The status of HH searches at the LHC

International Conference on Supersymmetry
and Unification of Fundamental Interactions (SUSY 2019)

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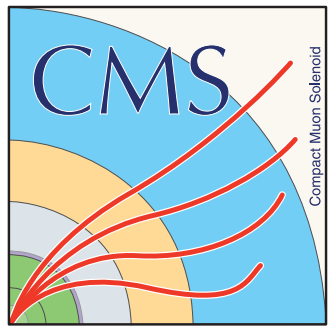


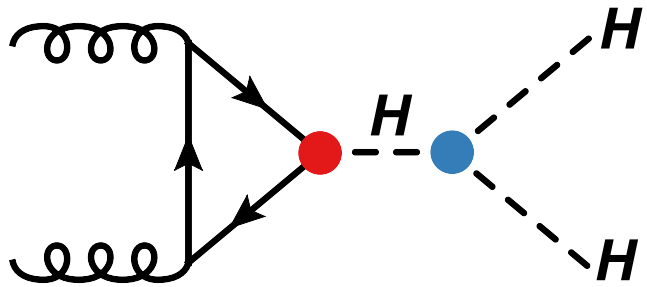
SM Higgs Boson Pair Production

- After discovering the Higgs boson, the ultimate probe of the Standard Model is to fully measure the Higgs potential

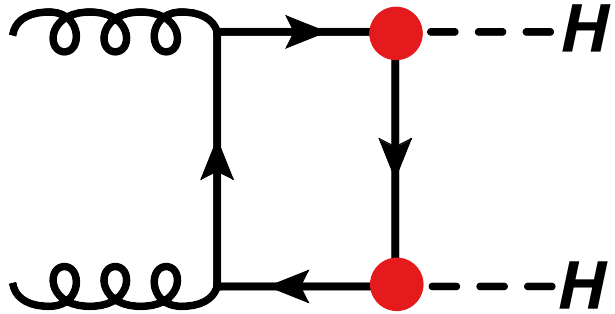
- Higgs self-coupling fundamental parameter of the Standard Model
  $V(\Phi) = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4 = \lambda\nu^2h^2 + \lambda\nu h^3 + \frac{1}{4}\lambda h^4$
  mass term self-coupling terms

- Rare process of the Standard Model
  - Destructive interference
  - $\sigma_{\mathrm{SM}}(gg \to HH) = 33.5\,\mathrm{fb} \approx 1‰ \cdot \sigma_{\mathrm{SM}}(gg \to H)$ at 13 TeV

Higgs boson self-coupling

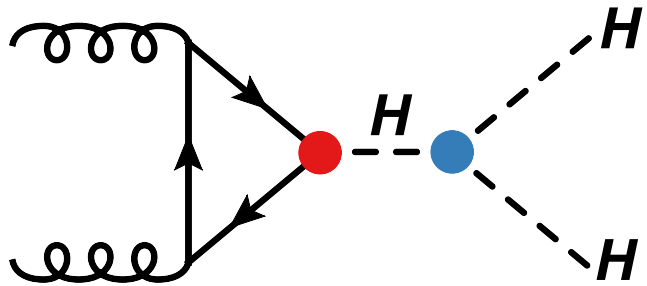


Higgs-fermion Yukawa coupling
(destructive interference)

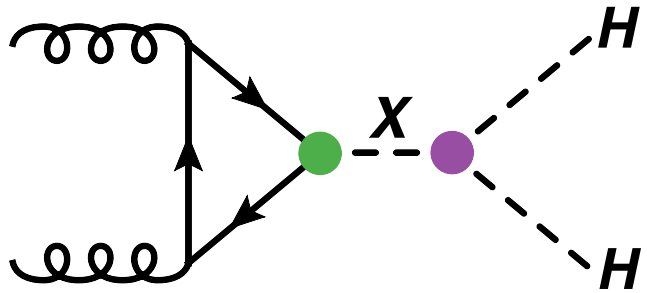


BSM Higgs Boson Pair Production

- Non-resonant HH production
  - BSM contribution can modify the Higgs boson coupling parameters and enhance the HH cross section

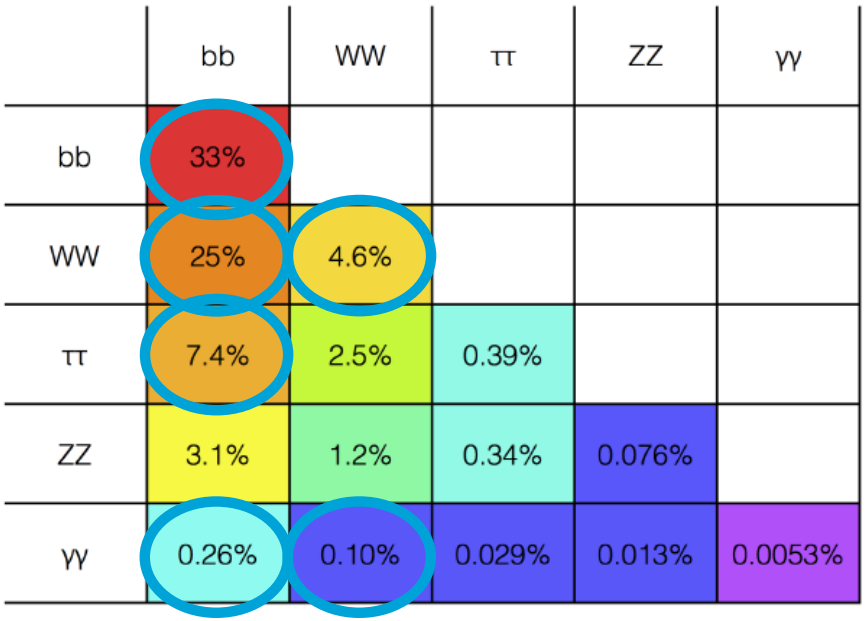


- Resonant HH production
  - Various models expect a new particle decaying into a Higgs boson pair
  - Randall-Sundrum graviton (spin-2): $G \to hh$
  - 2HDM heavy Higgs boson (spin-0): $H \to hh$



Higgs Boson Pair Decays

- Many final states to explore
- $bbbb$: largest branching fraction
- $bb\gamma\gamma$ and $WW\gamma\gamma$: clean diphoton signature
- Searches in marked final states will be presented using:
  - ATLAS: 2015-2016 dataset, 36.1 fb^{-1}
  - CMS: 2016 dataset, 35.9 fb^{-1}
- Also, see Agni Bethani's talk on ATLAS searches for VH/HH resonances



Searches for Higgs Boson Pair Production

Searches for Higgs Boson Pair Production in ATLAS

$HH \to bbbb$	JHEP 01 (2019) 030
$HH \to bbWW \to bbqq\ell\nu$	JHEP 04 (2019) 092
$HH \to bb\tau\tau$	Phys. Rev. Lett. 121, 191801 (2018)
$HH \to WWWW$	arXiv:1811.11028
$HH \to bb\gamma\gamma$	JHEP 11 (2018) 040
$HH \to WW\gamma\gamma$	Eur. Phys. J. C 78 (2018) 1007
Combination	New results paper in preparation

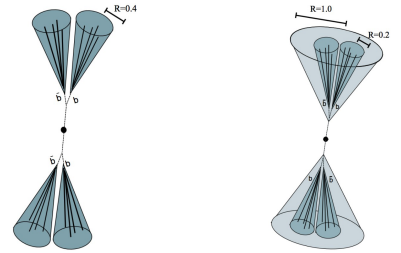
Searches for Higgs Boson Pair Production in CMS

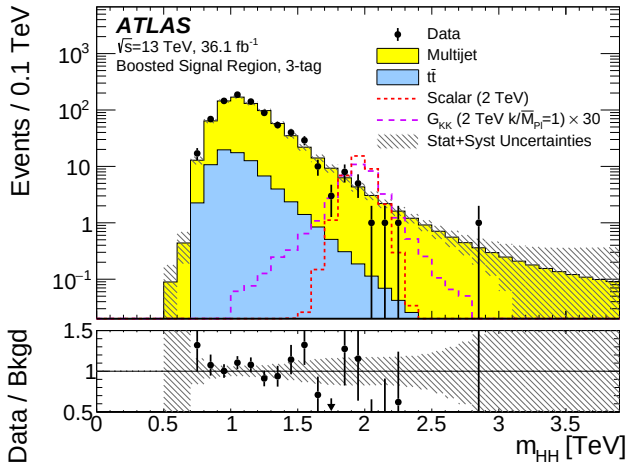
$HH \to bbbb$ non-resonant	JHEP 04 (2019) 112
$HH \to bbbb$ resonant	JHEP 08 (2018) 152
$HH \to bbqq\ell\nu$	arXiv:1904.04193
$HH \to bb\ell\nu\ell\nu$	JHEP 01 (2018) 054
$HH \to bb\tau\tau$	Phys. Lett. B 778 (2018) 101
$HH \to bb\gamma\gamma$	Phys. Lett. B 788 (2018) 7
Combination	Phys. Rev. Lett. 122, 121803 (2019)

