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

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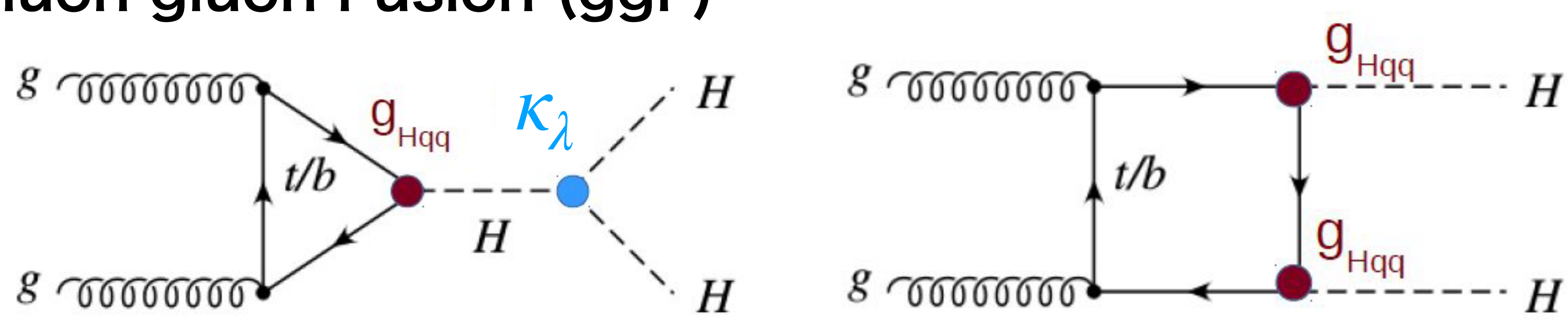
on behalf of the ATLAS

What we can access using HH production ~Non resonant signals~

gluon gluon Fusion (ggF)

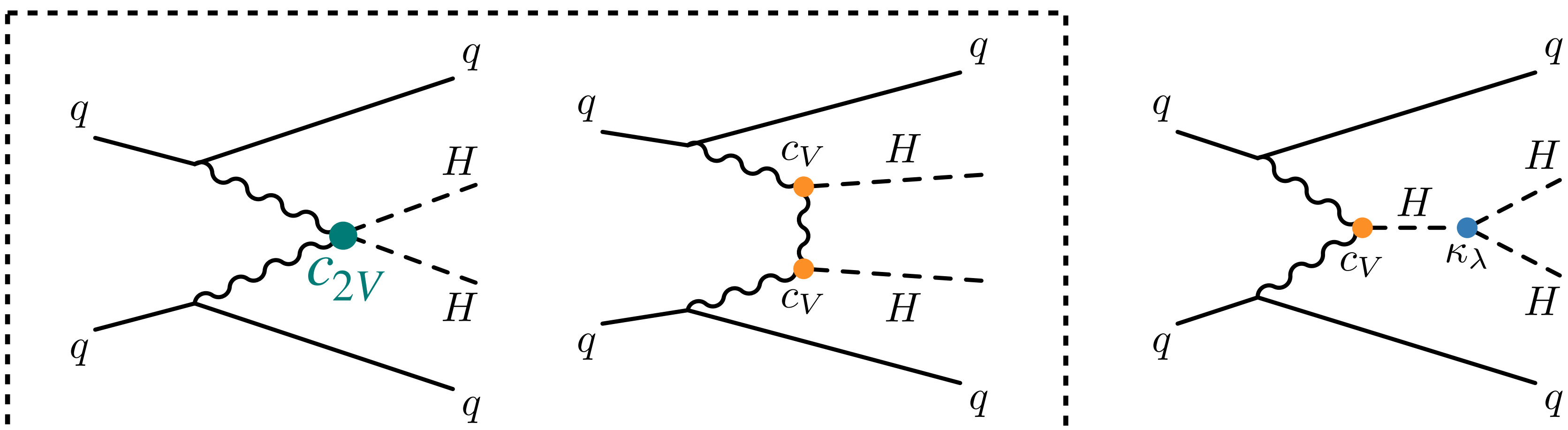


SM cross-section at 13 TeV: 31.05 fb.

Negative interference with box diagram

Possible BSM enhancements due to modified coupling strength of κ_λ

Vector Boson Fusion (VBF)



SM cross-section at 13 TeV: 1.73 fb.

In SM, each coupling strength is c_{2V}=1 and c_V=1, κ_λ=1.

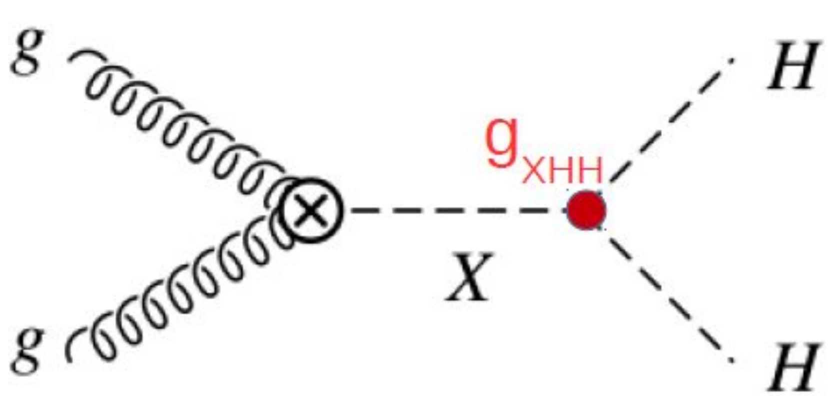
$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

[Eur. Phys. J. C (2017) 77:481]

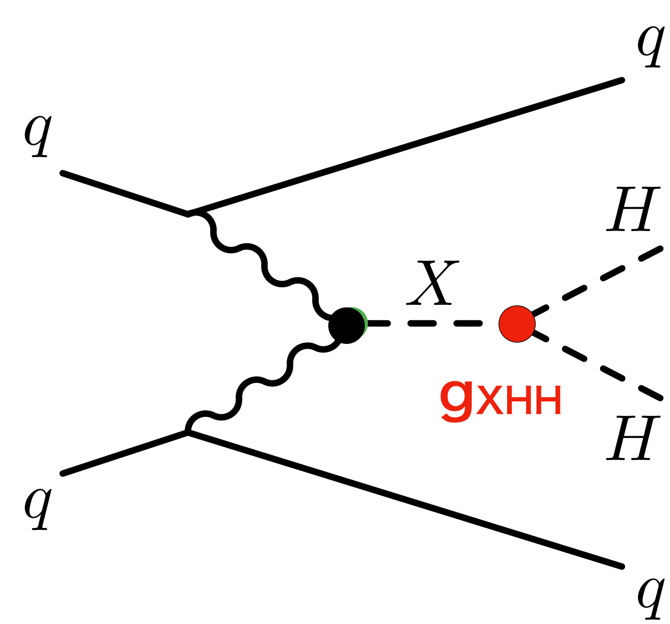
Possible BSM enhancements due to modified coupling strength of c_{2V}

What we can access using HH production ~BSM resonant signals~

gluon gluon Fusion (ggF)



Vector Boson Fusion (VBF)

