Searches for Higgs pair production with ATLAS

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Higgs pair production in the SM

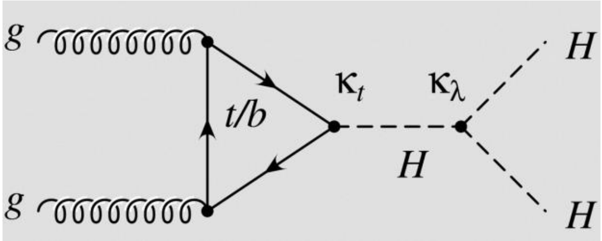
- The scalar terms of the SM Lagrangian after EWSB:

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

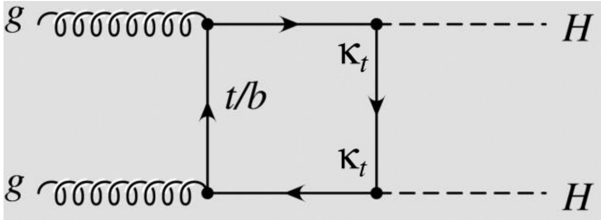
Mass term

Self-interaction terms

- So the SM predicts multi-H production with well-defined couplings (hence cross-section)
  - Measuring di-Higgs production is independent test for the shape of the Higgs potential



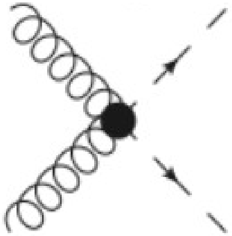
- In HH production, negative interference with box diagram
  - σ(HH) = ~34 fb (~1000x smaller than σ(H))

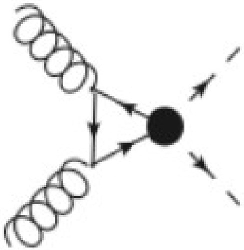


- $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$
  - Deviations from 1 ➔ new physics!

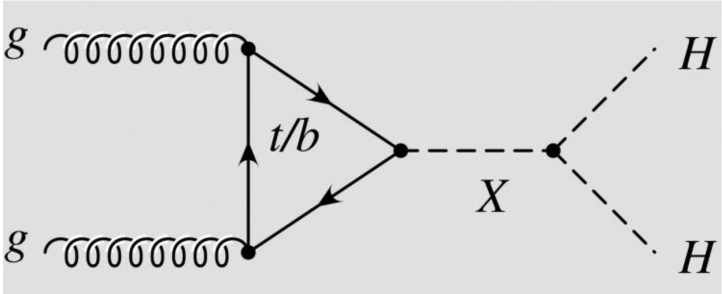
New physics in Higgs pair production?

- Non-resonant di-Higgs production
  - Cross-section can deviate from SM prediction due to non-standard couplings or new heavy states running in loops





- Resonant di-Higgs production
  - Many BSM theories predict heavy resonances decaying to a pair of Higgs bosons
    - Spin-0 (e.g. all 2HDM models: H→hh)
    - Spin-2 (e.g. RS Graviton: G→hh)



Di-Higgs searches in ATLAS – Overview

- Many final states, depending on decays of each Higgs boson
  - Trade-off between large branching fraction and low background

- ATLAS latest results for:

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→bbWW: JHEP 04 (2019) 092
HH→WWWW: JHEP 05 (2019)124

	bb	WW	ττ	ZZ	γγ
bb	33%*				
WW	25%*	4.6%*			
ττ	7.4%*	2.5%	0.4%		
ZZ	3.1%	1.2%	0.3%	<0.1%	
γγ	0.3%*	0.1%*	<0.1%	<0.1%	<0.1%

Di-Higgs branching fractions

In addition:

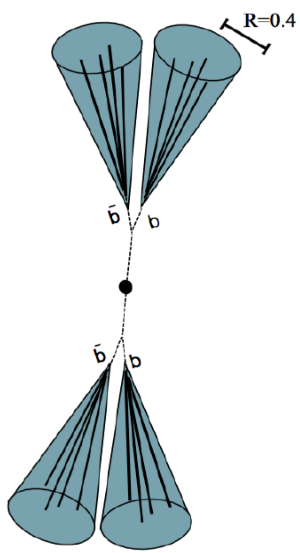
HH combination: ATLAS-CONF-2018-043 (paper about to be submitted)
Indirectly via single Higgs production: ATLAS-PUB-2019-009

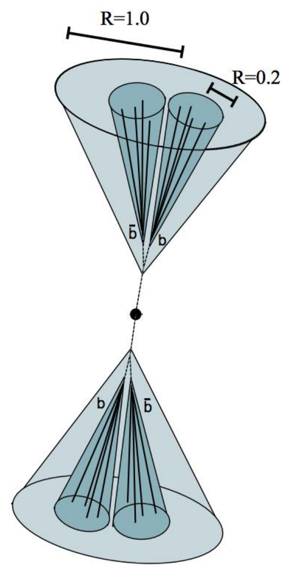
- Highest branching ratio: 1 in 3 di-Higgs events result in bbbb
  - But huge multi-jet background making analysis very challenging
    - Esp. triggers for non-res and low-mass resonances: rely on online b-tagging

- Two selections to cover the entire range of resonance masses:

Resolved
4 R=0.4 jets
(“small-R jets”)

m_X = 0.26–1.4 TeV



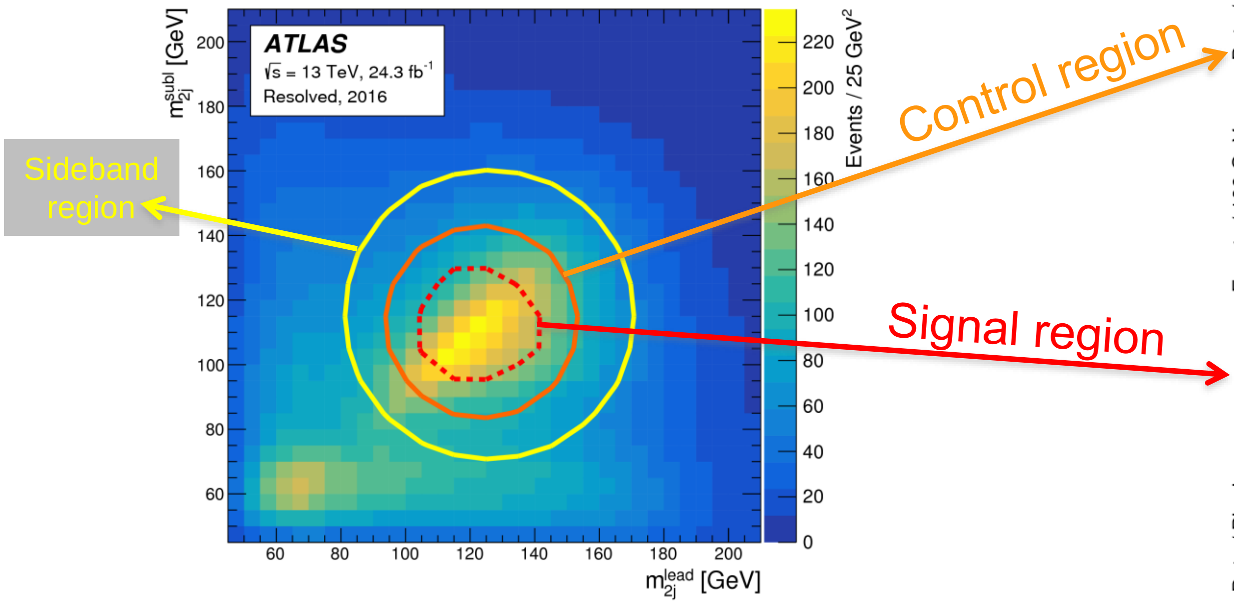


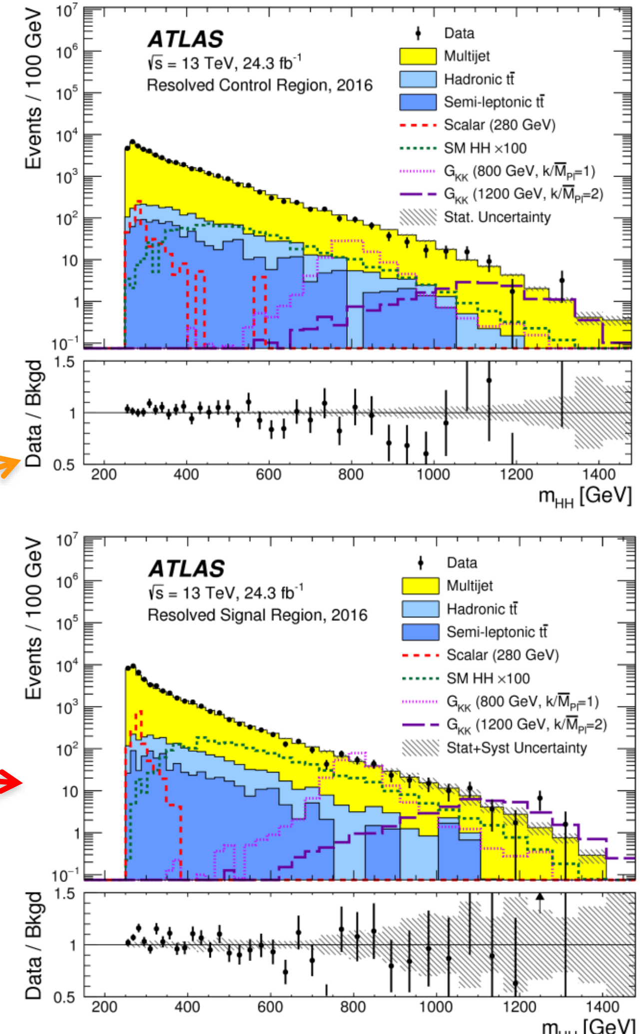
Boosted
2 R=1.0 jets
(“large-R jets”)

