Institute of High Energy Physics
Chinese Academy of Sciences

HH Production: CMS overview

Higgs pairs workshop

30 May 2021

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on behalf of the CMS Collaboration

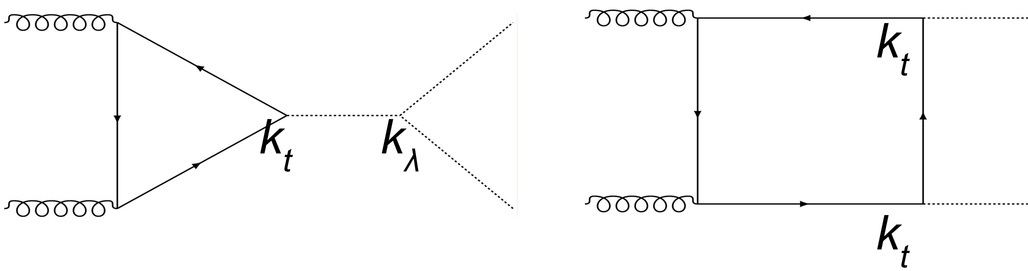
Outline

- Introduction and motivations
- Status of CMS HH searches

Non-resonant HH search

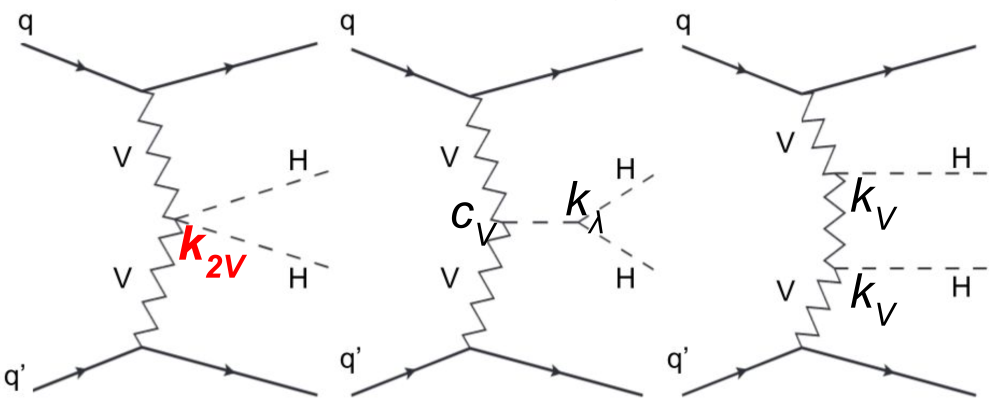
- HH production is sensitive to the Higgs trilinear coupling λ
- VBF HH is sensitive to c_{2V} coupling → $k_{2V} = c_{2V} / c_{2V(SM)}$

ggF production (ggHH) diagrams at LO

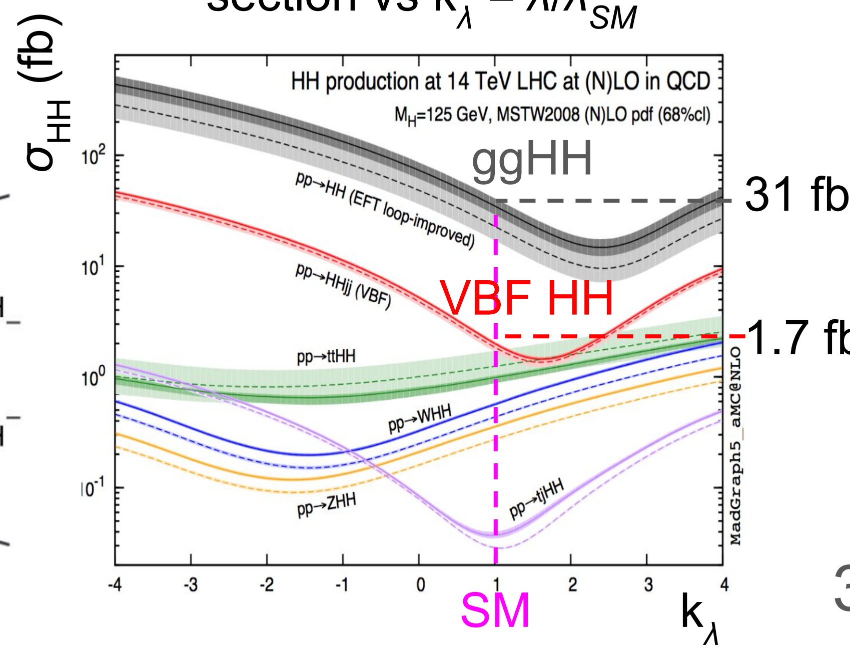


Fundamental tests of SM

VBF HH production diagrams at LO



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

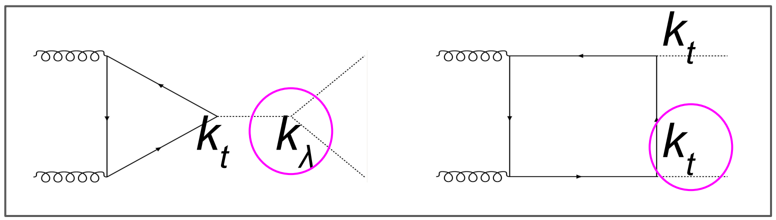


More on A. Carvalho talk

Sensitivity to effective field theory (EFT) couplings

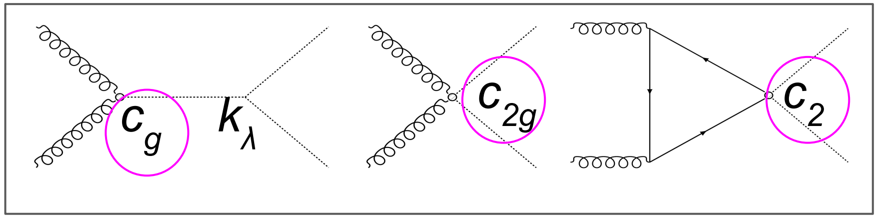
- ggHH production described by 5 diagrams:

SM terms

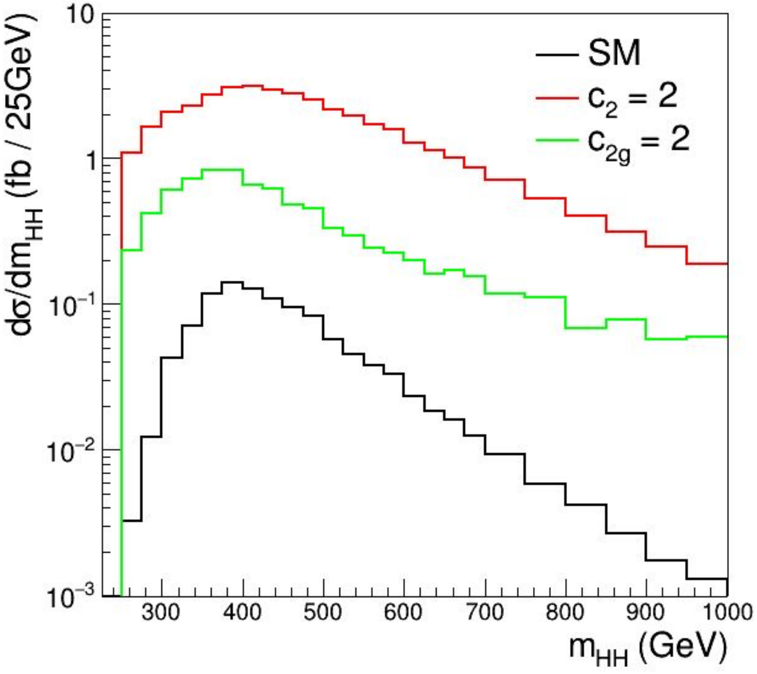


BSM terms

5 parameters



- Modification of total and differential XS



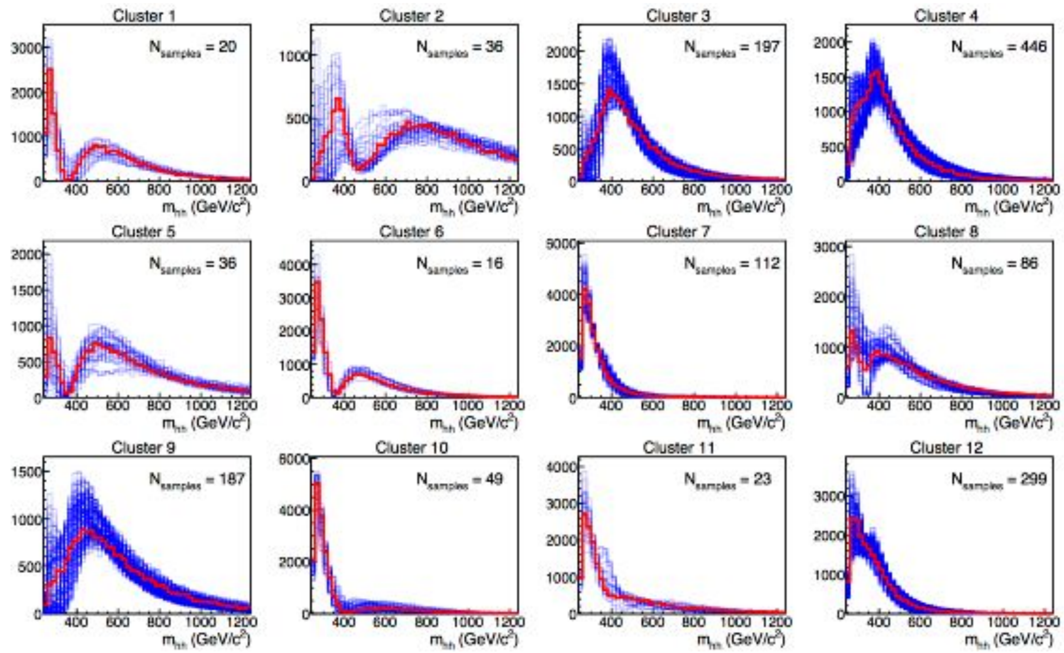
➢ 1D or 2D constraints on couplings, e.g. c_2 or (k_λ, k_t), …

Shape benchmarks of 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

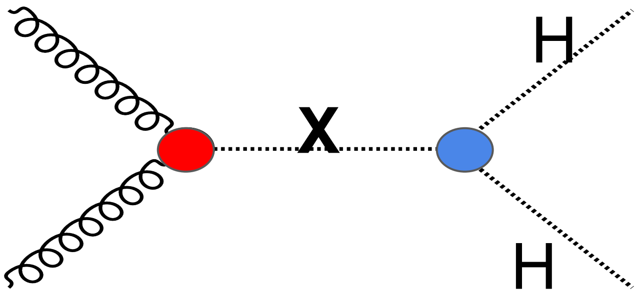
m_{HH} distribution for the 12 benchmarks



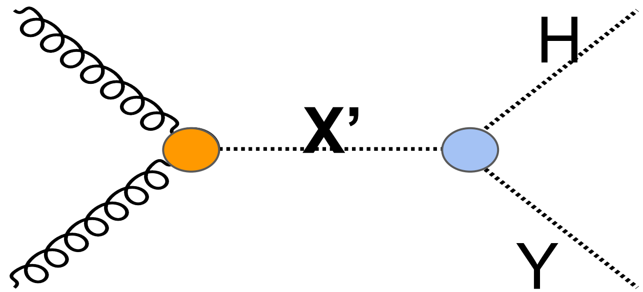
- ➢ Extract limit on the 12 benchmarks to explore EFT sensitivity
- ➢ Alternative shape benchmarks defined in JHEP03(2020)091

Resonant HH searches and possible interpretations

X→HH



X'→YH



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

\+ VBF production mechanism

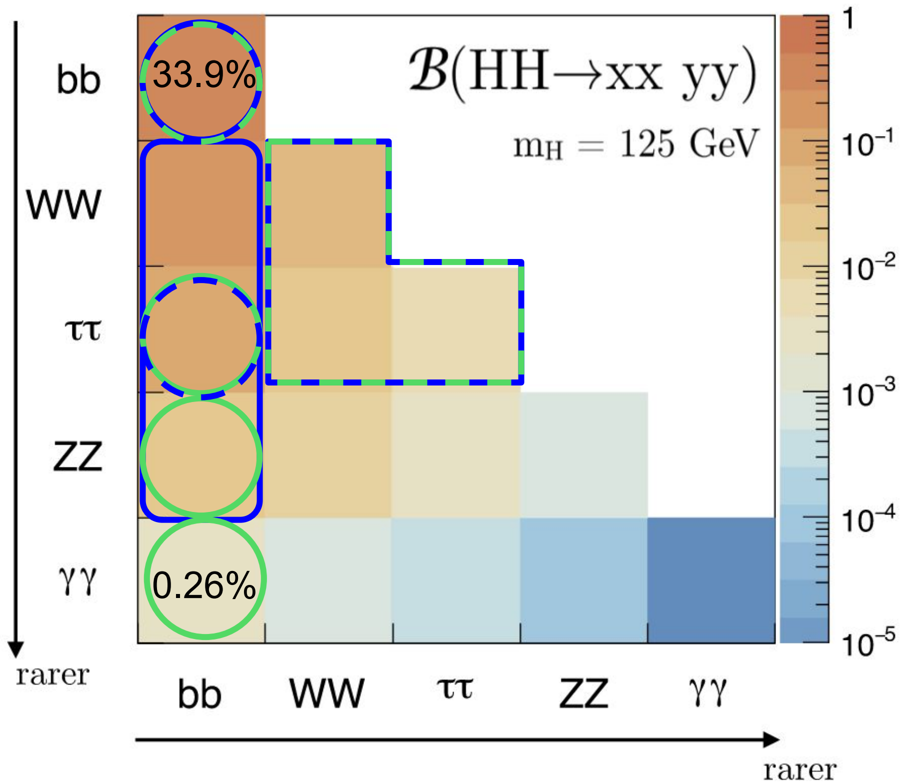
- Spin 0 resonances
  - Next-to-minimal supersimmetry models (NMSSM) JHEP07(2008)
  - Two-real-scalar-singlet extension of the SM (TRSM) E.P.J.C80,151(2020)

➢ Assuming resonances with narrow decay widths

Explored final states

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

Available **resonant** and **non-resonant** HH (or YH) searches with Run 2 data from CMS



➢ No HH golden channel
  ○ Channel sensitivities are complementary

➢ Many final states covered
  ○ resolved and/or boosted

➢ Stay tuned for new results!

Non-resonant HH searches

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

- No deviations from SM observed

Obs.(exp.) upper limit on σ(HH)

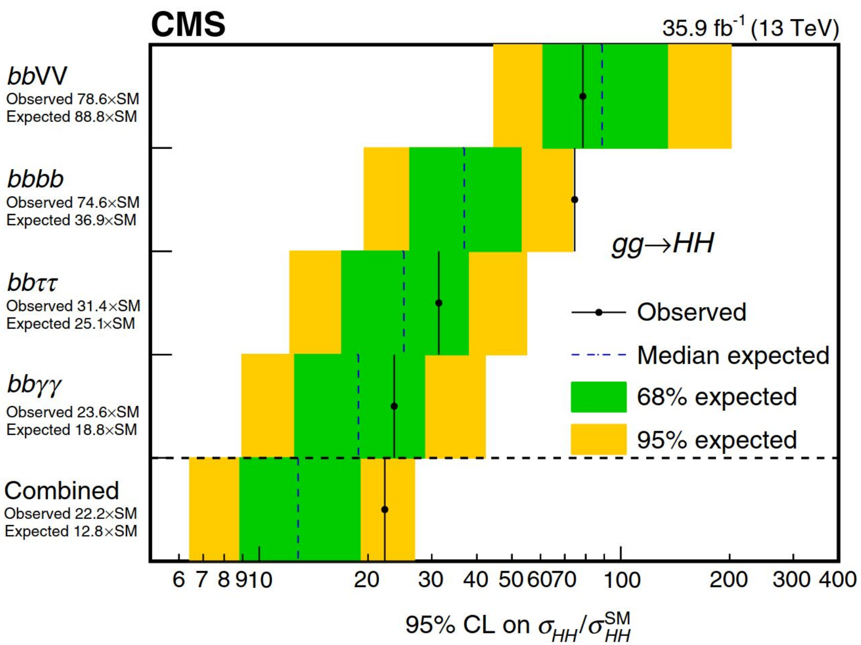
22.2(12.8)×SM from CMS

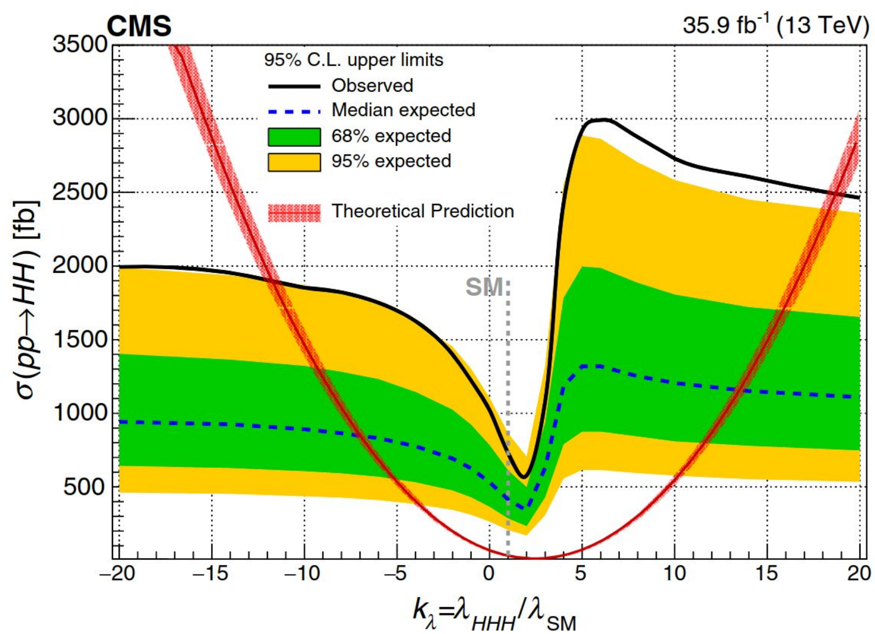
6.9(10)×SM from ATLAS

Obs. k_λ exclusion

−11 < k_λ < 17 @ 95% C.L. from CMS

−5 < k_λ < 12 @ 95% C.L. from ATLAS

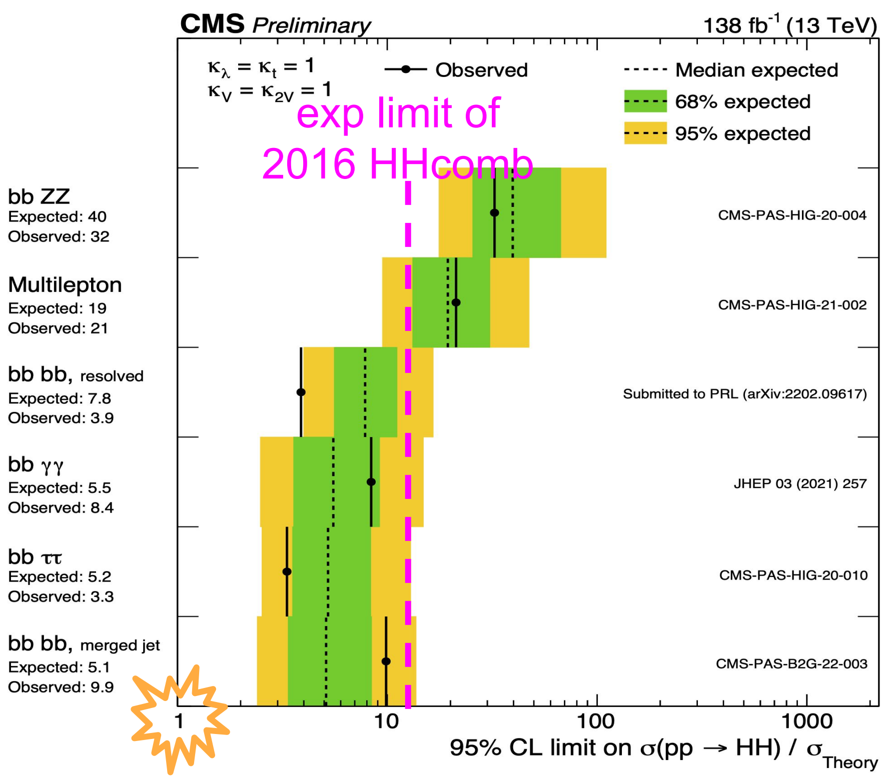




Results with full Run 2 dataset (~138 fb^{-1}) in this presentation

HH searches evolution since 2016

- HH searches results with full Run 2 dataset outperform previous results scaled by integrated lumi

