LAPP
Laboratoire d'Annecy-le-Vieux
de Physique des Particules

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

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EPS-HEP2019 July 10th-17th, Ghent

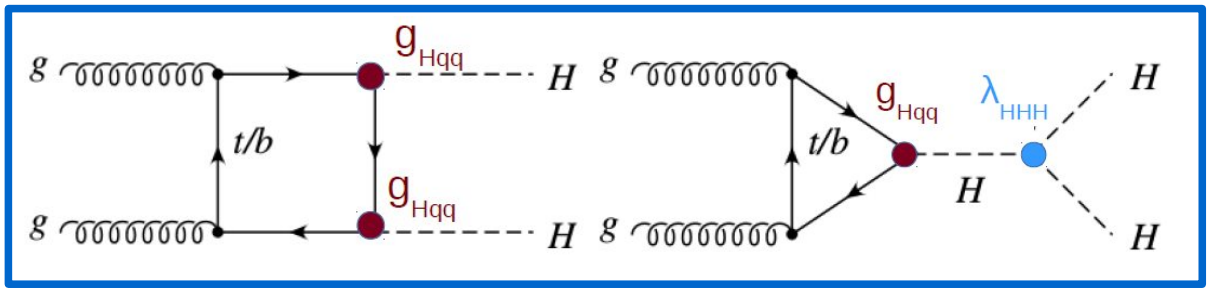
Motivation

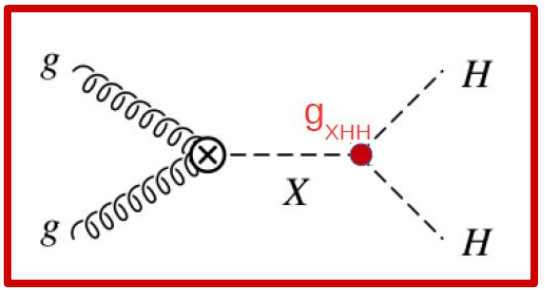
Non-resonant HH production

- Sensitive to Higgs trilinear coupling λ_{HHH}.
  - Its value in SM is determined by the v.e.v. and m_H.
  - Its measurement is a test of the shape of the Higgs potential.
- SM cross-section for *pp* collisions at 13TeV is $\sigma_{ggF}^{\mathrm{SM}} = 31.05\mathrm{fb}$.
  - Possible BSM enhancements due to modified λ_{HHH}.

Resonant HH production

- Models containing a heavy spin-0 particle coupling to SM Higgs:
  - Singlet extension;
  - 2HDM;
  - hMSSM;
  - …
- Models with heavy spin-2 particle:
  - Randall-Sundrum Graviton.

