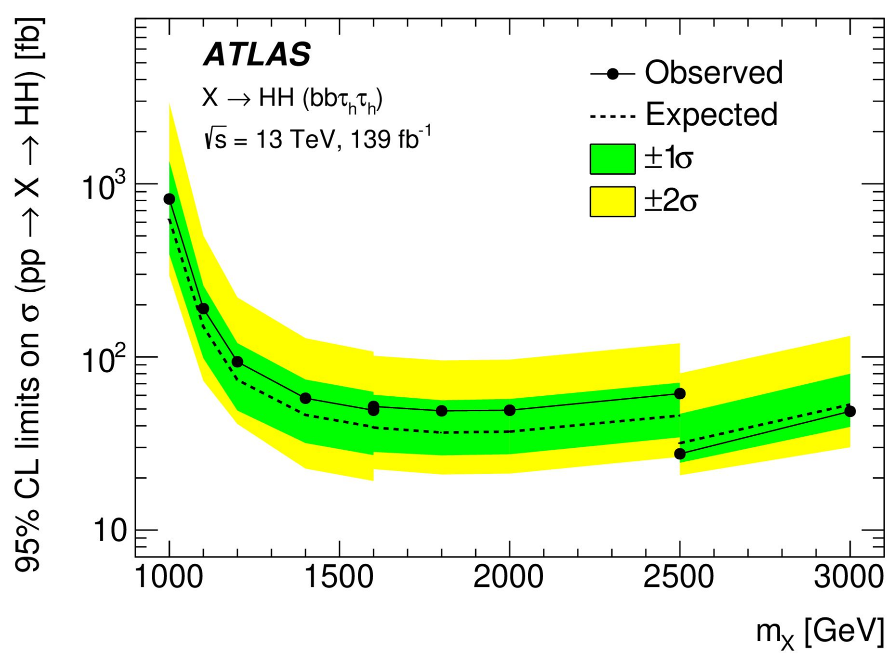
Boosted X→HH→bb$\tau_h\tau_h$ at ATLAS with 139 fb^{-1}

- For large m_X non-resolved $\tau_h\tau_h$ (and bb jets) pairs
  - ➢ Innovative reco and ID of non-resolved $\tau_h\tau_h$ pair
    Large-R jets with jet substructures

Reconstructed HH→bbττ candidate on ATLAS transverse plane

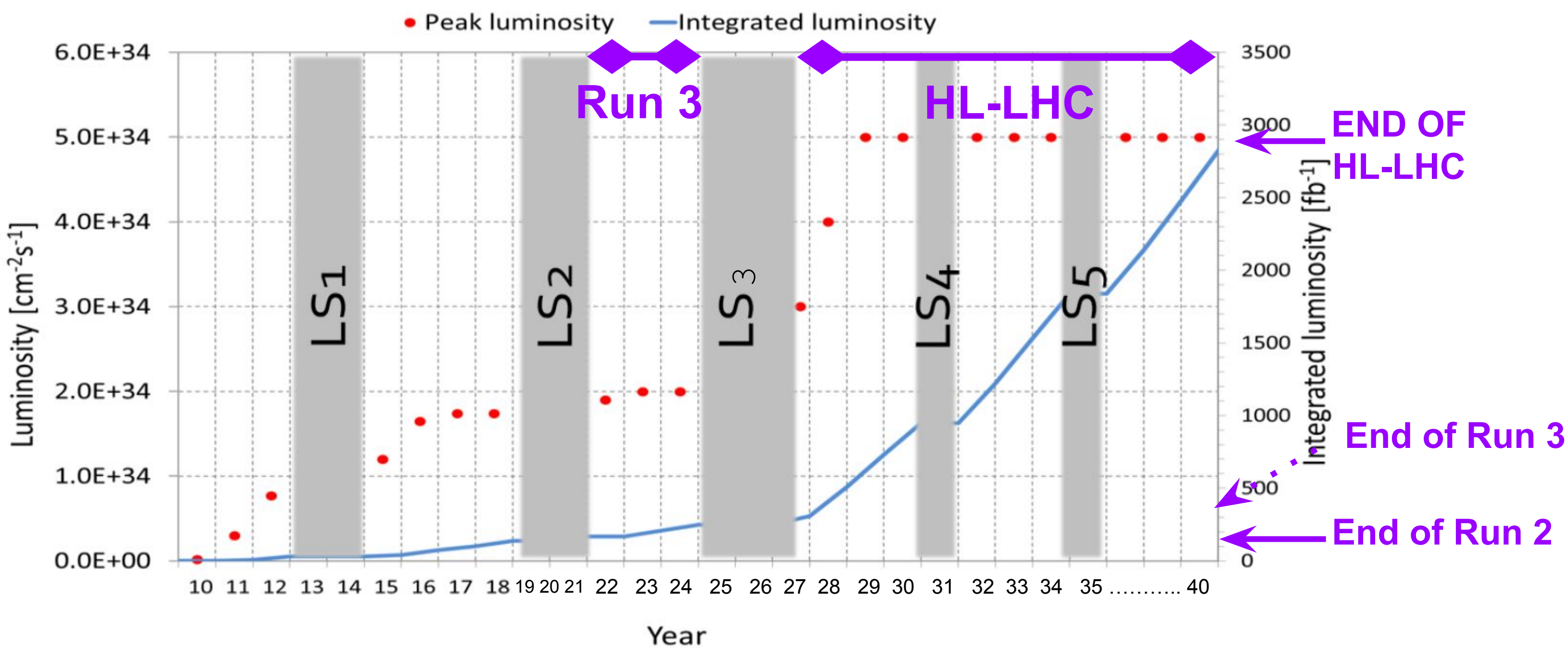






Prospects for HH search

- 3✕ increase of luminosity at HL-LHC
  - Data equivalent to 3000-4000 fb^{-1} in ~10 years of operation

