Higgs boson decays to two fermions and production in association with $t\bar{t}$ at the ATLAS experiment

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On behalf of the ATLAS Collaboration

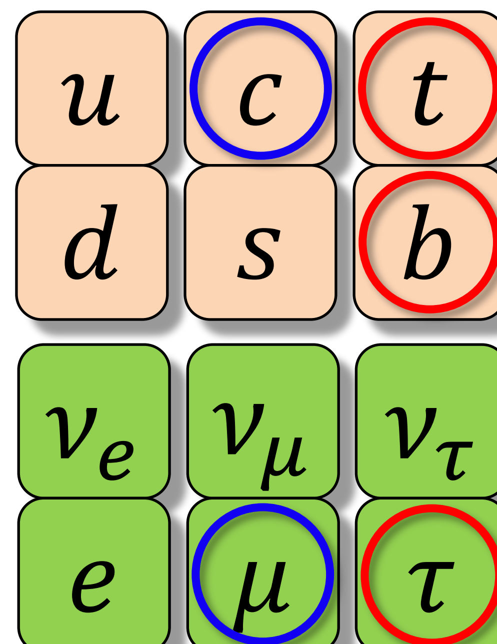
■ Higgs–Fermion Coupling

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+i\bar{\psi}\not{D}\psi + h.c.$$
$$+i\bar{\psi}Y\psi\phi + h.c.$$
$$+|D_\mu\phi|^2 - V(\phi)$$

- Higgs boson was discovered in 2012 by ATLAS and CMS
  - Next: precise understanding of its properties
- Yukawa interaction
  - Origin of the fermion mass in SM
  - But is it the full picture?
- LHC has provided O(10^7) Higgs bosons

<u>Only Higgs factory currently in operation</u>

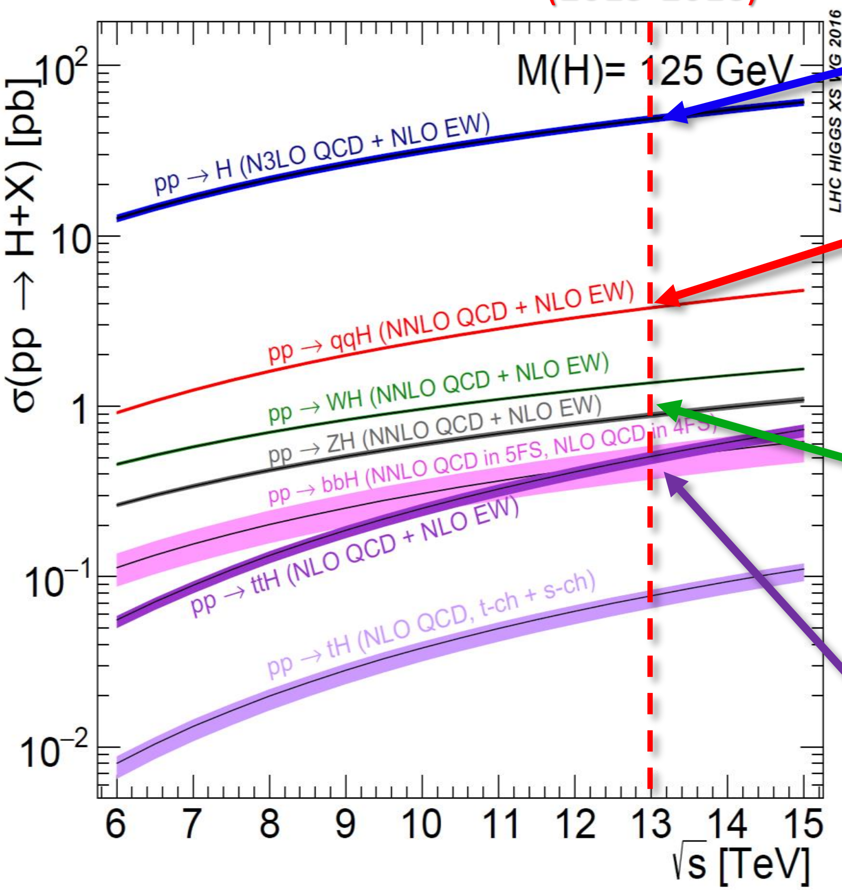
  - Higgs coupling to all of the **3rd-gen. fermions** have been confirmed
  - Measurements for the **2nd-gen. fermions** are also being pursed



■ Recent Measurements at ATLAS

- 4 main production processes at LHC
  - Different measurements use different signatures

LHC Run-2
(2015-2018)



Gluon-gluon fusion (ggF)
- Large x-sec

Vector-boson fusion (VBF)
- Two high-p_T jets to opposite η

} $H \to \tau\tau, \mu\mu$

Vector-boson association (VH) $H \to bb, cc$
- Clean signature thanks to an additional W or Z

VBF is also being tried

Phys. Rev. D 98 (2018) 052003

$t\bar{t}H$ production
- Direct coupling to t-quarks

Results use 36.1-79.8 fb^{-1} recorded in 2015-17 ($\sqrt{s}$ = 13 TeV)

arXiv: 1811.08856; 36.1 fb^{-1}

$H \to \tau\tau$: Analysis Strategy

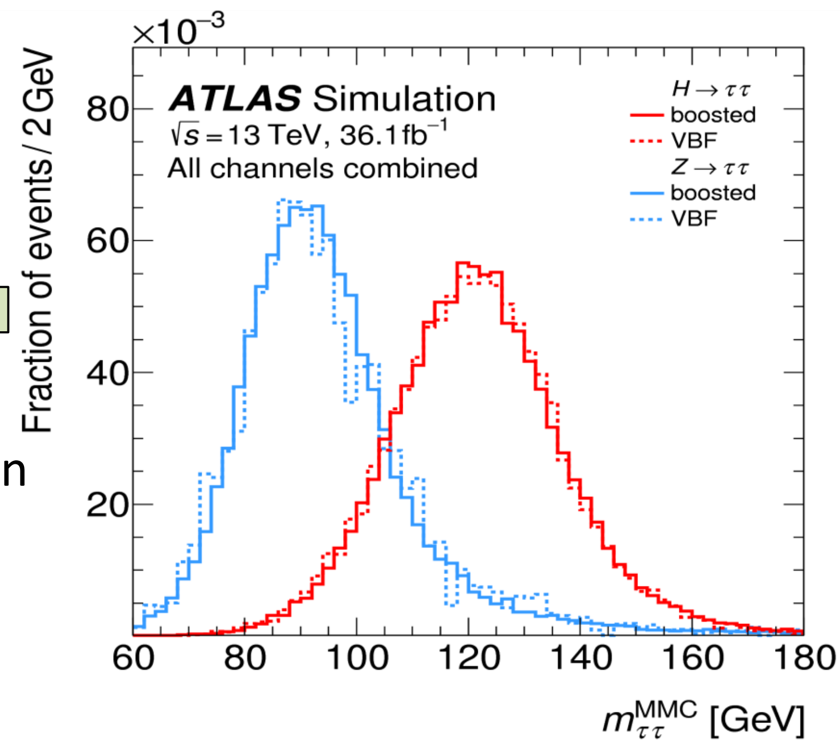
- Cleaner signature compared to other fermionic final states
  - Still reconstruction of two τ's is challenging
- Three different di-τ final states