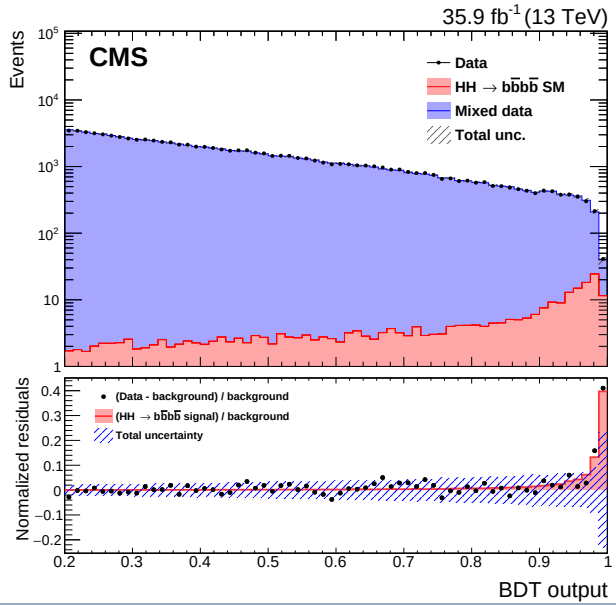
$HH \to bbbb$ Analyses

- Largest branching ratio
- Resolved and boosted topologies considered
- ATLAS
  - Resolved: b-jet triggers, 4 b-tagged jets
  - Boosted: large-R jet trigger, 2 large-R jets, with 2/3/4 small-R b-tagged track-jets
  - Signal region: both Higgs candidate masses consistent with expected m_h within resolution
  - Discriminating variable: m_{hh} invariant mass
- CMS
  - Resolved: jet (including b-jet) triggers, 4 b-tagged jets
  - Boosted: jet (including b-jet) triggers, 2 large-R jets, dedicated MVA "double-b-tagger" used to identify Higgs candidates
  - Discriminating variable: BDT score (resolved) and m_{hh} invariant mass (boosted)
- Main backgrounds: multi-jet and $t\bar{t}$

small-R jets large-R jets

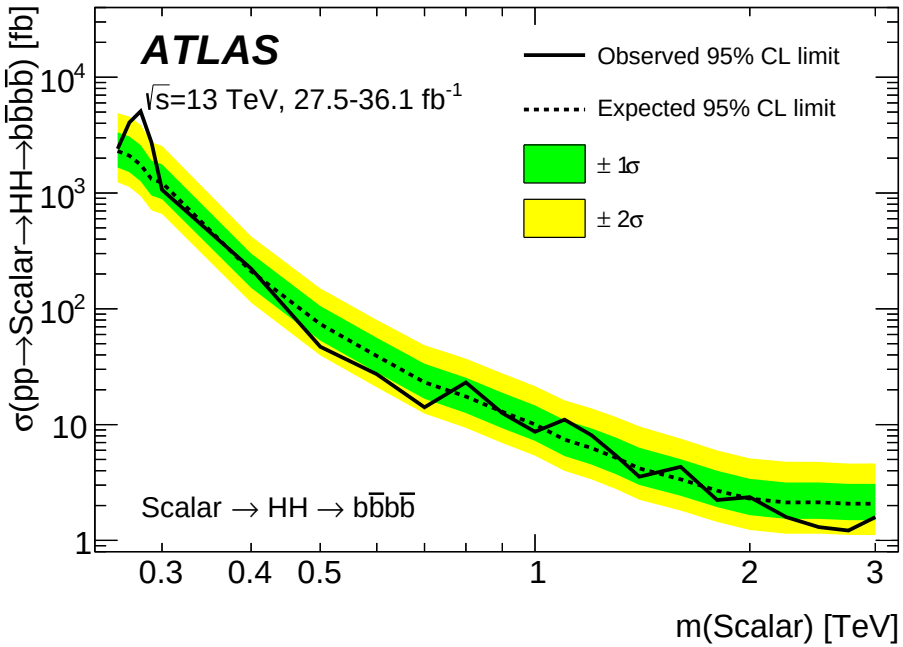


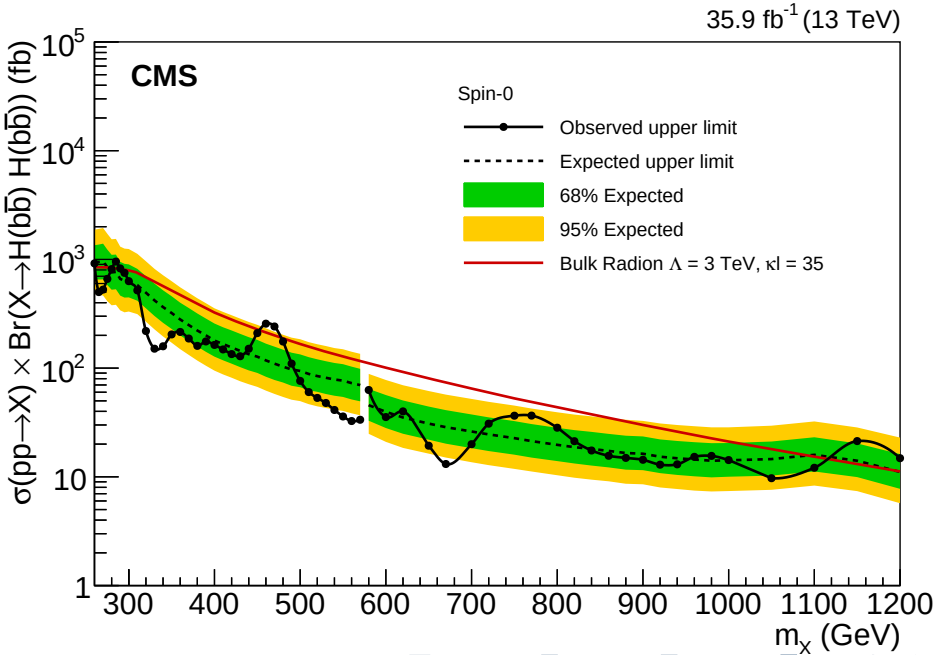




$HH \to bbbb$ Results

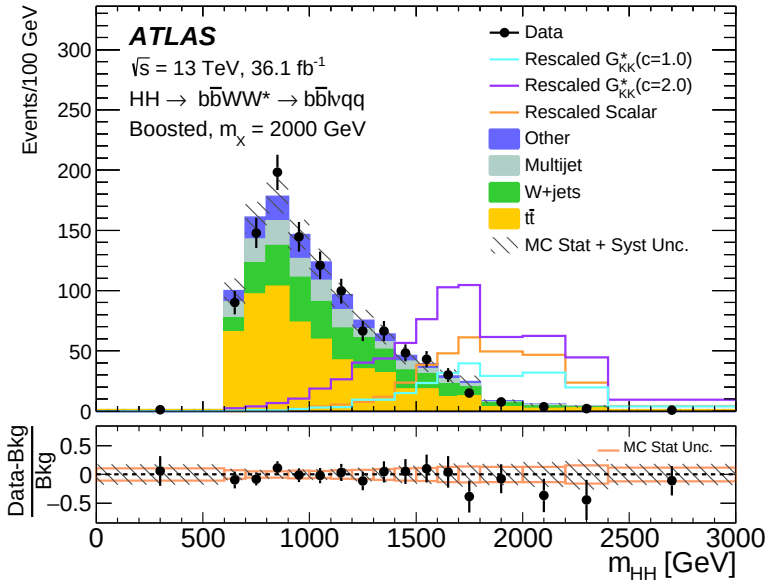
- Non-resonant hh production: observed (expected) 95% CL upper limit on $\sigma(hh) \times BR(bbbb)$:
  - ATLAS: 147 fb = 12.9·σ_{SM} (20.7·σ_{SM})
  - CMS: 847 fb (419 fb)
- Resonant hh production: 2HDM interpretation:
  - No significant excess observed
  - ATLAS: largest deviation at 280 GeV, 3.6σ local (2.3σ global) significance
  - CMS: largest deviation at 460 GeV, 2.6σ local significance