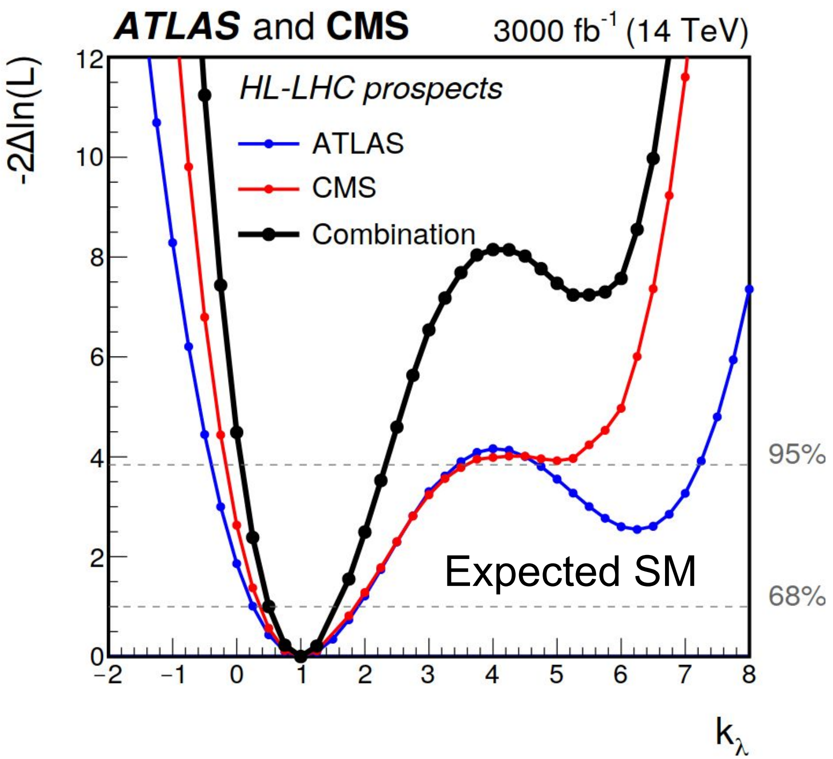


$\sigma(gg\rightarrow HH)$@14 TeV ~ 37 fb ➪ 10^5 *HH* events at 3000 fb^{-1}

CERN Yellow Rep. Monogr. 7 (2019) 221-584

Projections to HL-LHC

$0.52 < k_\lambda < 1.5$ @ 68% CL



k_λ=0 excluded @ >95% CL

Exp. significance on SM signal (standard deviations)	
ATLAS	CMS
3.0	2.6
4.0	

Evidence of a SM HH process by the end of HL-LHC

↓

Further improvement possible through new techniques & ideas→observation?

➢ Possible discrepancies from SM can arise much earlier!

Summary

- HH physics offers wide physics program at LHC
  - HHVV, tri-H couplings + effective BSM couplings
  - Search for BSM resonances

- Presented some of the first Run 2 results
  - No deviations from SM predictions observed so far
  - New techniques, approaches wrt 2016 analyses
  - More results will be available soon - stay tuned!

- Evidence of (SM) HH by the end of HL-LHC
  - Observation?
  - Discrepancies from SM can arise much earlier

Exciting times ahead!

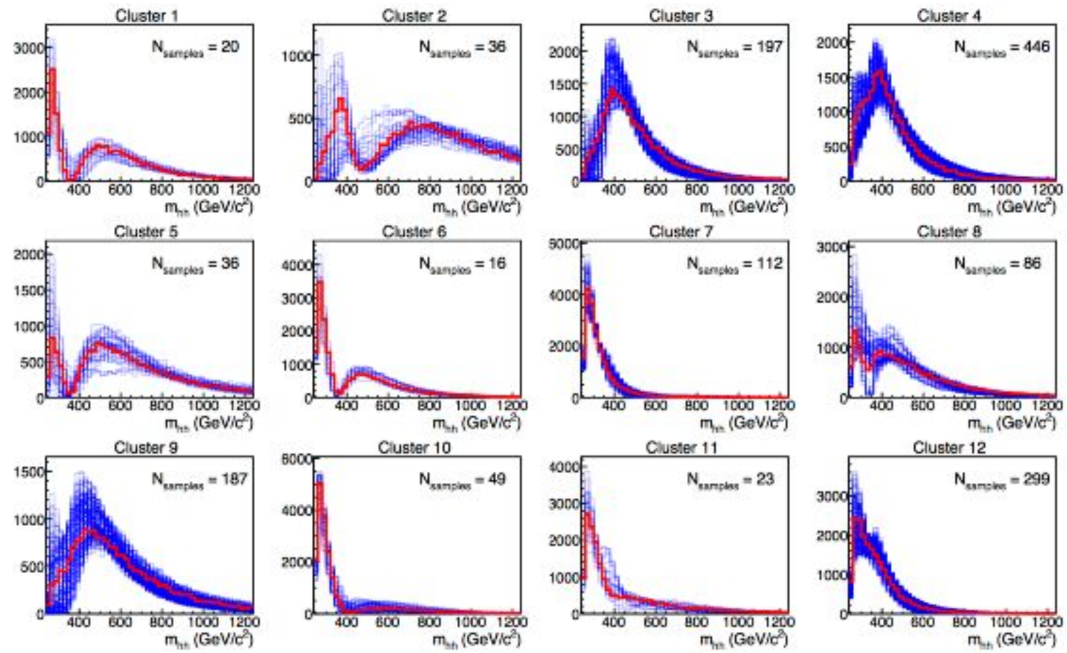
BACKUP

EFT HH benchmarks (JHEP04(2016)126)