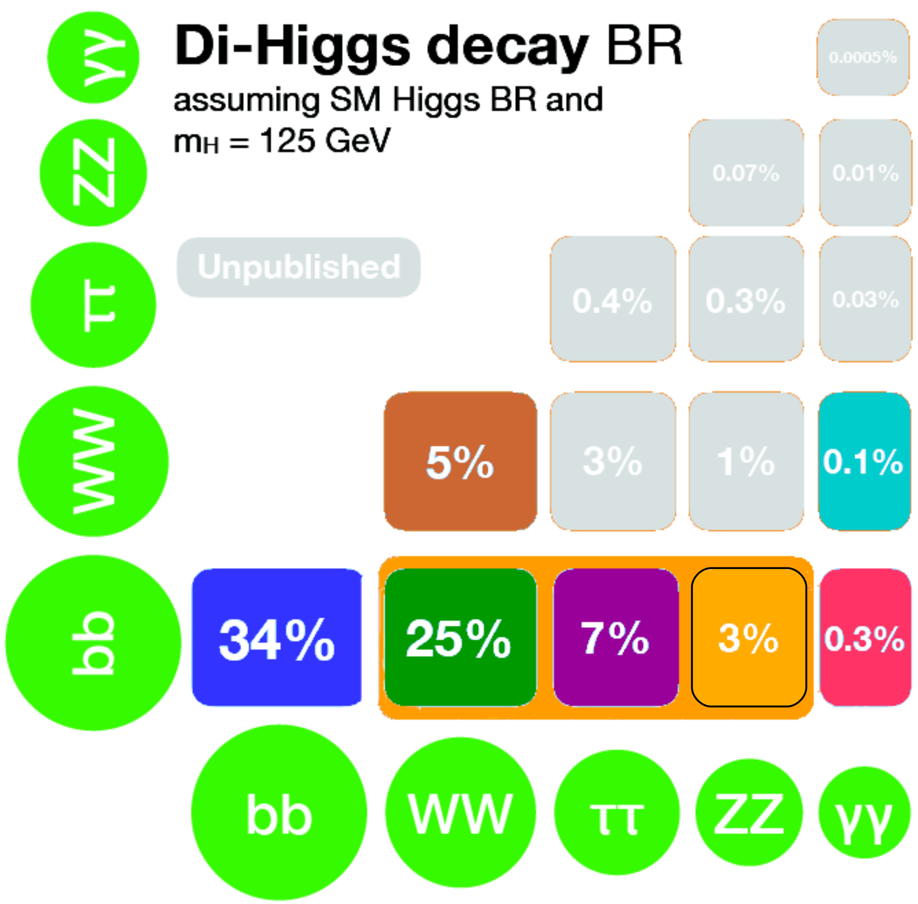


Models with a heavy **spin-0** particle: "Singlet extension", "2HDM", "hMSSM"
Models with a heavy **spin-2** particle: "Randall-Sundrum Graviton"

ggF and VBF are complementary to each other for the specific parameters due to different couplings at production.

Studied channels at 13 TeV

various decay channels in HH



Channels	$\int L$ [fb^{-1}]	Reference
☆ bbbb	27.5-36.1	JHEP 01 (2019) 030
☆ $bb\tau\tau$	36.1	Phys. Rev. Lett. 121 (2018) 191801
☆ $bb\gamma\gamma$	36.1	JHEP 11 (2018) 40
WWWW	36.1	JHEP 05 (2019) 124
$WW\gamma\gamma$	36.1	Eur. Phys. J. C 78 (2018) 1007
bbWW	36.1	JHEP 04 (2019) 092
☆ combination	36.1	1906.02025

New this summer

☆ bblvlv	139	-
☆ VBF bbbb	126	ATLAS-CONF-2019-030

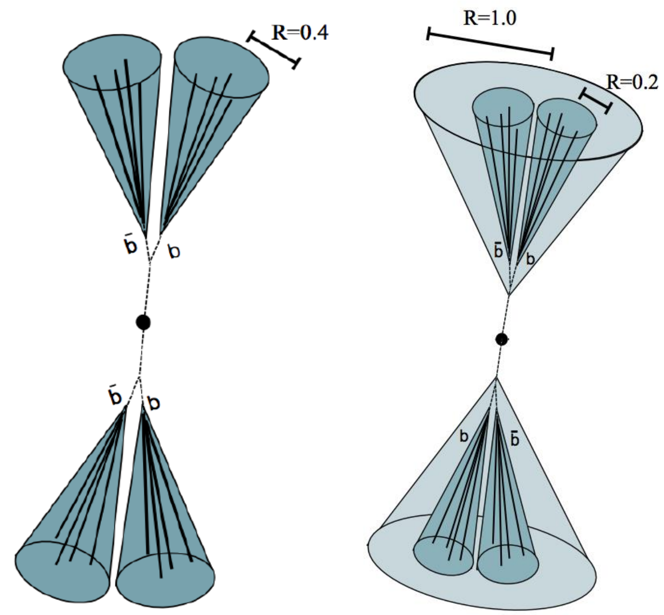
Today, will report "☆" that are the selected ggF analyses and the combination of them, two new analyses, and HL-LHC prospect of ggF analyses.

ggF HH→bbbb

27.5-36.1 fb^{-1}

JHEP 01 (2019) 030

- Feature: **high statistics**
- Two approaches for low mass and high mass regions



Resolved:

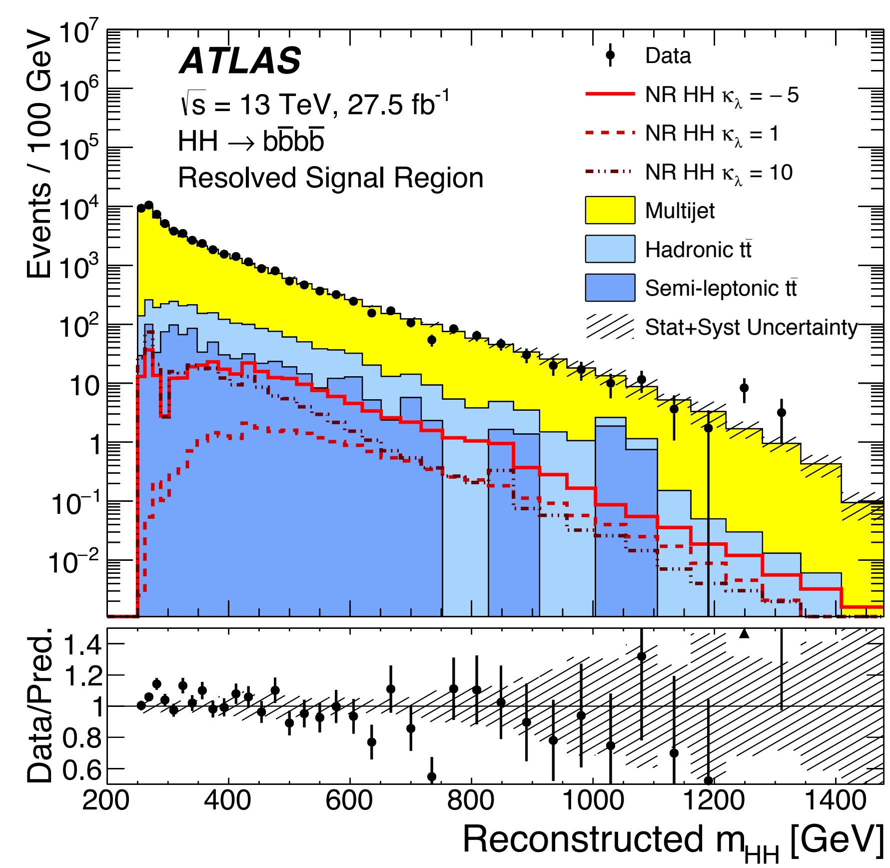
- 4 R=0.4 jets ("small-R jets")
- Relies critically on b-jet triggers

Boosted:

- 2 R=1.0 jets ("large-R jets")
- 3 categories(2,3,4 b-tags), based on number of b-tagged "track jets" associated with the large-R jets

- Backgrounds
  - **Multijet (95%): Data-driven** estimation in CRs with reduced b-tagging for multijet bkg.
  - ttbar (5%): MC
- Uncertainty: dominated by QCD modeling unc.
- Observation is consistent with no enhanced di-Higgs production hypothesis. →
- The limits on κ_λ will be shown at the combination results.

