Measurements of the Higgs boson properties at the ATLAS experiment

with 80 fb^{-1} 13 TeV dataset

Paul Glaysher (DESY), on behalf of the ATLAS collaboration

28 Aug 2018

QCD@LHC Dresden 2018

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

ATLAS EXPERIMENT

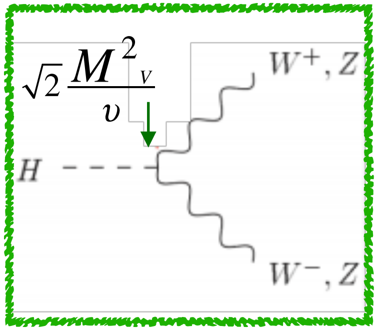
DESY.

Higgs boson in the Standard Model

- ➡ The Higgs discovery in 2012 allows for the exploration of a new sector of the SM Lagrangian
- ➡ Two types of tree-level coupling to other SM particles determine Higgs boson production and decay modes

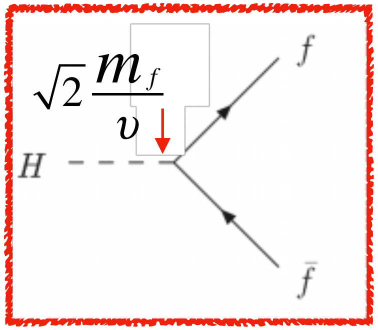
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + |D_\mu\phi|^2 - V(\phi) + \bar{\psi}_i y_{ij}\psi_j\phi + h.c.$$

coupling to Bosons



Two type of tree-level coupling

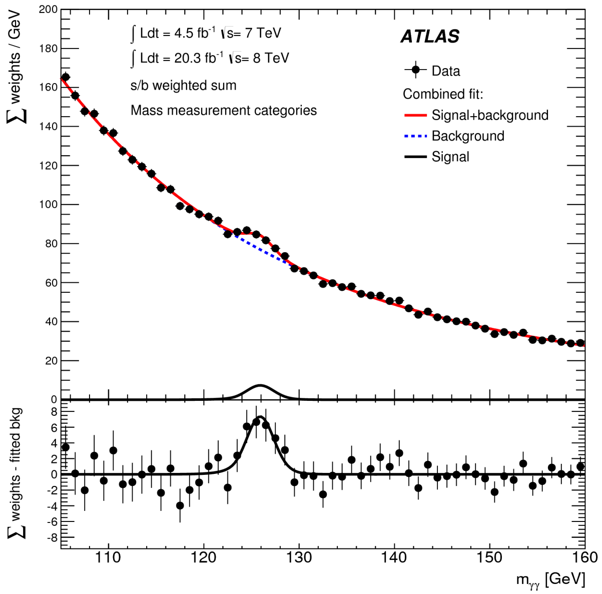
coupling to Fermions

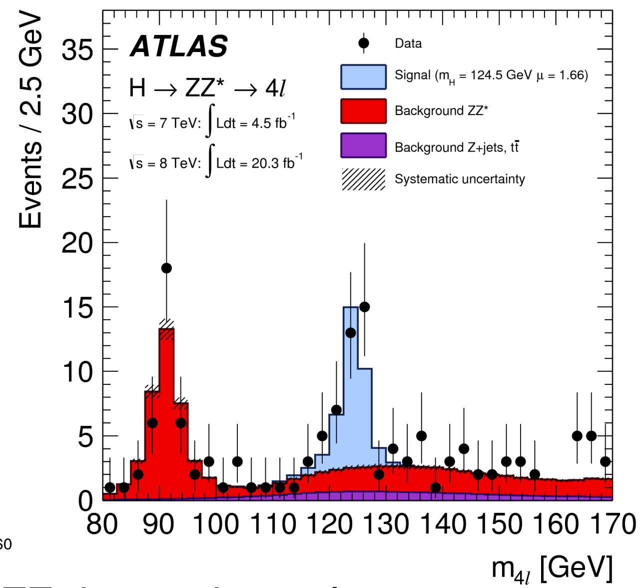


LHC Run 1 legacy

> The LHC Run 1 dataset (2011-2012), with 7/8 TeV proton-proton collisions already established the presence of a SM-like Higgs boson with mass of 125 GeV

> Higgs boson mass: fixed free parameter in SM predictions





High mass resolution in γγ, ZZ decay channels
Width measurement is limited by detector resolution.

Run 1 signal significance by decay mode [JHEP08(2016)045] :

	ATLAS	CMS
$H \to \gamma\gamma$	5.0	5.6
	(4.6)	(5.1)
$H \to ZZ$	7.6	7.0
	(5.6)	(6.8)
$H \to WW$	6.8	4.8
	(5.8)	(5.6)
$H \to \tau\tau$	4.4	3.4
	(3.3)	(3.7)
$H \to bb$	1.7	2.0
	(2.7)	(2.5)

- Higgs boson couplings were measured to 10-25% precision.
- Experimental precision of vector boson coupling higher than to fermions.
- Decays with bosonic coupling allow for precision measurements of other properties.
- Fermionic couplings pose larger experimental challenge and not yet fully established.

Higgs boson production at the LHC

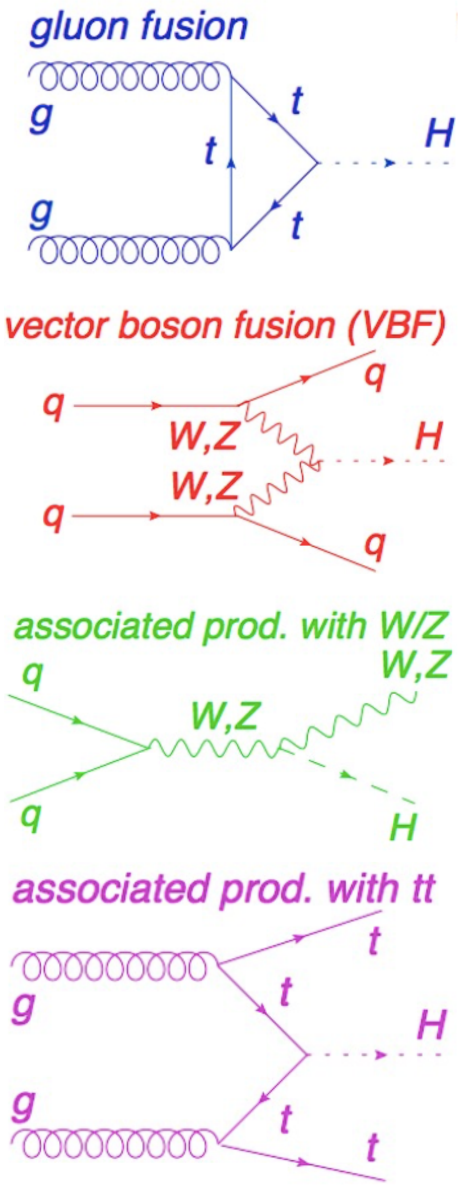
Number of Higgs boson events in Run 2 dataset (2015-2017)

