Search for di-Higgs production at 13 TeV and prospects for HL-LHC with ATLAS detector

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on behalf of the ATLAS collaboration

Di-Higgs at the SM

- The scalar part of the SM Lagrangian after EWK symmetry breaking is:

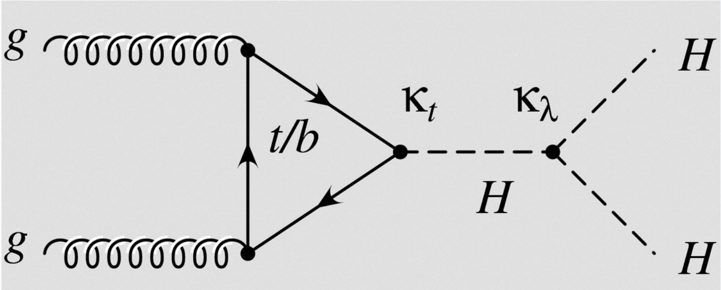
$$\mathcal{L}_H = \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \lambda v^2 H^2 - \lambda v H^3 - \frac{1}{4}\lambda H^4$$

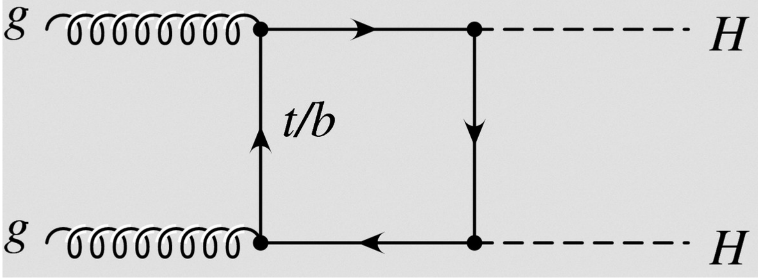
Mass term: ~125 GeV (measured at the LHC)

Higgs vacuum expectation value: υ~ 246 GeV (known from Fermi constant)

There are vertices with 3 and 4 Higgs bosons

Therefore in the SM we expect multi-Higgs production at tree-level with already known couplings





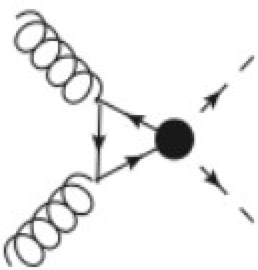
However, still very small cross section:
σ(HH) = 34 fb (c.f. σ(gg→H) ~50 pb)
due to negative interference with box diagram

Di-Higgs beyond the SM

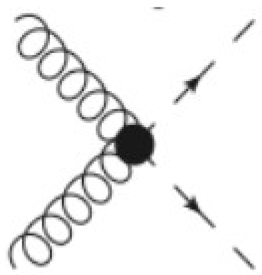
- Vertices with 3 and 4 Higgs bosons have not been directly probed: leaves several options for beyond SM scenarios

- Anomalous couplings
- New states running in the loops

Predict anomalous *non-resonant* production of Higgs pairs



qqHH

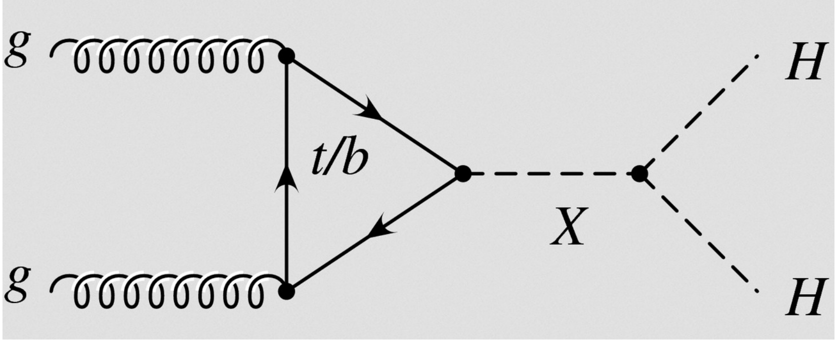


ggHH

- Also possibility for di-Higgs resonant production

- Theories that include an extended Higgs sector (e.g. MSSM, NMSSM, …)
- More exotic option with heavy resonances decaying to HH, e.g. a Lagrangian modification:

$$\mathcal{L}_H = \cdots - \lambda_S S^2 H^2 + \lambda_v V_\mu V^\mu H^2$$



A survey of HH final states

- By looking at the Branching ratios we can get a first idea which channel is more important

HH → bbbb: JHEP 01 (2019) 030
HH → bbττ: PRL 121, 191801 (2018)
HH → bbγγ: JHEP 11 (2018) 040

HH → WWγγ: EPJC 78 (2018) 1007
HH → WWbb: JHEP 04 (2019) 092
HH → WWWW: arXiv:1811.11028

HH combination: ATLAS-CONF-2018-043
(update to be submitted to journal soon)

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Direction of largest BR

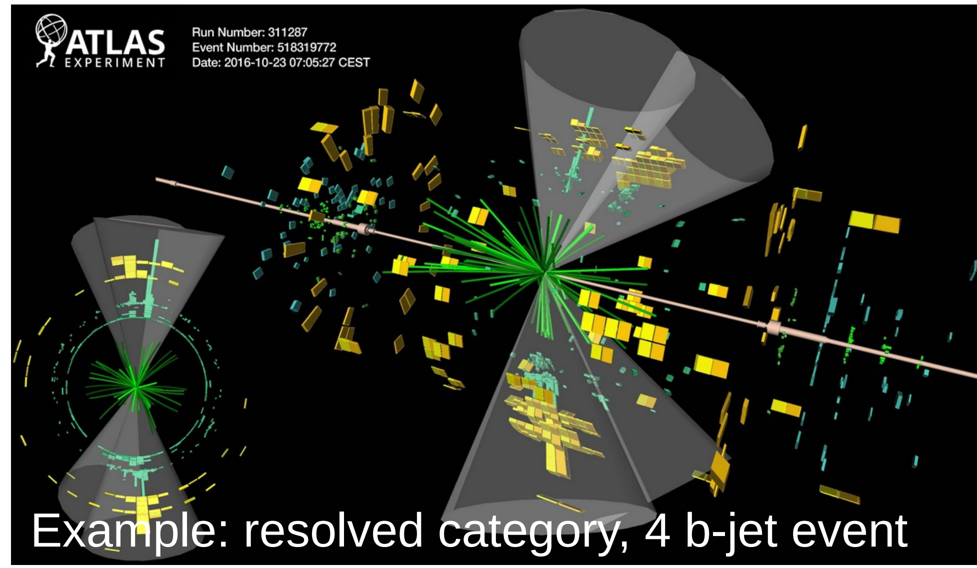
Indirectly via single Higgs production: ATLAS-PUB-2019-009

JHEP 01 (2019) 030

HH → bbbb

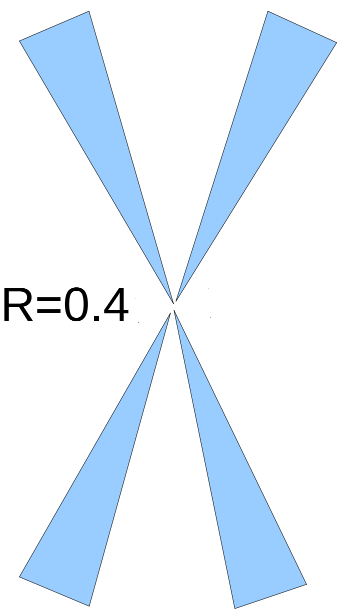
- Highest BR, but penalized due the large background

- 2 categories:

