Double Higgs boson searches overview

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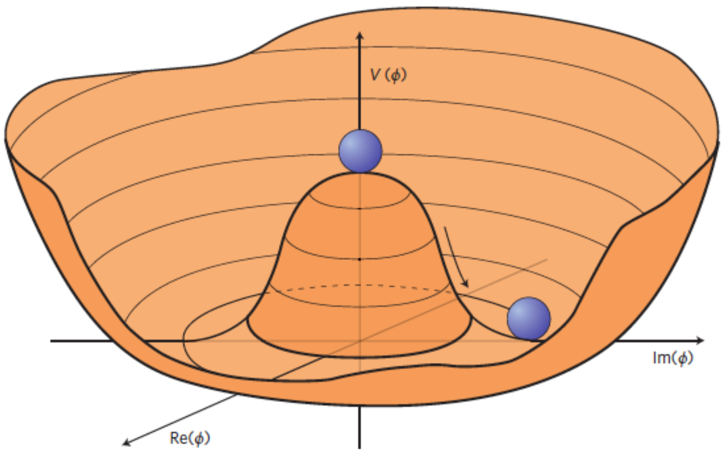
Introduction and motivation

- Di-Higgs production provides an important test of the Standard Model (SM) electroweak symmetry breaking

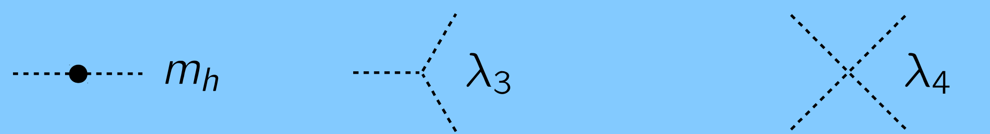
Higgs field potential



Potential expanded around minimum

$$V^{SM}(h) = \frac{m_h^2}{2} h^2 + \lambda_3^{SM} v h^3 + \lambda_4^{SM} h^4$$

mass term — **trilinear** self-coupling — **quartic** self-coupling



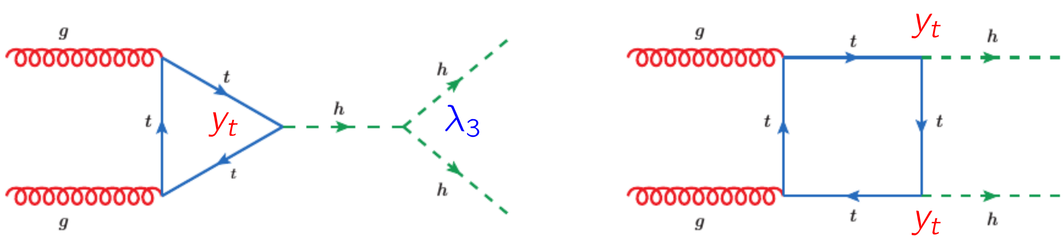
$$\lambda_3^{SM} = \frac{m_h^2}{2v^2} \qquad \lambda_4^{SM} = \frac{m_h^2}{8v^2}$$

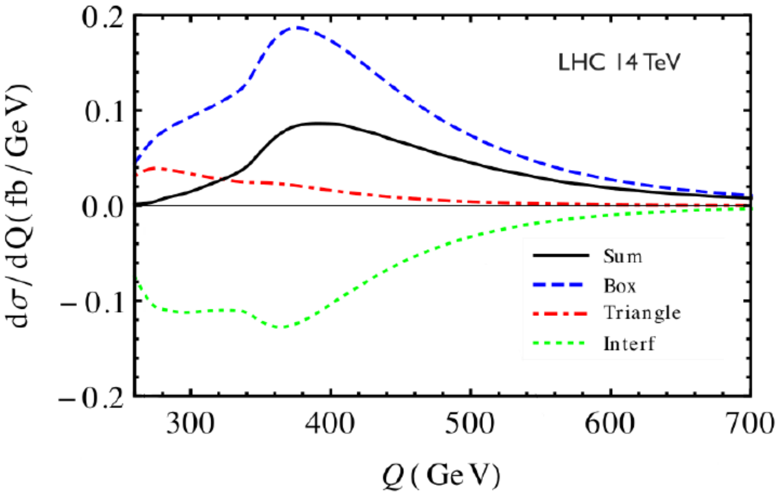
Di-Higgs production

- In general, di-Higgs production can be resonant or non-resonant

SM di-Higgs production dominated by non-resonant gluon-gluon fusion production

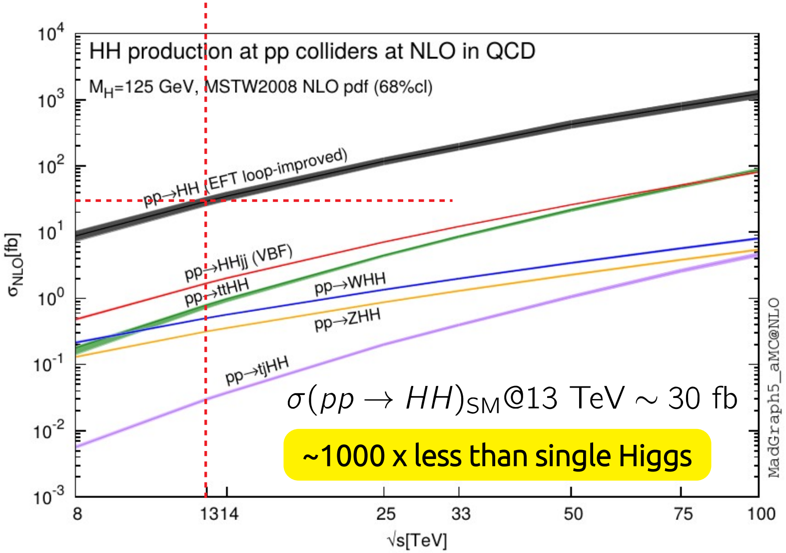
- Two diagrams below interfere destructively





At the leading order (LO), probing the trilinear Higgs coupling λ_3 requires di-Higgs production

In addition, the SM di-Higgs production provides access to the top-Higgs Yukawa coupling y_t

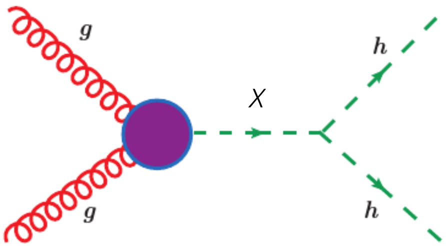


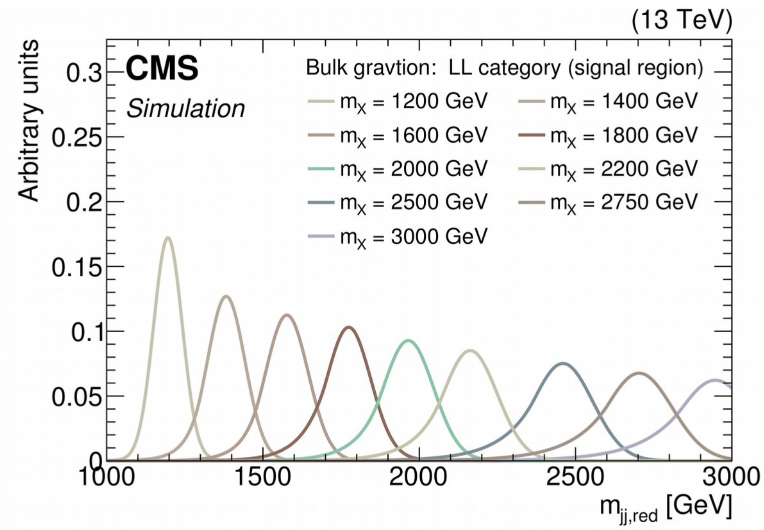
Di-Higgs production (cont'd)

- BSM production can be resonant and non-resonant

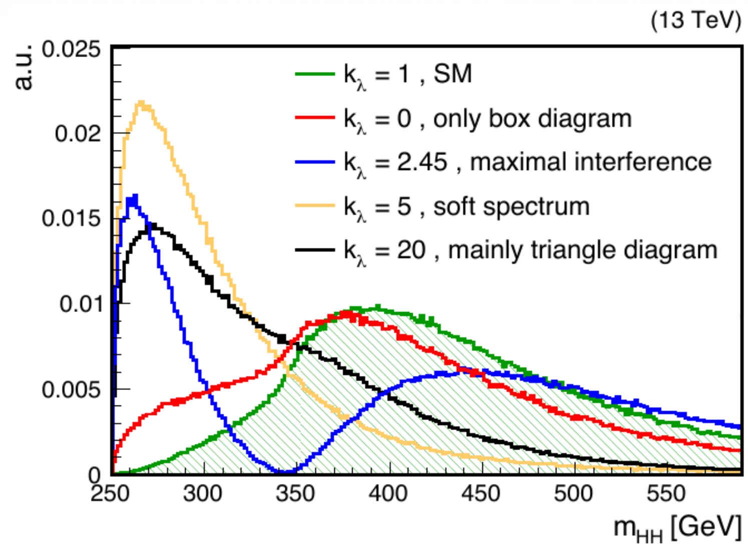
Resonant BSM production proceeds through the production of a new heavy resonance *X* that decays into two Higgs bosons