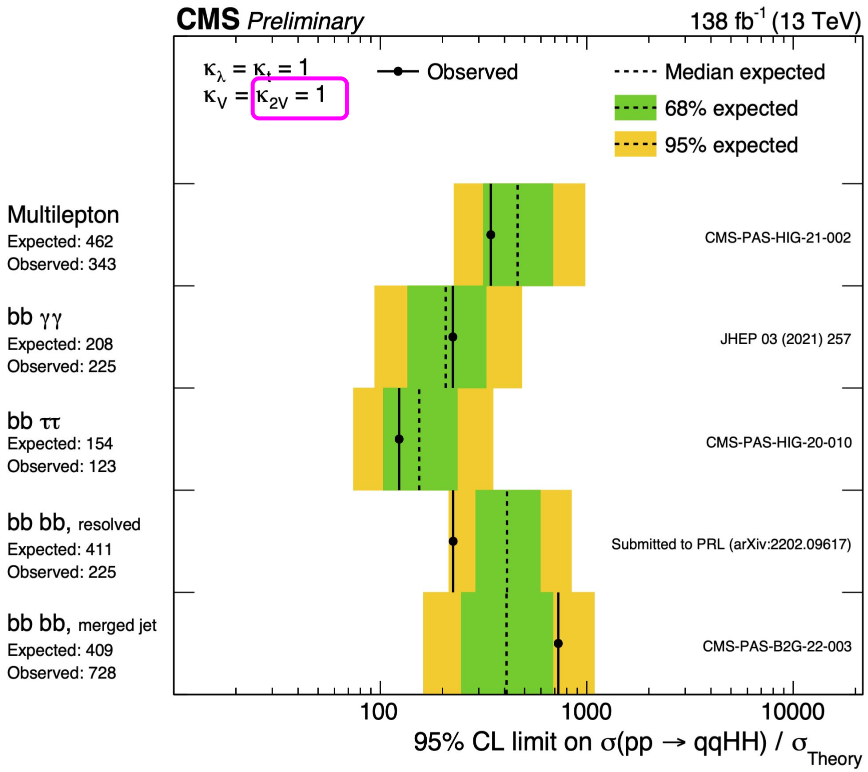


- Extensive usage of machine learning
- Boosted topologies
- Selections targeting VBF HH production mechanism
- Additional final states

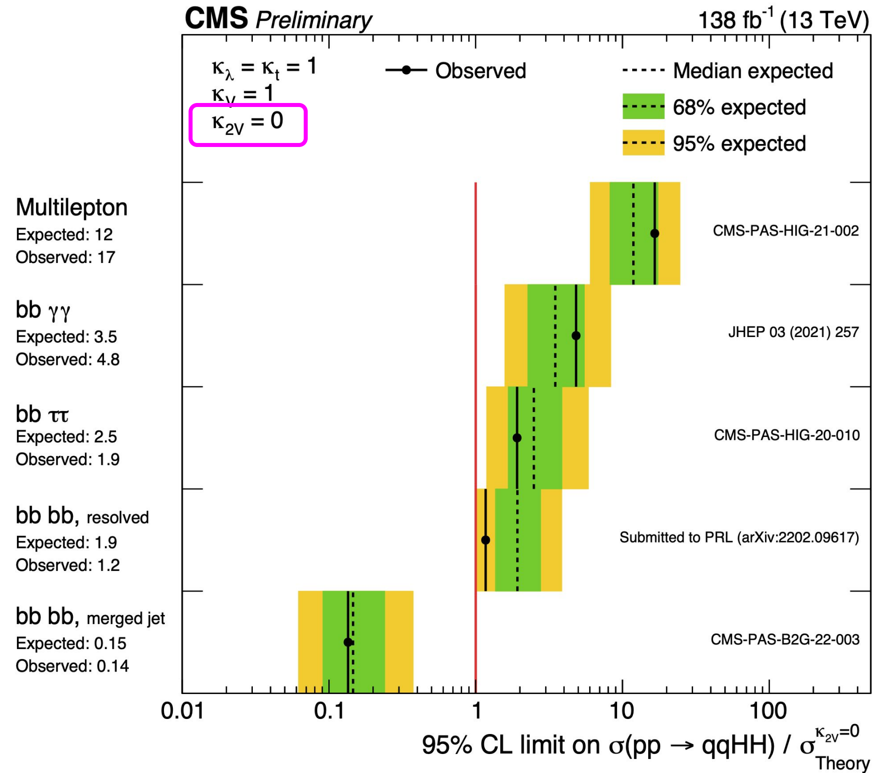
➢ We are quickly approaching to 1 (Run 3?)
  - 2.6σ significance expected at HL-LHC →improvements possible as proven by Snowmass studies (N. Lu and P. Meade talks)

Constraints on the VBF HH production

Upper limits on VBF HH XS assuming k_{2V} = 1 (SM)



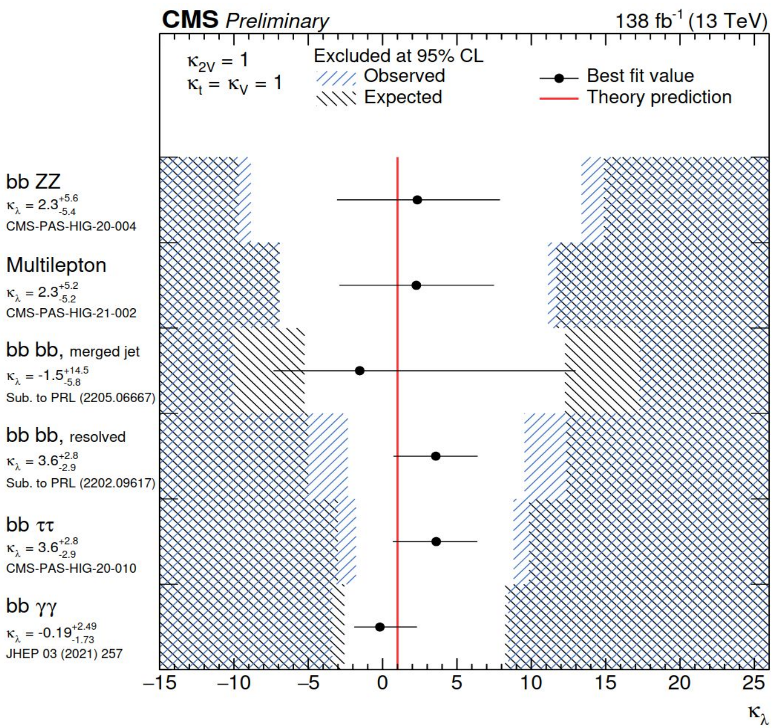
Upper limits on VBF HH XS assuming k_{2V} = 0



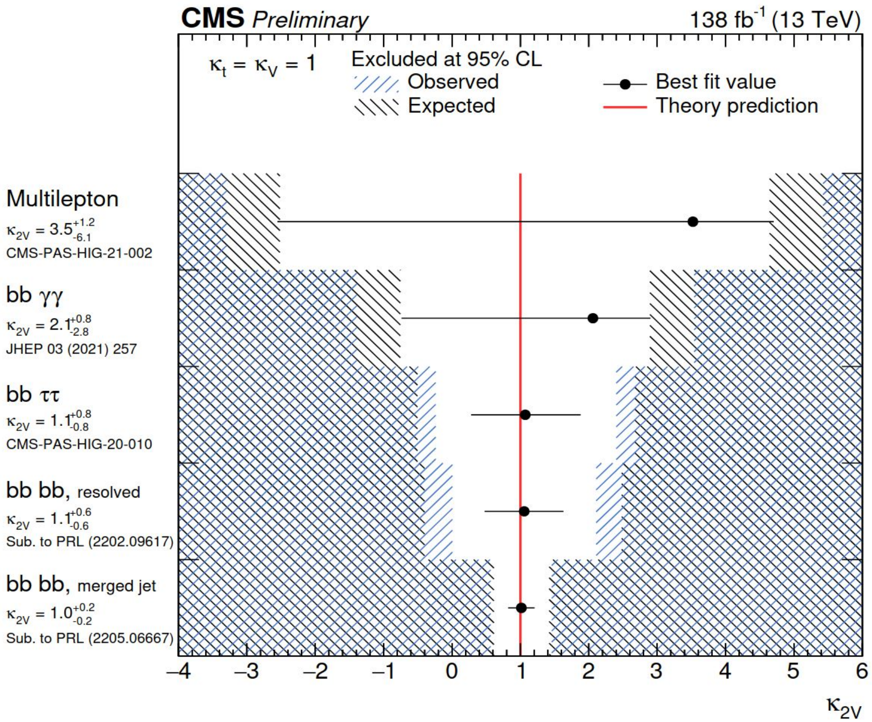
- ➢ Exclusion of k_{2V} = 0 at 95% C.L.
- ➢ Complementarity of the final states depending on the specific SM/BSM interpretation

Constraints on k_λ and k_{2V}

Best fit and constraints at 95% CL on k_λ



Best fit and constraints at 95% CL on k_{2V}

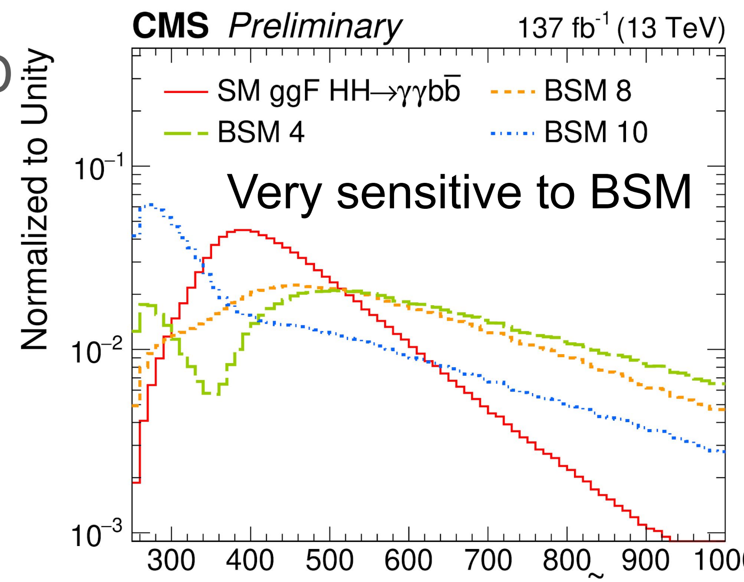


- ➢ Good compatibility to SM predictions in all channels

Non-resonant HH→bbγγ with full Run 2 - overview

- Clean but rare final state
  - γ pair + b-jets pair resonant on m_H
  - bkg from jets(+γγ) → γ and b-jet ID requirements
- MVA strategy to optimize signal-bkg separation
  - BDT to separate ggF or VBF HH from γ(γ)+jets events
  - DNN to separate HH from ttH(γγ) events

ggHH $m^*_{bb\gamma\gamma}$ for some shape benchmark



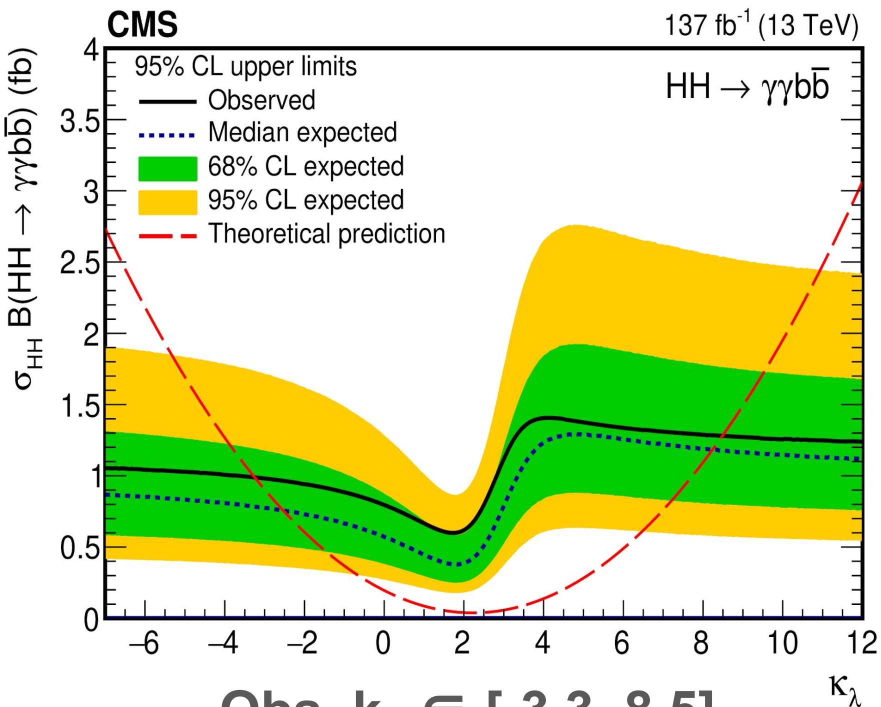
$m^*_{bb\gamma\gamma} = M_{\gamma\gamma jj} - M_{\gamma\gamma} - M_{jj} + 250$ GeV

- Optimize sensitivity to SM, anomalous k_λ, and k_{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}

Non-resonant HH→bbγγ with full Run 2 - results

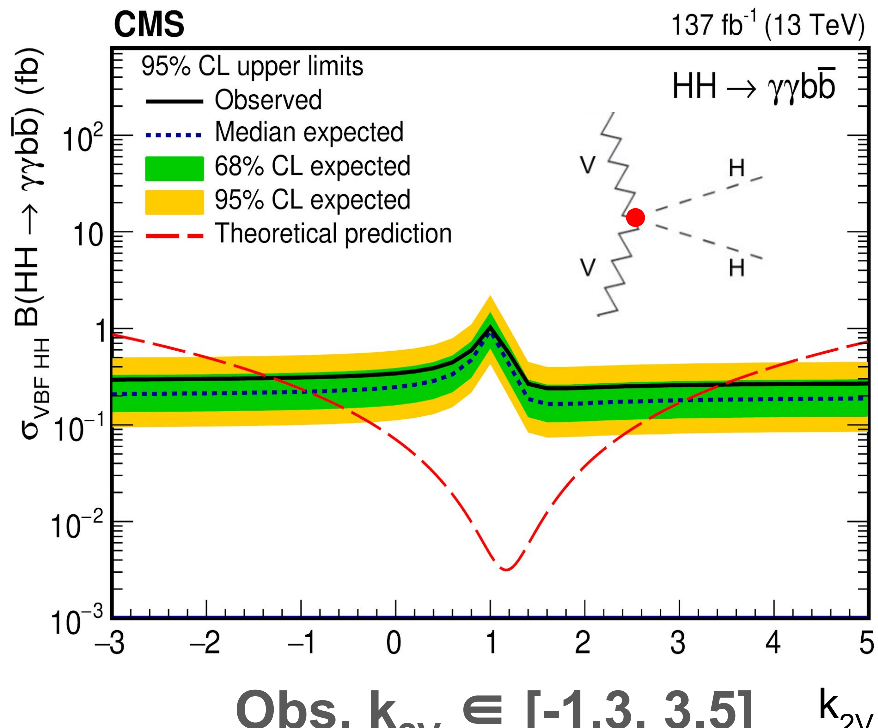
- No deviations from SM observed
- **Obs.**(exp.) upper limit on HH signal strength **7.7**(5.2)

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}

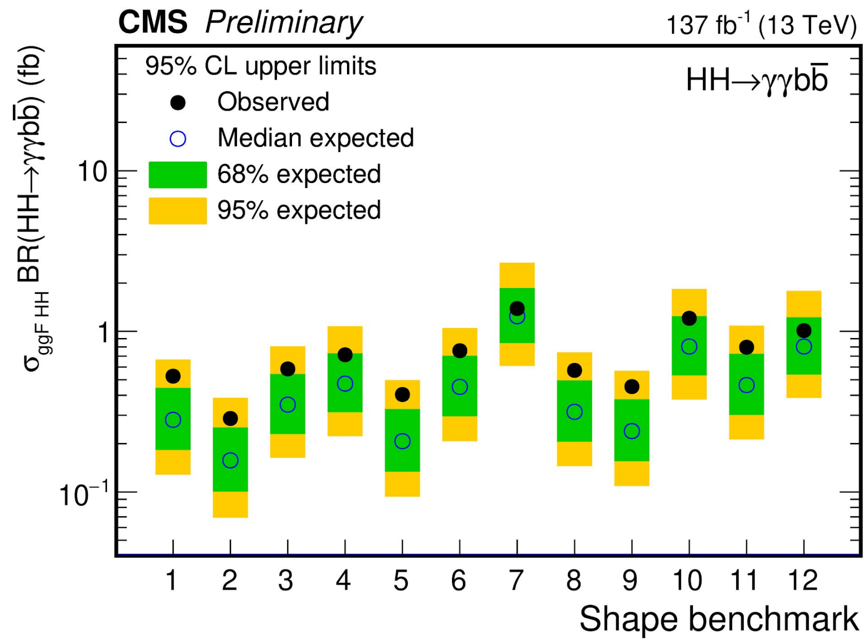


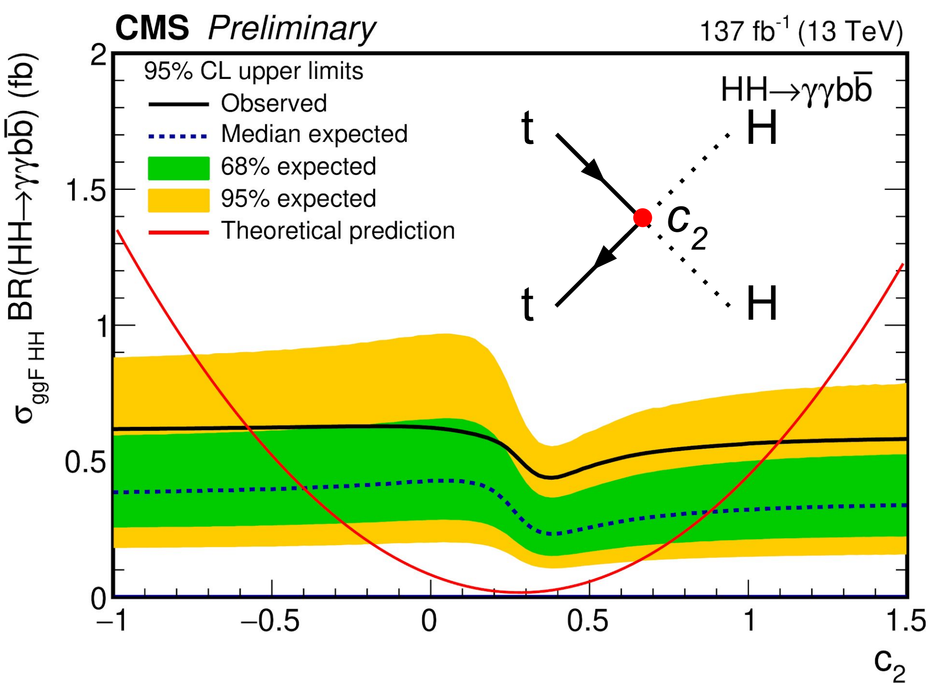
Obs. k_{2V} ∈ [-1.3, 3.5]
Exp. k_{2V} ∈ [-0.9, 3.0]

Non-resonant HH→bbγγ with full Run 2 - 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