m_X = 0.8–3.0 TeV

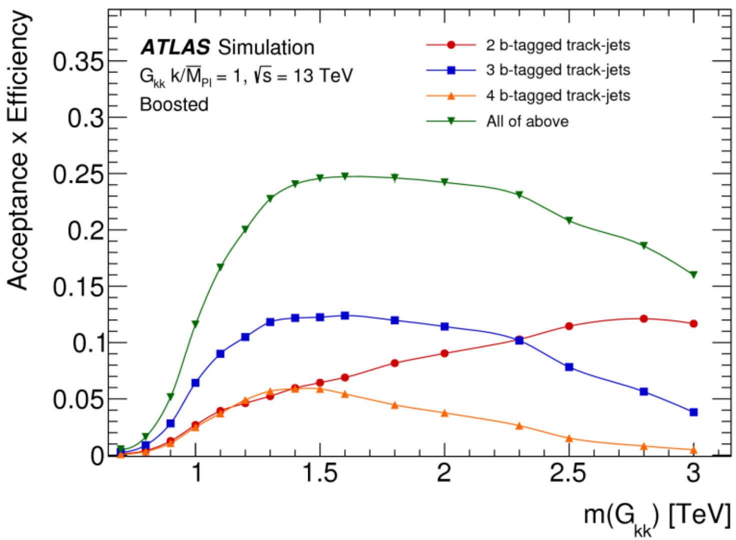
HH→bbbb – “resolved” analysis

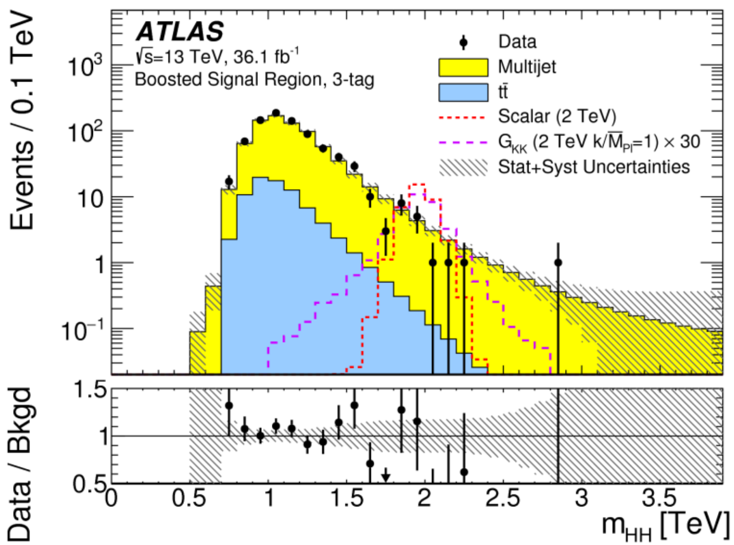
- Requires 4 b-tagged jets with p_T > 40 GeV
- Relies critically on b-jet triggers
- Background: ~90% multijet, ~10% ttbar
- Data-driven bkg model: “2-b-tag”→”4-b-tag”





- Requires 2 large-R jets with p_T > 450/250 GeV
- 3 categories(2,3,4 b-tags), based on number of b-tagged “track jets” associated with the large-R jets
- Dominant background is again multi-jets
  - Similar data-driven background model as in resolved analysis





Expressed in terms of $\mu_{HH}=\sigma(HH)/\sigma_{SM}(HH)$

Non-resonant results:
(using only resolved analysis)

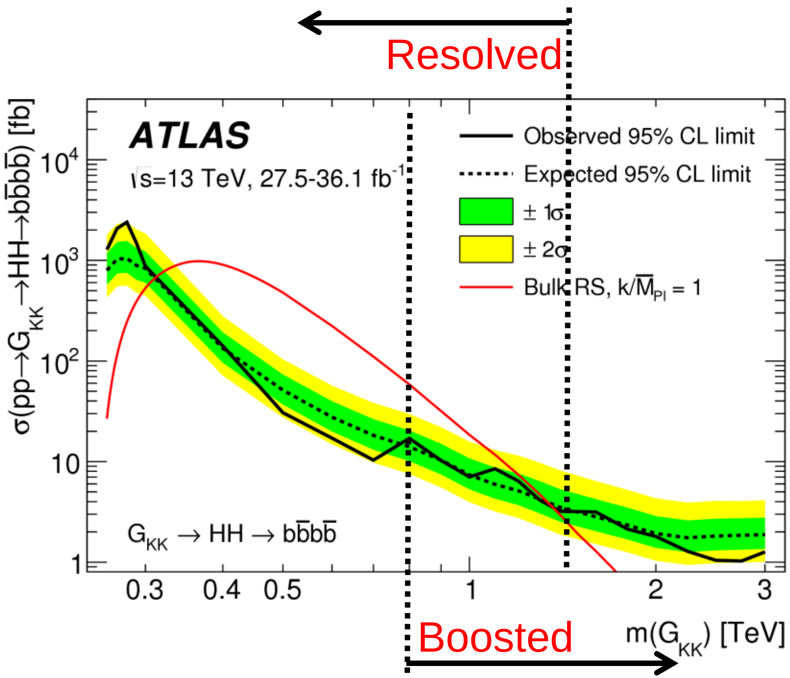
Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
12.9	11.1	14.9	20.7	30.0	43.6

Resonant search results:

Resolved and boosted analyses kept orthogonal and combined

An excess with 2.3σ global significance at m_X ~ 280 GeV

Sensitivity to cross-sections down to a few fb



Two channels, based on decays of the tau leptons

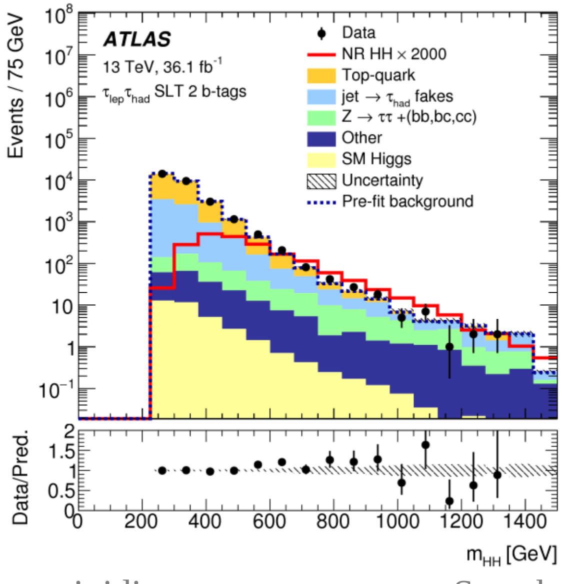
τ(lep)τ(had)

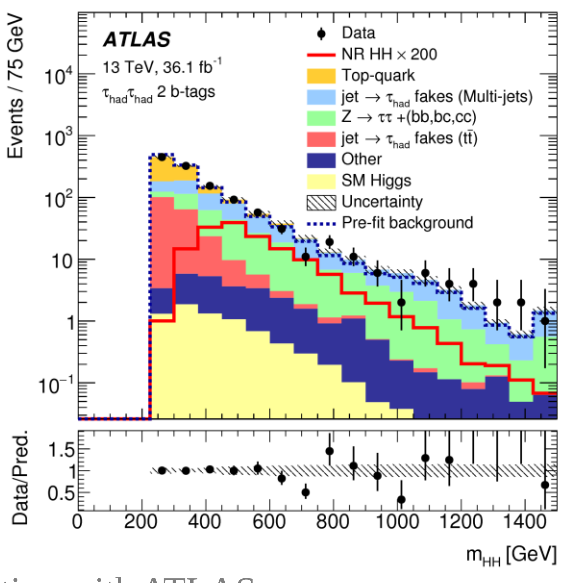
Single lepton (e/μ) trigger (SLT)
+
SLT + single hadronic τ trigger

τ(had)τ(had)

Single hadronic τ trigger
+
Double hadronic τ trigger

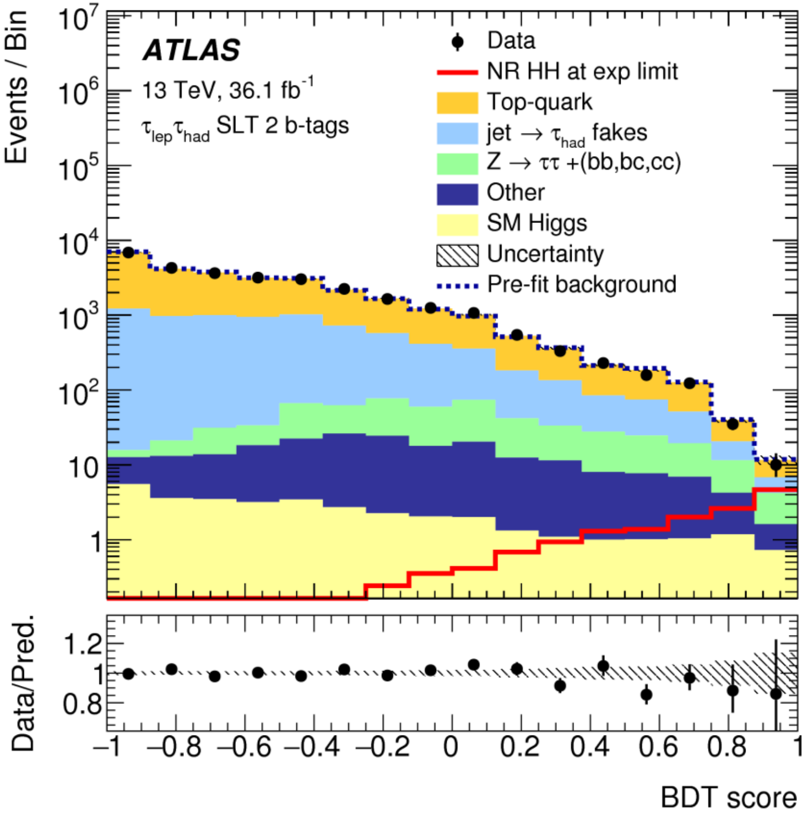
In both channels: 2 b-tagged jets and $m_{\tau\tau}$ > 60 GeV





Boosted Decision Trees (BDT) used to enhance the analysis sensitivity:

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



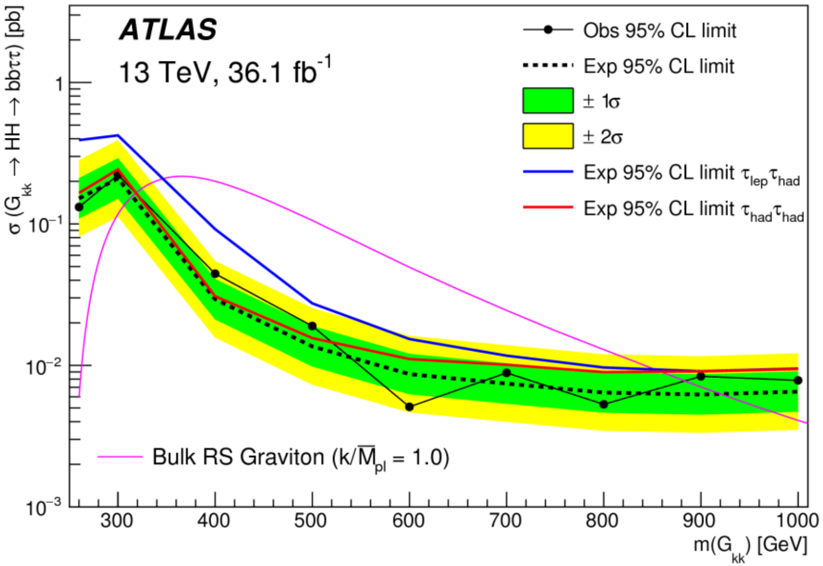
HH→bbττ – results

Non-resonant search results:

		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

This is currently the single most sensitive channel for non-resonant HH production

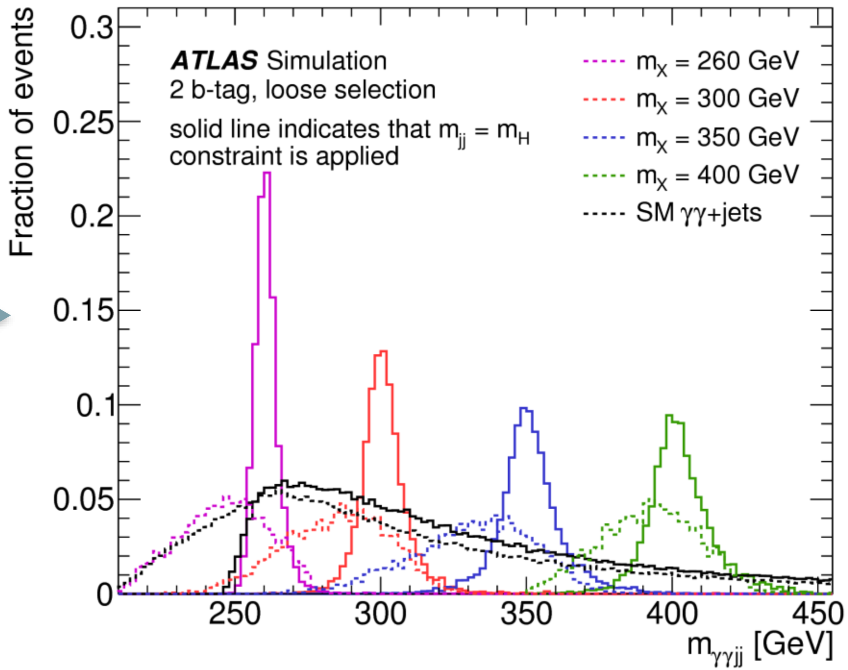
Resonant search results:



HH→$bb\gamma\gamma$

- Requires 2 “tight”, isolated photons
- Two event categories, based on number of b-tagged jets (1,2)
- Loose/tight selection for resonance mass below/above 500 GeV
- Bkg: 80-90% “diphoton+jets”

Using the Higgs mass constraint for m_{bb}, improves significantly the sensitivity for the resonant search

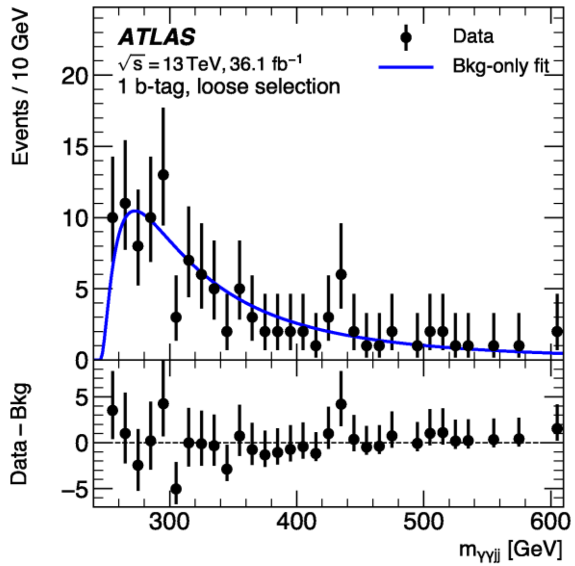


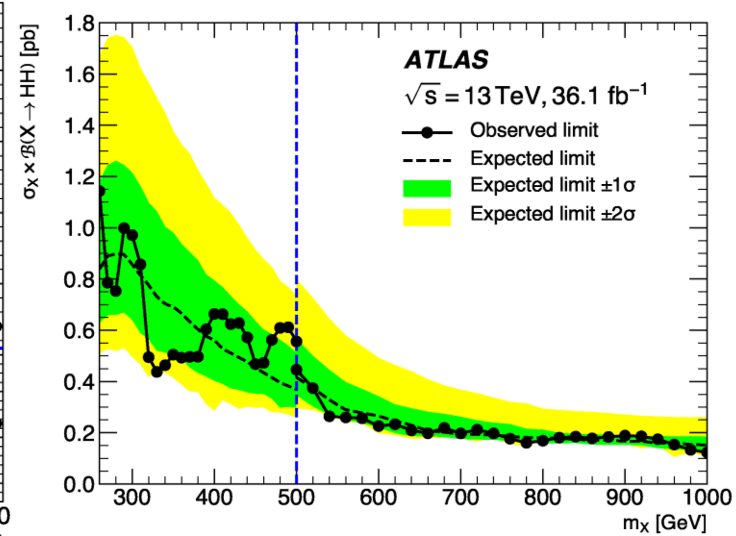
Non-resonant search results:
($m_{\gamma\gamma}$ as discriminant)

