HH review for ATLAS and CMS

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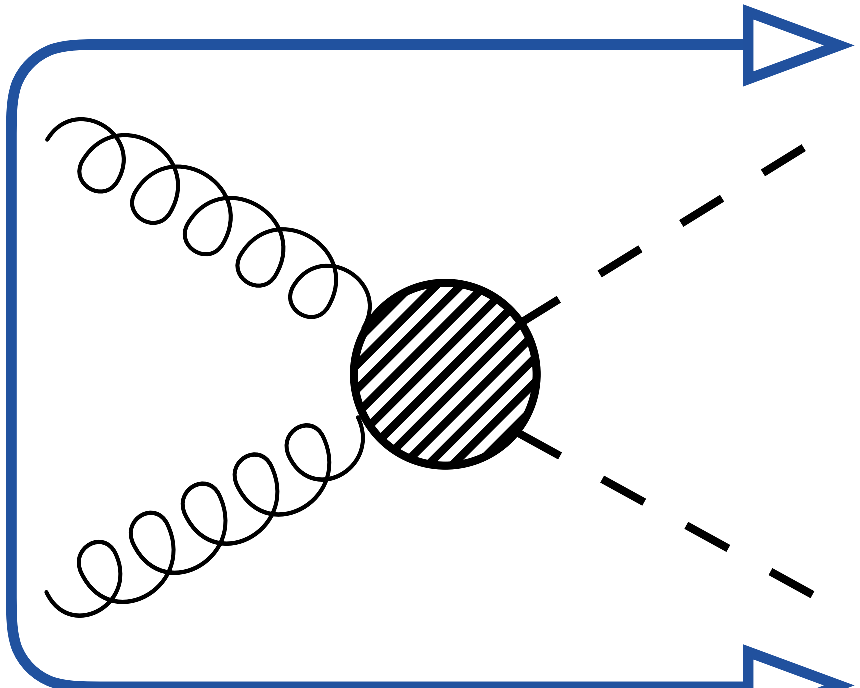
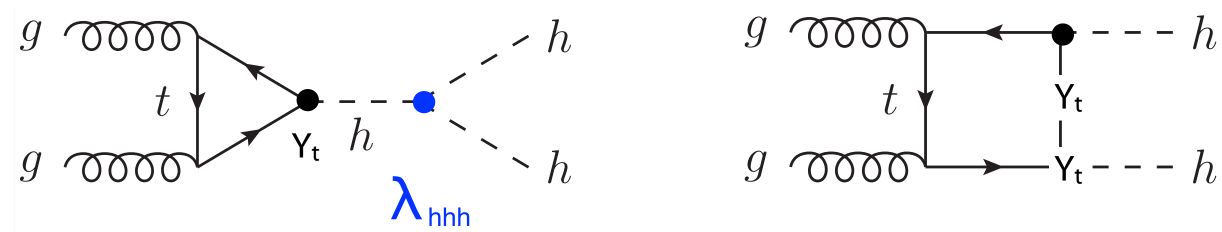
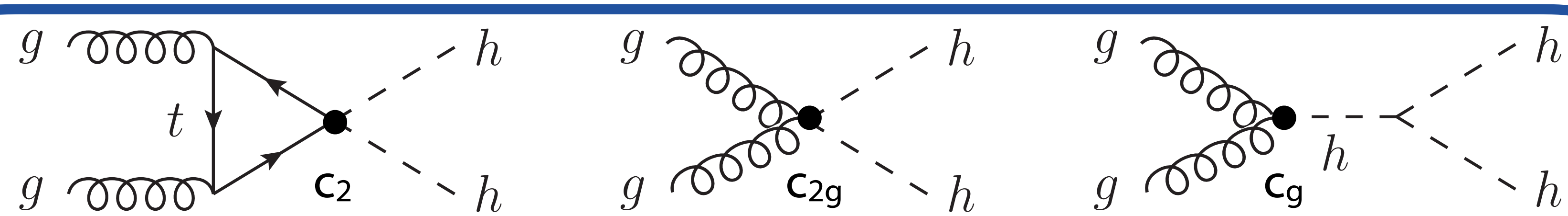
Why looking for HH?

Non-resonant production

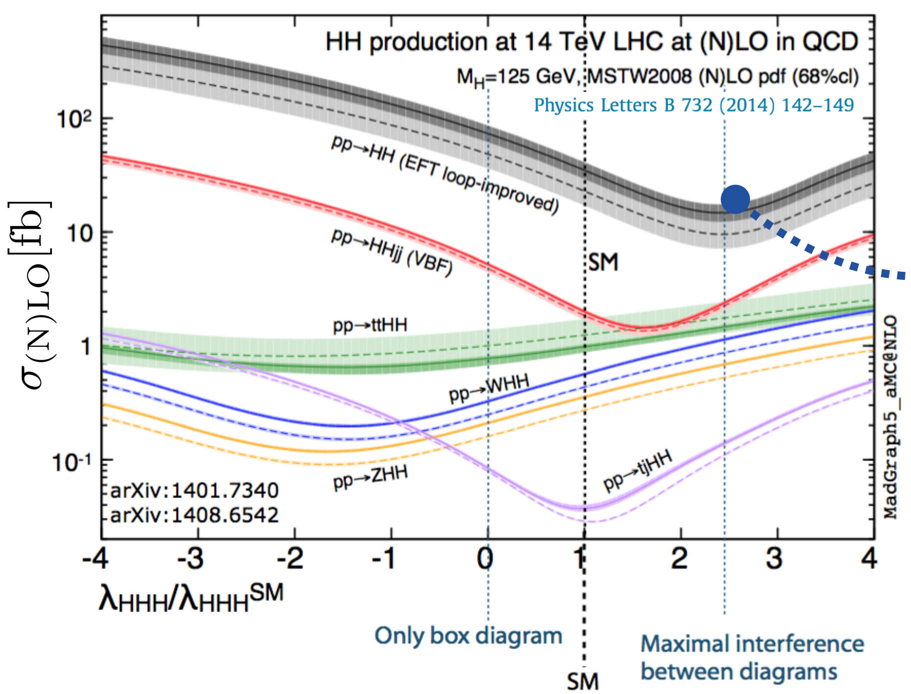




- SM prediction @13 TeV [NNLO+NNLL]
  $\sigma_{pp\rightarrow hh}$ = 33.49$^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb
  [HXSWG, arXiv:1610.07922]
- Main way to extract trilinear coupling λ_{hhh}
- No sensitivity at LHC with current luminosity



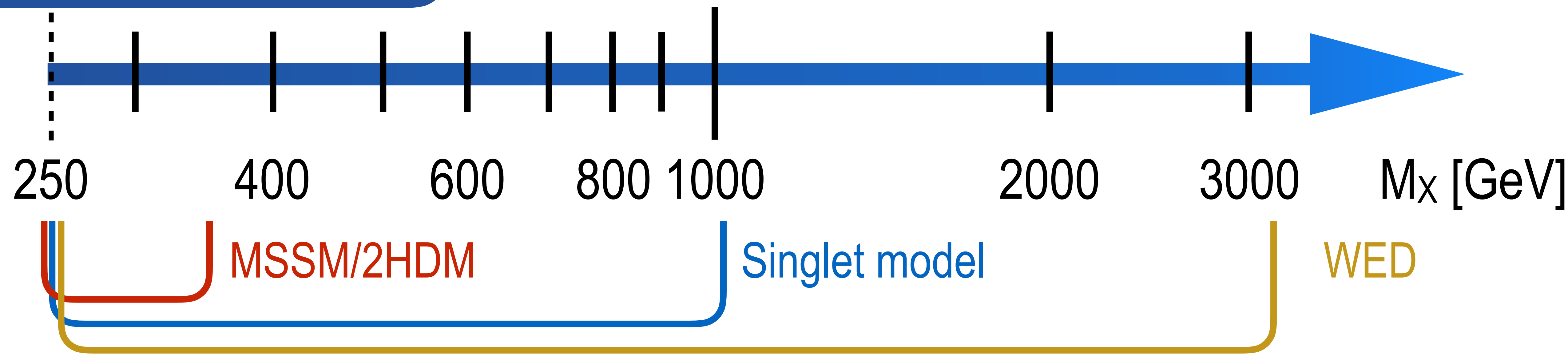
- Sizeable effects from BSM physics
  - σ enhancement, kinematics modification
- Parametrised with effective Lagrangian using 5 independent parameters: λ_{hhh}, y_t, c_2, c_g, c_{2g}
- Here focus on main production mode: gg fusion
  - VBF and other modes presently out of reach



Why looking for HH?

Resonant production

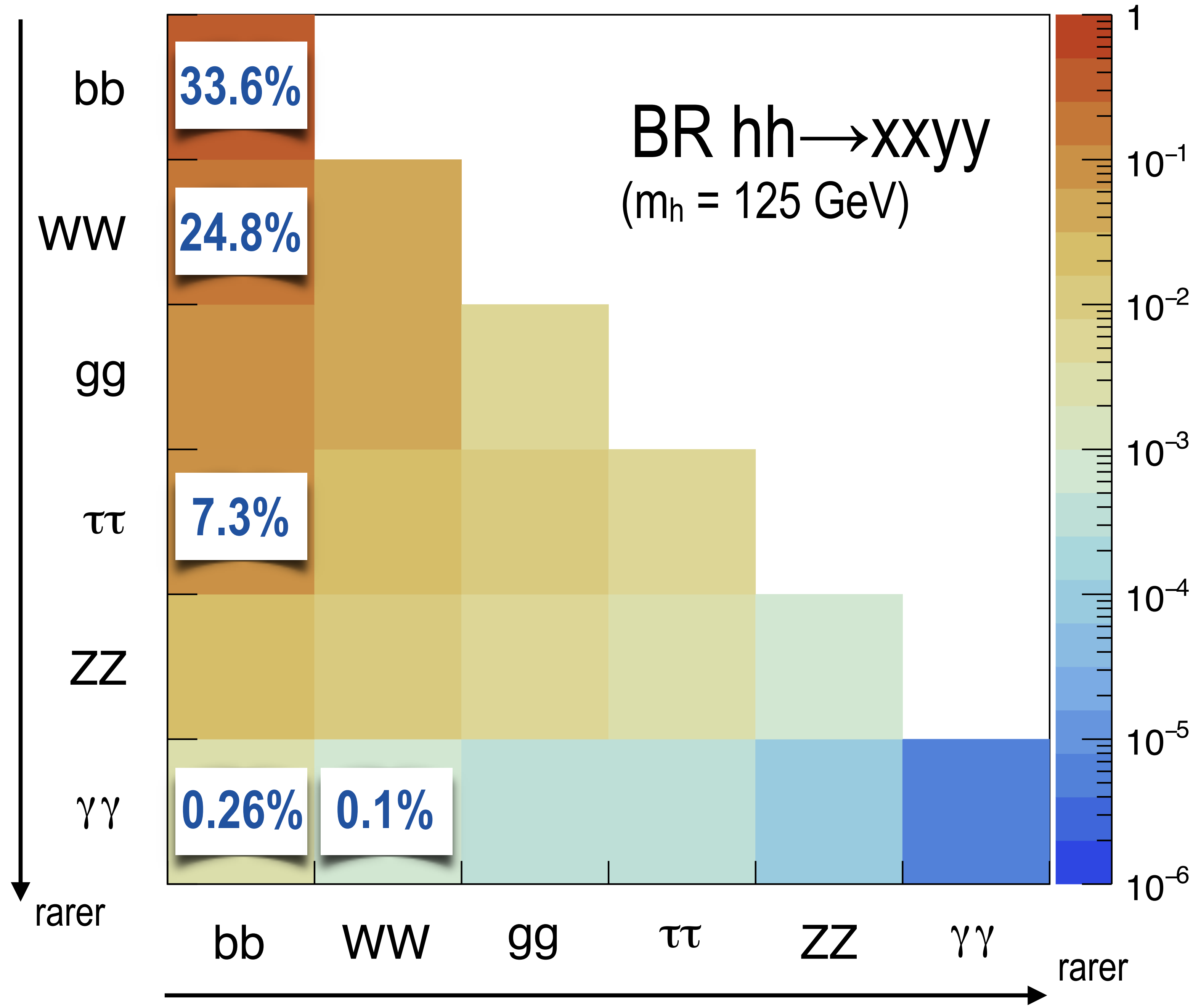
Resonant HH production not predicted in the SM
Any observation would be a sign of new Physics



- **MSSM/2HDM**: additional Higgs doublet gives CP-even scalar H
  - probe the low m_H - low tanβ region of the MSSM plane where BR ($H \rightarrow hh$) is sizable
- **Singlet model**: additional Higgs singlet S gives an extra scalar H
  - sizable BR beyond $2 \times m_{top}$, non negligible width at high m_H
- **Warped Extra Dimensions**: spin-2 (KK-graviton) and spin-0 (radion) resonances
  - different phenomenology if SM particles are allowed (bulk RS) or not (RS1 model) to propagate in the extra-dimensional bulk

How looking for HH?