~4M

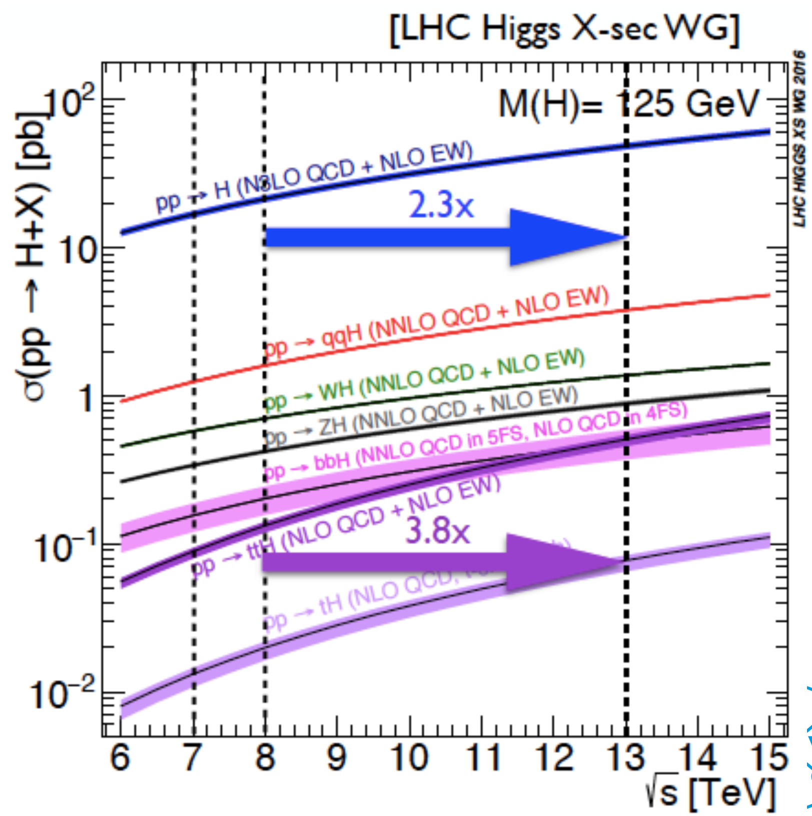
~300K

~200k

~40k

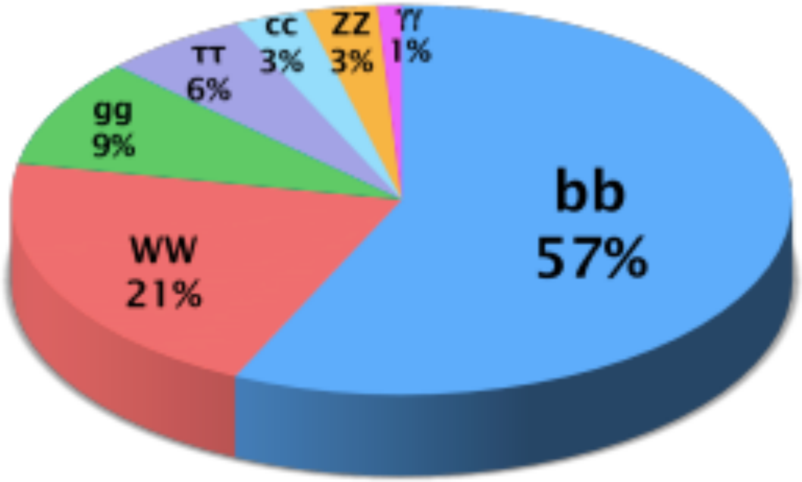


- Increase in production cross section due to higher centre of mass energy in Run 2
- Enhances feasibility of measuring ttH, e.g.



Higgs boson decay modes

- ZZ, γγ: high mass resolution and precise differential measurements
  - Low Branching Ratio (BR)
  - Measurements greatly improved with larger dataset
- WW: High BR, but low mass resolution
- μμ: very small BR, but access to coupling of 2nd generation fermions
- ττ, bb: high BR, but low S/B, important to directly probe Higgs boson coupling to fermions



Overview

Current results of Higgs boson properties with up to 80 fb^{-1} 13 TeV data

- mass, width and differential cross sections in the H->ZZ and H->γγ decay modes

Higgs to fermion coupling:

- Bottom quark: VH, H->bb associated production mode (V=W/Z)
- Top quark: in ttH associated production mode

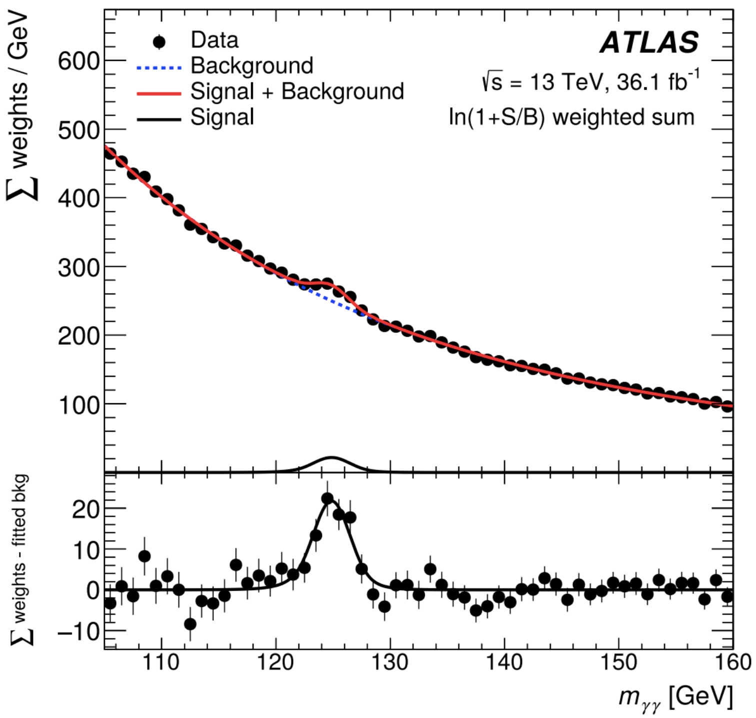
- Combined coupling measurements

Higgs boson mass

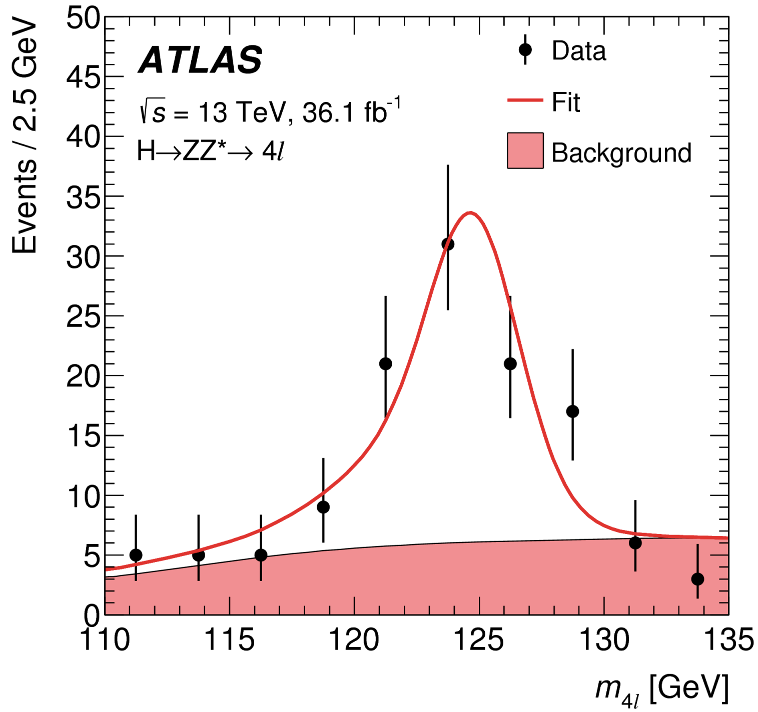
[Phys. Lett. B.2018.07.050]

- Determining the mass is vital to determining other properties of the Higgs boson