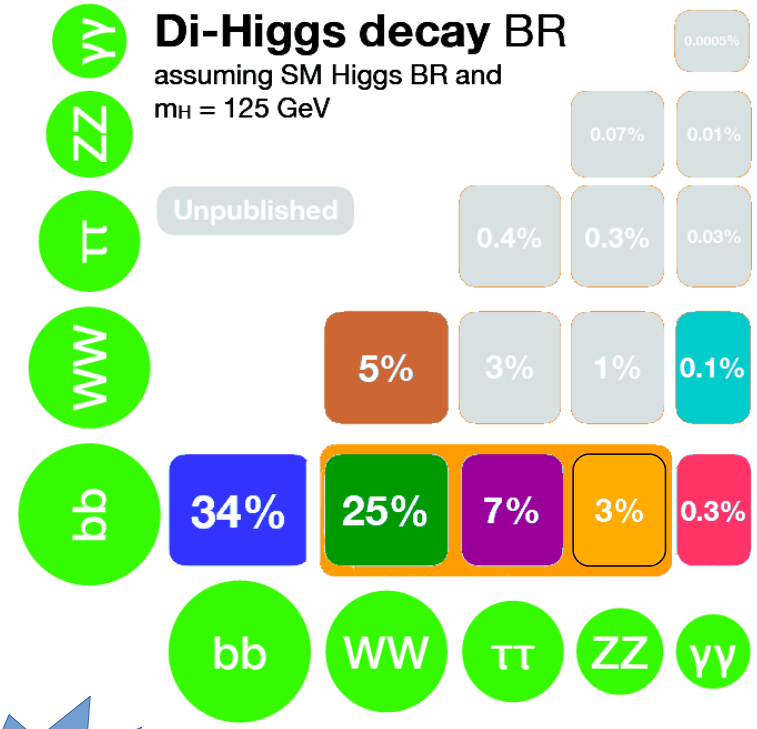




ATLAS Run2 publication summary

Channel	L [fb^{-1}]	Reference
$b\bar{b}b\bar{b}$	27.5-36.1	*JHEP 01 (2019) 030*
$b\bar{b}W^+W^-$ ($b\bar{b}\ell\nu qq$)	36.1	*JHEP 04 (2019) 092*
$b\bar{b}\tau^+\tau^-$	36.1	*Phys. Rev. Lett. 121 (2018) 191801*
$W^+W^-W^+W^-$	36.1	*JHEP 05 (2019) 124*
$b\bar{b}\gamma\gamma$	36.1	*JHEP 11 (2018) 40*
$W^+W^-\gamma\gamma$	36.1	*Eur. Phys. J. C 78 (2018) 1007*
combination	36.1	*1906.02025*
$b\bar{b}\ell\nu\ell\nu$	139	
VBF $b\bar{b}b\bar{b}$	126	*ATLAS-CONF-2019-030*

New!

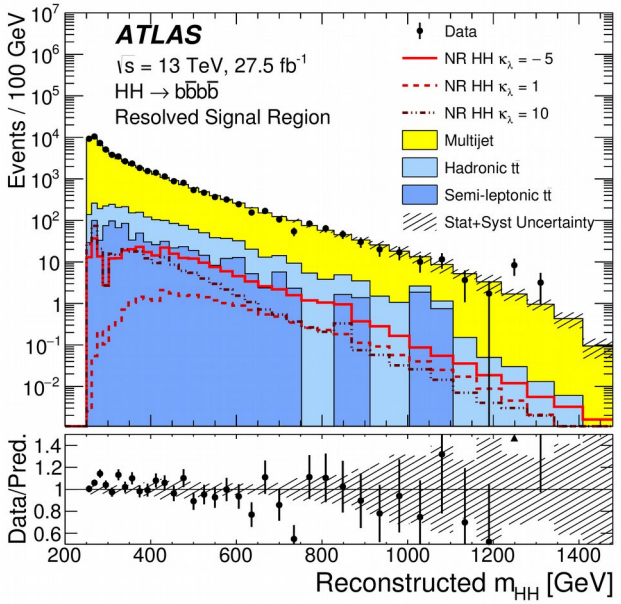


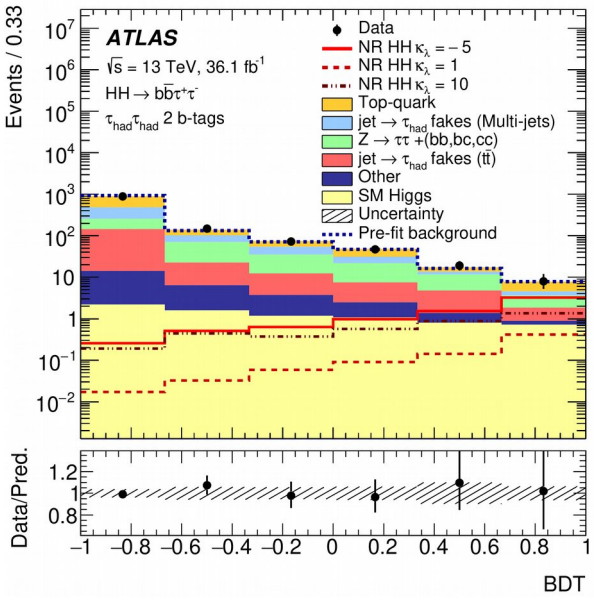
HH Combination

1906.02025

HH → bb̄bb̄: *JHEP 01 (2019) 030*

- To recover efficiency at high reconstructed m_{HH}:
  - **Resolved**: 4 *anti-k*$_t$ jet with *R=0.4* tagged as *b-jet*.
  - **Boosted**: 2 *anti-k*$_t$ jets with *R=1.0* both with at least a sub-jet with *R=0.2* tagged as *b-jet*.
- Main background: QCD **multijet** production.
  - **Data-driven** estimation in CRs with reduced b-tagging.
- Signal extraction by means of a fit on reconstructed m_{HH}.





HH → bb̄τ⁺τ⁻: *Phys. Rev. Lett. 121 (2018) 191801*

- Considering $\tau_e\tau_{had}$ and $\tau_{had}\tau_{had}$ final states.
- Main source of uncertainties comes from $t\bar{t}$ modelling (±17%) and MC statistics (±16%).
- Signal extraction by means of a fit on **BDT** output used to separate signal vs SM background.
- Single channel with the **most stringent constraints on non-resonant SM *HH* production**.

HH Combination (cont'd)

1906.02025

HH → bb̄γγ: *JHEP 11 (2018) 40*

- **Loose selection**: (sub-)leading jet p_T>40(25) GeV used for λ_{HHH} analysis and resonances with m_X<500 GeV.
- **Tight selection**: (sub-)leading jet p_T>100(30) GeV used m_X>500 GeV.

