Search and prospects for HH production

Luca Cadamuro

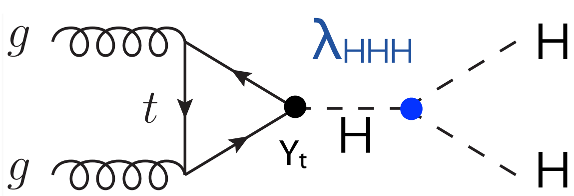
on behalf of the ATLAS and CMS collaborations

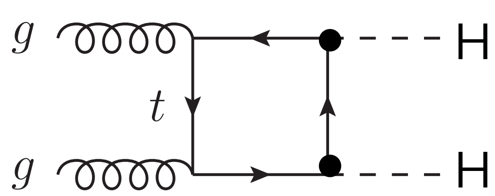
LLR – École polytechnique

52nd Rencontres de Moriond, EW session

March 19th, 2017 – La Thuile

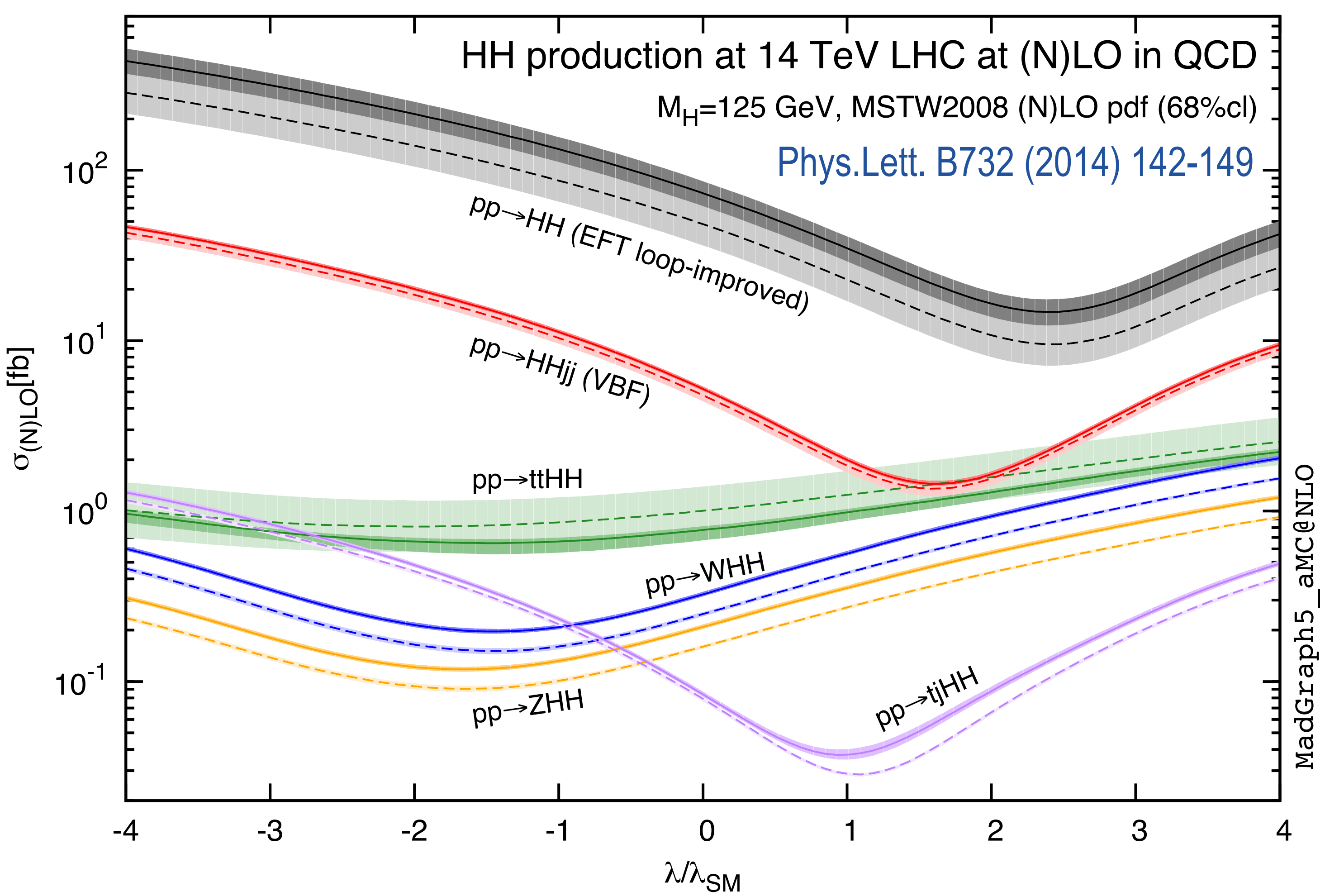
Non-resonant HH production





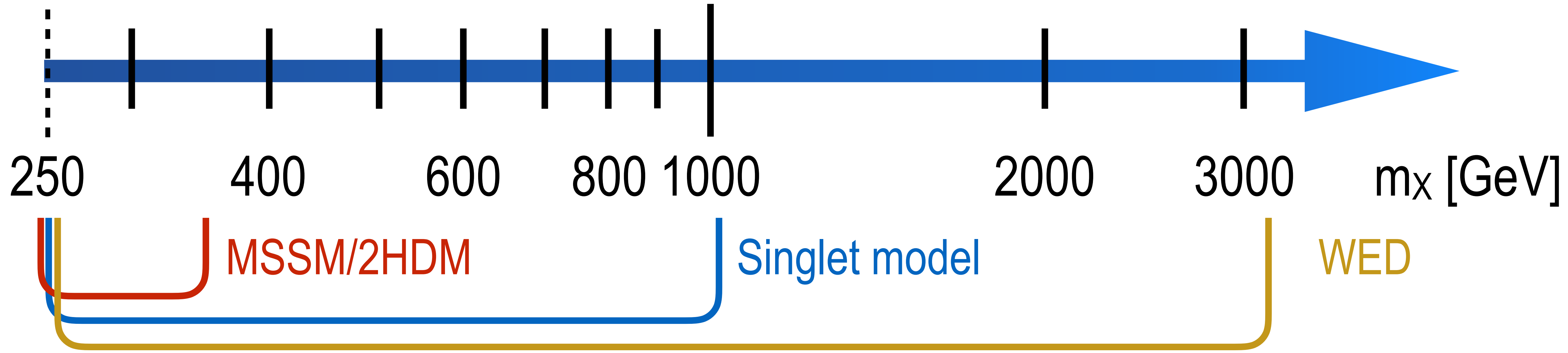
$\sigma_{gg \to HH} = 33.49^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

[13 TeV, NNLO + NNLL with top mass effects, HXSWG, arXiv:1610.07922]



- σ_{HH} : main way to extract Higgs trilinear coupling λ_{HHH}
  - direct information on the shape of the scalar Higgs potential
  - dominated by gg fusion, other production modes out of reach with current data
- Destructive interference of the two diagrams → small σ_{HH}
- Effective lagrangian used to model BSM effects: anomalous λ_{HHH} and y_t couplings and three new contact interactions
  - large modification of σ_{HH}

Resonant HH production

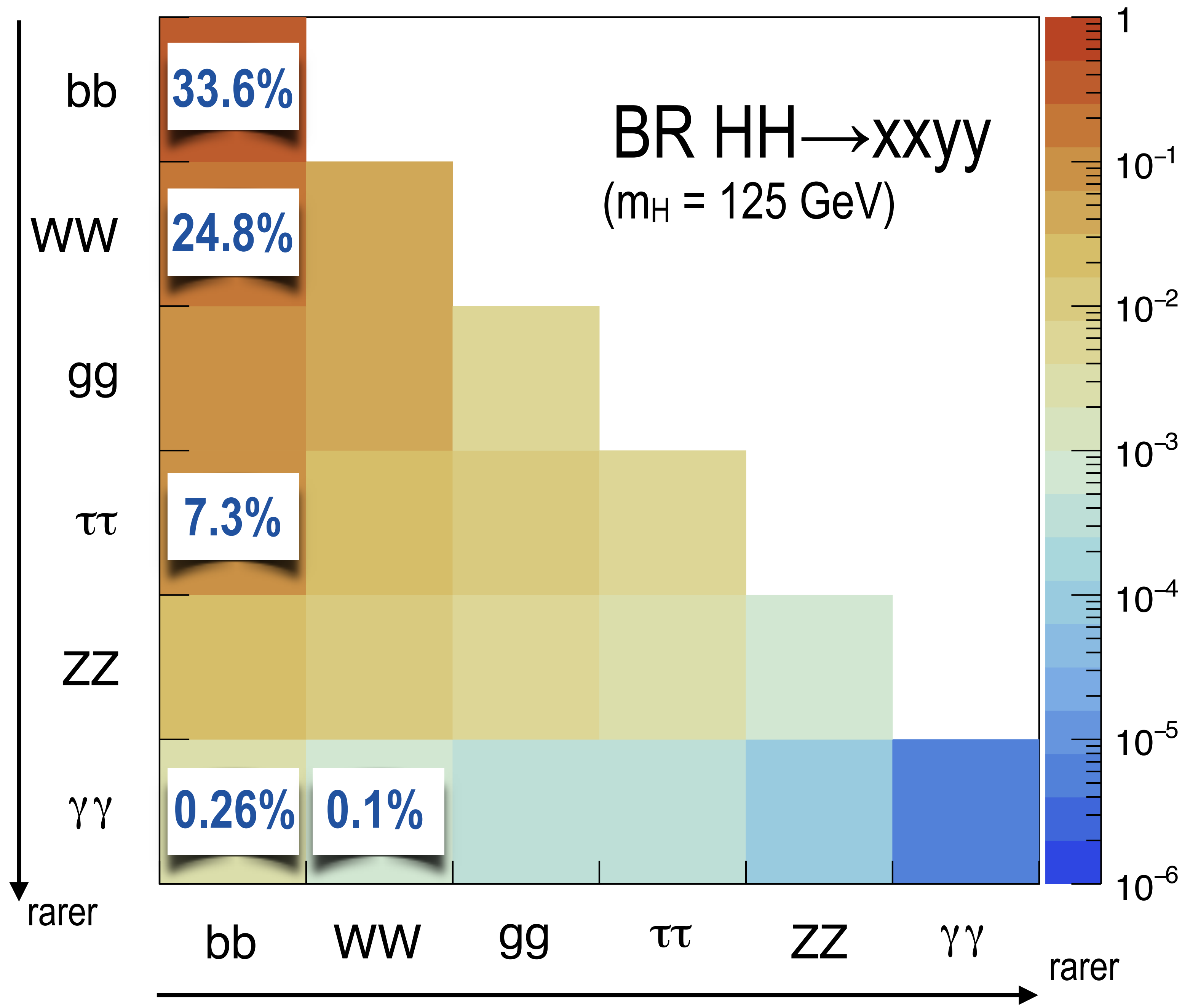


- Many different theories predict resonant Higgs pair production X→HH
  - just a few examples quoted in the scheme!
- Very different theoretical motivation, but similar experimental signature
- Full coverage of a broad m_X range is crucial to maximize the sensitivity to different models
  - no “golden” channel, multiple analysis techniques

Resonant HH production would be evidence for a new state, not predicted by the SM

Which final state?

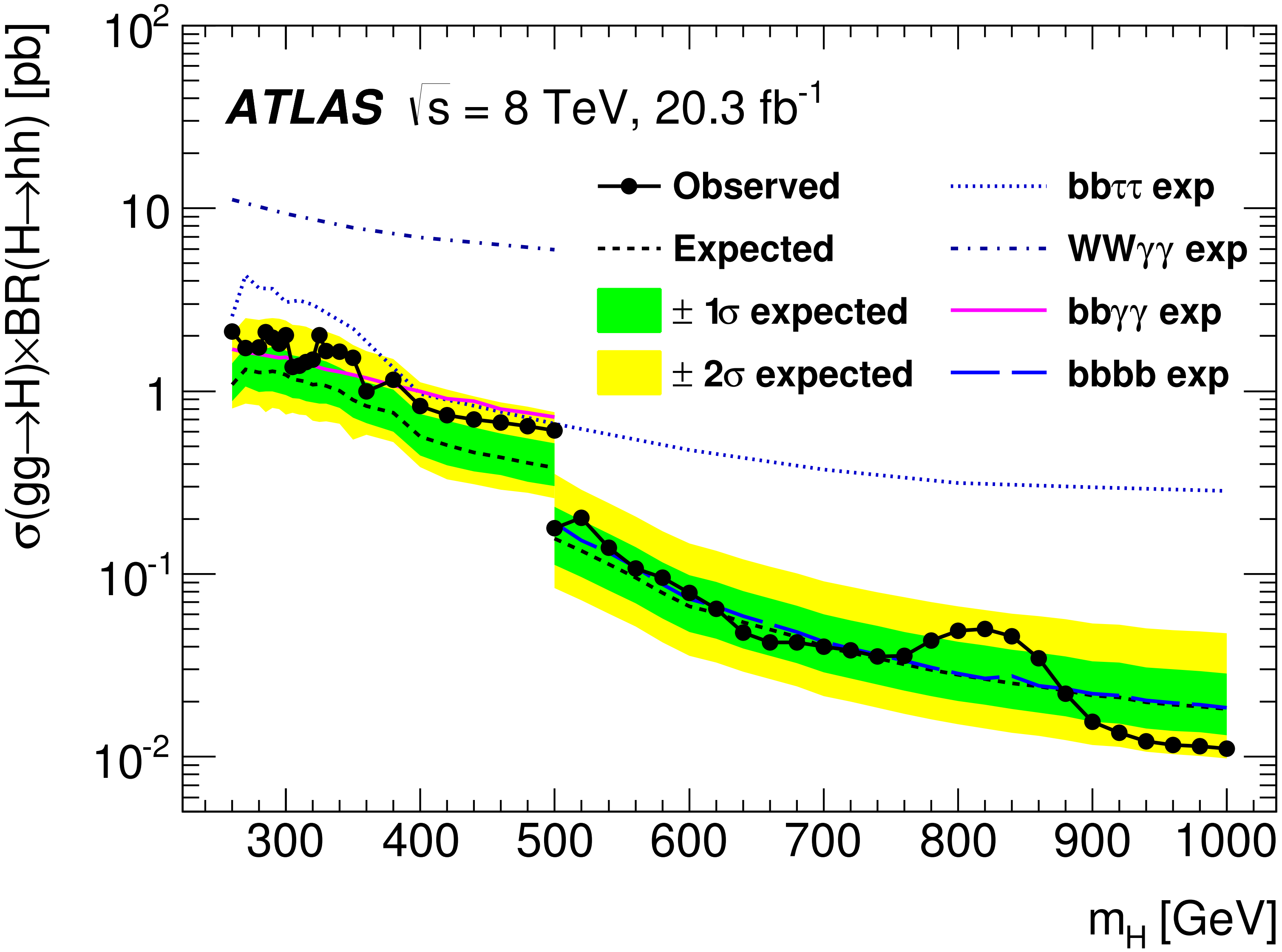
- Phenomenologically rich set of final states
- One H→bb or H→WW decay required to keep BR high enough
  - common techniques across analyses (e.g. b-tagging) + channel-specific challenges
- Complementarity of the channels
  - similar sensitivity to non-resonant production
  - different coverage in m_X