$H \rightarrow \gamma\gamma$



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

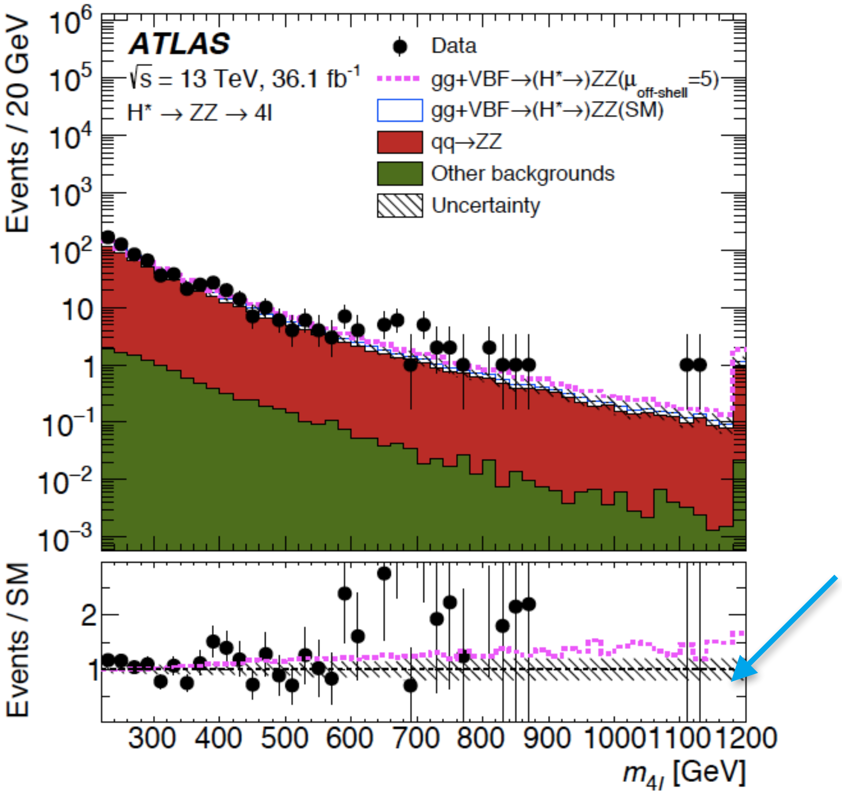


- Measured as best fit value of signal distribution given by parametric function vs data, with free parameter m_H and width=4.1 MeV
- Detector response systematics on signal estimated from MC as a function of m_H
    - m_H = 124.86 ± 0.27 ± (0.18 stat. only) GeV

Higgs boson width

[arXiv:1808.01191]

- The SM prediction of the Higgs boson width is 4 MeV and too small to be measured directly. Instead, cross section ratio of on- to off-shell H->VV is sensitive to width.
- assume effective coupling modifiers **κ** to SM couplings of ggF production and H->ZZ decay process (**κ**$_g$, **κ**$_Z$) and that $\kappa_{off-shell} = \kappa_{on-shell}$



$$\sigma_{off-shell} \propto \kappa^2_{g,off-shell} \cdot \kappa^2_{Z,off-shell}$$

$$\sigma_{on-shell} \propto \frac{\kappa^2_{g,on-shell} \cdot \kappa^2_{Z,on-shell}}{\Gamma_H/\Gamma_H^{SM}}$$

<u>for ggF+VBF:</u>

$$\mu_{off-shell} = \frac{\sigma_{off-shell}}{\sigma_{off-shell,SM}} < 3.8\ (3.4\text{exp.})$$

Obtain a width:

$$\Gamma_H < 14.4\ \text{MeV}\ (15.2\ \text{MeV exp.})$$

Ratio of data and $\mu_{off-shell}$=5 example to SM with $\mu_{on-shell}$=1.

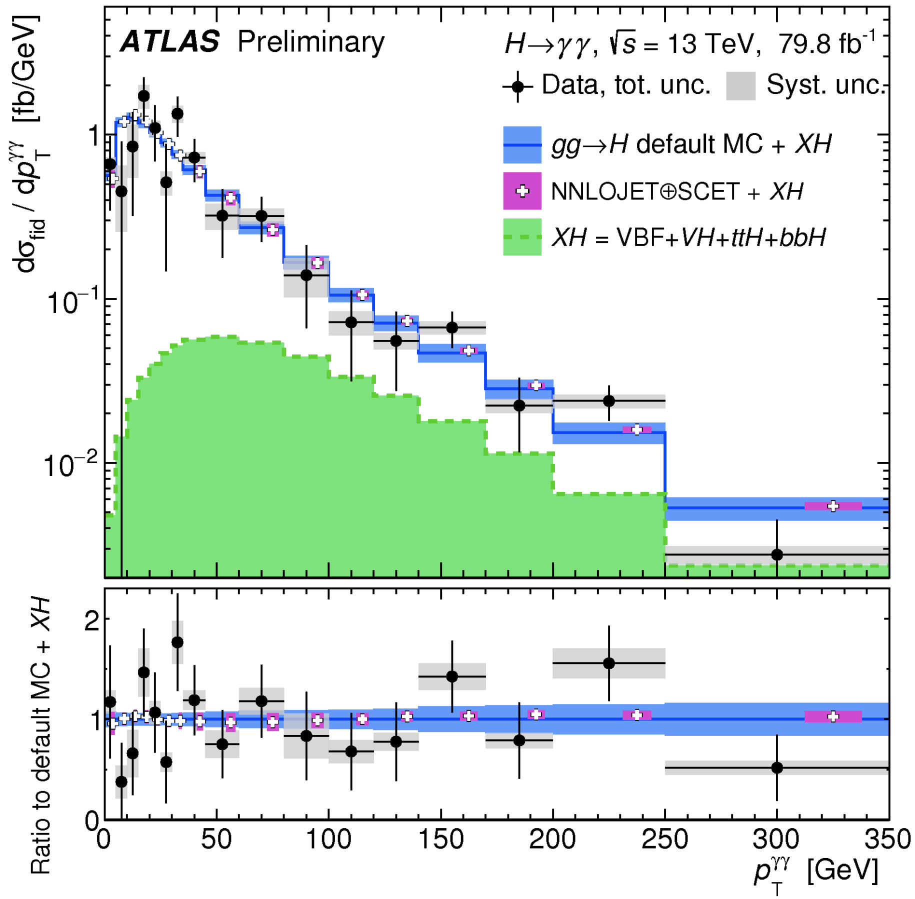
- Sizeable negative interference between off-shell signal and gg->ZZ bkg. taken into account.
- Use m(ZZ) depended NLO k factors.
- Improvement of ~2 over Run 1 results.

Run-2 measurement of off-shell cross-section for H → ZZ* → 4l / 2l 2v

Differential cross sections

[ATLAS-CONF-2018-028]

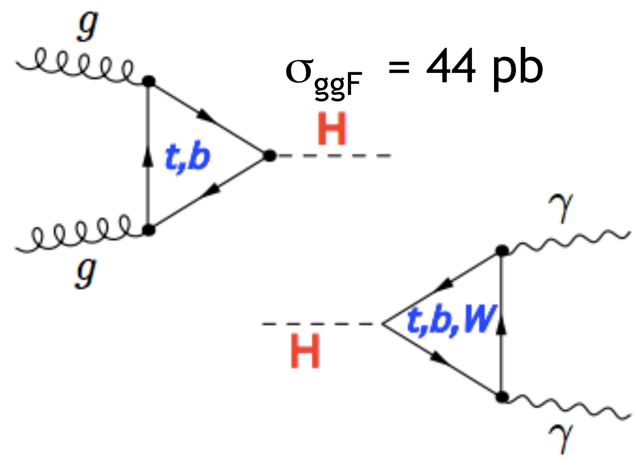
- Precise differential measurement could test the SM and show signs of new physics
- Here Higgs transverse momentum (p_T) in H->γγ channel
- Higgs p_T is a probe of the QCD radiative processes in the initial state
- New particles could contribute to loop production and alter the pt spectrum
- High Higgs p_T tail shows no hint of new physics (yet?)
- In good agreement with predictions



Subtract background and correct for detector effects via unfolding.
Compare data to ggF signal from Powheg NNLOPS or NNLOJET+SCET calculation.

Higgs boson couplings to fermions

- Indirect probes through loops in ggF and H->γγ set limits on fermion coupling
- Direct probes to bottom and top quarks possible in VH, H->bb and ttH measurements



σ_{ggF} = 44 pb

VH production allows to suppress QCD Background by selecting a charged lepton. Largest BR, **H->bb**, only recently observed.