- Signal extracted by means of a fit on m_{HH} ($m_{\gamma\gamma}$) for (non-)resonant production.
- Analysis dominated by statistical uncertainties.

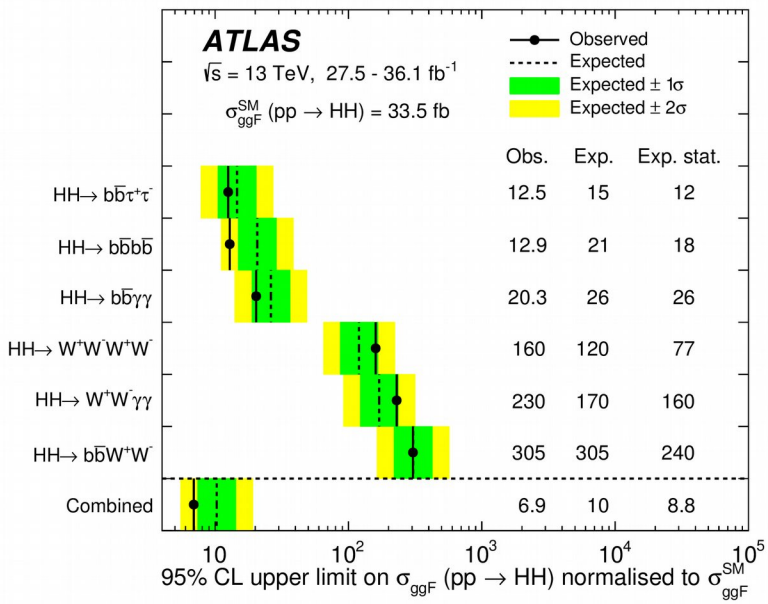
- Simultaneous fit to data for cross-section of the signal process and nuisance parameters modelling statistical and systematic uncertainties, using the CLs approach.

Channel	Discriminant: Resonant [non-resonant]
$b\bar{b}b\bar{b}$	m_{HH} [m_{HH}]
$b\bar{b}W^+W^-$ ($b\bar{b}\ell\nu qq$)	c.e. [m_{HH}]
$b\bar{b}\tau^+\tau^-$	BDT [BDT]
$W^+W^-W^+W^-$	c.e. [c.e.]
$b\bar{b}\gamma\gamma$	$m_{\gamma\gamma}$ [m_{HH}]
$W^+W^-\gamma\gamma$	$m_{\gamma\gamma}$ [$m_{\gamma\gamma}$]

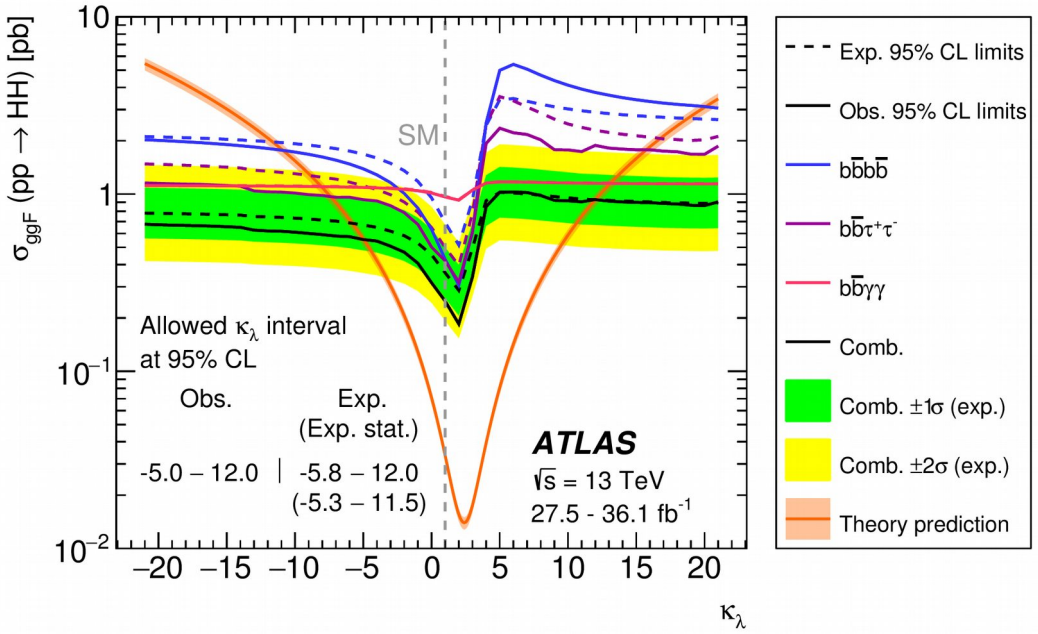
Combination results: non-resonant production