- Production cross section significantly enhanced



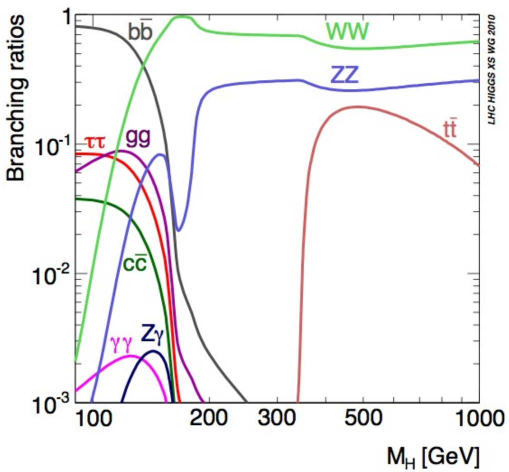


Non-resonant BSM production can arise from anomalous couplings κ_λ and additional contact interactions → Can lead to large modifications in the production cross section and shapes of kinematic distributions

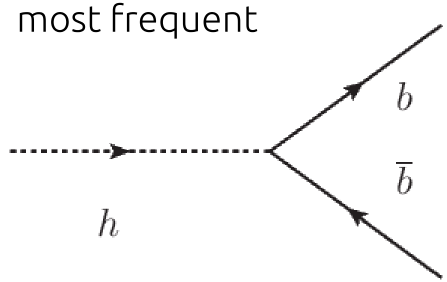


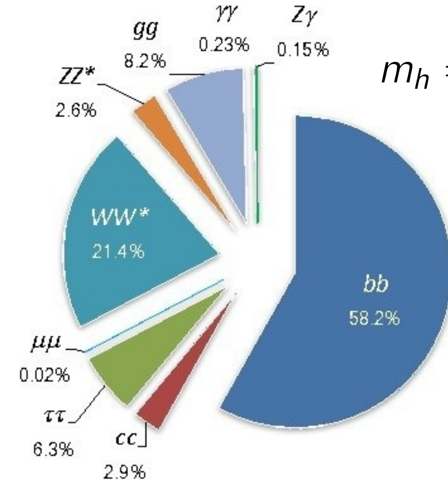
Final state signatures

- Higgs boson decay modes

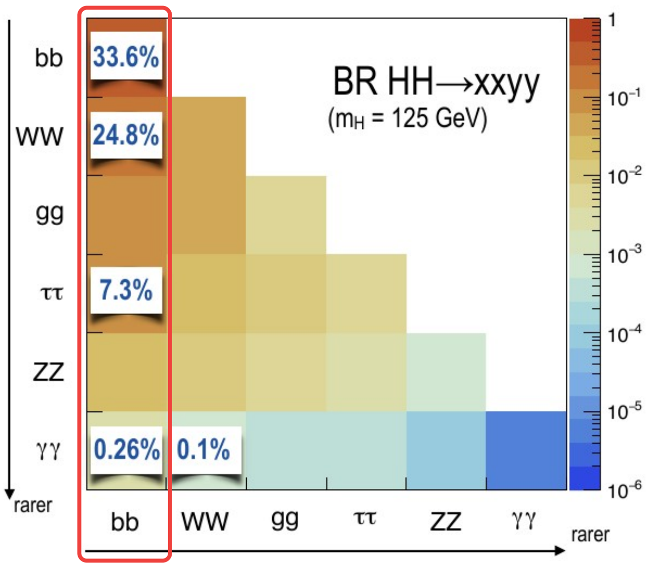


$h \to b\bar{b}$
most frequent





$m_h = 125$ GeV



Di-Higgs final state signatures

- Searches prioritize on high branching fractions and clean final states
- Main final states include b jets → b tagging algorithms play an important role

Recent experimental results

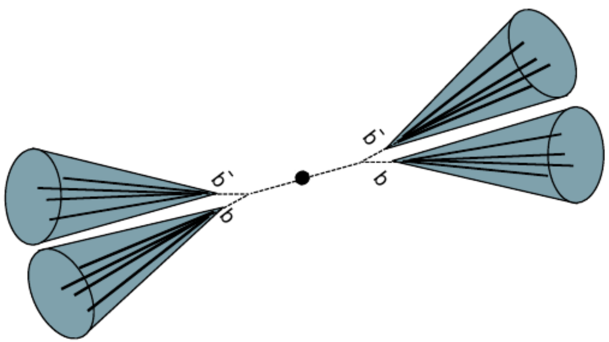
- In the following slides recent experimental results for different final states from ATLAS and CMS will be presented
  - Results mostly based on 2015 and 2016 data
- Due to limited time, focus on the final results without going into various analysis details
  - Trigger strategy, Monte Carlo sample production, event selection, background estimation, definition of sideband and control regions, use of MVA techniques,…
- More details can be found in provided references

$hh \to 4b$

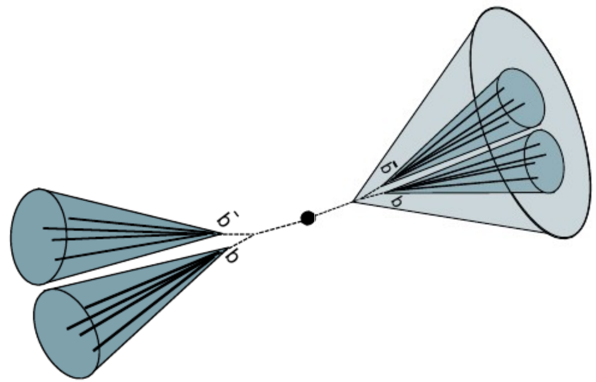
References	
ATLAS	arXiv:1804.06174
CMS	JHEP 08 (2018) 152, CMS-PAS-HIG-17-017, Phys. Lett. B 781 (2018) 244, arXiv:1808.01473

hh→4b

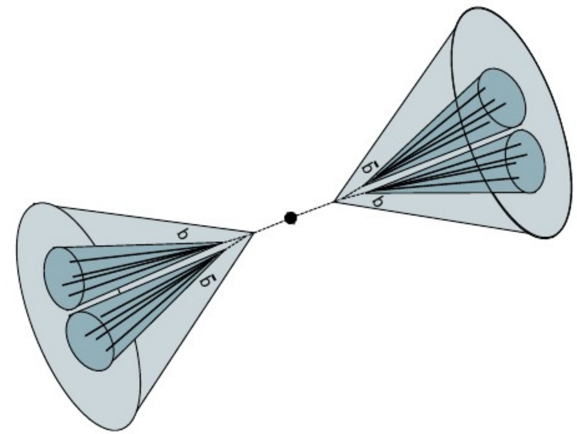
- Both resonant and non-resonant signatures being looked for
- Final state topology can be resolved, semi-resolved or merged



Resolved



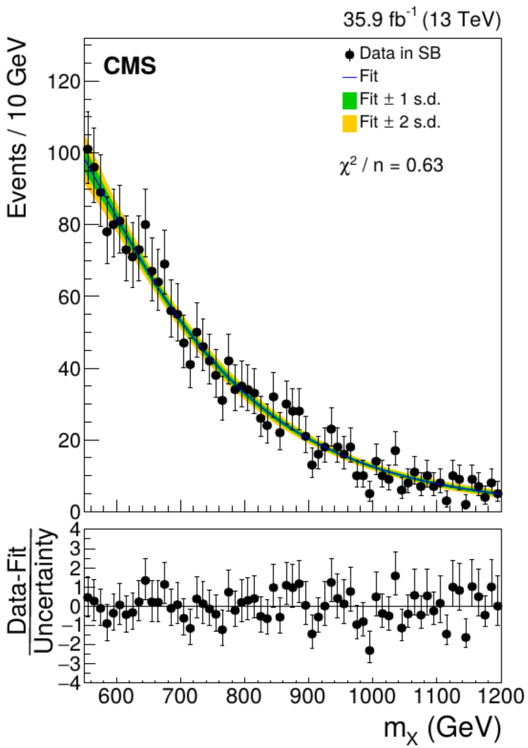
Semi-resolved



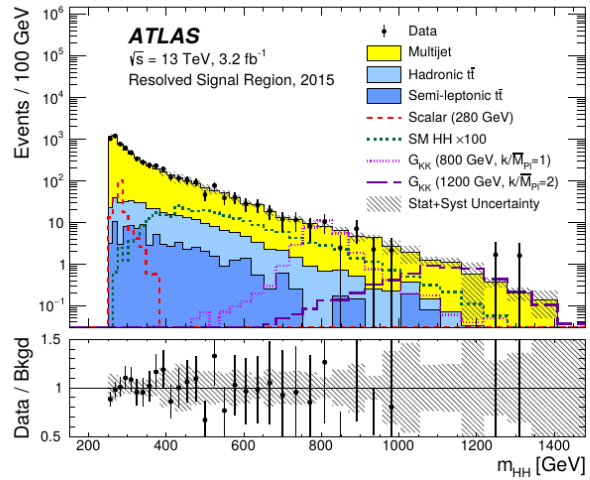
Merged

hh→4b (resolved)