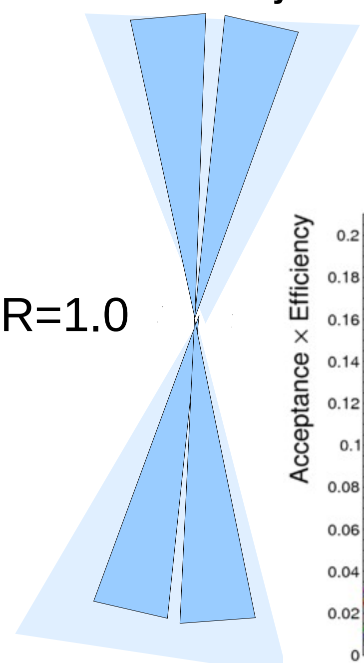


Example: resolved category, 4 b-jet event

resolved vs boosted jets

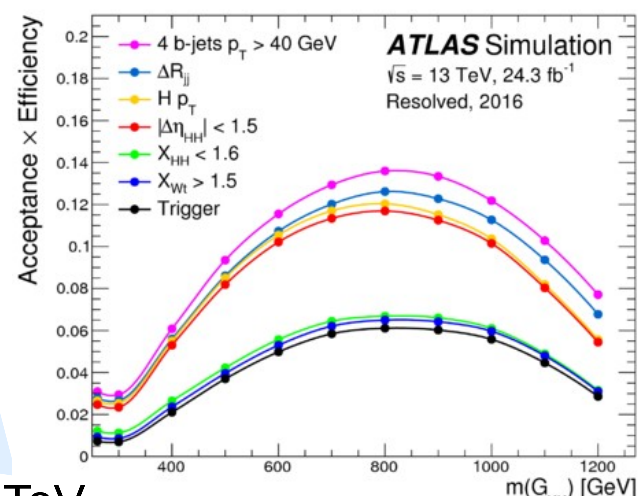


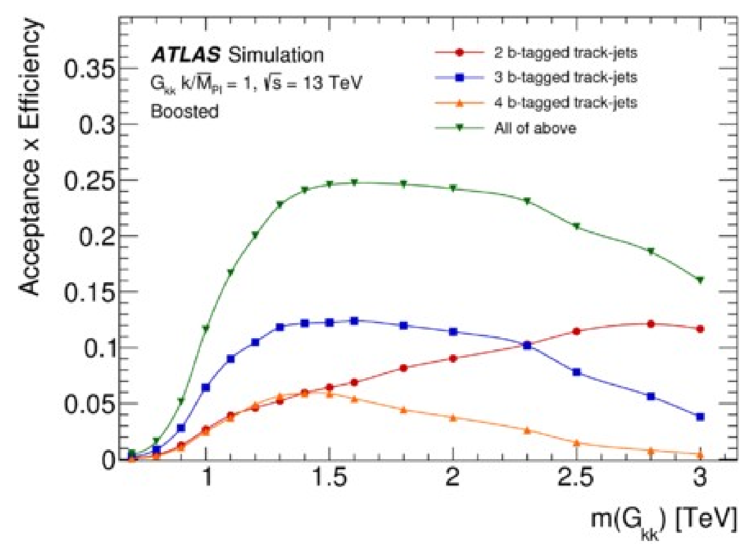
R=0.4



R=1.0

m_X: 0.26–1.4 TeV m_X: 0.8 – 3 TeV



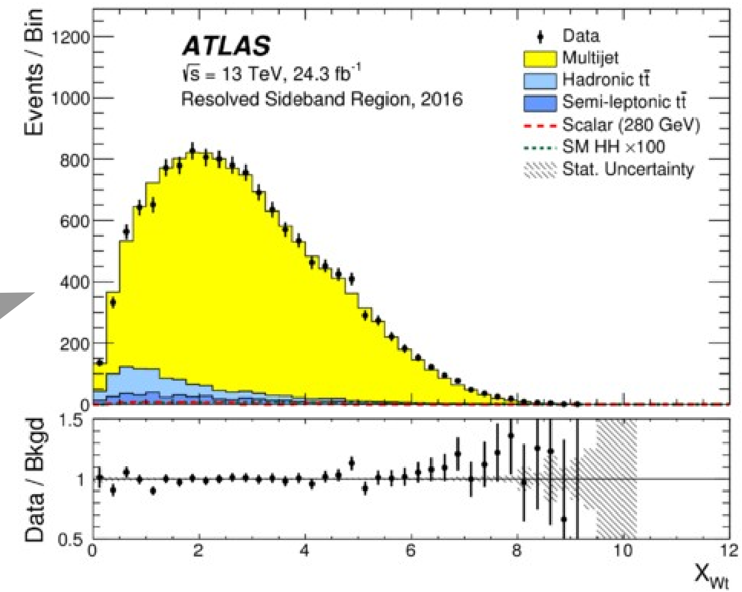


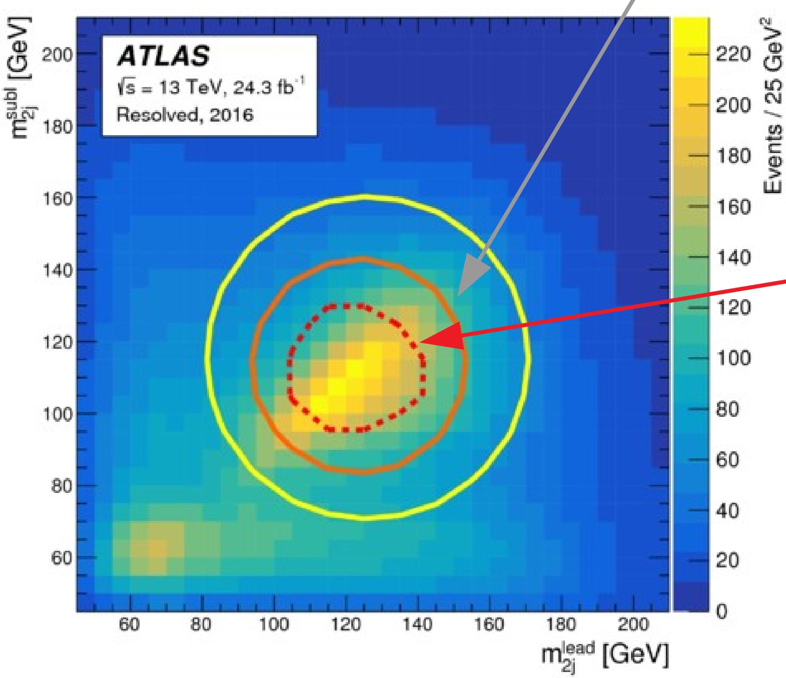
HH→ bbbb: resolved category

- Resolved category:
  - 4 b-jets, p_T > 40 GeV
  - major bkg: multi-jet

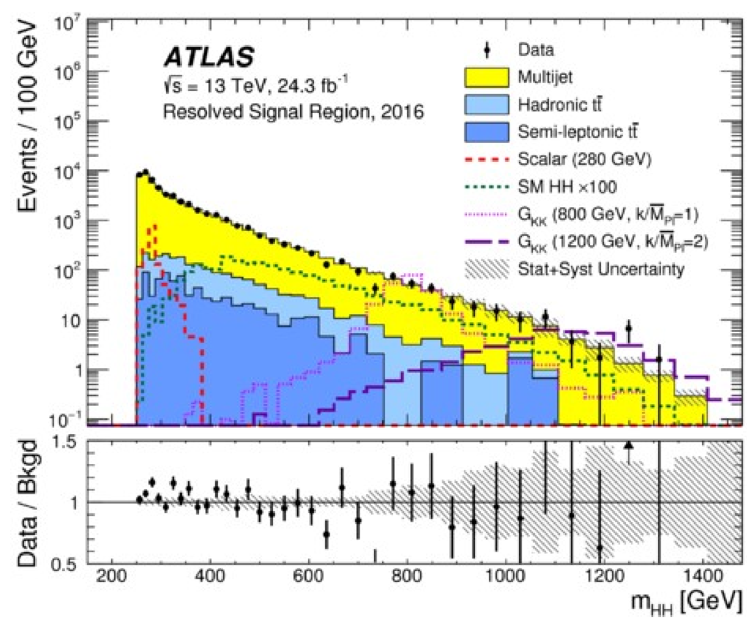
sideband

Signal region



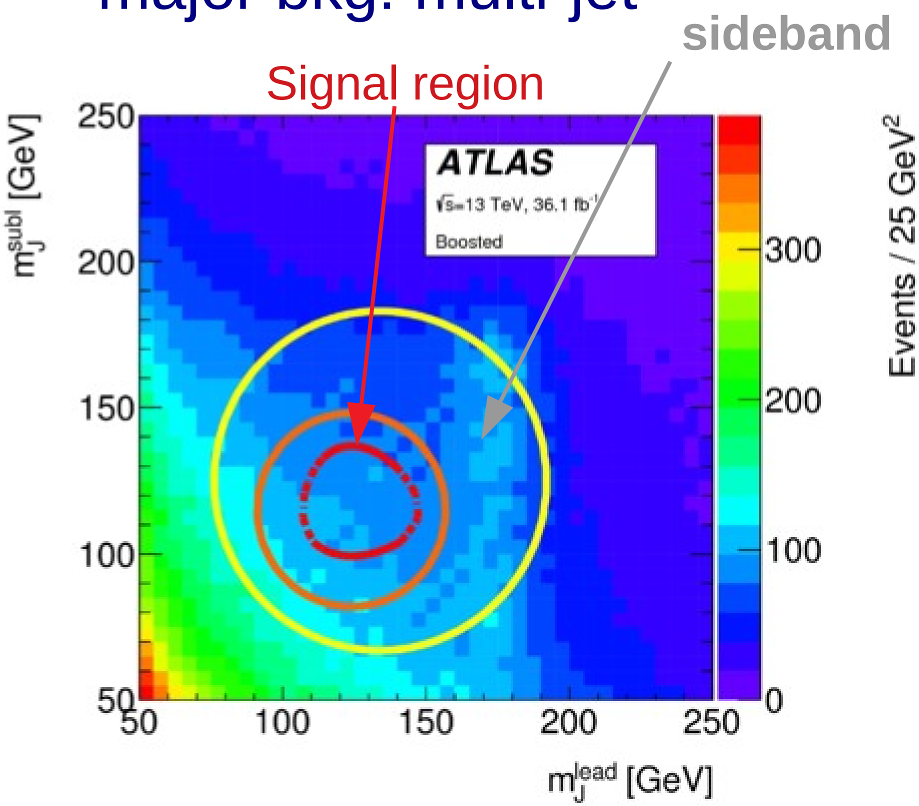


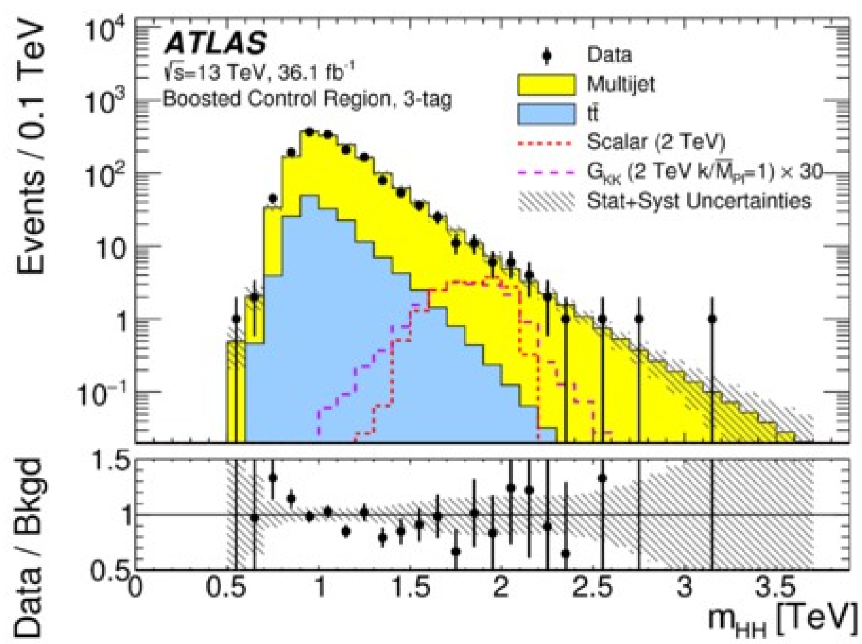
Estimated multi-jet bkg



HH → bbbb: boosted category

- Boosted category:
  - 2 large R=1.0 jets, p_T > 450, 250 GeV, m_J > 50 GeV, |Δη| < 1.7
  - categories depending on how many b-jets in large R jet substructure (2, 3 and 4 b-jets)
  - major bkg: multi-jet





HH→ bbbb: results

- Non resonant search

Resolved analysis only used here

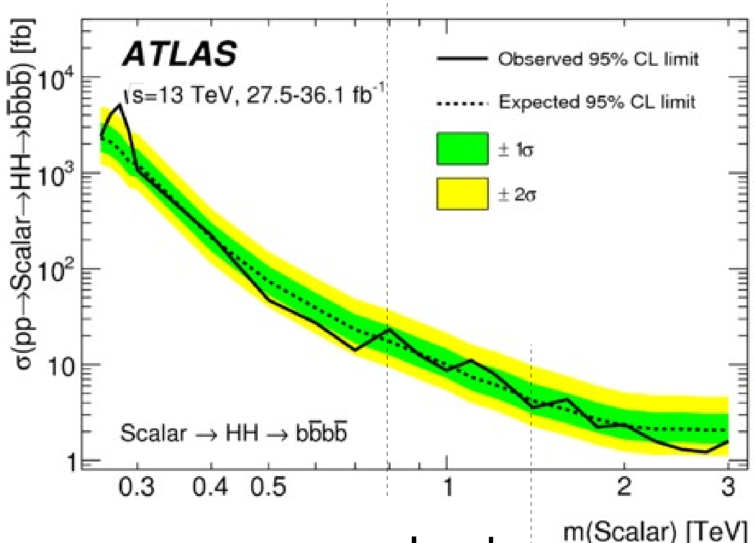
Limits in units of the SM prediction for σ(pp→ HH→ bbbb)

Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
12.9	11.1	14.9	20.7	30.0	43.6

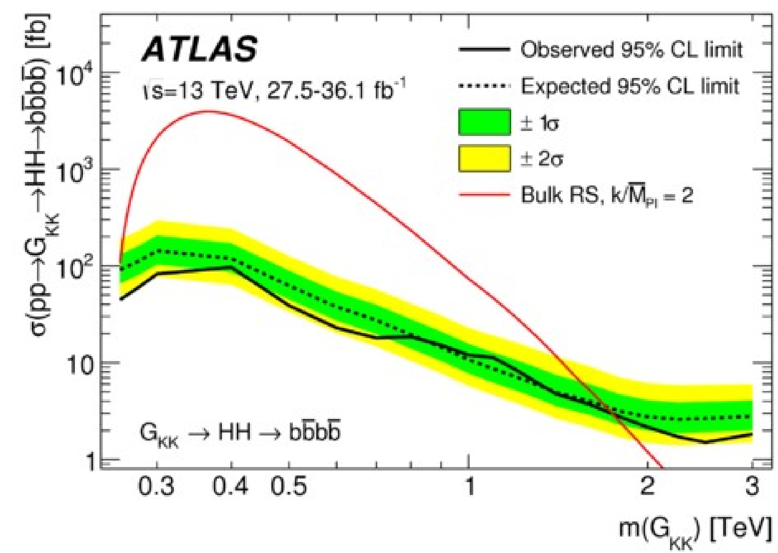
- Resonant analysis

boosted

Largest excess: 3.6 σ at 280 GeV (local significance)



resolved



HH → bbττ

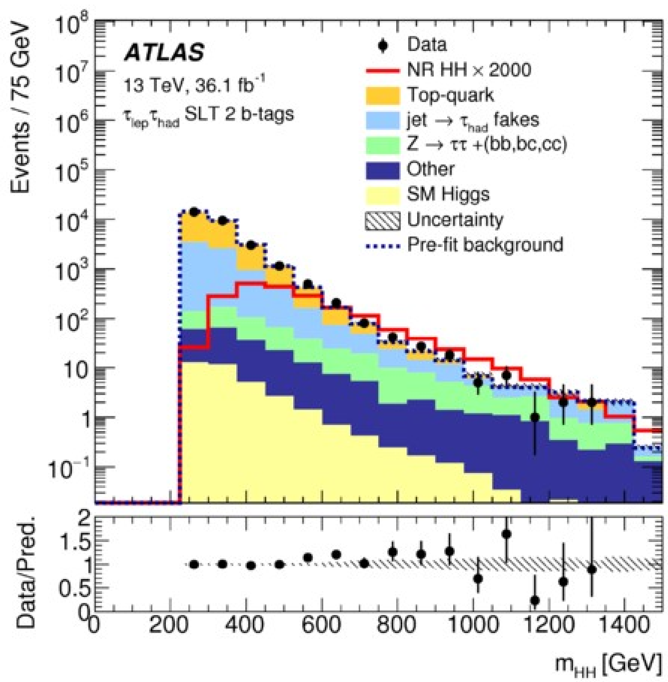
PRL 121, 191801 (2018)