- HH production and decays are decoupled effects
  - assume SM BRs in the analyses
- Require one h→bb or h→WW decay to keep BR sufficiently high
- Tradeoff between BR and background contamination in the choice of final state
  - various channels are complementary
  - different sensitivities in different mass ranges



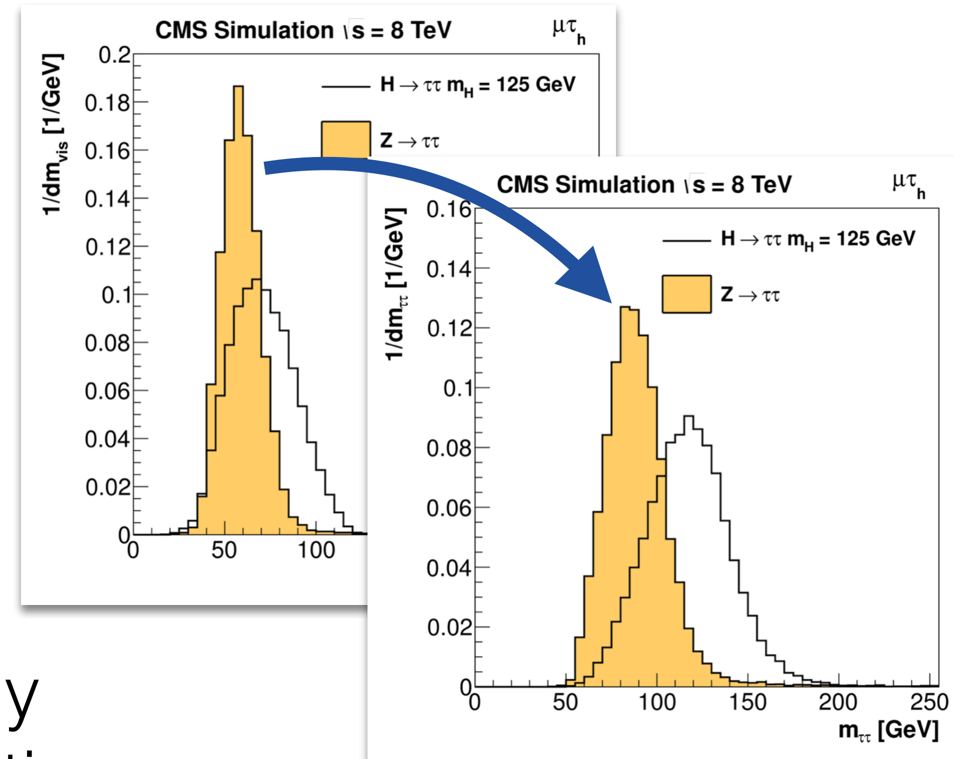
Searches outline

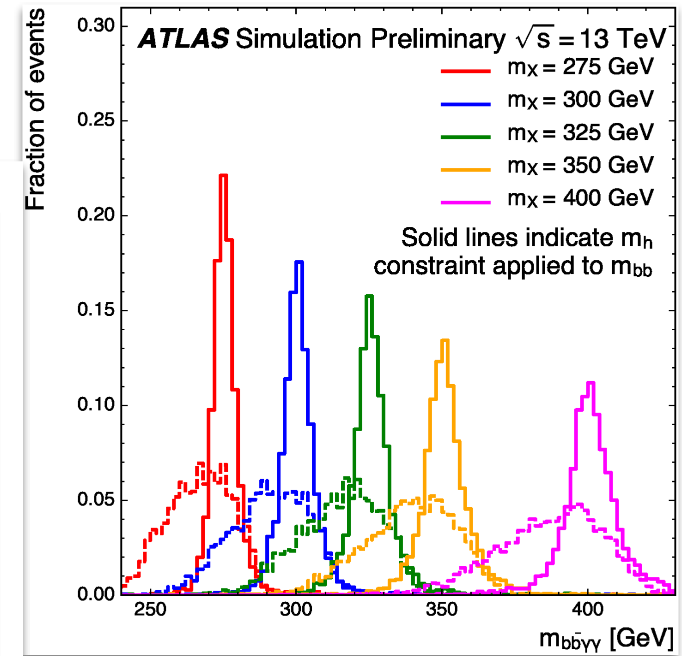
Channel	Lumi analysed @13 TeV [fb^{-1}] ATLAS	CMS
bbbb	13.3	2.3/2.7
bbWW	-	2.3
$bb\tau\tau$	-	12.9
$bb\gamma\gamma$	3.2	2.7
$\gamma\gamma WW$	13.3	-

- Run I searches on ~20 fb^{-1} of data
  - bbbb, $bb\tau\tau$, $bb\gamma\gamma$, $\gamma\gamma WW$, lepton+photons
  - ATLAS performed a combination of the 4 channels analysed
  - 13 TeV searches sensitivity is already close (or higher!) to Run I despite the smaller luminosity
  - Only 13 TeV results are presented here
- Different luminosities collected at 13 TeV are analysed in the various channels
- Both resonant and non-resonant searches in all final states
  - extended coverage to non-resonant BSM couplings in bbWW and $bb\tau\tau$ (CMS)
  - resonance mass range from 250 GeV to 3 TeV depending on the analysis

Experimental challenges

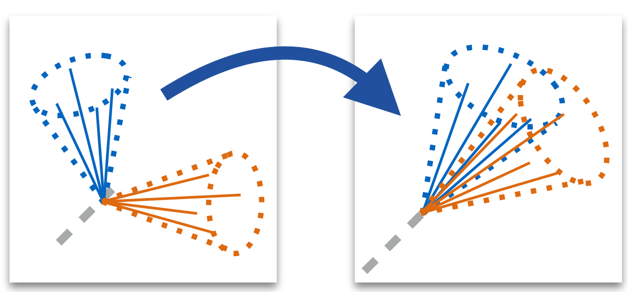
- Difficult event reconstruction
  - Limited resolution on b jet invariant mass → regression / m_H rescale
  - Missing energy in $\tau\tau$ searches → likelihood methods



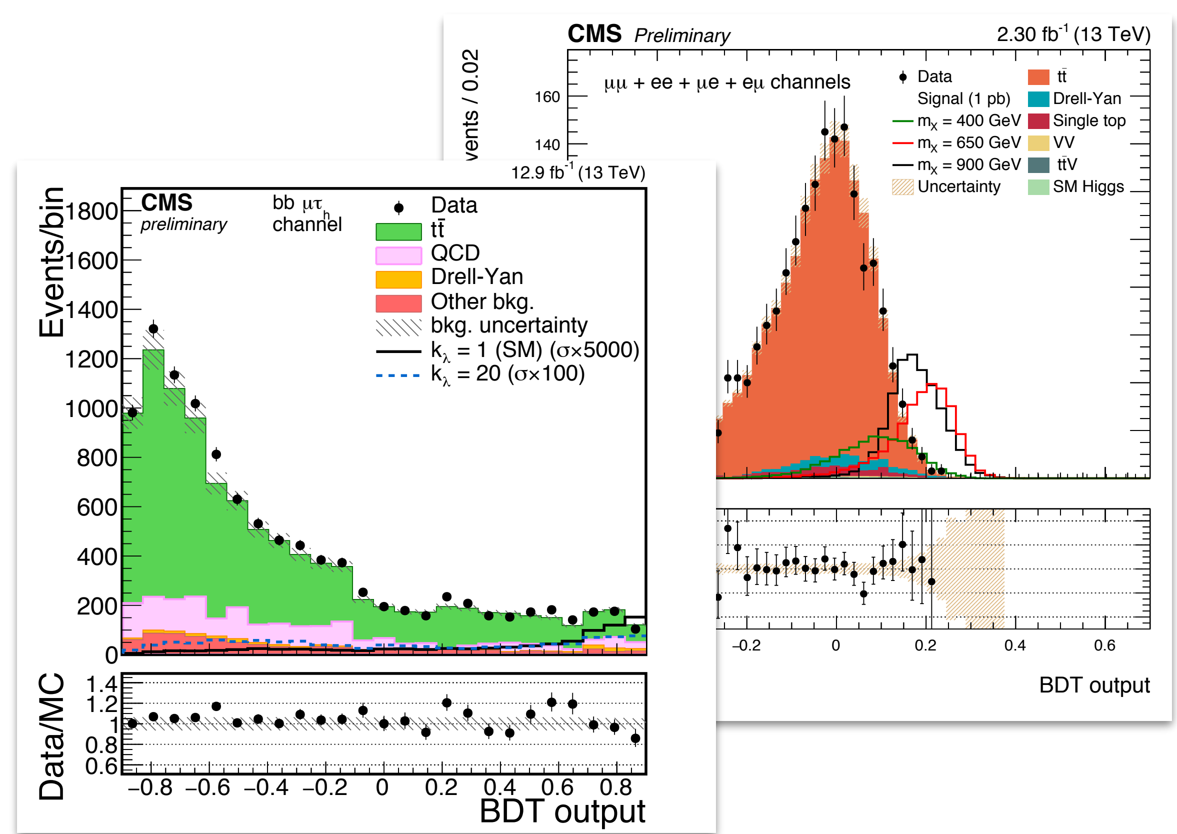


- Looking for signal using 4-body invariant mass: improve resolution with kinematic fit

- b-jets from high mass resonances overlap → jet substructure techniques

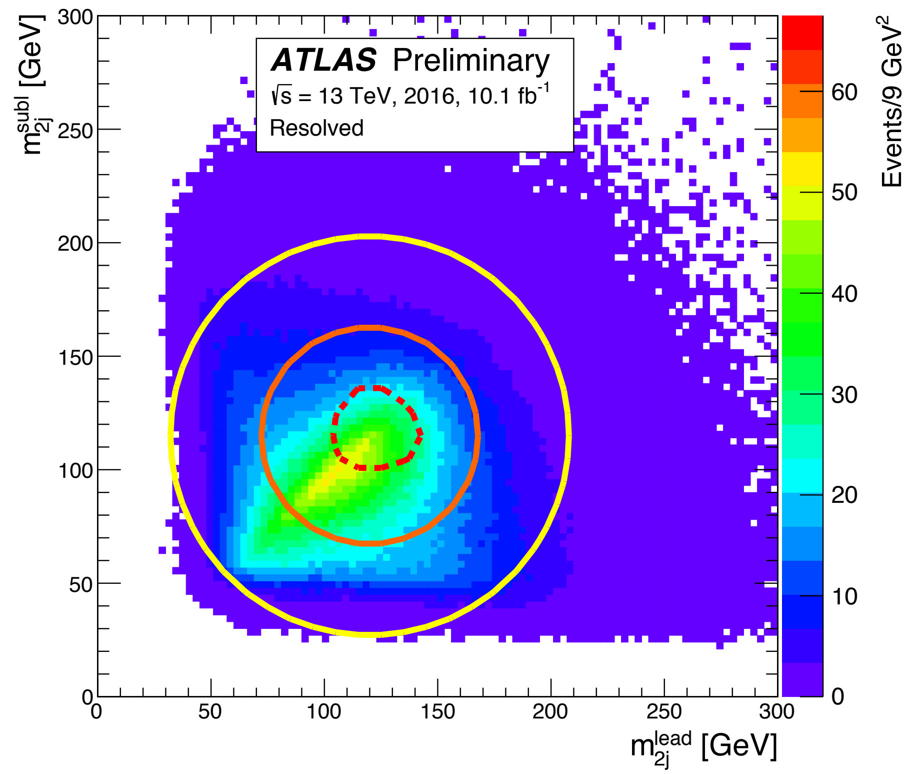


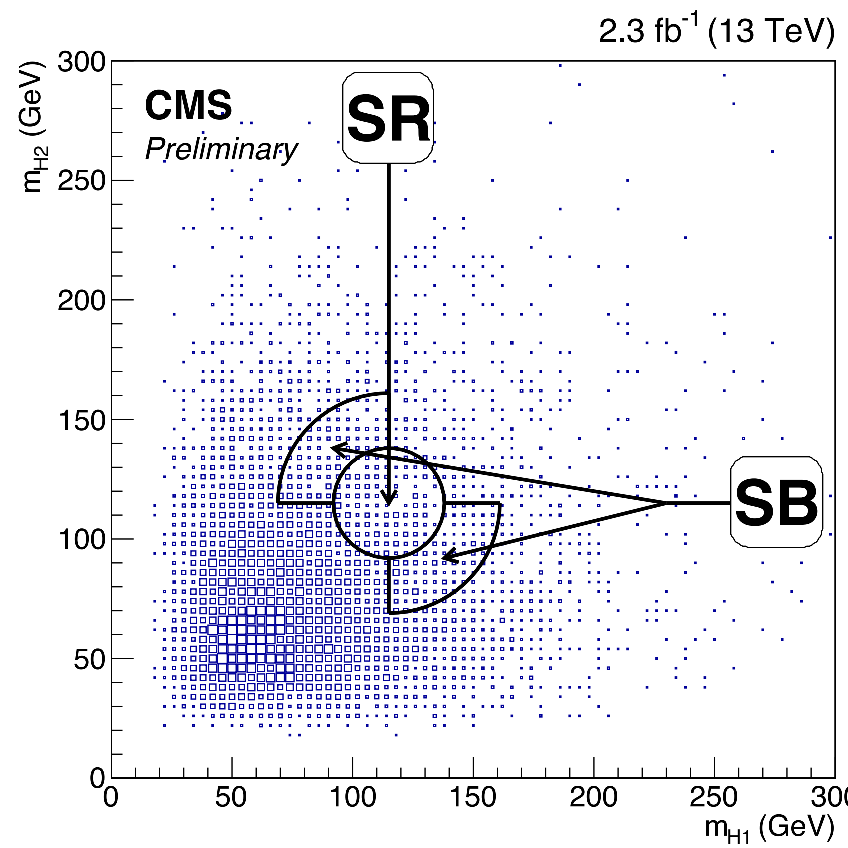
- Small signals with large backgrounds → MVA methods to separate from overwhelming backgrounds



