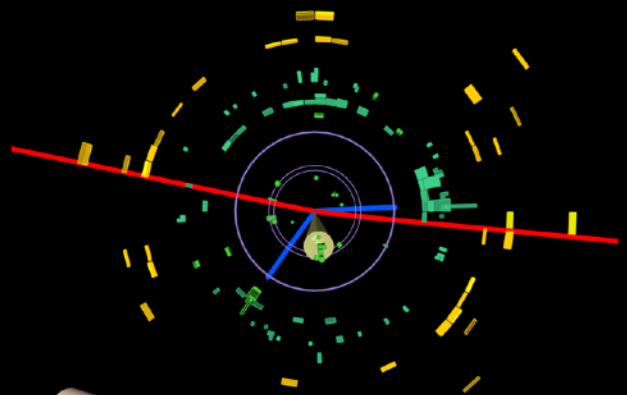
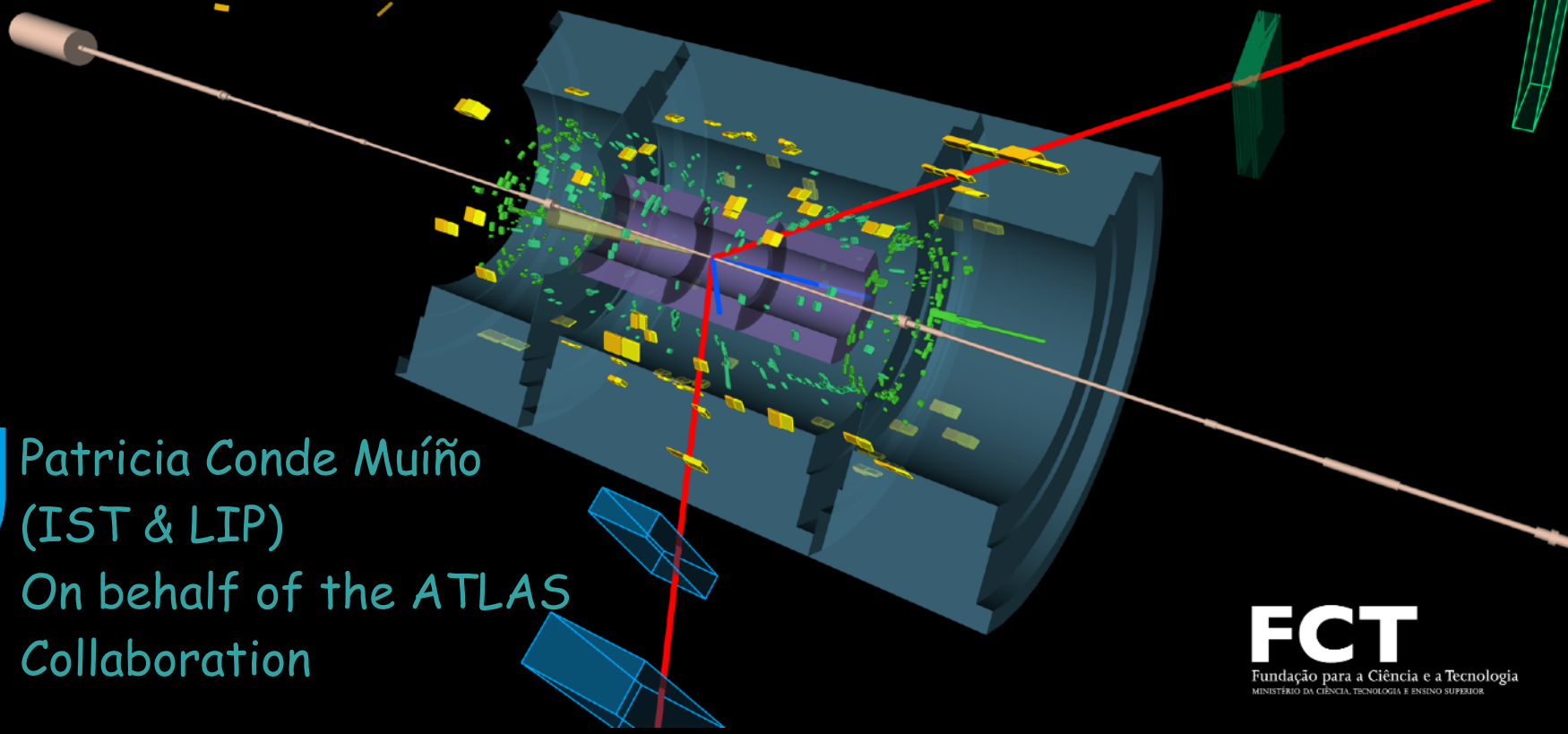
Overview of Higgs Physics results at ATLAS





Patricia Conde Muíño
(IST & LIP)
On behalf of the ATLAS Collaboration

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

SM Higgs Lagrangian

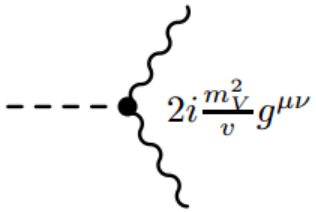
$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

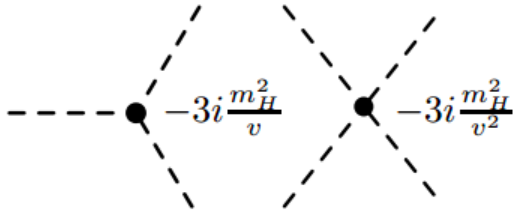
Couplings to EW gauge bosons

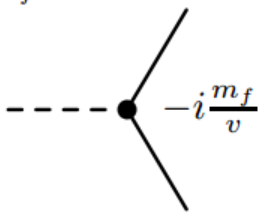
Higgs self-couplings

Couplings to fermions

$$\left[m_W^2 W^{\mu+} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \tfrac{h}{v}\right)^2 \qquad -\mu^2 h^2 - \tfrac{\lambda}{2} v h^3 - \tfrac{1}{8}\lambda h^4 \qquad -\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



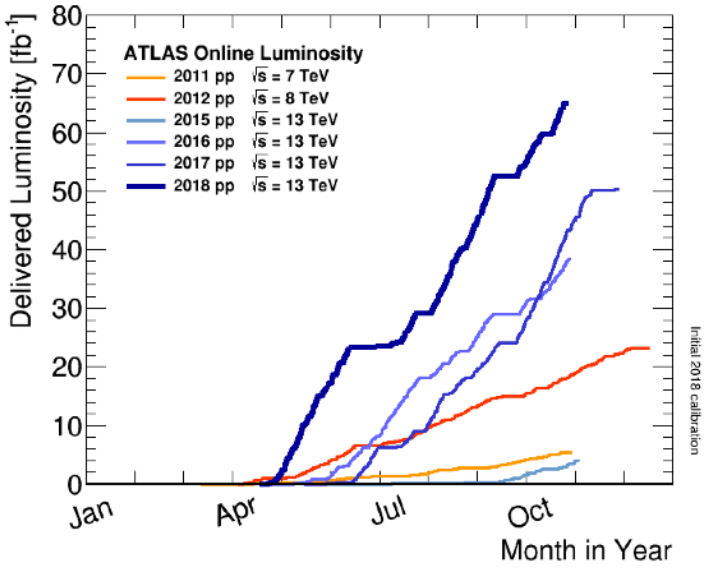


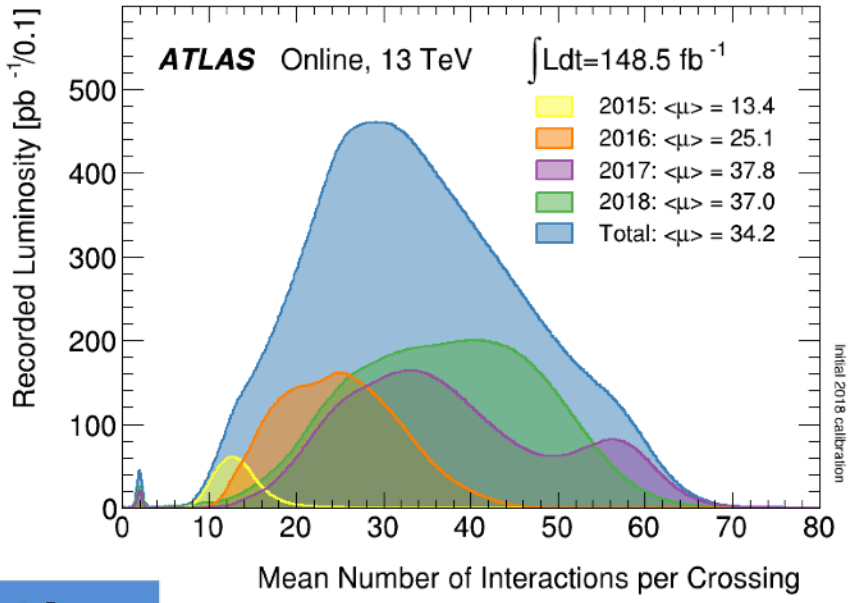


$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value})$$

- ★ Would like to probe the SM predictions by
  - ★ Measuring the Higgs properties: mass, spin & CP, …
  - ★ Couplings and interactions: probe each term in the Lagrangian

ATLAS and LHC operation





ATLAS pp data: April 25-October 24 2018

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.8	100	99.7	100	99.8	99.7	100	100	100	99.6

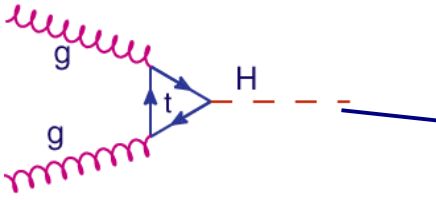
Good for physics: 97.5% (60.1 fb^{-1})

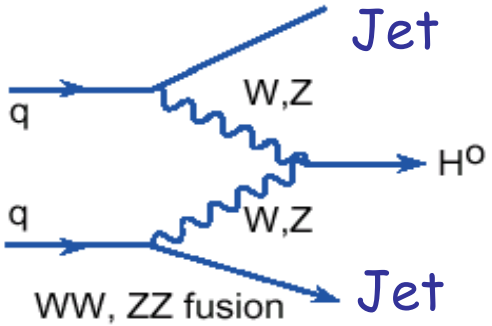
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions at √s=13 TeV between April 25 – October 24 2018, corresponding to a delivered integrated luminosity of 63.8 fb^{-1} and a recorded integrated luminosity of 61.7 fb^{-1}. Dedicated luminosity calibration activities during LHC fills used 0.7% of recorded data and are included in the inefficiency. The luminosity includes 193 pb^{-1} of good data taken at an average pileup of μ=2.

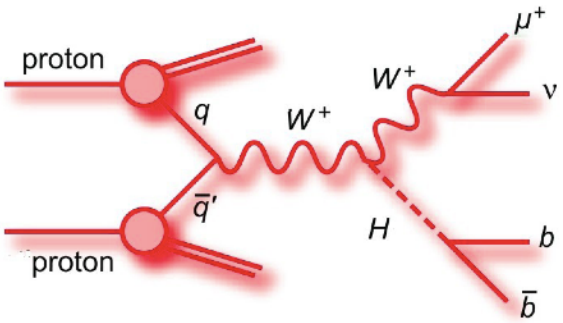
★ Integrated luminosity
- ➡ 158 fb^{-1} delivered
- ➡ 140 recorded

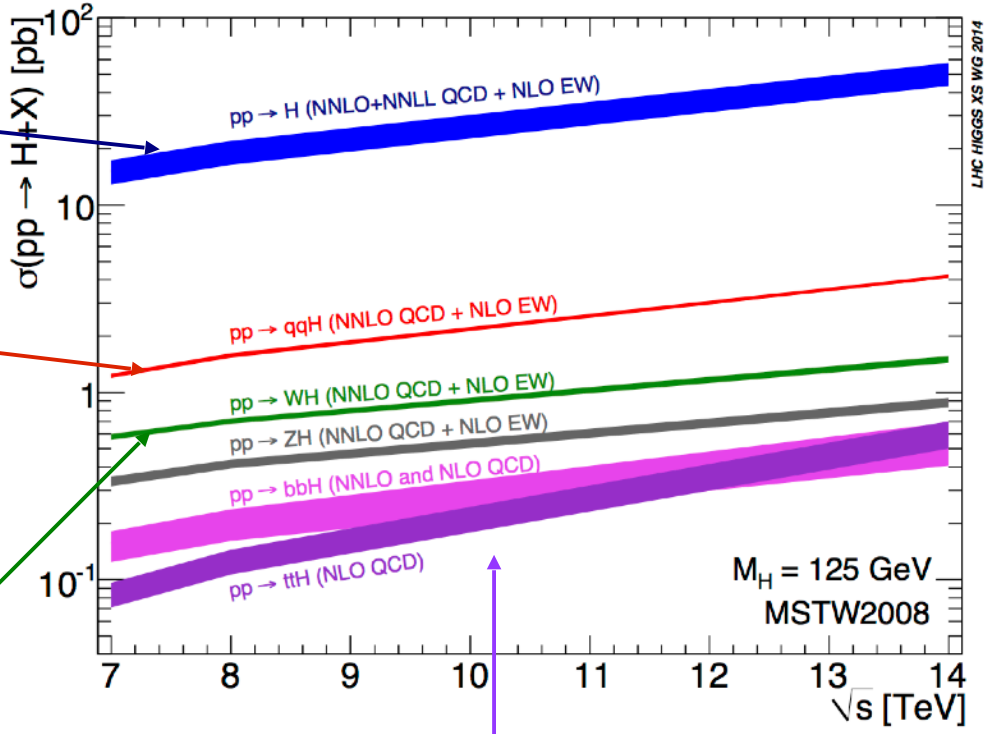
★ Average pile-up at 13 TeV
- ➡ 34.2 interactions/BX

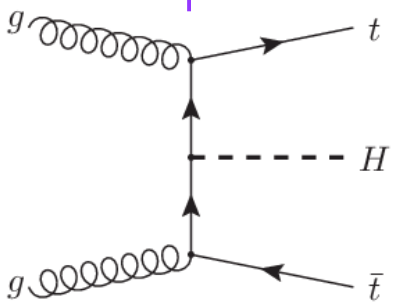
Higgs production at the LHC











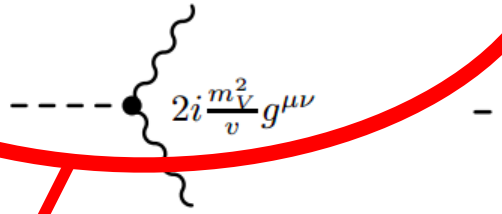
At the LHC… can only measure production and decay together

Higgs coupling to vector bosons

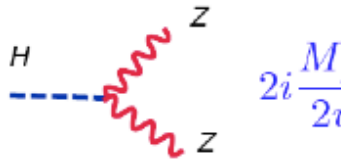
$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger$

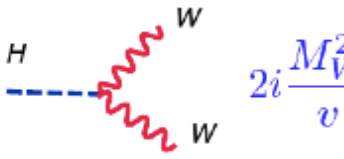
Couplings to
EW gauge bosons

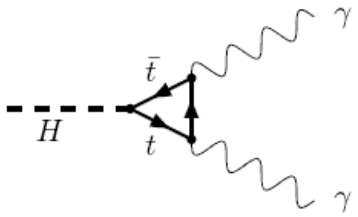
$[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0] \cdot (1 + \frac{h}{v})^2$



$m_H = \sqrt{2}\mu = \sqrt{\lambda}v \ (v =$







- ★ H → WW
- ★ H → ZZ
- ★ H → γγ

- ★ First observation
- ★ Cross sections at 7, 8 and 13 TeV
- Differential distributions