12 kinematically representative points in the 5D parameters space

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
0	7.5	1.0	-1.0	0.0	0.0
1	1.0	1.0	0.5	-0.8	0.6
2	1.0	1.0	-1.5	0.0	-0.8
3	-3.5	1.5	-3.0	0.0	0.0
4	1.0	1.0	0.0	0.8	-1.0
5	2.4	1.0	0.0	0.2	-0.2
6	5.0	1.0	0.0	0.2	-0.2
7	15.0	1.0	0.0	-1.0	1.0
8	1.0	1.0	1.0	-0.6	0.6
9	10.0	1.5	-1.0	0.0	0.0
10	2.4	1.0	0.0	1.0	-1.0
11	15.0	1.0	1.0	0.0	0.0

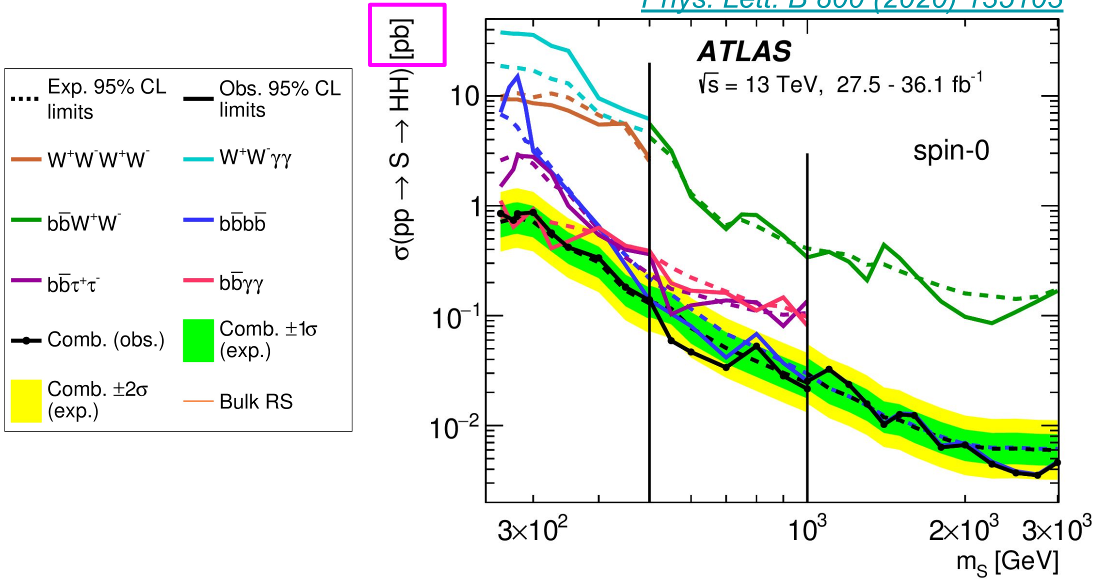
m_{HH} distribution for the 12 benchmarks



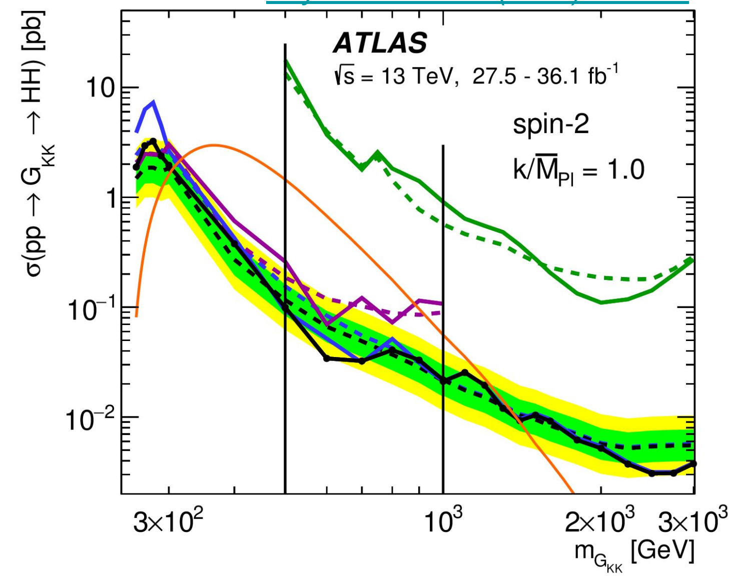
➢ Extract limit on the 12 benchmarks to explore EFT sensitivity