1906.02025

HH production cross-section:



Higgs trilinear coupling:



95% CL upper limit for $k_\lambda \equiv \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} = 1$**:**

- 6.9 x $\sigma_{ggF}^{\mathrm{SM}}$ (obs)
- 10.0 x $\sigma_{ggF}^{\mathrm{SM}}$ (exp)

95% CL confidence intervals:

- Kλ ∈ [-5.0,12] (obs), [-5.8,12] (exp)

ATL-PHYS-PUB-2019-009

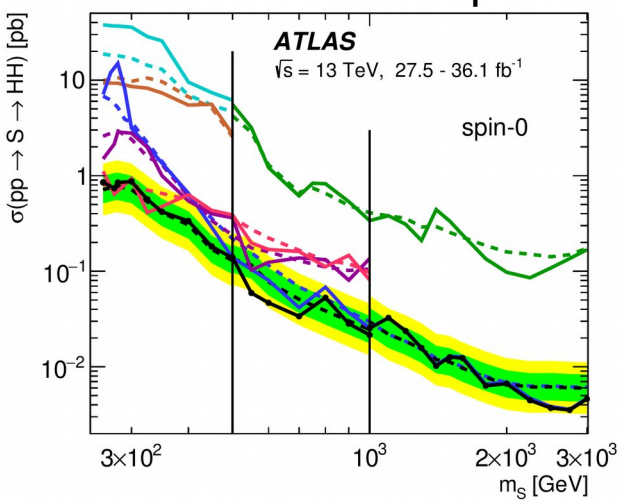
- Indirect limits from single Higgs differential production and decay measurement (80fb^{-1}):
  - Kλ ∈ [-3.2,11.9] (obs), [-5.8,12.0] (exp)

Combination results: resonant production

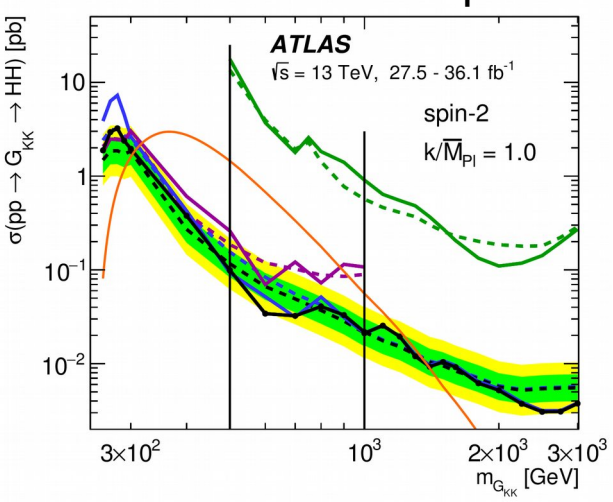
1906.02025

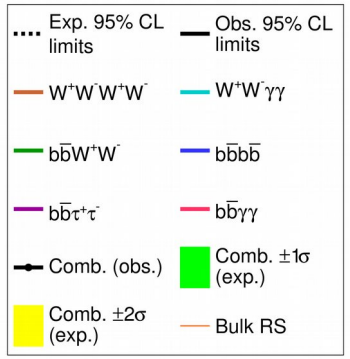
- Same statistical treatment as described for non-resonant production.

spin-0



spin-2





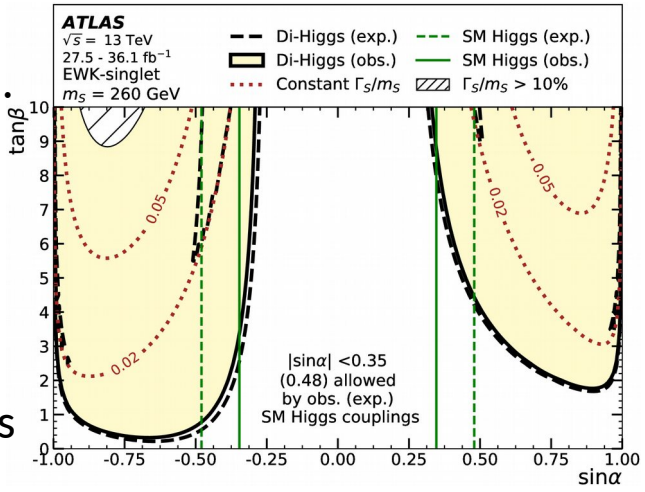
Singlet:

- First ATLAS interpretation of HH results within this model.
- Exclusion in *(ms, sinα)* and *(sinα, tanβ)*.