Channel	BR	Main BG
$\tau \to h\nu, \tau \to h\nu$	~42%	$Z \to \tau\tau$, fake τ
$\tau \to h\nu, \tau \to l\nu\nu$	~45%	$Z \to \tau\tau$, fake τ
$\tau \to l\nu\nu, \tau \to l\nu\nu$	~12%	$Z \to \tau\tau$, $Z \to ll$

Main irreducible background

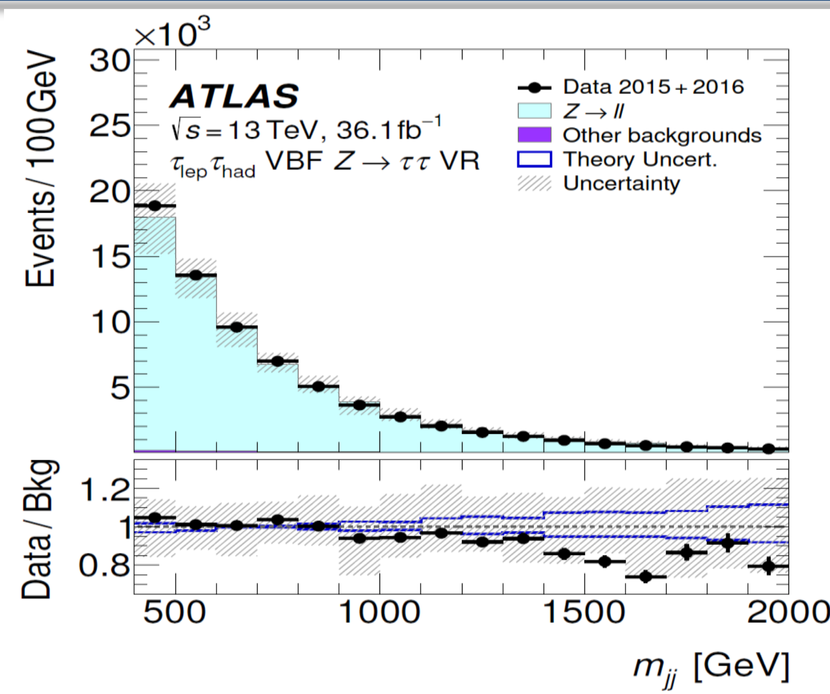
→ Different analysis optimisation is needed

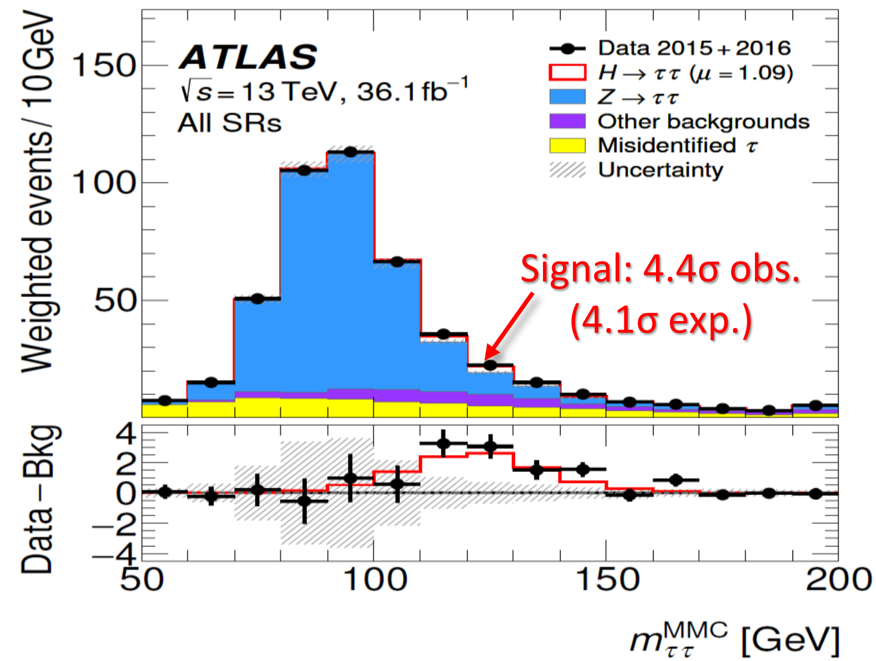
- Missing mass calculator to obtain Di-τ mass Nucl. Instrum. Meth. A 654 (2011) 481
  - Recover missing kinematics
  - Method provides best $m_{\tau\tau}$ resolution
  - → Discriminating variables in the fit



arXiv: 1811.08856; 36.1 fb^{-1}

$H \rightarrow \tau\tau$: Results





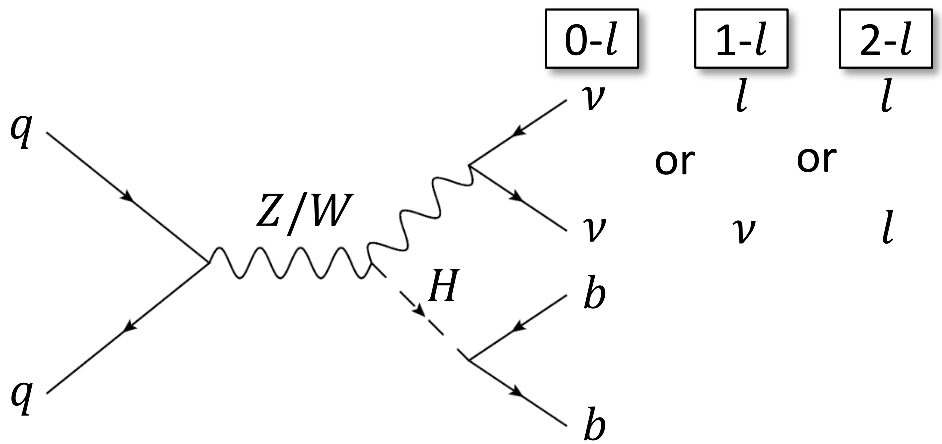
- $Z(\rightarrow \tau\tau)$ + jet to be precisely understood
  - Kinematics affects $m_{\tau\tau}$ shape
  - It is checked with $Z(\rightarrow ll)$ + jet samples

