Measurement of differential and production mode cross sections of the Higgs in decays to bosons using the ATLAS detector

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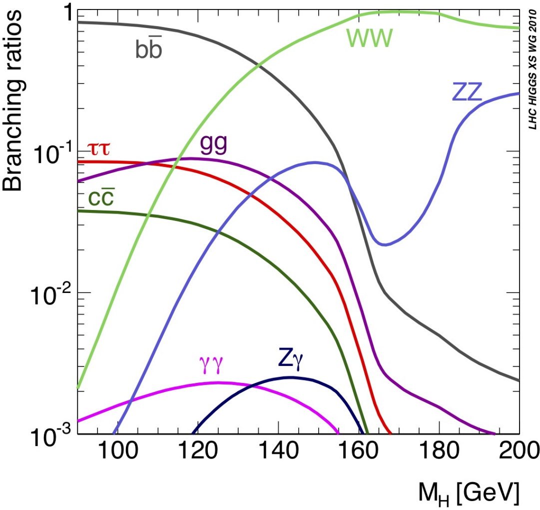
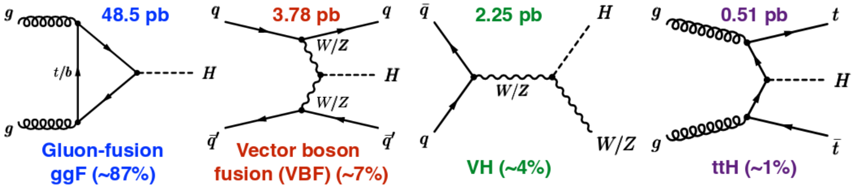
The Higgs Boson

- Existence of Higgs-like particle confirmed in 2012 with a mass of 125 GeV
- Bosonic decays of the Higgs key in discovery



Introduction: Higgs Production/Decay at the LHC (arXiv:1610.07922v2)



- Largely dominated by gluon-gluon fusion
- Vector boson fusion is distinguished by the presence of widely separated jets in the event

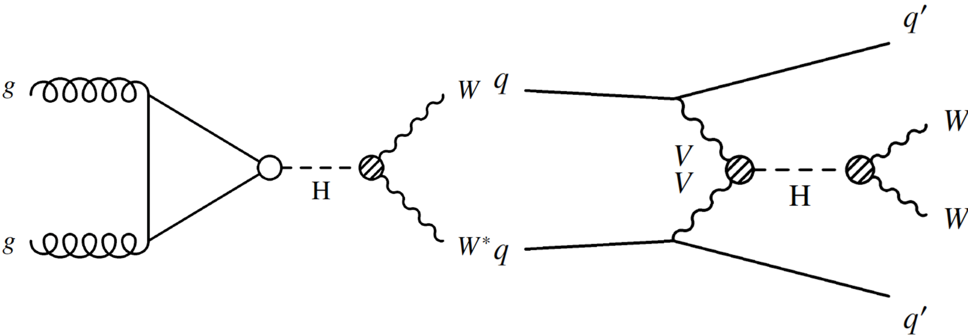
Decay channel	SM BR [%] with m_H=125.09 GeV
$H\to bb$	58.1
$H\to WW$	21.5
$H\to \tau\tau$	6.26
$H\to ZZ$	2.64
$H\to \gamma\gamma$	0.23
$H\to \mu\mu$	0.022
$H\to Z\gamma$	0.154
$H\to cc$	2.88
$H\to gg$	8.18

Outline

Results presented in this talk:

- ggF and VBF production cross-section measurement using $H \rightarrow WW \rightarrow e\nu\mu\nu$ decays (36.1 fb^{-1})
- $VH, H \rightarrow WW \rightarrow \ell\nu\ell\nu$ (36.1 fb^{-1})
- $H \rightarrow \gamma\gamma$ differential cross-section and couplings measurement (79.8 fb^{-1})
- $H \rightarrow ZZ$ differential cross-section and couplings measurement (79.8 fb^{-1})

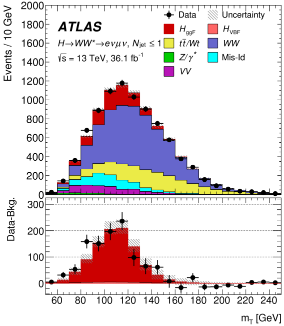
$H \to WW \to e\nu\mu\nu$: ggF and VBF production[1]

