Overview of recent di-Higgs ATLAS and CMS results

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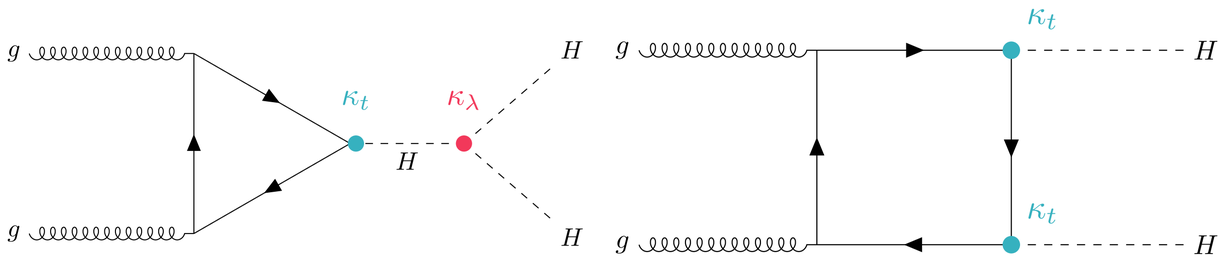
2/12/2021

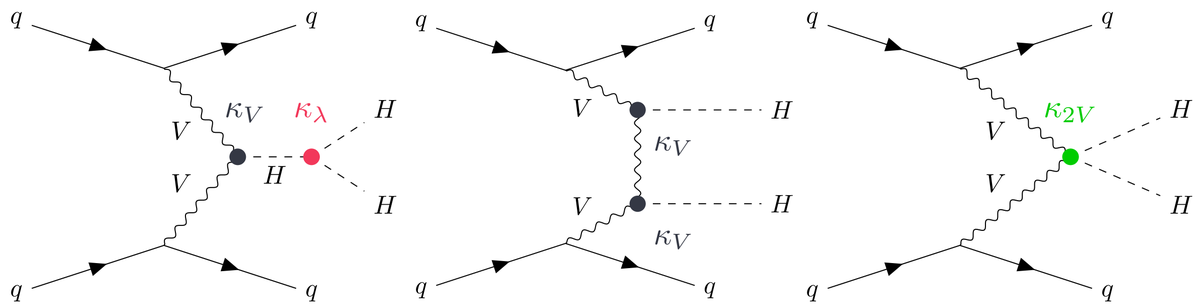
di-Higgs searches

Non-resonant HH production

gluon-gluon Fusion (ggF): $\sigma_{ggF}^{SM} = 31.05$ fb

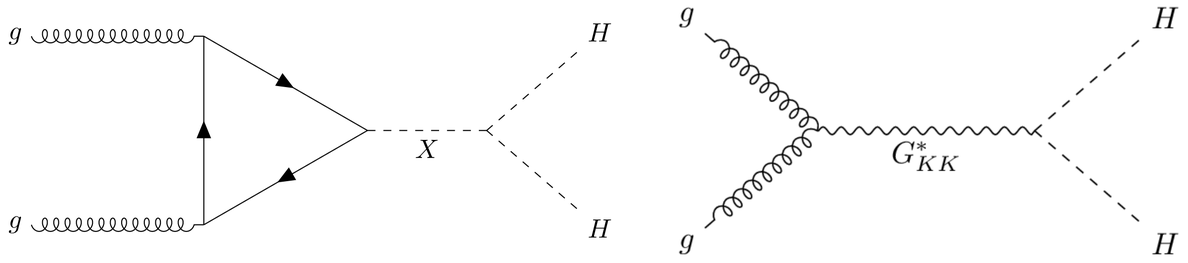


vector-boson-fusion (VBF): $\sigma_{VBF}^{SM} = 1.73$ fb

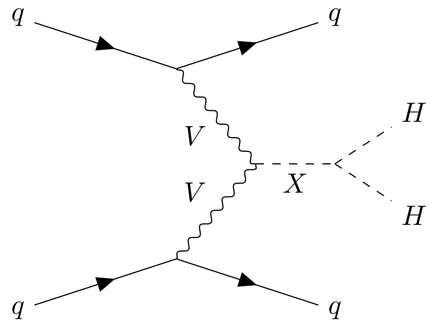


Resonant HH production

Spin-0 and spin-2 resonances ggF X->HH



Spin-0 resonances VBF X->HH



di-Higgs searches

Many different final states given by all possible combinations of Higgs Boson decays

Results from ATLAS and CMS with full Run 2 data covering decay channels with at least one H->bb given the large BR

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Covered in this presentation

Non-resonant searches with full Run 2 data

ATLAS:
VBF HH->4b (resolved)
HH->bbll (resolved)
HH->bbττ (resolved)
HH->bbγγ (resolved)

CMS:
HH->4b (resolved)
VBF HH-> 4b (boosted)
HH->bbZZ(4l) (resolved)
HH->bbγγ (resolved)

Resonant searches with full Run 2 data

ATLAS:
VBF HH->4b (resolved)
HH->4b (resolved and boosted)
HH->bbττ (resolved)
HH->bbττ (boosted)
HH->bbγγ (resolved)

CMS:
HH->4b (boosted)
HH->bb1l/2l (boosted)

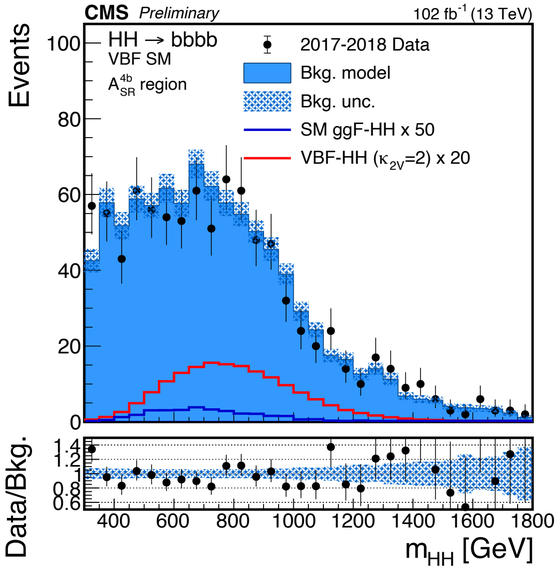
CMS non-resonant HH -> bbbb resolved

- Search for non-resonant HH production
- At least 4 b-tagged central small-radius jets ($R = 0.4$)
- Jet pairing to form the Higgs candidates based on Higgs mass requirements

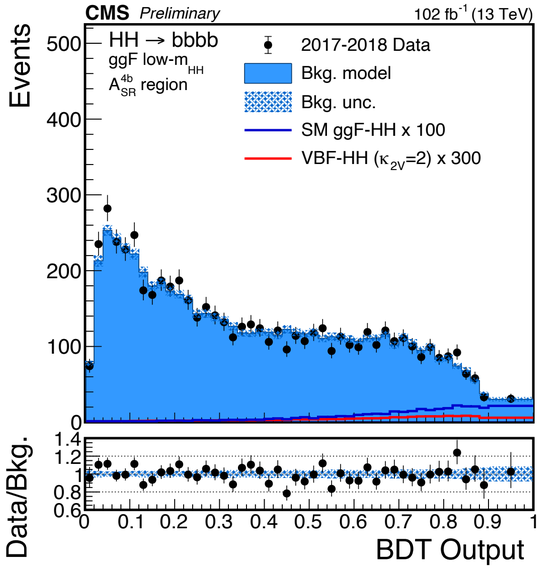
- Targeting ggF and VBF production modes with dedicated categories
  - Non-b-tagged jets with opposite η considered as VBF jets
  - BDT to discriminate ggF vs VBF for events with VBF jets
- Signal regions defined by selections in the 2D m_{H1}-m_{H2} plane
- ggF and VBF categories split to enhance sensitivity to SM and BSM couplings giving a total of 4 signal regions categories
  - ggF split based on m_{HH} selection
  - VBF split based on BDT output

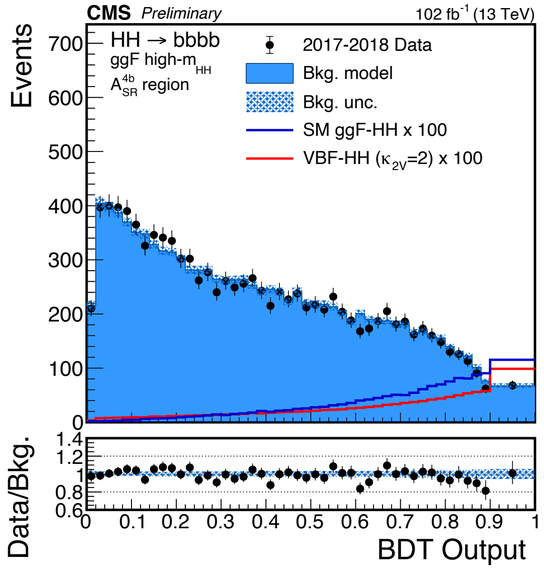
- QCD and ttbar multi-jet backgrounds estimated from data in control regions

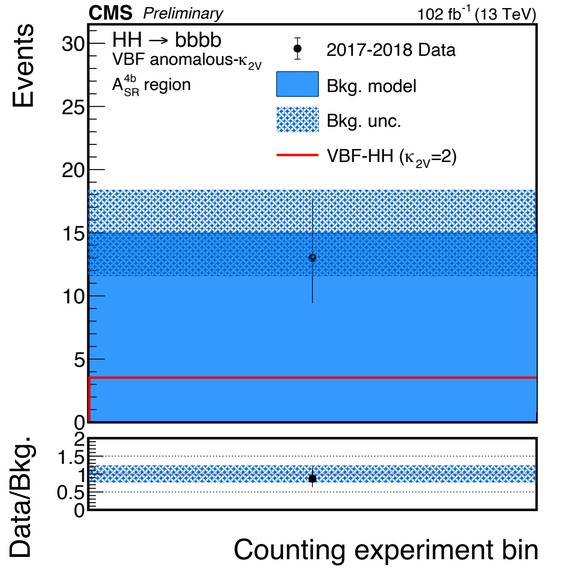
BDT outputs used as final discriminants in the ggF categories, m_{HH} and event yields used as final discriminants in the VBF categories



CMS-PAS-HIG-20-005



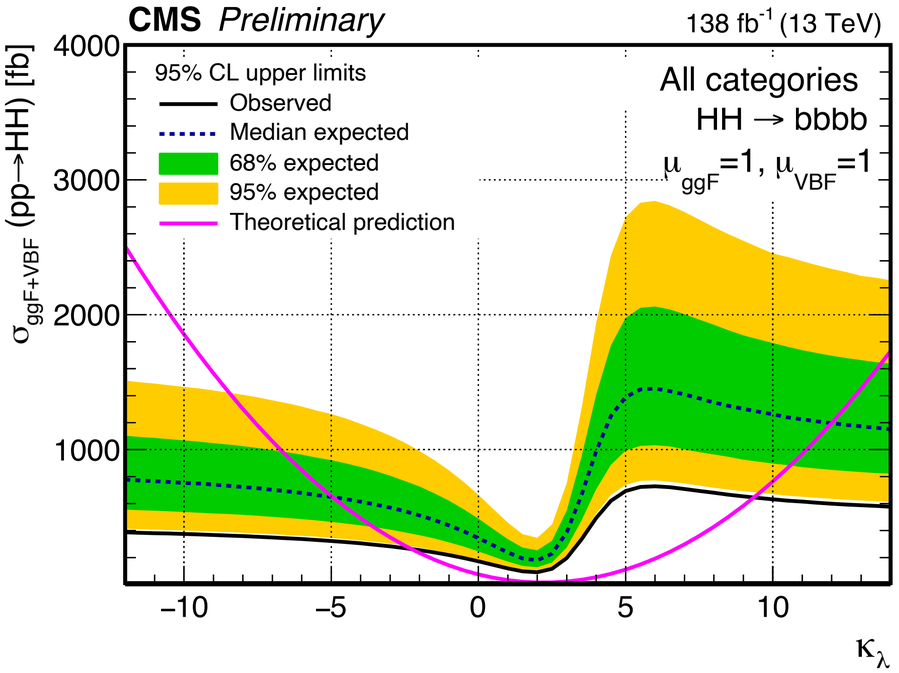




CMS non-resonant HH -> bbbb resolved

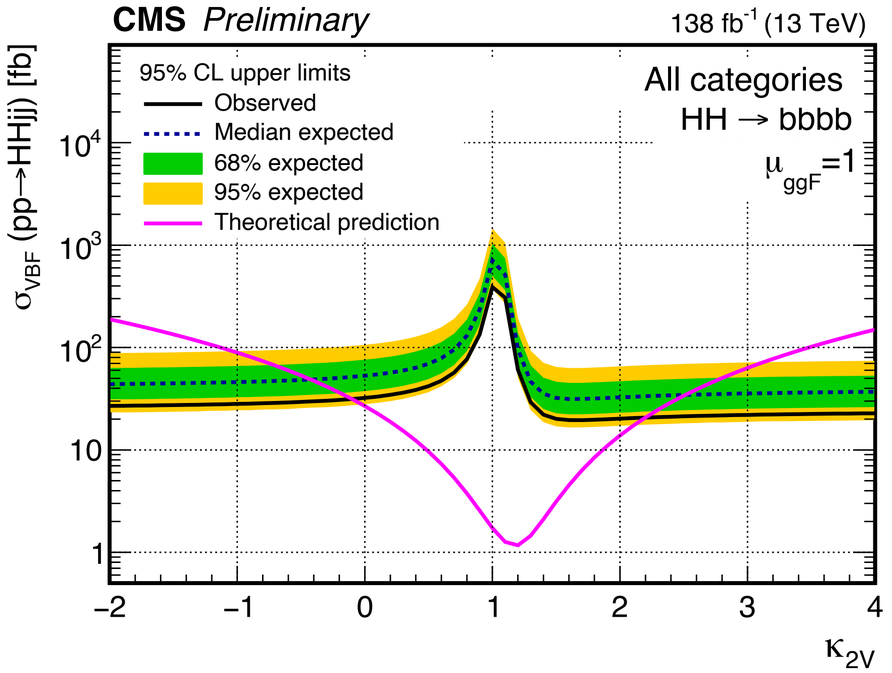
Upper limit on the non-resonant HH cross section of
3.6 x SM observed (7.3 x SM expected)

CMS-PAS-HIG-20-005



$-2.3 < \kappa_\lambda < 9.4$ at 95% CL

(expected $-5.0 < \kappa_\lambda < 12.0$)



$-0.1 < \kappa_{2V} < 2.2$ at 95% CL

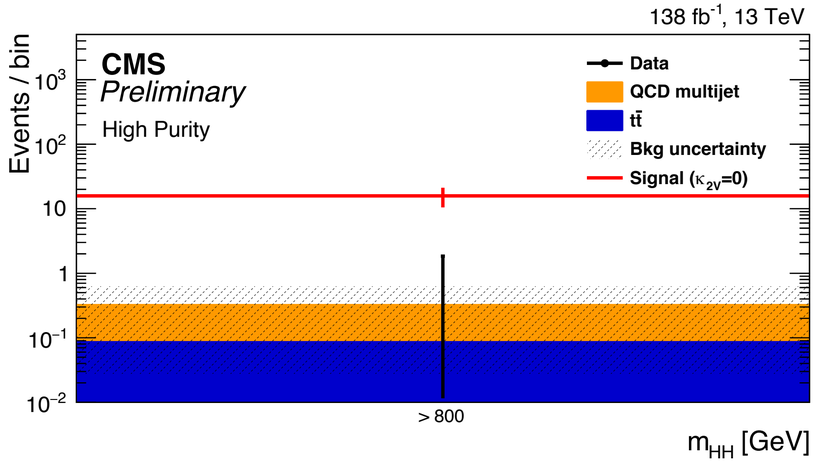
(expected $-0.4 < \kappa_{2V} < 2.5$)