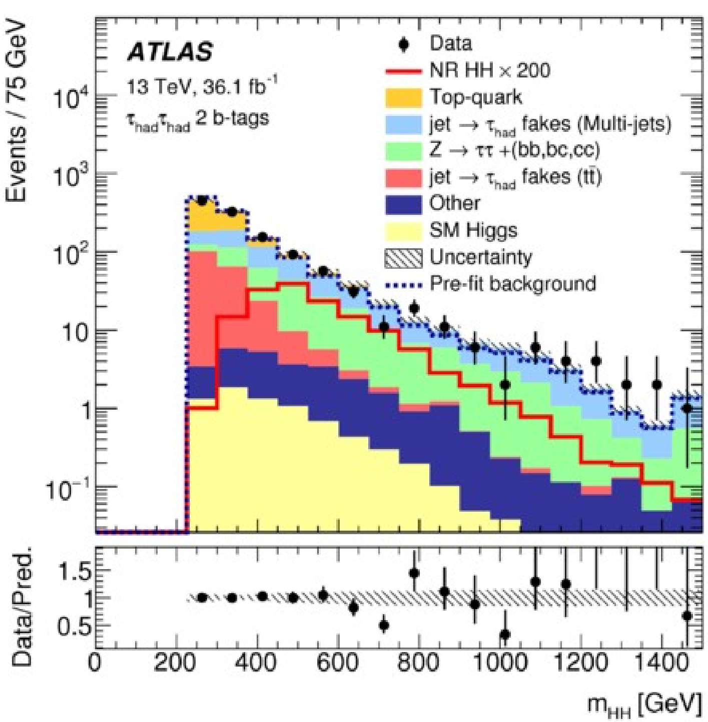
- Channels depending on the tau lepton decay

- τ(lep) τ(had)
  - single lepton trigger (SLT)
  - lepton + hadronic tau trigger (LTT)
  - 1 electron or muon, 1 hadronic tau

- τ(had) τ(had)
  - single hadronic tau trigger (STT)
  - di hadronic tau trigger (DTT)
  - 2 hadronic taus

Common: 2 b-jets, m(ττ) > 60 GeV

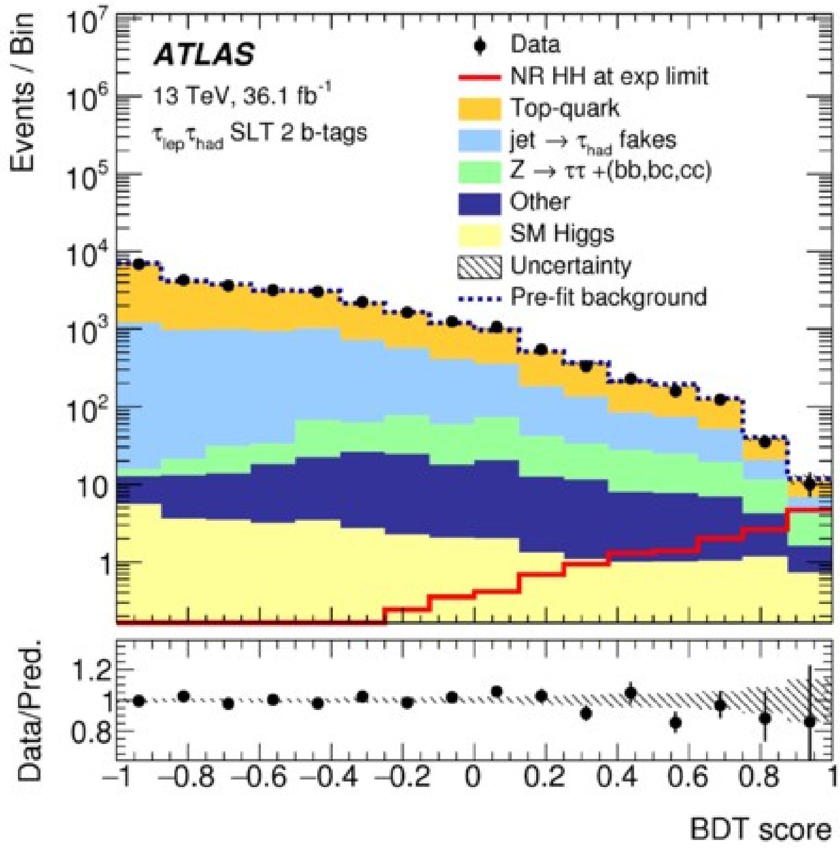




HH→ bbττ

- Multivariate technique is used to boost sensitivity (BDT)

Variable	$\tau_{\rm lep}\tau_{\rm had}$ channel (SLT resonant)	$\tau_{\rm lep}\tau_{\rm had}$ channel (SLT non-resonant & LTT)	$\tau_{\rm had}\tau_{\rm had}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\rm MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	✓
$E_{\rm T}^{\rm miss}$	✓		
$E_{\rm T}^{\rm miss}$ ϕ centrality	✓		✓
$m_{\rm T}^{W}$	✓	✓	
$\Delta\phi(H,H)$	✓		
$\Delta p_{\rm T}({\rm lep},\tau_{\rm had\text{-}vis})$	✓		
Sub-leading b-jet $p_{\rm T}$	✓		

