EXPERIMENTAL SEARCH FOR HH PRODUCTION

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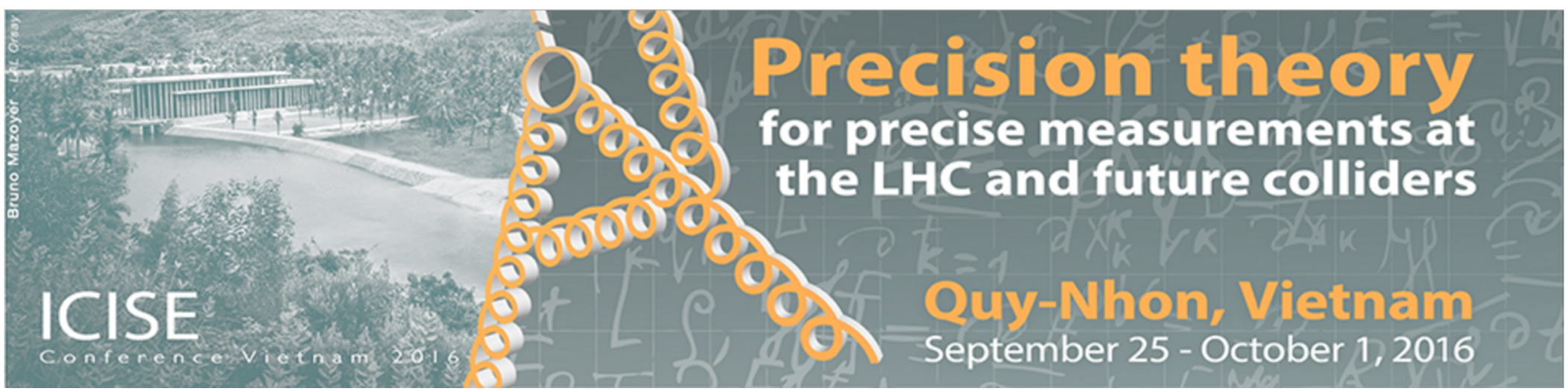
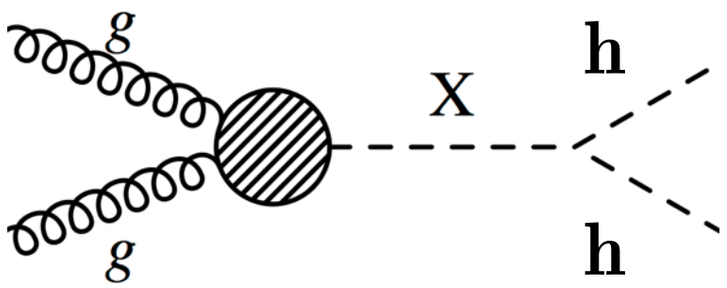


BEYOND THE STANDARD MODEL

- Higgs pair (di-Higgs) productions
  - resonant
  - non-resonant
- Searches status per decay channel
  - bb bb
  - bb WW
  - bb ττ
  - bb γγ
  - γγ WW*
- BSM in non-resonant hh searches
- Future prospects

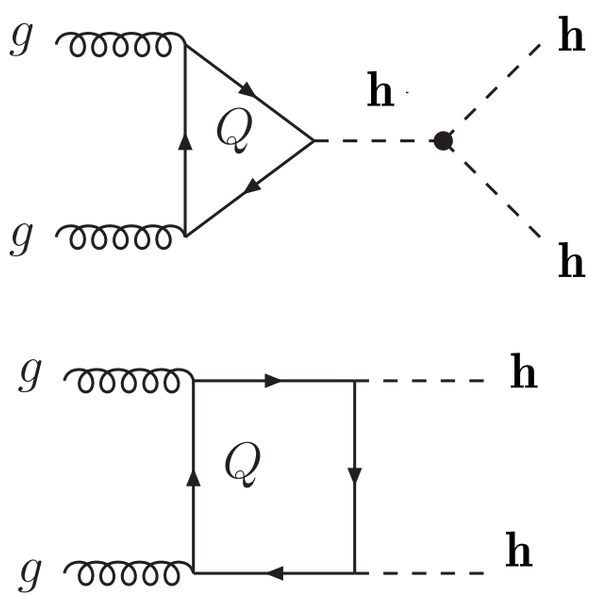
HIGGS PAIR PRODUCTION

RESONANT



- New resonances could be spotted out studying the Higgs boson pair production
- Different BSMs describe such a scenario, assuming the two final state Higgs are SM-like
- **Higgs singlet model**
- **hMSSM**
- **Randall-Sundrum Warped Extra Dim**

NON-RESONANT

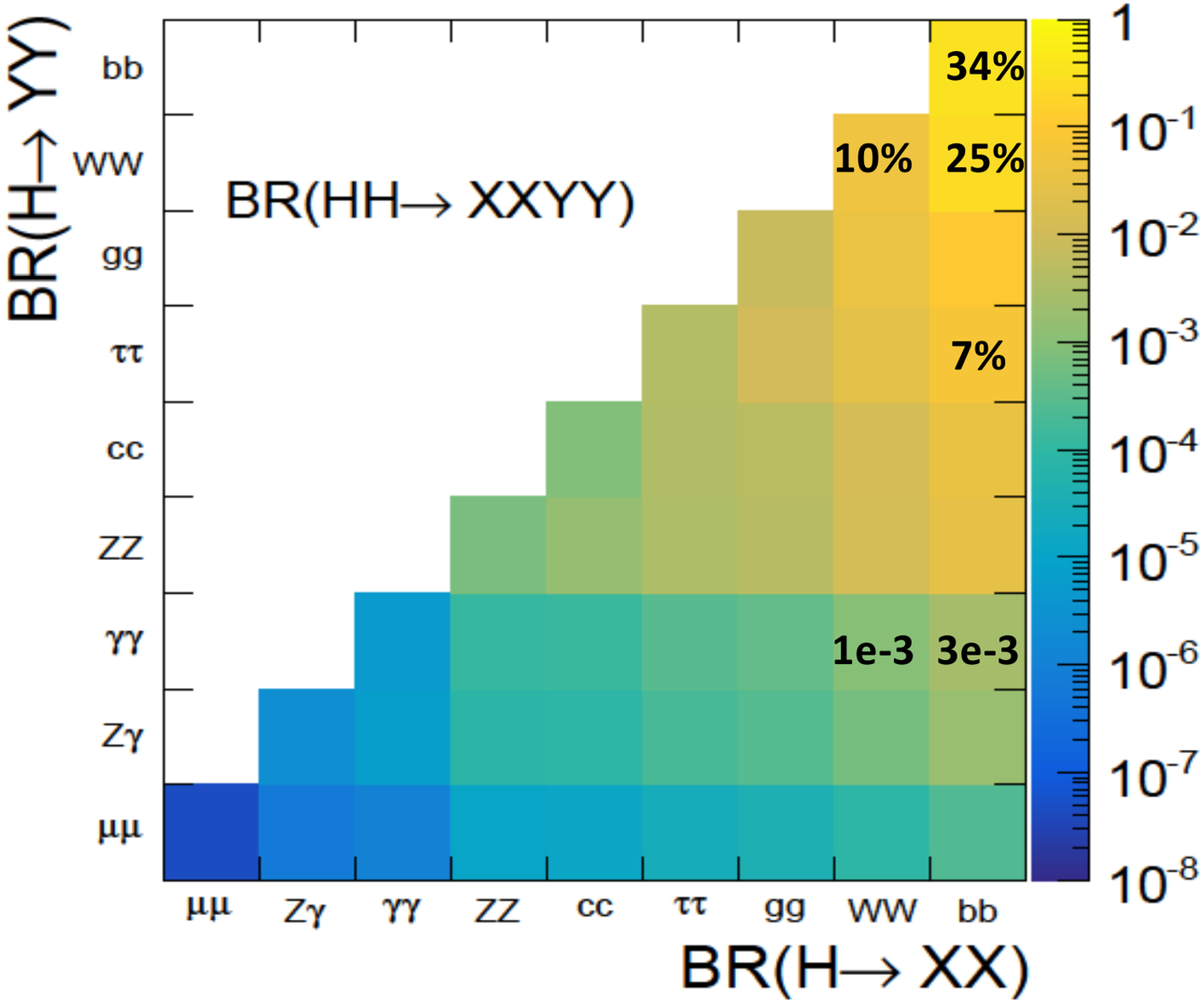


- Double Higgs production is the principal way to extract info about the Higgs trilinear coupling (λ_{hhh})
- Run2 will not give us enough sensitivity to measure λ_{hhh}
- Many **BSMs** are in agreement with the measured Higgs' properties, although they predict a **different λ_{hhh}**
  - BSM models could lead to an enhancement of non-resonant di-Higgs production

SEARCHES

NON-RESONANT | RESONANT

di-Higgs searches can be performed looking at different final states



Four main decay channels

- **bb bb** : higher BR, high QCD/tt contamination
- **bb WW** : high BR, large irreducible tt
- **bb ττ** : relatively low background
- **bb γγ** : high purity, very low BR

in addition:

- **γγ WW***

All challenging searches –> More Higgs More Fun

SEARCHES

NON-RESONANT | RESONANT

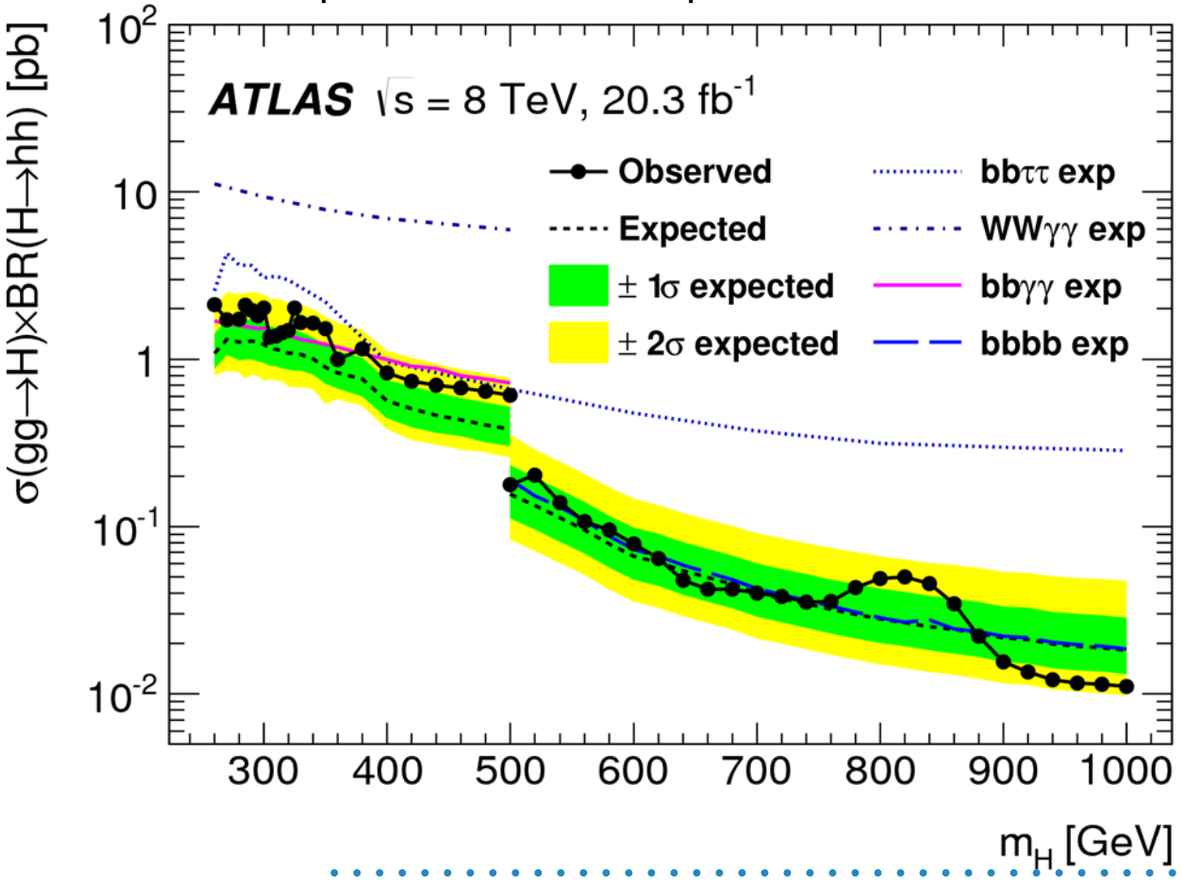
LHC Run1 (8 TeV, ~20 fb^{-1})

ATLAS: Phys. Rev. D 92, 092004 (2015)
CMS: https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/SummaryResultsHIG

ATLAS

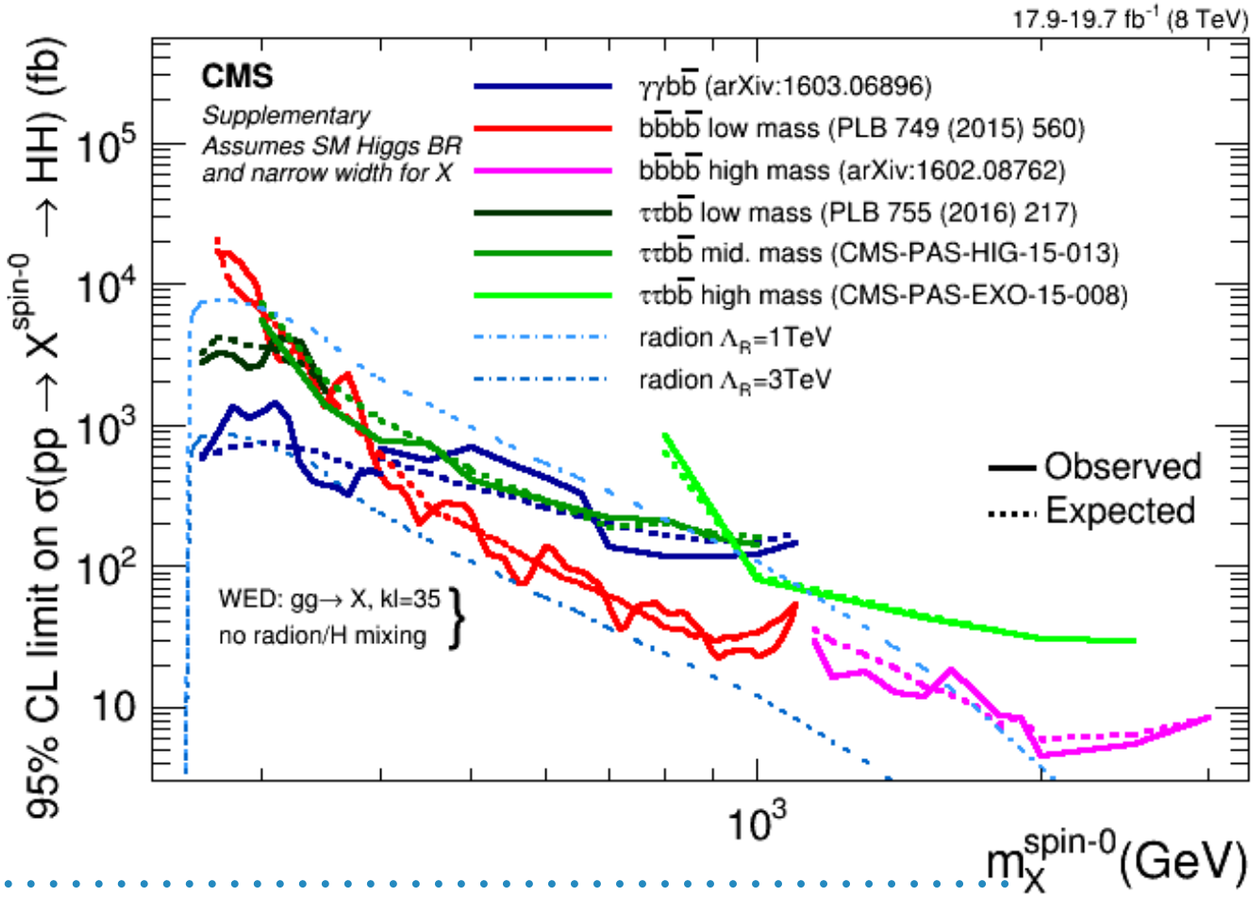
Run1 Results Combination:

- 2b2γ, 2b2τ, 4b e 2γ2W



CMS

Run1 Results Summary



- No excess observed for **resonant** searches
- Upper limit set on SM **non-resonant** hh production.
  Observed limit:
  - **ATLAS (hh->bbbb) > 63 X σ_{SM}**
  - **CMS (hh->bbγγ) > 91 x σ_{SM}**

SEARCHES

NON-RESONANT | RESONANT

LHC Run2 (13 TeV)