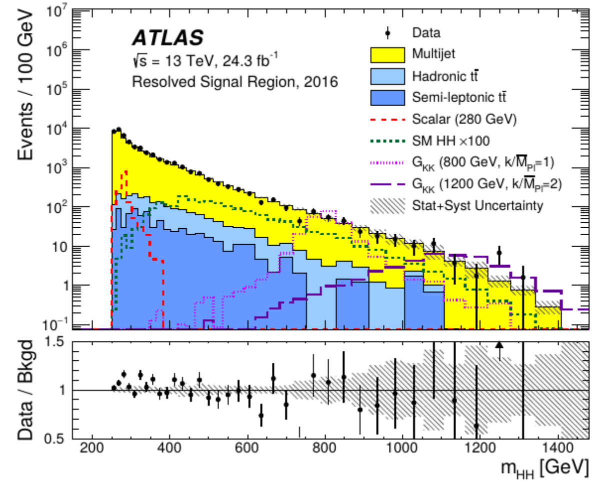
Resolved resonant



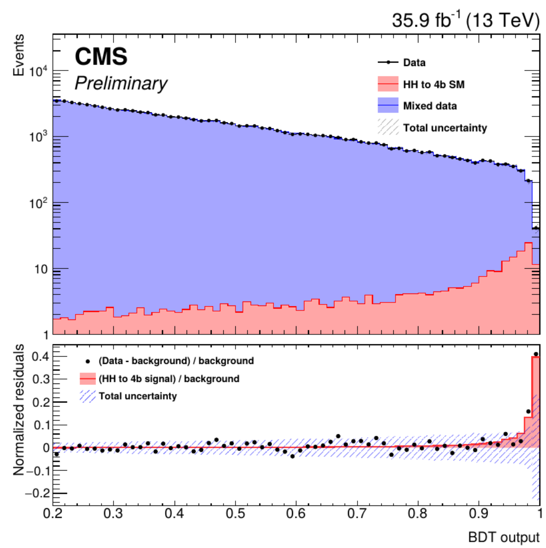
Resolved



(a) 2015 dataset



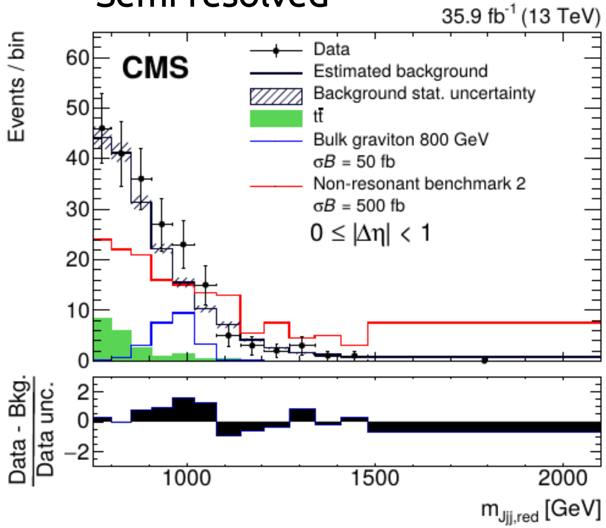
(b) 2016 dataset



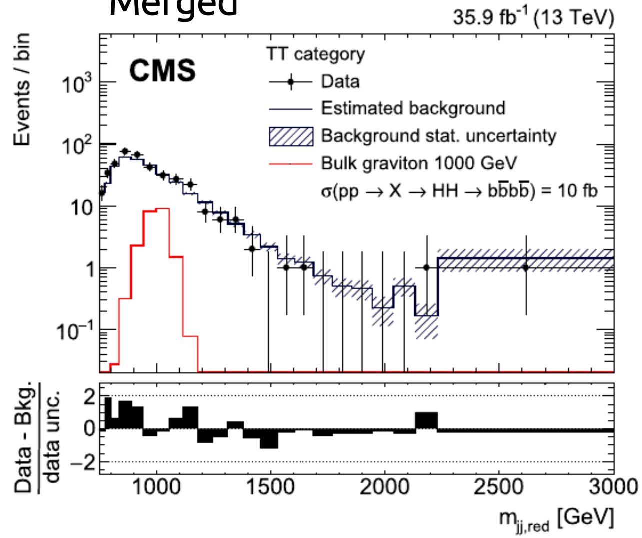
Resolved non-resonant

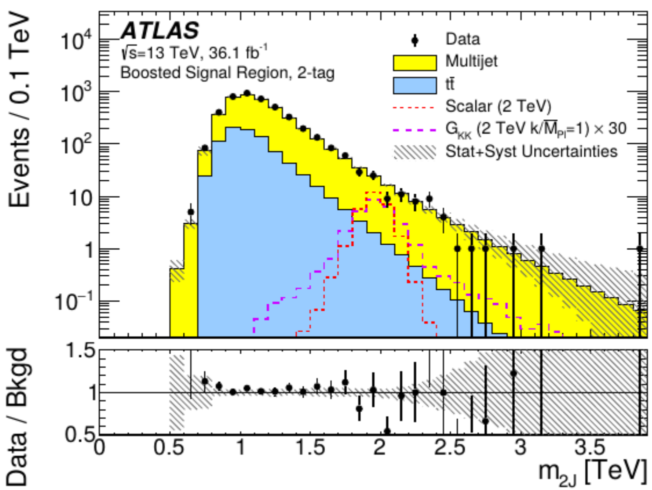
hh→4b (merged)