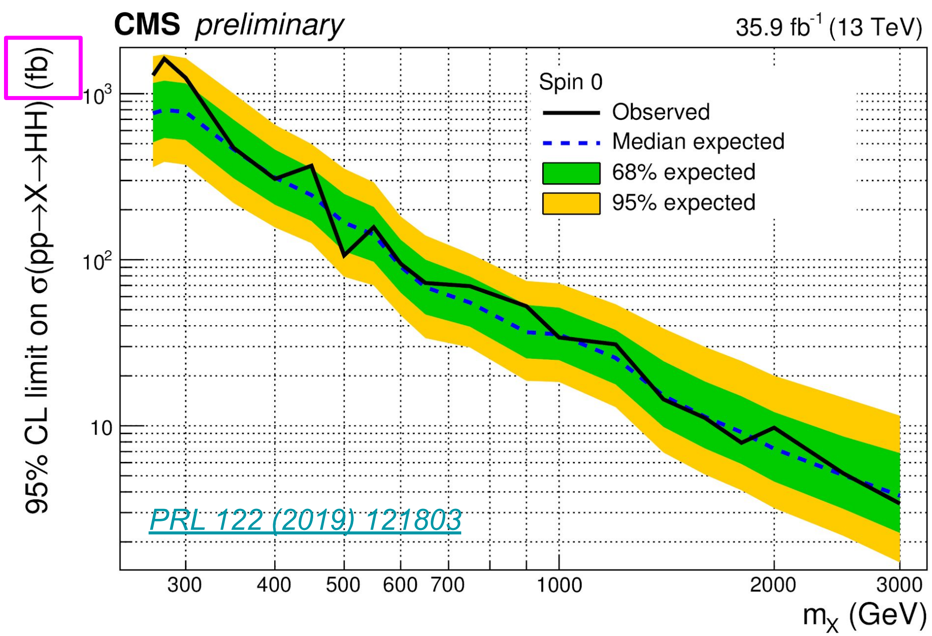
Limits on spin 0 and 2 X→HH with 2016 dataset