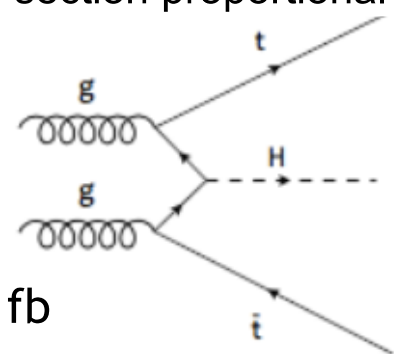
H->bb uncertainty driving factor in Higgs width determination and sensitivity to H->invisible decays

Yukawa coupling λ_t is proportional to the mass of the fermion ,Top quark is the heaviest particle in the SM

$$\lambda_t = \sqrt{2}\frac{m_t}{v} \approx \sqrt{2}\frac{173\text{ GeV}}{246\text{ GeV}} \approx 0.99 \approx 1.$$

➡ **ttH** production gives a direct way to probe the top quark Yukawa coupling

➡ Tree-level process, cross-section proportional to λ_t^2

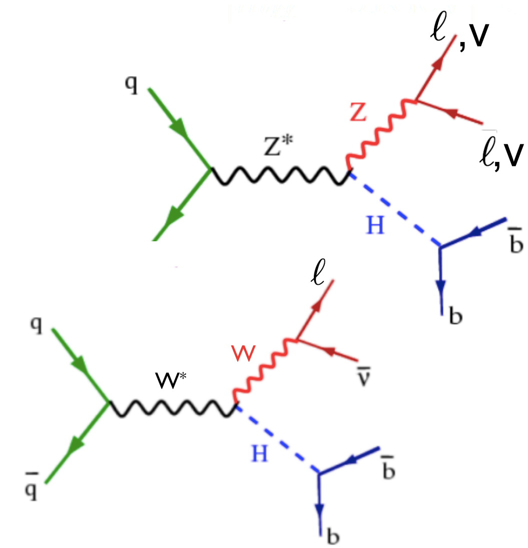


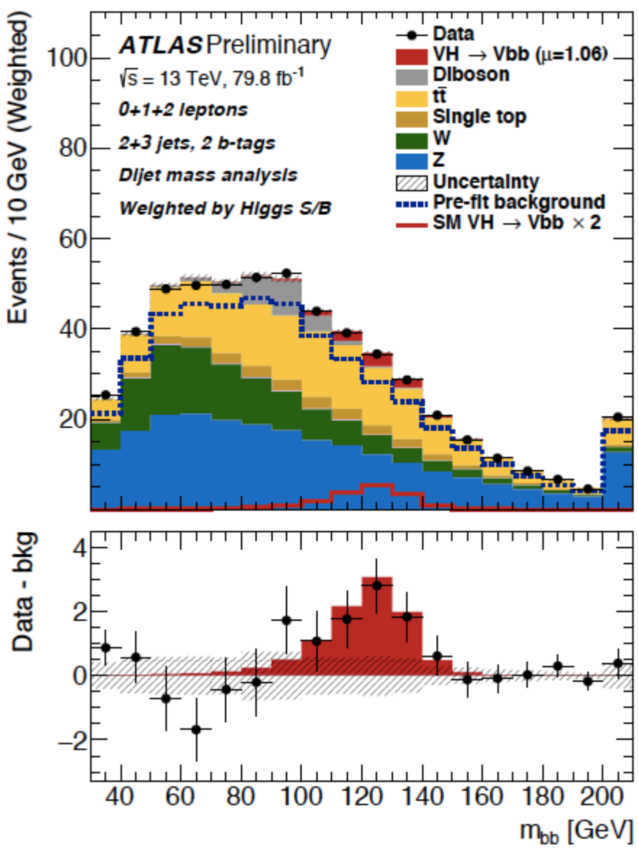
only: σ_{ttH} = 508 fb

VH production, H->bb

[ATLAS-CONF-2018-036]

- Make use of 0,1 or 2 charged lepton channels
- VH is most sensitive mode to measure H->bb at the LHC
- Select 2 b-tagged jets and pT(V) > 75 or 150 GeV
- Main discriminant variables m(bb), pT(V) and ΔR(bb) (combined into a Boosted Decision Tree)





Non-resonant backgrounds:

ttbar, single top (NLO, PowHeg)

W+jets

Z+jets

(NLO for up to 2 extra jets, Sherpa 2.2.1)

Run 2 best fit result $\mu = \sigma_{measured}/\sigma_{SM}$:

$$\mu = \sigma_{\mathrm{meas}}/\sigma_{\mathrm{SM}} = 1.16^{+0.27}_{-0.25}$$

Significance: **4.9σ** (4.3σ expected)

Combined with Run 1:

$$\mu = 0.98 \pm 0.14(\mathrm{stat.})^{+0.17}_{-0.16}(\mathrm{syst.})$$

Significance: **4.9σ** (5.1σ expected)

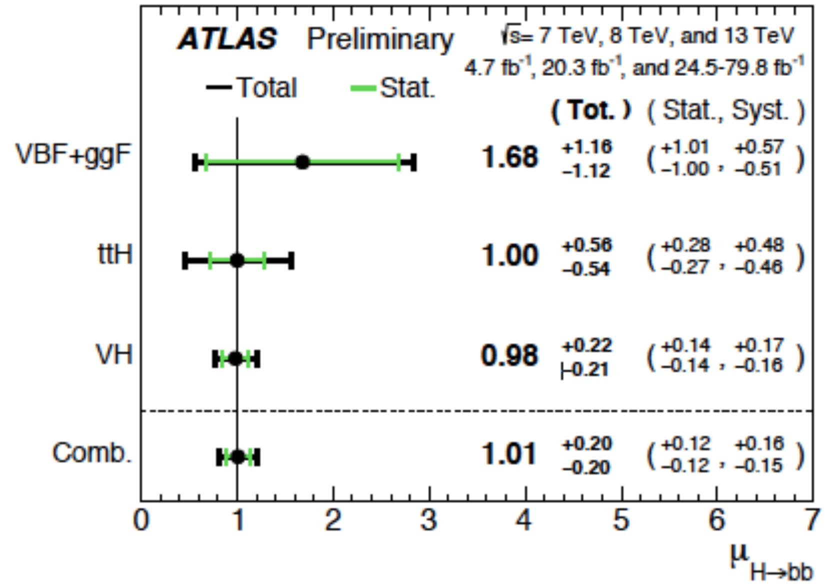
MC predictions normalised to data in fit.

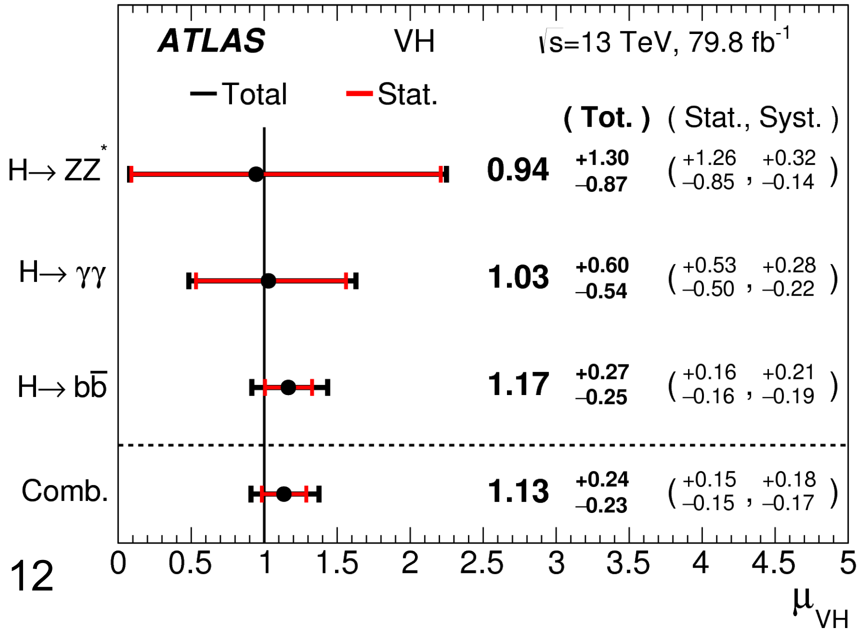
VH, H->bb combined with other channels

[ATLAS-CONF-2018-036]