Searches at 8 TeV

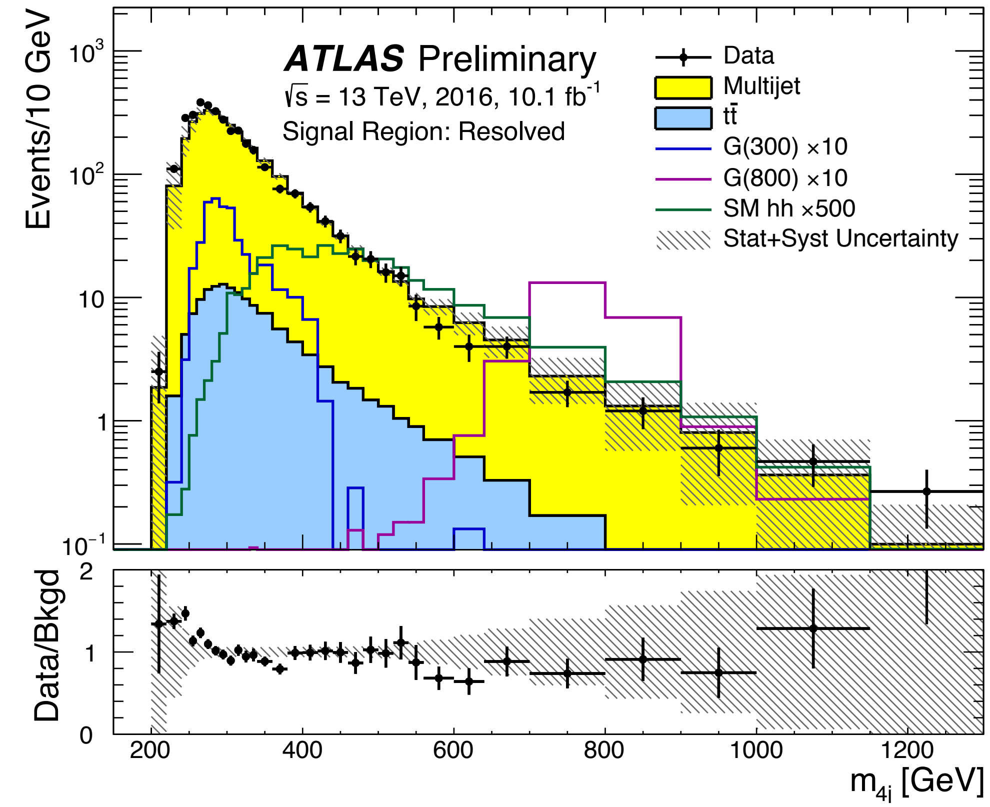
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

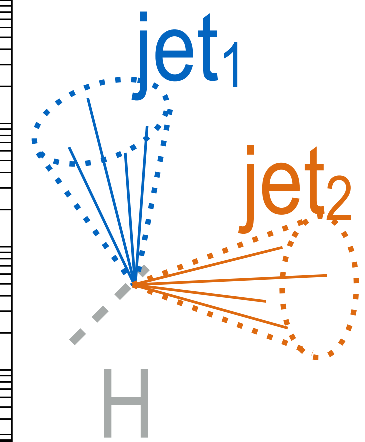
- Four channels explored and combined in ATLAS
  - bb$\gamma\gamma$ and bb$\tau\tau$ with similar sensitivity at low mass, bbbb dominant at high mass
- bb$\gamma\gamma$ + bb$\tau\tau$ + bbbb explored in CMS but not combined yet
  - exclude 58 X SM (bb$\tau\tau$), 74 X SM (bb$\gamma\gamma$)

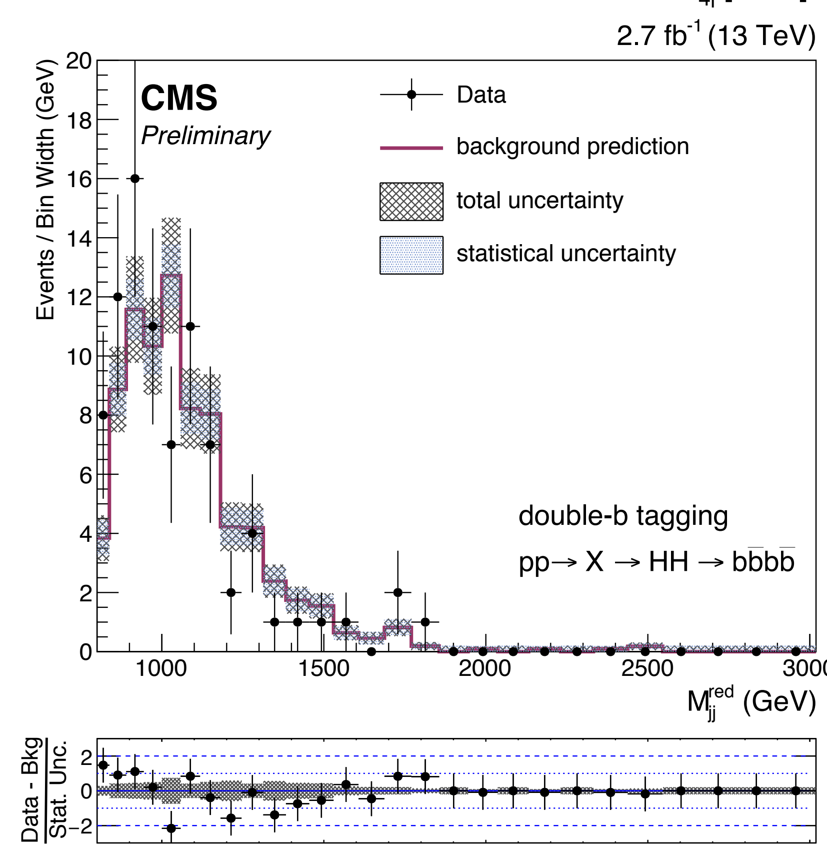


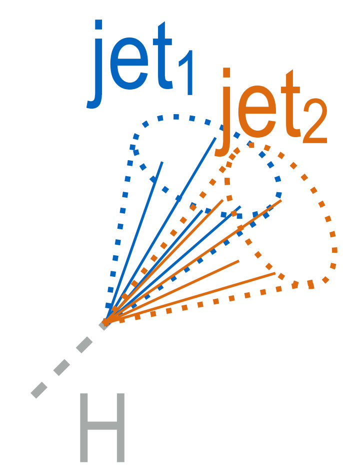
HH → bbbb

- High BR, large contamination from multijet background
  - estimated from data
- Two event topologies explored
  - resolved: four separate jets
  - boosted: jets from H→bb decay overlap, use jet with radius 0.8/1.0 + substructure techniques
- Crucially relies on b-tagging
  - b-tag at trigger level for resolved analyses
  - double b-tagging on 0.8 radius jet based on multivariate method for CMS boosted analysis
- Invariant masses of selected jets used to search for a signal