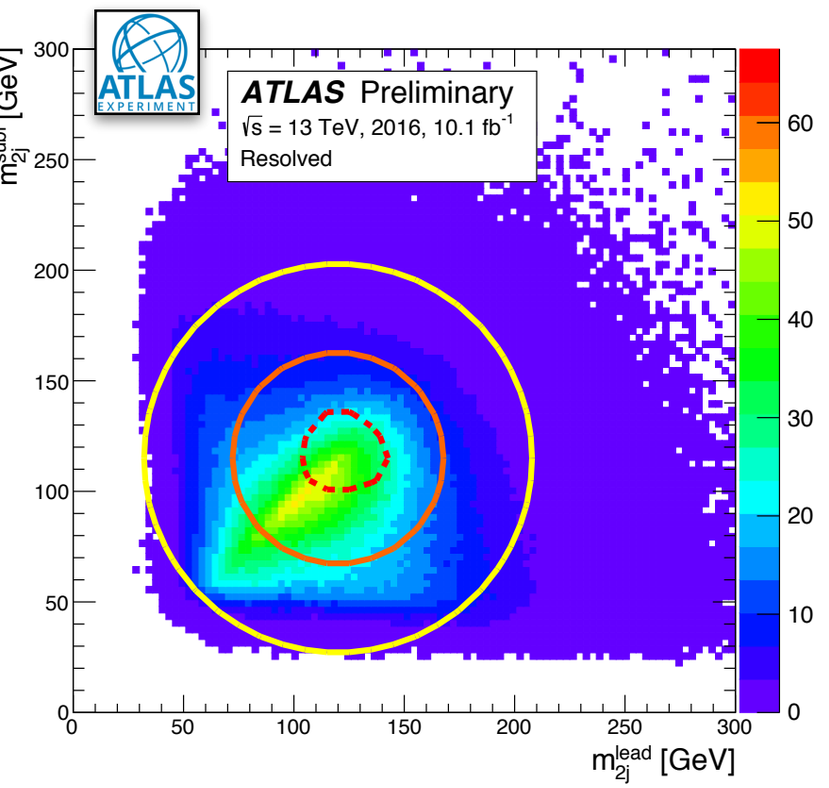
	ATLAS		CMS	
	resonant	non-resonant	resonant	non-resonant
hh→bbbb	Eur. Phys. J. C75* ATLAS-CONF-2016-049***		CMS-PAS-HIG-16-002*, CMS-PAS-B2G-16-008*	CMS-PAS HIG-16- 026*
hh→bbWW	-		CMS-PAS-HIG-16-011*	CMS-PAS-HIG-16-024*
hh→bbττ	-		CMS-PAS-HIG-16-029**	CMS-PAS-HIG-16-028**
hh→bbγγ	ATLAS-CONF-2016-004*		CMS-PAS HIG-16-032*	
hh→γγWW	ATLAS-CONF-2016-071***		-	

- * 2015 data (~ 3 fb^{-1})
- ** 2016 data (~ 13 fb^{-1})
- *** 2015+2016 data combination (~ 13 fb^{-1})

di-Higgs resonant searches

Search for H→hh→bbbb

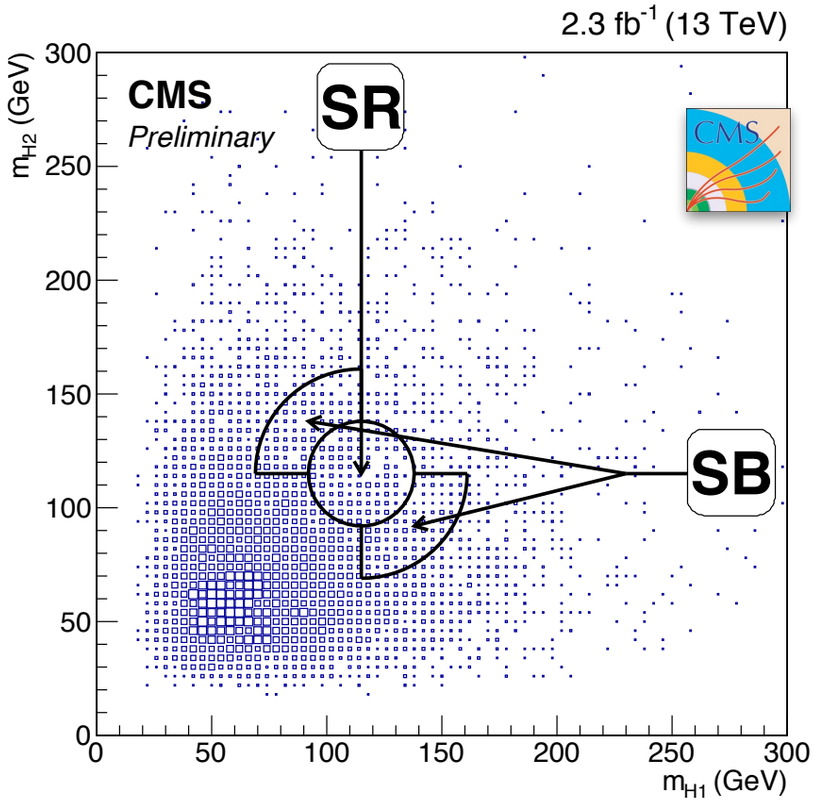
RESONANT

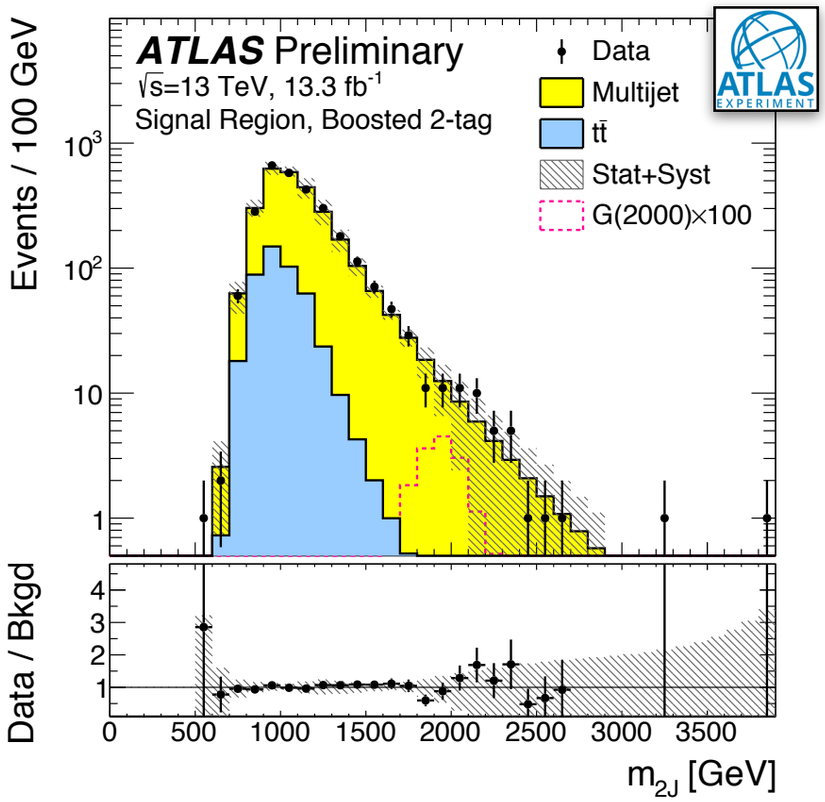


ATLAS: ATLAS-CONF-2016-049
CMS: CMS-PAS-HIG-16-002, CMS-PAS-B2G-16-008

Resolved Analysis:

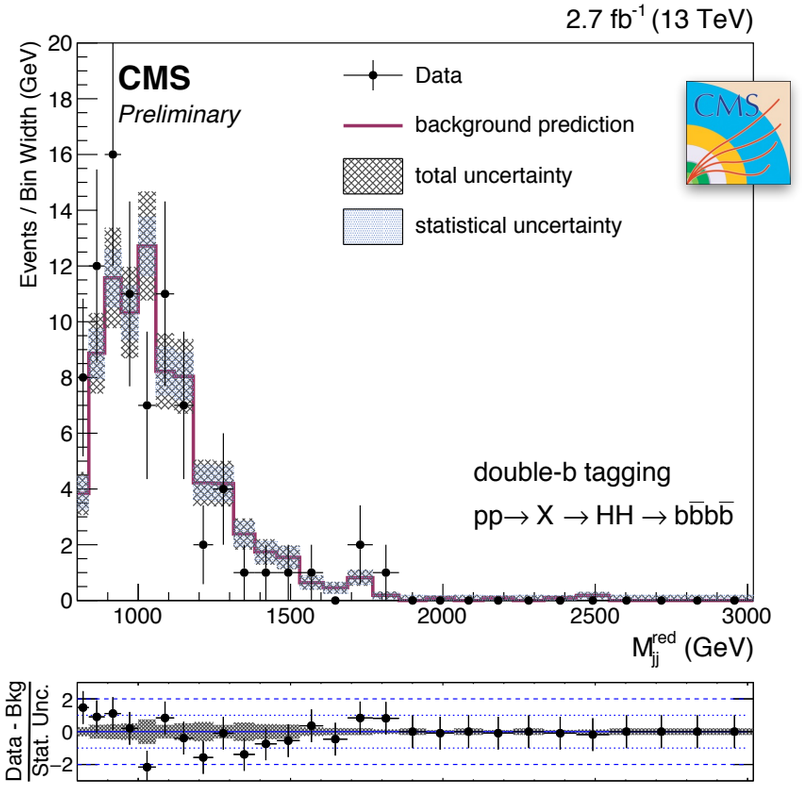
- Resolve all decay products
- 2 strategy for CMS:
  - Low mass (mH<400 GeV)
  - High mass (mH<1200 GeV) regions
- Limit extraction on m_{4j} distribution





Boosted Analysis:

- Optimised for higher mass (m_{hh}>1TeV) resonant hh.
- high-momentum Higgs bosons-> high boosted 2 b-jets are in a ‘large’ jet.
- Apply substructure techniques. Limit extracted on M of 2 ‘large’ jets.



Search for H→hh→bbbb

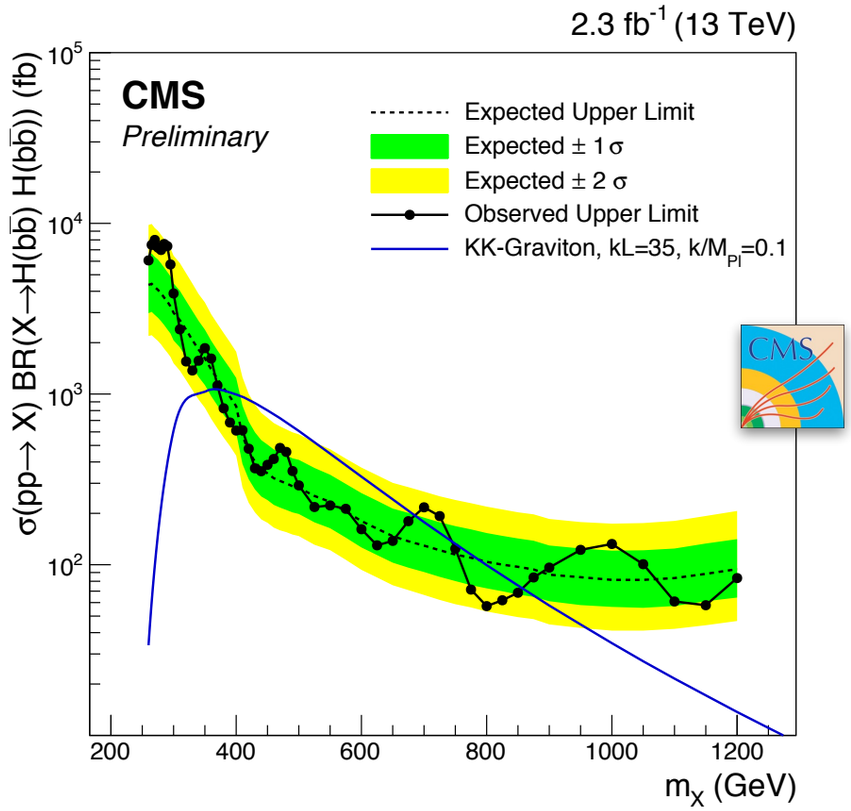
RESONANT

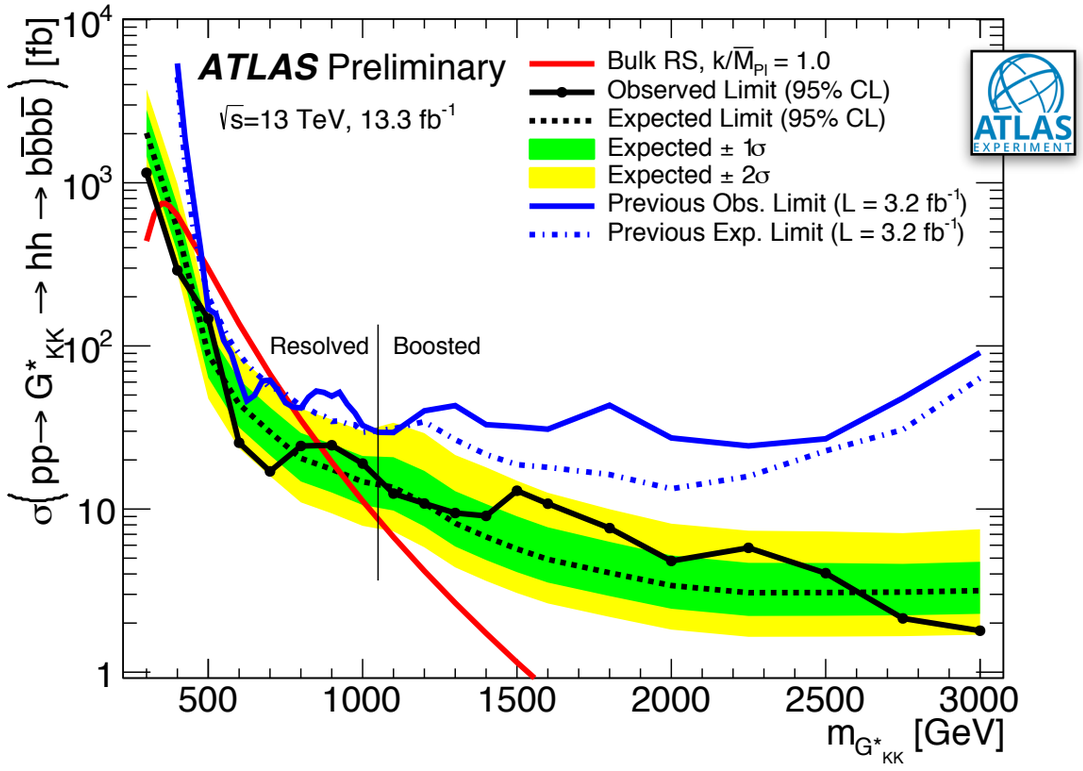
ATLAS: **ATLAS-CONF-2016-049**
CMS: **CMS-PAS-HIG-16-002, CMS-PAS-B2G-16-008**

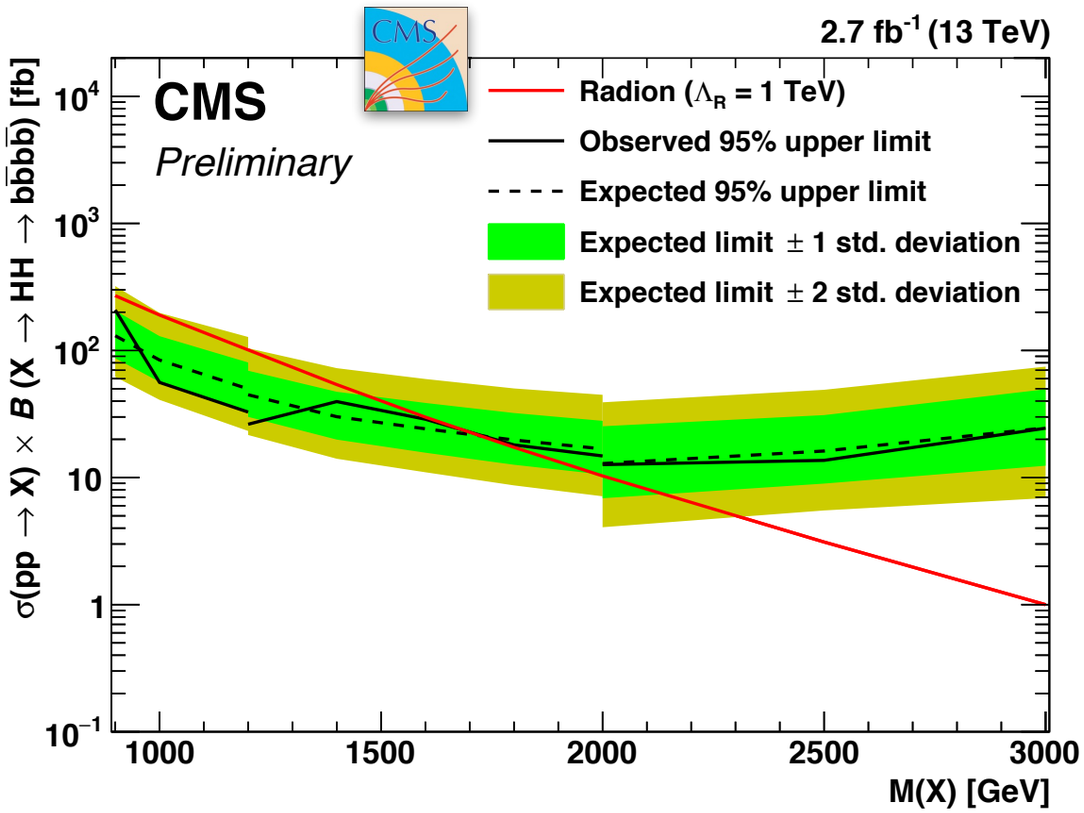
Exclusion at 95% CL :

- CMS:
  - $1000<m_H<1720$ GeV for Radion (Λ_R = 1 TeV) -boosted.
  - $350 < m_H < 725$ GeV.
- ATLAS:
  - $360 < m_H < 869$ GeV for Graviton.