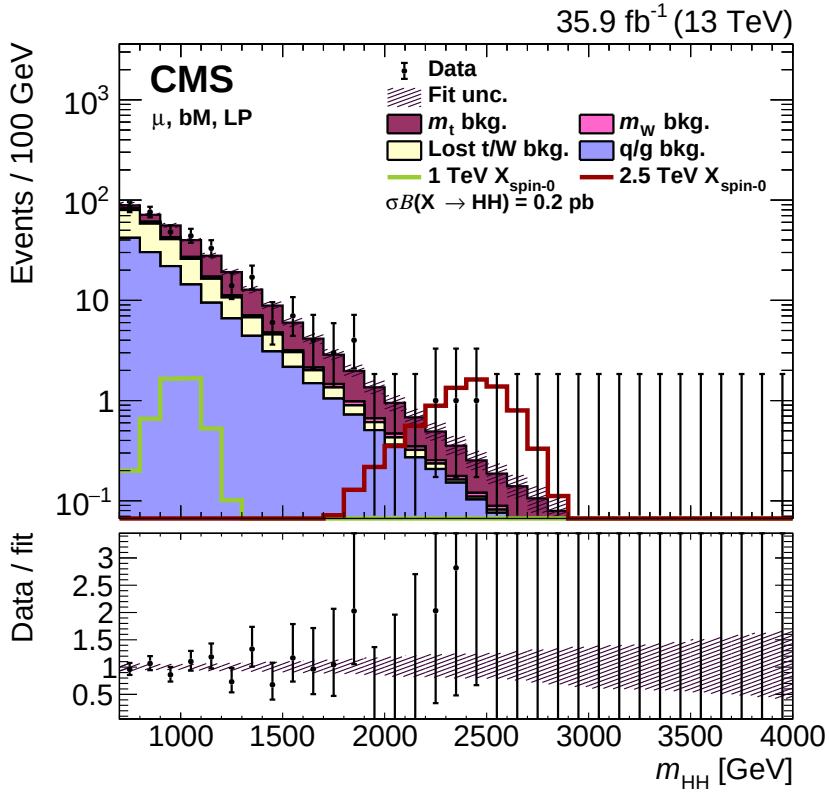




$HH \to bbWW$ Analyses

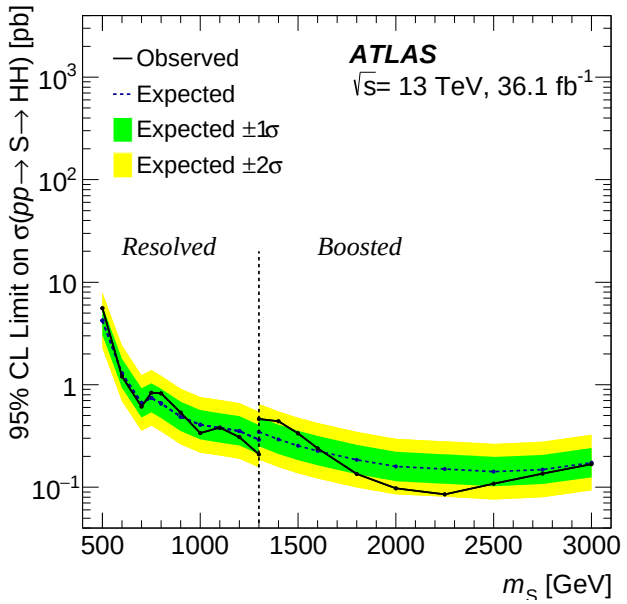
- ATLAS ($bbqq\ell\nu$)
  - Resolved: 1 ℓ, $E_{\mathrm{T}}^{\mathrm{miss}}$, 4 small-$R$ jets (2 b-jets)
  - Boosted: 1 ℓ, $E_{\mathrm{T}}^{\mathrm{miss}}$, 1 large-$R$ b-jet, 2 small-R jets
  - Discriminating variable: m_{HH} invariant mass
- CMS
  - $bbqq\ell\nu$:
    - 1 ℓ, $E_{\mathrm{T}}^{\mathrm{miss}}$, 1 large-$R$ b-jet, 1 large-R jet
    - Likelihood fit in 2D plane of m_{bb} and m_{HH}
  - $bb\ell\nu\ell\nu$:
    - 2 OS leptons (e or μ), 2 b-tagged jets
    - Discriminating variable: DNN output
- Dominant backgrounds: $t\bar{t}$, W+jets, multi-jet

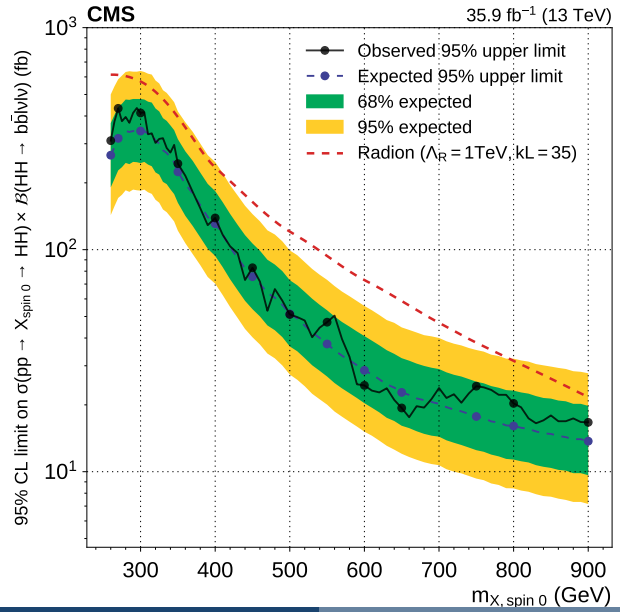


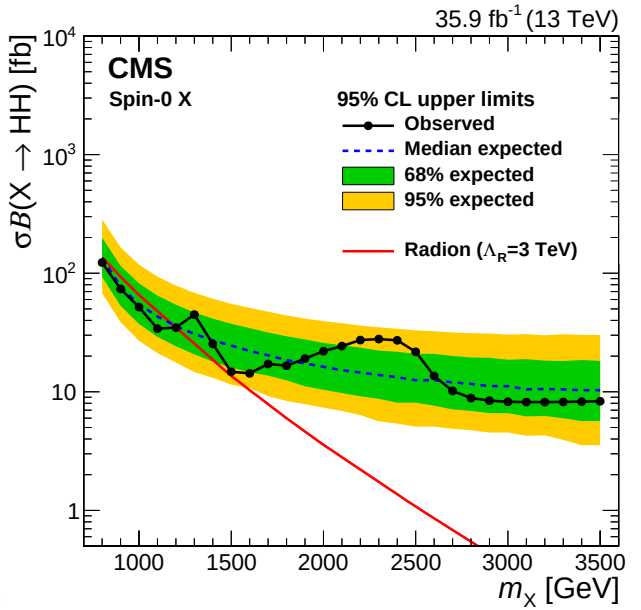


$HH \to bbWW$ Results

- Non-resonant hh production: observed limits
  - ATLAS $\sigma(hh) \times BR(bbWW) = 2.5$ pb ($300\sigma_{\mathrm{SM}}$)
  - CMS $\sigma(hh) \times BR(bb\ell\nu\ell\nu) = 72$ fb ($79{\cdot}\sigma_{\mathrm{SM}}$)
- Resonant hh production: 2HDM interpretation:
  - ATLAS ($bbqq\ell\nu$): set limits between 5.6 pb ($m_X = 500$ GeV) and 0.2 pb ($m_X = 3$ TeV)
  - CMS ($bbqq\ell\nu$): set limits between 123 fb ($m_X = 800$ GeV) and 8.3 fb ($m_X = 3.5$ TeV)
  - CMS ($bb\ell\nu\ell\nu$): set limits between 430 fb ($m_X = 260$ GeV) and 17 fb ($m_X = 900$ GeV)

