MEASUREMENTS OF THE HIGGS BOSON PROPERTIES AT THE ATLAS EXPERIMENT

DISCRETE 2018, 6TH SYMPOSIUM ON PROSPECTS IN THE PHYSICS OF DISCRETE SYMMETRIES

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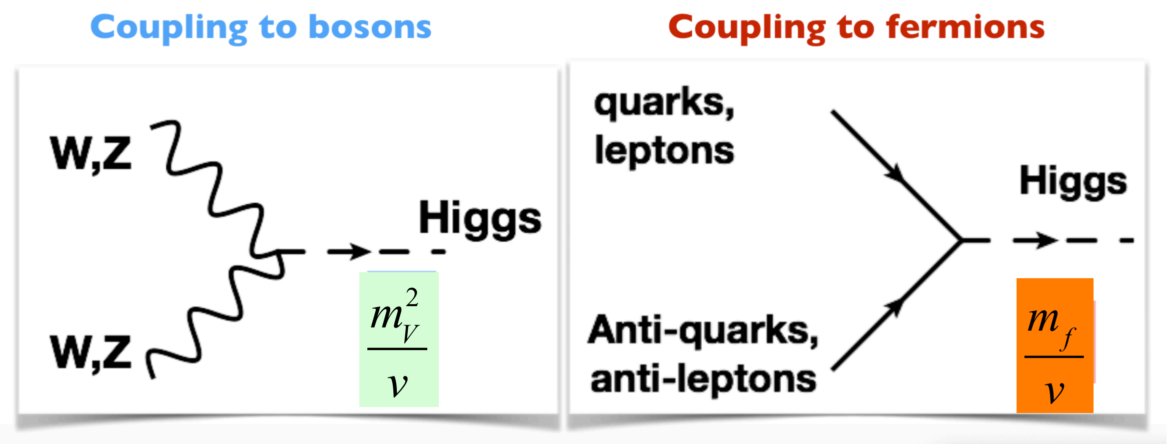
On the behalf of the ATLAS Collaboration

The Higgs boson in the Standard Model

- The Higgs boson discovery in 2012 opened the way to the exploration of the SM sector responsible for EW symmetry breaking
- By interacting with all the SM bosons and fermions, the Higgs field gives them mass

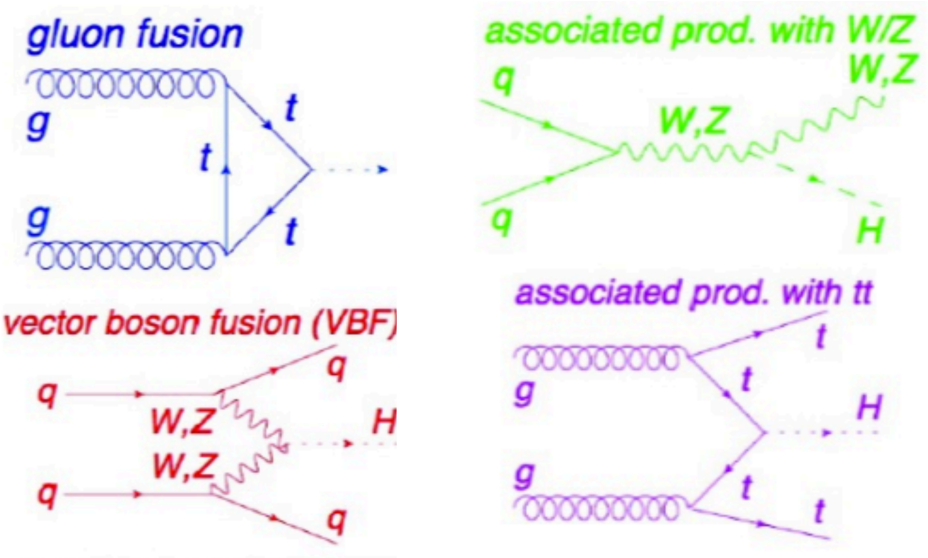


- Property measurements are vital to test theoretical models
  - Mass and width
  - Production and differential cross sections, decay and coupling
  - Di-Higgs production and Higgs self-coupling

- In this talk I will present the measurements of the Higgs boson properties from recent ATLAS Run2 data analyses

Higgs Boson Production and Decay @ LHC

Production:



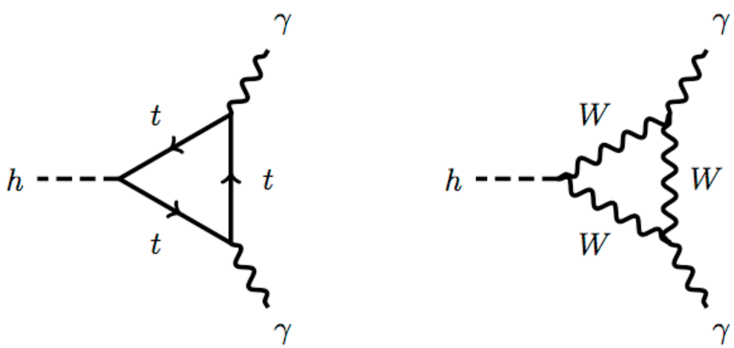
Process	cross-section $\sqrt{s}$=13 TeV m_H=125 GeV (pb)	Accuracy
ggF	48.6	N3LO QCD + NLO EW
VBF	3.78	NNLO QCD and NLO EW
WH	1.37	NNLO QCD and NLO EW
ZH	0.88	NNLO QCD and NLO EW
ttH	0.51	NLO QCD + NLO EW

Decay:

Decay BR for

m_H = 125 GeV

- H→bb: 58 %
- H→WW*: 21%
- H→$\tau^+\tau^-$: 6.3%
- H→ZZ*: 2.6%
- H→γγ: 0.2%

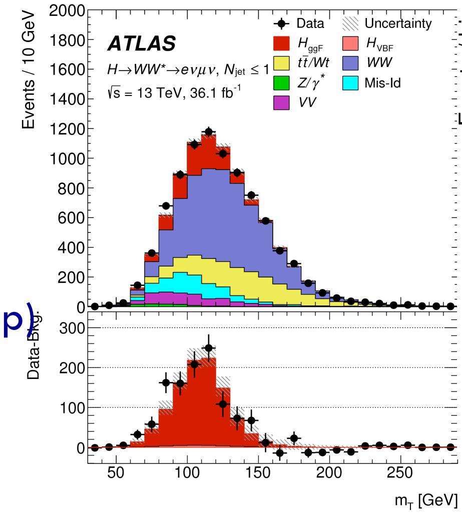


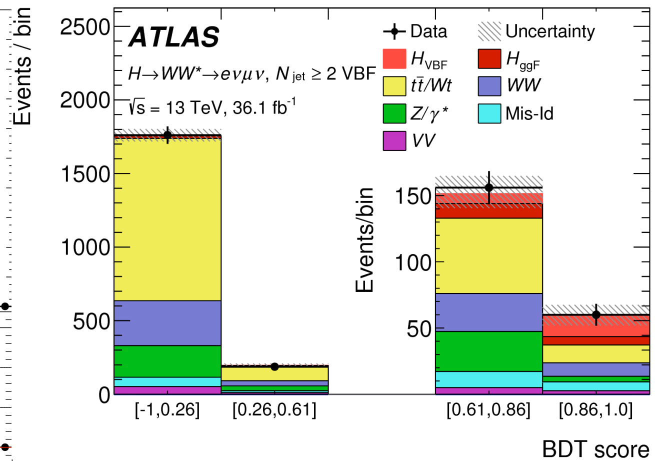
Bosonic Decay : H→WW [arXiv:1808.09054]