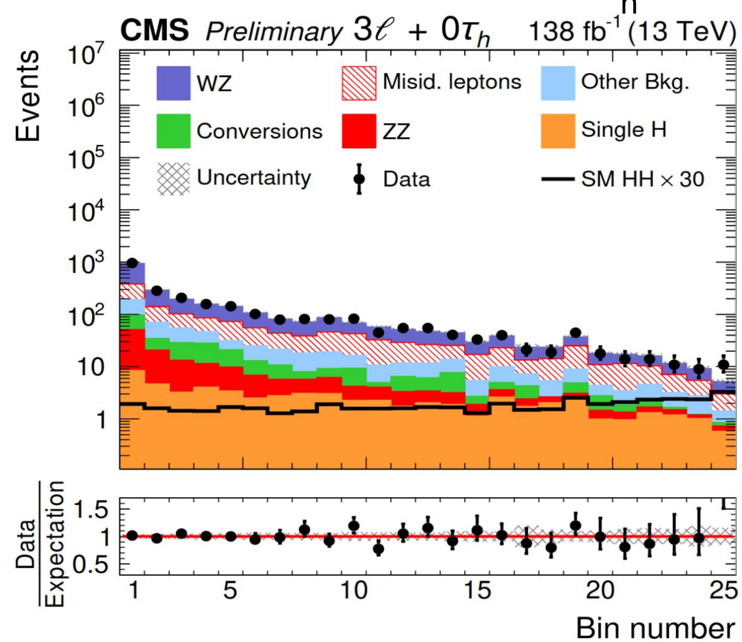
- Special role of H and t in several BSM theories
- HHtt effective coupling

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

Non-resonant (& resonant) HH multilepton - overview

- Target WWWW, WWττ, and ττττ final states with μ, e, or τ_h
  - First search in these channels!
- Selections on p_T^{miss} and on $m(\ell^+\ell^-)$ to reduce DY and ZZ bkg
- bkg dominated by di-boson production and events with mis-identified ℓ or τ_h (fake bkg)
  - Modeling of fake bkg from data, and of all other bkg's from simulation
- 7 categories distinguished by ℓ^+, ℓ^-, and τ_h multiplicity
- BDT classifiers to separate sig from bkg
  - Optimized separately for SM, EFT, res. spin-0, and res. spin-2 sig's

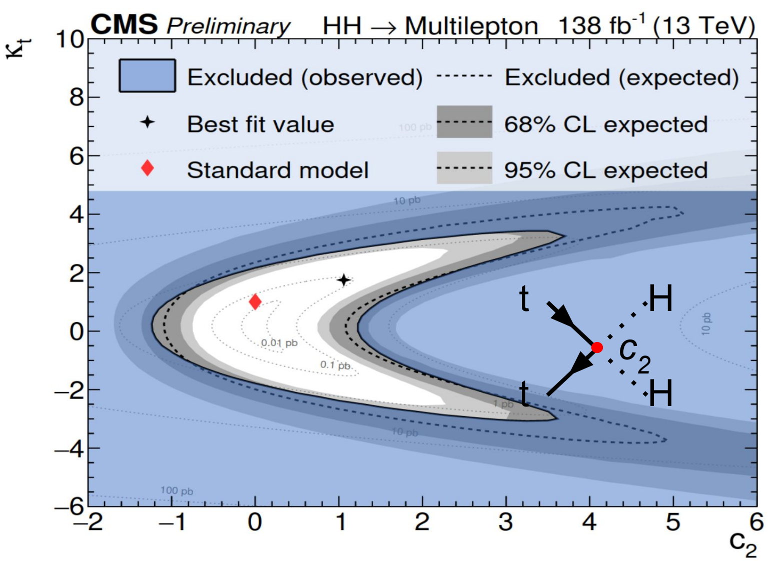
BDT score in the $3\ell+1\tau_h$ cat'



HH multilepton - non-resonant search results

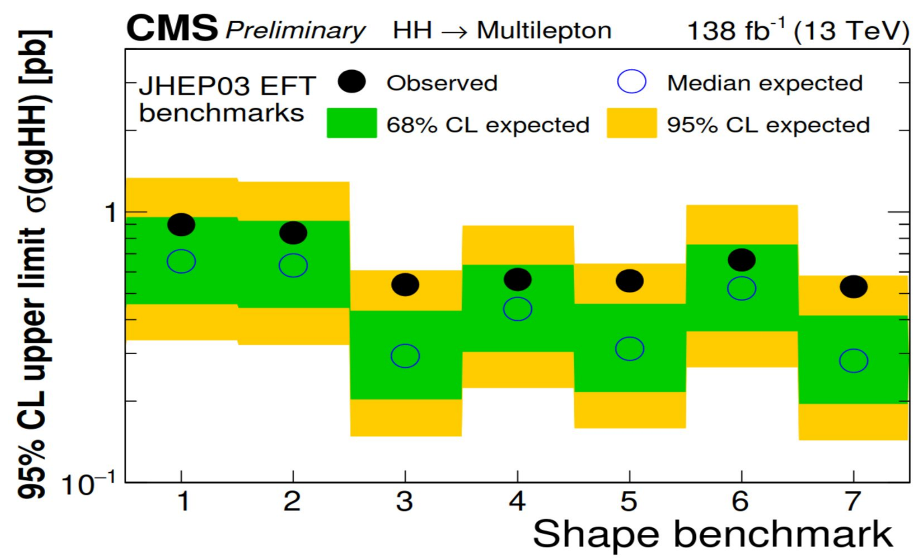
- All observations consistent with SM predictions
- **Obs.**(exp.) upper limit on HH XS **21.8**(19.6)×SM
- **Obs.**(exp.) constraint to k_λ **$-7.0 < k_\lambda < 11.2$**($-7.0 < k_\lambda < 11.7$)

Upper limits on σ(HH) vs (c_2, k_t)



➢ Extensive test of Higgs-top interaction

Upper limits on σ(HH) for shape benchmarks of JHEP03(2020)091



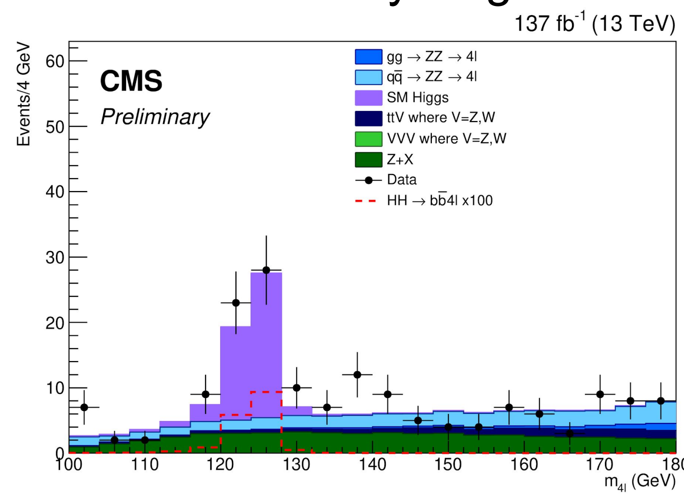
➢ First constraint on these benchmarks

Constraints on benchmarks of JHEP04 and on resonant production in backup

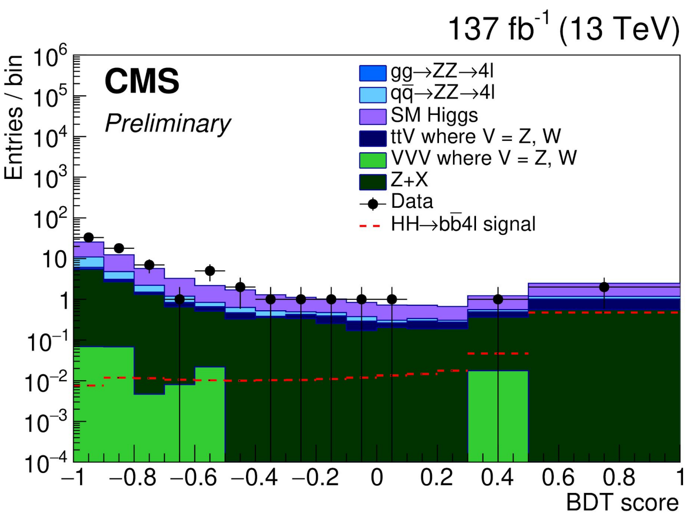
Non-resonant HH→bbZZ(4ℓ)

- 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

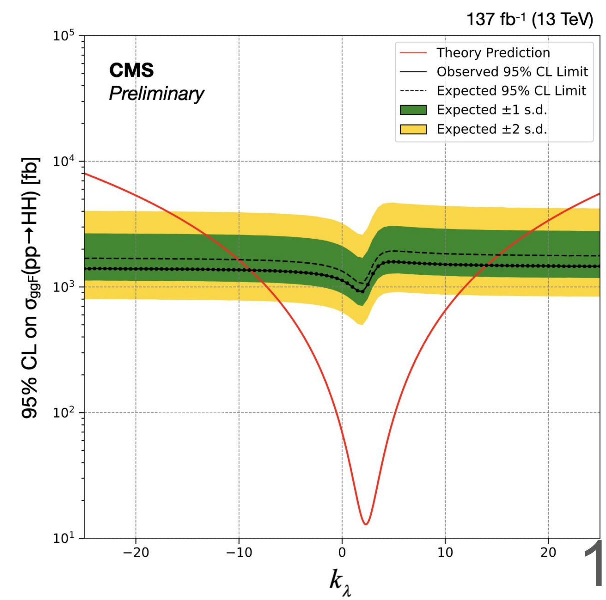


sig extraction from BDT distribution fit



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)

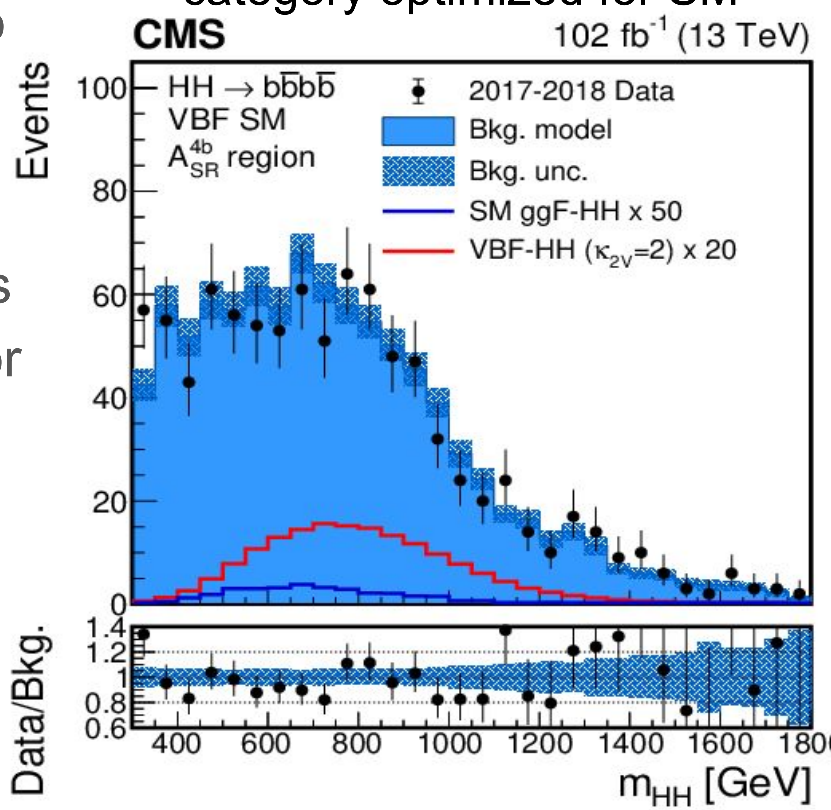


➢ First non-res results for this channel

Non-resonant resolved HH→4b - overview

- Final state with four b-jets (+ extra jet pair for VBF HH)
- H(bb) reconstruction correct in >82(91)% of ggF(VBF)
- bkg dominated by QCD and tt
  - DNN-based b-jet ID & lepton veto
  - bkg estimation from data
- VBF HH signal region
  - BDT classifier to reject ggHH+jets
  - Two BDT score cat's optimized for anomalous k_{2V} and SM
  - Fit to m_{HH}
- ggHH signal region
  - Two 4-body mass cat's
  - BDT classifier to reduce bkg
  - Fit to BDT shape

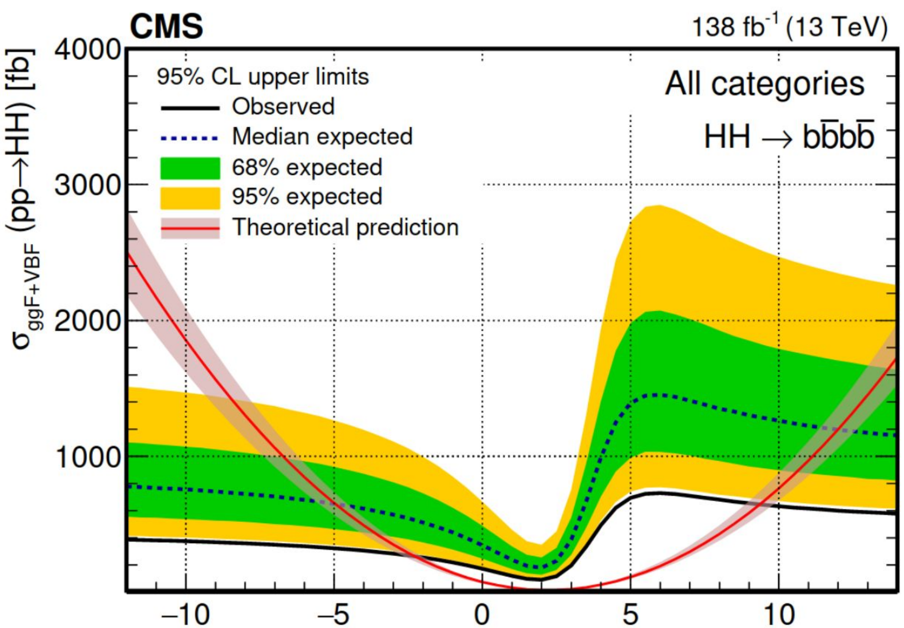
m_{HH} distribution for VBF-enriched category optimized for SM



Non-resonant resolved HH→4b - results

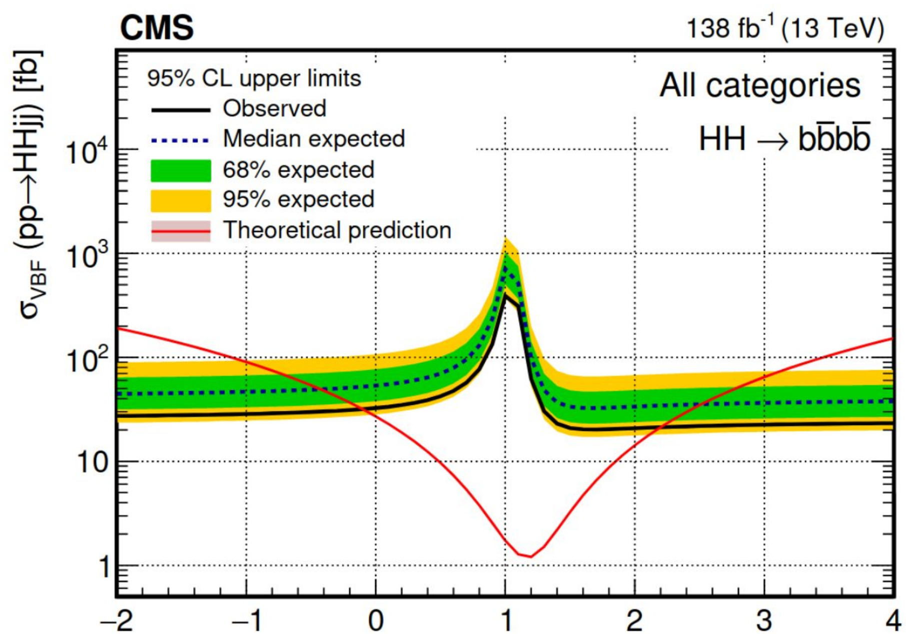
- **Obs.**(exp.) upper limit on HH XS of **3.9**(7.8)×SM

Limit on HH XS vs k_λ



Obs. $\mathbf{k_\lambda \in [-2.3, 9.4]}$
Exp. $k_\lambda \in [-5.0, 12.0]$

Limit on VBF HH XS vs k_{2V}



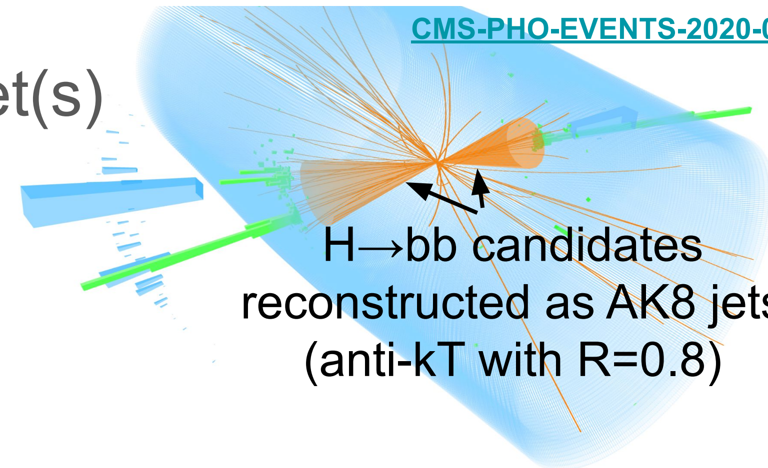
Obs. $\mathbf{k_{2V} \in [-0.1, 2.2]}$
Exp. $k_{2V} \in [-0.4, 2.5]$

➢ Obs < exp limits because of small data under-fluctuation

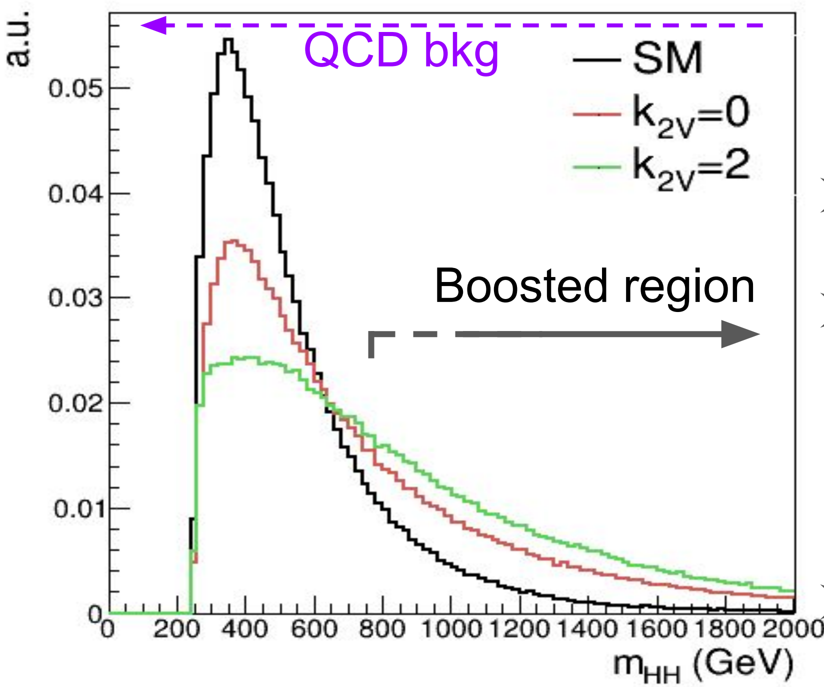
Boosted HH topologies

- Boosted H→bb candidate(s) reconstructed as large radius jet(s)
  - Possible also for $H\rightarrow\tau_h\tau_h$

Boosted ggHH→4b event candidate



gen-level m_{HH} for VBF HH events



➢ Enhanced for anomalous k_{2V}

➢ Optimal approach to search for X→HH or YH resonances with $m_X \gtrsim$ 1 TeV

➢ Higher m_{HH} ~ lower QCD bkg

- H→bb ID using jet substructure info
  - Excellent performance through usage of “ParticleNet” graph NN