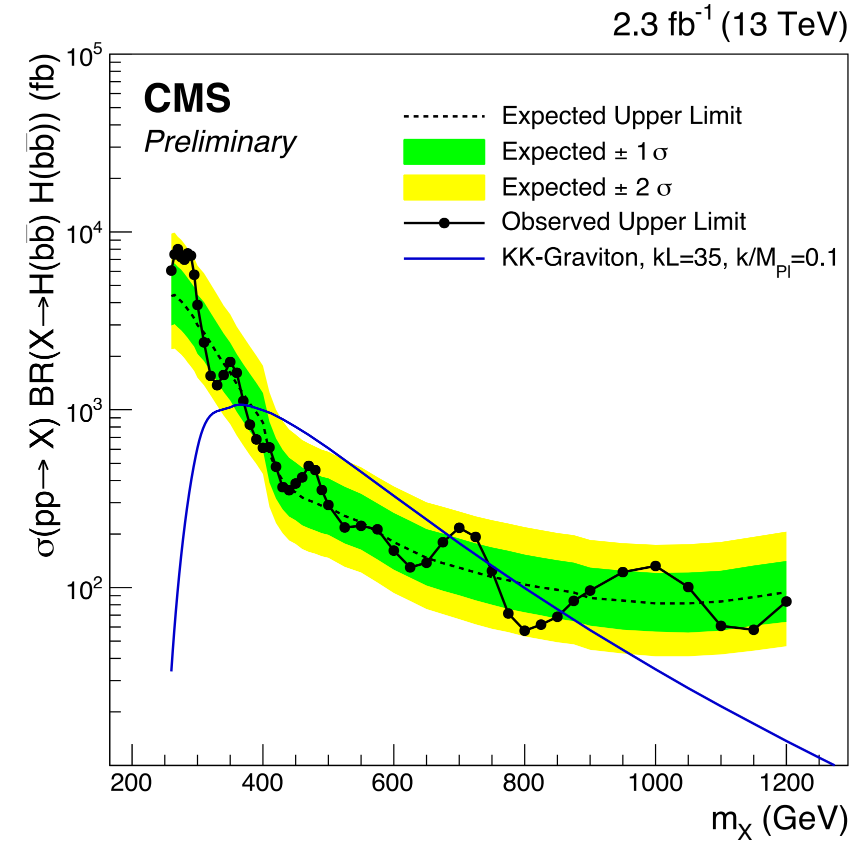


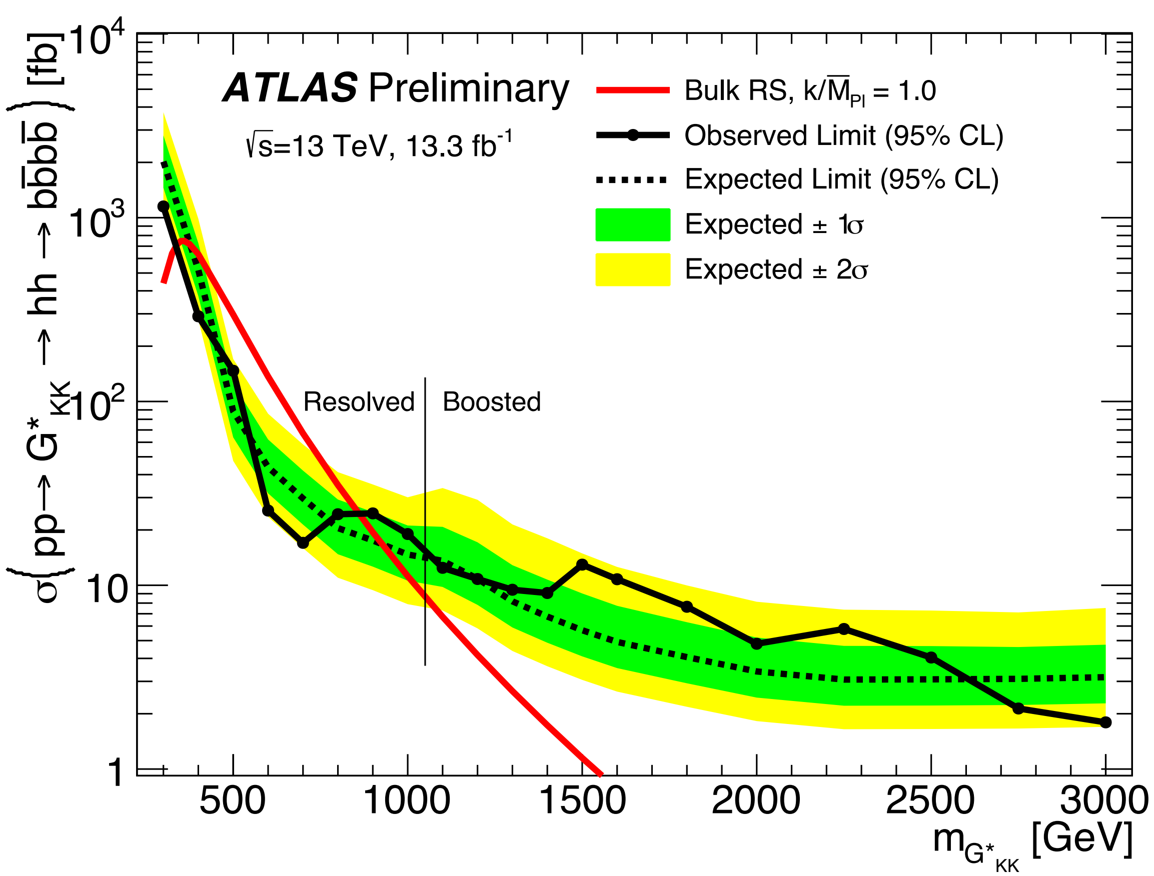


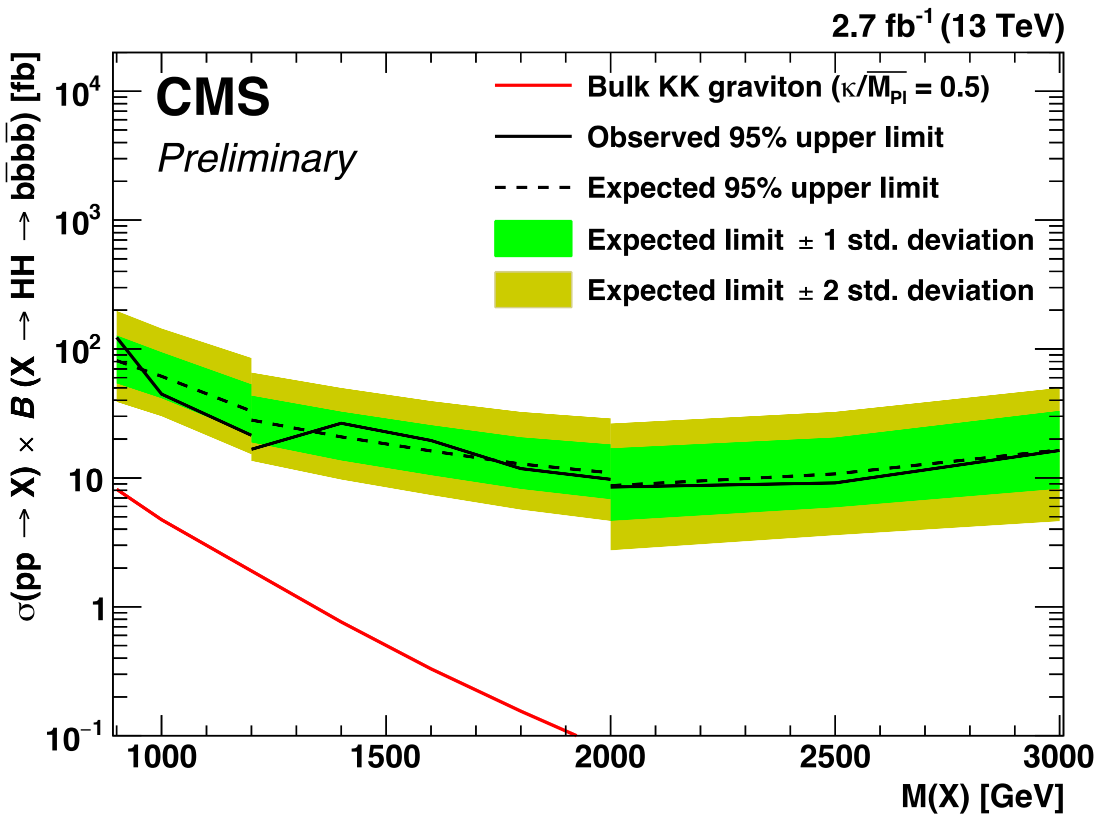


HH → bbbb

- ATLAS:
  - 13.3 fb^{-1} analyzed
  - non-resonant search excludes 29 X SM
- CMS
  - 2.3/2.7 fb^{-1} analyzed
  - non resonant search excludes 324 x SM
  - search for both spin-0 and spin-2 resonances

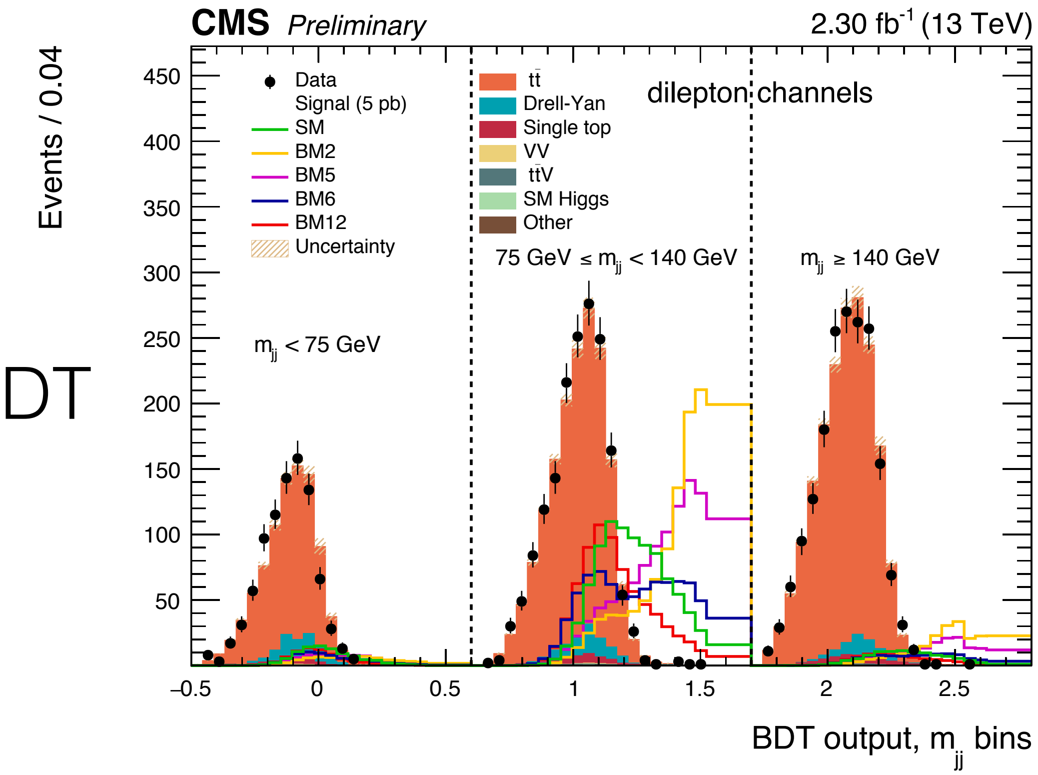


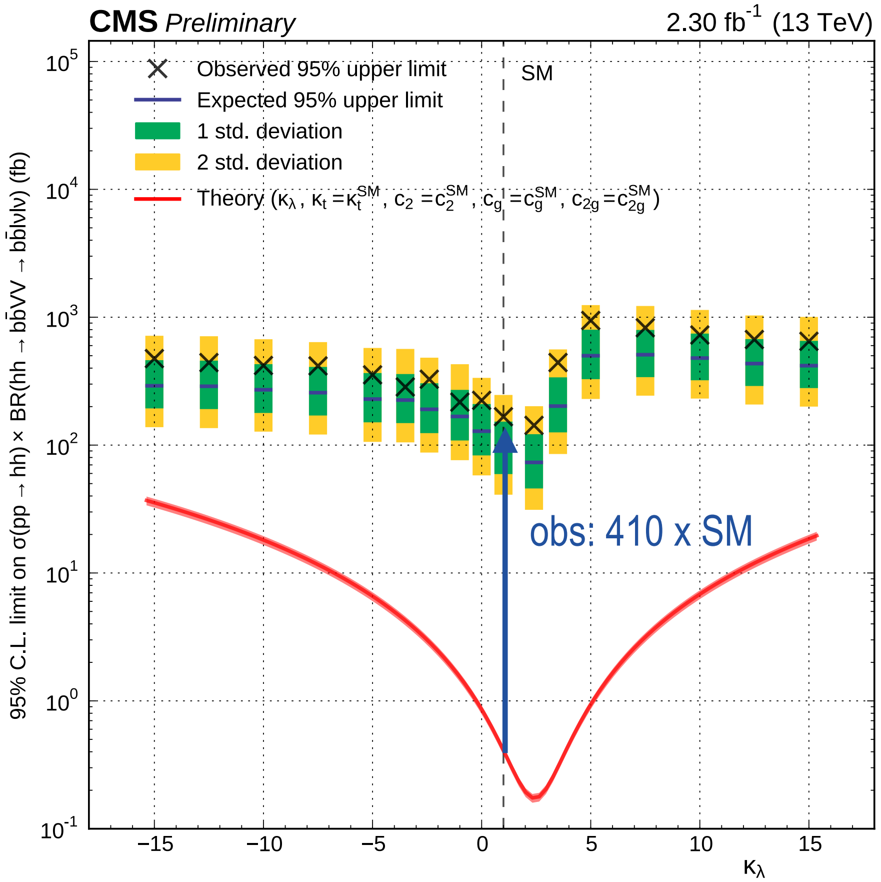


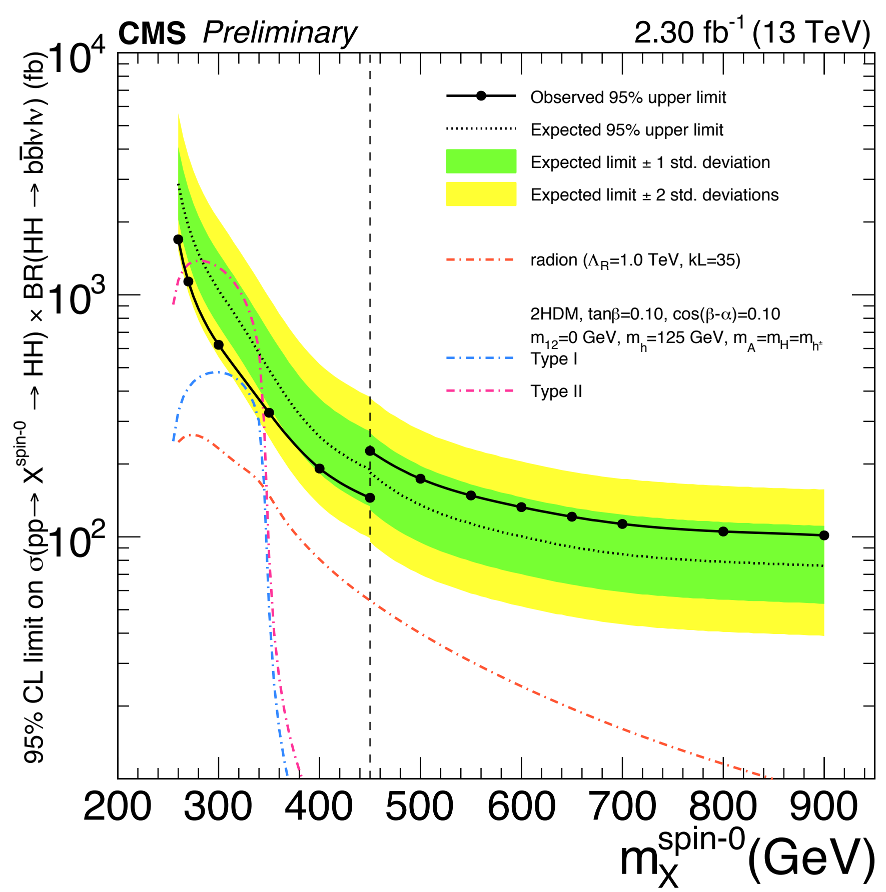


HH → bbWW

- $WW \to \ell\nu_\ell\,\ell\nu_\ell$ (ℓ = e, μ) ⟹ bbee, bbμμ, bbeμ
- Dominant background: tt (same final state)
  - constrained from m_{bb} sideband
- Exploit event kinematics to select signal using BDT
  - used as final discriminant
- Updated results on 35.9 fb^{-1} are coming for Moriond QCD!