Phys. Lett. B 800 (2020) 135103



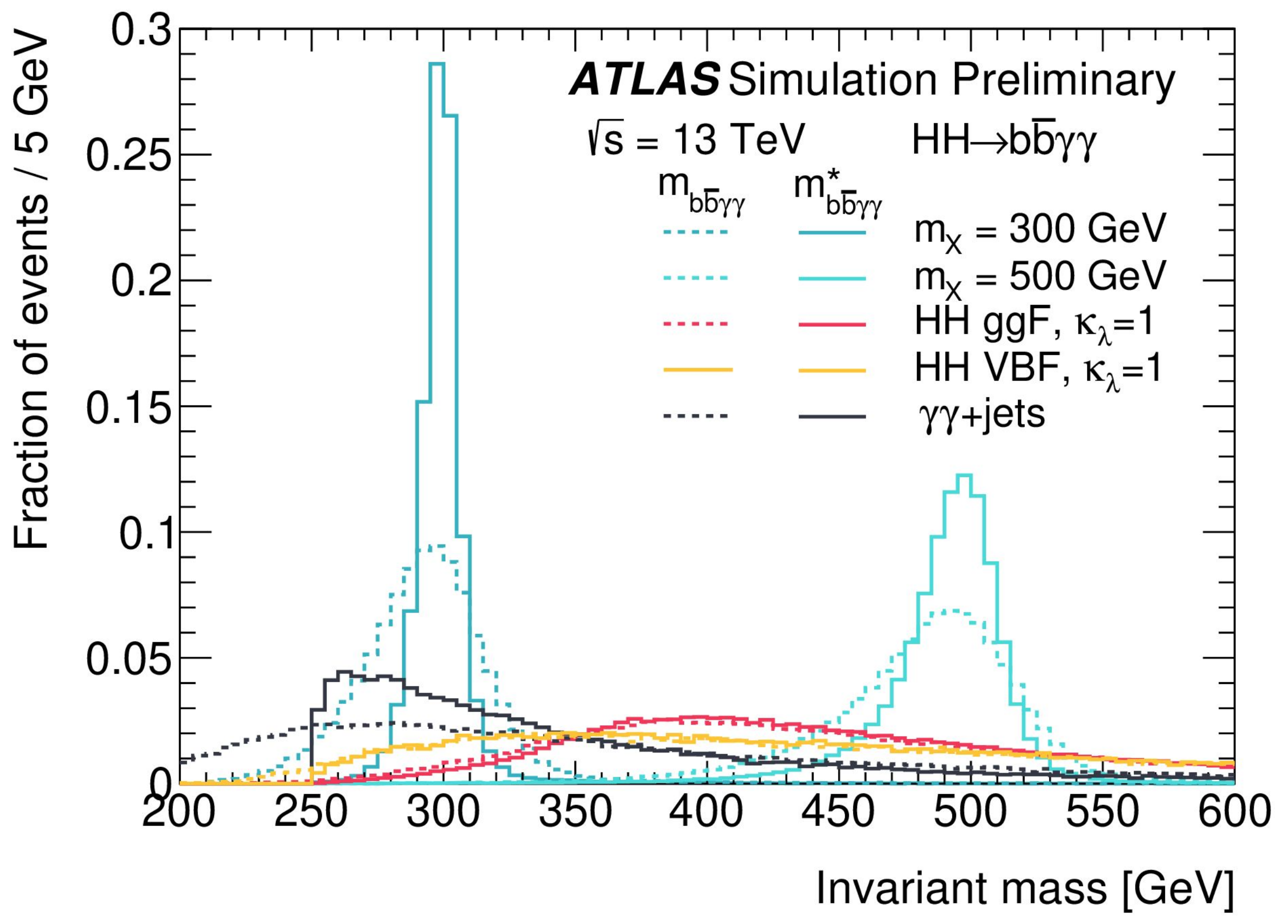
Phys. Lett. B 800 (2020) 135103





$m^*_{bb\gamma\gamma}$ advantages

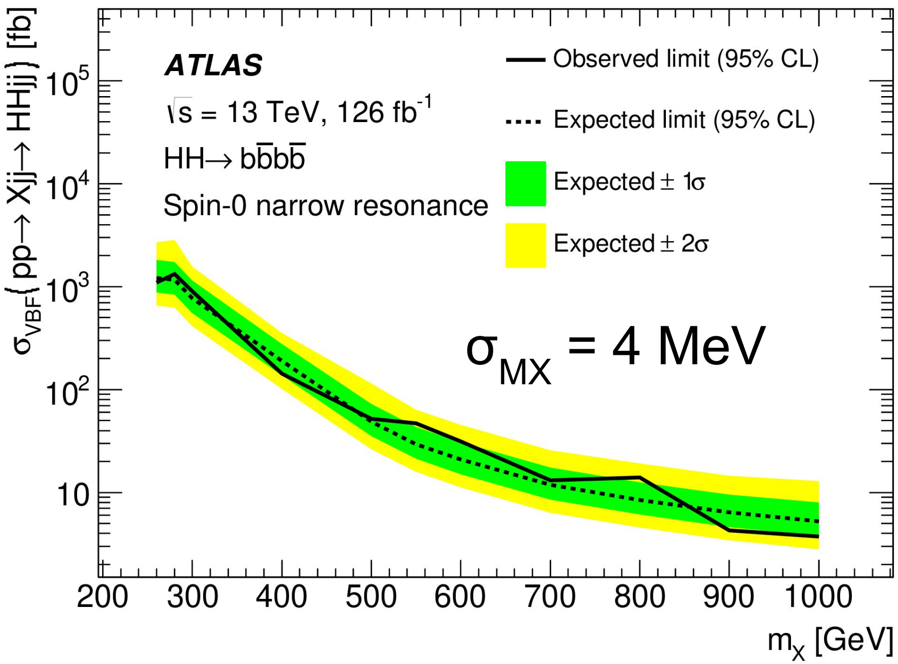
- Reduce effect of jet and photon energy resolution
- ~falling shape for non-resonant bkg
- peak at m_X for resonant HH signal



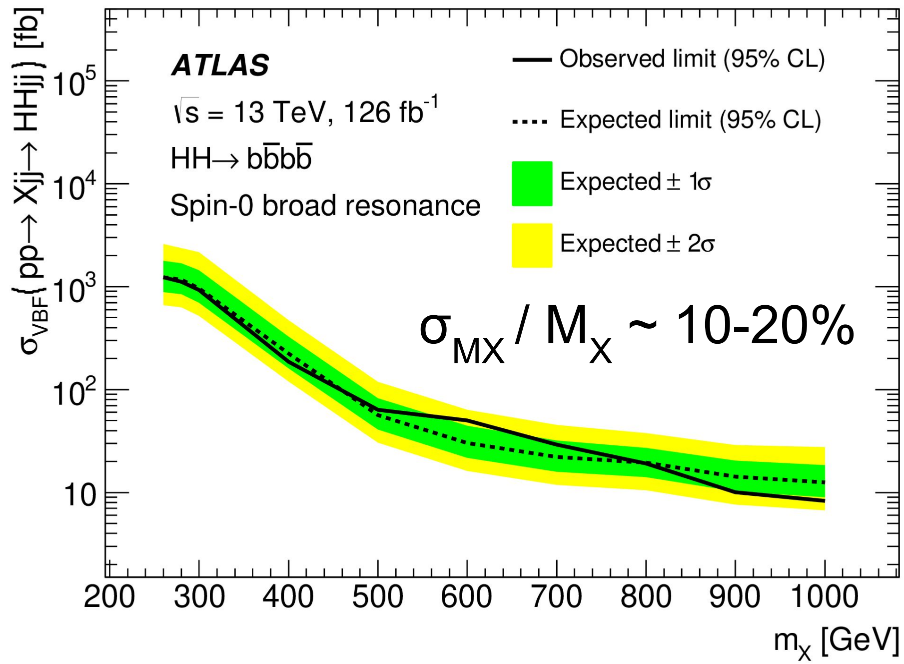
Impact of resonance width on X→HH sensitivity