Non-resonant boosted HH→4b - overview

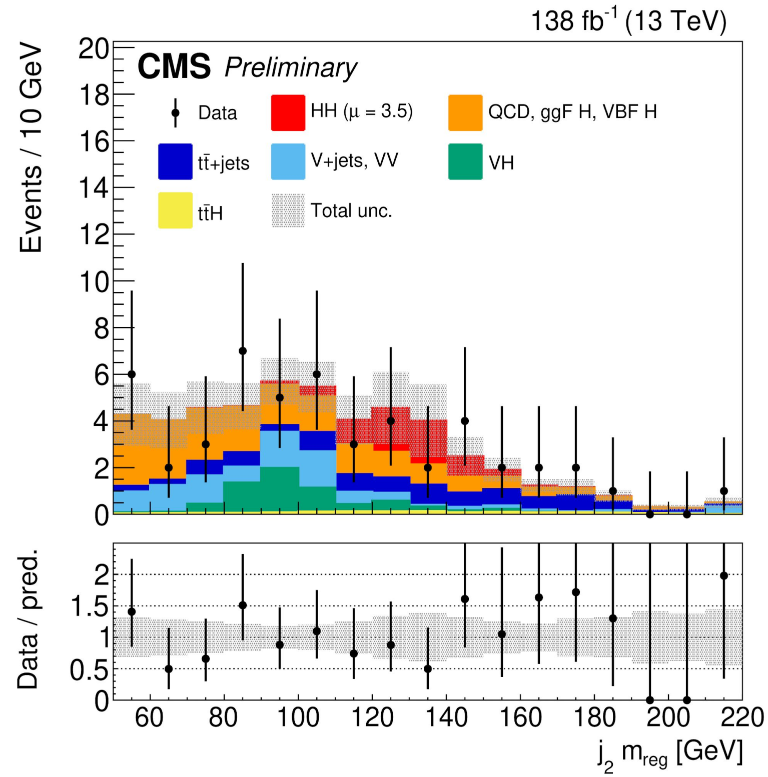
- Final state with two AK8 jets (+extra jet pair in VBF HH)
- Main bkgs from QCD and tt
  - H→bb ID using jet substructure
  - Regression to improve H→bb mass resolution

  ParticleNet-based
  - bkg estimation from data

➢ 3 VBF HH - enriched categories
  - Classification on ParticleNet score
  - sig extraction from fit to m_{HH}

➢ 3 ggHH-enriches categories
  - BDT classifier to separate sig from bkgs & to define categories
  - Signal extraction from fit to subleading jet mass

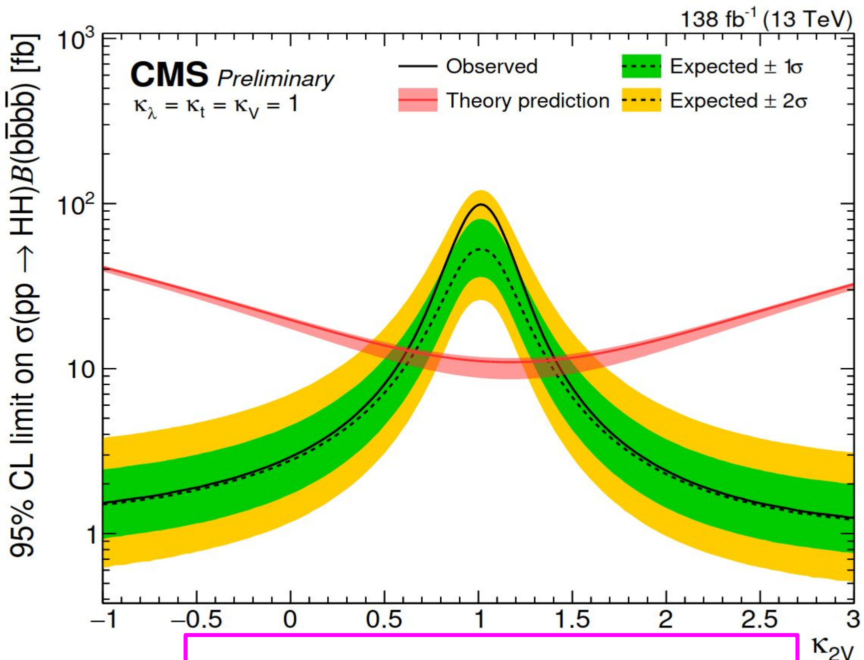
Regressed mass of one AK8 jet in a ggHH(4b) category



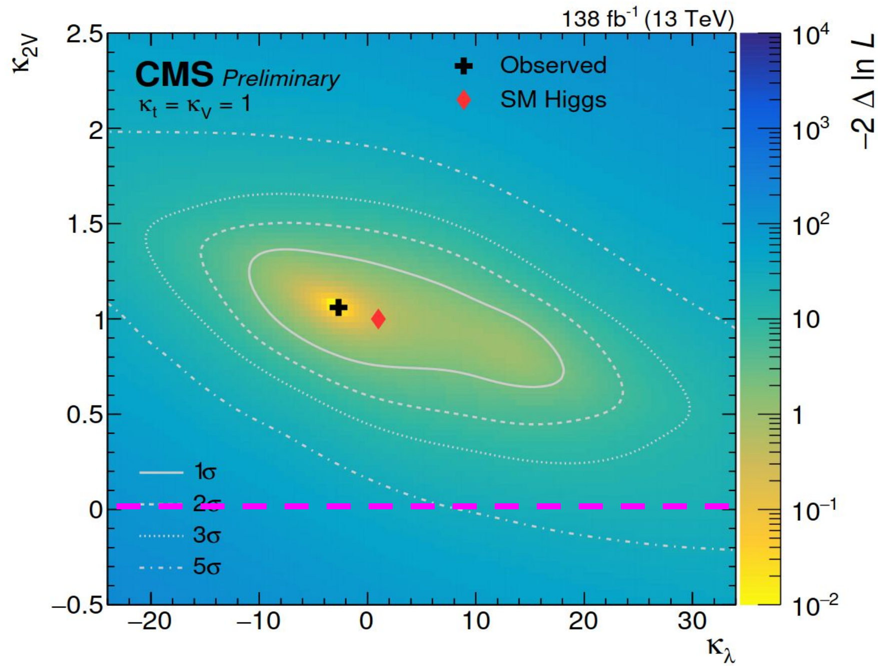
Non-resonant boosted HH→4b - constraints on k_{2V}

- No deviations from SM observed

Limit on VBF HH XS×BR vs k_{2V}



2D likelihood scan of (k_λ, k_{2V})



Obs. $k_{2V} \in$ [0.62, 1.41]
Exp. $k_{2V} \in$ [-0.9, 3.0]

➢ k_{2V} = 0 excluded at >5σ assuming $k_\lambda = k_t = k_V = 1$

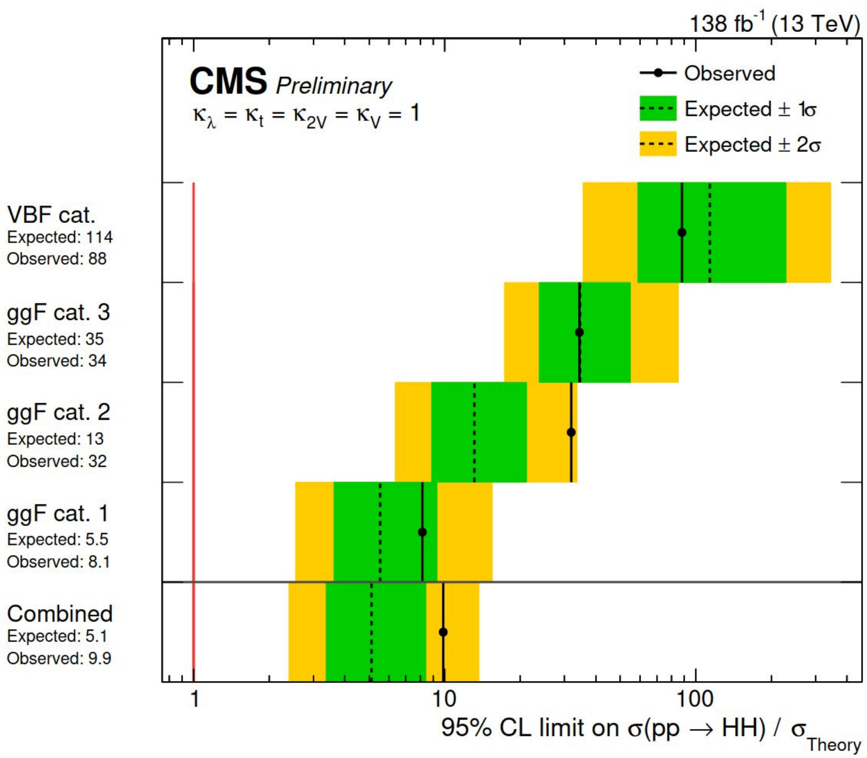
➢ k_{2V} = 0 excluded at >3σ for any value of k_λ

➢ Most stringent constraint on k_{2V} to date

Non-resonant boosted HH→4b - constraints on k_λ&SM

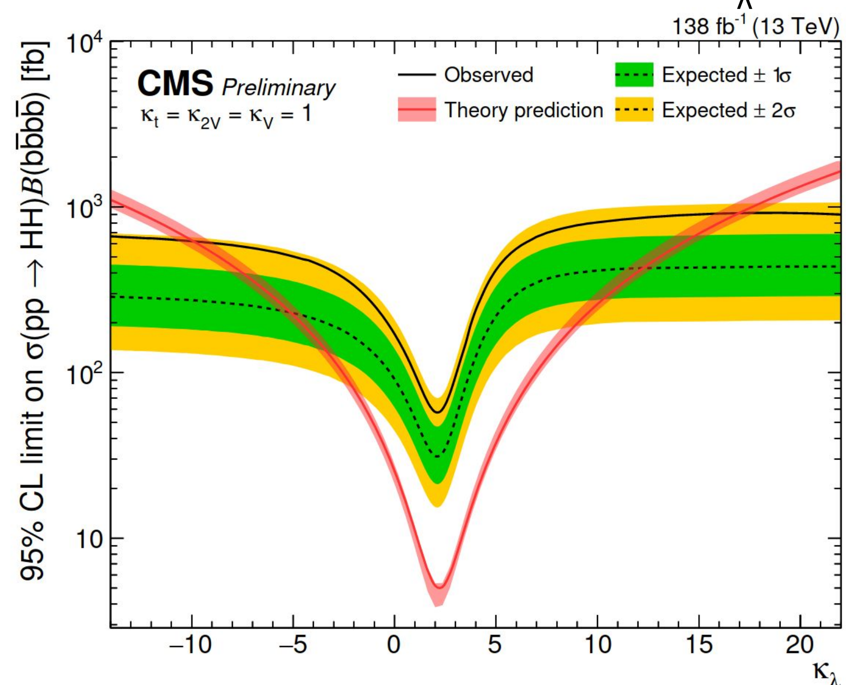
- Good constraints on HH signal strength and k_λ thanks to ggHH boosted categories

Limit on HH XS split by categories



obs(exp) UL = **9.9**(5.1)×SM

Limit on HH XS×BR vs k_λ



Obs. $k_\lambda \in [-9.9, 16.9]$

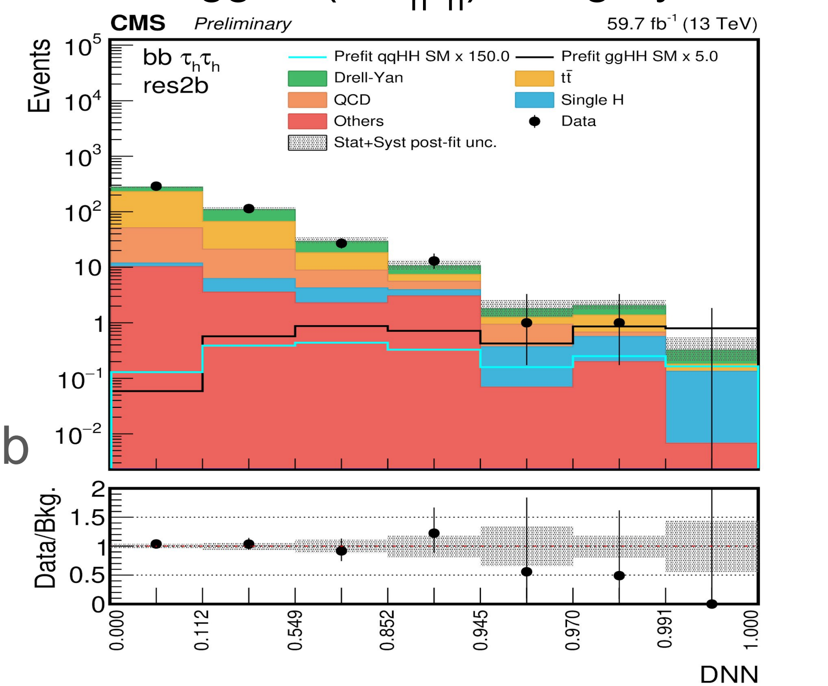
Exp. $k_\lambda \in [-5.1, 12.2]$

Non-resonant HH→bbττ with full Run 2 - overview

- $\tau_h\tau_h$, $\tau_h e$, and $\tau_h\mu$ final states → ~88% of H→ττ BR
- Online selections for single-lept., lept.+τ_h, $\tau_h\tau_h$ and VBF $\tau_h\tau_h$
- bkg from tt, QCD, and DY events
  - Kinematic selections on (m_{bb}, $m_{\tau\tau}$)
  - Lepton ID+iso & b-jet ID
- Event categorization on production mode and final state

×3 ττ final states:
  - 1 category for VBF HH
  - 1 cat' for ggHH with boosted H→bb
  - 2 cat's for ggHH with resolved H→bb

DNN score in one resolved ggHH(bb$\tau_h\tau_h$) category



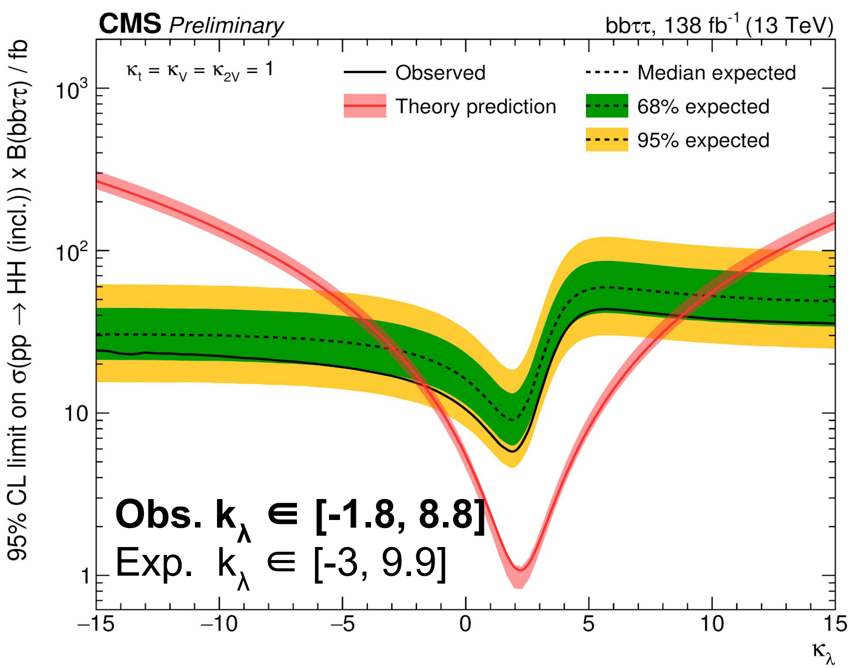
- DNN classifiers to maximize sig vs bkg separation
- Signal extraction from fit to DNN score

Non-resonant HH→bbττ with full Run 2 - results

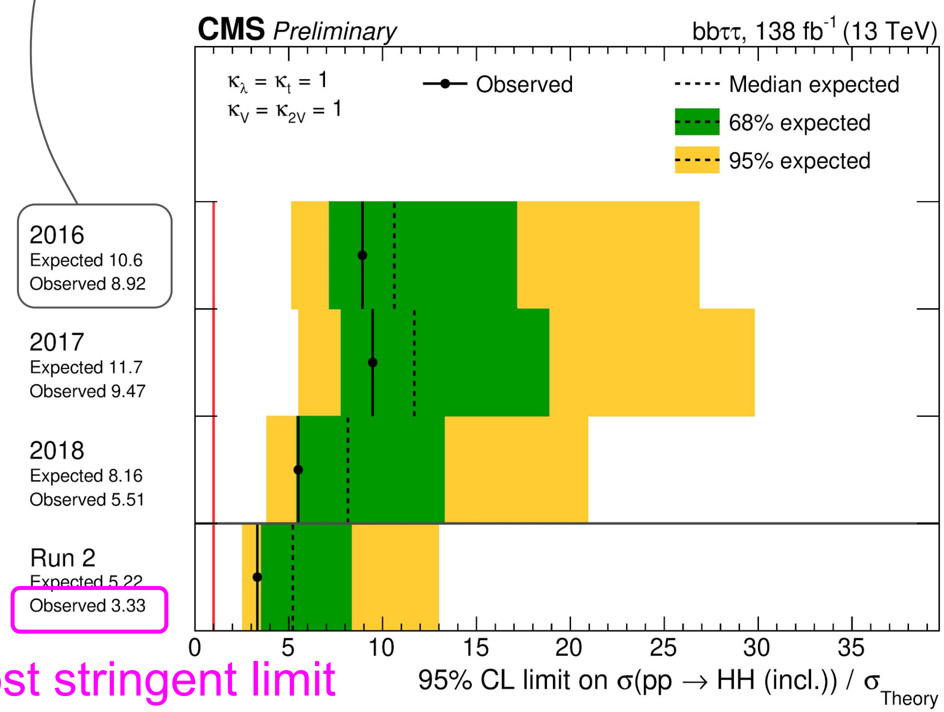
- No deviations from SM observed

~2× better than HH→bbττ search with 2016 dataset

Upper limit on HH XS×BR vs k_λ



Upper limit on inclusive HH XS



Most stringent limit @CMS to date!

Most stringent to date!