Phys. Lett. B 784 (2018) 345

Phys. Lett. B 786 (2018) 114

Phys. Lett. B 786 (2018) 223

HEP 10 (2017) 132

Phys. Rev. D 98 (2018) 052005

ATLAS-CONF-2018-018

JHEP 03 (2018) 095

ATLAS-CONF-2018-018/

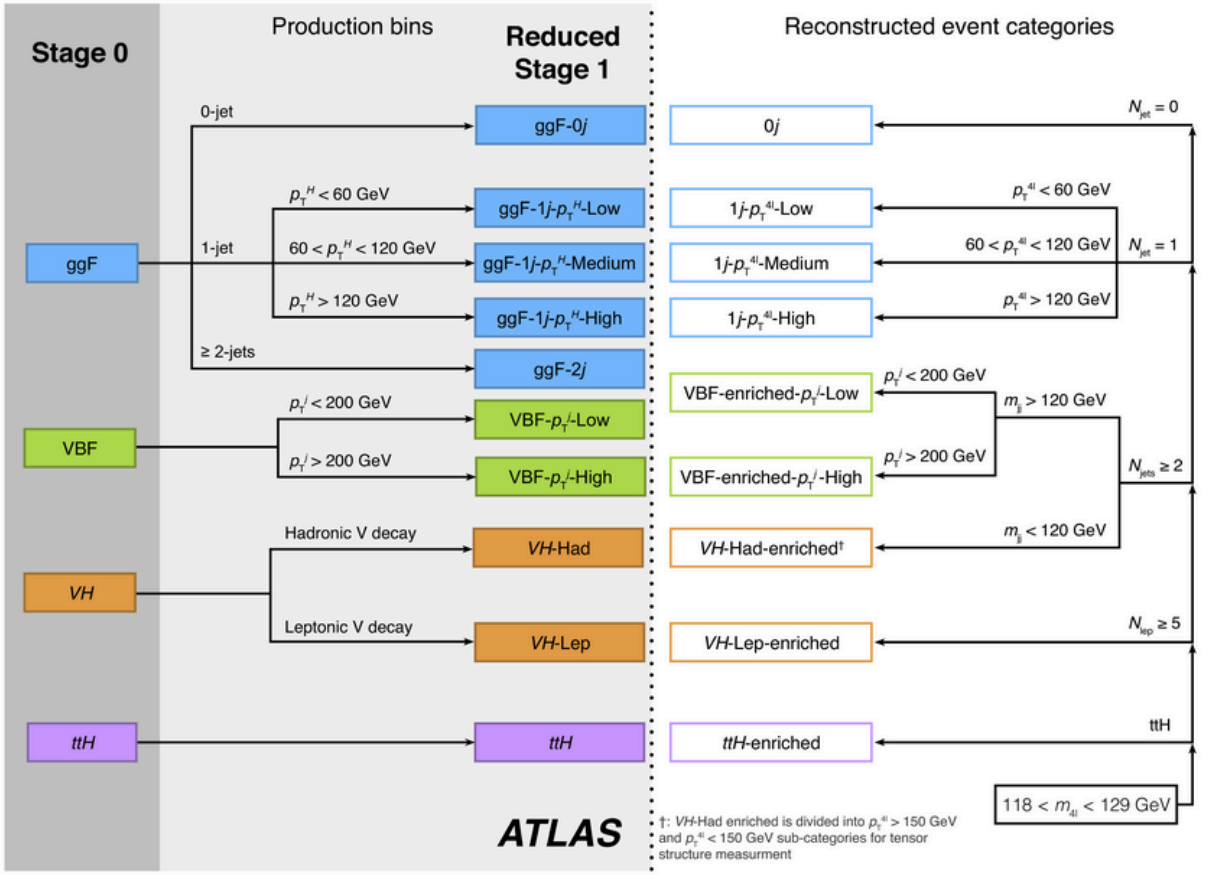
Phys. Lett. B 789 (2019) 508

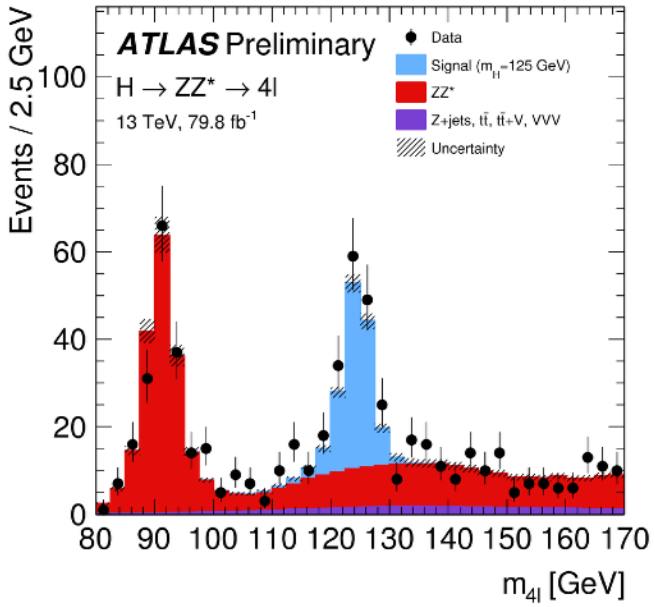
H→ZZ* →4ℓ cross section measurements

ATLAS-CONF-2018-018

★ Simplified template cross section (STXS)

➡ Definition of production bins



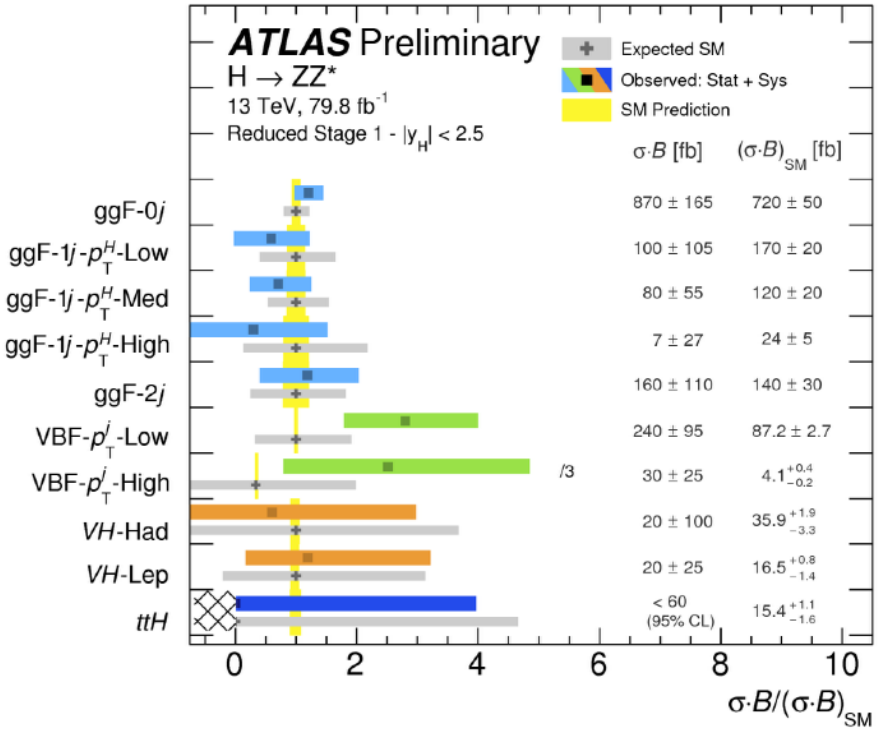


★ BDT used for discrimination of various production modes

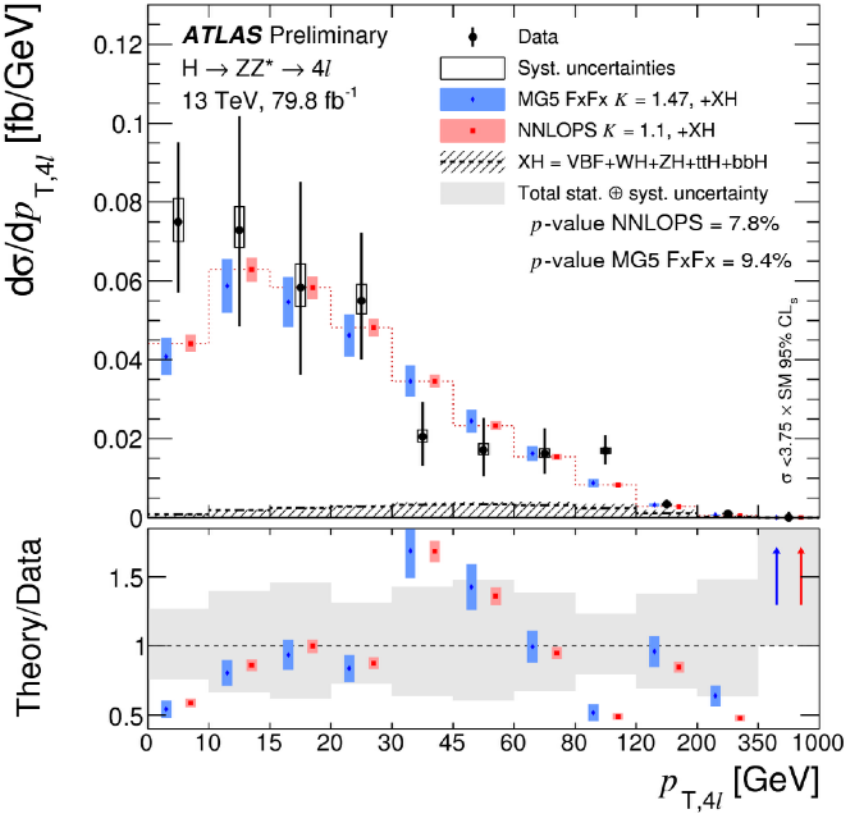
★ Fit templates for signal & background in each event category

$H \to ZZ^* \to 4\ell$ cross section measurements

★ Simplified template cross section stage 1



★ Fiducial differential cross section vs $p_T^{4\ell}$



★ Many more distributions in ATLAS-CONF-2018-018

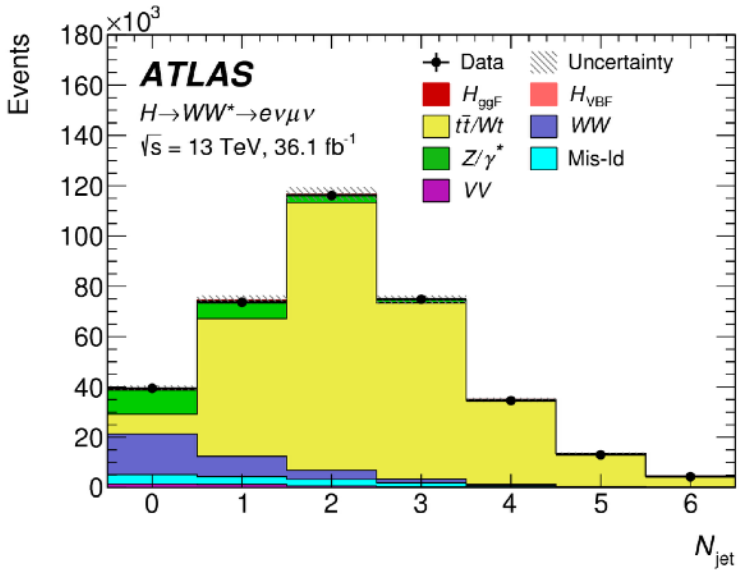
H→WW* →$e\nu\mu\nu$

Phys. Lett. B 789 (2019) 508

★ Run 2 analysis with 36 fb^{-1}

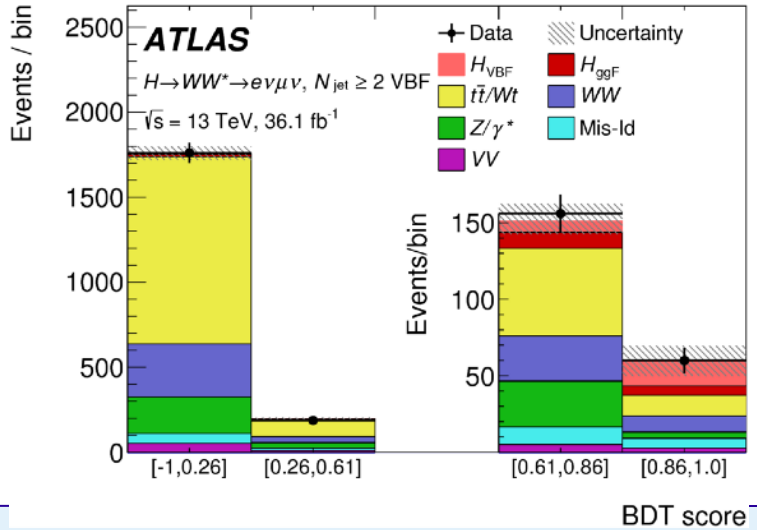
★ H→WW* →$e\nu\mu\nu$ analysis

- ➡ Second largest BR (22%)
- ➡ Clean signature: 2 leptons, large E_T^{miss}
- ➡ Many SM backgrounds
  - Non-resonant WW, top, Z→$\tau\tau$ normalised using CR
  - Mis-identified leptons fully data driven



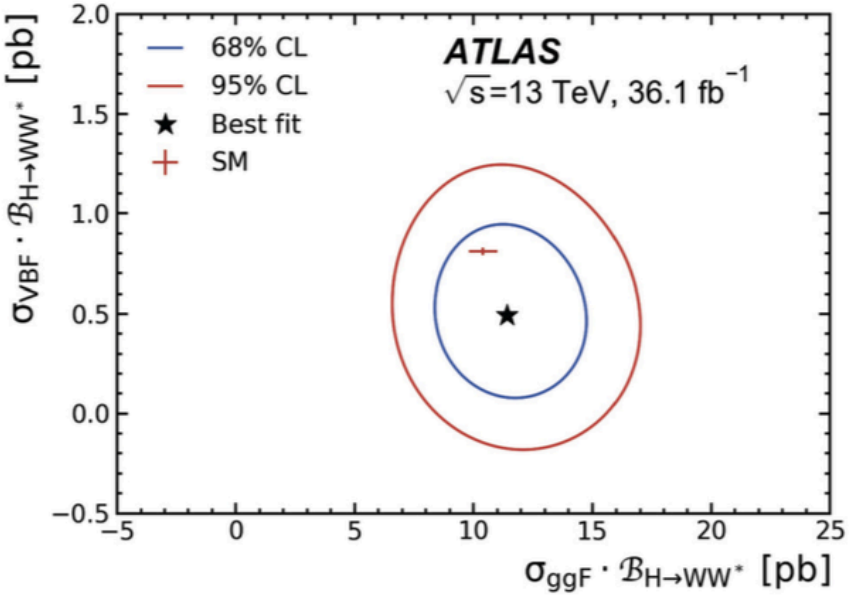
★ VBF category

- ➡ Use number of jets to separate from ggF, central jet veto, require central Higgs decay
- ➡ Enhanced with a BDT that combines event topological variables
- ➡ 4 BDT event categories



Coupling measurement in H→WW* →$e\nu\mu\nu$

- ★ Combined fit
  - ➡ m_T in ggF, 16 SR categories
  - ➡ BDT in VBF, 4 categories
  - ➡ 1 parameter of interest per production mode
- ★ Dominating uncertainties
  - ➡ VBF: statistics
  - ➡ ggF: systematics (12% theory, 12% experiment)
- ★ Results compatible with SM with 1σ

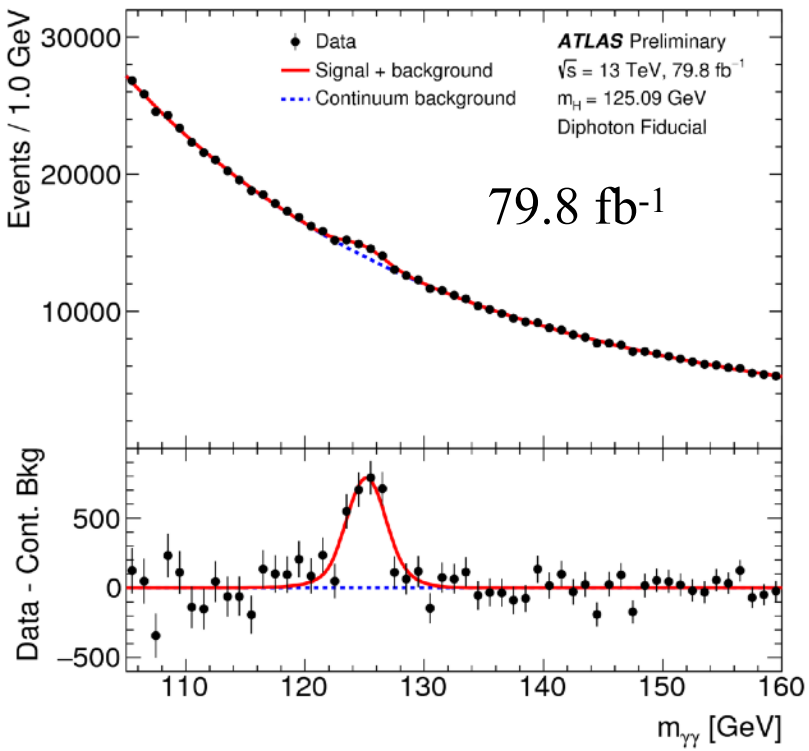


$$\mu_{\mathrm{ggF}} = 1.10^{+0.10}_{-0.09}(\mathrm{stat.})^{+0.13}_{-0.11}(\mathrm{theo\ syst.})^{+0.14}_{-0.13}(\mathrm{exp\ syst.}) = 1.10^{+0.21}_{-0.20}$$