- ATLAS X→HH→bb search with 127 fb^{-1}

Limit on spin 0 resonance with mass m_X and narrow width



Limit on spin 0 resonance with mass m_X and broad width

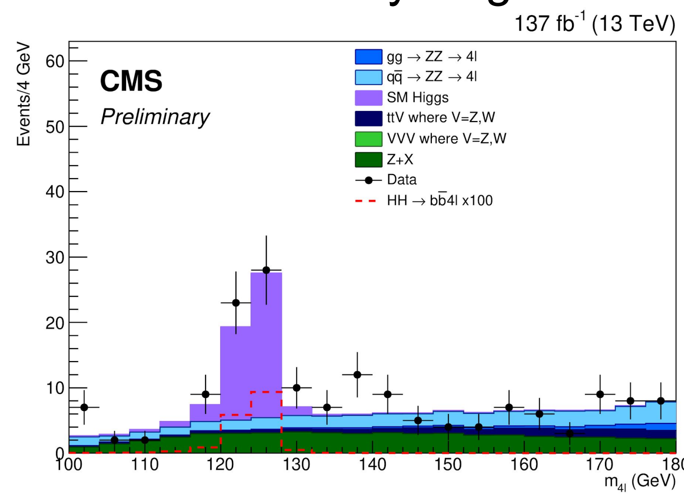


CMS-PAS-HIG-20-004

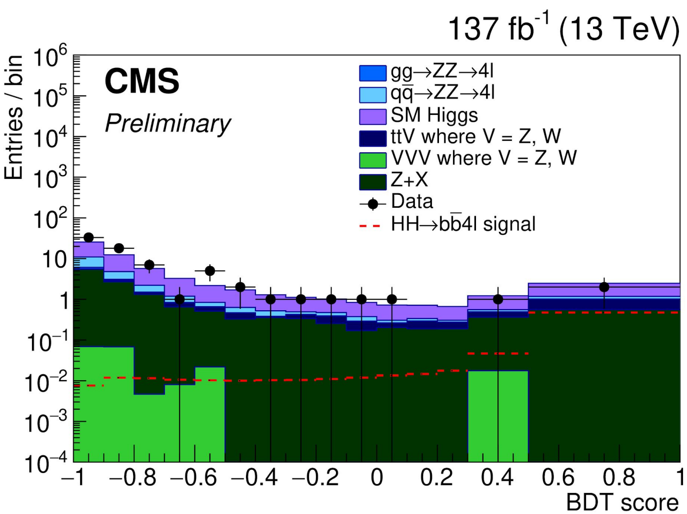
HH→bbZZ(4ℓ) at CMS with 137 fb^{-1} of data

- Final state with 4ℓ + 2 b-jets
  - Clean signature over continuum bkg
  - Small BR of ~10^{-4}
- BDT classifier to optimize signal separation from bkgs
  - kin. info of ℓ's and jets + b-tag score

After preselections bkg dominated by single-H



sig extraction from BDT distribution fit

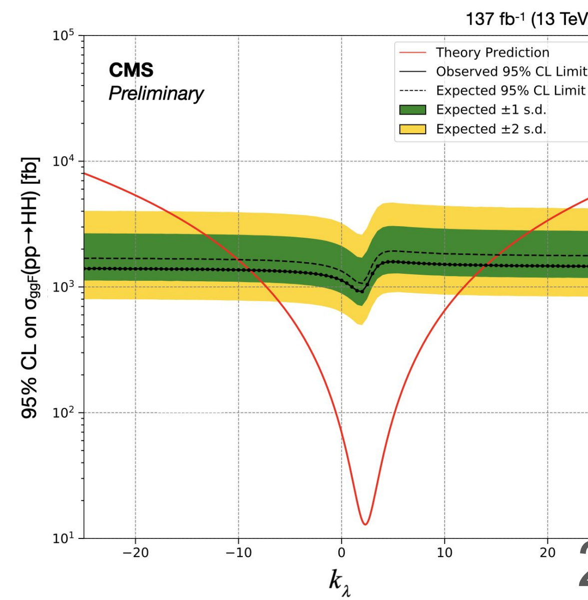


obs.(exp.) upp. lim. on SM HH XS

30(37)✕SM

obs.(exp.) k_λ excl. @95%C.L.

-9(-11) < k_λ < 14(16)