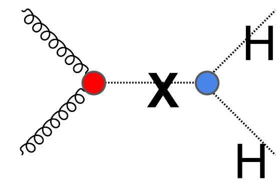
+ **obs**(exp) UL on VBH HH XS of **124**(154)×SM

+ obs(exp) k_{2V} constraints: $-0.4 < k_{2V} < 2.6$ ($-0.6 < k_{2V} < 2.8$)

Resonant HH searches

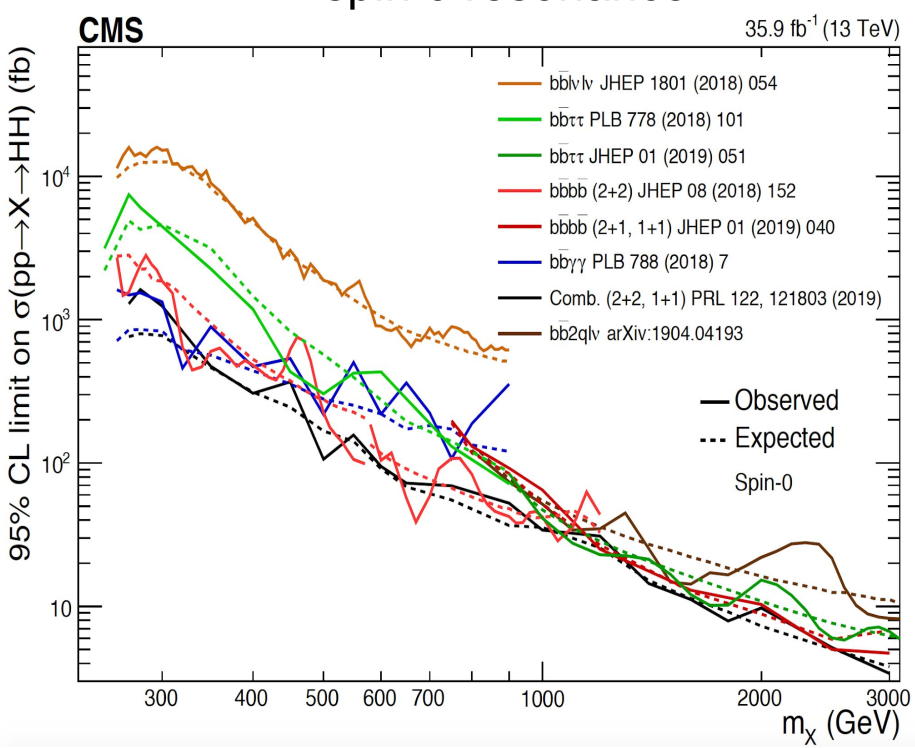
Resonant HH comb with 2016 data (~36 fb^{-1})

- No significant excess found

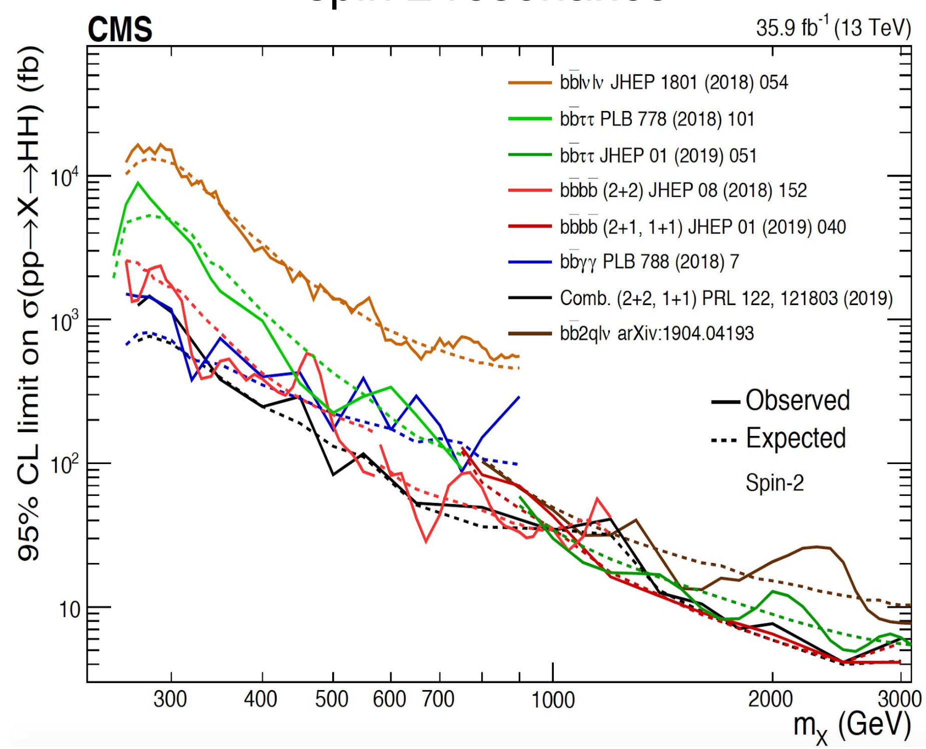


Upper limit on σ(pp→X→HH)

spin 0 resonance



spin 2 resonance

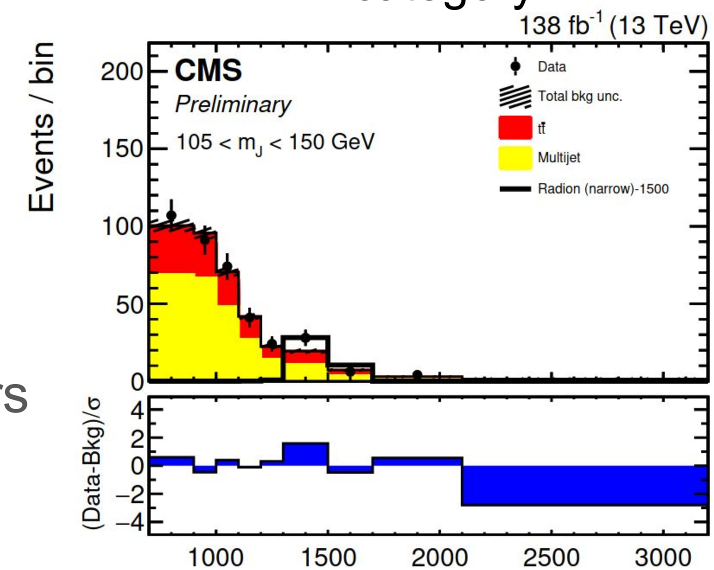


Results with full Run 2 dataset (~138 fb^{-1}) in this presentation

Resonant X→HH→4b - overview

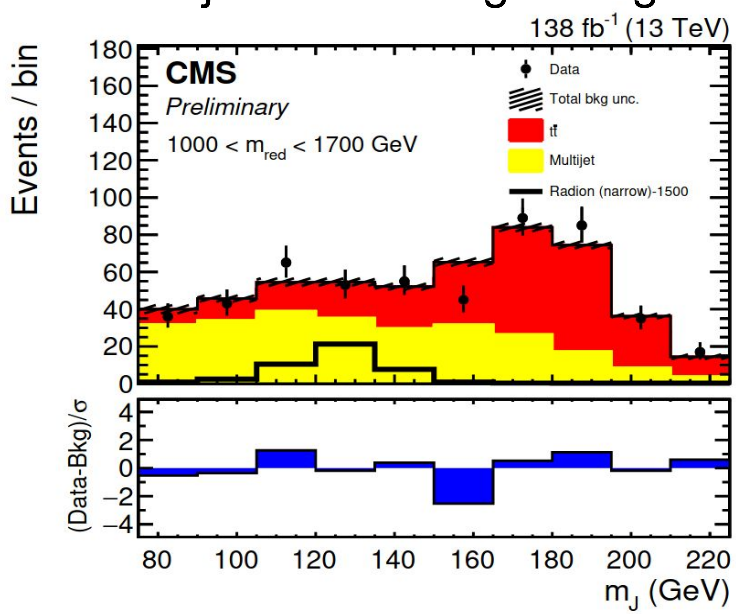
- $m_X \in [1, 3]$ TeV and spin 0 or 2
- Final states with 1 or 2 boosted H
  - 2 AK8 jets, or 1 AK8 + 2 AK4 jets
- main bkg from QCD and tt
  - b-jet ID based on DNN discriminators
  - modeling from data assisted by MC

m^*_{HH} in high b-tag scores category



$m^*_{HH} = m_{HH} - m_{H1} - m_{H2} + 250$ GeV

lead AK8 jet mass in high b-tag scores cat'



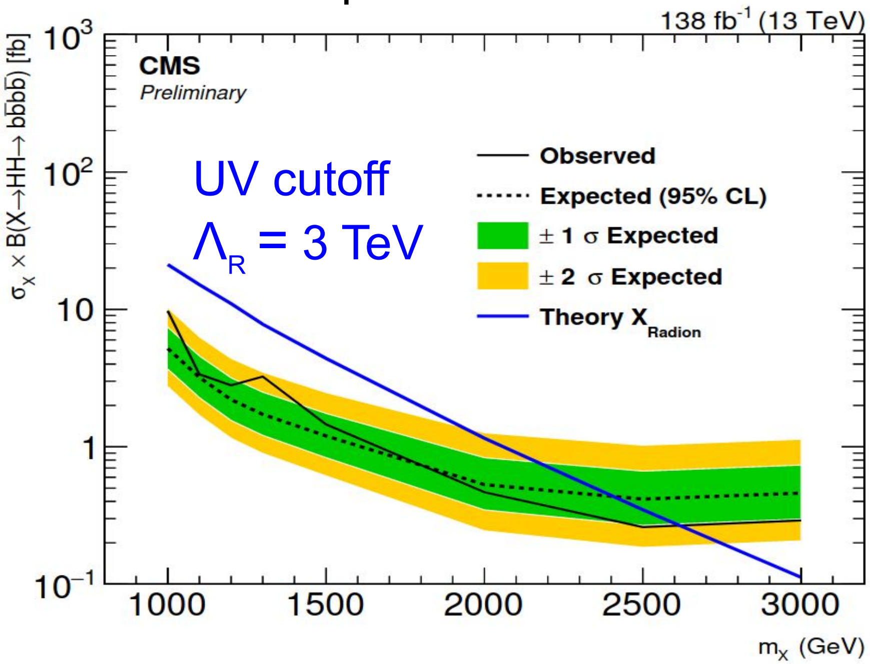
- One category for semi-boosted + two cat's for fully-boosted based on the b-tag scores
- Signal extraction from fit to m^*_{HH} and leading AK8 jet mass

Resonant X→HH→4b - results

- No significant excess found in the 1-3 TeV m_X range

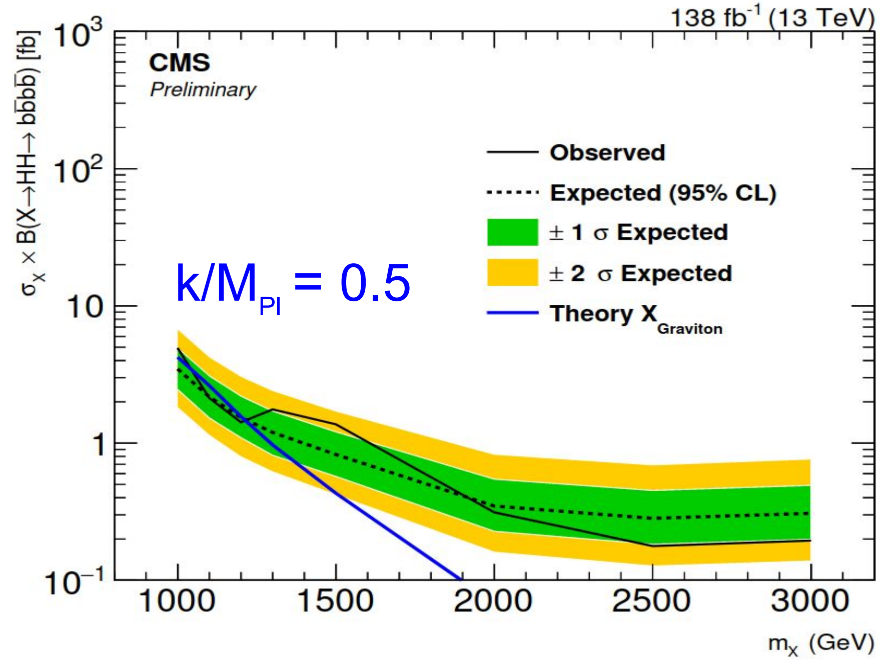
Upper limit on σ(pp→X→HH→4b)

spin 0 resonance



limits from 4.94 to 0.19 fb

spin 2 resonance



limits from 9.74 to 0.29 fb

➢ For Λ_R = 3 TeV & k/M_{Pl} = 0.5, radion with m ∈ [1, 2.6] TeV and graviton with m ∈ [1, 1.2] TeV excluded @95% CL

Resonant boosted X→HH→bb+leptons - overview

- Resonance with $m_X \in$ [0.8, 4.5] TeV and spin = 0 or 2
- Target HH decays bbWW(qqℓν) + bbττ(2ℓ4ν) + bbVV(2ℓ2ν)

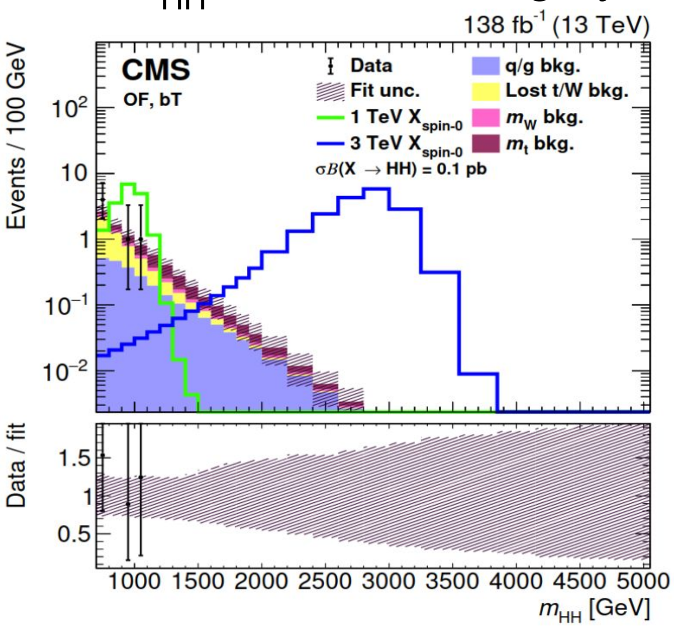
single-lepton (SL) final state = large radius jet + nearby lepton + p_T^{miss}

di-lepton (DL) final state = 2 leptons + p_T^{miss}

+ H→bb reconstructed as a large radius heavy-flavored jet

- Main bkg from tt and Z+jets modeled with simulation

m_{HH} in one DL category



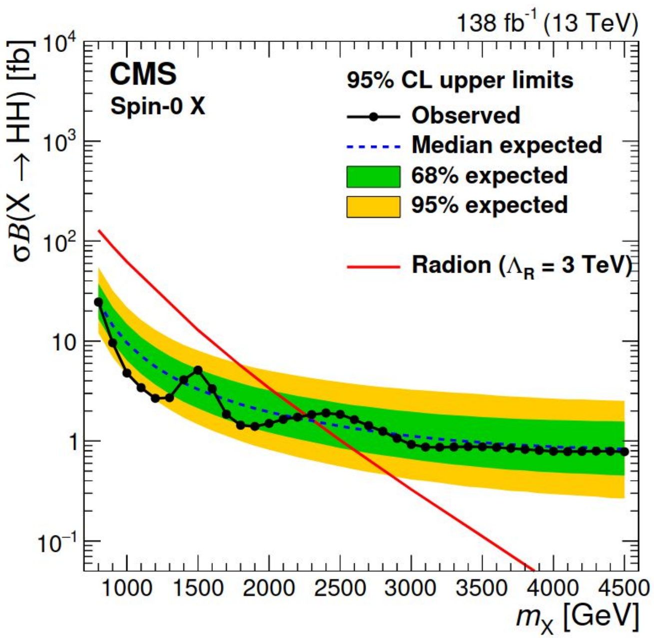
- Event categorization on lept. flavour, b-tag score, and other variables providing good sig-bkg separation
  - 8 SL categories + 4 DL categories
- 2D fit to (m_{HH}, m_{bb})

Resonant boosted X→HH→bb+leptons - results

- No significant excess found

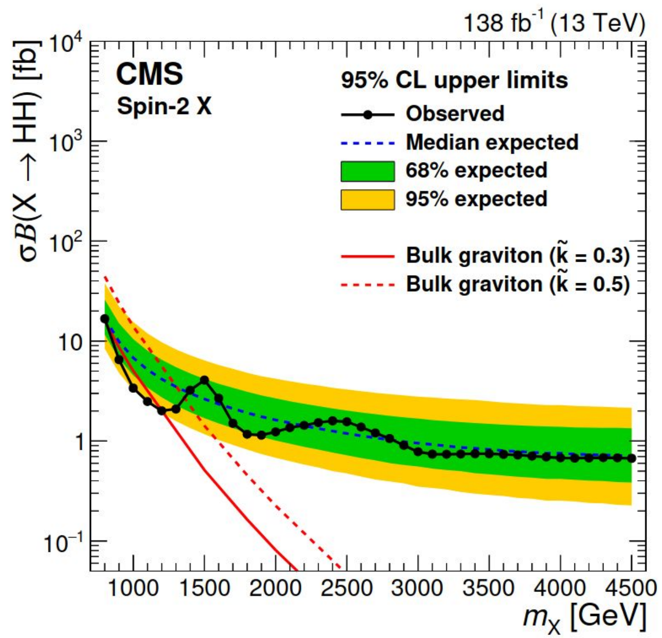
Upper limit on σ(pp→X→HH)

spin 0 resonance



Upper limits from 24.5 to 0.78 fb

spin 2 resonance

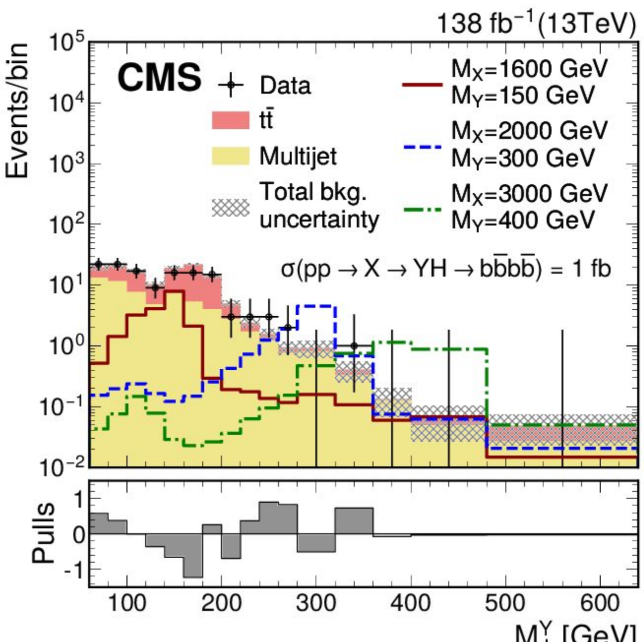


Upper limits from 16.7 to 0.67 fb

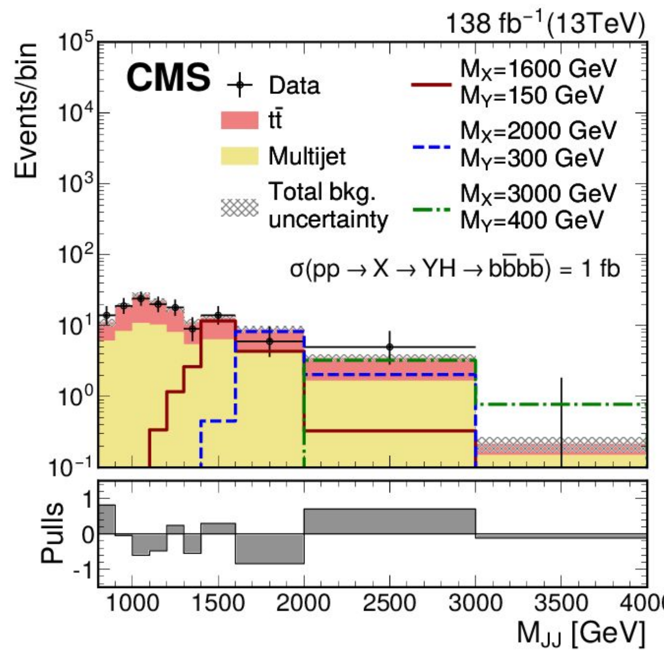
➢ Sensitivity similar to search for X→HH→4b

Resonant boosted X→YH→4b - overview

- $m_X \in [0.9, 4]$ TeV and $m_Y \in [60, 600]$ GeV → boosted H & Y
- Similar final state and bkgs of boosted non-resonant HH(4b)
  - Similar ParticleNet-based strategy for H(bb) ID, m_{bb} regression and event categorization
- Modeling of QCD bkg from data and of tt from simulation
  - Data control regions for validation & to improve data/MC agreement
- 2D fit to reconstructed m_X and m_Y of signal candidates



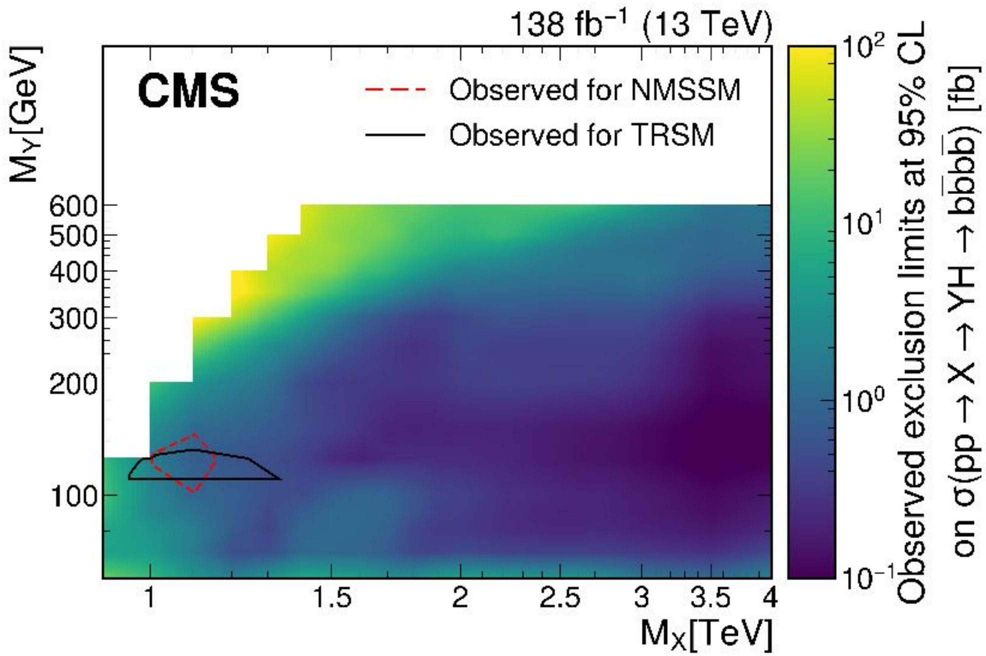
reco m_Y and m_X in the highest ParticleNet score category