Semi-resolved

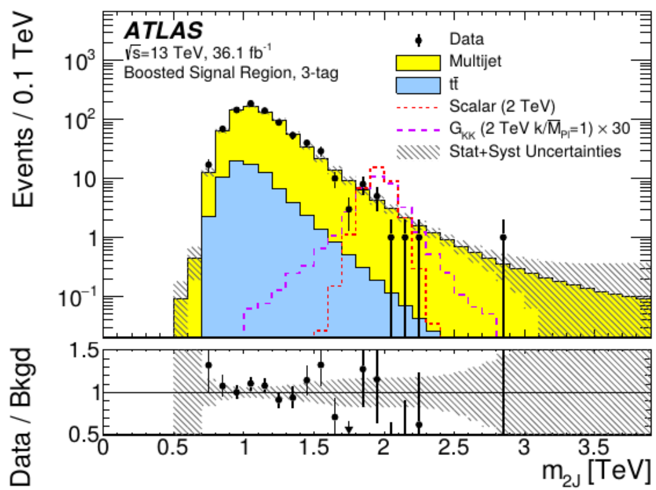


Merged

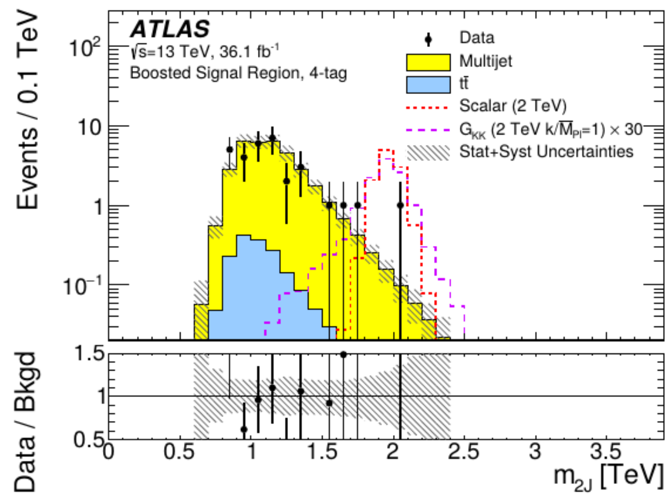




(a) Two-tag



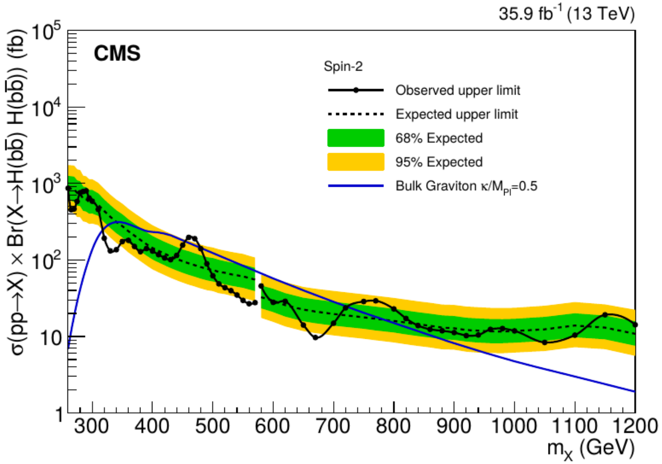
(b) Three-tag

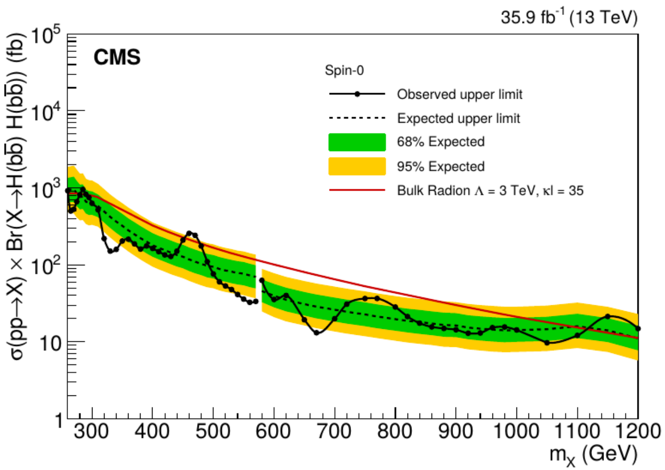


(c) Four-tag

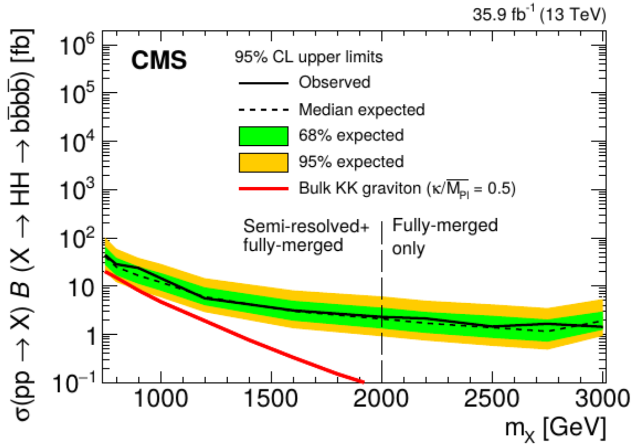
hh→4b (resonant)

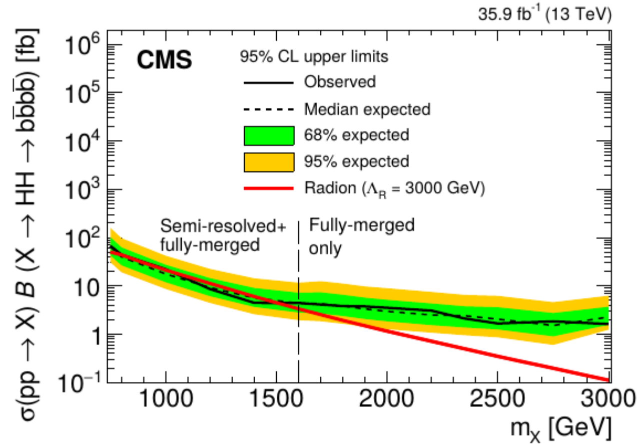
Resolved resonant



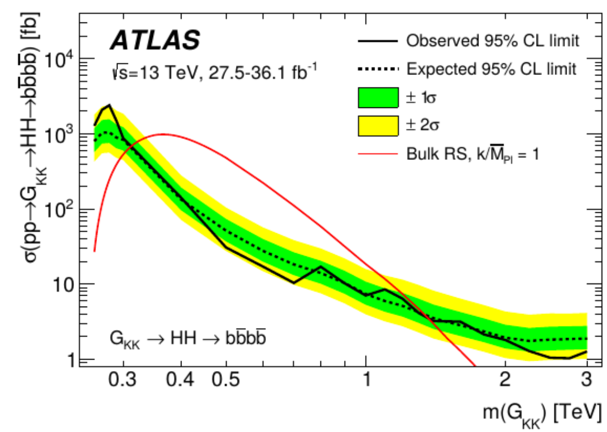


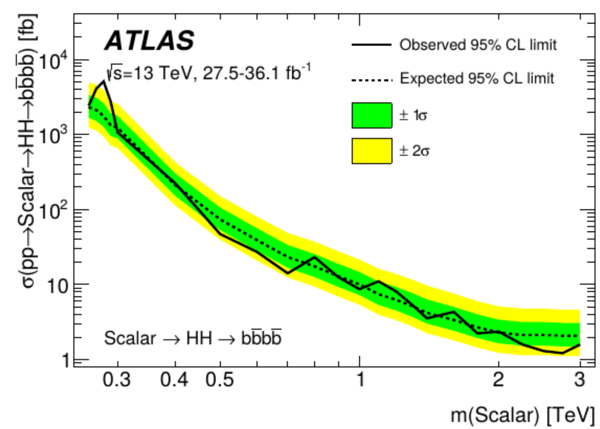
Merged resonant



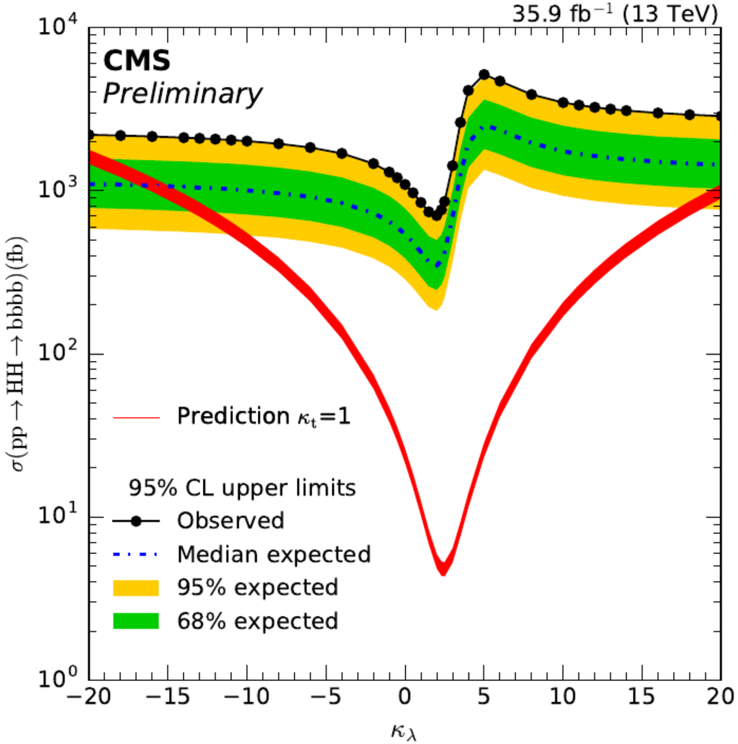


Resonant





hh→4b (non-resonant)



Limit on σ/σ^{SM}
Observed: 74
Expected: 37

ATLAS

Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

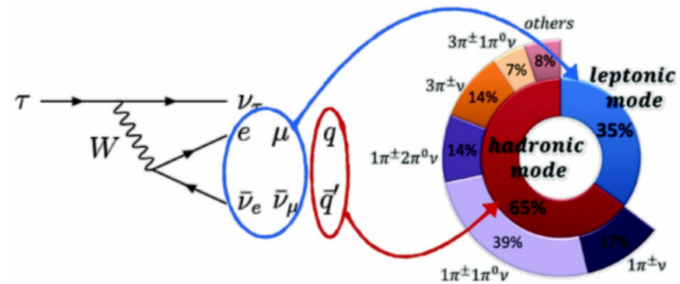
$\frac{\sigma}{\sigma^{SM}}$

hh→bbττ

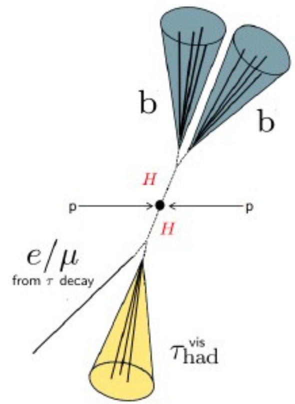
References	
ATLAS	arXiv:1808.00336
CMS	Phys. Lett. B 778 (2018) 101, arXiv:1808.01365