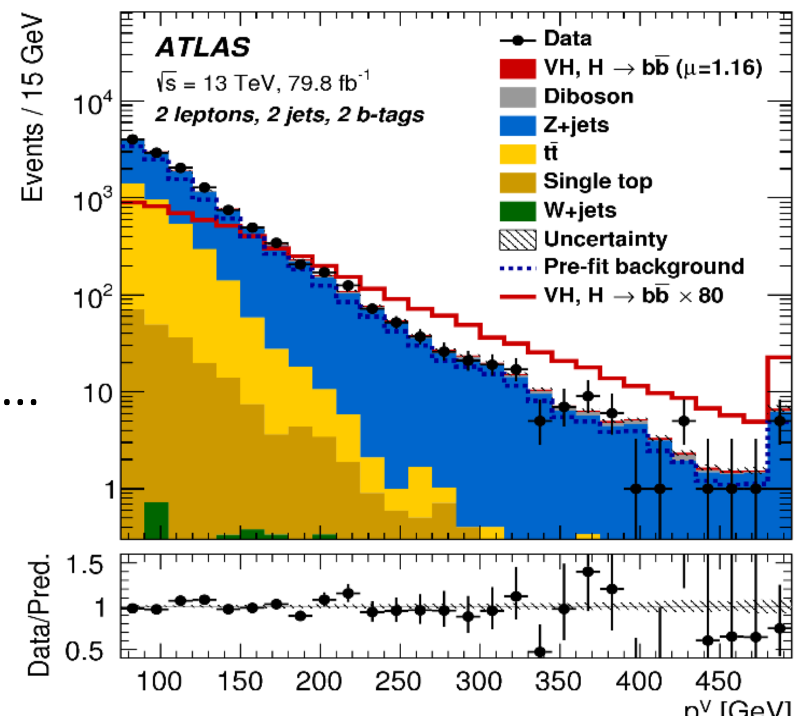
  → MC distributions agree with data within generator uncertainty (Sherpa)
- Run-1 + 2: 6.4σ observed (5.4σ expected)
  - ATLAS standalone observation of $H \rightarrow \tau\tau$
  - STXS is also measured

Phys. Lett. B 786 (2018) 59; 79.8 fb^{-1}

■ $H \to bb$ (VH Production)

- Huge background from $pp \to bb$ (σ_b = O(10^7) times $\sigma_{H\to bb}$!)
  - Use the VH process
    → Small x-sec but much cleaner thanks to V decaying leptonically
- Event categorisation based on $N_{leptons}$

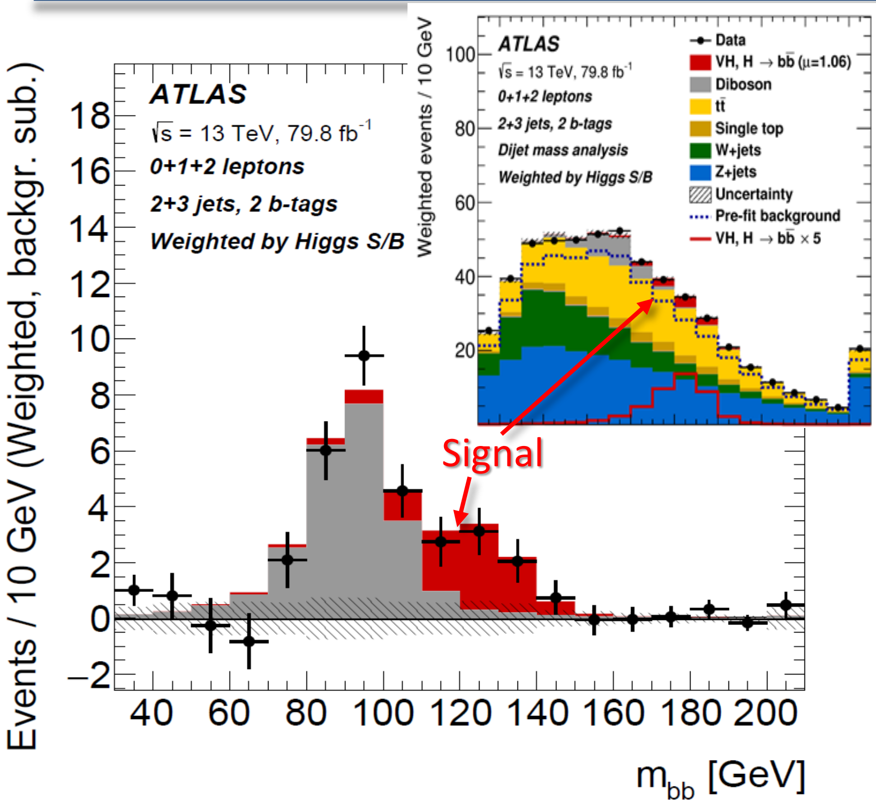


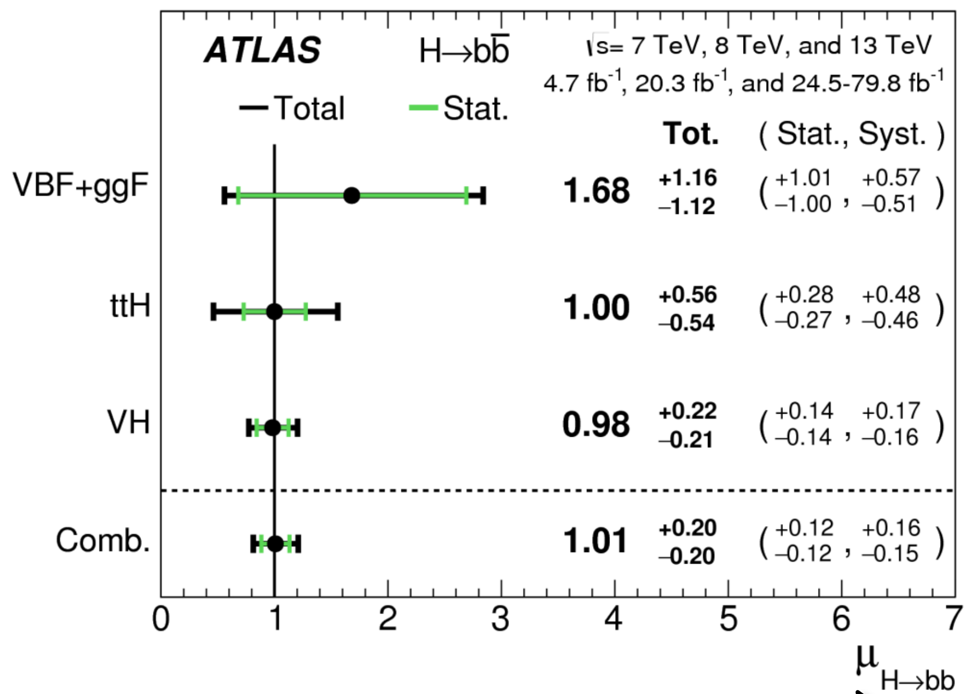


- Multivariate analysis based on BDT
  - Inputs from kinematics: m_{bb}, p_T of V, …
  - Main backgrounds are normalised by control region measurements in combined fit

