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

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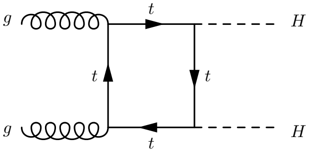
on behalf of the ATLAS Collaboration

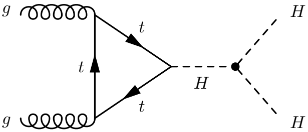
Higgs Couplings 2019, Oxford

02/10/2019

Higgs-boson pairs can be produced at the LHC via gluon-gluon fusion (ggF), accounting for more than 90% of the total cross section, via two Standard Model (SM) diagrams at LO:

box diagram (B) with top-quark Yukawa coupling and triangle diagram (T) with also the trilinear Higgs self-coupling





- In the SM destructive interference yields a small cross section of $\sigma_{ggF}^{SM}(pp \rightarrow HH) = 33.5$ fb at 13 TeV
- Needs very high statistics to be observed, but interesting to set an upper limit on the overall cross section and direct constraints on the Higgs self-coupling $\lambda_{HHH} = \frac{m_H^2}{2v}$
- Beyond Standard Model (BSM) physics could manifest as modifications of the couplings changing the production rate and the kinematics

Considering variations of the couplings, with two diagrams contributing at LO:

- B=box diagram, amplitude proportional to κ_t^2, $\kappa_t = y_t / y_t^{SM}$
- T=triangle diagram, amplitude proportional to $\kappa_t \kappa_\lambda$, $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

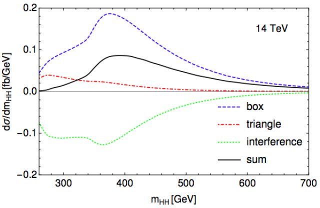
Amplitude: $A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$

Cross section

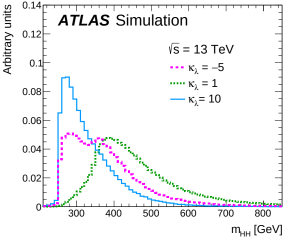
$$\sigma(\kappa_t, \kappa_\lambda) \sim \kappa_t^4 |B|^2 + \kappa_t^3 \kappa_\lambda (BT + TB) + \kappa_t^2 \kappa_\lambda^2 |T|^2$$

- cross section: 2nd order polynomial in κ_λ
- kinematics depends on relative contributions and interference of the two diagrams modifying the m_{HH} distribution

New! arXiv:1910.00012



arXiv:1906.02025



→ information used in the double-Higgs analyses to set constraints on κ_λ

Many different final states in the Higgs pair decay

di-Higgs decay BRs given by all possible combinations of observed Higgs decays:

	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%

ATLAS di-Higgs searches performed in 6 decay channels using 36 fb^{-1} of LHC 13 TeV *pp* collisions data:

- $b\bar{b}b\bar{b}$: highest BR
- $b\bar{b}\tau^+\tau^-$: good compromise between high BR and clean signature
- $b\bar{b}\gamma\gamma$: clean signature from the γs

3 most sensitive channels

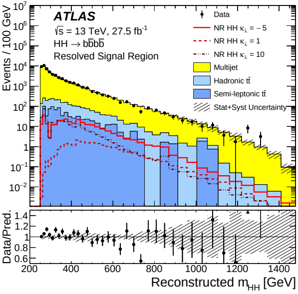
- $b\bar{b}W^+W^-$
- $W^+W^-W^+W^-$
- $W^+W^-\gamma\gamma$

3 channels exploiting high BR and clean signature of the γs, but difficult reconstruction of the Higgs candidate in W^+W^-

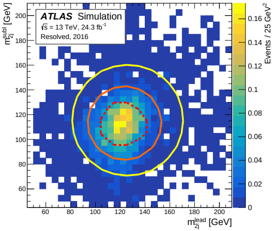
ATLAS di-Higgs analyses: $b\bar{b}b\bar{b}$

- b-jet triggers
- At least 4 b-tagged jets
- 4 jets b-tagged jets used to build the Higgs candidates, with pairing based on angular and invariant mass information
- Signal region defined by 2D requirements in the Higgs boson candidate's mass plane
- Largest background: QCD
  $\rightarrow$ data-driven from control regions
- Final discriminant variable: m_{HH}