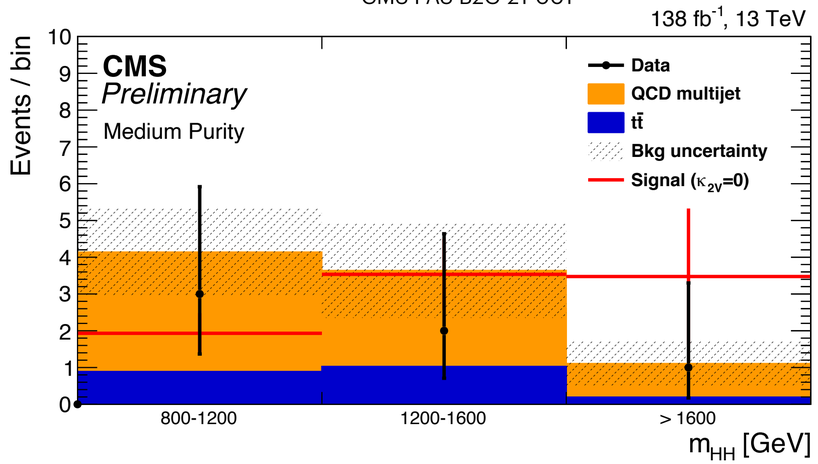
CMS non-resonant VBF HH -> bbbb boosted

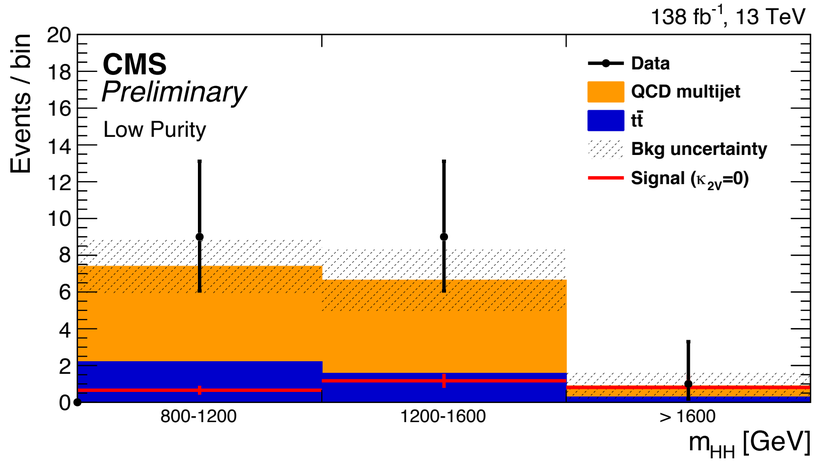
- Search for non-resonant VBF HH production
- 2 large-radius jets ($R = 0.8$, boosted topology)
- 2 forward small-radius jets ($R = 0.4$) with large pseudo-rapidity separation and large invariant mass as VBF jets
- First use of new boosted H->bb tagging algorithm, based on graph neural network to identify the H->bb decays and infer the mass of the Higgs boson candidate (ParticleNet)
- 3 orthogonal categories defined depending on the tagger efficiency working point passed by the large-radius jets
- Signal region selection defined by $110\,\mathrm{GeV} < \mathrm{m_J^{lead}} < 150\ \mathrm{GeV}$ and $100\,\mathrm{GeV} < \mathrm{m_J^{sublead}} < 145\ \mathrm{GeV}$
- Multi-jet background from data in control regions included in the fit

m_{HH} used as final discriminant variable in the 3 signal region categories and in the control regions

CMS PAS B2G-21-001

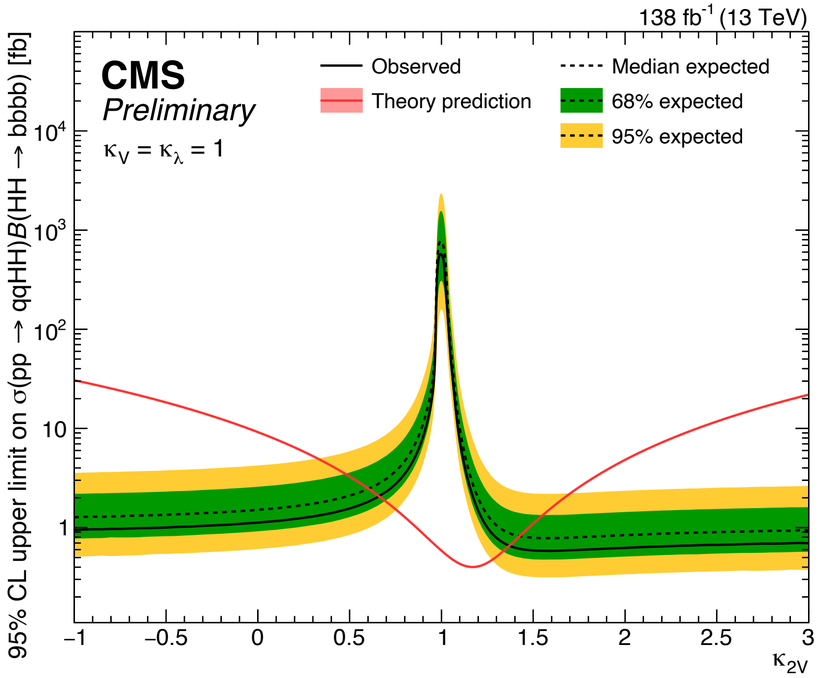






CMS non-resonant VBF HH -> bbbb boosted

CMS PAS B2G-21-001

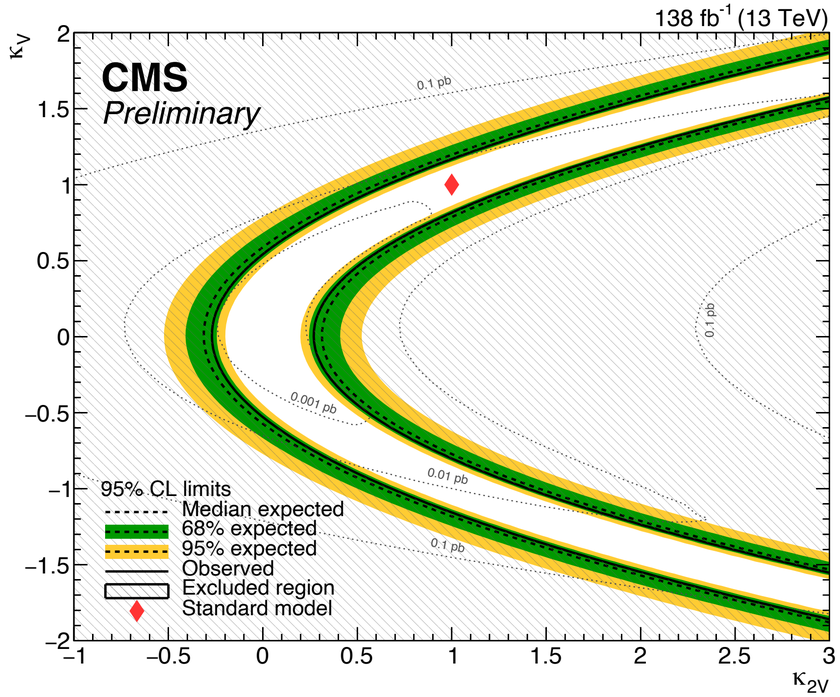


$0.6 < \kappa_{2V} < 1.4$ at 95% CL

(expected $0.6 < \kappa_{2V} < 1.4$)

Best constraints on κ_{2V} up to now!

$\kappa_{2V} = 0$ excluded at a CL higher than 99.99%



Much weaker exclusion on κ_{2V} when varying also κ_V

but $\kappa_{2V} = 0$ remains excluded at 95% CL or higher

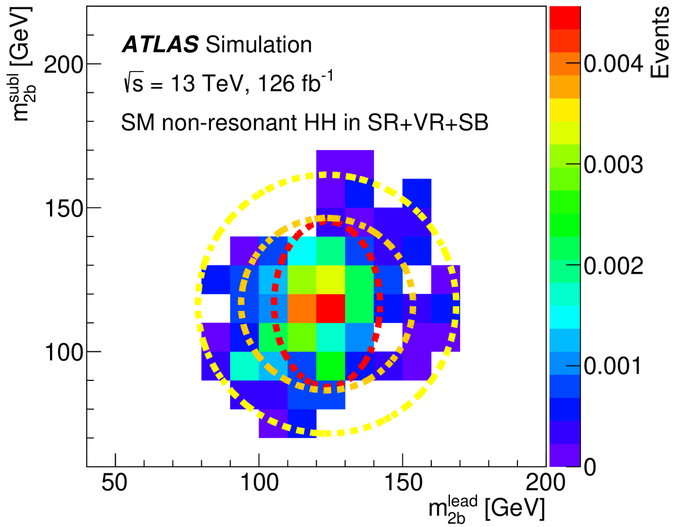
for all values of $\kappa_V > 0.5$

($\kappa_{2V} = 0$ strongly disfavored for values of κ_V within uncertainties from single-Higgs measurements)

ATLAS VBF HH -> bbbb resolved

- Search for non-resonant and resonant VBF HH production in the mass range 250 GeV - 1 TeV
- 4 central b-tagged small-radius jets (resolved topology)
- Jet pairing to form the Higgs candidates based on Higgs mass requirements
- 2 forward jets with large pseudo-rapidity separation and large invariant mass as VBF jets
- Multi-jet background data-driven from control regions (95% of total bkg)
- Signal region defined by selections in the 2D m_{H1}-m_{H2} plane

m_{HH} used as final discriminant variable in the signal region



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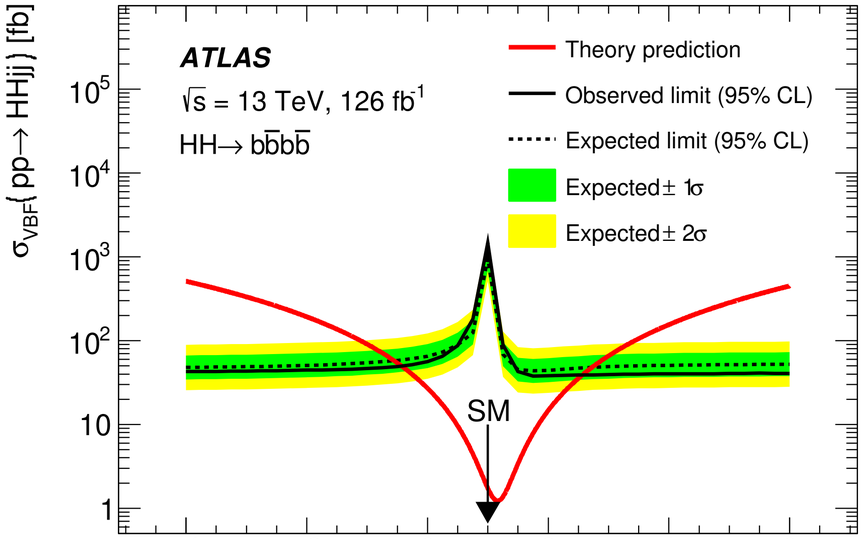
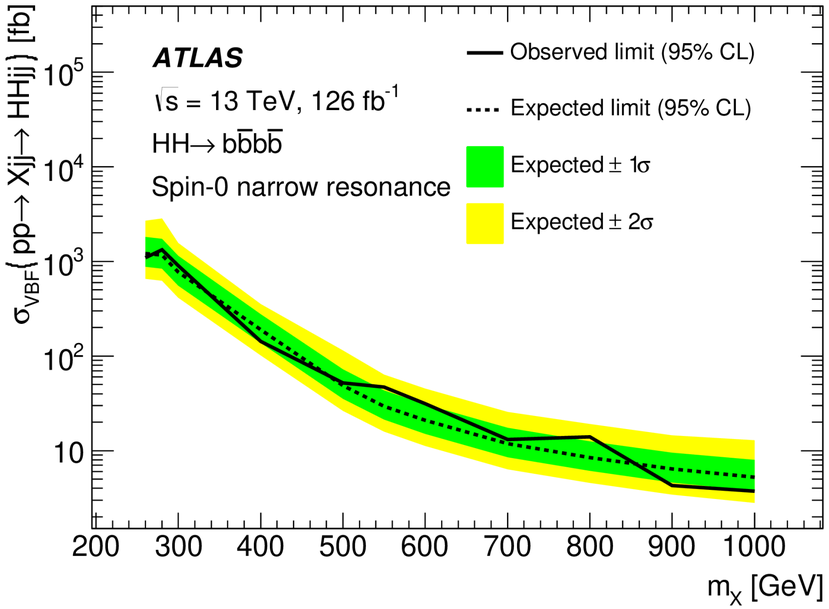
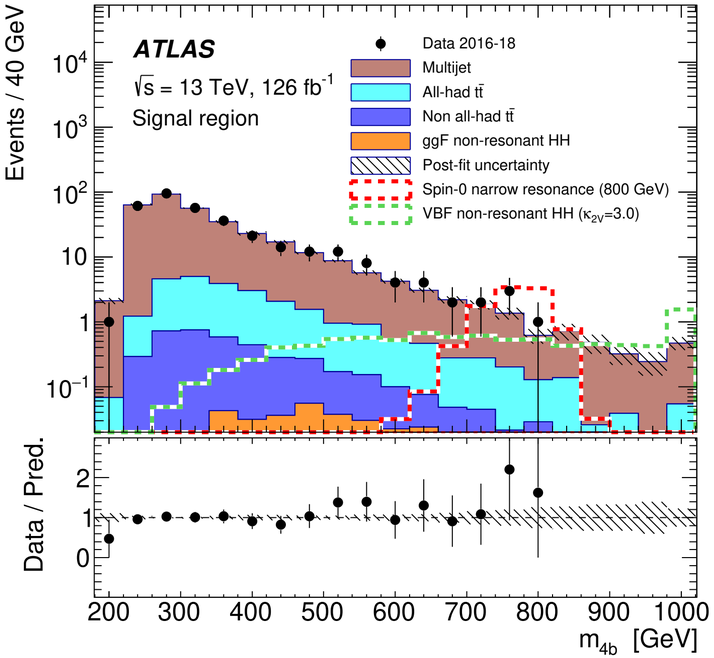


$-0.43 < \kappa_{2V} < 2.56$ at 95% CL

(expected $-0.55 < \kappa_{2V} < 2.72$)





CMS resonant HH -> bbbb semi-boosted and boosted

- Search for resonant HH production in the mass range 1 - 3 TeV

Semi-boosted category:

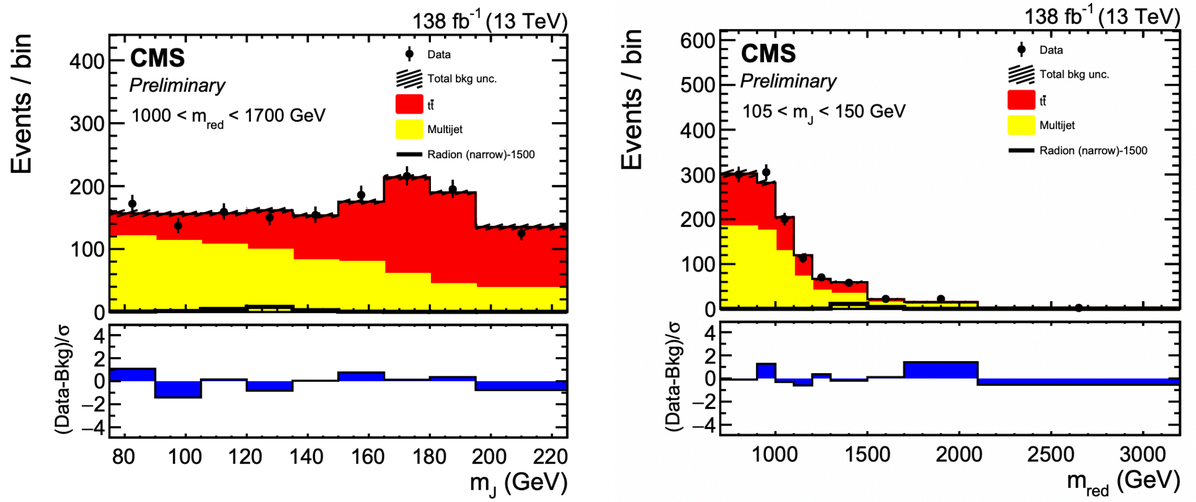
- At least 2 b-tagged small-radius jets ($R = 0.4$) and 1 large-radius jet ($R = 0.8$)
- Boosted H->bb candidates identified using neural-network based tagger (DeepAK8)

Boosted category:

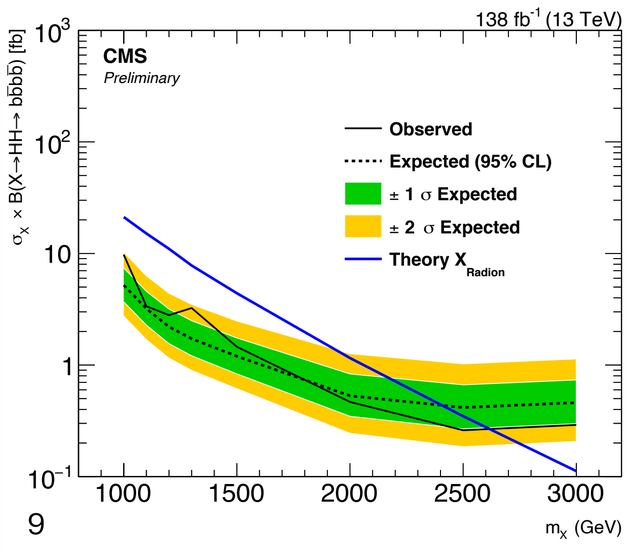
- 2 large-radius jets ($R = 0.8$)
- Boosted H->bb candidates identified using neural-network based tagger (DeepAK8)
- 2 orthogonal categories defined depending on the tagger efficiency working point passed by the large-radius jets

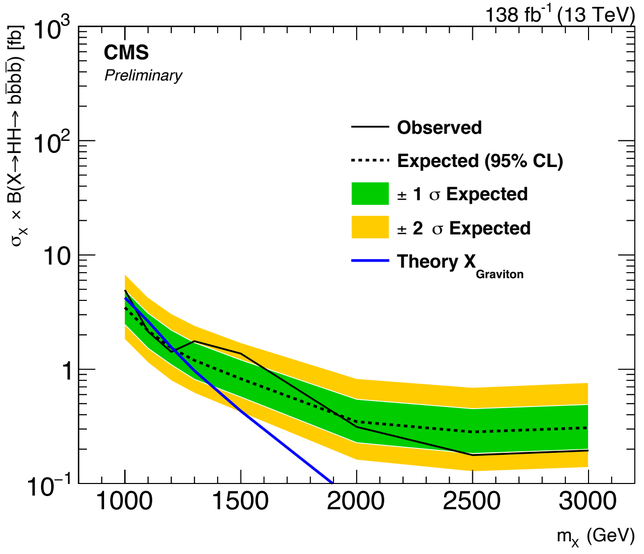
- QCD and ttbar multi-jet backgrounds estimated from data in control regions included in the fit
- Simultaneous fit of 10 categories: 3 signal regions (1 semi-boosted and 2 boosted) and 7 control regions for QCD and ttbar multi-jet backgrounds

Fit in 2D bins of m_{HH} and m_J in all the categories



CMS-PAS-B2G-20-004





ATLAS resonant HH -> bbbb resolved and boosted

- Search for resonant HH production in the mass range 250 GeV - 3 TeV

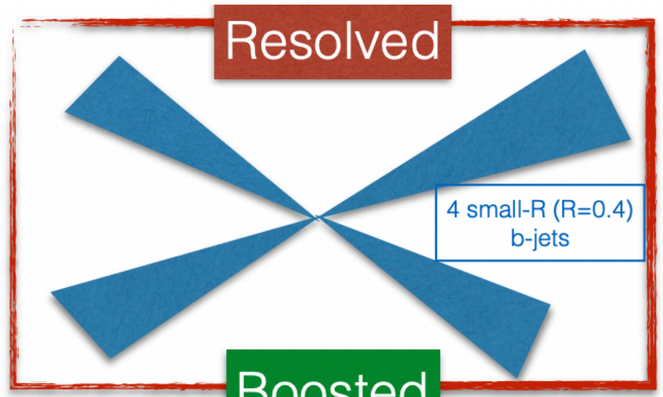
Resolved category:
- mX ∈ [250, 1500] GeV
- At least 4 b-tagged small-radius jets ($R = 0.4$)
- Boosted Decision Trees used to pair the 4 b-jets to form the 2 Higgs candidates
- Fully data-driven total background estimation from control regions

(95% QCD multijet, 5% ttbar)

Boosted category:
- mX ∈ [900, 3000] GeV
- At least two large-radius jets ($R = 1.0$)
- 2b, 3b and 4b categories

(depending on number of matched b-tagged VR track jets)
- Fully data-driven QCD multi-jet background estimation from control regions (70%-90%)
- ttbar from Monte Carlo simulations (30-10%)

Signal regions defined by selections in the 2D m_{H1}-m_{H2} plane



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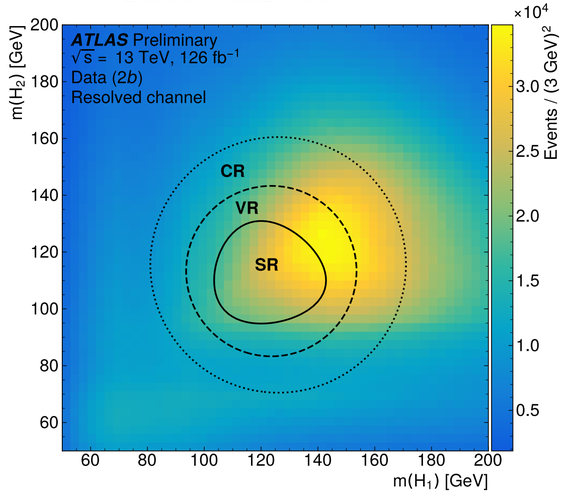
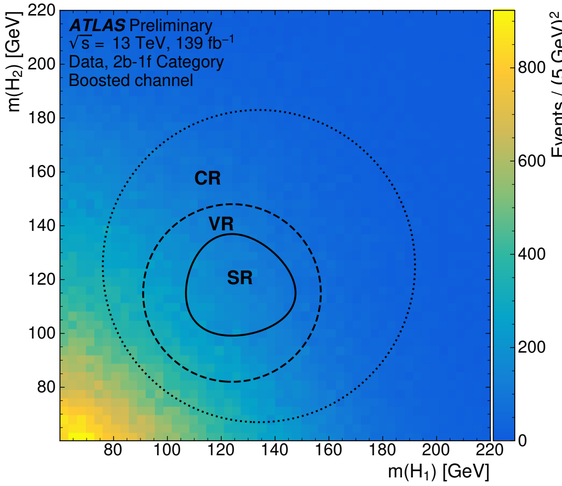
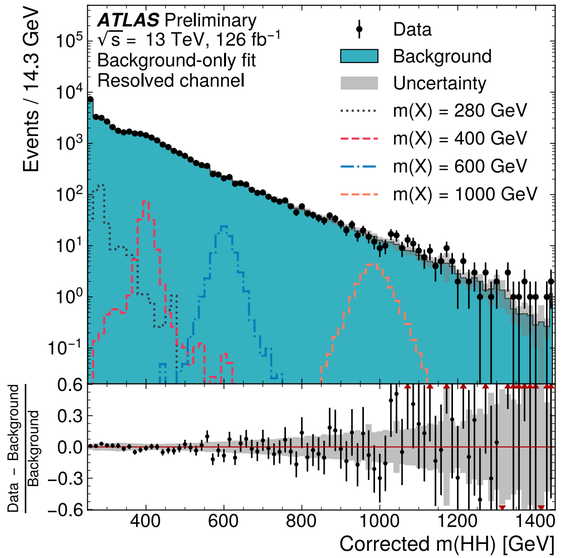
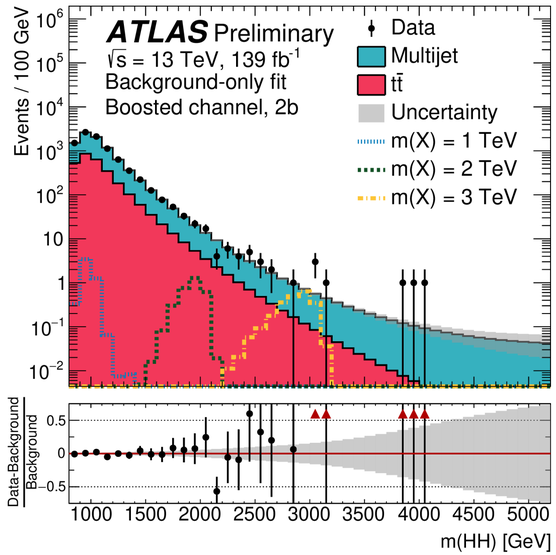


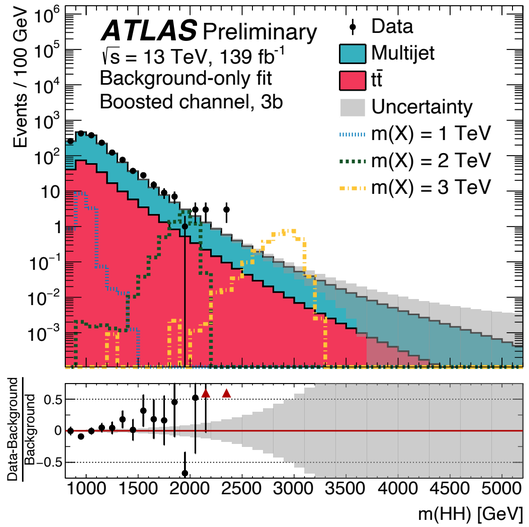


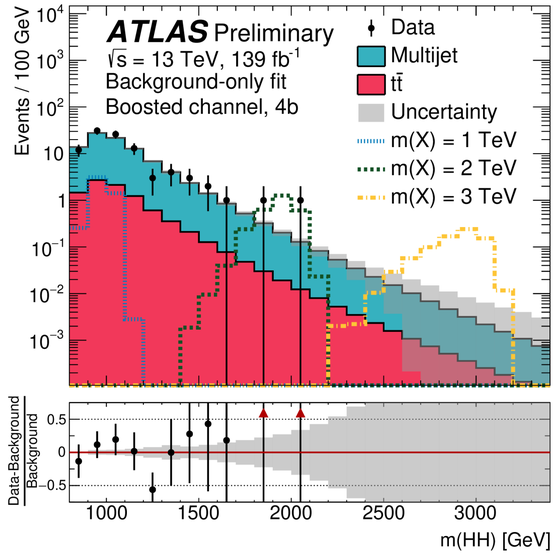
ATLAS resonant HH -> bbbb resolved and boosted

m_{HH} used as final discriminant variable in all signal region categories









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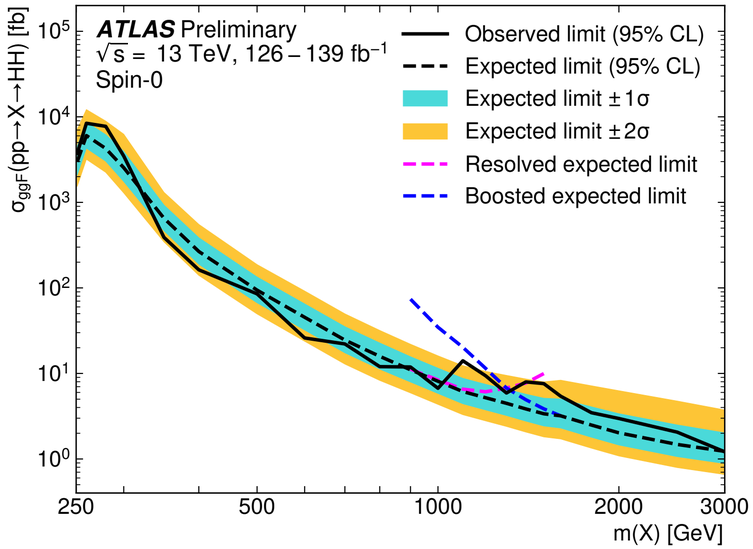
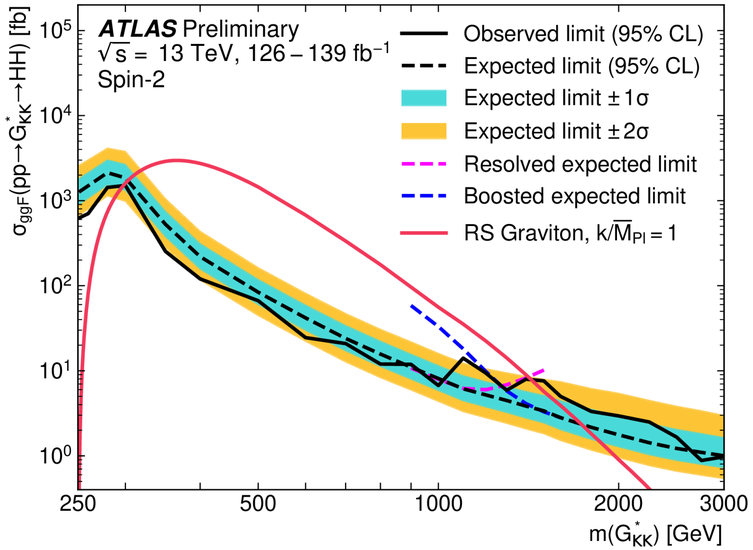