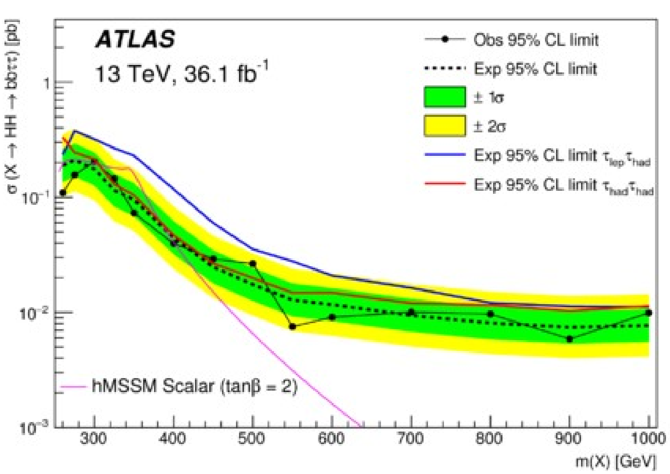


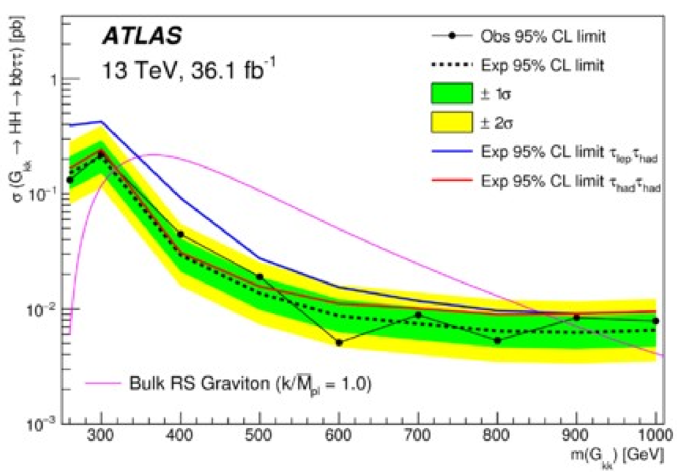
HH→ bbττ: results

- Non-resonant analysis: limits on hh production

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

- Resonant analysis

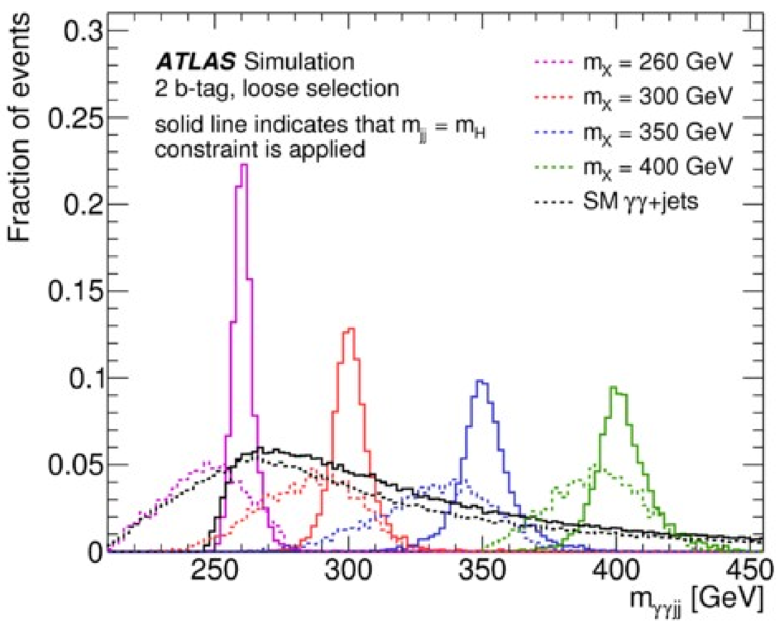


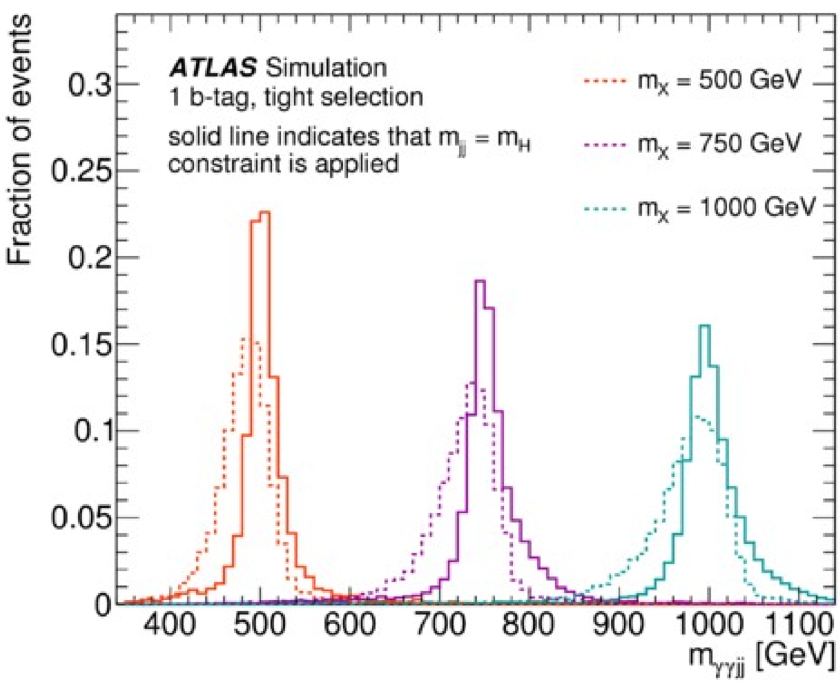


HH → bbγγ

JHEP 11 (2018) 040

- Selection:
  - 2 photons, $m_{\gamma\gamma}$: 105-160 GeV
  - 2 jets; categorization in 1 b-tagged and 2 b-tagged jets
  - low mass (m_X: 260-500 GeV) and high mass (m_X > 500 GeV) categories





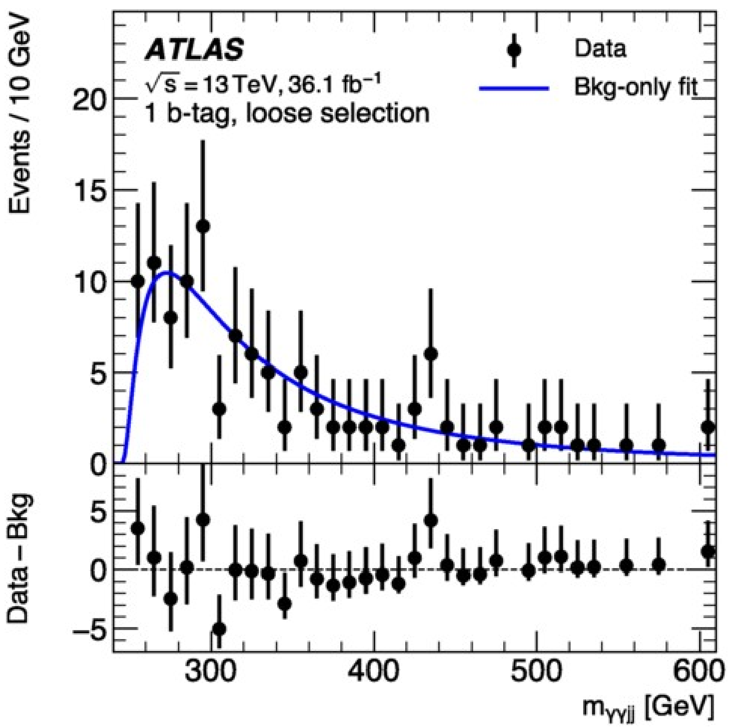
HH → bbγγ

- Results

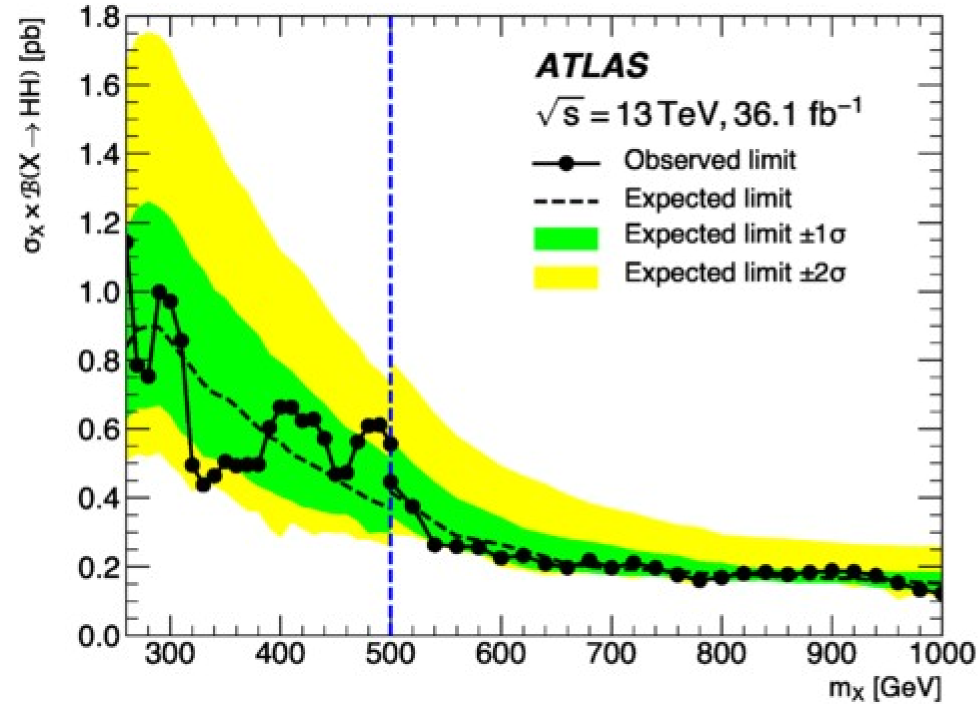
Non resonant analysis: limits on hh production

	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\to HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

Example of final fit distribution:

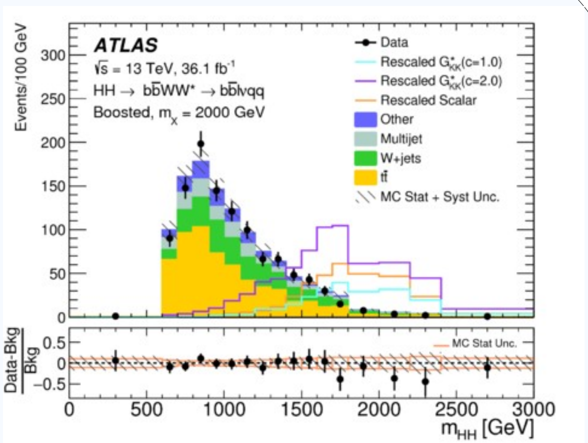


resonant:

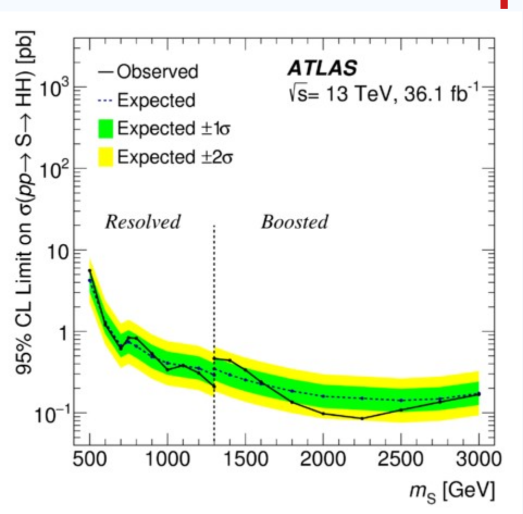


Other channels

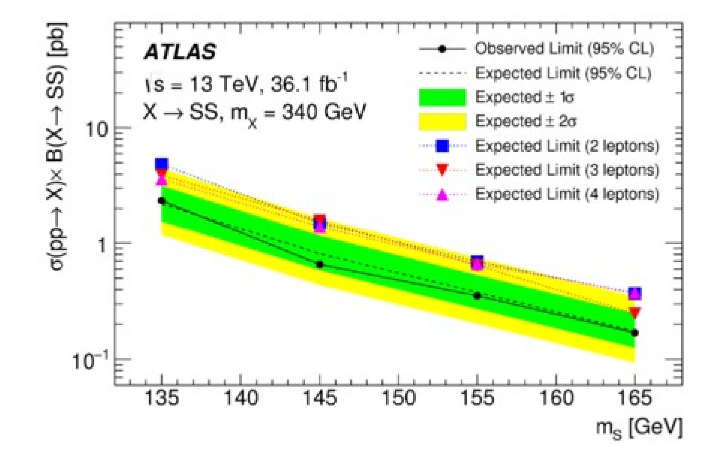
- Brief mention of other channels that are less sensitive to λ but still very relevant heavy resonant production