- The recent VH, H->bb measurement when combined with other channels leads to observation of H->bb decay and VH production mode

Observation of H->bb !
Significance: 5.4σ observed (5.5σ expected)
Run 1+ Run 2 measurements:
VH, H → bb
VBF(+ggF), H → bb
ttH, H → bb





Observation of VH production !
Significance: 5.3σ observed (4.8σ expected)
Run 2 measurements:
VH, H → bb
VH, H → γγ
VH, H → ZZ*

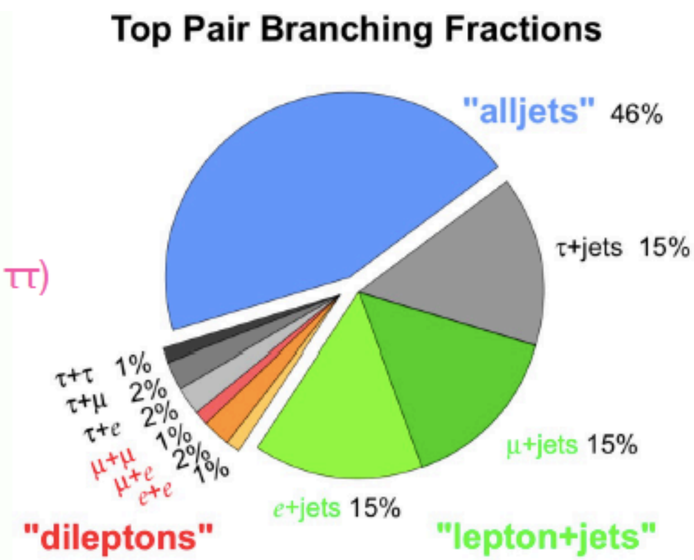
Assumes SM BR.

ttH production

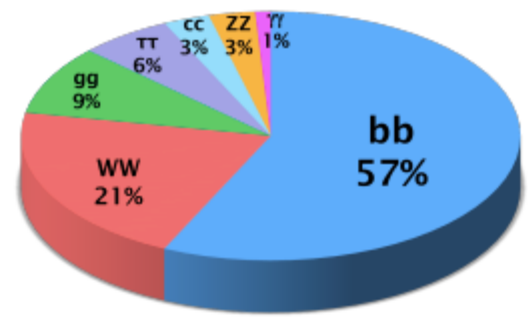
- ttH cross section only 508 fb, ~1% of total Higgs boson cross-section at 13 TeV
- Need to target all Higgs and top decay modes

Channels

- tt(1-2 e/μ) + H(bb)
- tt(1-2 e/μ/τ-had) + H(WW, ZZ*, ττ)
- tt(0-2 e/μ) + H(ZZ*)
- tt(0-2 e/μ) + H(γγ)

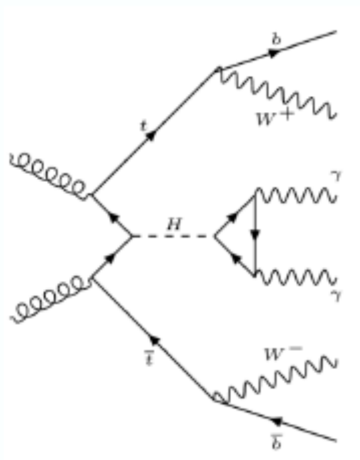


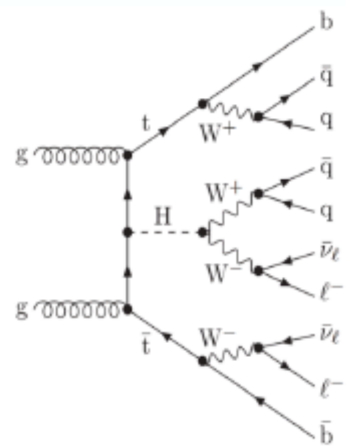
Higgs branching ratios

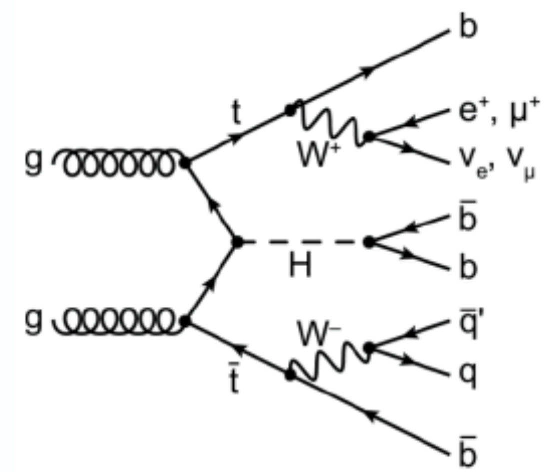


- Complex final states: γ, e, μ, τ-hadronic, high jet and b-jet multiplicities
- Sensitivity enhanced by dedicated channels

ttH channels







$$H \rightarrow ZZ^* \rightarrow 4\ell$$
$$H \rightarrow \gamma\gamma$$

$$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$$
$$H \rightarrow \tau\tau$$
(multi-leptons)

$$H \rightarrow b\bar{b}$$

Higher cross section x branching ratio

Higher signal purity

ttH, H->ZZ and H->γγ

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

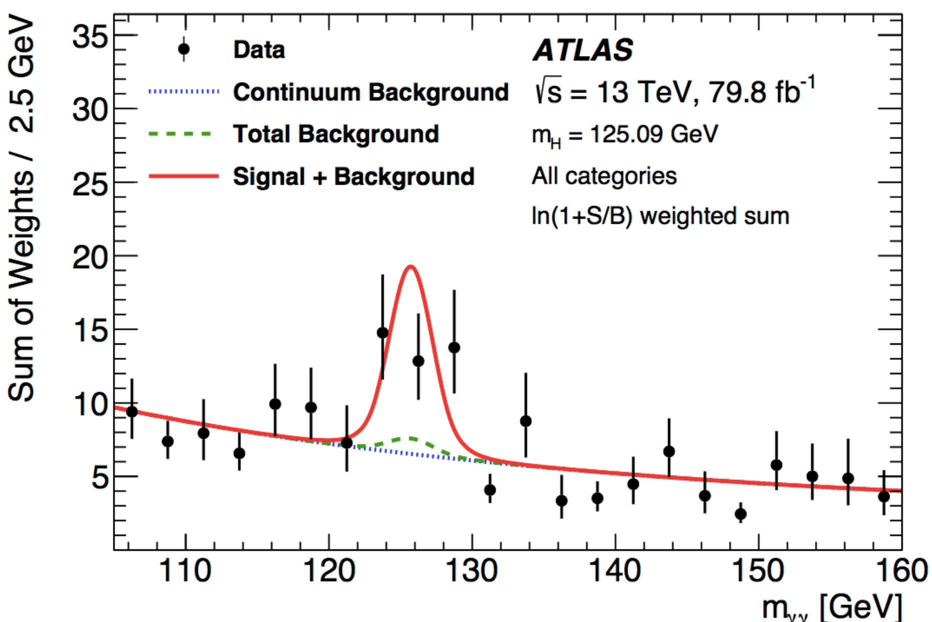
- Consider ttH enriched regions from inclusive studies of H→ZZ→4l and H→γγ searches
- Employs BDT to isolate ttH from other Higgs production modes

H→ZZ:

- Select events as
  - $115 < m_{4l} < 130$ GeV + b-jets
- Orthogonal to 4l ML (ZZ veto)
- Very rare but clean channel
- Zero ttH events observed, 0.6 ttH (0.4 Bkg) expected
- Upper limit on μ_{ttH} of 1.77 at 68% C.L.
- Will become more important as more data is gathered

H→γγ:

- Select events based on $m_{\gamma\gamma}$ + b-jets
- Significance: 4.1σ (3.7σ exp.)