CMS on 2015 data, ATLAS on 2015+2016 data.







Search for H→hh→bbWW

RESONANT

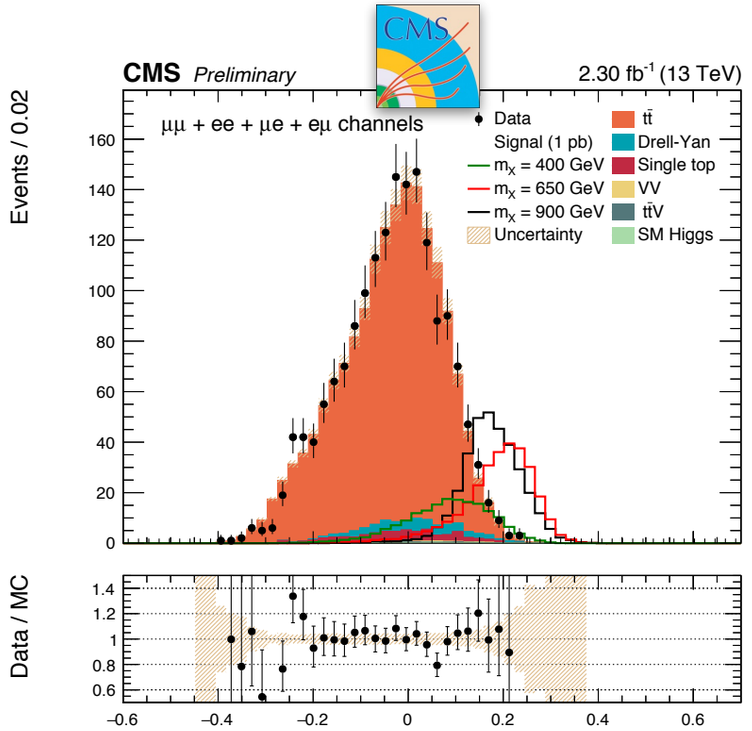
CMS: **CMS-PAS-HIG-16-016**

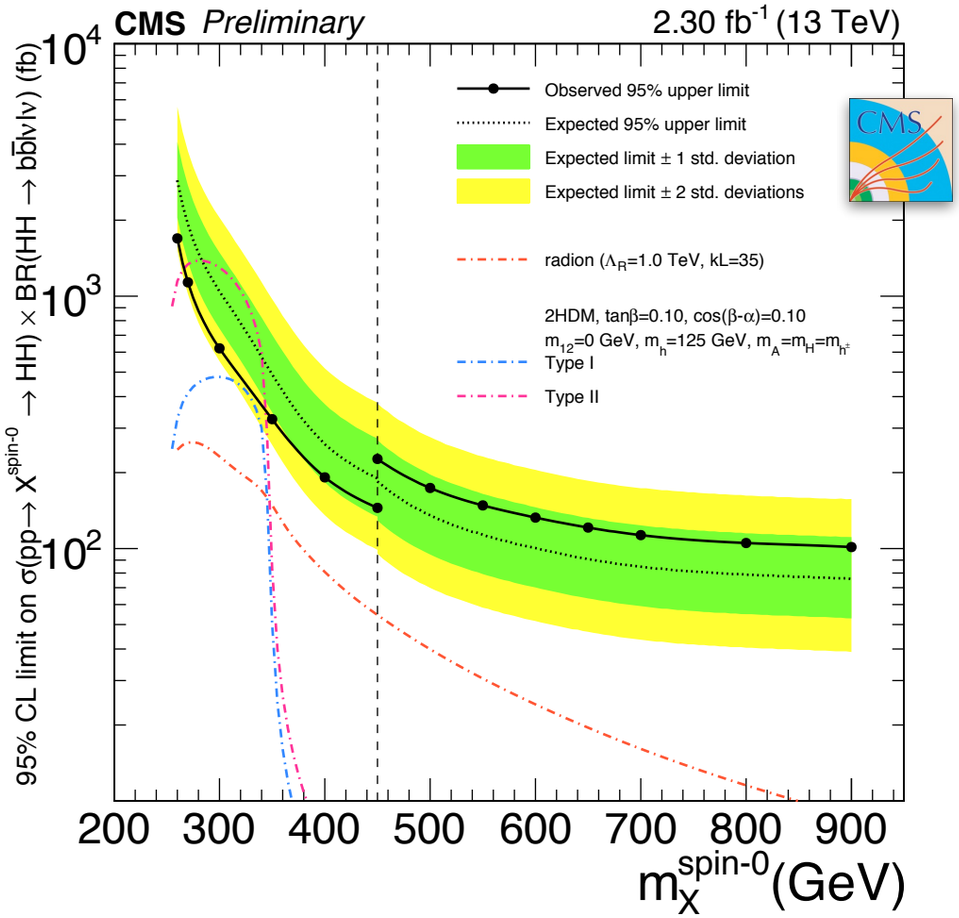
Search strategy:

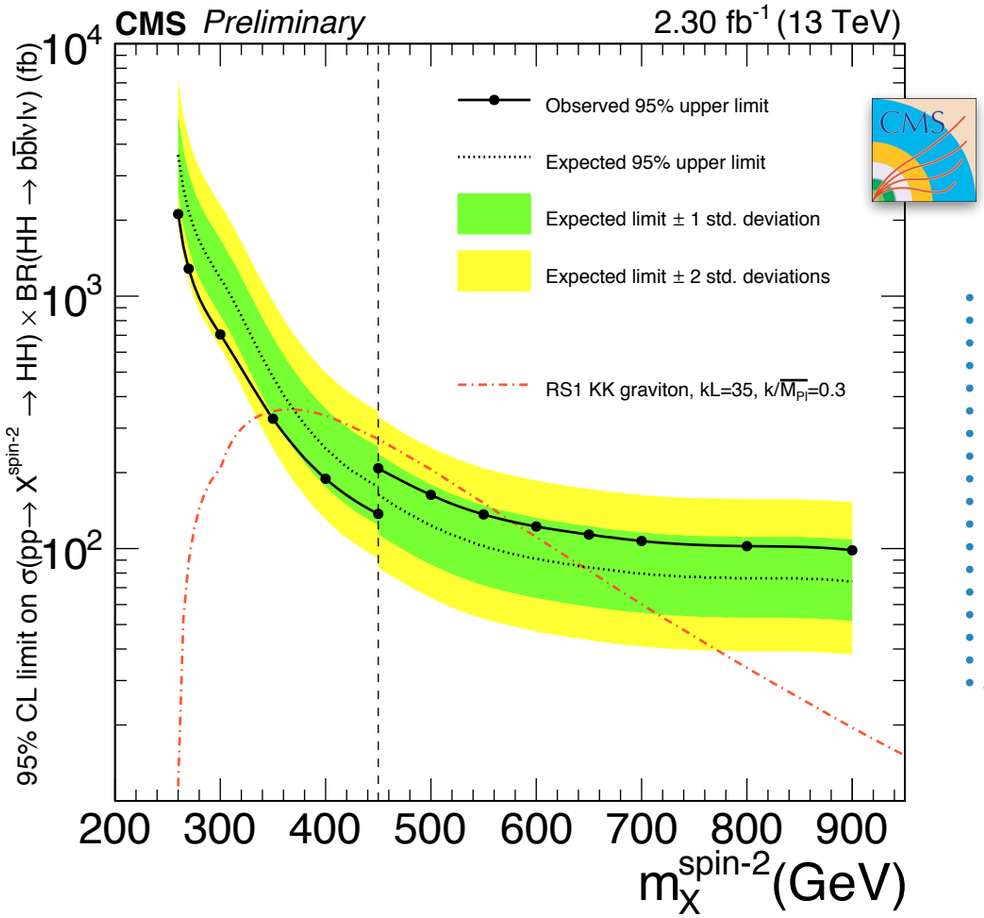
- dilepton triggers
- two oppositely charged leptons (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$) and 2 b-tagged jets
- BDT: m_{ll}, ΔR_{ll}, ΔR_{jj}, $\Delta\varphi_{ll,jj}$,p_T^{ll}, p_T^{jj}, min($\Delta R_{j,l}$) and MT(ll,MET)
  - Two BDT trained for m_H<450 GeV and for m_H>450 GeV
  - tt, Drell-Yann, single top production, SM Higgs as background

Signal extraction:

- 4 categories: (m_{bb}-peak,m_{bb}-SB)x(lowBDT,highBDT).







Exclusions:

Spin-2 RS1 KK-graviton

m_H < 600 GeV

Search for H→hh→bbττ

RESONANT

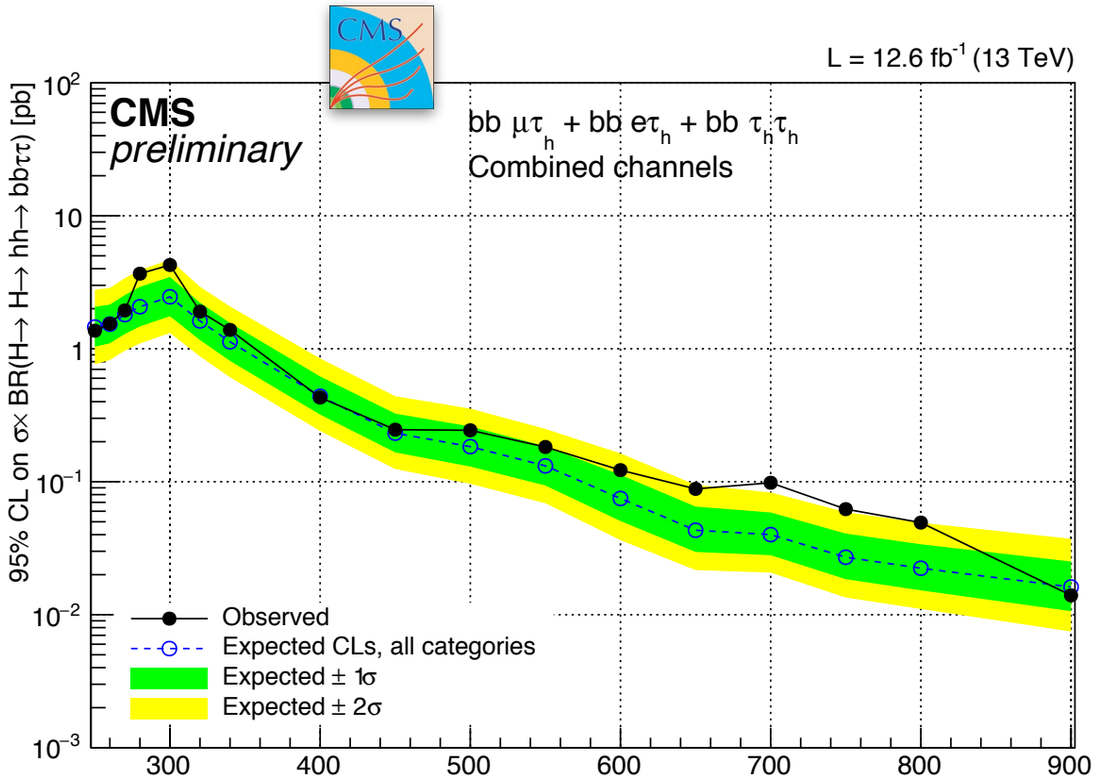
CMS: **CMS-PAS-HIG-16-029**

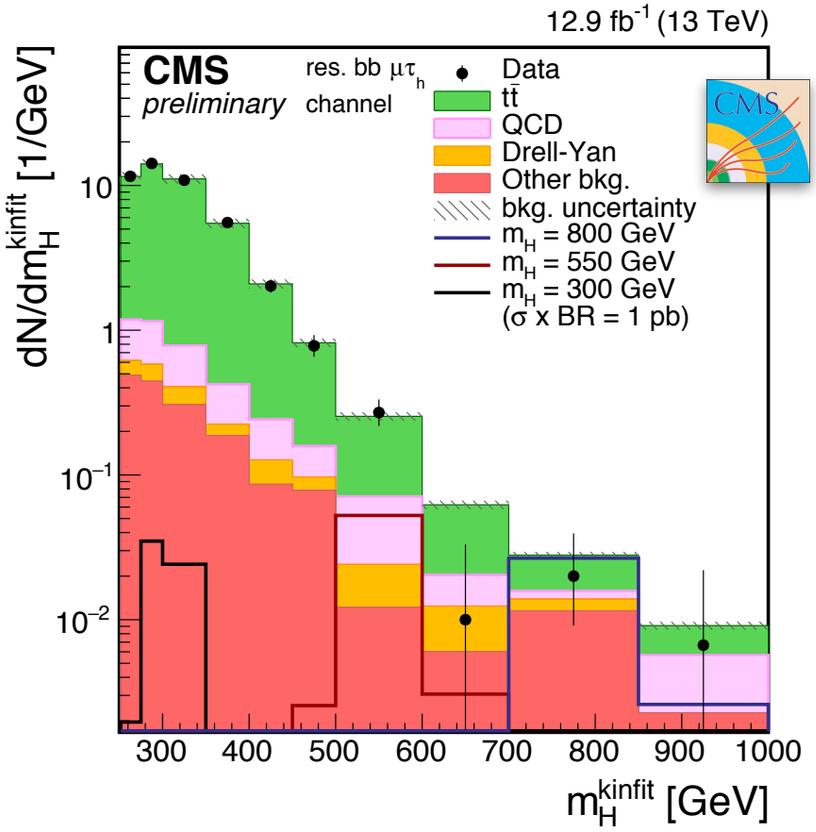
Search strategy:

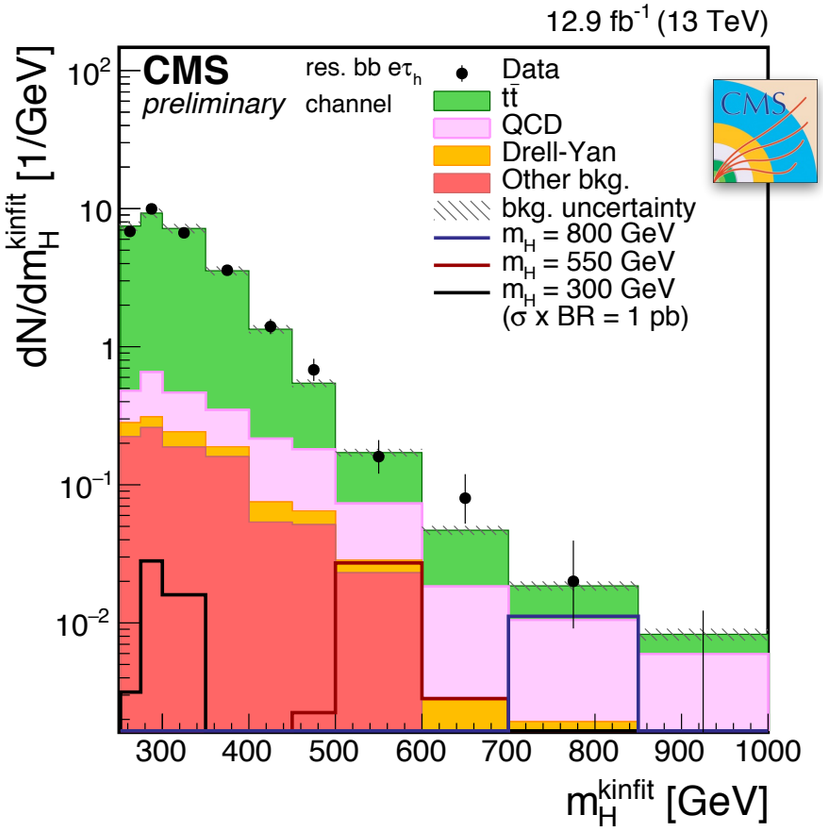
- 3 final states: eτ_H, $\mu\tau_H$, $\tau_H\tau_H$
- Final state: 1τ_H + 1 isolated leptons (e, μ,τ_H) + 2 b-jets
- Main bkgs: $t\bar{t}$(from MC),
  QCD multijet (from data in control regions).