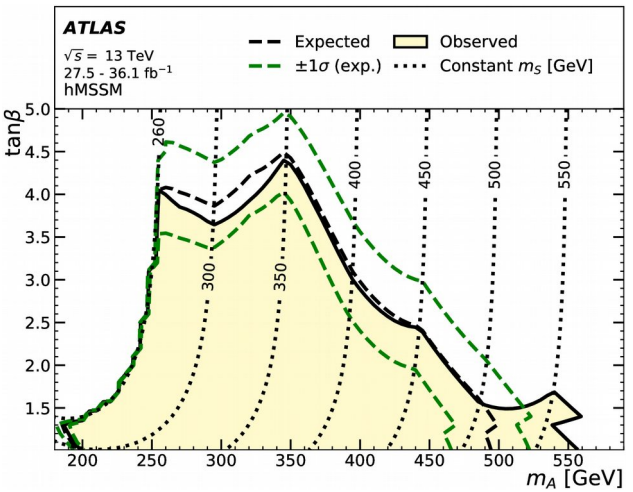
hMSSM:

- Exclusion in *(mA, tanβ)*.
- Exclusion more than twice as Run1 in both m_A and *tanβ*.

Singlet



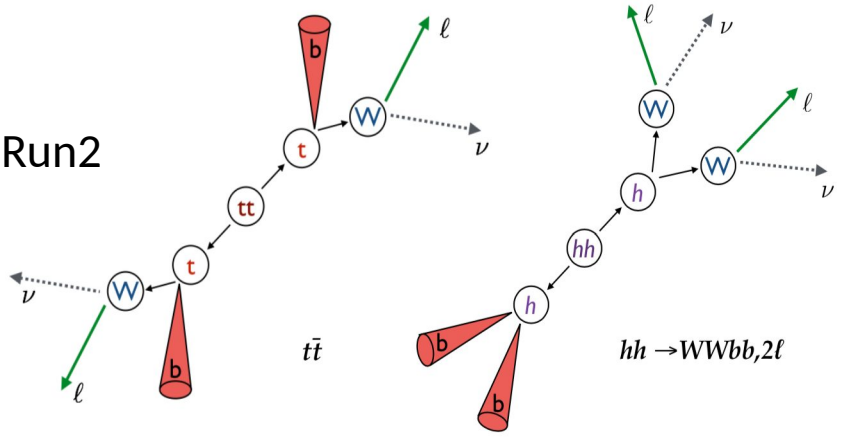
hMSSM



$bb\ell\nu\ell\nu$: Analysis Strategy

New!
Full Run2

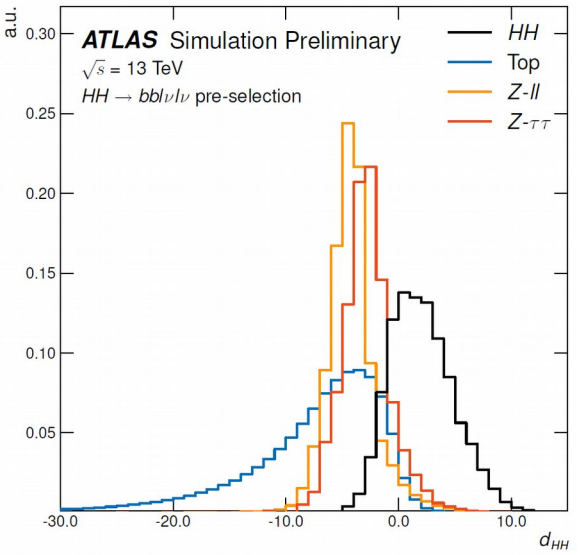
- New channel in ATLAS addressing the 2ℓ decay of $HH \to bbWW^*/ZZ^*/\tau^+\tau^-$.
- First HH published analysis exploiting the full LHC-Run2 dataset ($139 fb^{-1}$).
- Main backgrounds:
  - **Irreducible** (~80%): **Top** ($t\bar{t}$ and tW), **Z+HF**.
    - Normalization from control regions.
  - **Reducible**: **non-prompt leptons** from heavy flavour hadrons.
    - Data-driven estimate from events with same sign leptons.



- 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:

$$d_{hh} = \ln\left(\frac{p_{HH}}{p_{Top} + p_{Z-\ell\ell} + p_{Z-\tau\tau}}\right)$$

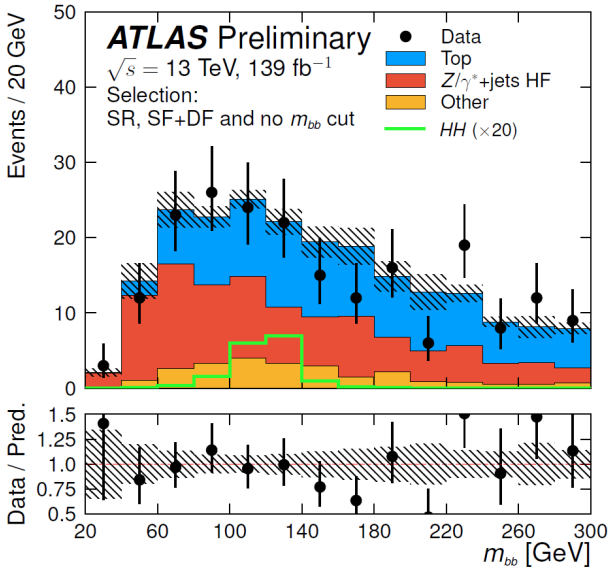
- m_{bb} and $m_{\ell\ell}$ are uncorrelated to d_{hh} and are used to define SR.