Resolved SR



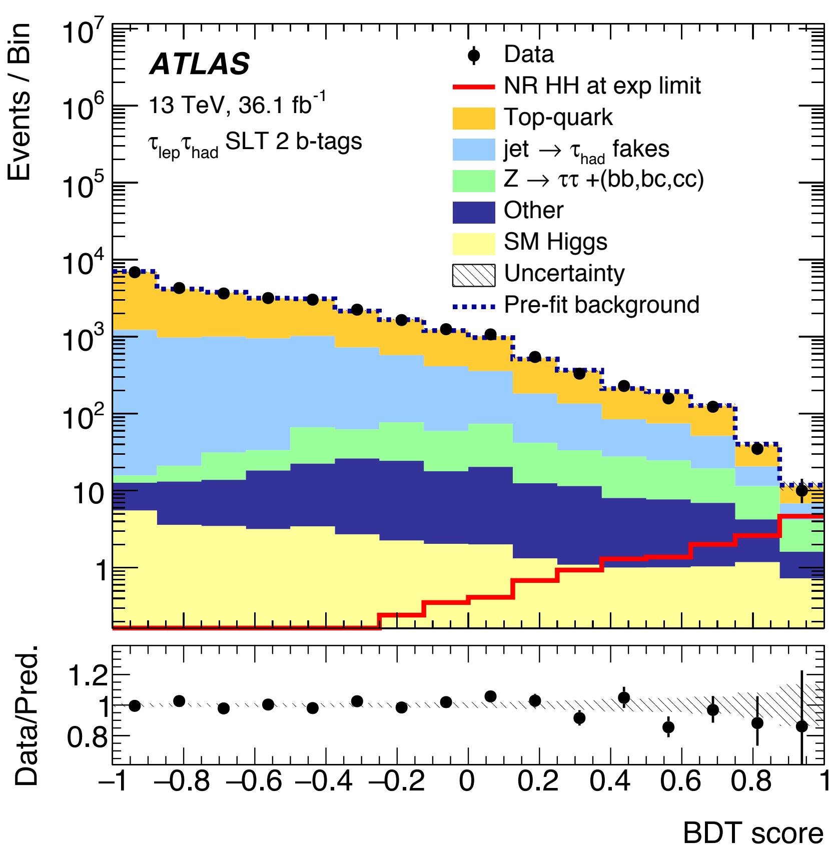
ggF HH→bb$\tau\tau$

36.1 fb^{-1}

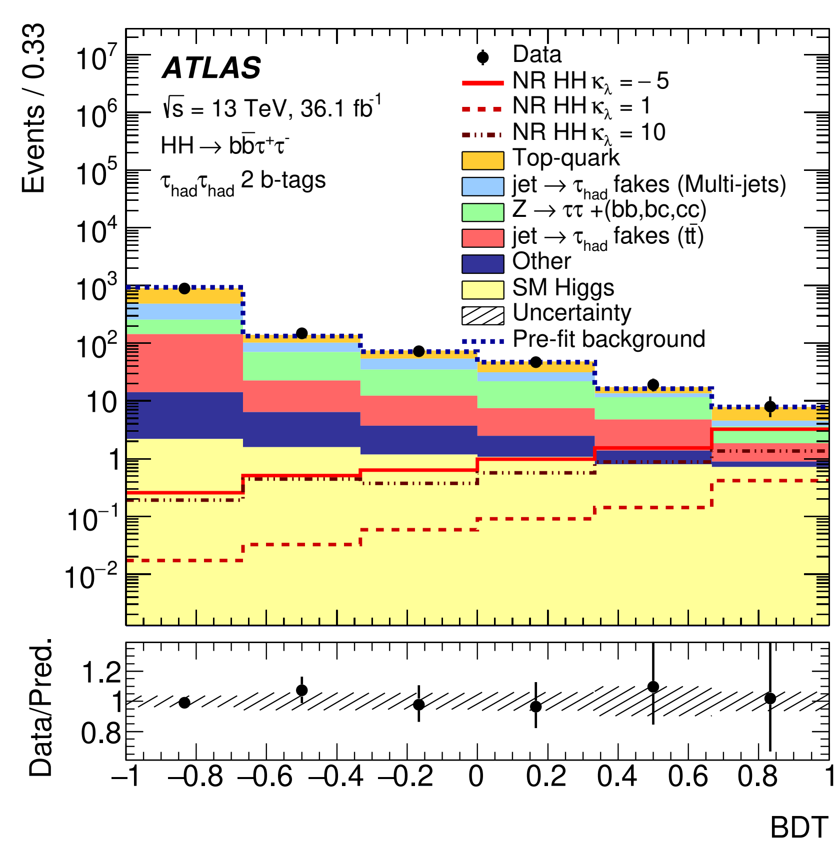
Phys. Rev. Lett. 121 (2018) 191801

- Feature: **Fairly high statistics, clean with lepton channel**
- Two channels, based on decays of the tau leptons: $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
  - Boosted Decision Trees (BDT) used to enhance the analysis sensitivity
- Backgrounds: ttbar (MC), QCD multijet(data driven), Z+HF(MC)
- Uncertainty: dominated by statistical uncertainties
- Observation is consistent with no enhanced di-Higgs production hypothesis.