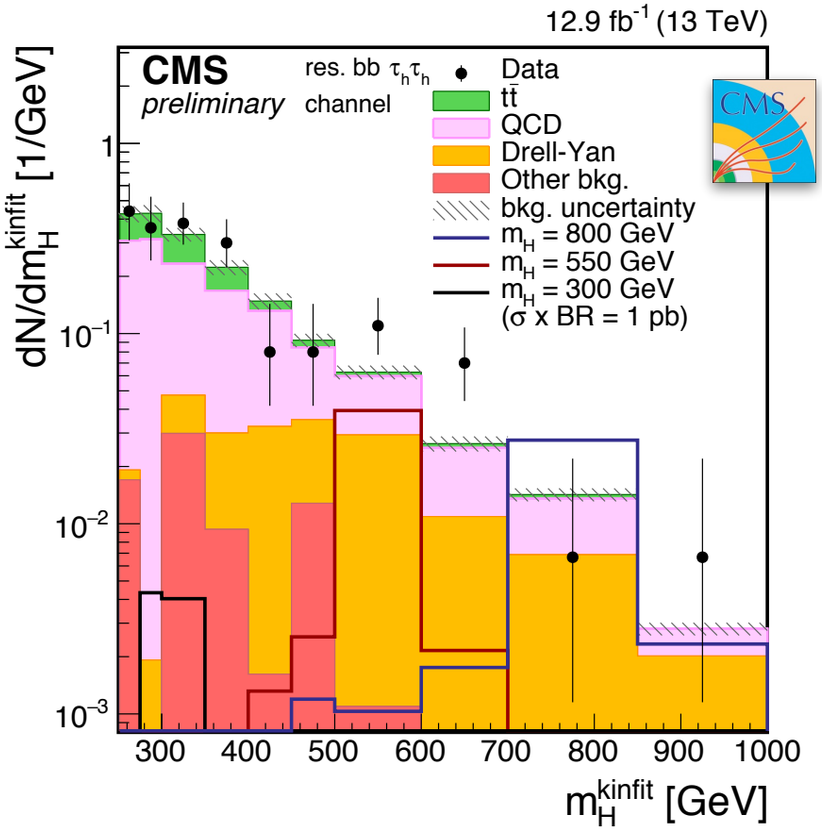
Signal extraction:

- 3 categories: 1b-jet, 2b-jet, boosted b-jets category.









Search for H→hh→bbγγ

RESONANT

ATLAS: **ATLAS-CONF-2016-004**
CMS: **CMS-PAS-HIG-16-032**

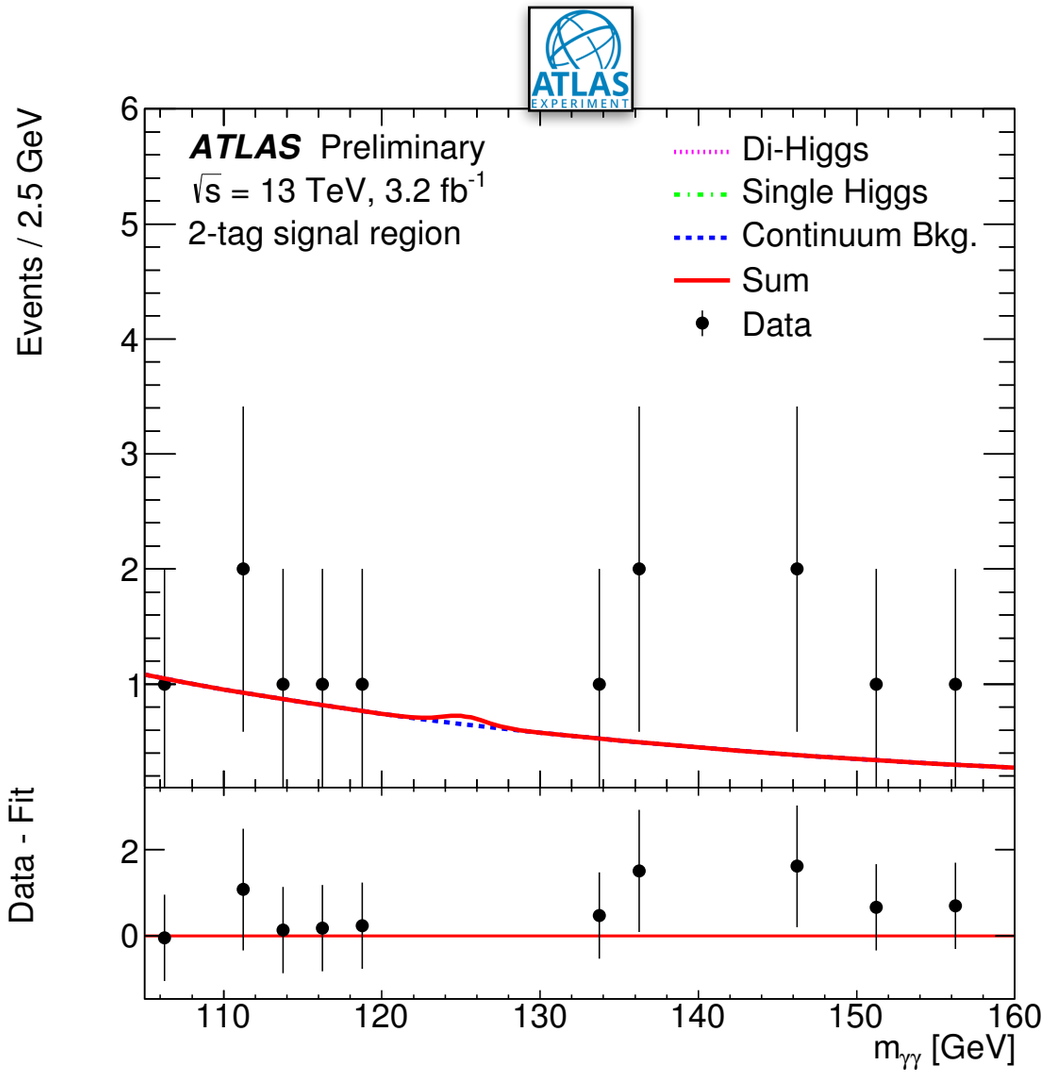
Lowest BR among all channels, but excellent resolution on $m_{\gamma\gamma}$

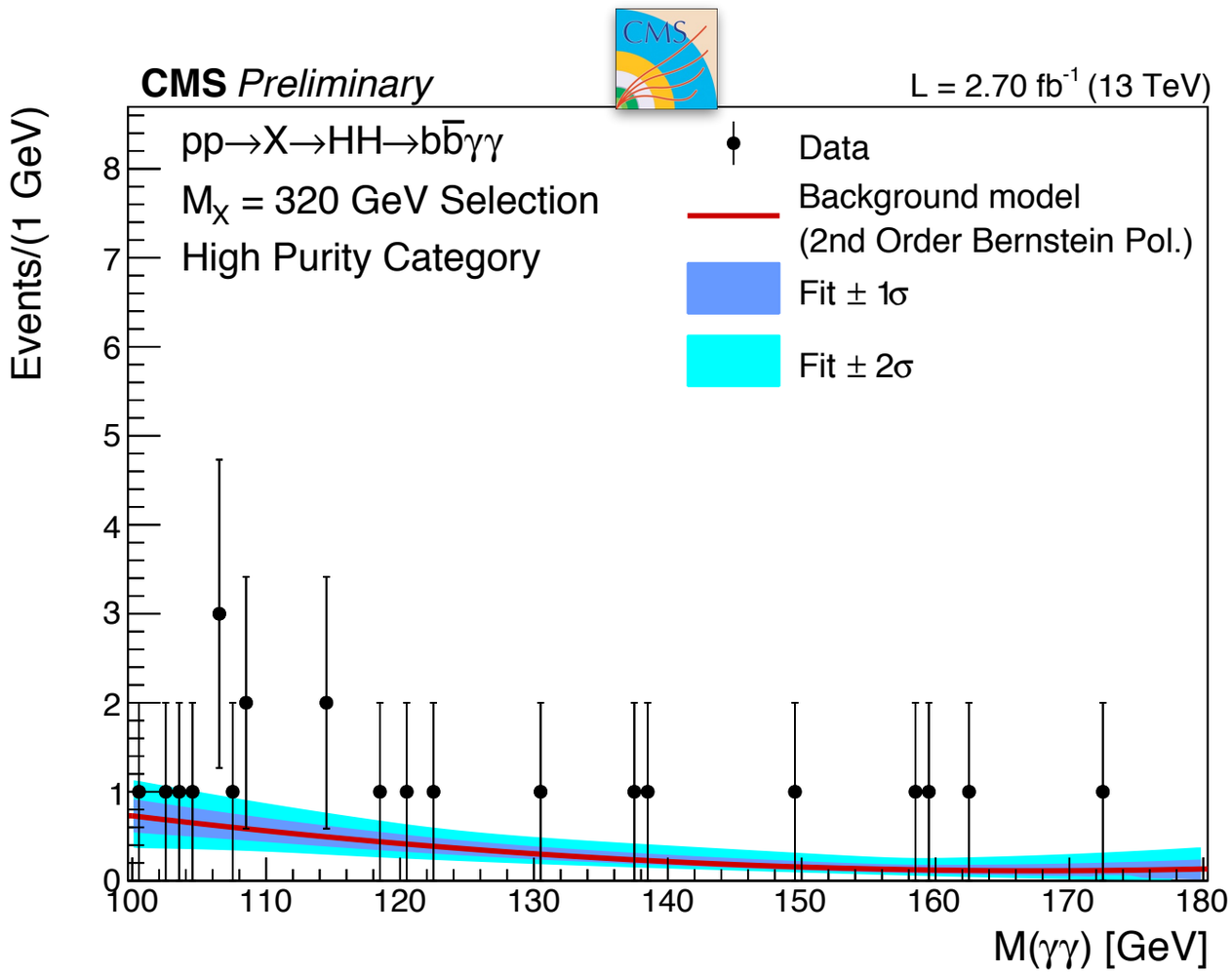
Search strategy:

- Similar event selection both for ATLAS and CMS
- Select mass window in M(jjγγ) around resonance mass.
- Two categories based on b-tagging (one for high mass region).

Signal extraction:

- CMS: 2D unbinned fit in m_{jj} and $m_{\gamma\gamma}$
- ATLAS:
  - selection on m_H region
  - Counting experiment with fit on $m_{\gamma\gamma}$



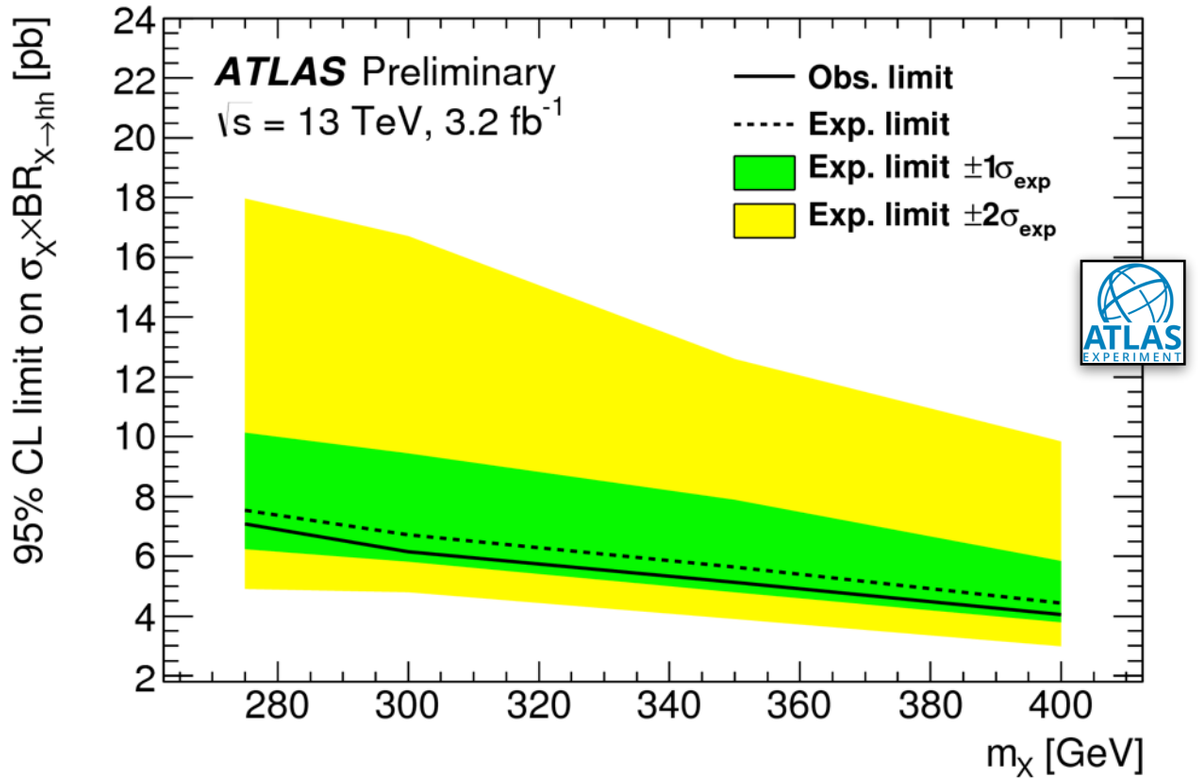


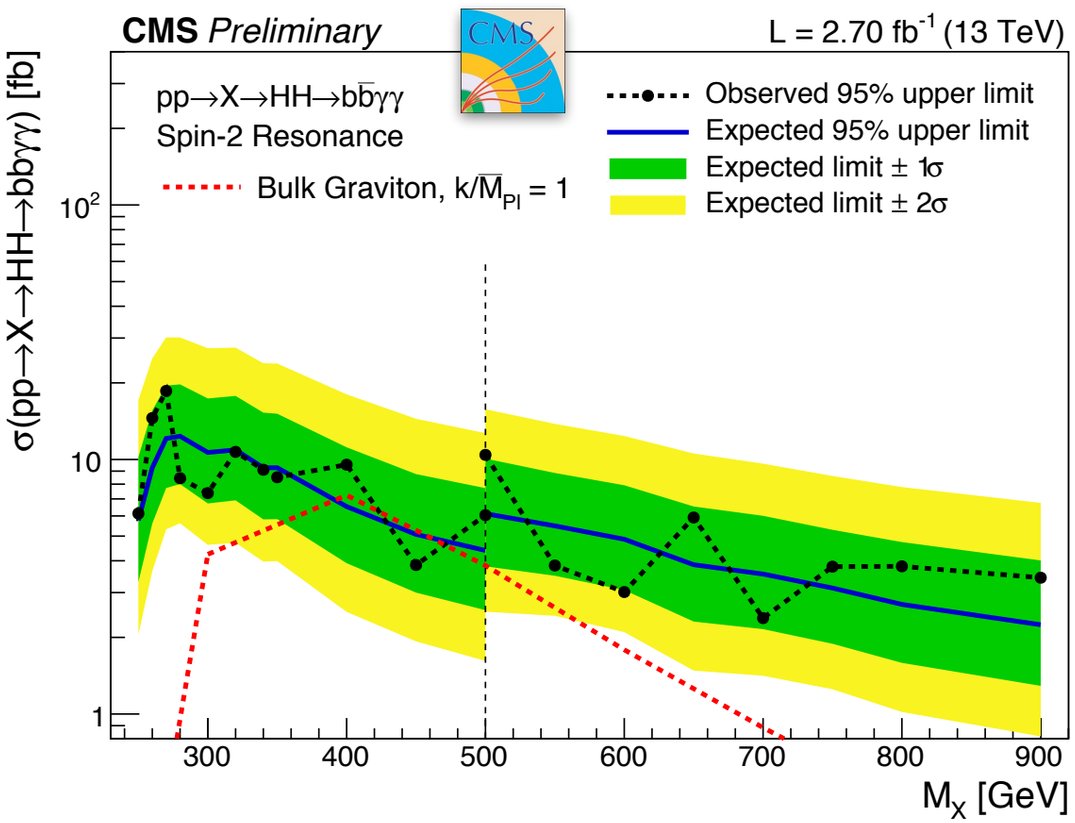
Search for H→hh→bbγγ

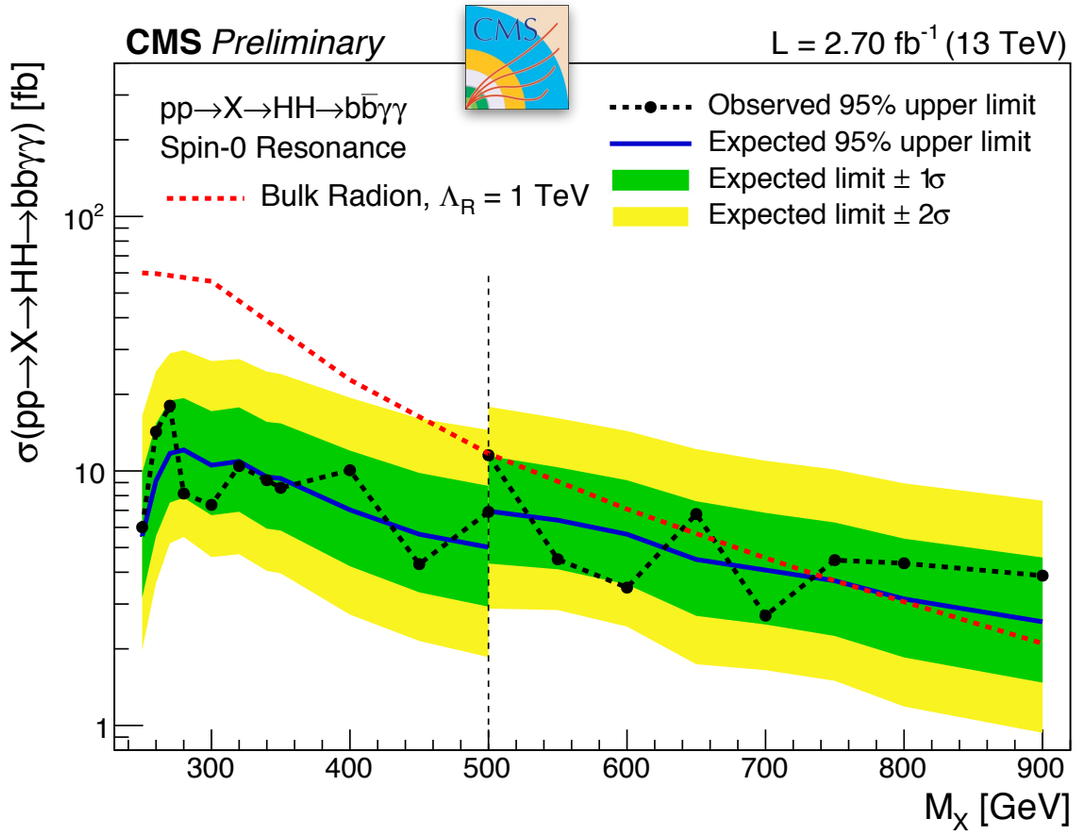
RESONANT

ATLAS: **ATLAS-CONF-2016-004**
CMS: **CMS-PAS-HIG-16-032**

- No significant excess in both CMS and ATLAS.
- Exclusions at 95%:
  - CMS: Spin-0 Radion below 750 GeV (except 650 GeV vicinity)
  - ATLAS: ~5 pb cross sections limits on narrow scalar
- σ(pp→X→hh→bbγγ) for m_X=400
  - CMS < 8 fb, ATLAS < 12 fb