Phys. Lett. B 786 (2018) 59; 79.8 fb^{-1}

$H \rightarrow bb$: Results





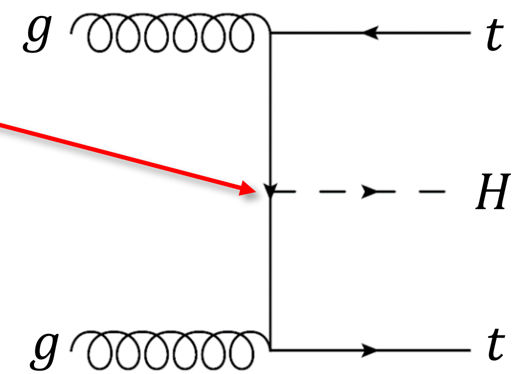
σ/σ_{SM}

- Observed significance of 4.9σ in VH (4.3σ expected)
- Combined with Run-1 result and all the processes,

  First observation of $H \rightarrow bb$ with 5.4σ achieved (5.5σ exp.)
- STXS results on VH(bb) ATLAS-CONF-2018-053

$t\bar{t}H$: Measurement Strategy

- $t\bar{t}H$ to measure the top-Yukawa coupling
  - $H \to tt$ is prohibited (m_H = 125 GeV < m_{tt} = 346 GeV)
  - Small cross-section due to three massive particles
  - Various Higgs decays are used



$H \to \tau\tau, WW^*, ZZ^*$

Results in 2018

Channel	$H \to \gamma\gamma$	$H \to ZZ^*$ (4-l)	$H \to bb$	$H \to$ multi-lep.
BR_{SM}	0.23%	1.2 x 10^{-4}	58%	12.5%
Latest result	79.8 fb^{-1} Phys. Lett. B 784 (2018) 173	79.8 fb^{-1}	36.1 fb^{-1} Phys. Rev. D 97 (2018) 072016	36.1 fb^{-1} Phys. Rev. D 97 (2018) 072003

Good S/N — Large BR

- $H \to$ multi-lepton and $H \to \gamma\gamma$ are sensitive channels

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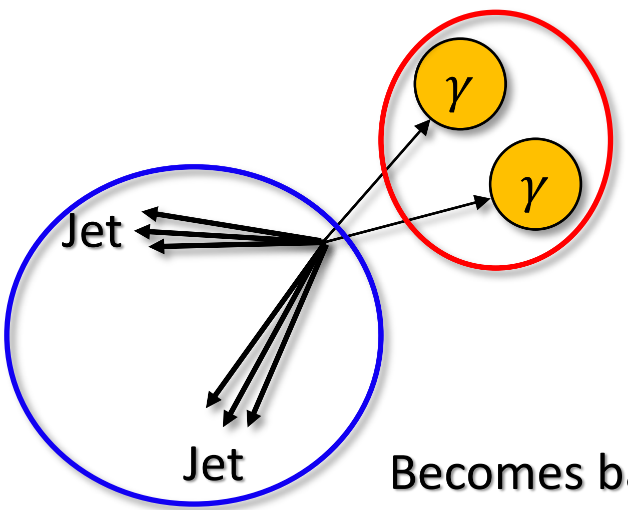
$t\bar{t}H$: $H \rightarrow \gamma\gamma$

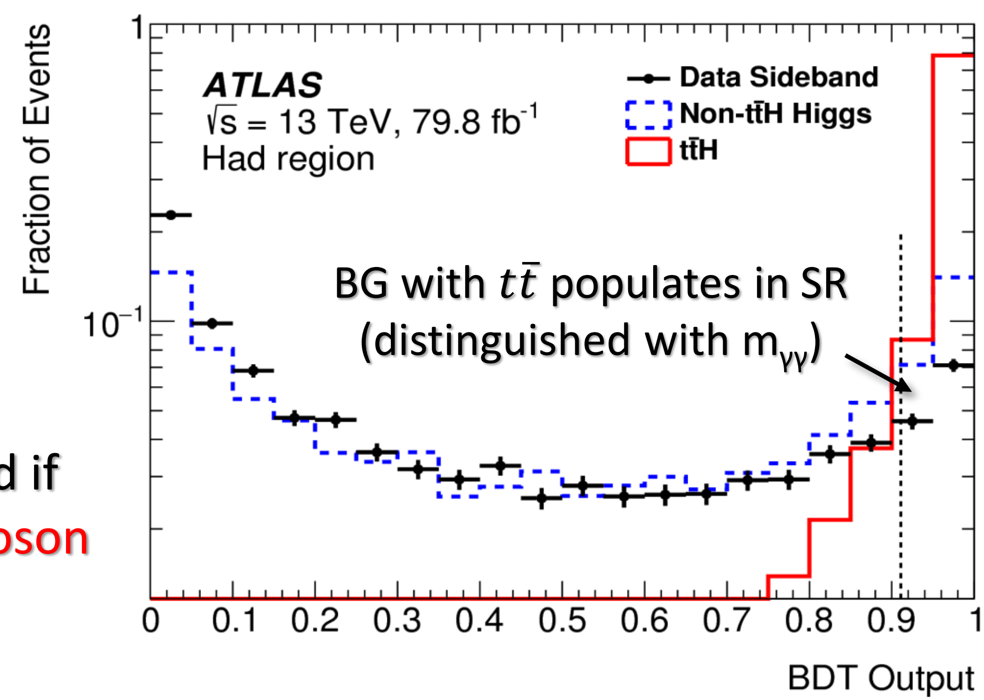
- Categorisation depending on t-quark decay