$\tau_{lep}\tau_{had}$ SR



$\tau_{had}\tau_{had}$ SR



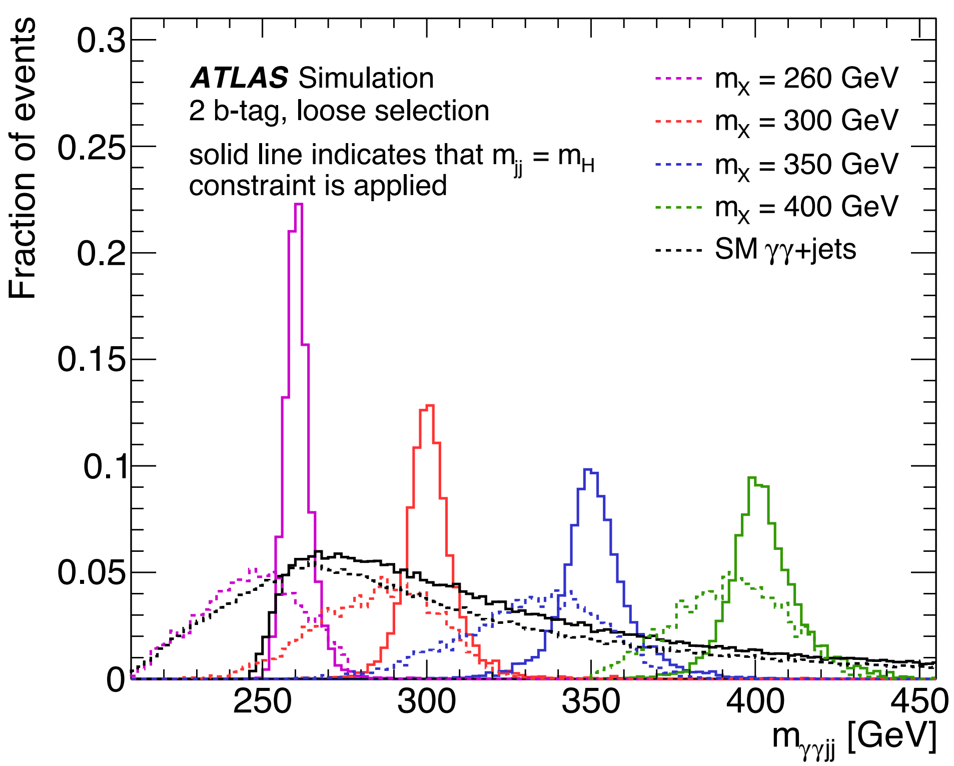
ggF HH→bb$\gamma\gamma$

36.1 fb^{-1}

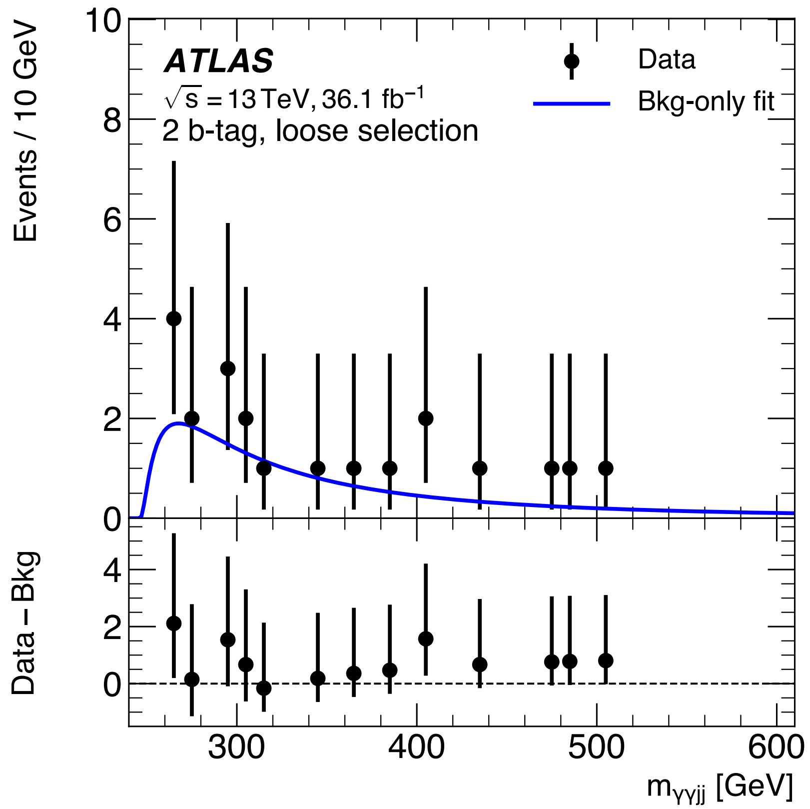
JHEP 11 (2018) 40

- Feature: **Low background**
- Two categories for low mass and high mass regions
  - **Loose selection**: (sub-)leading jet pT > 40(25) GeV used for κ_λ analysis and resonances with m_X < 500 GeV.
  - **Tight selection**: (sub-)leading jet p_T > 100(30) GeV used for m_X > 500 GeV.
- Background: single higgs (MC), continuum $m_{\gamma\gamma}$ (data driven)
- Uncertainty: dominated by statistical uncertainties
- Observation is consistent with no enhanced di-Higgs production hypothesis.

Signals in loose SR



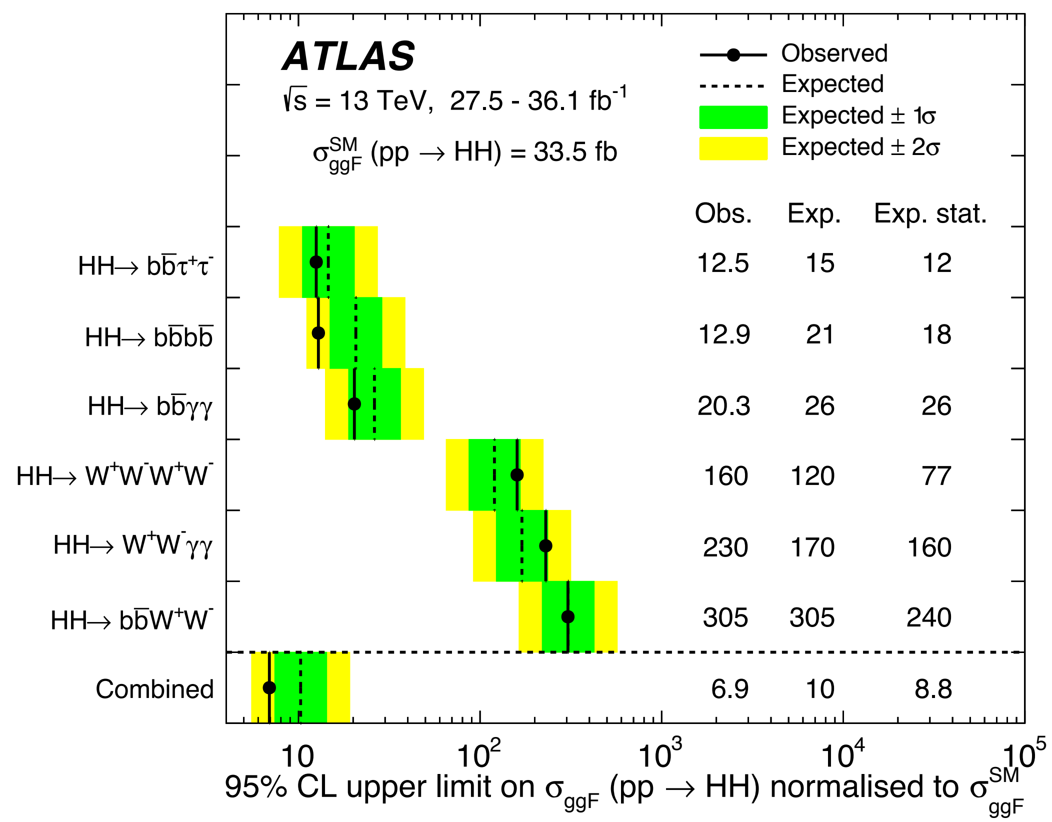
Data in loose SR



Results of the ggF combination ~Interpretation on non-resonant signal~

Simultaneous fit to data for cross-section of the signal process and nuisance parameters modeling statistical and systematic uncertainties, using the CLs approach.