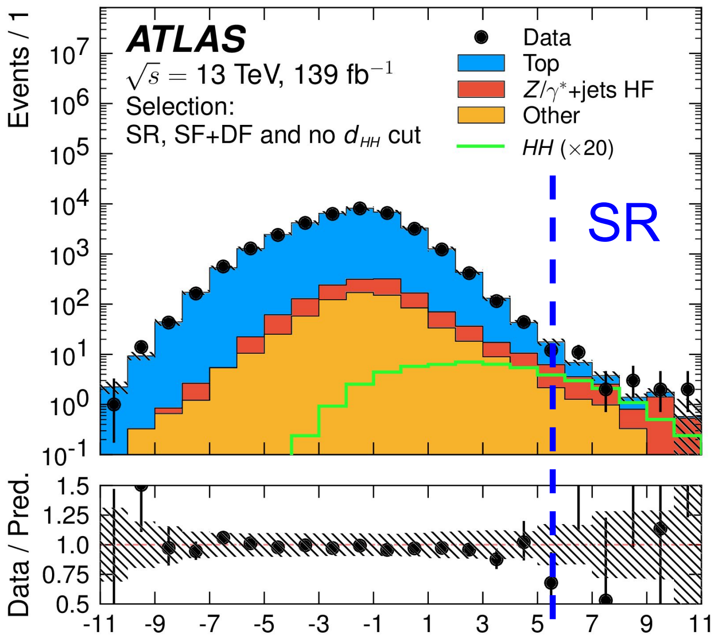
➢ First non-res results on this channel

Phys. Lett. B 801 (2020) 135145

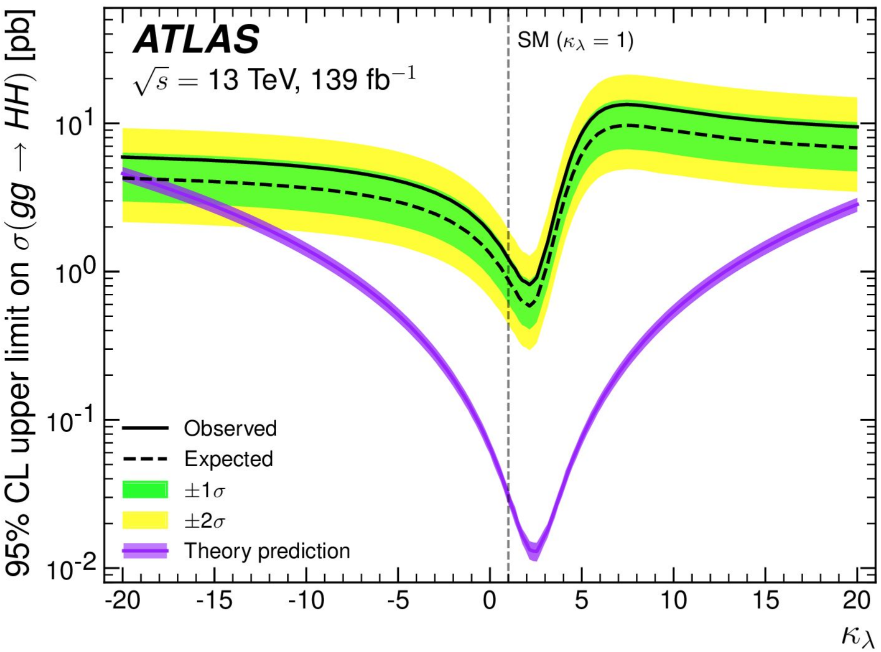
HH→bb2ℓ at ATLAS with 139 fb^{-1} of data

- H→**W*W** / Z*Z / ττ final states with 2ℓ
  - lept. and b-jet ID
  - selections on $m_{\ell\ell}$ and m_{bb}
- DNN multiclassifier to optimize signal vs bks separation
- Counting experiment in high DNN score region

Main backgrounds from `tt+X` and `Z/ɣ*+heavy-jets` events



DNN score for signal class



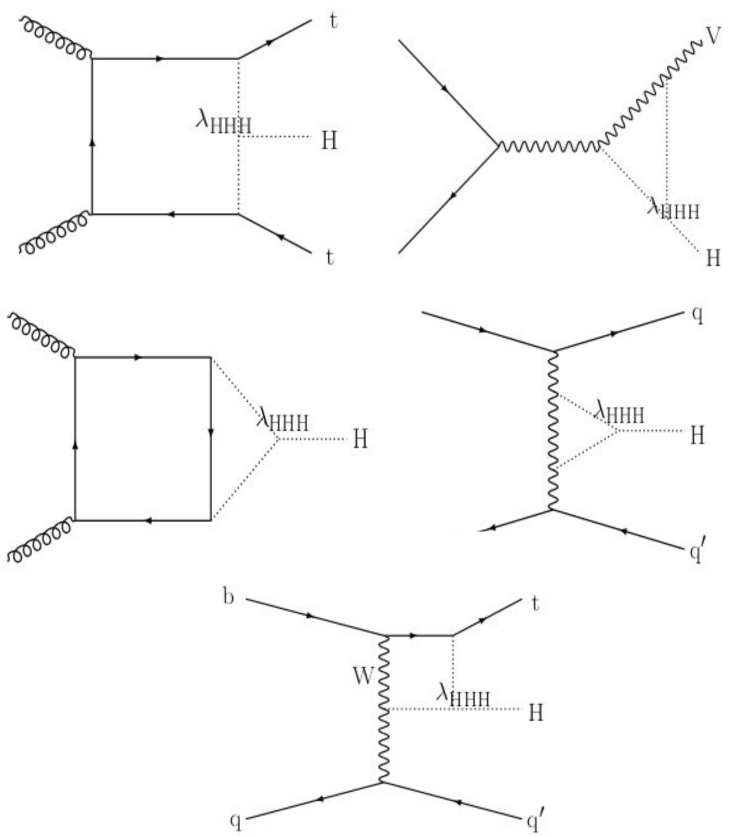
obs.(exp.) upp. lim. on SM HH XS

40(29)✕SM

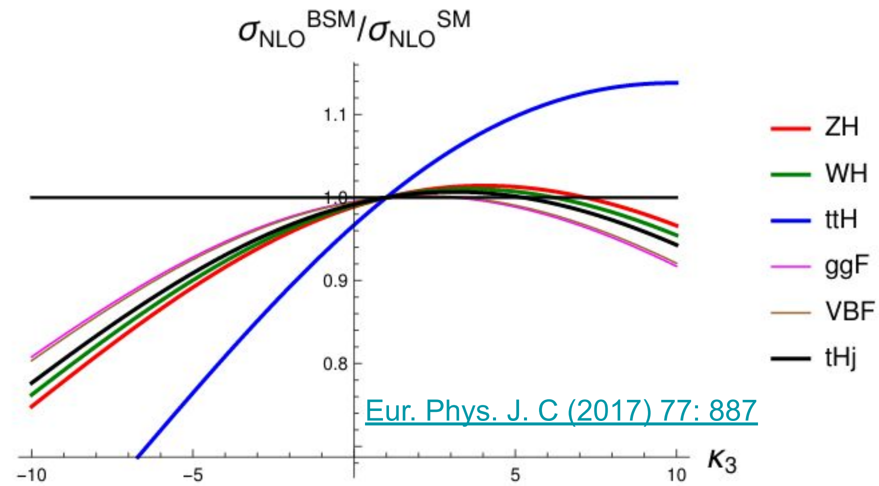
Trilinear self-coupling in single-H mechanisms