Channel	Hadronic	Leptonic
Requirement	≥2 jets + 2 b-jets 0 l (isolated)	2 b-jets 1 l (isolated)
Targetted t decay	$t \rightarrow bW(\rightarrow qq)$ $t \rightarrow bW(\rightarrow qq)$	$t \rightarrow bW(\rightarrow qq)$ $t \rightarrow bW(\rightarrow l\nu)$

- Main BG: jets + $\gamma\gamma$ background



Becomes background if $\gamma\gamma$ mimics a Higgs boson and jets as a $t\bar{t}$ pair



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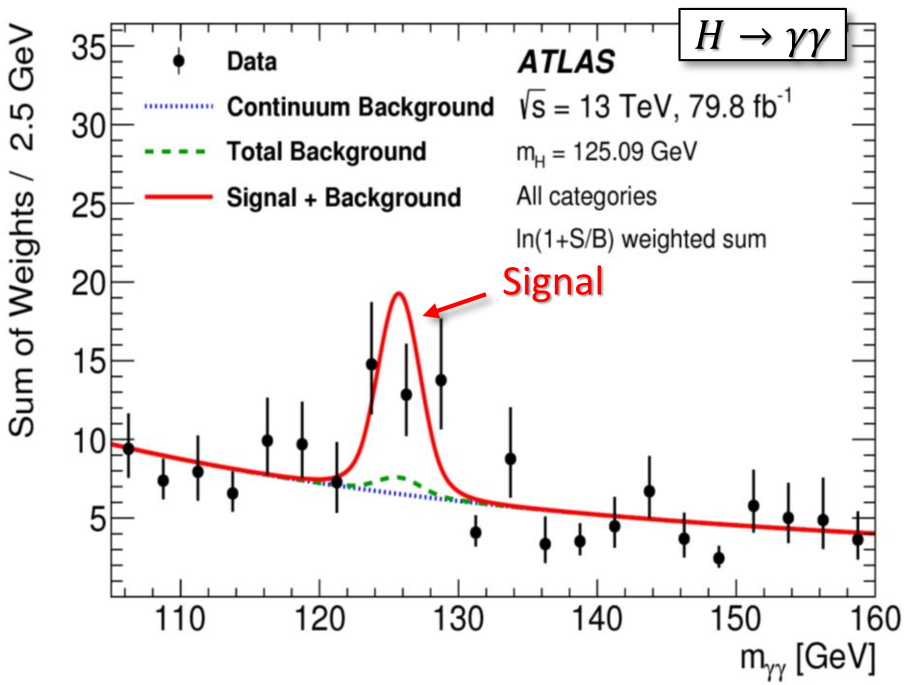
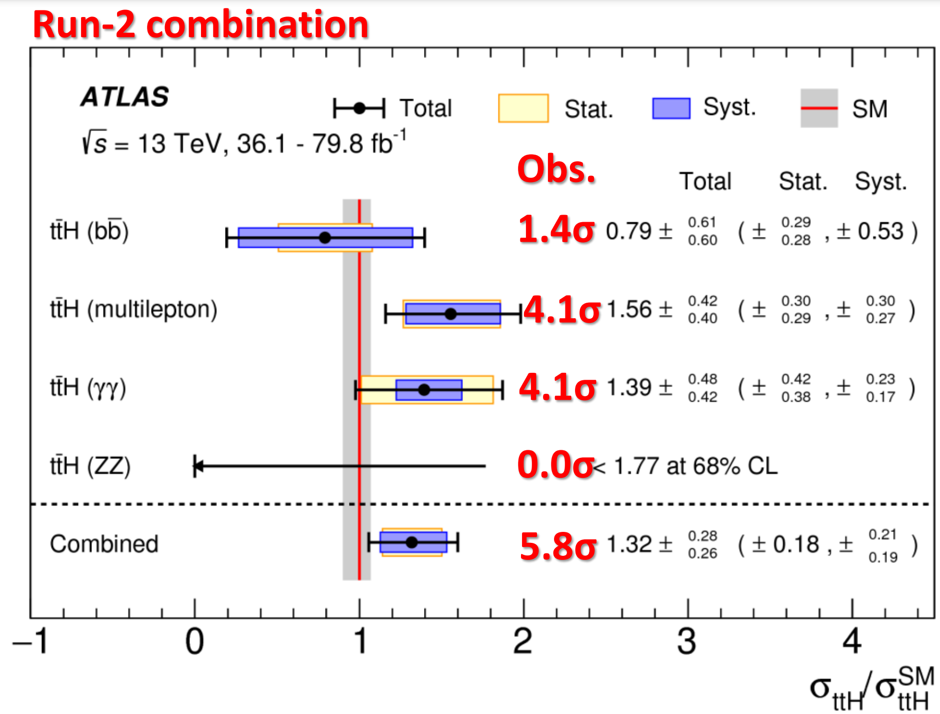
■ $t\bar{t}H$: Results





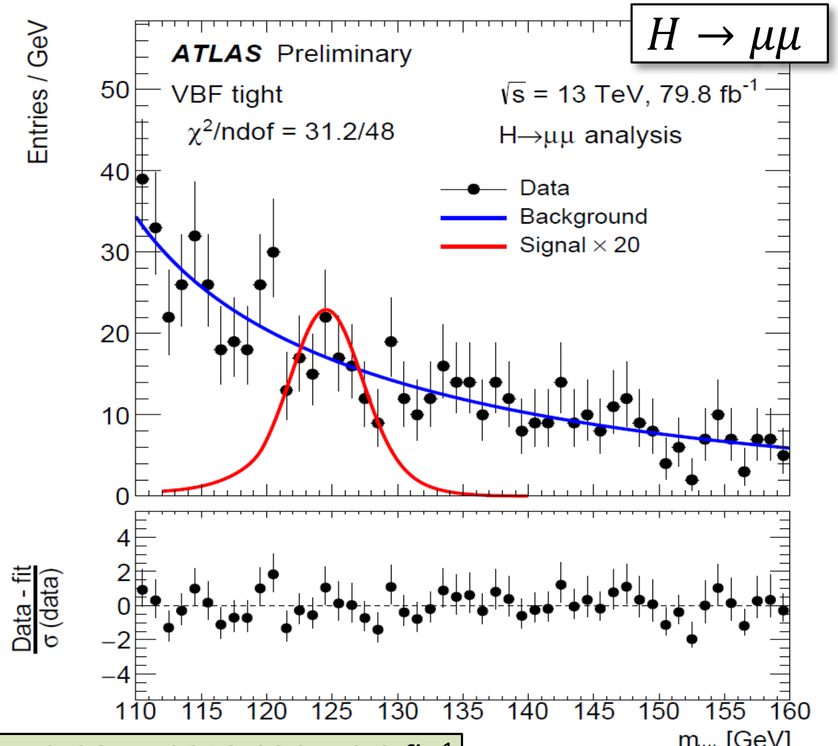
- First evidence of the $t\bar{t}H(\to \gamma\gamma)$ process
  - Observed significance is 4.1σ (3.7σ expected)
- Combination with other three channels (Run-1 + 2):