Resonant boosted X→YH→4b - results

- No significant excess found

Observed limits on σ(pp→X→YH→4b) at 95% CL as a function of (M_X, M_Y)



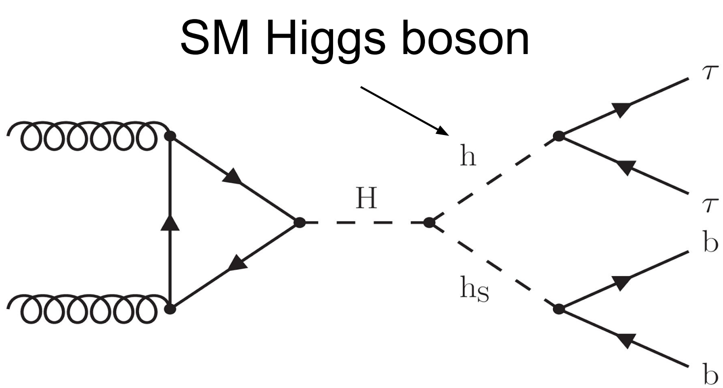
➢ Limits range from 0.1 fb to 150 fb

Assuming maximally allowed NMSSM and TRSM XS's

➢ NMSSM excluded within M_X∈ [1, 1.15] TeV and M_Y∈ [101, 145] GeV

➢ TRSM excluded within M_X∈ [0.95, 1.33] TeV and M_Y∈ [110, 132] GeV

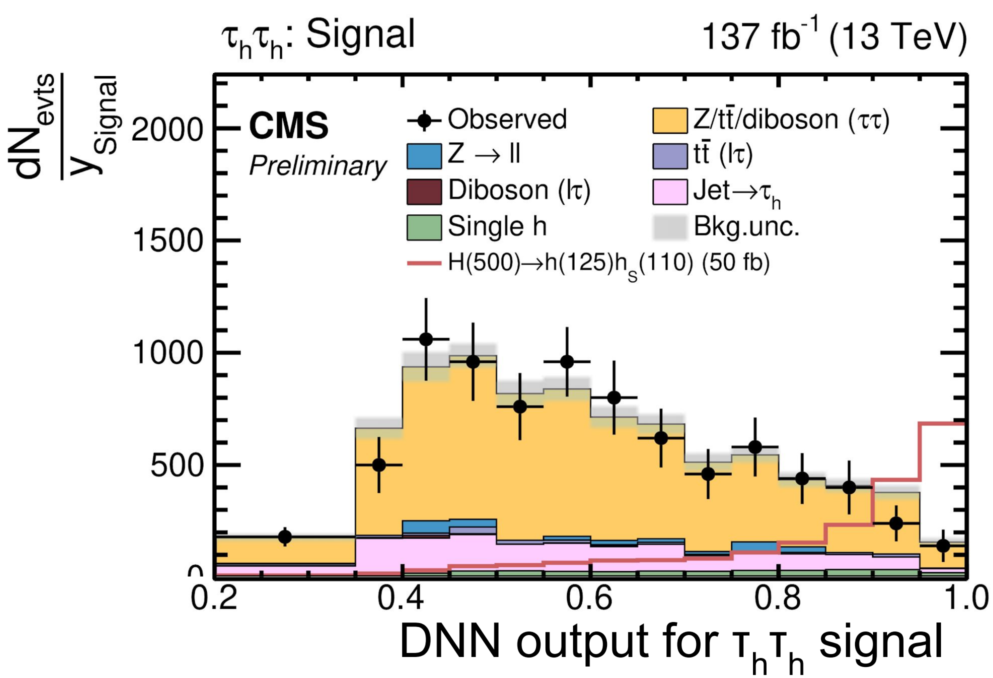
Resonant $H \to h_S h \to bb\tau\tau$ (= $X \to YH \to bb\tau\tau$) - overview



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

Require ID of exactly 1 or 2 b-jets

- Main backgrounds from QCD, tt, and Z+jets

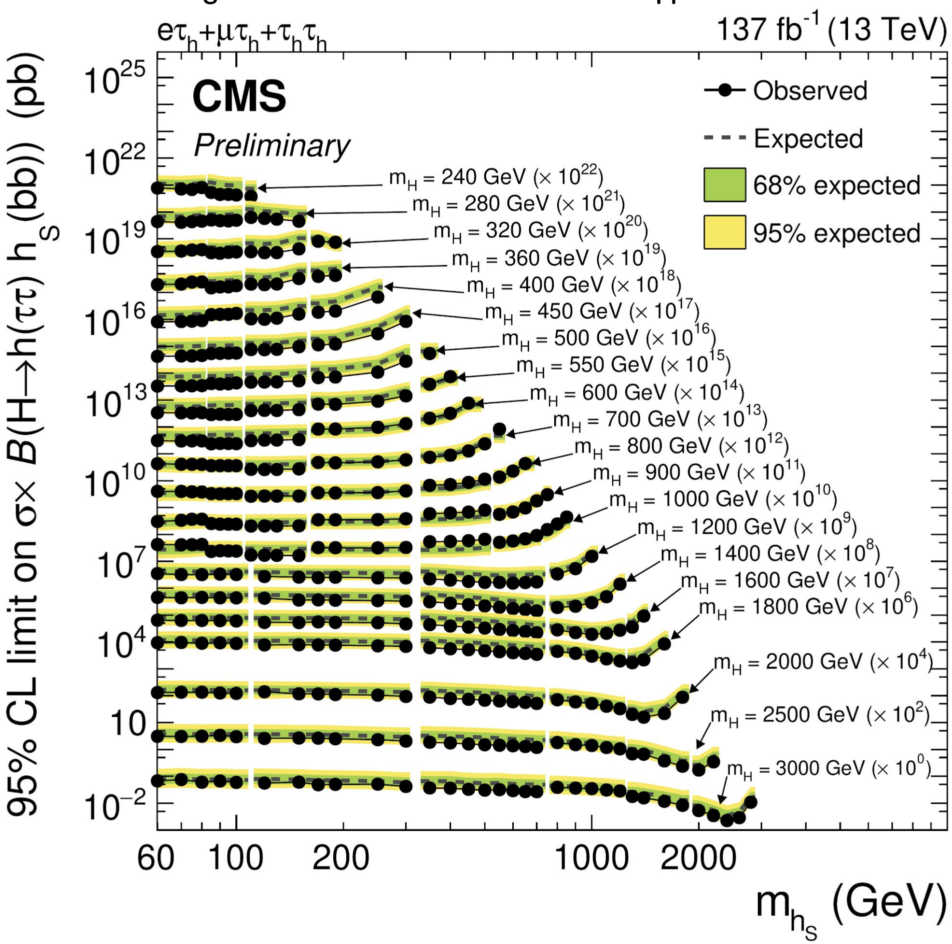


➢ Optimize signal vs bkgs separation with NN multiclassifier
  - Signal region dominated by events with genuine τ_h

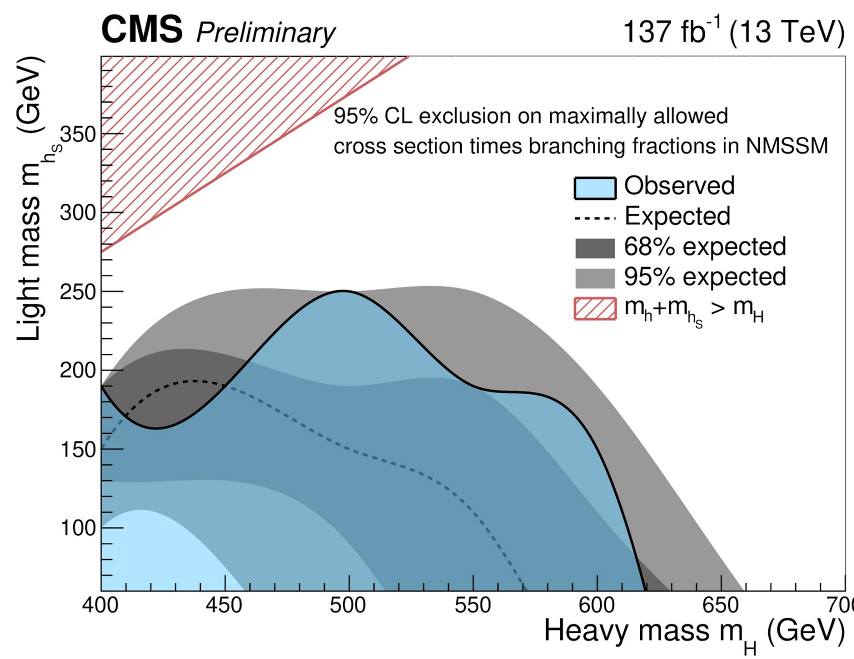
H→h_Sh→bbττ at CMS with full Run 2 - results

- 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→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

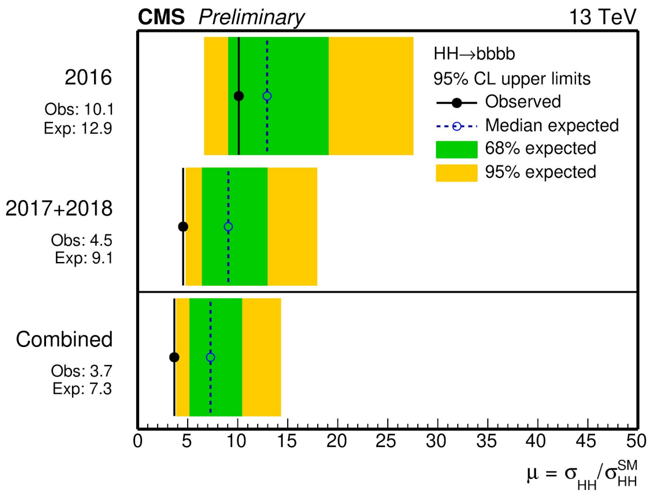
Summary

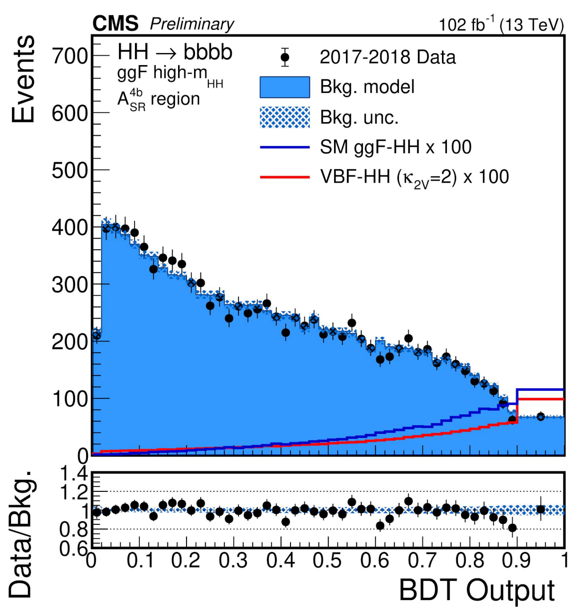
- HH physics offers wide physics program at LHC
  - HHVV, tri-H couplings + effective BSM couplings
  - Search for BSM resonances
- Presented CMS Run 2 results
  - No deviations from SM predictions observed so far
  - New techniques and approaches wrt 2016 analyses
  - Other interesting results coming - stay tuned!
- Quickly approaching to upper limit on HH XS equal to SM
  - Run 3?

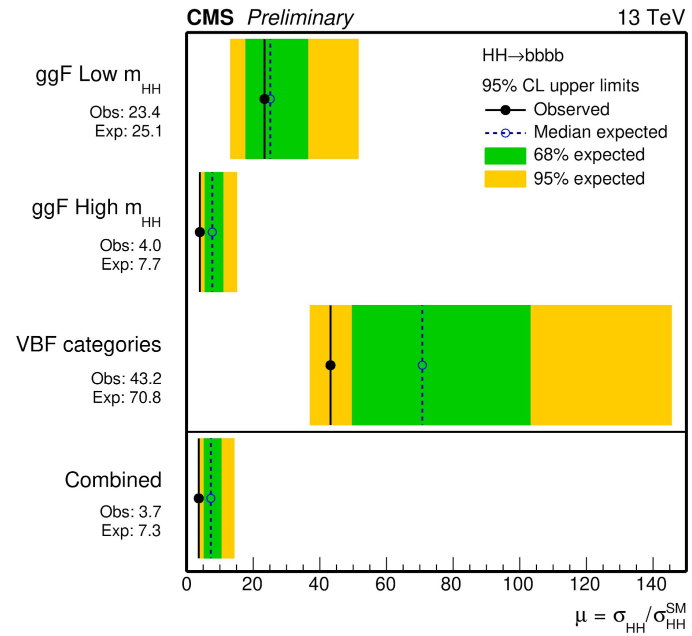
Exciting times ahead!

BACKUP

Non-resonant resolved HH→4b results by category and by year





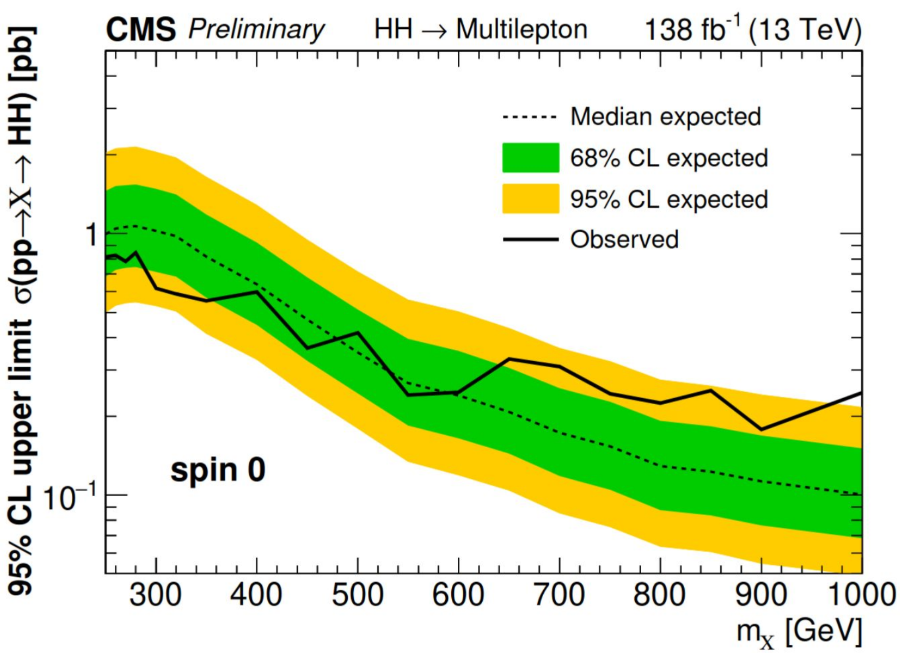


HH multilepton - resonant search results

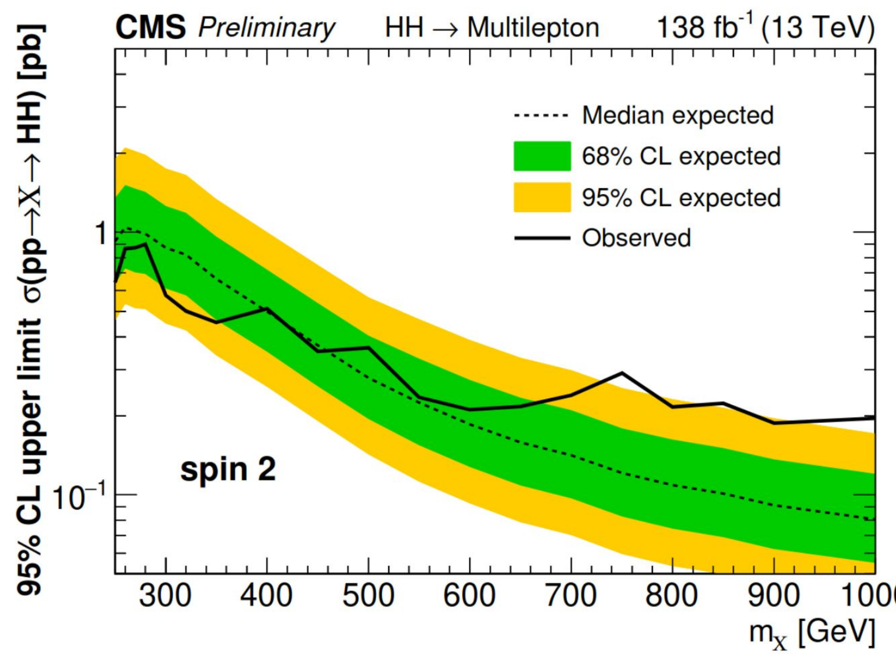
- No significant excess found

Upper limit on σ(pp→X→HH→4b)