SM HH production cross-section

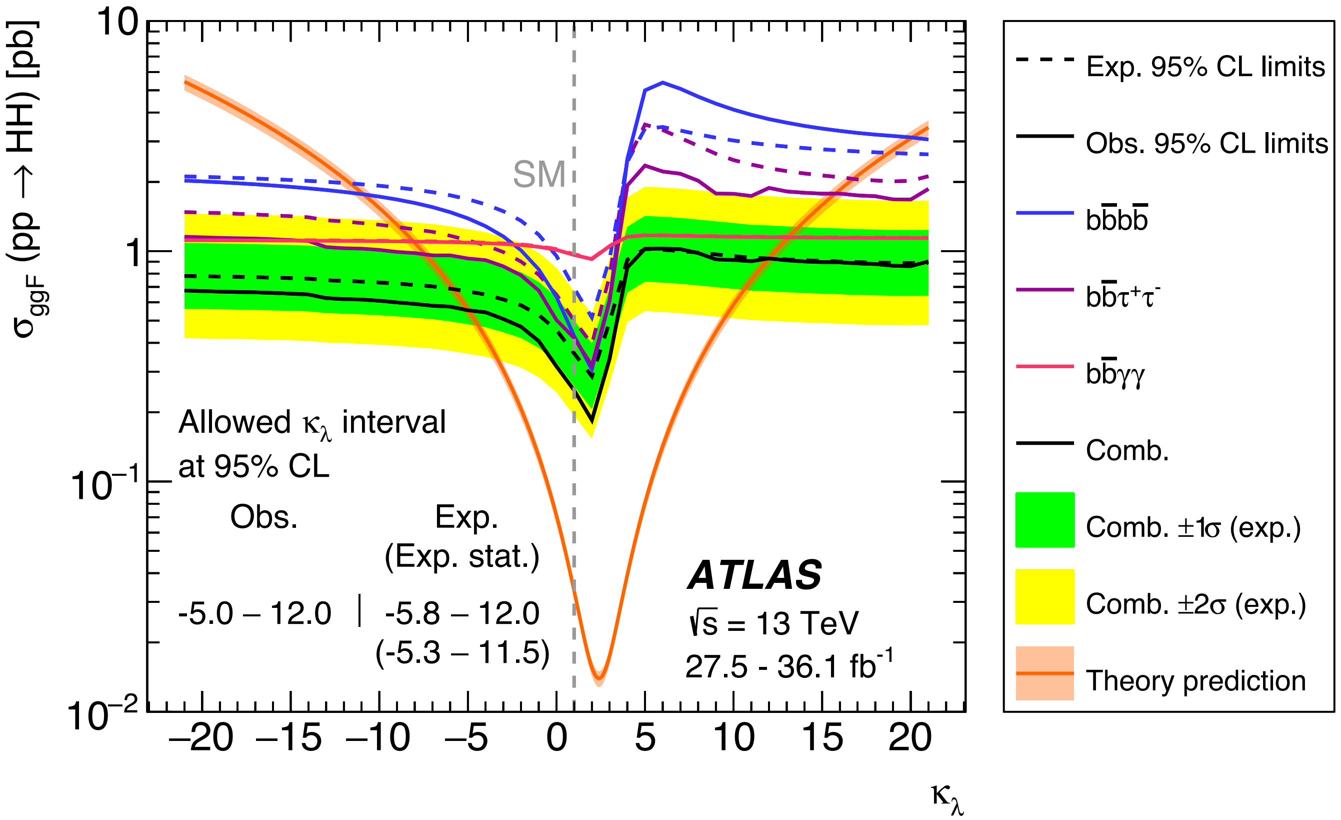


95% CLs upper limit

6.9 x $\sigma_{\rm ggF}^{\rm SM}$ (obs)

10 x $\sigma_{\rm ggF}^{\rm SM}$ (exp)

Higgs trilinear coupling



95% CLs upper limit for $\kappa_\lambda \equiv \frac{\lambda_{HHH}}{\lambda_{HHH}^{\rm SM}} = 1$

$\kappa_\lambda \in [-5.0, 12](\text{obs}), [-5.8, 12](\text{exp})$

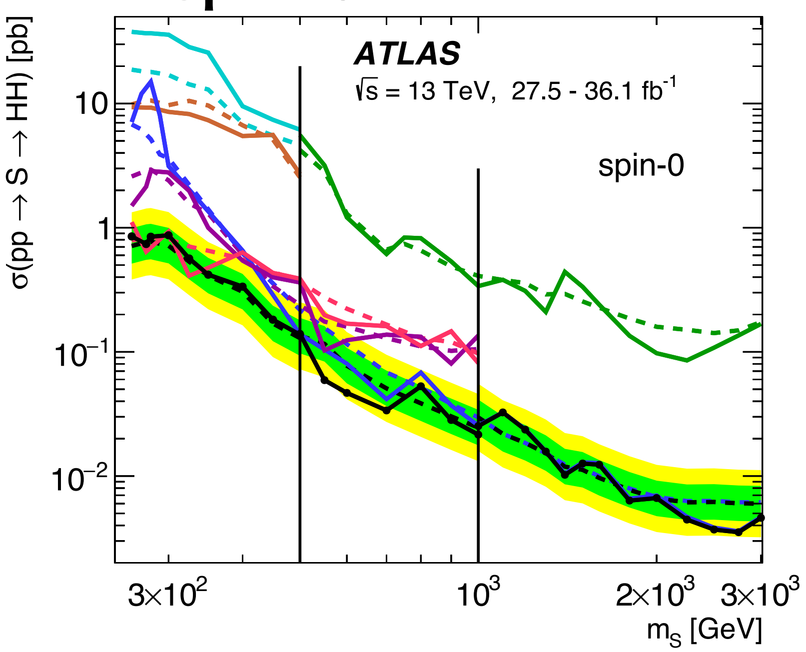
Indirect limits from single Higgs differential production and decay measurement (80fb^{-1}):

$\kappa_\lambda \in [-3.2, 11.9]$ ATL-PHYS-PUB-2019-009

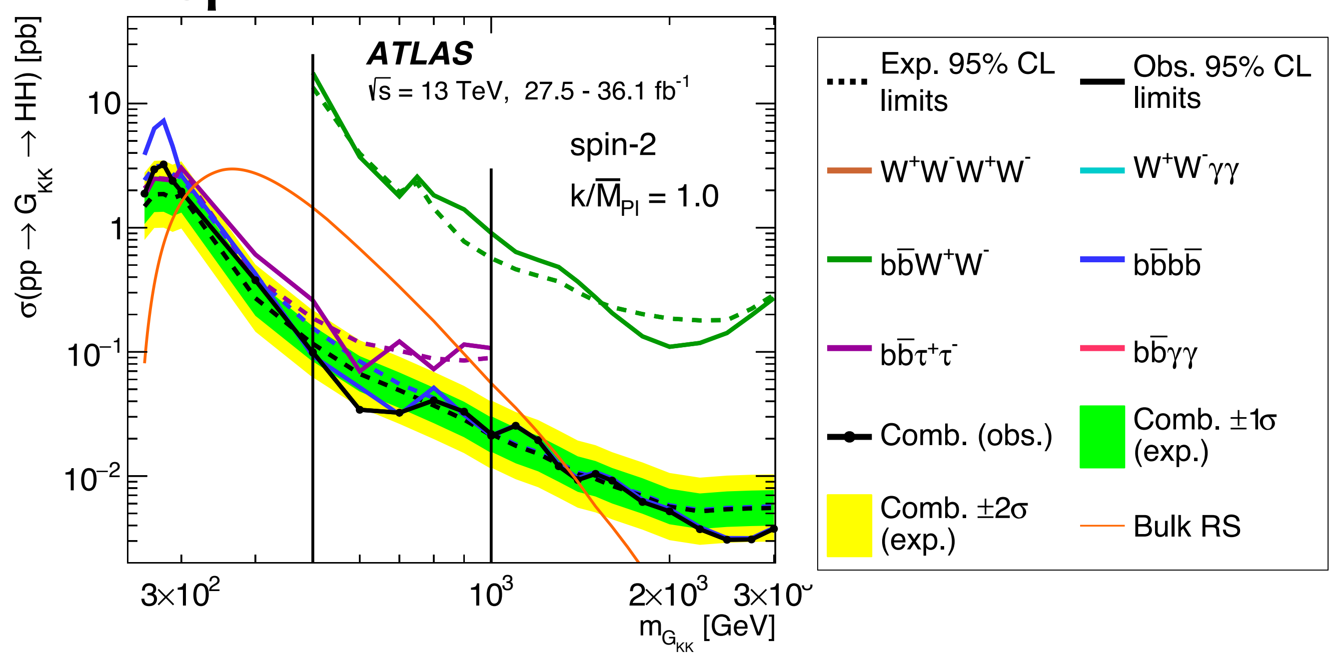
Results of the ggF combination ~Interpretation on resonant signal~