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

H→γγ cross section measurements

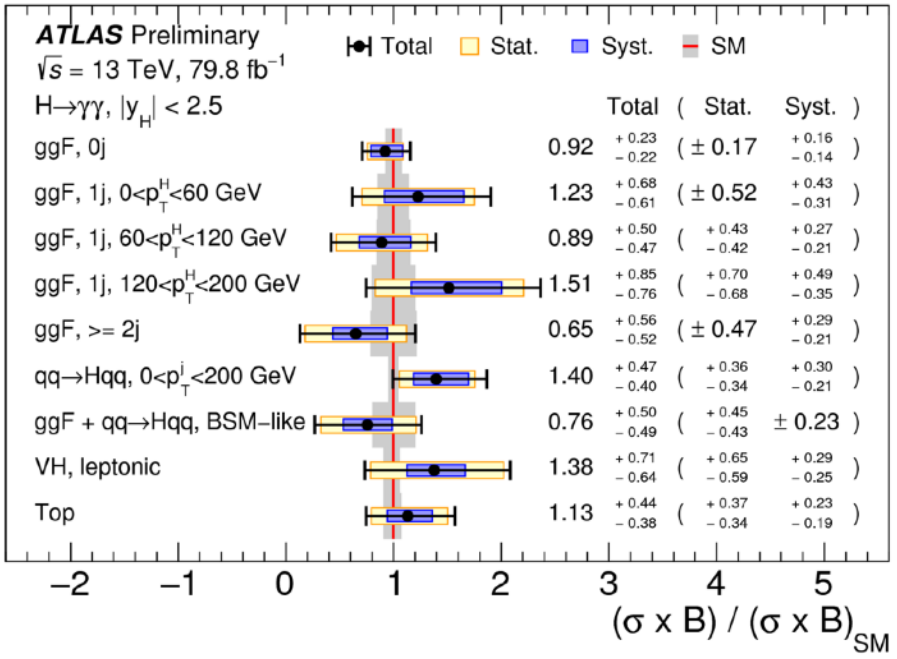
ATLAS-CONF-2018-028



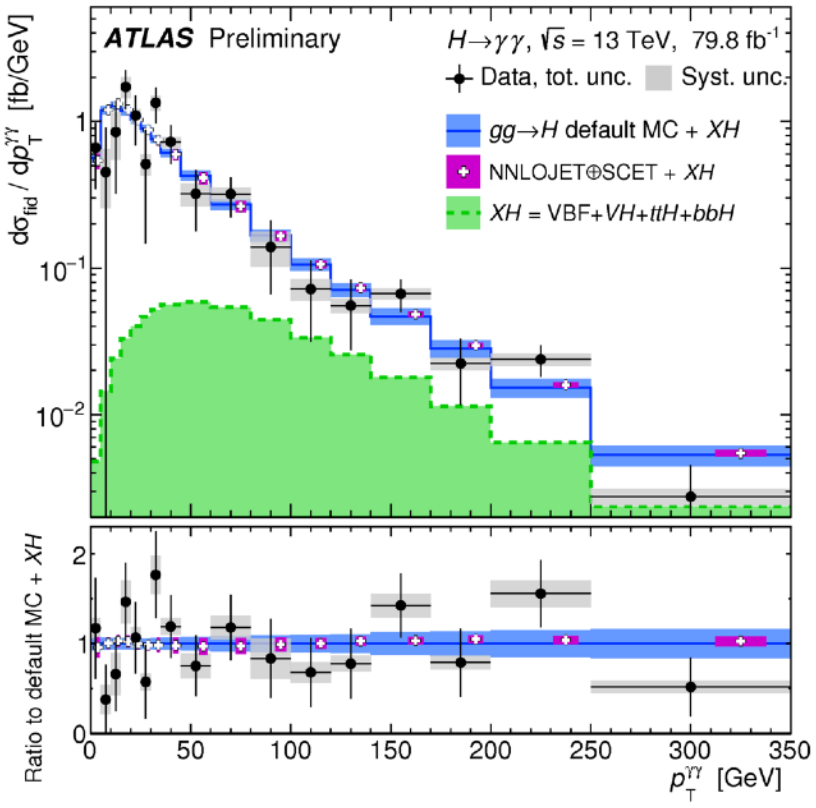
★ Fiducial inclusive and differential cross section measurements with 79.8 fb-1

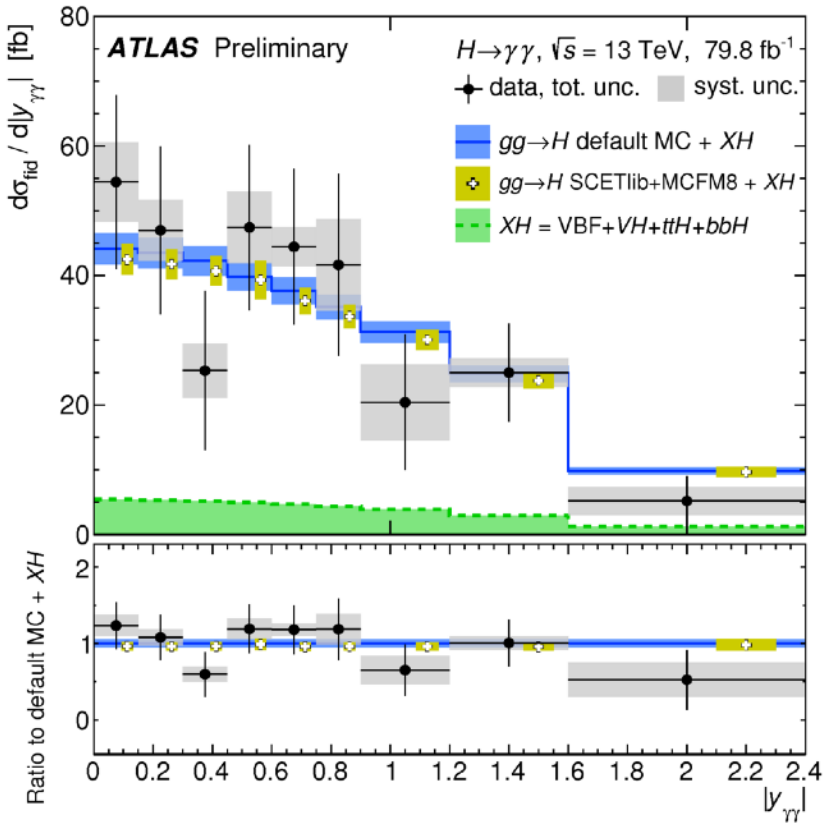
$$\sigma_{\text{fid}} = 60.4 \pm 6.1\,(\text{stat.}) \pm 6.0\,(\text{exp.}) \pm 0.3\,(\text{theo.})\ \text{fb}$$

SM prediction 63.5 ± 3.3 fb



H→γγ cross section measurements





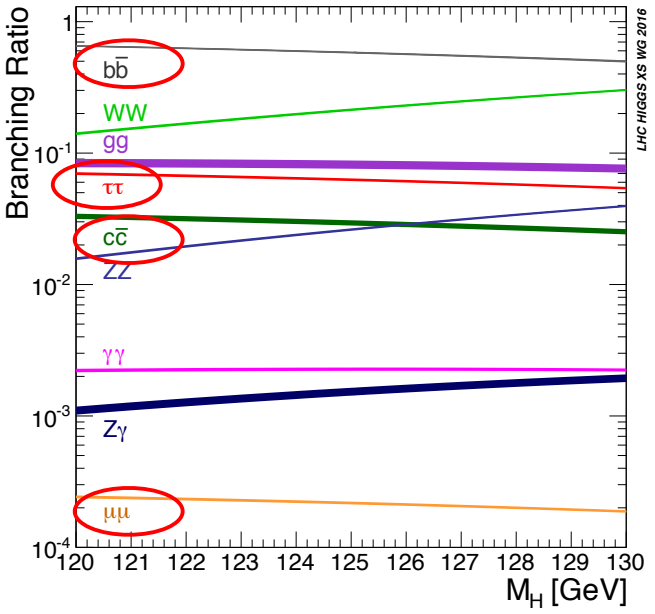
★ Precision improved with respect to previous measurements

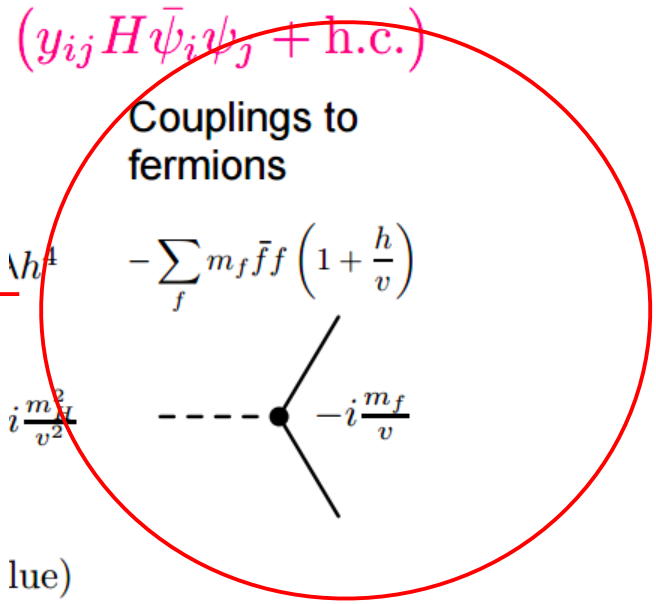
➡ But still statistics limited

★ All results compatible with SM predictions

Higgs couplings to fermions

- ★ Couplings to fermions
- ★ Experimental measurements:
  - Decay rates to quarks & leptons
  - ttH associated production
  - Indirect: gg fusion production mode
    - But model dependent —> need direct probes!
  - Rare decays





Phys. Lett. B 786 (2018) 134

Phys. Rev. Lett. 120 (2018) 211802

Phys. Lett. B 786 (2018) 59

Phys. Rev. D 98 (2018) 052003

ATLAS-CONF-2018-053 ATLAS-CONF-2018-026

arXiv:1811.08856 Phys. Lett. B 784 (2018) 173

H→bb decay

★H→bb:

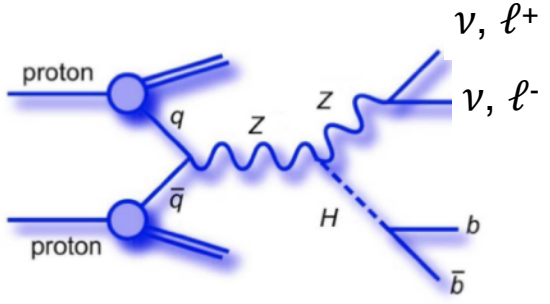
- Largest BR in the SM (~58%)
- Huge background —> use non-dominant production

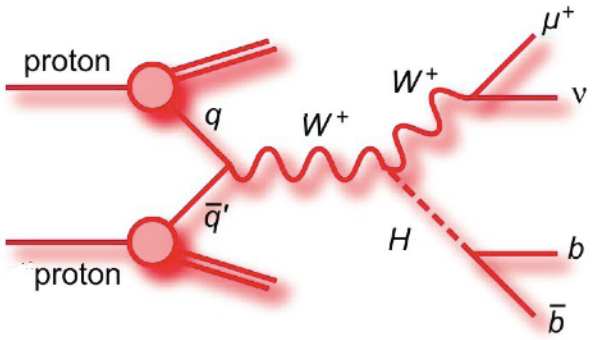
★WH and ZH associated production (VH)

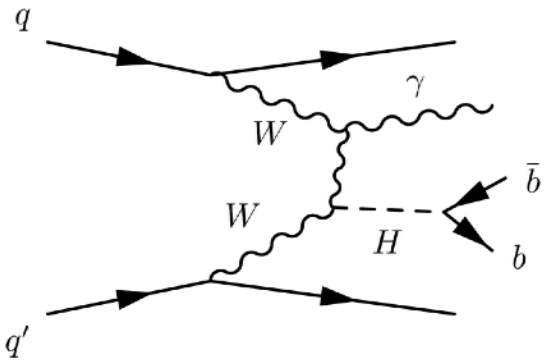
- Three different channels: 0, 1 and 2 charged leptons
- Boosted regime (high p_T^V) improves S/B
- Analysis categories:
  - 2/3 jets (0/1lepton)
  - 2/≥3jets (2lept.)
  - p_T^V bins

★VBF analysis

- Considered final states with/out additional γ
  - Final state photon helps reducing the background due to interference effects for the background





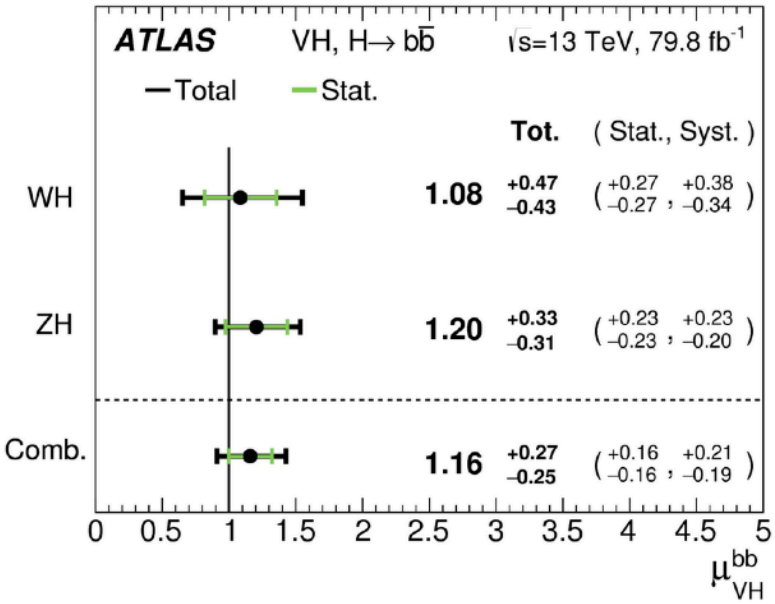


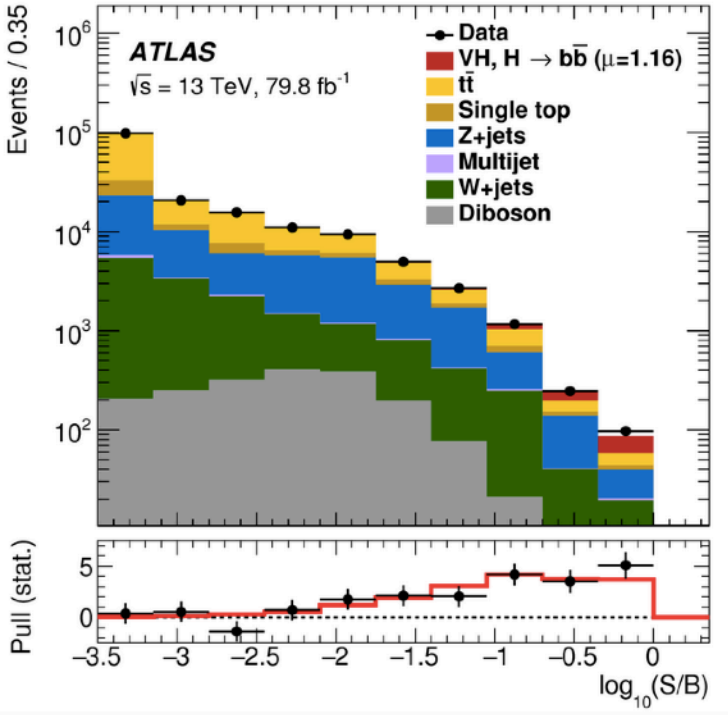
WH and ZH with H→bb results

Phys. Lett. B 786 (2018) 59

- 79 fb^{-1} of pp collisions at $\sqrt{s}$= 13 TeV
  - 4.9σ evidence observed (4.3σ expected)
  - systematic uncertainties start to dominate!!

$$\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$$





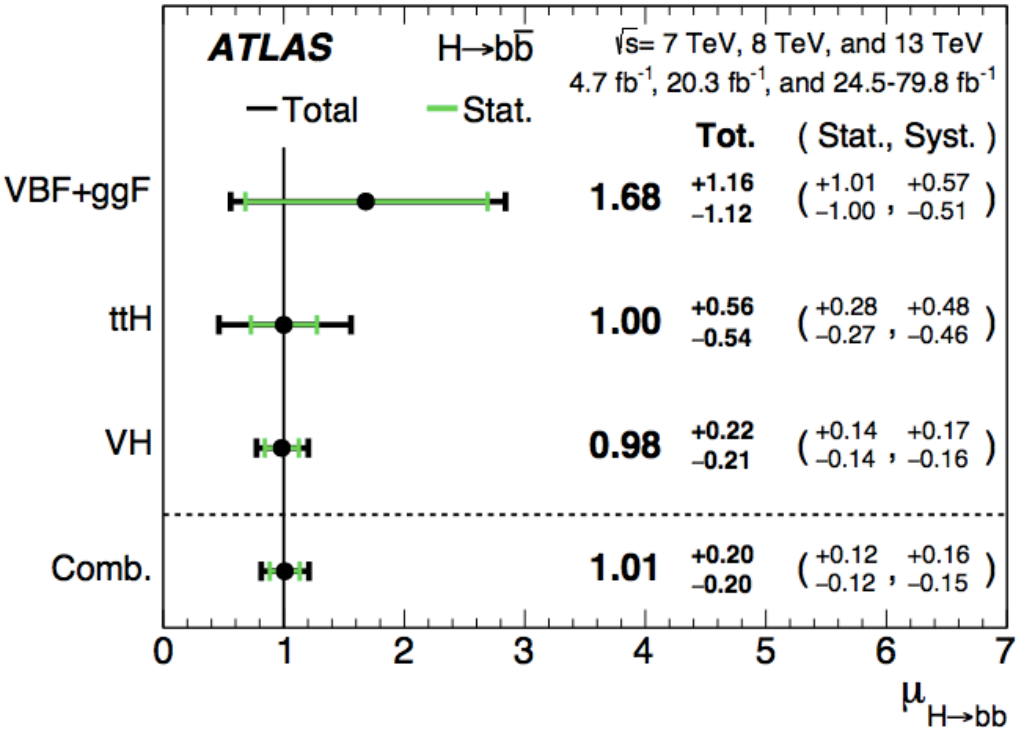
Dominant systematics from b-tagging, background normalization & modelling (W+jets, Z+jets, top)

H→bb Run 1 + Run 2 combination

Phys. Lett. B 786 (2018) 59

★ Includes ttH and vector boson fusion (with H->bb) channels

★ 5.4σ observation!! (5.5σ expected)

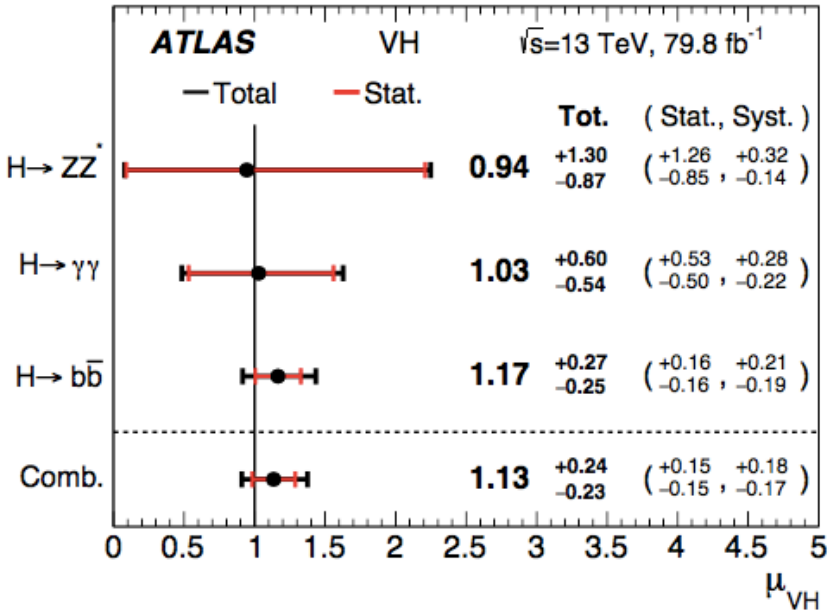


Observation of VH production

Phys. Lett. B 786 (2018) 59

- ★ Combination of H→bb with two more channels
  - ➡ Four leptons (ZZ*)
  - ➡ γγ
- ★ Direct observation of the Higgs produced in association with vector bosons!