Signal model: double-sided Crystal Ball

Background model: data driven by inverting γ ID or isolation, or removing b-tagging; shape+normalisation from fit to $m_{\gamma\gamma}$

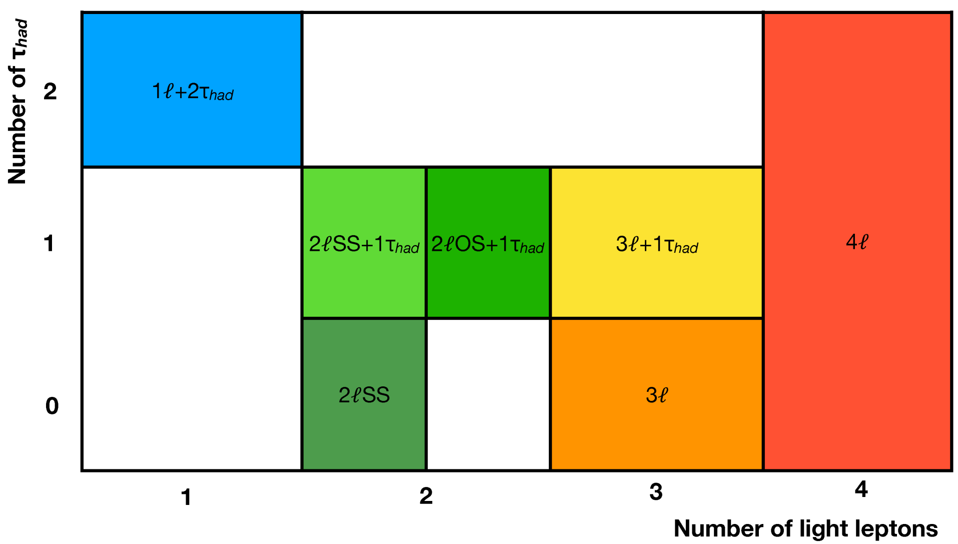
ttH, H to multi lepton states

[Phys. Rev. D. 97 (2018) 072003]

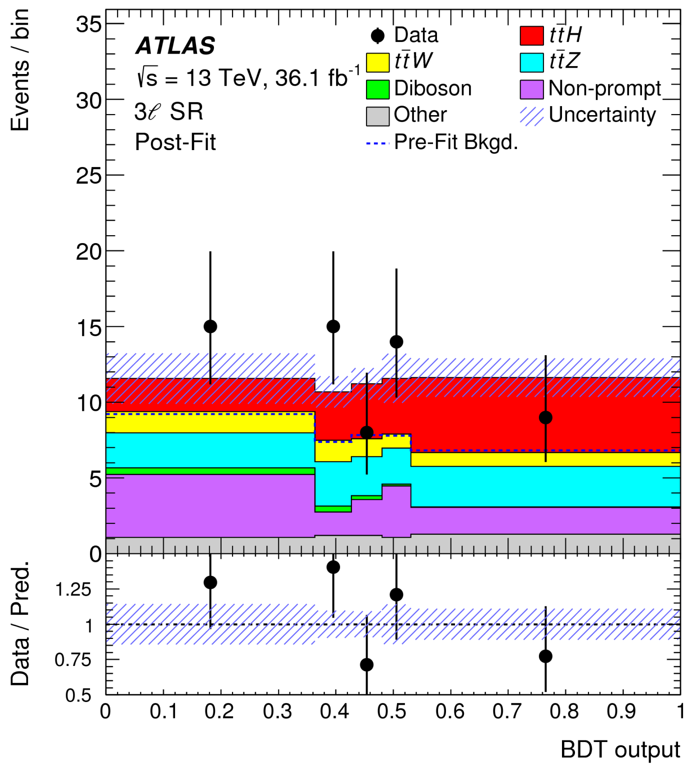
Many possible final states, Focus on those with clean signature and low background

- Select electron/muon from Higgs and top decay
- Requiring same-sign leptons or 3leptons with charge sum ±1 reduces large QCD background from tt background
- Remaining background from $t\bar{t}$ + misidentified leptons, Signal/Background ratio up to 1.8
- H→WW most sensitive channel, H→ττ next sensitive
  - Hadronic τ reconstruction has larger uncertainties

Overview of analysis categories:



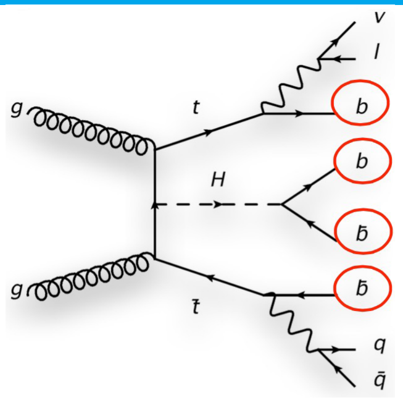
Extract signal from BDT discriminant



ttH, H->bb

[PhysRevD.97.072016]

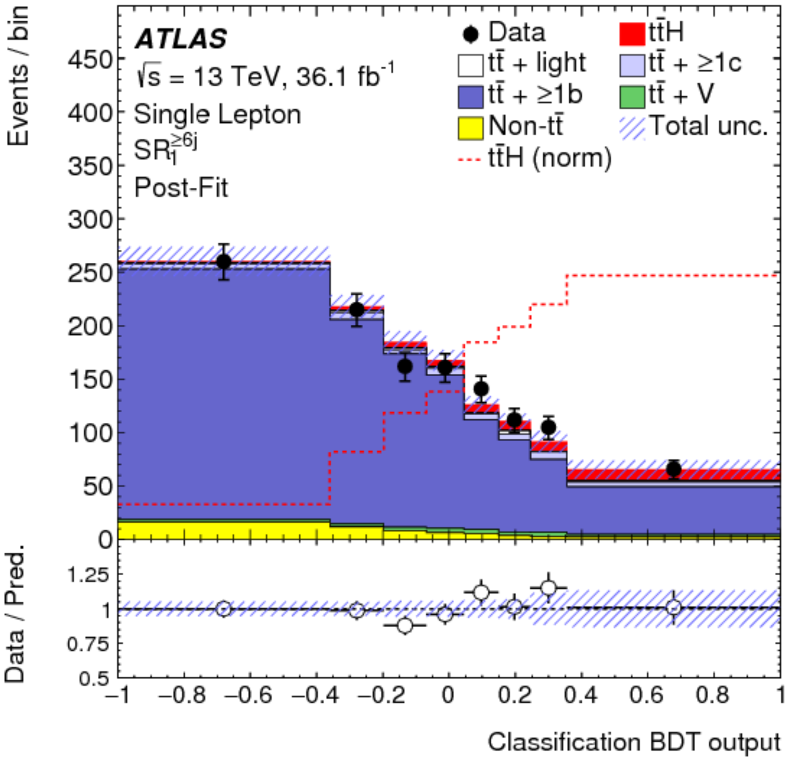
- Largest H->bb branching ratio of 58.1%
- Suffers from large irreducible QCD background from tt+ b-jets
- Ambiguous event reconstruction due to final state with high combinatorics of b-jets



- Define signal rich and background rich regions based on b-tagging discriminants
- Signal/Background ratio up to ~5%
- Rely on Boosted Decision trees to further separate Signal from Bkg.