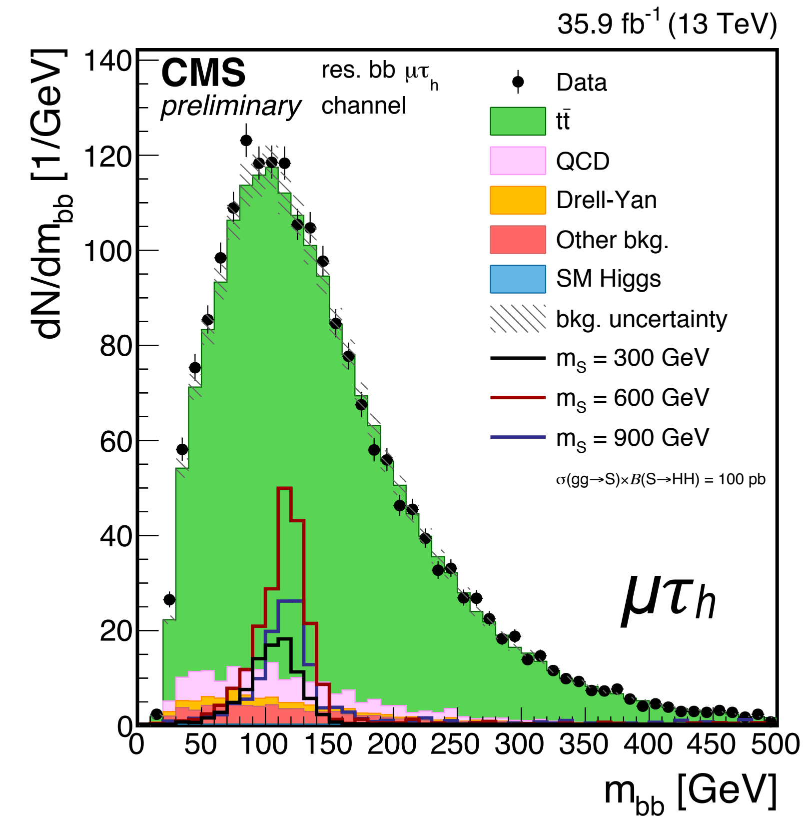


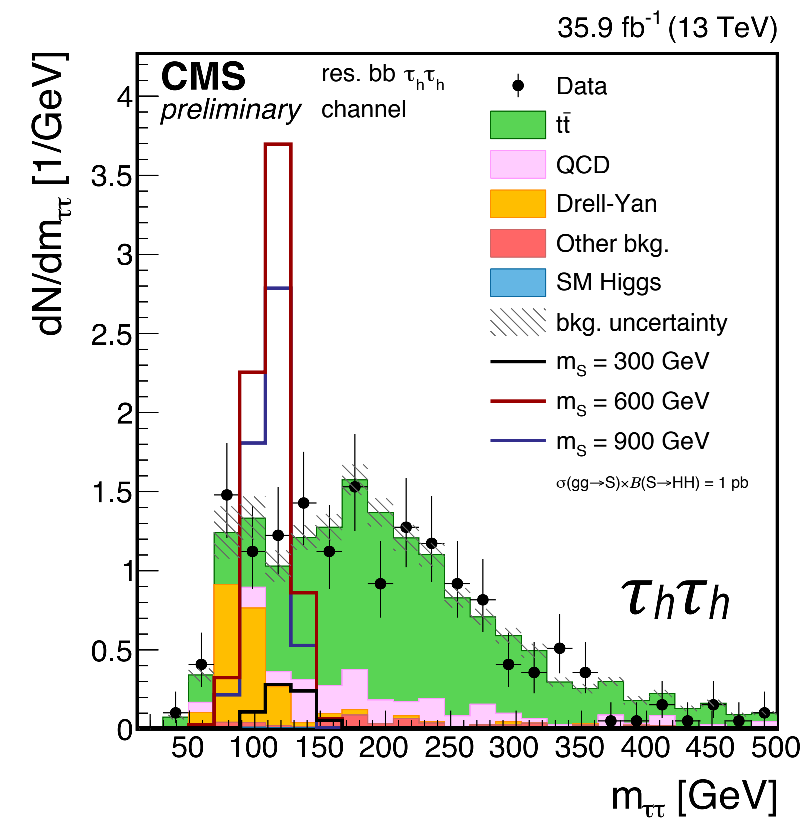




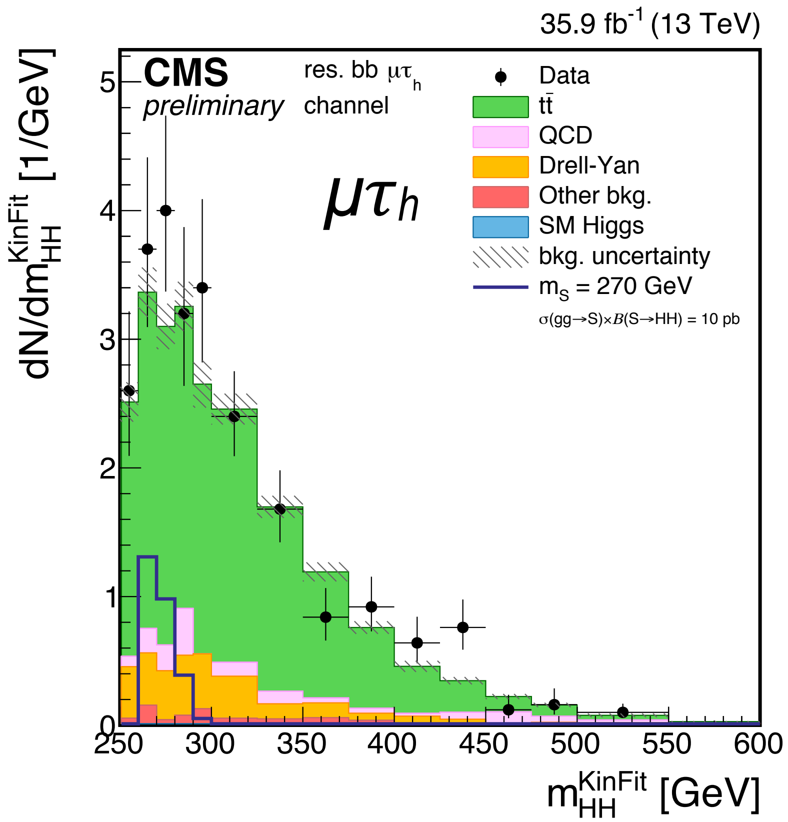
$HH \to bb\tau\tau$ new results!

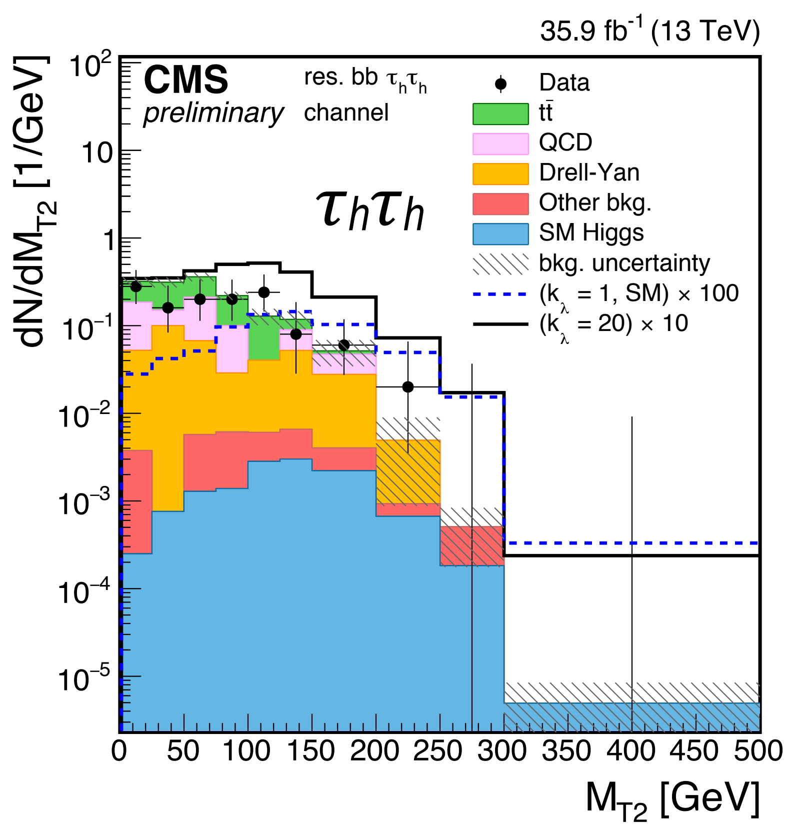
- 3 $\tau\tau$ final states: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$
  - require the presence of μ, e, τ_h candidates and 2 jets in the event
  - $m_{\tau\tau}$ (from likelihood technique) and m_{bb} must be compatible with m_H = 125 GeV
- Main backgrounds:
  - tt : from MC simulation
  - Drell-Yan : MC simulation corrected in data $Z\to\mu\mu$ sideband
  - multijet : from data sideband
- Categorization on the selected $H\to bb$ jet candidates
  - 2b-tagged jet category
  - 1b-tagged jet + 1 untagged jet category
  - “boosted” category with a R=0.8 jet to improve reconstruction H decays at high m_X



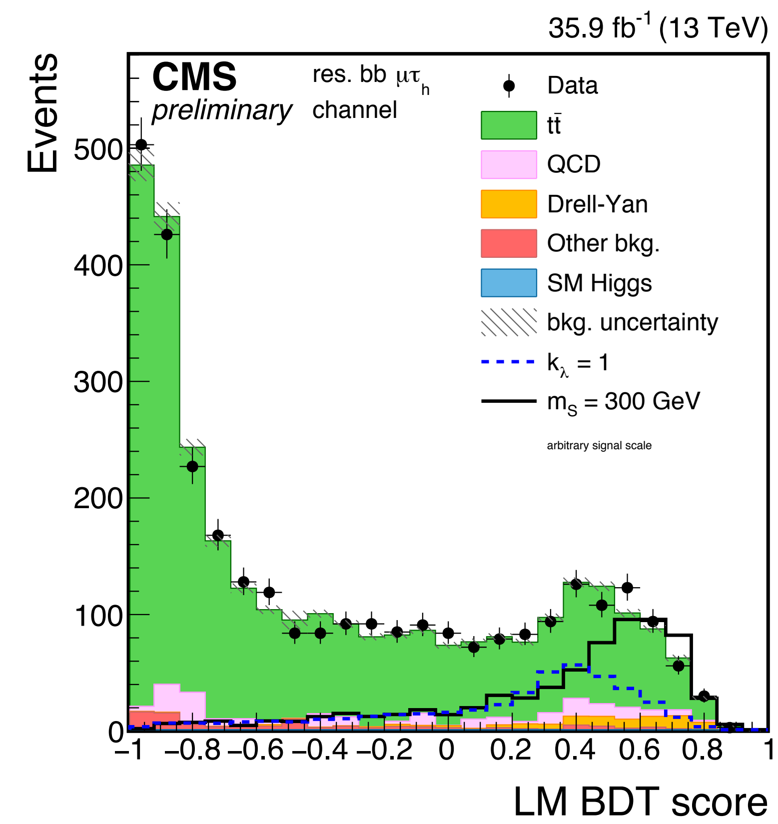


$HH \rightarrow bb\tau\tau$ new results!





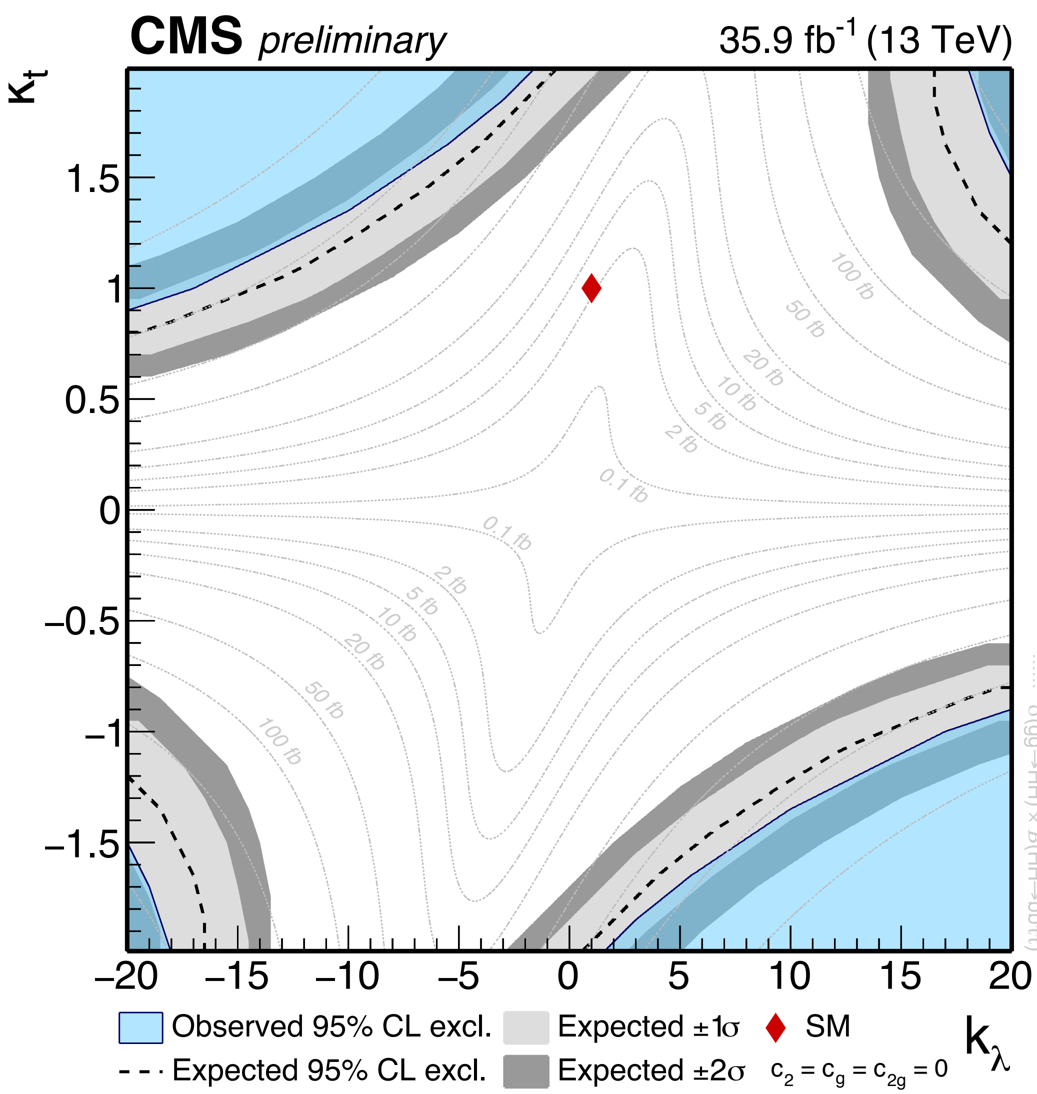
- tt background rejected with BDT method in $\mu\tau_h$ and $e\tau_h$ final states
  - based on angular separation of leptons and reconstructed H candidates and m_T
- Fitted observables:
  - resonant search: kinematic reconstruction of HH decay
  - non-resonant search: “stransverse mass” M_{T2} that has optimal separation of signal from background

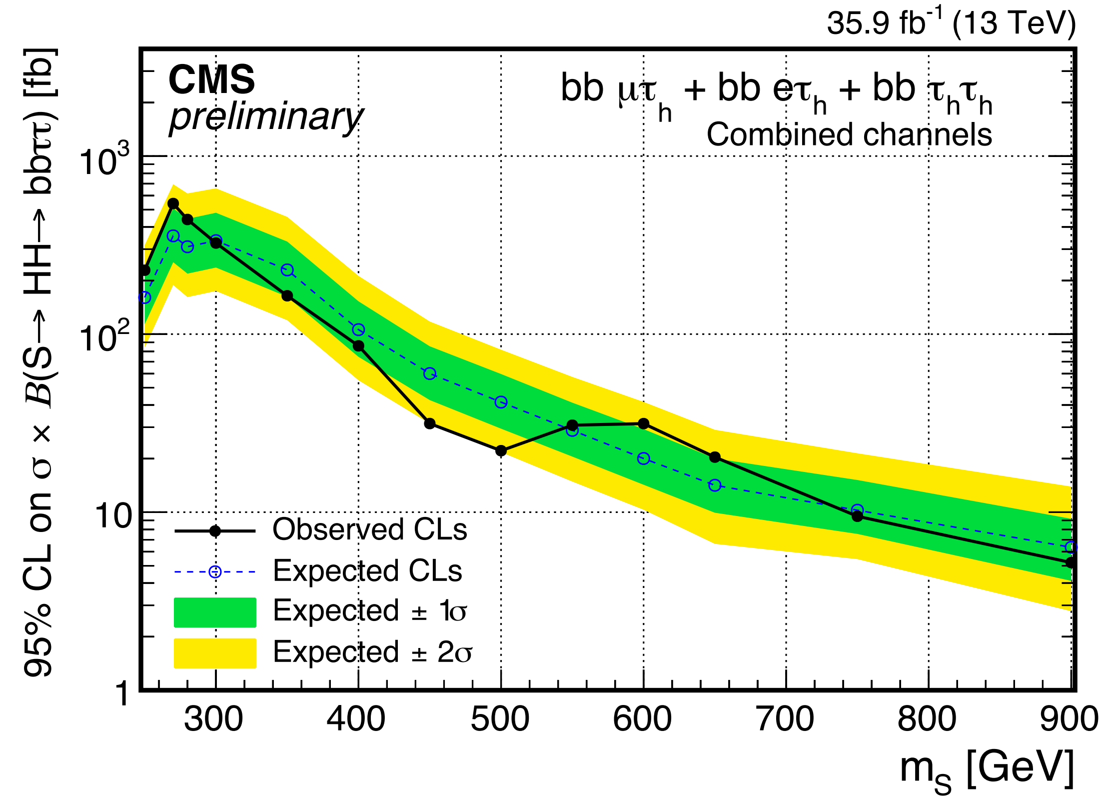


$$m_{T2} \equiv \min_{\boldsymbol{p}_{T1}+\boldsymbol{p}_{T2}=\boldsymbol{p}_T^{\tau\tau}} \{\max[m_T(m_{b1},\boldsymbol{p}_T^{b1},m_{vis}^{\tau1},\boldsymbol{p}_{T1}),m_T(m_{b2},\boldsymbol{p}_T^{b2},m_{vis}^{\tau2},\boldsymbol{p}_{T2})]\}$$