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

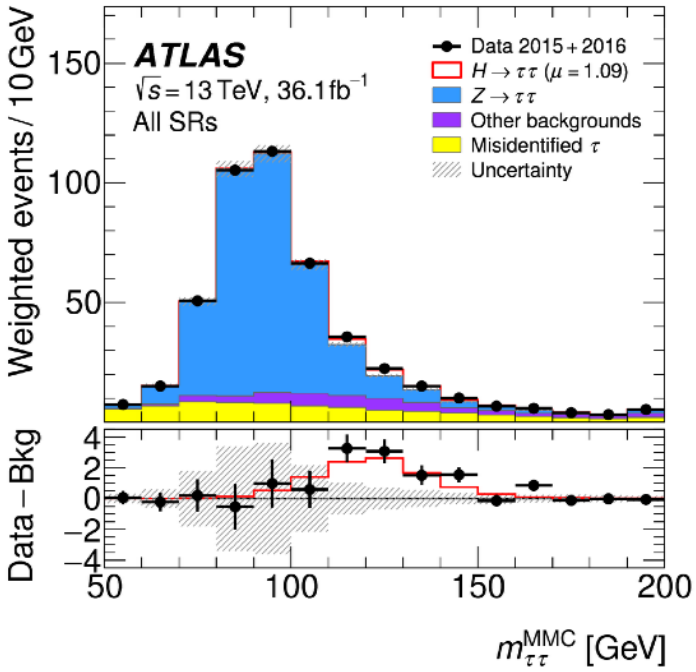


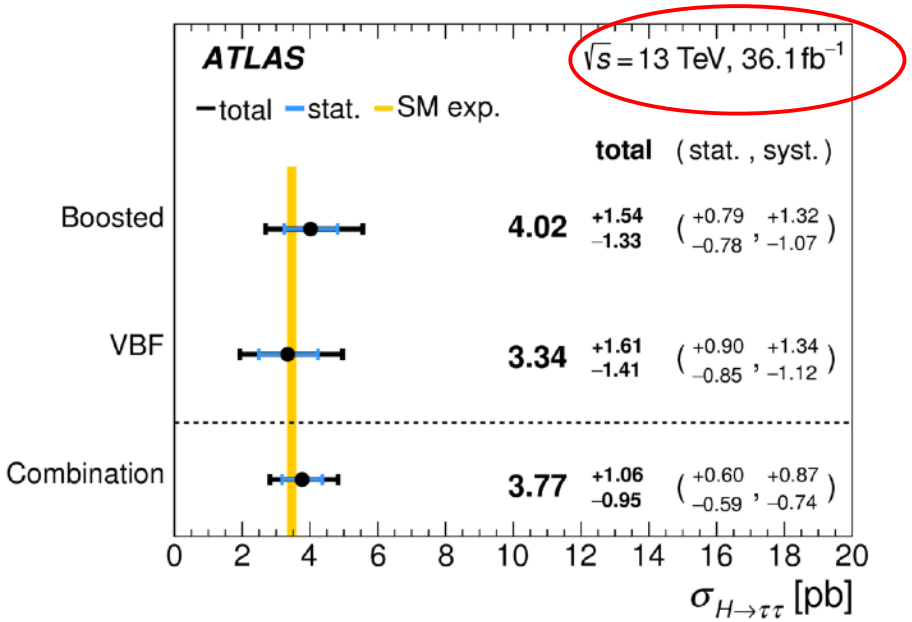
ATLAS observation of $H \to \tau\tau$

arXiv:1811.08856

★ 13 different signal regions considering

- ➡ Final state of the τ decays
- ➡ VBF optimised category
- ➡ Boosted H ($p_T^{\tau\tau}$>100 GeV) category, dominated by ggF



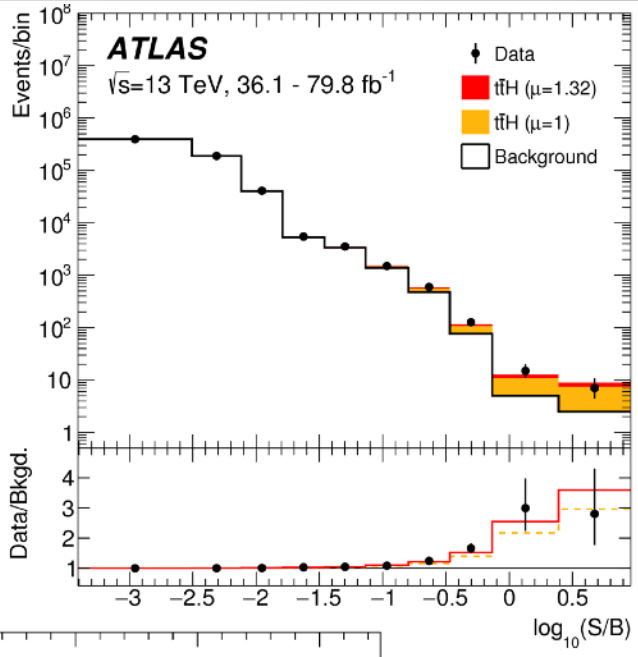


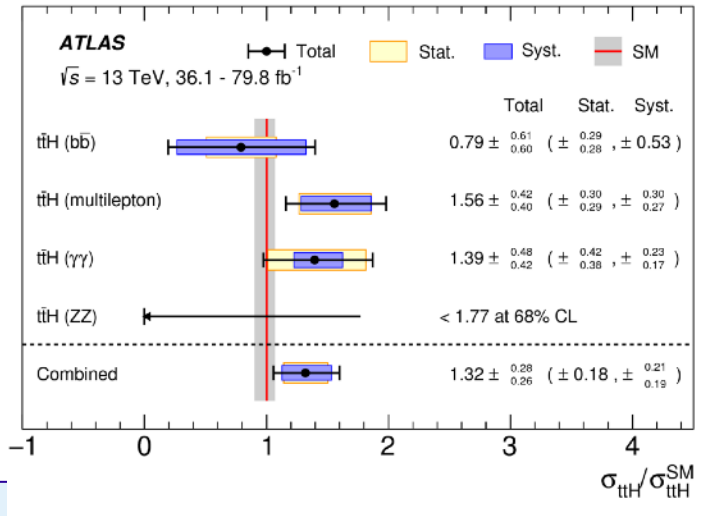
★ Run 1+Run2 combined significance: 6.4σ observed (5.4σ expected)

Observation of ttH production

Phys. Lett. B 784 (2018) 173

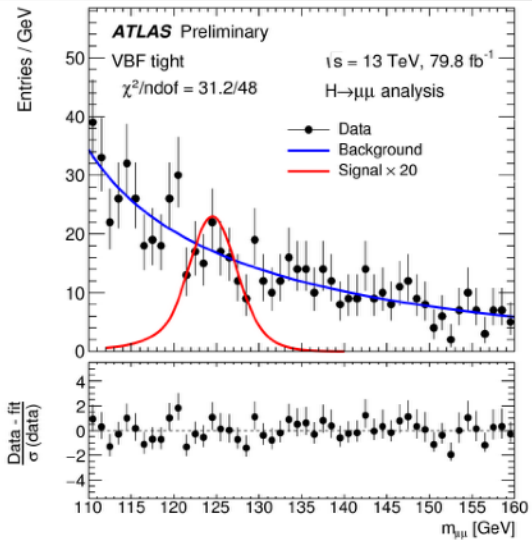
- ★ Direct probe of the top Yukawa coupling
- ★ Use all available final states:
  - ➡ H→bb, H→$\gamma\gamma$, multi-leptons (H→$\tau\tau$, H→WW*, H→ZZ*), H→ZZ* →4ℓ
- ★ Combined Run 1 & Run 2 significance:
  - ➡ Expected: 5.1σ
  - ➡ Observed: 6.5σ
- ★ Dominant systematic uncertainties
  - ➡ tt+HF background in H→bb
  - ➡ Non-prompt/fake lepton in multi-lepton channel
  - ➡ Signal modelling
  - ➡ Jet energy scale

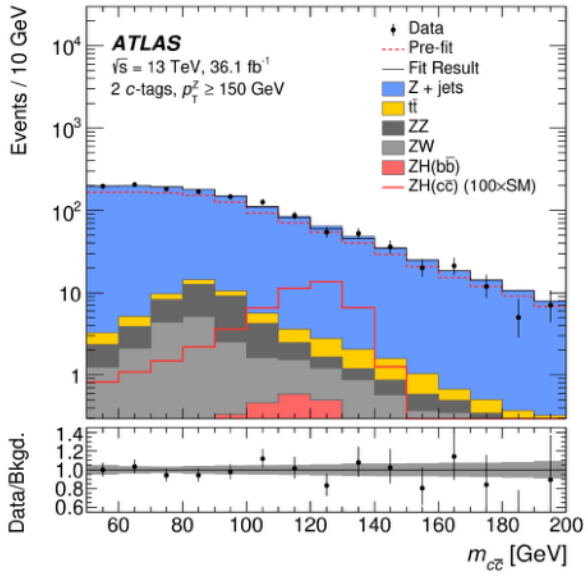




Phys. Rev. Lett. 120 (2018) 211802 ATLAS-CONF-2018-026

Second generation: H→μμ and H→cc





★ H→μμ

- ➡ Very low branching fraction but sensitivity reaching close to SM

★ H→cc:

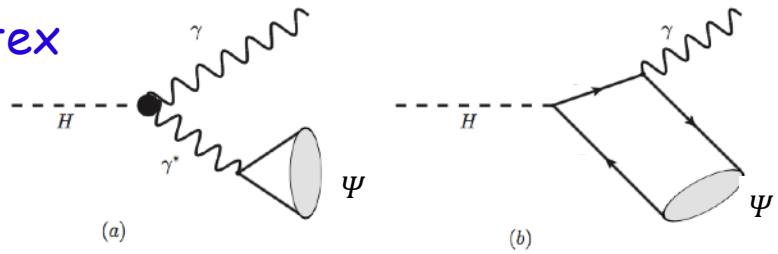
- ➡ Extremely challenging: huge backgrounds
- ➡ Similar strategy as VH with H→bb
- ➡ Expected sensitivity ~150×SM

	$\int \mathscr{L}\,dt$	95% CL upper limit	
		Expected	Observed
H→μμ	78.9 fb^{-1}	2×SM	1.5×SM
H→cc	36.1 fb^{-1}	150^{+80}_{-40}	110×SM

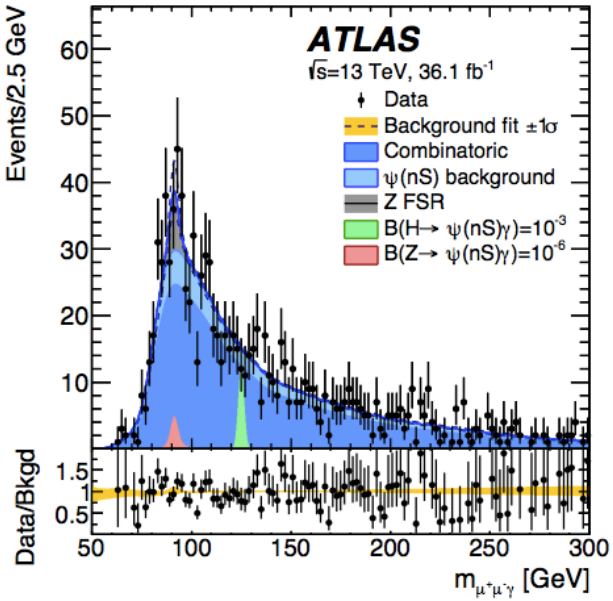
Hcc and Hbb vertices

Phys. Lett. B 786 (2018) 134

- ★ Rare decays sensitive to Hcc or Hbb vertex
  - ➡ Direct and indirect contributions
- ★ Could be enhanced due to BSM physics
- ★ No signal observed
  - ➡ Imposed limits on BR



BR ($H \to J/\Psi\gamma$) ~3×10^{-6} BR ($H \to \Upsilon\gamma$) ~10^{-9}



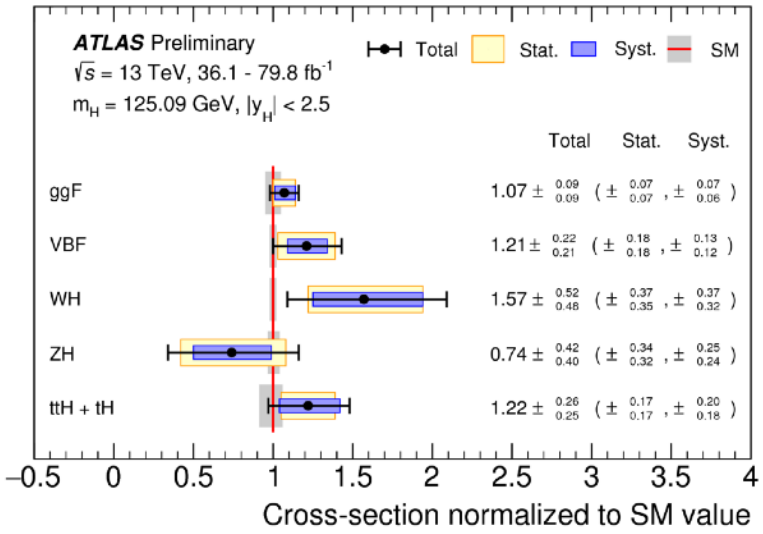
Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi(2S)\,\gamma)\,[\,10^{-4}\,]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi(2S)\,\gamma)\,[\,10^{-6}\,]$	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[\,10^{-6}\,]$	$2.8^{+1.2}_{-0.8}$	2.8
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[\,10^{-6}\,]$	$3.8^{+1.6}_{-1.1}$	1.7
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[\,10^{-6}\,]$	$3.0^{+1.3}_{-0.8}$	4.8

Combination of all decays and productions

ATLAS-CONF-2018-031

★ Inputs:

- 79.8 fb^{-1} for H→ZZ*→4ℓ, H→$\gamma\gamma$ and H→μμ
- 36.1 fb^{-1} for H→WW*→e$\nu\mu\nu$, H→$\tau\tau$, VH with H→bb and ttH

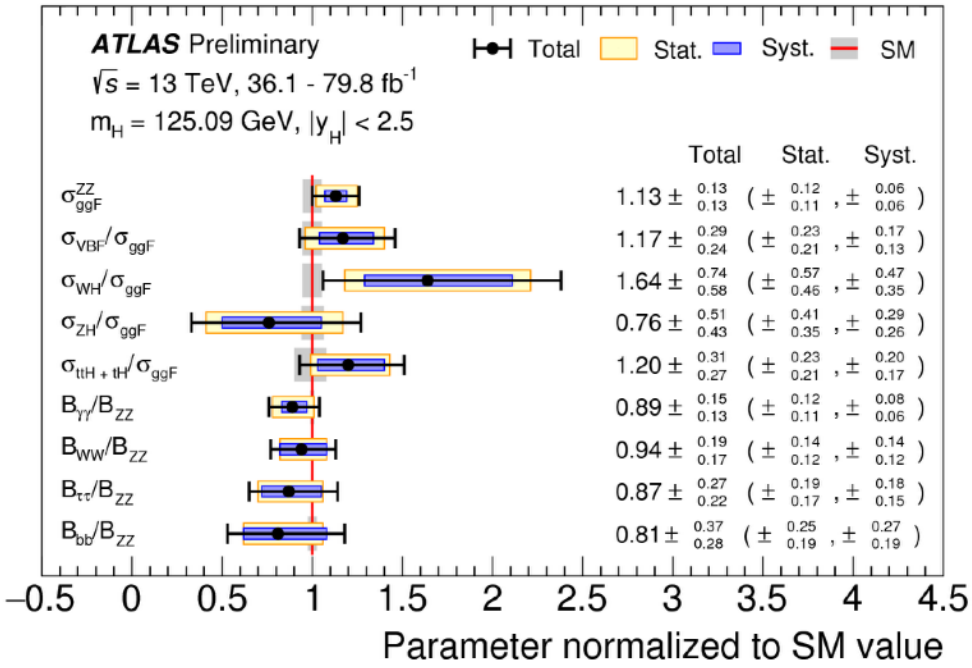


★ VBF significance:

★ 6.5σ observed (5.3σ expected)

Ratios of σ×BR with respect to ZZ channel

★ 9D compatibility with SM: 83%



Kappa framework

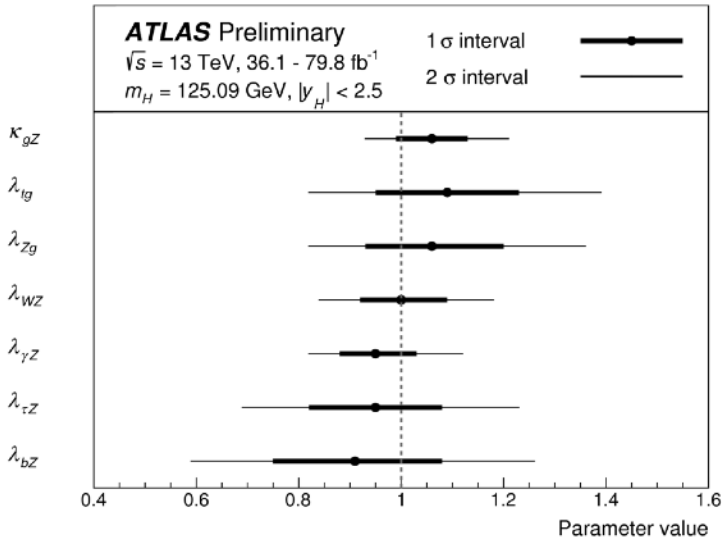
★ Assign a κ_x modifier to each tree level Higgs coupling and effective modifiers for g and γ

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

★ Assuming parameters to be positive but no assumptions on total width

➡ Unprecedented precision with respect to previous results!

Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	1.06 ± 0.07
λ_{tg}	κ_t / κ_g	$1.09^{+0.14}_{-0.14}$
λ_{Zg}	κ_Z / κ_g	$1.06^{+0.14}_{-0.13}$
λ_{WZ}	κ_W / κ_Z	$0.99^{+0.09}_{-0.08}$
$\lambda_{\gamma Z}$	κ_γ / κ_Z	$0.95^{+0.08}_{-0.07}$
$\lambda_{\tau Z}$	κ_τ / κ_Z	0.95 ± 0.13
λ_{bZ}	κ_b / κ_Z	$0.91^{+0.17}_{-0.16}$



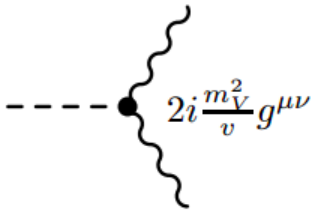
7D compatibility with SM: 86%

Higgs mass, self interactions

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

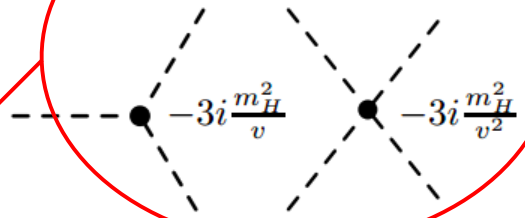
Couplings to EW gauge bosons

$$\left[m_W^2 W^{\mu+} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \tfrac{h}{v}\right)^2$$



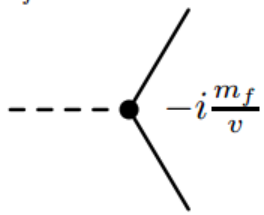
Higgs self-couplings

$$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$$



Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value})$$

★Higgs properties: mass, self interactions,

★Experimental measurements:

- Mass: H→γγ and H→ZZ→4ℓ decays
- Width
- HH production

Phys. Lett. B 784 (2018) 345

Phys. Lett. B 786 (2018) 223

Phys. Rev. Lett. 121 (2018) 191801

Eur. Phys. J. C 78 (2018) 1007

arXiv:1811.11028 JHEP 11 (2018) 040

arXiv:1811.04671 arXiv:1804.06174

ATLAS-CONF-2018-043

Phys. Lett. B 784 (2018) 345

Higgs mass from $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$

★ $H \to 4\ell$:

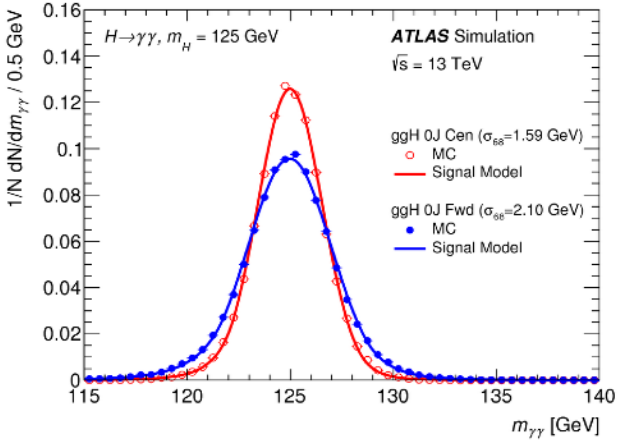
- ➡ Z mass-constrained kinematic fit
- ➡ BDT used for event classification
- ➡ Per-event detector response modelling

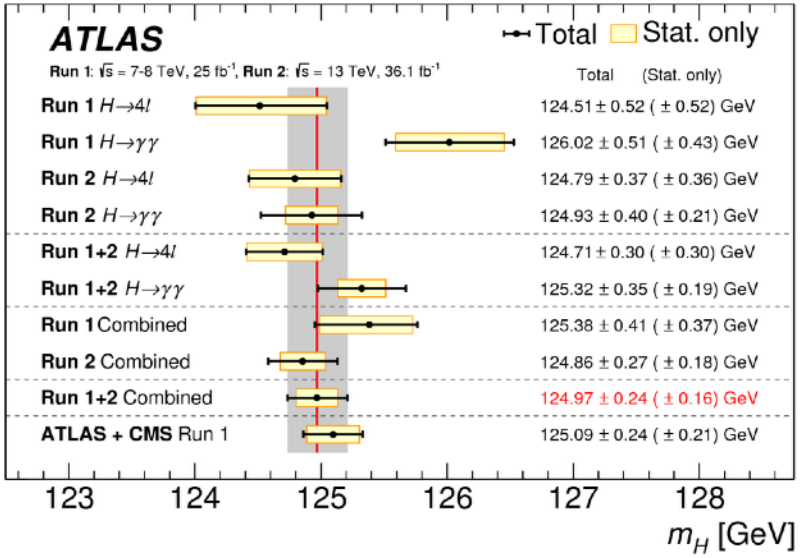
★ $H \to \gamma\gamma$:

- ➡ Double-sided Crystall-ball to model $m_{\gamma\gamma}$
- ➡ 31 event categories
  Different resolutions and S/B.
- ➡ Main systematic uncertainty:
  γ energy scale

★ With 36 fb^{-1} @13 TeV achieved same accuracy as Run 1 ATLAS+CMS combination!

$$m_H = 124.97 \pm 0.24 \text{ GeV}$$





Phys. Lett. B 786 (2018) 223

Higgs width from H→ZZ* decays

★ Indirect measurement assuming same off-shell/on-shell coupling modifiers

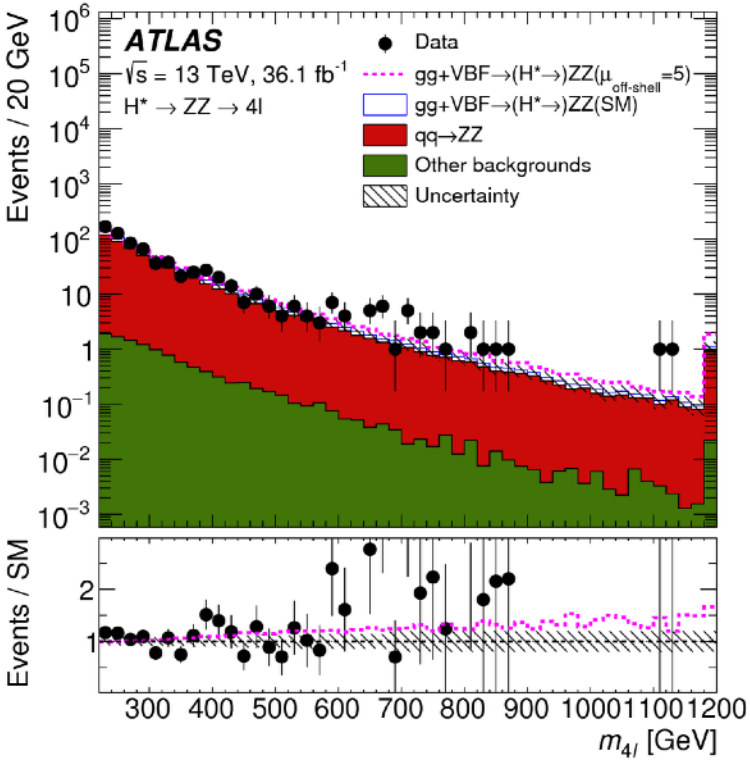
$$\mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}}$$

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

★Using 4ℓ and $2\ell 2\nu$ final states

★ 95% CL upper limit

		Observed	Expected		
			Median	$\pm 1\,\sigma$	$\pm 2\,\sigma$
$\mu_{\text{off-shell}}$	$ZZ \to 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ \to 2\ell 2\nu$ analysis	5.3	4.4	[3.4, 5.5]	[2.8, 7.0]
	Combined	3.8	3.4	[2.7, 4.2]	[2.3, 5.3]
$\Gamma_H/\Gamma_H^{\text{SM}}$	Combined	3.5	3.7	[2.9, 4.8]	[2.4, 6.5]



Limits a factor of two better than in Run 1!

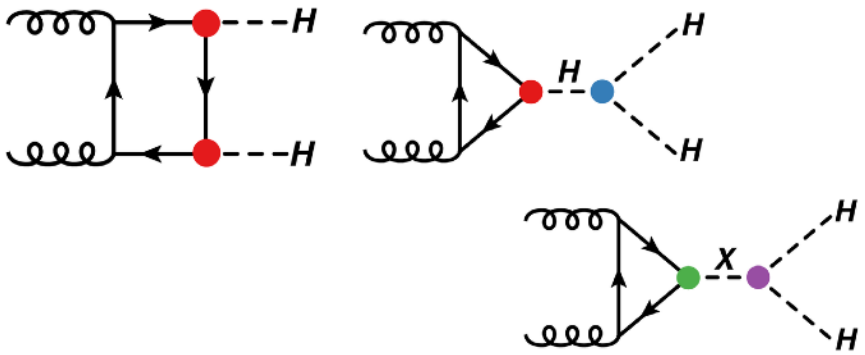
Phys. Rev. Lett. 121 (2018) 191801
arXiv:1804.06174
JHEP 11 (2018) 040

Search for di-Higgs production

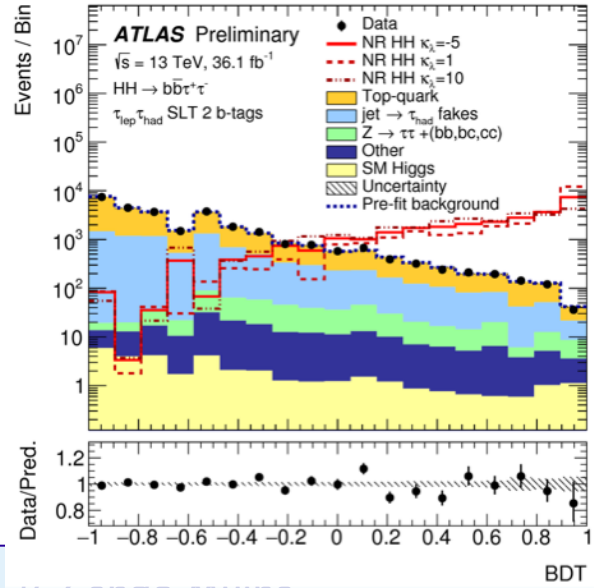
★ Sensitive to Higgs self coupling and new physics

★ Many different final states studied
- ➡ WW*WW*, bbbb, bb$\tau\tau$, bb$\gamma\gamma$, bbWW*

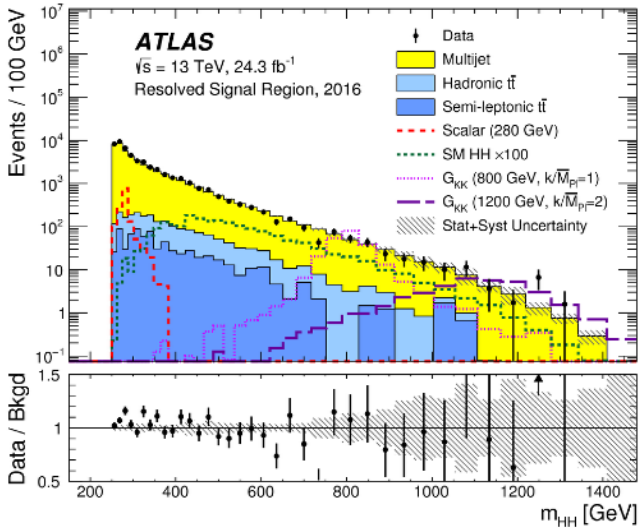
★ No signal observed yet



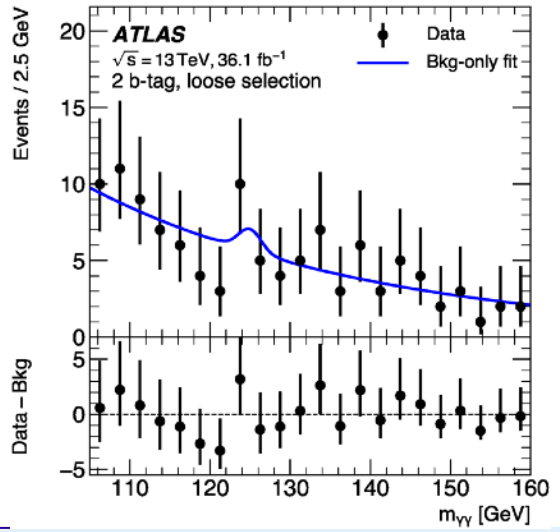
HH→bb$\tau\tau$



HH→bbbb



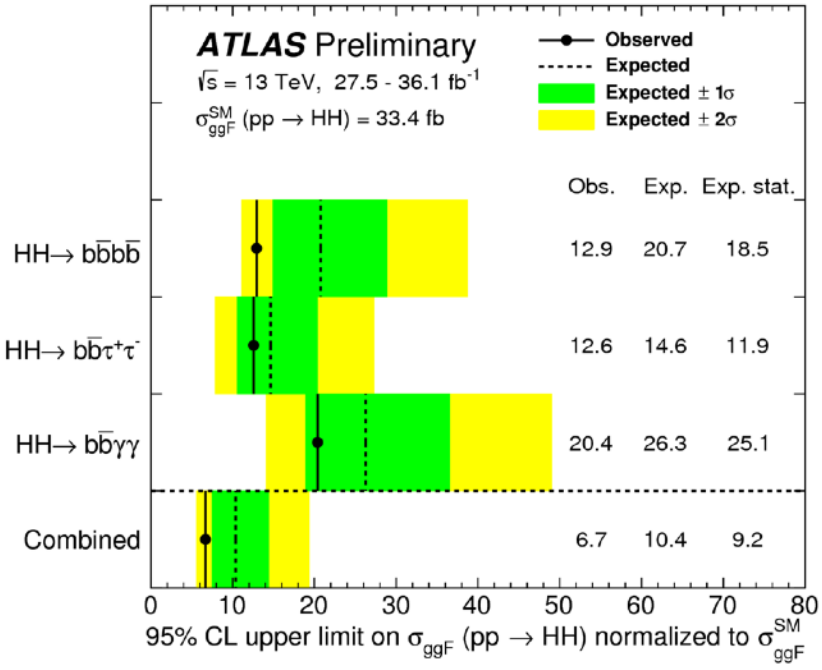
HH→bb$\gamma\gamma$

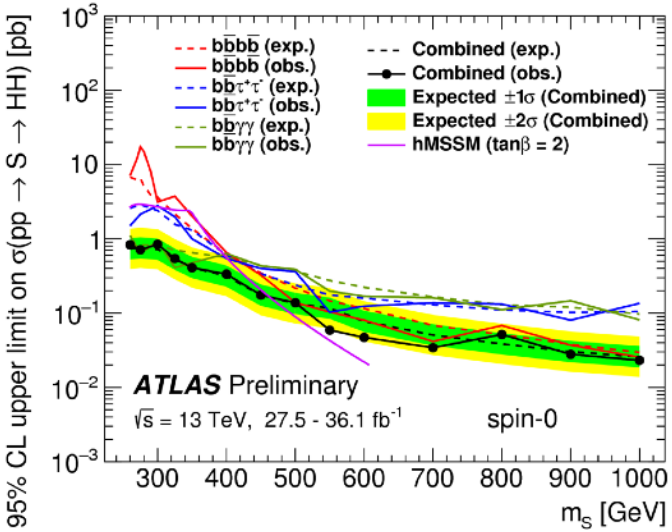


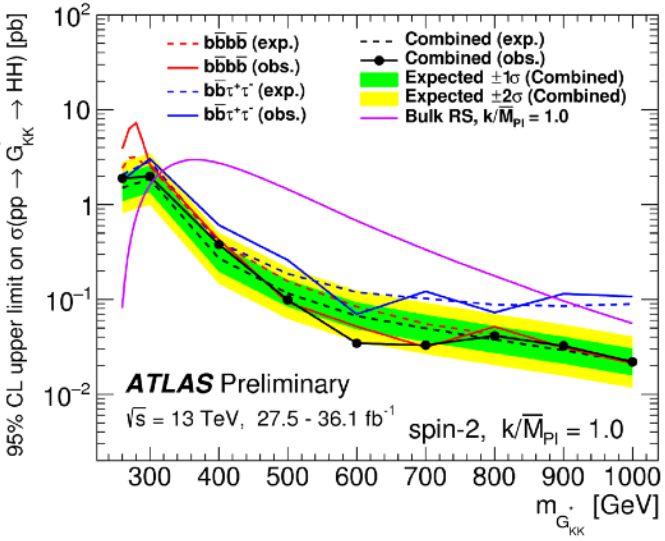
Combination of di-Higgs searches

ATLAS-CONF-2018-043

- ★ Channels included: bbbb, bb$\tau\tau$, bb$\gamma\gamma$
- ★ Integrated luminosity: 36 fb-1