- Dominant modelling uncertainty of tt+ b-jets:
    - Determined from comparison of PowHegPythia8 to Sherpa ttbar generators

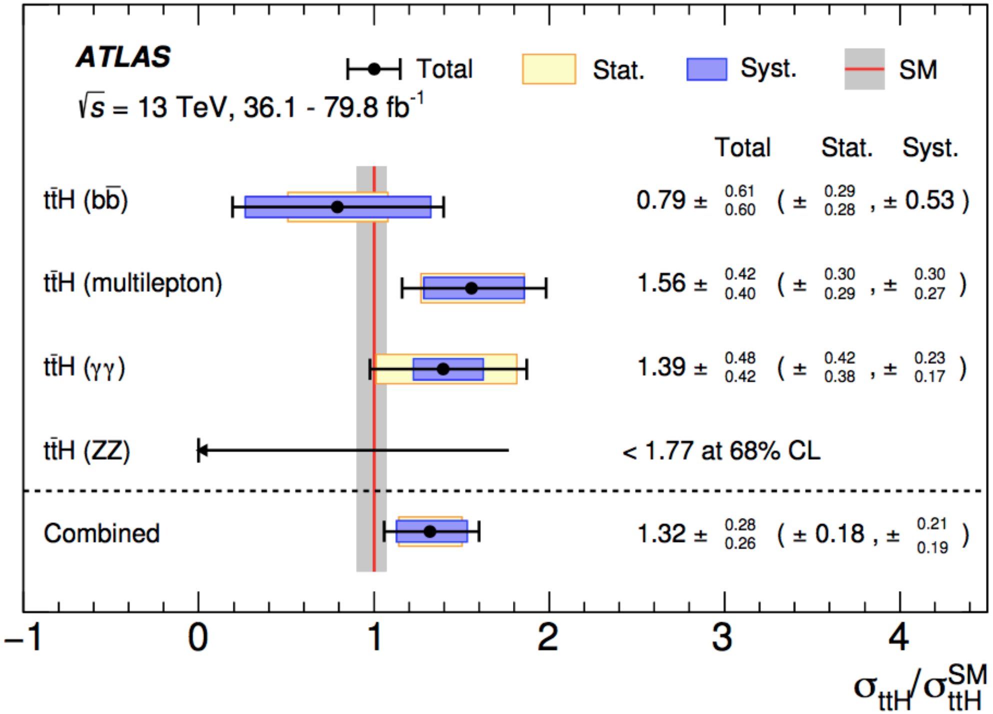
- Uncertainties and background normalisation controlled in simultaneous fit over signal-rich and background-rich regions



Combination of ttH results

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

- Observation of ttH production !



Compute signal strength σ_{ttH}/σ_{SM} from profile likelihood fit over all channels. Correlate systematic uncertainties were appropriate.

Sensitivity limited by theory uncertainties on signal and background modelling.

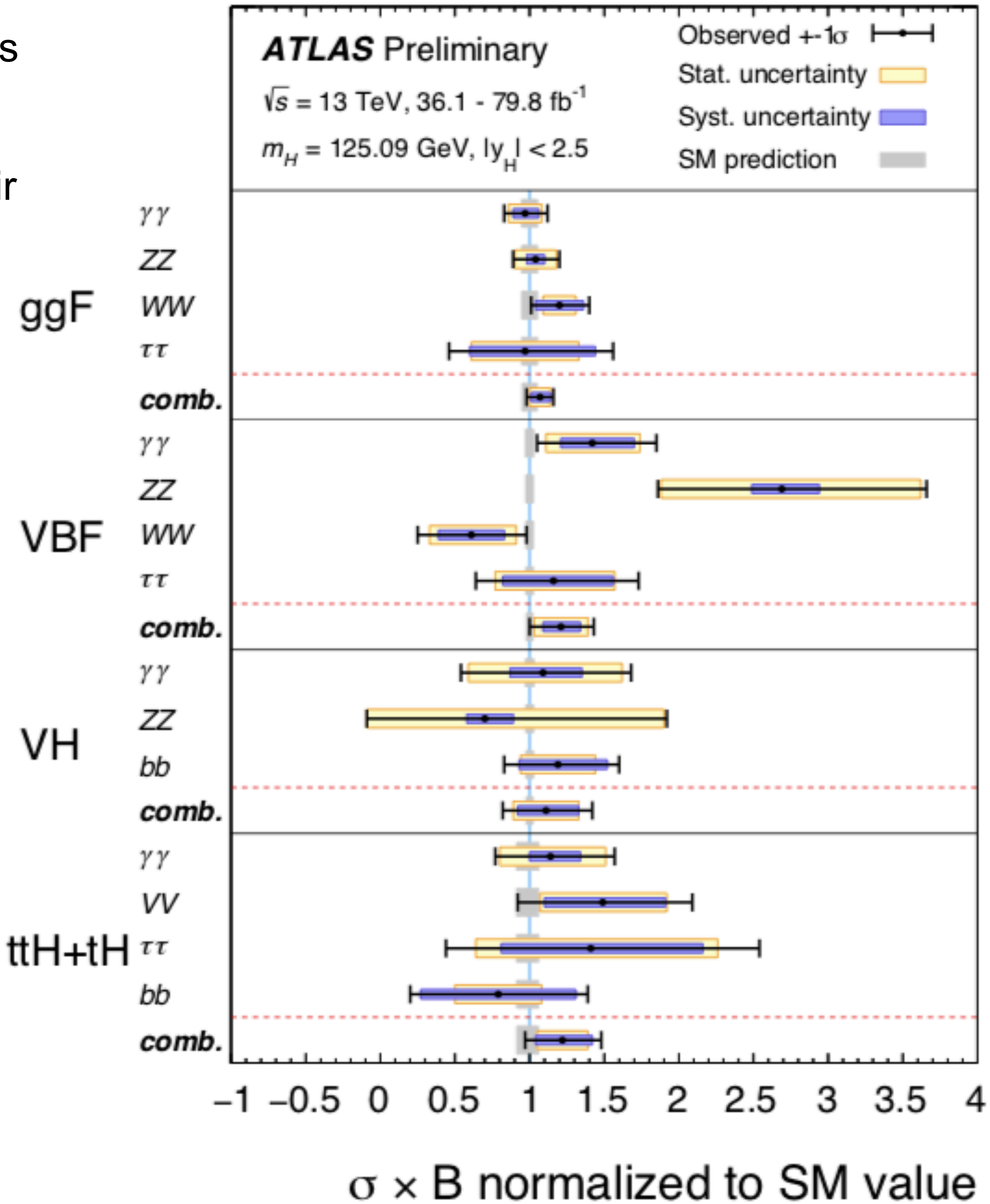
Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, E_T^{miss}	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-leptons	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

ATLAS (up to 80 fb-1)
Run-2: 5.8σ (4.9σ exp.)
Run-1+Run-2: 6.3σ (5.1σ exp.)

Measurements of all Higgs production modes

- combined production cross-section times branching fraction results for ggF, *V*BF, *VH* and *ttH*+*tH* production in each relevant decay mode, normalised to their SM predictions.
- obtained from a simultaneous fit to all decay channels, for each production mode
- 9% precision on ggF
- VH: assume SM WH/ZH cross section ratio & SM expectation for H->ττ
- Statistically limited in ZZ & γγ
- Overall combined signal strength, i.e. if the SM signal yield in all channels were scaled by a single factor

$$\mu = \frac{(\sigma \times B)_{if}}{(\sigma \times B)_{if}^{SM}} = 1.13^{+0.09}_{-0.08}$$