6.3σ observed (5.1σ expected)

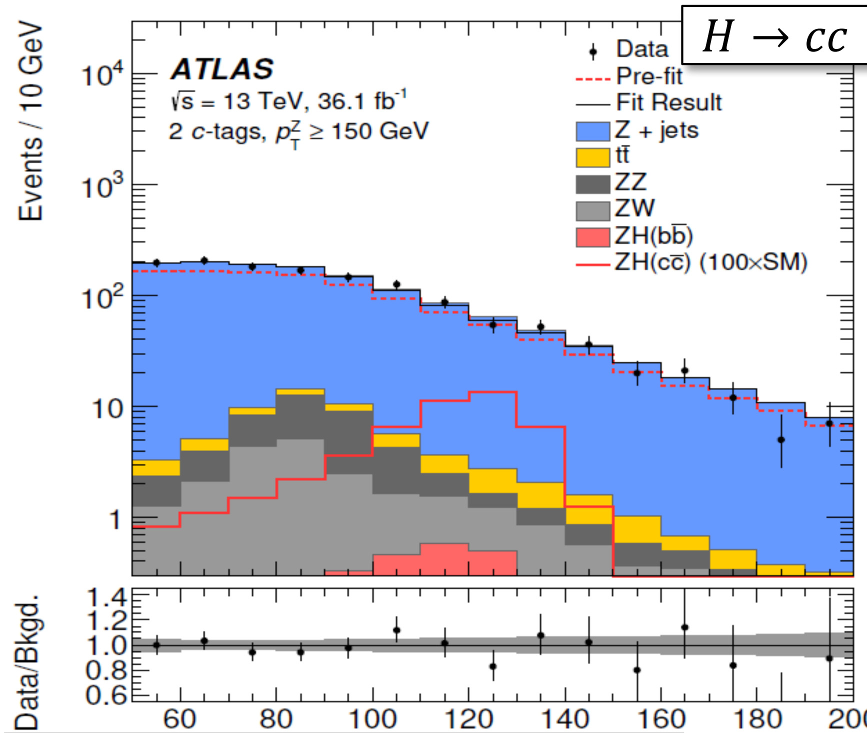
Observation of the $t\bar{t}H$ production at ATLAS

■ Second Generation: $H \to \mu\mu$ and cc

- BRs are small because of small mass
  - $H \to \mu\mu$ has clear di-μ signature but small BR: $BR_{\mathrm{SM}} = 2.1 \times 10^{-4}$
  - $H \to cc$ is very difficult in c-jet separation from b- and light-jets (Repurposed ZH(bb) analysis with c-tagger instead of b-tagger)



ATLAS-CONF-2018-026; 79.8 fb^{-1}



Phys. Rev. Lett. 120 (2018) 211802; 79.8 fb^{-1}

$\mu < 2.1$ (95% C.L.)

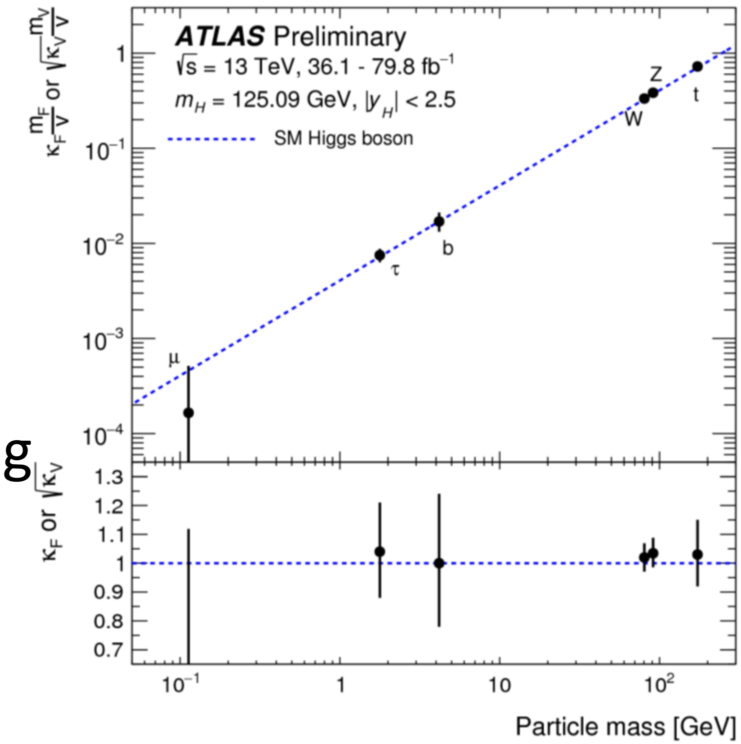
$\mu < 110$ (95% C.L.)

Confirmation is possible by high-lumi. LHC (2026-) ATL-PHYS-PUB-2018-006

■ Summary and Prospects

ATLAS-CONF-2018-031

- Results from 36.1-79.8 fb^{-1} data are presented at $\sqrt{s}$ = 13 TeV
  - Most of them are included in the latest experimental combination by ATLAS



- ATLAS established Higgs-boson coupling to the 3-gen fermions
  - Measured couplings are consistent with the SM prediction

- We have more data: 140.5 fb^{-1} are collected at $\sqrt{s}$ = 13 TeV
  - More interesting results with more statistics will be coming soon