Expressed in terms of $\mu_{HH}=\sigma(HH)/\sigma_{SM}(HH)$

	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

Resonant search results:
($m_{\gamma\gamma bb}$ as discriminant)

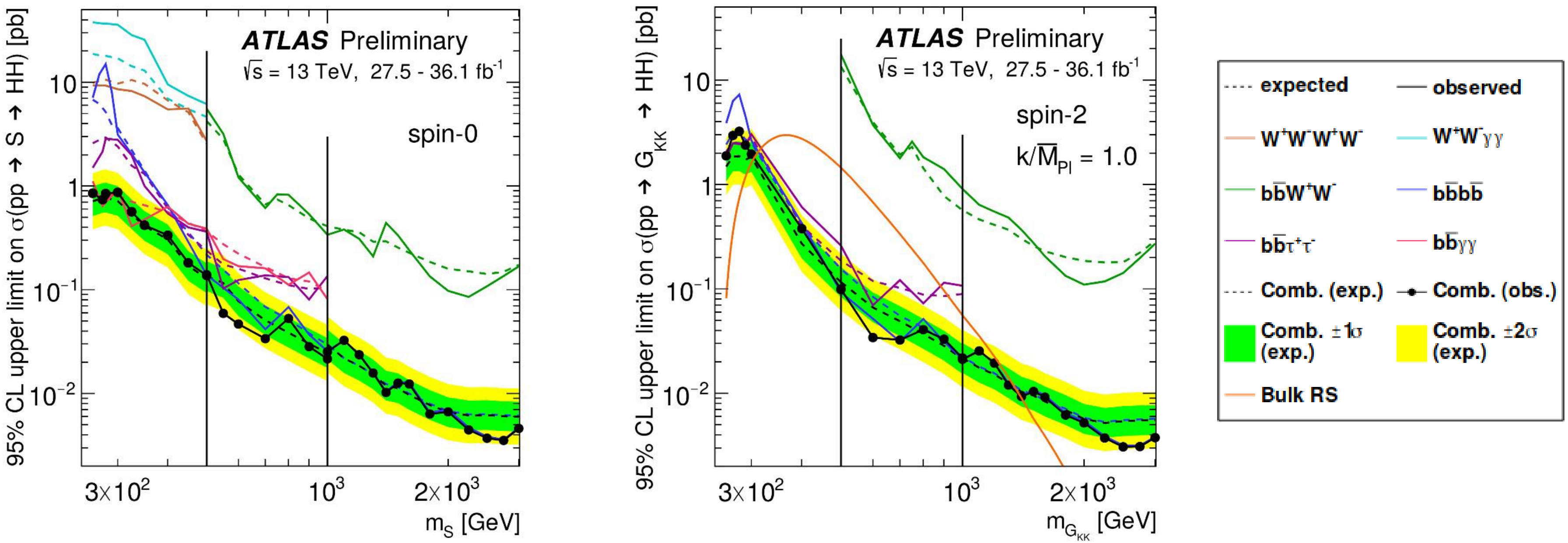




Combination – resonant HH production

Cross section limits combination for spin-0 and spin-2 resonances

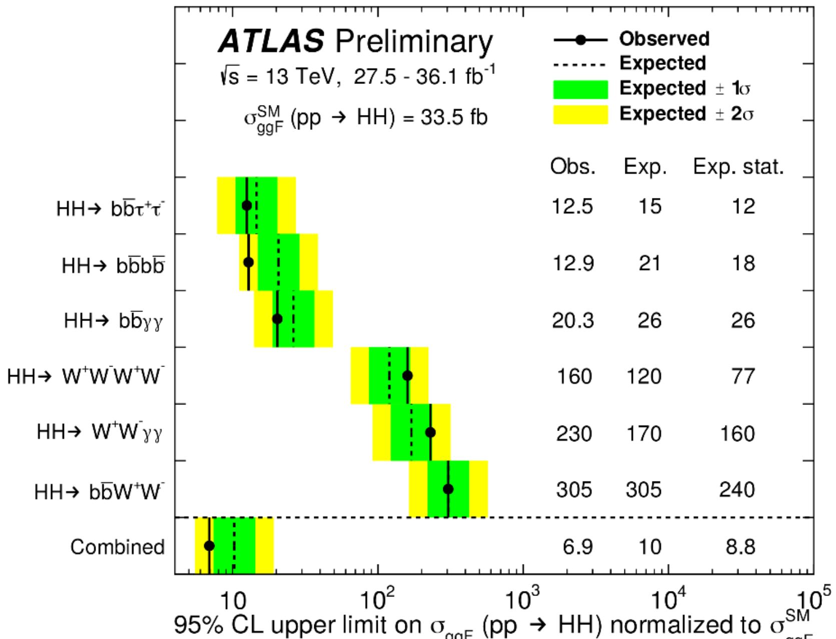
Channel	Range (GeV)	Spin-0	Spin-2
bbbb	260-3000	☑	☑
bbττ	260-1000	☑	☑
bbγγ	260-1000	☑	
bbWW	500-3000	☑	☑
WWWW	260-500	☑	
WWγγ	260-500	☑	