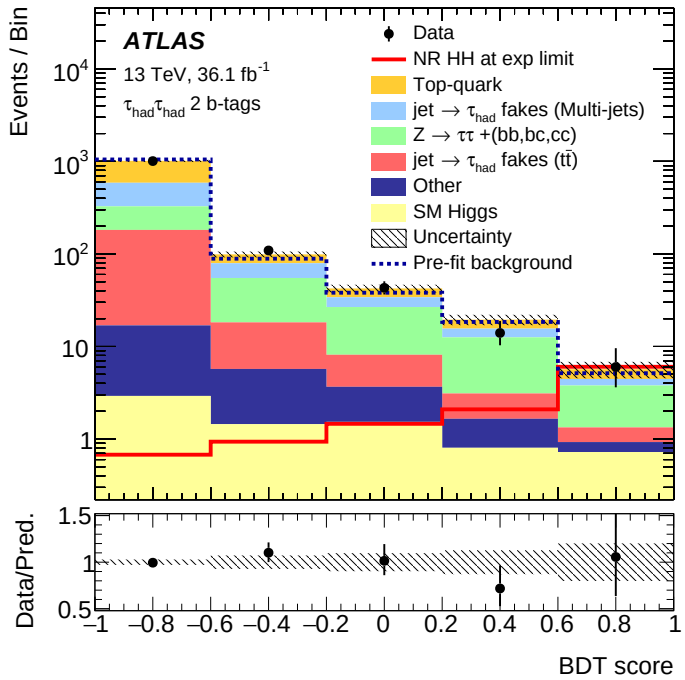


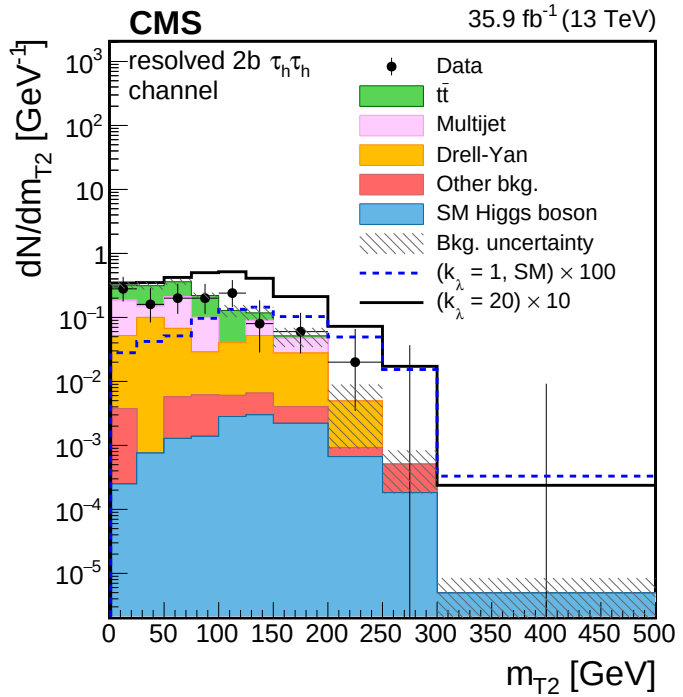




$HH \to bb\tau\tau$ Analyses

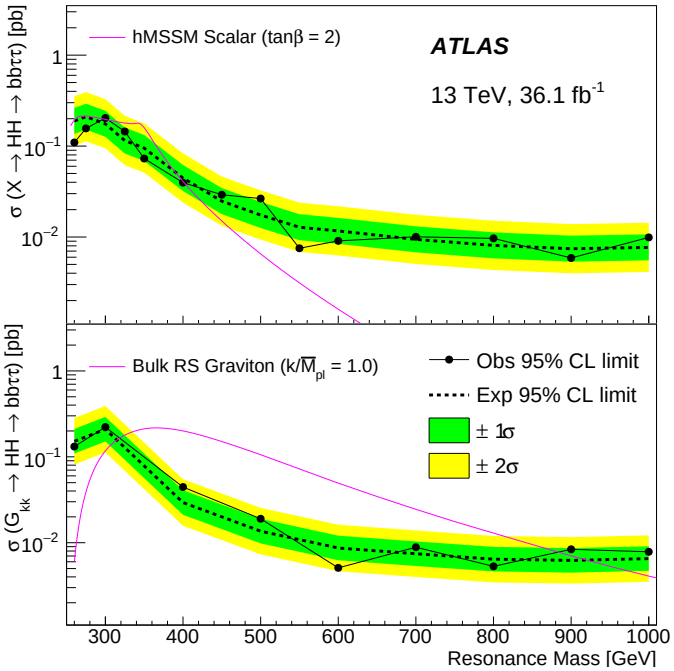
- ATLAS
  - Two channels:
    - two hadronicaly decaying taus
    - one hadronicaly and one leptonicaly decaying tau
  - 2 taus (at least one hadronicaly decaying), 2 small-R or 1 large-R b-jets
  - BDT trained to discriminate signal from backgrounds, separate BDT for each mass hypothesis
  - Discriminating variable: BDT score
- CMS
  - Two channels:
    - two hadronicaly decaying taus
    - one hadronicaly and one leptonicaly decaying tau
  - $e/\mu/\tau_{\mathrm{h}}+\tau_{\mathrm{h}}$, 2 small-$R$ or 1 large-R b-jets
  - Discriminating variable: m_{HH}^{KinFit} (resonant), m_{T2} (non-resonant)
- Dominant backgrounds: $t\bar{t}$, multi-jet, Z+jets

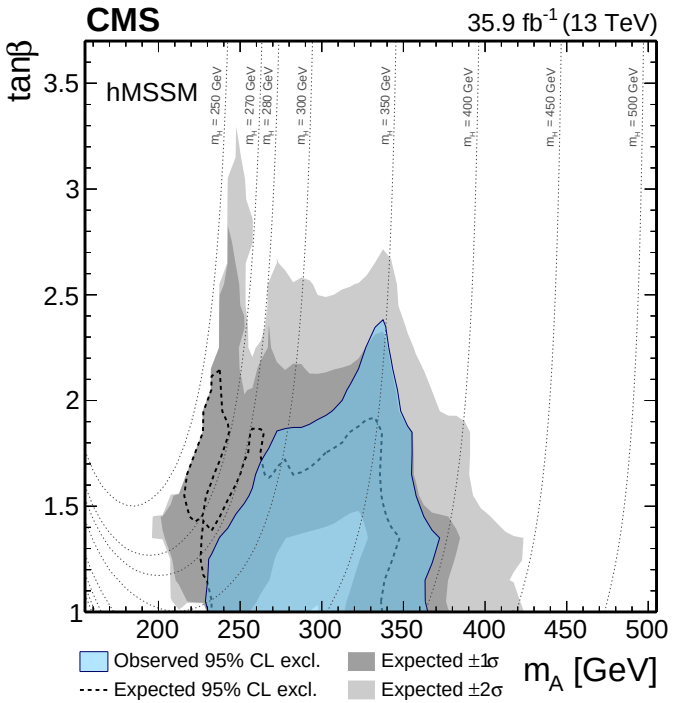




$HH \to bb\tau\tau$ Results

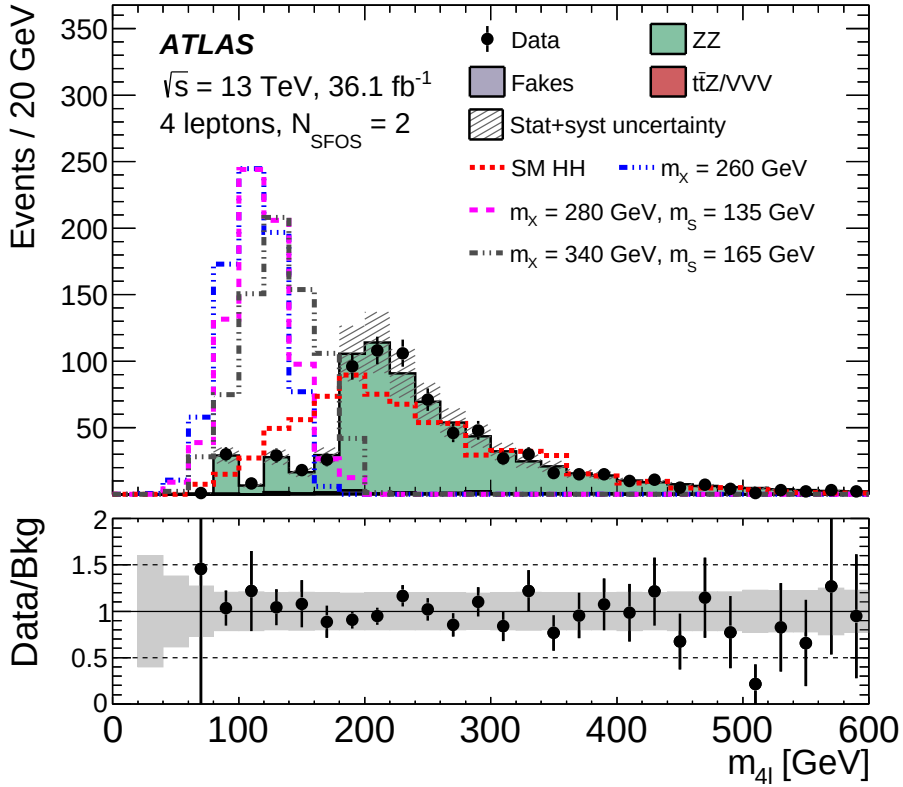
- Non-resonant hh production: observed (expected) 95% CL upper limits on $\sigma(hh) \times BR(bb\tau\tau)$:
  - ATLAS: 30.9 fb $= 12.7 \cdot \sigma_{\mathrm{SM}}$ (36.0 fb)
  - CMS: 75.4 fb $= 30 \cdot \sigma_{\mathrm{SM}}$ (61.0 fb)
- Resonant hh production: hMSSM interpretation:
  - No significant excess observed
  - ATLAS: masses between 305 GeV and 402 GeV excluded for $\tan\beta = 2$
  - CMS: masses between 230 GeV and 360 GeV excluded for $\tan\beta = 1$
- The $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets

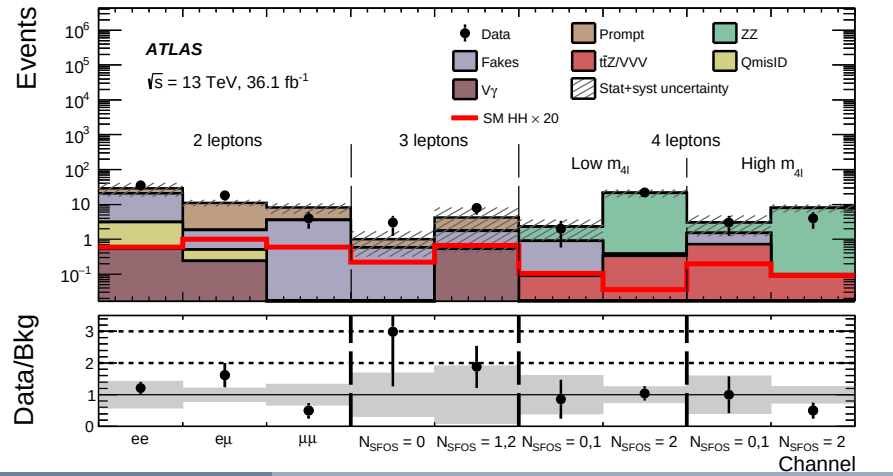




$HH \to WWWW$ Analyses

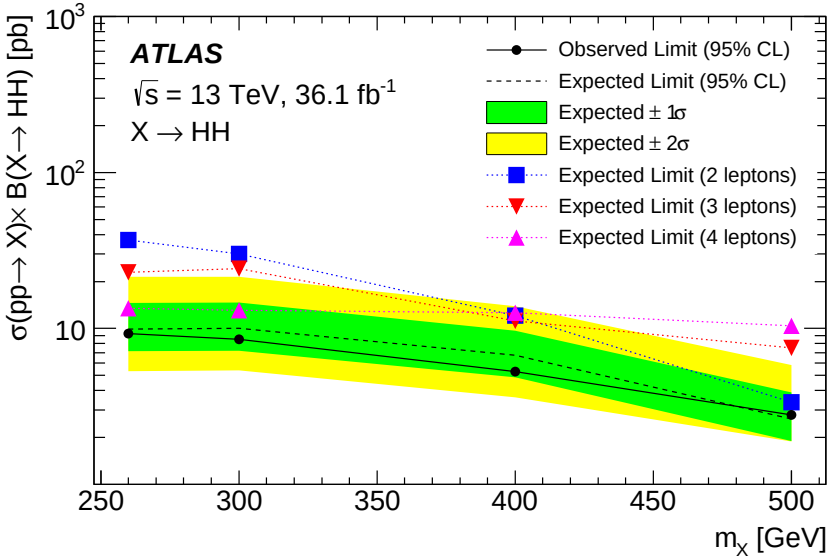
- Cut and count analysis
- Three channels defined by number of leptons
  - Two (same sign) leptons: ee, $e\mu$, $\mu\mu$, $E_{\mathrm{T}}^{\mathrm{miss}}$, at least two jets, b-jet veto
  - Three leptons: total charge ± 1, $E_{\mathrm{T}}^{\mathrm{miss}}$, at least two jets, b-jet veto
  - Four leptons: total charge 0, b-jet veto
- Dominant backgrounds: Diboson, tV, ttV/H and VVV, W+jets, $t\bar{t}$





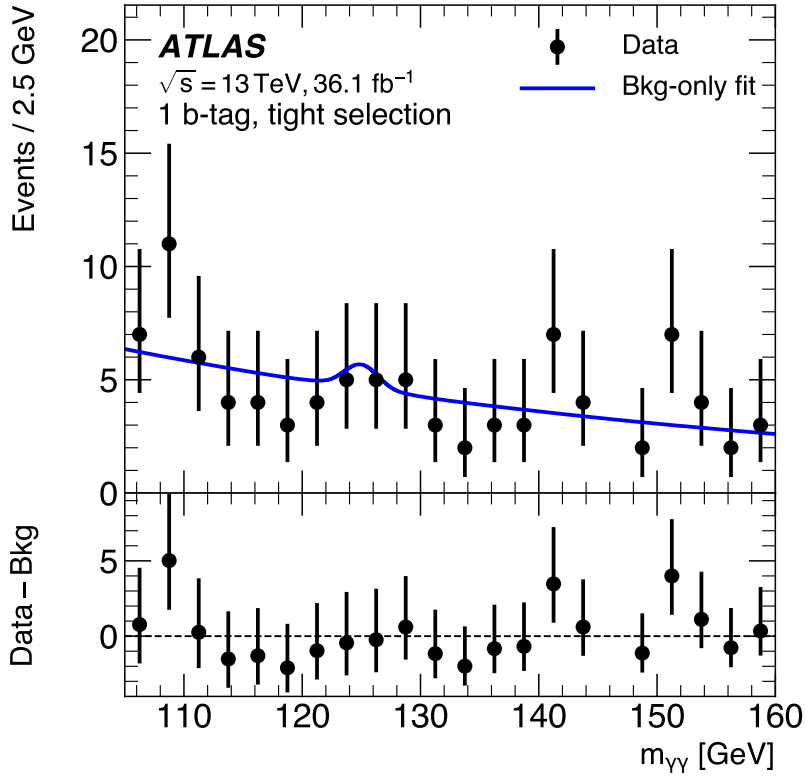
$HH \to WWWW$ Results

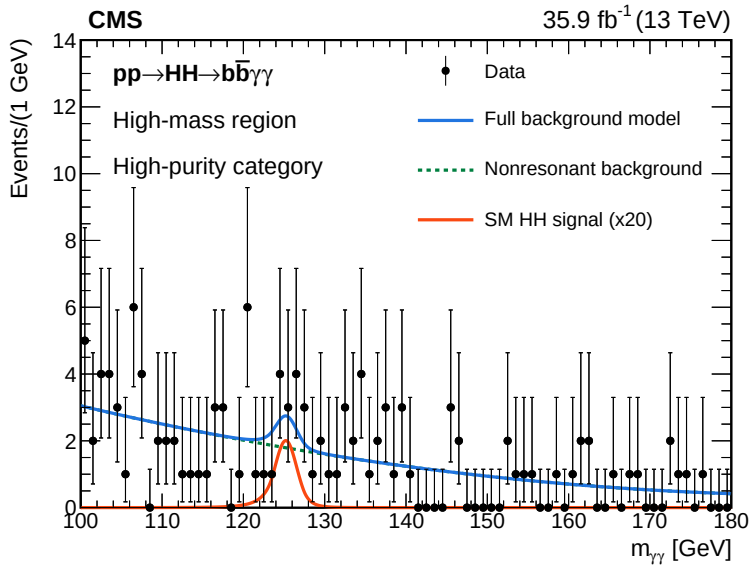
- Non-resonant hh production: observed (expected) 95% CL upper limits on $\sigma(hh)$:
  - ATLAS: 5.3 pb $= 160 \cdot \sigma_{\mathrm{SM}}$ (3.8 pb)
- Resonant hh production: 2HDM interpretation:
  - No significant excess observed
  - ATLAS: set limits between 9.3 pb ($m_X = 260$ GeV) and 2.8 pb ($m_X = 500$ GeV)