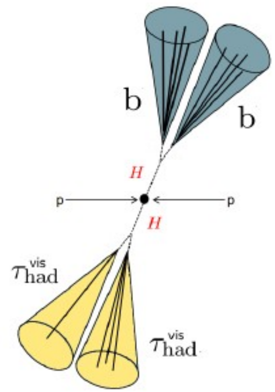
hh→bbττ

- Third largest branching fraction and relatively clean compared to other final states



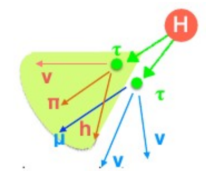
- To maximize the analysis sensitivity, using both leptonic and hadronic τ decay modes (approx. 88% of all ττ decays)



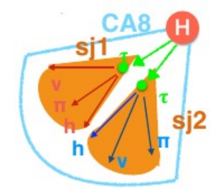


- As in the 4b case, looking for resonant and non-resonant signatures in both resolved and boosted (currently CMS only) final state topologies

Boosted $\tau_{lep}\tau_{had}$ pair

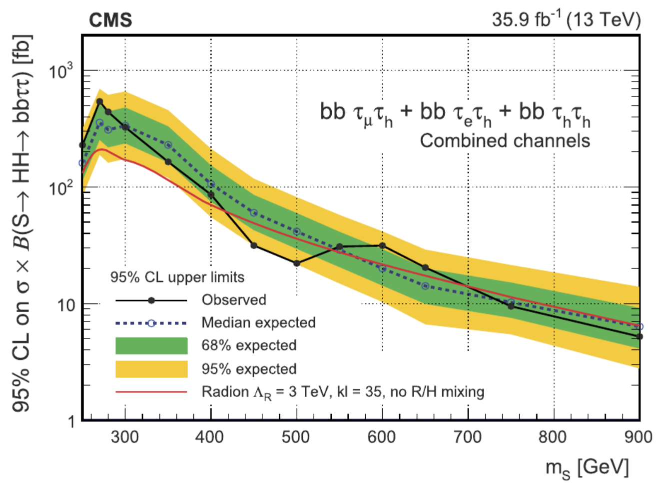


Boosted $\tau_{had}\tau_{had}$ pair

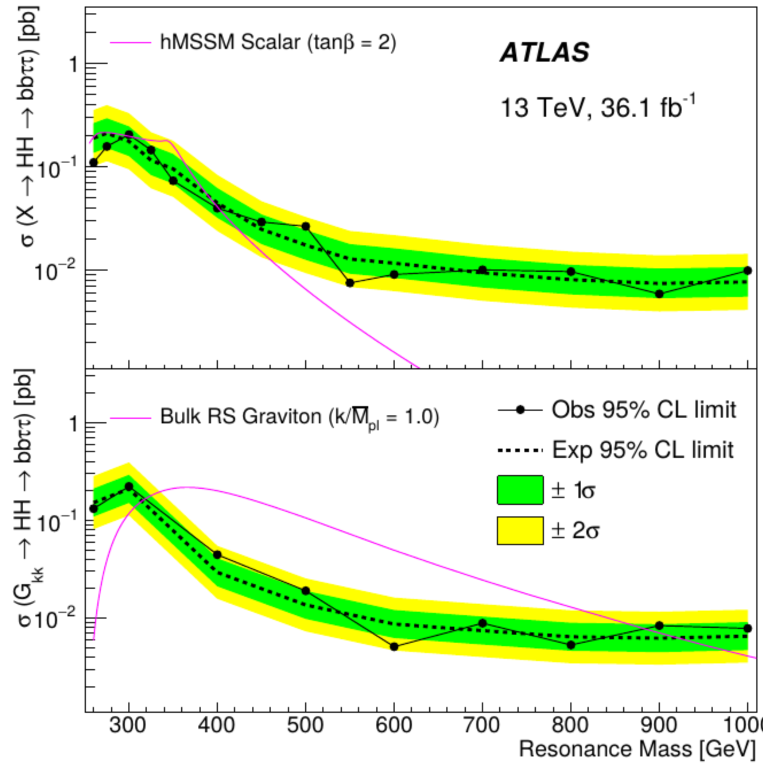


hh→bbττ (resonant)

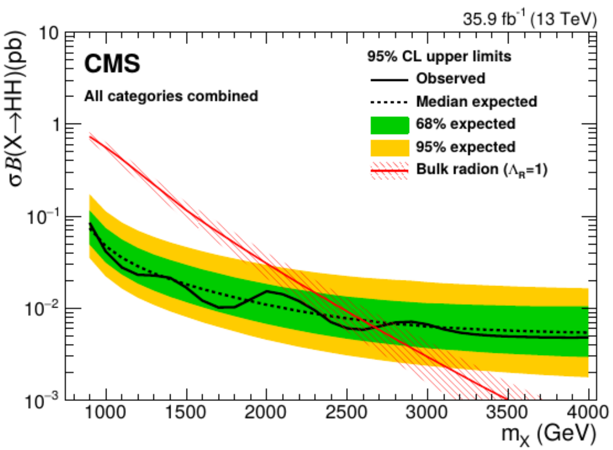
Resolved

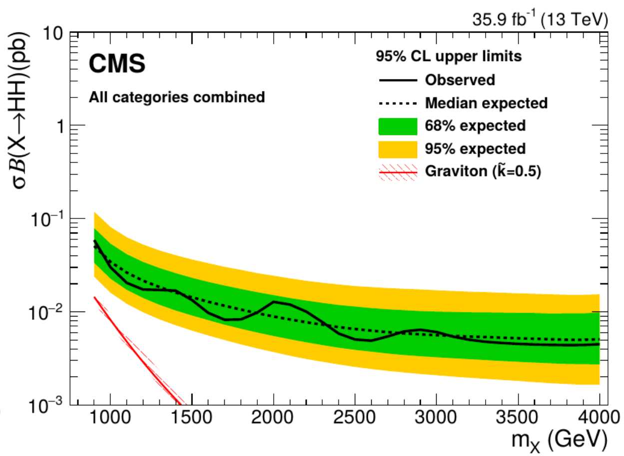


Resolved

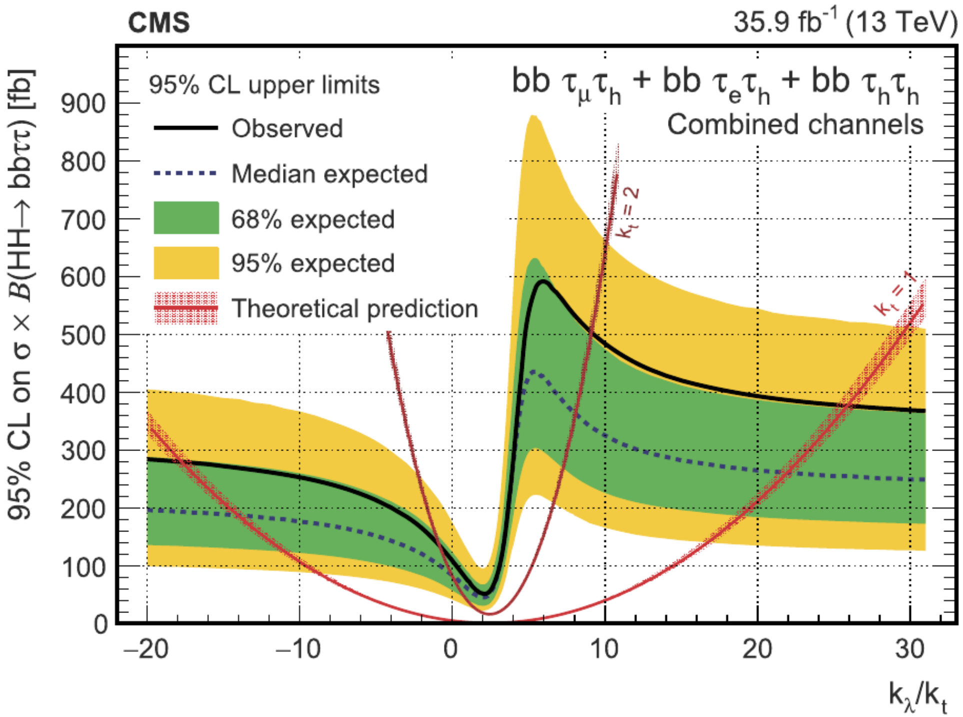


Merged





hh→bbττ (non-resonant)