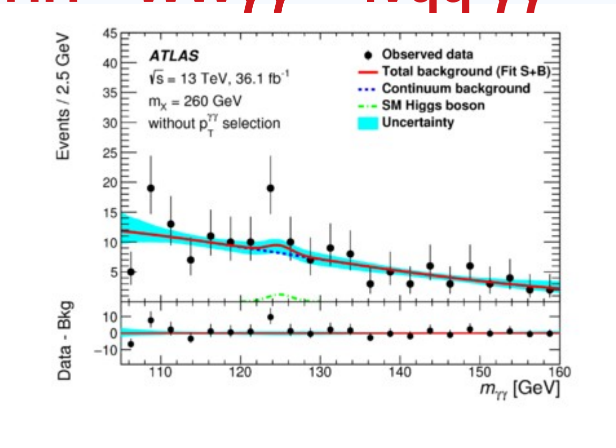
HH → bbWW → bb lνqq

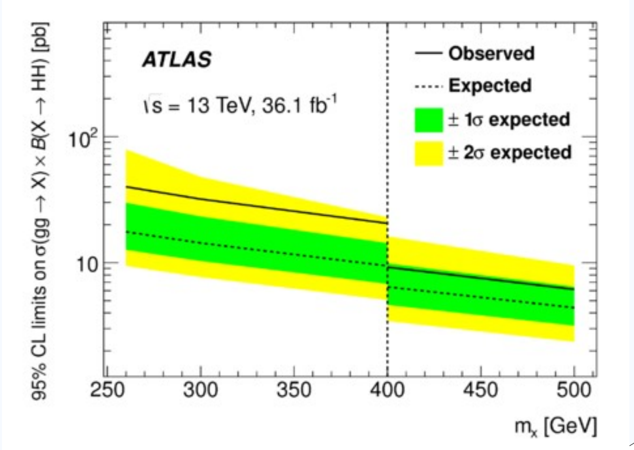


HH → 4W in 2, 3, 4 lep final states, incl X → SS with various S masses



HH → WWγγ → lνqq γγ

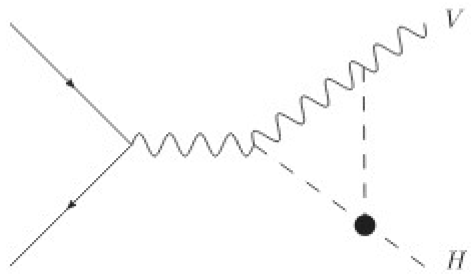


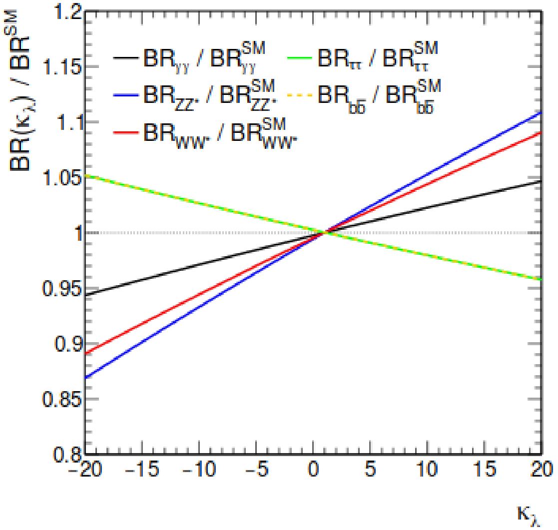


Constraints from single Higgs production

- By measuring differential cross sections of single Higgs production you can also constrain Higgs self coupling (λ)

Example Feynman diagram:
λ effect in production





Example: λ effect on branching ratios

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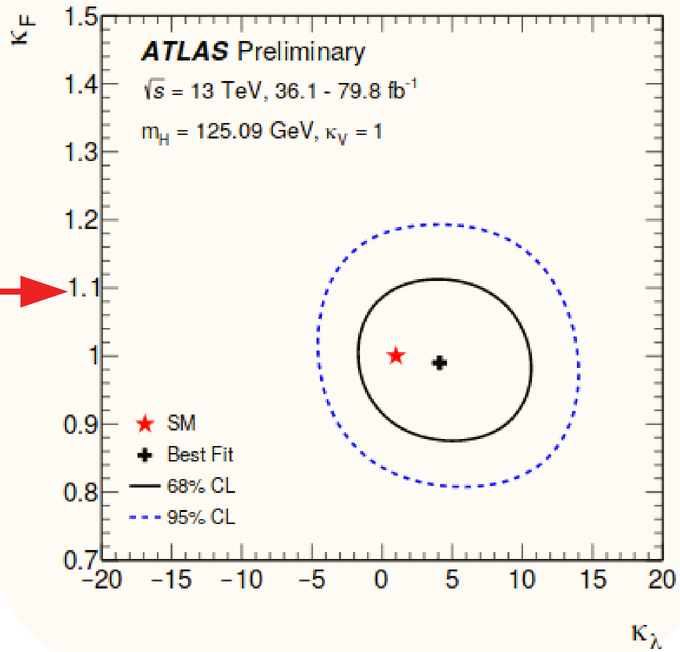
Results I:
- assuming that only $\kappa_\lambda = \lambda/\lambda_{SM}$ changes

Best fit value: $\kappa_\lambda = 4.0^{+4.3}_{-4.1}$

Excluded @ 95% CL: κ_λ **< -3.2** κ_λ **> 11.9**

Results II:
- assuming that $\kappa_\lambda = \lambda/\lambda_{SM}$ and κ_F or κ_V change