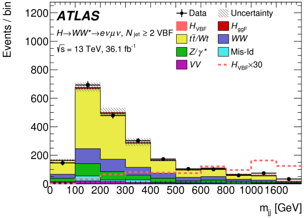


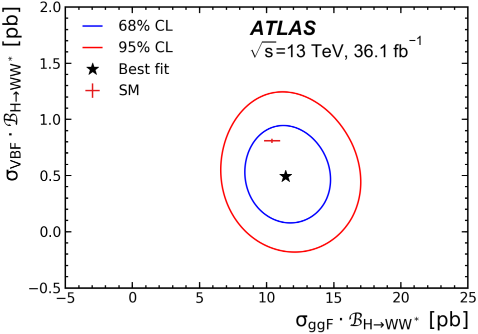
- Measurement of the ggF and VBF production cross-section
- Separate between two production modes using jet multiplicity of the event
  - ggF: 0-1 jet
  - VBF: $\geq$ 2 jets

[1]Phys. Lett. B 789 (2019) 508

$H \to WW \to e\nu\mu\nu$: Results

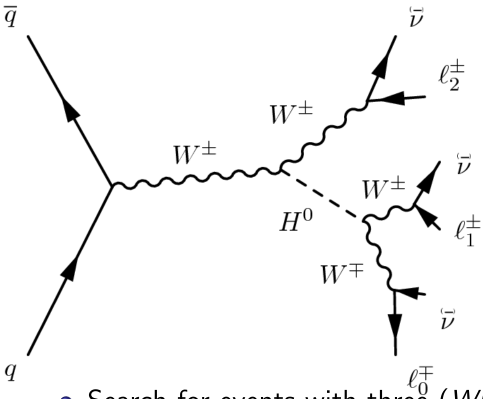


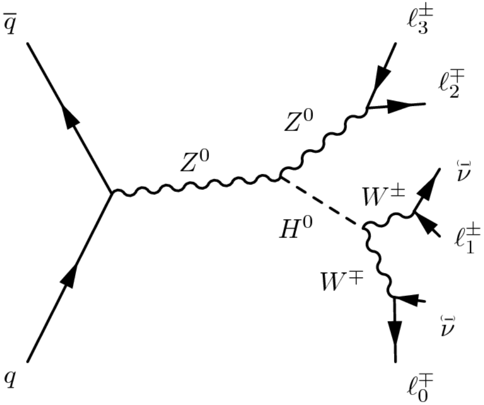




- The observed (expected) ggF and VBF signals have significances of 6.0 (5.3) and 1.8 (2.6) σ
- Reasonable agreement with SM

$VH, H \to WW \to \ell\nu\ell\nu$ (arXiv:1903.10052)





- Search for events with three (WH) or four (ZH) charged leptons (electrons and muons)
- Background processes dominated by WZ, $qq \to ZZ$, $t\bar{t}$ & $t\bar{t}V$
- Use b-tagging to supress top-quark related processes

NEW!

$VH, H \to WW \to \ell\nu\ell\nu$: Analysis Strategy

WH **analysis**

- Three leptons and missing transverse energy coming from the neutrinos

Two Signal Regions:

- Z-dominated: one same-flavour Opposite-sign pair
- Z-depleted: No Same-flavour Opposite-sign
- BDTs used to discriminate against diboson and Top background

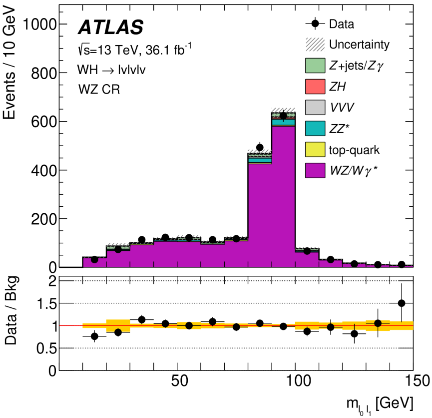
ZH **analysis**

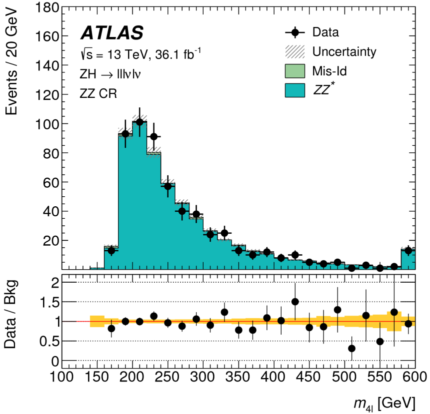
- Four leptons, with a pair close to the *Z* boson mass