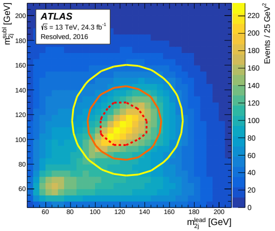
arXiv:1804.06174, arXiv:1906.02025



SM double-Higgs signal



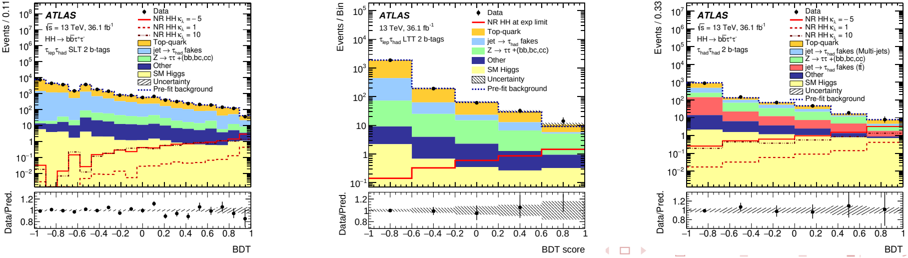
Multijet background



- Signal region inside the inner red dashed curve
- Validation region outside the signal region and within the orange circle
- Control region outside the validation region and within the yellow circle

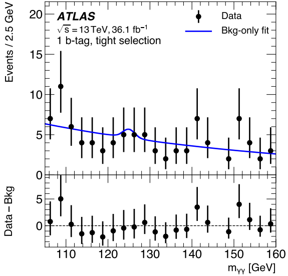
- Divided in two channels depending on τ-lepton pair decay mode: $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$
- $\tau_{lep}\tau_{had}$:
  - single-lepton (SLT) and lepton-τ_{had} (LTT) triggers
  - 1 light lepton (e/μ) and 1 τ_{had} with opposite charge
- $\tau_{had}\tau_{had}$:
  - single-τ_{had} and di-τ_{had} triggers
  - 2 τ_{had} with opposite charge
- 2 b-tagged jets
- Main backgrounds: $t\bar{t}$, $Z \to \tau\tau$ + heavy flavour jets and QCD
  $\to$ data-driven backgrounds with jets faking τ_{had}
- Final discriminant variable: Boosted Decision Tree (BDT) score distribution
- Simultaneous fit of 3 categories: $\tau_{lep}\tau_{had}$ SLT, $\tau_{lep}\tau_{had}$ LTT and $\tau_{had}\tau_{had}$

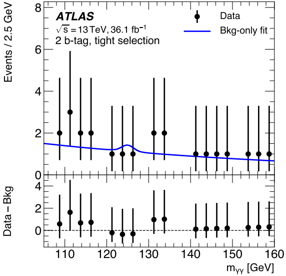
arXiv:1808.00336, arXiv:1906.02025



- Di-photon triggers
- At least 2 γ and at least 2 jets
- 2 categories: 2 b-tagged jets and 1 b-tagged jet
- Signal region defined by: $105 < m_{\gamma\gamma} < 160$ GeV, $90 < m_{jj} < 140$ GeV
- Final discriminant variable: $m_{\gamma\gamma}$
- Continuum $\gamma\gamma$ + jets background modelled in $m_{\gamma\gamma}$ with a functional form obtained from a fit to the data and single Higgs background described by a double-sided Crystal Ball determined from a fit to simulated samples
- Simultaneous fit of 2 categories: 1 b-tag and 2 b-tags

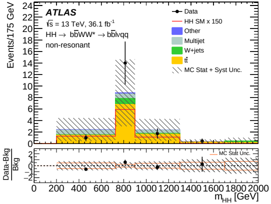
arXiv:1807.04873, arXiv:1906.02025





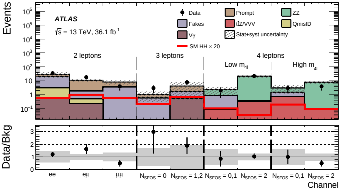
$b\bar{b}W^+W^-$:
arXiv:1811.04671, arXiv:1906.02025

- $bbl\nu qq$ final state
- Event-counting analysis (1 category)