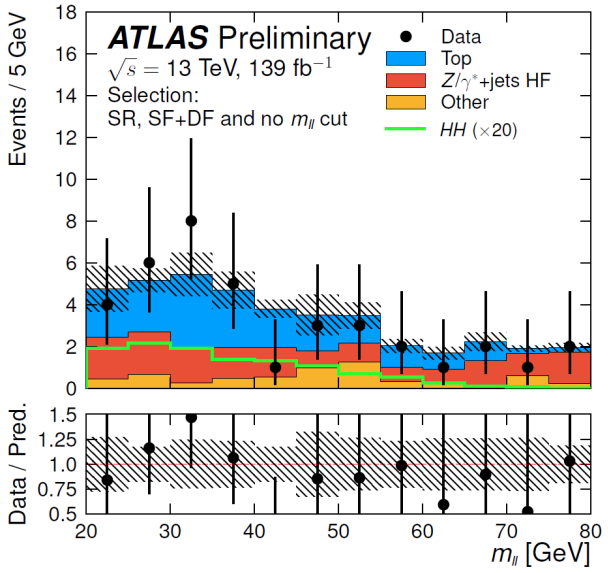


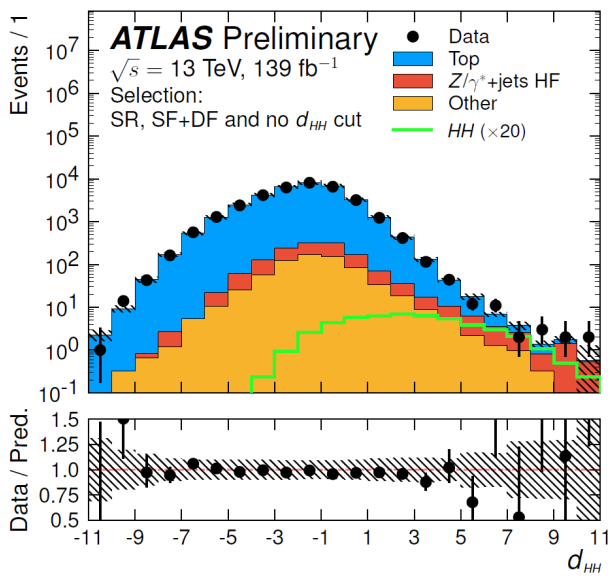
$bb\ell\nu\ell\nu$: results

New!
Full Run2

- Observation is consistent with no enhanced di-Higgs production hypothesis.







95% CL upper limit at $k_\lambda = 1$ (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