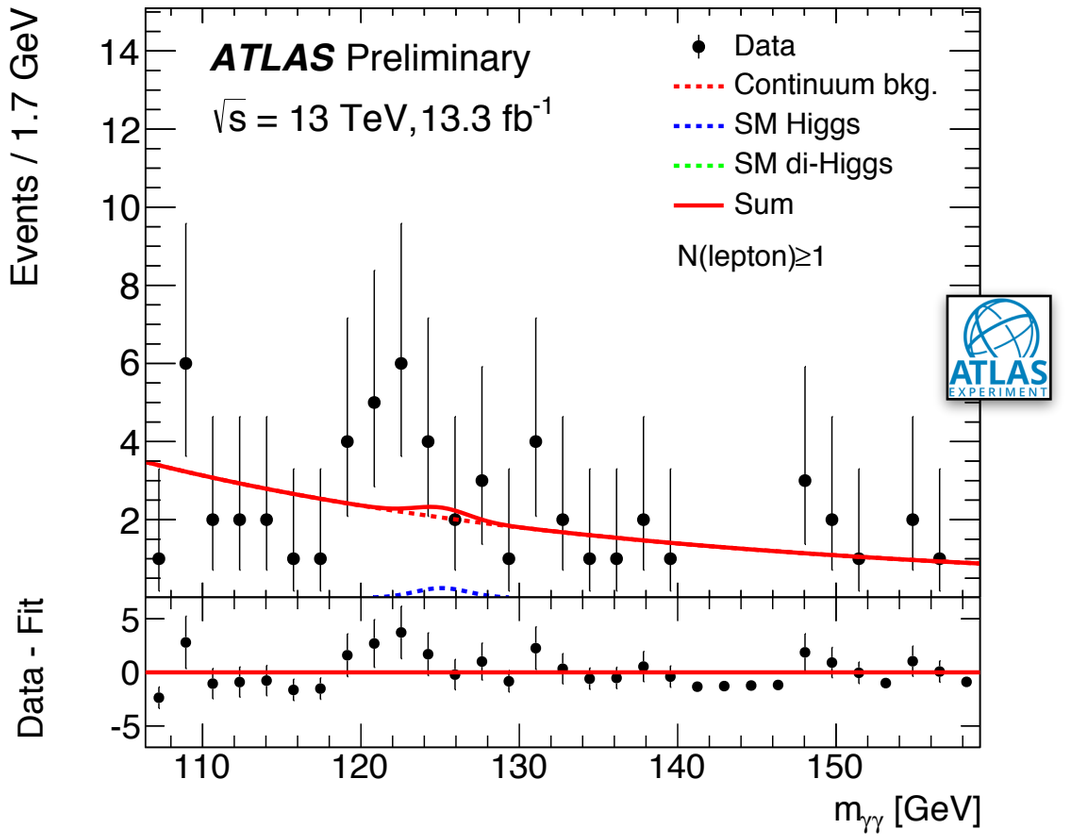
Search for H→hh→WWγγ

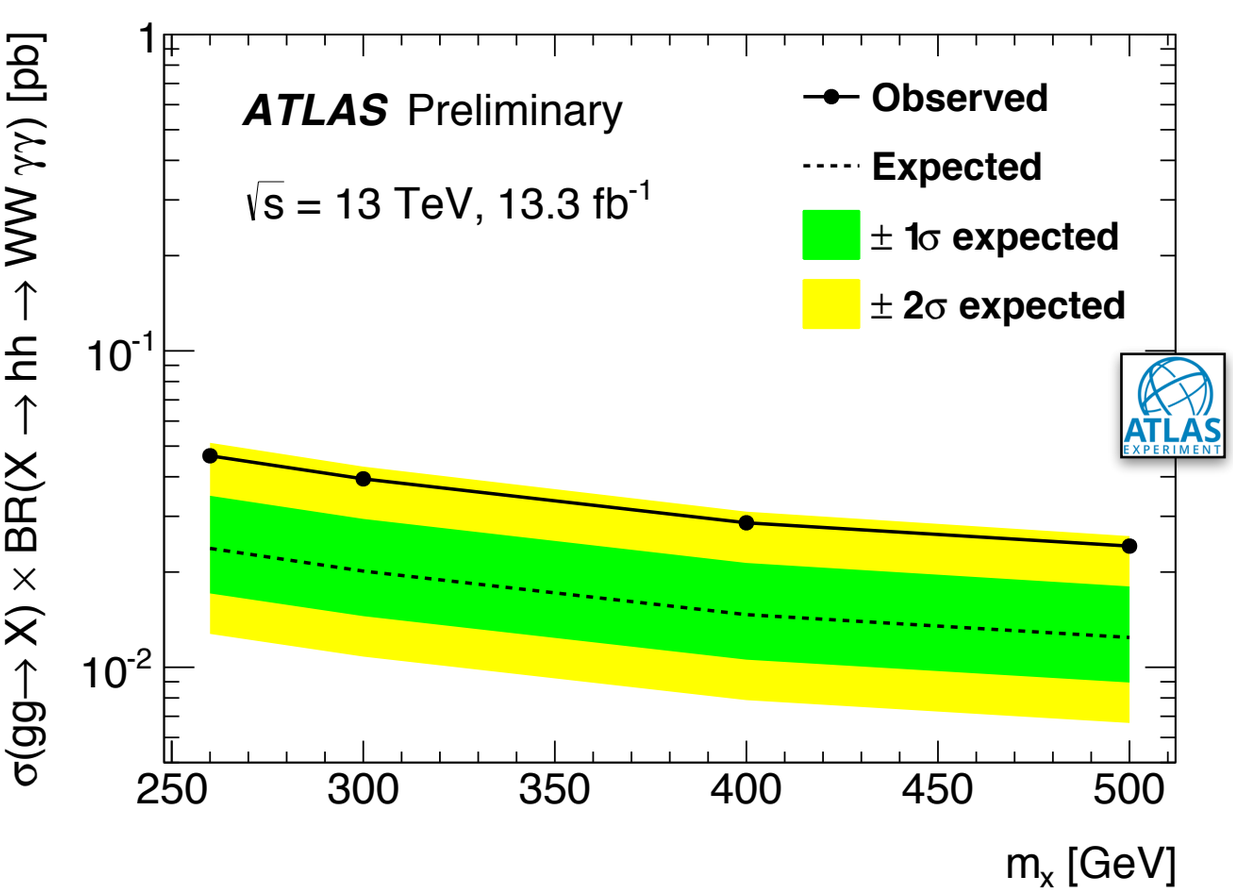
RESONANT

ATLAS: **ATLAS-CONF-2016-071**

Final state γγlνqq'

- 2 photons, at least 2 jets and no b-jet
- 105 GeV< $m_{\gamma\gamma}$ < 160 GeV
- Signal Region:
  - One lepton region - requiring at least one lepton
  - The di-photon mass $m_{\gamma\gamma}$ within a 2σ window of the Higgs boson mass ($\sigma_{\gamma\gamma}$ = 1.7 GeV)





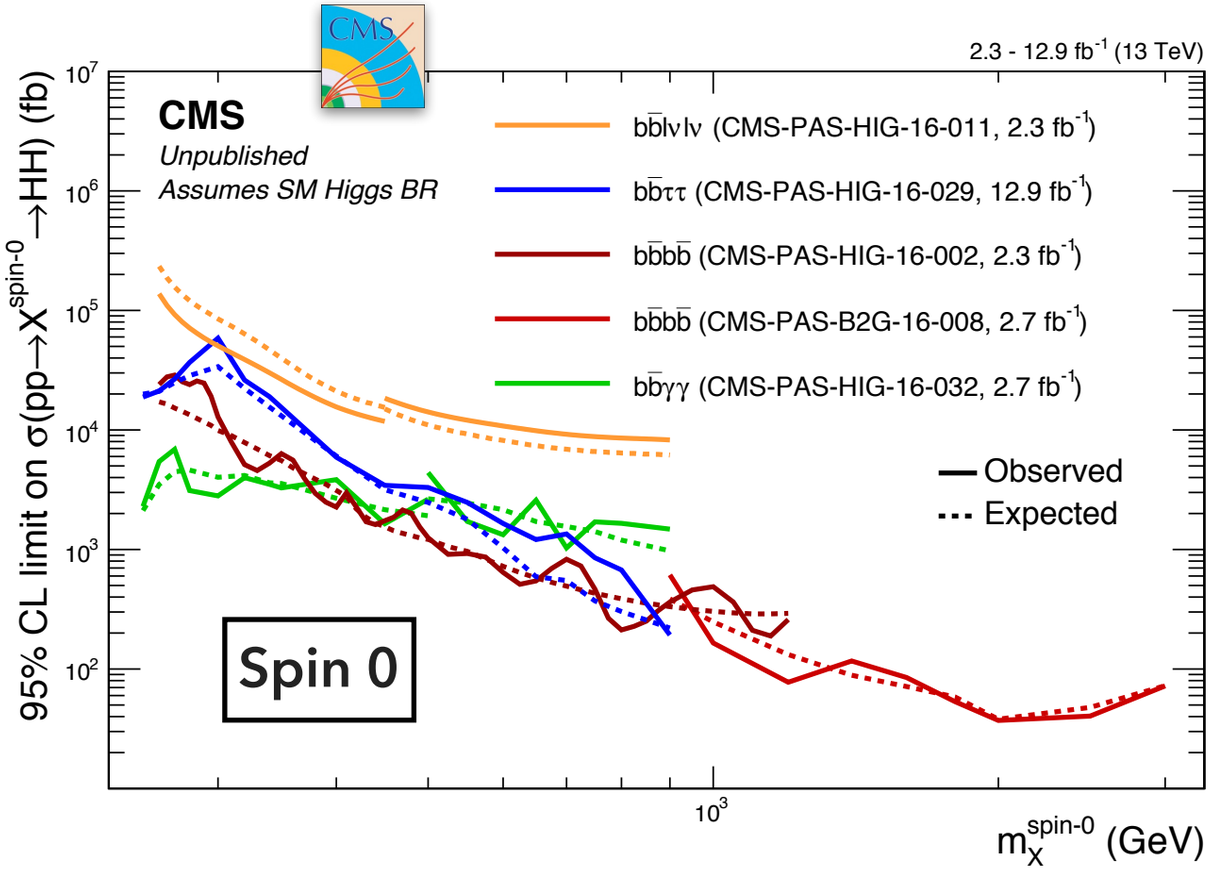
Limits in σ(pp→X→hh)

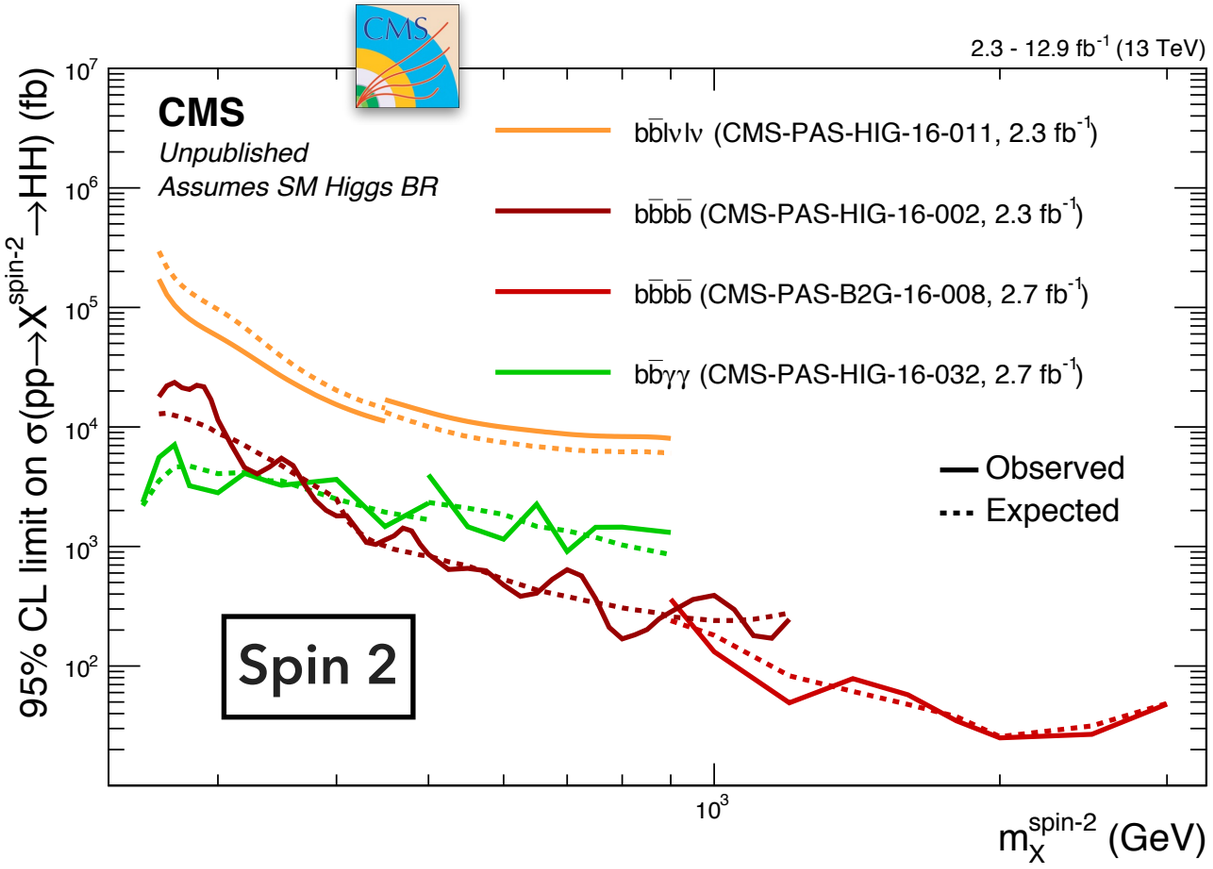
- **47.7 pb** (expected 24.3 pb) at m_X= **260 GeV**
- **24.7 pb** (expected 12.7 pb) at m_X= **500 GeV**

Summary of resonant searches

RESONANT

- **Atlas**: no excess in any channel.
  - No official combination yet.
- **CMS**: Summary plots including all the latest results:
  - Range from 2 x m_h to few TeVs covered.
  - hh->4b still provides best limit in a wide mass range.
  - hh->bbγγ has strong power in low mass regions.





di-Higgs non-resonant searches

BSM non-resonant hh

NON-RESONANT

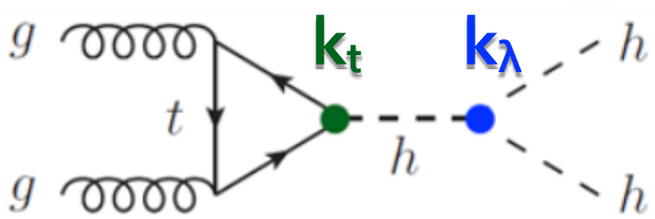
- The non-resonant Higgs bosons pair is a golden channel to study the Higgs potential.
  - Probe the Higgs trilinear coupling (λ_{hhh}).
  - No sensitivity in Run2
- Variation of λ_{hhh} wrt to SM value can be investigated with di-Higgs.
- EFT could model BSM effects adding dim-6 operators. 5 parameters space

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v\, h^3 - \frac{m_t}{v}(v + \kappa_t h + \frac{c_2}{v} h\, h)\,(\bar{t_L} t_R + h.c.)$$

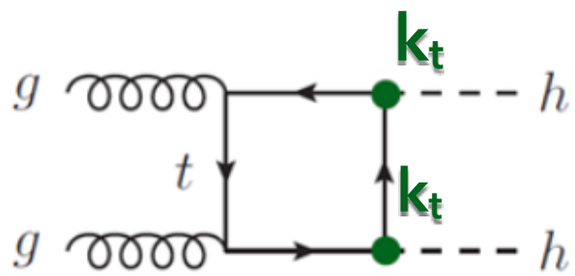
$$+ \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g h - \frac{c_{2g}}{2v} h\, h\right) G^{\mu\nu} G_{\mu\nu}\,.$$

where $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$; $k_t = y_T/y_T^{SM}$;
$\lambda_{SM} = m^2_H/(2v^2) = 0.129$.