- λ-dependent NLO electroweak corrections to single-H XS

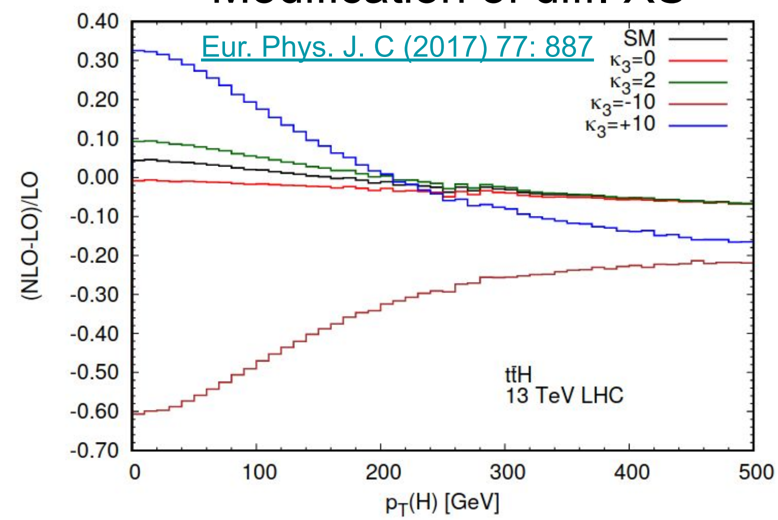
Examples of λ-dependent diagrams for single-H mechanisms



Modification of total XS

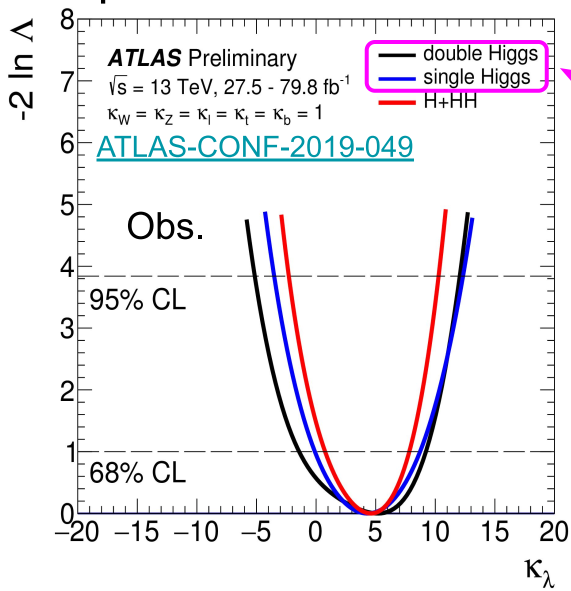


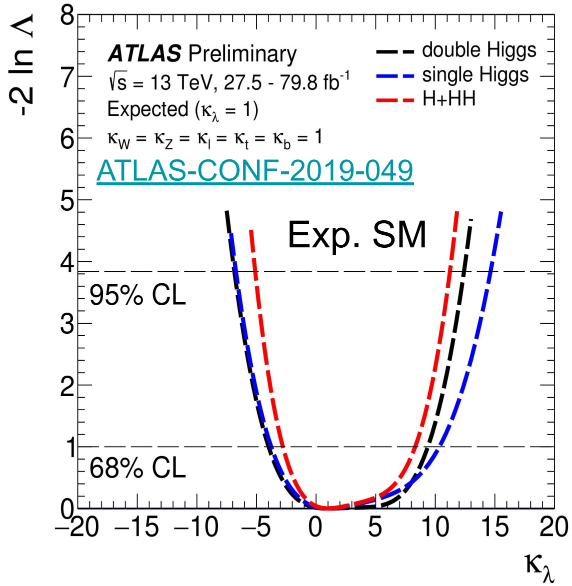
Modification of diff. XS



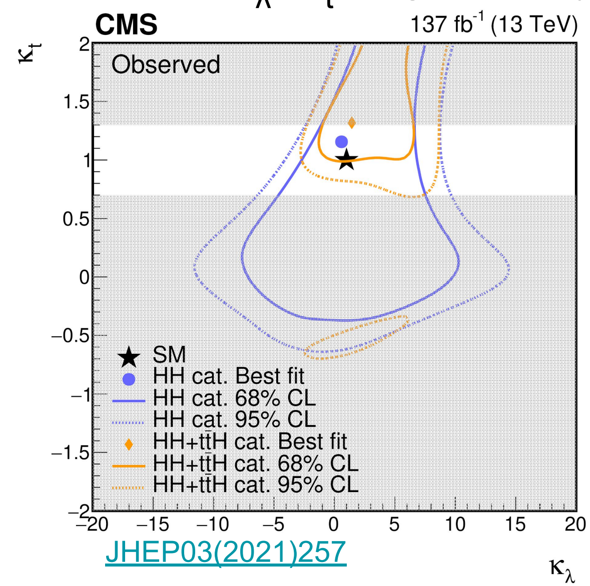
λ measurement from single-double H comb

Comparable sensitivities to λ





Reduce k_λ- k_t degeneracy



- Treatment of experimental overlap between H and HH sig regions
- Data interpretation currently with k-framework + k_λ effects