Small data excess at 1.1 TeV,
local (global) significance of 2.6σ (1.0σ) for spin-0
and of 2.7σ (1.2σ) for spin-2

CMS resonant HH -> bb1l/2l boosted

- Search for resonant HH production in the mass range 800 GeV - 4.5 TeV
- bb + 1 lepton and 2 leptons final states, covering bbWW, bbττ and bbZZ HH decays (optimized for bbWW and bbττ)

1 lepton channel:

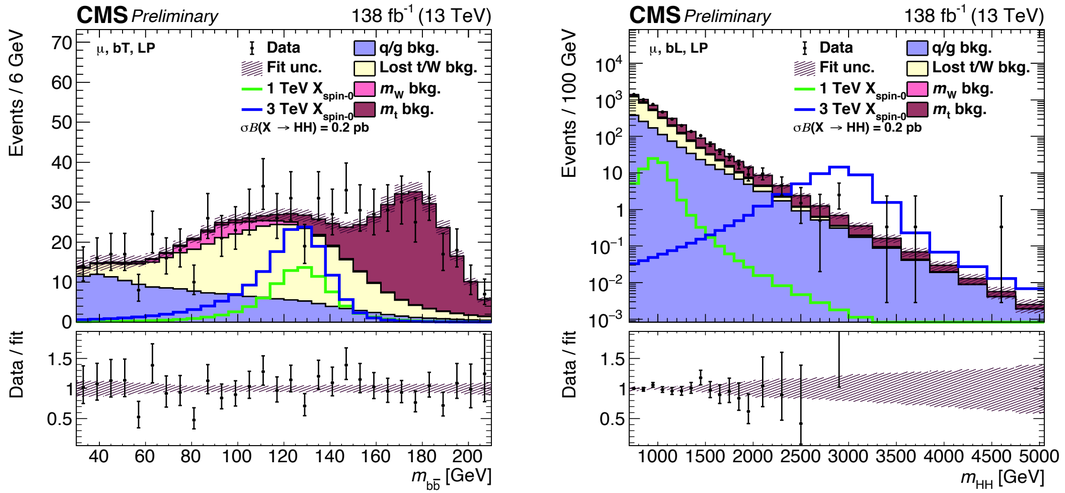
- 2 large-radius jets, from H->bb identified using neural-network based tagger (DeepAK8) and from W->qq, and 1 lepton

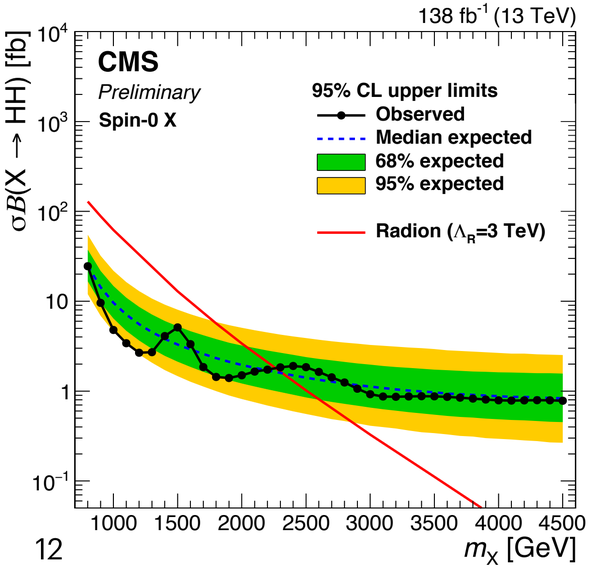
2 leptons channel:

- 1 large-radius jet from H->bb identified using neural-network based tagger (DeepAK8) and 2 leptons

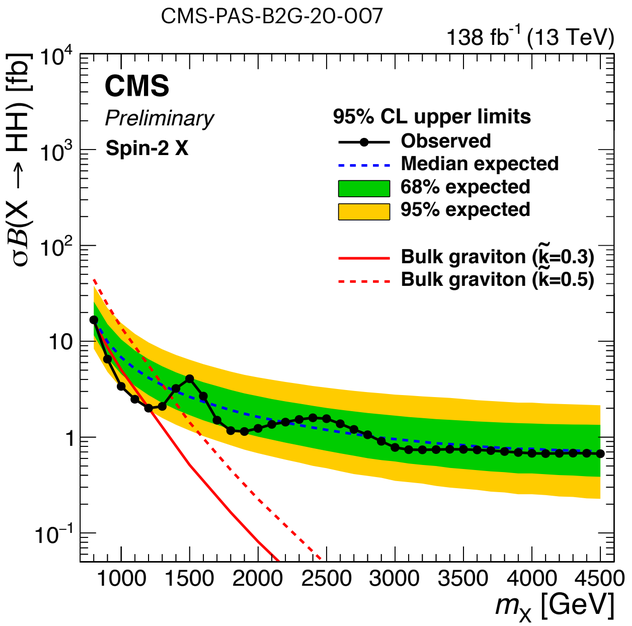
- Events categorized based on number of leptons, lepton flavor, H->bb tagger efficiency working point and jet substructure information of the large-radius jets, giving a total of 12 categories (8 for 1 lepton and 4 for 2 leptons)

Fit in 2D bins of m_{HH} and m_J in all the categories





CMS-PAS-B2G-20-007



ATLAS non-resonant HH -> bbll resolved

- Search for non-resonant HH production in the bbll final state, covering bbWW, bbττ and bbZZ HH decays with 2 leptons (optimized for bbWW being 90% of total signal)
- At least 2 b-tagged jets and exactly 2 leptons (e/μ) with opposite charge
- 2 categories: same-flavour (SF) and different-flavour (DF) for the lepton pair
- Signal region defined by: $20 < m_{\ell\ell} < 60$ GeV, $110 < m_{bb} < 140$ GeV and a cut on a discriminant built from the outputs of a multi-class deep neural network classifier (d_{HH})
- Event-counting analysis with a simultaneous fit of 2 signal regions and 2 control regions for top and Z+HF bkgs

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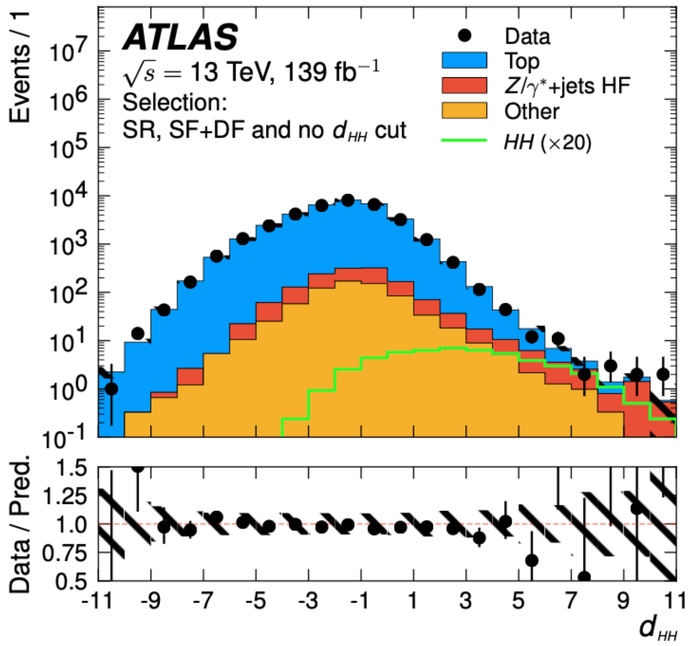
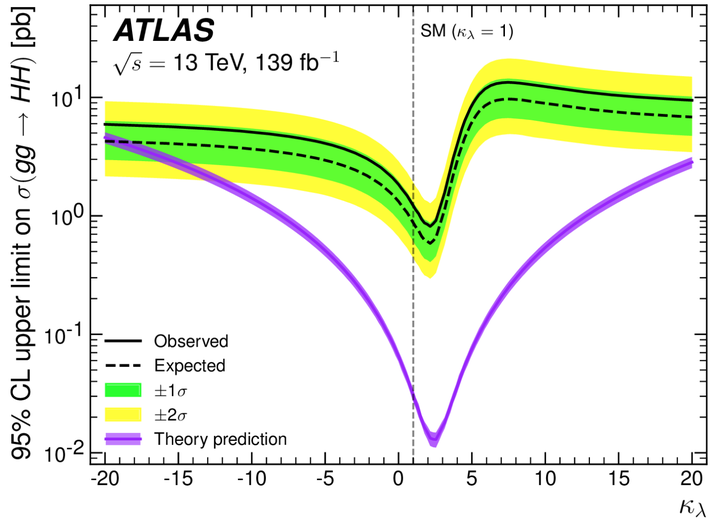


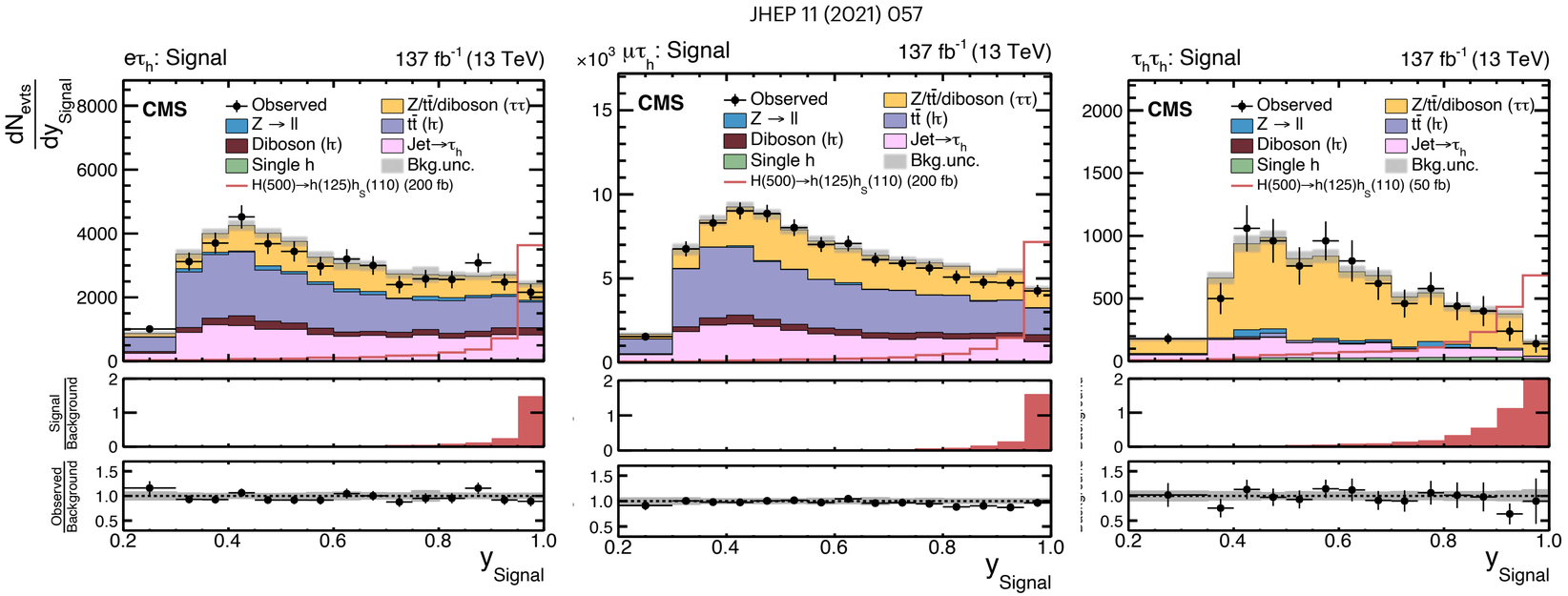
	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma\,(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma\,(gg \to HH)\,/\sigma^{\mathrm{SM}}\,(gg \to HH)$	14	20	29	43	62	40

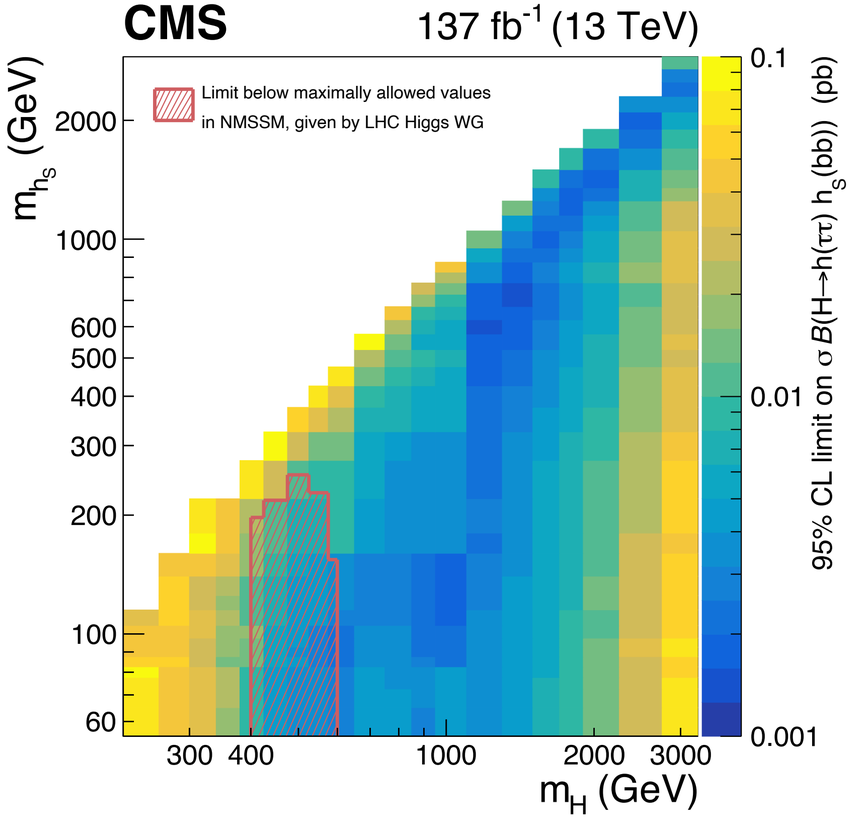


CMS resonant X->SH -> bbττ

- Search for resonant X->SH, with $m_S \neq 125$ GeV and $m_H = 125$ GeV
- S->bb and H->ττ
- Mass ranges $240\ \text{GeV} < m_X < 3\ \text{TeV}$ and $60\ \text{GeV} < m_S < 2.8\ \text{TeV}$
- e/μ+τ and ττ channels
- At least 2 jets, with at least 1 b-tagged jet
- Multiclass Deep Neural Network (DNN): events categorized based on highest score of the DNN in 5 categories, 4 background categories and 1 signal region category, for each signal mass hypothesis in each final state