Two Signal Regions:

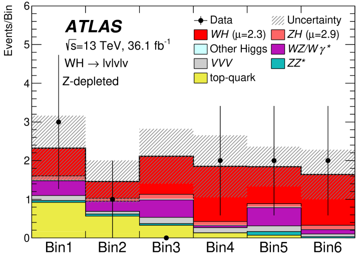
- One Same-flavour Opposite-sign pair: very good S/B ($\sim$2)
- Two Same-flavour Opposite-sign pair: dominated by $ZZ \to 4\ell$ background, S/B ($\sim$0.4)
- *ZZ* Background shape estimated from MC and normalised in a control region

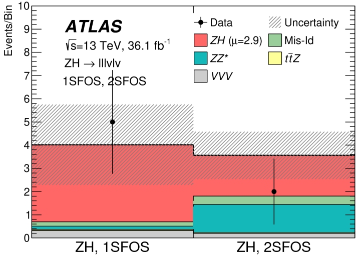
$VH, H \to WW \to \ell\nu\ell\nu$: Background estimation

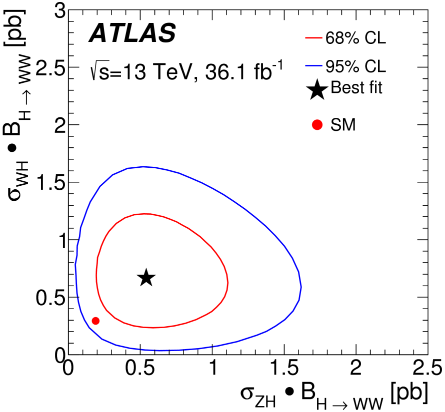




- Dedicated control regions used to normalise the prompt lepton background
- Orthogonal to Signal region by reversing selection criteria



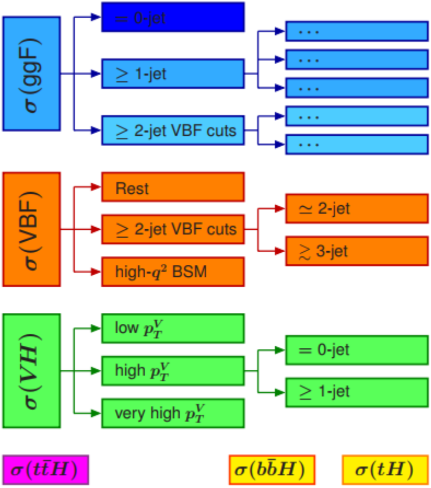




- BDT score results used to classify events in various bins
- Consistent with SM within **1.5**σ

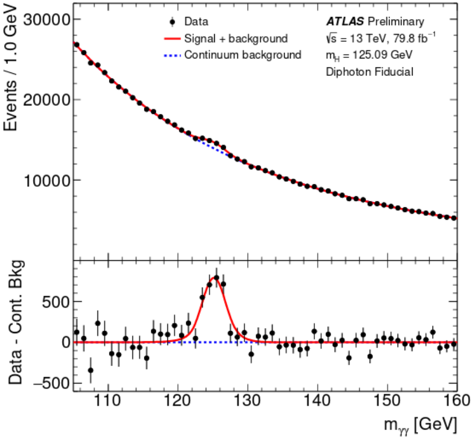
Simplified template xsec (STXS)[2]

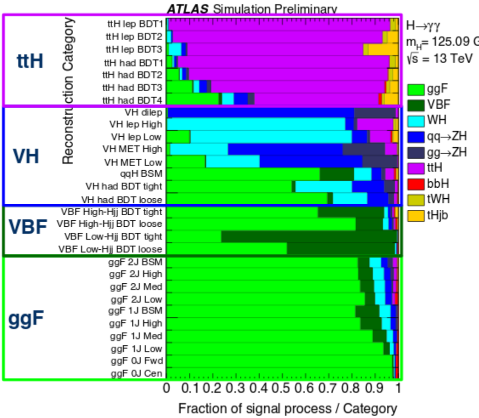
- Events categorised within a particular production mode
- Aim to maximise the sensitivity of measurements by choosing regions of phase space which minimise theoretical uncertainties
- All decay channels can be combined
- Results obtained for each production mode