Limit on σ/σ^{SM}
Observed: 30
Expected: 25

ATLAS

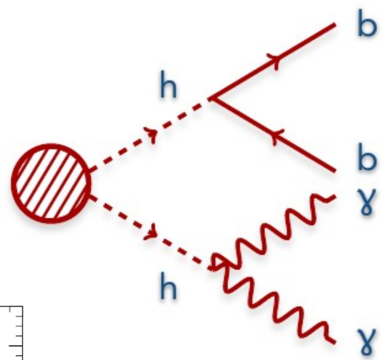
		Observed	-1σ	Expected	$+1\sigma$
$\tau_{lep}\tau_{had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	σ/σ_{SM}	23.5	20.5	28.4	39.5
$\tau_{had}\tau_{had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	σ/σ_{SM}	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	σ/σ_{SM}	12.7	10.7	14.8	20.6

hh→bbγγ

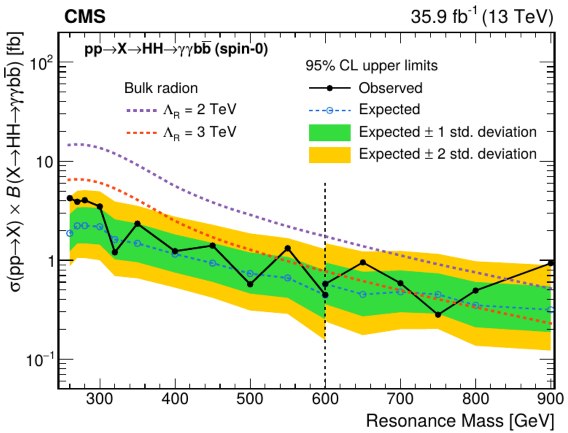
References	
ATLAS	arXiv:1807.04873
CMS	arXiv:1806.00408

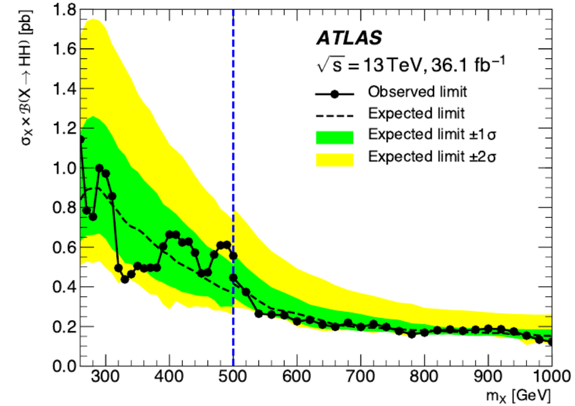
hh→bbγγ

- Small branching fraction but clean final state due to the presence of photons
- Good energy resolution for photons
- Fully reconstructible final state

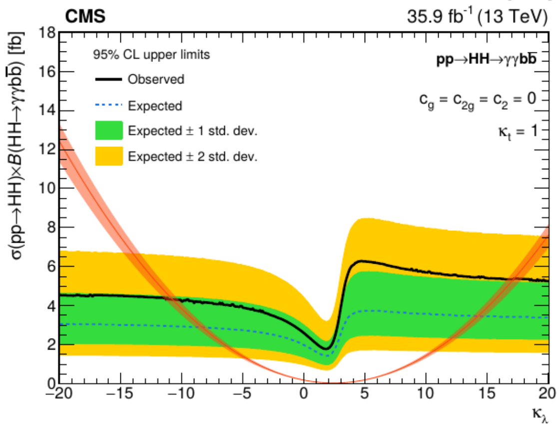


Resonant

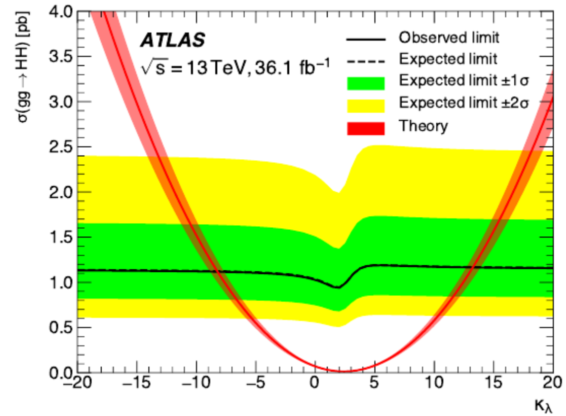




Non-resonant



Observed limits
$\sigma/\sigma^{SM}<24$
$-11<\kappa_\lambda<17$



Observed limits
$\sigma/\sigma^{SM}<22$
$-8.2<\kappa_\lambda<13.2$

Other final states

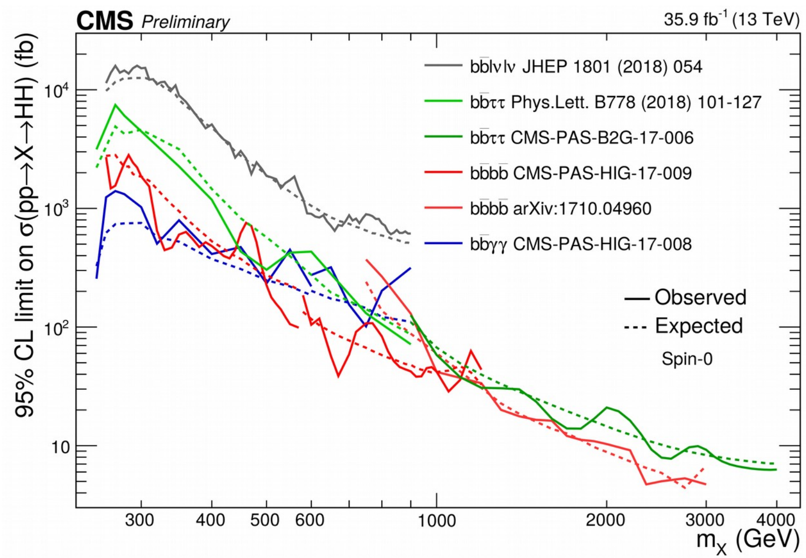
- $hh \rightarrow WW\gamma\gamma$
  - ATLAS: arXiv:1807.08567 (NR σ/σ^{SM}<230@95% CL)
- $hh \rightarrow bbWW$
  - ATLAS: Preliminary result (NR σ/σ^{SM}<300@95% CL)
  - CMS: JHEP 01 (2018) 054 (NR σ/σ^{SM}<79@95% CL)
- Other more exotic final states being explored as well
  - bbZZ
  - $\tau\tau\tau\tau$
  - WWWW