$H \to \tau\tau$: Triggers and Cuts

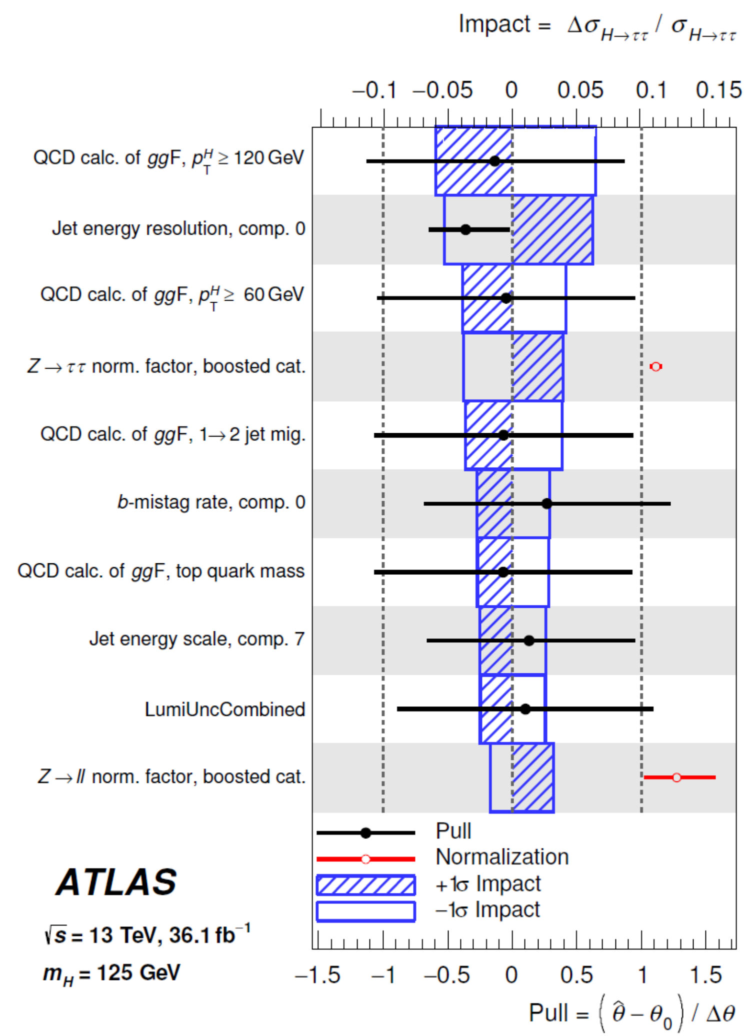
- Triggers and cuts

Analysis channel	Trigger	Analysis p_T requirement [GeV] 2015	2016
$\tau_{lep}\tau_{lep}$ & $\tau_{lep}\tau_{had}$	Single electron	25	27
	Single muon	21	27
$\tau_{lep}\tau_{lep}$	Dielectron	15 / 15	18 / 18
	Dimuon	19 / 10	24 / 10
	Electron+muon	18 / 15	18 / 15
$\tau_{had}\tau_{had}$	Di-$\tau_{had\text{-}vis}$	40 / 30	40 / 30

$\tau_{lep}\tau_{lep}$ $ee/\mu\mu$	$\tau_{lep}\tau_{lep}$ $e\mu$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
$N_{e/\mu}^{loose} = 2$, $N_{\tau_{had\text{-}vis}}^{loose} = 0$		$N_{e/\mu}^{loose} = 1$, $N_{\tau_{had\text{-}vis}}^{loose} = 1$	$N_{e/\mu}^{loose} = 0$, $N_{\tau_{had\text{-}vis}}^{loose} = 2$
e/μ : Medium, gradient iso.		e/μ : Medium, gradient iso.	
		$\tau_{had\text{-}vis}$: Medium	$\tau_{had\text{-}vis}$: Tight
Opposite charge		Opposite charge	Opposite charge
$m_{\tau\tau}^{coll} > m_Z - 25$ GeV		$m_T < 70$ GeV	
$30 < m_{\ell\ell} < 75$ GeV	$30 < m_{\ell\ell} < 100$ GeV		
$E_T^{miss} > 55$ GeV	$E_T^{miss} > 20$ GeV	$E_T^{miss} > 20$ GeV	$E_T^{miss} > 20$ GeV
$E_T^{miss,\ hard} > 55$ GeV			
$\Delta R_{\tau\tau} < 2.0$		$\Delta R_{\tau\tau} < 2.5$	$0.8 < \Delta R_{\tau\tau} < 2.5$
$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$		$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$	$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$
$0.1 < x_1 < 1.0$		$0.1 < x_1 < 1.4$	$0.1 < x_1 < 1.4$
$0.1 < x_2 < 1.0$		$0.1 < x_2 < 1.2$	$0.1 < x_2 < 1.4$
$p_T^{j_1} > 40$ GeV		$p_T^{j_1} > 40$ GeV	$p_T^{j_1} > 70$ GeV, $\lvert\eta_{j_1}\rvert < 3.2$
$N_{b\text{-jets}} = 0$		$N_{b\text{-jets}} = 0$	

$H \to \tau\tau$: Systematic Uncertainties

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ [%] Observed	Expected
Theoretical uncert. in signal	+13.4 / −8.7	+12.0 / −7.8
Background statistics	+10.8 / −9.9	+10.1 / −9.7
Jets and E_T^{miss}	+11.2 / −9.1	+10.4 / −8.4
Background normalization	+6.3 / −4.4	+6.3 / −4.4
Misidentified τ	+4.5 / −4.2	+3.4 / −3.2
Theoretical uncert. in background	+4.6 / −3.6	+5.0 / −4.0
Hadronic τ decays	+4.4 / −2.9	+5.5 / −4.0
Flavor tagging	+3.4 / −3.4	+3.0 / −2.3
Luminosity	+3.3 / −2.4	+3.1 / −2.2
Electrons and muons	+1.2 / −0.9	+1.1 / −0.8
Total systematic uncert.	+23 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −25	+27 / −24



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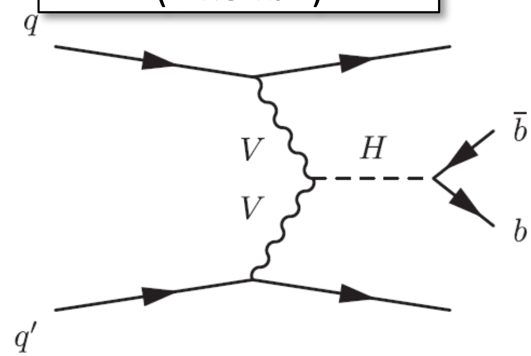
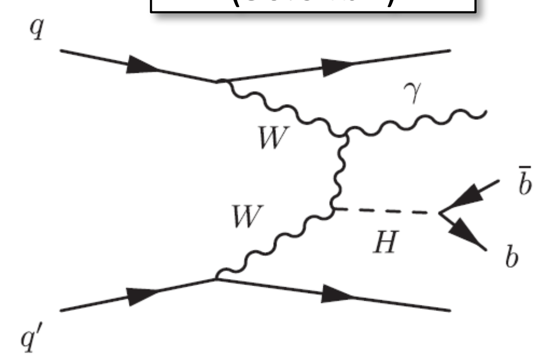
■ $H \to bb$ (VBF Production)