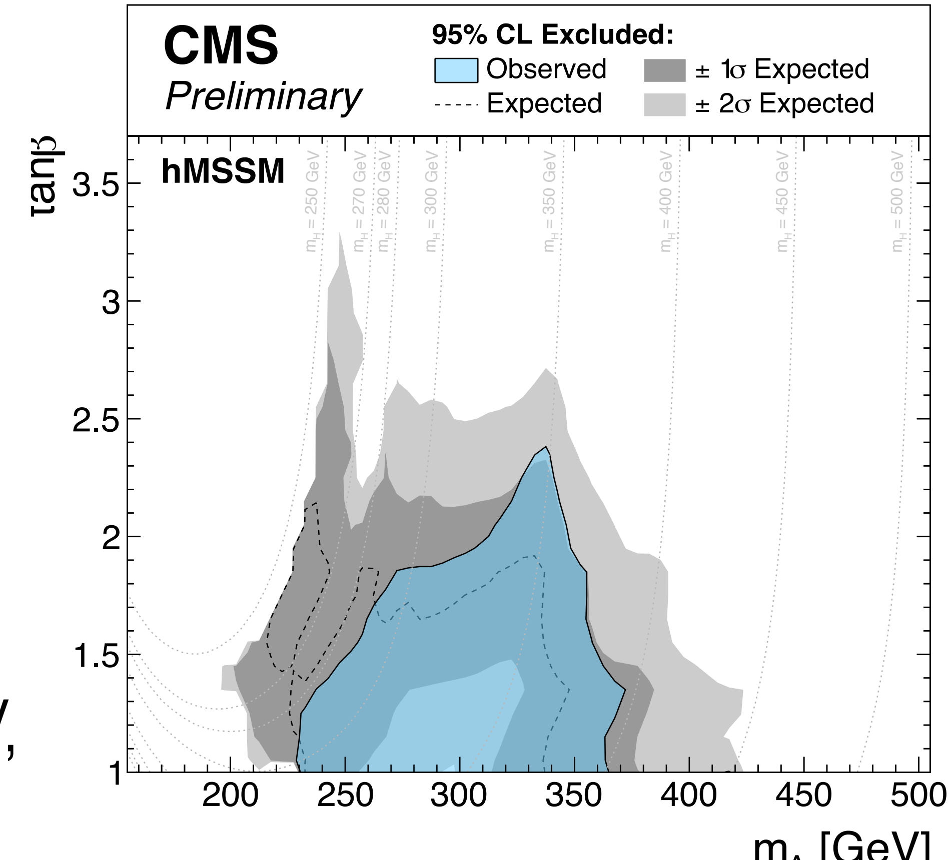
HH → bbττ

new results!



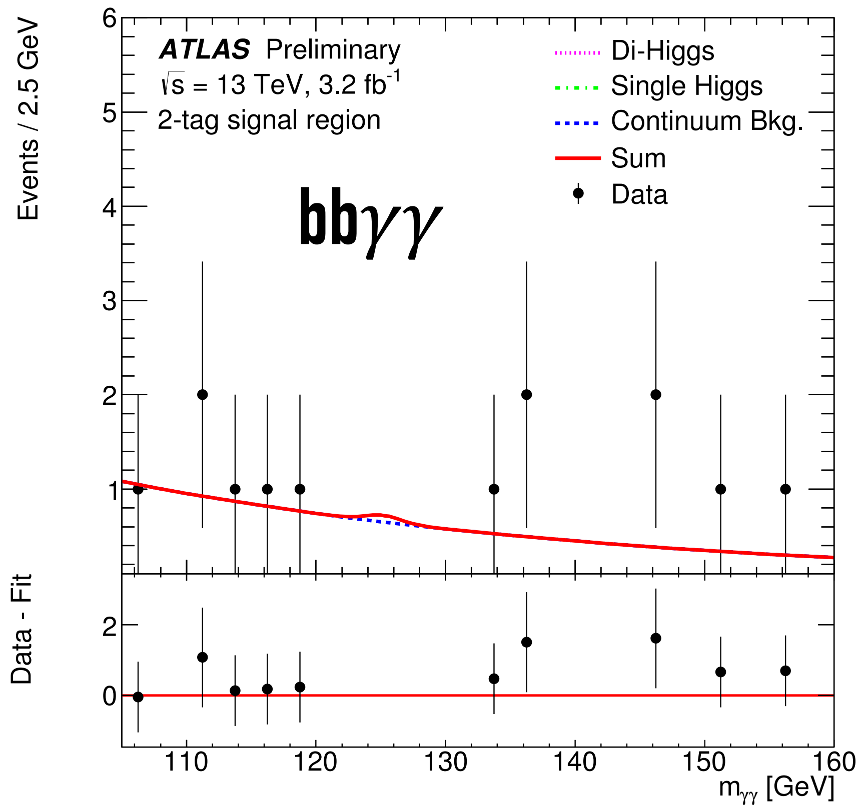


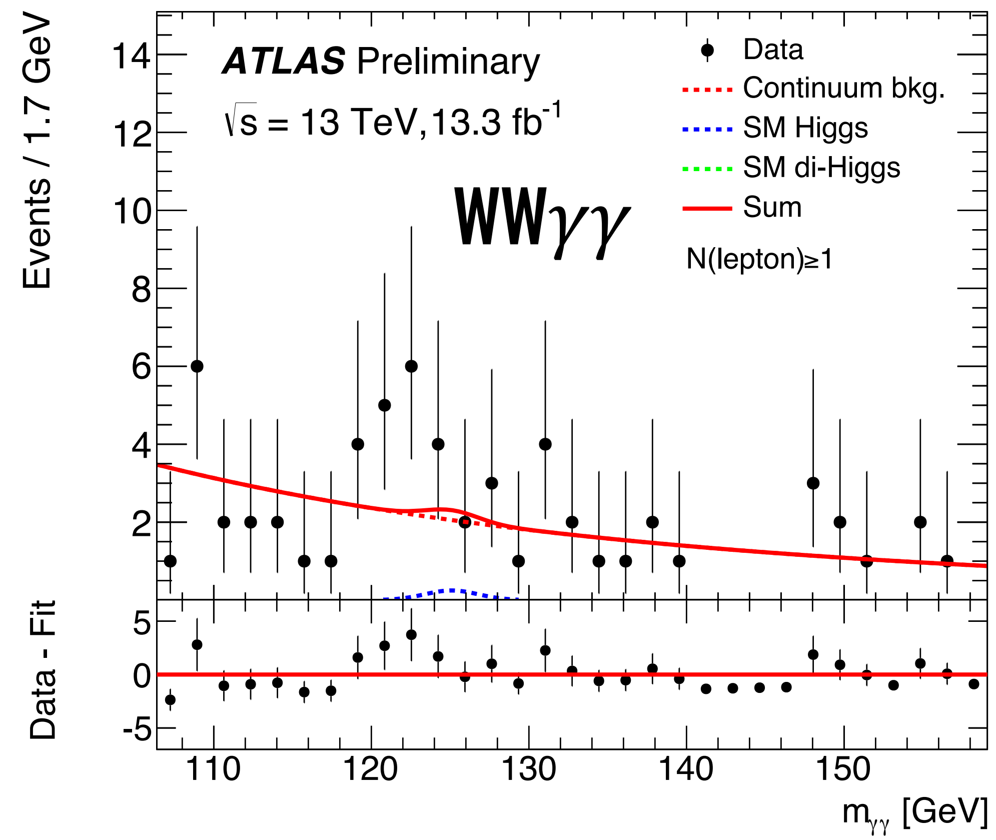
- Non-resonant search excludes 28 times the SM
  - anomalous λ_{HHH} and y_t couplings tested
  - sensitive to the sign of y_t
- Resonant production tested up to m_X = 900 GeV, and interpreted in the hMSSM

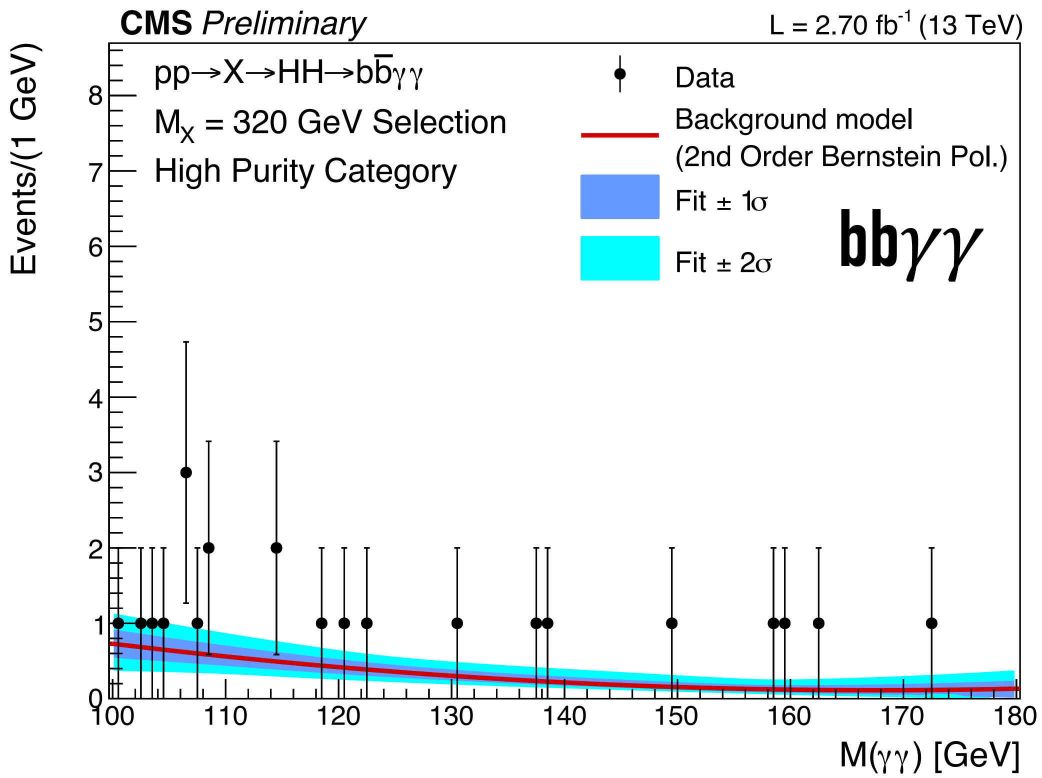


HH→bb$\gamma\gamma$ / WW$\gamma\gamma$

- Rare but very clean final states
  - large signal acceptance
  - main background from continuum jj$\gamma\gamma$ (+ℓ) production estimated from data
  - exploit excellent resolution on $m_{\gamma\gamma}$ to look for a signal