1906.02025

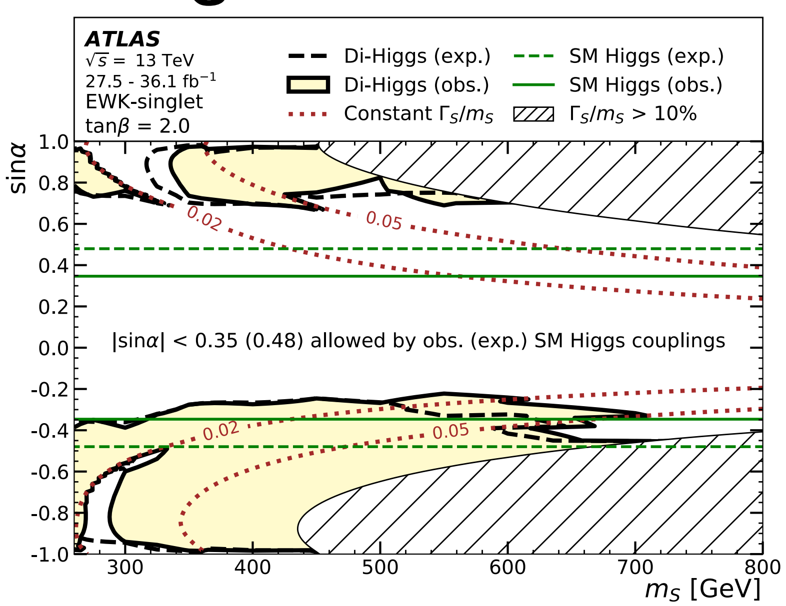
spin-0



spin-2

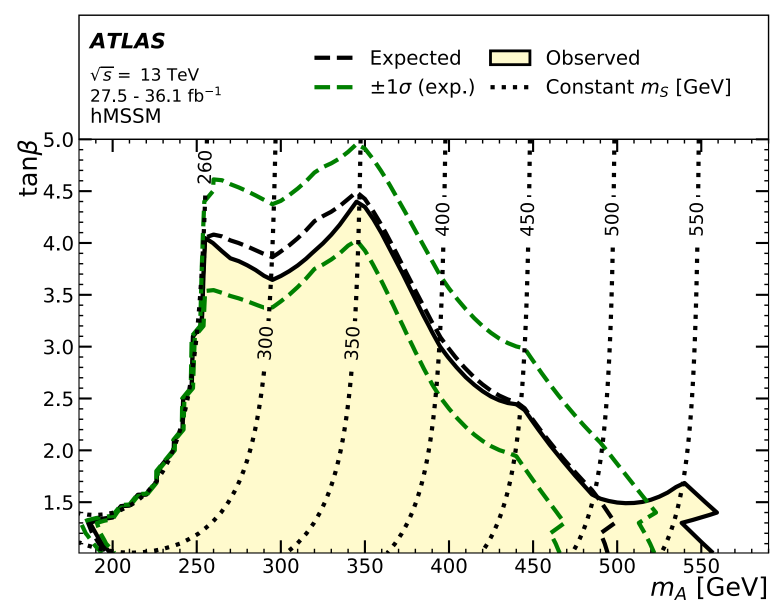


singlet extension



First ATLAS interpretation of HH results within this model

hMSSM



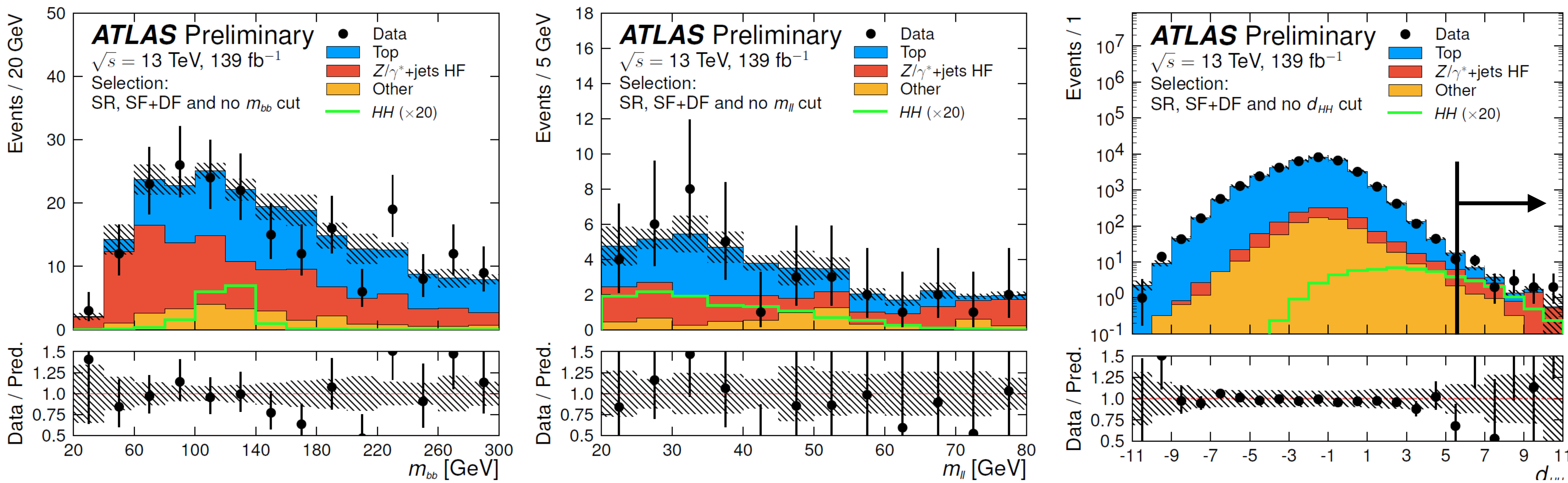
Over double the Run 1 exclusion in both mA and tan β.

- The limits on the cross-section for each model are set close to the expected values.
- Enlarged excluded region for spin-0/2 models.

New!
Full Run2

ggF HH→bblvlv

- New channel in ATLAS addressing the 2l decay of HH→bbWW*/ZZ*/$\tau\tau$
- The analysis relies on a **DNN classifier** to distinguish the **signal** from the main backgrounds: Top, $Z\to e^+e^-/\mu^+\mu^-$, and $Z\to\tau^+\tau^-$.
- The four outputs of the DNN, are combined: $d_{HH} = \ln\left(\frac{p_{HH}}{p_{\mathrm{Top}} + p_{Z\to ll} + p_{Z\to\tau\tau}}\right)$
- Observation is consistent with no enhanced di-Higgs production hypothesis.
- The factor 10 improvement on previous bbWW result of upper limit at $\kappa_\lambda=1$.



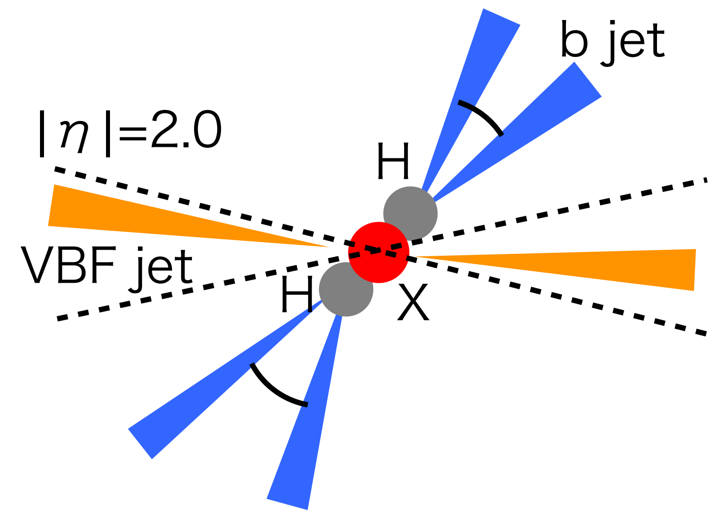
95% CL upper limit at kλ = 1 (SM)

	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma(gg\to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg\to HH)/\sigma^{\mathrm{SM}}(gg\to HH)$	14	20	29	43	62	40