$HH \to bb\gamma\gamma$ Analyses

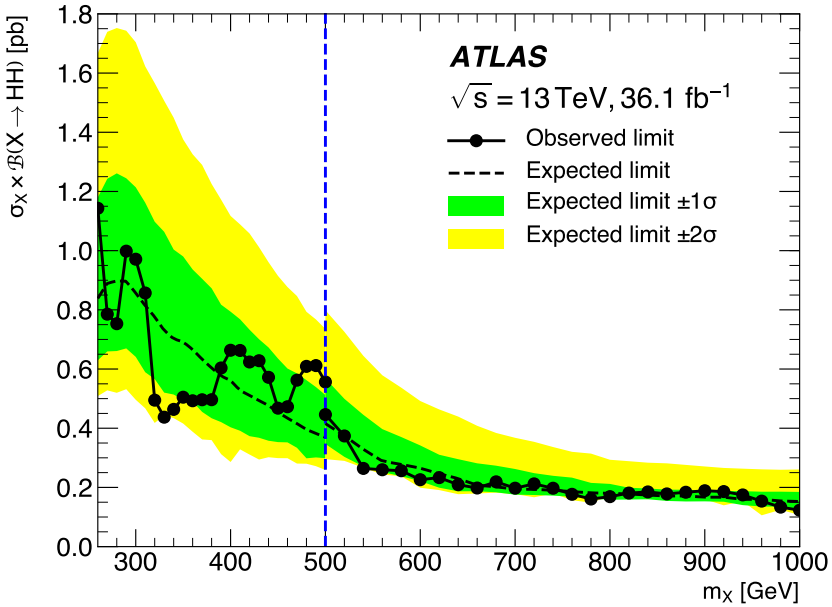
- ATLAS
  - 2 photons, 2 jets (1 or 2 b-tags)
  - m_{jj} invariant mass compatible with the mass of the Higgs boson
  - Discriminating variables: $m_{\gamma\gamma}$ (non-resonant) and $m_{\gamma\gamma jj}$ (resonant)
  - Particularly sensitive at low masses
- CMS
  - 2 photons, 2 jets
  - $m_{\gamma\gamma}$ and m_{jj} in Higgs mass window
  - BDT classifier, including b-tagging information to select signal-like events
  - Discriminating variable: $m_{\gamma\gamma}$ and m_{jj}
- Dominant backgrounds: $\gamma\gamma$-continuum, single Higgs

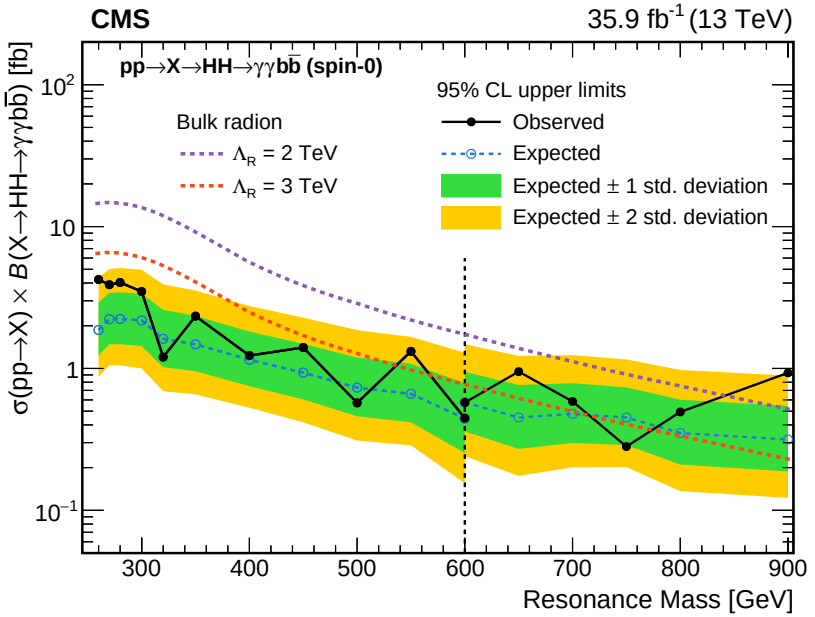




$HH \to bb\gamma\gamma$ Results

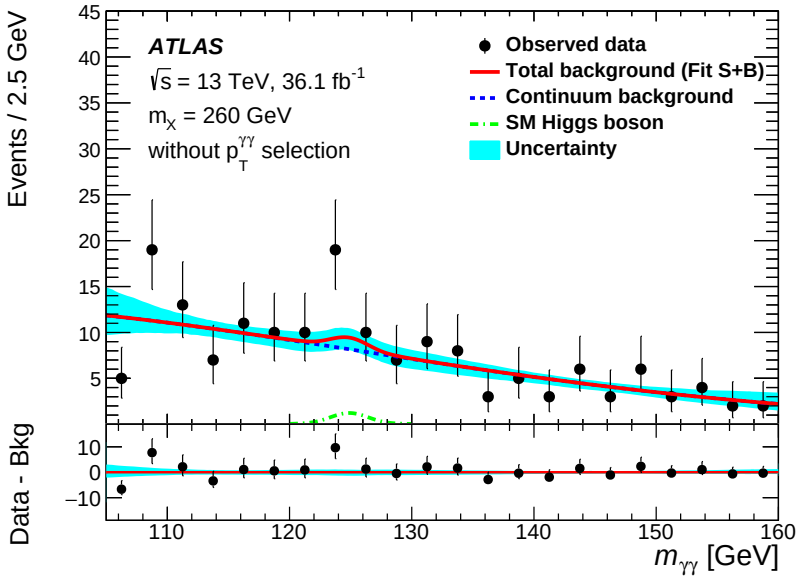
- Non-resonant hh production: observed (expected) 95% CL upper limits on $\sigma(hh)$:
  - ATLAS: 0.73 pb $= 22 \cdot \sigma_{\mathrm{SM}}$ (0.93 pb)
  - CMS: 0.79 pb $= 24 \cdot \sigma_{\mathrm{SM}}$ (0.63 pb)
- Resonant hh production: 2HDM interpretation:
  - No significant excess observed
  - ATLAS: set limits between 1.14 pb ($m_X = 260$ GeV) and 0.12 pb ($m_X = 1$ TeV)
  - CMS: set limits between 0.23 fb ($m_X = 250$ GeV) and 4.2 fb ($m_X = 750$ GeV)