SM processes:

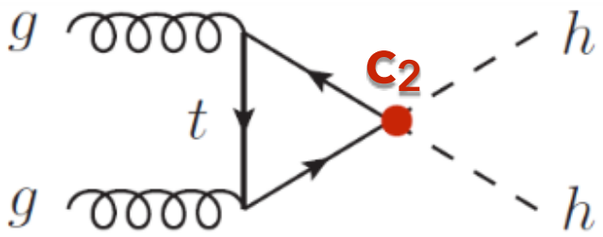


Tri-linear coupling

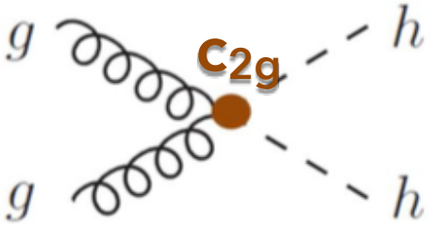


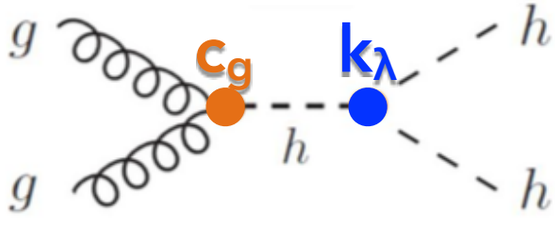
Yukawa interaction

BSM processes:



ttHH interaction





Higgs-gluon contact interactions

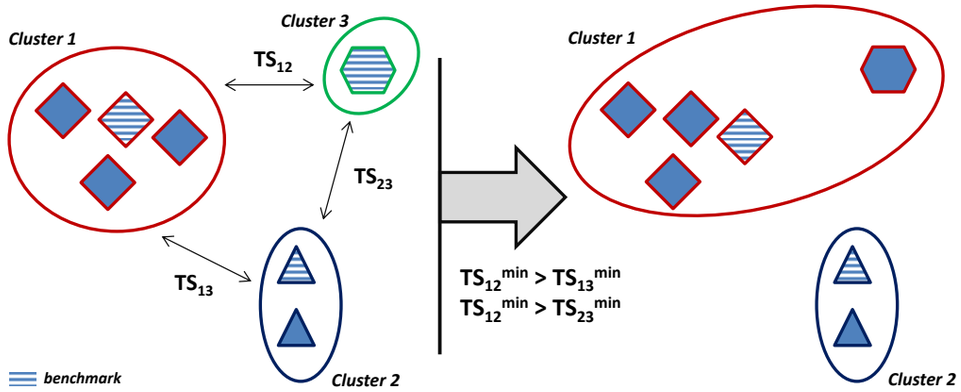
BSM non-resonant hh

http://arxiv.org/abs/1507.02245
http://cds.cern.ch/record/2199287

NON-RESONANT

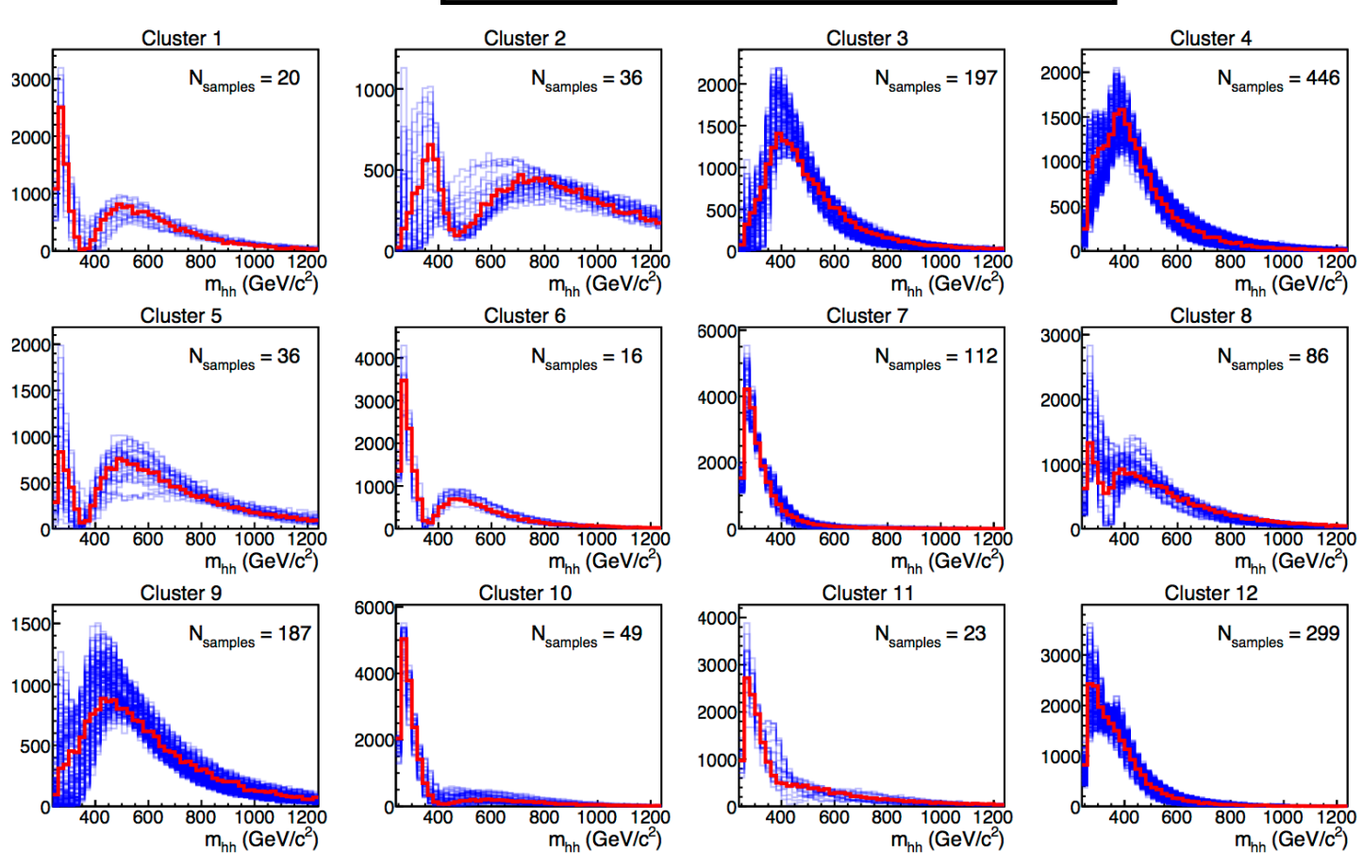
- Variation of the 5 parameters (couplings) implies a variation of the di-higgs kinematics.
- Developed a technique based on test statistic (TS) to group parameters space points and to identify benchmarks of each cluster based on final state kinematics.
- Study performed on 1500 initial points:
  - compute TS for each sample.
  - use TS to group samples in clusters.
  - iterate procedure to get 12 final clusters.

Clustering Technique



Run 2 CMS searches have been based on this parametrization.

Clusters and Benchmarks



Search for hh→bbbb

NON-RESONANT

ATLAS: ATLAS-CONF-2016-049
CMS: CMS-PAS-HIG-16-026

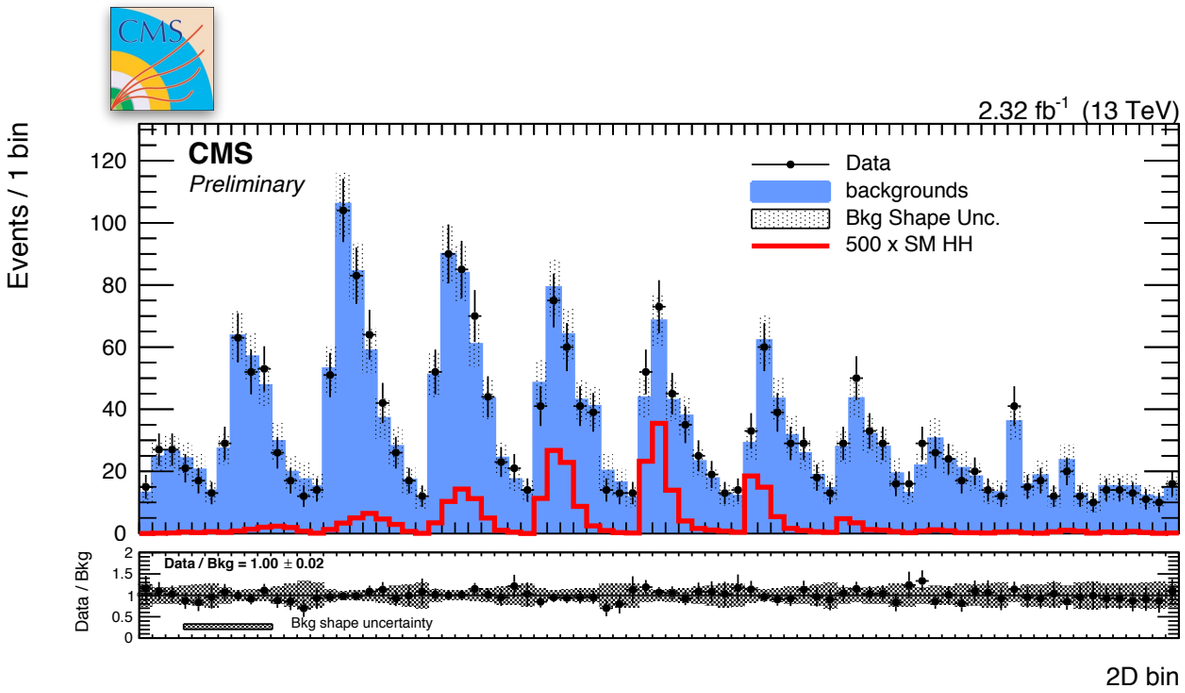
hh->bbbb channel studied only the SM production so far

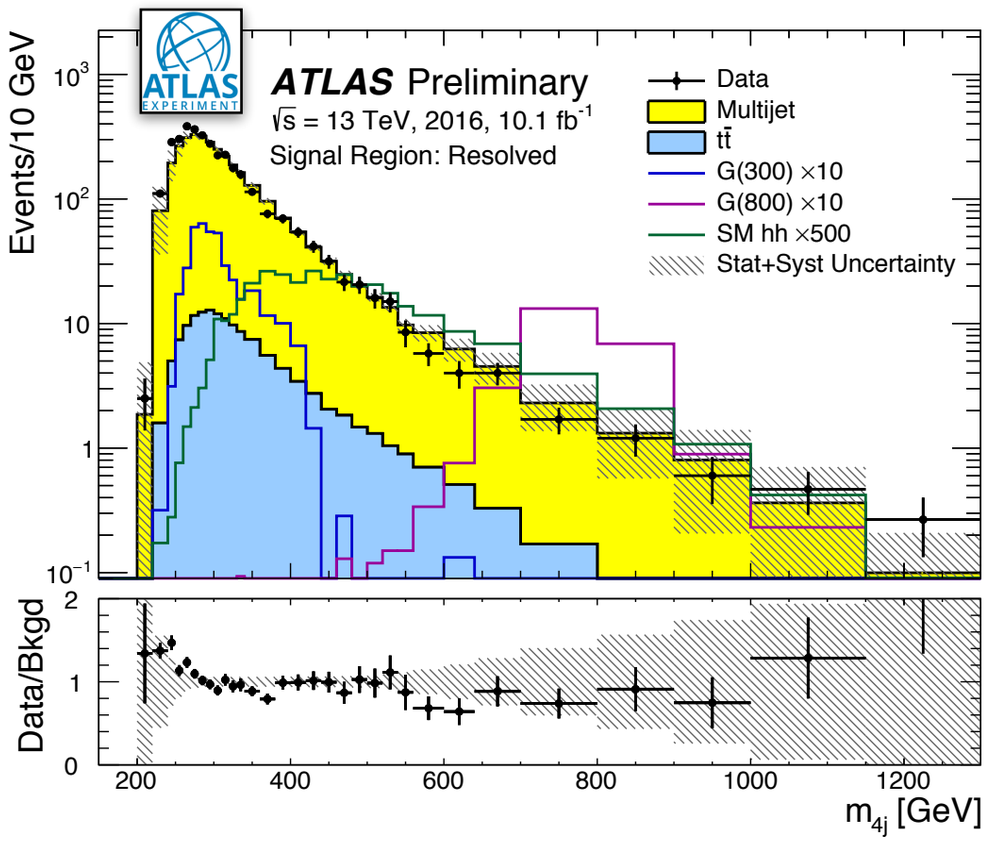
Search strategy:

- ATLAS: same analysis strategy of the low mass resonant hh search. **2015+2016 data (13.3 fb^{-1}).**
- CMS: dedicated analysis to the non-resonant search. **Only 2015 data.**
  - Same trigger as resonant (3b-tag).
  - First 4 jets sorted in b-tag.
  - BDT trained on QCD and tt (di-jet kinematics).

Signal extraction:

- CMS: 2D fit in [m(bb),m(bb)] plane to extract the limit.





ATLAS - SM observed LIMIT (13.3 fb^{-1}):

$\sigma(pp \to hh \to bbbb) < 330$ fb ~ **29 x σ_{SM}**

Improved wrt 2015 (3.2 fb^{-1}): ~ **108 x σ_{SM}**

CMS - SM observed (exp) LIMIT (2.32 fb^{-1}):

$\sigma(pp \to hh \to bbbb) < 3880$ (3490) fb ~ **342 x σ_{SM}**

Search for hh→bbWW

NON-RESONANT

CMS: **CMS-PAS-HIG-16-024**

Search strategy:

- bbWW→bb2l2ν
- 2 isolated OS leptons + 2 b-jets in the final state
- Main backgrounds: tt, DY, single top
- 1 single BDT trained for non-resonant searches.

Signal extraction:

- 2D fit in [m(bb), BDT score] to extract the limits

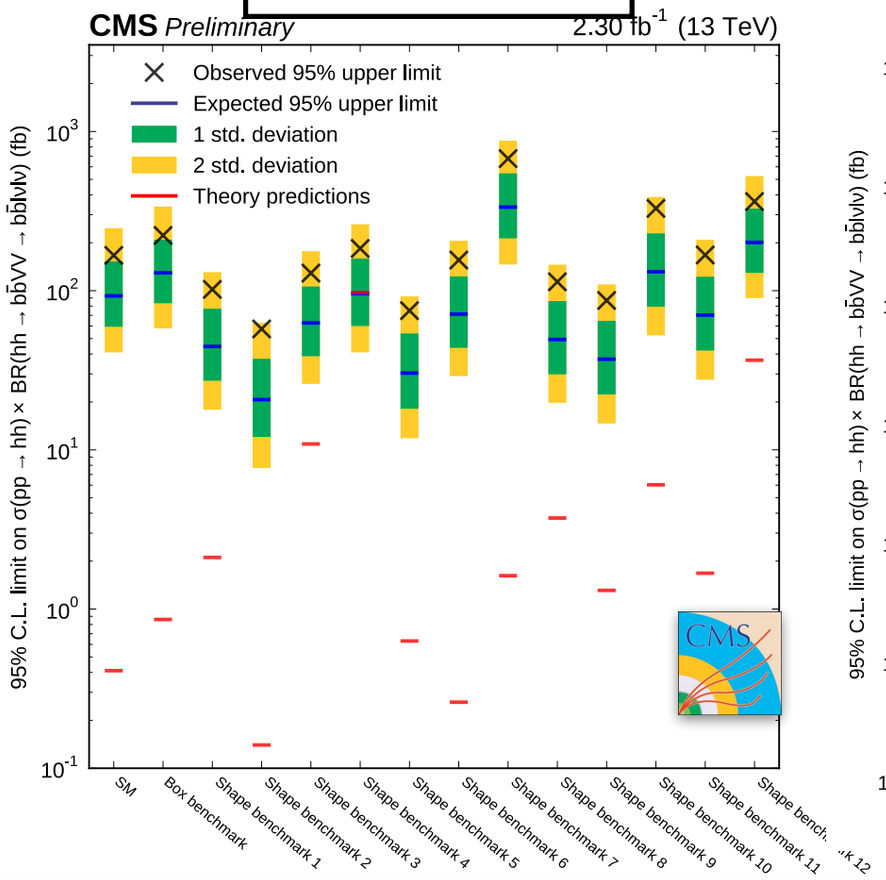
SM observed (exp) LIMIT:

$\sigma(pp \to hh \to bb2l2\nu) < 116.7\ (92.8)$ fb ~ 400 x σ_{SM}

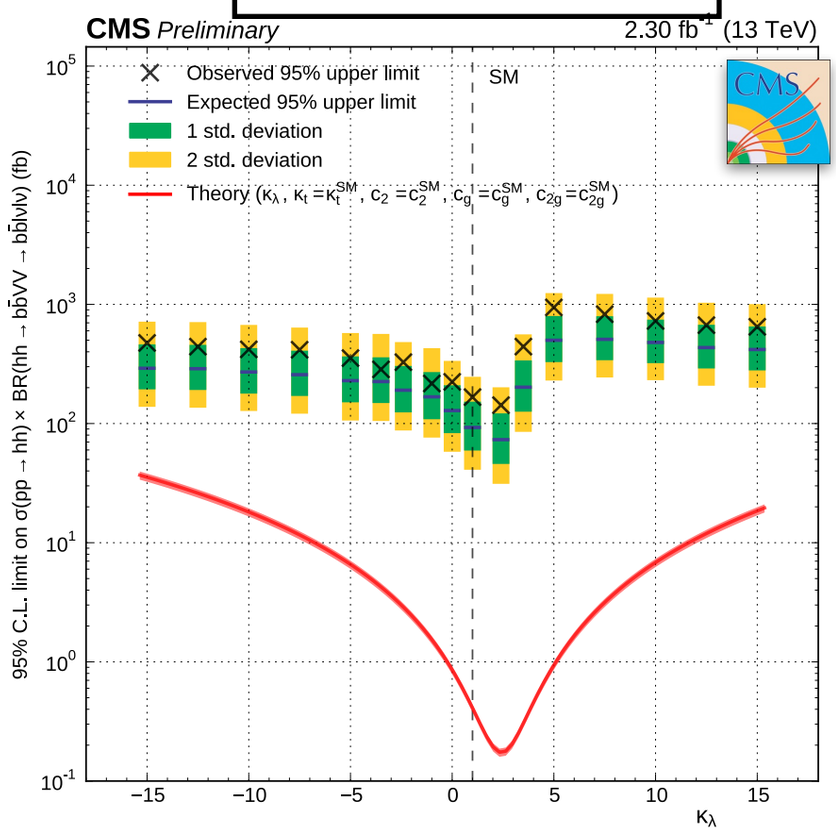
BSM SEARCHES:

- Performed on 12 benchmarks
- Extended to the 5-D parameter space

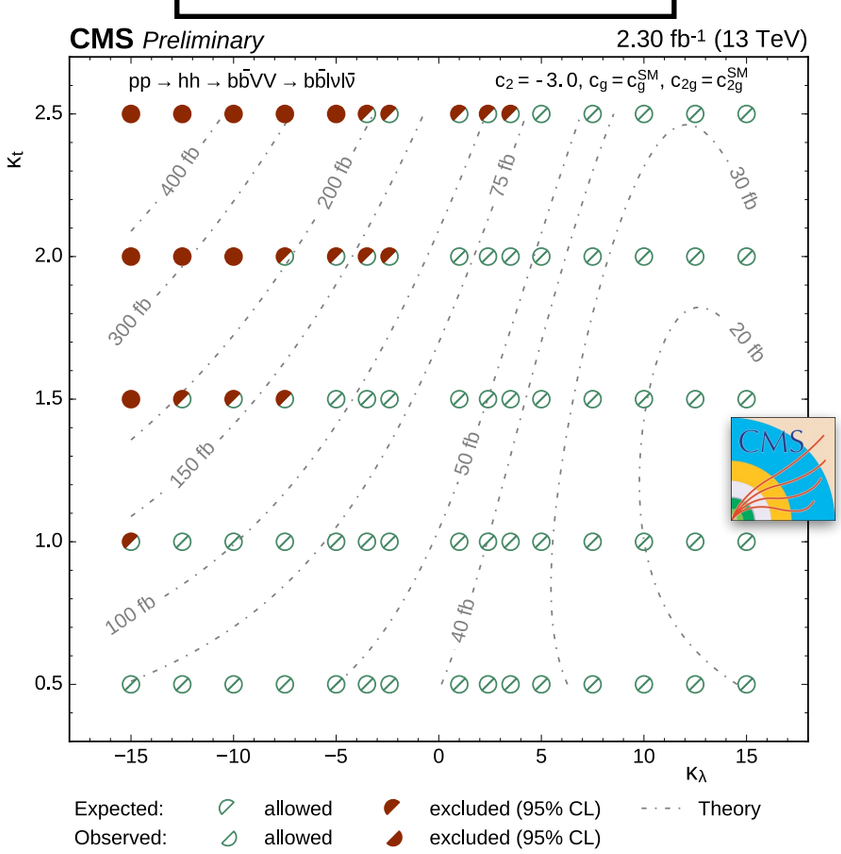
12 Benchmarks



Limit on different k_λ



Limit on k_λ - k_t plane



Search for hh→bbττ

NON-RESONANT

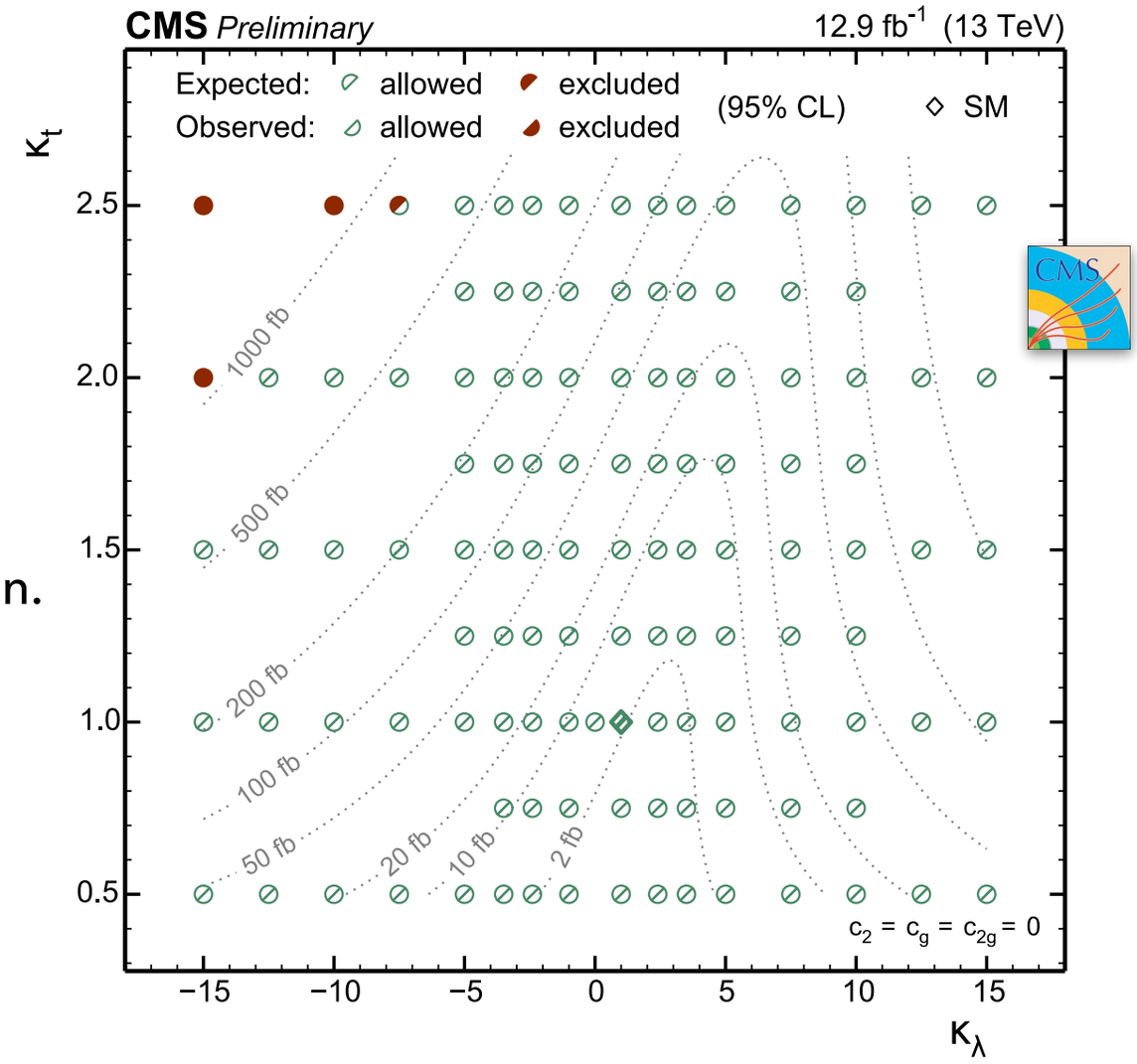
CMS: **CMS-PAS-HIG-16-028**

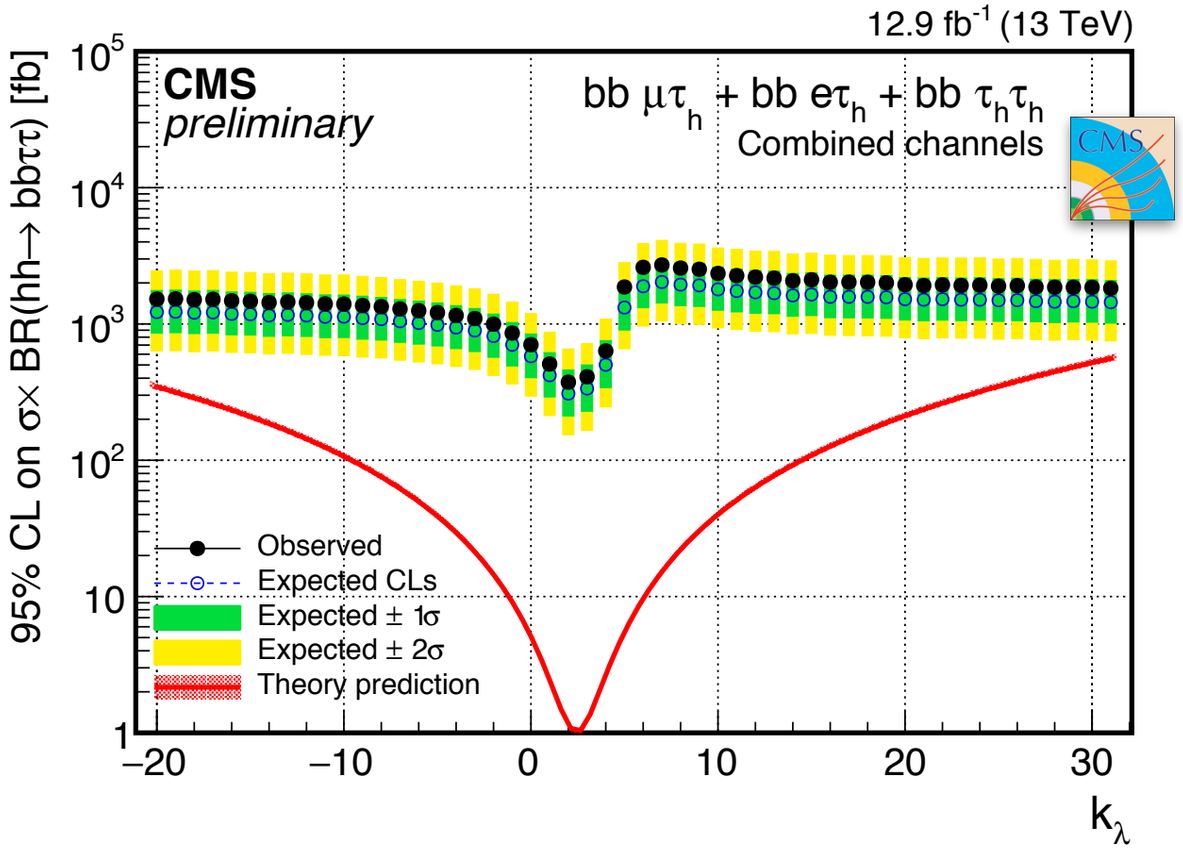
Search strategy:

- $e\tau_H$, $\mu\tau_H$, $\tau_H\tau_H$
- Final state: $1\tau_H$ + 1 isolated leptons + 2 b-jets
- Main backgrounds:
  - tt (from MC)
  - QCD multijet (from data in control regions).
- BDT discriminant to reduce tt, only angular information.

Signal extraction:

- limit extracted on four body mass.





SM observed (exp) LIMIT:

$\sigma(pp \to hh \to bb\tau\tau) < 508\ (420)$ fb ~ **200 x σ_{SM}**

BSM SEARCHES:

k_λ variations (k_t, c_2, c_g, c_{2g} = SM value).

k_λ - k_t plane with $c_2 = c_g = c_{2g} = 0$

Search for hh→bbγγ

NON-RESONANT

ATLAS: **ATLAS-CONF-2016-004**
CMS: **CMS-PAS-HIG-16-032, arxiv:1603.06896**

Search strategy:

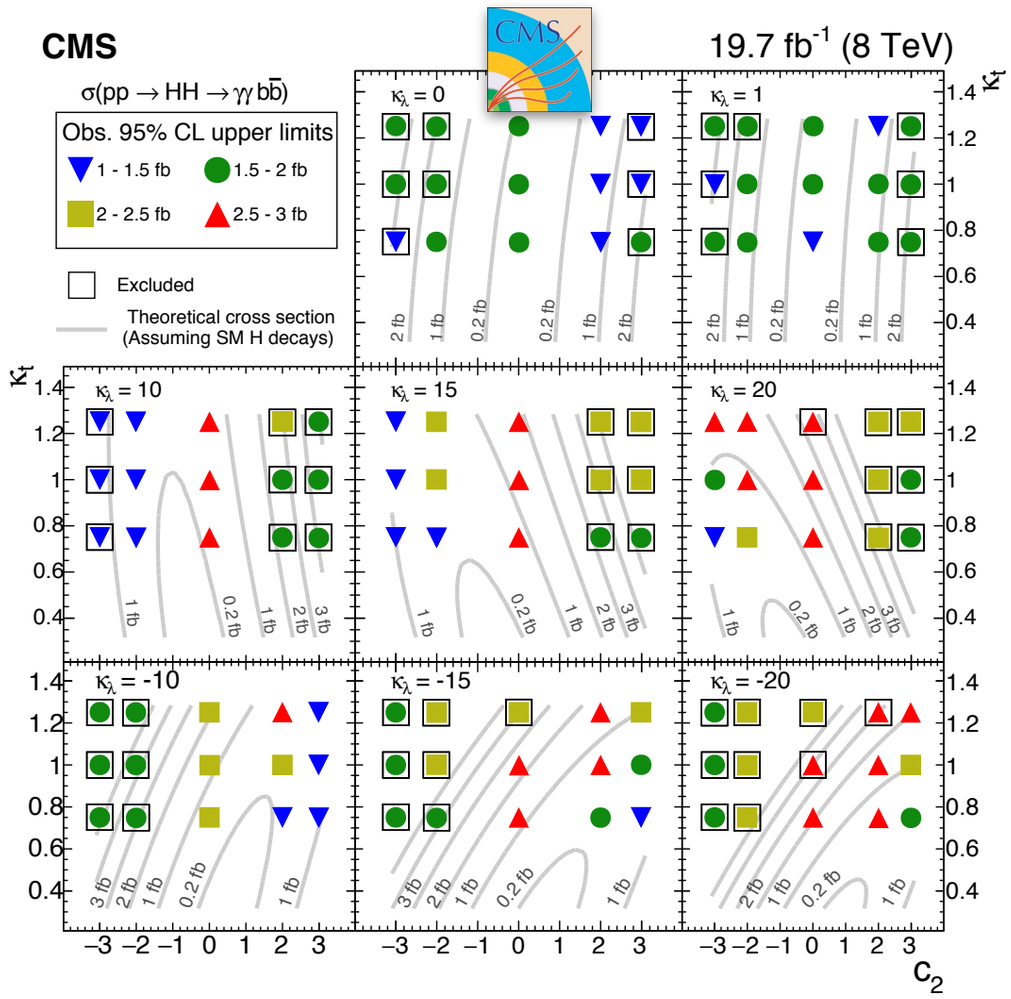
- Almost the same strategy of resonant search for both ATLAS and CMS

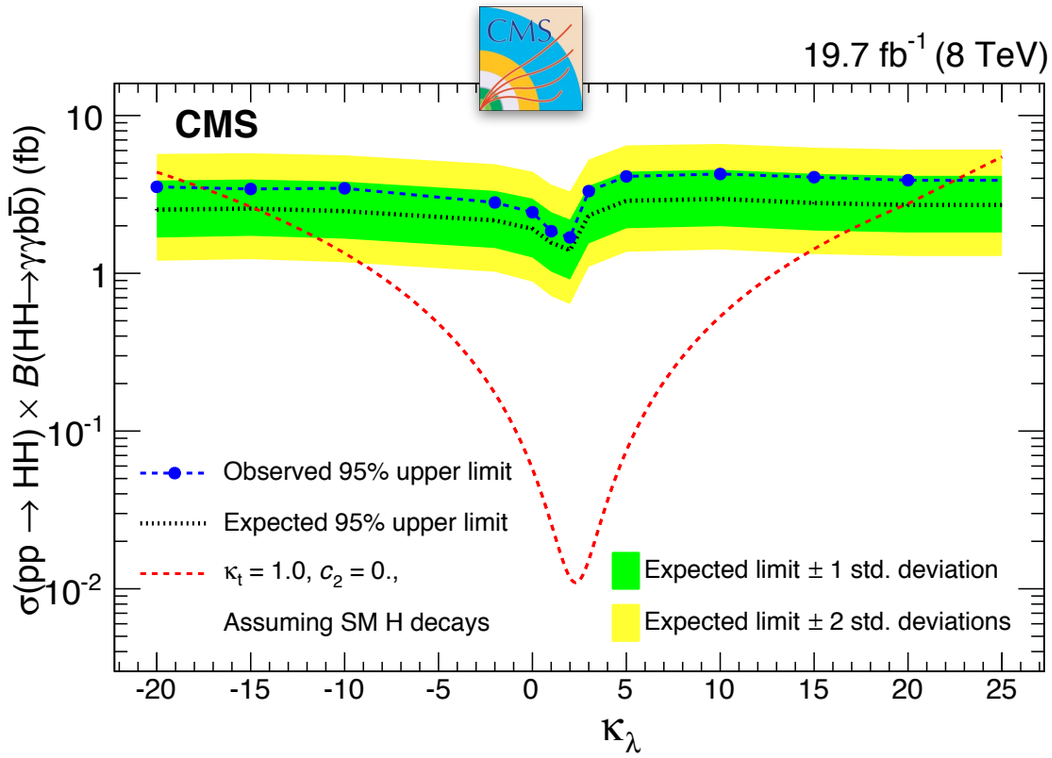
ATLAS - SM observed (exp) LIMIT:

$\sigma(pp \to hh \to bb\gamma\gamma) < 10\ (14)$ fb ~ **115 x σ_{SM}**

CMS - SM observed (exp) LIMIT:

$\sigma(pp \to hh \to bb\gamma\gamma) < 7.9\ (7.85)$ fb ~ **91 x σ_{SM}**





BSM SEARCHES (8TeV):

- Interpretation with BSM samples still not performed on 13 TeV data.
- Previously done on 8 TeV data -> exclusion limit set in the 5 parameter space.