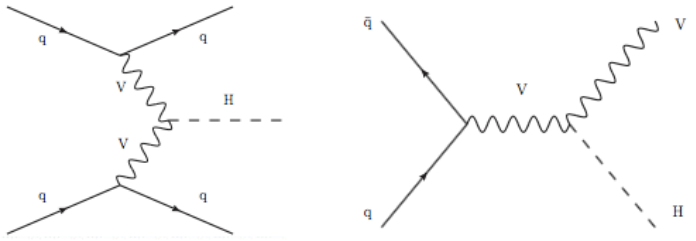


H→invisible

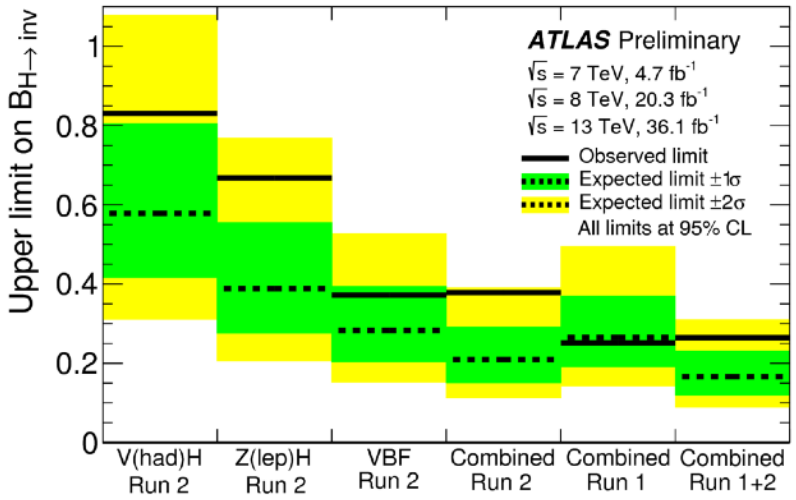
ATLAS-CONF-2018-054

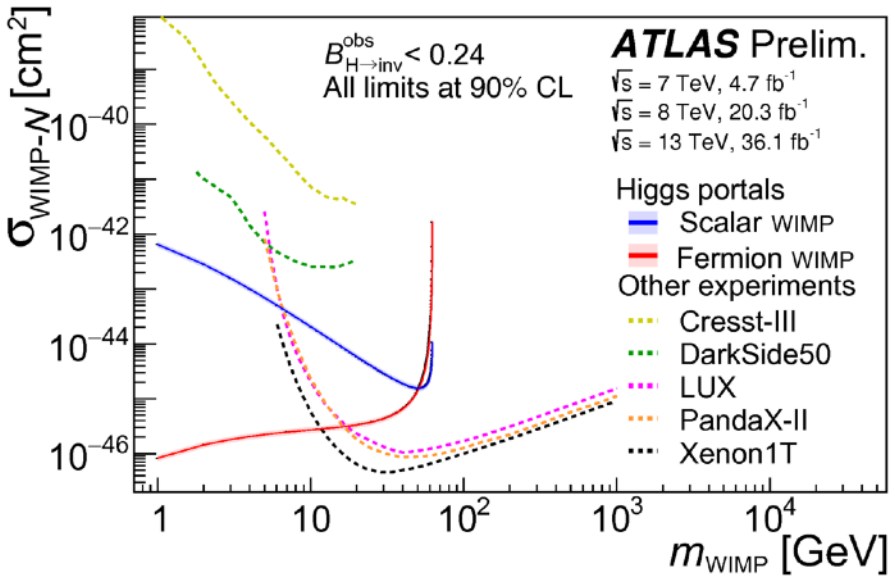
★ Search for dark matter in Higgs decays

- ➡ Signatures: E_T^{miss} plus leptons and/or jets
- ➡ Several channels used in the combination
  - VBF H(inv)
  - Z($\ell\ell$)H(inv)
  - V(had)H(inv)



★ Run 1+ Run 2 observed (expected) limit: $\mathcal{B}_{H\to\text{inv}} < 0.26\ (0.17^{+0.07}_{-0.05})$ at 95% CL





BSM Higgs bosons searches

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

JHEP 11 (2018) 085

JHEP 09 (2018) 139

Phys. Rev. D 98 (2018) 052008

JHEP 10 (2018) 031

Phys. Lett. B 787 (2018) 68

Eur. Phys. J. C 78 (2018) 293

Phys. Rev. D 98 (2018) 032015

Phys. Lett. B 783 (2018) 392

ATLAS-CONF-2018-025

arXiv:1808.10515

arXiv:1808.01899

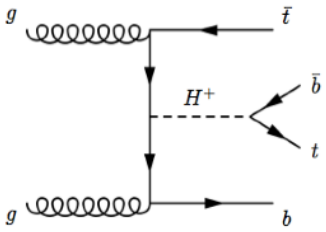
Only
few selected results
(personal choice)

JHEP 11 (2018) 085

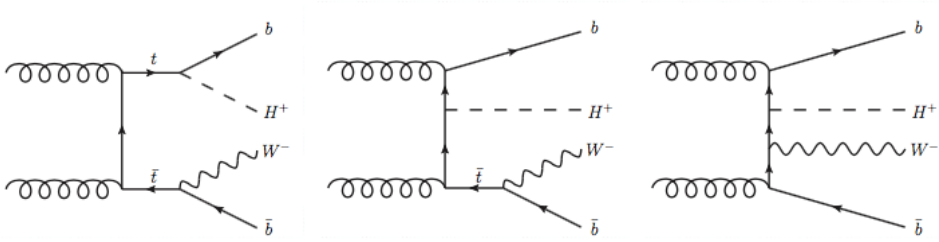
JHEP 09 (2018) 139

Charged Higgs

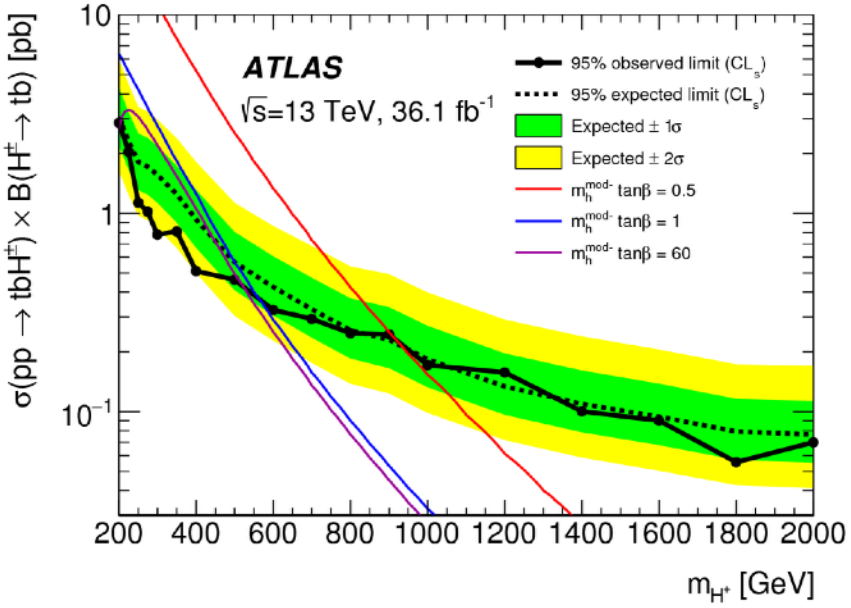
★ $H^+ \to tb$

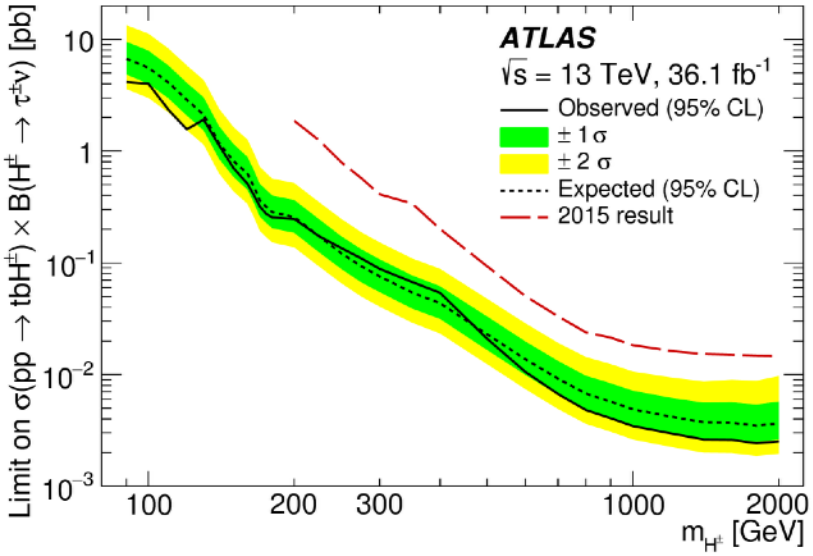


★ $H^+ \to \nu\tau$



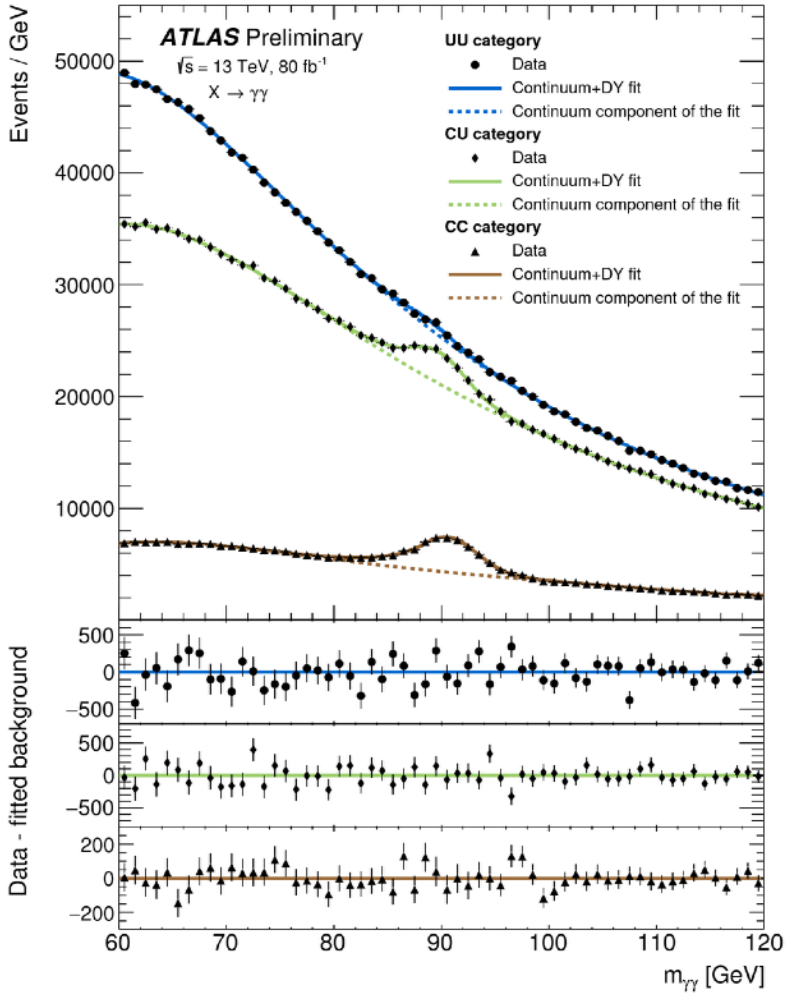
★ Combination of ℓ+jets and $\ell\ell$ final states

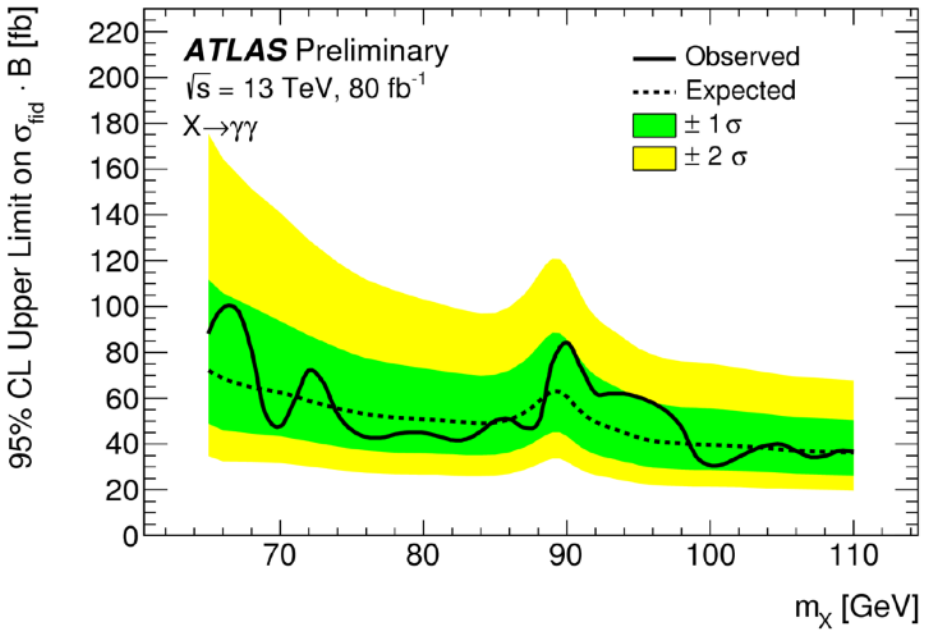




Low mass H→γγ

ATLAS-CONF-2018-025





★ No significant excess observed

Conclusions

★ The outstanding performance of the LHC and the ATLAS detector brought a large increase in the available pp collisions

★ A wealth of new results on SM Higgs boson studies

- ➡ Main decay and production modes now observed!!
  - Direct observation of the Higgs coupling to top and bottom quarks
  - Observation of VH, VBF production
- ➡ Combination of all channels for measurement of couplings
- ➡ Differential measurements with increased precision
- ➡ First simplified template cross section measurements

★ All results are compatible with SM predictions

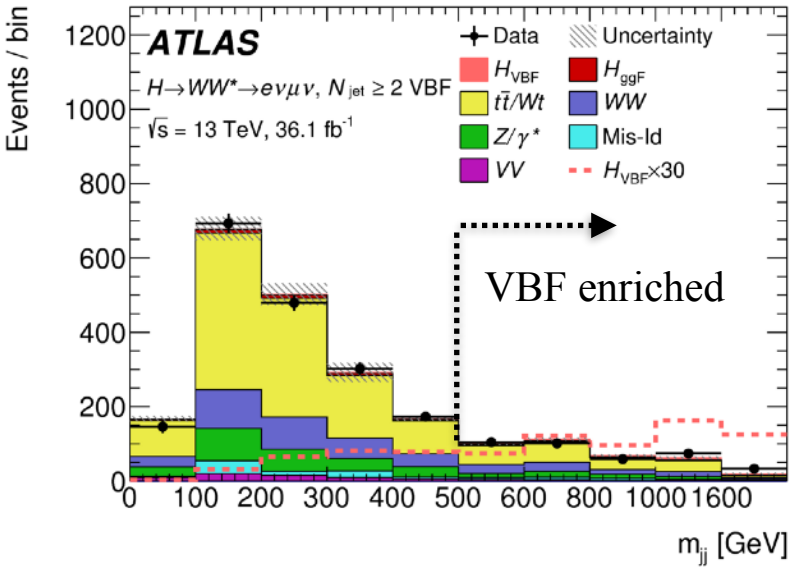
★ Searches for new physics and additional Higgs bosons continue