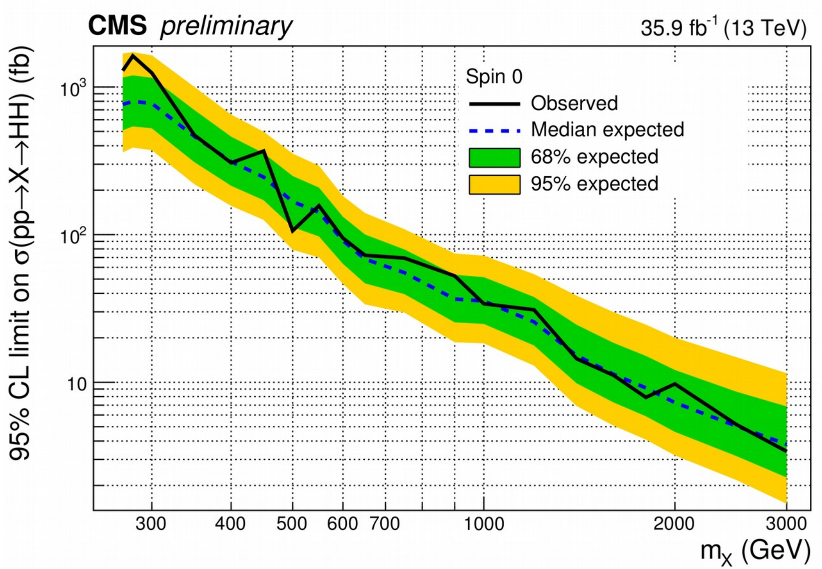
Combination

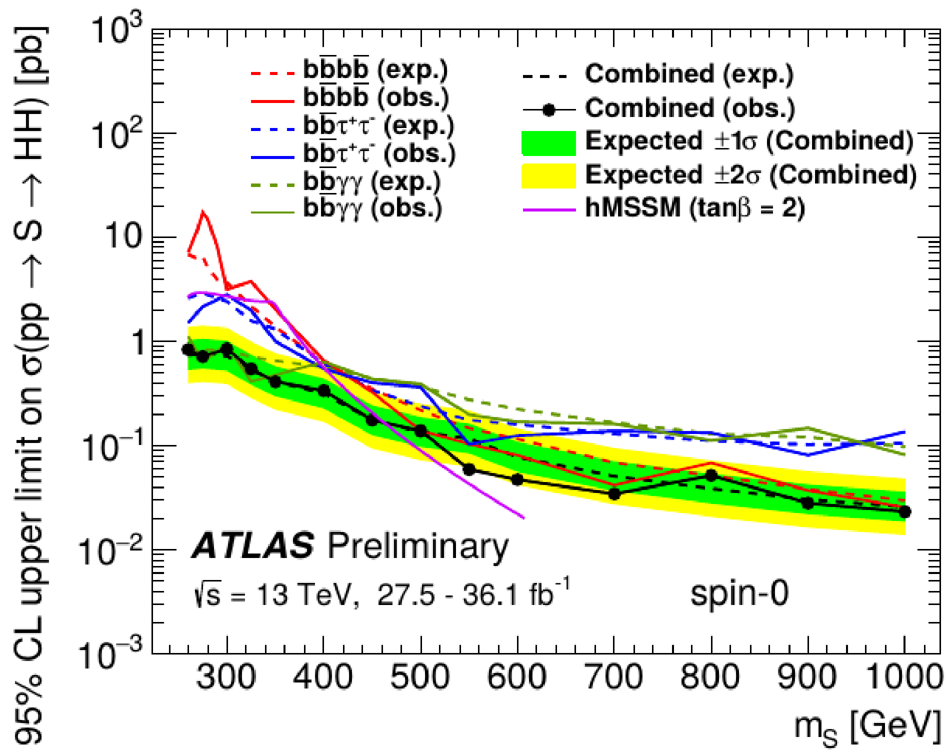
- Different channels combined to improve sensitivity to the di-Higgs production

References	
ATLAS	Higgs Summary Plots
CMS	Higgs Summary Plots, CMS-PAS-HIG-17-030

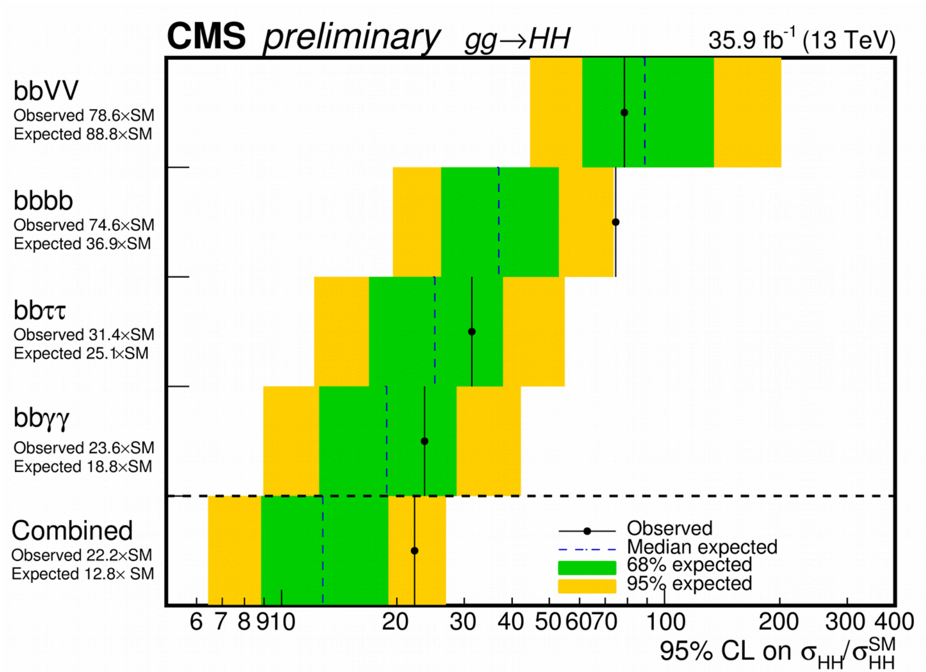
Combination (resonant production)

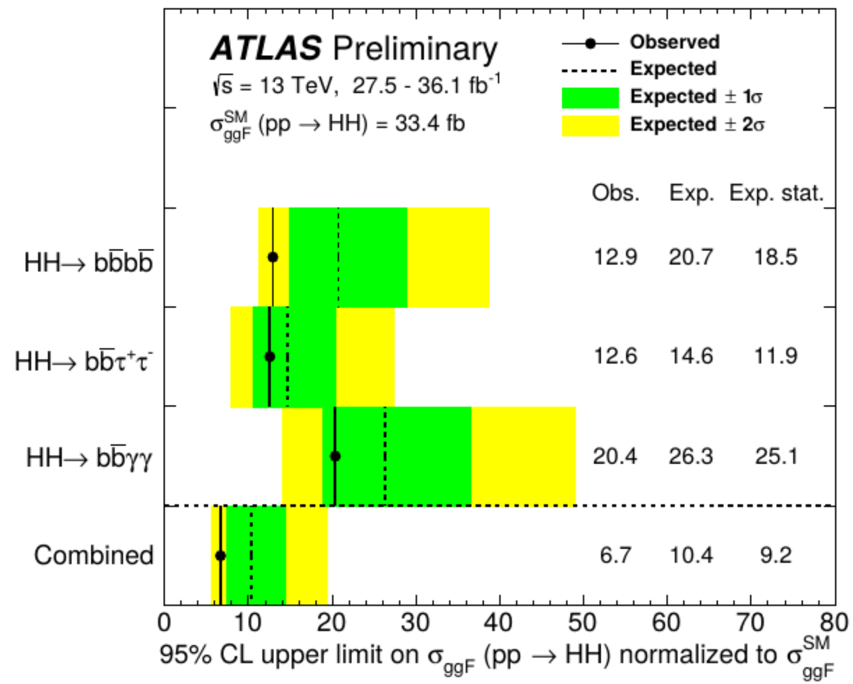






Combination (SM hh production)

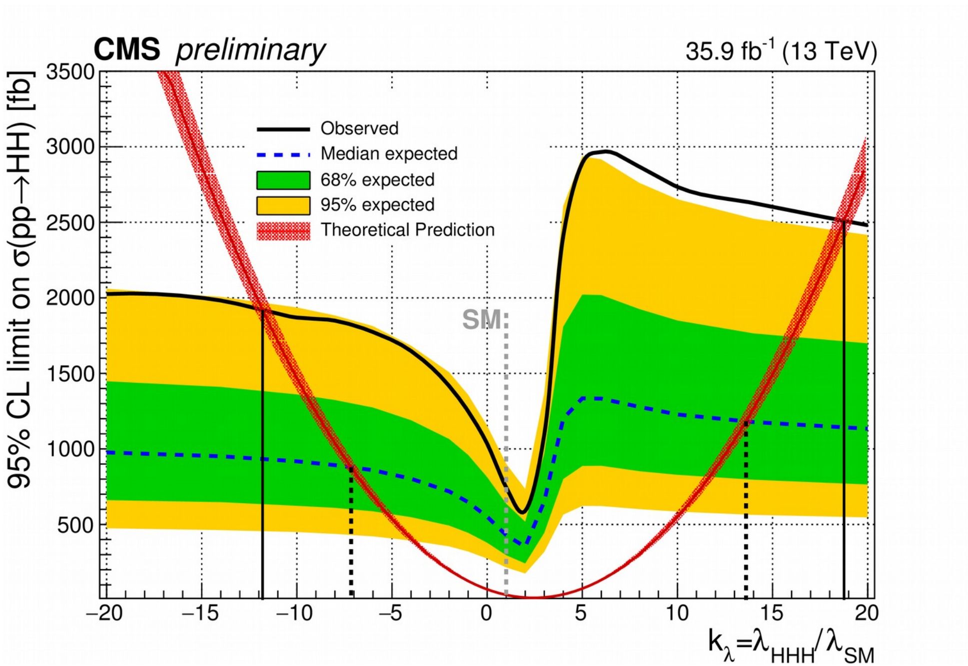




Combined limit on σ/σ^{SM}
Observed: 22.2
Expected: 12.8

Combined limit on σ/σ^{SM}
Observed: 6.7
Expected: 10.4

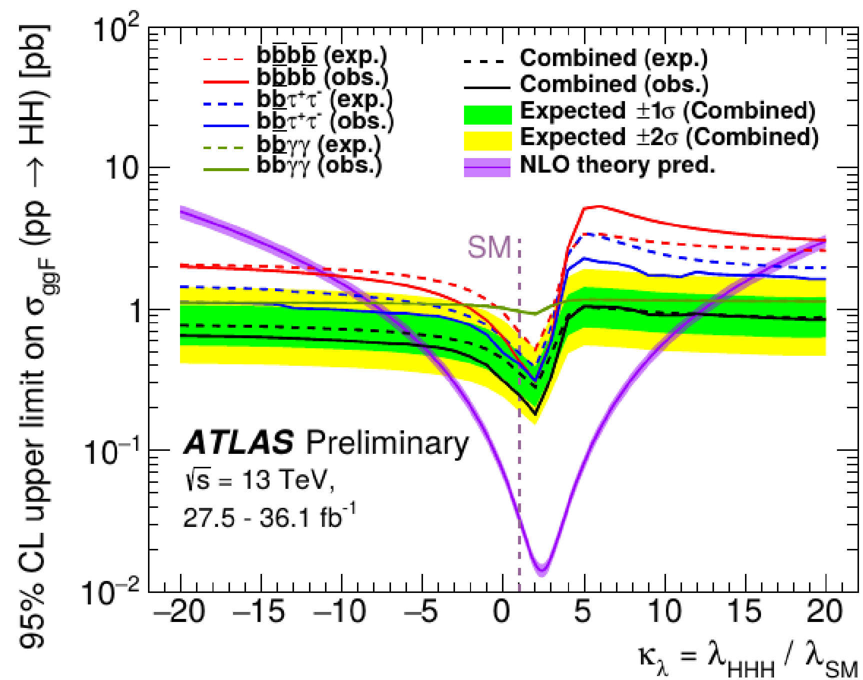
Combination (trilinear self-coupling)