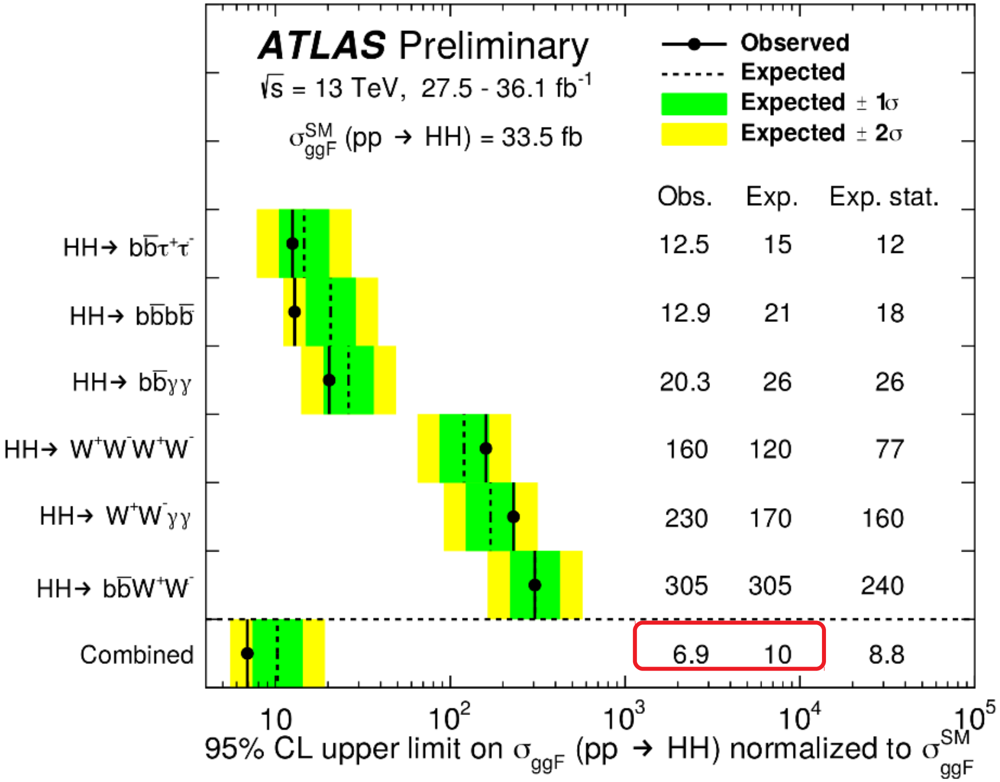
NEW

Combination: non-resonant

- Combination all channels for the non-resonant production

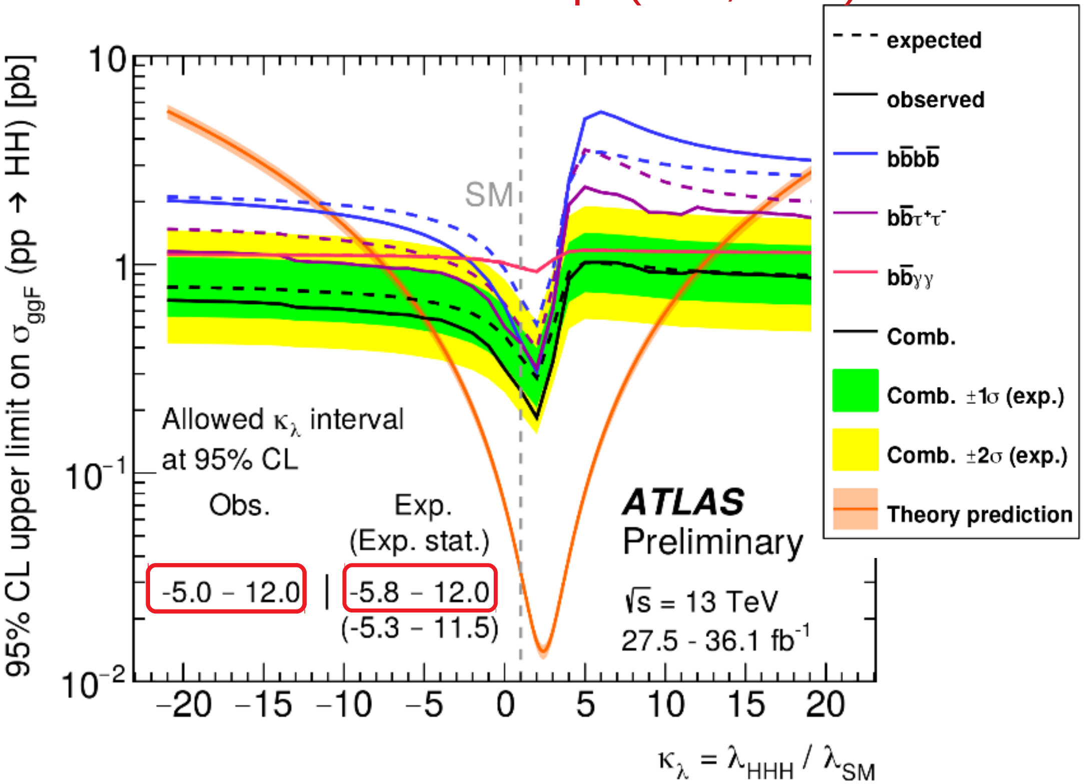
Production cross section

$$\frac{\sigma(gg \rightarrow HH)}{\sigma(gg \rightarrow HH; SM)} > 6.9 \text{ (obs)} \quad 10 \text{ (exp)}$$



Higgs self-interaction coupling

Constraint on κ_λ: obs. (-5.0, 12.0)
exp. (-5.8, 12.0)



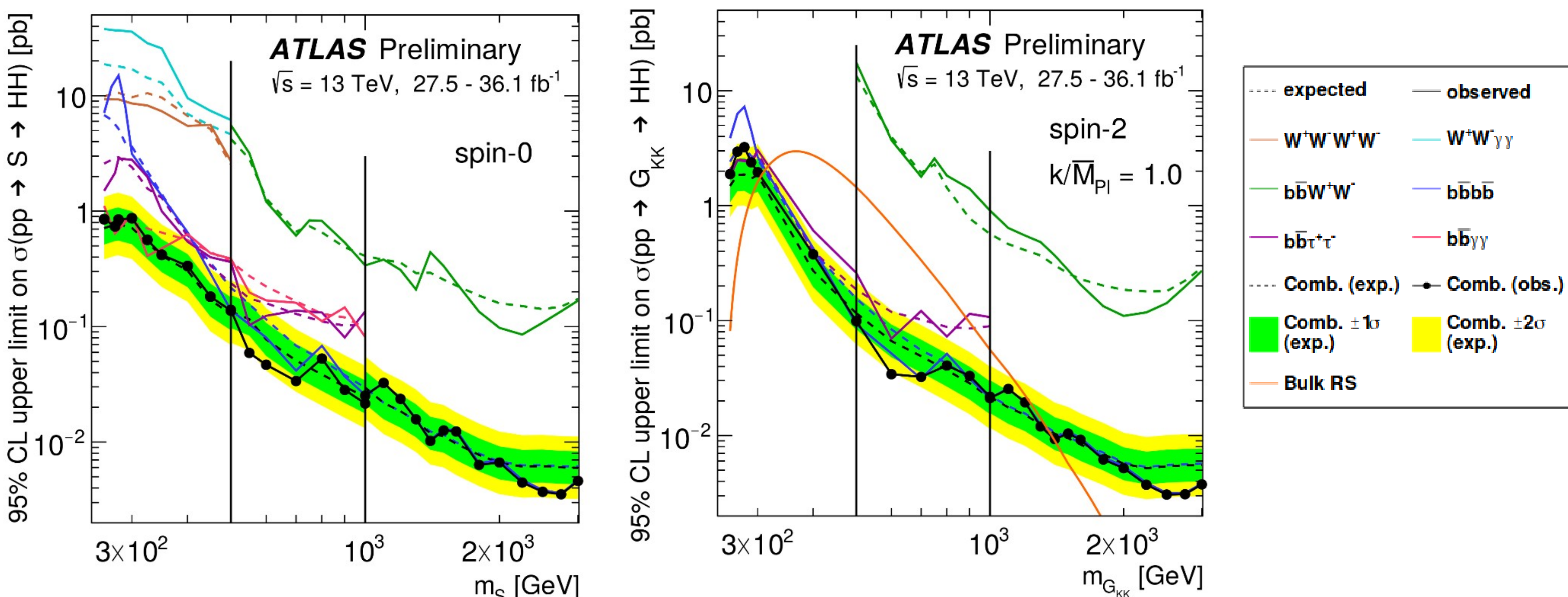
NEW

Combination: resonant

- Cross section limits combination for spin 0 and spin 2

bbbb, bbττ, bbγγ, WWγγ, WWWW | bbbb, bbττ, bbγγ, bbWW, WWWW | bbbb, bbWW

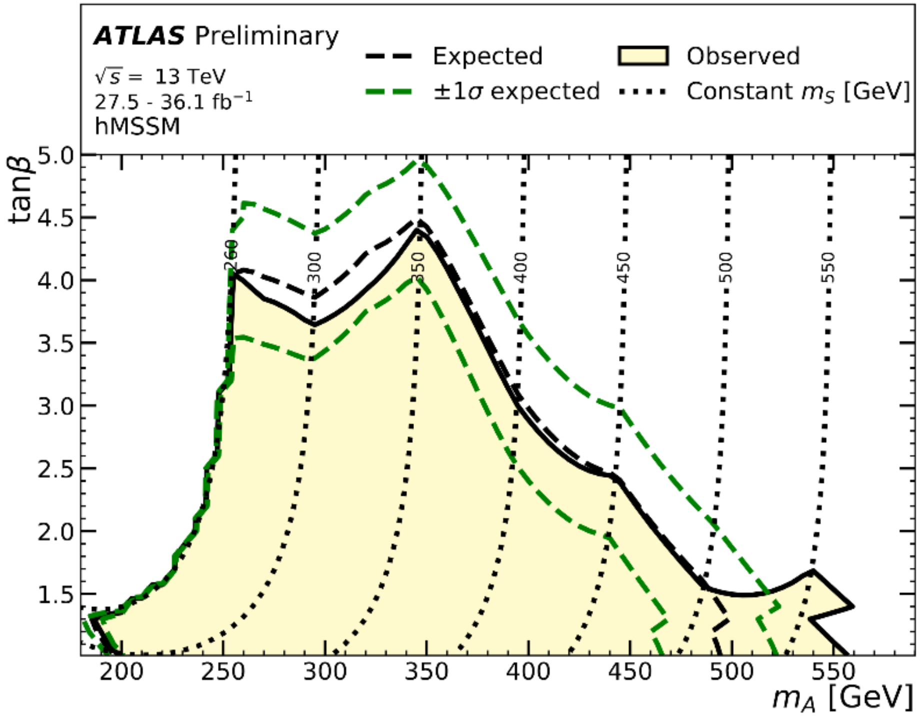
bbbb, bbττ | bbbb, bbττ, bbWW | bbbb, bbWW