Run2 analysis based on 36/fb

- Already observed with Run1 data
- Events classified into 3 categories

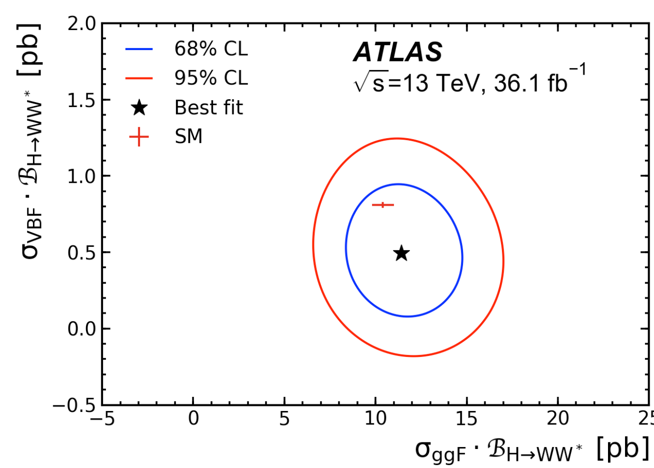
  based on the number of jets :
  - (0,1) jet: target ggF, main bkg (WW, top)
  - 2 jets : target VBF, main bkg top





- non-resonant WW, top and Z→ττ normalised to data via CRs , mis-identified leptons (~10% of total bkg) data-driven
- Several SR defined for the ggF category, 4 BDT bin

  for the VBF category
  - Enhance sensitivity, different bkg composition

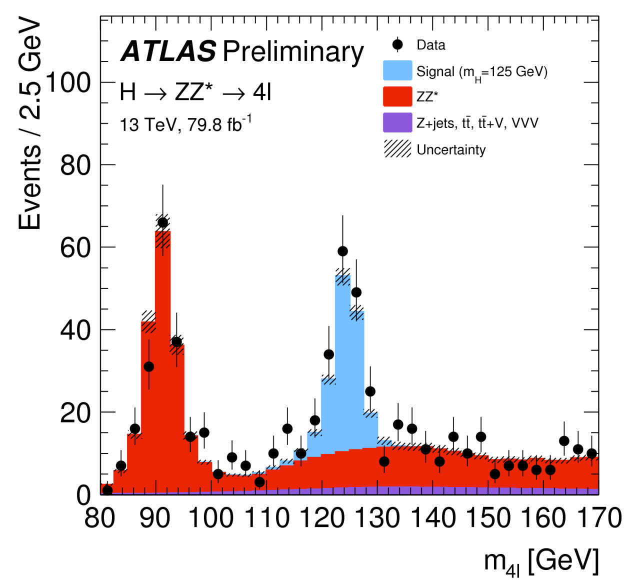


$$\mu_{\mathrm{ggF}} = 1.10^{+0.10}_{-0.09}(\mathrm{stat.})^{+0.13}_{-0.11}(\mathrm{theo\ syst.})^{+0.14}_{-0.13}(\mathrm{exp\ syst.}) = 1.10^{+0.21}_{-0.20}$$

$$\mu_{\mathrm{VBF}} = 0.62^{+0.29}_{-0.27}(\mathrm{stat.})^{+0.12}_{-0.13}(\mathrm{theo\ syst.}) \pm 0.15(\mathrm{exp\ syst.}) = 0.62^{+0.36}_{-0.35}.$$

Bosonic Decays : H→ZZ→4l [ATLAS-CONF-2018-018]

Run2 analysis based on 79.8/fb

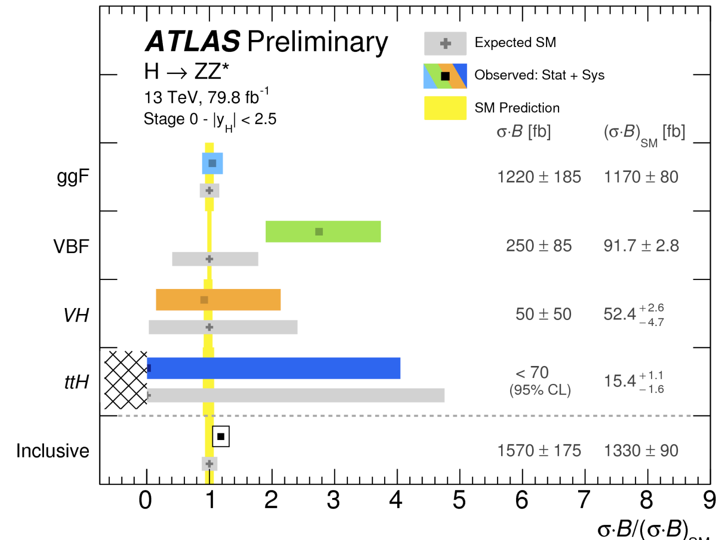


- Clean signature and excellent invariant mass resolution
- Main bkg SM qq(gg)→ZZ estimated from simulation and validated in side-bands
  - Mis-identified lepton bkg mainly from data
- Templates for the signal and the background are fit to the m4l distribution in each category
- Fiducial cross sections, corrected for detector effect, minimal model dependence

$$\sigma_{\text{fid}} = 4.04 \pm 0.41(\text{stat.}) \pm 0.22(\text{syst.})\ \text{fb}$$

σ^{SM}=3.35±0.15 fb

- Production cross-sections, their decomposition into exclusive phase-space domains (Stage-1 STXS)



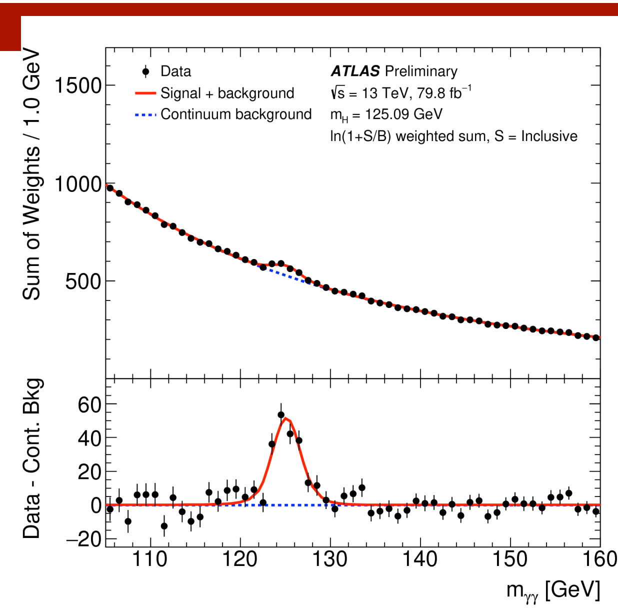
Bosonic Decay : H→γγ [ATLAS-CONF-2018-028]