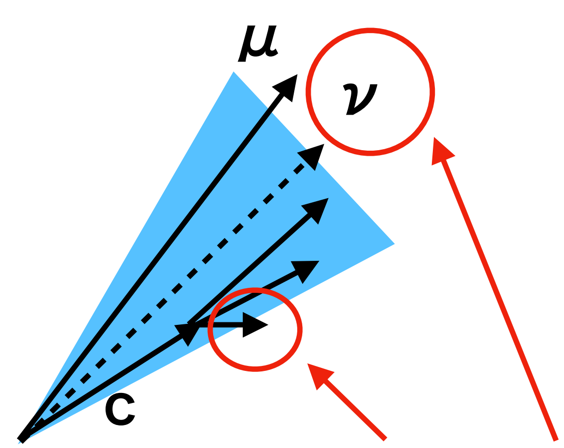
New!
Full Run2

VBF HH→4b

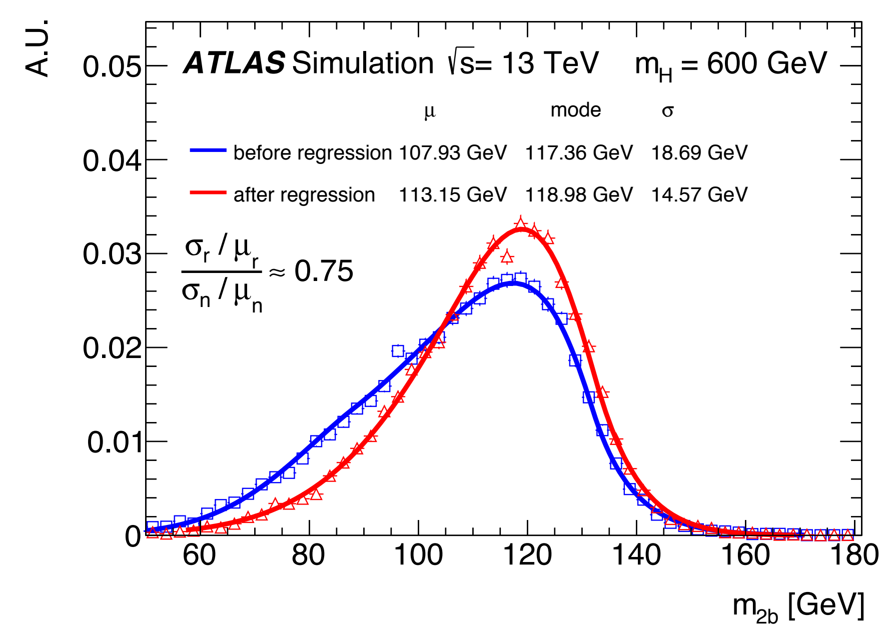
ATLAS-CONF-2019-030



- **New VBF HH analysis in LHC**, using the full Run-2 dataset
  - The VBF jet selections are added to di-Higgs selection from ggF resolved analysis.
  - The invariant mass of 4b is reconstructed.
- The b-jet energy regression based on BDT is implemented to account for energy loss due to:
  - Neutrinos in b-jets due to semi-leptonic B decays
  - Soft particles result in out-of-cone leakage



correct the energy loss
(New in ATLAS HH analysis)



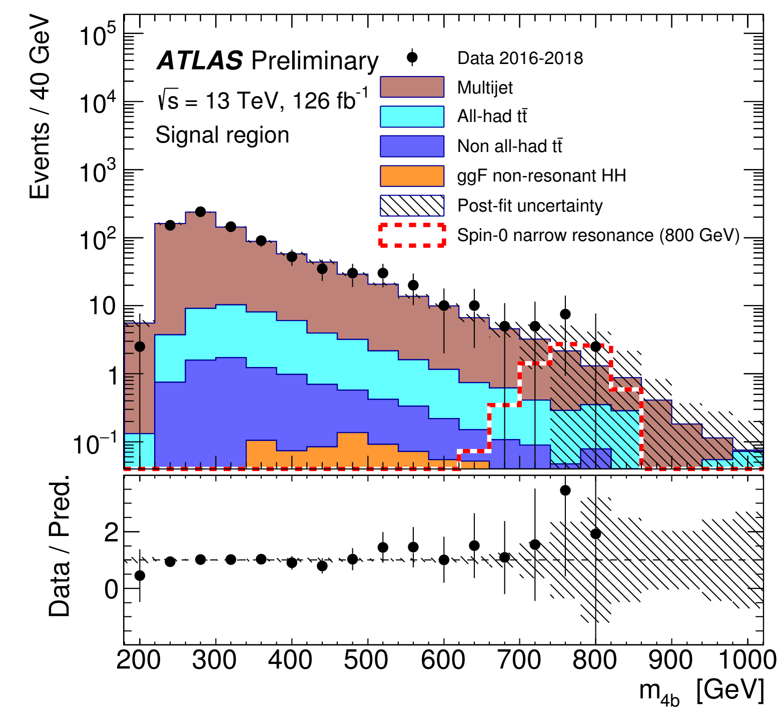
- Background: **~90% Multijet**, ~10% ttbar
  - **Data-driven** estimation in CRs with reduced b-tagging.

New!
Full Run2

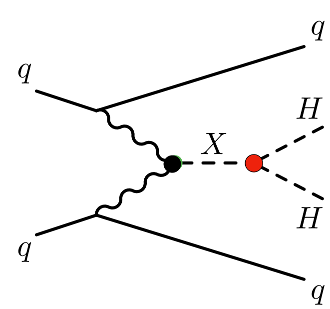
VBF HH→4b: Results

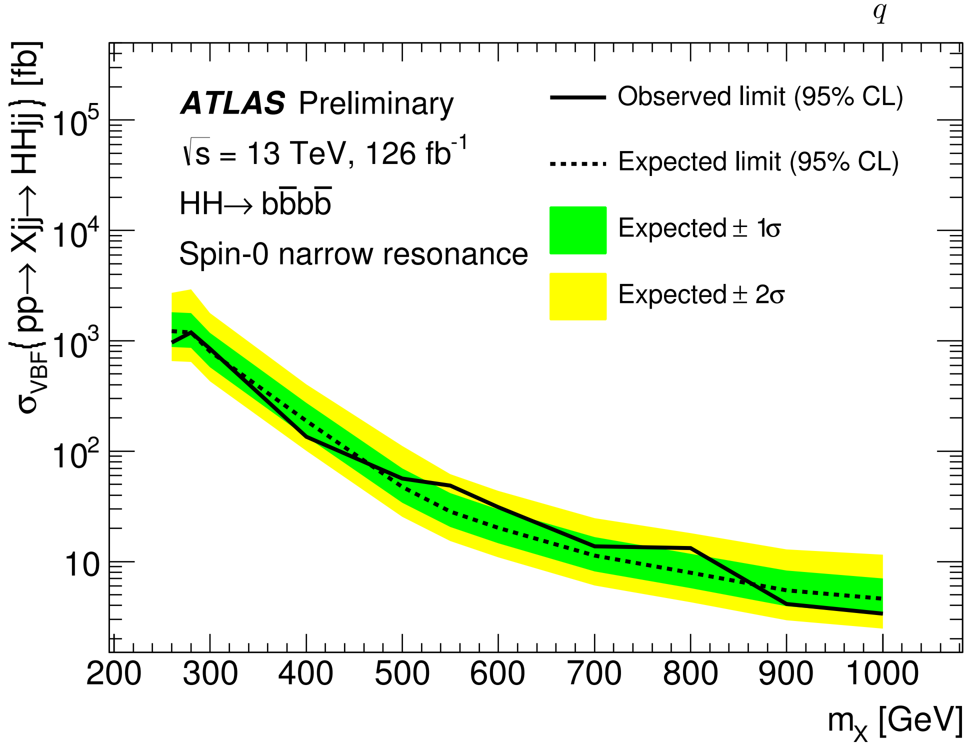
ATLAS-CONF-2019-030

- No significant deviation observed. Local 1.5 σ excess at ~550 GeV is largest deviation and set limits near expected values.
- World's first limit on VVHH coupling strength: c_{2V} < -1.02 and 2.71 < c_{2V} is excluded with 95% CLs.