Combined limits on κ_λ

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

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



Combined limits on κ_λ

Observed: $-5.0<\kappa_\lambda<12.1$

Expected: $-5.8<\kappa_\lambda<12.0$

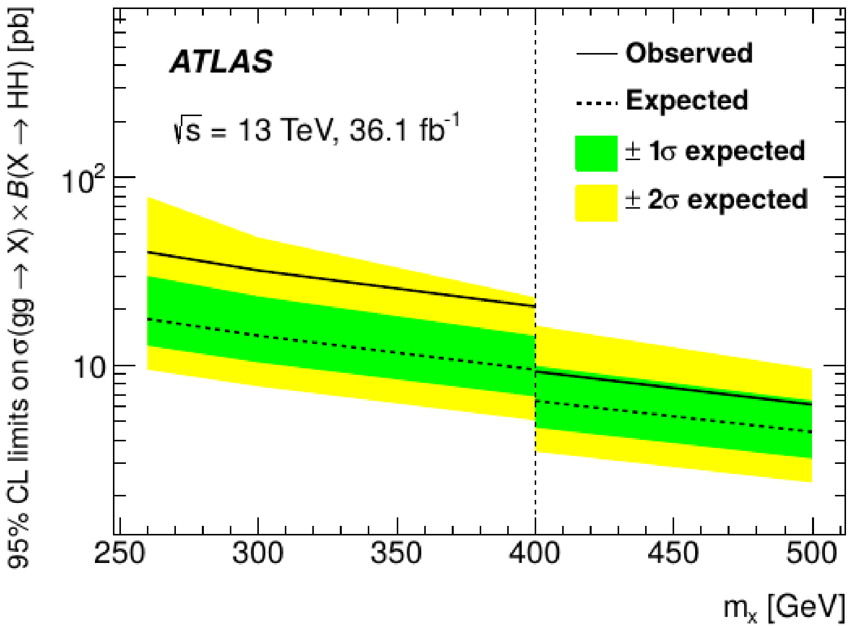
Summary and outlook

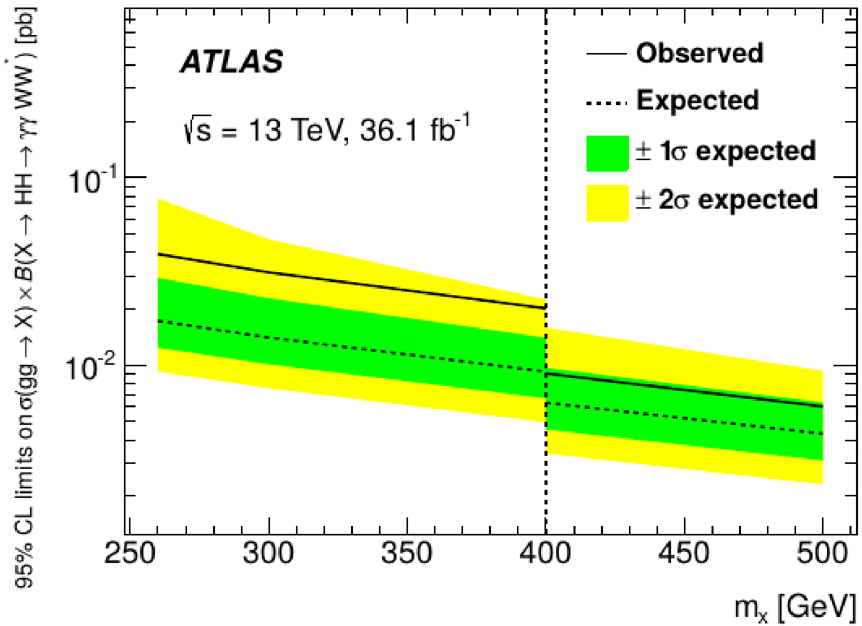
- Rich phenomenology of di-Higgs production and decay
- Equally rich program of di-Higgs searches established at both experiments
  - Sophisticated reconstruction and analysis techniques developed
  - New final states being explored
- So far no signs of new physics
- Not yet sensitive to the Standard model di-Higgs production
  - Best sensitivity from $bb\gamma\gamma$ and $bb\tau\tau$ (but also some differences between ATLAS and CMS in this regard)
- Important to exercise existing analyses and test their reach in preparation for future larger data sets

Backup Slides

hh→WWγγ

Resonant





Non-resonant

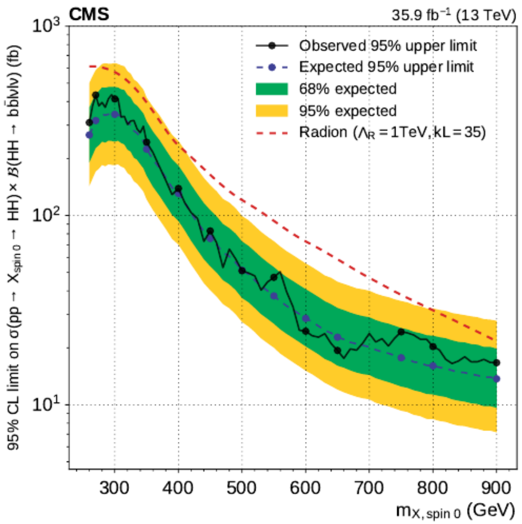
	$+2\sigma$	$+1\sigma$	Median	-1σ	-2σ	Observed
Upper limits on $\sigma(HH)$ [pb]	12	8.0	5.4	3.9	2.9	7.7
Upper limits on $\sigma(HH) \times B(\gamma\gamma WW^*)$ [fb]	12	7.8	5.3	3.8	2.8	7.5
Ratios of limits over the SM $\sigma(HH)$	360	240	160	120	87	230

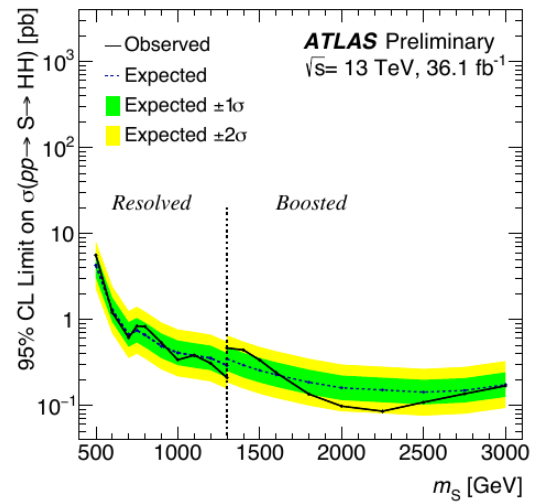
hh→bbWW

CMS: hh→bbWW→bblνlν

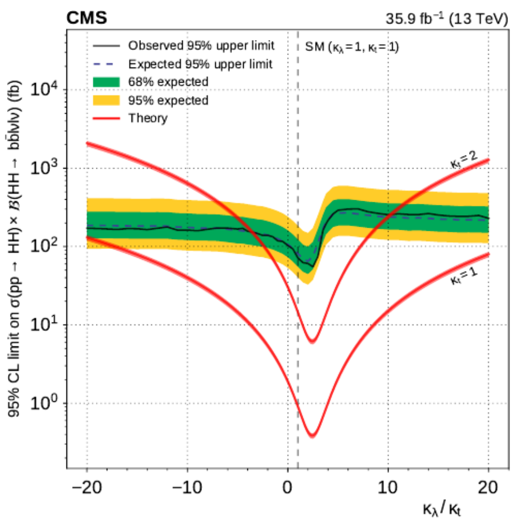
ATLAS: hh→bbWW→bblνqq

Resonant





Non-resonant



CMS limit on σ/σ^{SM}
Observed: 79
Expected: 89

ATLAS limit on σ/σ^{SM}
Observed: 300