[2] https://arxiv.org/abs/1610.07922

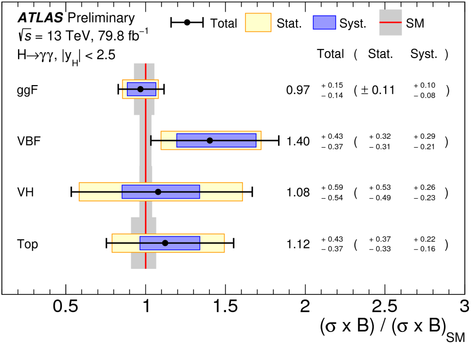
H→ $\gamma\gamma$: ATLAS-CONF-2018-028

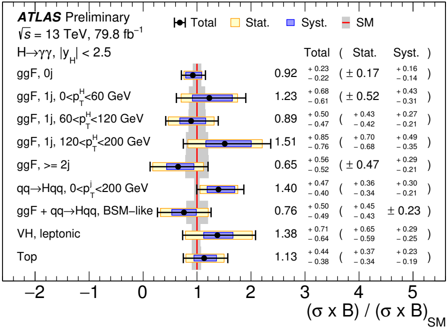




- Large background, but excellent sensitivity ensured by very good photon efficiency and resolution
- Analysis categories designed to isolate out events from different production modes.

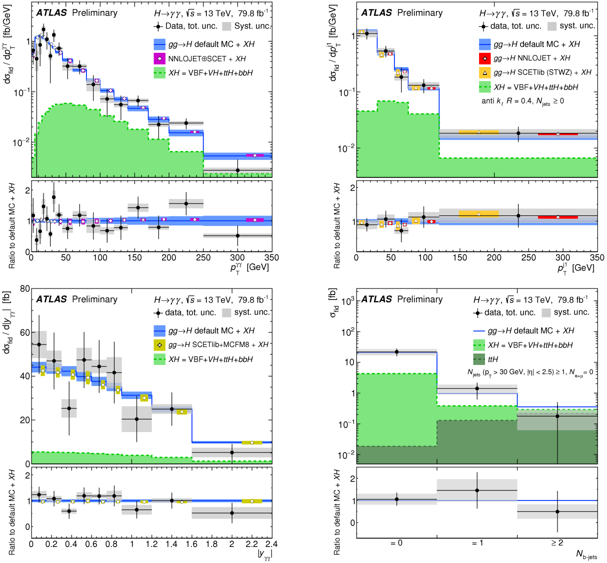
H→ $\gamma\gamma$: STXS Stage-0 and 1





- Find good agreement with SM expectation within 1σ

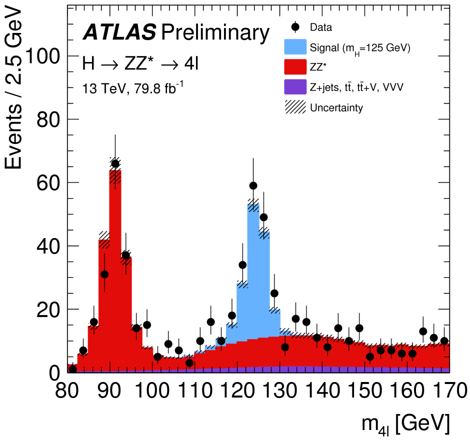
H$\rightarrow \gamma\gamma$: Differential cross-sections

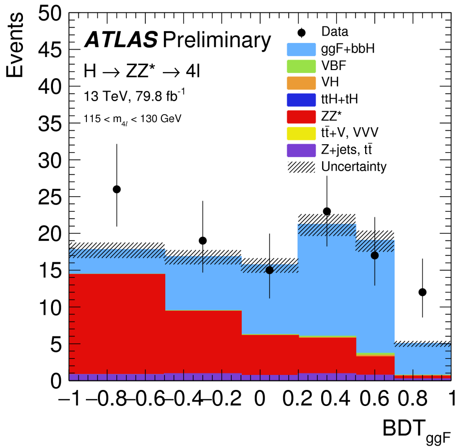


Distribution	$p(\chi^2)$ with Default MC Prediction
$p_T^{\gamma\gamma}$	31%
$\lvert y_{\gamma\gamma}\rvert$	56%
$p_T^{j_1}$	88%
$N_{b\text{-jets}}$	84%

- Cross-section measured differentially in dilepton p_T and rapidity, leading jet p_T and number of b-jets

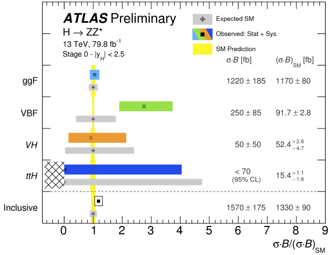
$H \to ZZ^* \to 4\ell$: ATLAS-CONF-2018-018