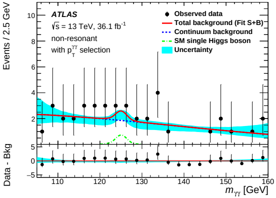
$W^+W^-W^+W^-$:
arXiv:1811.11028, arXiv:1906.02025

- Three channels:
  $l\nu l\nu 4q$ (2 leptons),
  $l\nu l\nu l\nu 2q$ (3 leptons)
  and $l\nu l\nu l\nu l\nu$ (4 leptons)
- Divided in categories according to the lepton flavour, the number of same-flavour and opposite charge lepton pairs and invariant mass
- Event-counting analysis with a simultaneous fit of 9 categories



$W^+W^-\gamma\gamma$:
arXiv:1807.08567, arXiv:1906.02025

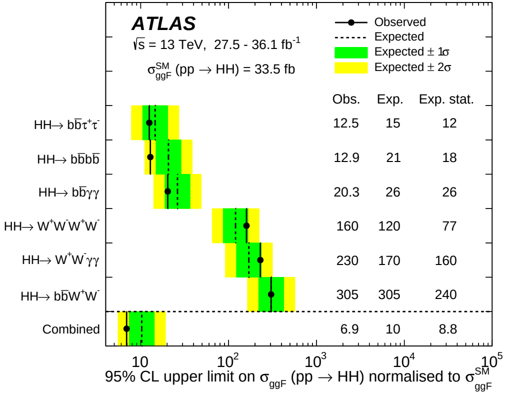
- $l\nu qq$ final state
- Final discriminant variable: $m_{\gamma\gamma}$ (1 category)



di-Higgs combined results: cross section

6 decay channels included in the di-Higgs combination with 36 fb^{-1} to set a 95% C.L. upper limit on the ggF di-Higgs production cross section

arXiv:1906.02025



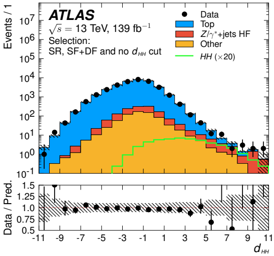
Observed (expected) combined upper limit of $6.9 \times \sigma_{ggF}^{SM}$ $(10 \times \sigma_{ggF}^{SM})$

Results dominated by statistical uncertainties on data, $\sim$10% impact of systematics on expected limit

New analysis recently performed with full Run-2 dataset of 139 fb^{-1}

- Looking for the HH decays with $H \to b\bar{b}$ and $H \to WW, ZZ, \tau\tau \to l\nu l\nu$
- At least two b-tagged jets and exactly two leptons (e/μ) with opposite charge
- 2 categories: same-flavour (SF) and different-flavour (DF) for the lepton pair
- Signal region defined by: $20 < m_{ll} < 60$ GeV, $110 < m_{bb} < 140$ GeV and a cut on a discriminant built from the output of a multiclass deep neural network (DNN) classifier ($d_{HH} > 5.45(5.55)$ for SR-SF (SR-DF))
- Event-counting analysis with a simultaneous fit of 2 signal regions: SF and DF

arXiv:1908.06765

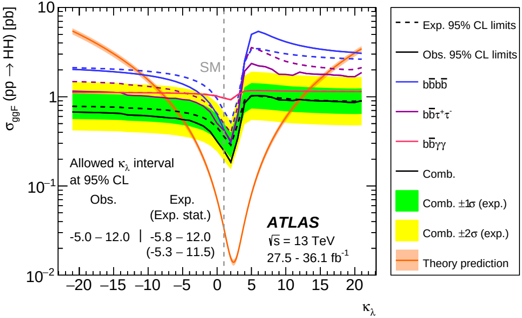


- Set a 95% C.L. upper limit on the ggF di-Higgs production cross section:
  Observed (expected) upper limit of
  $40 \times \sigma^{SM}_{ggF}$ $(29 \times \sigma^{SM}_{ggF})$
- Limits comparable to the previous leading searches for di-Higgs production
  $\to$ interesting new channel to include in the full Run-2 di-Higgs combination!