$hh \rightarrow bbbb$

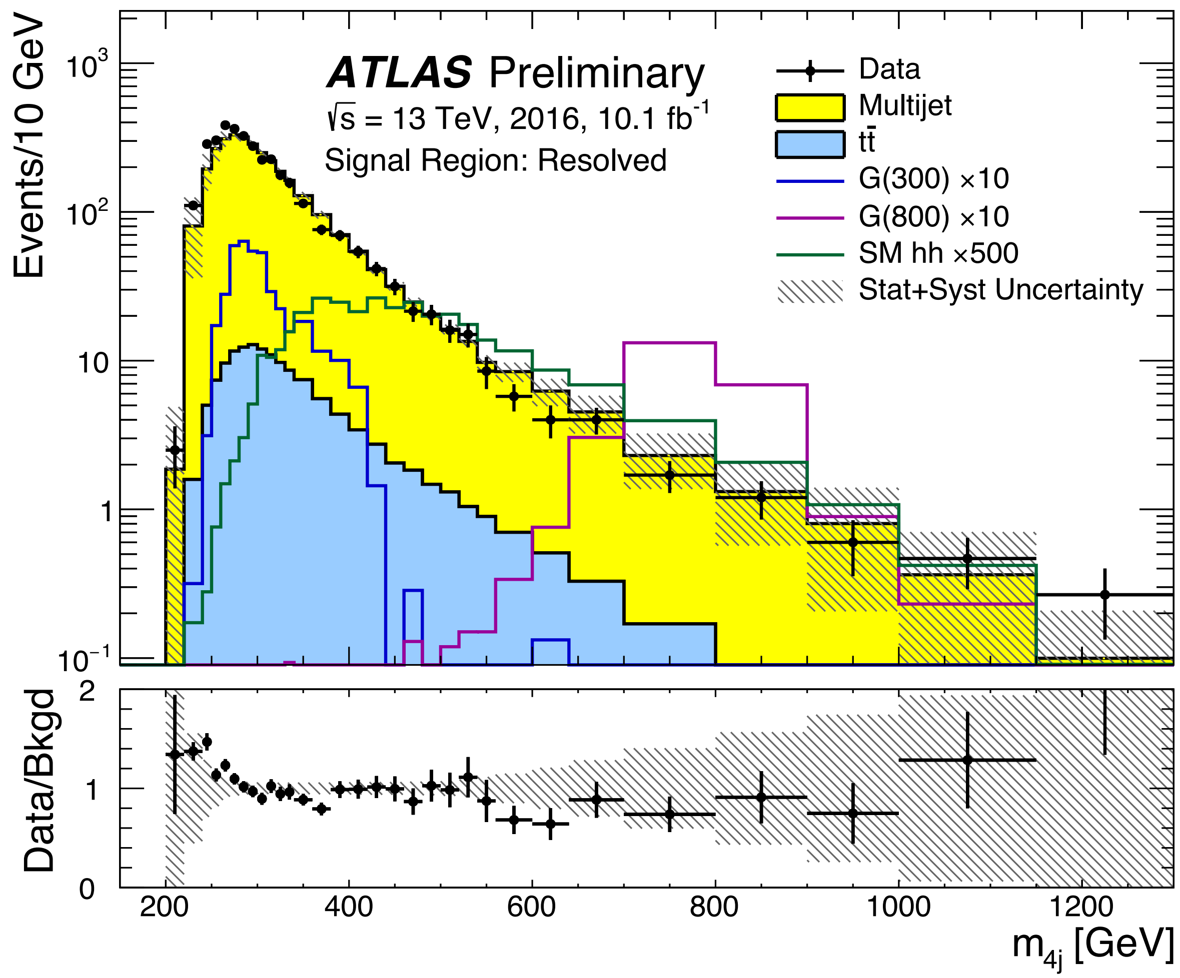
- b-tagging at trigger level, require 4 b-tagged jets offline
- Signal and control regions defined in the (m_{jj}^{lead}, $m_{jj}^{sublead}$) plane
- Main background: QCD multijet. Estimated from data
  - ATLAS: relaxed b-tag and inverted mass sideband
  - CMS resonant: fit to data in mass sideband
  - CMS non-resonant: “hemisphere mixing” to create background template mixing data events topologies

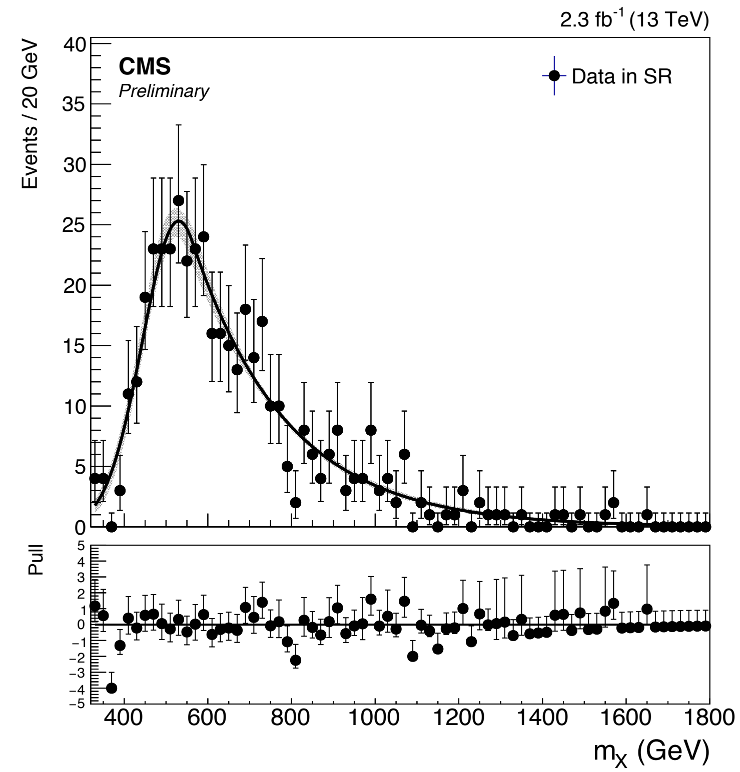


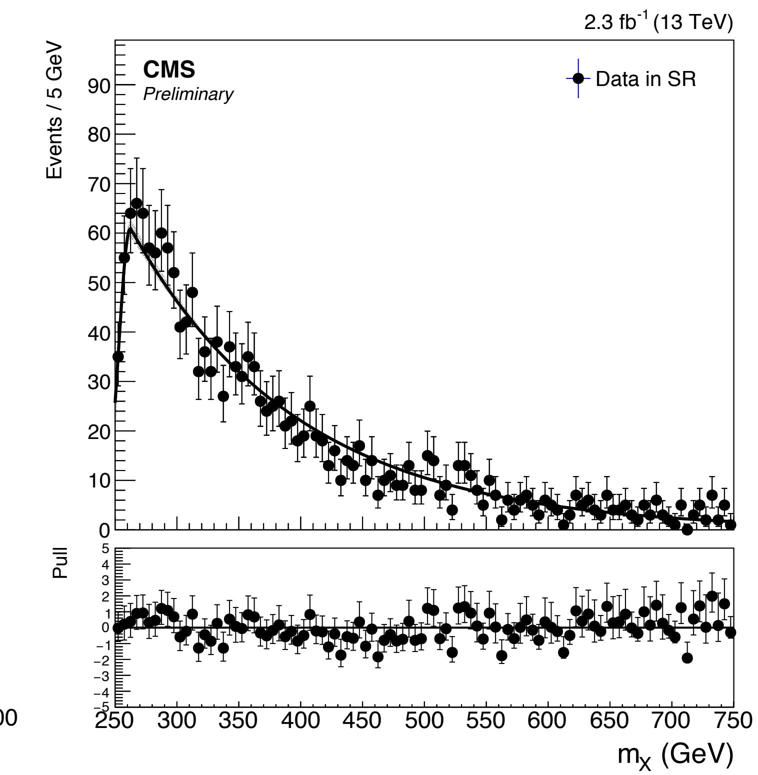


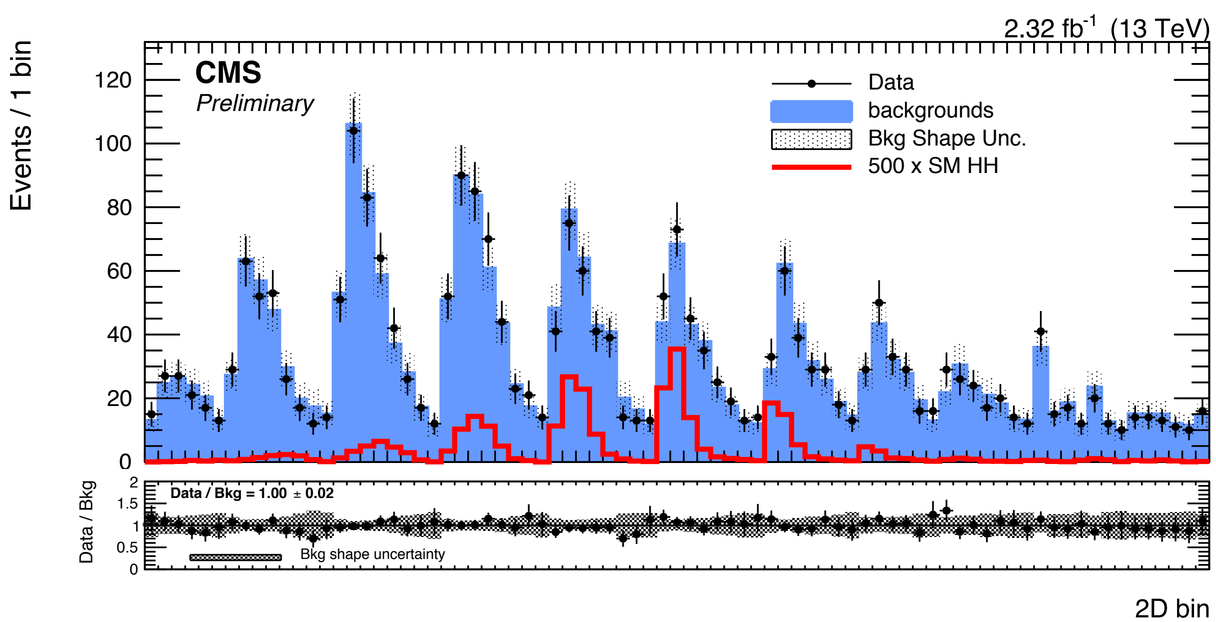
ATLAS-CONF-2016-049
CMS-PAS-HIG-16-002 , CMS-PAS-HIG-16-026