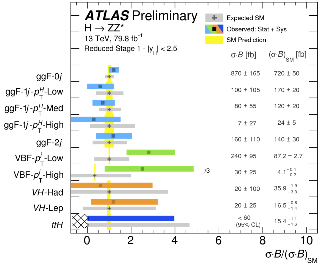


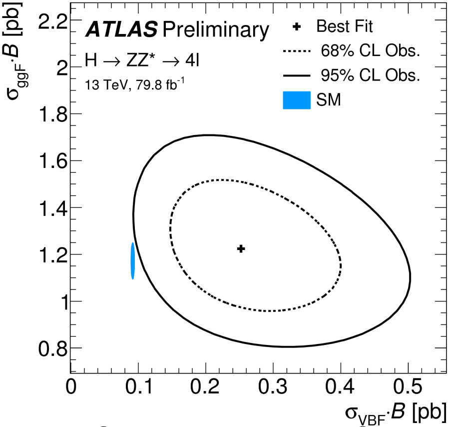


- The "golden channel": Very clean channel with high S/B
- Boosted decision tree used to suppress background and discriminate between production modes

$H \to ZZ^* \to 4\ell$: STXS Stage-0 and 1 and 2-D contour

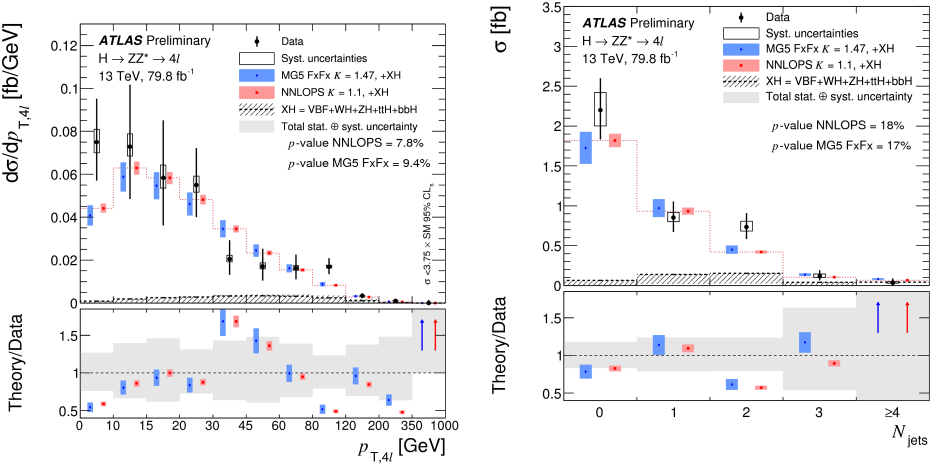






- All Stage-0 and reduced Stage-1 ggF measurements agree with the predictions for the SM Higgs boson within 2σ

$H \to ZZ^* \to 4\ell$: Differential fiducial cross-section



- xsec measured differentially in terms of the $p_{T_{4\ell}}$ and jet multiplicity for the ggF production mode
- Compared observed results to NNLOPS and MadGraph5 predictions

Conclusions

- Various measurements of the Higgs boson presented
- Still fairly limited by statistics... but still a good fraction of the Run-2 dataset left to investigate
- So far all compatible with SM expectation
- As usual, stay tuned!

BACKUP SLIDES

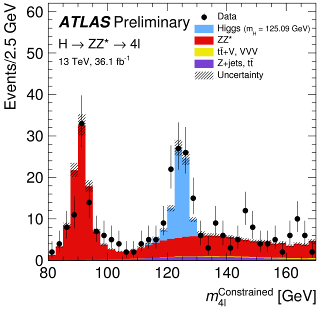
$H \to ZZ^* \to 4\ell$: the golden channel

Many useful features:

- Large signal to background ratio (S/B $\sim$ 2) & excellent mass resolution ($\sim 1-2\%$)
- Main draw-back is the small branching ratio ($\sim$ 0.02%) $\to$ limited statistics

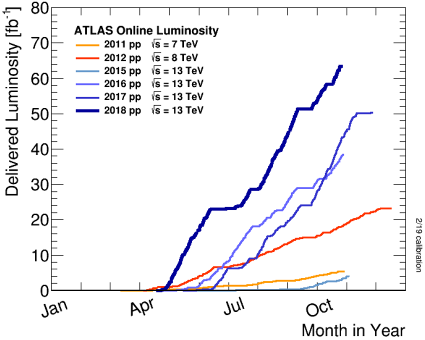
Analysis strategy:

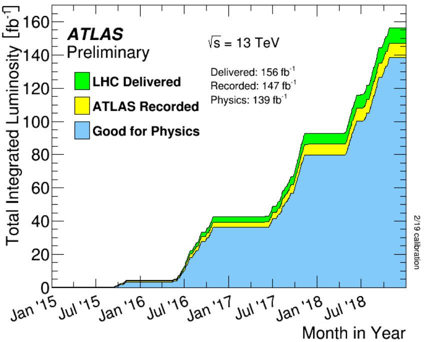
- ATLAS uses invariant mass of the four-lepton system ($m_{4\ell}$) as your observable
- Non-resonant background coming from ZZ (reduced via MVA)



- Leptons from the Z* are low p_T $\to$ more prone to background contamination
- Fake background estimated in Control regions

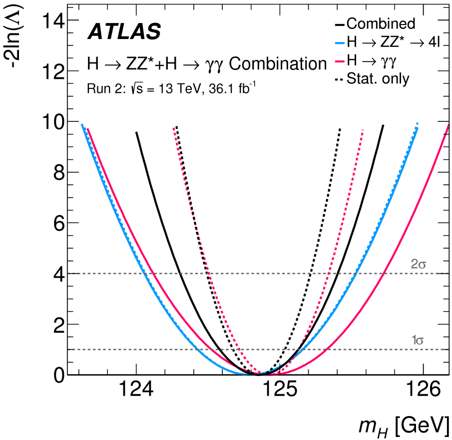
Performance of the LHC & the ATLAS detector





- The LHC & ATLAS has been working remarkably well, generally exceeded expectations
- Currently in shutdown until mid-end 2021

Higgs boson mass: Results

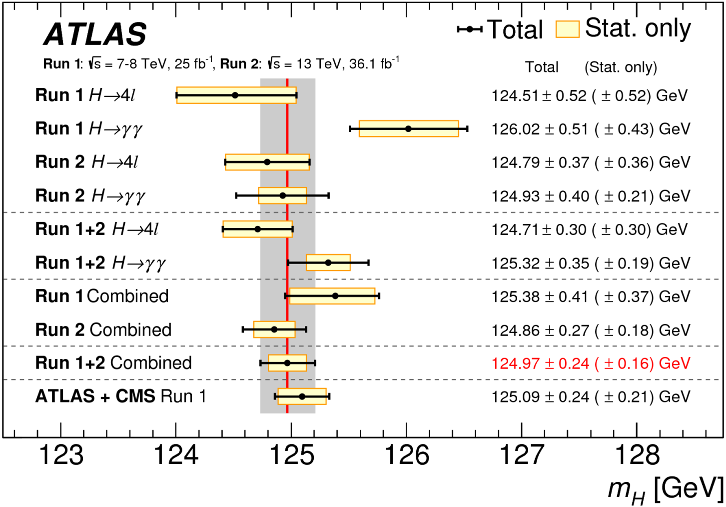


Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

$$m_H^{ZZ^*} = 124.79 \pm 0.37 \text{ GeV}$$
$$m_H^{\gamma\gamma} = 124.93 \pm 0.40 \text{ GeV}$$