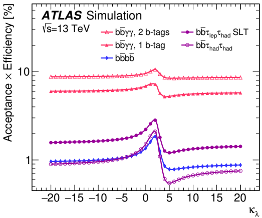
	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \to HH)/\sigma^{\text{SM}}(gg \to HH)$	14	20	29	43	62	40

Combined results: Higgs self-coupling

3 most sensitive channels included in the di-Higgs combination with 36 fb^{-1} to set 95% C.L. upper limits on the ggF di-Higgs production cross section as a function of κ_λ:



- Shape determined by the inverse of the signal acceptance
- Comparing to the theoretical cross section predictions, 95% C.L. allowed k_λ range: $-5 < \kappa_\lambda < 12$



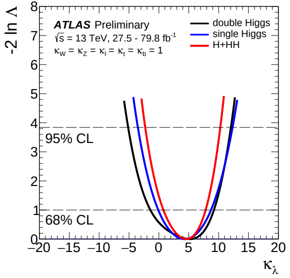
arXiv:1906.02025

	Allowed κ_λ interval at 95% CL		
Final state	Obs.	Exp.	Exp. stat.
$b\bar{b}b\bar{b}$	−10.9 — 20.1	−11.6 — 18.8	−9.8 — 16.3
$b\bar{b}\tau^+\tau^-$	−7.4 — 15.7	−8.9 — 16.8	−7.8 — 15.5
$b\bar{b}\gamma\gamma$	−8.1 — 13.1	−8.1 — 13.1	−7.9 — 12.9
Combination	−5.0 — 12.0	−5.8 — 12.0	−5.3 — 11.5

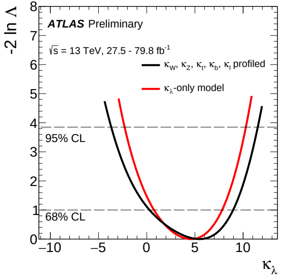
Combination of di-Higgs and single-Higgs analyses — NEW!

- Analysis to constrain κ_λ using single-Higgs measurements with up to 80 fb^{-1} also performed ATL-PHYS-PUB-2019-009 (see talk by Eleonora Rossi)
- Di-Higgs κ_λ analysis very recently combined with the single-Higgs κ_λ analysis, NEW RESULTS:

κ_λ-only model:



generic model:



di-Higgs and single-Higgs combination allows:

- Significant improvement in constraining κ_λ: $-2.3 < \kappa_\lambda < 10.3$, assuming all other SM couplings
- Constraints on κ_λ set in a more generic model with less assumptions on the other Higgs couplings: $-3.7 < \kappa_\lambda < 11.5$, in the generic model

New! ATLAS-CONF-2019-049

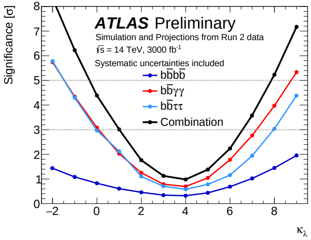
Model	$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\ell{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ-only	1	1	1	1	1	$4.6^{+3.2}_{-3.8}$	[−2.3, 10.3]	obs.
						$1.0^{+7.3}_{-3.8}$	[−5.1, 11.2]	exp.
Generic	$1.03^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$	$1.00^{+0.12}_{-0.11}$	$1.03^{+0.20}_{-0.18}$	$1.06^{+0.16}_{-0.16}$	$5.5^{+3.5}_{-5.2}$	[−3.7, 11.5]	obs.
	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.12}_{-0.12}$	$1.00^{+0.21}_{-0.19}$	$1.00^{+0.16}_{-0.15}$	$1.0^{+7.6}_{-4.5}$	[−6.2, 11.6]	exp.

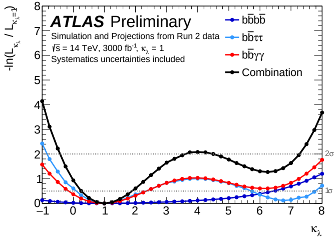
Prospects measurements at the HL-LHC

Prospect study for the search for di-Higgs production at the HL-LHC performed assuming 3000 fb^{-1} at 14 TeV,
using the combination of the 3 most sensitive channels: $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$

- $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ analyses based on extrapolating the Run-2 analyses
- $b\bar{b}\gamma\gamma$ dedicated new analysis using simulations at 14 TeV

ATL-PHYS-PUB-2018-053, arXiv 1902.00134





Expected significance for $\kappa_\lambda = 1$: 3σ, evidence!