- Two channels

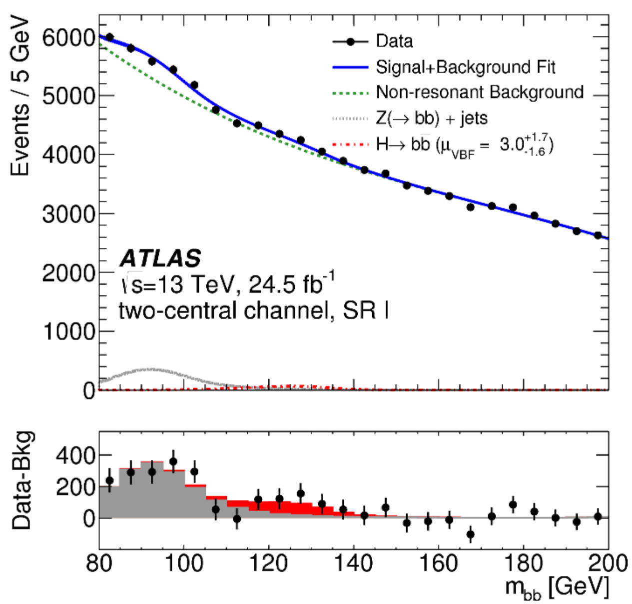
All-hadronic channel (24.5 fb^{-1})

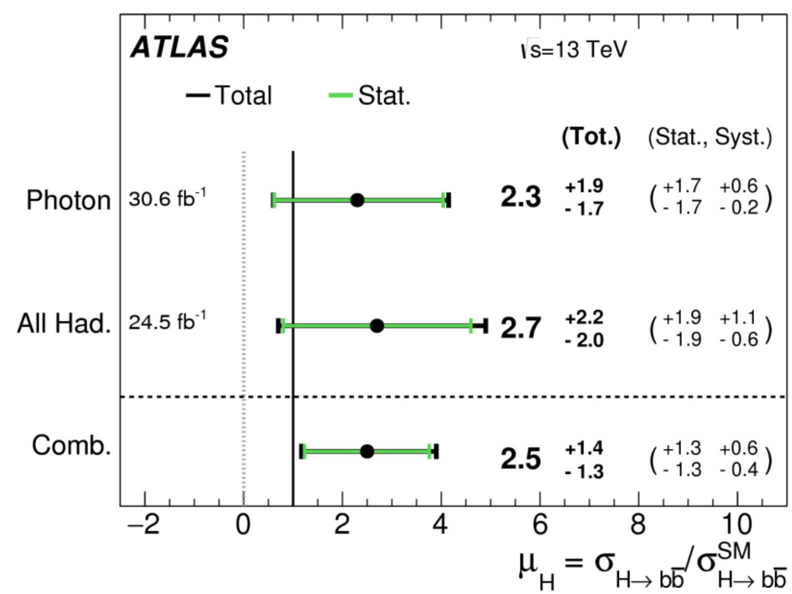


Photon channel (30.6 fb^{-1})



- BDT is trained w.r.t. main backgrounds
  - Non-resonant multi jets (+ photon in the case of the photon channel)





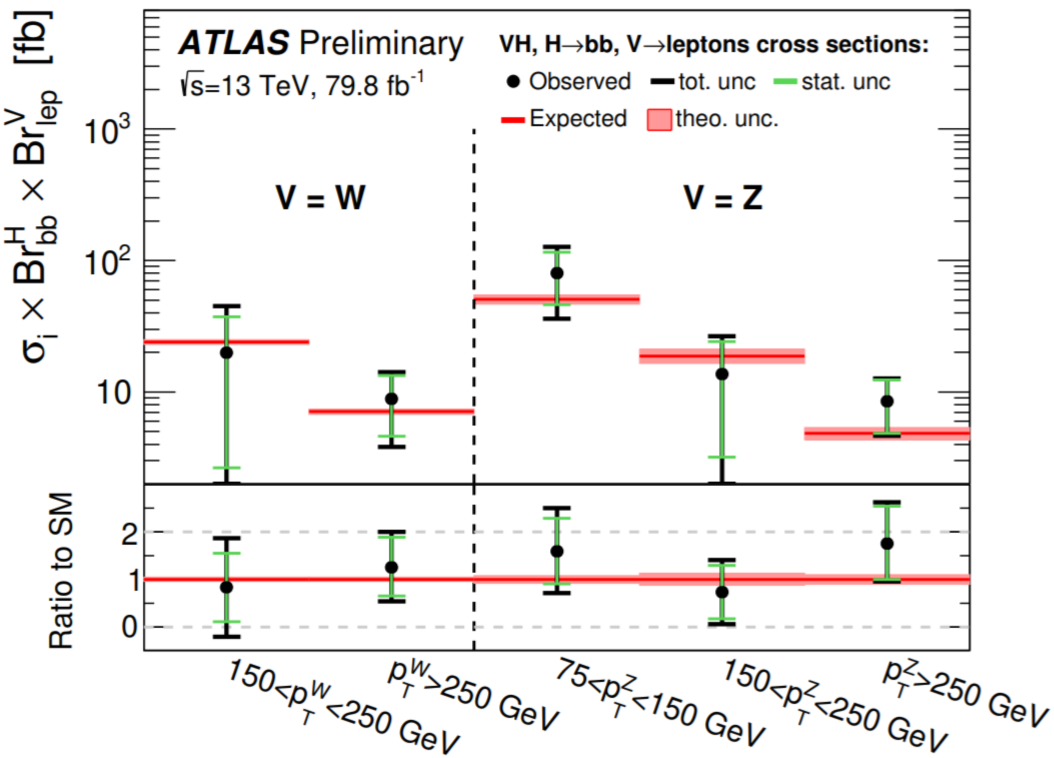
Stage-1 STXS Results

- $H \rightarrow \tau\tau$ arXiv: 1811.08856; 36.1 fb^{-1}

Process	Particle-level selection	σ [pb]	σ^{SM} [pb]
ggF	$N_{jets} \geq 1$, $60 < p_T^H < 120$ GeV, $\lvert y_H \rvert < 2.5$	1.79 ± 0.53 (stat.) ± 0.74 (syst.)	0.40 ± 0.05
ggF	$N_{jets} \geq 1$, $p_T^H > 120$ GeV, $\lvert y_H \rvert < 2.5$	0.12 ± 0.05 (stat.) ± 0.05 (syst.)	0.14 ± 0.03
VBF	$\lvert y_H \rvert < 2.5$	0.25 ± 0.08 (stat.) ± 0.08 (syst.)	0.22 ± 0.01

In good agreement with the SM expectation

- $H \rightarrow bb$ ATLAS-CONF-2018-053



Phys. Lett. B 786 (2018) 59; 79.8 fb^{-1}

$H \to bb$: Systematic Uncertainties

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