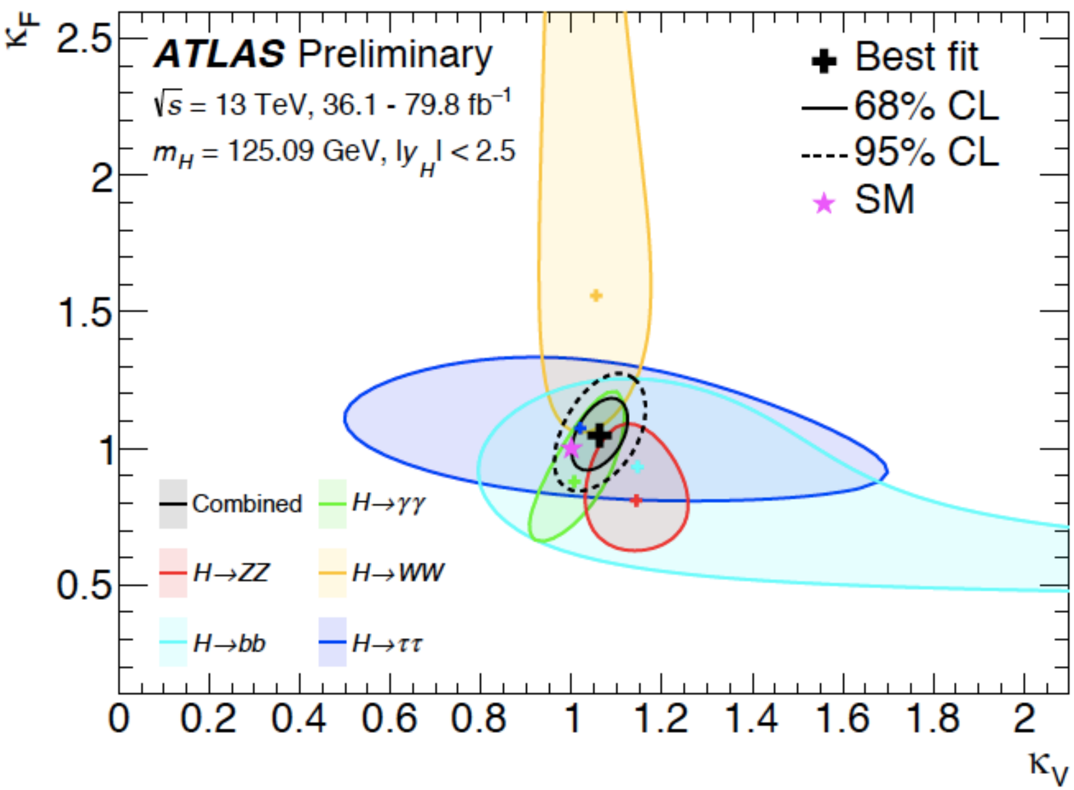
[ATLAS-CONF-2018-031]

Coupling from combining all channels

- Use all production and decay modes to measure couplings expressed in **κ**-scales. Scale SM production process (i), decay width to final state f and the Higgs total width
- κ_i, κ_f can be parameterised as combinations of Higgs to SM particles tree-level coupling

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

- Effective gluon, photon coupling, assumes no BSM contributions
- Assuming uniform **κ** modifier for vector boson and fermion couplings:



Best fit value in good agreement with SM

$$\kappa_V = 1.06^{+0.04}_{-0.04}$$

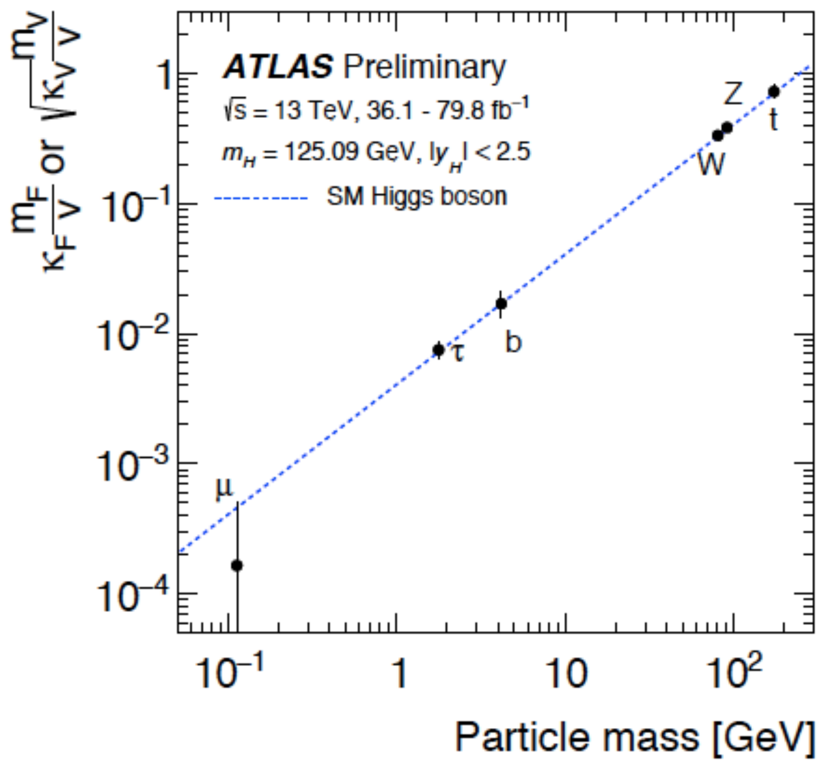
$$\kappa_F = 1.05^{+0.09}_{-0.09}.$$

[ATLAS-CONF-2018-031]

Coupling results

[ATLAS-CONF-2018-031]

- For vacuum expectation value of the Higgs field ν =246 GeV, reduced coupling $\kappa_F \frac{m_F}{\nu}$ and $\sqrt{\kappa_V}\frac{m_V}{\nu}$ are proportional to the fermion or boson particle mass
- Results show high agreement to SM over full mass range
- For direct and indirect coupling measurements



Parameter	Result
κ_Z	$1.07^{+0.11}_{-0.10}$
κ_W	1.04 ± 0.10
κ_b	$1.00^{+0.24}_{-0.22}$
κ_t	$1.03^{+0.12}_{-0.11}$
κ_τ	$1.04^{+0.17}_{-0.16}$
κ_μ	< 1.63 at 95% CL.

- Assumes expected coupling for other SM process and zero BSM contribution
- The compatibility of the measurements corresponds to a p-value= 79%

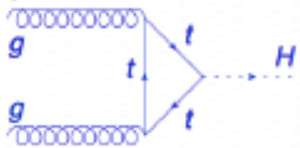
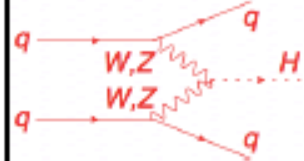
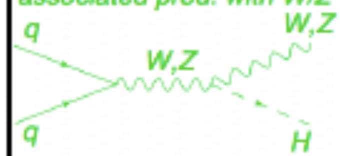
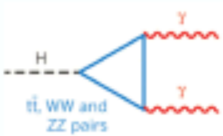
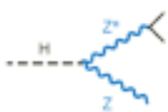
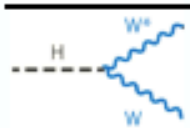
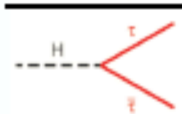
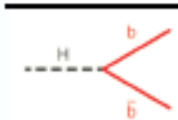
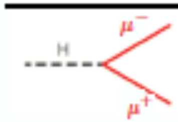
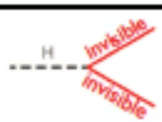
Conclusion

- With the large Run 2 dataset of 36-80 fb^{-1} the properties of the Higgs boson can be determined with unprecedented precision at the ATLAS experiment
- ~3x improvement in precision for bosonic channels over Run 1 results
- Direct observation achieved for the main production and decay modes
  - Recent **observation of VH production** shown
- Confirmation of coupling to 3rd generation fermions
  - Recent **observation bottom and top quark Higgs coupling** were presented
- All measurements of the Higgs boson are compatible with the Standard Model
- Precise knowledge of the Higgs boson properties will enhance searches for new phenomena, use the Higgs boson as a probe for beyond the SM effects
- Only a fraction of the total expected LHC luminosity analysed to date
  - Rich Higgs boson properties program still lies ahead

Backup

Inputs to combination

CMS
ATLAS

Decay \ Production	gluon fusion 		vector boson fusion (VBF) 		associated prod. with W/Z 		associated prod. with tt 	
	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS
	✓	✓ 80 fb^{-1}	✓	✓ 80 fb^{-1}	✓	✓ 80 fb^{-1}	✓	✓ 80 fb^{-1}
	✓	✓ 80 fb^{-1}	✓	✓ 80 fb^{-1}	✓	✓ 80 fb^{-1}	✓	✓ 80 fb^{-1}
	✓	✓	✓	✓	✓		✓	✓
	✓	✓	✓	✓			✓	✓
	✓				✓	✓	✓	✓
	✓	✓ 80 fb^{-1}	✓	✓ 80 fb^{-1}				
	✓		✓		✓			