Channel	Statistical-only	Statistical + Systematic
$HH \to bbbb$	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

4σ from ATLAS+CMS combination

Expected 40% precision on μ for $\kappa_\lambda = 1$

Channel	Measured μ (Statistical-only)	Measured μ (Statistical + Systematic)
$HH \to bbbb$	1.0 ± 0.6	1.0 ± 1.6
$HH \to b\bar{b}\tau^+\tau^-$	1.0 ± 0.4	1.0 ± 0.5
$HH \to b\bar{b}\gamma\gamma$	1.0 ± 0.6	1.0 ± 0.6
Combined	1.00 ± 0.31	1.0 ± 0.4

Expected $-0.4 < \kappa_\lambda < 7.3$ at 95% C.L. for $\kappa_\lambda = 1$

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	$0.25 \le \kappa_\lambda \le 1.9$	$-0.4 \le \kappa_\lambda \le 7.3$

Summary and outlook

- Latest ATLAS results on di-Higgs production and the Higgs self-coupling
- Combination of 6 decay channels to set an upper limit on the di-Higgs production cross section: $6.9 \times \sigma_{ggF}^{SM}$
- Combination of the 3 most sensitive channels to set constraints on the Higgs self-coupling modifier κ_λ: $-5 < \kappa_\lambda < 12$
- New results from the combination of di-Higgs and single-Higgs analyses to set constraints on κ_λ: $-2.3 < \kappa_\lambda < 10.3$
- Future prospects for the search for di-Higgs production and test κ_λ at the HL-LHC: possible to reach evidence for di-Higgs production at the end of the HL-LHC

ATLAS di-Higgs analyses with full Run-2 dataset ongoing!

Back-up slides

Signal simulation

SM di-Higgs signal:

- Generated at NLO in QCD with MADGRAPH5_aMC@NLO
- Using the CT10 NLO PDF set
- Parton shower and hadronisation simulated with HERWIG++
- Using parameter values from the UE-EE-5-CTEQ6L1 tune

- FTApprox method used to include finite top-quark mass effects in the real-radiation NLO corrections, virtual loop corrections realised assuming infinite top-quark mass
- Generator level bin-by-bin reweighting of the m_{HH} distribution applied to take into account the finite top-quark mass effect in full NLO corrections

Signal normalised to $\sigma^{SM}_{ggF} = 33.5$ fb,
calculated at NLO in QCD with finite top-quark mass effects and corrected at NNLO in QCD matched with the NNLL resummation in the heavy top-quark limit

Signal simulation

di-Higgs signal with κ_λ variations:

$b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:

- Generated at LO with MADGRAPH5_aMC@NLO
- Using the NNPDF 2.3 LO PDF set
- Showered using PYTHIA 8.2
- Using the A14 tune

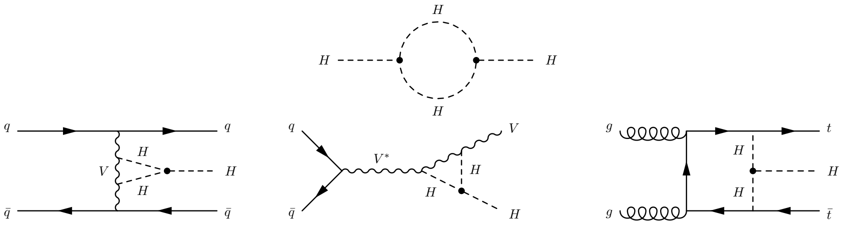
- 3 LO samples generated with $\kappa_\lambda = 0, 1, 20$
- Used in linear combinations to obtain LO signal distributions for any κ_λ
- Weights derived in m_{HH} bins from the ratio of any κ_λ to the SM and used to reweight the NLO SM sample
- Reweighted NLO signal samples used to compute signal acceptance and distributions for any κ_λ

$b\bar{b}\gamma\gamma$:

- Shape of $m_{\gamma\gamma}$ described by the double-sided Crystal Ball function (Gaussian core with power-law tails)
- Signal acceptance parameterised from MC simulated samples

Normalisation for any κ_λ obtained by multiplying the SM cross section by the ratio $\sigma_{ggF}(\kappa_\lambda)/\sigma_{ggF}^{SM}$ computed at NNLO+NNLL in the heavy top-quark approximation

Single-Higgs processes do not depend on κ_λ at LO,
but the Higgs trilinear self-coupling enters in the NLO electroweak corrections via Higgs self energy loop corrections and additional diagrams



$\rightarrow$ an indirect constraint on κ_λ can be set comparing precise measurements of single-Higgs production yields to the SM predictions with κ_λ-dependent NLO EW effects

Theoretical framework for a global fit to constrain the Higgs trilinear coupling from single-Higgs measurements proposed in papers from F.Maltoni et al.