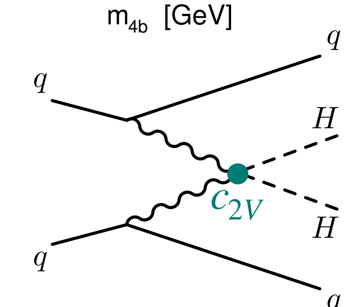


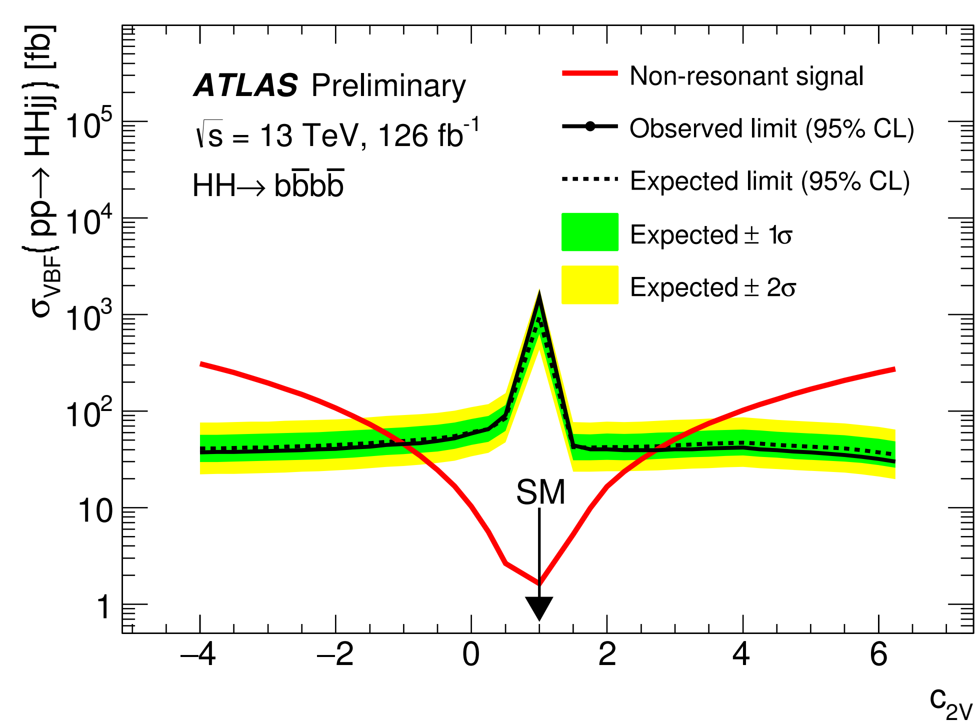
Spin-0 resonant production XS





Non-resonant production XS



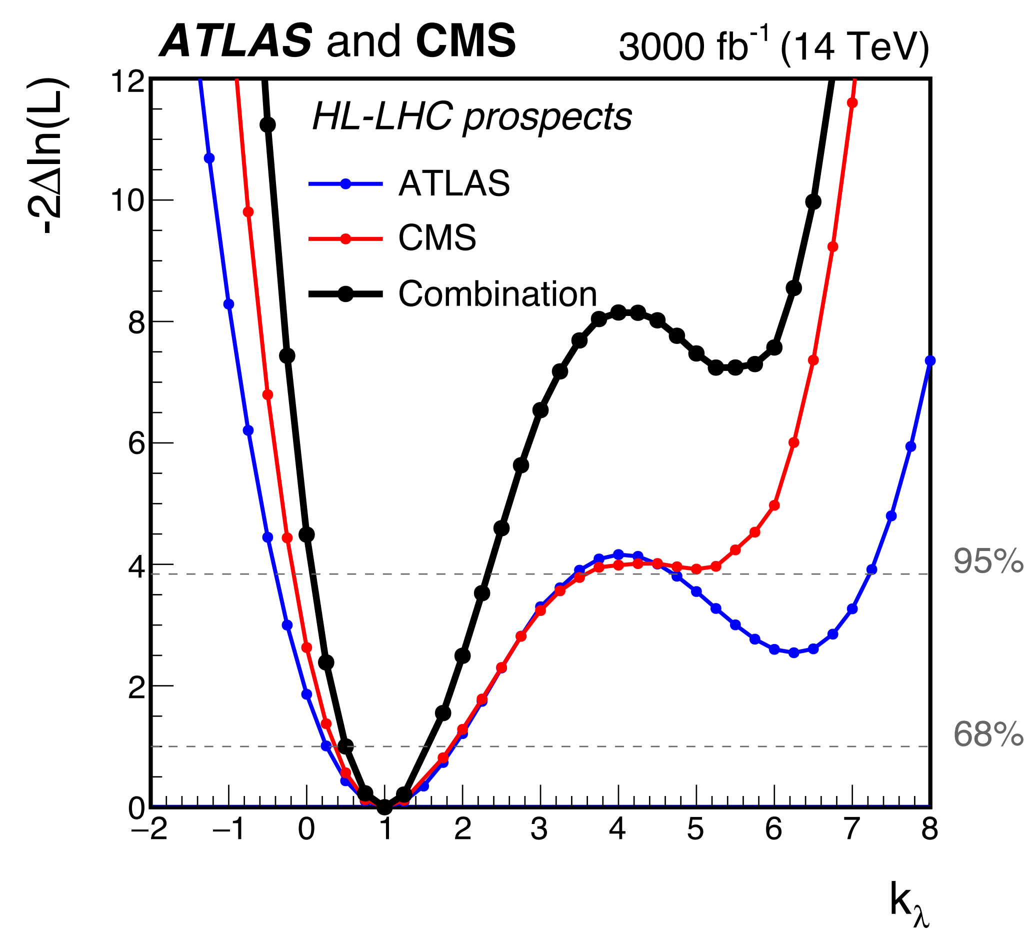


HL-LHC prospects on SM non-resonant

1902.00134

- HL-LHC will deliver ~3000 fb^{-1} at 14 TeV by late 2030's
- Latest HL-LHC projections published in the Yellow Report by a joint ATLAS+CMS+Theory effort.
  - HH→bbbb and HH→bb$\tau\tau$: Extrapolation from Run2 analysis
  - HH→bb$\gamma\gamma$: Dedicated analysis with parametric smearing based on upgraded detector performance
  - Systematics are estimated with expected potential gains in technique
- HH combination
  - No correlation considered (shown to have negligible impact).
  - Signal (SM) significance: 4σ expected for ATLAS+CMS
  - κ_λ measurement (assuming SM value):
    - $0.1 < \kappa_\lambda < 2.3$ [95% CLs]

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



Summary

- HH studies can access the SM higgs couplings and BSM physics.
- A **combination of all 2015-16 ATLAS analyses** and **two new analyses performed on the full LHC-Run2 dataset** ($bbl\nu l\nu$ and VBF HH→4b) have been presented.
  - No observation for enhanced di-Higgs production has been found up to now.
  - The most stringent constraint on di-Higgs production cross-section (SM) is set and is **6.9(10) x σ^{SM}_{ggF} obs (exp)**.
  - The first constraint on VVHH coupling strength has been set: **c_{2V} < -1.02 and 2.71 < c_{2V} is excluded** with 95% CLs.
  - Limits on heavy spin-0/2 particles are set
- Stay tuned for more & more results with the full Run-2 dataset.
- The HL-LHC prospects at 3000 fb^{-1} at 14 TeV shows **discovery significance of 4σ** and **κ_λ measurement of 0.1 < κ_λ < 2.3** by ATLA+CMS. New channels, ideas for physics analysis, and improved detector performances can improve the measurement.