RESULTS

NON-RESONANT

LHC Run2 (13 TeV)

Observed upper limit on σ(pp->hh)SM x BR

	ATLAS SM	CMS SM	CMS BSM interpretation
hh→bbbb	29 X σ_{SM} (13.3 fb^{-1})	342 X σ_{SM} (2.32 fb^{-1})	-
hh→bbWW	-	410 X σ_{SM} (2.3 fb^{-1})	√
hh→bbττ	-	200 X σ_{SM} (12.9 fb^{-1})	√
hh→bbγγ	115 X σ_{SM} (3.2 fb^{-1})	91 X σ_{SM} (2.7 fb^{-1})	√
hh→γγWW	700 X σ_{SM} (13.3 fb^{-1})	-	-

- No excess in Run 2 searches
- Results on the SM prod. cross section extracted with 2015 data are compatible with Run 1
- ATLAS bbbb result put the tighter limit on the SM process
- CMS investigate also BSM effects, searching for Higgs anomalous couplings
  - No excess has been observed
  - Exclusion limit set to points of the parameter space far from SM couplings

Prospects

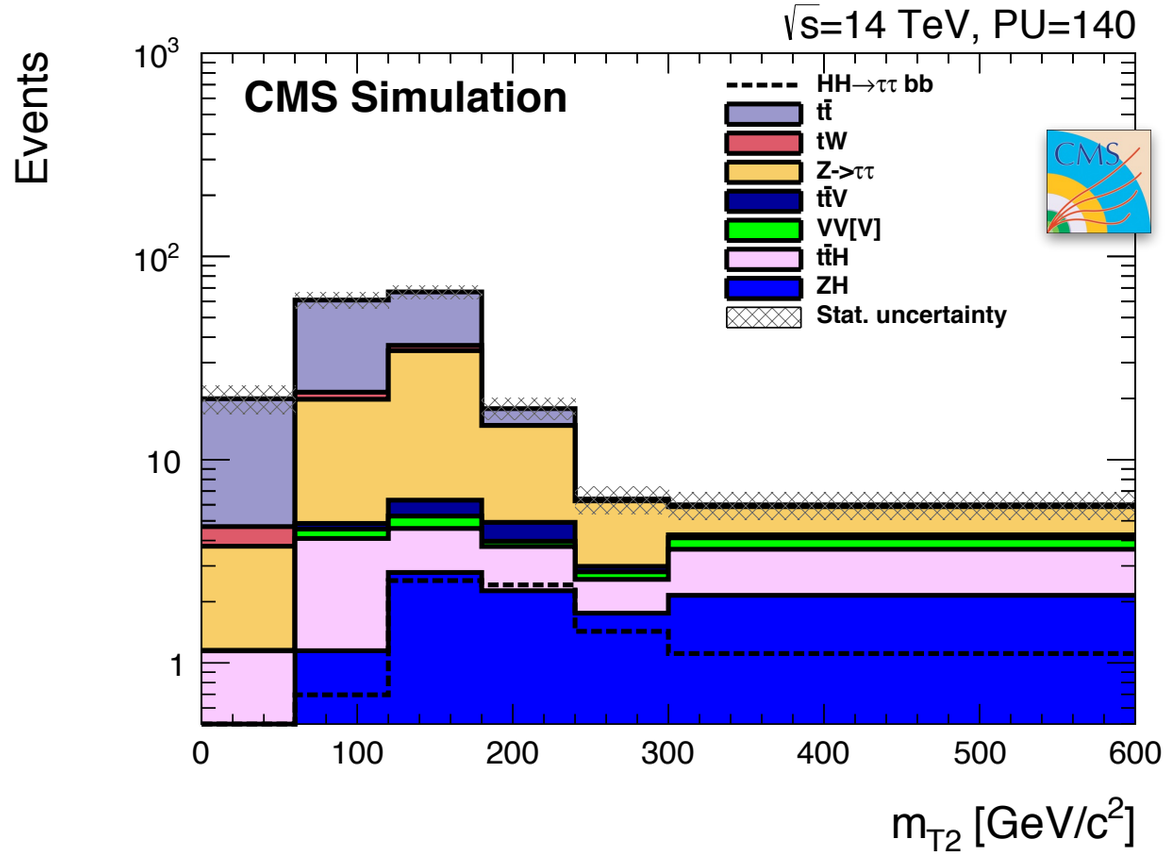
PROSPECTS

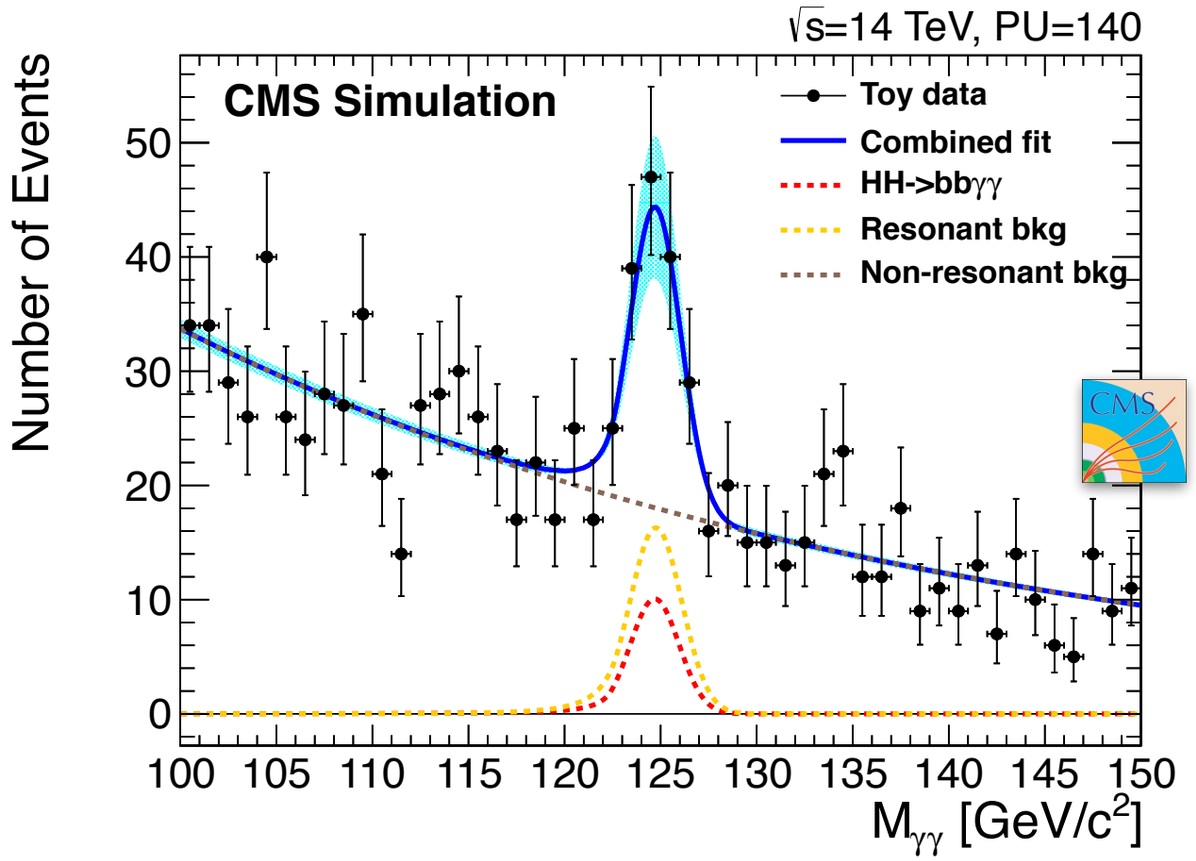
CMS-PAS-FTR-15-002

HL-LHC condition - **3000 fb^{-1}**

bbττ, bbγγ, bbWW channels:

- Delphes simulation used
- Simplified Run1 analysis flow
- Phase II Upgrade conditions included
- SM signal and background
- Main focus is on SM non-resonant production





SM expected:

Combining **bbττ** and **bbγγ**

expected **significance = 1.9 sta dev.**

PROSPECTS

ATL-PHYS-PUB-2015-046
ATL-PHYS-PUB-2014-019

HL-LHC condition - **3000 fb^{-1}**

bbττ channel:

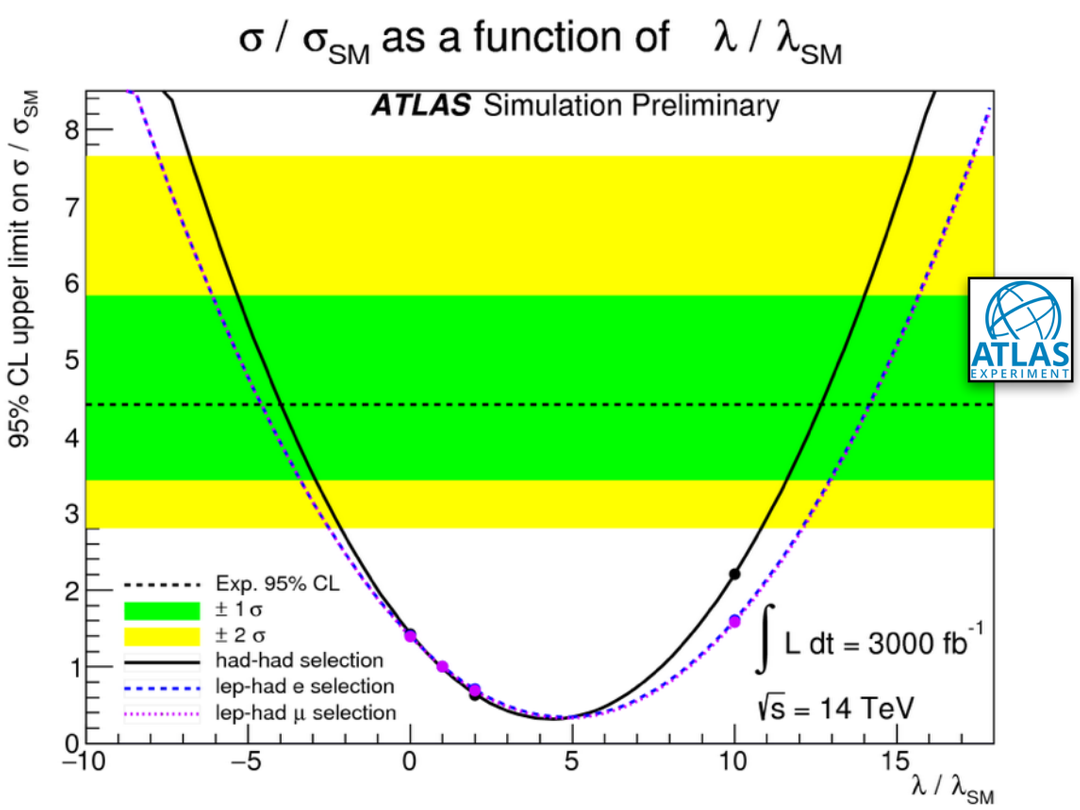
- Simple cut based analysis
- SM signal and background
- BSM using an EFT for the Higgs potential

SM expected LIMIT:

$\sigma(pp \to hh \to bb\tau\tau) \sim$ **4.3 x σ_{SM}**

BSM SEARCHES:

exclusion of $k_\lambda < -4$ and $k_\lambda > 12$



bbγγ channel:

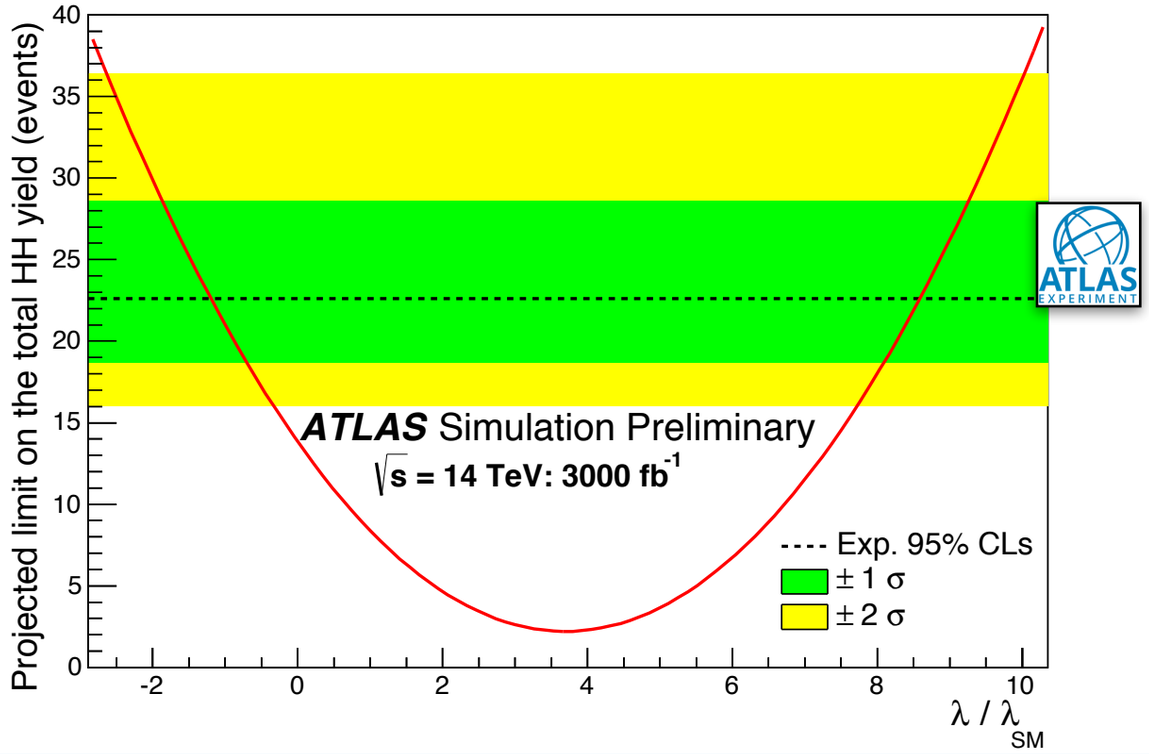
- Gen-level MC used
- Simple cut based analysis
- BSM using an EFT for the Higgs potential

SM expected:

8 events - **significance= 1.3 std dev.**

BSM SEARCHES:

exclusion of $k_\lambda < -1.3$ and $k_\lambda > 8.7$



Conclusions

Conclusions

LHC Run 2:

- HH production searches at LHC started to be an interesting topic
- Excellent coverage in different decay modes
  - resonant searches: bbbb, bbWW, bbττ, bbγγ, γγWW
  - non-resonant searches: bbbb, bbWW, bbττ, bbγγ
- SM process still out of range, but tight limit are set by ATLAS with 2016 data
- Higgs anomalous coupling parametrized by Effective Lagrangian
  - Clustering technique developed to identify benchmarks
  - First exclusion limit set by CMS searches
- No excess in BSM resonant searches

Prospects:

- 2016 dataset will provide a strong improvements in each final state searches
- Investigation on BSM effects on non-resonant hh production using Run2 data

Backup