(https://arxiv.org/pdf/1607.04251.pdf, https://arxiv.org/pdf/1607.04251.pdf)

Single-Higgs κ_λ analysis based on this framework

Combination of di-Higgs and single-Higgs analyses: single-Higgs κ_λ analysis theoretical framework

Higgs production cross sections and decay BRs modified by parameters representing their ratio to the SM values as a function of κ_λ

For a given production process i the cross section modifier as a function of κ_λ can be written as:

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\rm BSM}}{\sigma^{\rm SM}} = Z_H^{\rm BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\rm EW}^i}\right],$$

where $Z_H^{\rm BSM}(\kappa_\lambda)$ is defined as:

$$Z_H^{\rm BSM}(\kappa_\lambda) = \frac{1}{1-(\kappa_\lambda^2-1)\delta Z_H} \quad \text{with} \quad \delta Z_H = -1.536\times10^{-3},$$

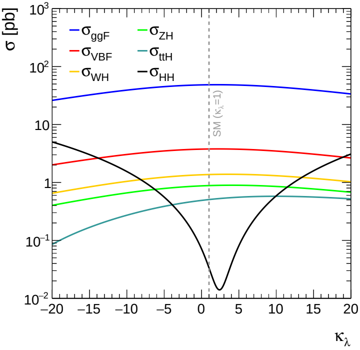
For a given decay channel f the BR modifier as a function of κ_λ can be written as:

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\rm BSM}}{\mathrm{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\rm SM}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}.$$

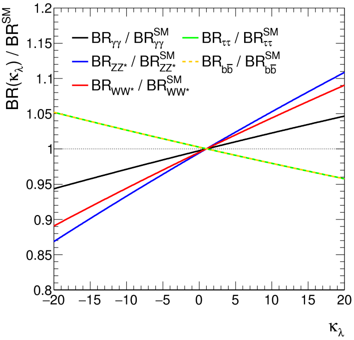
- $\kappa_{EW}^i = \frac{\sigma_{NLO}^{SM,i}}{\sigma_{LO}^{SM,i}}$ accounts for the NLO EW corrections to the cross section for $\kappa_\lambda = 1$
- $C_{\mathbf{1}}^i$ is a process- and kinematic-dependent coefficient
- $\kappa_i = \frac{\sigma_{LO,i}^{BSM}}{\sigma_{LO}^{SM,i}}$ represent the modifiers to other Higgs boson couplings that can also be considered

Double-Higgs and single-Higgs cross sections and Higgs decay branching fractions as a function of κ_λ

New! ATLAS-CONF-2019-049



ATL-PHYS-PUB-2019-009



Combination of di-Higgs and single-Higgs analyses: data and input measurements

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (excluding $t\bar{t}H, H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H, H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau^+\tau^-$	36.1
$VH, H \to b\bar{b}$	79.8
$t\bar{t}H, H \to b\bar{b}$	36.1
$t\bar{t}H, H \to$ multilepton	36.1
$HH \to b\bar{b}b\bar{b}$	27.5
$HH \to b\bar{b}\tau^+\tau^-$	36.1
$HH \to b\bar{b}\gamma\gamma$	36.1

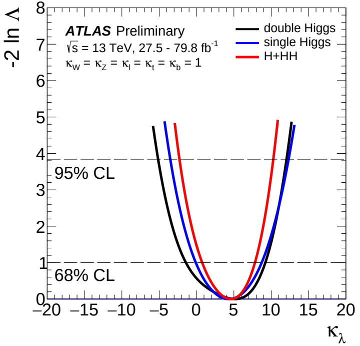
Same input analyses used in the HH combination and in the H combination, except the $ttH, H \to \gamma\gamma$ analysis that has been removed from this combination because of large overlap in the events between the $ttH, H \to \gamma\gamma$ and $HH \to bb\gamma\gamma$ analyses (50%)