Combining with the 7 and 8 TeV dataset: $m_H = 124.97 \pm 0.24$ GeV

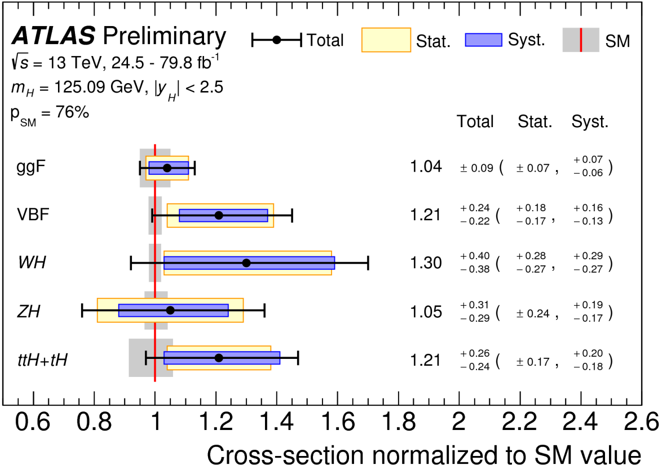
Higgs boson mass: Summary

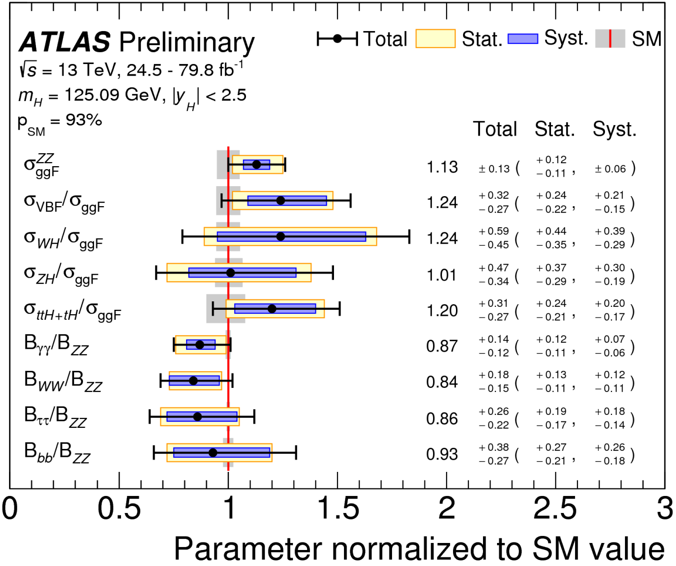


Current best result published in Phys. Lett. B 784 (2018) 345

Higgs Boson Production xsec: ATLAS-CONF-2019-005

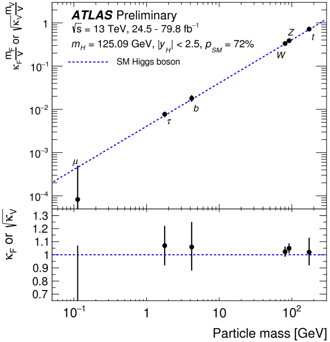
- Obtained combining $\gamma\gamma$, ZZ^*, WW^*, $\tau\tau$, $b\bar{b}$ and $\mu\mu$ final states



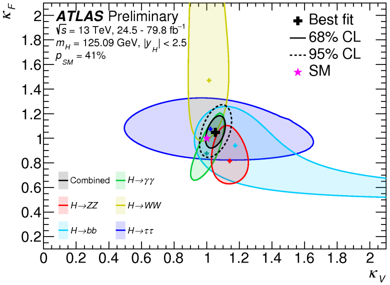


ATLAS Preliminary
√s = 13 TeV, 24.5 - 79.8 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
p_SM = 93%
Total
Stat.
Syst.
SM
Total Stat. Syst.
σ^ZZ_ggF 1.13 ± 0.13 (+0.12 −0.11 , ± 0.06)
σ_VBF/σ_ggF 1.24 +0.32 −0.27 (+0.24 −0.22 , +0.21 −0.15)
σ_WH/σ_ggF 1.24 +0.59 −0.45 (+0.44 −0.35 , +0.39 −0.29)
σ_ZH/σ_ggF 1.01 +0.47 −0.34 (+0.37 −0.29 , +0.30 −0.19)
σ_ttH+tH/σ_ggF 1.20 +0.31 −0.27 (+0.24 −0.21 , +0.20 −0.17)
B_γγ/B_ZZ 0.87 +0.14 −0.12 (+0.12 −0.11 , +0.07 −0.06)
B_WW/B_ZZ 0.84 +0.18 −0.15 (+0.13 −0.11 , +0.12 −0.11)
B_ττ/B_ZZ 0.86 +0.26 −0.22 (+0.19 −0.17 , +0.18 −0.14)
B_bb/B_ZZ 0.93 +0.38 −0.27 (+0.27 −0.21 , +0.26 −0.18)
0 0.5 1 1.5 2 2.5 3
Parameter normalized to SM value

Higgs Boson Couplings



- Interpret the results in the κ framework as a function of the particle mass assuming no BSM contributions to total width

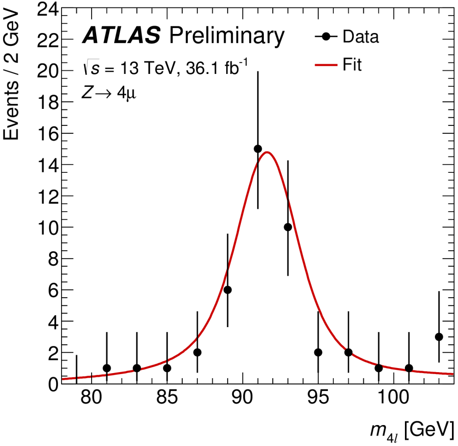


- Probing universal coupling strength factors for fermions (κ_f) and bosons (κ_V)
- Best fit shows values of κ_f and κ_V $!=$ 1.0, but compatible with SM within uncertainties