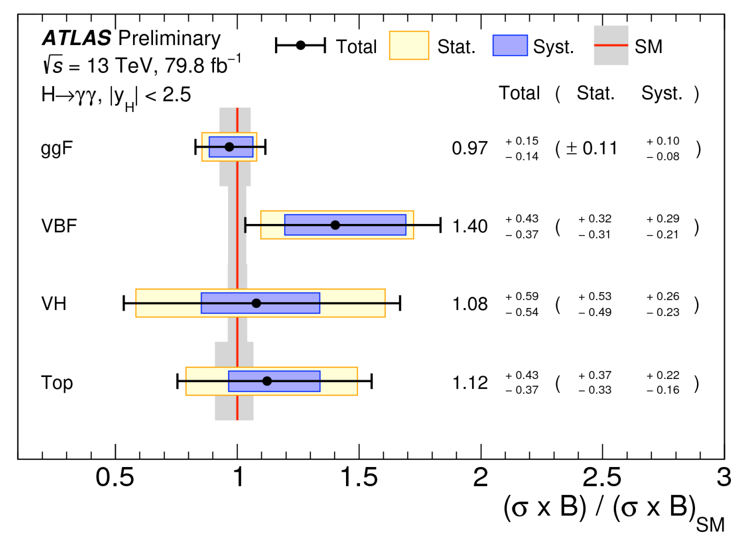
- Fit $m_{\gamma\gamma}$ distribution as superposition of signal + background to extract signal inclusively and each production mode-enhanced region or differential cross section bin

- Analysis based on 79.8/fb

$$\sigma_{\rm fid} = 60.4 \pm 6.1\,(\text{stat.}) \pm 6.0\,(\text{exp.}) \pm 0.3\,(\text{theo.})\ \text{fb},$$

SM prediction of 63.5 ± 3.3 fb





Fiducial Differential cross sections

- Differential cross sections measurement probe the kinematic properties of the Higgs boson, which may be sensitive to new physics.
- $H \rightarrow \gamma\gamma$ [ATLAS_CONF_2018_028]

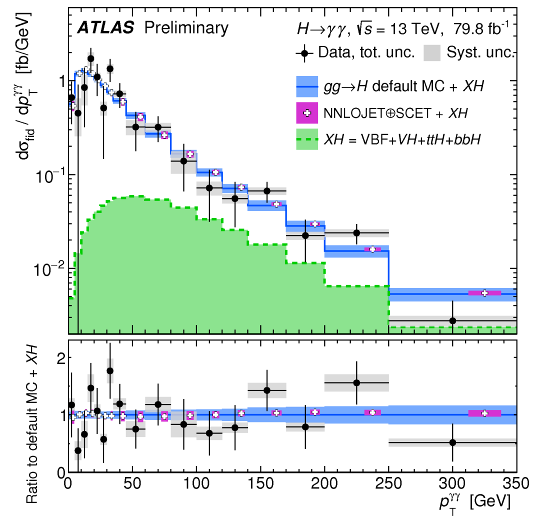
  and

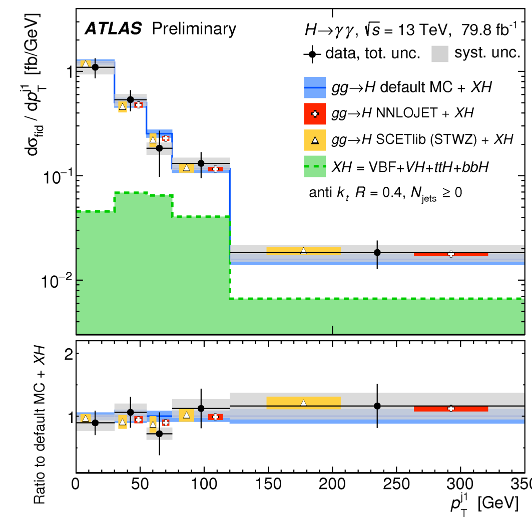
  $H \rightarrow ZZ^* \rightarrow 4l$

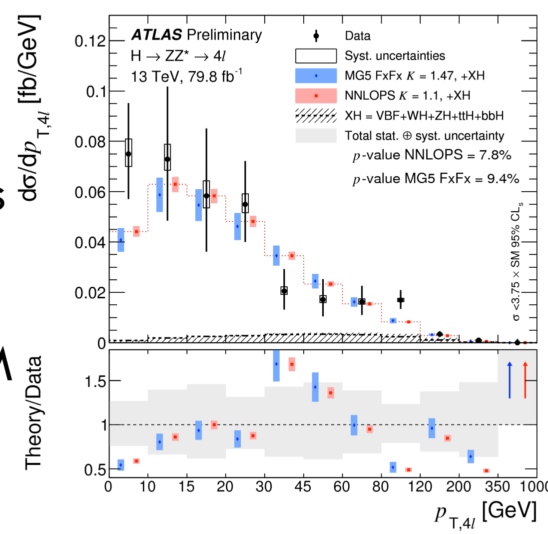
  [ATLAS_CONF_2018_018]

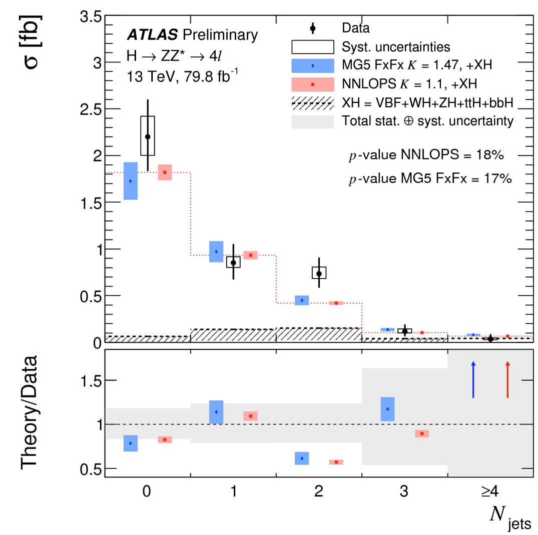
  results based on 79.8/fb

- Various differential measurements and unprecedented precision reached
- Results are all compatible with SM prediction.





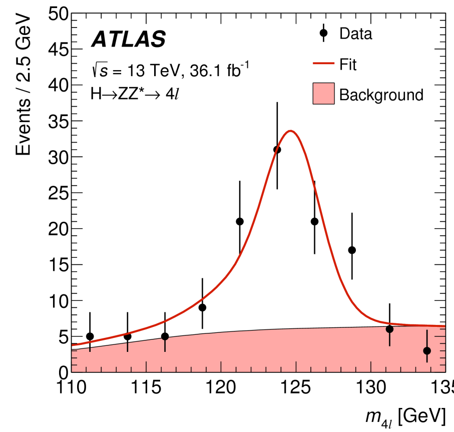


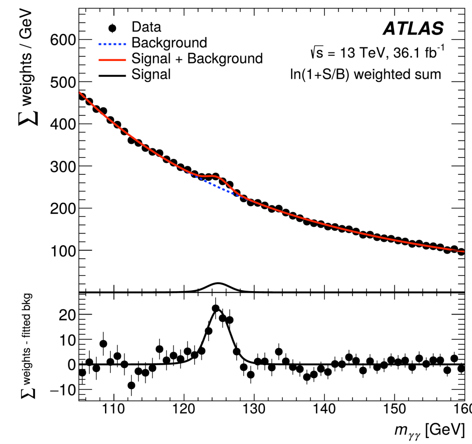


Mass Measurement [Phys. Lett. B 784 (2018) 345]

- Mass measurement done with $H \rightarrow ZZ^{*} \rightarrow 4l$ ($l=e,\mu$) and $H \rightarrow \gamma\gamma$ channels with 36/fb