hh → bbbb





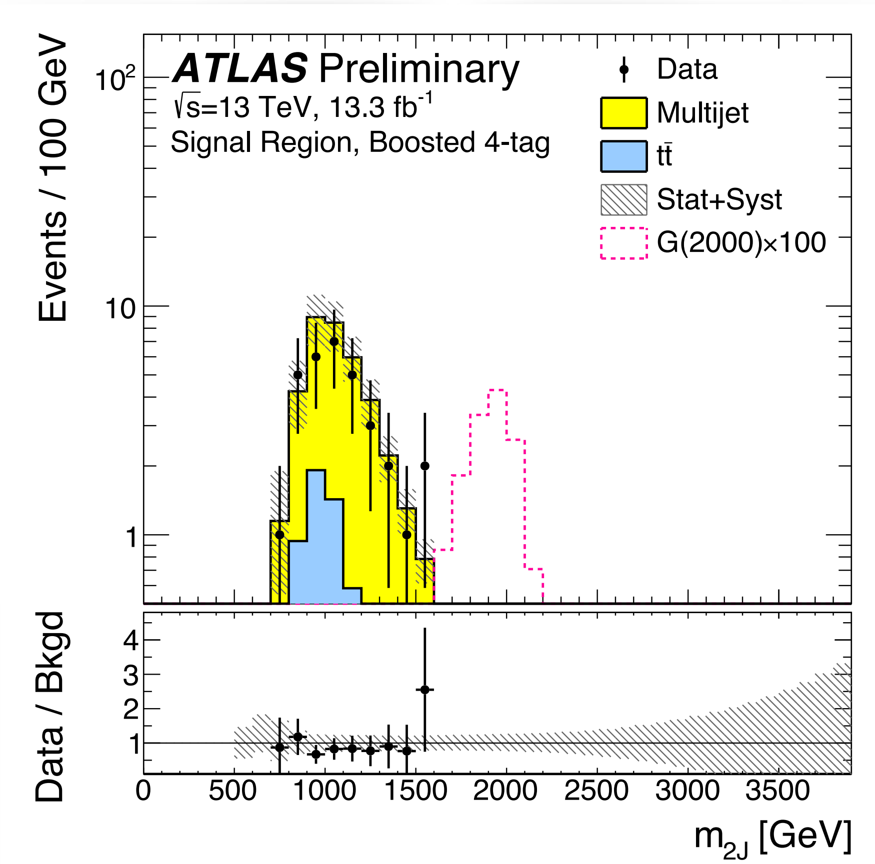


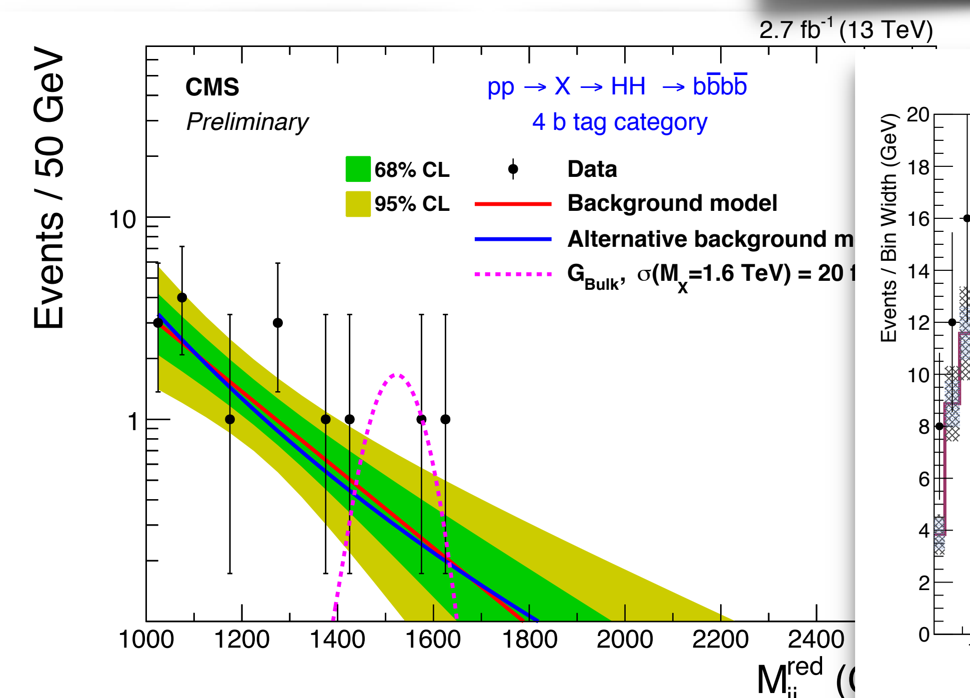


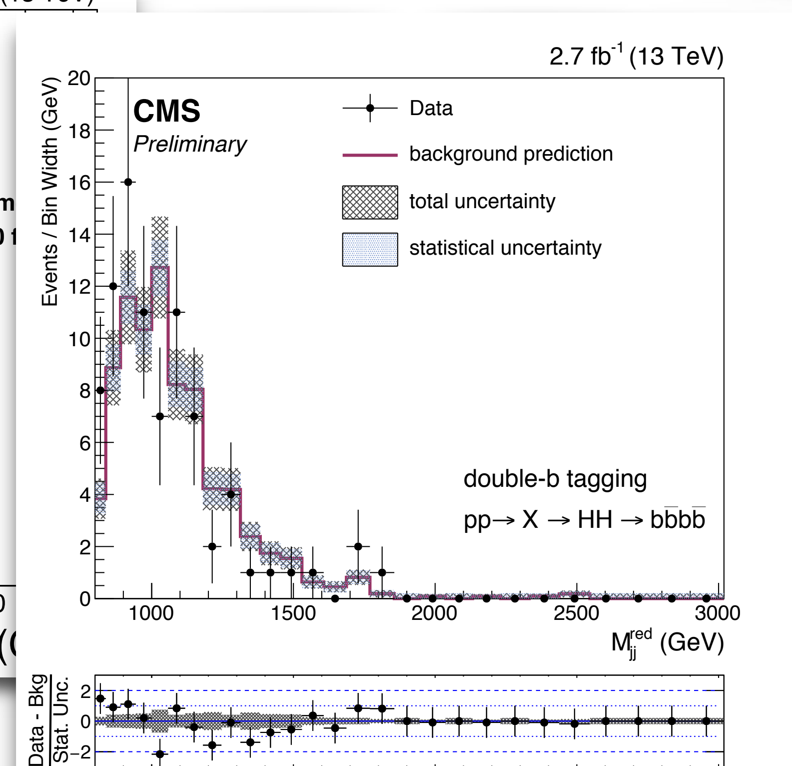
- Exploit invariant mass of objects to look for a signal
  - ATLAS, CMS resonant: exploit 4j invariant mass. CMS does a separate study of low and medium mass regions
  - CMS non-resonant: 2D fit in (m_{jj}^{lead}, $m_{jj}^{sublead}$) plane

hh → bbbb : boosted

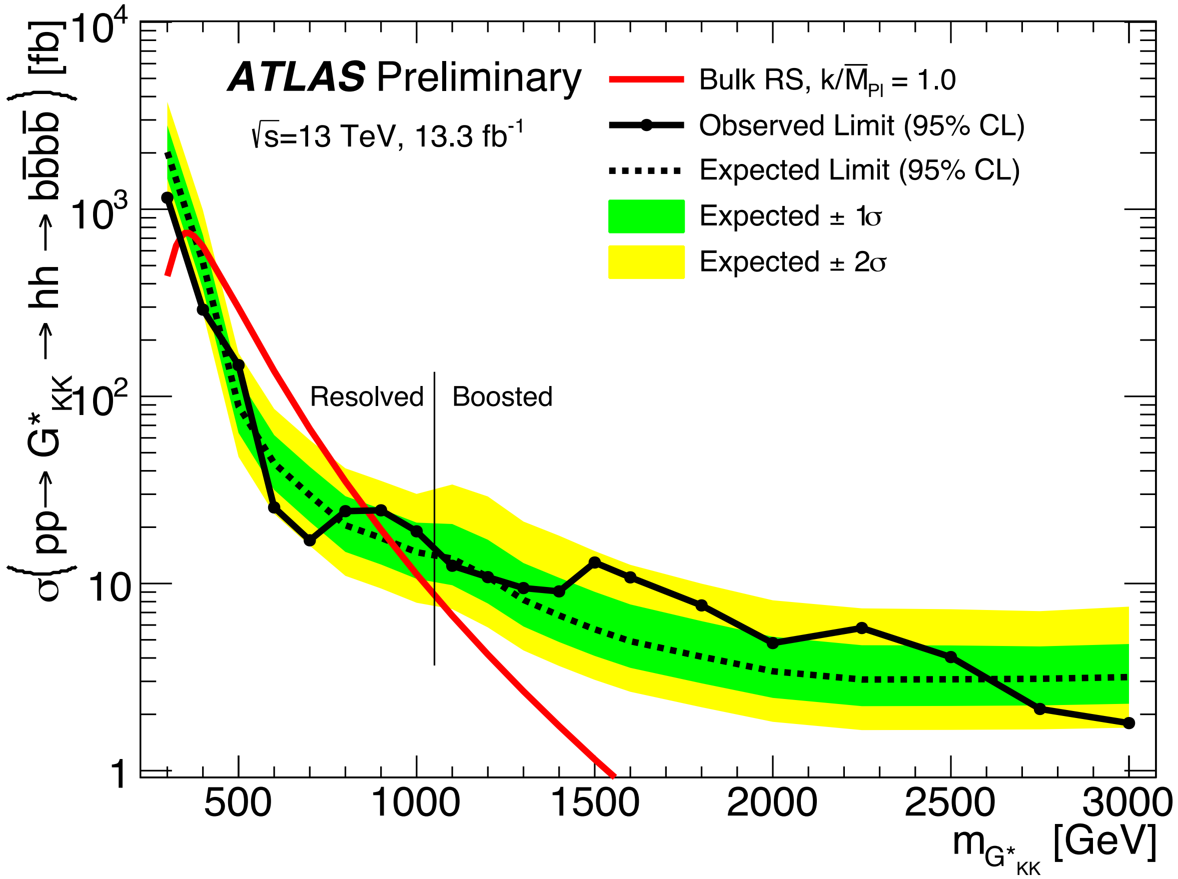
- Require two jets with cone 1.0 (ATLAS) / 0.8 (CMS)
  - trigger: one R=1.0 jet (ATLAS), jets+ H_T sums (CMS)
- b-tag criteria applied
  - ATLAS: categories with 2/3/4 b-tagged track-jets matched
  - CMS: two separate methods
    1) b-tag on sub-jets + 3-4 tag categorization /
    2) double-b tagging MVA algorithm on R=0.8 jet
- Background from data
  - ATLAS: multijet+tt yield simultaneous fit to jet-mass distribution in sideband. Multijet shape from data.
  - CMS: two separate methods
    1) simultaneous functional fit of signal and bkg to data
    2) interpolation of b-untagged/ b-tagged event ratio vs. m_J^{lead} into the signal region



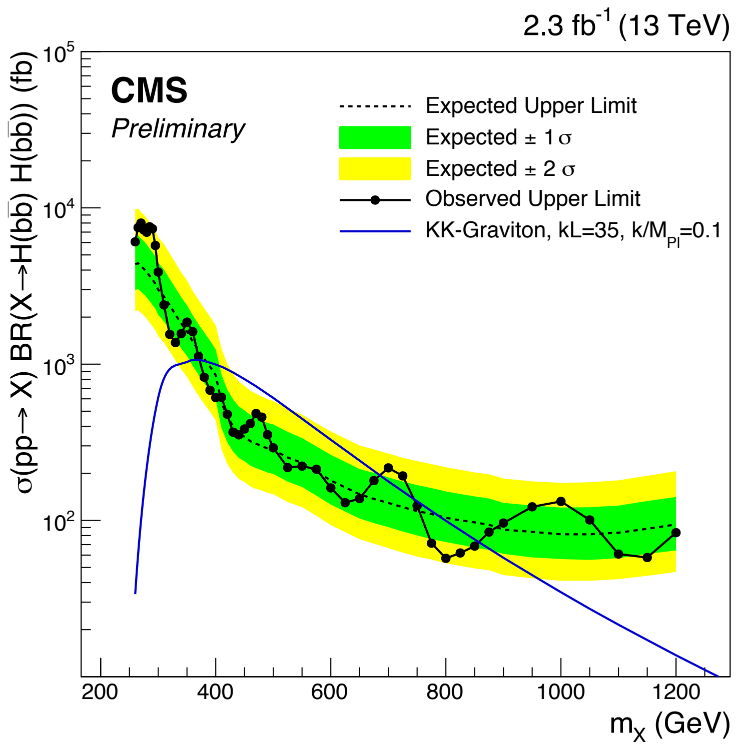


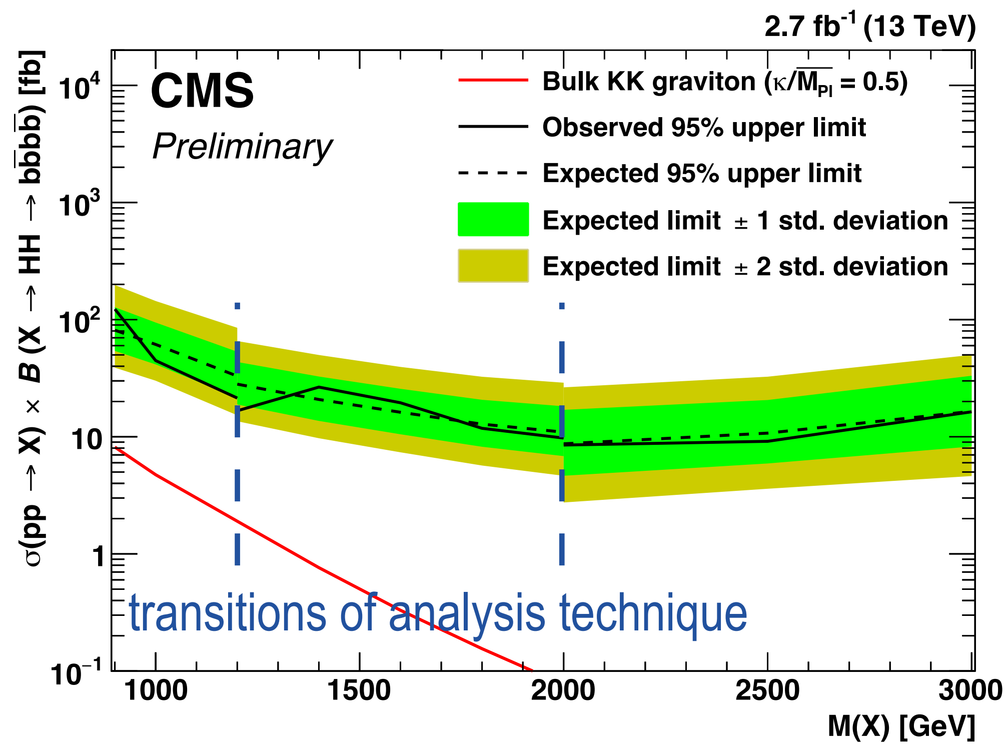


hh → bbbb : results



- 13.3 fb^{-1} of data analysed by ATLAS, 2.3/2.7 fb^{-1} by CMS
- Limits set for resonant (spin-0 and spin-2) and non-resonant production
- Sensitivity to non-resonant production still O(10)-O(100) X SM

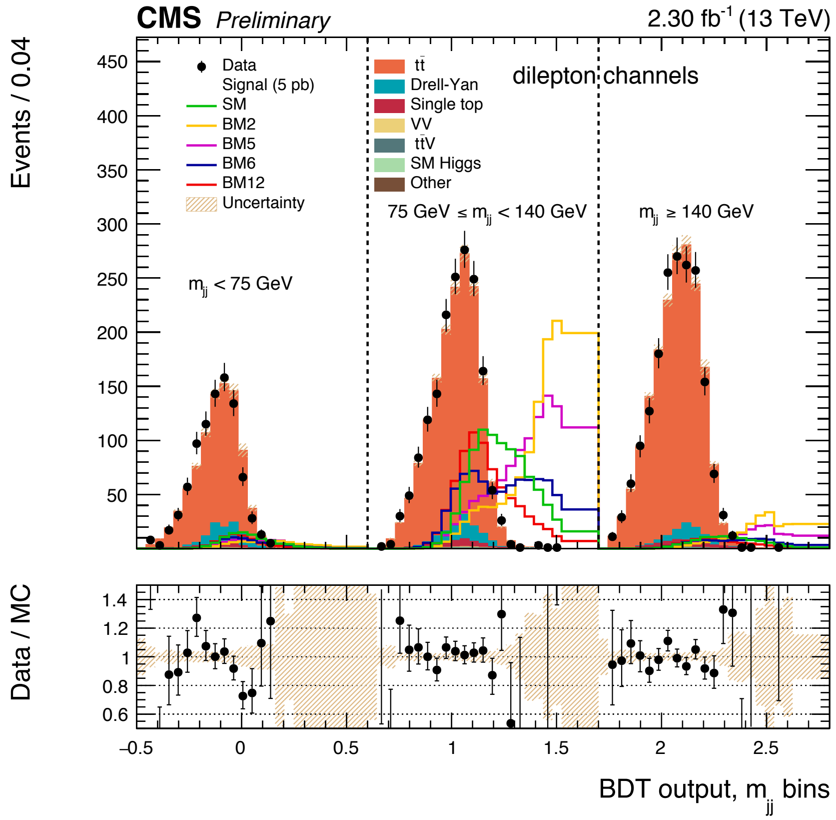


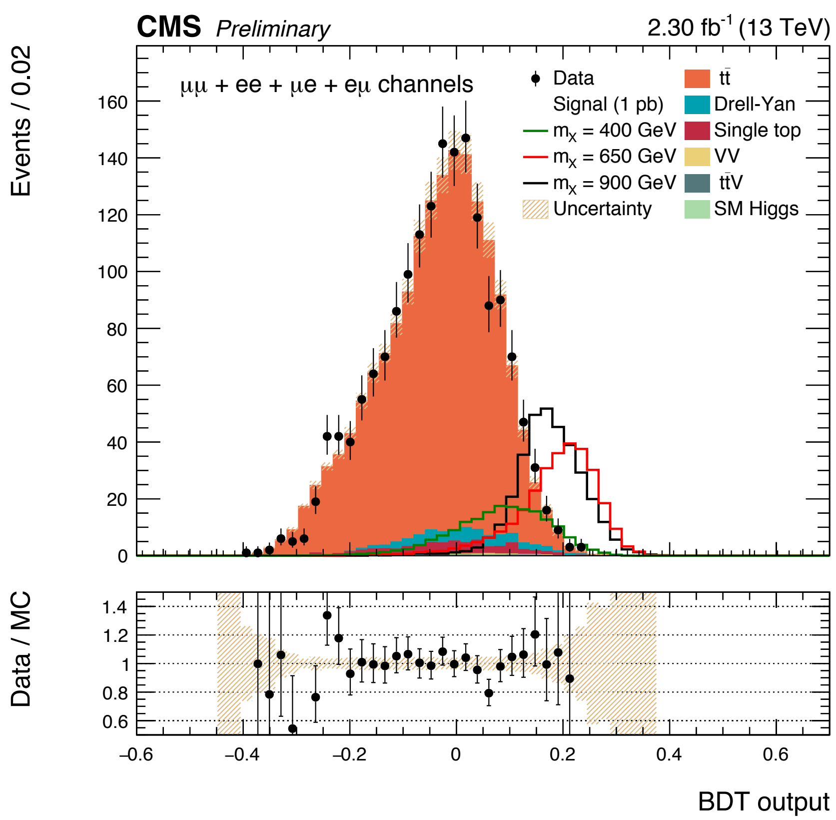


Obs (exp) limit on non-resonant σ (pp⟶hh) x BR (hh⟶bbbb)	
ATLAS	330 (-) fb [obs : 29 x SM]
CMS	3880 (3490) fb [obs: 342 x SM]