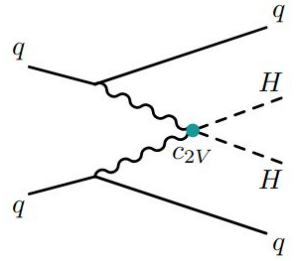
VBF-HH→$b\bar{b}b\bar{b}$

ATLAS-CONF-2019-030

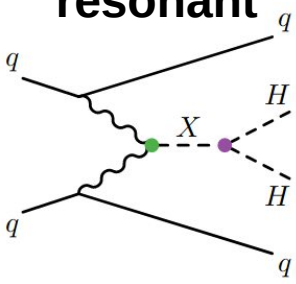
New! Full Run2

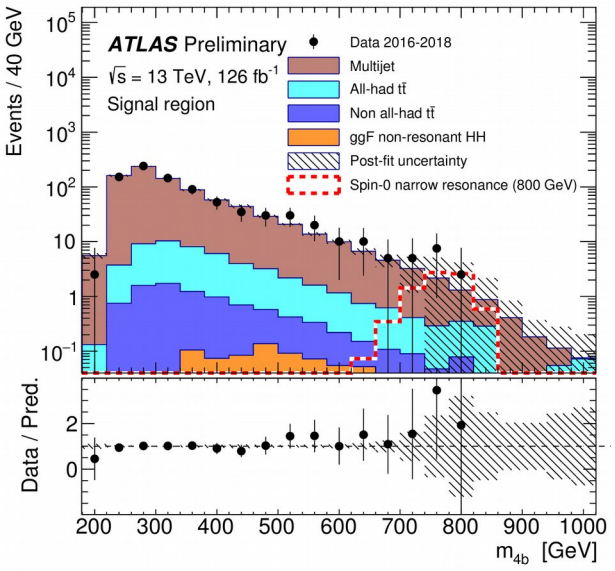
- Target signature: $HH \to b\bar{b}b\bar{b}$ process with 2 final state VBF jets.
- Motivation: **first study of VVHH vertex.**
- Similar analysis strategy as in inclusive $HH \to b\bar{b}b\bar{b}$.
  - Additional selection of 2 VBF jets: $|\eta| > 2$ and in opposite hemispheres.
  - Main background is QCD multijet: data-driven estimation in 2b-CR.
- **Improved b-jet energy resolution** (~25%) with BDT-based regression.
- Signal extracted from fit on m_{4b}. No statistically significant excess found.

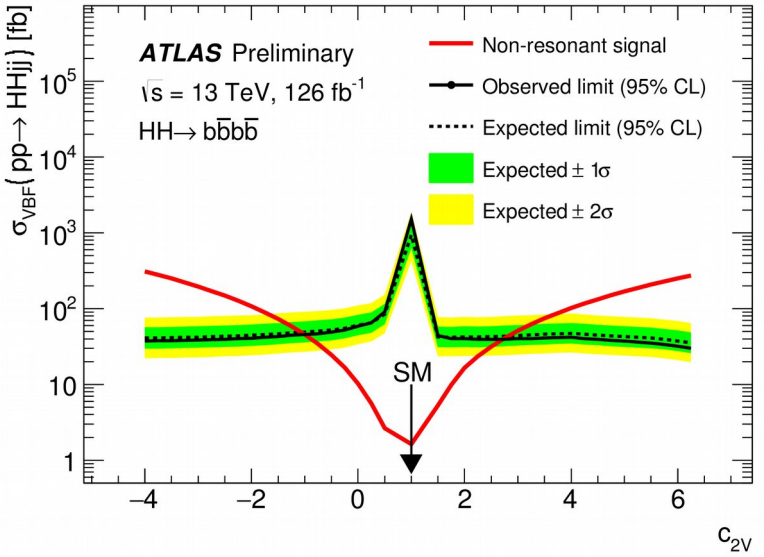
non-resonant



resonant







Stringent limits on c_{2V}!

95% CL intervals:

$c_{2V} \in [-1.0, 2.7]$ obs.

$c_{2V} \in [-1.1, 2.8]$ exp.

- Results for the search of resonant production in the talk by R. Jansky [link].

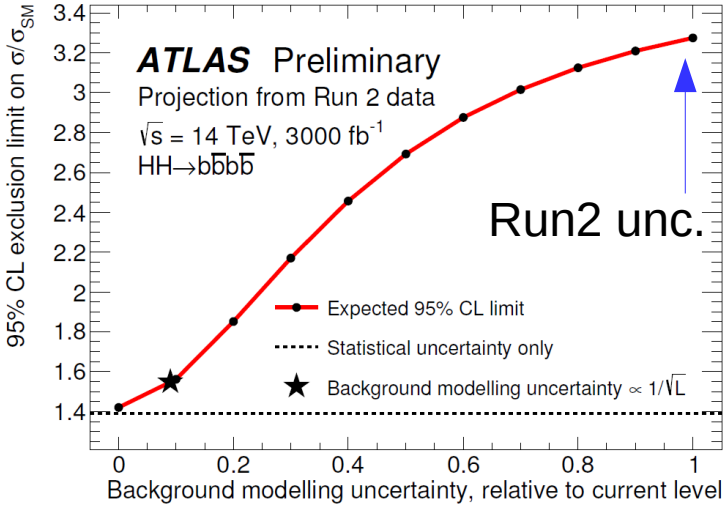
HL-LHC projections: HH→$b\bar{b}b\bar{b}/b\bar{b}\tau^+\tau^-/b\bar{b}\gamma\gamma$

1902.00134

Latest HL-LHC projections published in the *Yellow Report* by a joint ATLAS+CMS+Theory effort.