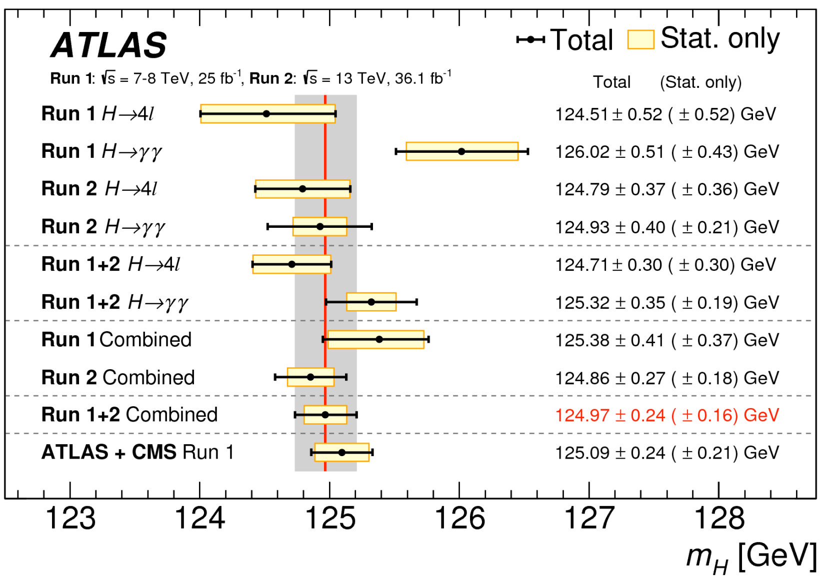
- detailed performance studies to achieve the optimal calibration of photon/lepton





- $H \rightarrow 4l$: Z mass kinematic fit and event by event detector response modeling in 4 BDT bins. Statistically limited

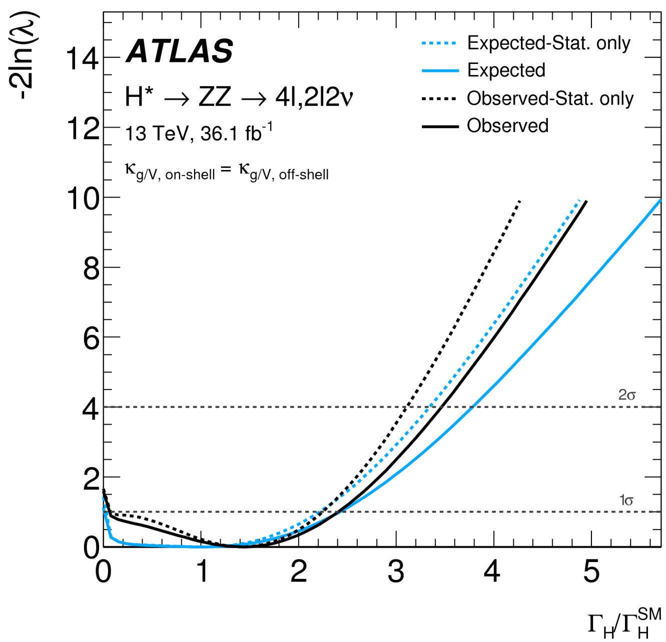
- $H \rightarrow \gamma\gamma$: fit to $m_{\gamma\gamma}$ distribution modelled with a double-sided Crystal-ball for 31 categories with different resolutions and S/B. Main systematic uncertainty from photon energy scale



ATLAS Run2 measurement in agreement and with a similar precision to the ATLAS+CMS Run1 combination

Width Measurement [Phys. Lett. B 786 (2018) 223]

- It is impossible to directly measure Higgs boson width (~4.1 MeV predicted in SM)
- Indirect limit can be set from measuring the on- and off-shell signal strength (assuming the same on-shell and off-shell couplings)
- ATLAS Run2 measurement with 36/fb based on $H \rightarrow ZZ^* \rightarrow 4l$ and $2l2\nu$ final states



$$\mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}}$$

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

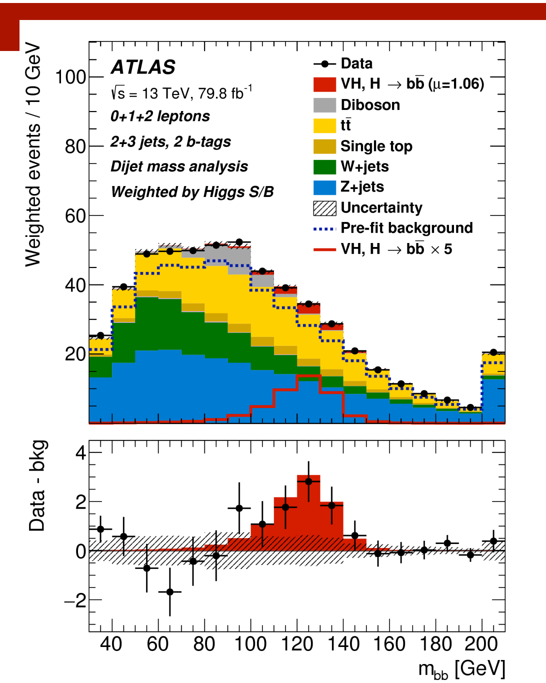
Γ_H <14.4 MeV @ 95% CL (15.2 MeV exp.)

factor ~2 better then Run1 measurement

Fermionic Decay : H→bb [PLB786 (2018) 59]

Run2 analysis based on 79.8/fb

- *H*→*bb* takes the largest BR~58% → drives the size of the total decay width → measurements of absolute couplings and constrain on BSM BR allowed



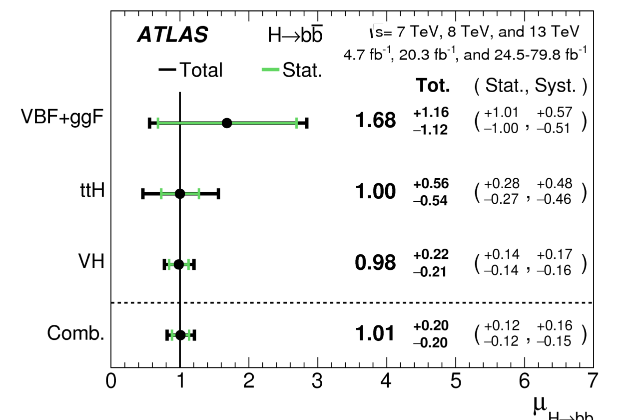
- The most sensitive ***VH, H→bb*** analysis, has 3 channels 0-, 1-, 2 charged leptons → final states Z→νν, W→*l*ν and Z→*ll*
  - MVA to improve S/B
  - Control regions to derive bkg normalizations. Shapes from MC.
  - Analysis dominated by systematic uncertainties (main signal modeling)

Observation of H→bb decay (Run1+Run2)

H→bb comb σ_{obs}=5.4 (exp 5.5)

Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \to b\bar{b}$ combination	5.5	5.4

assuming the production cross sections



Run-1 *VH*(*bb*) ATLAS+CMS combined significance **2.6 σ (3.7 σ exp.)**

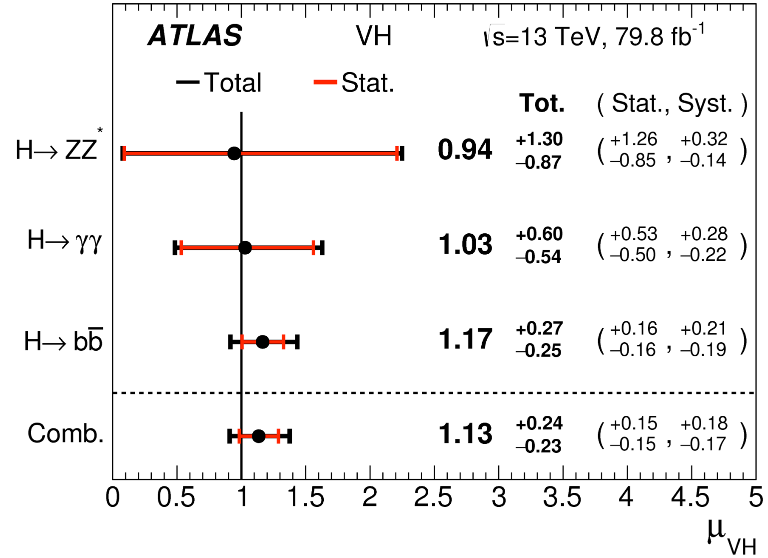
Observation of VH production

[PLB786 (2018) 59]