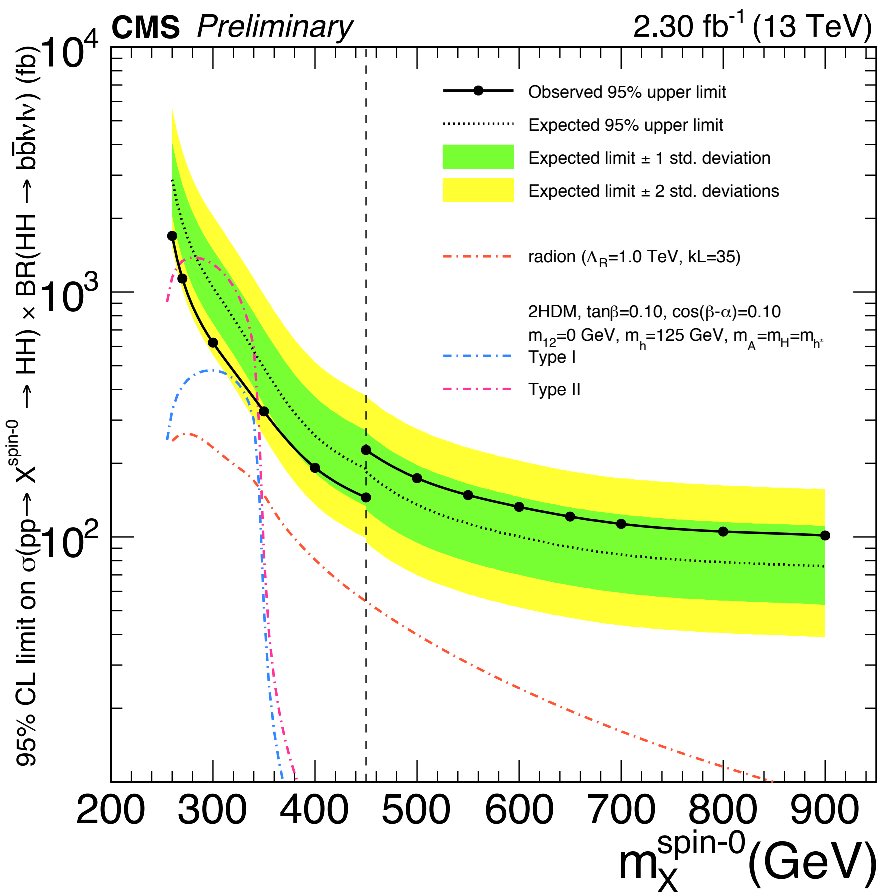
hh → bbWW

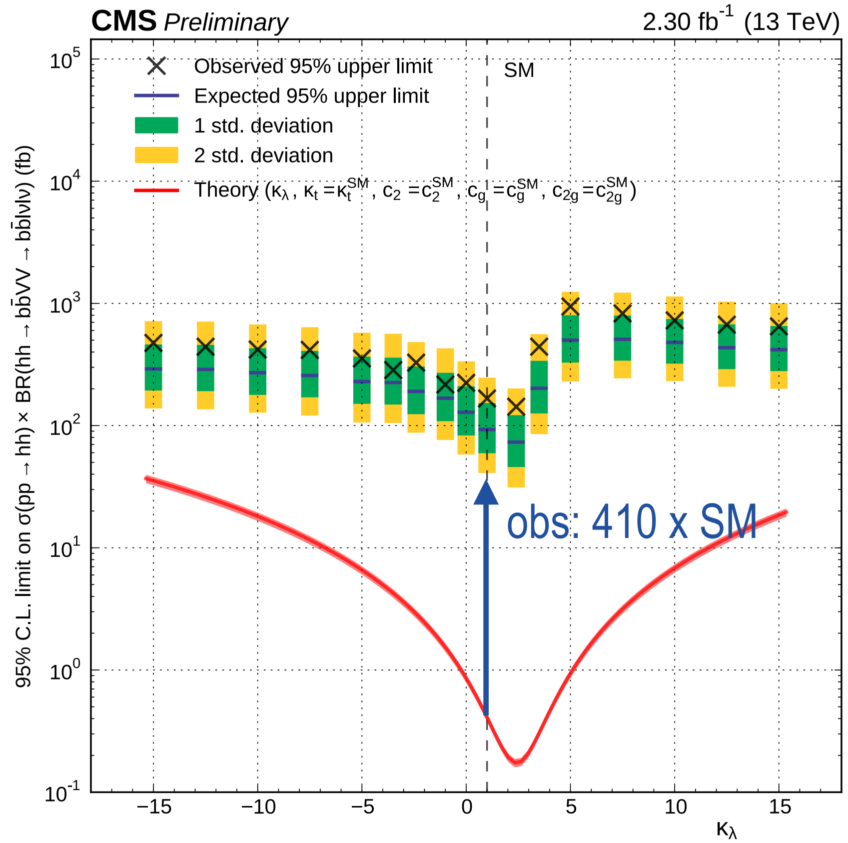
- WW→lν$_l$ lν$_l$ (l = e, μ) ⟹ bbee, bbμμ, bbeμ
- Dominant background: tt (same final state)
- Exploit event kinematics to select signal using BDT method
  - resonant search: low and high-mass BDT trainings
  - non-resonant search: common BDT trained on optimal BSM topology
- Simultaneous fit of BDT distribution in signal region and m_{jj} sideband to constrain background

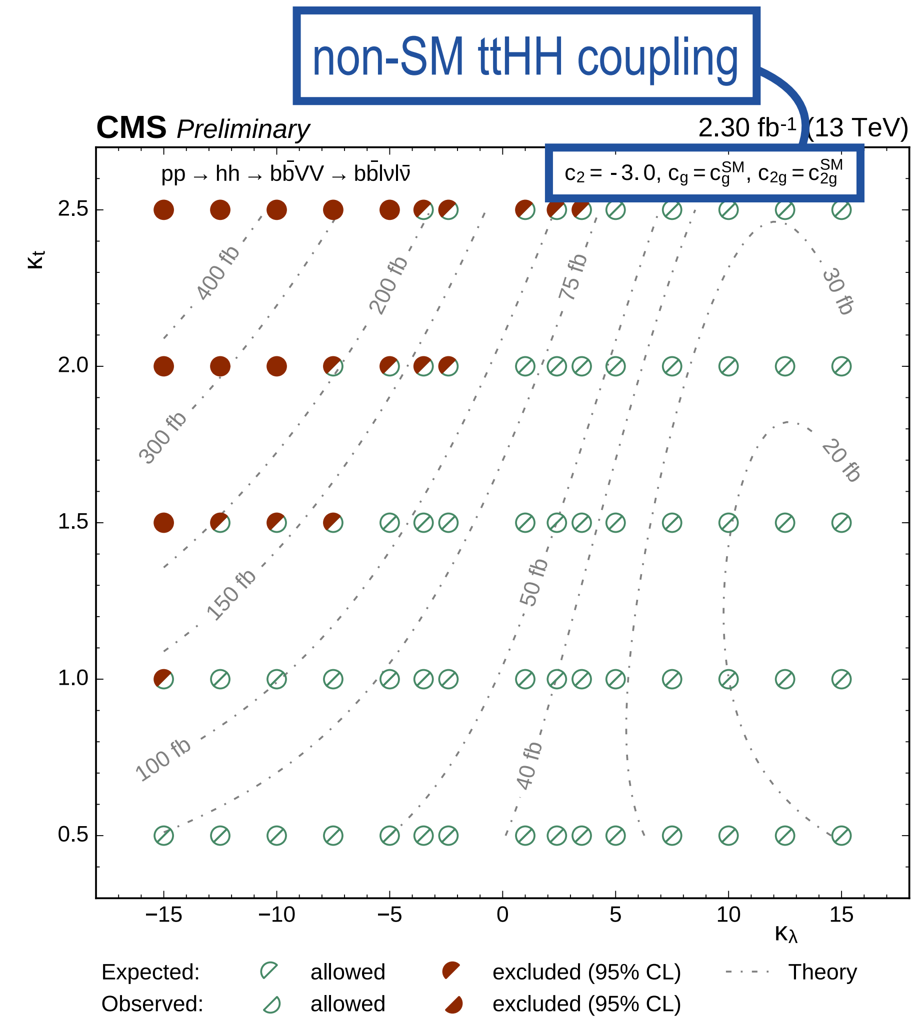




hh → bbWW: results



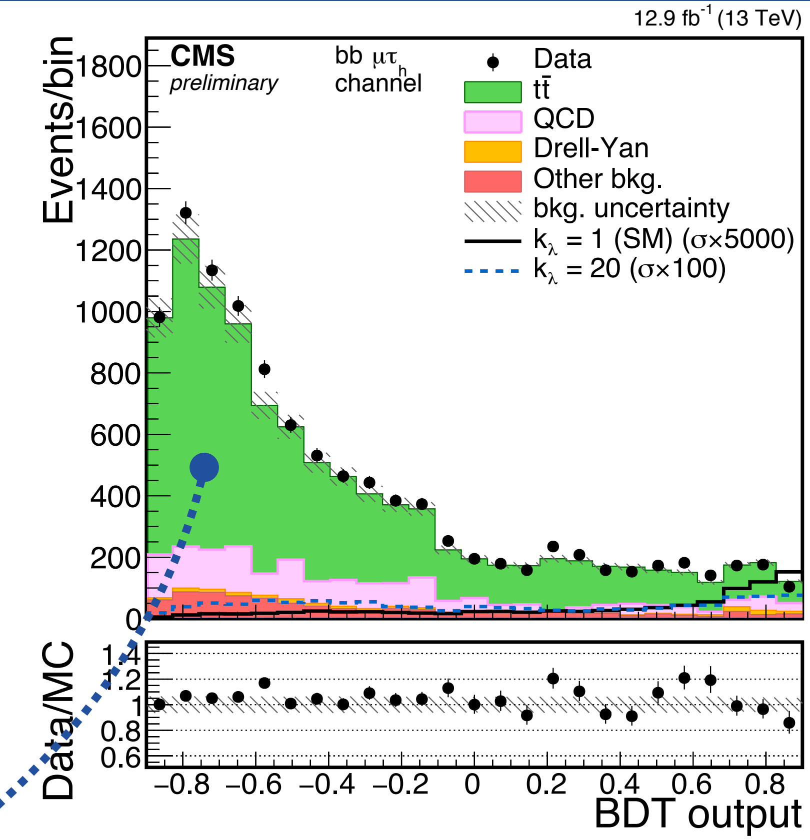


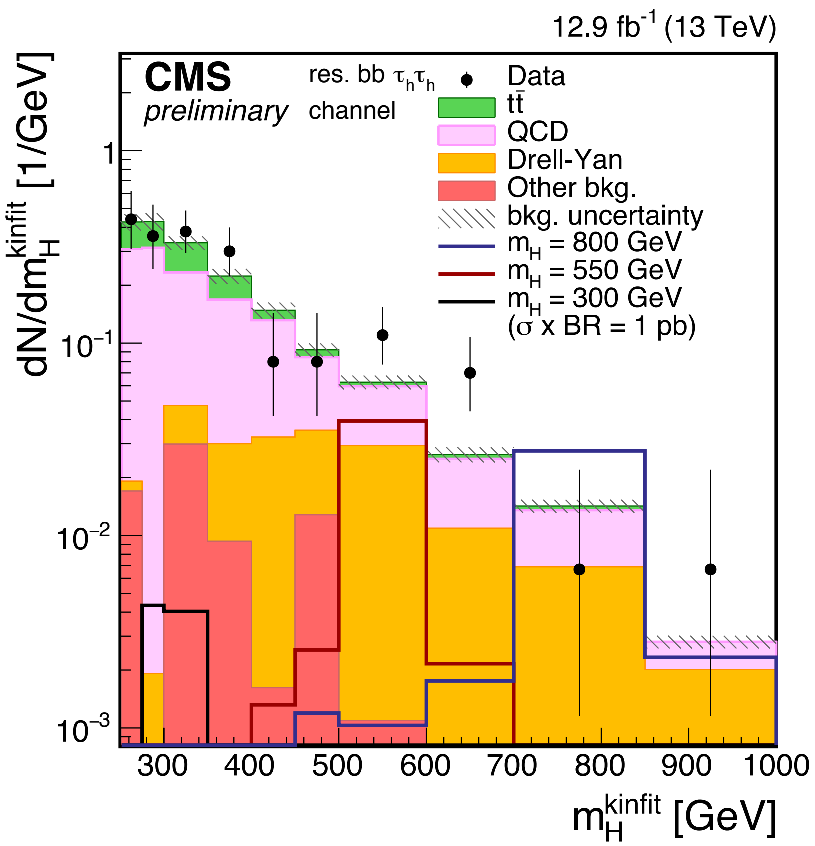


- Limits set for spin-0 and spin-2 resonances in the mass range [250, 900] GeV
  - similar sensitivity to both spin hypotheses
- Test of anomalous couplings
  - 1-dimensional scan of the 5 effective Lagrangian parameters
  - some corners of effective Lagrangian phase space parameters start to be excluded

hh → bb$\tau\tau$

- Main backgrounds: tt, QCD multijet, DY
- $\tau\tau$ mass reconstructed with likelihood method
- Signal extracted using 4-body mass
- Resonant case
  - b-jet categorisation
  - boosted b-jets topologies
  - kinematic fit of four-body mass
- Non-resonant case
  - BDT to reject tt background based on angular variables
- Background estimation
  - tt: from MC with p_T reweighting
  - QCD: from data same-sign sideband
  - DY: MC shape + data-driven yield in μμ sideband