★ Full Run 2 statistics being analysed

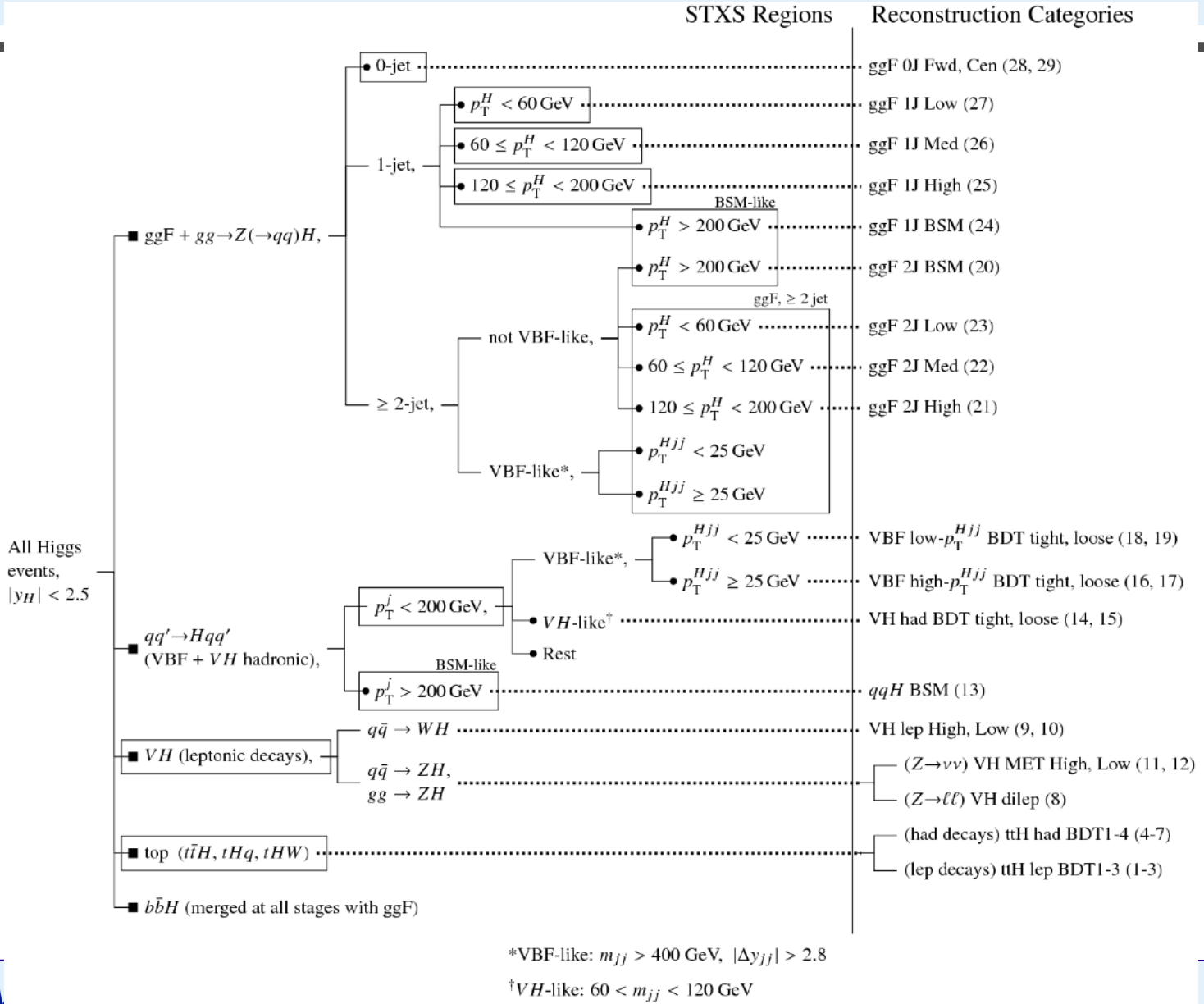
- ➡ Stay tuned!

Thank you!

Thanks to the support from CERN/FIS-PAR/0008/2017 , OE, FCT


ATLAS
$H \to WW^* \to e\nu\mu\nu$, $N_{jet} \geq 2$ VBF
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Data
Uncertainty
H_{VBF}
H_{ggF}
$t\bar{t}/Wt$
WW
Z/γ^*
Mis-Id
VV
$H_{VBF}\times30$
VBF enriched
Events / bin
m_{jj} [GeV]
0
200
400
600
800
1000
1200
100
300
500
1600

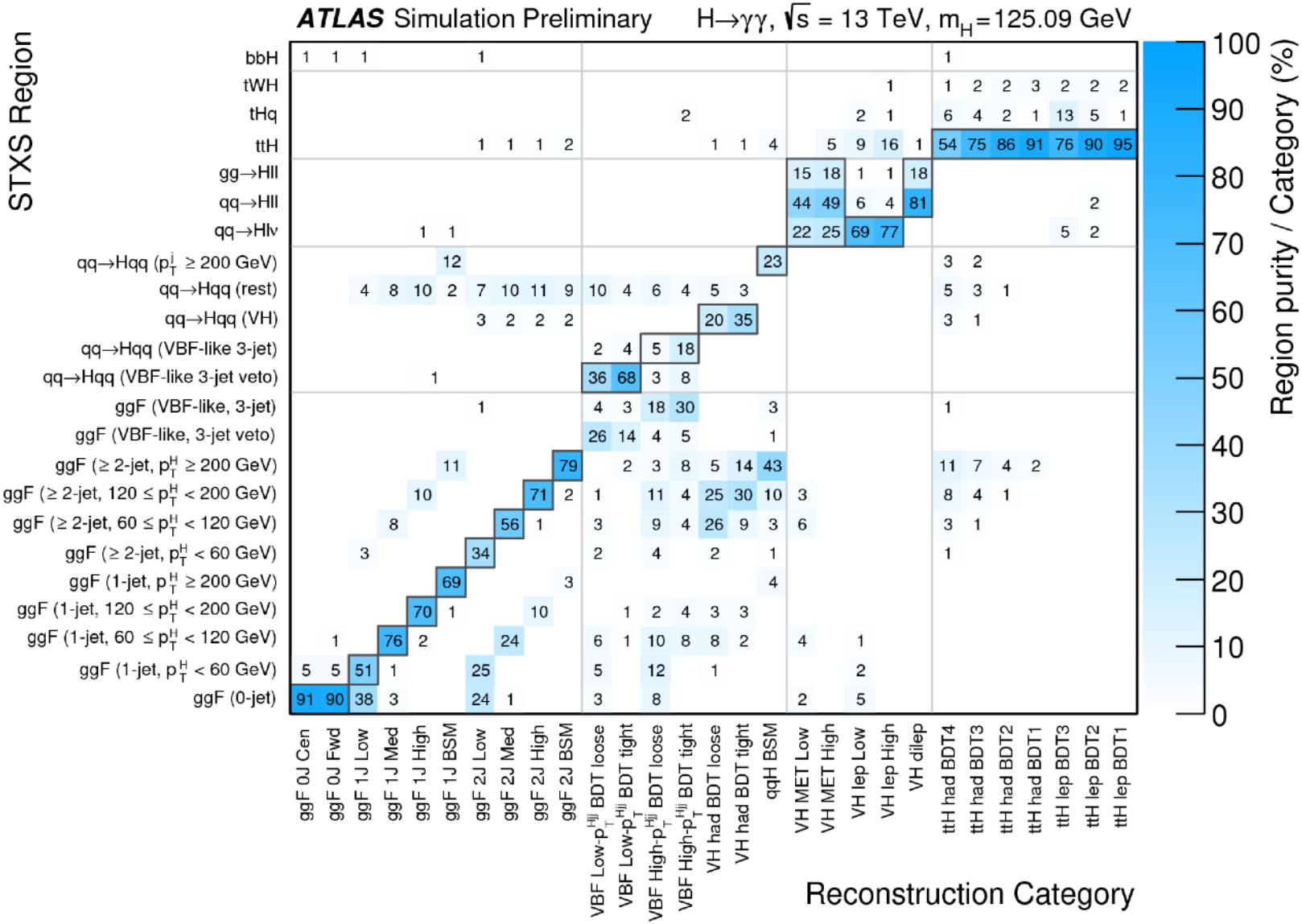
H→γγ cross section measurements



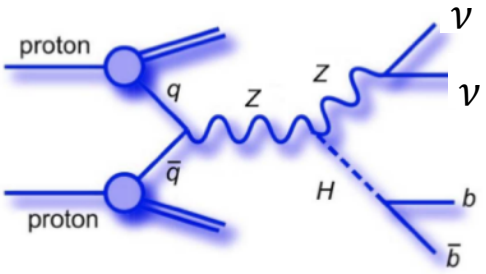
*VBF-like: $m_{jj} > 400$ GeV, $|\Delta y_{jj}| > 2.8$

†VH-like: $60 < m_{jj} < 120$ GeV

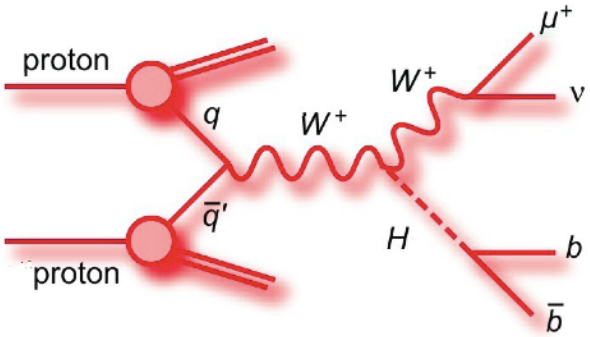
H→γγ cross section measurements



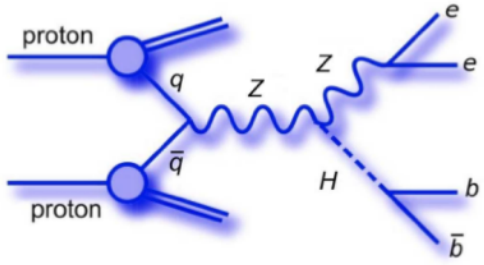
VH(bb) searches: 3 channels



- 0-lepton:
  - E_T^{miss} > 150 GeV



- 1-lepton:
  - e/μ, p_T>25 GeV
  - Tight isolation
  - Missing E_T >30 GeV (e chn)
  - p_T^V > 150 GeV

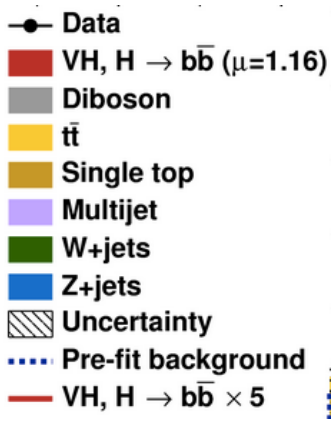


- 2-leptons:
  - Isolated ee, μμ
  - p_T^1>25 GeV, p_T^2>7 GeV
  - p_T^V > 75 GeV
  - m_{ll} compatible with m_Z

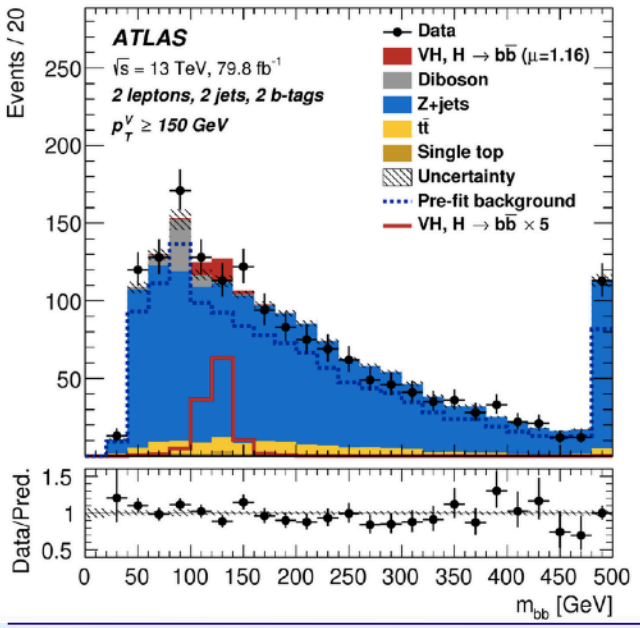
- Two jets
  - anti-kT with R=0.4
  - P_T^{j1}>45 GeV
  - ➡ p_T^{j2}>20 GeV
- B-tagging
  - Eff: 70%, light jet mistag rate: 0.3%, charm mistag rate: 8%
- Analysis categories:
  - 2/3 jets (0/1lepton)
  - 2/≥3jets (2lept.)
  - p_T^V bins

VH(bb) Main backgrounds

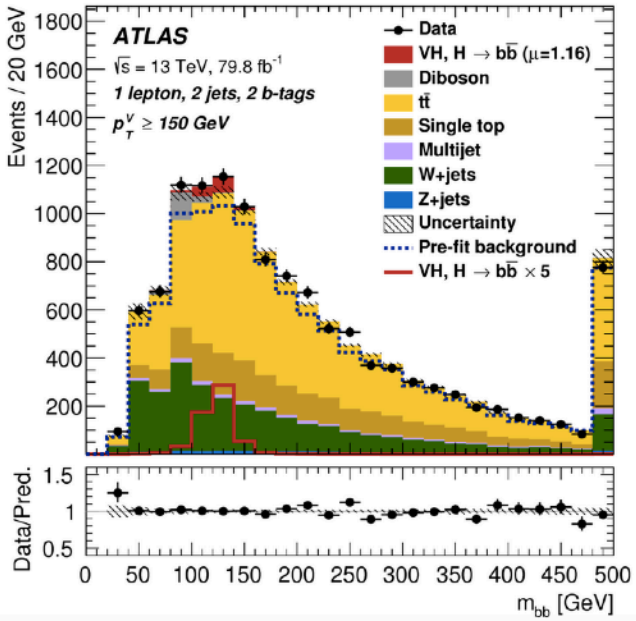
- Dominant backgrounds dependent on channel
  - Z+bjets dominates in 0, 2 lepton channels
  - Top quark and W+jets in 1 lepton channel
  - Multi-jet important in 1 lepton channel



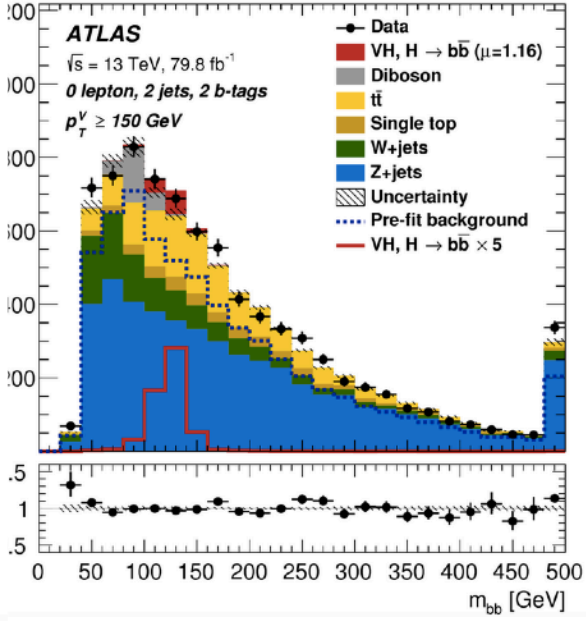
0 lepton



1 lepton



2 leptons



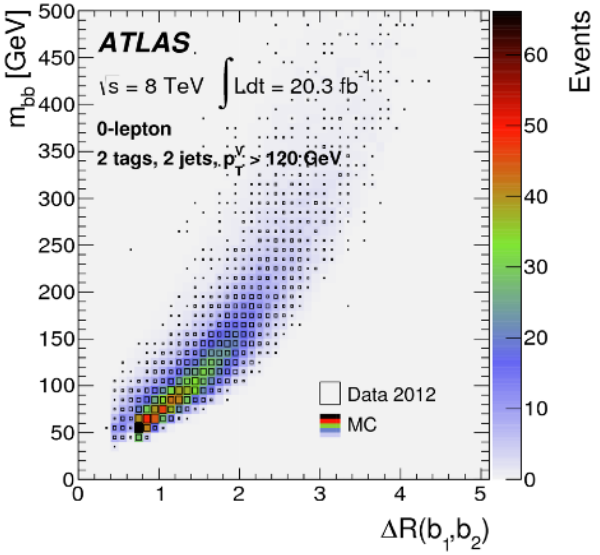
Multi-variate analysis

- Boosted decision tree (BDT)

  Combine many different variables

  Trained in 8 categories: 3 lepton, 2/3 jets, low/high p_T^V bin (2 lepton channel)