Run2 analysis based on 79.8/fb

- ~ 3% of the total Higgs boson production @ LHC
- Driving channel H→bb, only leptonic V decays
- H→ZZ and H→γγ also have regions for hadronic categories
- Assume SM Higgs boson branching fractions
- **VH comb σ_{obs}=5.3 (exp 4.8)**

Channel	Significance	
	Exp.	Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3



Fermionic Decay : H→ττ

[ATLAS-CONF-2018-021]

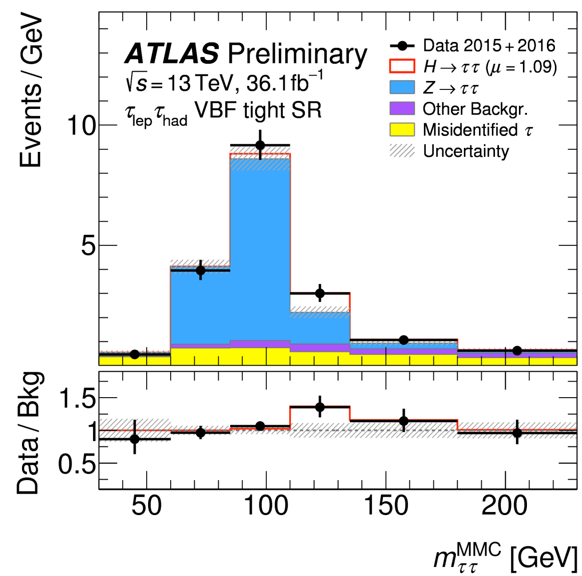
Run2 analysis based on 36.1/fb

- 3 channels targeting all possible decay modes:

  two reconstructed taus in *ll*, *l*h and *hh* decay modes
- Many categories to target VBF and ggF in the boosted regime
- 6 CRs to normalize bkg (Z→ll, top),

  mis-identified leptons and τ_{had} data driven,

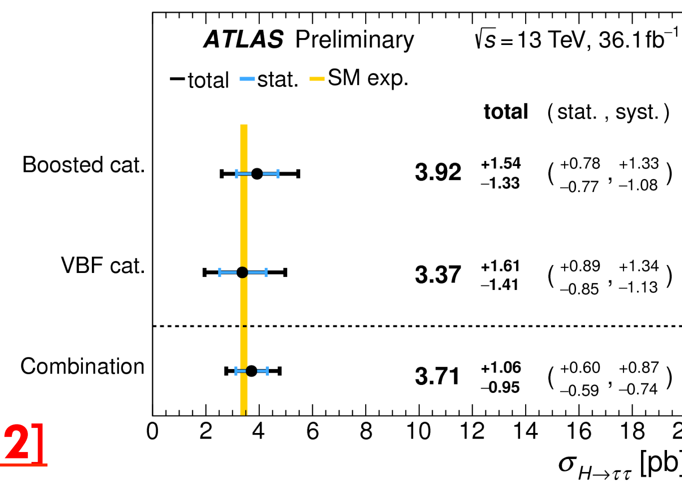
  Z→ττ validation region



- Main discriminant variable: $m_{\tau\tau}$, crucial to

  discriminate and constrain (normalize) the large

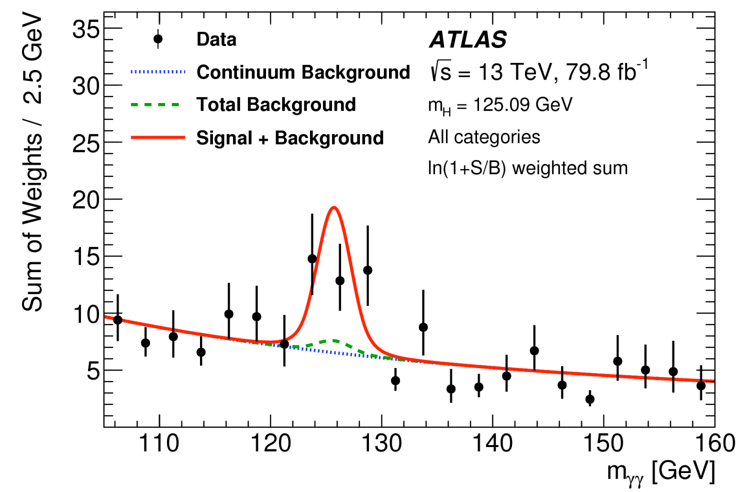
  $Z \rightarrow \tau\tau$ bkg
  - $Z \rightarrow \tau\tau$ shapes from (corrected) simulation



- **observation with of 6.4 σ (exp 5.4 σ) [Run1+Run2]**

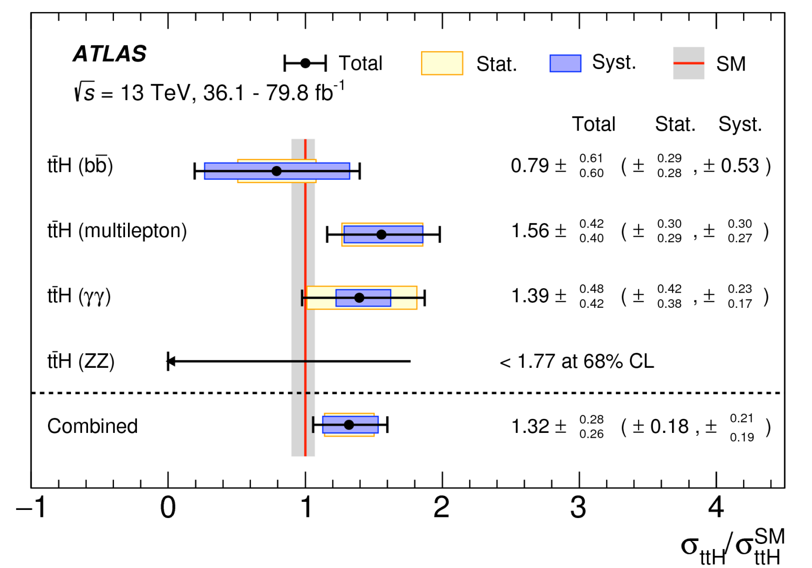
ttH Production [Phys. Lett. B 784 (2018) 173]

- ttH production: direct Higgs coupling to top quark, largest Yukawa coupling
- Run2 analysis combines different decay channels
- **Observation of ttH production: combined Run1+Run2 observed significance is 6.3σ (exp 5.1σ)**
- Dominant contribution to systematics are tt+HF uncertainties in H→bb and ttH uncertainties



$$\sigma^{obs} = 670 \pm 90(stat.)^{+110}_{-100}(syst.)\, fb\ @\sqrt{s} = 13\ TeV$$