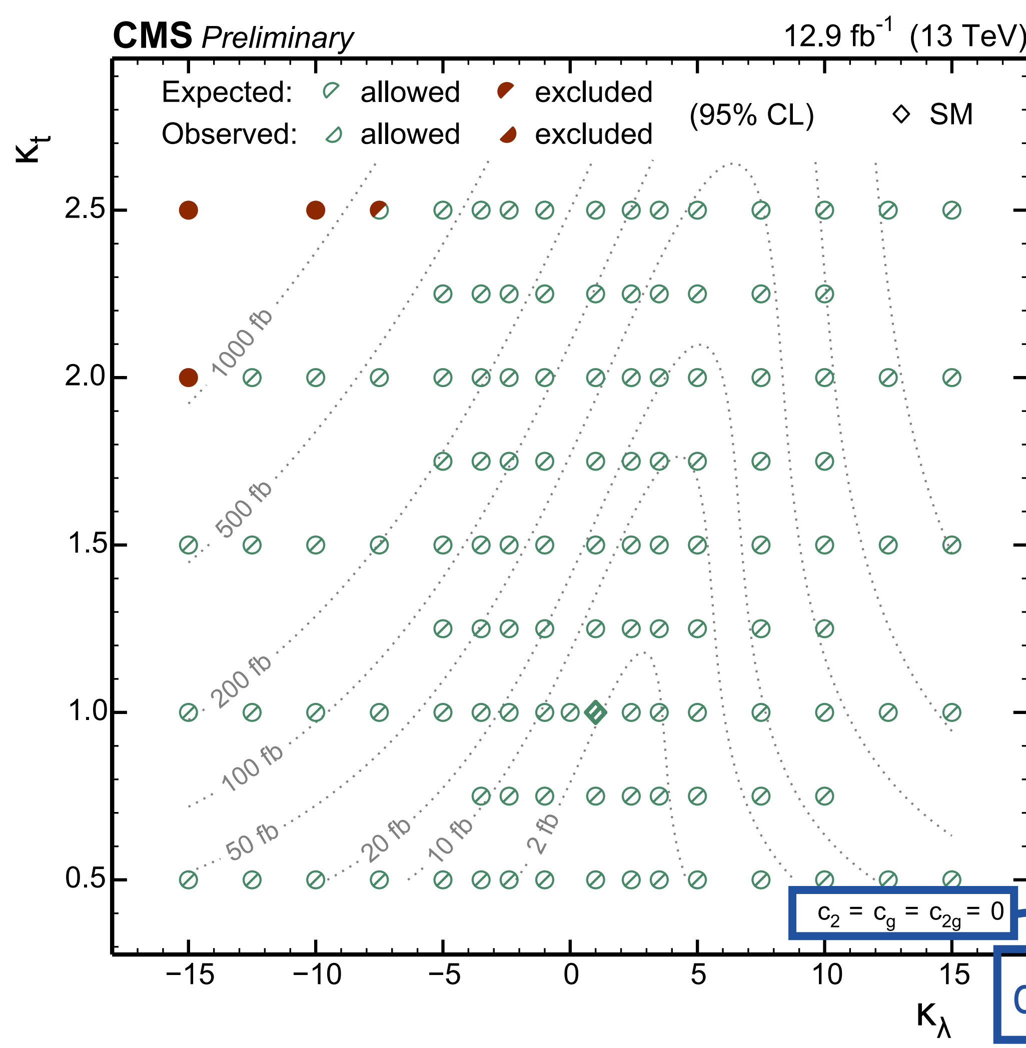




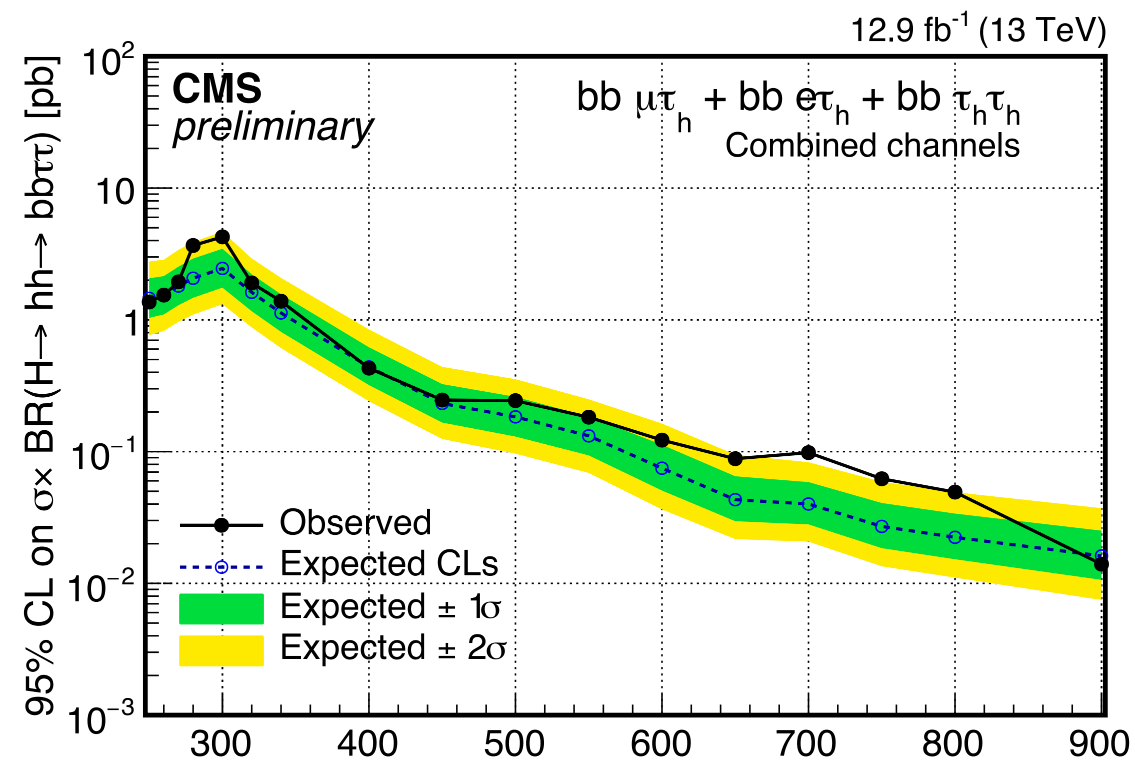
CMS-PAS-HIG-16-028
CMS-PAS-HIG-16-029

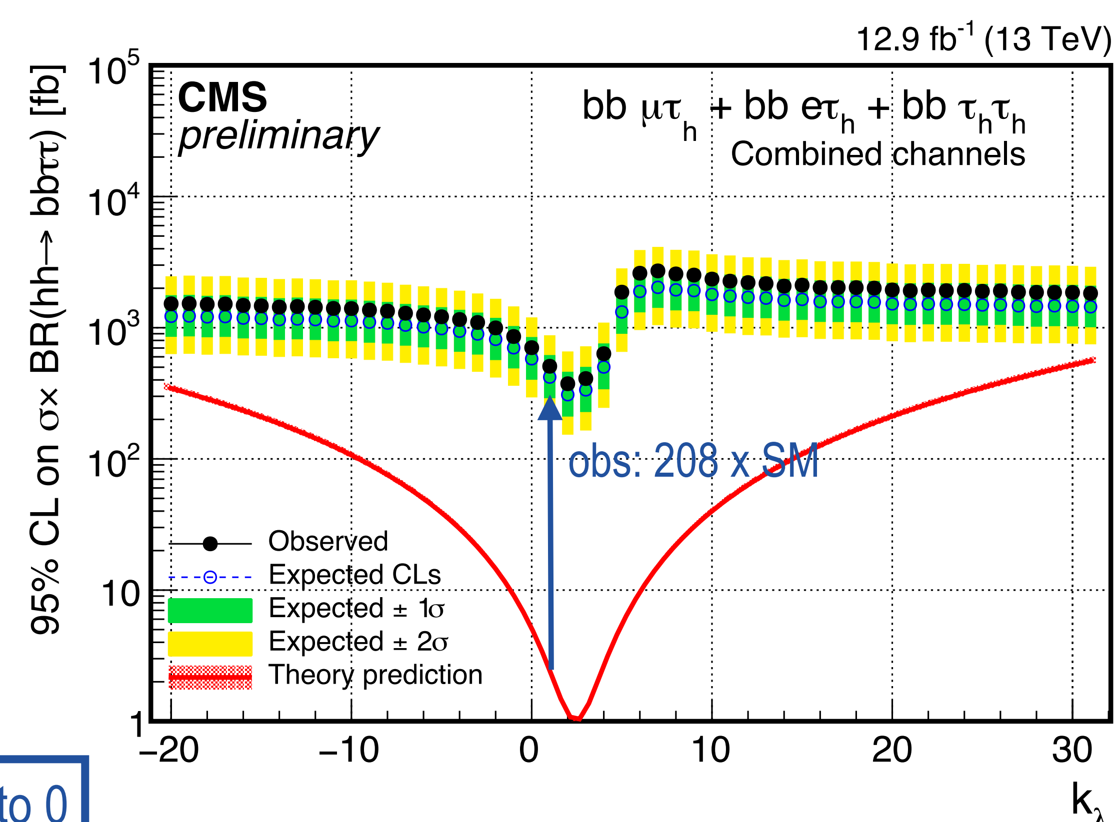
$hh \rightarrow bb\tau\tau$: results

- 3 final states combined: $bbe\tau_h$, $bb\mu\tau_h$, $bb\tau_h\tau_h$
- Limits to resonant production in range [250, 900] GeV
- Test of anomalous couplings (including modified signal kinematics)
  - 1D and 2D scans of $k_\lambda = \boldsymbol{\lambda}_{hhh}^{SM}/\boldsymbol{\lambda}_{hhh}$, $k_t = y_t^{SM}/y_t$