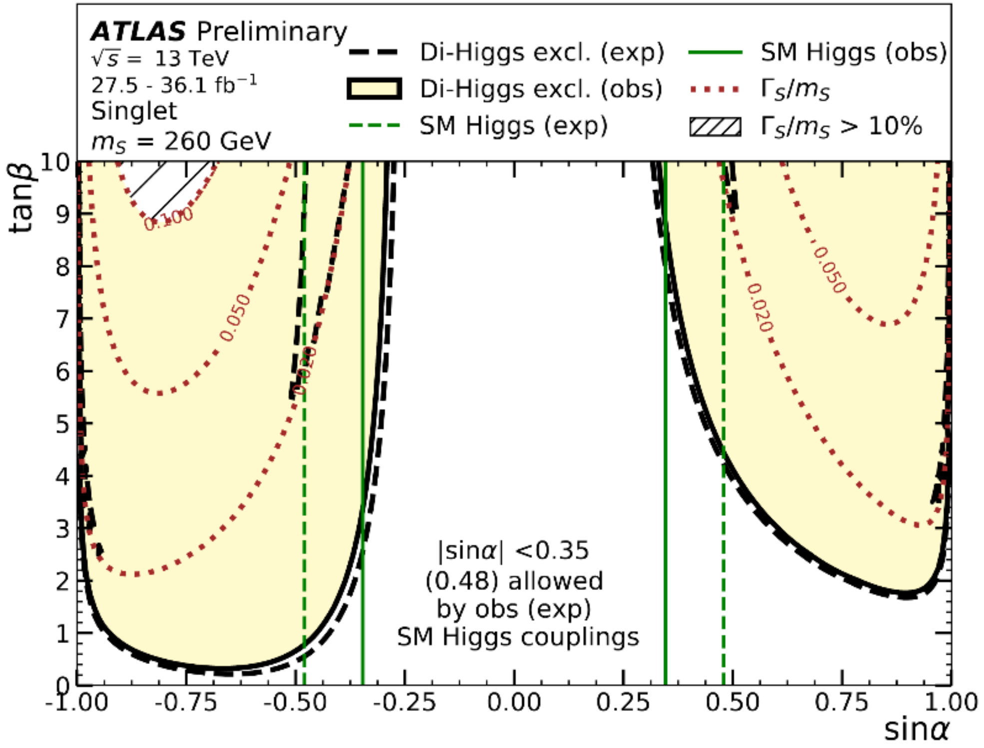
NEW Combination: interpretations

- Electroweak singlet and hMSSM approximation

hMSSM: large mass on Susy particles apart from Higgs bosons, + other assumptions



Real EWK singlet extension of the SM: one extra scalar, one extra vev and a mixing angle (α)

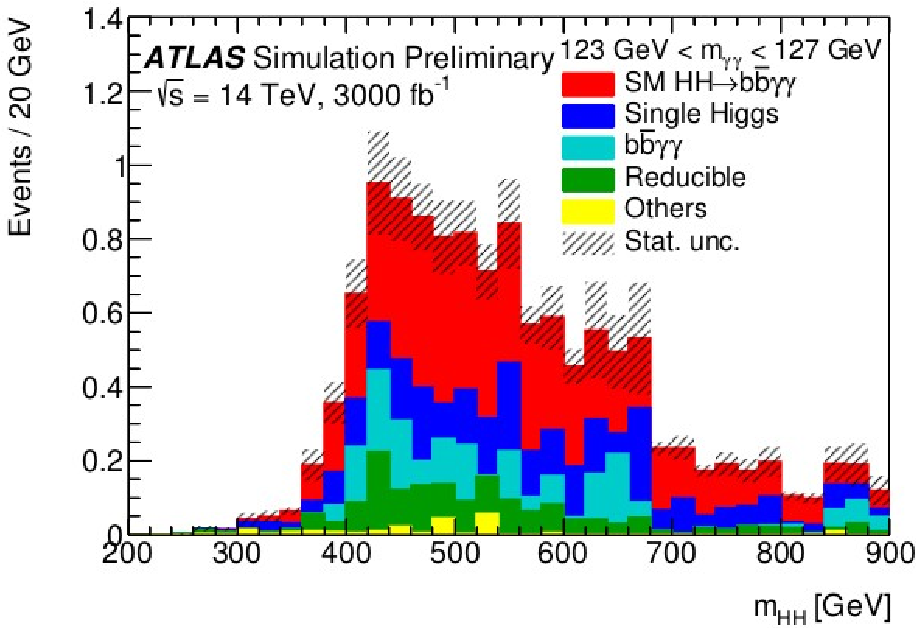


Prospects for the HL-LHC

- Sensitivity estimation of the 3 major Run-II channels (bbbb, bbττ, bbγγ) with some assumptions on how the detector performance will be in the HL-LHC detectors

- Does not take into account the performance of other channels
- Extrapolation of current results for bbbb & bbττ, i.e. no future analysis improvements are considered
- analysis have not yet been optimized for λ measurements

- New multivariate analysis for bbγγ
- Assumed that improvements in reconstruction algorithms will mitigate the effect of higher pile-up



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Prospects for the HL-LHC

- Results of the study:

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

Significance for the observation of HH production for 3000 fb^{-1}

Self-coupling constraint:

assuming $\kappa_\lambda = 1$ (SM)

Scenario	1σ CI	2σ CI
Statistical uncertainties only	$0.4 \leq \kappa_\lambda \leq 1.7$	$-0.10 \leq \kappa_\lambda \leq 2.7 \cup 5.5 \leq \kappa_\lambda \leq 6.9$
Systematic uncertainties	$0.25 \leq \kappa_\lambda \leq 1.9$	$-0.4 \leq \kappa_\lambda \leq 7.3$

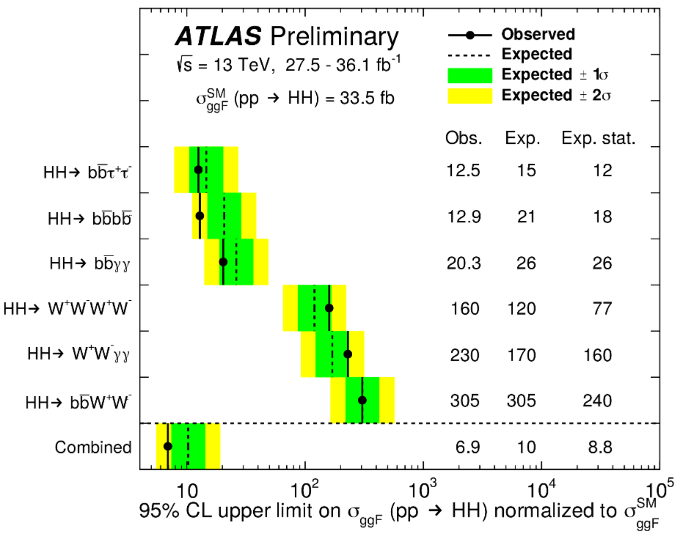
assuming $\kappa_\lambda = 0$

Scenario	1σ CI	2σ CI
Statistical uncertainties only	$-0.5 \leq \kappa_\lambda \leq 0.5$	$-0.9 \leq \kappa_\lambda \leq 1.1$
Systematic uncertainties	$-0.6 \leq \kappa_\lambda \leq 0.7$	$-1.3 \leq \kappa_\lambda \leq 1.5$

Conclusions

- The way from limits till the observation of HH production will be long

Today (2019, expected): σ(HH)/σ(HH;SM) < 10



HL-LHC (203x?):

3 sigma observation
(with 3 channels)
(more with more channels + analysis optimization)

But who knows there may be more interesting things appearing on the way there!

Thank you for your attention!