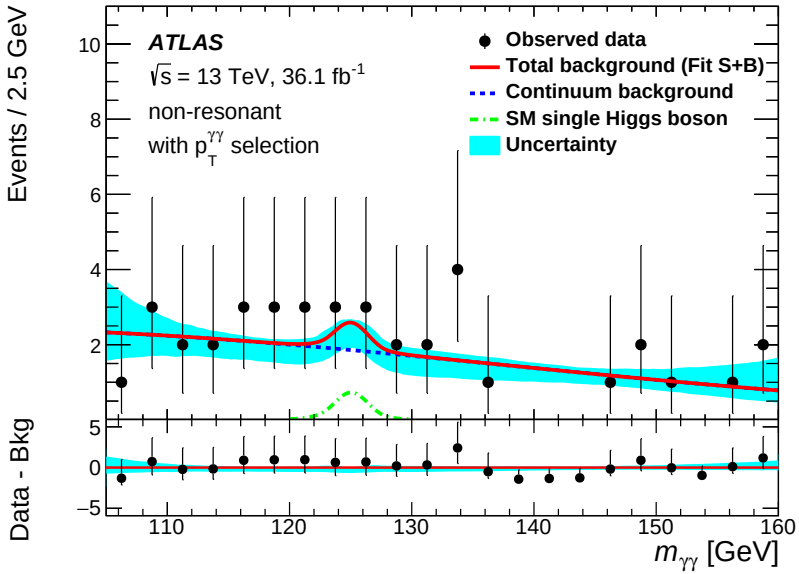




$HH \to WW\gamma\gamma$ Analyses

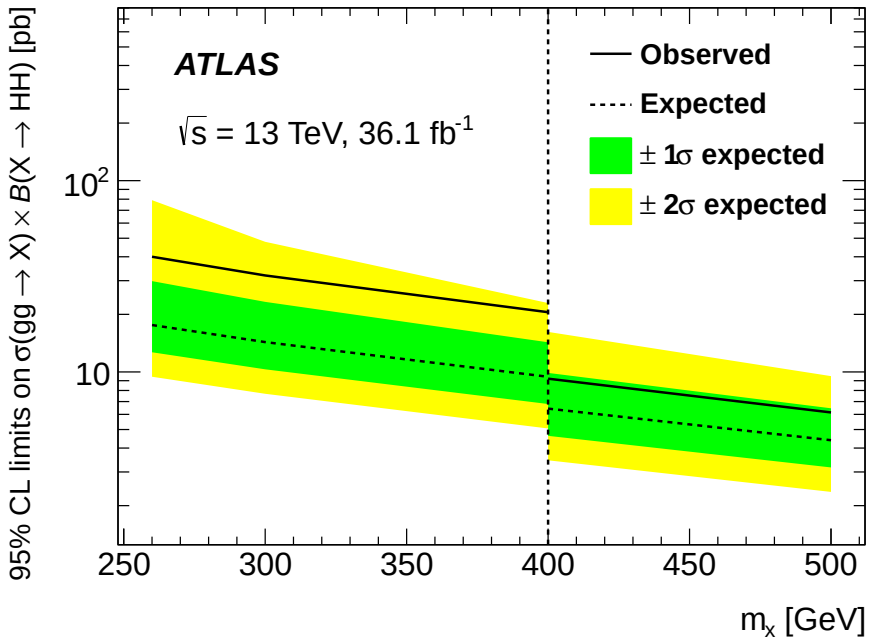
- 2 photons, 1 e or μ, 2 jets ($WW \to \ell\nu qq$)
- Parameterized fit to $m_{\gamma\gamma}$
- Dominant backgrounds: $\gamma\gamma$-continuum, single Higgs





$HH \to WW\gamma\gamma$ Results

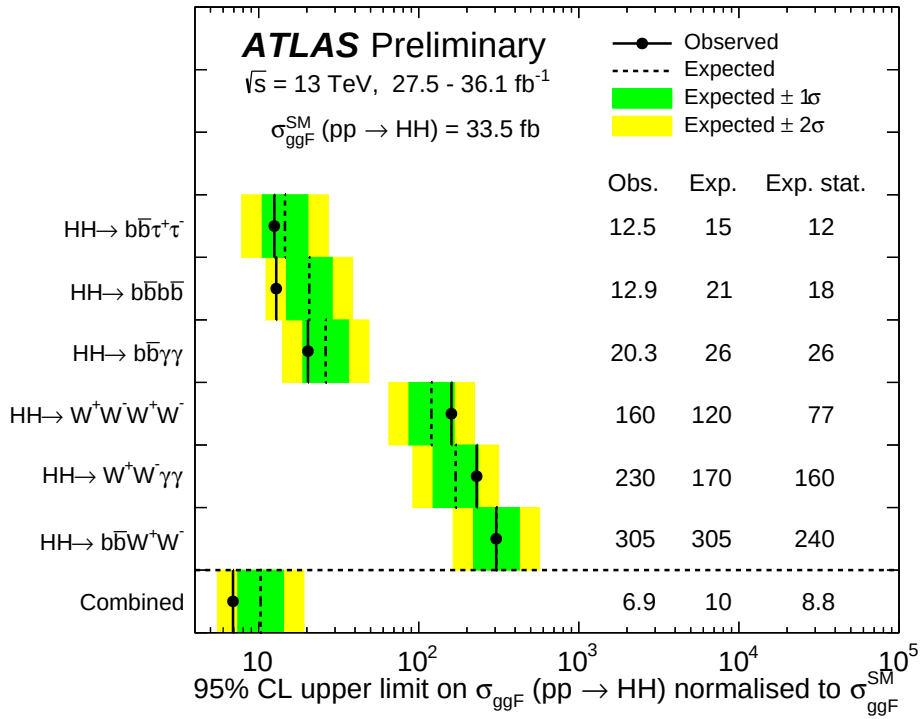
- Non-resonant hh production: observed (expected) 95% CL upper limit on $\sigma(hh) \times BR(WW\gamma\gamma)$
  - ATLAS: 7.5 fb $= 230 \cdot \sigma_{\mathrm{SM}}$ (5.3 fb)
- Resonant hh production: 2HDM interpretation:
  - No significant excess observed
  - ATLAS: set limits between 40 pb ($m_X = 260$ GeV) and 6.1 pb ($m_X = 500$ GeV)

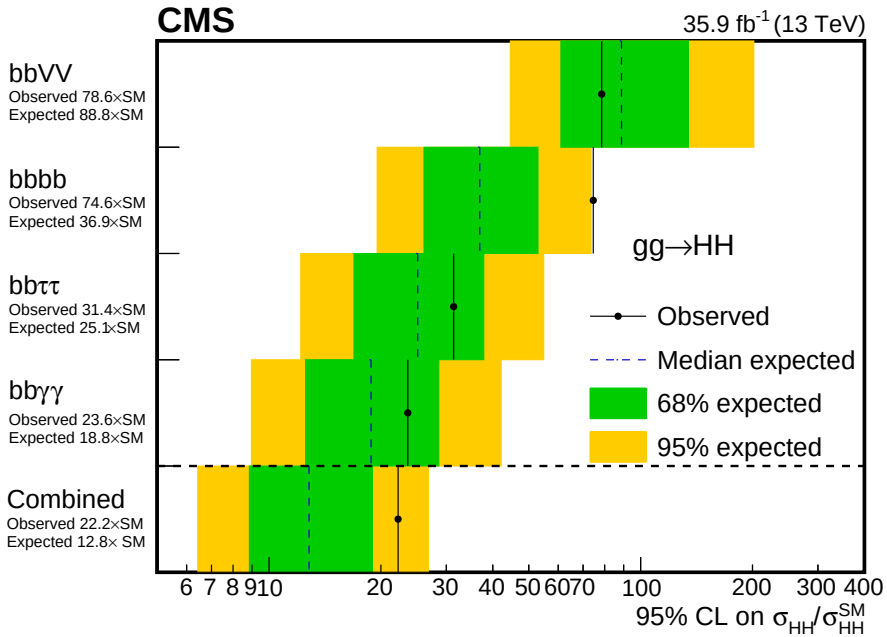


Combinations

Non-resonant HH production

- Statistical combination of the most sensitive individual channels
- ATLAS new results:
  - $HH \to bbbb$
  - $HH \to bbWW$
  - $HH \to bb\tau\tau$
  - $HH \to WWWW$
  - $HH \to bb\gamma\gamma$
  - $HH \to WW\gamma\gamma$
  - Observed: $6.9 \cdot \sigma_{\mathrm{SM}}$
  - Expected: $10.0 \cdot \sigma_{\mathrm{SM}}$
- CMS:
  - $HH \to bbbb$
  - $HH \to bb\tau\tau$
  - $HH \to bb\gamma\gamma$
  - $HH \to bbVV$ $(V = W$ or $Z)$
  - Observed: $22.2 \cdot \sigma_{\mathrm{SM}}$
  - Expected: $12.8 \cdot \sigma_{\mathrm{SM}}$