DNN outputs used as final discriminants in the signal region and control regions





ATLAS HH -> bbττ resolved

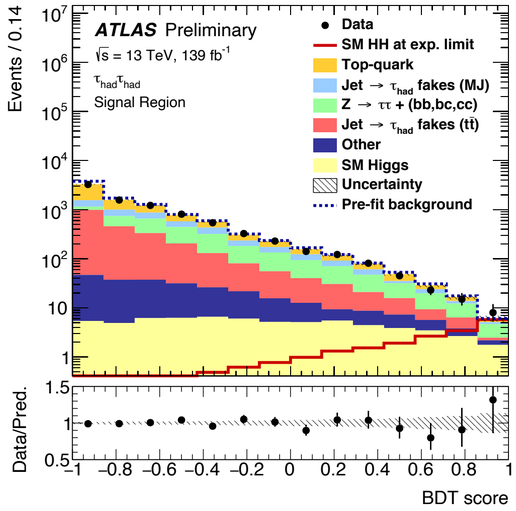
- Search for non-resonant and resonant HH production in the mass range 250 GeV - 1.6 TeV
- e/μ+τ and ττ channels
- 2 b-tagged jets
- 3 signal regions defined depending on the di-τ system decay mode and trigger decision

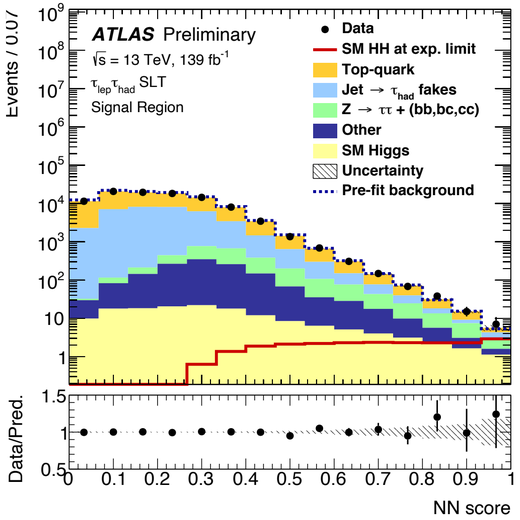
Main backgrounds:
- ttbar and Z+heavy flavour jets (with real τ), modelled with Monte Carlo simulations
- Events with jets faking hadronically decaying τ from ttbar and QCD multi-jet (data-driven methods)

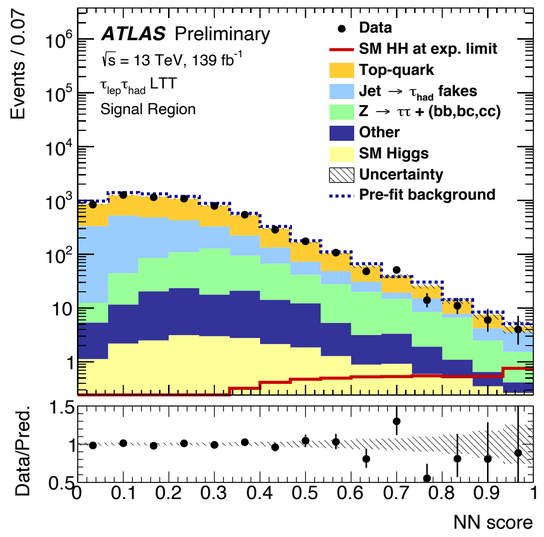
- Multi-variate analysis discriminants (BDT and NN) used to separate signal from background
- MVA outputs used as final discriminants in the 3 signal region categories

- Simultaneous fit of 3 signal regions and 1 control region for the ttbar and Z+HF backgrounds normalizations

ATLAS-CONF-2021-030







ATLAS HH -> bbττ resolved

		Observed	$-2\,\sigma$	$-1\,\sigma$	Expected	$+1\,\sigma$	$+2\,\sigma$
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	265	124	167	231	322	432
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{\text{ggF+VBF}}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	4.65	2.08	2.79	3.87	5.39	7.22

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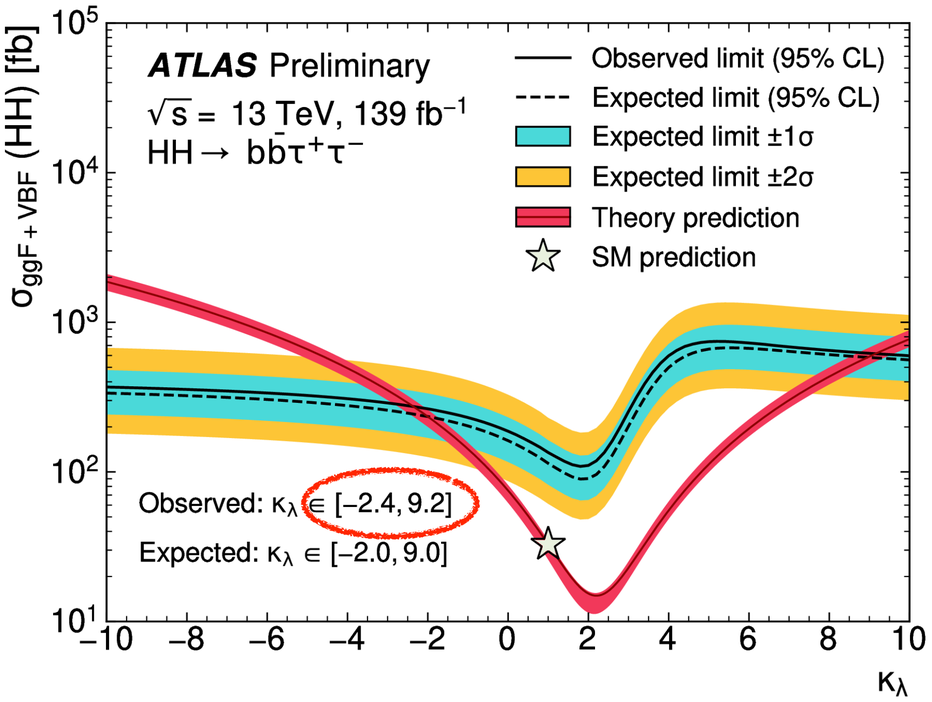
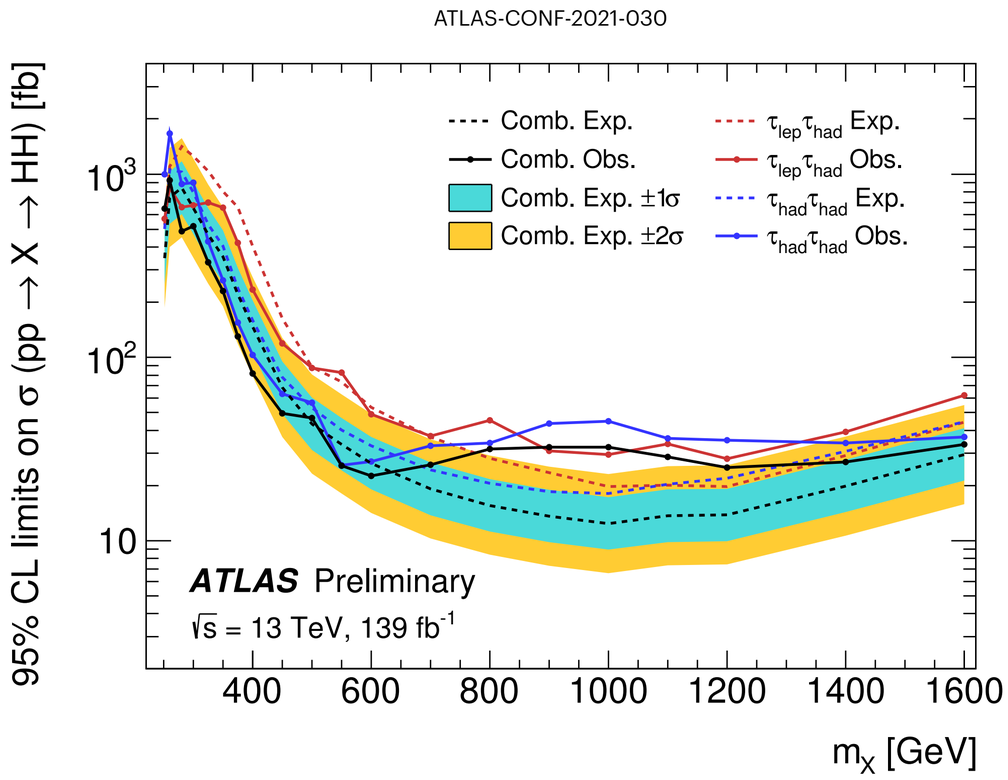


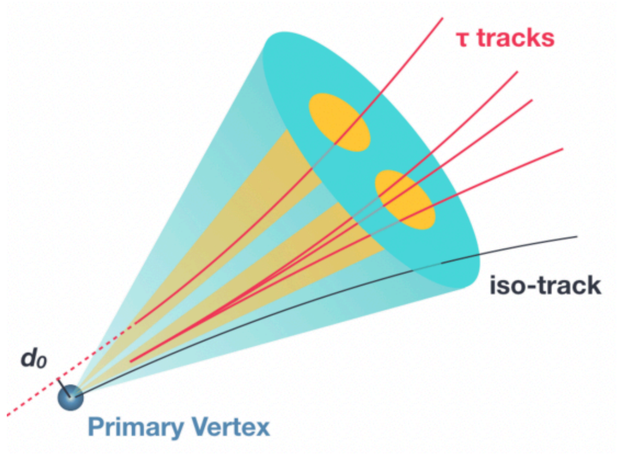
ATLAS-CONF-2021-030



Small data excess between 800 GeV and 1.1 TeV, largest significance at 1 TeV, 3σ (2σ) local (global)

ATLAS resonant HH -> bbττ boosted

- Search for resonant HH production in the mass range 1 - 3 TeV
- First use of boosted di-τ reconstruction and identification algorithm for the boosted H->ττ decay, based on a BDT applied on large-R jet ($R = 1.0$) with 2 sub-jets ($R = 0.2$)
- Boosted H->bb decay: large-R jet with 2 b-tags
- Mass-dependent m_{HH} cut to define signal region
- Counting experiment in the signal region



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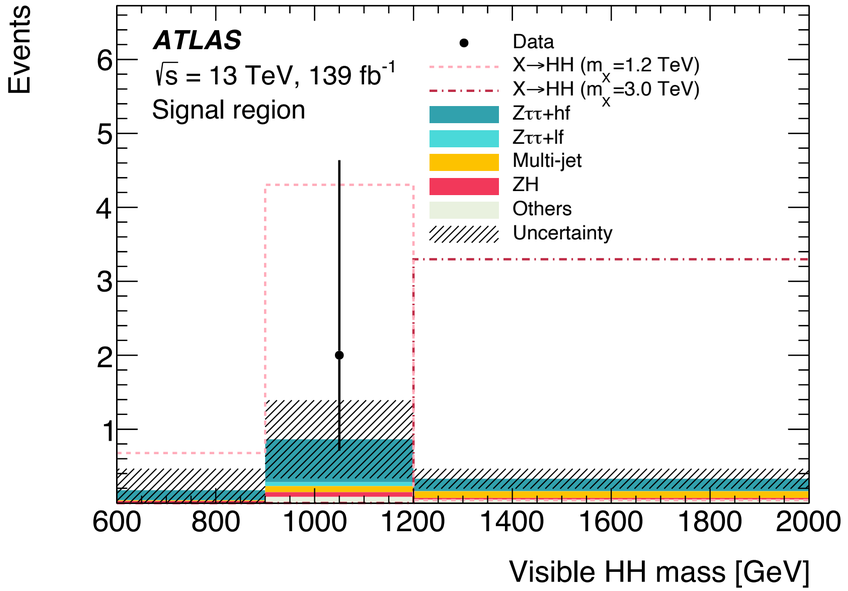
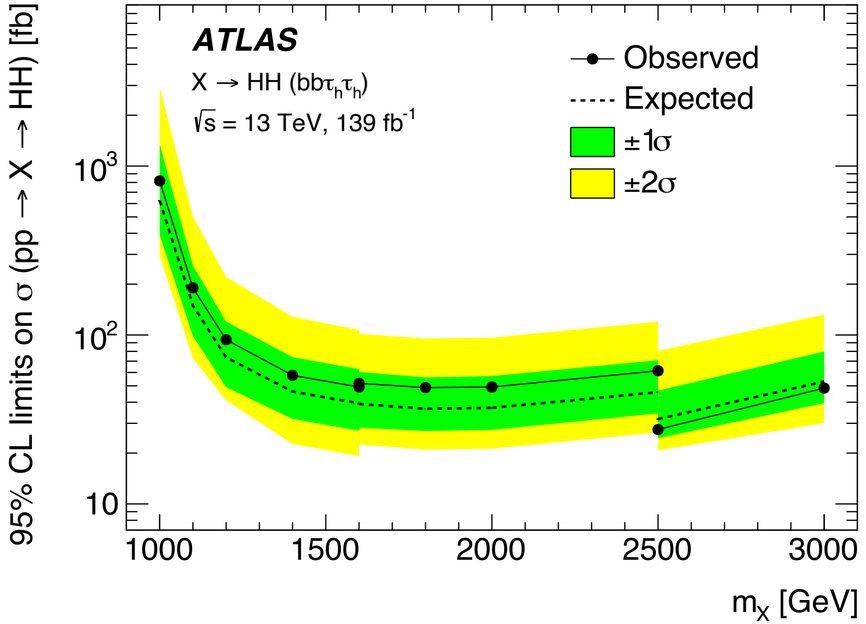
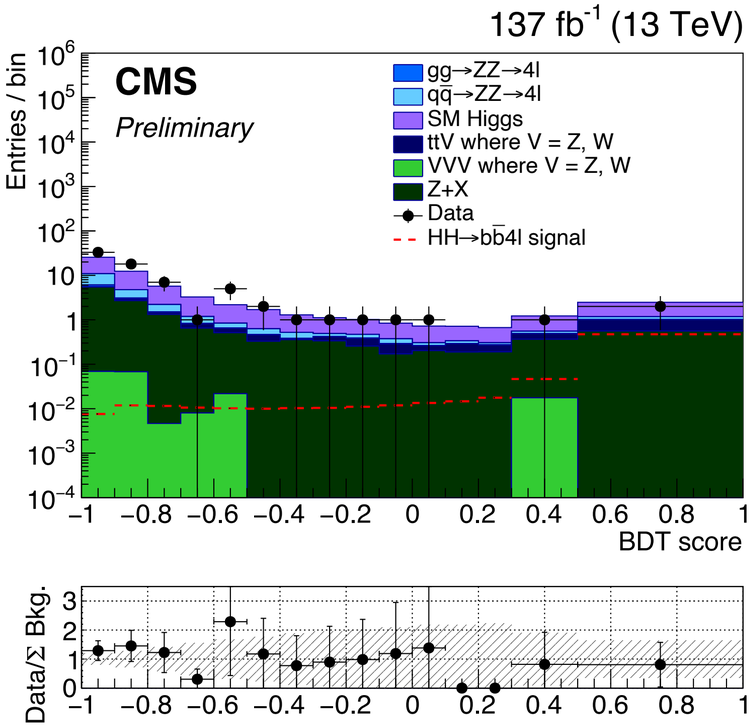