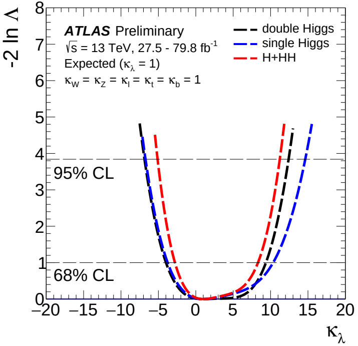
- Removing $ttH, H \to \gamma\gamma$ worsens the expected constraint on κ_λ by 4%, removing $HH \to bb\gamma\gamma$ instead would worsen it by 15%
- The remaining categories have a maximum overlap of less than 2% of the events in the double-Higgs categories and the impact of the overlapping categories on the final result is of about 1% so they are kept

- For the κ_λ-only model where all couplings are set to SM values except κ_λ

Likelihood scan as a function of κ_λ

New! ATLAS-CONF-2019-049



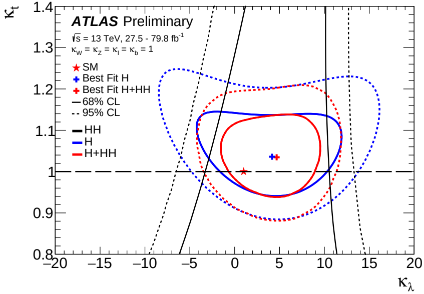


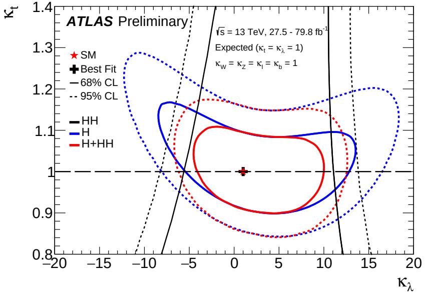
Combination of di-Higgs and single-Higgs analyses: results

- For more generic models: model where all coupling modifiers are set to the SM values except κ_λ and κ_t

Contours in the $\kappa_\lambda - \kappa_t$ plane

New! ATLAS-CONF-2019-049

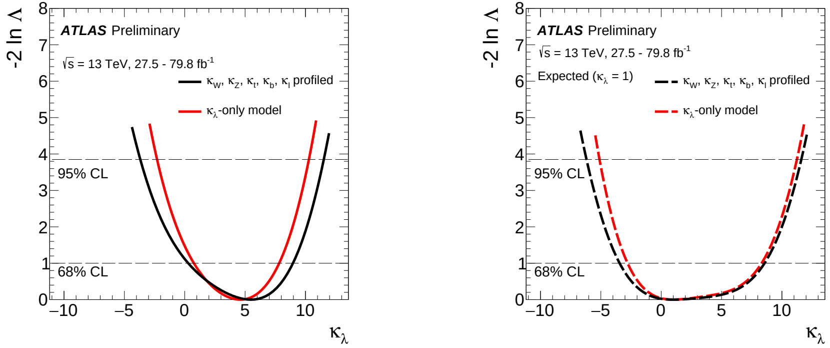




- For more generic models: model where $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_l$ and κ_λ are fitted simultaneously

Likelihood scan as a function of κ_λ with $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_l$ profiled, compared to the likelihood scan from the κ_λ-only fit

New! ATLAS-CONF-2019-049



Likelihood split per production mode and decay mode

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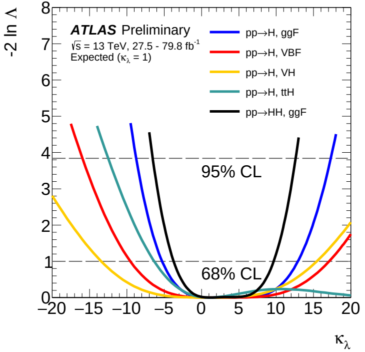
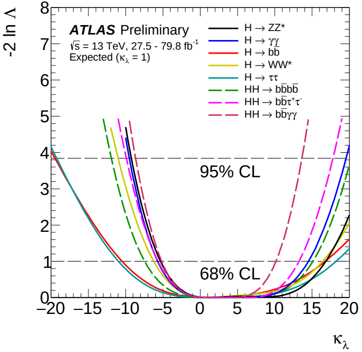