spin 0 resonance

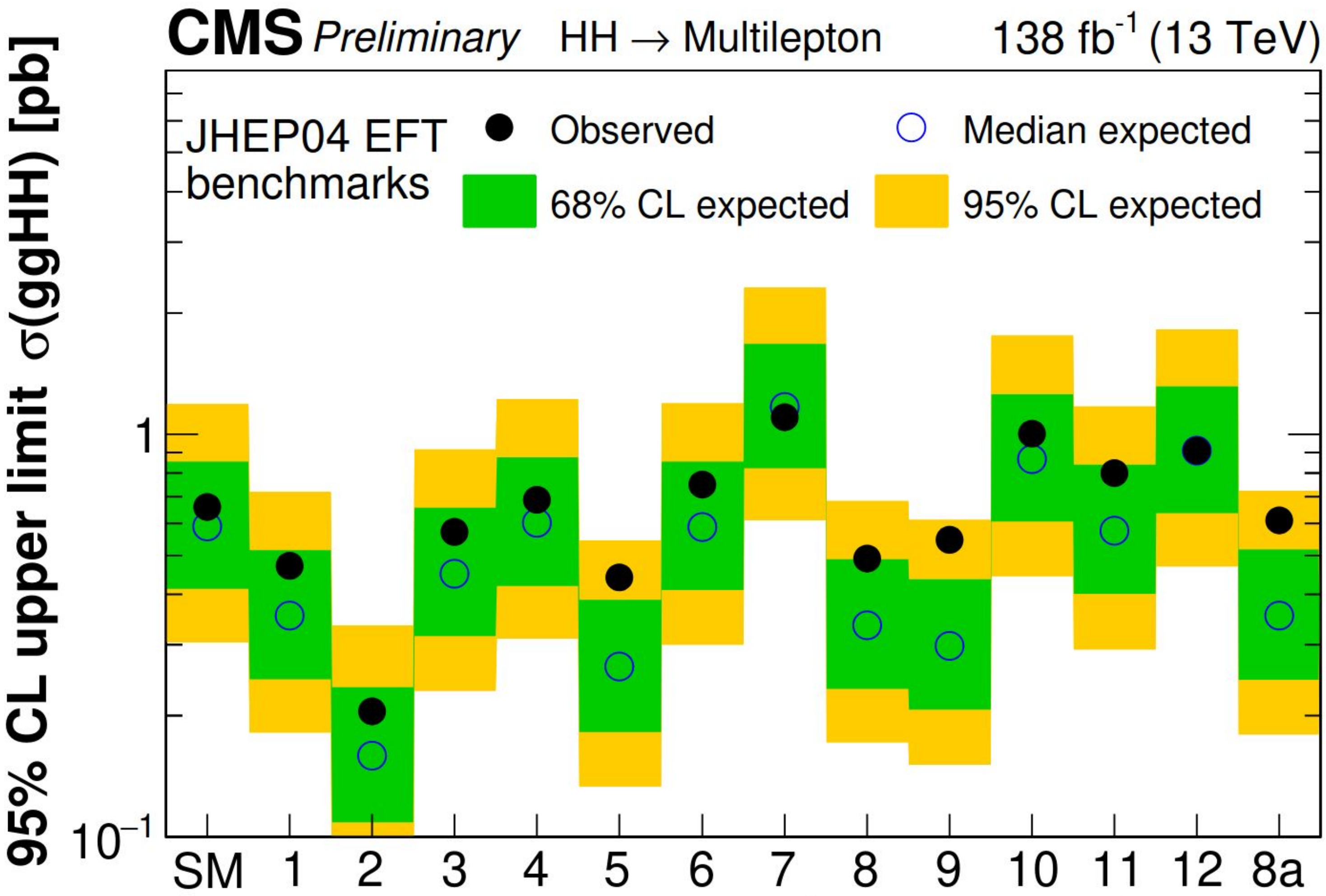


spin 2 resonance



HH multilepton - JHEP04 benchmark results

- No significant excess found

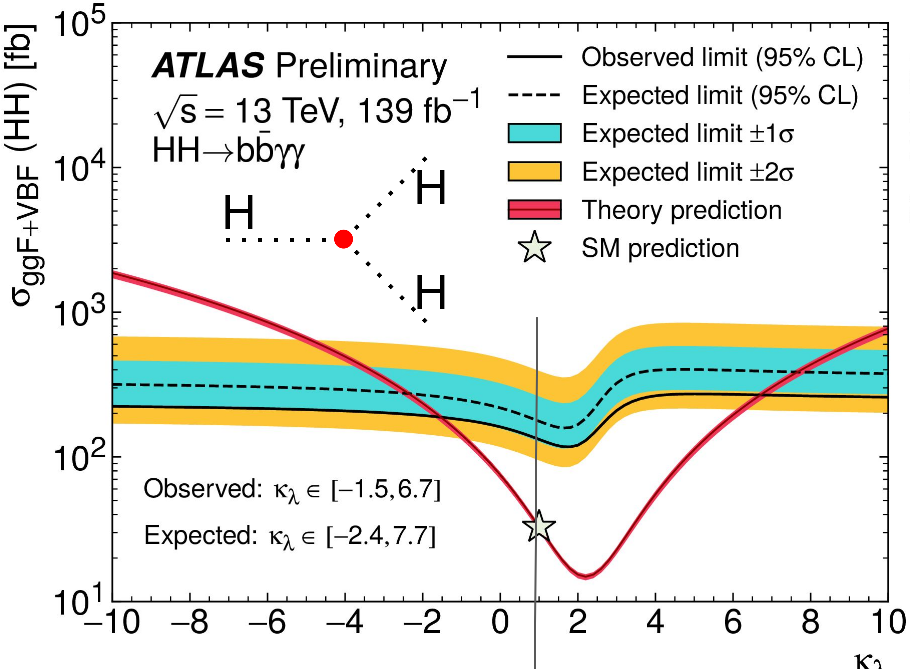


ATLAS-CONF-2021-016

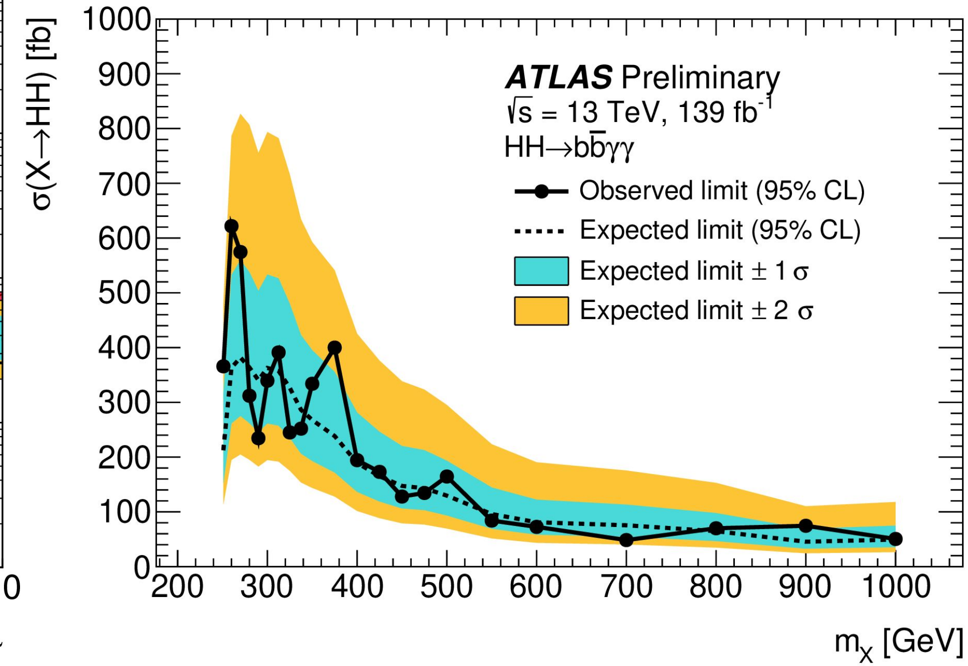
HH→bbγγ at ATLAS with 139 fb^{-1} - results

- No deviations from SM observed

Limit on HH XS vs k_λ



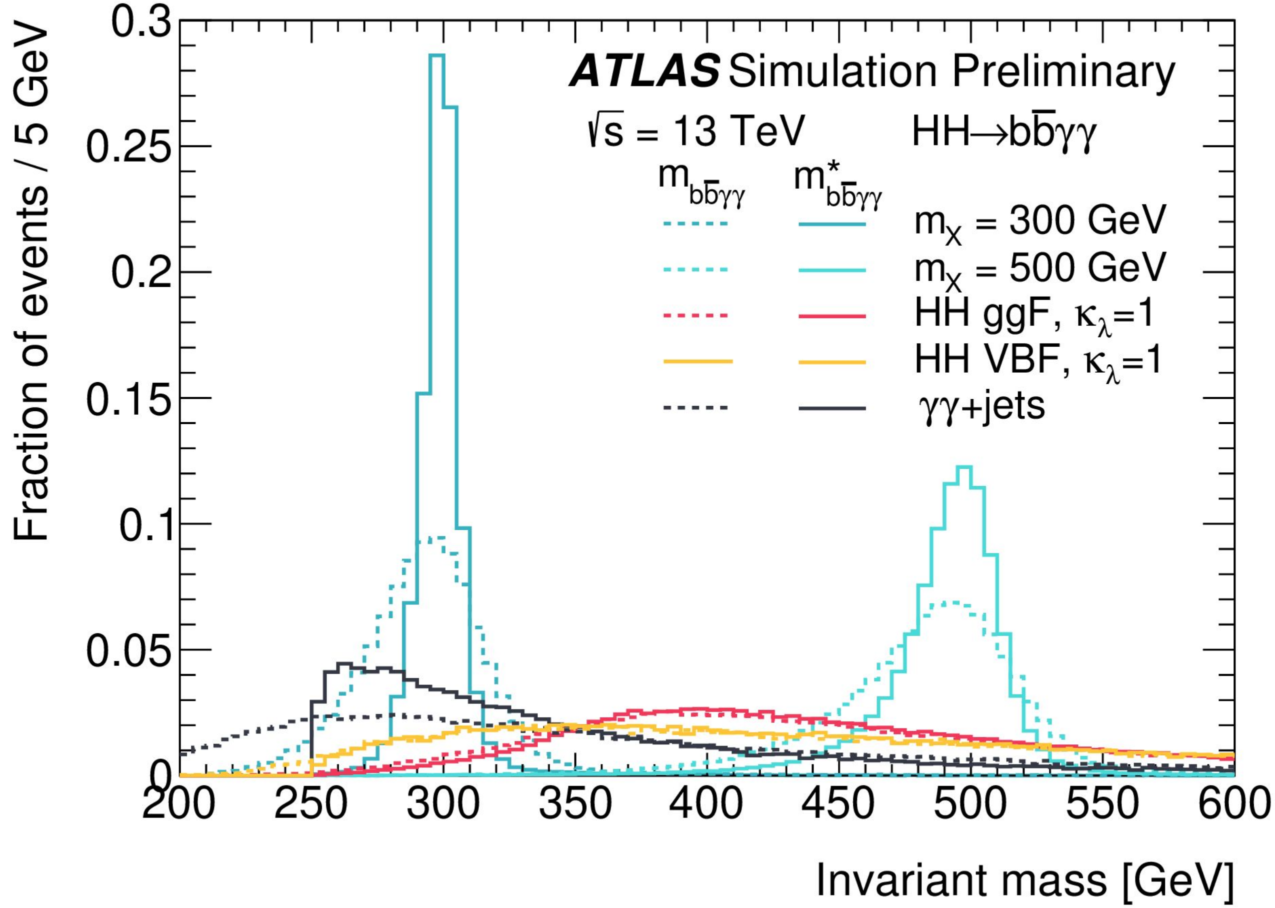
Limit on spin 0 resonance with mass m_X and narrow width



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

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

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

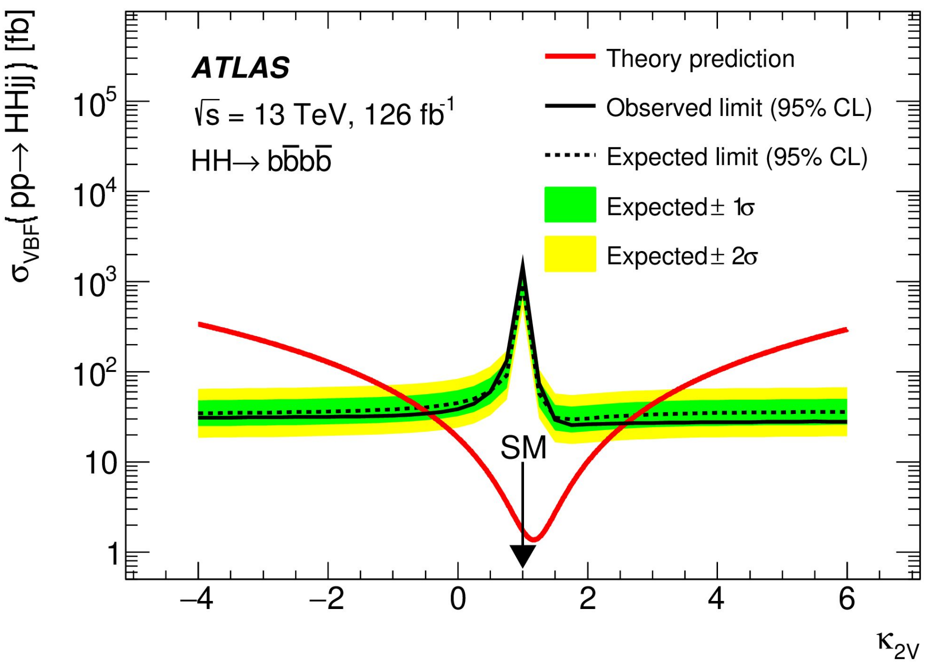


JHEP07(2020)108

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

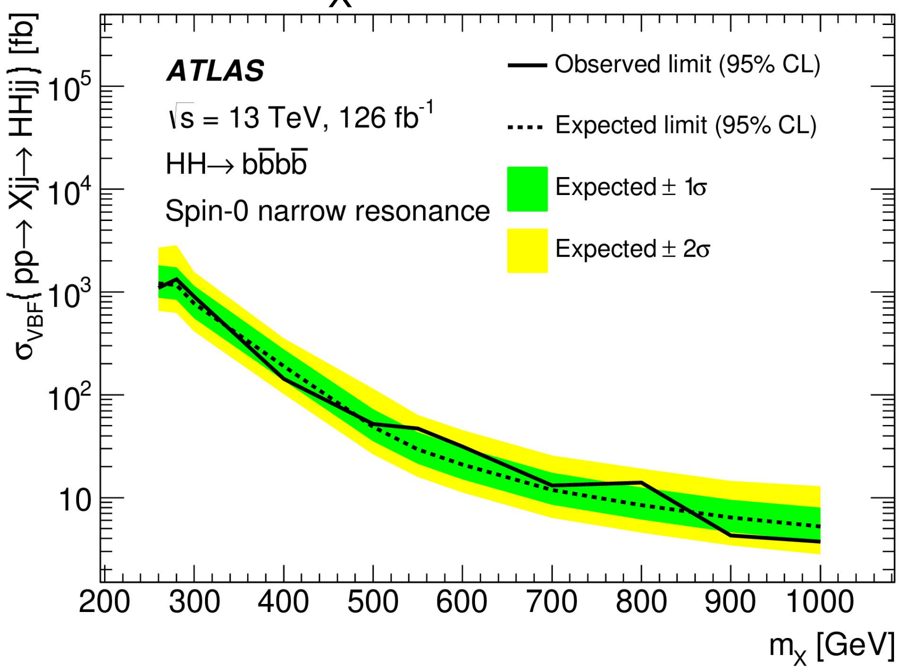
- No deviations from SM observed

Limit on VBF HH XS vs k_{2V}



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

Limit on spin 0 resonance with mass m_X and narrow width



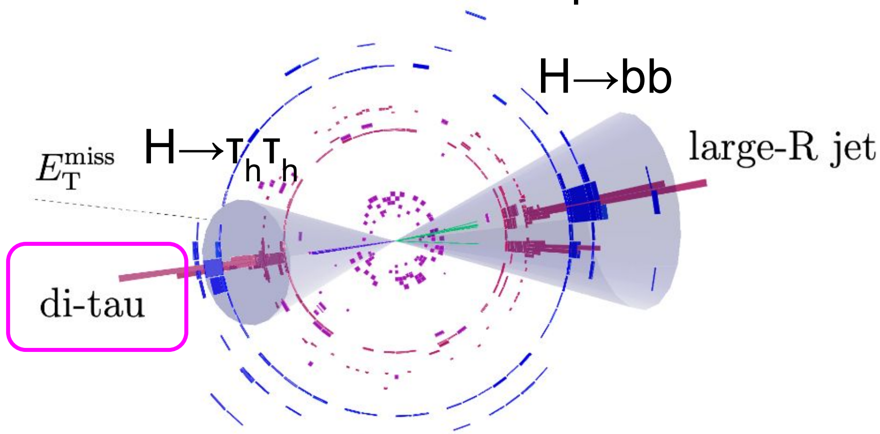
Obs. limit between 10^3 and 4 fb for m_X∈ [260, 1000] GeV

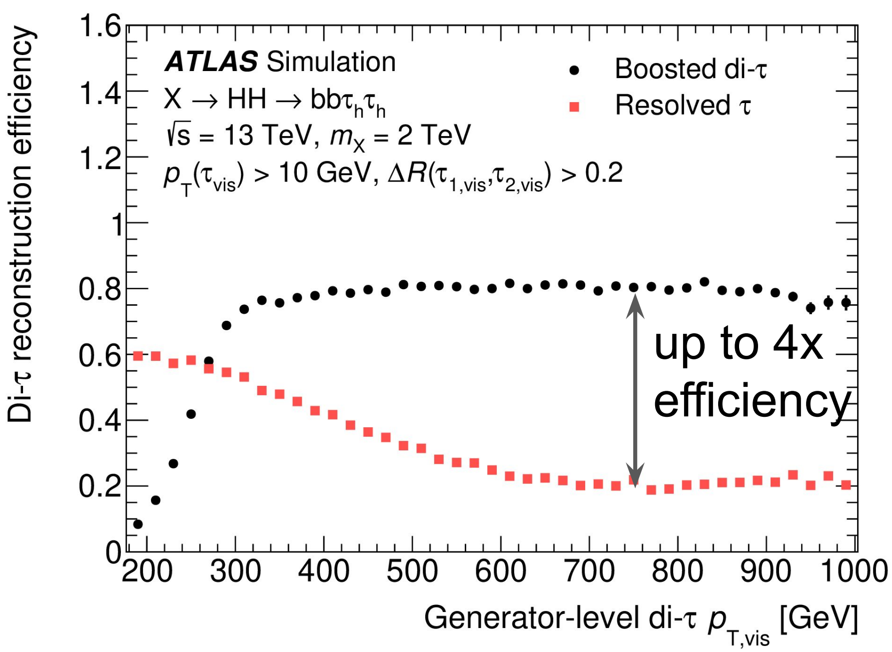
JHEP11(2020)163

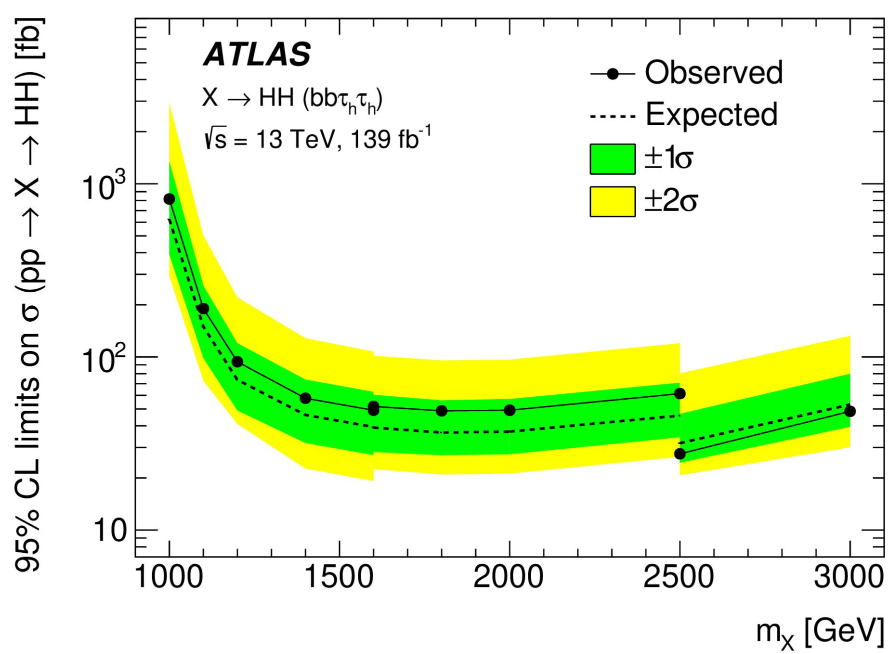
Boosted $X \to HH \to bb\tau_h\tau_h$ at ATLAS with 139 fb^{-1}

- 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







 CERN Yellow report Vol. 7 (2019), CMS-PAS-FTR-22-001/ATL-PHYS-PUB-2022-018

HH projection for HL-LHC at CMS and ATLAS

- Focus on most sensitive HH decay channels
- Based on MC simulations with pileup conditions and detector performance expected for HL-LHC
- Analyses optimized for 3000 fb^{-1} of integrated lumi
- Studies extended for Snowmass 2021
  - New analysis techniques, additional HH production modes and final states

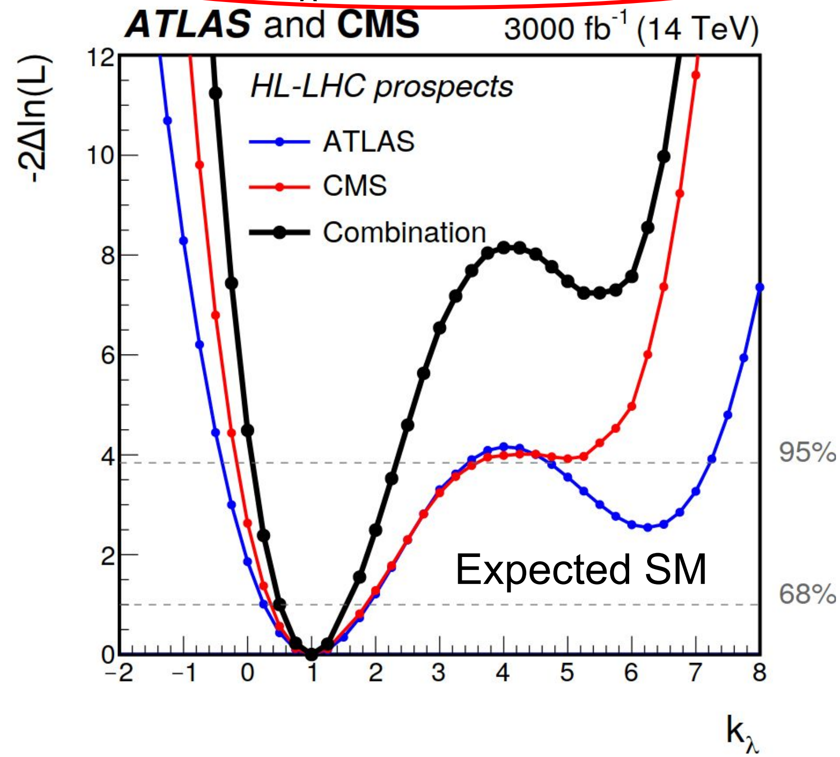
CMS-ATLAS HH combination @HL-LHC

CERN Yellow report Vol. 7 (2019)