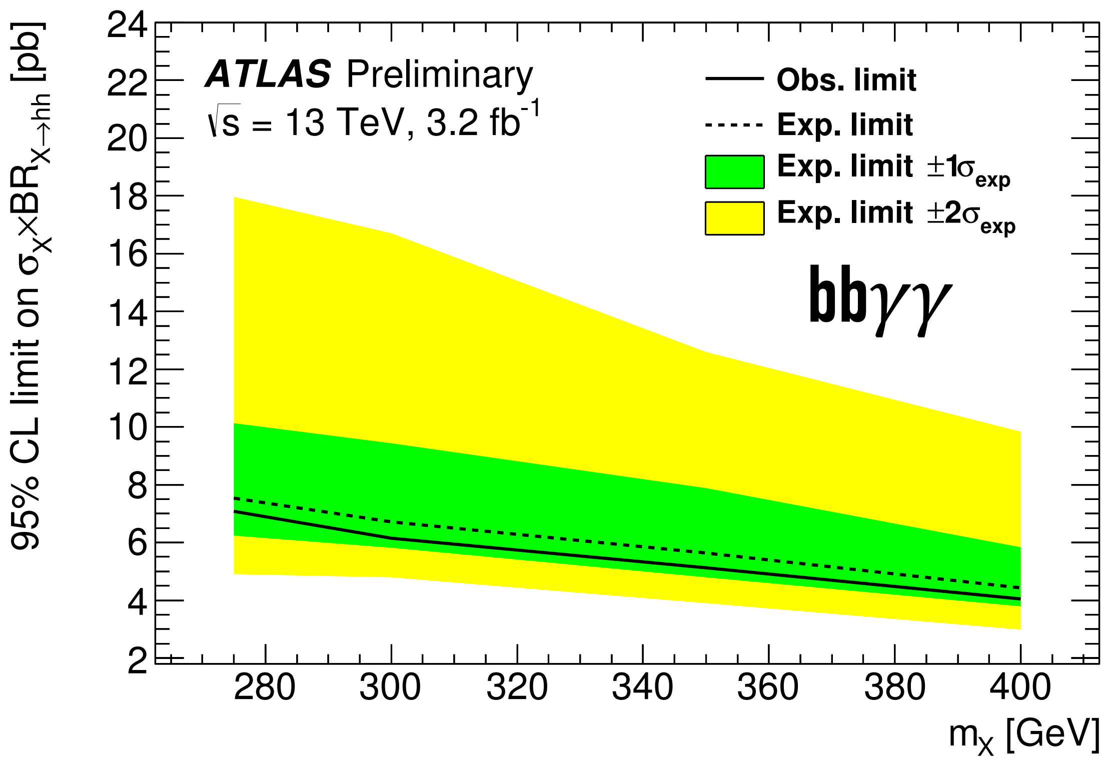


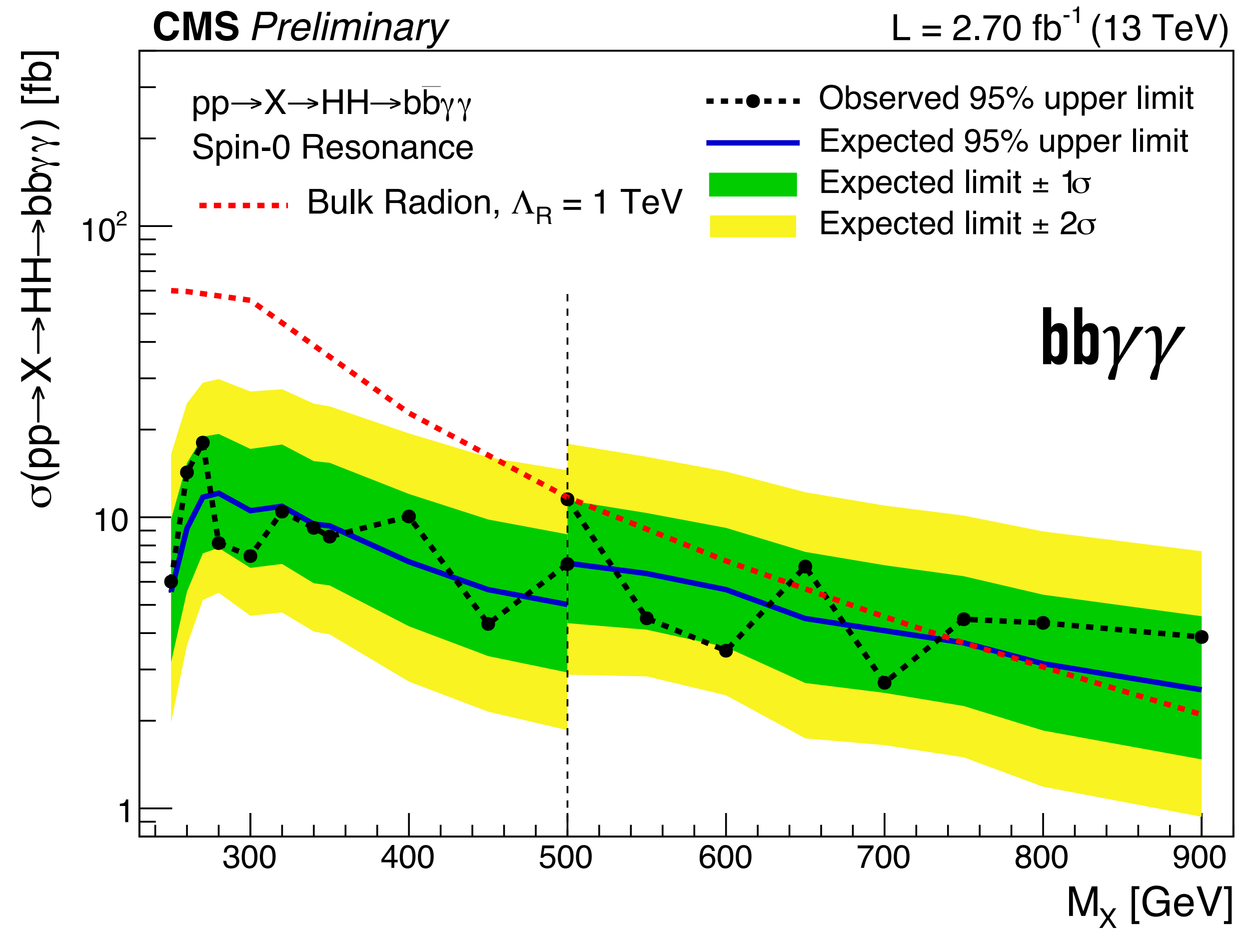


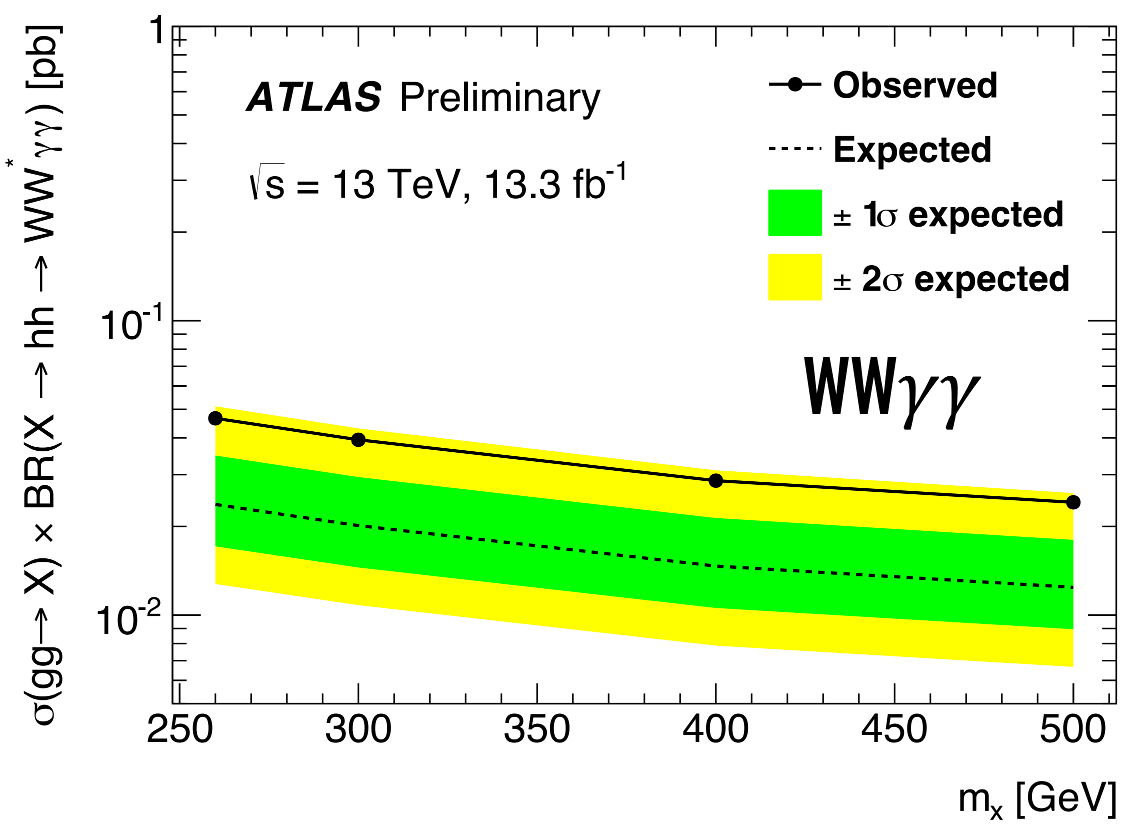


- Two photons and two jets in the event for bb$\gamma\gamma$
- One additional lepton for WW$\gamma\gamma$→jjℓ$\nu_\ell\gamma\gamma$
- Dedicated methods to improve m_{bb} resolution
- Additional categories with 2 and 1 b-tagged jets for CMS bb$\gamma\gamma$

$HH \rightarrow bb\gamma\gamma$ / $WW\gamma\gamma$

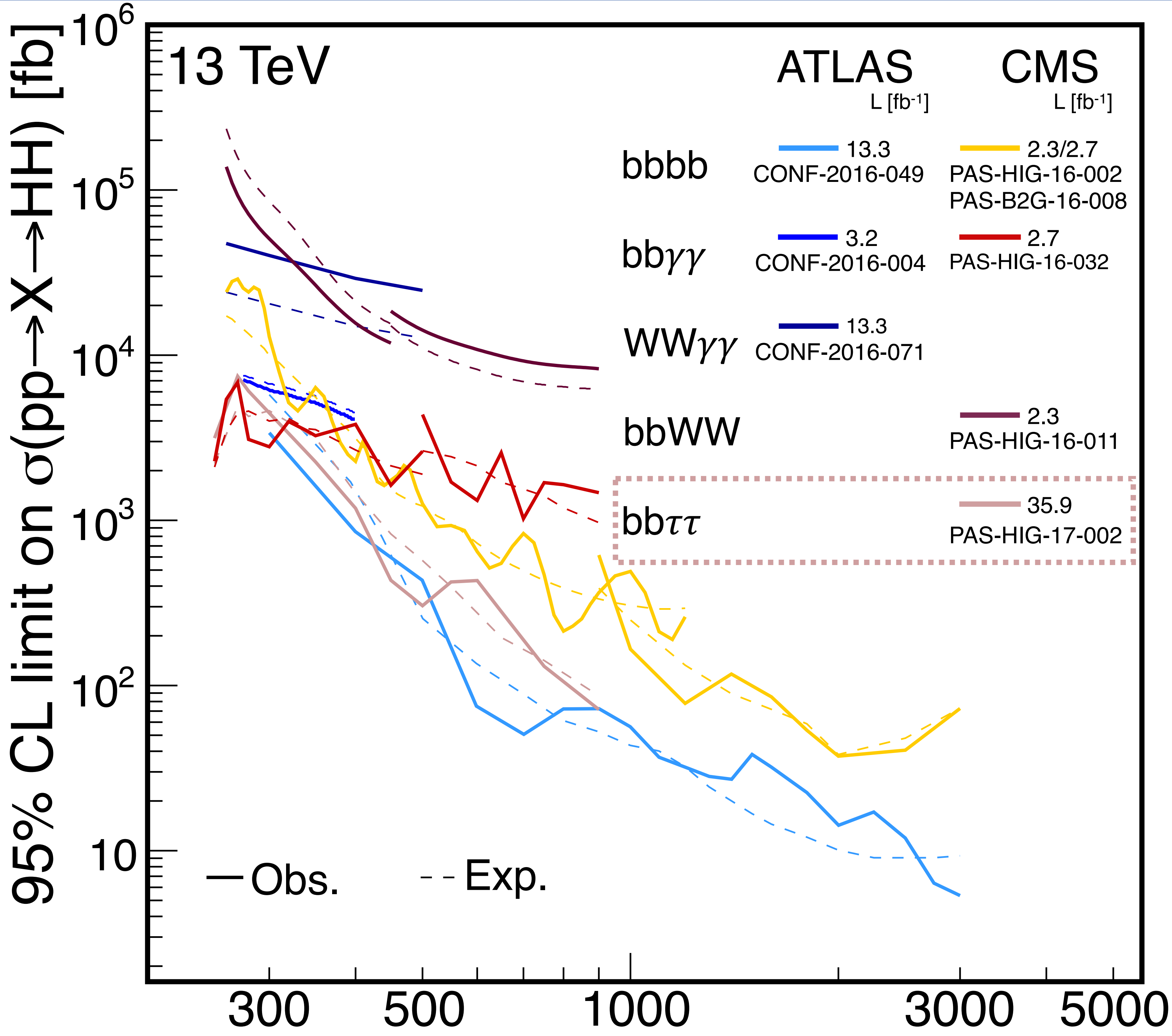






Obs (exp) limit on non-resonant production		
	$bb\gamma\gamma$	$WW\gamma\gamma$
ATLAS EXPERIMENT	117 (161) X SM	747 (386) X SM
CMS	91 (90) X SM	-

Results overview



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

Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM} ATLAS	CMS
bbbb	29 (38)	342 (308)
bbWW	-	410 (227) ▣
bbττ	-	28 (25) ▣
bbγγ	117 (161)	91 (90)
WWγγ	747 (386)	-

2.3-3.2 fb^{-1} | 13.3 fb^{-1} | 35.9 fb^{-1}

▣: Test of anomalous HH couplings

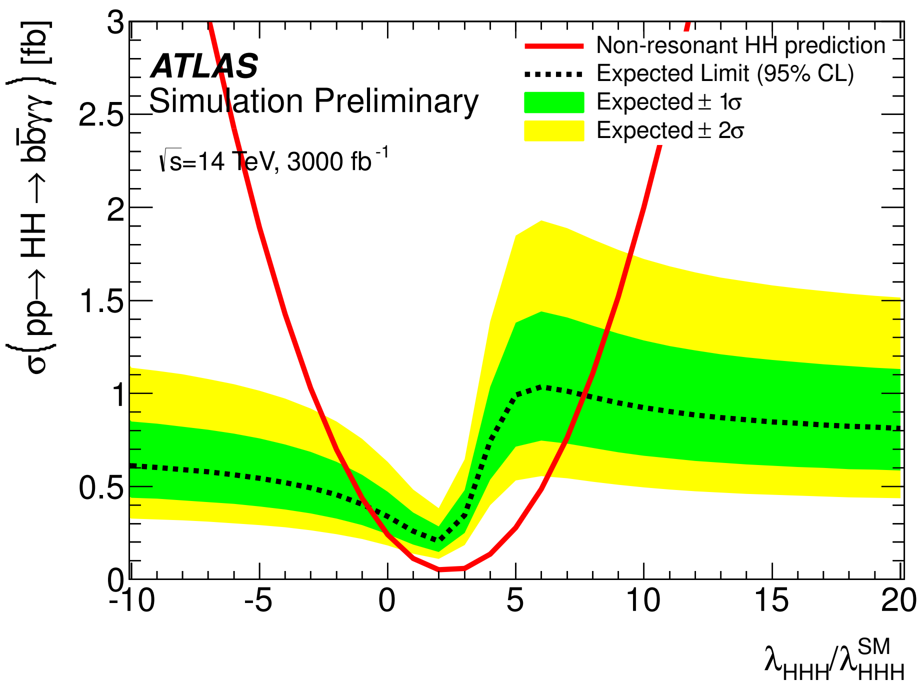
- Complementarity in different mass ranges
  - much to gain from a combination!