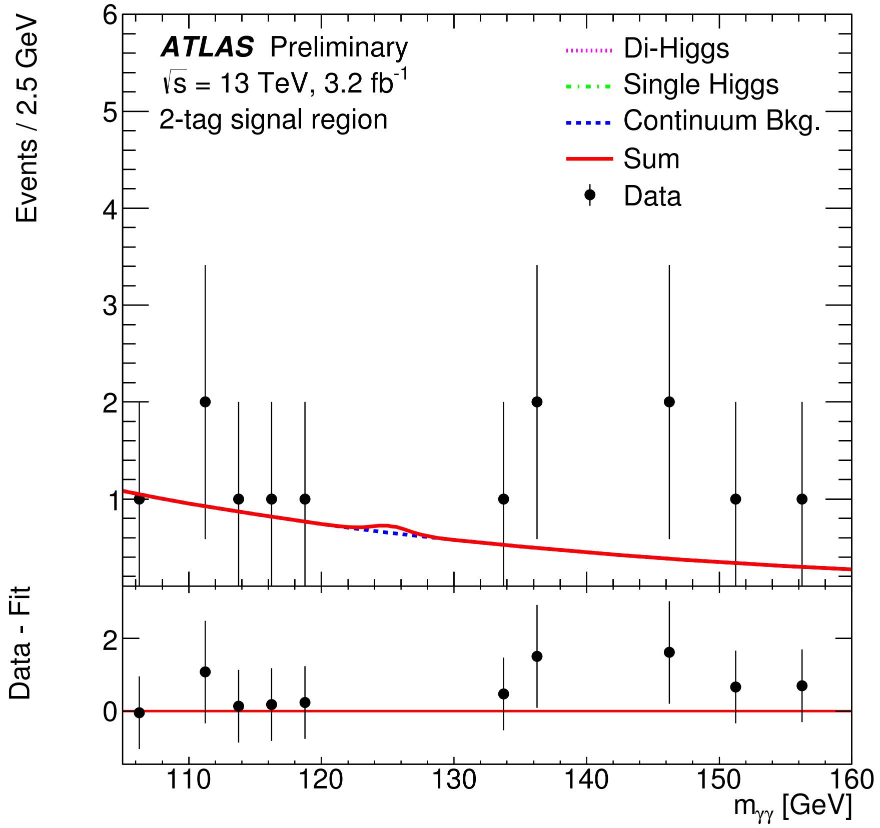


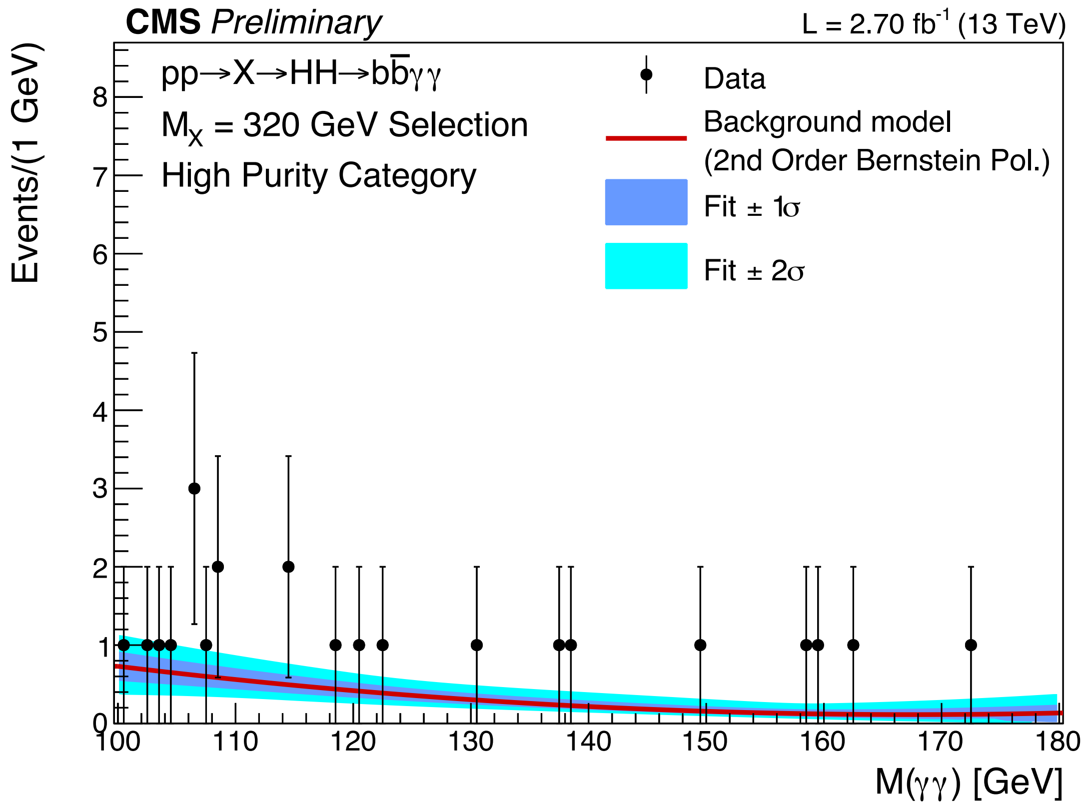
other BSM couplings set to 0





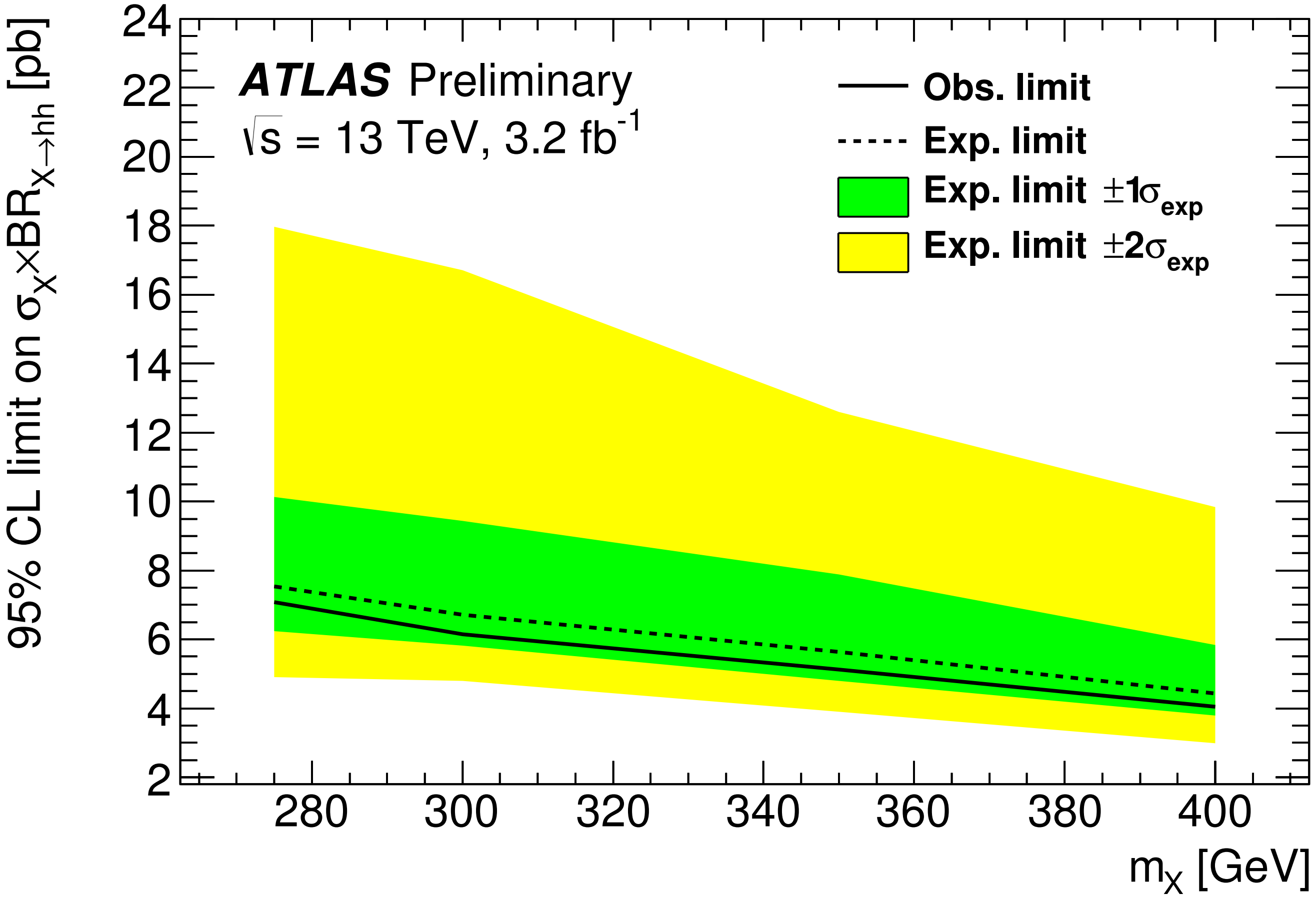
$hh \to bb\gamma\gamma$

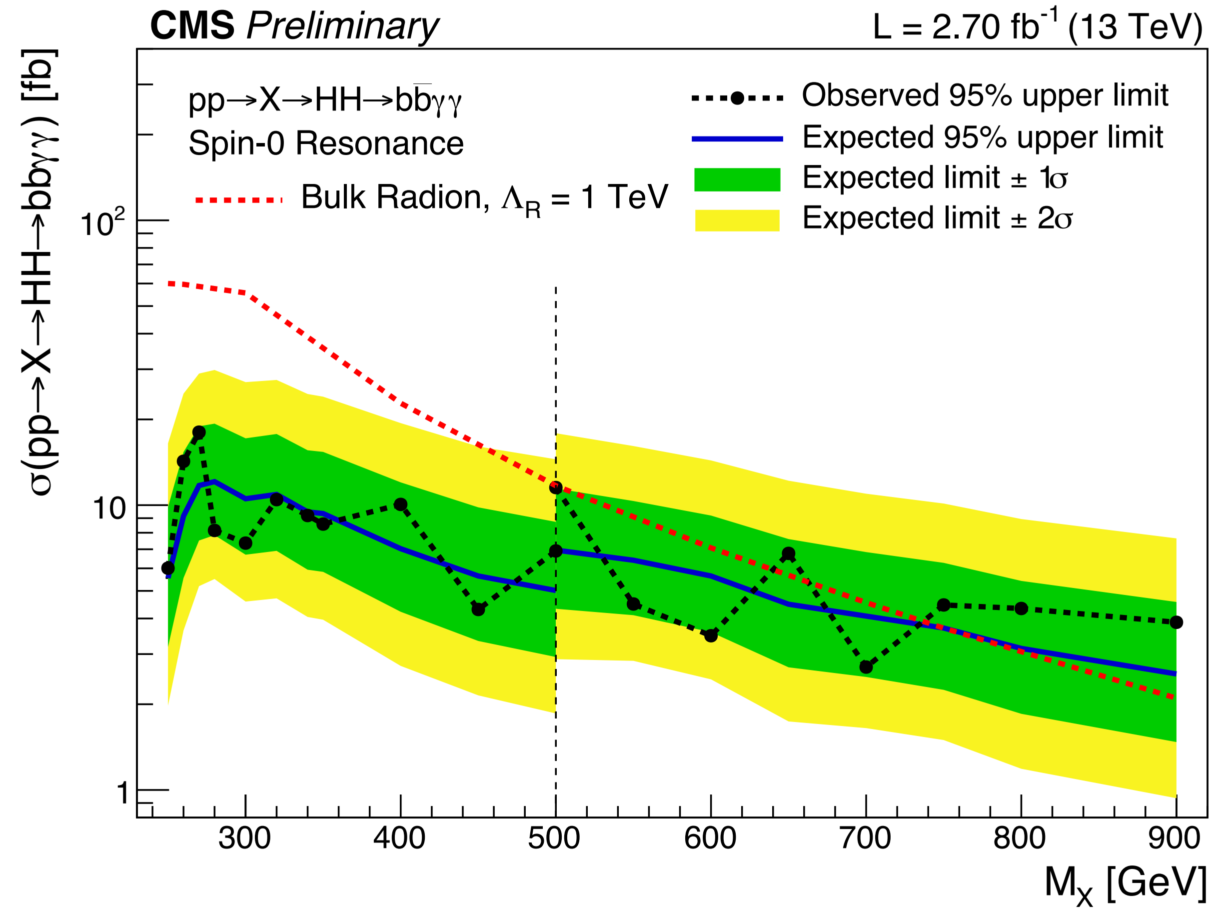




- $\gamma\gamma$ trigger, require offline two photons and two b-tagged jets
  - MVA for $\gamma\gamma$ vertex identification taken from $H\to\gamma\gamma$ analyses
- m_{bb} resolution improvement with rescaling to H(125) mass (ATLAS) and multivariate regression (CMS)
- Main background: continuum $jj\gamma\gamma$ production
- Background from data
  - 0 b-tag sideband (ATLAS) or functional fit in signal region (CMS)
- Exploit excellent $m_{\gamma\gamma}$ resolution in signal extraction
  - ATLAS non-resonant: fit on $m_{\gamma\gamma}$
  - ATLAS resonant: counting exp. in $m_{bb\gamma\gamma}$ window
  - CMS: 2D unbinned fit on $(m_{bb}, m_{\gamma\gamma})$

$hh \rightarrow bb\gamma\gamma$: results





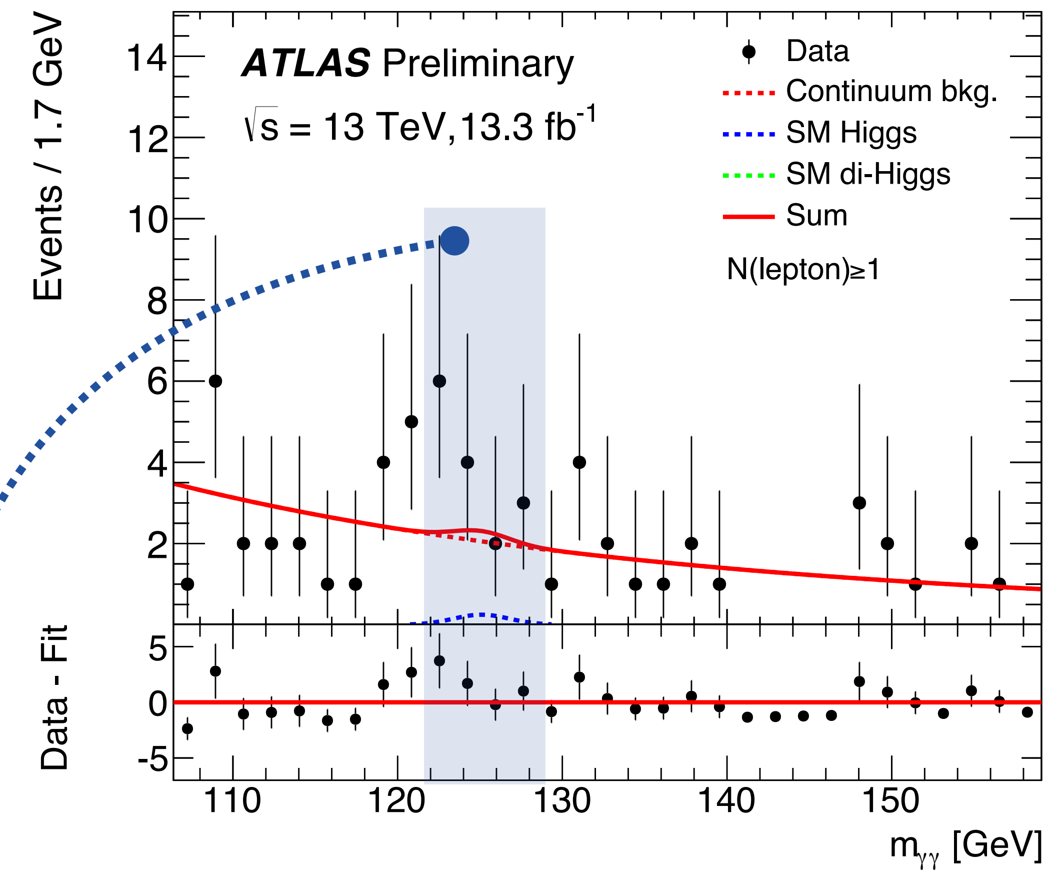
- Limits set for resonance masse up to 400 (ATLAS) and 900 (CMS)
  - both spin-0 and spin-2 hypotheses tested for CMS, very similar sensitivity
- Sensitivity O(100) times the SM production