HH channel	Significance (standard deviations)	
	ATLAS	CMS
bbbb	0.61	0.95
bbττ	2.1	1.4
bbγγ	2.0	1.8
bbVV(ℓℓνν)	-	0.56
bbZZ(4ℓ)	-	0.37
Combined	3.0	2.6
Combination	**4.0**	

w/o syst. uncertainties 4.5σ

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

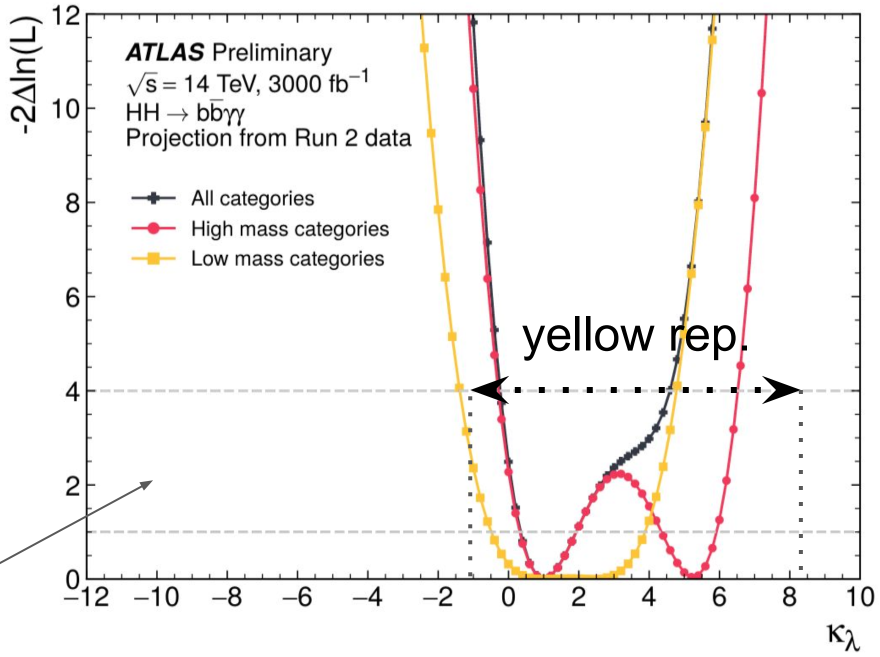


$k_\lambda=0$ excluded @ >95% CL

- ➢ Evidence of SM HH expected with 4σ
- ➢ Minimization of syst. uncertainties will be crucial
  - ○ Theory, heavy-flavor jet ID, τ reconstruction & ID, …

Improvements from Snowmass studies

- ATLAS Run 2 HH→bbɣɣ and bbττ results projected to 3 ab^{-1}
  - 30(10)% improvement on SM HH bbττ(bbɣɣ) wrt yellow report mostly from improved analysis techniques
  - bbɣɣ precision on k_λ improved through event classification on 4-body mass



- CMS HH→bbɣɣ projection re-optimized with updated MVA architecture and VBF HH cat's
  - 20% improvement wrt yellow report
  - \+ New projections for HH→WWɣɣ and ττɣɣ final states

HH projections for HL-LHC with Snowmass updates

- Naive combination assuming no correlations between channels and experiments

HH channel	Significance (standard deviations)	
	ATLAS	CMS
bbbb	0.61	0.95
bbττ	~~2.1~~ 2.8	1.4
bbɣɣ	~~2.0~~ 2.2	~~1.8~~ 2.16
bbVV(ℓℓνν)	-	0.56
bbZZ(4ℓ)	-	0.37
WWɣɣ + ττɣɣ	-	0.22
My naive combination	~~**4.0**~~ **4.6**	

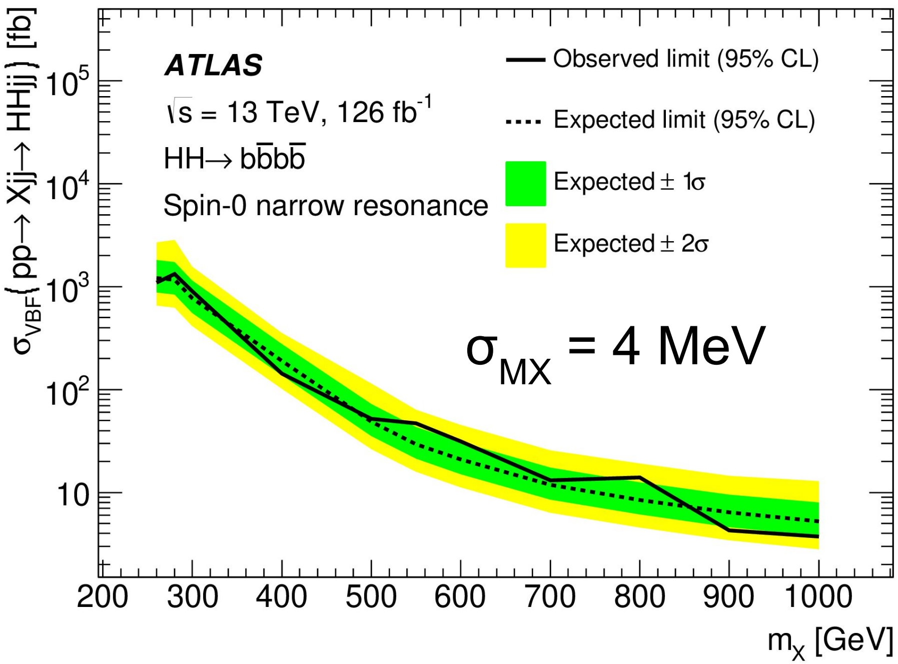
+ upper limit on ttHH(4b) XS of 3.14 ×SM @95% CL

➢ Improvement of results possible through new techniques & ideas→observation of HH?

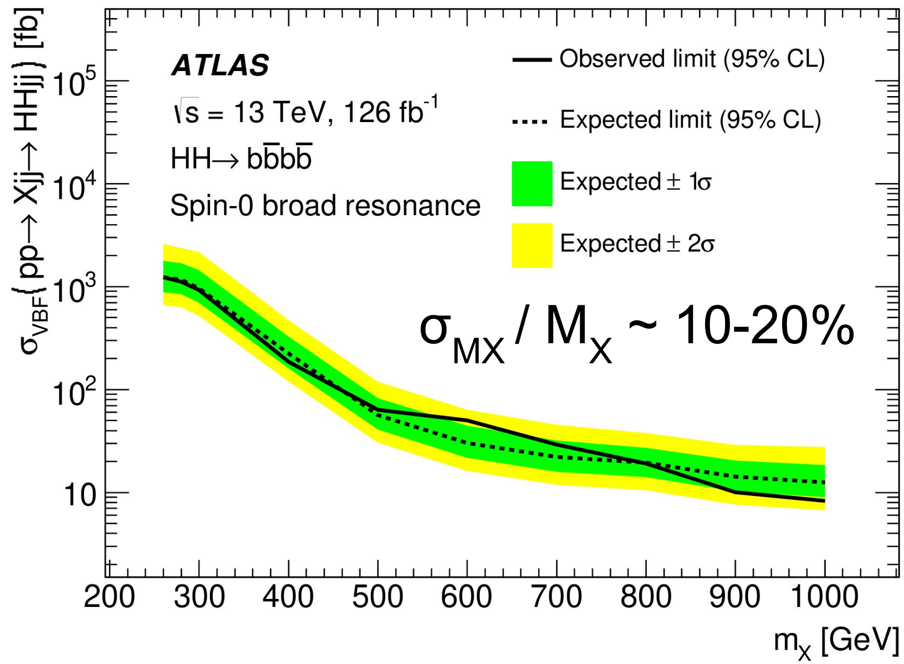
Impact of resonance width on X→HH sensitivity

- 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

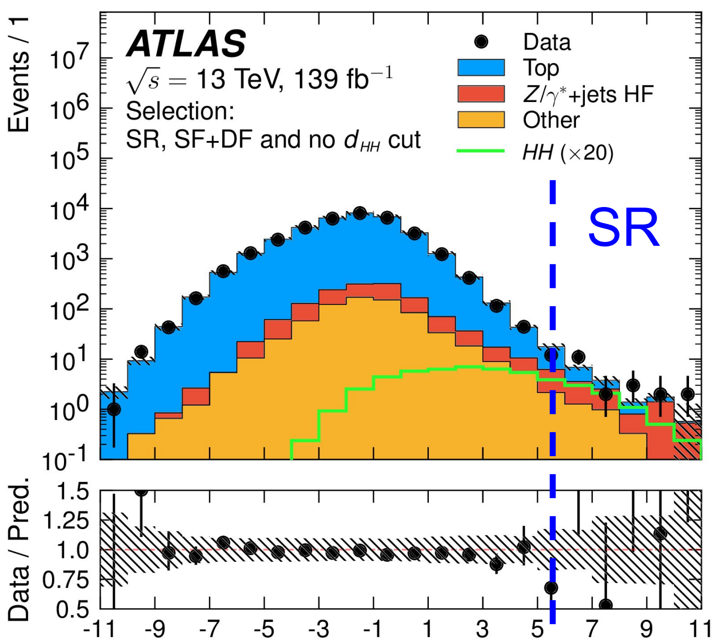


Phys. Lett. B 801 (2020) 135145

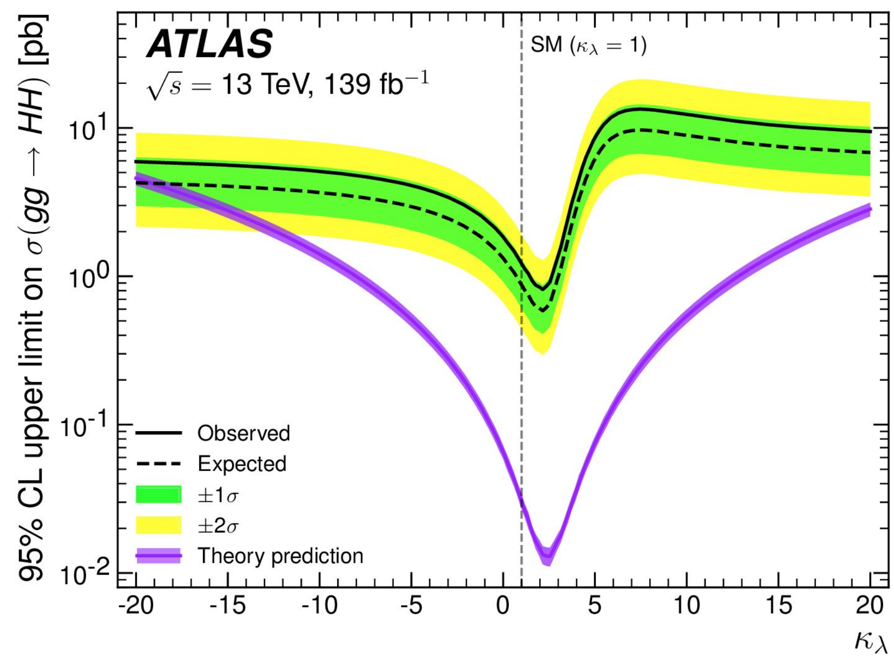
HH→bb2ℓ at ATLAS with 139 fb^{-1} of data

- 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/γ*+heavy-jets` events



DNN score for signal class



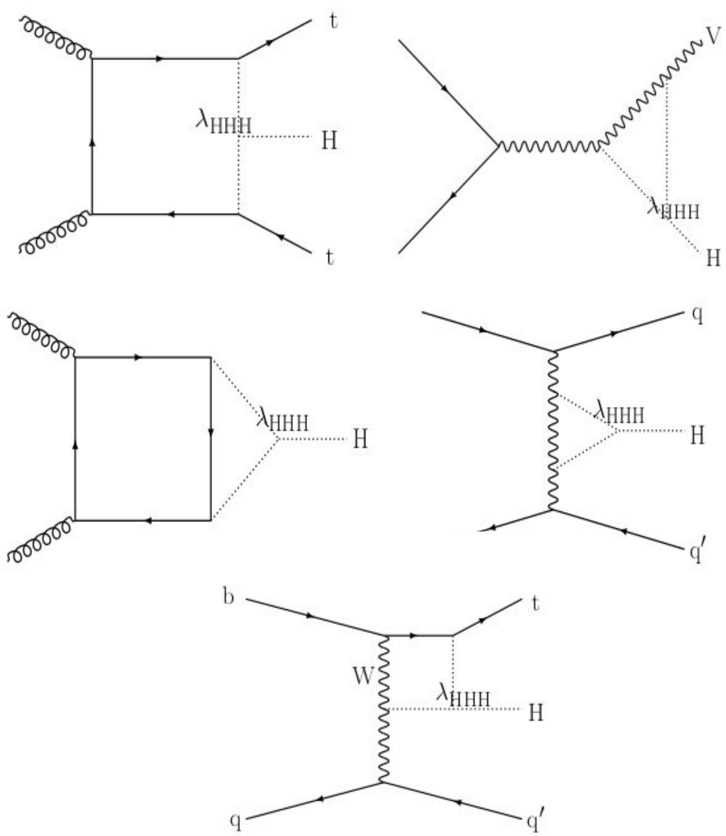
obs.(exp.) upp. lim. on SM HH XS

40(29)✕SM

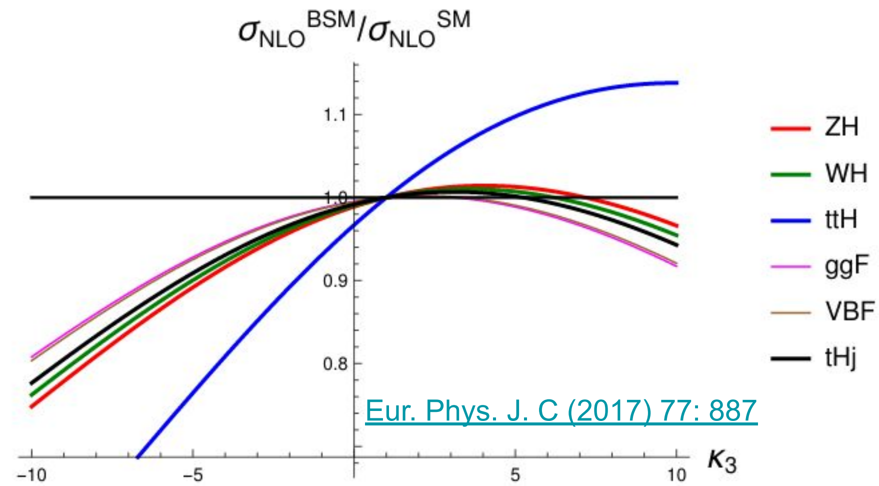
Trilinear self-coupling in single-H mechanisms

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

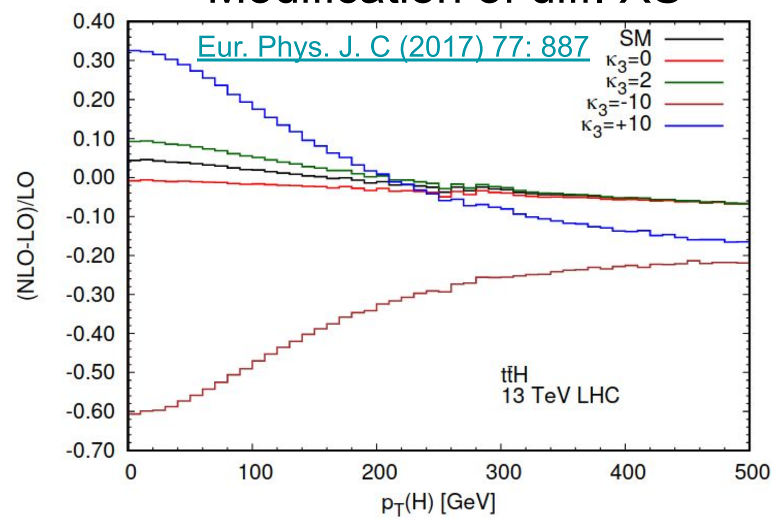
Examples of λ-dependent diagrams
for single-H mechanisms



Modification of total XS

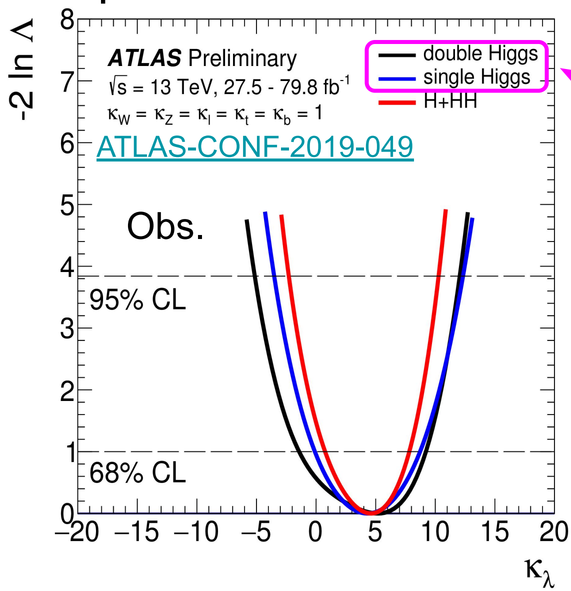


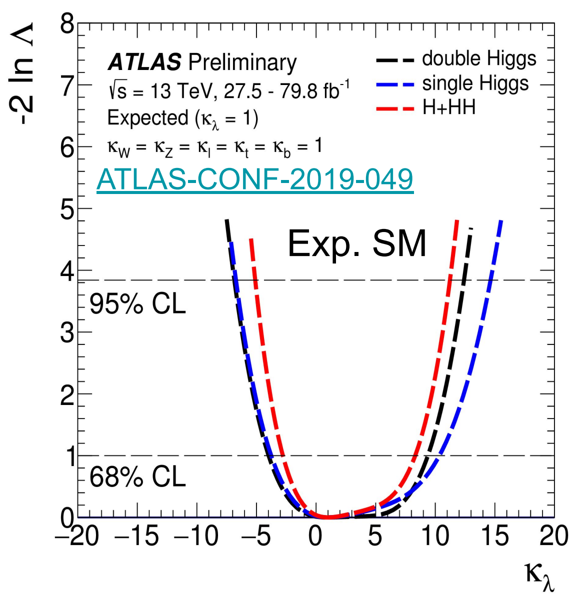
Modification of diff. XS



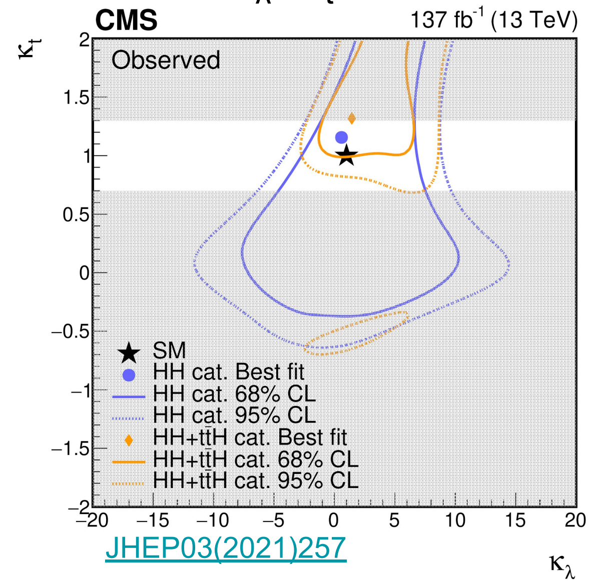
λ measurement from single-double H comb

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