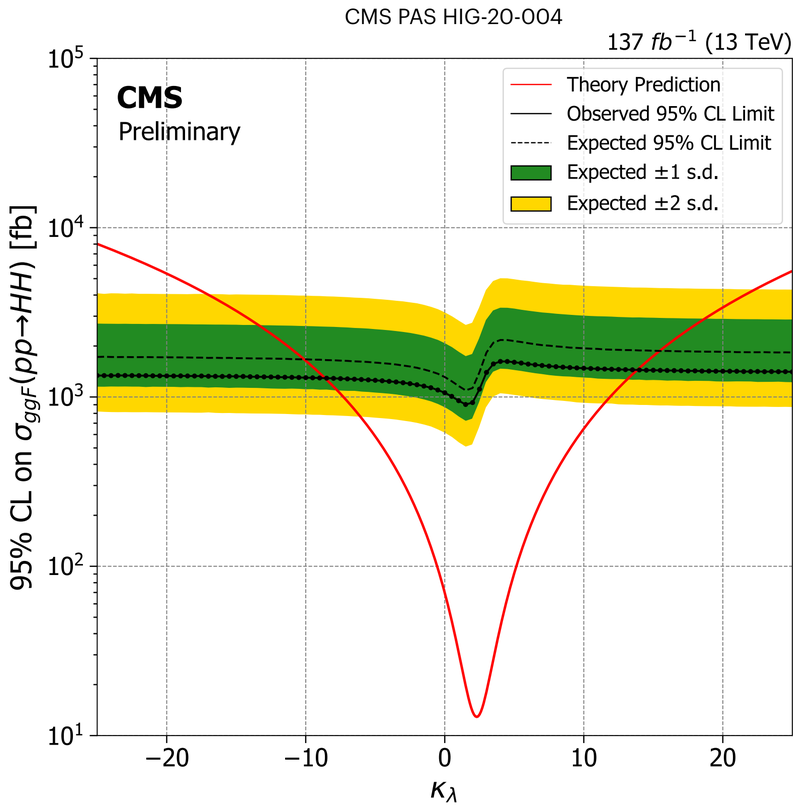


CMS non-resonant HH -> bbZZ(4l)

- Search for non-resonant HH production in the bb4l final state, targeting the bbZZ HH decay
- 4 leptons, 2 pairs of opposite charge leptons (4e, 4μ, 2e2μ), and 2 b-tagged jets
- Signal region defined by $115\ \text{GeV} < m_{4\ell} < 135\ \text{GeV}$
- Boosted Decision Tree used to separate signal from background
- BDT output used as final discriminant



Upper limit on the non-resonant HH cross section of 30 x SM observed (37 x SM expected)



$-9 < \kappa_\lambda < 14$ at 95% CL

(expected $-10.5 < \kappa_\lambda < 15.5$)

ATLAS HH -> bbγγ

- Search for non-resonant and resonant HH production in the mass range 250 GeV - 1 TeV
- 2 photons and 2 b-tagged jets
- $105\ \text{GeV} < m_{\gamma\gamma} < 160\ \text{GeV}$

- Major backgrounds: γγ+jets estimated from data in the sidebands and single-Higgs modelled from Monte Carlo simulations

BDTs used to separate signal and background and define the signal regions:

- Non resonant search: 4 signal region categories defined based on m_{HH} and BDT output selections, targeting SM and BSM signals
- Resonant search: 1 signal region defined by (mass-dependent) BDT output selection

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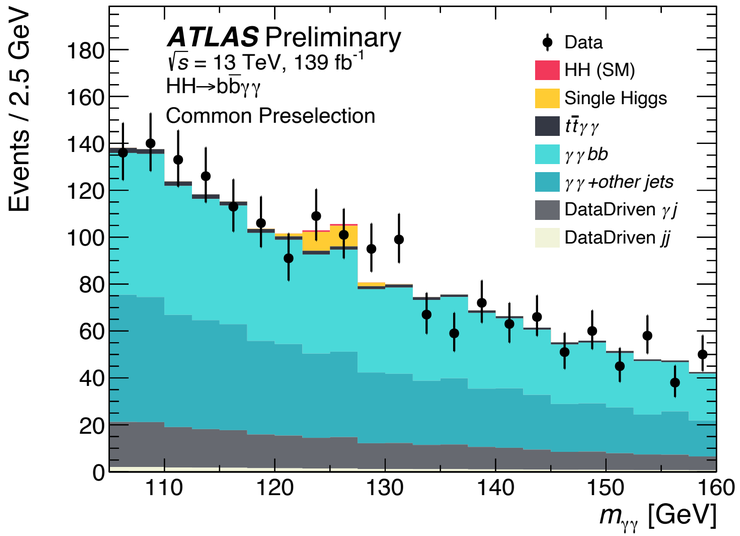
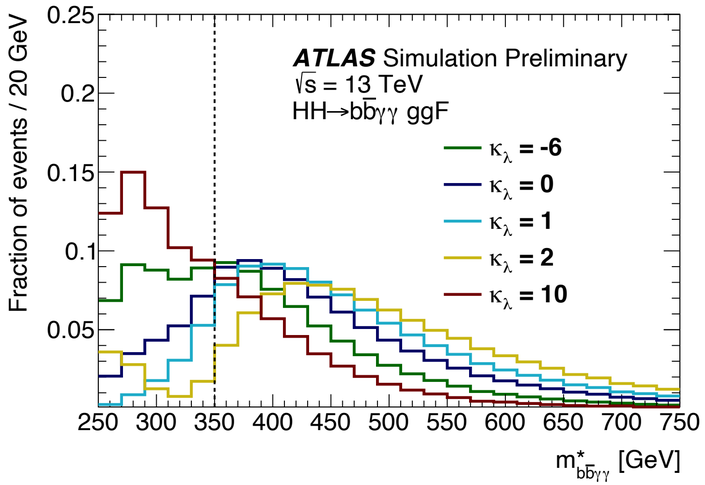
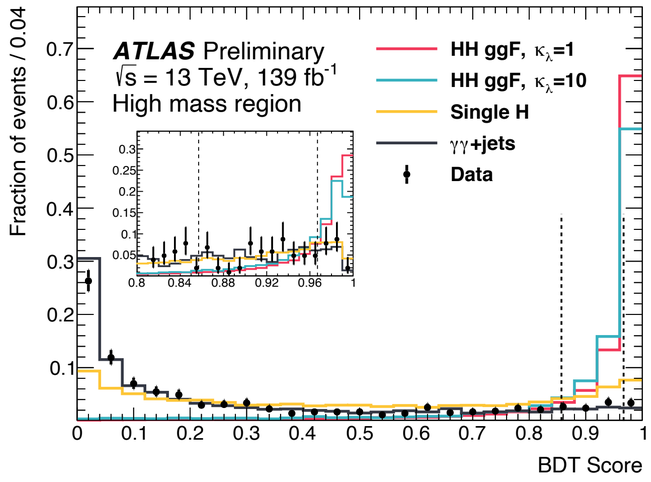
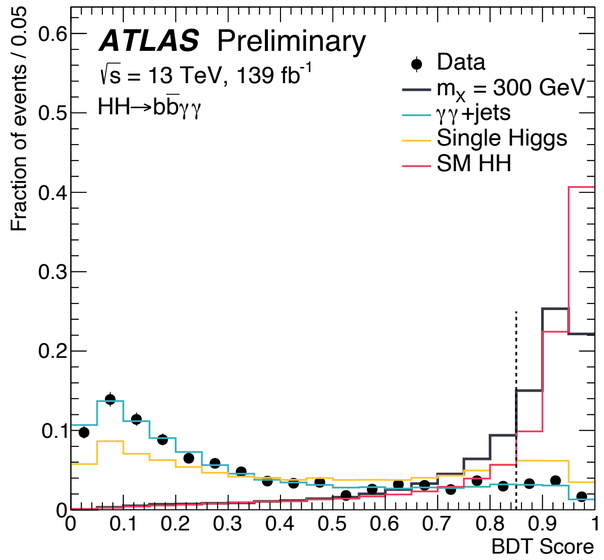


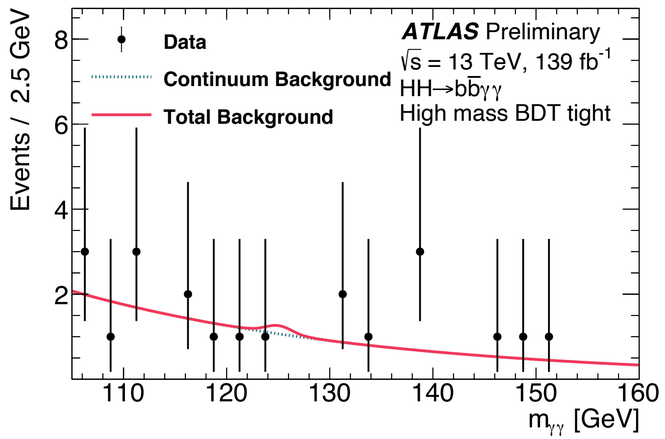


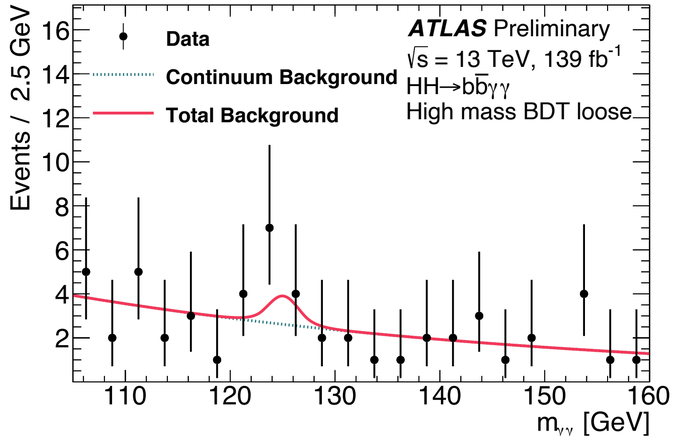


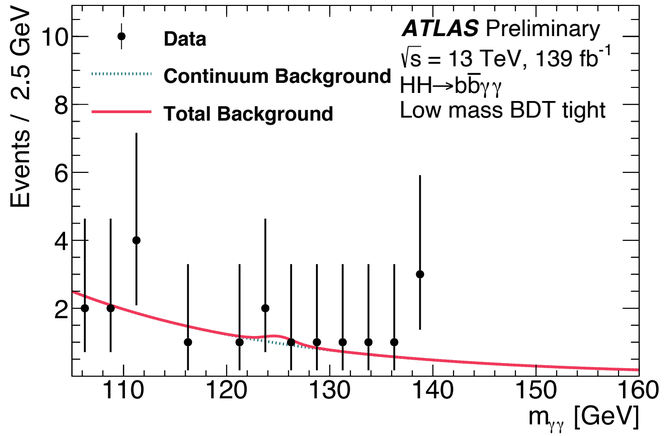


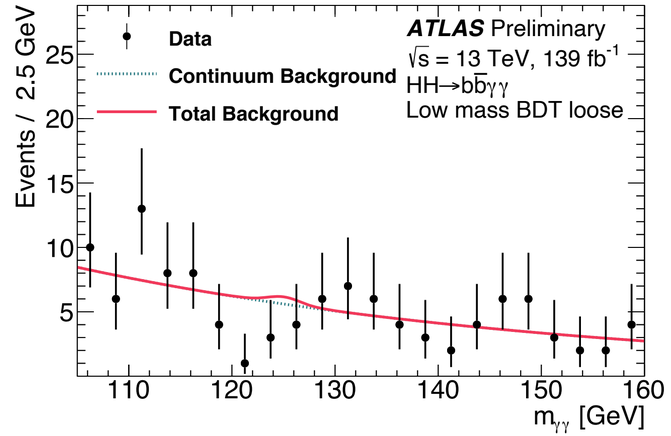
ATLAS HH -> bbγγ

$m_{\gamma\gamma}$ used as final discriminant variable in the signal regions









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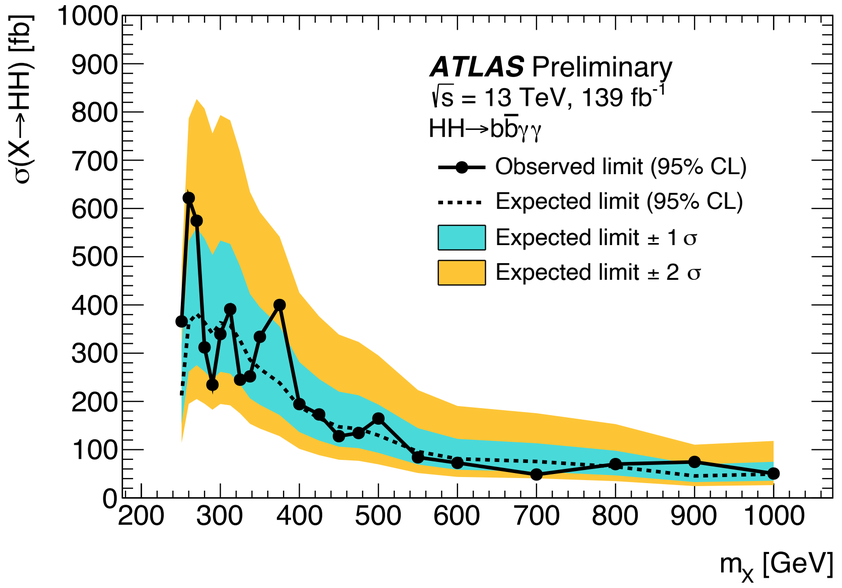

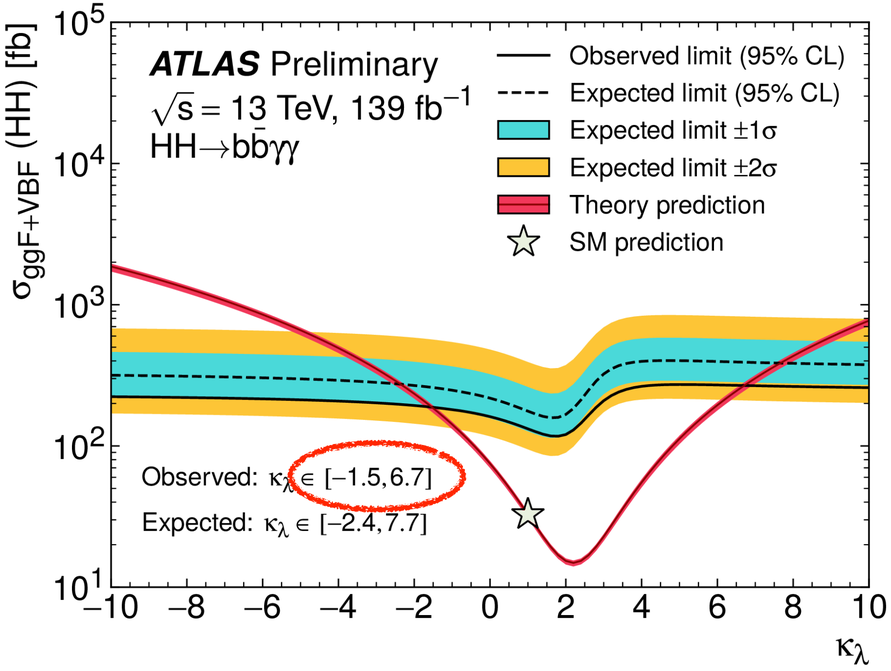

Upper limit on the non-resonant HH cross section of 4.1 x SM observed (5.5 x SM expected)