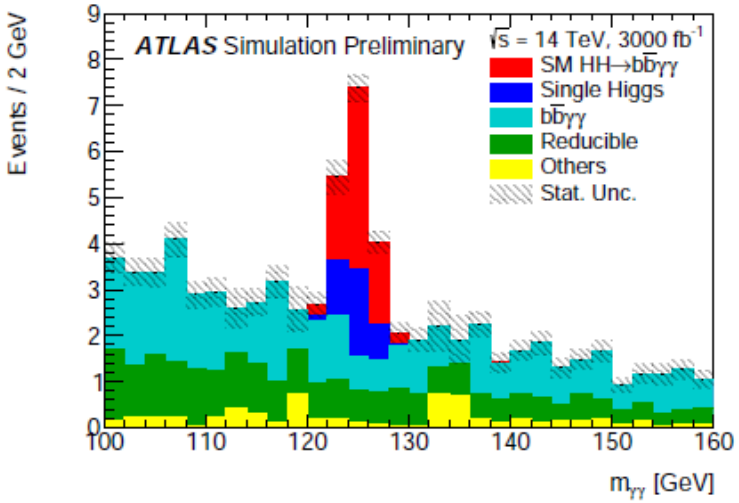
HH → $b\bar{b}b\bar{b}$: Extrapolation from Run2 analysis.

- Fit of m_{HH} distribution.
- Main systematic: **data-driven** multijet modelling.
  - Conservative assumption: uncertainty as in Run2.
  - Alternative assumption: scale as $1/\sqrt{L}$.



HH → $b\bar{b}\tau^+\tau^-$: Extrapolation from Run2 analysis.

- BDT output used as final discriminant.
- Main source of uncertainty in Run2 analysis is MC statistics: included in extrapolation.



HH → $b\bar{b}\gamma\gamma$: Dedicated analysis with parametric smearing based on upgraded detector performance.

- **$m_{\gamma\gamma}$ resolution ~1.6GeV**.
- BDT to reject continuum background and single Higgs background (mainly $t\bar{t}H$).
- Very small impact from systematic uncertainties.

ATLAS + CMS HH combination

1902.00134

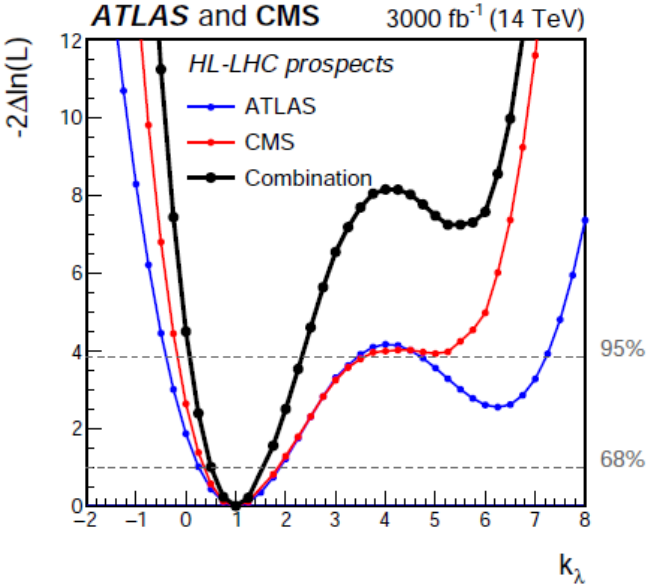
- Combined values channel-by-channel:
  - No correlation considered (shown to have negligible impact).
  - Systematic uncertainties included.
- Signal (SM) significance:
  - 4σ expected for ATLAS+CMS!
- Signal (SM) injection test:
  - μ_{inj} = 1: μ measured with ~30% unc.
  - μ_{inj} = 0: SM di-Higgs production excluded at 95% CL.
- k_λ measurement (assuming SM value):

$$0.1 < k_\lambda < 2.3 \ [95\% \ \mathrm{CL}]$$
$$0.5 < k_\lambda < 1.5 \ [68\% \ \mathrm{CL}]$$

  - 2nd minimum excluded at 99.4% CL thanks to m_{hh} shape information.

	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	

4σ expected for ATLAS+CMS!



Conclusions

- The discovery of di-Higgs production and the measurement of the Higgs trilinear self-coupling are among the **main goals of the (HL-)LHC** physics programme.
- The most recent results of the ATLAS collaboration on the topic have been presented.

LHC Run2

- A combination of all 2015-2016 ATLAS analyses and **two new analyses performed on the full LHC-Run2 dataset** ($bb\ell\nu\ell\nu$ and VBF-HH→$b\bar{b}bb$) 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 assuming kλ=1 (SM) is set by the **ATLAS HH combination** and is $6.9\ (10) \times \sigma_{ggF}^{\mathrm{SM}}$ obs (exp).
- Strong constraints on the VVHH vertex have been set.

HL-LHC

- The first comprehensive assessment of the HL-LHC physics programme has been recently published in the **Yellow Report**.
- The YR predicts that the full HL-LHC potential is going to be needed for ATLAS+CMS to reach a **discovery significance of 4σ** and an **uncertainty on *K*λ measurement of 50%**.
- Past experience tells us that these results will be outperformed with the help of new ideas on object reconstruction and physics analysis.