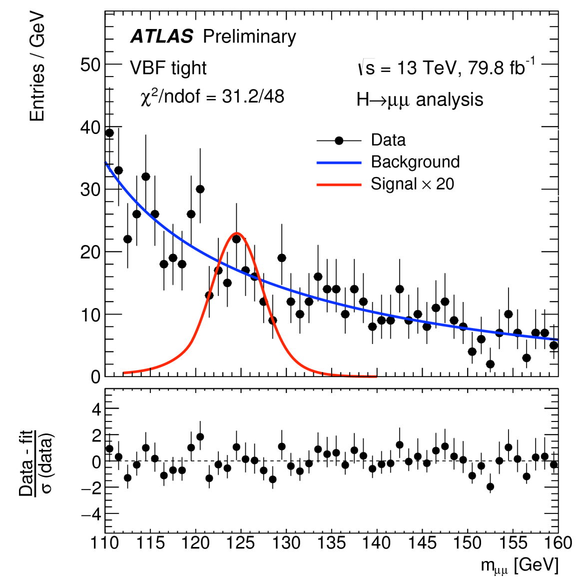
$$\sigma^{\exp} = 507^{+35}_{-50}\, fb$$



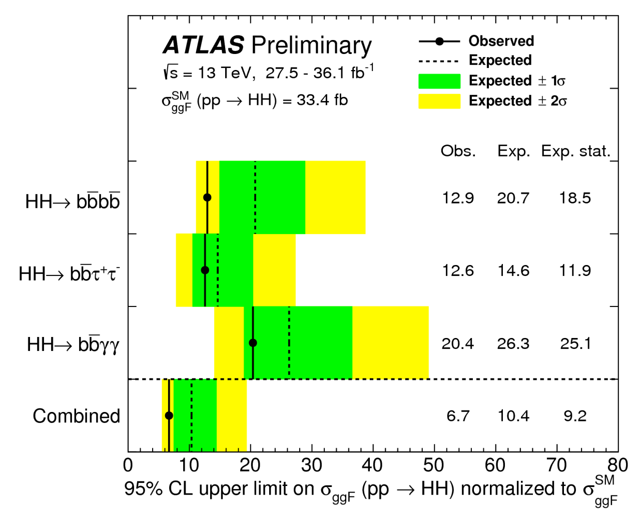
Run-1 ATLAS+CMS combined obs. significance 4.4 σ (2.0 σ exp.)

Other searches

- 2^{nd} generation fermions:
  - H→cc [Phys. Rev. Lett. 120 (2018) 211802]
    - Run2 analisys on 36/fb
    - Observed upper limit
      $\sigma(pp\rightarrow ZH)\times BR(H\rightarrow cc) < 2.7$pb at 95% CL
      (σ_{SM} = 26 fb)
    - μ < 110 w.r.t. SM exp.
  - H→μμ [ATLAS-CONF-2018-026]
    - Run 2 analysis (80/fb) getting close to SM sensitivity
    - μ < 2.1 obs. at 95% CL (2.0 exp.)
    - Signal strength measurement $\mu = 0.1^{+1.0}_{-1.1}$



- Di-Higgs Production [ATLAS_CONF_2018_043]
  - Limit from ATLAS HH combination: μ <6.7 (10.4 exp.) at 95% CL
  - Long term goal is to reach SM sensitivity in HL-LHC era

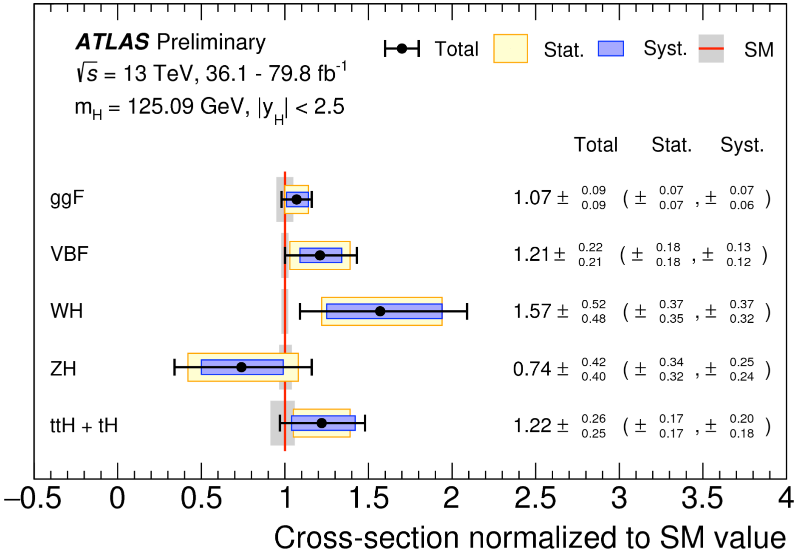


Combined Results [ATLAS-CONF-2018-031]

- Combined measurements of Higgs production cross sections and couplings with datasets up to ~80/fb

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	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, $H \to b\bar{b}$	36.1
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1

- Production cross-sections for ggF, VBF, WH, ZH and ttH measured with the assumption of SM branching fractions
- **All main production modes have been observed !**
  - **first single experiment observation of VBF production with a observed significance of 6.5 σ (exp 5.3σ)**



Global signal strength:

Uncertainties dominated by signal modelling (QCD and PDF uncertainty on ggF inclusive cross section)

$$\mu = \frac{(\sigma \times \mathrm{B})_{if}}{(\sigma \times \mathrm{B})_{if}^{\mathrm{SM}}},$$

$$\mu = 1.13^{+0.09}_{-0.08} = 1.13 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$$

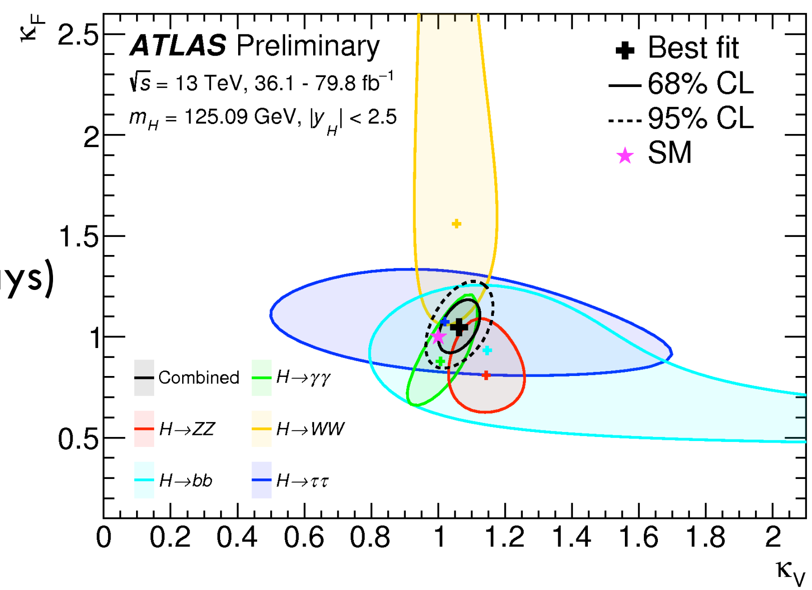
Combined Results in the κ Framework

[ATLAS-CONF-2018-031]

- κ_X effective modifiers applied to the tree-level couplings between the Higgs boson and other SM particles. The modifiers κ^2_i and κ^2_f applied to the production cross-sections and partial widths, can be expressed in terms of κ_X.

$$(\sigma \times \mathrm{B})_{if} = \kappa_i^2 \sigma_i^{\mathrm{SM}} \frac{\kappa_f^2 \Gamma_f^{\mathrm{SM}}}{\kappa_H^2 \Gamma_H^{\mathrm{SM}}},$$