CMS non-resonant HH -> bbγγ

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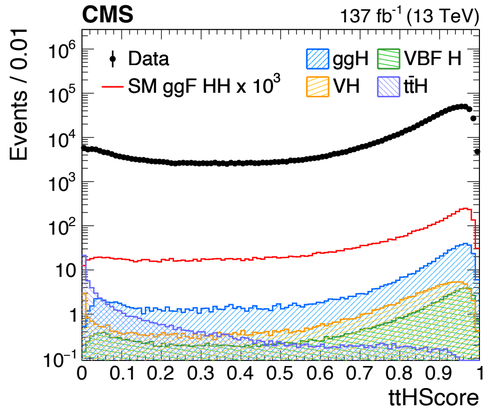
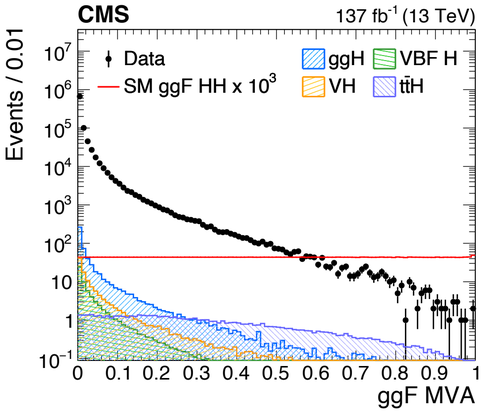
- Search for non-resonant HH production
- 2 photons and 2 b-tagged jets
- $100\ \text{GeV} < m_{\gamma\gamma} < 180\ \text{GeV}$
- $70\ \text{GeV} < m_{bb} < 190\ \text{GeV}$

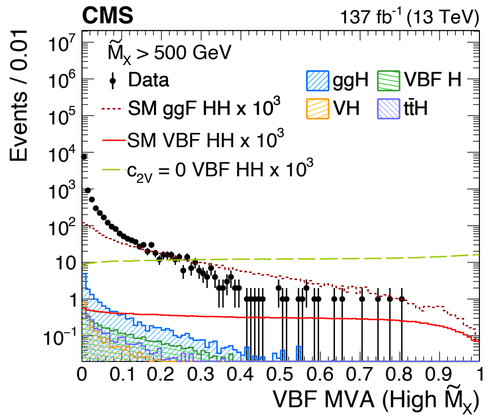
- Targeting ggF and VBF production modes with dedicated categories
  - Non-b-tagged jets with large pseudo-rapidity separation and large invariant mass as VBF jets defining the VBF category

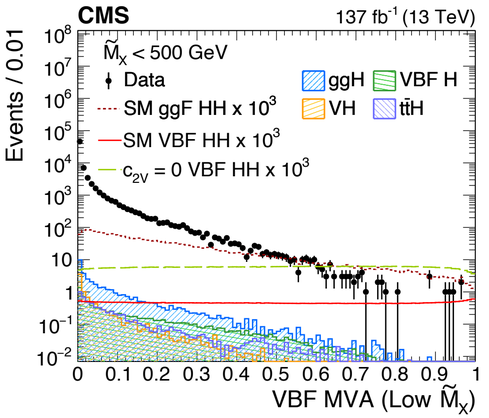
- Major backgrounds: γγ+jets estimated from data in the sidebands and single-Higgs modelled from Monte Carlo simulations

- DNN to discriminate between HH signal and ttH background
- BDTs to discriminate between HH signal and non-resonant background in the ggF and VBF categories



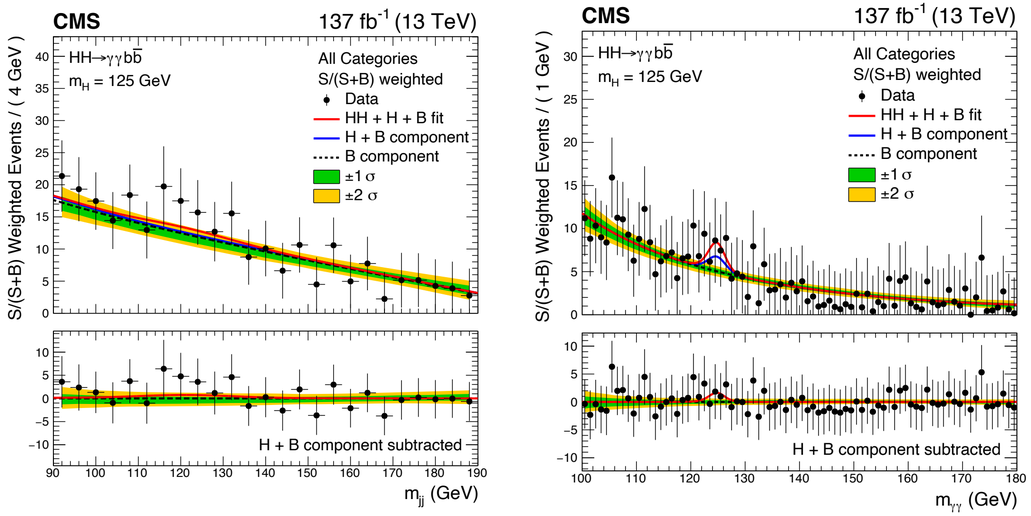






- ggF and VBF categories split to enhance sensitivity to SM and BSM couplings according to MVA output and m_{HH} selections
  - ggF split in 12 categories (3 MVA x 4 m_{HH} categories)
  - VBF split in 2 categories (2 m_{HH} categories plus MVA selection in each category)

CMS non-resonant HH -> bbγγ



Fit 2D in $m_{\gamma\gamma}$, m_{bb} in all categories

Upper limit on the non-resonant HH cross section of 7.7 x SM observed (5.2 x SM expected)

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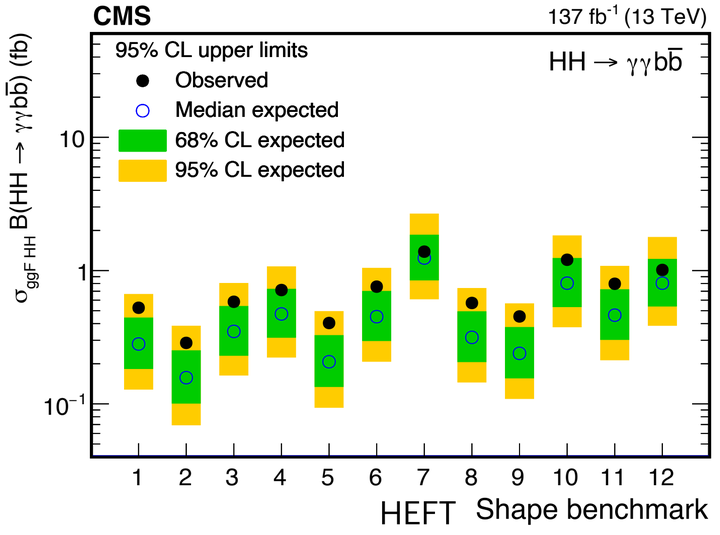
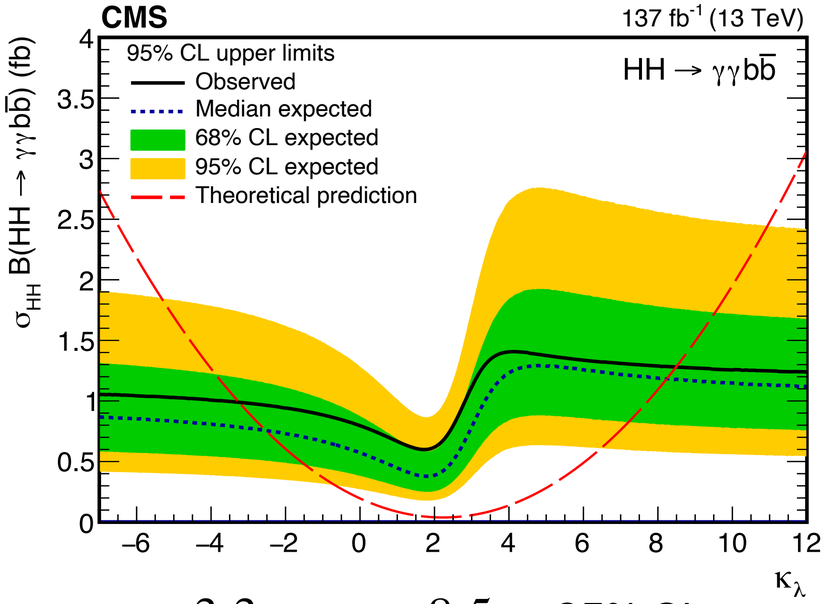
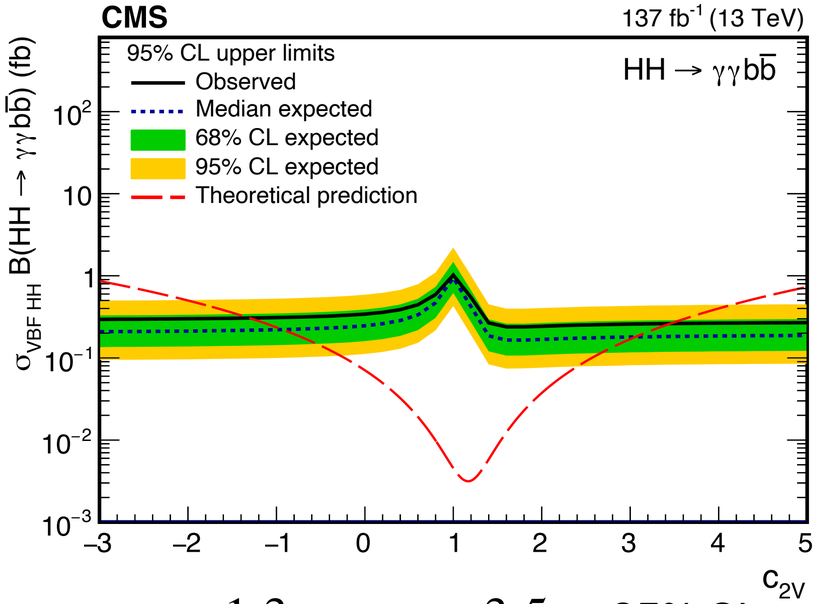




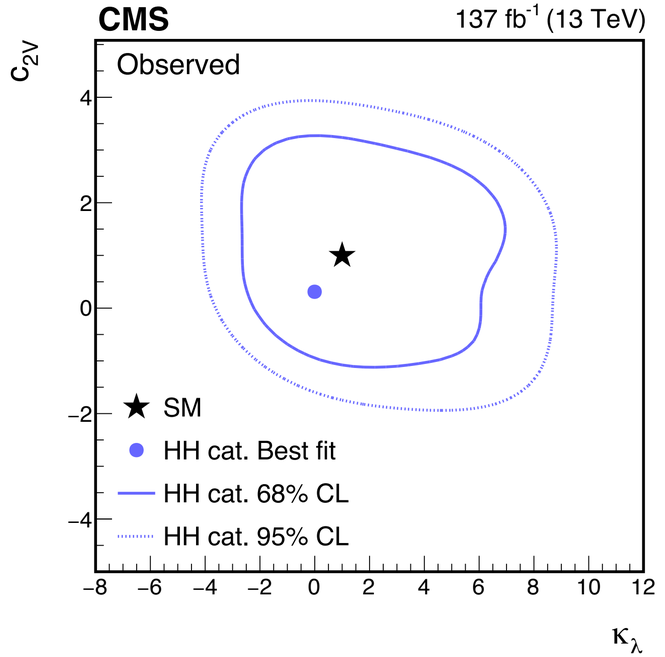
$-3.3 < \kappa_\lambda < 8.5$ at 95% CL

(expected $-2.5 < \kappa_\lambda < 8.2$)



$-1.3 < \kappa_{2V} < 3.5$ at 95% CL

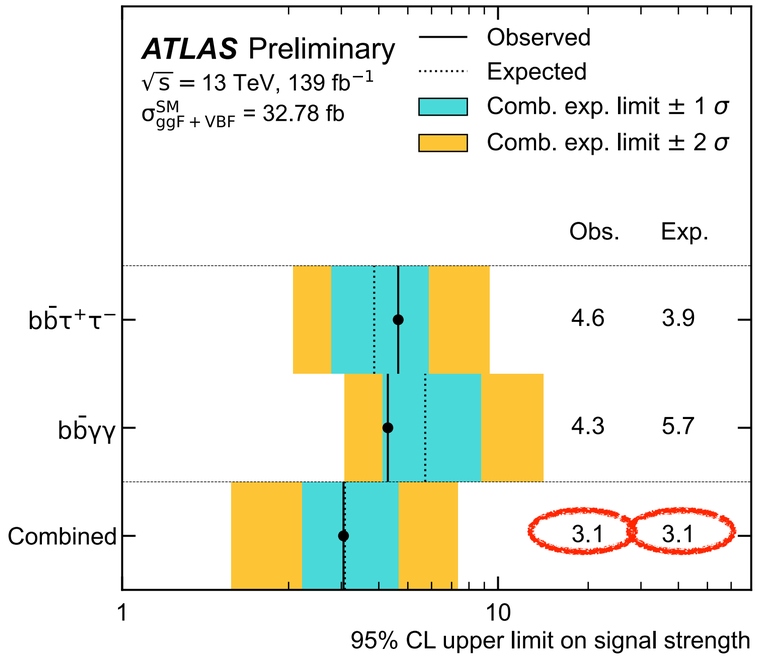
(expected $-0.9 < \kappa_{2V} < 3.1$)

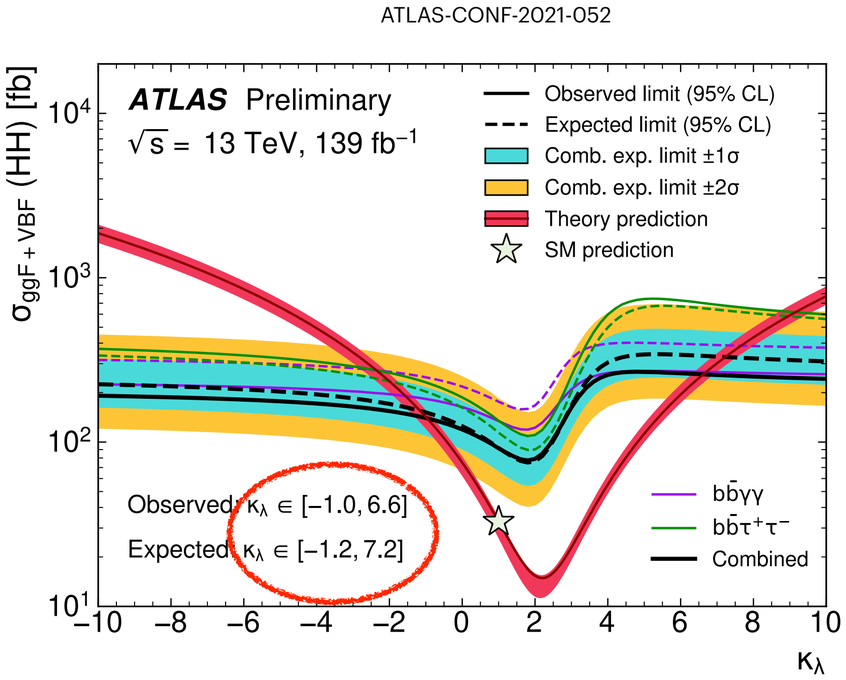


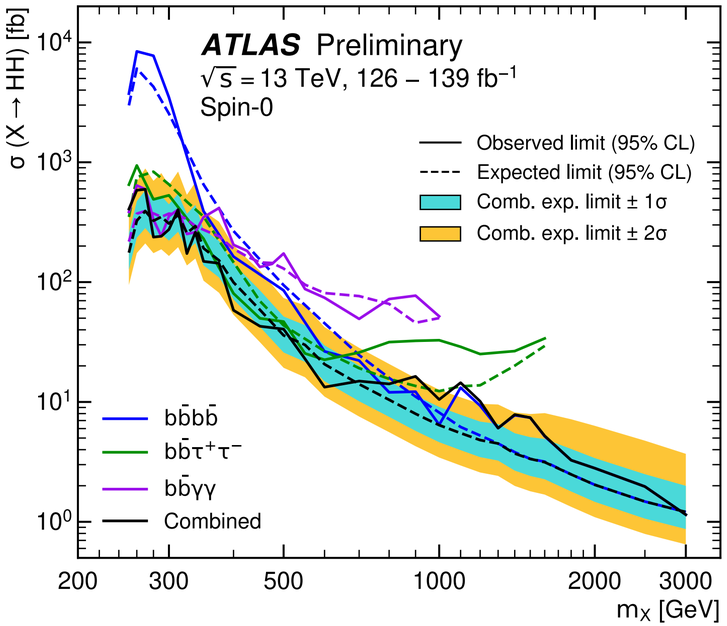
ATLAS HH combination

Combination of HH analyses performed in 3 decay channels using full Run 2 LHC data:

- bbττ and bbγγ channels for non-resonant HH production
- bbττ, bbγγ and bbbb channels for resonant HH production







Small data excess at 1.1 TeV,
significance 3.2σ (2.1σ) local (global)

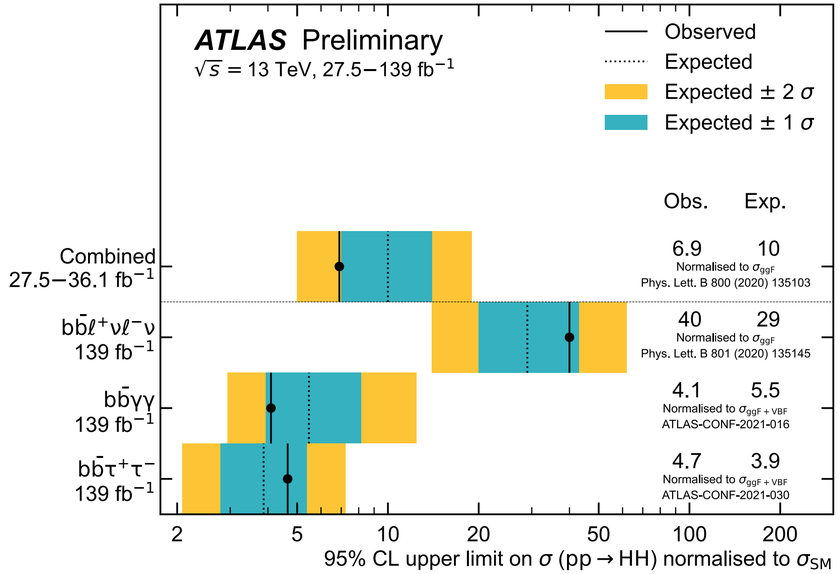
Best upper limit on non-resonant HH production and constraints on κ_λ up to now!

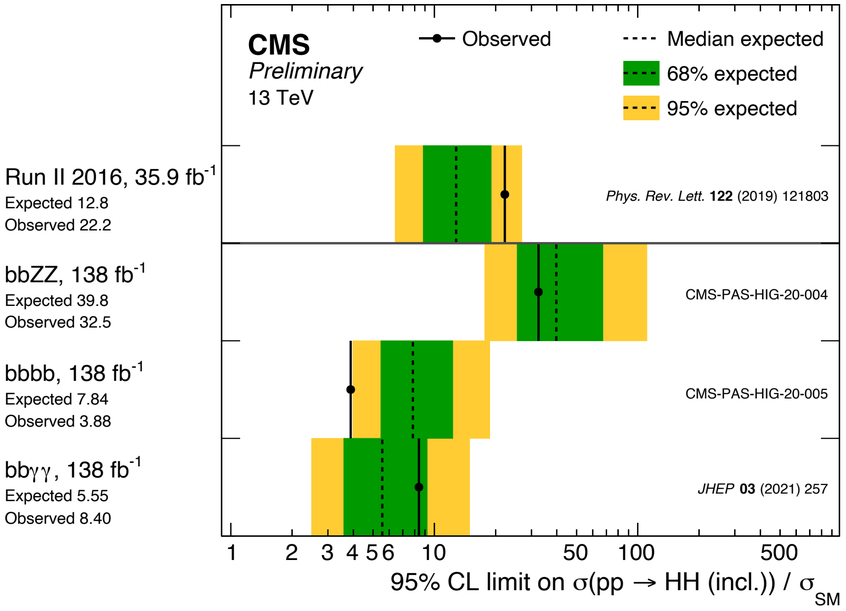
Summary and conclusions

Presented results from ATLAS and CMS
di-Higgs non-resonant and resonant searches
with full Run 2 data performed in several HH decay channels

Results from both experiments significantly
improved compared to partial Run 2 results,
improvements beyond luminosity increase thanks to
improved objects reconstruction and analysis techniques

More analyses ongoing in both experiments,
stay tuned for new results
covering more decay channels
and more interpretations!





Thank you for your attention!

Back-up slides

Partial Run 2 dataset results

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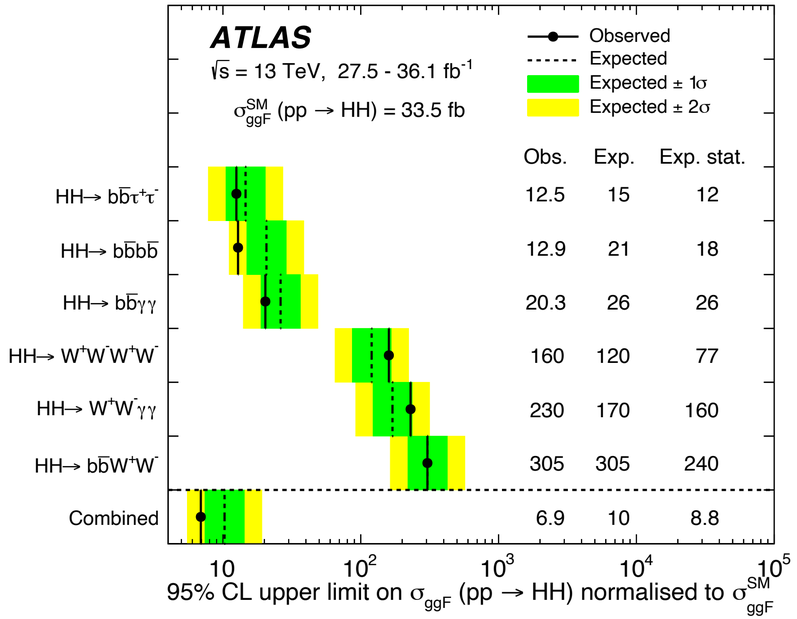
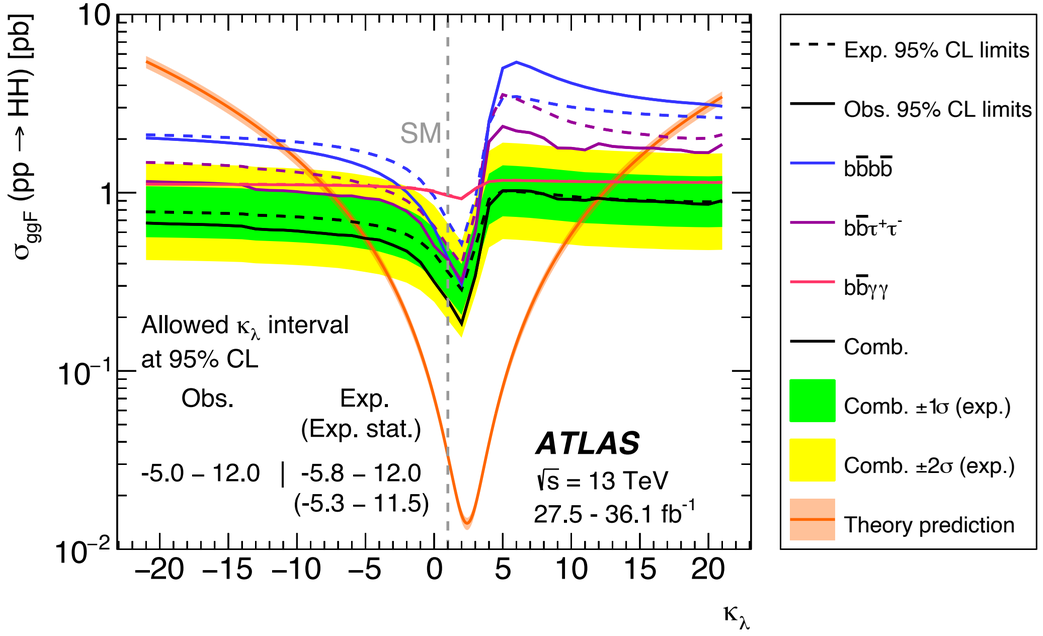
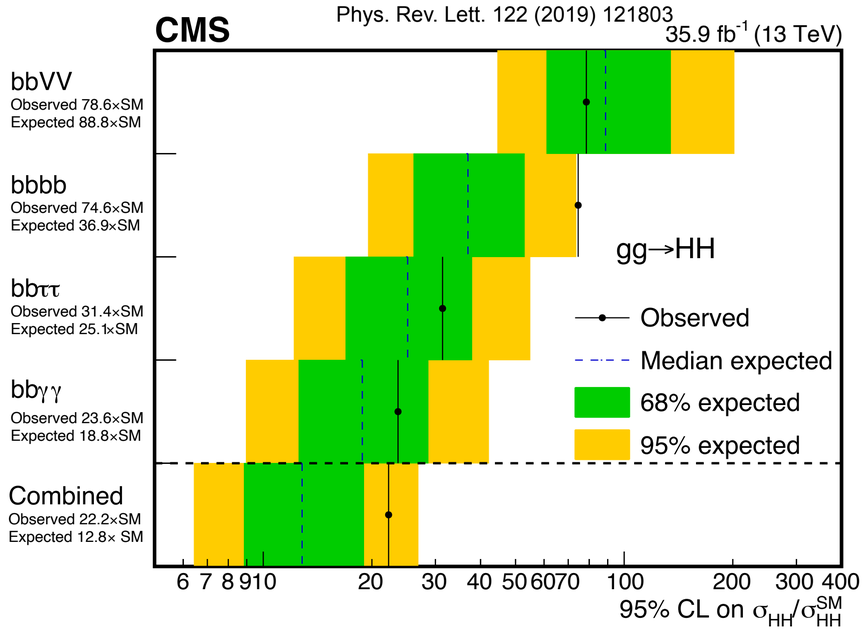
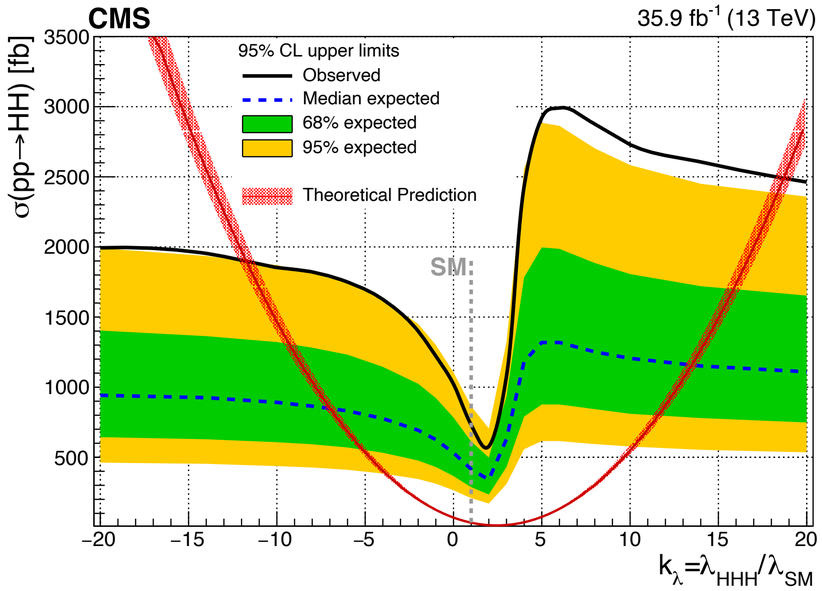




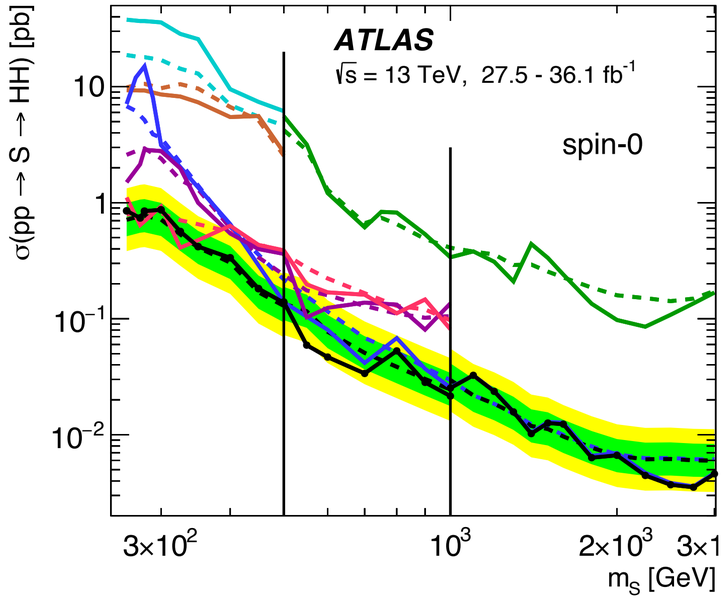
Phys. Rev. Lett. 122 (2019) 121803

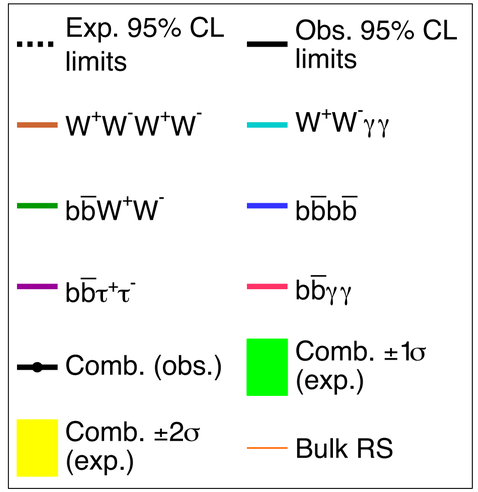




Partial Run 2 dataset results

Phys. Lett. B 800 (2020) 135103





Phys. Rev. Lett. 122 (2019) 121803