Combination – non-resonant HH production

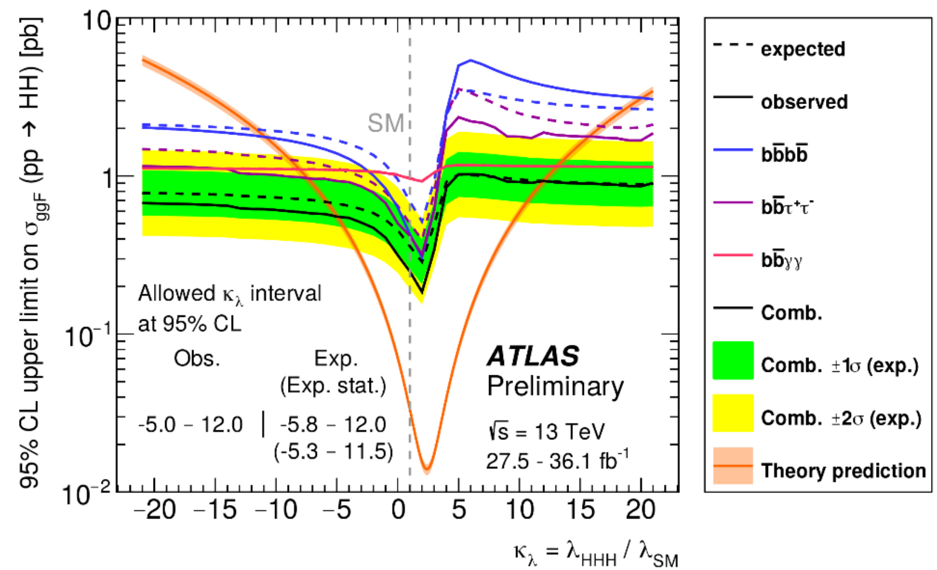
HH production cross-section

$$\mu_{HH} = \frac{\sigma(gg\rightarrow HH)}{\sigma_{SM}(gg\rightarrow HH)} > \begin{matrix} 6.9\ (\text{obs}) \\ 10.0\ (\text{exp}) \end{matrix}$$



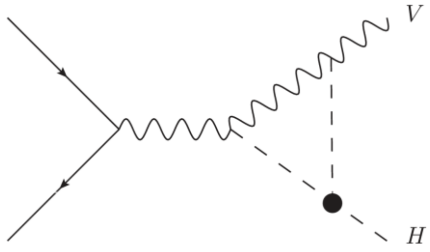
Higgs self-coupling

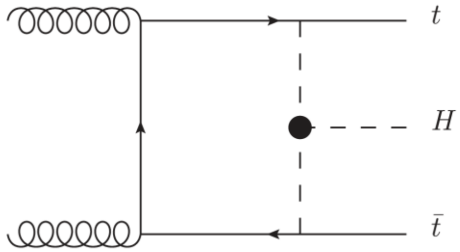
Constraints on κ_λ: (-5.0, 12.0) (obs)
(-5.8, 12.0) (exp)



H self-coupling from single Higgs production

- Single Higgs production cross-sections can provide info on Higgs self-coupling!

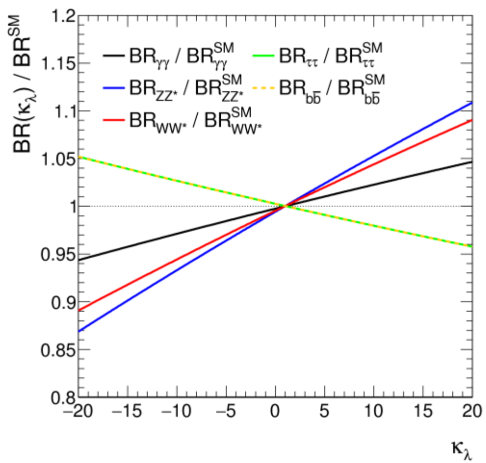


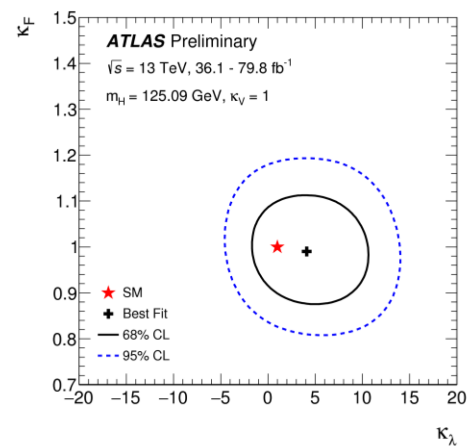


Results assuming only effect of new physics is in κ_λ:

Constraints on κ_λ: (-3.2, 11.9) (at 95% CL)

Looser constraints on κ_λ if κ_F or κ_V are allowed to float:

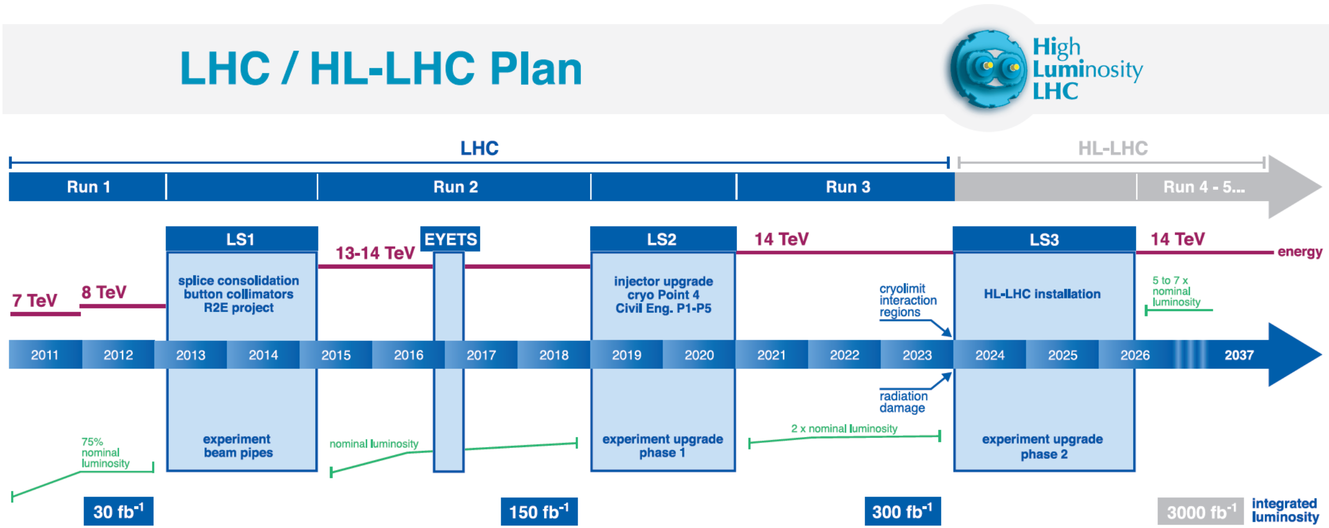




Future prospects

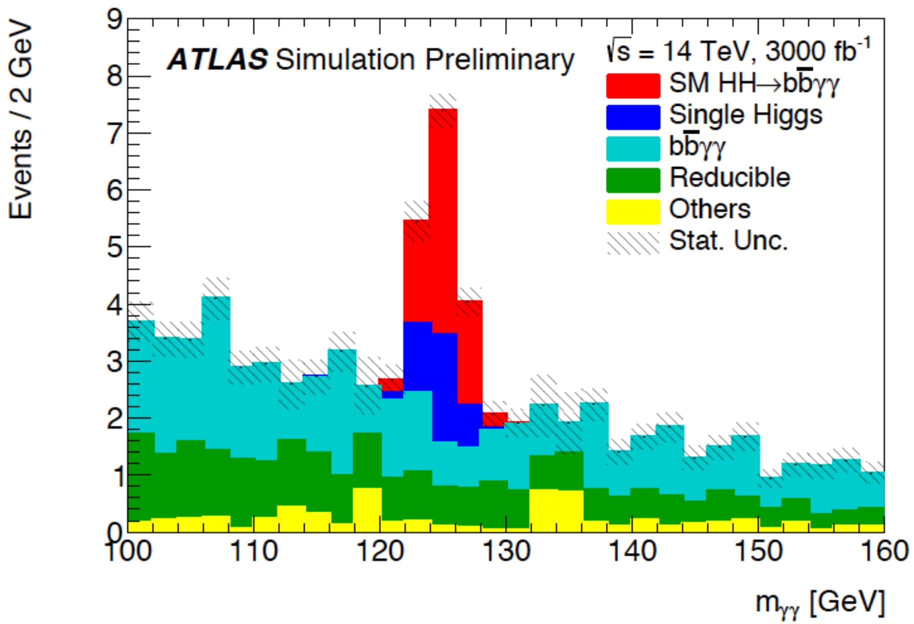
- Current results use only ¼ of full Run-2 dataset (~140 fb^{-1})
  - ==> A factor ~2 improvement in σ(HH) sensitivity (ATLAS $<\mu_{HH}>$~5)
  - Another factor ~2 improvement with Run-3 data and ATLAS+CMS
  - With analysis improvements, likely to reach $<\mu_{HH}>$~2 by start of HL-LHC

- HL-LHC to deliver ~3000 fb^{-1} by late 2030's



HL-LHC projections for HH

- Sensitivity projections and combination of bbγγ, bbττ and bbbb
  - Assumed improvements in reconstruction algorithms will mitigate impact from increased pile-up
  - For bbττ and bbbb, pure extrapolation of Run-2 analyses, i.e. not considering improvements that may be achieved
  - An MVA-based analysis for bbγγ, with improved sensitivity wrt Run-2



With 3000fb-1

ATL-PHYS-PUB-2018-053

Significance for observing SM HH:

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

Similar projections and sensitivity by CMS.
ATLAS+CMS combined would reach 4σ.

CERN-LPCC-2018-04

Self-coupling constraints:

Assuming κ_λ=1 (SM):

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

Assuming κ_λ=0:

(σ_{HH} larger for κ_λ=0)

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

Summary/Conclusions

- Search for Higgs pair production exciting but challenging
  - Test of the SM and a window for new physics
- Current ATLAS expected sensitivity for non-resonant HH production is 10xσ_{SM}
  - Could reach 5xσ_{SM} with full Run-2 dataset
- The road to >3σ on the SM HH production will require the full HL-LHC luminosity
  - But there is always a chance for exciting new physics along the way!