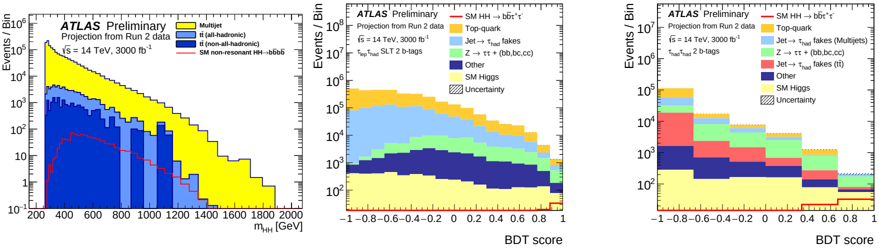


Prospects measurements at the HL-LHC: extrapolation method

$b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ analyses based on extrapolating the Run-2 analyses:

- Scaling of the distributions used in the fit of the published analyses
- Signal normalisation scaled to account the increase of collision energy from 13 TeV to 14 TeV (using recommendations from the LHCXSWG)
- Background normalisations corrected to account the increase of collision energy from 13 TeV to 14 TeV (scaling the normalisation by 1.18 accounting for the change in gluon-luminosity)
- Experimental systematic uncertainties kept constant with their Run-2 values
- Statistical uncertainties on data-driven backgrounds scaled following Poisson statistics corresponding to the target dataset size
- MC statistical uncertainties neglected

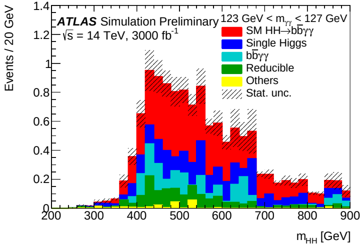
ATL-PHYS-PUB-2018-053, arXiv 1902.00134



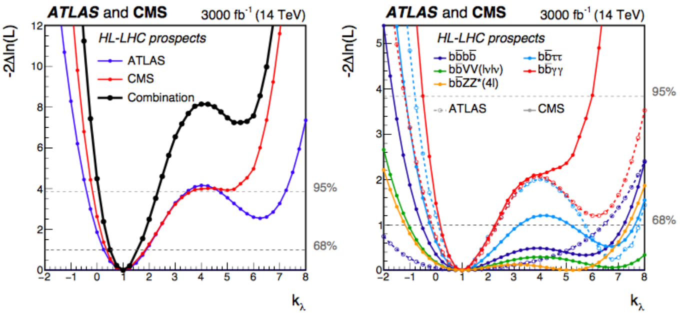
$b\bar{b}\gamma\gamma$ dedicated new analysis using simulations at 14 TeV:

- Truth-level simulations with smearing applied to emulate the upgraded ATLAS detector response
- Systematic uncertainties kept constant with their Run-2 values
- Signal region defined applying a cut on the output of a BDT and $123 < m_{\gamma\gamma} < 127$ GeV
- Final disciminant: m_{HH} distribution

ATL-PHYS-PUB-2018-053, arXiv 1902.00134



arXiv 1902.00134

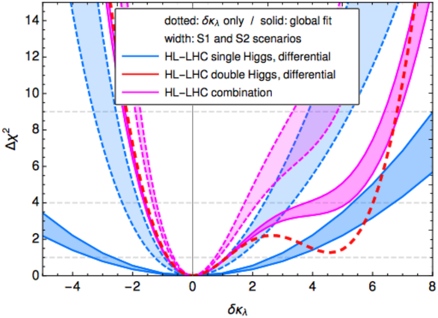


	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6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

- Expected 4σ for $\kappa_\lambda = 1$
- Expected allowed $0.1 < \kappa_\lambda < 2.3$ at 95% C.L.

Prospects measurements at the HL-LHC: double-Higgs ans single-Higgs combination

arXiv 1902.00134



- κ_λ-only fit and global fit possible in single-Higgs
- Double-Higgs is driving the bound, but single-Higgs data allow to perform a global fit and to remove the degenerate minima around $\kappa_\lambda = 5$