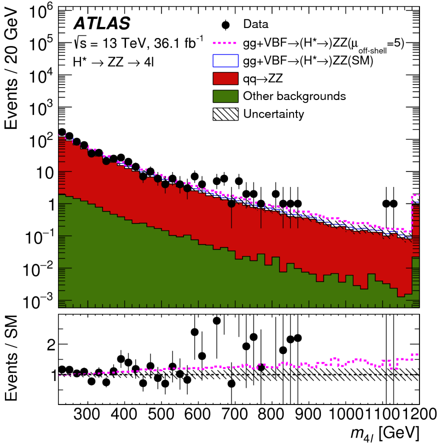
Higgs boson mass: per-event method ($ZZ \to 4\ell$)

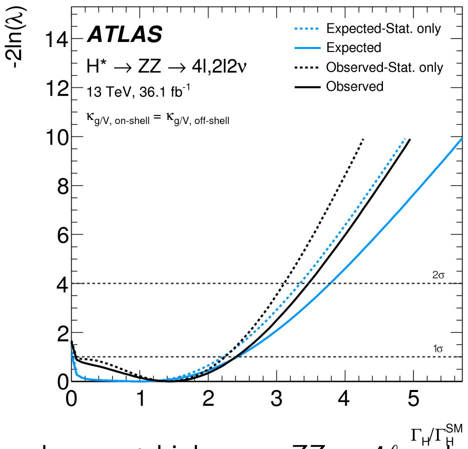
- $m_{4\ell}$ signal distribution modelled as the convolution of the intrinsic Higgs boson lineshape and a four lepton invariant mass response function
- The response function gives the probability of measuring a value $m_{4\ell}^{meas}$ for a truth mass $m_{4\ell}^{true}$
- Validate the method by testing it with the Z boson

Category	m_Z in simulation [GeV]	m_Z in data [GeV]
4μ	$91.19^{+0.41}_{-0.41}$	$91.46^{+0.42}_{-0.41}$
$4e$	$91.19^{+1.02}_{-1.03}$	$91.75^{+1.08}_{-1.06}$
$2\mu 2e$	$91.18^{+1.11}_{-1.11}$	$91.31^{+1.62}_{-1.33}$
$2e2\mu$	$91.19^{+0.90}_{-0.90}$	$92.49^{+0.91}_{-0.94}$
Combined	$91.19^{+0.34}_{-0.34}$	$91.62^{+0.35}_{-0.35}$



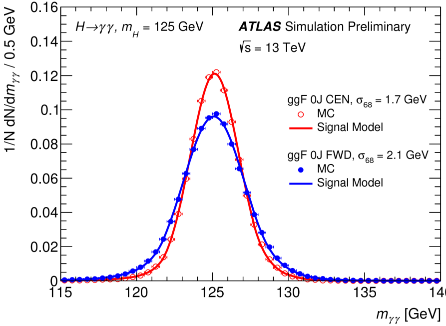
Off-Shell Analysis: Phys. Lett. B 786 (2018) 223

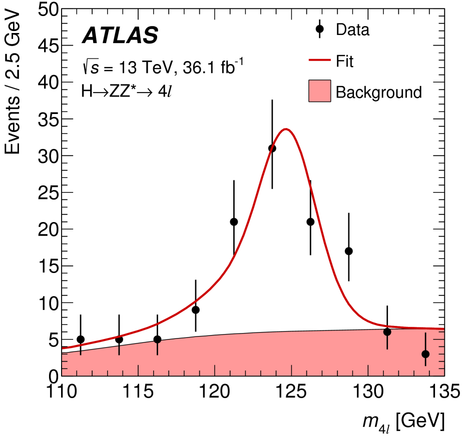




- Study off-shell production of Higgs boson at high mass $ZZ \to 4\ell$ and $2\ell\ell\nu\nu$ channels
- Assume same couplings in on-shell/off-shell regions to indirectly constrain Higgs boson total width

Higgs boson mass: Phys. Lett. B 784 (2018) 345





- Combination of $\gamma\gamma$ and 4ℓ final states
- Chosen for their excellent mass resolution