Future prospects

- Measurement of σ_{HH} and determination of λ_{HHH} are one of the main points of the physics programme at the HL-LHC (3 ab^{-1} of data)
- Two alternative approaches to estimate the sensitivity to HH production

ATLAS EXPERIMENT

- parametric simulation of upgraded detector response

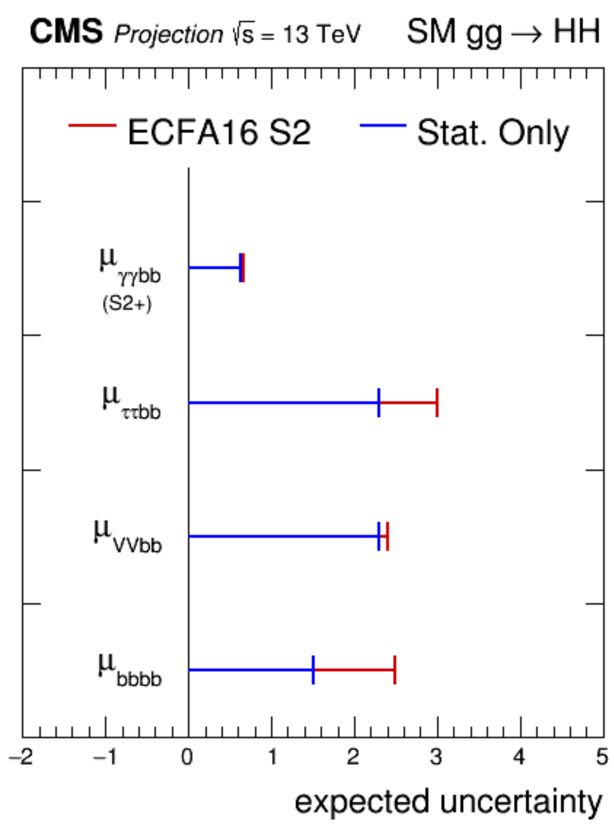


$bb\gamma\gamma$, $bb\tau\tau$ and bbbb studied

- Best significance is 1.05σ from $bb\gamma\gamma$

CMS

- extrapolation of results from 13 TeV, 2.3/2.7 fb^{-1} to HL-LHC (conservative: current results not optimal for high luminosity)



Significance

$bb\gamma\gamma$	1.6σ
$bb\tau\tau$	0.39σ
bbVV	0.45σ
bbbb	0.39σ

Combination of final states and of ATLAS and CMS will be crucial to observe HH production

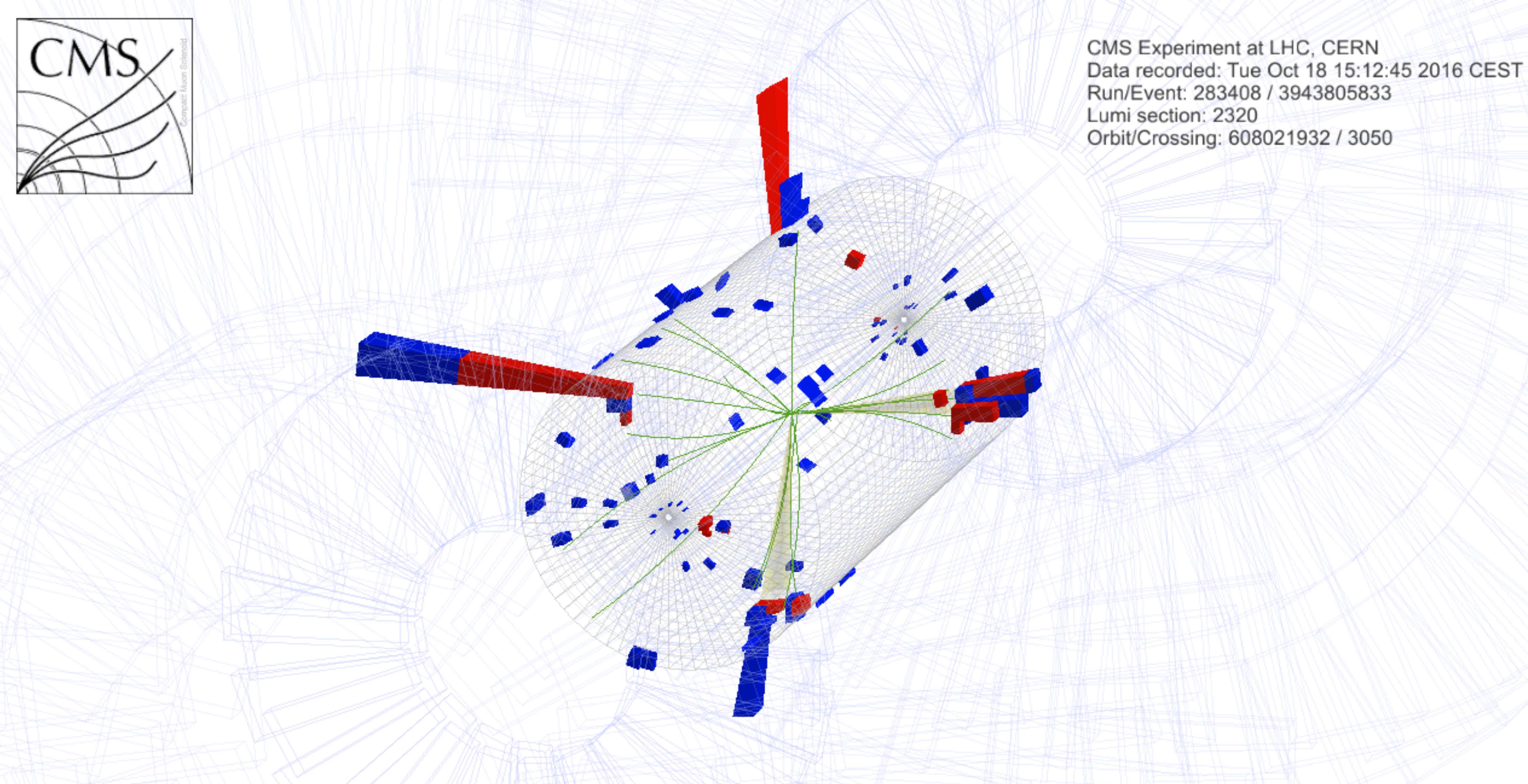
Conclusions

- What can we learn from HH production?
  - search for new physics via resonant production
  - probe the 5-dimensional structure of the BSM effective Lagrangian
  - access the shape of the scalar Higgs field via λ_{HHH}

- Where do we stand?
  - several HH final states explored at 13 TeV by ATLAS and CMS
  - no sign of (B)SM HH production yet: best limit is 28 x SM

- What's next?
  - more updated results with full 2016 luminosity
  - new HH final states and a combination are coming soon
  - projections show that in the long term (HL-LHC) we can have some sensitivity to SM HH, but analyses are evolving quickly, and we expect to do better!

HH is (almost) at reach!



HH→bb$\tau\tau$ or background?

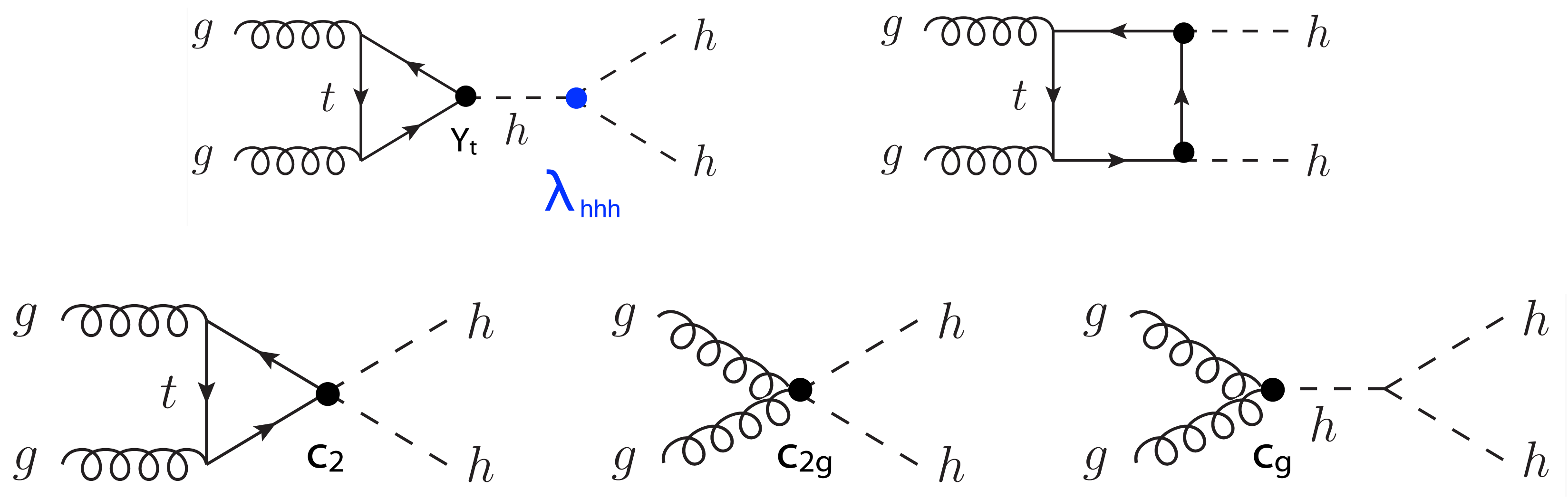
We expect to have already recorded a few HH events

Additional material

Effective Lagrangian parametrization

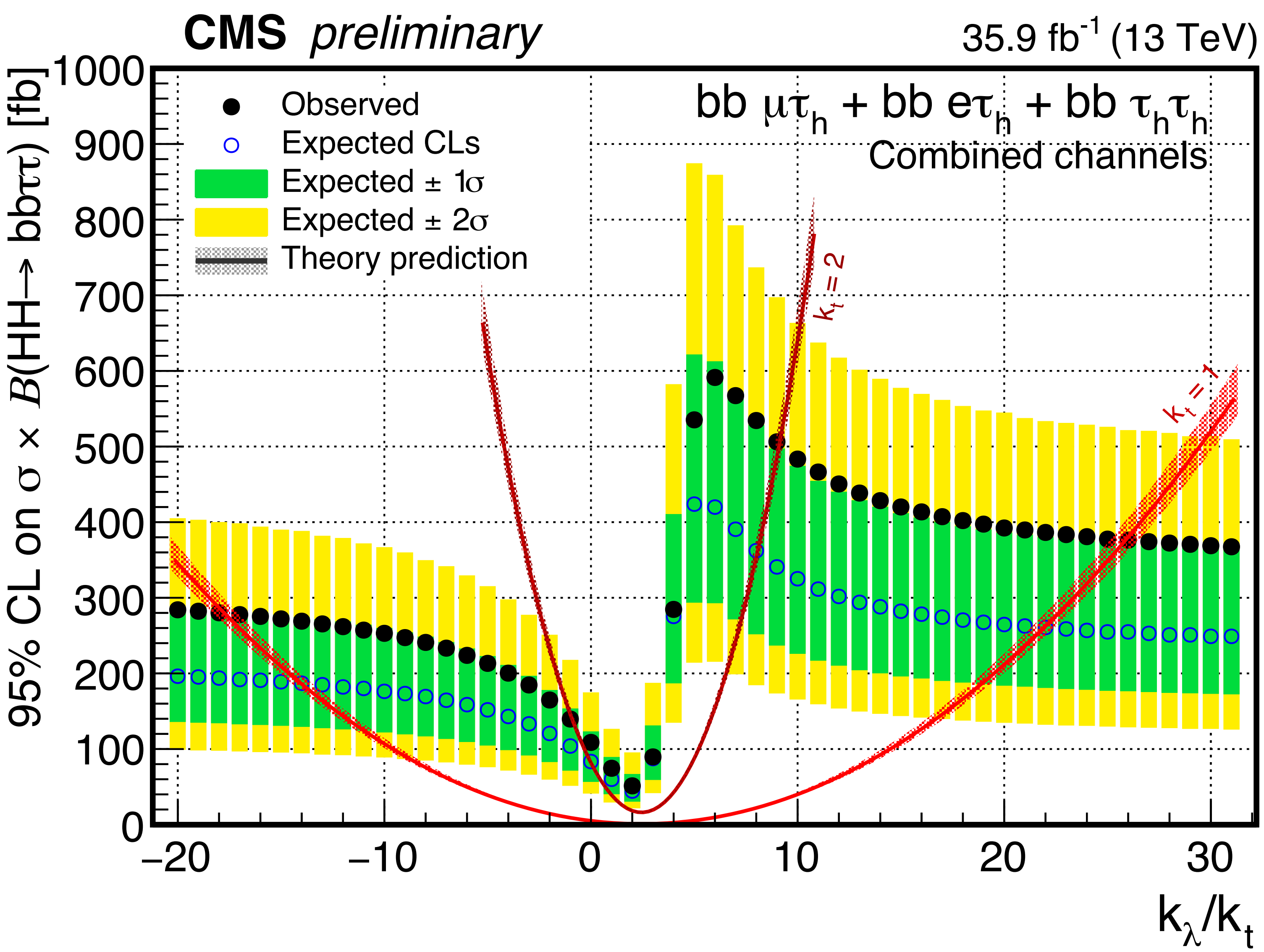
JHEP04 (2015) 167 , LHCHXSWG-2016-001

- Effective Lagrangian obtained by adding dim-6 operators to the SM Lagrangian
- Results in a modification of the SM λ_{HHH} and y_t couplings and introduces three new contact interactions
  - changing these 5 couplings affect σ_{HH} and the HH kinematics
- Analyses are exploring the 5-dimensional space of these couplings
  - a parametrization of $\sigma_{HH}(\lambda_{HHH}, y_t, c_2, c_g, c_{2g})$ is used