- Assuming common coupling modifiers for fermions (κ_f) and vector bosons (κ_V)
  - κ_g (ggH), κ_γ ($H\gamma\gamma$) and κ_H expressed in terms of κ_f and κ_V, assuming $B_{BSM} = 0$ (invisible/undetectable decays)

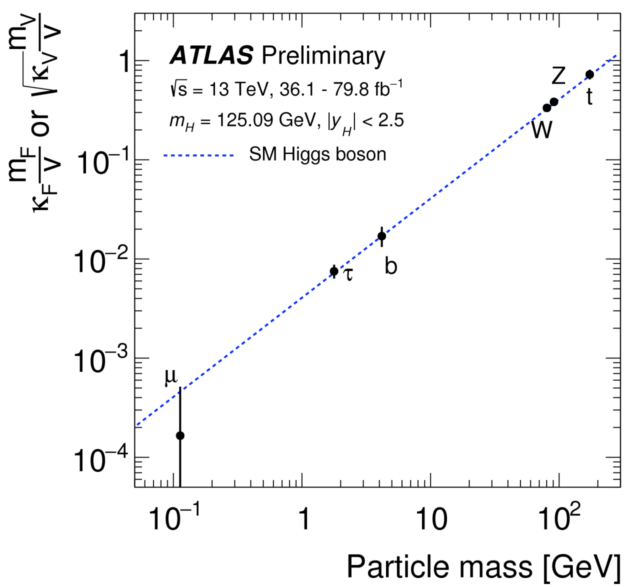


- Compatibility with SM predictions

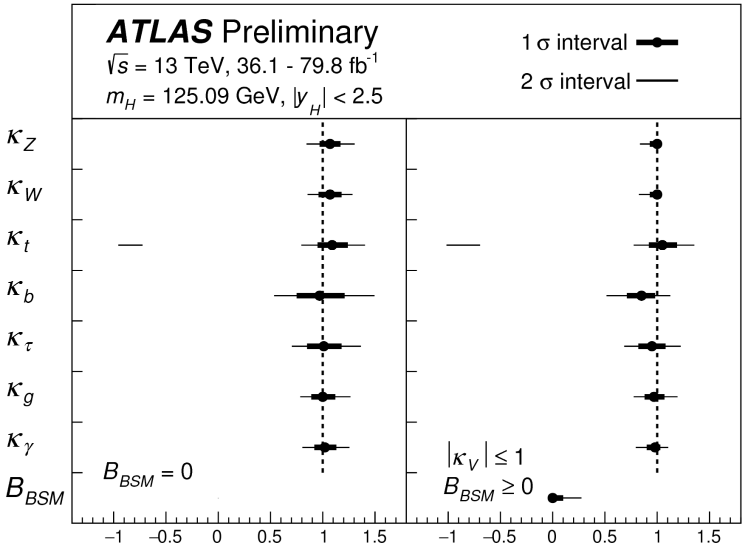
Combined Results in the κ Framework

[ATLAS-CONF-2018-031]

- Separate modifiers for couplings to vector bosons (κ_W, κ_Z) and for κ_b, κ_t, κ_τ and κ_μ - all the other modifiers set to SM value, assuming B_{BSM} =0
- Excellent agreement with the SM prediction over a range of 3 orders of magnitude in mass, from the muon to top



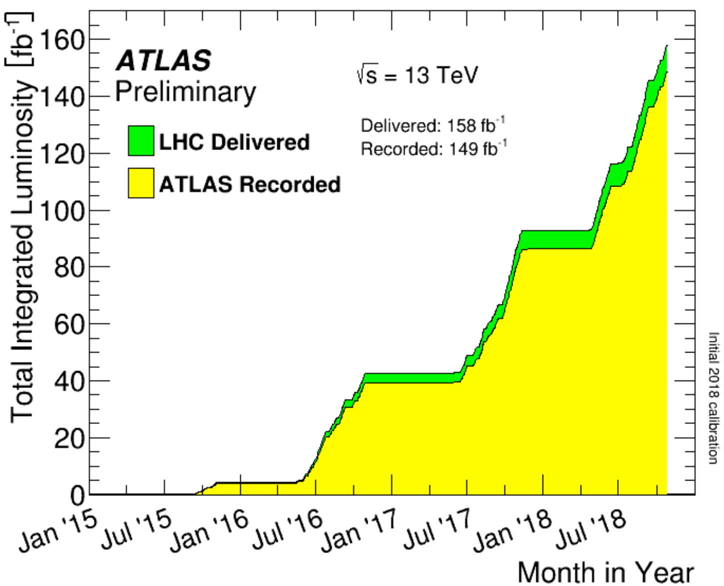
- probe for invisible/undetectable decays with possibility of new particles in $gg \to H$ production and $H \to \gamma\gamma$ decay i.e. κ_g and κ_γ modifiers left free in the fit
- two different assumptions on the Higgs total width (B_{BSM} = 0 and $B_{BSM} \geq 0$ and left free, $\kappa_{Z,W}$<1)
- Result : B_{BSM} < 0.26 at 95% CL



Conclusions

- Many impressive Higgs results come from the LHC Run 2 data (36/fb – 80/fb)
  - All main production/decay modes have been observed.
  - Higgs coupling to 3rd generation fermions are confirmed
  - The mass, width, couplings and differential cross section measurements reach unprecedented precision
  - No deviation from SM captured so far

- Waiting for the full Run-2 dataset and the HL-LHC (3000/fb) to reach a higher sensitivity to potential new physics



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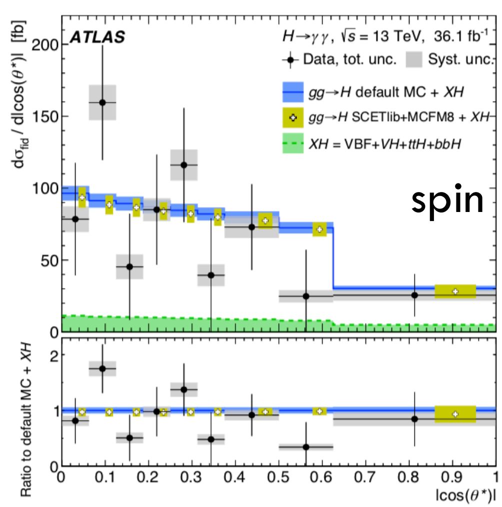
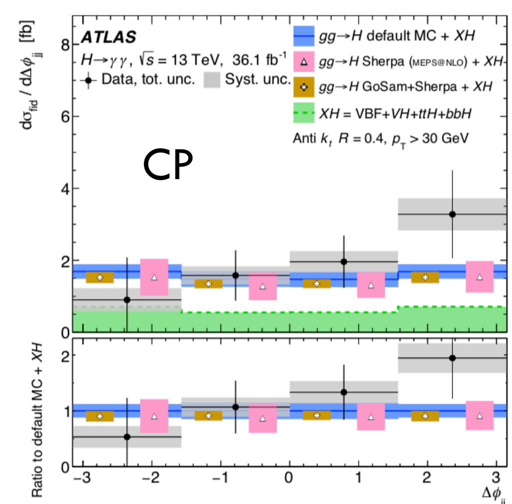
Higgs Spin/CP

Run-I: Eur. Phys. J. C75 (2015) 476
Run-2: arXiv:1802.04146, JHEP03(2018)095

- Spin and Parity of the Higgs boson measured in WW*/ZZ* final states using Run-I 7 TeV and 8 TeV data (~25/ fb). SM Higgs boson hypothesis, $J^P = 0^+$, tested against alternative spin scenarios, which were excluded at 99.9% CL