- Most discrimination from m_{bb} and $\Delta R(b_1,b_2)$

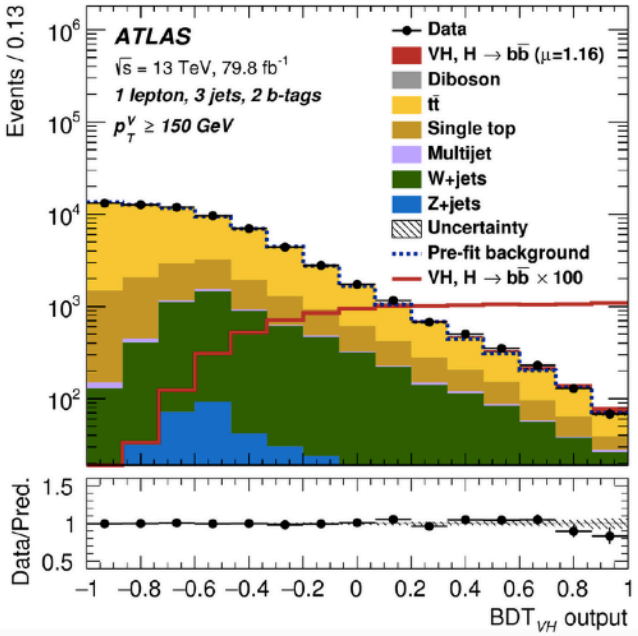


- New in run 2: m_{Top}, $|\Delta Y(V,H)|$ → +7% in sensitivity

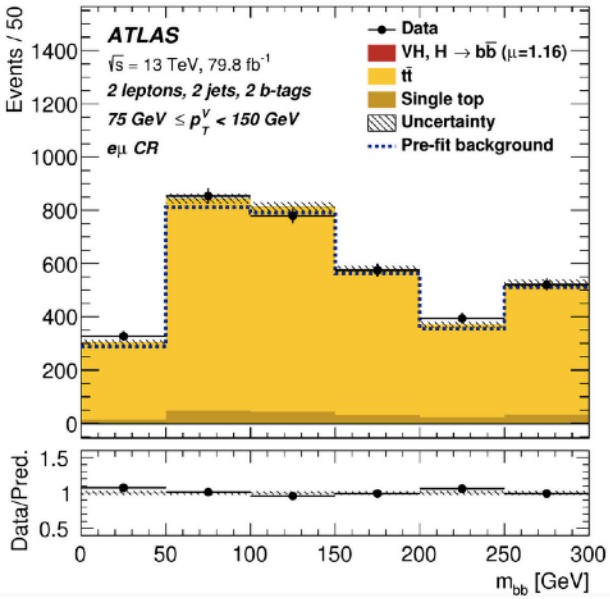
Variable	0-lepton	1-lepton	2-lepton
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	×	×
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b_1},\vec{b_2})$	×	×	×
$\lvert\Delta\eta(\vec{b_1},\vec{b_2})\rvert$	×		
$\Delta\phi(\vec{V},\vec{bb})$	×	×	×
$\lvert\Delta\eta(\vec{V},\vec{bb})\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\vec{\ell},\vec{b})]$		×	
m_{T}^{W}		×	
$m_{\ell\ell}$			×
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$			×
m_{top}		×	
$\lvert\Delta Y(\vec{V},\vec{bb})\rvert$		×	
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×

VH(bb) Combined fit

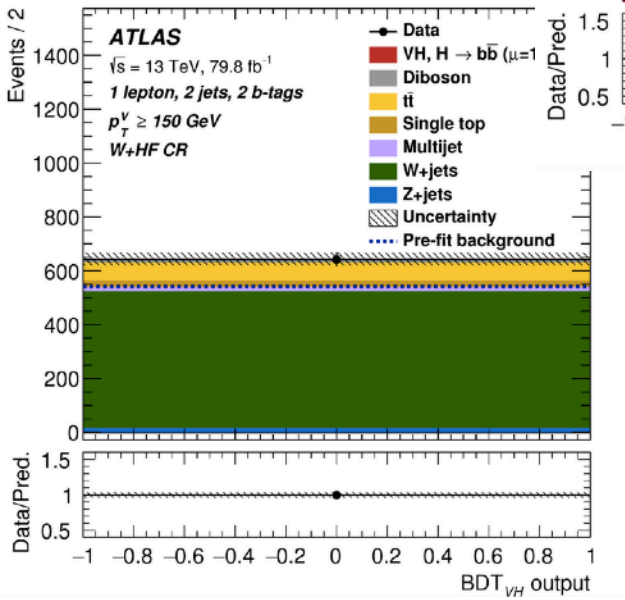
- Signal strength from profiled likelihood fit
  - Take into account all event categories
- Use BDT discriminant as input
- Control regions to constrain the backgrounds



Eμ control region



W+HF control region



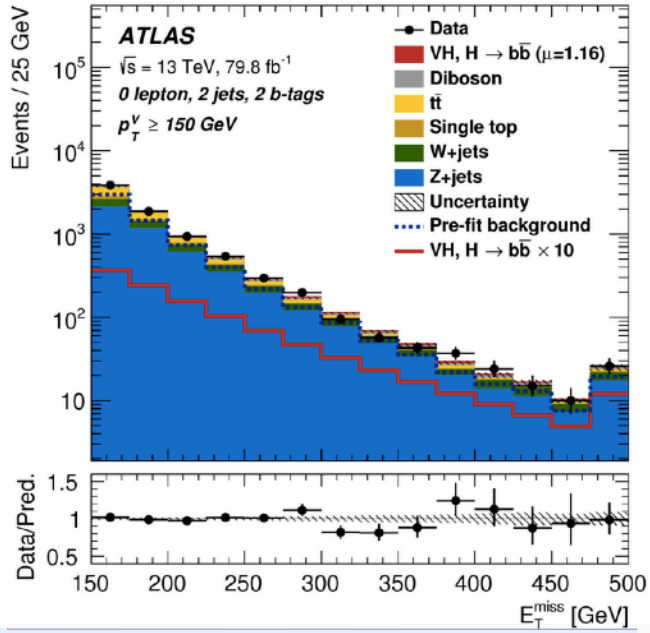
Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
W + HF 2-jet	1.19 ± 0.12
W + HF 3-jet	1.05 ± 0.12
Z + HF 2-jet	1.37 ± 0.11
Z + HF 3-jet	1.09 ± 0.09

Post-fit distributions

- Signal strength from profiled likelihood fit
  - Take into account all event categories
- Use BDT discriminant as input
- Control regions to constrain the backgrounds

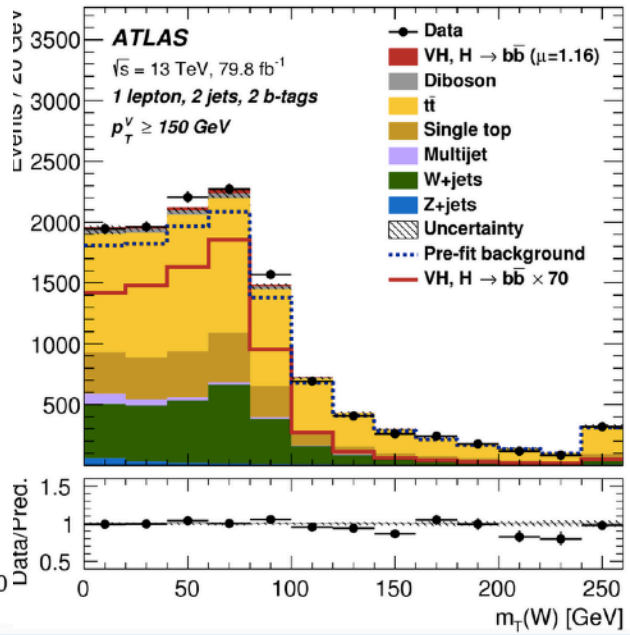
E_T^{miss}

0 lep. 2jets. 2btags



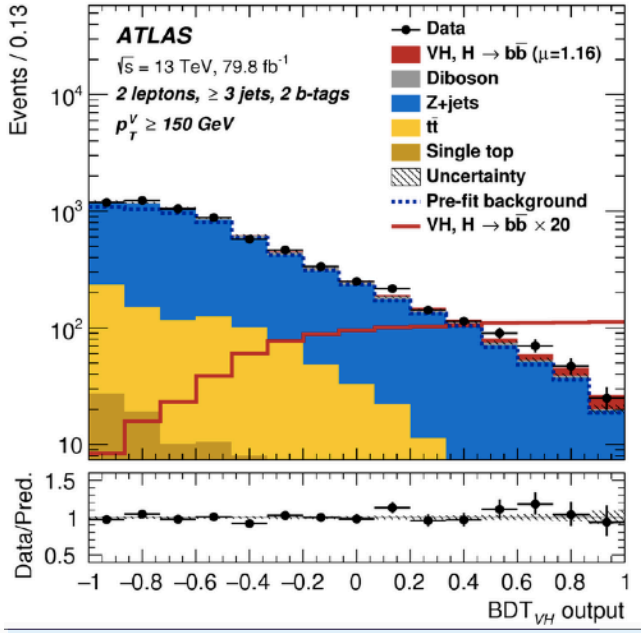
W transverse mass

1 lep., 3jets, 2 btags

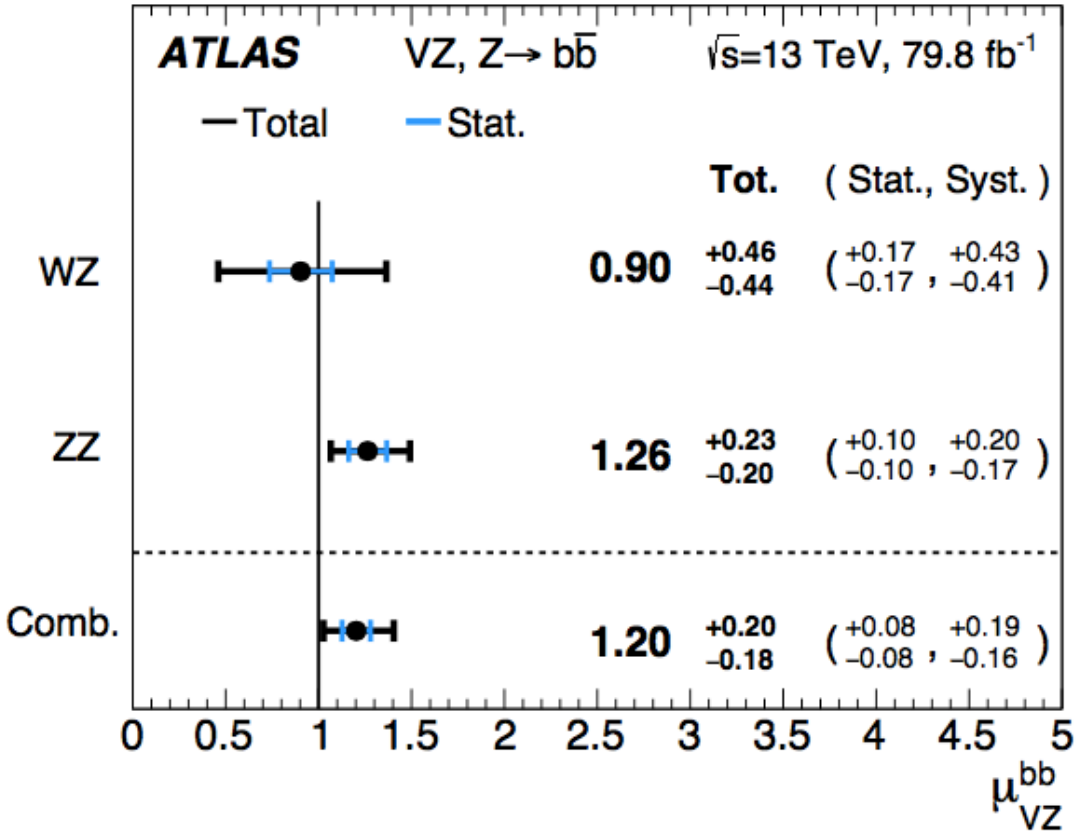


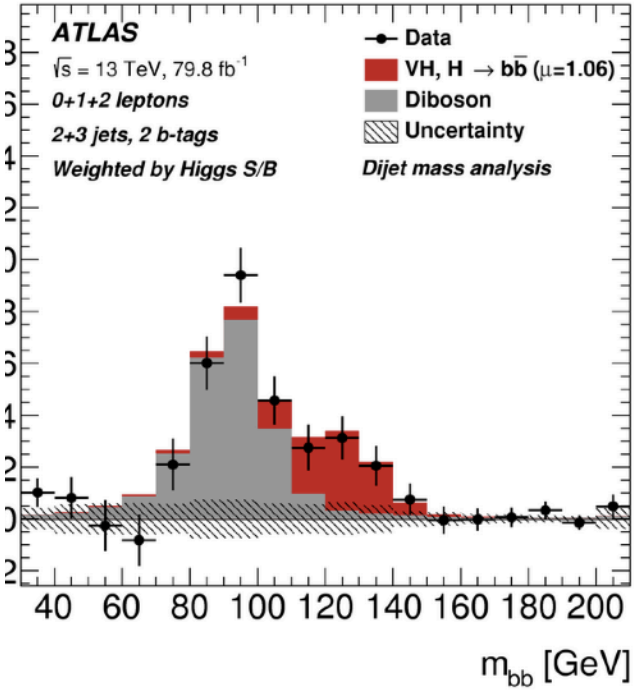
2 leptons, 2 tags, 2 jets

BDT discriminant

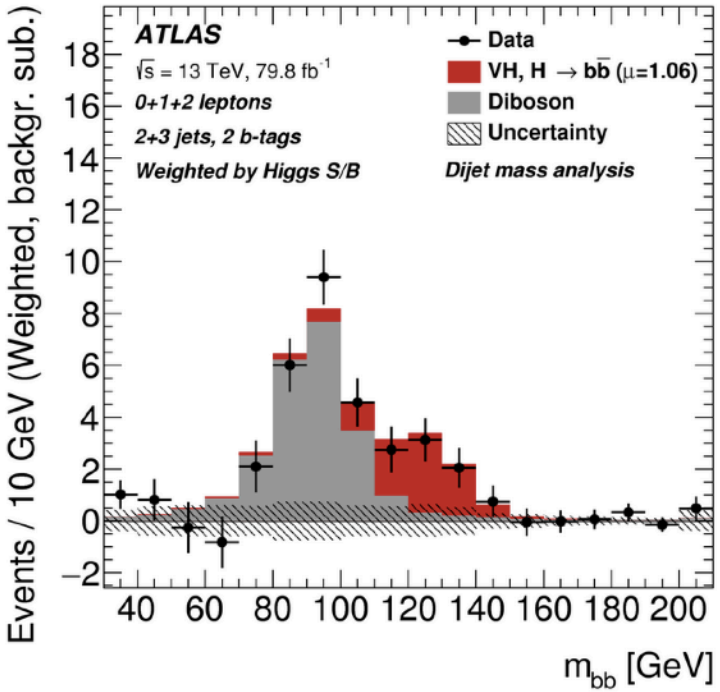


VH (Z→bb) analysis





Di-jet mass analysis



★ 3.6σ observed

★ 3.5σ expected

$$\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.})$$

Selection

Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV	1 *tight* electron $p_{\mathrm{T}} > 27$ GeV	1 *tight* muon $p_{\mathrm{T}} > 25$ GeV	2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} < 101$ GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_{T}	> 20 GeV for $\lvert\eta\rvert < 2.5$ > 30 GeV for $2.5 < \lvert\eta\rvert < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 GeV (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{b}\vec{b})$	$> 120^\circ$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^\circ$	–		–
p_{T}^V regions	> 150 GeV			75 GeV $< p_{\mathrm{T}}^V < 150$ GeV, > 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

Simulation samples

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH$ $\to \ell\nu b\bar{b}$	POWHEG-BOX v2 [76] + GOSAM [79] + MINLO [80,81]	NNPDF3.0NLO$^{(*)}$ [77]	PYTHIA 8.212 [68]	AZNLO [78]	NNLO(QCD)+ NLO(EW) [82–88]
$qq \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-BOX v2 + GOSAM + MINLO	NNPDF3.0NLO$^{(*)}$	PYTHIA 8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-BOX v2	NNPDF3.0NLO$^{(*)}$	PYTHIA 8.212	AZNLO	NLO+ NLL [89–93]
Top quark, mass set to 172.5 GeV					
$t\bar{t}$	POWHEG-BOX v2 [94]	NNPDF3.0NLO	PYTHIA 8.230	A14 [95]	NNLO+NNLL [96]
s-channel	POWHEG-BOX v2 [97]	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO [98]
t-channel	POWHEG-BOX v2 [97]	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO [99]
Wt	POWHEG-BOX v2 [100]	NNPDF3.0NLO	PYTHIA 8.230	A14	Approximate NNLO [101]
Vector boson + jets					
$W \to \ell\nu$	SHERPA 2.2.1 [71, 102, 103]	NNPDF3.0NNLO	SHERPA 2.2.1 [104, 105]	Default	NNLO [106]
$Z/\gamma^* \to \ell\ell$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
$Z \to \nu\nu$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
Diboson					
$qq \to WW$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$qq \to WZ$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$qq \to ZZ$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$gg \to VV$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	Default	NLO

Uncertainties in the signal strength

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
$E_{\mathrm{T}}^{\mathrm{miss}}$		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