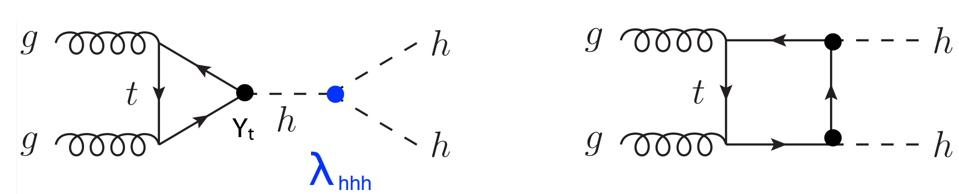


$HH \rightarrow bb\tau\tau$

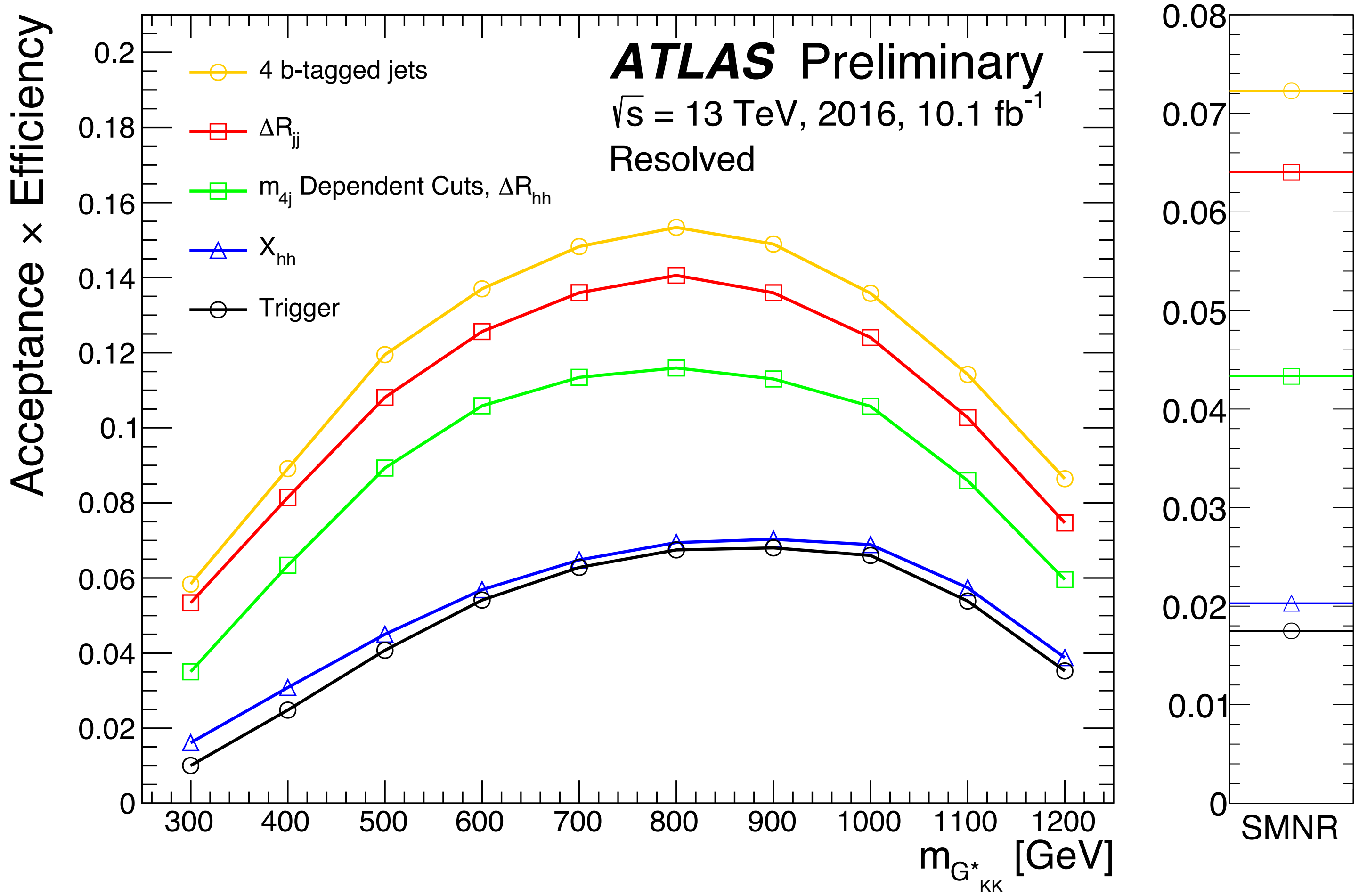
new results!

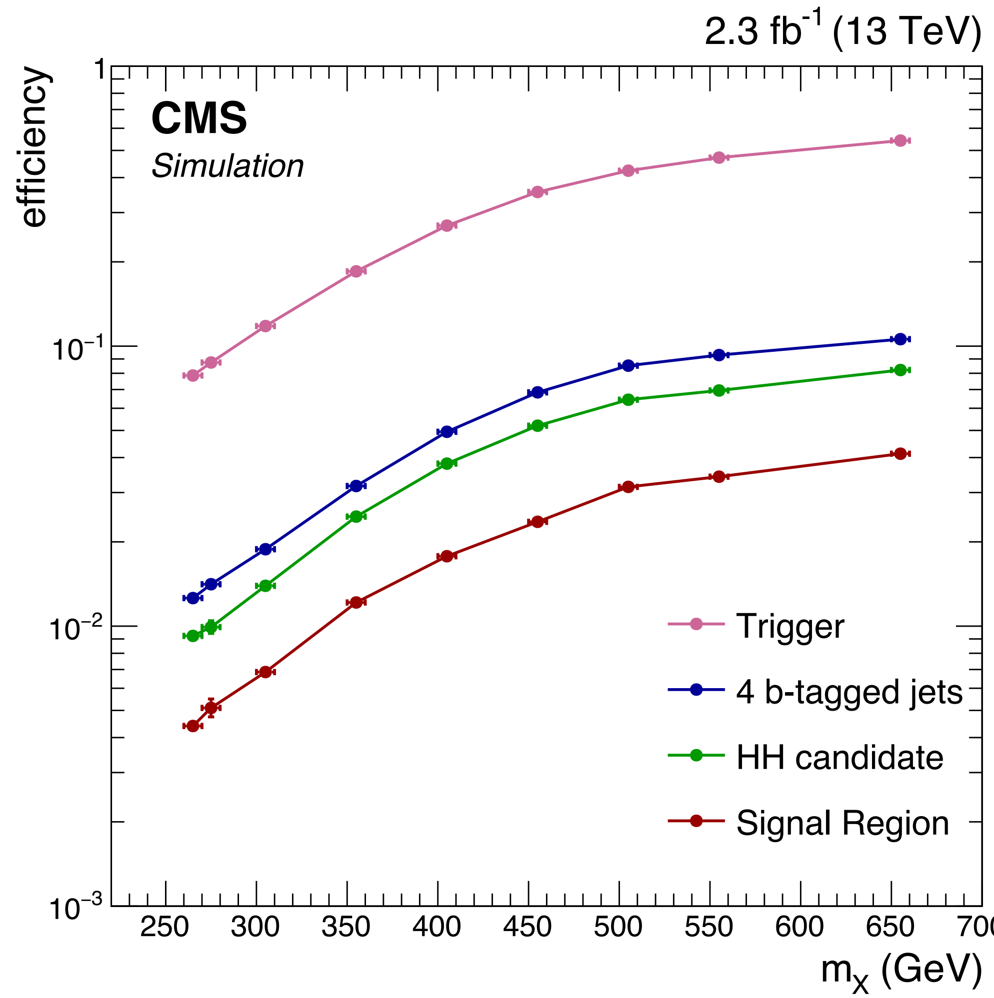


- Limit set as a function of the ratio k_λ/k_t with $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ and $k_t = y_t/y_t^{SM}$
- The shape of the signal depends only on the ratio of the couplings for the gg fusion mechanisms
  - under the assumption that the other BSM couplings c_2, c_g, c_{2g} are zero



HH → bbbb

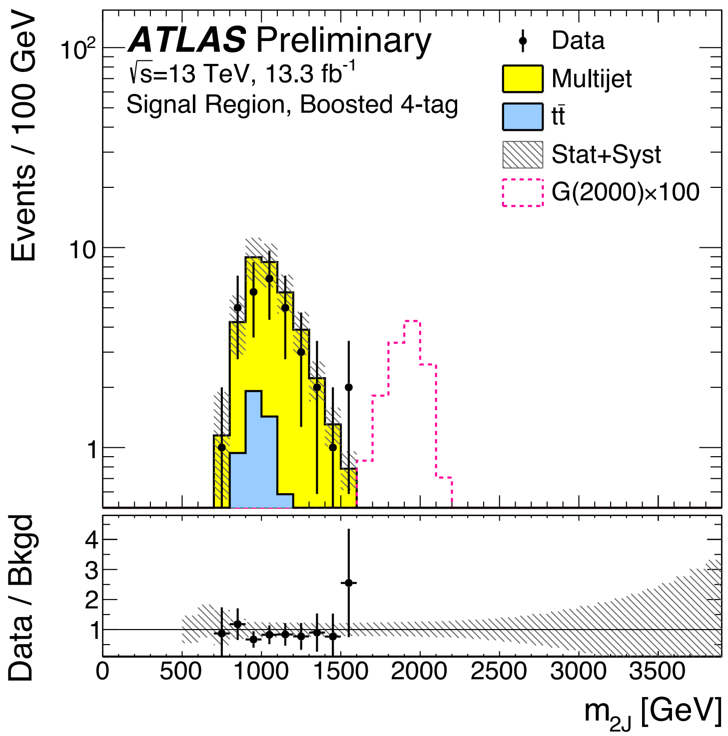




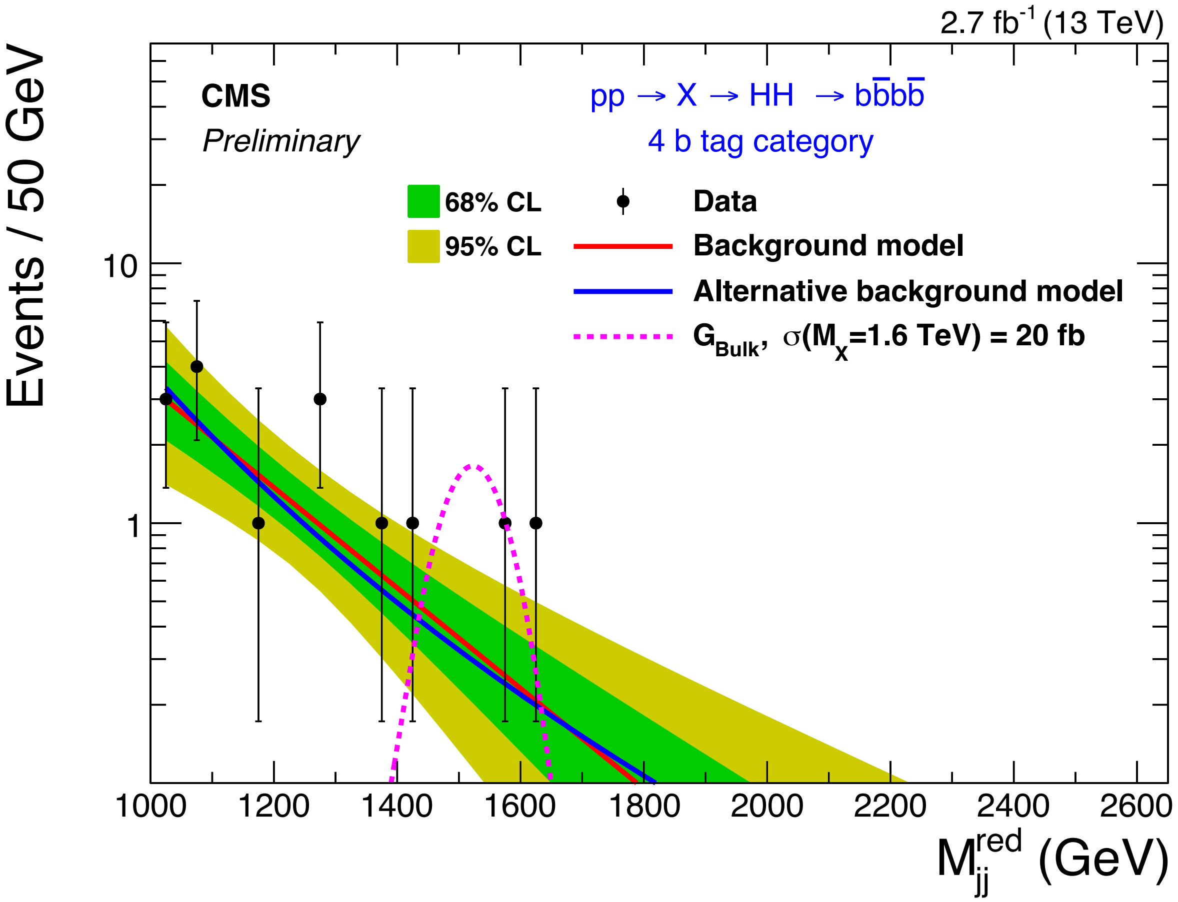
- 13.3 fb^{-1} (ATLAS) and 2.3 fb^{-1} (CMS) analyzed
- Different set of triggers used: require 1 or 2 b-tagged jets (ATLAS) or 3 b-tagged jets (CMS)
- Different definition of control regions: both use a mass sideband, but ATLAS also inverts the b-tag requirement

Boosted HH → bbbb

- 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



$HH \rightarrow bb\gamma\gamma$

Some details on the selections and techniques used in the two analyses

ATLAS

- 2 γ of $E_T/m_{\gamma\gamma} > 0.35$ (0.25)
- 2 jets of $p_T > 55$ (35) GeV, both b-tagged
- signal selection effciency is 5-8% (resonant with $m_X < 400$ GeV) and 10% (non-resonant)
- bb 4-momentum rescaled by m_H/m_{bb}
- fit over $m_{\gamma\gamma}$ for non-resonant search, counting experiment in $m_{\gamma\gamma bb}$ window in resonant search

CMS

- 2 γ of $E_T > 30$ (20) GeV and $E_T/m_{\gamma\gamma} > 0.33$ (0.25)
- 2 jets of $p_T > 25$ GeV, 1 and 2 b-tag categories
- signal selection efficiency is ~20% for $m_X < 400$ GeV
- multivariate regression method to estimate m_{bb}
- improved 4-body mass resolution using $m_X = m_{jj\gamma\gamma} - m_{jj} + 125$ GeV
- 2D fit over ($m_{\gamma\gamma}$, m_{bb}) in a window around $m_{bb\gamma\gamma}$ (resonant search) and for $m_{bb\gamma\gamma} > 350$ GeV (non-resonant search)