Obs (exp) limit on non-resonant σ (pp→hh) x BR (hh→bb$\gamma\gamma$)	
ATLAS	10.1 (14.0) fb [obs : 117 x SM]
CMS	7.90 (7.85) fb [obs: 91 x SM]

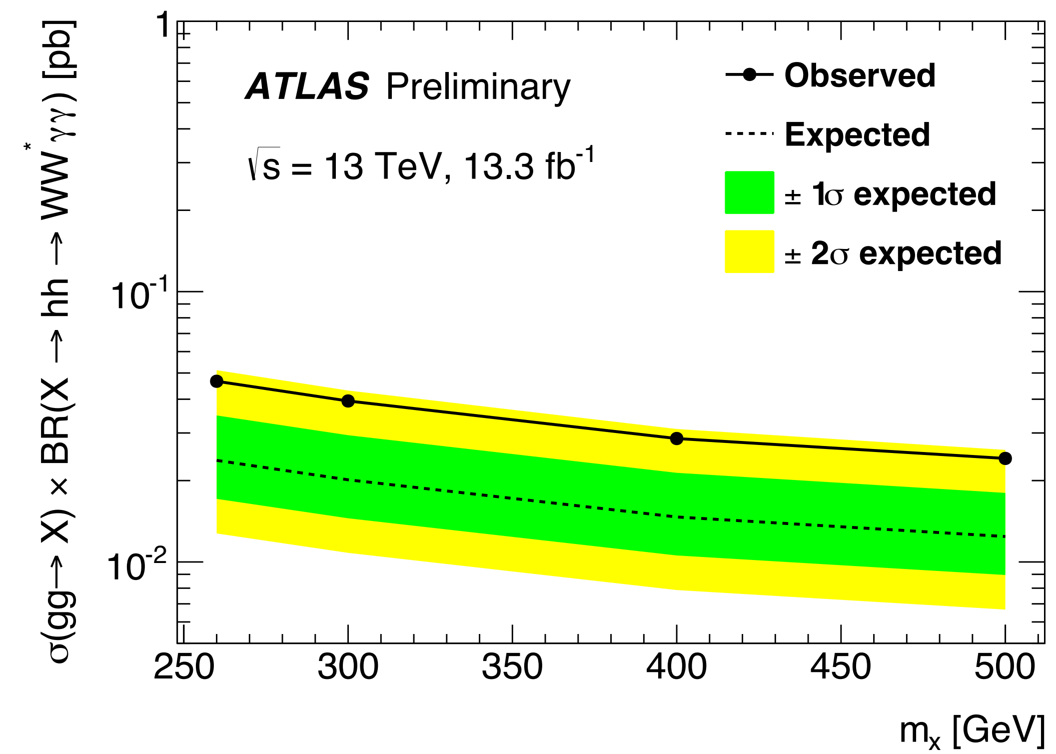
ATLAS-CONF-2016-071

hh → WW$\gamma\gamma$

- WW$\gamma\gamma$ → qq'lν_lWW$\gamma\gamma$ final state analysed
- $\gamma\gamma$ mass requirement compatible with H(125) within ± 2$\sigma_{\gamma\gamma}$ ($\sigma_{\gamma\gamma}$ = 1.7 GeV), two jets (w/ b-jet veto), one lepton in signal region
- Background yield estimated from data in $m_{\gamma\gamma}$ mass sideband, using acceptance calculated in zero-lepton sideband
- Signal extraction with counting experiment



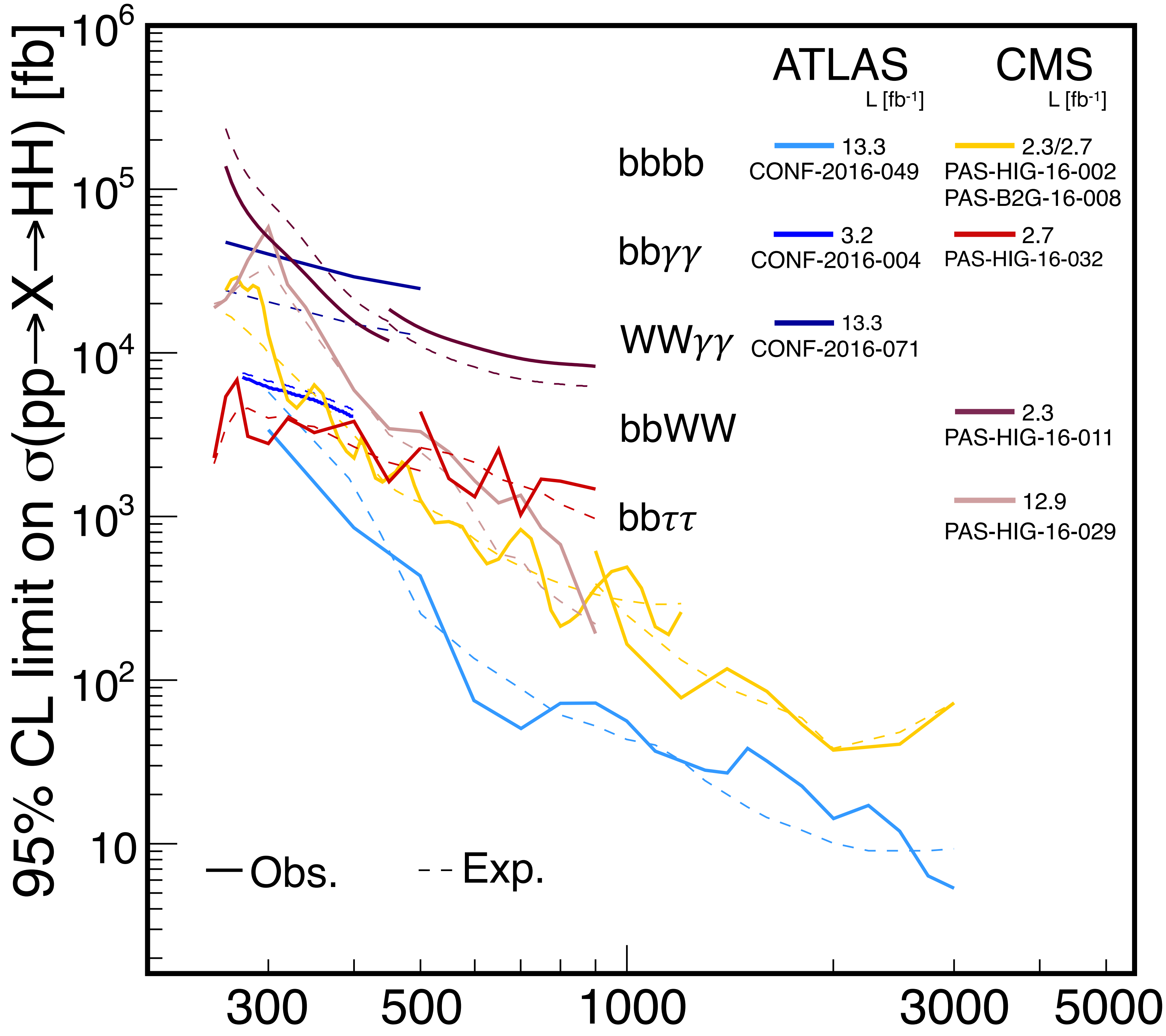
Process	Number of events	
Continuum background	7.26	± 1.23
SM single-Higgs	0.616	± 0.115
SM di-Higgs	0.0187	± 0.002 24
Observed	15	



Obs (exp) limit on σ (pp→hh) x BR (hh→WW$\gamma\gamma$) : 24.4 (12.6) fb [obs: 747 x SM]

Results overview – resonant searches

- Complementarity of searches in different mass ranges
- Similar sensitivity for many final states
  - much to gain from a HH combination!



NOTE: ATLAS bbbb limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypothesis

Result overview – non resonant searches

Channel	Obs. (exp) 95% C.L. limit on σ/σ_{SM} ATLAS	CMS
bbbb	29 (-)	342 (308)
bbWW	-	410 (227)
$bb\tau\tau$	-	208 (172)
$bb\gamma\gamma$	117 (161)	91 (90)
$\gamma\gamma WW$	747 (386)	-

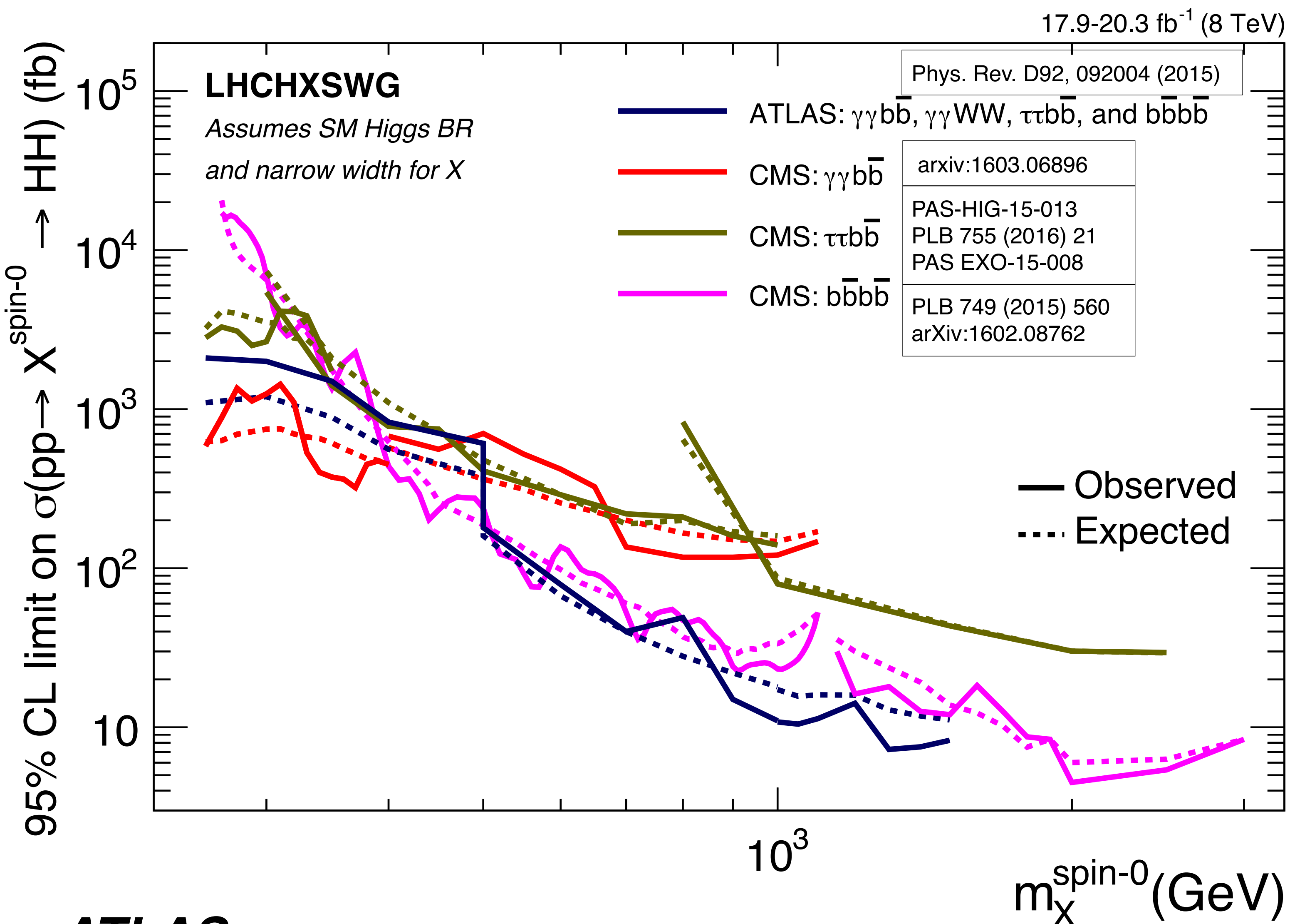
- Good complementarity between channels and experiments
  - bbbb and $bb\gamma\gamma$ with the best sensitivity to SM production at the moment
- Not the same amount of data analysed!
  - ranging from 2.3 to 13.3 fb^{-1}
- CMS studied also anomalous couplings hypotheses in the bbWW and $bb\tau\tau$ final states
  - shape variation from 5D effective Lagrangian parametrisation taken into account
  - limit scan of effective Lagrangian parameters
- Many interesting results from 8 TeV analyses not shown

Conclusions

- HH production at the LHC allows us to probe the scalar sector structure, test its extensions, and identify signs of new physics. It will ultimately give access to the Higgs boson trilinear coupling
- Both resonant and non-resonant production mechanisms must be explored to gain access to a broad range of underlying (new) physics
- The searches performed by the ATLAS and CMS collaborations with 13 TeV data are shown. Many different final states with complementary sensitivities are explored
- No sign of deviation from the SM is observed. Limits are set as a function of the $X \rightarrow hh$ resonance mass and for SM and BSM couplings in non-resonant production
  - still far in sensitivity from SM production
- About 2x/10x of the analysed luminosity has been collected this year
  - expect update from most analyses by Moriond 2017 and possibly a combination of different final states by the end of the year
- Looking forward for the results on the latest data!

Additional material

Summary of 8 TeV results



ATLAS

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

- Searches in bbbb, bb$\tau\tau$, bb$\gamma\gamma$, WW$\gamma\gamma$ (ATLAS only) final states
- ATLAS performed a combination of the four channels
  Phys. Rev, D92, 092004 (2015)
  - bbbb dominant at high mass
- Best obs (exp) sensitivity to SM HH production
  - CMS: 74 (62) x SM from bb$\gamma\gamma$
  - ATLAS: 78 (48) x SM from combination