- In Run2 Higgs boson spin-CP tested, e.g. in $\gamma\gamma$ decays, with angle distributions of photons and jets sensitive to these properties
  - For a scalar particle $|\cos\theta^*|$ shows a strong drop around 0.6





Bosonic Decay : H→WW [arXiv:1808.09054]

Systematic uncertaities

Source	$\Delta\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\to WW^*}$ [%]	$\Delta\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\to WW^*}$ [%]
Data statistics	8	46
CR statistics	8	9
MC statistics	5	23
Theoretical uncertainties	8	21
ggF signal	5	15
VBF signal	<1	5
WW	5	12
Top-quark	4	4
Experimental uncertainties	9	8
b-tagging	5	6
Modelling of pile-up	5	2
Jet	3	4
Electron	3	<1
Misidentified leptons	5	9
Luminosity	2	3
TOTAL	17	59

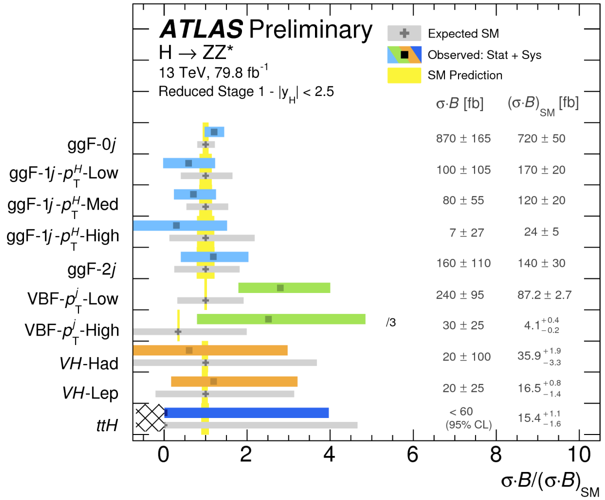
Bosonic Decay : H→γγ [ATLAS-CONF-2018-028]

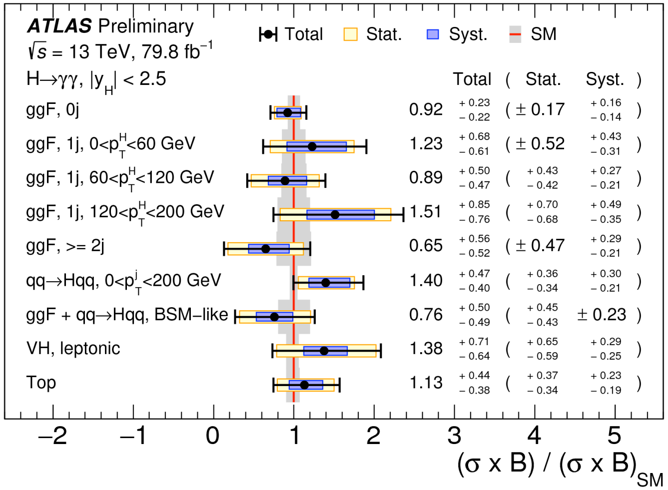
The breakdown of uncertainties on the inclusive diphoton fiducial cross section measurement.

Source	Uncertainty (%)
Fit (stat.)	10
Fit (syst.)	8.3
Photon energy scale & resolution	4.0
Background modeling (spurious signal)	7.3
Correction factor	5.2
Photon isolation efficiency	4.6
Pileup	1.9
Photon ID efficiency	1.3
Trigger efficiency	0.7
Dalitz Decays	0.4
Theoretical modeling	$^{+0.3}_{-0.4}$
Diphoton vertex selection	0.1
Photon energy scale & resolution	0.1
Luminosity	2.0
Total	14

H→4l [ATLAS-CONF-2018-018] and H→γγ [ATLAS-CONF-2018-028] Stage1 STXS

- Cross sections measured in exclusive regions of phase spaces ("truth bins"), specific to different production modes
- designed to
  - minimize the dependence on models and theoretical uncertainties folded into the measurements
    - acceptance better defined and less model-dependent
    - separate processes with higher/lower theory uncertainties
  - maximize experimental sensitivity
  - can be combined easily with other decay channel





Fermionic Decay : H→bb [PLB786 (2018) 59]

Breakdown of the contributions to the uncertainty in μ.

the systematic uncertainties due to the modelling of the signal play a dominant role, followed by the uncertainty due to the limited size of the simulated samples, the modelling of the bkgs and the *b*-tagging uncertainty.

The dominant experimental uncertainties originate from the *b*-tagging correction factors, determined from the difference between the efficiency measured in data and simulation, from the jet energy scale corrections and from the modelling of the jet energy resolution.

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	*b*-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Acceptance from scale variations	2.5 – 8.8%
Acceptance from PS/UE variations for 2 or more jets	2.9 – 6.2% (depending on lepton channel)
Acceptance from PS/UE variations for 3 jets	1.8 – 11%
Acceptance from PDF+α_S variations	0.5 – 1.3%
m_{bb}, p_T^V, from scale variations	S
m_{bb}, p_T^V, from PS/UE variations	S
m_{bb}, p_T^V, from PDF+α_S variations	S
p_T^V from NLO EW correction	S

Fermionic Decay : H→ττ

[ATLAS-CONF-2018-021]

Summary of different sources of uncertainty in decreasing order of their impact on $\sigma_{H\rightarrow\tau\tau}$.

Experimental uncertainties in reconstructed objects combine efficiency and energy/ momentum scale and resolution uncertainties.

Background statistics includes the bin-by-bin statistical uncertainties of the simulated backgrounds as well as misidentified τ backgrounds which are estimated using data.

Background normalization describes the combined impact of all background normalization uncertainties.

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\rightarrow\tau\tau}$ (%) Observed	Expected
Theoretical uncert. on signal	+13.5 / −8.7	+11.9 / −7.7
Background statistics	+11 / −10	+10.2 / −9.8
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	+11.5 / −9.3	+10.5 / −8.6
Background normalization	+6.8 / −4.8	+6.6 / −4.6
Misidentified τ	+4.5 / −4.2	+3.7 / −3.4
Theoretical uncert. on background	+4.6 / −3.6	+5.1 / −4.2
Hadronic taus	+4.7 / −3.0	+5.8 / −4.2
Flavour tagging	+3.3 / −2.4	+2.9 / −2.2
Luminosity	+3.3 / −2.3	+3.1 / −2.2
Electrons and muons	+1.2 / −1.0	+1.1 / −0.9
Total systematic uncert.	+24 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −26	+27 / −25

Combined Results [ATLAS-CONF-2018-031]

Summary of the relative uncertainties $\Delta\mu/\mu$ affecting the measurement of the combined global signal strength μ.

Only sources of systematic uncertainty associated with relative uncertainties of 0.1% or more are listed.

"MC stat." refers to uncertainties due to limited numbers of simulated events.

Uncertainty source	$\frac{\Delta\mu}{\mu}$ [%]
Statistical uncertainties	4.5
Systematic uncertainties (excl. MC stat.)	6.1
Theory uncertainties	4.8
Signal	4.3
Background	2.3
Experimental uncertainties	4.0
Luminosity	2.1
Fake leptons	1.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.3
Flavour tagging	0.9
Background modeling	1.2
Electrons, photons	2.2
Muons	0.3
τ-lepton	0.4
Other	1.5
MC stat. uncertainties	1.5