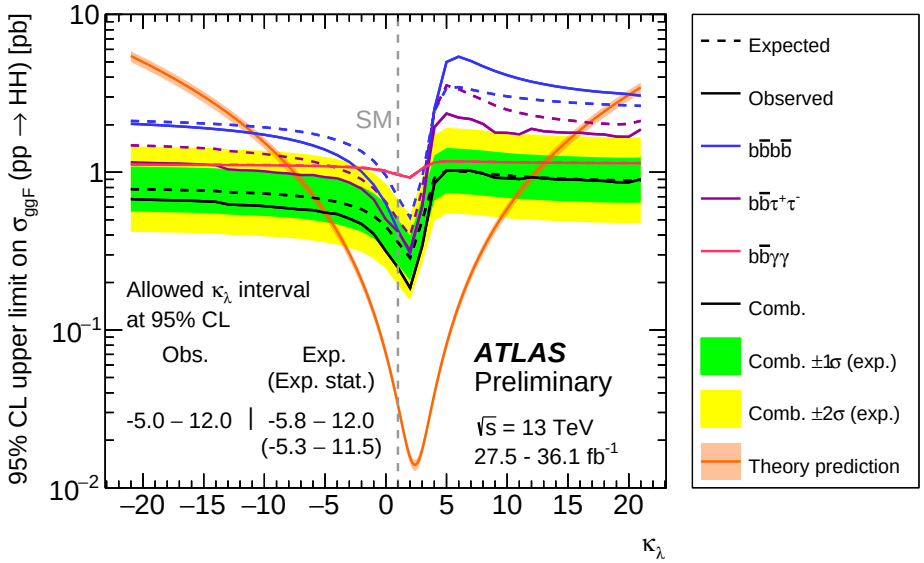


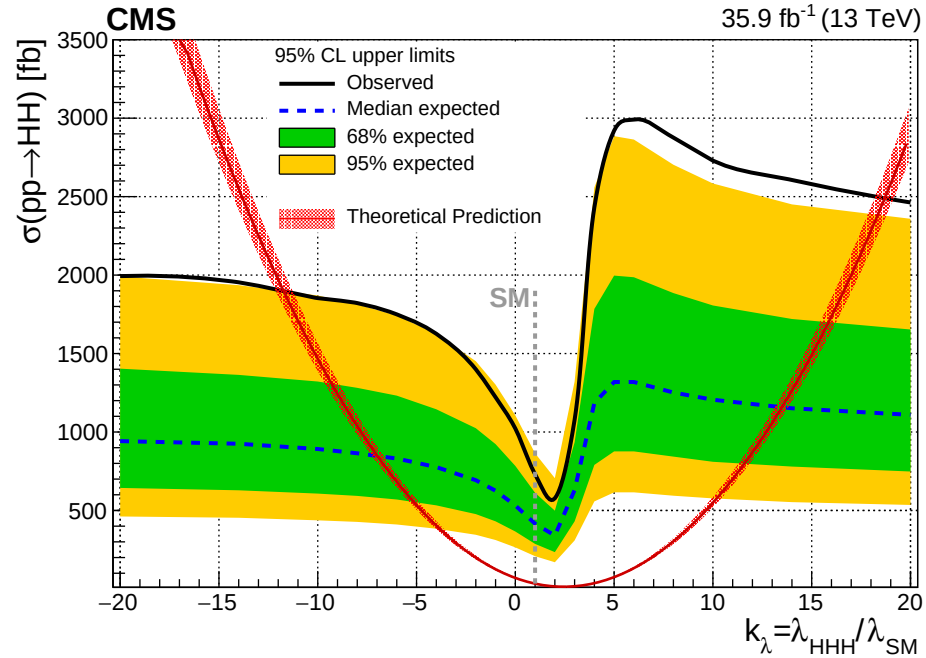


Combinations

Limits on κ_λ

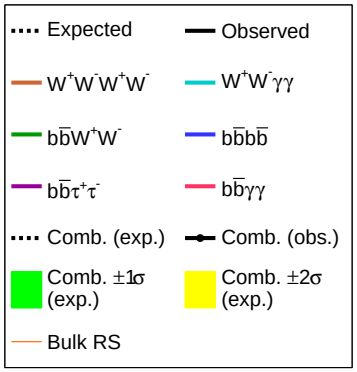
- Combined limits on $\kappa_\lambda = \lambda_{HHH}/\lambda_{\mathrm{SM}}$
- All couplings except the Higgs boson self-coupling λ_{HHH} set to their SM values
- ATLAS allowed range:
  - Observed: $-5.0 < \kappa_\lambda < 12.0$
  - Expected: $-5.8 < \kappa_\lambda < 12.0$
- CMS allowed range:
  - Observed: $-11.8 < \kappa_\lambda < 18.8$
  - Expected: $-7.1 < \kappa_\lambda < 13.6$

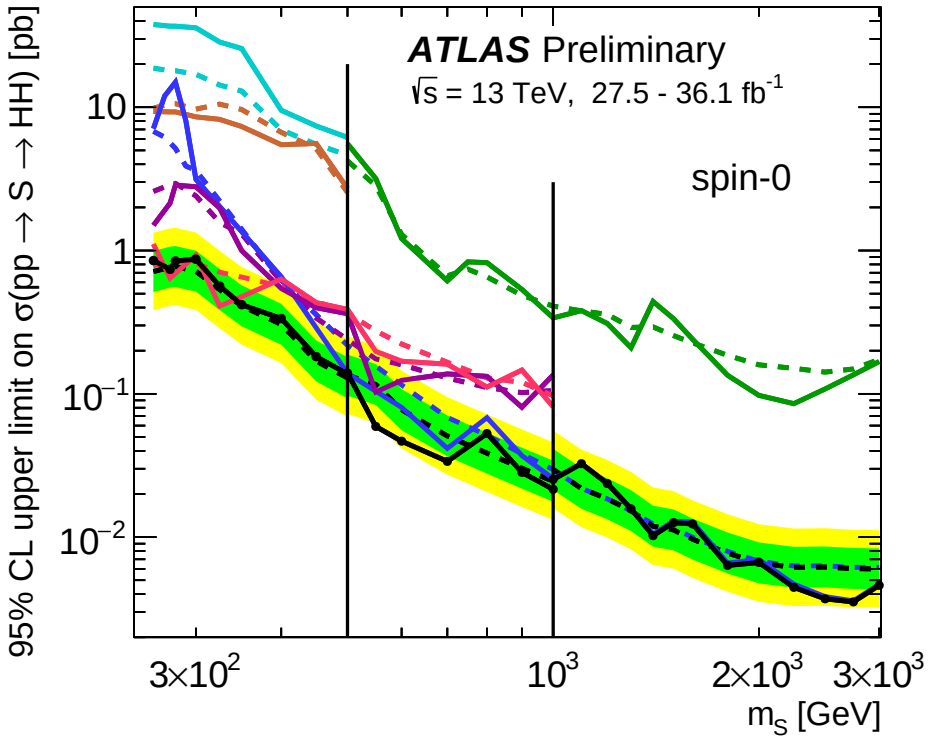




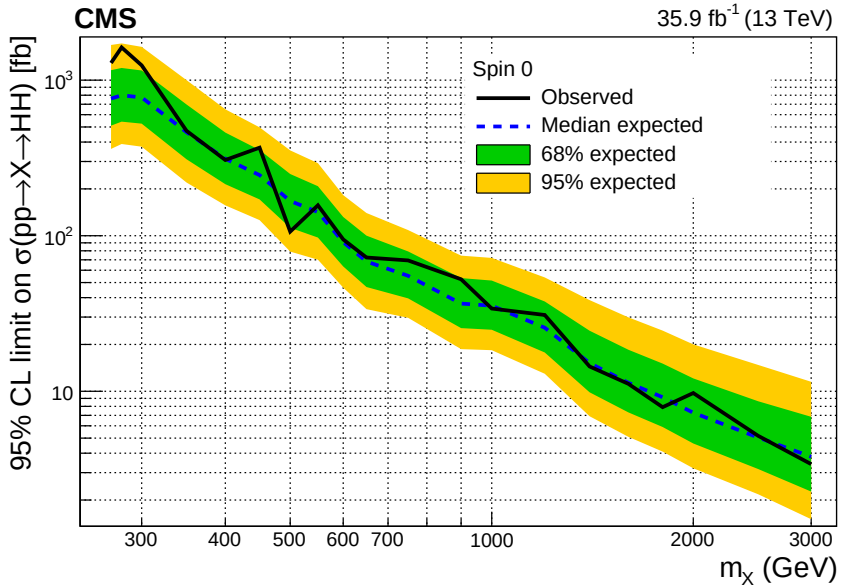
Combinations

Resonant HH production





- Combined limits on scalar resonance corresponding to CP-even heavy Higgs in hMSSM (2HDM) model
- No significant excess observed
- ATLAS: set upper limits between 4 fb and 1 pb
- CMS: set upper limits between 4 fb and 2 pb



Conclusions & Summary

- ATLAS and CMS are highly active in searching for Higgs boson pair production. Effort to cover maximum final states.
- Shown recent searches based on 36.1 fb^{-1} (ATLAS) and 35.9 fb^{-1} (CMS) of LHC Run-2 data
- Improved sensitivity using boosted techniques and machine learning
- No excess in non-resonant production, limits 6.9 - $22.2 \cdot \sigma_{\mathrm{SM}}$
- No significant excess observed in resonance search
- Analyzing full Run-2 dataset, 140 fb^{-1}